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MICROWAVE LANDING SYSTEM (MLS) DEVELOPMENT PLAN AS PROPOSED BY HAZELTINE CORPORATION DURING THE TECHNIQUE ANALYSIS AND CONTRACT DEFINITION PHASE OF THE NATIONAL MLS DEVELOPMENT PROGRAM. VOLUME II. MULTIPATH, SHADOWING AND TERRAIN

Hazeltine Corporation

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16. Abstract

This report details technical aspects of the Hazeltine Corporation proposed MLS hardware development.

Volume I discusses System Concept and Integration, Geometry Effects, Guidance Signal Generation and Guidance Receiver-Decoder.

Volume II covers Multipath, Shadowing and Terrain; Propagation and Polarization; DME Verification, Identification and Resolution of Remaining Technical Problems, System Trades; System Compatibility; System Performance Summary; and Signal Format Summary.

Volume III includes Report on MLS Data Formal Analog Computer Studies, and Preliminary Receiver/Processor Output Recommendations.

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1.1.1.1.E - MULTIPATH, SHADOWING AND TERRAIN.

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FIGURES

1.1.1.1.E - MULTIPATH, SHADOWING AND TERRAIN

1. Introduction, Summary and Conclusions.

The signal reflections (multipath) and signal shadowing by obstacles on the airport may cause serious problems for a microwave landing system (MLS). These problems have been addressed, based on a detailed review of airport layouts, and the methods for their resolution in the Doppler MLS are presented in this Chapter. These studies are summarized below and detailed discussion follows. The effects of ground reflection and of propagation in the atmosphere are included in Chapters 1.1.1.1.C and 1.1.1.1.F respectively.

The Hazeltine baseline system adds to the basic Doppler MLS some features for greatly reducing the multipath problem with simplicity in transmitter and receiver. This study has contributed the understanding and analytical tools which enable an adequate analysis of the problem and evaluation of multipath errors before and after reduction by the various features considered. In particular, the residual errors on a centerline approach are reliably reduced to be well within tolerances in azimuth (AZ) angle and negligible in elevation (EL-1 and EL-2) angle.

This chapter is directed to the most demanding application of MLS, the K configuration on a long runway.

The Airport Runway Environment. Figure 6-1 shows the airport runway environment. Two regions on the airport can be described which have special significance for a landing system.

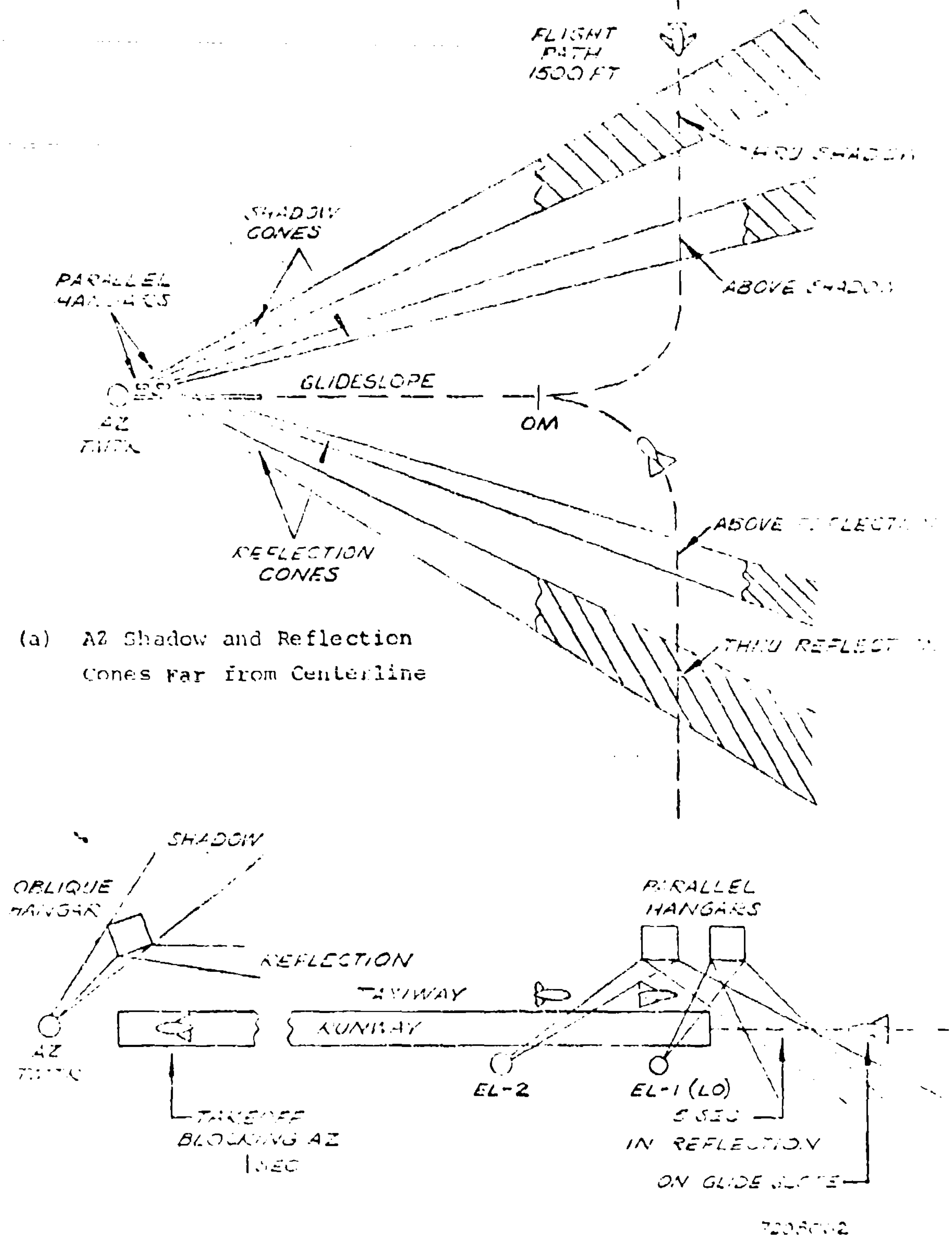
The first, shown in Figure 6-1(a), is the area away from the runway centerline, where a large hangar or other building may cause a cone of deep shadow and a cone of strong reflection. These cones may or may not be high enough to include the flight path. The deep shadow is a problem inherent in any microwave system using a low (AZ) antenna for wide-angle coverage (far from centerline); this problem will receive little attention in this chapter, other than identifying its cone of influence.

The second, shown in Figure 6-1(b), is the area near the runway centerline, which is free of any large fixed obstacle capable of causing a deep shadow or a strong reflection. Here the primary concern is any other aircraft intervening between the AZ transmitter, and the approaching aircraft (receiver). Such an aircraft may cause a momentary (1 sec) partial blocking on takeoff over the transmitter, or more persistent partial blocking while on the runway. Neither case is a deep shadow.

Not shown is the reflection from the tail fin of a large aircraft on the taxiway parallel to the runway. This is a matter of concern if located near the threshold. Its reflection is greatly reduced by the convex curvature of its face. If the same were located near the other end of the runway, the partial blocking or reflection of the AZ signal is of little concern.

The metal doors of a large hangar comprise the most effective reflector. The reflection is reduced somewhat if the doors are corrugated, which is typical of the largest hangars of recent construction.

The Doppler MLS offers a special feature, the instant comparison of direct and indirect signals in a multipath situation. The receiver is able to select the stronger (direct) signal if their



(a) AZ Shadow and Reflection Cones Far from Centerline

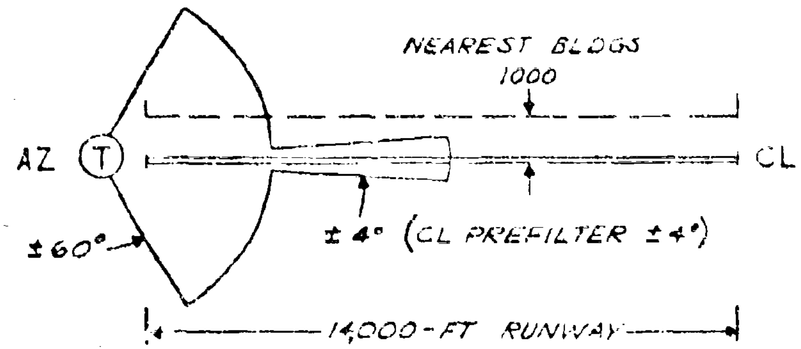
Figure 6-1. Airport Runway Environment

amplitude difference exceeds the noise level, which is very low in a critical region. The selection is based on "capture" in a limiter, as will be reviewed, and does not rely on any amplitude measurement or memory. This benefit results from simultaneous radiation of frequency coding over the entire angle range in a coverage sector. Incidental to this format, any reflected (indirect) signal (multipath) is received with the direct signal, but usually on a different frequency corresponding to a different angle of radiation.

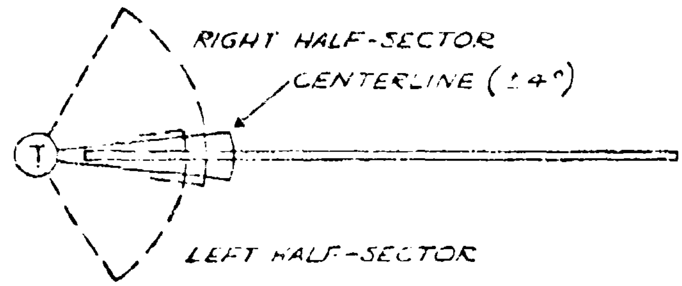
The Hazeltine approach is to reduce the multipath problem by space-pattern and frequency-band prefiltering ahead of the limiter. A thoughtful analysis of the environment problem has led to a simple plan for such prefiltering, one based on antenna design and a few fixed filters from which a selection is made by simple and reliable logic. Each is tailored to the principal problem of the environment for each function (AZ et al), so that the most protection (all that appears to be needed) is obtained with moderate complication and cost. The prefiltering concept gives added assurance of direct-signal capture, and also gives preference to direct-signal angle coding. The proposed patterns are shown in Figure 6-2.

Antenna-pattern shaping - AZ carrier. Figure 6-2(a) shows pattern shaping for AZ carrier emphasis near centerline. This gives extra assurance of the carrier integrity for centerline approach. However, it does not add to reflections in other directions, because there are no strong reflections from near centerline. (This might be applicable also to angle-coding sideband radiation in some type of antenna, but not in general, so it is not proposed.)

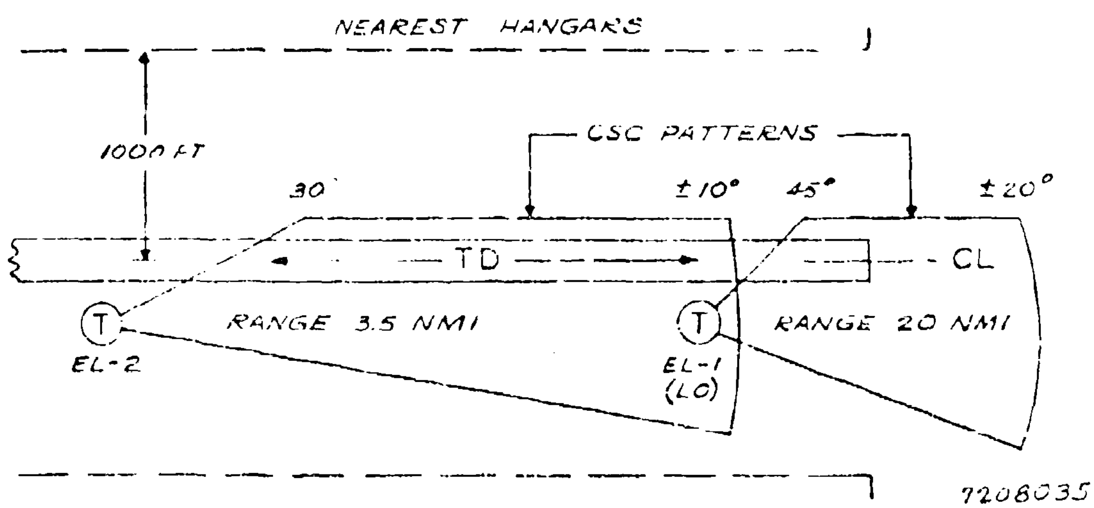
Fixed-frequency band prefilters - AZ angle coding. Figure 6-2(b) shows, in space-angle coordinates, the three fixed filters proposed for prefiltering of the angle-coding frequencies in the receiver. On a flight-path entering the MLS area far from centerline, the right or left half-sector filter is immediately



(a) AZ Carrier Radiation Pattern with Emphasis near Centerline



(b) AZ Sideband Frequency Prefilters (Fixed)



(c) EL Carrier and Sideband Fan Radiation Patterns with Emphasis near Centerline

Figure 6-2. Antenna Patterns and Frequency Prefilters for Reduction of Multipath Reflection Effects switched into circuit. On entering the narrow sector at centerline, the narrowband centerline filter is switched into circuit. The latter gives greatest protection of the direct signal during the centerline approach.

The half-sector prefilter is a feature based on a peculiarity of the environment. A reflection from a hangar on one side of the centerline will more probably radiate toward the opposite side. This is a certainty if the hangar is parallel. Otherwise the probability is about 2/3 and also a reflection cone on the opposite side is much wider and somewhat higher.

Antenna-pattern shaping - EL. Figure 6-2(c) shows pattern shaping for EL radiation emphasis near centerline, while covering the runway near enough to each transmitter. This applies to both carrier and angle-coding sidebands. In each case there is a major reduction of radiation toward a hangar on either side. Also, in a lesser degree, toward an aircraft on a taxiway. This feature is particularly helpful as applied to an EL fan beam, because there may be little or no coding difference between direct and indirect signals. This is a case of "in-beam" or "near-beam" multipath, where signal separation by angle coding may be difficult or impossible.

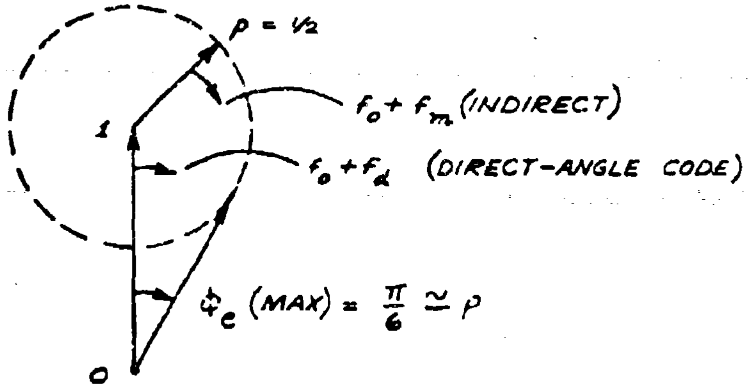
Frequency postfiltering in the time domain. There are three forms of time-domain filtering that could be used after the limiter. One is multiscan motion averaging, which will be reviewed further. Another is the self-tracking digital narrowband postfilter. This is helpful for further reduction of errors from different angle coding, but that may not be needed and is not included in the baseline system. The third is the pairing of samples, which may be useful for smoothing the angle data.

Multiscan motion averaging. This is inherent in the Doppler multiscan signal format. The receiver aircraft motion tends to reduce the residual error by averaging over several scans. The amount of reduction is greatest where it is needed most, in the late glide-slope and the flareout. It is particularly helpful in the EL case of in-beam multipath, where the indirect signal cannot be rejected on the basis of different angle coding.

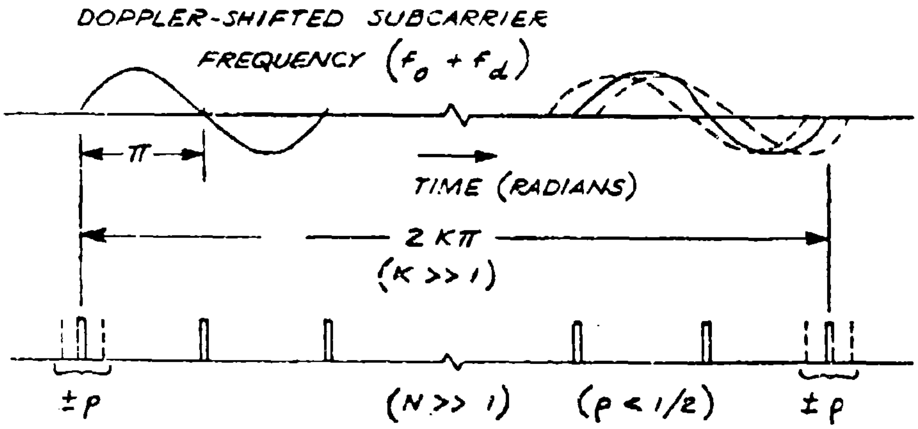
The cause of a multipath error in angle decoding. Figure 6-3 is a review of the simplest process for decoding the angle in the receiver. In each scan, the angle tone is put through a limiter and zero-crossing detector. The number of cycles (or half-cycles) in each scan is counted and timed. Over one multiscan, the counts and times are added for computing the average frequency. This figure shows how a weaker indirect signal, of amplitude ρ times the direct, may cause a phase shift, and thereby a shift in the timing of zero-crossings. This may cause a timing error as much as $\rho/2\pi$ cycles at either end of the scan, or a total of ρ/π cycles. This places an upperbound of ρ/π beamwidth on the multipath error in decoding. Among the various features for error reduction, some operate by reducing ρ before the limiter, and others operate by reducing its effect in the decoding process.

The multipath error formula, developed during this study and discussed in Part 11, is a major contribution toward the understanding and the evaluating of such errors. It is based on a single direct signal and a single weaker indirect signal. It includes various phenomena in separable form, notably the multiscan motion averaging.

The residual errors. The features of Figure 6-2, together with the features inherent in Doppler multiscan, are found to leave any residual errors well within tolerances or even negligible. This conclusion is based on 5 examples chosen to represent situations most likely to cause errors, however improbable of occurrence. The time profile of residual errors is discussed and an interesting example is shown in Figure 6-4. This is regarded as an extreme (but not unlikely) situation, and the error is well within tolerances.

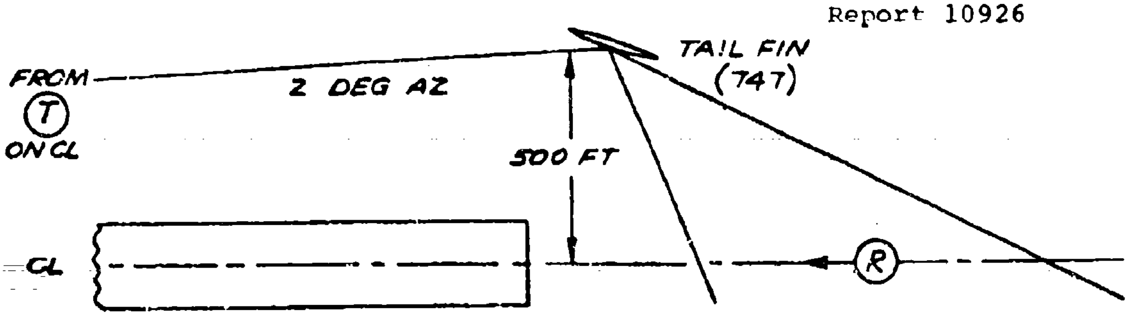


(a) Phasor Diagram of the Phase Modulation Caused by a Weaker Signal on a Different Frequency.

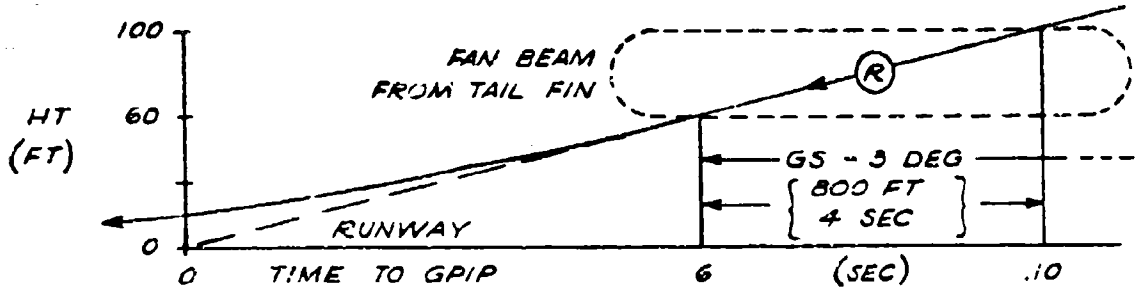


(b) Appearance of Phase Difference in Zero-Crossing Counting and Timing. 7208063

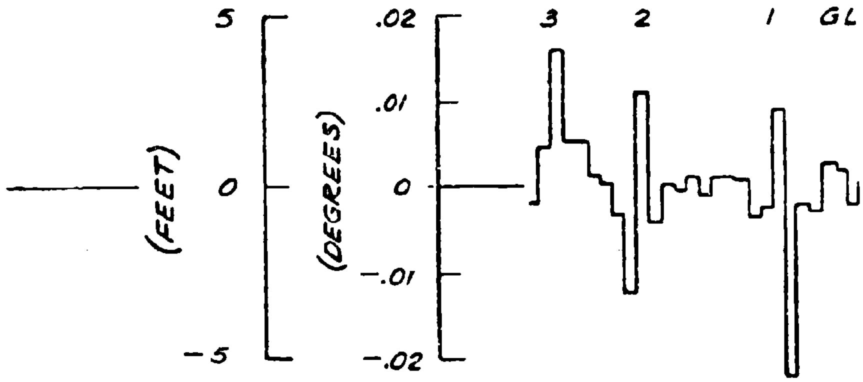
Figure 6-3. The Effect of an Indirect Signal in the Frequency Decoding of the Guidance Angle.



(a) Reflection from Tail Fin near threshold.



(b) Flight Path through Fan Beam from Tail Fin.



(c) Error Profile - Samples 7 per Sec, 4 Sec.

(d) Smoothed Profile - Samples Paired.

Figure 6-4. Computed Error Profile, AZ Example, Tail Fin Near Threshold

Conclusions.

Five problems are identified with multipath effects:

(1) The airport runway environment presents serious problems for a microwave landing system.

(2) A deep shadow and loss of signal far from centerline can be caused by a large building near the AZ transmitter. This is inherent in a microwave system using a low antenna.

(3) Partial blocking of the AZ signal on centerline may be caused by an intervening aircraft. It may last about one second if this aircraft is on takeoff over the AZ transmitter and in this case it will have little effect on the operation.

(4) Diffraction effects, separate from shadowing and reflection, appear to be very small, and are further reduced by the proposed filtering.

(5) Reflection is the principal cause of multipath signals. The strongest reflectors are:
   (a) the metal doors of a large hangar, the reflection usually being reduced by corrugation.
   (b) the tail fin of a large aircraft, the reflection being much reduced by the convex curvature of the face.

Seven features of the Hazeltine sytem are provided to overcome multipath problems:

(1) Space-pattern prefiltering is proposed for emphasis of radiation near centerline. It is proposed for AZ carrier and for the entire signals of EL-1 and EL-2. Each one gives extra assurance of integrity and error reduction on the final approach over centerline.

(2) Fixed-frequency-band prefiltering in the receiver is proposed for the AZ angle-coding signal, in the form of half-sector and centerline filters. The selection of the proper one, at any time during the approach, provides a reduction of multipath error from the most likely causes, particularly during the final approach near centerline.

(3) The motion averaging which is inherent in a Doppler multiscan format, reduces the residual error near the threshold, which is the most critical region.

(4) The capture in the limiter instantly provides in the receiver the most reliable selection of a direct signal in preference to a slightly weaker indirect signal.

(5) Detection with a STALO in the receiver may be used as insurance against carrier weakness or contamination and is planned to be implemented in the "K" feasibility receiver.

(6) Other frequency filtering, not included in the baseline system, is available if still further reduction of errors were needed.

(7) The baseline system is expected to hold the residual multipath errors well within tolerances in AZ angle and down to a negligible value in EL angle, even in situations chosen to be the most susceptible.

2. The Problem.

In the MLS, each transmitter radiates frequency-coded signals over a range of angles, and it is necessary for the receiver to select and to decode the direct signal. This must be accomplished in spite of any indirect signals that may reach the receiver by reflection from objects at differenct angles from the transmitter, hence with different frequency coding.

In general, a microwave signal is reflected in some degree from a large object. In an airport, this may be a hangar or another aircraft (other than the one carrying the receiver). Therefore this environment should be described in terms of such opportunities for indirect signals to reach the receiver. Then it becomes possible to plan preventive or remedial measures such that the direct signal is decoded in spite of any indirect signals that may be expected.

In the Doppler MLS, the angle-coded signal comprises a reference carrier and an angle-tone sideband, which serve different but complementary purposes in the receiver. They are radiated concurrently but they present two different problems in the multipath environment.

<u>The carrier</u> is radiated alike at all angles, only its frequency being utilized in the receiver. The principal problem is to avoid an interference pattern in space, where the received signal might suffer from either of these two defects:

(a) Amplitude falling below the required strength.
(b) Phase varying with receiver motion to cause excessive modulation of the frequency.

If these defects exceed tolerances, the received carrier may be replaced by a stable local oscillator (STALO). It is intended that the received carrier be adequate for performing its function as a frequency reference.

The sideband is radiated at a frequency coded for the angle of radiation. The problem is to select the strongest (direct) signal and then to measure its frequency in spite of any weaker (indirect) signals reaching the receiver. More specifically, these are the principal considerations.

(a) Keep the amplitude ratio of indirect/direct signals below unity by a sufficient margin.
(b) Reduce the interference from indirect signals radiated at different angles and frequencies.

Since the sideband carries the angle information, there is no substitute for its proper reception and decoding.

The requirements relative to the runway centerline. Each MLS installation is associated with a runway and there are two levels of performance that are related to receiver location in an approach flight path.

(a) Near the centerline, the highest accuracy and integrity are needed for the glide slope, flareout and touchdown.
(b) Far from centerline, whatever accuracy is needed for aircraft separation and guidance to the centerline.

Therefore special attention will be given to (a) while obtaining an economical and reliable compromise for (b). For example, shadowing by a large hangar would be avoided near the centerline, so this problem would not exist.

With these considerations in view, the airport environment will be described.

3. Obstacles in an Airport.

In relation to the guidance system for one runway, any object above the ground is potentially a cause of multipath or shadowing. This is inherent in a microwave system. See Figure 6-1. Location, size, shape and any motion are factors determining the effect of one object on the coding and decoding of angle from one transmitter. In this Section, various obstacles will be described and classified with respect to their potential to cause shadowing and multipath effects. The reflection from the ground, within and near the runway, is related mainly to the transmitter antenna properties, so it is not discussed here.

Characteristics of principal obstacles. There are several characteristics of an obstacle which determine whether it is a threat to the angle accuracy in the MLS system. The principal obstacles may be rated in the following terms, which will be discussed in more detail.

	Relevant to:	
	Shadowing	Reflection
(a) Location relative to the runway	yes	yes
(b) Size	yes	yes
(c) Shape and material	no	yes
(d) Direction of reflection	no	yes

The location. These are the principal considerations.

(a) Proximity to the runway.
(b) Proximity to the transmitter, which is near one end of runway.
(c) Proximity to the receiver, which is near threshold for a short time from the lower part of glideslope to the touchdown.
(d) Angle proximity to the runway centerline, as seen from AZ transmitter.

The size. The size of an obstacle has to be compared with some reference, such as the following:

(a) Relative to the first zone of diffraction as determined by the wavelength and the distances from transmitter and receiver.

(b) Relative to the distance from transmitter, which decreases the angle subtended in AZ and EL.

In either case, the reference size increases with distance or, conversely, the effect of a certain size is greater at a lesser distance, as would be expected.

The shape and material. An obstacle of a certain size has its reflection factor decreased by any of these properties.

(a) Convex curvature, causing divergence of the reflected radiation. This is typical of the tail fin of an aircraft (on a taxiway).

(b) Roughness, such as corrugation, causing some pattern of divergence.

(c) Absorption, reducing the amount of power in the reflected radiation. This may be associated with openings (windows) or lossy dielectric building materials (any except metal).

These are all compared with a perfect reflector, which is approximated by a flat smooth metal sheet.

The direction of reflection. As compared with a vertical wall parallel to the runway, these departures may be noted:

(a) Horizontal rotation of the reflector to an oblique angle. Some angle may direct the reflection into a sensitive area.

(b) Vertical tilt of the reflector, which is unlikely for a flat wall but is typical of the tail fin of an aircraft (on a taxiway). The tilt of the latter lifts the reflection above the horizontal to an angle where it may not reach the receiver or its effect may be transient. (The same is true of the height of the lower edge above ground.)

Examples of principal obstacles to be considered. In order to have a basis for evaluation of the effects, these two obstacles are defined as the closest and largest that may be encountered in conjunction with a long runway (14000 ft):

(a) A large hangar with a vertical wall which is mostly made of corrugated metal doors.

Stationary and predictable
Height = 100 ft.
Area = 500 × 500 ft.
Width of reflecting wall = 500 ft.

Location relative to runway.

Offset 1000 ft.
Opposite some point on the runway.

(b) A large aircraft (747). See Figure 6-10 below. May be on a taxiway parallel to the runway.

Offset 500 ft.
Tail fin (convex),

Height 30 to 60 ft from ground.
Width 30 ft.
Thickness 0 - 4 ft.
Radius of curvature 100 ft.

May intervene between T and R.

Fuselage (cylinder),

Diameter 22 ft.
Length about 200 ft.

In general, the hangar is expected to cause the greatest cone of shadowing and strong reflection, while the tail fin is expected to be the closest reflector. The fuselage is the main obstacle that may intervene during a centerline flight path.

Examples of lesser obstacles. The following obstacles in or near an airport have been considered but will only be listed here. Their effects have been estimated to be so small as to deserve little or no further discussion here.

(a) Terrain outside the airport. (A certain hill will be evaluated.)
(b) Large buildings outside the airport, water tower, radio tower, tall chimney.
(c) Large buildings far from the runway.
(d) Small buildings in the airport.
(e) Airport surveillance antennas.
(f) ILS antennas.
(g) Fuel trucks, panel trucks.

Some justification for this estimation will be found in the next section.

Motion of an obstacle. Because the receiver is moving at a high speed (taken to be 120 kt or 200 ft/sec during the approach) it is found that the motion of any mobile obstacle, such as another aircraft on a taxiway, is relatively negligible.

4. Shadowing, Reflection and Diffraction.

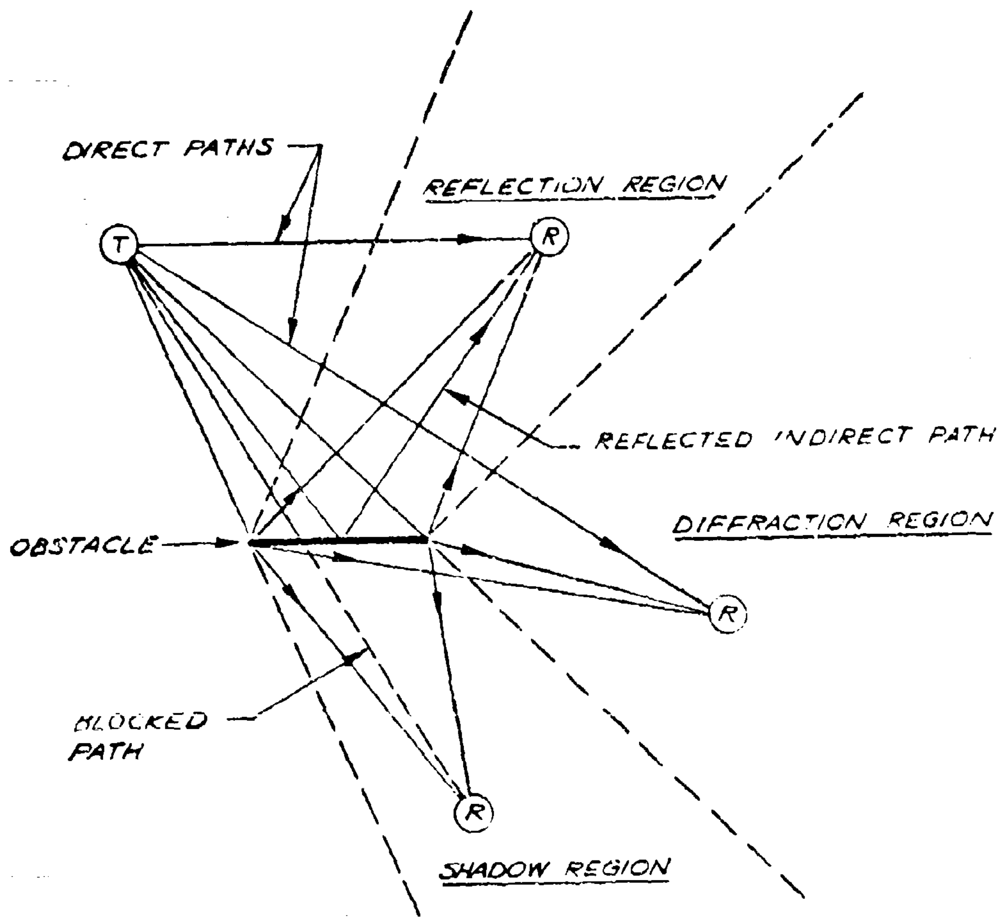
As shown in Figure 6-1 an obstacle in an airport may be associated with well-defined regions of shadow and reflection. In the shadow region, the direct path is blocked and the signal at the aircraft receiver arrives only by diffraction paths. In the reflection region, a direct path is accompanied by indirect paths of both reflection and diffraction. This is shown in Figure 6-5 in general terms, where a diffraction region is also defined. The multipath indirect signal is the combination of all reflected and diffracted signals.

For the MLS, the two cases that are most important are the blocked path in a shadow and the indirect path by reflection. Figure 6-6 summarizes the various characteristics of obstacles in the direct and indirect paths which are relevant to the AZ angle guidance in MLS. From these characteristics the magnitude, duration, and variation of the effects on angle decoding can be estimated.

Shadowing, which is the result of blocking of the direct signal path, poses two problems for the MLS. The greater problem is the predictable reduction in system coverage caused by the shadow of a large building near the transmitter. The lesser problem is the momentary blocking caused by an aircraft on takeoff, or conceivably by its tail fin while on a taxiway near the transmitter.

Figure 6-7 shows profiles of the risk of shadowing and reflection from buildings on one side of a long runway, for the AZ radiation. Figure 6-8 shows the conceivable shadowing of the AZ radiation by a hangar or tail fin on the ground in some areas.

From these figures, it is observed that shadowing by buildings is not a problem in the region between the outer marker and the



NOTE: ALL PATHS NOT LABELED ARE DIFFRACTED INDIRECT PATHS

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Figure 6-5. Shadow, Reflection and Diffraction Regions

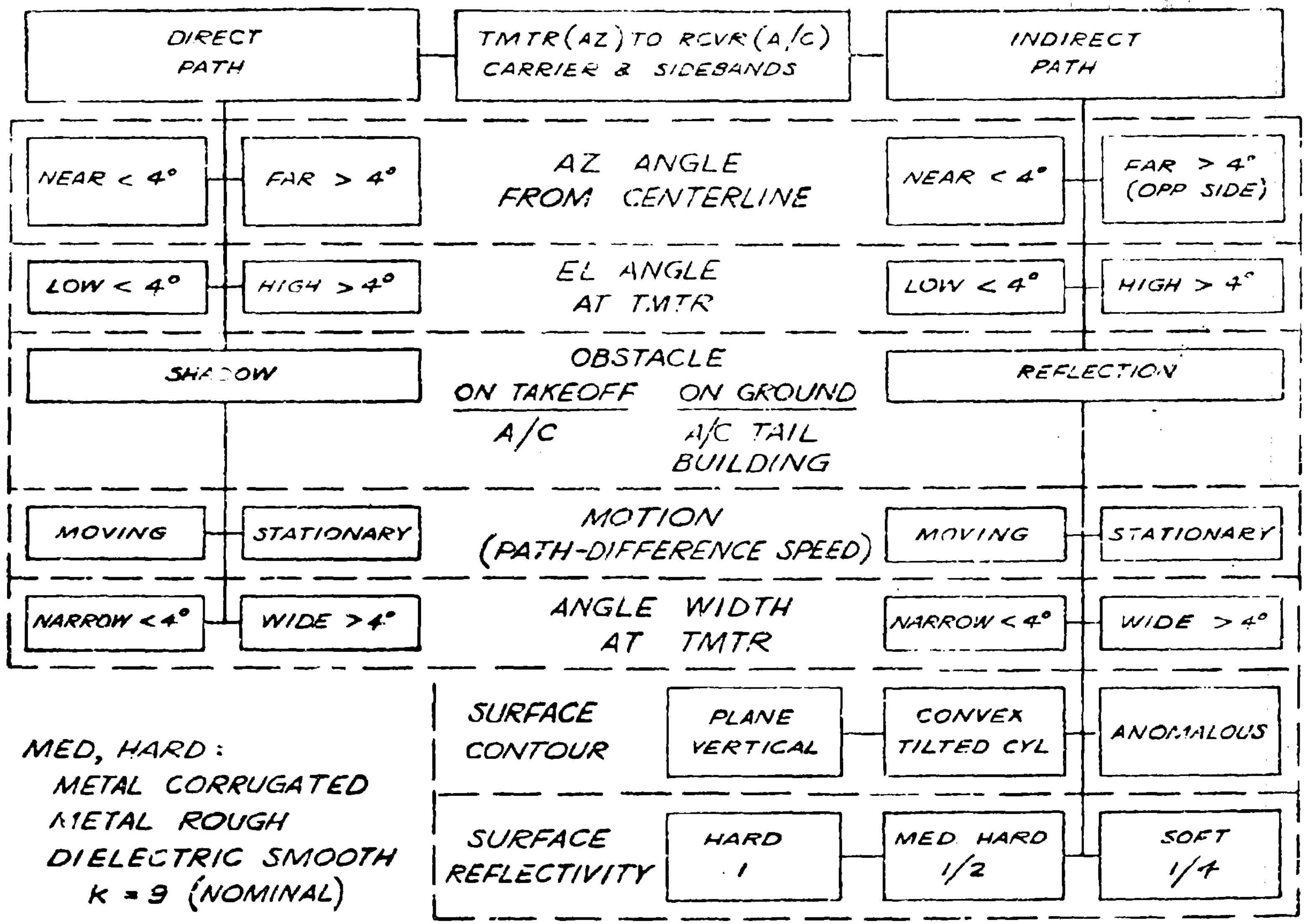

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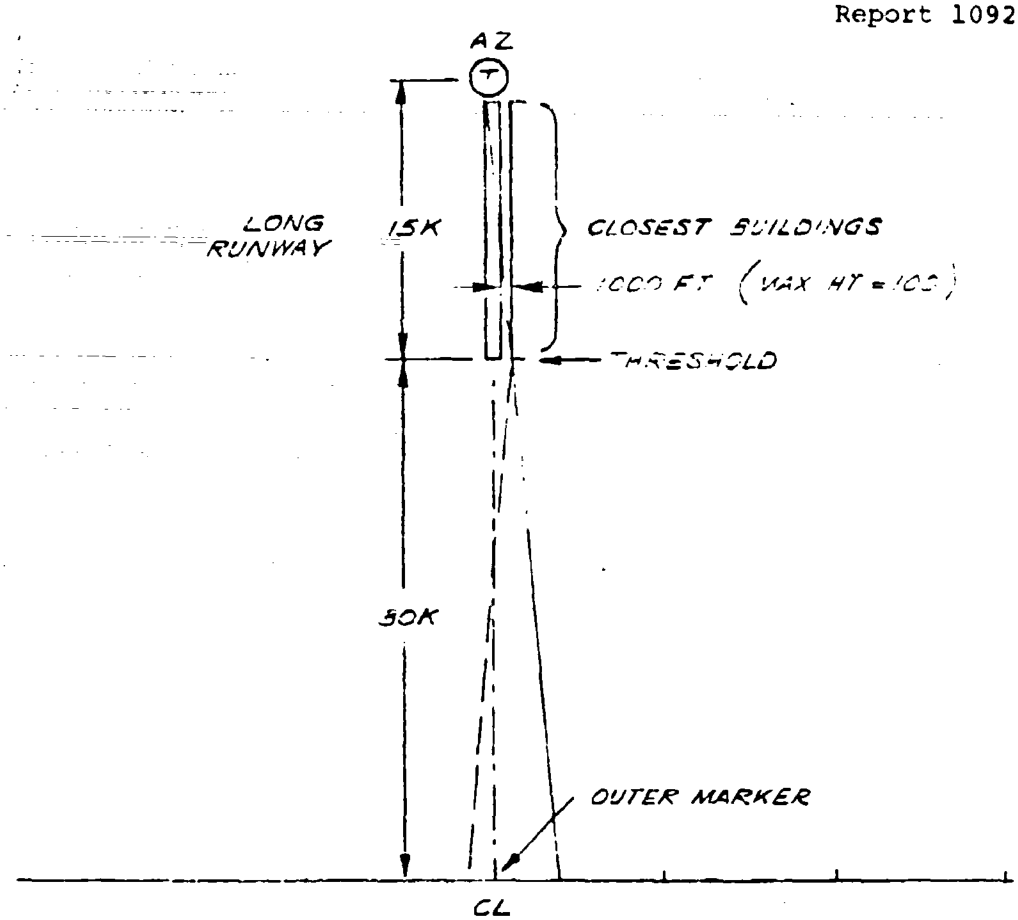
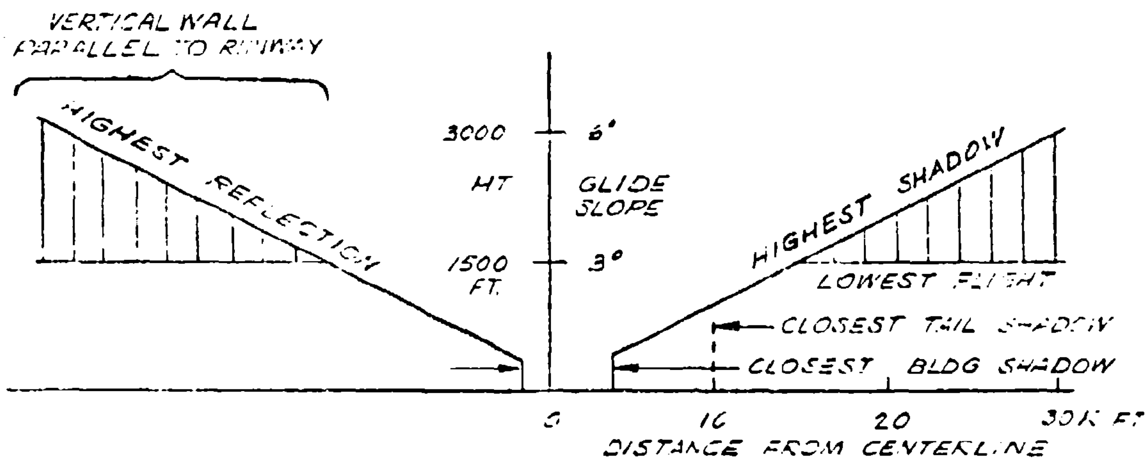
Figure 6-6. Characteristics of Obstacles in Direct and Indirect Paths

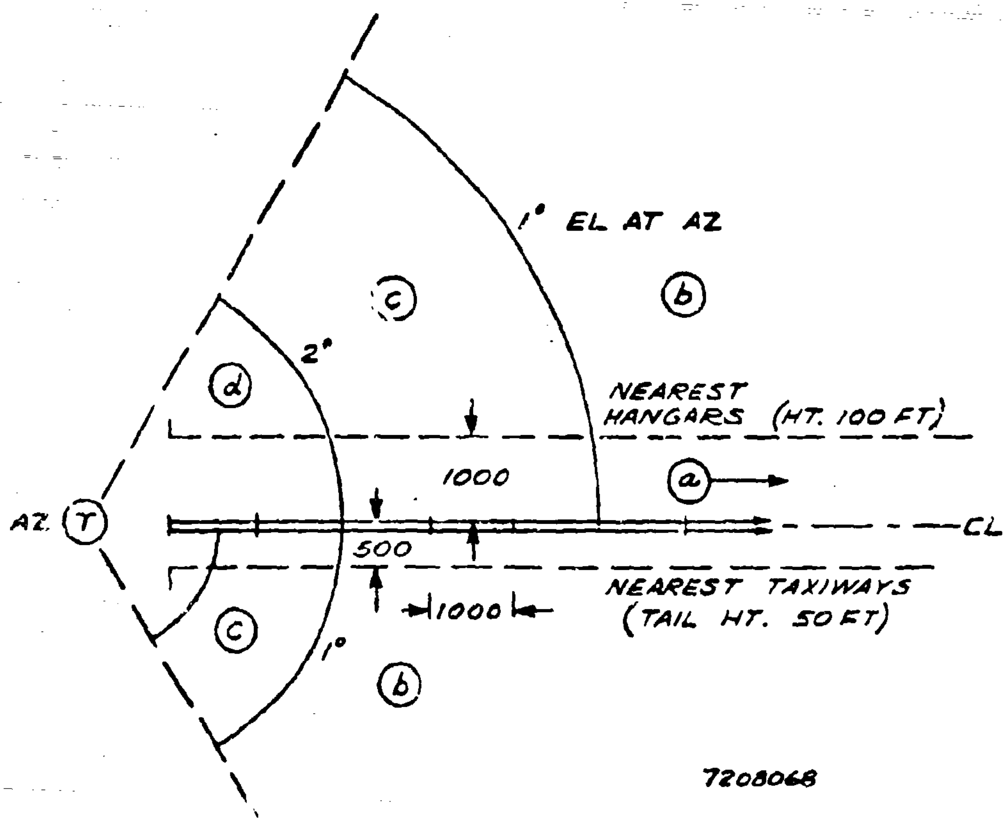


(a) Plan.



(b) Interception on Plane at Outer Marker.

Figure 6-7. Profiles of Risk of Shadowing and Reflection From Buildings on One Side of Long Runway



(a) No shadow near CL.

(b) No shadow above 1°, or above 1500 ft at 15 nmi.

(c) No shadow above 2°, or above 1500 ft at 7.5 nmi.

(d) Hangar shadow above 2°, or above 1500 ft at 7.5 nmi.

Figure 6-8. Shadowing of AZ Radiation by a Hangar or Tail Fin on the Ground in Some Areas touchdown. However, a flight path far from centerline may experience shadowing from a large building or a tail fin located near the AZ transmitter.

There will be given a few examples to illustrate some relations that are relevant to shadowing. Each is applied to:

AZ radiation, C-band, $\lambda = 0.2$ ft.

In each example, the size of the reflecting surface is compared with the diffraction zone. Here we use the $\lambda/8$ zone, whose width is

$$\sqrt{\lambda d_o}$$

This width is 1/2 of the $\lambda/2$ zone width, commonly termed the first Fresnel zone. It is chosen because:

(a) It is the minimum aperture width that will transmit a signal nearly equal to the free-space signal.

(b) The shadowing effect behind the center of a strip of this width reduces the signal to about 1/2 its free-space voltage.

The "effective distance" (d_o) is formulated in Figure 6-9; it is somewhat less than the lesser of the distances between the obstacle and the transmitter or receiver. A typical value is 2000 ft, in which case the $\lambda/8$ zone width is 20 ft. This is somewhat smaller than a large tail fin and much smaller than a building. It is comparable with the diameter of a large fuselage.

Example - Shadowing of AZ by a large building (such as a hangar) located rather near the transmitter.

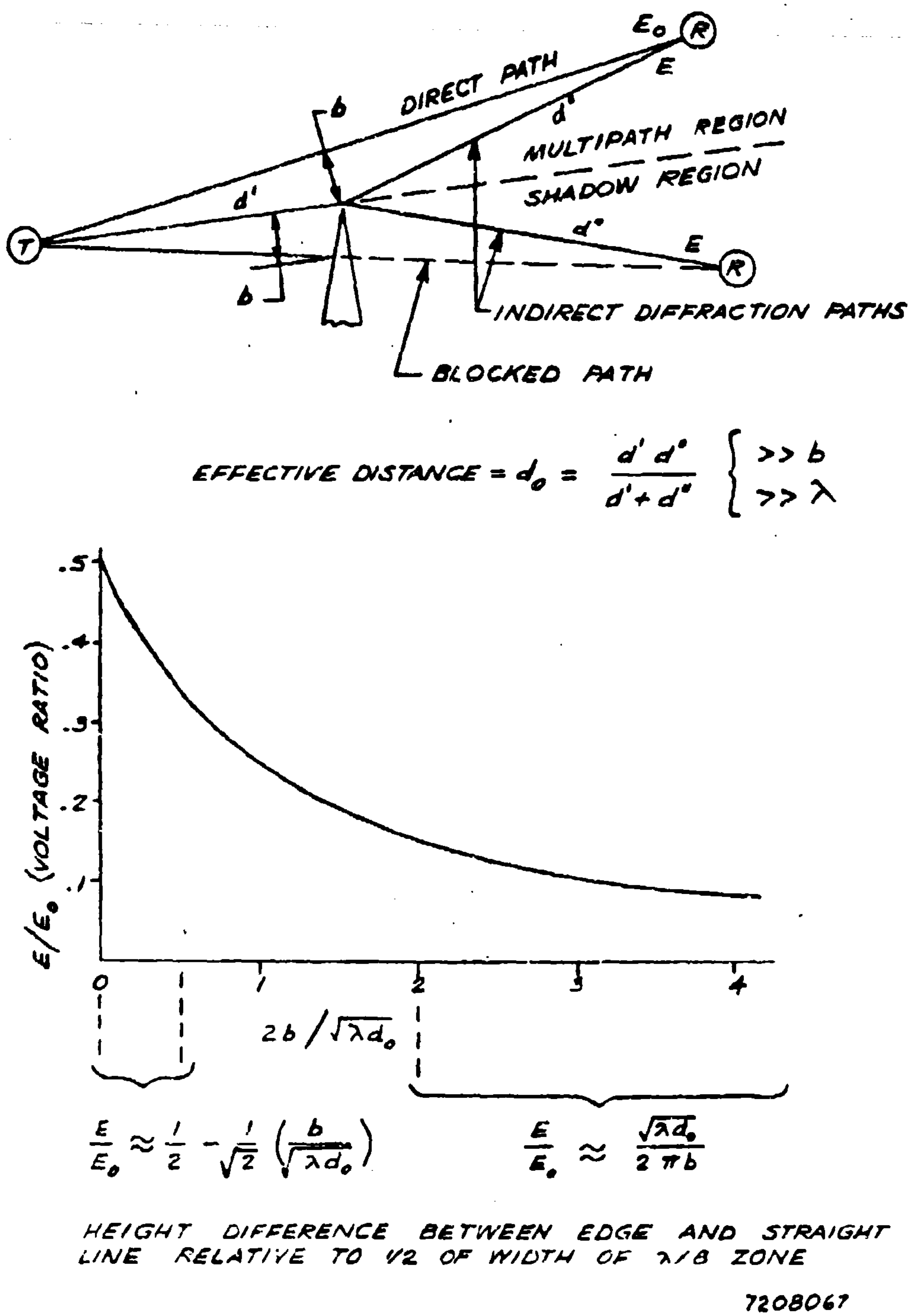


Figure 6-9. Forward Diffraction from Horizontal Edge, Downward in Shadow or Upward in Multipath Region

Building:

Direction - 45° off centerline

Distance - 1500 ft from transmitter

Height - 100 ft.

Projected width - 500 ft.

Receiver position:

Direction - 45° off centerline

Distance - 10 nmi from transmitter

Height - 1500 ft.

The decrease in signal level can be estimated from the results of the solution to the knife-edge diffraction problem. The formulas and a graph of signal ratio are presented in Figure 6-9. These formulas are valid when the projected width of the building, in a plane perpendicular to the direct line-of-sight, is greater than $2\sqrt{\lambda d_o}$, which is true here.

d_o = 1500 ft.

$\sqrt{\lambda d_o}$ = 17 ft.

b = 62 ft.

E/E_o = 0.044 (-27 dB)

Duration about 100 sec.

It is seen that this building is close enough to the transmitter, to cause a great reduction of signal strength for a long time.

<u>Computation of signal in shadow behind a strip.</u> Figure 6-9 can be used to evaluate the diffraction signal behind an aircraft on takeoff or by a tail fin while taxiing. In this case, the signal in the middle of the shadow region is the sum of two edge-diffracted components whose magnitude can be estimated from the strip-diffraction model. For this model, the ordinate of the graph in Figure 6-9 is doubled for a strip of width w = 2b. From the middle toward either edge, the signal oscillates between the difference

and the sum of the two edge signals. The formulas are valid if the projected length of the strip, on a plane perpendicular to the direct line-of-sight, is much greater than its width. Then this rule is found to be helpful:

> If the strip width is less than double the $\lambda/8$ zone width, the signal in the shadow region is between 1/2 and 1/4 of its value in free space.

The reduction by blocking is negligible if both width and projected length are less than one zone $\sqrt{\lambda d_o}$.

Shadowing by an intervening aircraft. Figure 6-10 shows some relevant dimensions of a large aircraft. These are to be used in examples of blocking by an intervening aircraft. Figure 6-11 shows some situations in which an aircraft A may intervene between T and R, all three being over the centerline. The signal reduction depends mainly on the fuselage width (22 ft for the 747). This is equal to double the $\lambda/8$ zone if

$$d_o = (11)^2/0.2 = 600 \text{ ft.}$$

If T and R are separated by more than 1500 ft, the lesser distance is less than 1000 ft. Then we have this rule:

> If the intervening aircraft is more than 1000 ft from the closer of T and R, the received signal exceeds 1/4 the free-space voltage.

Referring to Figure 6-11, the lesser distance would always exceed 1000 ft.

Example - Shadowing of AZ by an intervening aircraft on takeoff. Figure 6-11(b) shows the shadowing of AZ radiation by an aircraft on takeoff over the transmitter. The following case is calculated:

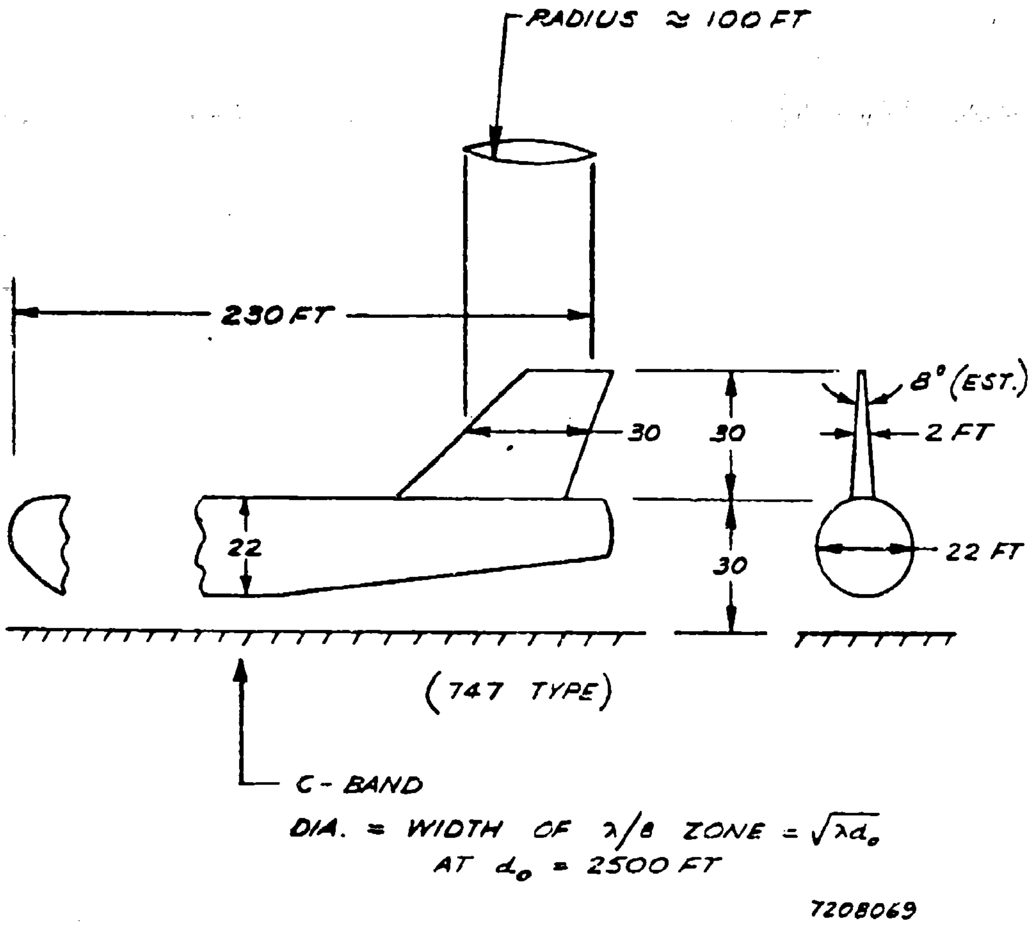
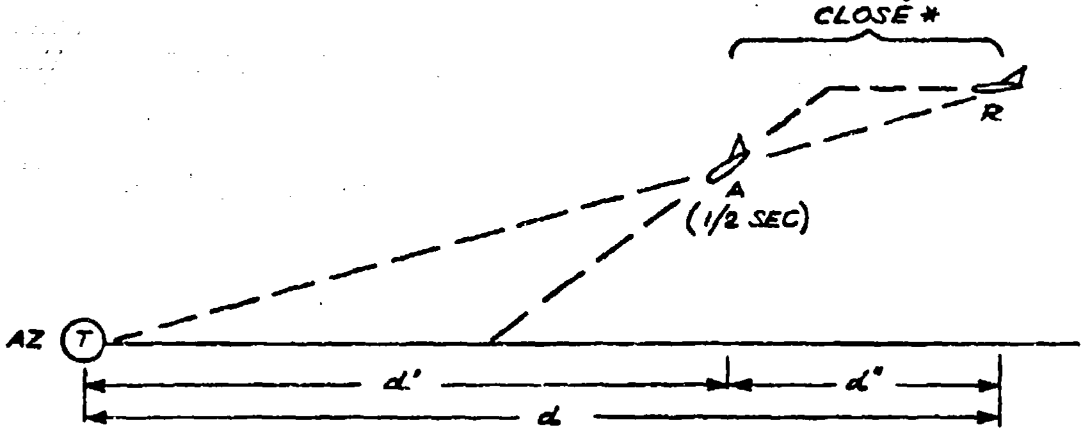
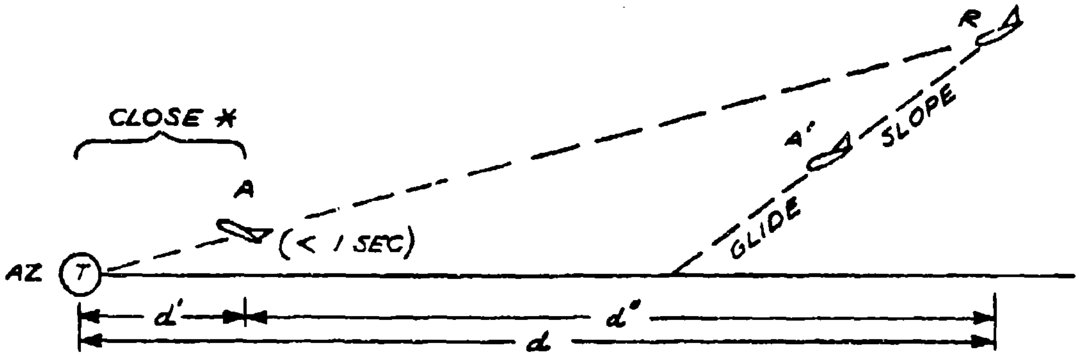


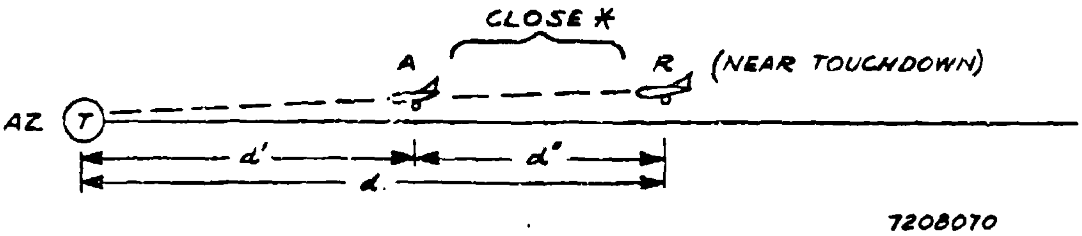
Figure 6-10. Some Relevant Dimensions of a Large Aircraft



(a) Shadow by Aircraft on Glideslope.



(b) Shadow by Aircraft on Takeoff.



(c) Shadow by Aircraft on Runway.

(*) If separation exceeds 3000 FT, the signal in shadow will exceed 1/2 and any angle error will be very small.

Figure 6-11. Shadowing of AZ Radiation by an Intervening Aircraft

Intervening aircraft (747) on takeoff:

Direction - on centerline

Distance - 1500 ft from transmitter

Height - 50 ft.

Fuselage width - 22 ft.

Fuselage length - 230 ft.

Receiver position:

Direction - on centerline

Distance - 45 Kft from transmitter (at outermarker)

Height - 1500 ft.

Computations: d_o = 1500 ft.

$\sqrt{\lambda d_o}$ = 17 ft.

w = 2b = 22 ft.

E/E_o = 1/2 to 1/4

Duration about 1 sec.

This is not serious, considering that the receiver is in a non-critical time in the flight path (not too low or too far).

Example - Shadowing by a large tail fin. As seen in Figure 6-8, a large tail fin near the AZ end of the runway might cast a shadow as high as a flight path.

Aircraft tail fin (747) on taxiway:

Direction - 20° off centerline

Distance - 1500 ft.

Height - 60 ft above ground
(about 20 ft above line-of-sight)

Width - 30 ft (perpendicular to line-of-sight)

Receiver position:

Direction - 20° off centerline

Distance - 10 nmi from transmitter

Height - 1500 ft.

Computations: d_o = 1500 ft.
$\sqrt{\lambda d_o}$ = 17 ft.
w = 2b = 30 ft.
E/E_o = 1/2 to 3/4
Duration about 6 sec.

Here again, this is not serious, considering that the receiver is in a noncritical time in the flight path (not too low or too far).

From the examples above, it appears that the most serious shadow problem is caused by buildings. This effect is predictable and stable so regions could be defined in the terminal airspace where MLS receivers would not be operated. A secondary and less predictable problem is the momentary decrease in signal caused by an intervening aircraft near the transmitter, on takeoff or on taxiway.

Reflection deserves special attention in MLS. It is the multipath caused by radiation from a transmitter being reflected from a large obstacle toward the receiver. It is inherently a problem for any microwave system, especially for one covering a wide angle from the runway centerline. The MLS differs from ILS in that it covers a wide angle in some applications.

The occurrence of a reflected signal in some particular sector is indicated in Figures 6-1, 6-5, 6-7 and some to follow. The principal reflecting obstacles are exemplified by a large hangar near the runway and the tail fin of a large aircraft on the parallel taxiway. The relevant qualities of these obstacles are noted above. The former has the greater effect, which occurs in a stable and predictable cone in space. Its effect is greater in AZ radiation, because this is utilized over a wide angle.

If the receiver traverses a cone of reflection, the indirect signal may be strong enough to approach the amplitude of the direct (perhaps 1/2 as great). Then it may cause an error in the angle decoding. In an extreme case, it is conceivable that it might temporarily exceed the direct and capture the limiter (as will be explained). The discussion here is directed to the occurrence of reflections and to the amplitude ratio of indirect/direct signal voltages as influenced by various factors. The reflection factors combine to give a reflection coefficient (ρ) which may be slightly less or much less than unity.

Table 6-1. Reflection Factors for Indirect Signals.

Reflection Factor		Phenomenon	Remarks
ρ_1	Path distance.	Distance ratio, direct/indirect.	Simple rule.
ρ_2	Surface size.	Relation to zone size, diffraction.	Surface is usually larger than $\lambda/8$ zone, so factor is near unity.
ρ_3	Surface contour (convex).	Reduction by divergence.	Locates image closer to reflector.
ρ_4	Surface reflectivity.	Reduction by diffusion and absorption.	Roughness, corrugation, materials, openings.
ρ =	product.	Voltage ratio, indirect/direct.	Does not include radiation pattern and environment.

Table 6-1 describes several factors entering into the reflection coefficient for an indirect signal caused by one obstacle in an airport. Each factor is to be evaluated and all are multiplied to determine the relative amplitude of the indirect signal. The reference for all factors is a perfect plane reflector large enough to develop an image substantially like the transmitter. A conceptual example would be a large, flat, metal, vertical wall.

The path-distance factor (in Table 6-1) gives the reduction factor resulting from the indirect path distance (d' + d") being greater than the direct (d). There are two situations which have different formulas for this factor.

(a) In free space, this factor would be

$$\rho_1 = \frac{d}{d' + d''}$$

This ratio is valid if the reflector is vertical and the receiver is high enough that the free-space field intensity is approximated. This height depends on the height and directional properties of the transmitter antenna.

(b) For a lesser height of receiver, the ground image causes the field intensity to be proportional to height. The path-distance factor becomes

$$\rho_1 = \left(\frac{d}{d' + d''}\right)^2$$

This ratio is valid for the AZ signal on a long runway, as the receiver approaches flareout and touchdown. This also is conditioned on a vertical reflector.

This factor is usually unimportant for the AZ transmitter, so the first form is usually valid and may be relevant to an EL transmitter.

The surface-size factor (in Table 6-1) includes the effect of reflector size relative to the $\lambda/8$ zone defined above.

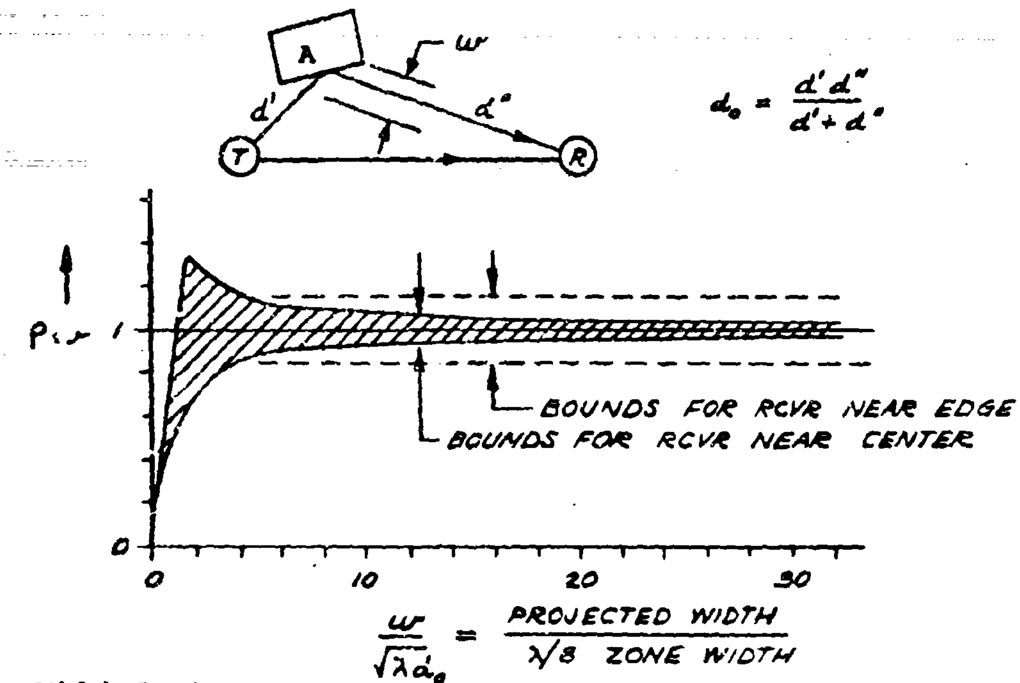
For a rectangular wall, Figure 6-12 shows how this factor may be described in terms of two components depending respectively on width and height:

$$\rho_2 = \rho_w \rho_h$$

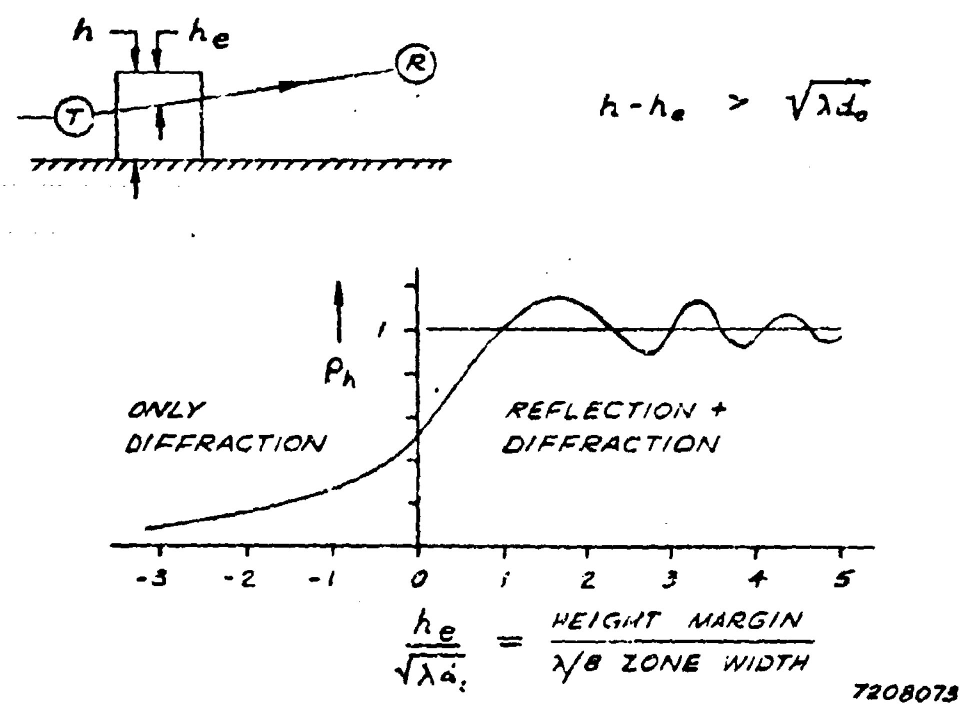
Figure 6-12(a) shows the projected width of a wall A acting as a reflector between T and R. The "effective distance" d_o and the $\lambda/8$ zone width $\sqrt{\lambda d_o}$ are formulated as above. If the projected width exceeds the zone width, ρ_w is near unity. The difference from unity is caused by edge diffraction, as indicated for the receiver location near the middle or one edge of the reflection sector (Figure 6-5). In practice, the width of a hangar wall is usually many times the zone width, so this factor is near unity.

Figure 6-12(b) shows the effect of the height of a vertical wall located on the ground. The height is taken to be much greater than the $\lambda/8$ zone width. The reflection point on the wall is identified, and the excess height above that point is denoted h_e. The graph shows the height factor ρ_h to be near unity if the excess height exceeds the zone width. This is true if the receiver is within the reflection cone by some margin.

The surface-contour factor (in Table 6-1) gives the effect of divergence in reflection from a convex surface. This is relevant especially to the tail fin of a large aircraft, also to its fuselage and to other obstacles such as a fuel truck or a water tower. It is assumed that the surface extends more than one $\lambda/8$ zone width (with due regard for the curvature) in all directions from the point of reflection. This effect is expressed in terms of ρ_3, the ratio of reduction of field intensity at the receiver. The reference is a perfect plane reflector located at the point of reflection.



(a) Width Factor.



(b) Height Factor.

Figure 6-12. Reflection Factors for a Rectangular Plane Vertical Wall

Figure 6-13(a) gives the general formula for curvature in either or both of the horizontal and vertical planes ($1/a_1$ and $1/a_2$).

Figure 6-13(b) gives another formula for the case of most interest here. It is a large thin tail fin with a convex surface of width w and thickness t. If T and R are on centerline (as in the AZ function on approach), c is approximately the offset of a taxiway from the centerline. (For a horizontal cylinder, just change b to a.)

Example - Reflection of AZ by a large tail fin (747) located on a taxiway near the threshold.

$$d' = 13500 \text{ ft}, \; d'' = 1500, \; d_o = 1350$$
$$c = 500 \text{ ft}, \; w = 30, \; t \approx 2$$
$$\rho_3 = 0.09 \; (-21 \text{ dB})$$

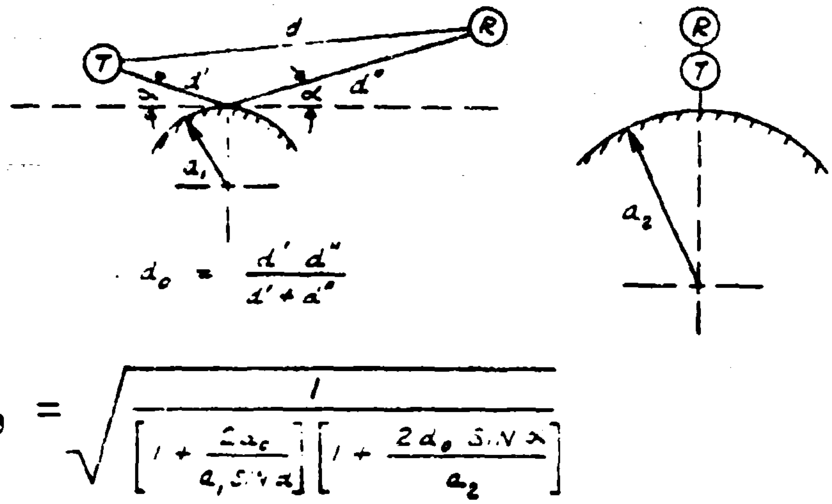
This illustrates the great reduction of the indirect signal by the curvature of the tail fin.

Example - Reflection of AZ by a hill located on one side of centerline, under the glide slope. This is an extreme (conceptual) case, included as another illustration of the effect of convex curvature. Figure 6-14 shows a configuration chosen to emphasize any detrimental effect and thereby to indicate the improbability of appreciable error from this cause. The curvature gives

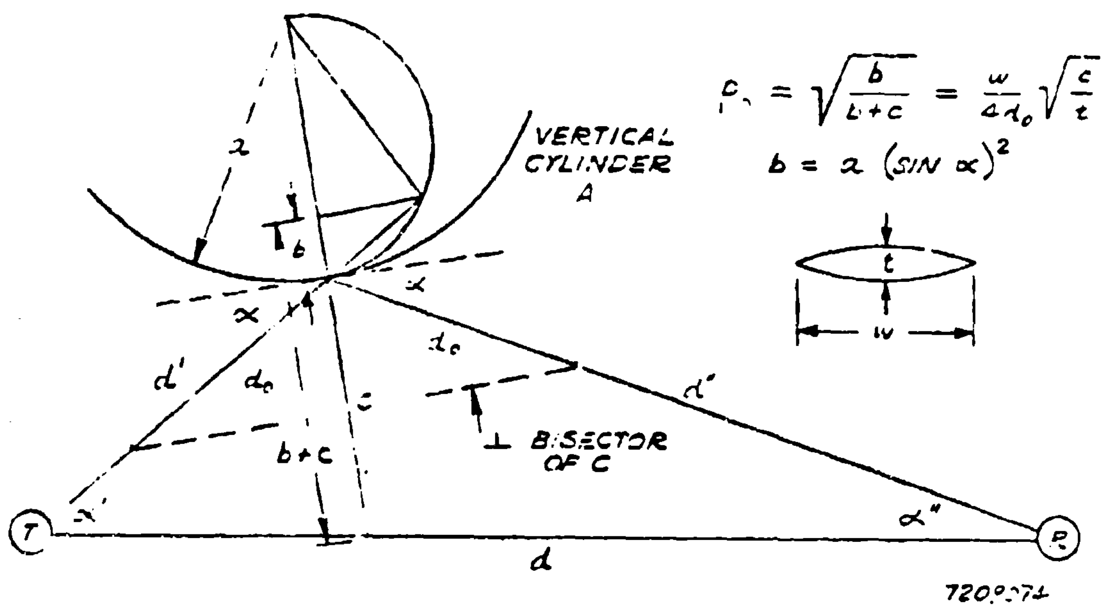
$$\rho_3 = 0.06 \; (-24 \text{ dB})$$

The indirect path is coded 0.5° (1/2 beamwidth) from centerline (T to R), which would give "in-beam" error of decoding, but it is too small to be noticeable.

The surface-reflectivity factor (in Table 6-1) gives the effective reflection coefficient ρ_4 of the surface. It includes scattering



(a) Formula for Doubly Convex Surface.



(b) Geometrical Evaluation for Convex Tail Fin.

Figure 6-13. Reflection Factor for a Convex Surface

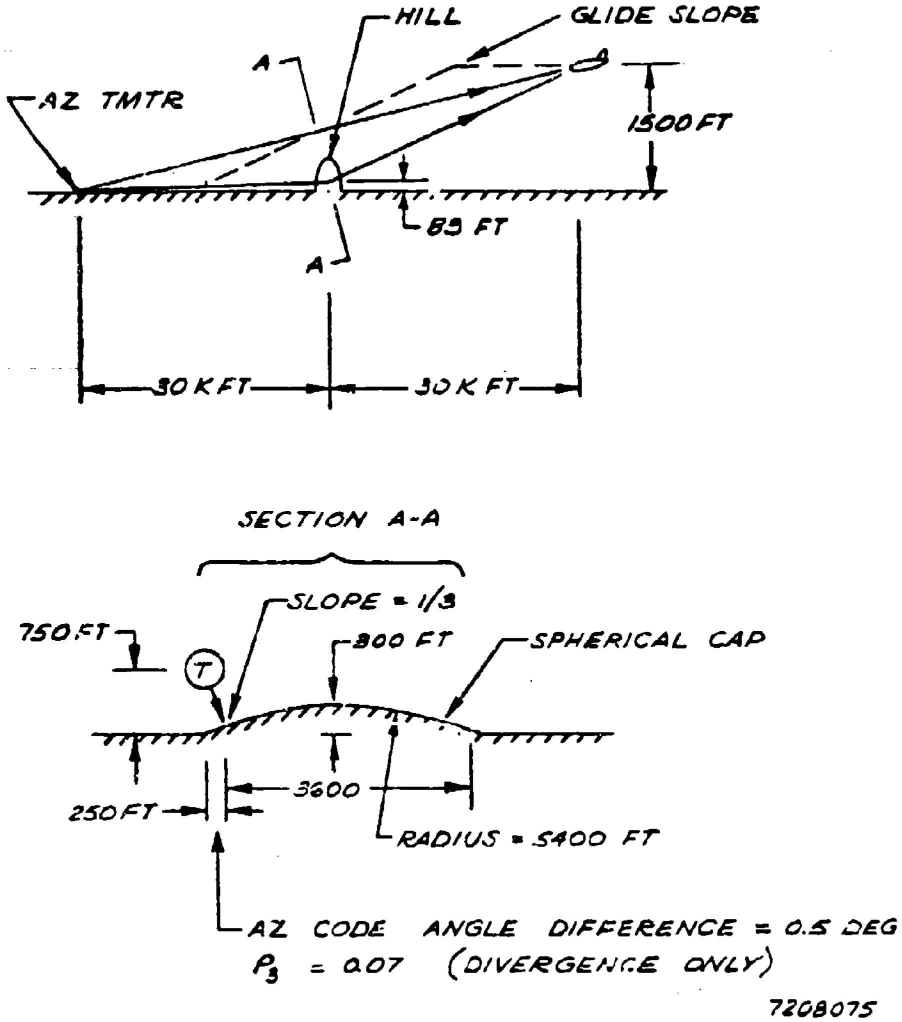


Figure 6-14. Reflection from Hill on one Side of Centerline, Showing Indirect Path with Different Angle Coding

by corrugation or roughness, and absorption by the material or openings. The following are some estimated values for a few cases:

Surface	Reflectivity (ρ_4)
Smooth metal tail fin of an aircraft	1
Flat metal door of a hangar	1
Corrugated metal door of a hangar	1/2, 3/4
Nonmetal side of a building	1/4

The tail fin has its reflection reduced by convex curvature, as discussed above. The flat metal door is believed not to be typical of a large hangar of recent construction. If it should appear in a critical situation, it might be necessary to reduce the reflection, as by applying a corrugated face.

The corrugated metal door of a large hangar deserves special attention because it is typical of the largest vertical wall to be encountered. Being metal, it re-radiates, in some directions, most of the incident-wave power. AZ and EL radiation is at C and Ku-bands, where the wavelength is less than the corrugation period, perhaps much less. Therefore the power is divided between equal-angle reflection and grating-lobe scattering in a number of other directions. A few corrugation contours have been noted, which are estimated to give a reflection coefficient (ρ_4) of about 1/2. Reference [4] reports measurements of one contour (not detailed) giving about 3/4 to 1/2 at 15-30° from grazing incidence for vertical ridges of corrugation. The computation and measurement of this effect on practical surfaces will receive more attention.

Table 6-2. Reflection Factors for Some Airport Obstacles.

OBSTACLE		(a) HANGAR DOOR				(b) BUILDING WALL				(c) AIRCRAFT TAIL FIN			
ANGLE CODED		AZ		EL -1	EL -2	AZ		EL -1	EL -2	AZ		EL -1	EL -2
RECEIVER LOCATION	AZ	0	30°	0	0	0	30°	0	0	0	30°	0	0
REFLECTION FACTORS													
SPACE PATTERN	ρ_x	1	1	0	$\frac{1}{3}$	1	1	0	$\frac{1}{3}$	1	1	0	$\frac{2}{3}$
PATH DISTANCE	ρ_1	1	1	$\frac{3}{4}$	$\frac{3}{4}$	1	1	$\frac{3}{4}$	$\frac{3}{4}$	1	1	$\frac{3}{4}$	$\frac{3}{4}$
SURFACE SIZE	ρ_2	1	1	1	1	1	1	1	1	1	1	1	1
SURFACE CONTOUR	ρ_3	1	1	1	1	1	1	1	1	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$
SURFACE REFLECTIVITY	ρ_4	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{8}$	1	1	1	1
PRODUCT	ρ	$\frac{3}{4}$	$\frac{3}{4}$	0	$\frac{3}{16}$	$\frac{1}{4}$	$\frac{1}{4}$	0	$\frac{1}{32}$	$\frac{1}{8}$	$\frac{1}{8}$	0	$\frac{1}{16}$

<u>A summary of reflection factors</u> is given in Table 6-2 for three cases of particular interest. They are estimates of typical cases, based on the preceding discussion. The receiver location is in terms of AZ angle from centerline (0 or 30°). It is noted that this table does not include other factors such as space patterns or frequency filters. The zero values for EL-1 indicate that these are nominally outside the AZ coverage angle of the fan beam. The AZ reflection from the corrugated metal door of a hangar (a) is the only case where ρ might be greater than 1/2.

The cone of reflection. Just as important as the reflection factor is the location of the cone of reflection. This determines whether a particular flight path will traverse the cone, and during what time in its approach pattern. The practical effect of this transit may be inferred in some typical cases. The practical effect is different for typical cases of reflection of AZ and EL radiation.

Parallel wall, AZ reflection. Figure 6-1(a) and 6-7 show this case. The reflection cone is on one side of centerline, opposite from the shadow cone and similar in shape. There is no reflection cone along the centerline. There is only a small chance that one cone will be traversed, requiring that it include the flight path in one of two locations:

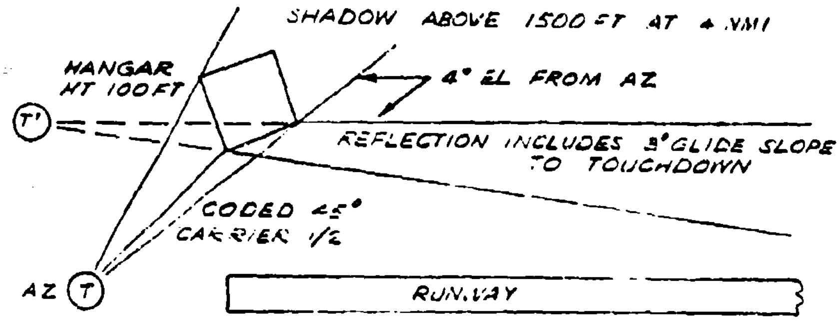
(a) At a great distance and far from centerline; and/or
(b) Below 200 ft and before touchdown.

Only in the latter case is it critical, and then the duration may be about 5 sec. In either case, the angle coding of the indirect and direct paths is much different, so the multipath error may be removed by frequency filtering.

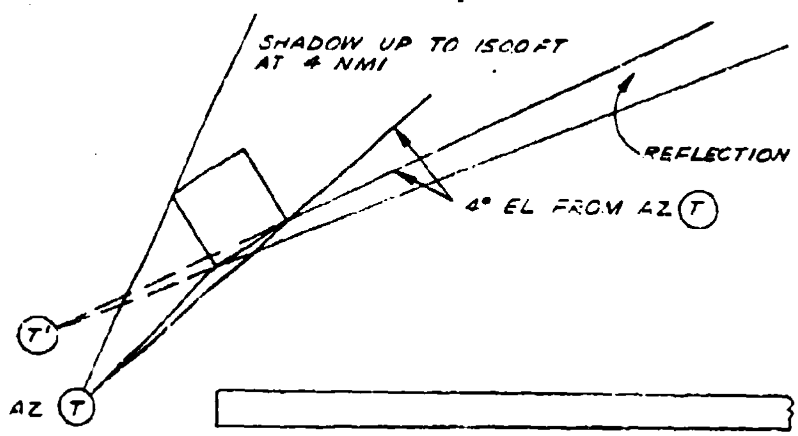
Oblique wall, AZ reflection. Some examples are shown in Figure 6-15. The reflection cone may include:

(a) The centerline over the entire glide slope and flareout to touchdown.
(b) A cone on the same side of centerline.
(c) A narrow, low cone near threshold, traversed during the flareout.

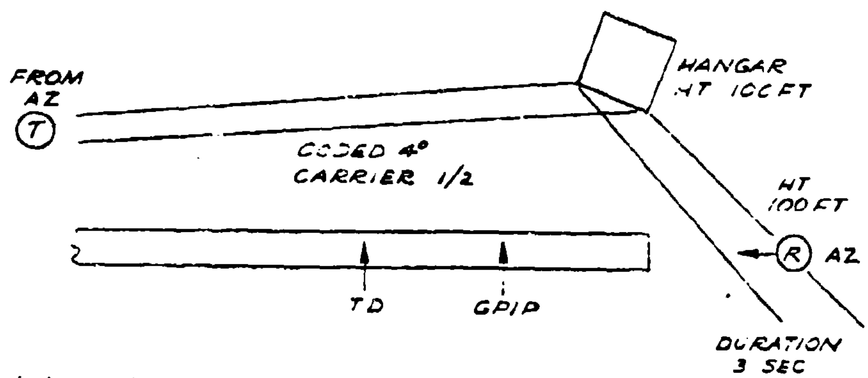
The relative angle coding of indirect and direct paths can be inferred in each case. Only one (b) has both angles far from centerline and on the same side, so they are not separated by the fixed prefilters discussed elsewhere herein.



(a) Reflection Toward Glide Slope.



(b) Reflection in Same Half-Sector.



(c) Reflection toward Transition From Glide Slope to Flareout

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Figure 6-15. Reflection of AZ Radiation from Oblique Vertical Wall

Nearby wall, EL reflection. Figure 6-16 shows some peculiarities of reflection cones in the vicinity of the EL radiators and the approach to touchdown. The hangar location illustrates two cases:

(a) The flight path traverses the EL-1 cone, but only during flareout after handover to EL-2;
(b) The flight path passes over the EL-2 cone, and before handover tc EL-2.

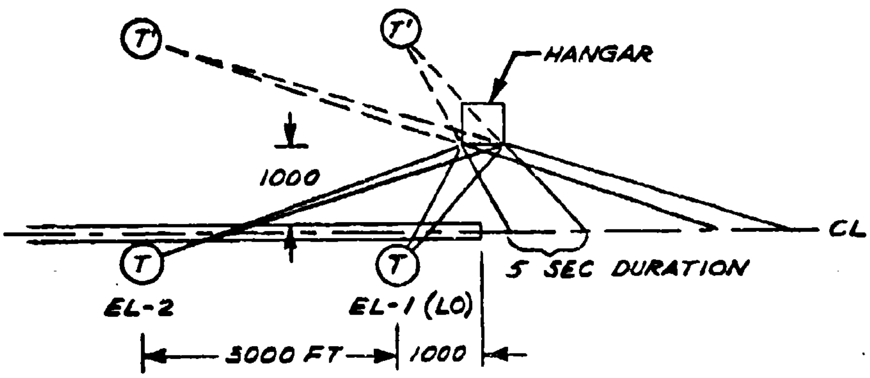
Therefore both of these reflection cones happen to be harmless.

Nearby tail fin on parallel taxiway. The cone of reflection has these peculiarities:

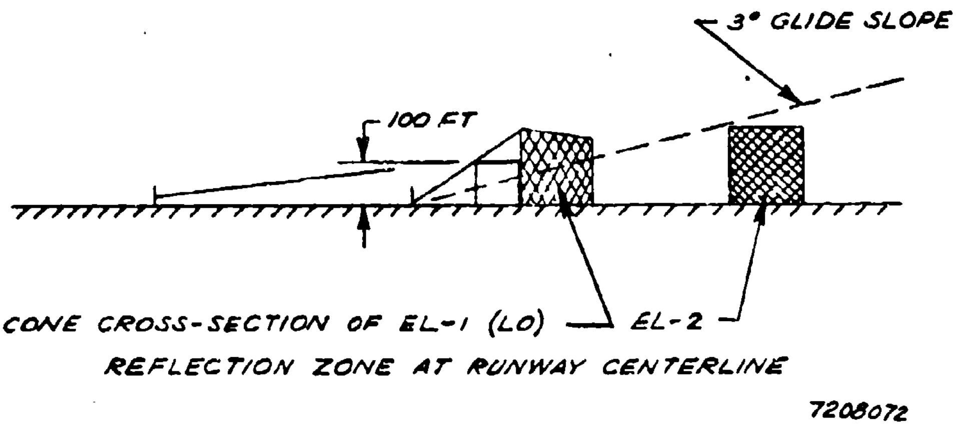
(a) It is spread in width by the convex curvature, so it covers a horizontal angle of about 30°.
(b) The vertical angle subtended at the transmitter is small (less than 3°) and is lifted both by the height of the fin above ground and also (about 8°) by its taper.
(c) The face is similar to a cylinder tilted both laterally and longitudinally, so there are components of curvature in both horizo· .al and vertical planes, see Figures 6-10 and 6-13(a).

The cone of reflection tends to be tilted upward, away from the flight path near touchdown. However, the double curvature makes it difficult to describe. Since the reflection factor is reduceu by convex curvature, this reflection has little effect on angle guidance.

Diffraction is the cause of multipath outside the regions identi- fied with shadowing and reflection, as indicated in Figure 6-5. The relative strength of the indirect signal is appreciable if the line-of-sight is separated from the obstacle by only a few times the zone width, as appears in Figure 6-9 and 6-12(b). This is associated with a well defined cone of shadowing or reflection.



(a) Plan



(b) Elevation

Figure 6-16. Reflection of EL Radiation from a Vertical Wall

One line-of-sight is unlikely to be close to more than one such cone at a time.

There are many objects on the ground which are illuminated by any one transmitter, especially the AZ. There is no realistic model that seems to give diffraction paths of appreciable strength, individually or collectively.

(a) A horizontal edge at the top of a high building gives diffraction mainly in line with the building and far beyond it. One or very few such edges would be in the same line, and typically much below the line-of-sight.

(b) Corners at the top of high buildings give diffraction in all directions but much weaker, even in the aggregate.

(c) Anomalous obstacles in or near the airport would contribute more numerous signals but so much weaker that their aggregate is hardly appreciable.

The RMS value of diffraction indirect signals, or the value of one principal component, is estimated to be around 0.01 of the direct. Also their contribution to the residual error is reduced by the AZ prefilter or the EL space patterns. They are regarded collectively as a low level of background noise.

Conclusions. Relative to these three phenomena, the following are the principal conclusions.

(a) Shadowing is unavoidable in a microwave system, but a deep shadow is caused only by a large building that happens to be located within some small fraction of the airport area. Its effect is stable and predictable.

(b) Reflection, in various amounts, is the principal cause of multipath effects. A large hangar door or a large tail fin is a reflector of some concern. An appreciation of the properties of reflectors forms a basis for evaluating and reducing the problems, as described in other sections.

(c) Diffraction, as separated from shadowing and reflection, does not cause appreciable multipath effects.

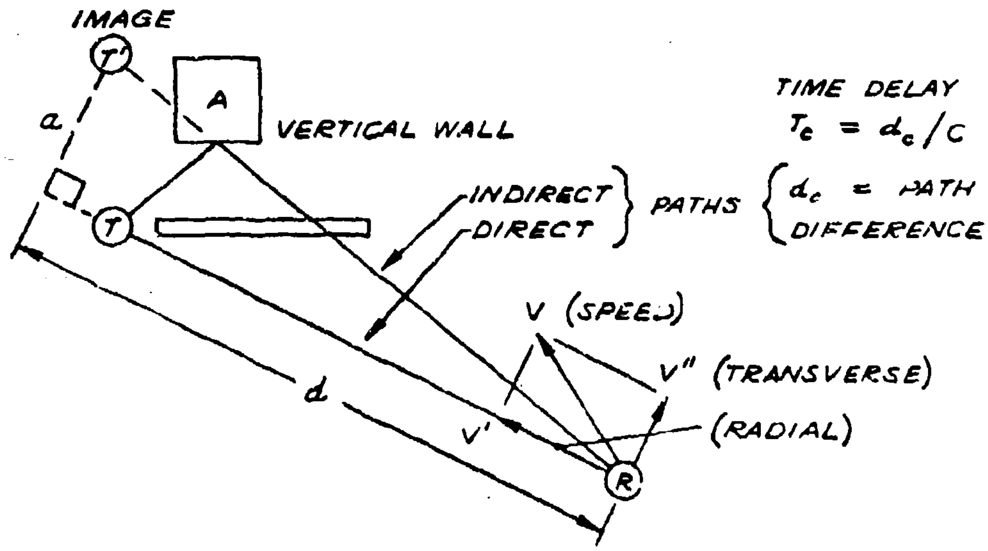
5. Path Difference and Motion.

In comparing indirect and direct paths of signal from transmitter to receiver, the amplitude ratio and angles have been considered, as well as the duration of traversal of a reflection cone. Here we shall consider two other quantities that affect the angle decoding in more subtle ways. These are the path difference and the path-difference speed. The latter causes a change of multipath error from scan to scan in a Doppler format, within one guidance function period. This change permits averaging so as to substantially reduce the multipath errors, as discussed in Part 12.

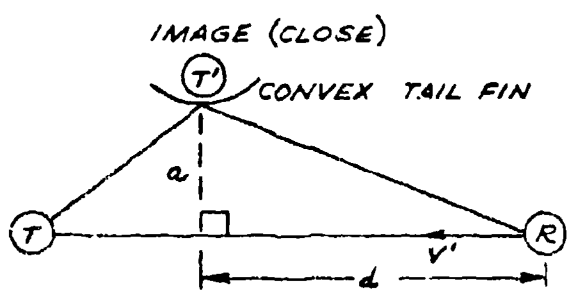
The path difference in multipath is the difference by which an indirect path is longer than the direct. Referring to Figure 6-17, it is expressed in length (d_c) or the equivalent time delay (T_c). It is relevant to the modulation envelope (AM or PM) of the angle coding of the radiated signal (carrier and sideband), as distinguished from the carrier phase.

The long-wave behavior refers to the space wavelength of the angle-coding modulation envelope. Its frequency is about 100 KHz (f_o or nearby) so its wavelength is about 3 Km or 10 Kft (λ_o). If the path difference is even a small fraction of this wavelength, this phase shift is reflected in the angle error caused by the indirect signal. This will appear in the error formula.

The path-difference speed is the rate of change of the path difference with time, as described in Figure 6-17. It is the difference of the velocity components in the directions from which indirect and direct signals reach the receiver. The path-difference speed (v_p) can be expressed as a path-difference frequency ($f_p = v_p/\lambda$). Its effect is related to its ratio over the frequency beamwidth so it is helpful to express its value in BW. It is here defined to



(a) **Vertical Wall.**



(b) Convex Tail Fin.

$$\text{PATH-DIFFERENCE SPEED} = V_p = V' \underbrace{\frac{a^2}{a^2 + 2d^2}}_{\text{(APPROX.)}} - V'' \underbrace{\sqrt{\frac{a^2}{a^2 + d^2}}}_{(\rightarrow a/d)}$$

$$\text{PD FREQUENCY} = f_p = V_p / \lambda$$

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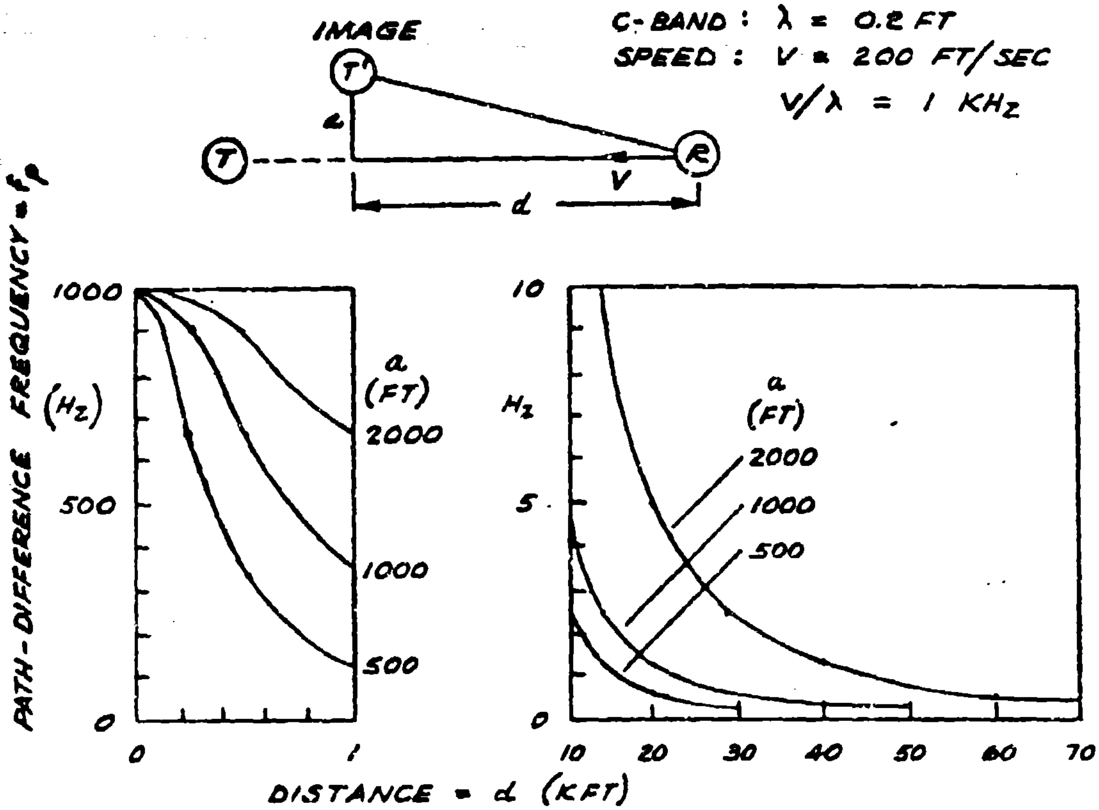
Figure 6-17. Path-Difference Relations for Images in Certain Reflectors have a positive value with increasing path difference, as when approaching the transmitter on a radial path.

The path-difference frequency at the receiver is the frequency of its crossing the hyperbolic space pattern of interference between direct and indirect signals. This becomes one of the significant quantities in the multipath error formula to be given. It is the basis for motion averaging to reduce the error.

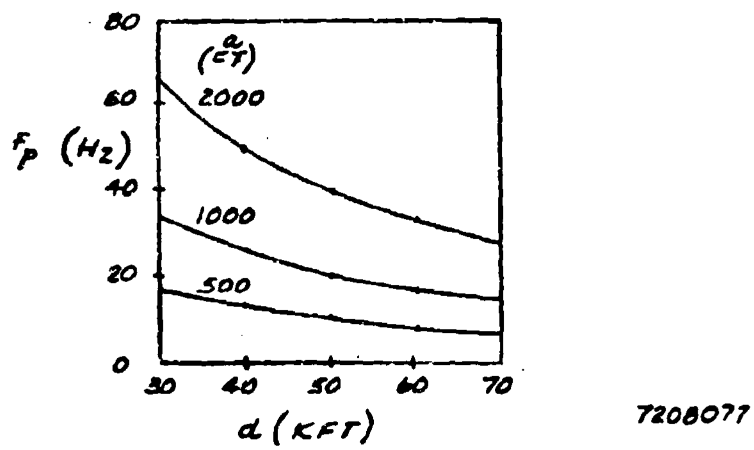
From the formulas in Figure 6-17, the graphs in Figure 6-18 show the variation of path-difference speed with location on the flight path. The frequencies (f_p) are between 0 and 1000 Hz, the latter being 3 BW in AZ or 1 BW in EL-1. Near the transmitter, this frequency may be one or more BW. Far from the transmitter, it is much smaller, especially on a radial path.

As will appear, there is particular significance to the crossing of multiples of the sampling frequency (such as 7 Hz).

The path-difference frequency, and its changing relation to the sampling frequency, tend to cause some cyclic variations in the time profile of the residual error. This will receive further attention.



(a) Radial Path (AZ Centerline).



(b) Transverse Path (AZ).

Figure 6-18. Path-Difference Frequency for Radial and Transverse Paths

6. The Proposed Method of Problem Reduction.

In the order of signal flow, these are the principal features proposed for reducing the multipath problem:

(a) Filtering in space. The radiators will be designed to strongly illuminate the required sectors but with reduced amplitude in other directions. Also to emphasize the AZ carrier near the centerline.

(b) Detection with a STALO instead of the received carrier. This option is available for avoiding any residual errors that might be caused by motion through the carrier interference pattern.

(c) Filtering in angle-coding frequency, before the limiter. A few specialized but simple prefilters will be designed and one at a time will be selected by a simple logic in operation.

(d) Capture in a limiter. This feature enables instant selection of the strongest (direct) angle-coding frequency over any weaker (indirect) interference.

(e) Multiscan motion averaging. This result of the Doppler multiscan system greatly reduces some multipath errors that might be caused by indirect signals whose angle coding differs from the direct by a fraction of one beamwidth. (So-called "in-beam" or "near-beam" multipath.)

(f) Self-tracking digital narrowband postfilter. This option is available for further reduction of any residual errors from different angle tones.

The limiter and the capture effect (d) will be discussed next, because it is a reference for all other features.

7. The Limiter and the Capture Effect.

The capture effect in a limiter is a well-known phenomenon which is here utilized for a specific purpose. It is used for instantly subordinating a weaker (indirect) signal to the stronger (direct signal). This is one of the principal features of the Doppler MLS.

The limiter is here regarded as a circuit which identifies zero-crossings to the exclusion of other properties of a signal, so the zero-crossings can be counted and timed for measurement of the average frequency over an interval. If one frequency component exceeds the sum of all others, it is known that this frequency becomes the average frequency of the zero-crossings.

This is termed the "capture effect". It is effective here for instant identification of the strongest (direct) signal. Referring to Figure 6-3, this phenomenon is illustrated. The weaker signal does not affect the number of zero-crossings. It does cause a phase perturbation which may cause some error in timing at the ends of the count.

Any reduction of the ratio of indirect/direct signals is most effective if it can be implemented ahead of the limiter. Then it contributes also to the margin of capture in the limiter. Space-pattern and frequency prefiltering are examples of this. Any remaining errors caused by indirect signals of different angle-coding can be further reduced after the limiter by frequency postfiltering.

8. Filtering in Space and Frequency.

As previously mentioned, prefiltering ahead of the limiter is doubly effective because it contributes also to the margin of capture in the limiter. Several patterns are shown in Figure 6-2. They fall in two classes:

(a) Space-pattern prefiltering.
(b) Frequency prefiltering.

They are applied differently for AZ and EL functions in MLS.

AZ carrier. Figure 6-2(a) shows a space pattern for emphasizing the carrier near the centerline. This gives extra assurance that the received carrier will be reliable for reception near the centerline where needed most. There are no strong reflections near centerline, so all indirect signals are reduced to 1/2. Therefore any interference pattern cannot have deep valleys.

AZ sidebands. Figure 6-2(b) shows three prefilter patterns in terms of angle-coding frequency bands. These optional fixed filters have two features:

(a) When the receiver is off to one side, before reaching centerline, the proper half-sector filter is switched in (from knowledge of the receiver location). This filter protects against any indirect signal reflected from the opposite side. As previously mentioned, the latter includes any reflection from a vertical wall close to the runway and parallel thereto.

(b) When the receiver is near centerline for glide slope, flare-out and touchdown, the narrowband centerline filter is switched in. This gives greatest selection against any indirect signal coded for either side of the runway.

EL-1(LO) carrier and sidebands. Referring to Figure 6-2(c), the space pattern of the fan beam is shaped to provide the needed coverage and is much reduced outside this sector. As a result, it avoids full illumination of the nearest hangars. (Also aircraft on the adjacent taxiway, except near the end of the runway.)

EL-2 carrier and sidebands. Again referring to Figure 6-2(c), the space pattern of the fan beam is shaped to provide the needed coverage and is much reduced outside this sector. As a result, it avoids full illumination of the nearest hangars, also the nearest aircraft on the adjacent taxiway.

Here it appears that space and frequency filtering may meet with different opportunities for carrier and sidebands, and for AZ and EL functions. In each case, the proposed feature reduces the multipath problem in a manner that is needed but not available by any other means.

Tracking narrowband prefilter. This is a recognized option which offers further reduction of an indirect signal coded for a different angle. It is most useful in the AZ function. Following the half-sector filter, it can select the direct signal over an indirect signal coded in the same half-sector. It requires special care in acquisition and tracking.

Time-domain postfilters. This class includes three features, the first of which is inherent in the proposed system.

(a) Multiscan motion averaging.
(b) Self-tracking narrowband digital postfilter.
(c) Sample-smoothing digital postfilter.

Each of these will be discussed in subsequent sections.

The proposed filtering. The proposed baseline system for the K configuration includes the following filtering:

(a) Space patterns shown in Figure 6-2.
(b) AZ fixed prefilters shown in Figure 6-2.
(c) Multiscan motion averaging.

9. Self-Tracking Digital Narrowband Filter.

Some kind of tracking narrowband filter in the receiver is one technique available for reduction of a multipath error on the basis of frequency selection. It is effective if the angle coding of indirect and direct paths is separated by a frequency difference exceeding one or two beamwidths (BW). The self-tracking digital postfilter is such a technique. It is a computer-type time-domain filter that can be incorporated in the frequency-measuring process as part of the angle decoder, see Figure 6-3. It is a natural modification of the decoder using counting and timing in every scan. Its function is complete in each scan.

In the Hazeltine proposal [2] this digital filter was described and suggested for further consideration. It will be described here in more detail, with an improvement which makes it self-adapting to any period of scan. It is not needed in the baseline system described herein, but it is available for further refinement if desired. In the rejection of indirect signals in terms of frequency difference, it offers slightly less discrimination for a small difference and much more for a large difference.

The following comprises the presentation included in the previous proposal, followed by more recent material relating to the implementation and performance of this filter.

<u>Digital filter.</u> The digital counter and timer in the receiver can be programed to perform the function of a narrowband filter that is self-tracking with the major frequency component, as a result of "capture" in the limiter. This process is analogous to tapering the aperture excitation of the antenna for suppressing sidelobes. The reasoning behind such a process will be outlined, then the manner of implementation and the extent of error reduction that

is readily obtainable. This computer filter differs from a physical narrowband filter in that it is free from "minimum-phase" delay and distortion, so the scan timing is retained.

Aperture taper. In presenting the Doppler scan, direct tapering at the aperture has been proposed, as a matter of principle, for suppressing sidelobes of the frequency spectrum. However, such tapering has no effect if the signal is to be decoded (without narrowband selection) by crossover counting and timing. The amplitude is ignored and the signal is usually passed through a limiter beforehand. The digital filter is a process for obtaining (after the limiter) some of the benefit usually associated with the principle of aperture tapering. In each scan, it is able to decrease the angle error of decoding, caused by a weaker reflected signal carrying a different frequency of angle coding and/or path-difference speed.

The self-tracking feature of the digital filter. Being located after the limiter, this filter operates on the direct-signal (stronger) frequency component that has "captured" the limiter. It performs a frequency averaging computation analogous to the time-integration in a narrowband filter, and the result is similar. However, the digital filter after the limiter inherently tracks the direct-signal frequency, irrespective of its initial value or even any "chirp" during a scan period. This yields a major simplification relative to a tracking filter before the limiter. (Being situated after the limiter, the digital filter naturally cannot protect the decoder from a reflected signal stronger than the direct-signal.)

The viewpoint of phase modulation. The (weaker) reflected signal, at a slightly different frequency, causes phase modulation at the difference frequency, as explained with reference to Figure 6-3. Some examples of this modulation are shown in Figure 6-19(a). A reflection coefficient, $\rho = 1/2$, is taken for these examples, so

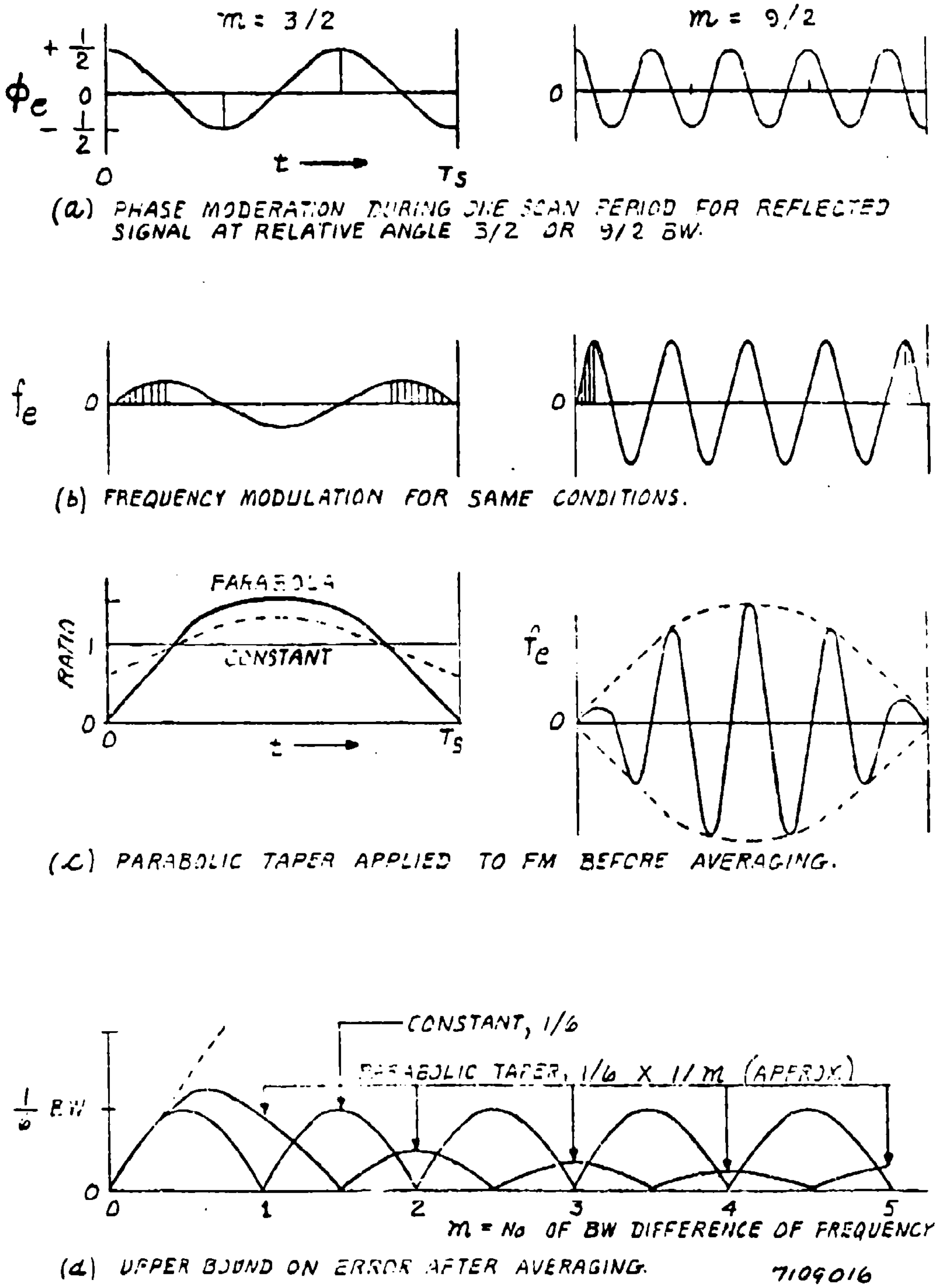


Figure 6-19. Measurement Error in Decoding, Caused by a Reflected Signal at an Angle Difference of M Beamwidths (Reflection Coefficient $\rho = 1/2$)

the phase modulation alternates within ± 1/2 radian. For m beamwidths (BW) of frequency difference, the phase modulation progresses m cycles (m × 2π radians) over the scan period (T_s). The two cases shown are for odd-half numbers of beamwidths of angle and frequency difference (3/2 and 9/2). The timing of this wave relative to the scan period is an accident of space geometry, including motion. The timing shown is that which gives the greatest phase difference between the end points. This is an upper bound on the phase error observed in the simple process described with reference to Figure 6-3. The amount of phase modulation is the same for any number of cycles (m).

The viewpoint of frequency modulation. The decoder is intended to respond to the coding frequency, which is the average frequency. Averaging is needed if there is any "chirp" on the angle coding. In any case, it is needed here to decrease the ability of the indirect signal to cause an error in measurement. Figure 6-19(b) shows the frequency modulation corresponding to the phase modulation (a). The amount of frequency modulation is proportional to the difference frequency (f_m) or the corresponding number of beamwidths (m) of angle separation. Averaging this modulation over the scan period leaves a residual error indicated by the shaded quadrants. This area is the same for any m and is greatest for odd-half values as in the examples. The time integral of 2πf gives ϕ. Therefore this area corresponds to the 1/2 radian of ϕ in (a).

Ordinary frequency averaging. Here we see that the simple counting and timing decoder (Figure 6-3) is equivalent to averaging the frequency modulation. It leaves an error of frequency measurement in proportion to 1/m of the extent of frequency modulation. This may be regarded as the result of averaging out all except a fraction of one cycle in the m cycles of modulation. The residue cannot exceed 1/2 of one cycle. The counter and timer may be regarded as averaging the "instantaneous" frequency measurements of all intervals between successive counts. Equal weight is given to every interval, which has the effect of ignoring the timing of all intervening crossovers and giving weight only to the lapsed time from the first to the last crossover. This process ignores much information that is available, namely, the timing of all intervening crossovers.

Weighted frequency averaging. In antenna aperture theory, sidelobes may be decreased by tapering the excitation over the aperture. The sidelobe reduction is the mathematical result of weighted averaging of all parts of the aperture. In the Doppler scan, the aperture excitation is scanned in time, so tapering or weighting may be achieved by a variation with time. In the counter and timer, this may be accomplished by applying a tapering or weighting factor over the scan time, as shown in Figure 6-19(c). As an alternative to the constant weighting, a parabolic taper is shown. In the computer, in principle, this weighting factor is applied to "instantaneous" frequency measurements in all counting intervals. With this weighting factor, the FM is then averaged. This average gives weight to the timing of all crossovers. Especially, the end quadrants no longer have a controlling effect on the average.

The resulting reduction of residual error. With reference to Figure 6-3, it has been stated that the ordinary counting and timing decoder leaves an error which has an upper bound of 1/6 BW. In Figure 6-19(d) the sine curve shows how the upper bound of this error goes through cyclic variations with angle. The corresponding upper bound is shown for the parabolic taper. Its envelope decreases in proportion to 1/m, as compared with the level envelope for constant weighting (no taper). The ratio of these two curves is the same as that of sidelobes for corresponding aperture excitations. The error reduction is substantial, since m may be as great as 60 BW from zero angle (broadside) or even 120 BW from an extreme side angle. In either case, the RMS error (over all equally probable conditions) is 1/2 the sidelobe envelope.

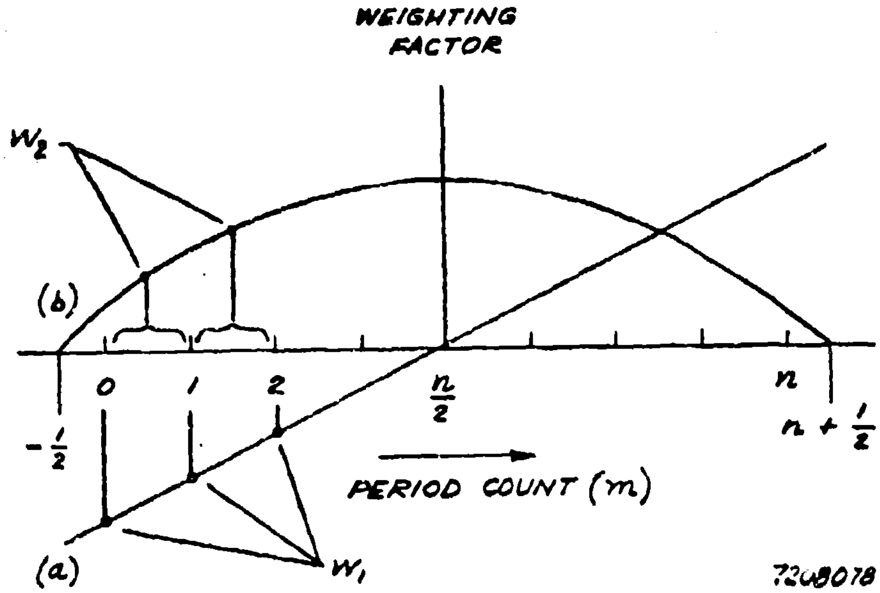
The filter effect obtained by a digital computer. The weighting function is the time-domain description of the equivalent frequency filter. Either weighting factor gives the following effects if $m > 1$:

	Constant	Parabolic
Equivalent frequency filter, sidelobe envelope proportional to	$1/m$	$1/m^2$
Angle decoding error (in beamwidths) not exceeding	1/6	$1/6m$

The optimum taper. The taper is seen to increase the error slightly if $m < 5/4$. For large m, the parabolic taper decreases the error further than needed. It may be preferable to use a fractional taper, as graphed by the dashed line in Figure 6-19(c). If the ends are 2/5 the middle weighting, as shown, the error envelope is the average of the two graphs (with due regard for sign) and levels off at 1/12 BW. By applying this freedom, the envelope may be leveled off at any fraction of 1/6 BW, and the increased tolerance of far sidelobes yields the advantage of decreasing the error near $m = 1$.

The decoder computer algorithm. The constant weighting is accomplished by the simplest computation. The parabolic taper is a routing variation but might pose a problem in anticipating the duration of computation in a particular scan. The following presents an algorithm for computing with the parabolic taper in a manner that can be stopped at any count. It is simple enough to be attractive for the system decoder. Figure 6-20 gives the basis for this process.

The problem of a scan period of unspecified duration. In the MLS receiver, the decoding process may be designed to be self-adapting to any value of the scan period. This is simply accomplished for



(a) $W_1 = \frac{6\,(2m - n)}{n(n+1)\,(n+2)}$

(b) $W_2 = \frac{6\,(n - m + 1/2)\,(m + 1/2)}{n(n+1)\,(n+2)}$ HERE M IS ODD-HALF-INTEGER

(a) Linear weighting factor (W_1) to be applied to lapsed time (t_m) at each count.

(b) Parabolic weighting factor (W_2) to be applied (effectively) to the period at each count.

Figure 6-20. The Relation Between the Two Weighting Factors over the Time Interval of Counting the measurement of average period of the coding frequency, because it is the quotient of period count over time count, the former being started just after the beginning and stopped just before the end of the scan period. However, the filter requires a computation subject to a weighting factor which varies in a prescribed manner over the scan period. For this weighting factor, there is just one form of taper which is naturally adaptable to continuous computation without prescribing the scan period. It is the parabolic taper, as will be described.

The parabolic taper of the weighting factor. This taper is analogous to a familiar form of aperture taper in the science of beam-forming radiators (for example, microwave-relay antennas). It comprises a parabola between zeros, as shown in Figure 6-20, or perhaps added to a constant ("pedestal"). The latter is a simple variation and will not be mentioned further herein because it is not related to the unusual problem in computation. The parabolic form is ideal here because it has constant curvature and therefore is adapted for continuous computation before the end point is known. No other symmetrical taper has this property. The manner of utilizing this property is the principal subject of this discussion.

Applying the weighting factor in real time. An objective in the present system is the proper weighting of each time observation for immediate summing over the scan period. In principle, the weighting factor W_m is applied to each observation of the period $(\Delta t)_m$ between one crossover and the next. Then the average period is

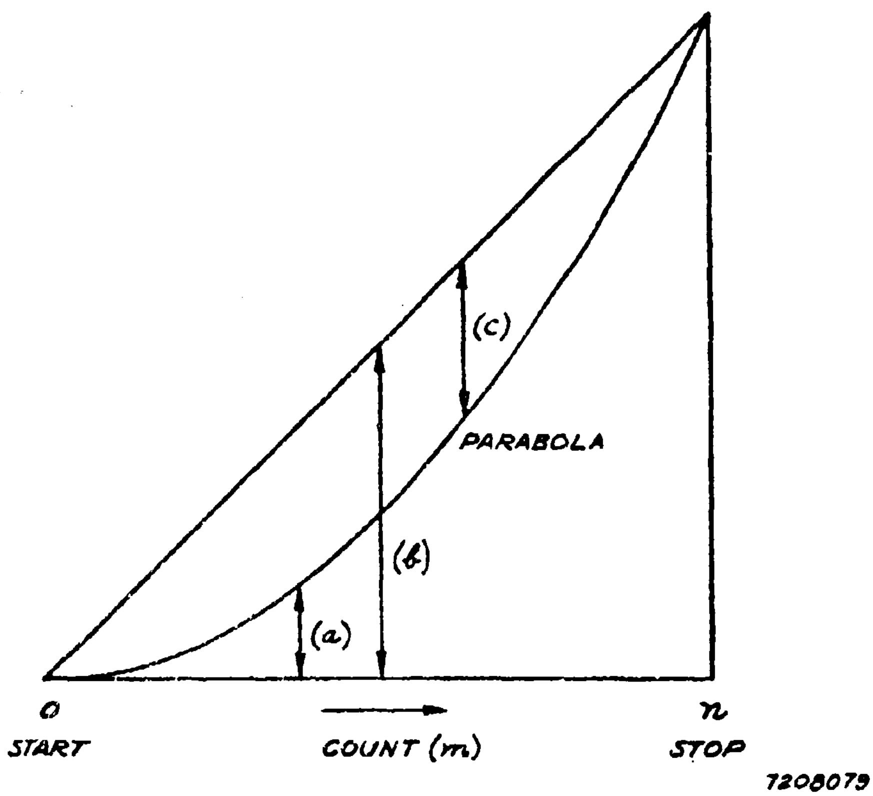
$$\frac{\sum_{1}^{n} {}_{m}\, W_m (\Delta t)_m}{\sum_{1}^{n} {}_{m}\, W_m} \qquad (1)$$

The weighting factor cannot be prescribed over an unspecified scan period, as here. However, it will be shown how two weighted sums can be combined at the end of the scan period, to achieve the same result.

The development of the parabolic taper in real time. Figure 6-21 shows two weighting factors, one parabolic (a) and the other linear (b). Both may be applied continuously with arbitrary scale factors and the weighted sums accumulated in separate registers. If the time observations yielded a constant period, the areas (a) and (b) would represent these sums. At the end of the scan, either or both of the scale factors is adjusted to equalize the two weighting factors at that point, as graphed in Figure 6-21. Taking the difference of these two sums is then equivalent to a retroactive application of the difference of the two weighting factors, which is a parabola between two zeros(c). In effect, this is to be applied as a tapered weighting factor in summing and averaging the observations of the period between one cross-over and the next.

The practical application of the parabolic taper. Instead of observing the period (Δt) at every count (m), and then applying the two weighting factors (a) and (b) in Figure 6-21, a simplification is found in a different procedure. It is based on observing the lapsed time (t_m) from zero (at m = 0) to each count (m). In effect, the summation of the lapsed times inherently provides a linear weighting factor by repeated addition of the earlier periods. This principle will be implicit in the procedure to be described. Another linear factor on the lapsed time provides the effect of a parabolic weighting factor.

The weighted average of all periods. First we shall state the selected weighting formula and summing from observed periods, because this is the principle to be implemented. Figure 6-20(b) shows this taper as a parabola between two zeros. The location



(a) Cumulative parabolic weighting factor.

(b) Linear weighting factor based on end points only, computed at end of interval.

(c) Difference representing the required parabolic taper.

Figure 6-21. The Development of a Parabolic Taper in Real Time over an Interval not Specified in Advance of these zeros is chosen to give equal weight to all time observations (t_m at m = 0 to n). If n is large, as is expected, this choice is not critical to performance, but it does yield the simplest computation in the end. Here we identify the periods with odd-half-integral values of m, then the weighting factor may be expressed as

$$W_2 = \frac{6(n-m+1/2)\ (m+1/2)}{n(n+1)\ (n+2)} \tag{2}$$

In the numerator, each factor provides one of the two zeros. The constant scale factors will be explained further on. The weighted average period is then

$$\frac{\sum_{m=1/2}^{n-1/2} W_2(\Delta t)_m}{\sum_{m=1/2}^{n-1/2} W_2} \tag{3}$$

in which $(\Delta t)_m \equiv t_{m+1/2} - t_{m-1/2}$.

The choice of scale factors in (2) makes the denominator in (3) equal to unity (see Dwight 29) so

$$\text{average period} = \sum_{m=1/2}^{n-1/2} W_2(\Delta t)_m \tag{4}$$

From this will be derived what is believed to be the simplest procedure for computation.

A simple formula for computation from observations of lapsed time. From (3) we shall derive a weighting factor, W_1 in Figure 6-20(a) which can be applied directly to the lapsed time. We require an unusual translation from the odd-half integral to the integral values of m. The principal factors in the numerator of (3) are here written in full,

$$(n-m+1/2)\ (m+1/2)\ (t_{m+1/2} - t_{m-1/2}) \qquad (5)$$

For each integral value of m, the time t_m is multiplied by the difference of two factors from the above. First, for m+1/2 substitute m; secondly, for m-1/2 substitute m:

$$[(n-m+1)\ (m) - (n-m)\ (m+1)]\ t_m = (2m-n)\,t_m \qquad (6)$$

Therefore we may formulate

$$\text{average period} = \sum_{\substack{o \\ m}}^{n} W_1 t_m \quad ; \quad W_1 = \frac{6\,(2m-n)}{n(n+1)\ (n+2)} \qquad (7)$$

in which W_1 corresponds to the formula and graph in Figure 6-20(a). This linear weighting factor applied to the observations of lapsed time has a simple significance in computing the average period. The times for low counts are subtracted from the times for high counts and this difference is translated to the average period. Some weight is given to every observation of time.

Measurements for computation. Figure 6-22 shows first the observations which are needed for the computations.

(a) From the receiver, the coding frequency is put through a limiter and crossover detector which delivers a pulse for every crossover to be utilized. This may occur every 1/2 cycle or one cycle or some small number of cycles, depending on the fineness required.

(b) From the receiver, the start and stop signals are derived from the scan transmission. They command the period counter to start or stop.

(c) The clock oscillator is used with a counter to evaluate the lapsed time from the initial (zero) crossover to each of the succeeding crossovers.

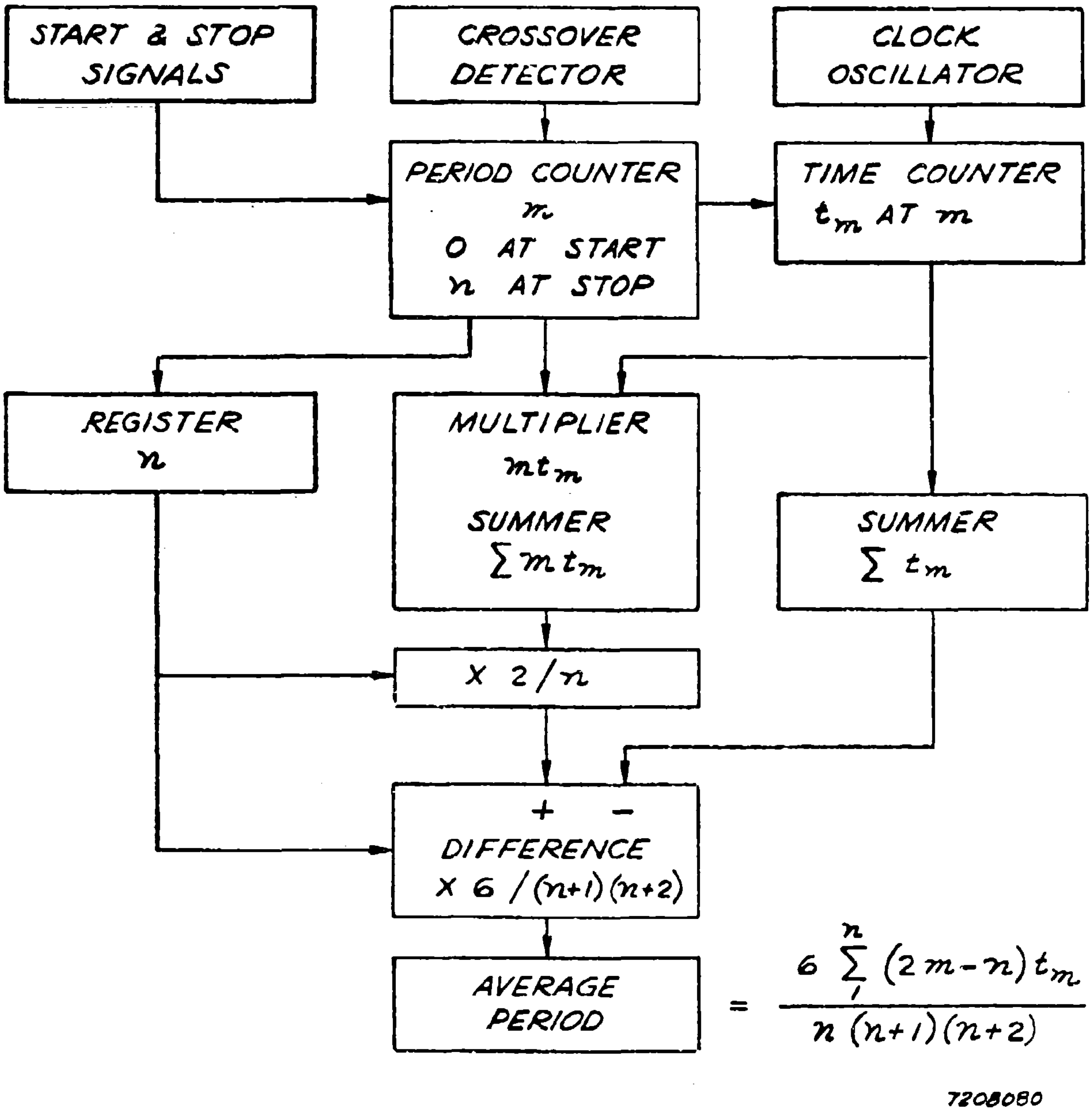


Figure 5-22. The Measurements and Computations for the Average Period

(d) At the stop signal, the last count (m) is identified (n) and stored for computations.

A procedure for computation. Figure 6-22 shows also a computation procedure in accordance with (7). In the numerator there are two parts:

(a) t_m is summed in process.

(b) mt_m is summed in process, then the sum is multiplied by 2/n at the end.

These correspond to (a) and (b) in Figure 6-21, but are not strictly parallel. Their difference is utilized for final computation of the average period. This procedure is completed in one scan. If multi-scan averaging is used, that should be a separate computation.

Symbols for computation of performance.

n = number of counts in one scan period
m = cycle count of crossovers (0 to n)
t_m = lapsed time from 0 to m count
T_s = scan period
T_a = count period computed by simple average (constant weighting factor)
T_w = count period computed by weighted average (parabolic taper)
f_1 = $1/T_s$ = frequency beamwidth (BW)
Δf = frequency difference of indirect and direct signals
k = $\Delta f\, T_s = \Delta f/f_1$ = frequency difference in BW
= number of cycles of relative rotation during one scan period
ρ = amplitude ratio of indirect/direct signals (small, say < 1/2)

Note (m): While defined as one count every 2π radians, it may be any number of π; it is to be regarded as a continuous variable over many counts (n) filling one scan period.

Note (Δf): This frequency difference may be caused by frequency coding at a different angle and/or Doppler shift by path-difference speed; it is regarded as constant during one scan.

Note (ρ): This is equal to the phase modulation (fraction of a radian) caused by the superposition of the indirect signal (ρ) on the direct signal (1) with some frequency difference ($\Delta f = kf_1 = k$ BW).

The direct and indirect signals, out of the crossover detector. Over the period of one scan, the crossover timing is taken to be perturbed by the phase modulation caused by the indirect signal, as follows:

$$t_m = \frac{1}{n} T_s (m + \frac{\rho'}{2\pi} \sin 2\pi km/n + \frac{\rho''}{2\pi} \cos 2\pi km/n) \tag{8}$$

The amplitude ratio is divided between two parts in quadrature:

$$\rho = \sqrt{\rho'^2 + \rho''^2} \tag{9}$$

The ratio between the parts is determined by the phase difference at the start of the scan period. The angle of relative rotation is k cycles during n counts. The rotation is taken to be proportional to the count. This is a close approximation in the range of interest, namely, a frequency difference much less than the coding frequency being counted.

The computation with constant weighting factor. As a reference, the computation is here performed without a taper. This is the simple counting-and-timing (TIC) method. The average period of count is

$$T_a = \frac{1}{n}(t_n - t_o) = \frac{1}{n}(\frac{1}{n} T_s)[n + \frac{\rho'}{2\pi} \sin 2\pi k + \frac{\rho''}{2\pi}(\cos 2\pi k - 1)]$$

$$= \frac{1}{n} T_s [1 + \frac{1}{n\pi}(\rho' \cos \pi k - \rho'' \sin \pi k) \sin \pi k] \tag{10}$$

Since one count is known to correspond to one BW, the error in BW has this frequency envelope for all values of initial phase angle:

$$\frac{\rho}{\pi} \sin \pi k \tag{11}$$

The computation with parabolic weighting factor. Following the procedure above, we substitute for the step summation (7) a continuous integration. Then the weighted-average period of count is

$$T_w = \int_0^n W_1 t_m d_m = \frac{6}{n^3}\int_0^n (2m - n) t_m d_m \tag{12}$$

Performing this integration and again expressing in terms of the half-angle πk,

$$T_w = \frac{1}{n} T_s [1 - \frac{1}{n\pi} \frac{3}{\pi k}(\rho' \cos \pi k - \rho'' \sin \pi k)(\cos \pi k - \frac{1}{\pi k} \sin \pi k)] \tag{13}$$

Here the error in BW has the frequency envelope,

$$\frac{\rho}{\pi} \frac{3}{\pi k}(\cos \pi k - \frac{1}{\pi k} \sin \pi k) \tag{14}$$

See Figure 6-19. The envelope of the frequency envelope, which is ρ/π in (11) without taper, is here multiplied by

$$\frac{3}{\pi k} \sqrt{1 + (1/\pi k)^2} \tag{15}$$

This factor may be used to indicate the amount of reduction of the error by the tapered filter. For a frequency difference of k BW, if $k > 1$, this envelope is about $1/k$. This is similar to the effect of one added resonance.

The limiting case of small frequency difference. If the frequency difference approaches zero, the frequency envelope approaches a constant slope that is independent of the weighting factor. In both (11) and (13), the frequency envelope of the error (in BW) becomes ρk. This value has mathematical significance for checking the relative coefficients of different formulas. It has little practical significance, because this amount of error is so small.

The RMS error for various conditions. Under the envelope of the frequency envelope, there are two sinusoidal variations whose phase may be regarded as accidental if $k > 1$:

(a) The initial phase difference, related to ρ'/ρ''.

(b) The cumulative phase difference over one scan, $2\pi k$.

Then, the RMS value ("one sigma") is 1/2 the envelope of (11) or (14).

The effect on the error caused by random noise. The frequency envelope for the filter multiplies the random-noise modulation by the factor (14) instead of the corresponding factor (11). This factor has a constant envelope over the frequency spectrum. The filter factor has a frequency-selective envelope (14) which may be compared with (11) to state its effective bandwidth. One easy method of computation is to sample (14) squared at every half-integral value of k and sum the two series (Dwight 48.002 and 48.14). Referred to the average frequency density of (11) squared, the effective (noise) bandwidth of the filter is 6 BW or ± 3 BW from zero. The result of the filter is a reduction of noise error in the ratio

$$\sqrt{\frac{6}{\text{no. of BW of coverage}}} \tag{16}$$

The denominator may be between 20 and 120, in which case the noise error may be reduced by a factor between 0.55 and 0.22. This rule is applicable during the time that the noise is weaker than the resultant of direct and indirect signals, before the limiter and therefore before this narrowband filter.

Comments. The computer-type filter is evaluated to show its effect in reducing the measurement error. The error caused by an indirect signal is reduced if the frequency difference is greater than about 5/4 BW, as appears in Figure 6-19(d). The ratio of reduction is about what one would expect from adding one resonance in a filter. The filter is essentially a computer implementation of the socalled "transversal filter" used for time-domain synthesis of a frequency-selective filter. Here the signal to be filtered is one-dimensional (time only, not amplitude) so the computation is simplified.

10. The Residual Errors.

General. The problems relating multipath and shadowing have been described in terms of the situations in which they may arise, and the remedies that may be available. Here we shall review these situations and arrive at some numerical values that may be representative of the remaining problems and the residual errors.

Shadowing. There are some locations where shadowing may be present, so the MLS signal will not reach the receiver with sufficient amplitude and purity. These are predictable situations, which may be present in some AZ paths far from centerline but not in EL paths. The MLS cannot be relied on if the receiver is in shadow, so the concept of residual errors is not applicable.

Multipath before filtering. There have been described, various situations where a substantial indirect signal may be reflected in some direction within the coverage region. (Each such case is usually associated with a shadow in another direction.) If the indirect signal is weaker than the direct, which is nearly certain, we can rely on these properties of the Doppler system:

(a) The reference carrier will remain intact, though it may be subject to contamination.
(b) The angle tone will be identified, though it may be subject to an error in decoding.
(c) Whatever angle error may be caused by multipath, it will be less than one beamwidth, and typically much less in view of the probabilities of several reducing factors.

It is concluded that the angle observed without selective filtering is nearly certain to be close to the correct angle, so it could be relied on for placement of a filter having a bandwidth at least as great as several beamwidths. This is true of the fixed filters that are here proposed for reducing the multipath problem.

Space filtering for the reference carrier. Except for shadowing, there is adequate assurance of the integrity of the reference carrier in all directions of coverage. This includes the proposed space filtering of the radiation for emphasis of the carrier near the centerline direction, to give extra assurance against carrier contamination in this direction. This should avoid appreciable carrier-related angle error in this most critical region. There will be further mention of such error, adding further assurance that it is not appreciable.

Fixed prefilters for the angle tone. Each of the proposed prefilters admits a fixed frequency band including a half-sector or a narrow angle near centerline. The prefilter is located ahead of the limiter, as an extra protection against temporary capture of the limiter by a stronger indirect signal. Such an occurrence is unlikely but conceivable, perhaps as a coincidence of different indirect signals in some region of space. The prefilter inherently serves to protect against angle error from an indirect signal outside its passband. A moderate amount of attenuation (say 1/4 to 1/16) is sufficient to fully protect against capture and against appreciable error from directions outside the passband. (In this evaluation, there is no tracking prefilter or self-tracking digital postfilter, because there is little or no remaining need that might justify the extra cost in the receiver.)

Inbeam multipath. In some cases, the indirect signal may be coded for an angle only slightly different from the direct signal. This is extremely unlikely for any strong indirect signals in AZ, but the EL coding is inherently susceptible to inbeam multipath when the receiver is at a small height. In such a case, frequency filtering is ineffectual but space filtering is proposed for angle sidebands as well as the reference carrier. Also motion averaging is found to be effectual in this situation. Near-beam and inbeam multipath will here receive special attention, leading to the conclusion that the proposed measures will hold the residual errors well within tolerance.

A cyclic time profile of error. In various ways, the time profile of a residual error may be cyclic at a frequency such that the error tolerance is decreased. This may result from:

(a) receiver motion through the multipath interference pattern in space;
(b) the correlation of this interference frequency with the sampling frequency of angle data.

These considerations will be included where relevant.

Evaluation of residual errors. The error eventually appears in a time profile where its significant characteristics are:

(a) amount,
(b) form,
(c) duration,
(d) timing of occurrence in the flight path,
(e) probability of occurrence.

A few examples will be given with reference to these factors.

A relation between RMS and upperbound values. A numerical estimate usually involves considerations of both RMS (one sigma) and upperbound (UB) values. In some cases, the RMS is so much less than the UB that it may be inadequate as a practical evaluation. A rule is here proposed and used, which appears to be helpful in such a case, as follows:

(a) If the RMS value is less than 1/4 the expected UB value, then 1/4 the UB is stated as the RMS value.

In recent studies, this has appeared to yield a reasonable value for comparison with other values logically computed as RMS. It is justified if we make this assumption:

(b) A tolerance stated in terms of sigma permits an extreme deviation of 4 sigma.

In the normal distribution of errors, exceeding this extreme has a probability of 1/15000. The use of this rule is a safeguard against using the RMS literally in a case where it might give an erron us impression of too small an error.

Numerical values. As will be detailed in Section 14, the multipath residual errors are mostly small in amount and/or probability, as follows:

(a) Near-centerline errors are typically around 0.01 BW (RMS) which is so small that any peculiarities are not important.
(b) Far from centerline, there is a conceivable AZ error of about 0.05 BW (RMS), which is unlikely to occur at all, and any occurrence is a predictable feature of the runway environment.

The next few sections give some rules and formulas used to estimate the errors.

11. The Error Formula.

Purpose. The multipath-error formula to be described here is based on an idealized case so defined as to bring out several factors that are essential and separable in predicting the error. It is intended to be helpful in understanding the Doppler MLS behavior toward multipath and in estimating the residual error. The formula is to be applied after taking into account any space filtering and frequency filtering that may be utilized ahead of the angle-tone frequency measurement (limiter, etc.) in the receiver.

Symbols.

t = time (variable)

$T_s = 1/f_s$ = period of one scan

T_c = time delay of path difference (indirect minus direct) (at $t = 0$ if moving model)

f = frequency (Hz)

$\omega = 2\pi f$ = radian frequency (radians/sec)

ω_c = radian frequency of reference carrier

ω_o = angle coding at zero angle (centerline)

$\omega_{od} = \omega_o + \omega_d$ = angle coding, direct path

$\omega_{om} = \omega_o + \omega_m$ = angle coding, indirect path

$\omega_{md} = \omega_m - \omega_d$ = angle coding difference

ω_p = radian frequency of increasing path difference (carrier radians/sec) (positive on AZ centerline approach)

m = modulation factor of each sideband

ρ = amplitude ratio, indirect/direct paths

S = number of scans in one multiscan

ϕ_c = carrier phase angle relative to average of pair of sidebands

BW = any quantity corresponding to one beamwidth of angle

$A + B + C$ = angle error (fraction of BW)

A = even term, sideband multipath

B = odd term, sideband multipath

C = odd term, reference-carrier multipath

SEDS = sequential dual scan (alternating single-sideband)

SIDS = simultaneous dual scan (double-sideband)

The physical model for the formula. Referring to Figure 6-23, the reference carrier and the angle-coding sidebands are radiated from the ground transmitter (T) and reach the airborne receiver (R) by two paths. The indirect path is off the straight line, by reflection from an obstacle (A). The paths are coded differently:

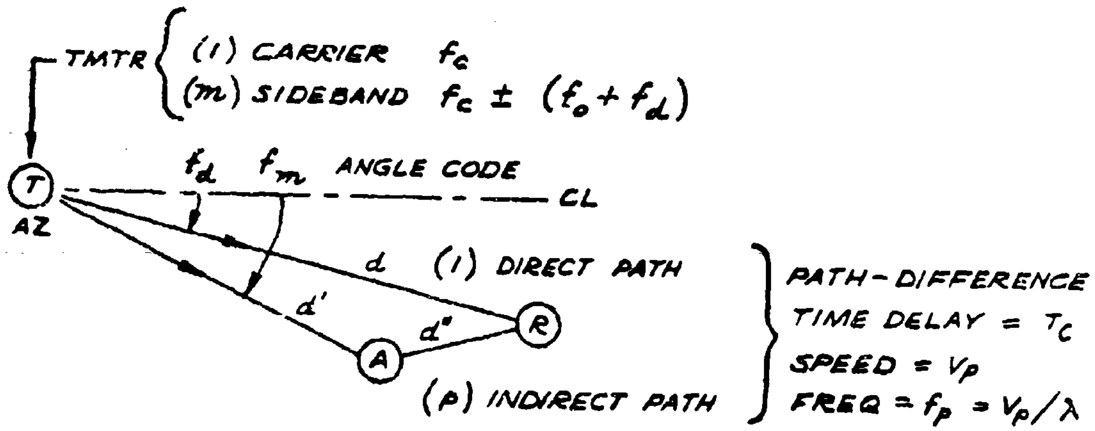
(a) The direct path is coded for the one direction ($f_o + f_d$),
(b) The indirect path is coded for a different direction ($f_o + f_m$).

The angle-coding signal. These are the essential properties of the angle-coding signal in space.

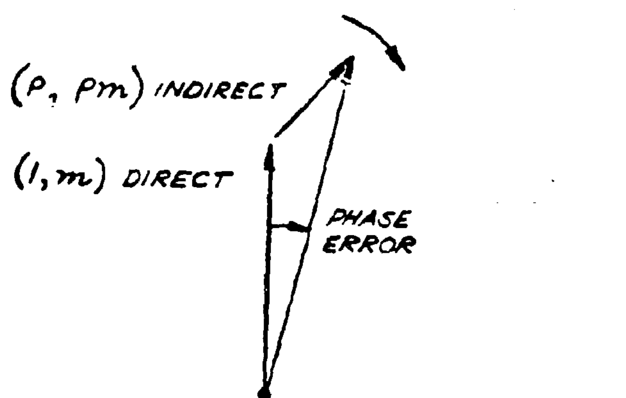
(a) Referring to the description of the signal format, the signal form is SEDS, which is the option proposed in SC-117 and herein. The same formula is also applicable to SIDS by merely removing the terms peculiar to SEDS, as will be noted.
(b) There is a multiscan format comprising S repeating scans, which means S/2 pairs in SEDS.
(c) For simplicity, the radiation of carrier and sidebands is assumed to come from a common phase center, with the same phase at midscan. This is not a condition for validity.

The path difference. The path-difference time (T_c) determines the relative phase of wave arrival. Its variation with motion in time is the path-difference speed (v_p) which is expressed in wavelengths to define the path-difference frequency (f_p). This is usually caused mainly by the motion of the receiver (R) and only incidentally by any motion of the obstacle (A). The time variation of the path-difference speed is negligible during one multiscan, so it is ignored in the formula. This variation will be discussed further on in relation to the sampling frequency.

The frequency measurement. The frequency is measured by uniscan counting and timing in each scan, then summing both over all the scans in a multiscan, then taking the quotient. This yields the



(a) Space, Time and Frequency.



(b) Phase Error.

Figure 6-23. Model for Computation of Multipath Error multiscan average frequency, without any error attributable to granularity in counting.

The direct and indirect signals. Referring further to Figure 6-23, the signals may be expressed as follows:

	Carrier	Sideband (±)	
Direct:	$\exp j(\omega_c t + \phi_c)$	$m \exp j(\omega_c \pm \omega_o \pm \omega_d)t$	(1)
Indirect:	$\rho \exp j[(\omega_c - \omega_p)t - \omega_c T_c + \phi_c]$	$\rho m \exp j[(\omega_c \pm \omega_o \pm \omega_m - \omega_p)t - (\omega_c \pm \omega_o \pm \omega_m)T_c]$	(2)

The expression of multipath phase distortion. For the first-order effects of the indirect signal ($\rho << 1$, say $\rho < 1/2$) we note separately the phase perturbation of each component of the direct signal:

$$\text{Carrier:} \quad \rho \sin(-\omega_p t - \omega_c T_c) \tag{3}$$

$$\text{Sideband } (\pm): \quad \rho \sin[(\pm\omega_m \mp \omega_d - \omega_p)t - (\omega_c \pm \omega_o \pm \omega_m)T_c] \tag{4}$$

These two parts are applied to a product detector, which adds these components of phase perturbation.

The error in uniscan frequency measurement. In one scan, the counter and timer senses a timing error at each end of scan. See Figures 6-23 and 6-3. It may be computed for either sideband (- LSB or + USB). The net error is the difference of the phase perturbations at the two ends, (4) minus (3). This difference is taken over a time interval of one scan (T_s).

The error in sequential dual scan (SEDS). Here the error is computed for two consecutive scans with opposite sidebands. The time intervals are a pair of scans centered on zero time ($-T_s$ to 0, 0 to $+T_s$). The net error is the sum of four pairs of sine terms. These terms give the frequency spectrum but do not give an understanding of the composite behavior. The sum is reduced to a few product terms by separating similar angles into sum and difference pairs, and quadratic factors (cosine and sine). The result will be given as three product terms with separable meanings.

The effect of multiscan averaging. Every scan behaves alike except for the motion frequency ω_p. The average of S scans (S/2 pairs) shows the effect of multiscan averaging, a behavior that is peculiar to the proposed Doppler MLS. The average is obtained by summing a series of S/2 periodic terms equally spaced in frequency.

Relations in terms of physical concepts. Some relations are noted here for simplification and for correlation with physical concepts.

(a) It is easily shown that a phase perturbation of ρ (radians) at one end of one scan may yield an error as great as $\rho/2\pi$ beamwidths in frequency and angle. This error at both ends of one scan may add up to ρ/π. Therefore each pair of phase errors will be expressed as a fraction of one beamwidth, with the coefficient ρ/π.

(b) The direct and indirect coding is reduced to the difference frequency

$$f_{md} = f_m - f_d$$

and $f_{md}T_s$ is the number of beamwidths by which the indirect direction of radiation and angle coding differ from the direct.

(c) The modulation envelope of the indirect signal has the coding modulation frequency

$$f_{om} = f_o + f_m$$

and $f_{om}T_c$ is the number of these cycles in the path difference. This frequency being much lower than the carrier frequency, the envelope in space is a "long wave".

(d) The carrier frequency and the path difference give f_cT_c as the number of wavelengths of path difference. This determines the space pattern of interference of "short waves".

(e) The path-difference motion frequency ($f_p = v_p/\lambda$) and the scan period give f_pT_s as the motion frequency in beamwidths. This will be related to "grating lobes" in multiscan motion averaging.

<u>The multipath error formula.</u> The sum of the following three parts is the multipath error expressed as a fraction of one beamwidth.

(A) Sidebands, even term.

(B) Sidebands, odd term.

(C) Carrier, odd term.

$$A = +\frac{\rho}{\pi}\,\frac{\sin \frac{S}{2}\omega_p T_s}{S\,\sin \frac{1}{2}\omega_p T_s}\,\sin \tfrac{1}{2}\omega_{md} T_s\,\cos(\omega_{om} T_c + \tfrac{1}{2}\omega_p T_s)\,\cos(\omega_c T_c - \tfrac{1}{2}\omega_{md} T_s)$$

$$B = +\frac{\rho}{\pi}\,\frac{\sin \frac{S}{2}\omega_p T_s}{S\,\cos \frac{1}{2}\omega_p T_s}\,\cos \tfrac{1}{2}\omega_{md} T_s\,\sin(\omega_{om} T_c + \tfrac{1}{2}\omega_p T_s)\,\sin(\omega_c T_c - \tfrac{1}{2}\omega_{md} T_s)$$

$$C = -\frac{\rho}{\pi}\,\frac{\sin \frac{S}{2}\omega_p T_s}{S\,\cos \frac{1}{2}\omega_p T_s}\,\cos 0\qquad \sin(0\qquad + \tfrac{1}{2}\omega_p T_s)\,\sin(\omega_c T_c - 0)$$

D	E	F	G	G'	G"	H	H'	H"
AMPLITUDE RATIO $\frac{\text{INDIRECT}}{\text{DIRECT}}$	MOTION AVERAGING FACTOR (S SCANS) < 1 ---- = 1 AT GRATING LOBE	ANGLE CODING FACTOR ---- FREQ. DIF. OF INDIRECT FROM DIRECT	LONG-WAVE FACTOR			SHORT-WAVE FACTOR		
			G'		G"	H'		H"
			LONG-WAVE ENVELOPE IN SPACE ---- SUB-CARRIER FREQ.		MOTION BETWEEN SCANS IN ONE PAIR	SHORT-WAVE INTERFERENCE PATTERN IN SPACE ---- CARRIER FREQ.		ANGLE CODING FREQ. DIF.

(D) This coefficient is the upperbound of each term.

(E) The motion-averaging factor will be discussed further. This factor gives each term the "even" or "odd" designation.

(F) The angle-coding factor reflects the modulation-frequency difference between indirect and direct signals.

(G) The long-wave factor includes (G') the subcarrier modulation-envelope phase delay in the extra path distance of the indirect signal. It also includes (G") the carrier phase shift by motion from one scan to the next.

(H) The short-wave factor includes (H') the carrier interference pattern in space. It also includes (H") the angle-coding phase difference seen also in (F).

The application to SEDS or SIDS. As mentioned above, the formula is derived for SEDS with a product detector responding to the received sidebands and reference carrier. This case requires all three parts. Each part is subject to some simplification in different cases, as follows:

(A) This part gives the entire error for SIDS, because the other two parts reflect the motion between upper and lower sidebands in SEDS. Furthermore (A) is simplified by removing the angles (G") and (H") which also reflect this motion.

(C) This part gives the error that may be caused in SEDS by detection with the received carrier subject to multipath motion contamination. If a STALO (stable local oscillator) at nearly the same frequency is substituted for the received carrier, (C) is excluded.

These simplifications may be summarized:

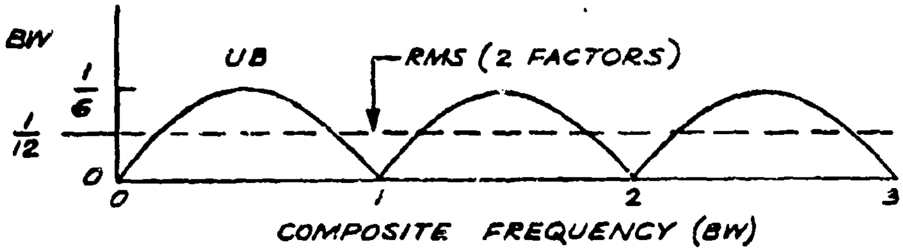
For SIDS, use (A) simplified, delete (B) and (C).
For SEDS with STALO, delete (C).

These simple rules are enabled by the expression of the error in "modal" form, such that (A) and (B) are orthogonal and (C) gives separately the effect of motion contamination of the carrier. In a stationary model, SEDS and SIDS become equivalent so only part of (A) remains. It is seen that the motion effects are essential to the error computation for either SEDS or SIDS.

The motion-averaging factor. A particular feature of Doppler MLS is motion averaging over a multiscan (S scans or S/2 pairs). This factor (E) is less than unity, and may be much less over a range of conditions. It is so important that its peculiarities will be discussed in a separate section.

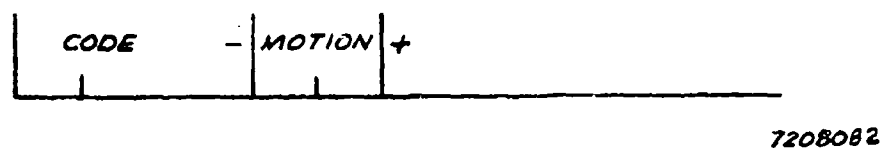
The angle-coding factor. The indirect and direct angle-coding modulation frequencies differ by a number of beamwidths (few or many). The angle-coding factor (E) reflects this difference and is typically accidental in occurrence.

Interaction of coding and motion frequencies. In the "modal" terms of the error formula, the spectral components of the modulation frequency are combined and not separately identified. The path-difference variation may cause the apparent coding frequency to shift oppositely in the opposite (±) sidebands. Figure 6-24(a) shows the angle-coding factor (F) in the first line (A) as it would appear for only one of a pair of scans in SEDS. The RMS level reflects also the short-wave factor (H). In SEDS, the alternate sidebands of the indirect signal are split into a pair of modulation frequencies, which would be relevant to any filtering after the detector. See Figure 6-24(b) and (c). Typically the motion shift of frequency is of the order of 1 BW or less, so it is not



(a) Angle Error in a Single Scan.

(b) Composite Frequencies for Coding Frequency Greater.



(c) Composite Frequencies for Motion Frequency Greater.

Figure 6-24. Relations between Decoding Error Factors and the Frequency Difference of Indirect and Direct Signals likely to be noticeable. In SIDS, this effect is absent if the two sidebands are compared directly for deriving the modulation frequency.

The long-wave factor. This factor (G) reflects the envelope phase difference between direct carrier and indirect sidebands. This angle determines how the multipath distortion is divided between phase and amplitude perturbation; only the former appears as an error. The two component angles (G' and G") may both have appreciable effect in SEDS, but the latter is deleted for SIDS. If both angles are small, the (B) and (C) terms may be negligible. This corresponds to small path difference and path-difference speed, as in a centerline approach while still far from the runway. The modulation frequency is near 100 KHz, so the long-wave length is about 10 Kft. The path difference is typically less than 1/4 wavelength or 2500 ft, for which either sine or cosine may be greater.

The short-wave factor. This factor (H) reflects the carrier-wave interference pattern in space and its changing effect from one scan to the next. Typically the flight path is crossing the grid of hyperbolic contours of constant path difference. The frequency of crossing is the path-difference frequency, which is typically less than 1 to 3 BW, usually much less. At distances moderately far from the runway, this causes a cyclic variation of the error in a frequency range that may be objectionable (of the order of 1 Hz). In general, the cyclic variation may correlate with the sampling frequency, with results to be discussed further on.

The probability of all factors. In the 3 lines (ABC), the distribution of each factor may be estimated as follows:

(E) From the preceding discussions, there are three regimes of path-difference speed:

(1) Small (< 1/4S BW) so the even term (A) is not reduced but the odd terms (BC) can be ignored.
(2) Moderate (around 1/4 BW) so all terms are reduced to a small fraction (about 1/S).
(3) Variable (around 1/2 to 3 BW) so there are critical conditions where a GL occurs with very small duration.

(F) The angle-coding difference is nearly always accidental.

(G) The long-wave factor usually includes a small angle (within the first quadrant) but also the path-difference speed in one of the three regimes mentioned above (E).

(H) The short-wave factor includes a carrier angle which is accidental but also a coding-difference angle which affects its relative phase in the three terms (ABC).

It is apparent that the four error-reduction factors have some pattern of correlation, but the pattern is not amenable to a simple description.

<u>The RMS value of independent cyclic factors.</u> If N cyclic factors of independent frequencies are multiplied, their RMS value is $(1/2)^{N/2}$. For example, 4 factors have an RMS value 1/4 the UB. This number is approaching a normal distribution, the 4-sigma value having zero instead of 0.045 probability of being exceeded.

A rule for comparing UB with RMS errors. In the preceding Section 10, it is proposed that a seldom-occurring UB be identified with the 4-sigma level of error. The rationale is, that 1/4 the UB is a sufficient allowance for an RMS value in a nonrandom situation where the random RMS would be much smaller. This rule will be applied in the regime (E-3) above, where a GL occurs during a small fraction of the time. For a typical multiscan (S = 16), it is noted that the factor (E) alone has an RMS value 1/4 the UB, and the other factors would further reduce the RMS, so 1/4 the UB may be regarded as an adequate allowance for the RMS.

12. Multiscan Motion Averaging.

The principle. The multipath error in one scan depends on the carrier angle difference ($\omega_c T_c$) between direct and indirect signals. If this angle changes from one scan to the next, an average over several scans tends to reduce the error. In a multiscan format, this is found to yield a very helpful reduction over a range of conditions. It becomes a particular feature of Doppler MLS.

The motion-averaging factor. This factor (E) is found in some form in each of the three terms (ABC) of the error formula. It is determined by the number of scans (S scans or S/2 pairs) and the motion angle ($\omega_p T_s$) from one scan to the next. Figure 6-25 shows its value and its envelope for the path-difference frequency in beamwidths ($f_p T_s$) which is equal to the path-difference speed in wavelengths per scan period. Typically this is a number less than 3; most of the time in one flight path it is much less. It has two forms, an even form in (A) and an odd form in (B) and (C).

Grating lobes. A peculiarity of the motion-averaging factor (E) is the "grating lobes" (GL). They are so designated by analogy to the radiation pattern of an optical grating, where the term originated. That pattern has the same mathematical form. The grating lobes appear in Figure 6-25, where the factor has a value of unity. At integral multiples of 1 BW, successive scans repeat so there is no reduction of error by averaging. This relation identifies the even series of GL, which appears in the first line (A) of the formula. This rule is directly applicable to SIDS, but also to line (A) for SEDS. At odd-half-integral multiples of 1 BW, pairs of scans repeat in SEDS, giving the odd series of GL which appears in the other lines (B, C).

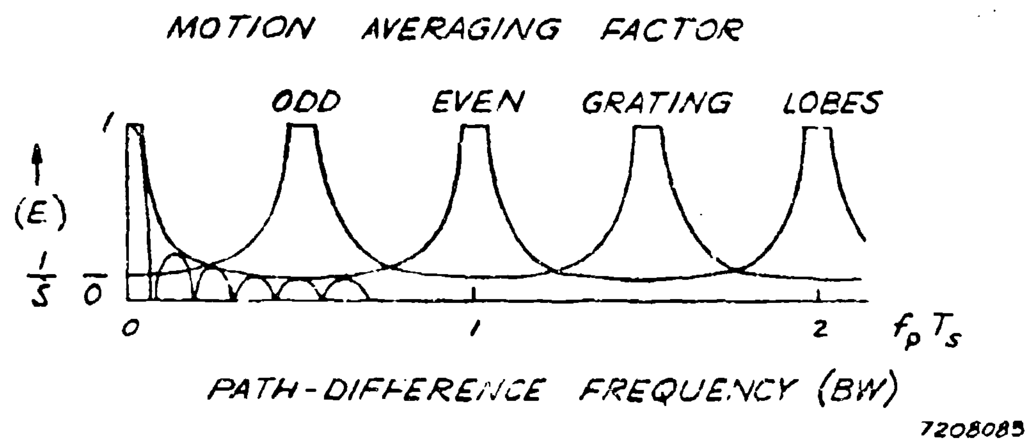


Figure 6-25. Multiscan Motion Averaging Factor

The occurrence of even grating lobes. The first line (A) has a grating lobe if $f_p T_s$ is an integral number (including zero). Then the other two lines (B, C) are zero.

$$A \text{ (even GL)} = + \frac{\rho}{\pi} \sin \frac{1}{2}\omega_{md}T_s \cos \omega_{om}T_c \cos (\omega_c T_c - \frac{1}{2}\omega_{md}T_s)$$

This is relevant for a small path-difference frequency (< 1/4S BW) which is typical of a centerline flight path at a distance far from the runway. Two of the three periodic factors are accidental, so the RMS value is less than $\rho/2\pi$.

The occurrence of odd grating lobes. The other two lines (B, C) have a grating lobe if $f_p T_s$ is an odd-half-integral number. Then the first line (A) is zero.

$$B \text{ (odd GL)} = + \frac{\rho}{\pi} \cos \frac{1}{2}\omega_{md}T_s \cos \omega_{om}T_c \sin (\omega_c T_c - \frac{1}{2}\omega_{md}T_s)$$

$$C \text{ (odd GL)} = - \frac{\rho}{\pi} \sin \omega_c T_c$$

These tend to cancel out if both $\omega_{md}T_s$ and $\omega_{om}T_c$ are small; their upperbound is $2\rho/\pi$. The odd-GL terms are relevant only for a rather critical condition. If this condition occurs at all, its duration is expected to be very small. As previously mentioned, the last line (C) goes out if a STALO is used; then the UB is ρ/π.

The UB and RMS values. The grating lobe is the sum of S equal cyclic terms of different frequencies at a time when they are all in phase. It is so expressed that this upperbound (UB) value is equal to unity, so its RMS value is $\sqrt{1/S}$. For a typical value (S = 16) the upperbound is "4 sigma". This will be discussed further with reference to the probability of the other error-reduction factors in the formula.

13. Sampling in Time.

The Doppler MLS is based on a scan period that is much smaller than the available time between data samples. For example:

Scan period	=	3 or 1 ms
Multiscan (S = 16)	=	48 or 16 ms
Time between samples	=	144 or 72 ms
Sample frequency	=	7 or 14 Hz

The signal format proposed in SC-117 and revised herein, allots to each function a minor part of the available time, but sufficient for a multiscan of many scans (16 or so). The result is a sampling of the angle data about 7 or 14 times per second.

With the path-difference speed, there are then two distinct phenomena:

(a) Motion averaging over a multiscan, depending on the path-difference frequency;

(b) A repeating correlation with the sampling frequency, depending on the changing path-difference frequency.

The former has been described; the latter is the subject of this section.

Figure 6-18 shows for some cases the variation of this motion frequency with distance, and hence with time, along the flight path. If continuously observed, the motion would cause a cyclic time variation of multipath error. During any time that the frequency is above some low value (say 2 Hz) the cycle variation could be smoothed and the error averaged to a much smaller value.

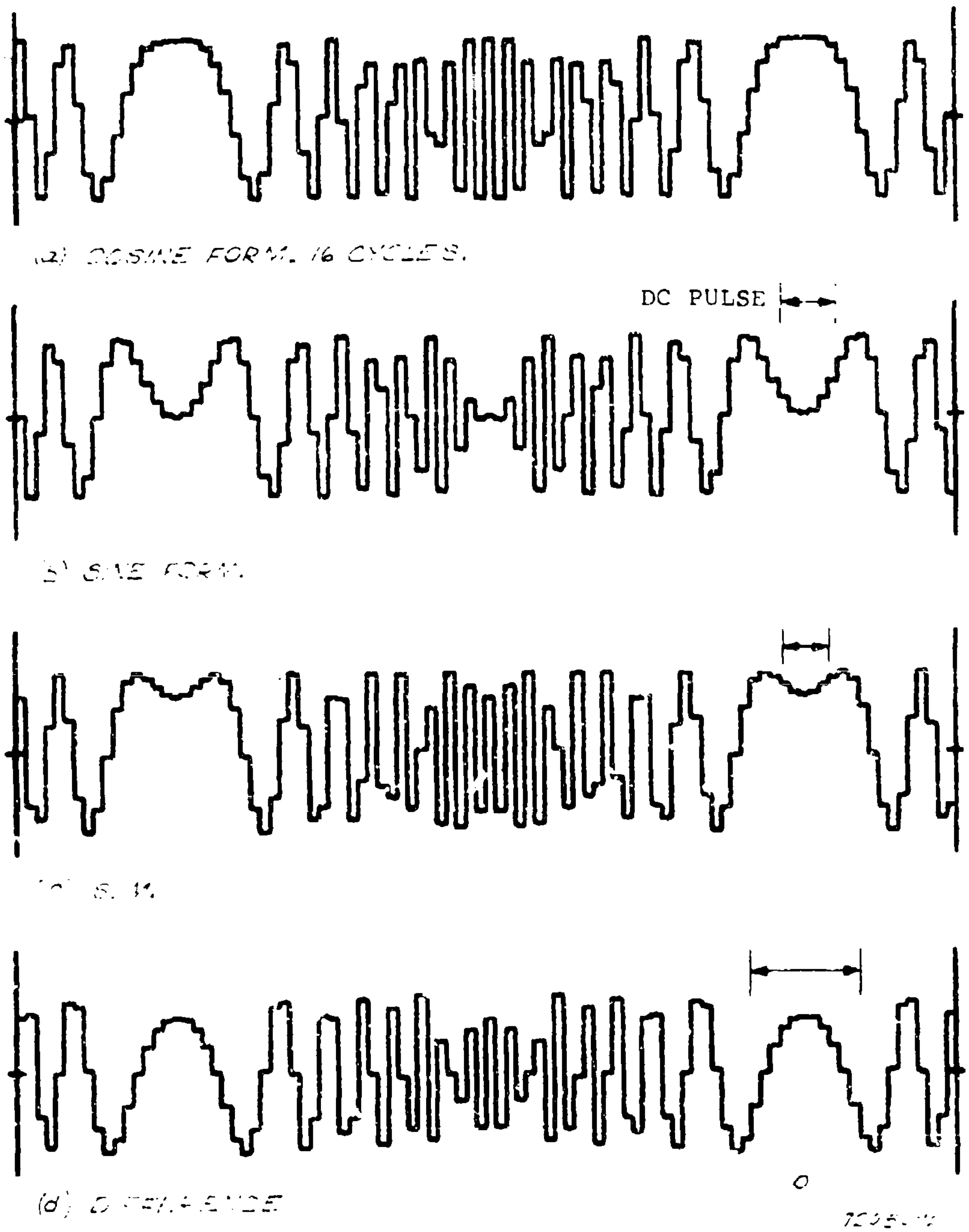


Figure 6-26. Sampling Error Signatures with Changing Path-Difference Frequency

In the sampling system, however, there is a correlation signature as the motion frequency sweeps through integral multiples of the sampling frequency. (These were discovered in computer runs of hypothetical error situations.) The result is, that the time profile of residual error has dominant components between zero and 1/2 the sampling frequency. This is around 2 Hz for 7 Hz sampling. It is apparent in Figure 6-18 that there are various situations where the motion frequency may sweep through some multiples of 7 or 14 Hz.

Figure 6-26 shows some computer runs for sampling at one frequency, another frequency sweeping at a constant rate between two integral multiples of the sampling frequency. Each of these signatures has several characteristics:

(a) The number of cycles while sweeping one period (16 in these graphs).

(b) The average frequency of these cycles is 1/4 the sampling frequency.

(c) In a practical situation, these two numbers are related to the time between coincidences in frequency (time = number ÷ average frequency).

(d) Which signature, is determined by the accident of phase correlation at the instants of coincidence. Four cases are shown.

The graphs shown happen to be representative of this example:

Sample frequency	= 7 Hz
Maximum frequency of cycling	= 3.5 Hz
Average frequency of cycling	= 1.75 Hz
Time between coincidences	= 9 sec
Receiver travel between coincidences	= 1800 ft = 0.3 nmi

The cyclic variation here passes through the average frequency in a very few cycles so it should not be objectionable in a control system.

Figure 6-18 shows some cases where a sweep of 7 Hz might occupy a period as long as miles and minutes. It is unlikely that any typical circumstances would ever cause such a long signature.

Two mathematical peculiarities of these signatures are interesting.

(a) The net area or "DC pulse" is equal to peak amplitude times the marked interval. It is relevant to the reaction of a control system. It is determined by the accidental phase already mentioned. The upperbound is shown in (c) and it can be positive or negative.
(b) In the intermediate time of highest frequency, the envelope has the same shape as the DC pulse.

Figure 6-27 shows one form of smoothing to remove the highest-frequency cycling. Each sample is averaged with the preceding sample. This is a time-domain filter placing a zero at that frequency. Such a filter has two desirable properties:

(a) No phase distortion.
(b) Minimum delay (1/2 the sampling period).

With more delay, a more sophisticated time-delay filter could be described. The simple pairing of samples is recommended as one economical element in the smoothing process.

If it should happen that the motion frequency is nearly constant over many seconds, the error might cycle continuously at some frequency between 0 and 1/2 the sampling frequency.

In 4 of the 5 examples to be presented for describing the residual error, it will be seen that the sampling signature has so few cycles as to include no persistent cycling of the error.

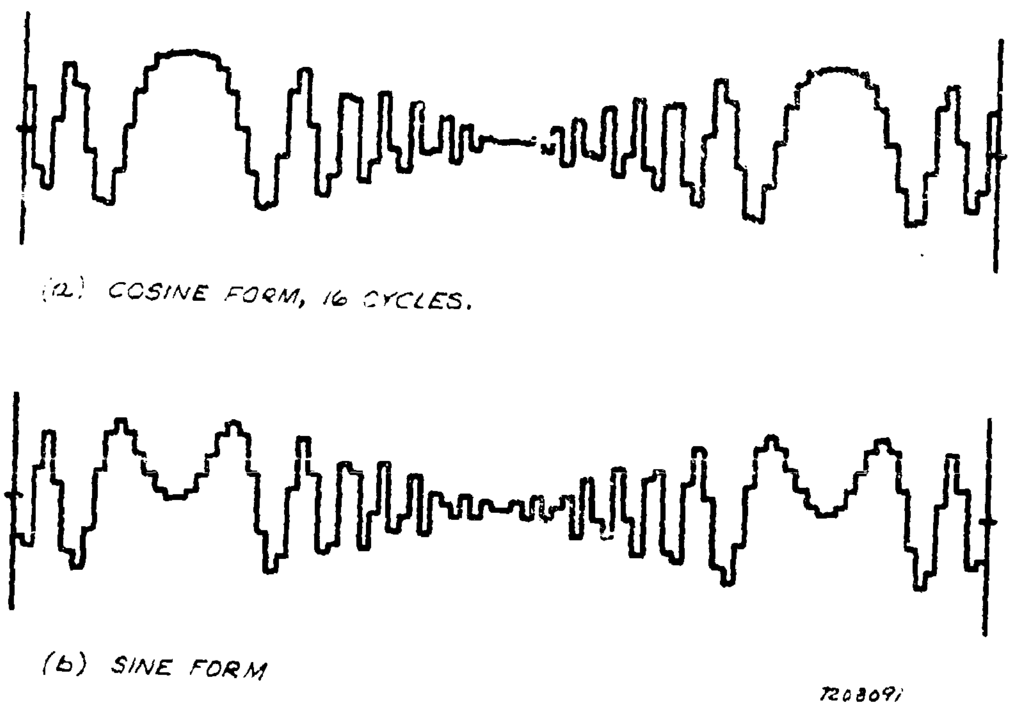


Figure 6-27. Sampling Error Signatures with Paired Samples

14. Time Profile of Residual Error.

The purpose of this multipath study is to challenge the Doppler MLS as to its susceptibility to angle errors from this cause. It will be seen that the Hazeltine baseline system includes features for reducing such errors to a tolerable or negligible quantity. In particular, the centerline approach to a long runway is insured against all risks that would be expected.

Shadowing is not considered further here, because it is a stable and predictable defect, in whatever degree it may be caused by the airport environment. A centerline approach is immune from the deep shadow of a large building, and the AZ blocking in a moderate degree by another aircraft is preventable in operation.

Diffraction, as a cause of indirect paths in multipath, is not considered further because it is found to be so small in its effects.

Reflection is the cause to be considered further here. Figure 6-2 shows some features for reducing this multipath problem. There will be presented here a number of examples which have been chosen to test some situations not fully protected by these features. In each case, a conscious effort has been made to choose a situation particularly susceptible to a residual error from a well-defined cause. Each is caused by a reflection from a large hangar or a large tail fin, located as close to the runway as would be expected in practice.

Figure 6-28 is a chart of the five examples to be presented. Each one is charted as to its occurrence in the flight path (from right to left) - where in the path, at what height, and for what duration. Figure 6-29 shows the geometry of each example, and an abstract of its behavior toward multipath error. The examples will be outlined briefly, after which they will be discussed in perspective.

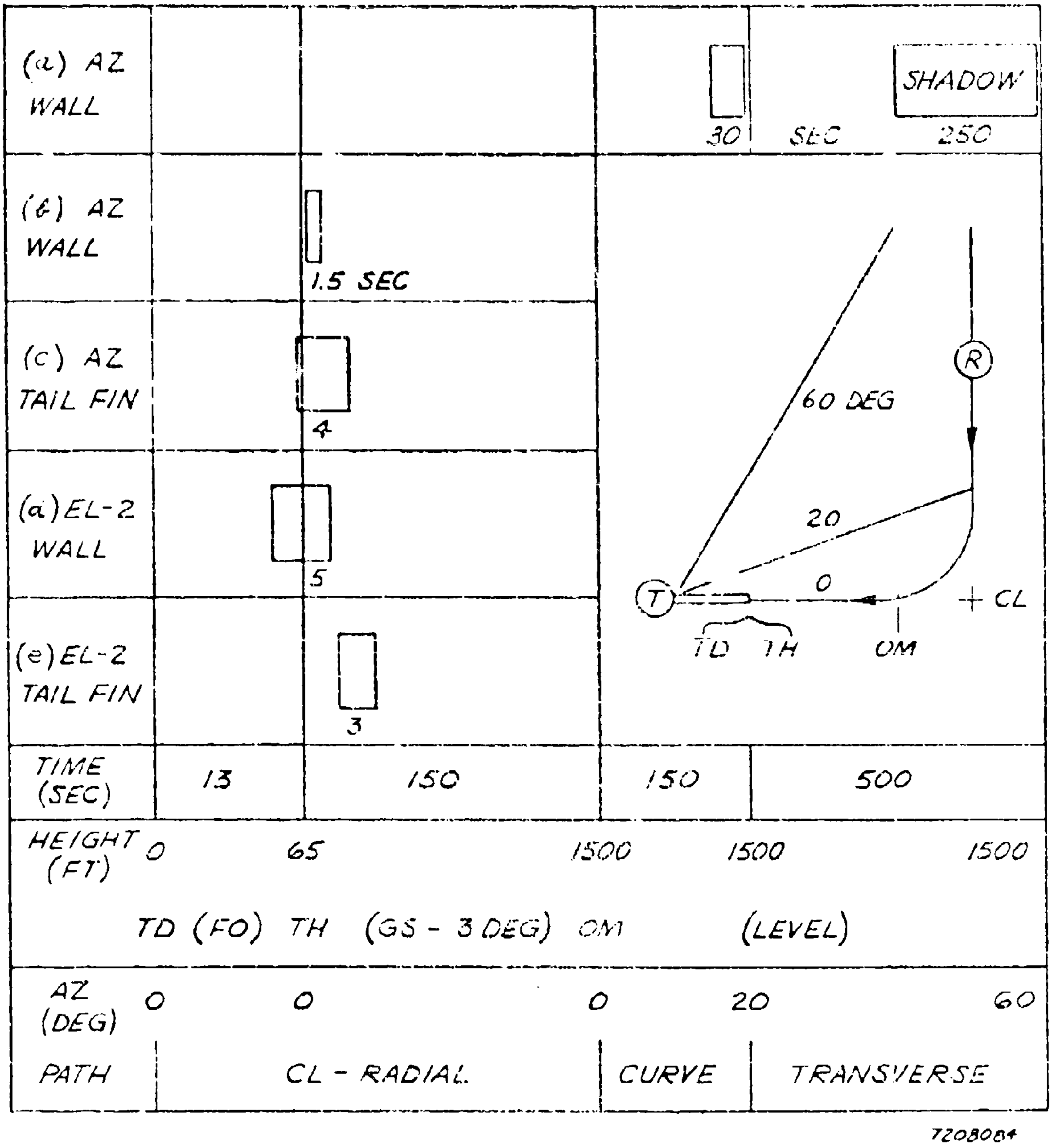
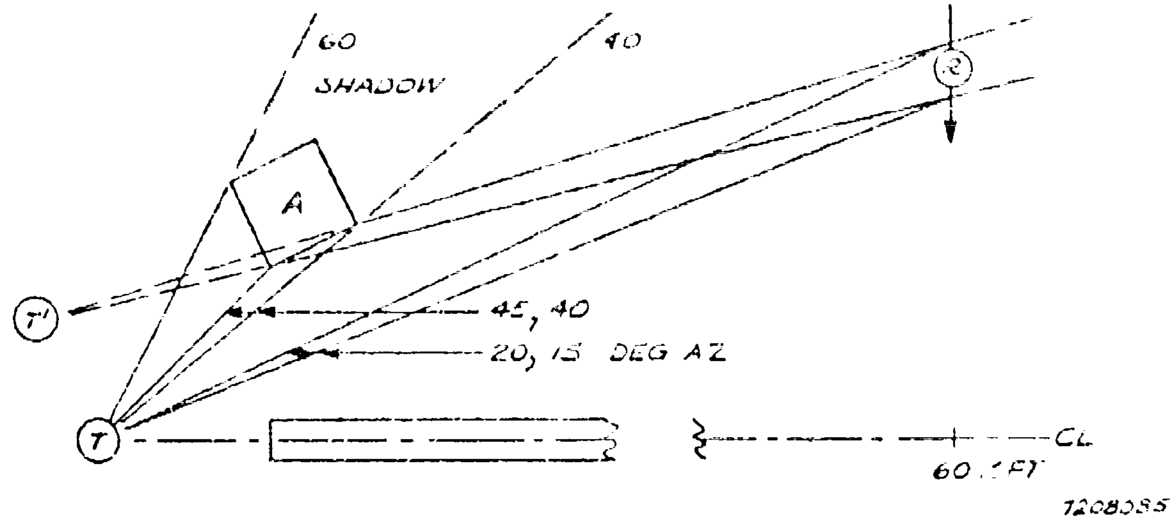


Figure 6-28. Chart of Multipath Situations in a Flight Path



AZ Transmitter.

Large hangar near transmitter, corrugated metal doors.

Receiver at distance = 60 Ktt

height = 1500 ft

Error PB = 0.1 deg (along flight path)

2 sigma = 0.1 (100 ft)

RMS = 0.05

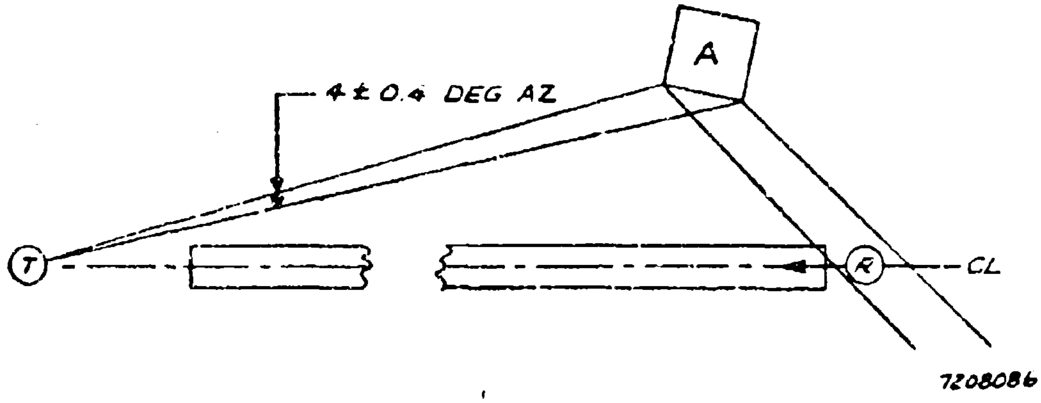
Duration 30 sec.

Slow cyclic variation, about 2 Hz.

Note: This is the extreme situation (unlikely to occur at all) in which there is no error reduction by space pattern and frequency filtering, and but little reduction by motion averaging.

(a) AZ Signal Reflected by Hangar near Transmitter.

Figure 6-29. Examples of Signal Reflections into a Flight Path



AZ Transmitter.

Large hangar near threshold, corrugated metal doors.

Receiver at height 65-80 ft.

Error UB = 0.10 deg (across flight path)

2 sigma = 0.05 (10 ft)

RMS = 0.025

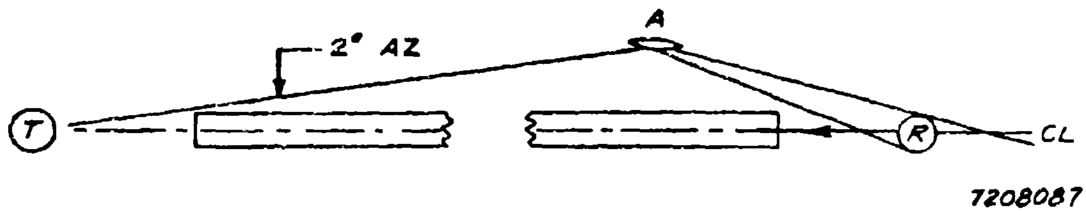
Duration 1.5 sec (10 samples)

Random variation.

Note: This is an extreme (and unlikely) situation in which the coding of the indirect signal is on the edge of the CL filter. The path-difference frequency passes quickly through the first even GL, otherwise the motion averaging reduces the error.

(b) AZ Signal Reflected by Hangar near Threshold

Figure 6-29. Examples of Signal Reflections into a Flight Path (cont.)



AZ Transmitter.

Large tail fin (747) near threshold.

Receiver at height 60-100 ft.

Error UB = 0.05 deg (across flight path)

2 sigma = 0.025 (5 ft)

RMS = 0.012

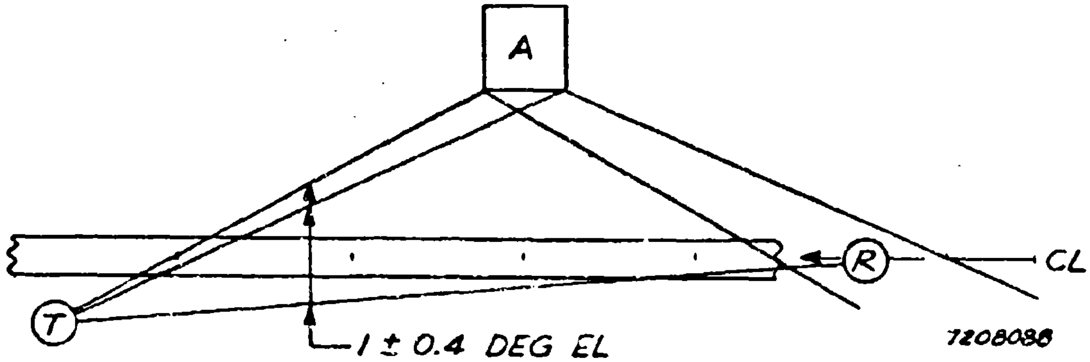
Duration 4 sec (28 samples).

Random variation.

Note: This is an extreme (but not unlikely) situation in which the coding of the indirect signal is accepted by the CL filter. The path-difference frequency passes quickly through each of the first 3 GL, otherwise the motion averaging reduces the error.

(c) AZ Signal Reflected by Tail Fin near Threshold

Figure 6-29. Examples of Signal Reflections into a Flight Path (cont.)



EL-2 Transmitter.

Large hangar near threshold, corrugated metal doors.

Receiver at heigh 40-90 ft on glide slope 3 deg.

Err UB = 0.005 deg = 0.01 BW (in EL).
sigma - 0.002 (0.1 ft)
RMS = 0.001

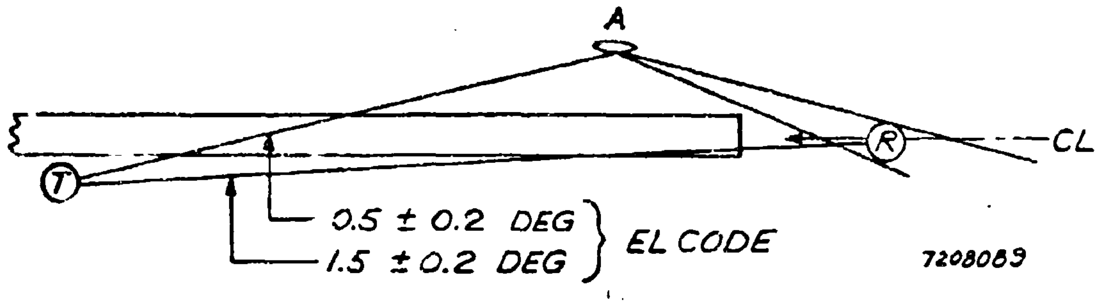
Duration 5 sec.

Random variation.

Note: This is in-beam multipath whose error is reduced by patternshaping and by motion averaging (between 0 and 1 GL).

(d) EL-2 Signal Reflected by Hangar

Figure 6-29. Examples of Signal Reflections into a Flight Path (cont.)



EL-2 Transmitter.

Large tail fin (707) near threshold.

Receiver at height 100-130 ft on glide slope 3 deg.

Error UB = 0.004 deg = 0.008 BW (in EL)

2 sigma = 0.002 (0.2 ft)

RMS = 0.001

Duration 3 sec.

Random variation.

Note: This is near-beam multipath whose error is reduced by convex surface of reflector and by motion averaging (between 0 and 1 GL).

(e) EL-2 Signal Reflected by Tail Fin.

Figure 6-29. Examples of Signal Reflections into a Flight Path (cont.)

<u>AZ reflection from a large hangar near the transmitter end of the runway.</u> Figure 6-29(a) shows an extreme situation, in which the reflection cone is between the shadow cone and the centerline. This results from a combination of circumstances whose probability of occurrence at one runway is estimated to be 1/1000. The angle error is still within tolerance for the region away from centerline (taken as double the tolerance near centerline). Its 2-sigma value is 100 ft along the flight path, or 30 ft across the path. There is a slow cyclic profile of error, which goes through zero every 5 sec, this period including about 5 cycles on and 5 off. This case is notable because it benefits the least from all error-reducing features in the baseline system.

<u>AZ reflection from a large hangar near the opposite end of the runway.</u> Figure 6-29(b) shows another extreme situation, in which the indirect and direct signals come from nearly the same direction at the transmitter. This results from another combination of circumstances whose probability is also very small (say 1/500). Then the centerline filter may not be narrow enough to reject the indirect signal by the frequency difference of its angle coding. At 4 degrees, this filter is assumed to reduce the indirect signal to 1/2 (as on the edge of its passband). The angle error is still within the tolerance for this centerline approach. Its 2-sigma value is about 10 ft. Its profile is irregular, which is the most tolerable, and it lasts only 1.5 seconds.

<u>AZ reflection from a large tail fin near the opposite end of the runway.</u> Figure 6-29(c) shows another situation in which the indirect and direct signals come from nearly the same direction at the transmitter. The angle is so small that the centerline filter does not reduce the indirect signal. However, the peculiarities of the tail fin, together with motion averaging, do reduce the error to a value less than 1/2 the tolerance for this centerline approach. Its 2-sigma value is about 5 ft, and it lasts only 4 seconds. Its irregular profile is particularly interesting, so

this case has been chosen as an example for a computer graph, Figure 6-4 to be discussed further on.

EL-2 reflection from a large hangar near the threshold. Figure 6-29(d) shows a situation where the residual error is reduced to a negligible value by space-pattern shaping and multiscan motion averaging. Incidentally, it has an irregular profile and lasts only 5 seconds. This case is notable because the "in-beam" multipath cannot be reduced by a narrowband filter.

EL-2 reflection from a large tail fin near the threshold. A somewhat smaller aircraft (707) is selected because its lower reflection cone may cover the greatest segment of the flight path. Here the residual error is reduced to a negligible value by the combined effect of the convex curvature of the tail fin and the multiscan motion averaging. Incidentally, it has an irregular profile and lasts only 3 seconds.

EL-1 reflections are not included among the examples, because the reducing measures of Figure 6-2(c) nominally exclude the directions of any large obstacle near the runway. The EL-1 transmitter being rather near the threshold, and its fan pattern being made rather narrow, its radiation should not strongly illuminate any large hangar or any large tail fin located opposite any part of the runway. If any such reflection were to be appreciable, it would be further reduced by multiscan motion averaging.

The duration of exposure in one cone of reflection. The occurrence of any angle error attributable to multipath would fall in one of two categories.

(a) Momentary exposure while crossing a narrow cone of reflection, or a wide cone at a short distance, usually lasting a few seconds.

(b) Persistent exposure associated with either of these cases:

(i) Figure 6-15 (a), a cone in nearly the same direction as the flight path (conceivable in a centerline approach). This is excluded in the AZ function by the centerline filter, and avoided in the EL functions by nonillumination. See Figure 6-2.

(ii) Figure 6-15(b), a narrow cone at a long distance (such as 5° at 10 nmi, lasting 1 nmi and 30 sec).

In Figure 6-29, the AZ example (a) is the only one showing persistent exposure (30 sec) and that is away from centerline. The other examples (all on centerline) show momentary exposure (1.5 to 5 sec).

The time profile. From 6-28, it appears that the exposure to any one cone of reflection is likely to occupy a time block which is a small fraction of the time in any one phase of the approach pattern. Exceptions are avoided by the combination of features for reducing the problem. Therefore there is no need for presenting a comprehensive error profile for the entire approach pattern. Instead, we emphasize the error profile in any time block identified with one reflection. Any overlap of time blocks from different causes is easily interpreted.

Figure 6-29(c) is the example chosen for showing its time profile, because it includes some interesting peculiarities. Figure 6-4(a) and (b) describe this case in more detail. The reflector is the tail fin of a large aircraft located on a taxiway near the threshold of the runway. The approach pattern of the receiver (R) traverses a shaped cone of AZ reflection, determined by the tilted convex face of the tail fin. It is so located as to include a critical segment of the approach pattern, the handover from EL-1 to EL-2 guidance at the transition from glideslope to flareout. The exposure to the reflection lasts 800 ft or 4 sec.

The error profile over the 4-sec time block is graphed in Figure 6-4(c), where the sampling is apparent. The details in the profile are related to accidental initial conditions and numerical assumptions in the computer run, but some characteristics are significant:

(a) The peak values of error happen to be less than the stated 2-sigma value and less than 1/2 the stated UB. This is regarded as typical.
(b) Each peak (single or pair) is identified with one GL in the motion averaging factor. The first 3 GL are traversed in this short time. The accidental other factors determine the amplitude of any one GL (odd or even). Each GL gives peak values for only one or two samples.
(c) Between the peaks, the error is reduced to a small value by motion averaging.
(d) The profile is irregular, so it does not pose any special problems for the control system.
(e) The error is very small, less than 5 ft either side of centerline, with no bias.

As previously mentioned for the sampling-error signature, pairing of samples may be used for smoothing. Figure 6-4(d) shows that principle applied to this case. Here it reduces the peak error to about 1/2.

The sampling effect. The AZ reflection in the first example, Figure 6-29(a), is computed to experience a motion frequency of about 9 Hz. From the nearest multiple of 7 Hz (the sampling frequency) this differs by 2 Hz. Hence there would occur a persistent cycling of the error at about 2 Hz. In the other examples, the motion frequency is changing so rapidly that the period of the sampling signature includes only a few cycles. Then its form is not clearly developed.

The small probability of some reflectors. Figure 6-29(a) and (b) are reflectors of AZ radiation, which were consciously chosen as extreme cases. They exemplify configurations where there might remain an error that is substantial, though not exceeding the tolerances. They are not further reduced or remedied in the baseline system because their probability of occurrence is so small. They are discussed here to illustrate what this means in a practical airport environment.

The following table gives an estimate of the probability that these mutually independent circumstances would exist at one long runway.

		Figure 6-29 (a)	Figure 6-29 (b)
(1)	A large hangar with metal doors is near the runway.	1/8	1/8
(2)	Its location is near the end which is relevant to this case.	1/8	1/8
(3)	Its doors face the runway.	1	1
(4)	Its doors are at an oblique angle with the runway.	1/2	1/2
(5)	This angle is such as to make a reflection cone within such a sector and with such a height as to include the flight path.	1/8	1/4
Composite probability		1/1000	1/500

This probability is so small that either of these cases is regarded as unlikely to occur at all. Furthermore, any occurrence of either case is stable and predictable.

By way of summary, an approach flight pattern may traverse some reflection cones during time blocks occupying a small fraction of the time. Each reflection cone involves radiation for one angle-guidance function (AZ et al). During any one time block, the error profile for this function can be described and evaluated. There are found, some AZ examples where the residual error is a substantial fraction of the tolerance, but these cases are extremely improbable and/or of short duration. The EL-2 examples show residual error so small as to be negligible.

15. Conversion Table.

Table 1. Conversion Factors Related to the Doppler MLS.
Reference: Configuration K, coding frequency proportional to angle.

Angle coded		AZ	EL-1	EL-2
Frequency band		C-band	C-band	Ku-band
Frequency range (f_c)	MHz	5190±60	5190±60	15500±90
Frequency (f_c) (approx.)	MHz	5000	5000	15000
Wavelength (λ_c) (approx.)	ft	1/5	1/5	1/5
Coding factor (f_d/θ)	kHz/deg	1/3	1	2
Angle beamwidth (θ_s)	deg	1	1	1/2
Frequency beamwidth (f_s)	kHz	1/3	1	1
Scan time ($T_s = 1/f_s$)	ms	3	1	1
No. of scans (S)	no.	12	12	12
Function time (S scans)	ms	36	12	12
Freq. shift for speed 120 kt	kHz	1	1	3
Same in beamwidths	BW	3	1	3
Path-difference speed (v_p):				
for $f_p = f_s = 1$ BW	kt	40	120	40
	ft/s	66	200	66
for $f_p = f_s/S = 1/S$ BW	kt	3.3	10	3.3
	ft/s	5.5	1.66	1.66

Distance: 1 nmi = 6000 ft (approx.)
Speed: 1 kt = 5/3 ft/s (approx.); 120 kt = 200 ft/s
Speed of EM wave in free space: c = 1000 ft/μs (approx.)

16. References.

[1] SC-117, "A New Guidance System for Approach and Landing," Vol. 2, RTCA DO-148; Dec. 18, 1970. (MLS)

[2] Hazeltine Corp., "Technical Proposal for the Development of a Microwave Landing System," Report 3-5252, Sep. 21, 1971.

[3] RAE, "A Review of Approach and Landing Guidance," TR 71186; Sep. 1971. (C-band shadowing by tail fin, pp. 43-44, Figs. 16-20.)

[4] P. S. Demko, "Polarization/multipath study," U. S. Army Electronics Command, VL-5-72; Jun. 1972. (Reflection from corrugated surfaces, Ku-band.)

1.1.1.1.F - PROPAGATION AND POLARIZATION.

1. Introduction, Summary and Conclusions.

A signal may experience attenuation, refraction and dispersion as it travels through the propagation medium along the direct path from the transmitter to the receiver. Some of these effects may impose limitations on system performance. In addition, the polarization of the signal is also a significant factor in the system design and performance. This section discusses these phenomena as they pertain to the MLS.

Rain attenuation is the effect of most concern in MLS. It may cause the signal strength to fall below the operating minimum in the receiver. Rain attenuation is small at C-band for AZ and EL-1 signals, out to the maximum range (28 nmi). Its rate is much greater at Ku-band for EL-2 signals, but this function is required out to a much smaller range. At full range, it is proposed to allow 20 dB for rain attenuation at Ku-band. In the EL-2 function in the K configuration, at the most critical distance around 1 nmi, it is estimated that this value might be exceeded 1.5 hours per year in the most severe climate (Asia). In the AZ and EL functions, in the portable configuration, at range of 20 nmi, the use of Ku-band might exceed this allowance as much as 30 hours per year in the most severe climate.

Vertical refraction in the atmosphere is variable with the changing values of temperature gradient near the surface. It may cause a random deviation in the observed elevation angle. The "two sigma" value of the resulting angle is less than the earth's curvature, which is very small as far as the outermarker. The earth's curvature would correspond to a height error of 0.3 ft for EL-2 at touchdown, or 22 ft for EL-1 at outermarker.

Rain refraction and dispersion effects are difficult to model and calculate. Little or no relevant experimental data is available for the relatively short and direct line-of-sight paths of the MLS. It is expected that these effects will be small, especially in the most critical region near the runway threshold. It is believed that only experimental work can provide meaningful data. Such tests might be conducted on a low-priority basis.

The polarization for the baseline system has been chosen to be vertical. This selection is based primarily on the behavior of a radiator mounted near a large metal surface. Wide azimuth coverage by a top or bottom flush antenna is possible only with vertical polarization. Another consideration is the reduction of reflection from some surfaces at an oblique angle not very near normal or grazing incidence. At different surfaces, this might favor vertical or horizontal polarization, but neither one very strongly in practice. Circular polarization would give further reduction of reflections in the receiver, but does not appear to be feasible in the airborne receiver antenna.

In the following Sections, there is a m e detailed discussion of rain attenuation, vertical refraction, . . polarization.

2. Rain Attenuation.

Some fundamental theoretical work and a great deal of experimental work has been performed for predicting the attenuation caused by rain. Much of this work has been summarized in several references [1] [2] [3] as related to the MLS. The analysis presented below is based on information from these sources.

Table 7-1 is an outline of the performance to be expected on the basis of one approach to this problem. It includes functions at both C-band and Ku-band.

Table 7-1. Rain Attenuation for Two Configurations

Configuration	K-CTOL		PORTABLE			
Function	AZ EL-1	EL-2	AZ EL			
Frequency (GHz) Band	5 C	15 Ku	15 Ku	Rainfall Rate (mm/hr)	Attenuation Rate (dB/nmi)	
Rain Attenuation Allowance (dB)	5	20	20		C	Ku
Penetration (nmi) through Solid Rainfall at each Rate	28	2	2	50	0.18	10
	more	6	6	15	less	3
	more	20	20	5	less	1
Full Range (nmi)	28	3.5	10 or 20			

Rain attenuation at C-band is usually said to be small, but this assessment may be undefined. Ref. [1] gives one definite set of graphs which are here used for C-band. One point is:

C-band	5 GHz
Rainfall	50 mm/hr
Attenuation	0.18 dB/nmi
	5 dB/full range (28 nmi)

This rate is taken as the average over the entire distance, so the probability of a greater attenuation should be very small.

On the other hand, rain attenuation at Ku-band is so great that full performance of these functions cannot reasonably be covered during heavy rainfall. Therefore there is proposed an allowance for rain attenuation, which is about the greatest that might be afforded in a compromise design. Then an attempt is made to state the corresponding distance through solid rainfall at various rates. These estimates should be regarded in the perspective of overall performance and economy. How much investment is justified for operation under conditions of various levels of severity?

Another approach to the Ku-band problem is to be outlined with reference to Figure 7-1 and Table 7-2. Reference [1] reports Krason [4] as authority for a helpful graphical presentation for evaluation of rain attenuation. It is reproduced here as Figure 7-1, after two conversions (which leave the graph the same):

(a) Doubling the attenuation for Ku-band instead of X-band.

(b) Halving the attenuation for one-way instead of two-way propagation.

This graph is stated for a path length of 20 nmi. Here it is applied to shorter distances by reasoning that the probability of any level of attenuation would decrease at least in proportion to distance.

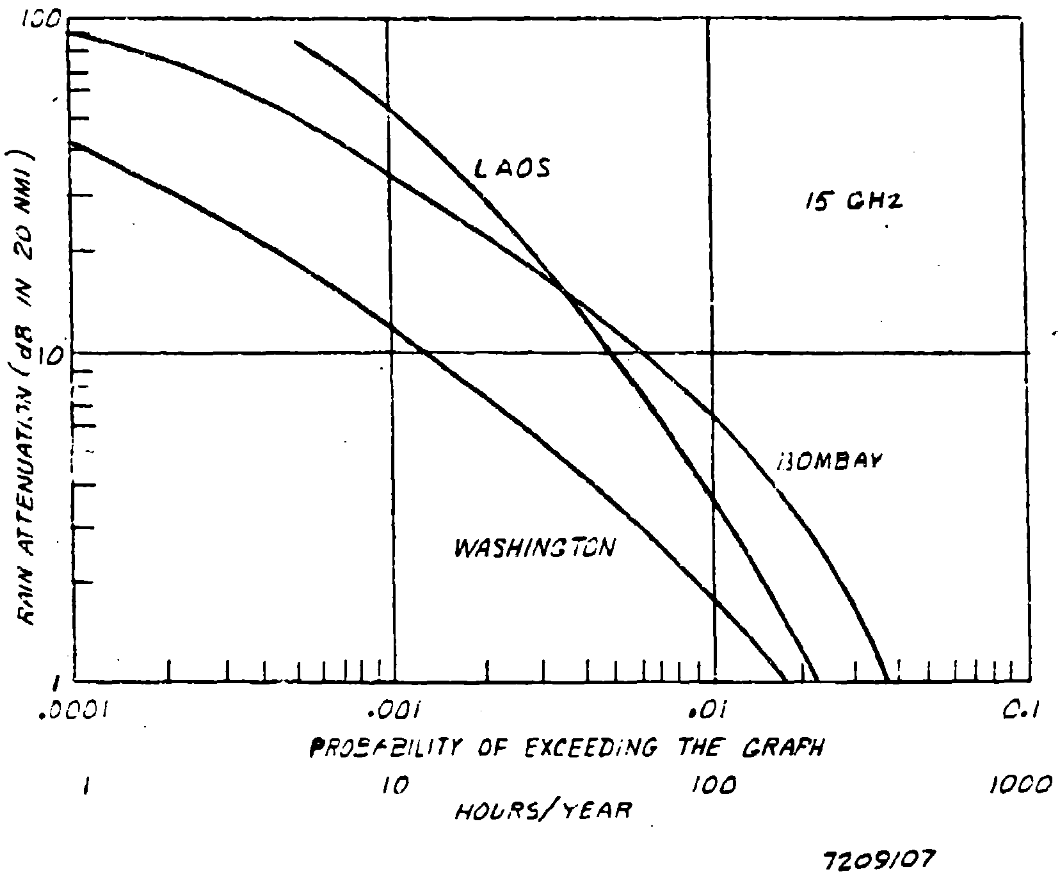


Figure 7-1. Probability of Rain Attenuation at Ku-Band, Based on the Krason Report

Table 7-2. Rain Attenuation for Ku-band Functions

Configuration, Function			K-CTOL EL-2		PORTABLE AZ, EL	
Distance		nmi	1	3.5	10	20
Rain Attenuation Allowance		dB	20	20	20	20
Probability of Exceeding Allowance	D.C.	ratio	.00002	.0001	.00025	.0005
		hr/yr	0.2	1	2.5	5
	Asia	ratio	.00015	.0005	.0015	.003
		hr/yr	1.5	5	15	30

On this basis, Table 7-2 gives a rough estimate of the probability that rain attenuation would exceed the allowance of 20 dB in some cases. One example deserves special attention. The EL-2 function is most critical at a distance of 1 nmi or less. It appears that the probability of exceeding this allowance is very small, only 1.5 hr/yr in the severest climate.

3. Vertical Refraction in Atmosphere.

Effect of gradient of temperature and density. The variations of temperature gradient in the air cause some random error in the coding of a small angle of elevation. This is found to be a minor problem, as will be seen from the small errors that are predicted from available information, reference [1], FAA-RD-70-47.

In the observation of an elevation angle by electromagnetic waves in the atmosphere, there is usually a small error caused by refraction. In the MLS, this effect is relevant to the evaluation of EL angle by frequency decoding in the airborne receiver. The system is particularly sensitive to EL error in the terminal phase of the approach flight path (glide slope, flareout and touchdown). Here the distance and the related angle of refraction are decreasing, along with the error tolerance in height above ground.

The refraction is caused by the vertical gradient of the density of the air. This has the effect of a prism tapered from the ground upward. The gradient has two components:

(a) The pressure gradient inherent in the atmosphere, the density decreasing with increasing height. Its normal bending effect is stated to be about 1/4 the earth's curvature. This is usually stated as the rule of 4/3 radius.

(b) The temperature gradient incidental to local conditions, decreasing or increasing with height.

Because the former is an average value which can be calibrated out, we are here concerned mainly with the uncertainty of the latter.

The refractive index of air is about the same for optical and radio waves. Its value (1.0003) differs so little from free space that it is customary to state the difference in parts-per-million, here termed "micro-units" and abbreviated "mics". The entire effect of the air is 300 mics.

Referring again to [1], the earth's curvature corresponds to a vertical gradient of 157 mic/Km. Any value to be given here will be stated as a multiple of this value.

The earth's curvature as a reference. The following values represent the effect of the earth's curvature (radius = 21 Mft) in our situation (ignoring refraction in the air):

(a) Angle deviation at the far end of a distance, as observed at the near end:

$$0.024 \text{ mil/Kft} = 0.0014 \text{ deg/Kft}$$

(b) Height deviation, on the same basis:

$$0.024 \text{ ft/(Kft)}^2$$

(c) Height of the arc relative to a straight line is 1/4 as great:

$$0.006 \text{ ft/(Kft)}^2$$

These quantities are diagramed in Figure 7-2. Some examples are given in the following table.

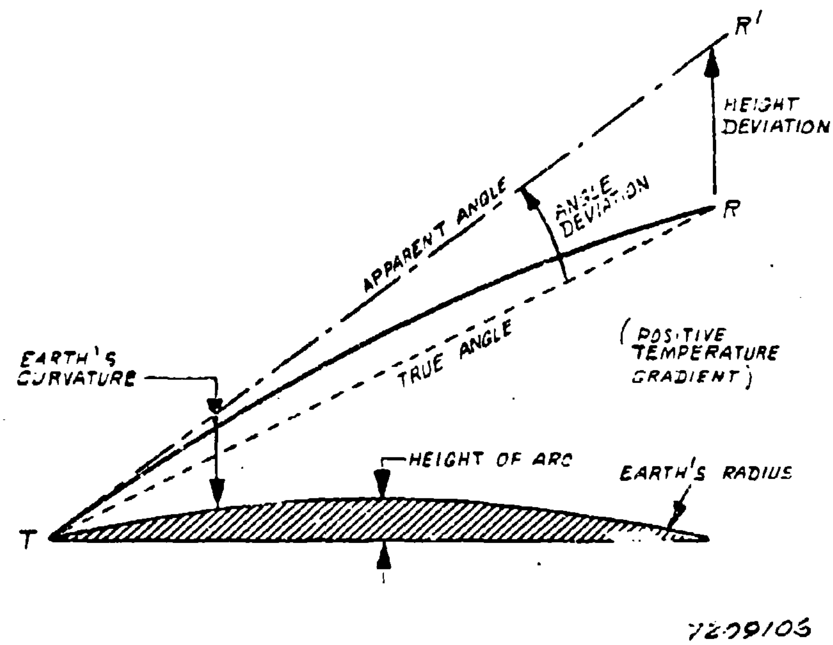


Figure 7-2. The Deviation Caused by Refraction Equal to the Earth's Curvature

Examples:	Distance (Kft)	Angle deviation (mil)	(deg)	Ht. dev. (ft)
(1) EL-2 to threshold	3.5	0.08	0.005	0.3
(2) EL-1 to outermarker	30	0.72	0.042	22
(3) 1 mil	42	1	0.057	42
(4) Max. range (28 nmi)	168	4.0	0.22	680

Note: On a long runway (14 Kft) the height of the arc is 1.2 ft.

At the handover from glide slope (EL-1) to flareout (EL-2), the height difference from these sites is less than the first line (0.3 ft), which is very small. At any distance, a refraction deviation (angle or height) can be expressed as a multiple of the earth's curvature.

The tolerance of error. One basis for stating the EL error tolerance is the following, applicable to random deviations of height at threshold.

2 sigma 1.4 ft at 3500 ft
about 5 × earth's curvature

This is stated for an error with less than 60 seconds duration or a departure from the 60-second average.

Experience records. Reference [1] reports the refraction effects at a number of airports, giving the distribution over seasonal periods. The effect is expressed in mic/Km, averaged over the range of 0 - 50 m above ground. This is the height range of greatest interest because it includes the period just before and after the handover from glide slope to flareout. This is about the last 20 seconds on a 3-degree approach.

These records for several U.S. airports showed 5 percent maximum probability of exceeding the earth's curvature (Long Beach in November) and a typical probability much less. It is concluded that the "two sigma" variation is less than the earth's curvature, perhaps 1/2.

The most extreme variation (Miami in November) showed 1 percent probability of exceeding 5 times the earth's curvature. This is within the stated tolerance. This refraction is downward so it would cause the indicated elevation to be too high (in the sense of failing "unsafe" but within tolerance). This extreme far exceeds a "normal" distribution, so the occurrence of such refraction at one time over a long path may be improbable.

Reference [6] reports one case in New Zealand where the corresponding error, at a height up to 100 ft, was -2 ft. In another case, it was reported to increase gradually at lower height, reaching -5 ft. It is not clear whether this is thought to occur over an appreciable fraction of time at various airports. One gradient profile is reported, showing a steep gradient confined to the height range of 0 - 70 ft. This location is tentatively regarded as an extreme case, but the report will be investigated.

Expectation of a small vertical deviation. From these considerations, two estimates may be stated.

First, the short-distance deviations have a "two-sigma" value less than the earth's curvature, particularly less than 0.3 feet in height at the handover from EL-1 to EL-2.

Secondly, the long-distance deviations have less than a proportionate increase because:

(a) The flight-path height is greater, and
(b) there is less than complete correlation of conditions over the entire distance.

It seems reasonable that the "two sigma" value would be less than 1/2 the earth's curvature, and particularly for EL-1, less than 10 feet at the outermarker.

Conclusion. The expected errors in elevation are negligible out to the outer marker. At greater distances (up to 25 nmi) the earth's curvature (up to 500 ft) may be taken into account. Its effect is reduced to 3/4 by the refraction of the normal density gradient (constant temperature).

4. Polarization.

The polarization of the transmitted signal is an important design consideration and may have a large impact on the cost, reliability and performance of the system. The factors which should be considered are the cost and simplicity of the ground and aircraft antennas and the performance advantages gained by using a particular polarization. For the MLS, the significant choice is between vertical, horizontal and circular polarizations for both the transmitter and receiver. There appears to be no advantage for a system which uses different transmitter and receiver polarization.

Table 7-3 outlines a comparison of the three polarizations with respect to several design and performance factors.

Item (1) is taken to be the one determining factor. The location of a flush radiator on the top or bottom of the fuselage would dictate vertical polarization for wide-angle AZ coverage in the forward half-circle. The reason is, that radiation near grazing incidence on a metal surface is possible only with perpendicular polarization, and only a horizontal surface would enable AZ coverage in front ± 90°. This is expected to be the available location, because the nose area is preempted by other functions that do not have any alternative.

Item (2) gives a definite advantage to either of the linear polarizations. The design of radiating elements or polarization-converting reflectors or screens for circularly-polarized ground antennas is feasible, but the added design complexity results in antennas which are much more complicated.

Item (3) would give some advantage to vertical polarization in reducing ground reflection in front of the transmitter antenna. However, the reflection is so near grazing incidence that it is nearly the same for either polarization.

Table 7-3. Advantages of Vertical, Horizontal or Circular Polarization

Problem	Polarization		
	Vertical	Horizontal	Circular
(1) Airborne antenna designing, flush radiator on top or bottom	[X]	[ ]	[ ]
(2) Ground antenna design, reflector or array type	[X]	[X]	[ ]
(3) Reduction of elevation lobing caused by ground reflection	[ ]	[ ]	[ ]
Reduction of reflection from wall of a large building			
(4) Any incidence on a metal wall	[ ]	[ ]	[X]
(5) Perpendicular incidence on a nonmetal wall	[ ]	[ ]	[X]
(6) Oblique incidence on a nonmetal wall	[ ]	[X]	[X]

Item (4) has been stated to give a great advantage to horizontal polarization in reducing the reflection from a corrugated metal door of a hangar. Ref. [5] arrives at this conclusion after a few experiments, but does not detail the door structure, so further inquiry is advised. Some corrugated doors have been inspected, and they are not expected to offer much advantage in this respect, perhaps no advantage on the average.

Items (4), (5) and (6) give an advantage to circular polarization in reducing the reception of reflection from any walls at any incidence. For the case of a flat metal wall at any incidence, there would be a nominal cancellation. Although the reception of such reflection is a problem, its reduction by the use of circular polarization does not appear to outweigh the advantages of items (1) and (2) for vertical polarization.

Item (6) indicates the expected advantage of horizontal polarization in reducing the oblique-angle reflection from a building wall of nonmetallic construction. This would be true of concrete, masonry and glass windows. This is a secondary problem and is not regarded as a determining factor.

It is concluded that vertical polarization should be retained in MLS.

5. References.

[1] C. A. Samson, B. A. Hart, R. E. Skerjanec, "Weather Effects on Approach and Landing Systems," ESSA, Report FAA-RD-70-47; July 1970.

[2] G. A. Beals, "Estimated Probabilities of Path-Cumulative Rain Intensity for Paths of 10 and 22 Nautical Miles in High Rain-Rate Areas," USAF Environmental Technical Application Center, Report FAA-RD-70-55; June 1970.

[3] R. M. Kalafus, G. J. Bishop, G. G. Haroulis, et al, "Microwave Scanning Beam Approach and Landing System Phased Array Antenna," TSC, Report DOT-TSC-FAA-71-29, Appendix D; Sept. 1971.

[4] H. C. Krason, "Effect of Rain on Precision Approach Radar System," Mitre Corp., Report MTR-962; 1970.

[5] P. S. Demko, "Polarization/Multipath Study," U.S. Army Electronics Command, Report VL-5-72; June 1972.

[6] "Air Traffic Control," Lincoln Lab., 15 Feb. 1972, issued 12 April 1972.

1.1.1.1.G DME Verification

SUMMARY

Investigative Effort

The major study effort in the DME portion of the TACD Phase was devoted to three inter-related areas:

- Coverage
- Accuracy
- Traffic Handling

Some of the guidelines of the DME activity were to arrive at the design approach that places the larger burden for accuracy on the transponder; that the cost of airborne equipment should be minimized; and that accuracies as specified by SC-117 refer to requirements at distances from near TD out to 7 to 10 nautical miles.

Some of the significant results of the study are:

o Multipath echoes that arrive during the rise time or the peak of the first pulse can cause substantial range errors; these errors do not vary randomly pulse-to-pulse and are, therefore, not subject to reduction by averaging.

o Almost complete immunity to echoes requires sharp rise time pulses (wide bandwidth) and a low decision threshold so that the time of arrival measurement is made before the echo arrives or before it causes significant leading edge distortion.

o Wide information bandwidths can be achieved with no sacrifice in selectivity by using the Two-Mode Ferris Discriminator.

o An attendant bias error is introduced when a fixed decision threshold is used for ranging on an increasing signal level; this bias error is quasi-predictable and can be kept <<20 feet by a simple one- or two-step programmed correction in the Interrogator.

o An analog acoustic surface wave delay line can provide the transponder system delay with drift free, jitter free properties.

o The use of sharp rise pulses, wide bandwidth processing, high speed clocks, and low jitter system delay results in a measurement accuracy of below 20 feet on one interrogation/reply and raises questions about the use of averaging.

o Range rate accuracy requirements can be met without averaging at a data rate of about 2.8 seconds, and at a data rate of about 0.75 seconds with averaging, when using an interrogation rate of 20 pp/s.

o The enhanced accuracy obtainable on a single measurement allows the use of a low interrogation rate (15 to 20 pp/s) to reduce the channel loading.

o With low interrogation rates and tight decoder tolerances, the false decode rate for a fully loaded system is entirely tolerable for a two-pulse code system. A three-pulse code system would make false-decoding vanishingly small, but would add to the decode time substantially such that the system delay would have to be increased from 50 μs to about 70 μs.

o Emphasizing time selectivity in the Interrogator by time gating in the IF, prior to frequency discrimination and decoding can be a very effective method of making the Interrogator immune to interfering signals. IF gating, however, negates both long time constant agc and the SC117 approach to identity coding.

o Under the heaviest traffic conditions, without IF gating, the Interrogator will have a high percentage (30 to 50%) of false decodes in the decoder output. This can seriously affect long time constant AGC and can also scramble the identity coding as proposed in SC-117.

o The signal strength required at the low elevation angles, in the critical phase of landing, can be supplied by a practical antenna design that will impose no penalty of higher transmitter power than what is required to obtain the 30 N. mi. operating range. The antenna will have a 4-foot vertical aperture, with the aperture center 4 feet above the ground; and will have azimuth beam shaping to place increased signal level along the center line ($\pm 4^{\circ}$).

o The airborne antenna system will be common to both the angle guidance receiver and the DME. It will be composed of a fore antenna, an aft antenna and a diversity technique, providing 360° azimuth coverage.

o The inclusion of a low noise figure front end amplifier in the ground transponder puts the requirement for peak power in the airborne transmitter at about 50 watts minimum. This compares favorably with the 250 watts minimum specified by SC-117 and makes an all solid state airborne implementation probable for the Prototype Phase; reducing the life cycle cost for the user and enhancing the adoption of the MLS.

DESIGN APPROACH

The design approach for signal processing in the Interrogator and Transponder, reflecting the results of the investigation made, can be summarized with the aid of two simplified block diagrams.

Interrogator

In the case of the Interrogator, figure 8-1, there are two cases where "final" design decisions have not been made and switches are shown to indicate that the feasibility equipment will be capable of running tests in either mode of operation: video gating or IF gating; averaging or no averaging. These choices are in the realm of "either approach will work, but which is better from an overall performance/cost point of view?" Decisions will be made in follow-on work.

Referring to figure 8-1, the operation of the Interrogator starts with the Random Pulser which synchronizes the Interrogator for range delay measurements. It initiates the transmitter, the distance measurement counter, and a gain-time-control (GTC) generator. The GTC generator has two outputs; one adjusts the gain of the IF amplifier as a function of time-after-transmission to keep the

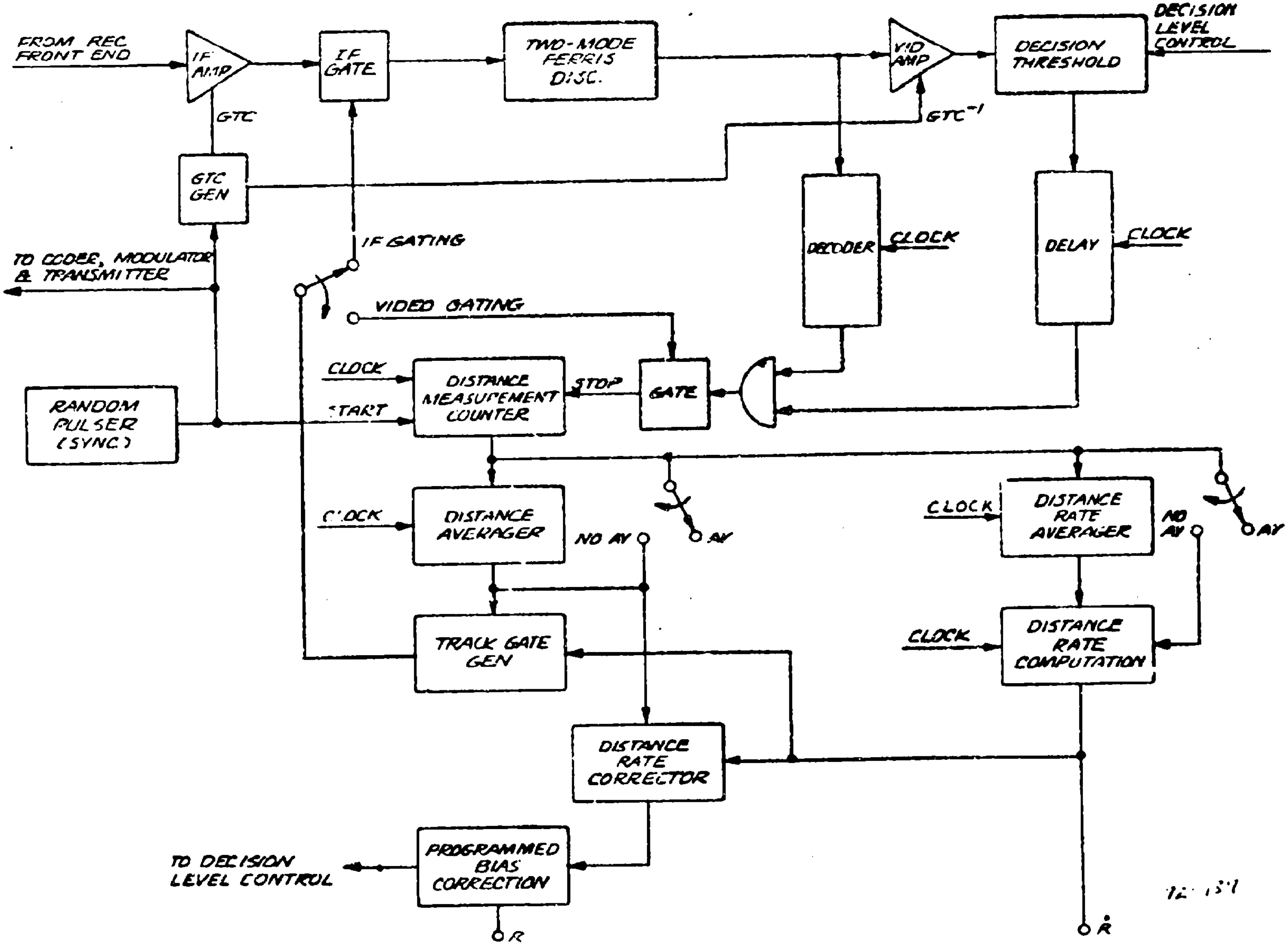


Figure 8-1. Interrogator Processor, Track Mode (With Flexibility for Feasibility Testing), Simplified Block Diagram

output amplitude approximately constant over the expected signal dynamic range; and the other GTC output restores the amplitude (by controlling the gain of a video amplifier) so that the low decision threshold sees a very sharp-rising absolute voltage for "early" decisions.

The diagram is shown for the Interrogator operating in the Track Mode. It is assumed that range lock-on has occurred, range-rate has been measured, and gates are available (from the Track Gate Generator) to "bracket" the reply.

Following a reply through the processor, it is amplified in the GTC IF amplifier and gated through at IF if the switch is so set, or allowed to pass for video gating. The reply is then fed to the Two-Mode Ferris Discriminator for frequency selectivity, which then feeds a fast rise-time pulse to both the decoder and the video amplifier/decision-threshold circuit. In the decision circuit, the sharply rising video pulse is applied to a low decision threshold which can be controlled as a function of range to insure best accuracy both at far range and in the critical phase of landing. The decision threshold output is a reconstituted pulse that is delayed in a shift register to fall inside the gate developed at the decoder output for a correctly coded pair input. The reconstituted pulse will then be gated through if video gating is used, or allowed to pass if already gated at IF, and stop the distance measurement counter which had been started by the synchronizer. The count in the counter is a measure of range and can be fed to an averaging circuit or used directly if "no-averaging" is chosen. The distance measurement is also fed to a distance-rate averager which can also be bypassed if "no-averaging" is chosen. The output of the distance-rate averager (or the distance measurement itself) is fed to a distance-rate computation circuit which computes distance-rate by measuring a change in distance Δd over a precisely known elapsed time Δt. The range-rate output is used to correct for lag in the distance measurement (if distance averaging is used), and, together with the distance measurement, for positioning the Track Gate Generator. In the case of temporary loss of signal, the distance-rate input to the Track Gate Generator will be used for "memory tracking" until the signal comes back, or a pre-specified time elapses in which case the Interrogator will go out of Track and into Search. The rate-corrected output distance measurement (which goes to the pilot and/or autopilot) is used to select (on a pre-programmed basis) both the decision threshold level and a simple bias correction. The bias correction is used to account for the increased amplitude of near range signals crossing a fixed threshold earlier than at longer ranges. This correction will probably be as simple as adding one or two clock counts to the distance output reading.

Transponder

Figure 8-2 is a simplified block diagram of the transponder signal processing circuits. Valid and invalid interrogations enter a wide bandwidth log IF amplifier which can handle a large dynamic range of adjacent signals without saturation and with retention of amplitude information which is useful in echo discrimination circuits. Two outputs are provided, a lin-log IF output and a log video output.

The IF output feeds both a Two-Mode Ferris Discriminator and a wide bandwidth acoustic surface wave delay line. The Ferris Discriminator provides rejection of all off-frequency signals and gates through wide band log video only when a correct frequency pulse is received. The wide band video is fed to an echo discriminator circuit that prevents low amplitude echoes of incorrectly coded interrogations from causing false decodes. This circuit will be optional, depending on the runway location. The echo discriminator feeds a decoder which is clocked (for example) at a 4 MHz rate and has a decoder tolerance of 0.5 μs. The decoded output is delayed sufficiently to produce an enabling pulse for an AND gate that is also fed by the detected output of the delay line.

The IF acoustic delay line introduces no jitter and has a drift of ±0.006 (3 feet) for ±50°C temperature variation. It can be set in the field to ±0.015 microseconds of a desired value in the range

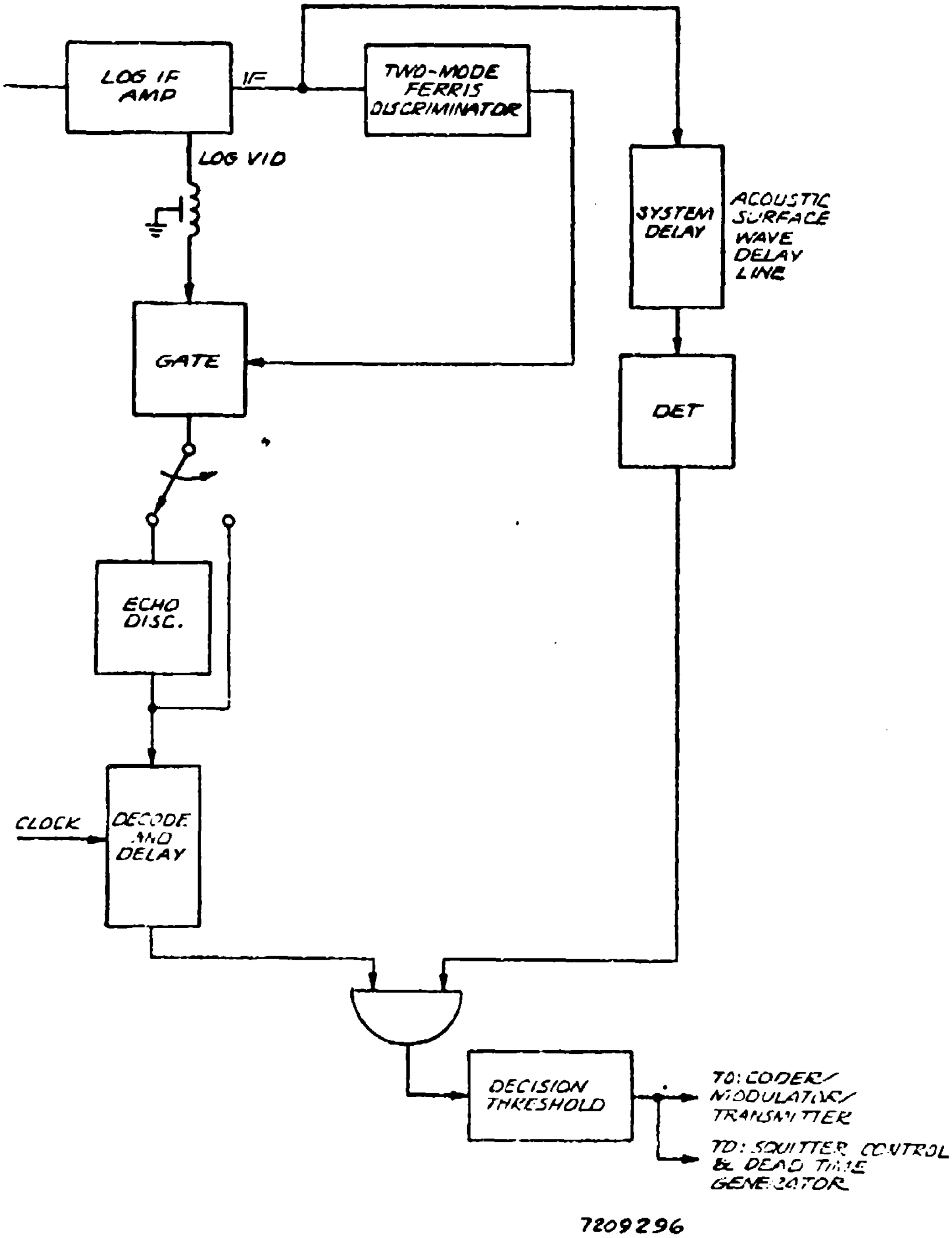


Figure 8-2. Transponder Signal Processing, Simplified Block Diagram

of 35 to 60 microseconds. It has a bandwidth of approximately 10 MHz and has very little effect on the pulse rise time. The delay line approach eliminates the quantization error associated with digital delays and the need for a high speed clock in the transponder. More of the error budget can be apportioned to the aircraft interrogator.

The leading edge of the system delayed first pulse of the 2-pulse code leaves the AND gate and is fed to a fixed decision threshold that is set 7 to 10dB above the noise level. As the aircraft approaches, the signal level increases and the decision level is reached earlier in the pulse. At near range, in the critical phase of landing, the decision level is reached before echoes arrive or can cause significant error. The bias error introduced is accounted for in the Interrogator. The output of the decision threshold circuit triggers the reply, the dead time generator, and squitter control circuits.

Features of Approach

A brief listing of some of the significant features of the DME approach presented in this report is as follows:

- o Immunity to multipath echoes
- o Stable, jitter free system delay
- o Accuracy can exceed SC-117 requirements
- o Low Interrogation rates - better traffic handling
- o Low Peak Power in Airborne Equipment
- o Cost effective coverage for 8 feet height at TD
- o Potential for low cost airborne equipment

1. Requirements

a. Functional

The basic function of the MLS DME is to provide distance information over the volume of approach paths described by SC 117 in Report DO-148. The DME will be used:

(1) to provide progress information along straight-in approach paths

(2) to provide the information currently provided by ILS markers

(3) for speed control when on centerline or via an area navigation computer

(4) to provide distance and distance-rate information which in conjunction with the EL2 subsystem and siting constants are used to derive altitude and altitude rate information required in the flare computer

(5) for two-step glideslope maneuvers

(6) for decision height computation

(7) for runway guidance and high speed turnoff

(8) for distance information on missed approaches

The most stringent accuracy requirements for the DME are imposed by the computations required to execute flare initiation and two-step glideslope maneuvers for Category III landings.

b. Quantitative

The following quantitative requirements for the DME refer to the configuration K requirements as specified by SC 117. The major effort during TACD was applied to resolving the technical issues involved in meeting these requirements in a cost effective approach.

(1) Coverage: Azimuth $\pm 60°$
Elevation 0° to 20°
Range 0 to 30 N. Mi
Back Azimuth $\pm 40°$
Back Elevation 0° to 20°
Back Range 0 to 5 N. Mi

(2) Accuracy: Range - Random Error: 20 ft. (1σ)
Bias Error: 20 ft.
Range Rate - 10 ft/sec (1σ)

(3) Number of channels: 200 (in 125 MHz Band at C-Band) (20 frequencies, each pulse-code multiplexed 10 times)

(4) Channel Loading: 66 Interrogators (primary service)
100 Interrogators (ground testing)
396 Interrogators on correct frequency but incorrect pulse code (interfering)

(5) Data Rate: 5 Hz

The principal differences between the present L-Band DME and the MLS C-Band DME, other than the frequency band of operation, are in the more stringent accuracy requirements (20 ft. vs. 600 ft.); in the provision of 10 channels on each frequency via pulse code multiplexing for MLS whereas presently each channel is on a different frequency; in the shorter operating range for MLS (30 N. mi vs 300 N. mi); in the specification of range-rate capability of 10 ft/sec accuracy for MLS whereas there is no requirement for range-rate in the present DME; and in the specification of a 5 Hz data rate for MLS whereas there is no data rate specification for present DME.

2. Critical Technical Issues - Definition and Resolution

In this section, the technical problem areas that must be dealt with and resolved to meet the quantitative requirements are identified and described, and approaches for their resolution are presented. Although each technical issue is separated out for discussion, they are in many instances inter-related and the solution for one affects the solution for another. The resolution of each issue as contained in this section was arrived at by simultaneous consideration of interacting parameters. In some cases, quantification of the problem resulted in the recognition that it was not a serious problem, thereby providing the issue's resolution.

a. Coverage

(1) Definition of Issue

To provide the coverage required as defined above (see Requirements, 1.1.1.1.G.1) there are three problem areas that need to be resolved. These are:

- o What transponder antenna design approach can be employed to achieve strong signals (without unduly high transmitter power) at the low elevation angles that exist during the critical phase of the landing maneuver, such as flare initiation?
- o What airborne antenna/processing approach can be employed to assure that the aircraft will have 360° azimuth coverage?
- o What power/sensitivity budget provides the most cost effective approach to meeting the range requirements?

(2) Low Elevation Coverage

For a complete discussion of low elevation coverage, refer to Section 1.1.1.1.C which presents the problems, avenues of solution and recommended design as applied to the azimuth guidance antenna; these are identical to the low elevation coverage for DME. The discussion here will be largely excerpted from that section and also the section describing the azimuth reference antenna, which is identical to the DME ground antenna.

(a) General Problem

The problem of providing antenna gain at low elevation angles arises due to the presence of the ground. Refer to figure 8-3. A phase-reversed ground reflection of propagated rf from a small aperture antenna close to the ground causes a cancellation of energy at 0° elevation. As we move up in elevation, the direct and reflected waves are no longer at 180° relative phase, and the cancellation is reduced, with a resultant increase in signal strength. The rate at which the relative phase changes is a direct function of the antenna height and is inversely related to the wavelength. To provide energy at low elevation, the design parameter is antenna height (assuming wavelength is not design variable). However, for small apertures, the increase in height will cause a lobing pattern as a function of elevation angle explained by the phase difference between the direct and reflected waves passing through several cycles. If the aperture is increased, the antenna directivity is increased and less energy reaches the ground which in turn reduces the reflected signal. This has the effect of reducing the lobing experienced with a small aperture. For an aperture-to-height ratio of unity, the lobing is quite small.

(b) Quantitative Goals

The goal of the TACD antenna studies was to determine effective and economical measures for controlling this undesirable influence of the ground on the system performance. Specifically, the major technical problems to be solved were:

- Provide adequate DME signal at a range of 25 nmi and 2000 feet altitude without excessive transmitter power, using a practical antenna design.

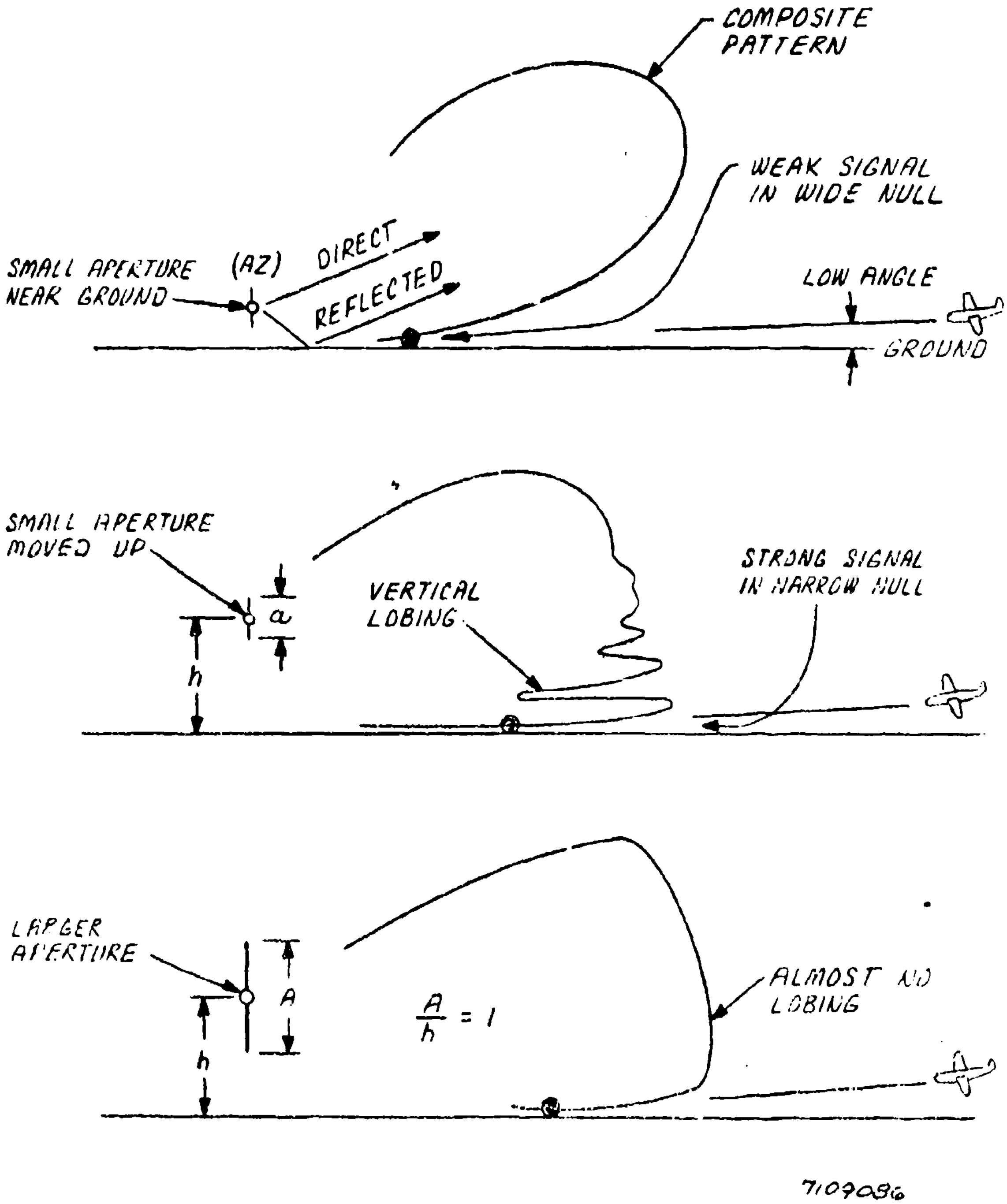


Figure 8-3. Need for Height and Vertical Aperture DME Ground Antenna

- o Provide adequate DME signals for autoload 14000 feet away from the transmitter at a height of only 8 feet, without excessive transmitter power.

(c) Solution

The antenna design to meet the goals will have an aperture of 4 feet, with a height (aperture center-to-ground) of 4 feet, resulting in a height-to-aperture ratio of unity. See figure 8-4. This will provide an elevation pattern shape as shown in figure 8-5. The azimuth pattern will be shaped to have increased directivity (+6 dB) along the center line ($\pm$ 4°) which will provide increased signal strength for the difficult condition of autoload for aircraft that have antennas as low as 8 ft above the ground.

The azimuth pattern is shown in figure 8-6. To achieve the azimuth pattern characteristics the antenna will be composed of approximately 15 columns having a horizontal aperture of about 1.5 feet, with a special feed network. Back course coverage is provided by coupling off energy and feeding three columns of slot radiators mounted back-to-back with the forward radiating columns.

(d) Signal Levels at Landing

For Category III, it is important to provide accurate information to the autopilot down to touchdown. The most critical point in the landing profile with regard to DME accuracy occurs at flare initiation. A plot was made of the expected signal level as a function of range (from 26000 ft from the DME antenna through TD (about 14,000 ft) and into Rollout) for a typical landing profile (2.5° G/S). It is shown in figure 8-7. Note that the signal level is strong at flare initiation and drops down but remains sufficiently high at TD for a commercial airliner such as the 707. After TD, the signal level increases as the effective elevation angle increases. With the nominal S/N at 30 nmi (R max.) designed to be 13 dB, the S/N at flare initiation is approximately 34 dB and at touchdown 26 dB. At these S/N ratios

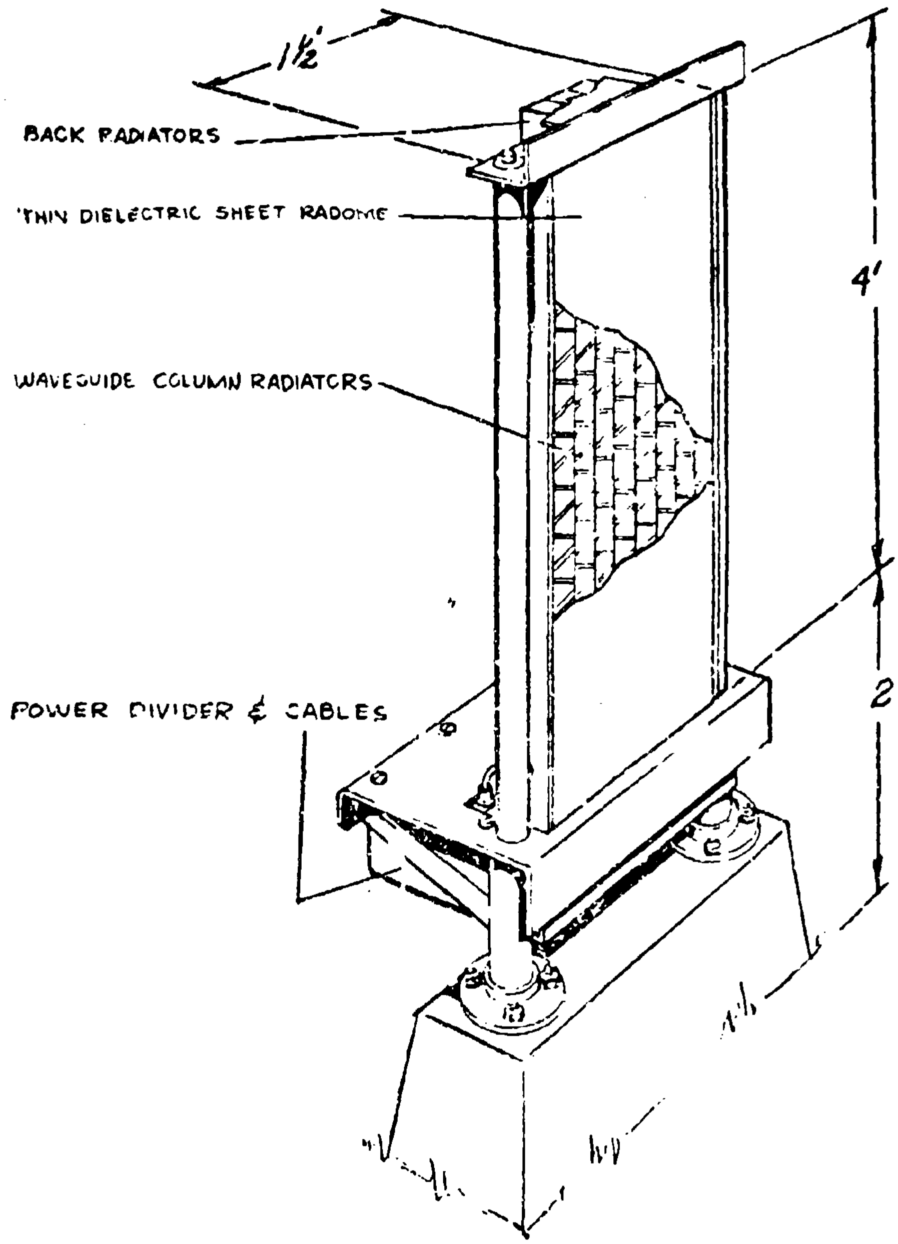


Figure 8-4. DME Ground Antenna - Configuration K

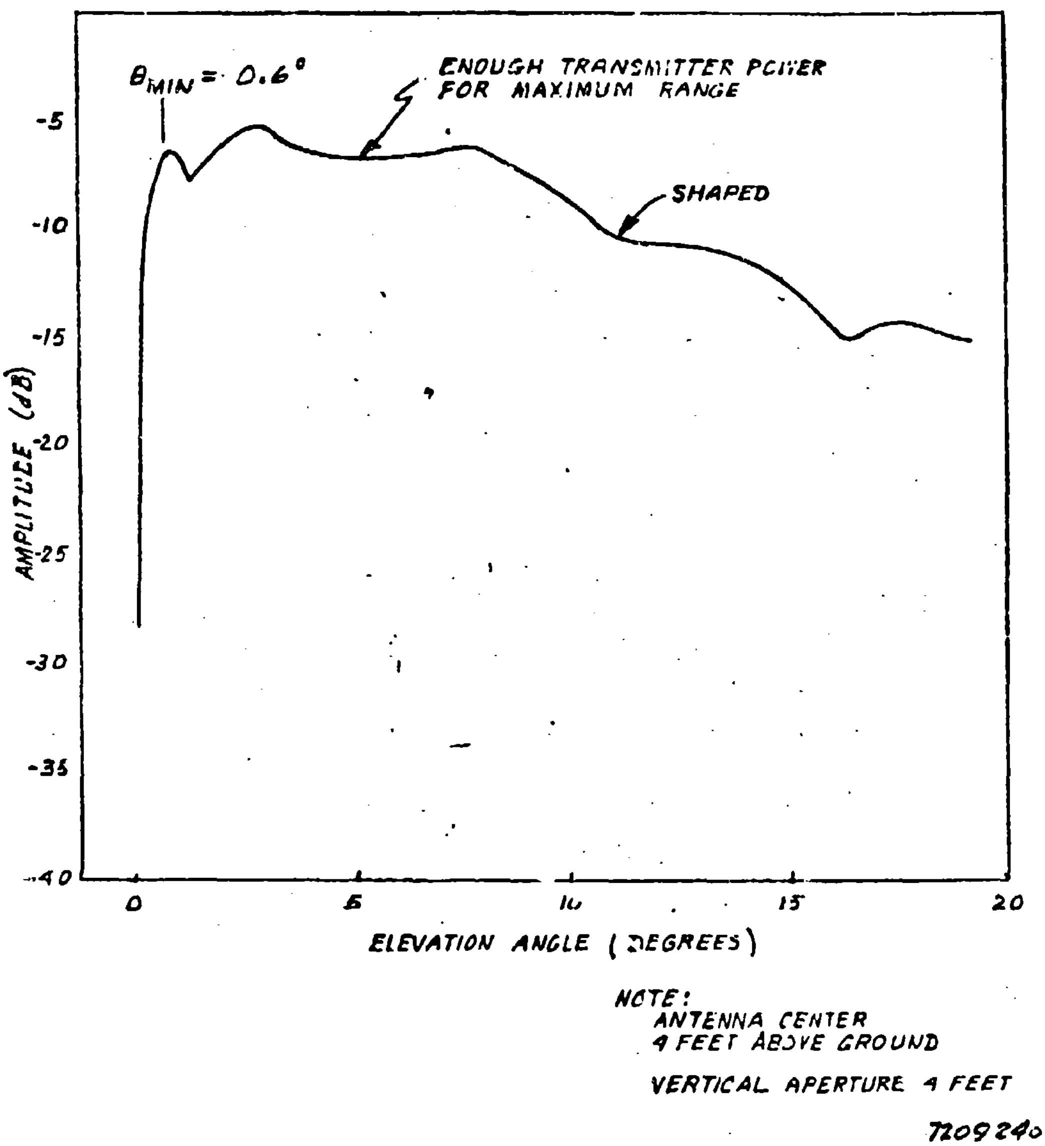


Figure 8-5. Elevation Pattern of DME Ground Antenna

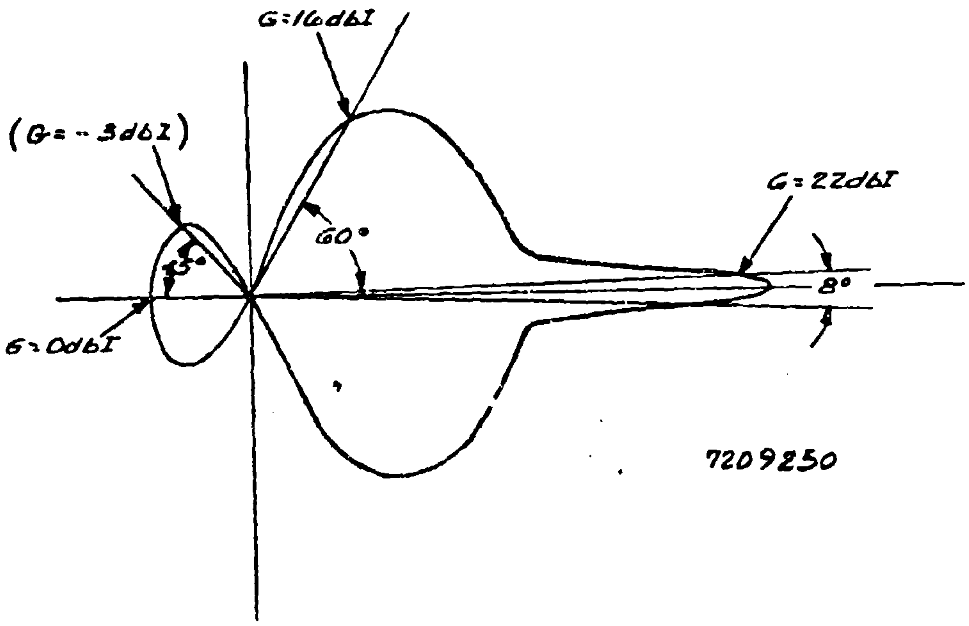


Figure 8-6. Azimuth Radiation Pattern for DME Ground Antenna

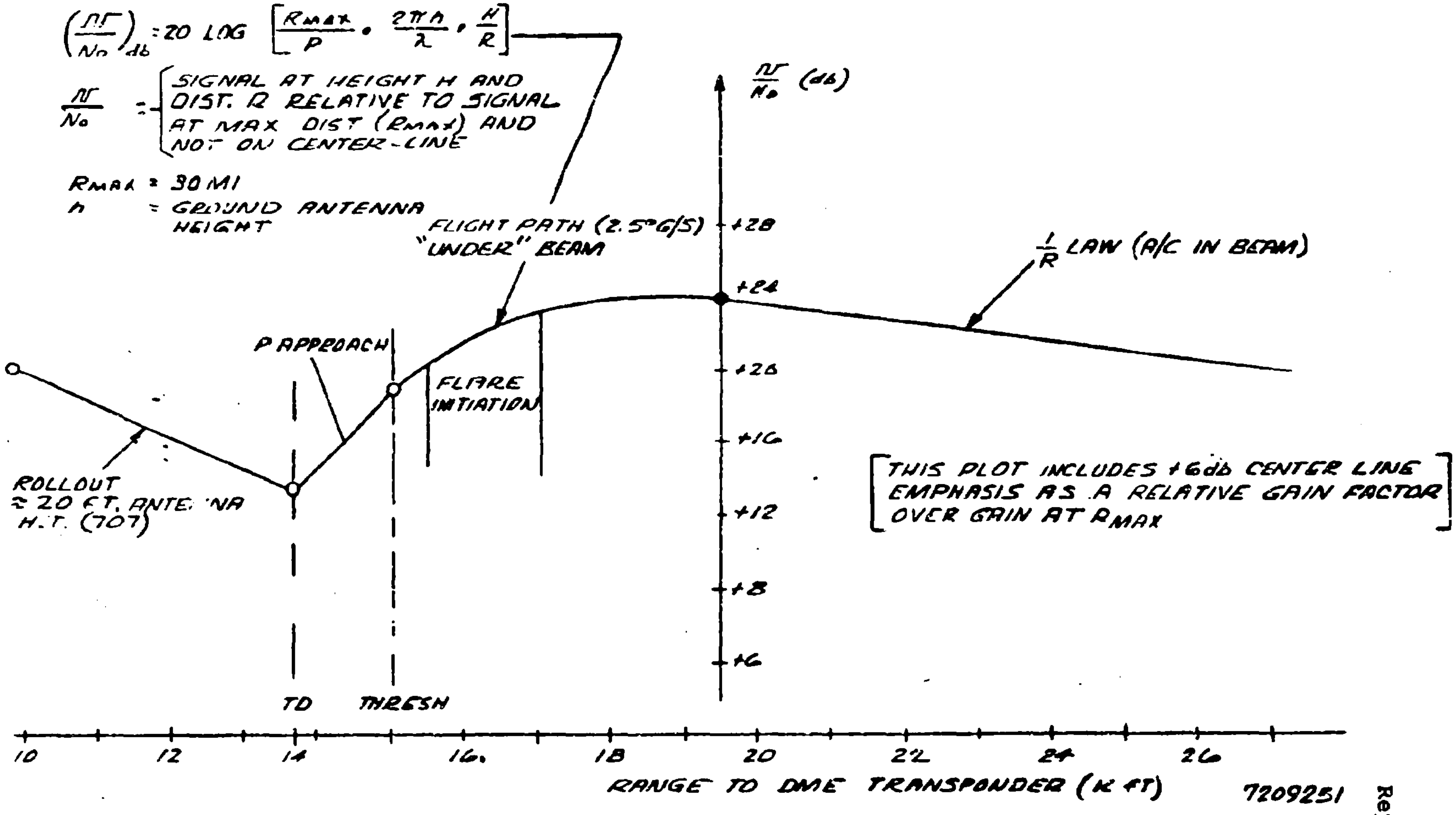


Figure 8-7. Relative Signal Power vs Range to DME

high accuracy DME is assured. For an 8' high aircraft antenna, the S/N ratio comes down to 17 db at TD, which is entirely adequate.

(3) Airborne Antenna Coverage

The airborne DME antenna is common to the angle guidance receiver antenna. Section 1.1.1.1.D presents a full discussion covering the problems, approaches and proposed solution. Only a brief description of the approach will be presented here.

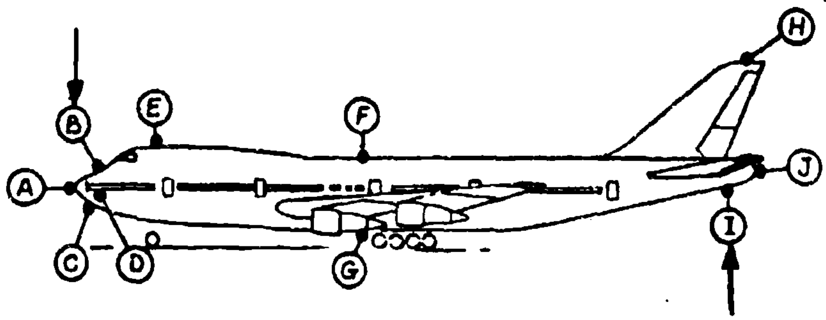
(a) Problem

The problem centers on providing 360° azimuth coverage, while using as little surface area of the aircraft and maximizing signal levels to the receiver.

(b) Solution

To achieve 360° azimuth coverage, a two-antenna diversity system is required. Locations B and I as shown in figure 8-8 are proposed as the best locations for the two antennas. These locations provide the required coverage with vertical polarization and should be available on almost all aircraft for mounting the MLS antennas. The forward location has the added advantages of airframe shielding from some multipath signals and a height-above-ground advantage when the aircraft is near touchdown. This latter factor results in significantly stronger DME signals during the most critical period of the aircraft landing. Cardioid patterns for the two antennas, pointed in the appropriate directions, are near optimum for the overall antenna system performance. The design of these antennas are simple and straightforward. Their nominal gain is 6 dB above an isotrope.

The diversity technique proposed is to sample the fore and aft antennas at a 2 Hz rate: if the fore antenna has a signal level 3 dB greater than the minimum sensitivity signal of the angle channel, the fore antenna will be selected and the sampling discontinued. This diversity technique is described in greater detail in Section 1.1.1.1.D.



LOCATION	ADVANTAGES	DISADVANTAGES
A	GOOD FORWARD COVERAGE ANY POLARIZATION	NOT AVAILABLE ON MOST AIRCRAFT
B	GOOD FORWARD COVERAGE VERT. POLARIZATION HEIGHT-ABOVE-GROUND NEAR TOUCHDOWN	
C	GOOD FORWARD COVERAGE, VERT. POLARIZATION	
D	GOOD FORWARD COVERAGE, HOR. POLARIZATION	NEED ANTENNA ON OPPOSITE SIDE AND DIVERSITY
E	FAIR FORWARD COVERAGE, VERT. POLARIZATION	
F	MINIMUM COMPUTATION FOR AIRCRAFT ATTITUDE CORRECTION	POOR DOWNWARD COVERAGE
G	MINIMUM COMPUTATION FOR AIRCRAFT ATTITUDE CORRECTION	POOR UPWARD COVERAGE
H	BEST POTENTIAL FOR 360° AZIMUTH COVERAGE WITH ONE ANTENNA	POOR DOWNWARD COVERAGE, NEED LONG FEED CABLE, DIFFICULT INSTALLATION
I	GOOD REAR COVERAGE, VERT POLARIZATION	
J	GOOD REAR COVERAGE, ANY POLARIZATION	

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Figure 8-8. Locations on Aircraft for Mounting Antennas

(4) Power/Sensitivity Budget

(a) Problem

The problem in defining the power budget to achieve 30 nmi operating range centers on achieving the most cost effective approach of specifying the airborne power/ground sensitivity link and the ground power/airborne sensitivity link.

(b) Solution

With the very large ratio of airborne to ground equipments required to implement a viable MLS, the approach proposed is to provide a high sensitivity system on the ground coupled with low peak power in the aircraft; and low sensitivity in the aircraft coupled with high peak power in the ground equipment. This creates the opportunity for realizing (probably in the prototype phase) the airborne transmitter with an all solid state approach. The large increase in life expectancy of solid state transmitters relative to tubes would drastically reduce the life cycle costs to the user of the MLS system and enhance its universal adoption.

The unbalanced power budgets are presented in tables 8-1 and 8-2. In sections 1.1.1.1.G.4.a and 1.1.1.1.G.4.b, more detailed discussions are presented concerning the hardware implementions.

b. Accuracy: Range

(1) Definition of Issue

In the TACD Phase the range accuracy goal for the high performance Category III system was set at 20 ft. (1σ) for random errors and 20 ft. (1σ) for bias errors as defined in the requirements above. The data rate specification applicable to the random error was taken as 5 Hz, per SC-117. Although these specifications are subject to change pending the results of continuous investigation into the landing system dynamics, control, and error budgets, they serve as a reasonable quantified target for investigation and validation of approaches for achieving high accuracy in the landing system environment.

TABLE 8-1

DME POWER BUDGET (AIR-TO-GROUND LINK)

Noise Power in 7 MHz BW..................	-105.5 dbm	
Receiver Noise Figure		
@ input to Front End Amplifier.........	6.0 db	
RF Losses before Front End Amplifier.....	4.0 db	
Circulator, Preselector		
Limiter, Cable		
Antenna Losses (Network & Columns).......	2.0 db	
Equivalent Noise Power @ Antenna.........	-93.5 dbm	
P_R required for S/N = 13 db..............	-80.5 dbm	←
Rec Ant Gain (incl. 2 db lobing loss)....	14 db	-
XMT Ant Gain.............................	3.5 db	-
(incl. lobing loss)		
XMT Cable & Circulator Loss..............	4 db	+
Path Loss (30 nmi) = $10 \log \left(\frac{4\pi(180,000)}{\lambda=1/5}\right)^2$	141 db	+

in dBm:

$P_T = P_R + 141 + 4 - 3.5 - 14 = P_R + 127.5$ db

$P_T = 47$ dbm = + 17 dbw

$P_T = 50$ Watts

Specify 100 W ± 3 db

TABLE 8-2

DME POWER BUDGET (GROUND-TO-AIR LINK)

Noise Power in 7 MHz BW..................	-105.5 dbm	
Receiver NF..............................	14.5 db	
Cable, Mismatch, Filter Ripple Losses....	4.5 db	
Equivalent Noise Power @ Antenna.........	-86.5 dbm	
P_R required for S/N = 13 db..............	-73.5 dbm	←
Rec Ant Gain (incl. 2.5 db lobing loss)..	3.5 db	-
XMT Ant Gain (incl. 2 db lobing loss)....	14.0 db	-
XMT Cable + Circulator Loss..............	3 db	+
Path Loss (30 nmi).......................	141 db	+

in dbm:

$P_T = P_R + 141 + 3 - 14 - 3.5 = P_R + 126.5$ db

= 73.5 dbm +126.5

= 53 dbm = + 23 dbw

P_T = + 23 dbw = 200 watts

Specify P_T = 400 Watts ± 3 db

The technical issue of achieving high distance accuracy involves the following simultaneous considerations:

- o Inherently, wide bandwidth and/or high signal-to-noise ratio are required to achieve high accuracy of range measurement. Conflicting with these are the limited band in which 200 channels must be supported, the desire to minimize transmitter power requirements (particularly for the airborne interrogator), and the requirement to provide wide angle coverage.
- o Multipath echoes that arrive during an interval starting with the leading edge of the direct path first pulse and ending with the direct path second pulse (assuming a 2-pulse code) can cause errors in distance measurement to various degrees, depending on the measurement technique used to determine the time-of-arrival of the reply or interrogation. After employing means to minimize multipath, the avenue of approach must be based on identifying and using the difference between the direct and reflected waves to discriminate against the reflections.
- o Sources of drift must be minimized and monitoring/adjust techniques must be used to reduce bias errors. Also, any known sources of bias error must be compensated for by built-in techniques.

(2) General Considerations

(a) Decision-Level

The time of arrival (t_d) of a pulse is established as the instant when its leading-edge reaches a specified "decision-level" (e_d). It is desirable that this decision-level occur:

- o Very early in the pulse, so that it can be reached before echoes of the start of the pulse.

- Where the slope of the leading-edge is steep to minimize the error produced by echoes which arrive before the decision-level is reached and to reduce the time-jitter caused by the thermal noise and by the tolerance in establishing the decision threshold. Note that application of the above capitalizes on the difference between the direct and reflected waves (time of arrival) to eliminate or minimize errors due to reflections.

The decision-level can be established at a constant fraction of the peak pulse amplitude (A), which may be variable, say 0.5A, or a constant absolute voltage level, say 1.0 volt.

Establishing the decision-level at a constant fraction of the peak pulse amplitude has the advantage that the measured time of arrival of the pulse (t_d) is independent of the peak pulse amplitude and therefore produces no distance-bias error even if the pulse amplitude varies as the aircraft's distance from the beacon changes. This scheme has been used successfully in an L-Band beacon made by AEROCOM and tested by NAFEC. However, the much greater duty cycle handled by the Pulse-Multiplexed C-Band DME beacon receiver presents additional problems. This scheme requires that the amplified and detected first pulse be a linear reproduction of the input pulse; that its peak amplitude be measured and stored long enough to measure its fractional part. Some form of agc which acts on the first pulse must be used. Since the transponder must accept pulses of any amplitude in a random sequence, the amplitude of one pulse cannot be stored to control the next pulse as can be done with long time-constant agc. The agc cannot be obtained from decoded signals because the second pulse arrives too late to control the first pulse. The delays required would be impractical.

Because it is multiplexed ten times and the IF bandwidth may be as much as 7.0MHz, the C-Band Transponder may be called upon to handle as many as 22,000 interrogations per second in its IF amplifier as against 2,700 per second for the L-Band DME. If the agc derived on the first pulse acts for the code interval, whose average duration is 20 μs, the total time taken by the agc is $22,000 \times 20 \times 10^{-6} = 0.44$ sec./sec. During this time the beacon will not respond to smaller pulses. This reduces the Beacon Reply Efficiency by a corresponding amount. The cost of this scheme is about $2,000.00 in material higher than the cost of the method which uses a decision-level at an absolute voltage level.

<u>Establishing the decision-level at an absolute voltage</u> has the advantage that the signal amplitude rises as the aircraft approaches the beacon, and:

- The decision level is reached earlier in the pulse, which eliminates most echoes.
- The slope of the leading-edge, at the decision-level is automatically increased.
- A steeper slope is achieved at the decision level for the same receiver bandwidth because of the greater amplitude.
- The method is far simpler and less costly than the one making use of a decision-level at a fixed fraction of the peak pulse amplitude.

On the other hand, it has the disadvantage of introducing a small negative distance bias error (max -60') which varies with distance. However, this bias error can be easily minimized, partly calibrated-out, or programmed-out dynamically as shown below, by the interrogator.

Because the interrogator can control the amplitude of the reply, by agc or open loop gain-time-control (gtc) in the i-f amplifier, it can vary the amplitude of the detected video reply inversely with the distance from the beacon to restore high amplitude at rear range. It can then establish a decision-level which is a known fraction of the known peak pulse amplitude and therefore easily correct for a fixed bias error.

As stated above the transponder cannot do this with ease. For these reasons, the decision level will be set: in the transponder at a fixed absolute voltage level, and in the interrogator at two or more constant fractions of the peak pulse amplitude (as a function of distance); a bias adjustment will be made which will correct, at least partly, for the bias error in the transponder. (see section 1.1.1.1.G.2.b.(4))

(b) Bandwidth

To provide a pulse whose leading edge rises as rapidly as possible, the information bandwidth of the "Two-Mode-Ferris-Discriminator" will be set at 7.0 MHz, although the selectivity bandwidth will be kept at 1.5 MHz for absolute rejection of all off-frequency channels. Since the rise-time of the incoming rf pulse is $t_o = 0.1$ us, the rise-time of the output pulse is:

$$t_r = (t_o{}^2 + (0.7BW)^2)^{1/2} = (0.1^2 + (0.7/7.0)^2)^{1/2} = 0.14 \text{ us.}$$

(c) Shape of Pulse (for analysis)

A pulse whose leading-edge is described by: $e_1 = \frac{E}{2}(1 - \cos 2\pi t/T)$ rises from $e_1 = 0$ at $t = 0$ and reaches $e_1 = E$, a maximum value, at $t = T/2$. It rises gradually and reaches its peak gradually. It can be made to decay the same way. Its duration at the 50% points is well defined. In addition, its spectrum distribution can be shown to be the product of independent functions of the rise-time and duration. For these reasons, it is a truer representation of the actual pulse than either the Gaussian pulse or the trapezoidal pulse. The Gaussian pulse does not have a finite start time and is never equal to zero. The trapezoidal pulse has a discontinuous slope. For these reasons, the proposed pulse will be used in calculations except where it introduces greater complexity.

The proposed pulse rises to: $e_1 = E/2$ at $t = T/4$

The proposed pulse rises to: $e_1 = E$ at $t = T/2$

The rise-time from 0.1E to 0.9E is $t_r = 0.295$ T, or $T = 3.39t_r$

$= 3.4t_r$ approx.

$= 3.4 \times 0.14$

$= .48\ \mu s$

(3) Description of Errors due to Multipath

(a) Medium Delay Echoes

Echoes of the first pulse, which arrive just before or during the second pulse, distort the shape of the second pulse, null it or can create spurious additional pulses whose spacing may be accepted by the decoder.

If the time of arrival of the second pulse is used for ranging, such echoes can produce unacceptable errors. It is, therefore, planned to use the time of arrival of the leading-edge of the first pulse for distance measurement. Then the second pulse of the pair serves only to identify the channel's code.

(b) Short Delay Echoes

Echoes of the first pulse, which arrive during the leading edge of the direct pulse and before the decision level is reached by the direct pulse leading edge can cause unacceptable bias errors (20 feet), especially at low altitudes and short distances when the aircraft is in the critical phase of landing.

Contrary to recently held belief, the error caused by a leading edge does not vary randomly from interrogation to interrogation as the aircraft approaches the beacon and therefore cannot be averaged out over several interrogations (see section F.1). Thus what was earlier considered to be the major source of random error is not applicable and a lower prf is possible because less averaging is required to achieve the 20 ft. (1σ) accuracy.

To combat this source of bias error, the following factors are noted: A low value of decision-level increases the probability that the direct pulse leading edge will reach the decision level before the echo arrives, and therefore increases the probability of excluding the echo error. In addition, a steep leading edge minimizes the error produced by an echo which arrives before the decision level is reached. These two effects, which exist when employing a low decision threshold, combine to reduce the bias errors in range measurement that are due to short delay echoes to a point where they are only a minor portion of the total error.

Example

Figure 8-9 shows a direct pulse whose leading edge rises according to:

$$e_1 = \frac{E}{2}\left(1 - \cos 2\pi t/T \right) \qquad E = 2.0 \text{ volts}, \quad T = 0.48 \text{ microseconds}$$

An echo (shown at B), with an amplitude 0.5E arrives after a delay of

$$30° = T/12 = 0.04\ \mu s = 20'$$

Curves C and D of figure 8-9 show the leading edge of the resultant pulse when the echo respectively adds and subtracts from the direct pulse. Line E shows the decision-level at 1.0 volt = 0.50E. It intersects the leading edge of the direct pulse at (a) t_d = 90° = 0.25T = 60'.

It intersects curve C at (c) t'_d = 79° = 0.22T = 52.5'

It intersects curve D at (d) t''_c = 120° = 0.33T = 80'

Therefore, at a decision level of 1.0 volt (0.5E) the maximum error is 80 - 60 = 20 ft.

If the decision level is reduced from 1.0 o 0.5 volt (from 0.5E to 0.25E), the equivalent bias error is reduced to +4.5'.

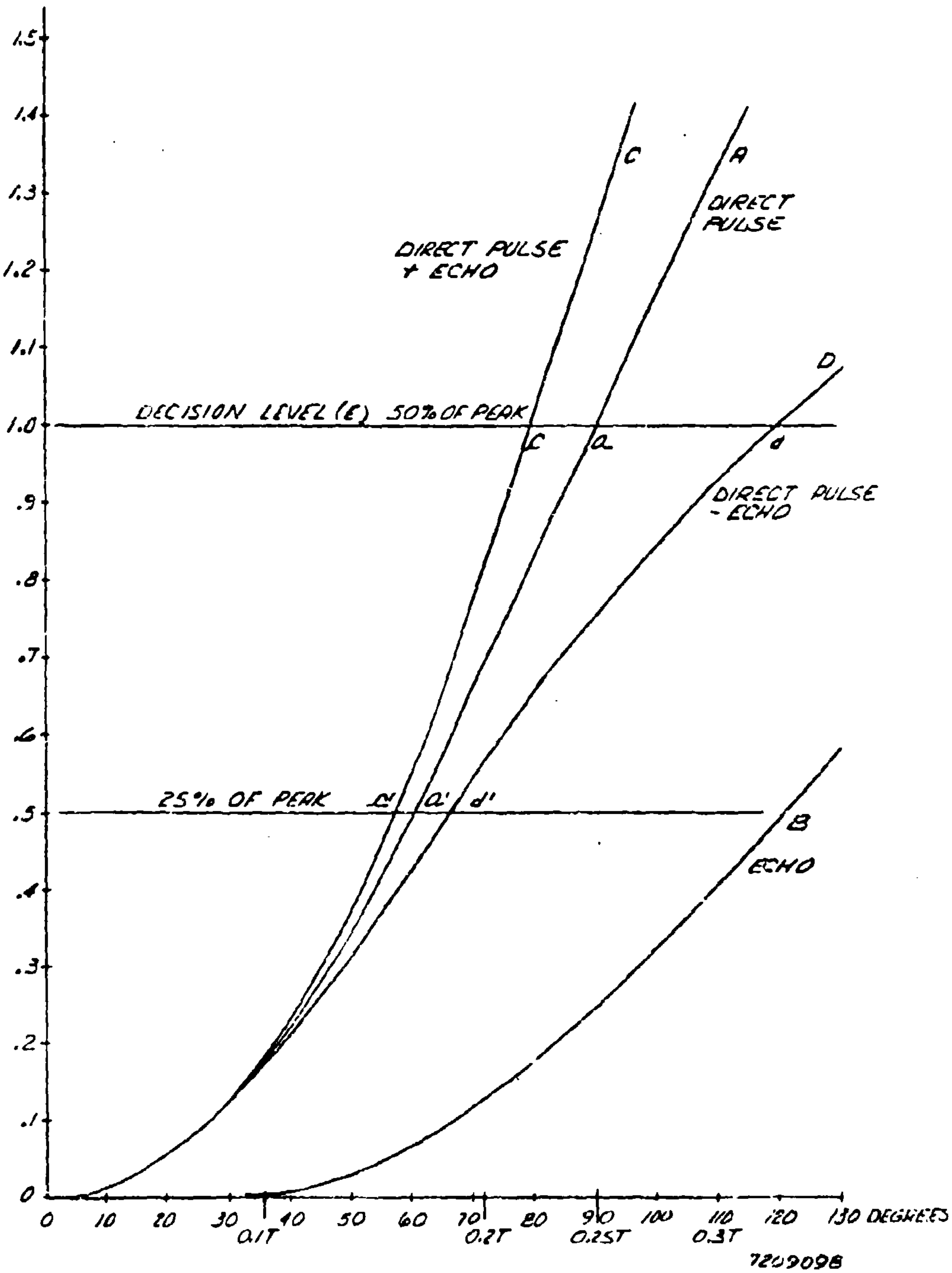


Figure 8-9. Effect of Decision Level on Errors Due to Echoes

If the decision level is chosen at 0.25 volt (0.125E), the echo is excluded because it arrives after the decision-level is reached by the leading-edge of the pulse. The example shows how a low threshold sharply reduces or eliminates errors due to short delay multipath.

Figure 8-10 shows the same 2-volt direct signal (E) as in figure 8-9. Curves B and C represent the "direct signal ± an echo". The echo's amplitude is 0.2E (-14 dB). It arrives after zero delay. A decision-level of 1.0 volt = 0.5E results in a bias error of 12'. If the decision-level is reduced to 0.5 volt = 0.25E, the maximum bias error is 4.2'. These examples show that a decision level of 0.25 of the direct signal amplitude reduces the multipath bias error to a negligible value.

(4) Description of Errors due to Method of Time-Measurement

As discussed under "General Considerations", the transponder uses a fixed decision level since it cannot easily control the amplitude of the received pulse. The interrogator can adjust its decision level as a function of range so that the decision level introduces a known bias for nominal power levels, which can be subtracted out relatively simply in the interrogator digital ranging circuits. To arrive at a viable means of utilizing a low threshold, which practically eliminates multipath errors, while at the same time introducing only small bias errors, the following approach was used.

Assume the leading edge of the received signal to be expressed by

$$e_1 = \frac{E_p}{2} [1 - \cos 2\pi t/T]$$

where E_p is the voltage produced by an a/c 30nmi away

Then the voltage received from an a/c at a distance(d)nmi it

$$e_1 = \frac{E_p}{2} \frac{30}{d} [1 - \cos 2\pi t/T]$$

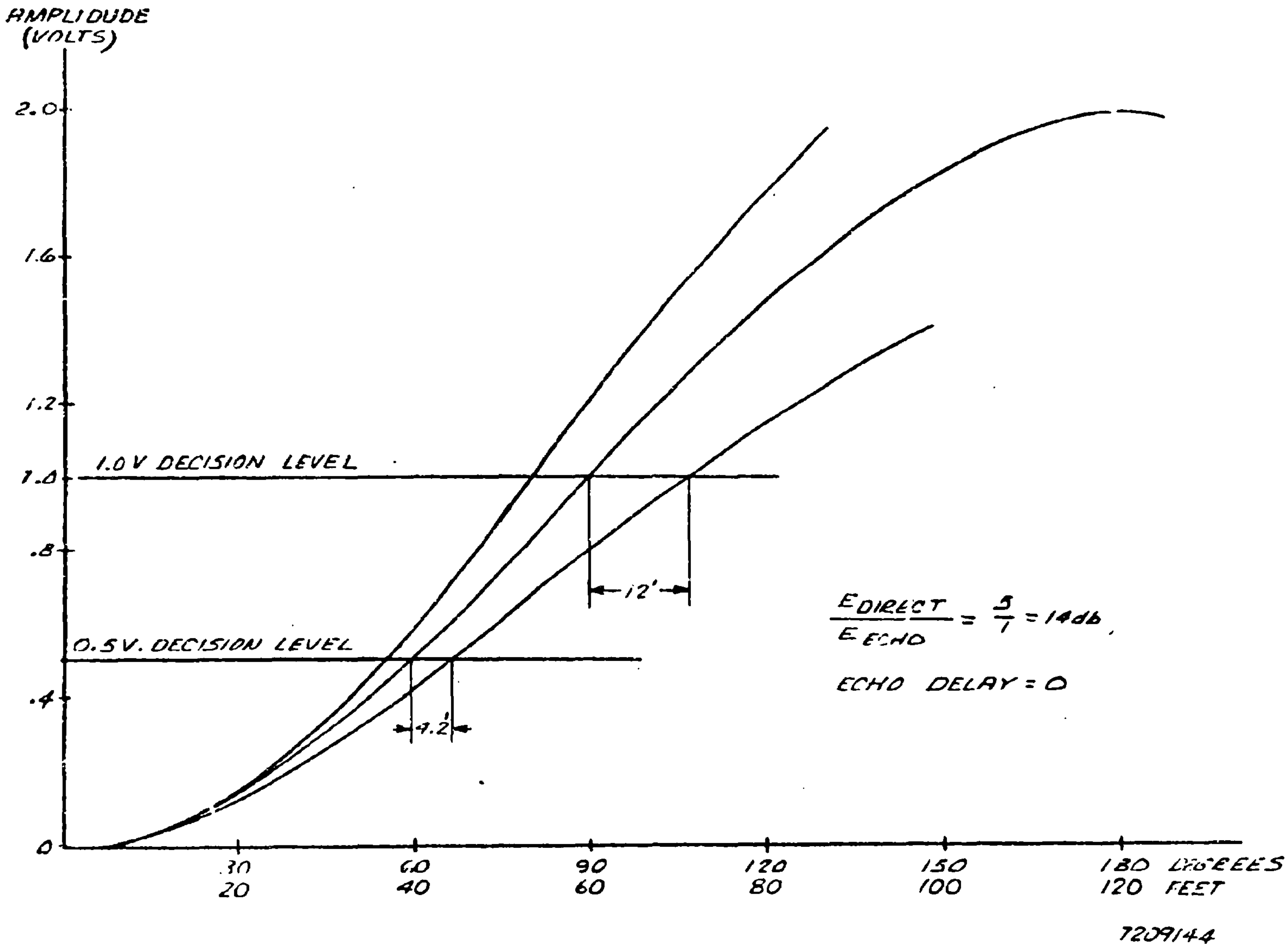


Figure 8-10. Effect of Low Decision Level on Zero Delay Echo

The leading edge reaches the decision level E_d at time t_d; letting $E_d = aE_p$ then

$$E_d = aE_p = E_p \frac{15}{d} [1 - \cos 2\pi t_d/T]$$

cancelling E_p and solving for t_d:

$$t_d = T/2\pi \cos^{-1} \left[1 - \frac{ad}{15}\right]$$

The reference time t_p is taken when d = 30 nmi and t = T/4, so that the time bias is

$$t_d - T/4 = T/2\pi \cos^{-1} \left[1 - \frac{ad}{15}\right] - T/4 \ \mu\text{sec}$$

The distance bias error, x, is:

$$x = 500\ T/2\pi \cos^{-1} \left[1 - \frac{ad}{15}\right] - 500\ T/4 \text{ feet}$$

if T = 0.048 μsec;

$$x = 38.2 \cos^{-1} \left[1 - \frac{ad}{15}\right] - 60 \text{ feet}$$

let a = 0.5 for the nominal value of E_p
a = 0.25 for the nominal value of E_p + 6db
a = 1.0 for the nominal value of E_p - 6db

and solving for x (the distance bias error):

d:	30	15	7.5	6	3	2	1	n.mi.
x, for nominal signal level:	0	-20	-32	-36	-43	-46	-50	ft.
x, for +6db level:	-20	-32	-41	-43	-48	-50	-53	ft.
x, for -6db level:	60	0	-20	-25	-36	-40	-46	ft.

if the interrogator read-out adds 40' to all values:

x (nominal):	+40	+20	+8	+4	-3	-6	-10	ft.
x +6db	+20	+8	-1	-3	-8	-10	-13	ft.
x -6db	+100	+40	+20	+15	+4	0	-6	ft.

We see that all bias errors are within ±20' for all distances from 7.5 nmi to zero miles.

A dynamic bias correction as a function of distance may be applied; then if the error is corrected for nominal power levels, a ±6db power variation will result in:

d(nmi):	30	15	7.5	6	3	2	1	nmi
x (nominal):	0	0	0	0	0	0	0	ft.
x (+6db):	-20	-12	-9	-7	-5	-4	-3	ft.
x (-6db):	+60	+20	+12	+11	+7	+6	-4	ft.

Note that in a practical sense all bias errors are within the 20 feet specification (the -6db level at 30 nmi would not be detected with regularity).

In the tables presented it was assumed that the received signal voltage increased linearly with range. This condition exists only up to the point where the aircraft begins to fly "under" the beam as discussed in the seciton on low elevation coverage. This means that the bias error for d less than 3 nmi as presented in the tables is not exactly represented. However, figure 8-11, a plot of decision time vs. signal/threshold, is presented which shows that if the Interrogator is adjusted to have zero bias error for the nominal levels expected at flare initiation, the most critical phase of landing, a plus or minus 10db deviation from nominal will introduce entirely tolerable bias errors. This relative insensitivity to power levels will permit the bias correction to be simply made for the region where maximum accuracy is required, with only small errors for deviations from nominal signal levels.

A method for setting up the interrogator to correct for bias errors is shown in figure 8-12. Referring to the figure, the interrogator synchronizing trigger is fed to both the ranging circuitry and the external precise controllable delay device. The delayed trigger initiates the transmitter, a small amount of signal is coupled from the transmitter output to a test transponder via an adjustable attenuator. The transponder provides

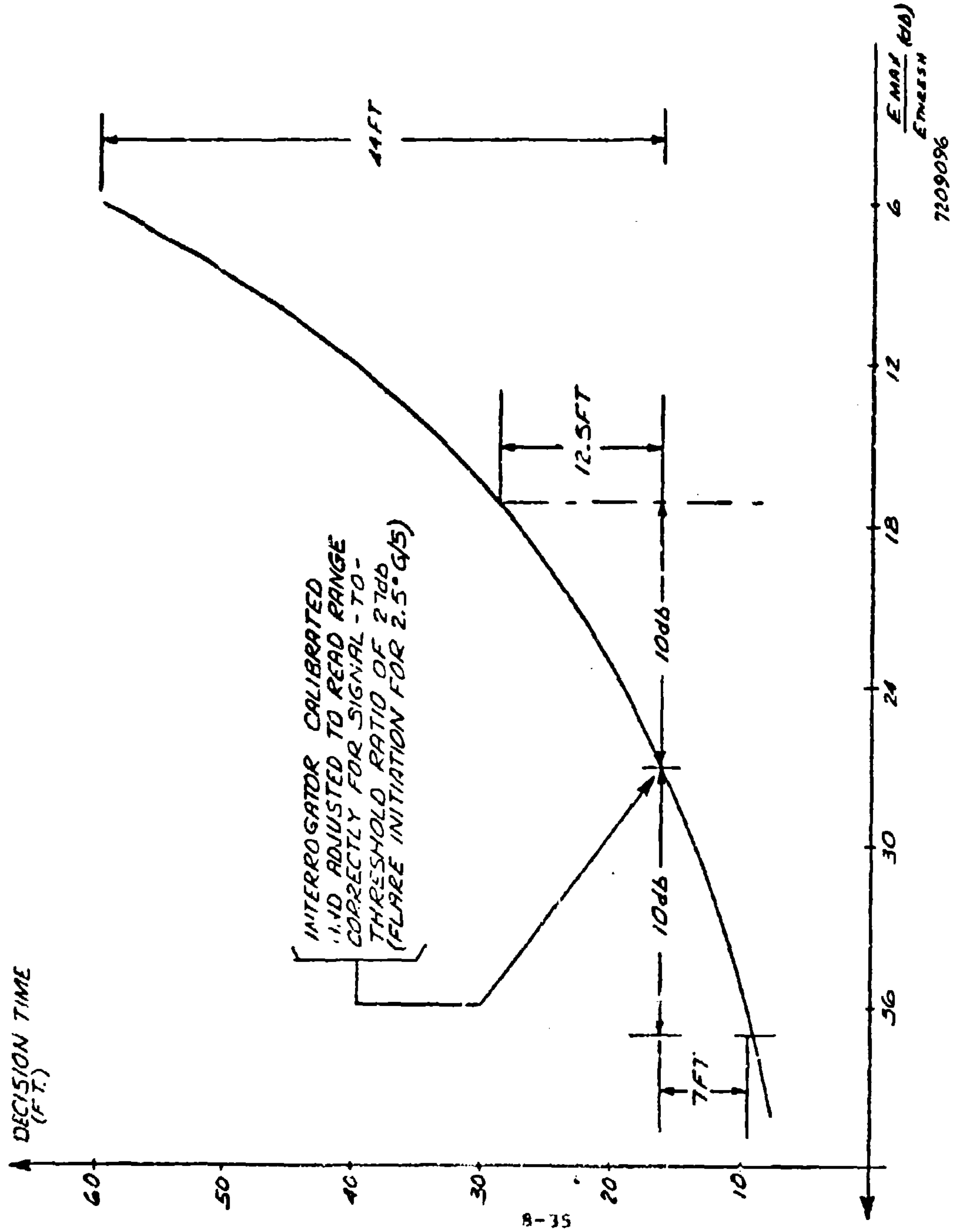


Figure 8-11. Bias Error Characteristic - Fixed Threshold Ranging

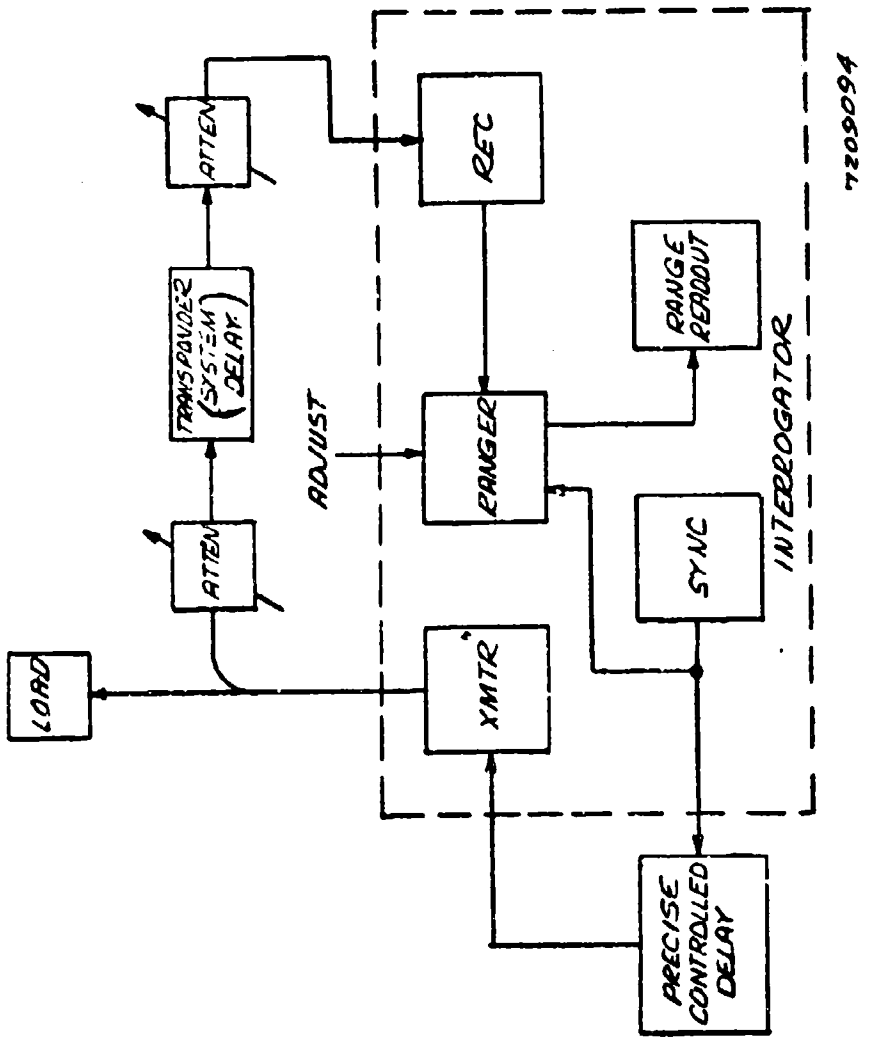


Figure 8-12. Simplified Block Diagram Interrogator Calibration and Adjustment

the 50-microsecond system delay and its output is fed to the Interrogator receiver through another adjustable attenuator. The Interrogator performs ranging measurements on the received pulse and the range readout is compared to the precise delay setting which simulates propagation delay.

To set the Interrogator up for a corrected bias error at flare initiation, the following may be done: An initial test is run with the precise delay simulating 30 n.mi. range and the attenuators adjusted to provide the 30 n.mi. nominal signal levels to the transponder and interrogator receivers. The interrogator threshold for this range will be at the 50% amplitude point. Delay trim is adjusted so that the reading agrees within measuring accuracy with the precise delay setting. The second test is run with the precise delay set for the mean range for flare initiation, where the highest accuracy is required. The transponder and interrogator received signal levels are set for the nominal value expected. The interrogator threshold is now set at a low level, say 25% of peak amplitude, and the range measurement should be in error by approximately -40 feet. A 12.5 MHz clock counts in 40 feet increments. Thus, for this frequency clock, the Interrogator will add a count for this range. This additional count can be used for ranges from about 10 n.mi. on in to touchdown and the bias error will be within 20 feet for a ±6db variation in power levels, and for an even higher power variation at the critical ranges near flare initiation.

(5) Description of Random Errors

(a) Listing of Sources

Random errors in distance measurement consist of:

- Jitter due to receiver thermal noise: the thermal noise of the receiving system adds (or subtracts from) the received signal and distorts it, causing the leading edge to cross a reference point both earlier and later than a noise-free signal in a random fashion pulse-to-pulse.

- o Jitter due to a varying decision threshold, limited to the accuracy of holding a d.c. reference. It is assumed conservatively that the uncertainty is 10%.
- o Jitter due to time-quantization which occurs when digital clocks are used to measure or introduce delay of analog signals.
- o Jitter that occurs in the modulator/transmitter between the input video pulse and the output rf pulse.
- o Jitter due to the reception of unsynchronized replies in the interrogator track gate.
- o Jitter due to moving multipath reflections which can cause echoes to distort the leading edge of the direct path pulse.

(b) Quantitative Estimates - Transponder

In the transponder, the sources of random error and estimates of their σ's are;

	SOURCE	
σ_{nj}	thermal noise (varies with distance) + decision level noise	$\pm .008\mu s$ (@5 n.mi. range) (see 1.1.1.1.G.6.b)
σ_{n}	Moving Multipath (estimate)	$\pm .01\mu s$
$\sigma_{m/t}$	Modulator/Transmitter	$\pm .01\mu s$

$$\sigma_{TRANSPONDER} = \sqrt{(\sigma_{nj})^2 + (\sigma_m)^2 + (\sigma_{m/t})^2} = 0.016\ \mu s = 8\ \text{feet}$$

Note that there is no quantization error in the transponder. System delay is achieved via an acoustic surface wave delay line which does not introduce any jitter. The delay line is described in section 1.1.1.1.G.4.b.(2).

In the Interrogator, the sources of random error and estimates of their σ's are:

SOURCE

σ_{nj}	Thermal noise (varies with distance) + Decision level noise	±.008μs (@5 nmi range)
σ_q	Quantization (12.5 MHz clock)	.023μs
σ_f	Unsynchronized replies (see ref. 1)	.014μs
σ_m	Moving multipath (estimate)	.010μs

$$\sigma_{INTERROGATOR} = \sqrt{(\sigma_{nj})^2 + (\sigma_q)^2 + (\sigma_f)^2 + (\sigma_m)^2} = 0.03\mu s = 15 \text{ feet}$$

Note that there is no modulator/transmitter error in the Interrogator, this is because the output of the transmitter is used to initiate the range measuring circuits. This avoids the error which would occur if the pulse signal to the modulator was used to initiate the range measuring circuits.

If we combine these errors to get the round trip standard deviation we get

$$\sigma_{TOTAL} = \sqrt{2(\sigma_{nj})^2 + 2(\sigma_m)^2 + (\sigma_f)^2 + (\sigma_{m/t})^2} = 0.034\mu s = 17 \text{ feet (5 nmi)}$$

If a digital system delay were used in the transponder, with a 12.5 MHz clock rate, the errors would be

$\sigma_{TRANSPONDER} = 0.028\mu s = 14$ feet (5 nmi)

$\sigma_{TOTAL} = .041\mu s = 20.5$ feet (5 nmi)

Ref. 1 "Errors in ILS/DME Caused by Responses to Other Aircraft, AGC Signals, and Identification Signals" Appendix B, J. J. Gibson, AD 427 721 (Accurate DME For Use With ILS) by C. J. Hirsch

(6) Effect of Averaging

Although it appears that the accuracy requirement of 20 feet (1σ) can be met on a single interrogation/reply, it may be desirable to average several measurements to provide a margin of confidence with a moderate increase in complexity. In any event, an investigation of averaging effects and means of implementation have been made to provide an avenue of design approach open for application if it is concluded that averaging provides a cost effective benefit.

If we neglect acceleration for simplicity of explanation (leaving its inclusion for section 1.1.1.1.G.6.e), we can express the range of an aircraft that is approaching a beacon as X_o at time t_1. Further, if it approaches with a velocity v, and the interrogation period is T, the sum of n measurements of distance (x) is:

$$\sum_1^n x_n = nx_o - \frac{n(n-1)}{2} vT \pm \sqrt{n}\, \sigma_x \quad \text{(see 1.1.1.1.G.6.e)}$$

where σ_x is the error associated with each measurement. The average of the n measurements is:

$$\overline{x} = \frac{1}{n} \sum_1^N x_n = x_o - \frac{n-1}{2} vT \pm \frac{\sigma_x}{\sqrt{n}}$$

The <u>random</u> error is reduced by $1/\sqrt{n}$. However, a lag is introduced, in that the average of the n measurements gives the range for the time of the $\frac{n-1}{2}$ measurement and not for the last (nth) measurement, which is "now". To update the average so that it corresponds to the range at the nth measurement, we can identify the correction needed as

$$\Delta x = -v \frac{(n-1)}{2} T$$

which when added to the average will yield

$$\overline{x} \text{ (corrected)} = x_o - (n-1)\ vT \pm \frac{\sigma x}{\sqrt{n}}$$

which is the range at the time of the nth measurement; with the σ_x reduced by $1/\sqrt{n}$.

Implementation of averaging and the means for lag correction are discussed in section 1.1.1.1.G.4.a which describes the interrogator for the K configuration system.

c. Accuracy: Range-Rate

(1) Definition of Issue:

The Technical issue is: how can a measure of the range-rate be obtained from a series of range measurements, in an approach most suitable for the Airborne Interrogator and having a standard deviation of 10 ft/sec? Fundamentally, if we assume constant range-rate motion, the range-rate is obtained by measuring the change in range (ΔR) over a known time interval (T). Errors in this measurement are due to errors in the range measurements (σ_x) and in the time interval (σ_t). If the assumed constant range-rate motion is incorrect (there are higher order motions involved such as acceleration and jerk) the simple method of $\Delta R/T$ will yield the average velocity in the interval, referred to the midpoint of the interval, and will be in error. For the dynamics of landing maneuvers it has been concluded that for the periods when accelerations do occur (in standard turns and in the deceleration after touchdown) the range-rate error is acceptable, especially since in less than two seconds after the accelerations are discontinued, the errors due to them become neglible.

(2) Quantification of Range-Rate Measurement

If an a/c travels a distance x in the time t, the average velocity is $v = x/t$. The error in measuring v, (dv), can be expressed as:

$$dv = \frac{\partial v}{\partial x} dx + \frac{\partial v}{\partial t} dt$$

where dx is the error in x; dt is the error in t substituting v=x/t:

$$dv = \frac{1}{t}\,dx - \frac{x}{t^2}\,dt$$

$$= \frac{1}{t}\,dx - \frac{v}{t}\,dt$$

Assuming that dx and dt are statistically independent:

$$(dv)^2 = \left(\frac{dx}{dt}\right)^2 + \left(\frac{v\,dt}{t}\right)^2$$

The design parameter that is used to meet a specified range-rate error, dv, with a given range measurement error, dx, is t, the elapsed time between range measurements. Solving for t in terms of dx and dv:

$$t = \frac{dx}{\sqrt{(dv)^2 - \left(\frac{v\,dt}{t}\right)^2}}$$

Examination of the term $v\frac{dt}{t}$ reveals that for a conservative estimate of time measurement accuracy of 1 x 10^{-3} (dt); for an interval of roughly 1 second (t); and for a velocity of 1000 ft/sec (v), the term $\frac{vdt}{t}$ can be neglected with negligible effect on the calculation for t (when dv is specified as 10 ft/sec.). Thus:

$$t = \frac{dx}{dv} = \frac{dx}{10}$$

The error dx is actually made up of the two errors made in measuring the distance x: at the start of the interval t, and at the end of the interval. Therefore, $dx = \sqrt{2}\,\delta_x$ where δ_x is the distance error per each measurement used in the range-rate computation.

If we further assume that δ_x is the average of N measurements of x, each of these measurements having an error of σ_x, then dx can be written:

$$dx = \sqrt{2}\,\delta_x = \sqrt{2}\,\frac{\sigma_x}{\sqrt{n}}$$

or

$$dx = \sqrt{\frac{2}{n}}\,\sigma_x$$

and t is now:

$$t = \sqrt{\frac{2}{n}}\,\frac{\sigma_x}{10}$$

In measuring range-rate then, the above analysis has assumed that we average N measurements of range, made over an interval N (Δt), where (Δt) is the time between measurements; then over the next N (Δt) interval we also average N measurements of range to obtain a later range measurement; these two averaged measurements are subtracted to get the range change over the interval between them (which is N (Δt)), and range rate is computed by dividing the range difference by N (Δt).

The time (t) required to achieve the 10 ft/sec accuracy is a function of Δt and N and can be computed for two typical Interrogation rates, 15 and 20, which correspond to Δt = 1/15 sec. and 1/20 sec. respectively.

Using

$$t = N\,(\Delta t) = \sqrt{2/N}\;\;\sigma_x/10$$

or

$$N = \left(\frac{\sigma_x}{7.1\,(\Delta t)}\right)^{2/3};$$

for σ_x = 20 feet:

$$N = (2.82/\Delta t)^{2/3}, \text{ then:}$$

Interrogation Rate	15/sec	20/sec
N	≈13	≈15
t	0.87 sec.	0.75/sec.

Note that the higher interrogation rate (prf) allows achievement of the required accuracy in a shorter time, as might be expected.

Also, an important point to realize is that the total time required to make the range rate measurement is 2t, because two successive averaging periods of t (N (Δt)) are required to obtain the averaged range measurements. Thus the total time (2t) between independent range-rate measurements is:

prf	2t
20	1.5 seconds
15	1.74 seconds

(3) Comparison with Optimum Averaging

If we make the same assumptions as in the above discussion; that the range-rate is constant and the errors due to uncertainties in time measurement are negligible, the minimum variance obtainable in an estimate of range-rate from a series of range measurements is (Reference 2):

$$\sigma_{\dot{x}}^2 = \frac{12 \sigma_x^2}{M(M^2-1)(\Delta t)^2} \approx \frac{12 \sigma_x^2}{M^3 (\Delta t)^2} \quad \text{(M large)}$$

where

$\sigma_{\dot{x}}^2$ = range-rate variance

σ_x^2 = range variance per measurement

M = total number of range measurements made

Δt = time between range measurements

This minimum variance is obtained by performing a linearly weighted average as described by:

$$1/M^3(\Delta t) \sum_{i=1}^{\frac{M+1}{2}} \left(\frac{M+1}{2} - i\right)\left(x_{M+1-i} - x_i\right)$$

$$= \frac{\left(\frac{M+1}{2} - 1\right)\left(x_M - x_1\right) + \left(\frac{M+1}{2} - 2\right)\left(x_{M-1} - x_2\right) + \text{etc.}}{M^3 \Delta t}$$

Reference 2: R. B. Blackman "Data Smoothing and Prediction" Chapters 7 and 8 Addison-Wesley Publishing Co. 1965 where

x_i = the i^{th} range measurement

Note that each successive range difference is weighted on a linearly decreasing scale. In words, if we take M range measurements, find the difference between the M^{th} and 1^{st}, the $(M-1)^{th}$ and 2^{nd}, etc. and weight the differences having the larger time separations heavier than the others in a linearly weighted average, we will obtain the minimum variance estimate of range-rate for the conditions assumed.

To compare the performance of the technique described in part b, called sub-optimum as against the optimum, we can compare the processing time required to achieve the specified 10 ft./sec accuracy. Using a σ_x = 20 feet, and an interrogation rate (prf) of 20/sec, we find M to achieve $\sigma_{\dot{x}}$ = 10 ft/sec:

$$\sigma_{\dot{x}}(\min) \approx \frac{\sqrt{12}\ \sigma_x}{M^{3/2}\ (\Delta t)}$$

or

$$M^{3/2} = \frac{\sqrt{12}\ \sigma_x}{\sigma_{\dot{x}}\ (\Delta t)} = \frac{\sqrt{12}\ 20}{10\,(1/20)} = 138.5$$

$$M = (138.5)^{2/3} = 26.8$$

$$M \approx 27$$

The processing (t_{opt}) time is then:

$$t_{opt} = M\ (\Delta t)$$

$$= 27\ (1/20)$$

$$= 1.35 \text{ seconds}$$

Comparing 2t of part b above with t_{opt} indicates that a slightly longer time is required in the suboptimum technique, about 11% more than in the optimum. Since the linearly weighted average technique would be more complex and require more storage and computations, the equally weighted average approach will be used to derive range-rate information in the Airborne Interrogator.

It is of interest to note that if we use no averaging; that is, we simply difference two range measurements and divide by the elapsed time between them, the time required to achieve the desired accuracy can be found from:

$$\sigma_{\dot{x}} = \frac{\sqrt{2}\,\sigma_x}{T}$$

where T is elapsed time

for $\sigma_x = 20$ ft. and $\sigma_{\dot{x}} = 10$ ft/sec.:

$$T = \frac{\sqrt{2}\ 20}{10} = 2.8 \text{ seconds}$$

This approach is somewhat simpler and the penalty of waiting every 2.8 seconds has not been clearly quantified as yet in the total landing system dynamics and control. This option will be kept open during the Feasibility Program and will be evaluated in the Factory and Flight Test Programs along with the averaging technique. The choice for the Prototype Program will be made during Feasibility.

The method of implementation for measuring range-rate using the straight forward averaging technique discussed above is described in section 1.1.1.1.G.4.a, which presents the Interrogator description.

d. Traffic Capacity

(1) Definition of Issue

The issue of traffic capacity involves the provision of 200 non-interfering channels in a limited band such that the accuracy requirements can be met; and in the heaviest traffic conditions, each Interrogator can obtain reliable distance information with highest integrity. To meet the conflicting demands of high accuracy and limited spectrum, the SC-117 recommended approach (adopted here) is to pulse-code multiplex each of twenty channel frequencies ten times; with the twenty frequency-channels separated by 3 MHz in a 60 MHz band. This brings up the questions of off-frequency channel interference when wideband processing is used for accuracy; and false decoding when many pulses are being transmitted on the same frequency.

(2) Channel Plan

Table 8-3 shows the Channel Plan recommended by SC-117. This plan has been adopted by Hazeltine. Investigations made during the TACD phase and as described below have verified the workability of this plan and no strong reason for altering it has arisen.

(3) Wide-Band Processing and Selectivity

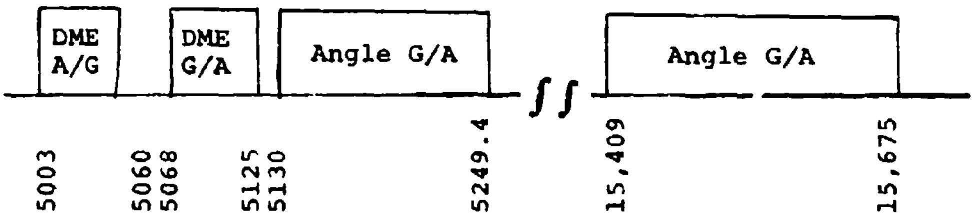
As discussed in the section on range accuracy, sharp rise time pulses and wide bandwidth (7.0 MHz) processing are beneficial in meeting the accuracy requirements, particularly in a multipath environment. Sharp rise-time pulses have considerable spectral energy outside the channel band. Figure 8-16 shows the condition for a 3 MHz channel separation and a 0.67 μsecond pulse width. Clearly, adjacent channels would interfere when using a wide bandwidth receiver. In order to provide simultaneous wide bandwidth processing with absolute rejection of off-channel signals, a Two-Mode Ferris Discriminator will be used. As described in Section 3.a.2, this circuit has a selectivity band of about 1.5 MHz which "screens" the input and allows only in-band signals to be processed in a wide band system. This circuit was experimentally verified during Phase I and a description of the tests and results are found in Section 3.a.2.

(4) Traffic Density

(a) General

The introduction of pulse-code multiplexing (by ten times) to achieve the required number of channels in the 60 MHz band raises the question of the susceptability of such a system to mutual interference in the form of false decoding. In general, the parameters that affect false decoding are the interrogation rate, the reply rate, the decoder tolerance, the coding technique, and time selectivity. In the section on accuracy it was shown that

Table 8-3. DME CHANNEL PLAN



10 channels created by pulse codes (see below): channels 1–10

Channel	DME A/G	DME G/A	Angle C-BAND	Angle Ku-Band
1	5003	5068	5130.0	15,409.0
2	5003	5068	5130.6	15,409.9
5	5003	5068	5132.4	15,412.6
6	5003	5068	5190.0	15,413.5
7	5003	5068	5190.6	15,414.4
10	5003	5068	5192.4	15,417.1
11	5006	5071	5133.0	15,418.0
15	5006	5071	5135.4	15,421.6
16	5006	5071	5193.0	15,422.5
181	5057	5122	5184.0	15,571.0
191	5060	5125	5187.0	15,580.0
195	5060	5125	5189.4	15,583.6
196	5060	5125	5247.0	15,584.5
200	5060	5125	5249.4	15,586.1

Pulse Codes per Frequency Channel:

per SC 117: A/G - Pulse Pair Spacing of 10 + 2 (n-1) μs

G/A - Pulse Pair Spacing of 28 - 2 (n-1) μs

where n = No. of Channel

for n=10: Minimum Spacing = 10 μs
Maximum Spacing = 28 μs

for each channel: (A/G + G/A) Spacing = 38 μs with the accuracy obtainable on a single interrogation, the prf of the interrogator can be lowered from the 40 PP/s of SC-117 to something substantially lower (10 to 20 PP/s) which reduces the pulse density proportionately. In the descriptions below, the traffic density problem is presented as a function of Interrogator prf to clearly show its affect.

(b) Transponder Traffic Handling

The table 8-4 below summarizes the maximum traffic seen by a transponder, per SC-117:

Table 8-4. MAXIMUM TRAFFIC AS SEEN BY A TRANSPONDER

	No. of Interro-gators	Interrogation Rate		
		prf=10 Int./sec	prf=15 Int./sec	prf=20 Int./sec
(1) Interrogators requiring primary DME service	66	660	990	1320
(2) Interrogators testing on the ground at a prf of 5 PP/s	100	500	500	500
TOTAL VALID INT. RATE		1160	1490	1820
(3) Interrogators on correct frequency but on wrong pulse-code (44 x 9)	396	3960	5940	7920
TOTAL INT. RATE		5120	7430	10,070

Spurious decodable pairs are created by the interrogators that are on the correct frequency but on the wrong pulse code. In the next section, which compares three-pulse coding against two-pulse coding, an expression is developed for the false decode rate. The expression is:

$$R_{F_2} = \text{False Decode Rate (2 pulse codes)} = \bar{A}_t^{\,2} \Delta\tau$$

where $\bar{A}_t$ = av. no. pulses per sec.

$\Delta\tau$ = decoder tolerance window

Note that $\bar{A}_t$ is the average number of pulses per second; and since there are two pulses per interrogation, $\bar{A}_t$ = 2 x no. of Interrogations/sec.

Using the number of interrogations per second from line (3) of the above Table, and a decoder tolerance of 0.5 μseconds, the following false decode rates are calculated:

prf	10	15	20
R_{F_2} (Decodes/sec)	32	72	128
% increase $\frac{\text{False}}{\text{Valid}}$ x 100)	2.8%	4.8%	7.1%

The percent increase due to spurious decodable pairs is considered negligible for all three prf's.

It is important to note that for a wide bandwidth IF (7.0 MHz), adjacent channel signals will be passed and the total received interrogation rate will become:

prf	Three-Channel Int. Rate
10	15,360 Int./sec
15	22,290
20	30,210

If echo suppression must be applied by detecting the peak amplitude of the first pulse and developing a threshold 6 dB down from that peak for the code length, unavailability of the beacon would be intolerable if the echo suppression circuit were implemented at IF. Echo suppression should be accomplished at video, after the Ferris Discriminator has eliminated off-channel signals.

(c) Interrogator Traffic Handling

A strong factor works to the benefit of the Interrogator with regard to its capability to handle high density traffic. This factor is that the Interrogator knows when to expect a reply and can use time selectivity as a means to obtain immunity to interfering pulses. This is especially true because the MLS DME operating range is only 30 nmi.

To illustrate the effectiveness of time selectivity consider the following:

There can be ten transponders transmitting on the same frequency, reaching the Interrogator (to assume a worst case). Each transponder may be transmitting at say 2700 replies per second; and one of these transponders is replying with the correct code while the others are not. There are therefore 2700 valid replies per second plus false decodes (F_2) at a rate:

$$F_2 = \bar{b}_t^{\,2} \left(\Delta\tau\right)$$

where $\bar{b}_t$ = av. no. of pulses per second

$\Delta\tau$ = decoder acceptance window

$\bar{b}_t$ = 2700 replies/sec x 10 transponders x 2 pulses/code = 54×10^3 pulse/sec

$\Delta\tau$ = 0.5 microseconds

$$\therefore F_2 = (54 \times 10^3)^2 \; 0.5 \times 10^{-6}$$

$$= 1460 \text{ false decodes/second}$$

The total number of decodes (false and valid) per second is 4160 per second. But if the Interrogator, in search, is responsive for only 360 microseconds for every interrogation, there are only

$$360 \times 10^{-6} \text{sec} \times 4160 \frac{\text{decodes}}{\text{sec}} = 1.5 \text{ false decodes/interrogation}$$

This rate of false decodes per <u>interrogation</u> is easily tolerable; its effect is to increase the search time somewhat. Search times of less than 0.45 seconds have been computed and are discussed in Section 4.a.3.

In track, where the gate can be narrowed by at least a factor of ten, the false decodes have a very minor effect on accuracy. This factor has been accounted for in the discussion on sources of random errors.

(d) Effect of False Decodes on Long Time-Constant AGC and Identity Coding

The following Table shows the false decode rate (F_2) and the increase in percent of accepted replies without time-gating in the Interrogator for different values of transponder reply rate (nr) - which is a function of the interrogation rate (q) - and for different values of decoder tolerance ($\Delta\tau$):

		q = 10	q = 15	q = 20
$\Delta\tau = 0.5\ \mu s$	n_r	1500	2000	2500
	F_2	450	800	1250
	$n_r + F_2$	1950	2800	3750
	$\left(\frac{F_2}{n_r + F_2}\right) \times 100$	23%	28.5%	33.3%
$\Delta\tau = 1.0\ \mu s$	n_s	900	1600	2500
	$n_r + F_2$	2400	3600	5000
	$\left(\frac{F_2}{n_r + F_2}\right) \times 100$	37.5%	44.5%	50%

The percentage of accepted replies is seen to be rather high. This could interfere with long-time constant agc, if used, because the agc will be determined in good measure by replies from other beacons as well as the desired one. Open loop gain-time-control in which gain is controlled as a function of range is proposed in the Hazeltine DME approach; this avoids the problem of agc'ing on false decodes.

The high number of spurious replies may also seriously confuse the "identity" coding proposed by RTCA SC-117 and scramble the message. (RTCA SC-117 suggested a reply identity coding by transmitting a reply code of 10.0 + 2 (n-1) for a logic (1) and 10.75 + 2 (n-1) for a logic (0). This subject must be studied in depth to prevent scrambled identity.

(5) Two-Pulse vs. Three-Pulse Coding

An investigation was made into the relative merits of 3-pulse codes vs. 2-pulse codes with regard to the generation of spurious pulse codes acceptable to either the transponder or interrogator decoder during heavy traffic conditions. A summary of the investigation is presented below.

(a) Transponder False Decode Rate

Characterization of Pulse Density

Appendix H of the SC-117 report DO-148 assumes that 44 interrogators on each of 9 different code multiplexed channels (but on the same frequency) can be reaching a transponder that is receptive to a different (10th) pulse code. The average pulse density, $\overline{a}$, under these conditions is given by

$\overline{a}$ = 44 interrogators x 9 codes x N pulse/code x n_r pulse codes/sec

$\overline{a}$ = 396 Nr_r average number of pulses per second (1)

The assumption is made that the aircraft interrogators have non-synchronized random interrogation frequencies, and are at random (and changing) ranges from the transponder. Under these conditions, the pulses that the transponder receives occur randomly in time, with the average rate given by 396 Nn_r. A random pulse train may be described by the Poisson probability distribution which says that the probability that K pulses occur in a time interval τ is given by

$$P(k,\tau) = \frac{(\bar{a}\tau)^K e^{-\bar{a}\tau}}{K!} \qquad (2)$$

where $\bar{a}$ is the average number of pulses per sec = 396 Nn_r

This representation of the pulse train seen by the transponder does not account for the fact that each pulse of an interrogation has companion pulses as part of the interrogation pulse code which are not random with respect to each other. However, the effect of this characteristic will be small and the approximation by the Poisson distribution is adequate for a relative comparison between 2-pulse and 3-pulse codes.

Solving for False Decode Rates

To determine the false decode rate of this randomly spaced pulse train, we can proceed as follows:

> For each pulse as it appears in time sequence at the transponder, determine the probability that at least one pulse appears in each of the later time slots that correspond to the decoder spacing and tolerance. (There is one later time slot for a 2-pulse code and two for a 3-pulse code.) This probability, multiplied by the average number of pulses per second, gives the average rate of false decodes.

Two-Pulse Code Computation

Applying the procedure to the case for a 2-pulse code, the probability that at least one pulse of the random pulse train will appear in the interval that will produce a decodable pair is given by (2):

$$P(K \geq 1,\Delta\tau) = 1 - \text{Probability of zero pulses in } \Delta\tau$$
$$= 1 - e^{-\bar{a}_2 (\Delta\tau)}$$

where $\bar{a}_2$ = the average no. of pulses per second for pulse pair coding

and $(\Delta\tau)$ = the decoder acceptance tolerance

If $\bar{a}_2 (\Delta\tau)$ is small, expanding $e^{-\bar{a}_2(\Delta\tau)}$ reveals that

$$P(K \geq 1, \Delta\tau) \approx \bar{a}_2 (\Delta\tau)$$

From (1):

$$\bar{a}_2 = 396\ N\ n_r$$

For pulse pair coding (N = 2), an interrogation frequency (n_r) of 20 pp/s, and a decoder tolerance $(\Delta\tau)$ of 0.5 microseconds:

$$\bar{a}_2 (\Delta\tau) = 16{,}000 \text{ pulses/second} \times 0.5 \times 10^{-6} \text{ seconds}$$

$$= .008$$

Thus

$$P(K \geq 1, \Delta\tau) \approx .008$$

The false decode rate for pulse pair coding (R_{F_2}) is now the product of $\bar{a}_2$ and $P(K \geq 1, \Delta\tau)$ which is:

$$R_{F_2} = .008 \times 16{,}000$$

or

$$R_{F_2} = 128 \text{ false decodes per second (ave.)}$$

Three-Pulse Code Computation

To realize the benefits of a 3-pulse code, the spacings between pulses of any code must be 1) different from each other, 2) different from any other spacings used in other codes, and 3) different from the sums of spacings of other codes. We choose to call codes having such properties as "ortogonal", in the sense that any code entering a decoder will produce no output unless the decoder is set up to receive that code; in which case there will be an output pulse at a known delay from the first input pulse.

Assuming a set of "orthogonal" 3-pulse codes, the same procedure is used to determine the false decode rate, R_{F_3}:

For each pulse of the random pulse train as it appears in time sequence at the transponder, the probability that there will be at least one pulse in both of the two later time slots that comprise the three-pulse code, multiplied by the average number of pulses per second, will yield the average false decode rate. The joint probability that both later time slots will be occupied is written mathematically as:

$$P(K \geq 1, \Delta\tau_1; K \geq 1, \Delta\tau_2) = P(K \geq 1, \Delta\tau_1)\ P(K \geq 1, \Delta\tau_2)$$

which says that the joint probability of having at least one pulse in time interval $\Delta\tau_1$, and at least one pulse in time interval $\Delta\tau_2$ is given by the product of the individual probabilities; because for the conditions assumed, the probabilities are statistically independent.

Following through:

$$P(K \geq 1, \Delta\tau_1)\ P(K \geq 1, \Delta\tau_2) = (\bar{a}_3 \Delta\tau_1)\ (\bar{a}_3 \Delta\tau_2)$$

where $\Delta\tau_1$ and $\Delta\tau_2$ are the decoder tolerances for the spacings between first and second pulses and the second and third pulses respectively; and $\bar{a}_3$ is the average number of pulses per second. If $\Delta\tau_1 = \Delta\tau_2 = \Delta\tau$:

$$P(K \geq 1, \Delta\tau_1)\ P(K \geq 1, \Delta\tau_2) = \bar{a}_3^{\ 2}\ (\Delta\tau)^2$$

Then the false decode rate, which is the product of this joint probability and the average number of pulses per second, is given by

$$R_{F_3} = \bar{a}_3^{\ 3}\ (\Delta\tau)^2$$

For the three-pulse code, $\bar{a}_3$ is obtained from (1), using $N = 3$ and $n_r = 20$/sec:

$$\bar{a}_3 = 396\ Nn_r = 396 \cdot 3 \cdot 20 = 23{,}760$$

or

$$\bar{a}_3 \approx 24{,}000 \text{ pulses per second}$$

Using a decoder tolerance of 0.5×10^{-6} seconds,

$$R_{F_3} = (24 \times 10^3)^3 \ (0.5 \times 10^{-6})^2$$

$$= 13.85 \times 10^{12} \times 0.25 \times 10^{-12}$$

$$= 3.46$$

or

$$R_{F_3} \approx 3.5 \text{ false decodes per second (ave.)}$$

Three-Pulse Code Generation

SC-117 has put forth a coding plan for two-pulse coding which provides ten different spacings per frequency channel. Since two-pulse coding is straightforward and the SC-117 coding scheme is as good as any, code generation effort was devoted to establishing ten "orthogonal" three-pulse codes.

Each three-pulse code is characterized by two spacings. If we call x_n the spacing between the first and second pulses, y_n the spacing between the second and third pulses and n refers to the nth code, we impose the following conditions of x_n and y_n to assure "orthogonality" in the sense previously described:

all x_n's are different by at least $2\Delta\tau$

all y_n's are different by at least $2\Delta\tau$

all (x_n+y_n)'s are different from any x_n or y_n by at least $2\Delta\tau$

all x_n's are different from all y_n's by at least $2\Delta\tau$

where $\Delta\tau$ is the decoder tolerance

A sample set of ten different codes that meets these conditions is as follows:

$\Delta\tau$ = 0.5 microseconds

Code No.	X_n	Y_n	$X_n + Y_n$
1	3 μs	4 μs	7 μs
2	5	6	11
3	8	9	17
4	10	12	22
5	13	14	27
6	15	16	31
7	18	19	37
8	20	21	41
9	23	24	47
10	25	26	51

Note that the decoding time gets rather long for the last several codes. This would mean that the minimum system delay in the transponder would have to be somewhat longer than the 35 μsec anticipated by SC-117, say about 55 μseconds.

(b) Interrogator False Decode Rate

Characterization of Pulse Density

There can be ten transponders transmitting on the same frequency, responding to random interrogations and squitter pulses. Assuming a worst case in which all of the transponders are transmitting at a maximum rate of say 2700 replies per second and the interrogator is receiving all of the transmissions, the interrogator sees a random pulse train having an average number of pulses per second, $\bar{b}$, given by:

$$\bar{b} = 10 \text{ transponders} \times N \text{ pulses/code} \times 2700 \text{ pulse codes per second}$$

$$\bar{b} = 27{,}000\ N \text{ average no. of pulses per second}$$

Since both the interrogations and squitter triggers occur randomly at the transponders, it is again concluded that the Poisson probability distribution characterizes the pulse train appearing at the interrogator. Note, however, that one of the ten transponders is transmitting the proper pulse code and the only method of discrimination against these unwanted replies that is effective in the interrogator is time selectivity, as will be seen below:

Solving for False Decode Rates

Two-Pulse Code Computation

Applying the same approach as used for the transponder calculations, the probability that at least one pulse of the random train will occur in the interval $\Delta\tau$ that will produce a decodable pair is given by

$$P(K \geq 1, \Delta\tau) \approx \bar{b}_2 \Delta\tau$$

From (3):

$$\bar{b}_2 = 27{,}000 \times 2 = 54{,}000 \text{ pulses/sec}$$

For a decoder acceptance interval $\Delta\tau$ of 0.5×10^{-6} seconds

$$P(K \geq 1, \Delta\tau) = 54 \times 10^3 \times 0.5 \times 10^{-6}$$
$$\approx .027$$

The false decode rate, F_2, for pulse pair coding is the product of this probability and the average number of pulses per second.

$$F_2 = .027 \times 54 \times 10^3$$

or

$$F_2 = 1460 \text{ false decodes/sec (ave.)}$$

These are in addition to the 2700 per second correctly coded replies being transmitted by the transponder that is selected by the interrogator, so that the total number of decodes per second is

$$F_{2_T} = 1460 + 2700 = 4160 \text{ decodes/sec (ave.)}$$

This would seem intolerable. However, if the interrogator processes only 30 n.mi. for each interrogation (as in the search mode) this time selectivity will result in a condition where the number of <u>false decodes per interrogation</u>, F_{2_I}, is given by

False decodes/sec x no. of seconds/interrogation

or

$$F_{2_I} = 4160 \frac{\text{decodes}}{\text{second}} \times 360 \times 10^{-6} \frac{\text{seconds}}{\text{interr.}}$$

$$F_{2_I} = 1.5 \text{ false decodes/interrogation (ave.)}$$

This is easily tolerable.

Three-Pulse Code Computation

For a three-pulse code system the average number of pulses per second, $\bar{b}_3$, appearing at the interrogator is simply

$$\bar{b}_3 = \frac{3}{2} \bar{b}_2 = 3/2 \; 54{,}000 = 81{,}000 \text{ pulses/second (ave.)}$$

The probability of a false decode is the joint probability that one or more pulses appear in <u>both</u> of the two time slots following each pulse of the random train. Following the procedure used for the transponder, the joint probability, P_J, is given by:

$$P_J = \left[P(K \geq 1, \Delta\tau)\right]^2 = (\bar{b}_3 \Delta\tau)^2$$

where $\Delta\tau$ is the decoder tolerance

The false decode rate, F_3, is then

$$F_3 = \bar{b}_3 P_J = \bar{b}_3^{\,3} (\Delta\tau)^2$$

$$= (81 \times 10^3)^3 \; (0.5 \times 10^{-6})^2$$

$$= (8.1)^3 \; (0.5)^2 = 133$$

$$F_3 = 133 \text{ false decodes/sec (ave.)}$$

Adding these to the correctly coded replies yields a total decode rate of

$$F_{3_T} = 2700 + 133 = 2833 \text{ total decodes/sec (ave.)}$$

For a 360 microsecond "on" time per interrogation, the number of false decodes per interrogation is given by

$$F_{3_I} = 2833 \times 360 \times 10^{-6}$$

$$= 1.04 \text{ false decodes/interr. (ave.)}$$

Note that there is no dramatic reduction in decodes per interrogation because a large portion of these are due to the correctly coded replies of the transponder selected by the interrogator. It may be concluded that the transponder stands to benefit substantially by three pulse coding while the interrogator benefit is minor.

(c) Summary

If we make the simplifying assumption that the unwanted pulses arriving at either the transponder or interrogator can be represented by pulse trains where the pulses occur randomly in time; and that the Poisson probability distribution, therefore, characterizes the random occurrance of pulses, then the following general results follow:

Transponder False Decode Rates are given by:

(a) for Two-Pulse Codes:

$$R_{F_2} = \bar{a}_t^{\,2} \Delta\tau \text{ false decodes/second (ave.)}$$

(b) for Three-Pulse "Orthogonal" Codes:

$$R_{F_3} = \bar{b}_t^{\,3} (\Delta\tau)^2$$

where

$\bar{a}_t$ = average no. of pulses per second (2-pulse code)

$\bar{b}_t$ = average no. of pulses per second (3-pulse code)

$\Delta\tau$ = decoder tolerance

and assuming that $a_t \Delta\tau$ and $b_t \Delta\tau$ are < 0.10

Interrogator False Decodes per Interrogation are given by:

(a) for Two-Pulse Codes

$$F_{2_I} = \left[\bar{a}_i^{\,2} (\Delta\tau) + n_r\right] T \text{ false decodes/interr. (ave.)}$$

(b) for Three-Pulse Codes

$$F_{3_I} = \left[\bar{b}_i^{\,3} (\Delta\tau)^2 + n_r\right] T \text{ false decodes/interr. (ave.)}$$

where

$\bar{a}_i$ = average no. of pulses per second (2-pulse code)

n_r = transponder reply rate

$\Delta\tau$ = decoder tolerance

T = "on" time per interrogation

$\bar{b}_i$ = average no. of pulses per second (3-pulse code)

and assuming that $a_i \Delta\tau$ and $b_i \Delta\tau$ are < 0.10

The parameters that contribute to false decoding are seen to be the interrogation rate (which affects $\bar{a}_t$ or $\bar{b}_t$), the reply rate (which affects $\bar{a}_i$ or $\bar{b}_i$ as well as n_r), the decoder tolerance, the range of the system (which affects T), and the coding technique (which is implicit in the expression for false decode rates). The selection of these parameters, however, must be made on a total system design basis because they affect accuracy, economy, integrity, etc. as well as traffic handling capability.

e. Integrity

(1) Definition of Issue

It is imperative that conditions causing false, misleading, degraded or missing information be detected and either corrected or identified quickly (flag alarm) to prevent incorrect landing maneuvers. The integrity of the DME information supplied to the pilot and/or autopilot can be degraded due to three different causes:

- o DME equipment failure or drift to out-of-specification condition.
- o Lock-on to echoes caused by periods (during search) of shadowing such that the direct path is blocked while an echo path is not.
- o Fading of the DME signal due to blockage, after the Interrogator is in the track mode.

(2) Monitoring of Equipment

It is planned to employ monitor and control concepts and techniques as described below to maintain the integrity of the DME information supplied to the pilot and/or autopilot.

(a) Transponder Monitor

The function of the transponder is to reply only to <u>valid</u> interrogations with correctly coded replies that have a precise, known delay; and to provide this service over a prescribed coverage in angle and range. The important parameters to monitor are:

Reply Delay
Triggering Level
Reply Efficiency
Receiver Frequency
Decoding Characteristic
Encoding Characteristic

Transmitter Power
Transmitter Pulse Shape
Transmitter Frequency
Antenna Pattern

Since the antenna is a passive device, it is considered that monitoring only the VSWR of the antenna connection will be sufficient after the antenna pattern has been verified upon installation. The block diagram of figure 8-13 depicts an approach that measures all of the other above mentioned parameters.

Referring to the figure, the crystal clock provides the timing source for the synchronizer, decoder and delay functions of the monitor. The synchronizer generates triggers (at a suitable prf) which initiate simulated valid r-f. interrogations to the transponder via the coder/modulator and also initiate the precise delay counter whose pre-set delay is compared with the transponder reply delay. The transponder reply delay and the monitor delay are set up to be equal when installed by varying the clock frequency and/or count of the monitor. The coincidence detector uses wide band circuits that will not respond unless the two delays are within $\pm$.02 useconds or $\pm$10 ft of range. Finer delay adjustments are made during installation with special test equipment. The trigger generator also feeds a reply efficiency counter circuit that compares the number of monitor interrogations with the number of correct, properly delayed replies. A threshold reply efficiency is selected and a "GO" "NO GO" decision as to the transponder status is made based on this threshold.

The attenuators are set so that the transmitter power and the triggering level (sensitivity) of the receiver are checked for meeting specifications.

The utilization of a superheterodyne receiver and Ferris Discriminator in the monitor will check the transmitter frequency

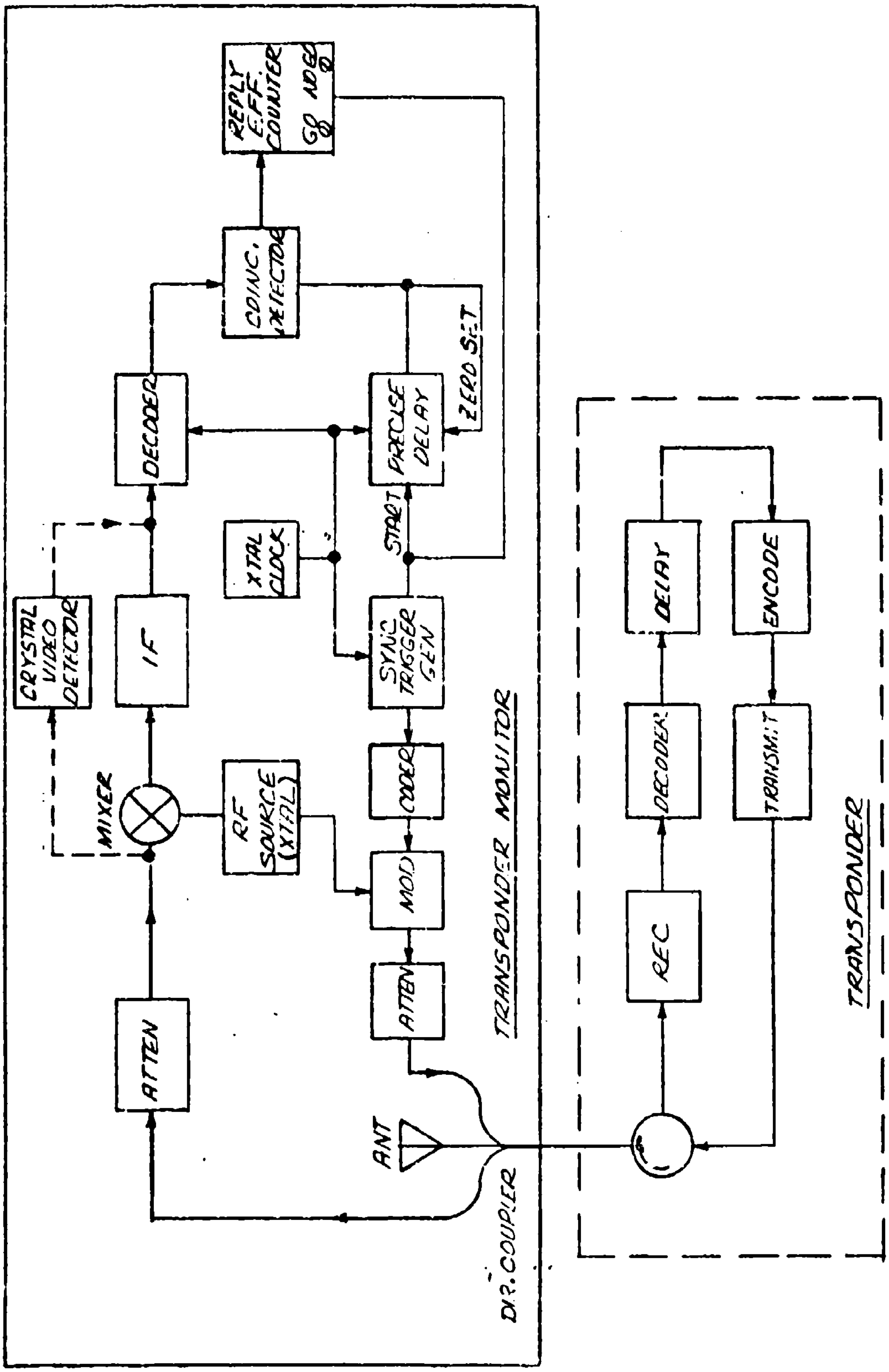


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Figure 8-13. Transponder Monitor Block Diagram directly. It may be concluded that this is not necessary due to the use of a crystal controlled r-f source; in which case, a simple microwave video detector may be used as shown dotted in the block diagram. However, since the transponder receiver must be tested with r-f, the expensive r-f source must be included in the monitor and it may be that only a small cost differential is involved between the superhet and video approaches. A choice between them will be made in the feasibility phase of the program.

The transponder monitor as configured in Figure 8.5.2 monitors all of the vital parameters of the transponder and presents a "go" "no go" display. The signals to the go, no go display will be used to control switchover to a standby transponder which will have its own monitor.

Periodic tests will be made to trim the monitor delay and to check the decoder, encoder, power, sensitivity, pulse shape, etc. characteristics for maximum effectiveness and reliability of monitoring.

(b) Interrogator Monitor

The monitor for the airborne interrogator will be considerably simpler then the transponder monitor, in order to keep aircraft equipment costs down. Ground testing will be used to supplement in-flight monitors and result in a cost effective approach for maintaining integrity of DME information. The airborne monitor will check transmitter power, receiver sensitivity, coding characteristics and decoding characteristics. Airport ground testing, using transponders and marked taxiway positions will check delay measurement accuracy, receiver frequency, and transmitter frequency in addition to duplicating and verifying the airborne monitor measurements.

A block diagram of a relatively inexpensive approach to the airborne interrogator monitor is shown in figure 8-14. The transmitter is monitored by coupling off a small amount of power and feeding a crystal video detector through an attenuator that is adjusted so that the transmitter power must be above the minimum specified to operate the "go" indicator. The decoder has a ± 0.5 usecond tolerance and checks the spacing of the transmitted pulse pair. The decoder and coder of the monitor must be selectable to correspond to the pulse pair coding of the channel (runway) selected by the interrogator.

The receiver is monitored by simulating correctly coded replies during the "dead time" intervals between interrogations and feeding these (at UHF) to the interrogator through an adjustable attenuator. The attenuator is adjusted so that the receiver is checked against the specification for minimum triggering level. A "go", "no go" display or equivalent is utilized to indicate whether the receiver is operating on the proper frequency and has the correct decoding characteristic.

If either the transmitter or the receiver monitors find a "no go" condition, the DME output display or autopilot input are declared nonuseable.

(3) False Lock-On

Echoes of the interrogation and reply signals are synchronized to the interrogation pulse. It is therefore possible, because of temporary conditions when searching, that the interrogator locks onto the echo and remains locked onto it during track. This occurs when the direct signal is shielded say by the a/c's banking but the echo is received. The return of the direct signal, falling out of the track gate, does not cause the interrogator to resume search, unless special means are provided to do so.

Prevention of false lock-on is enhanced by providing a two antenna diversity technique as described in section 1.1.1.1.G.2 d. (3). This approach will reduce the probability that the direct

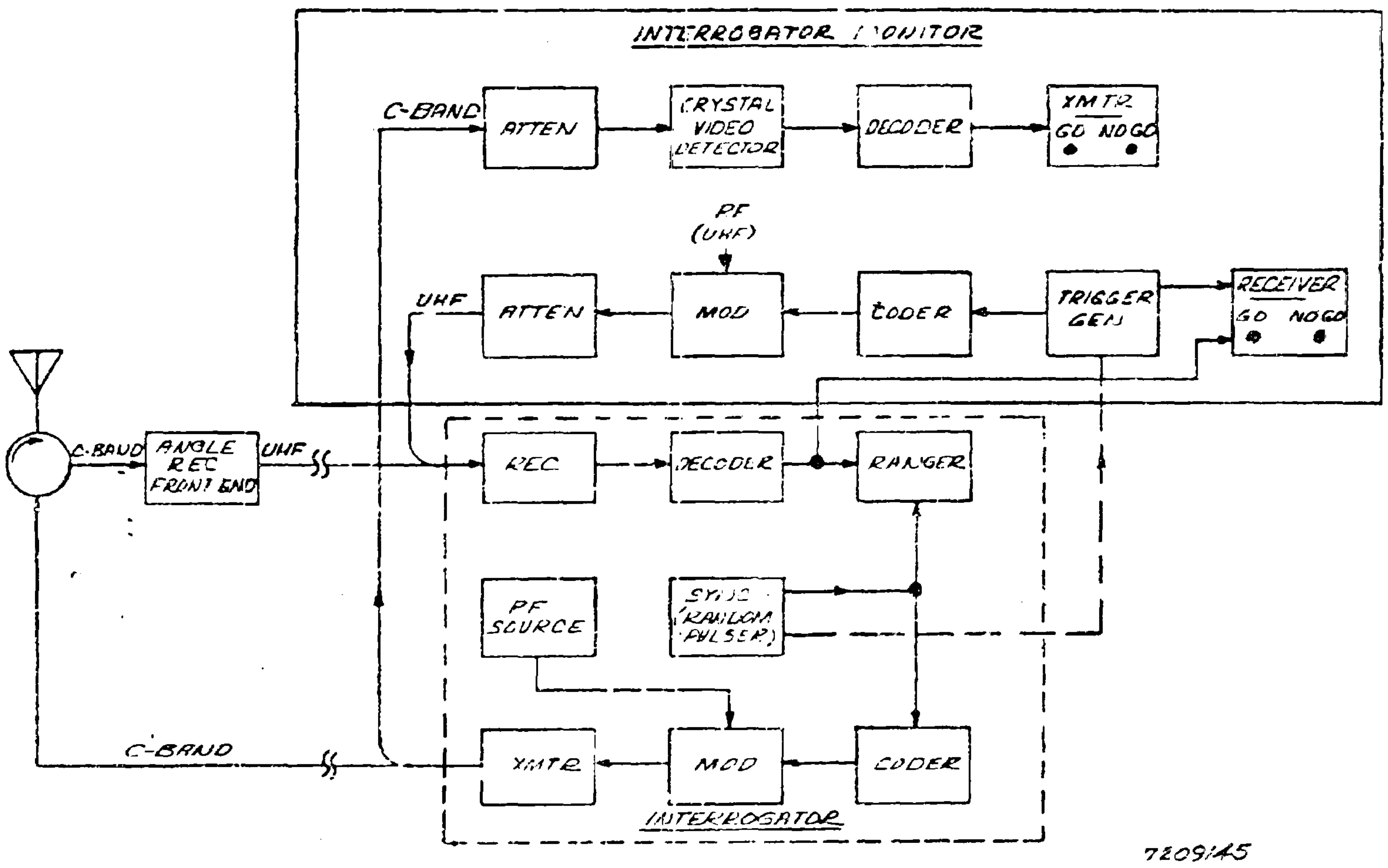


Figure 8-14. Interrogator Monitor, Block Diagram

path will be shadowed while the echo path is not. However, it is still possible that false lock-on will occur under temporary, special conditions.

To recognize that the direct signal has returned, it is planned to carry on search while in the track mode. Synchronous replies that occur earlier than the track gate, as determined by receiving two consecutive replies at the same range will throw the interrogator out of the track mode into the normal search mode. This will assure that only a temporary echo lock-on condition could exist. The implementation of this verification feature is described in Section 1.1.1.1.G.4.a. (3) dealing with Interrogator Search and Track Circuits.

(4) Memory Track Resume Search

During track, it is possible that blockage could occur for a few seconds due to other aircraft being in the line-of-sight and close to the DME antenna. During this loss of signal period it is planned to use the last range reading before loss of signal as the DME output, updated successively for every interrogation by the range-rate at the time of signal loss, until the signal is regained. A count will be taken as to the number of interrogations that have occured under the condition of lost signal; and after a specified time in the two to ten second range (to be determined in Phase II), to throw the Interrogator out of track and into the search mode.

3. Experimental Verification

a. Transponder Processing

A test program was initiated to verify the intended approach to transponder IF and Video processing. In particular, the following circuits were designed and tested:

o Log IF amplifier - This approach was tested in order to specify, with confidence, a receiver with large dynamic range without the requirement for instantaneous AGC.

- o Two Mode Ferris Discriminator (TMFD) - This approach was tested to insure absolute rejection of adjacent channel signals.

- o Echo discriminator - An echo discriminator was designed and tested to operate in conjunction with the log IF amplifier and Two Mode Ferris Discriminator in order to reject echoes having amplitudes more than 6 dB below the direct path signal. The intention is to prevent uncoded or incorrectly coded signals from being decoded due to echoes occurring with the correct delay.

(1) Log IF Amplifier

The DME transponder is expected to process signals having a large dynamic range. In addition, large variation in signal strength is expected from pulse pair to pulse pair. The available choices to staisfy these requirements are:

- o Linear IF amplifier with instantaneous AGC
- o Linear amplifier with large dynamic range (no AGC required)
- o Log IF amplifier

The linear IF amplifier with instantaneous closed loop AGC was discarded because of the difficulty in designing a stable AGC loop that would be capable of responding instantaneously. An AGC possibility for this choice would be to use a log IF amplifier to provide the AGC for the linear amplifier. This approach would increase the cost of the DME transponder and would be redundant since the log IF amplifier would, by itself satisfy the requirement for dynamic range. The second choice, linear amplifier with large dynamic range and no AGC, would require the design of complex low current drain class B push-pull stages or, the use of IF transistors with large signal handling capability with resulting high current drain in the class A mode of operation.

A log IF amplifier has none of the draw backs of the above designs. Wide dynamic range is obtained due to the fact that maximum output signal is obtained by all stages working in parallel. Therefore, AGC is not required and less input power is required than would be needed if a single stage had to handle the full output signal.

A Hazeltine designed log IF amplifier, presently incorporated in transponders and interrogators manufactured by Hazeltine, was tested for dynamic range. The amplifier is designed with six stages of the Plessey SL521EAT wide band amplifier. Each stage provides 11 db voltage gain and a maximum RF output of $1.2V_{p-p}$. Band pass limiting of the IF amplifier is accomplished at the amplifier input.

Figure 8-15 is a plot of the transfer characteristics of the log IF amplifier. The input dynamic range of 60 db is compressed down to an output dynamic range of 20 db, a more manageable range for the video processing circuits. In addition to compressing the dynamic range, the transfer characteristic maintains a constant slope of output volts vs. db input changes over the useful operating range. Echo descrimination is thus facilitated since; for a given ratio of echo level below the main pulse, a constant voltage difference will be obtained over the signal dynamic range.

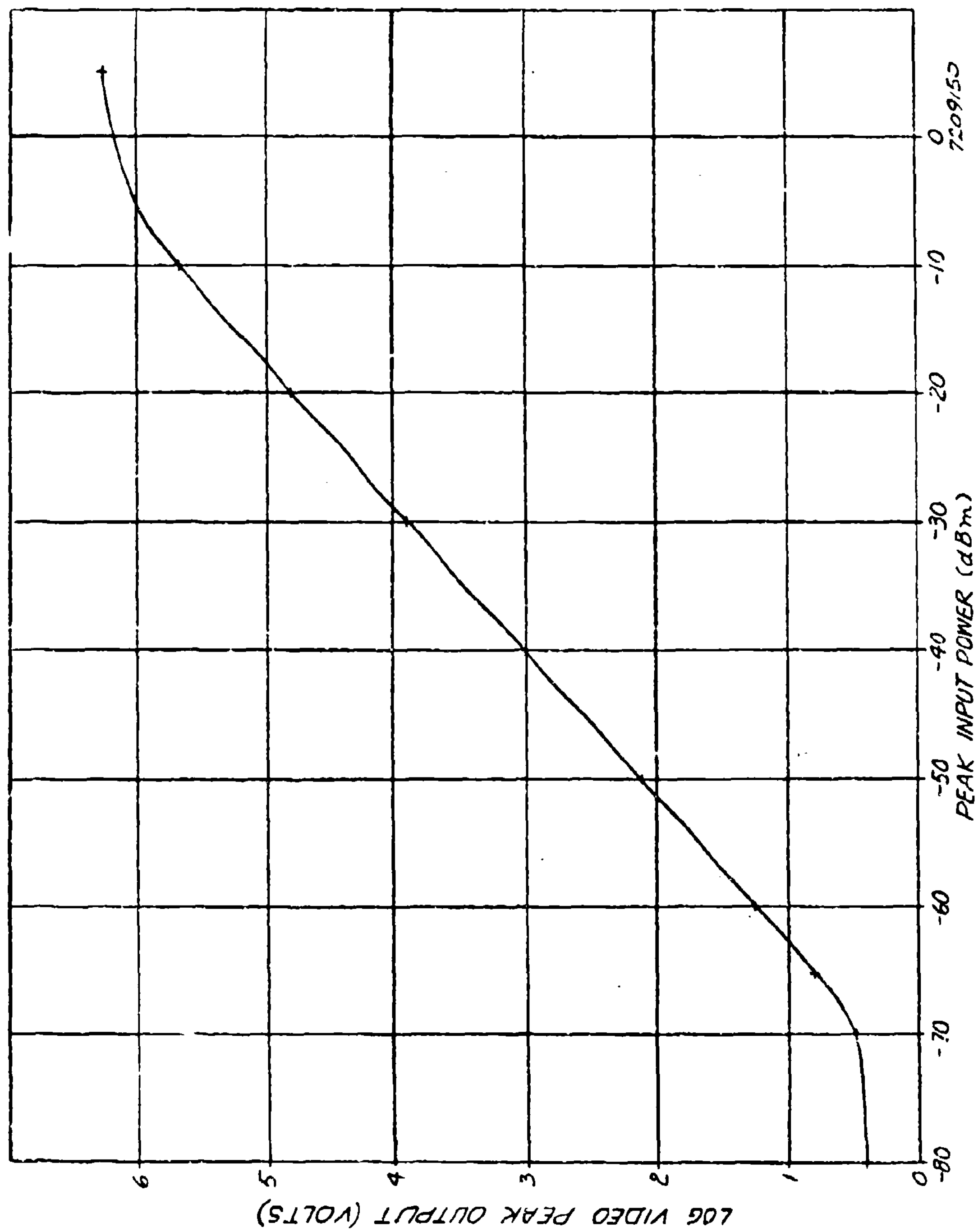


Figure 8-15. Transfer Characteristic of Log IF Amplifier

(2) Two-Mode Ferris Discriminator (TMFD)

The DME transponder is required to operate with a minimum receiver bandwidth of 7MHz and a channel separation of 3MHz. A method must therefore be provided for absolute rejection of the adjacent channel signal in order to prevent false decodes from occuring due to the adjacent channel signal. One method of providing this function is through the use of a Two-Mode Ferris Descriminator (TMFD).

Figure 8-16 is a simplified block diagram of the TMFD and the signal energies involved in its operation. The TMFD contains two envelope detectors, one providing a positive narrow band output and the other providing a negative wide band output, and both tuned to the carrier frequency of the on-channel signal. The bandwidth of the narrow band detector is selected such that it intercepts most of the energy in the main lobe centered about the on-channel carrier frequency. Only a portion of the energy contained in the side lobes of the adjacent channel signal is intercepted by this detector. The bandwidth of the wide band detector is selected such that the carrier frequency of the adjacent-channel signal lies at the edge of the band. Therefore, half the energy in the main lobe and of several side lobes of the adjacent-channel signal is intercepted by the wide band detector. Rejection of the adjacent channel signal is accomplished by adjusting k such that the total adjacent channel energy in the summing network due to the narrow band filter is exactly equal to the total adjacent channel energy in the summing network due to the wide band filter. The value of k, so chosen, allows the on-channel narrow band energy in the summing network to be much greater than the on-channel wide band energy. Therefore, TMFD output will only be provided when an on-channel signal is present. This narrow band on channel signal may then be used to gate the wide band on-channel signal (through an appropriate delay line) into the DME transponder processing circuits. Since no TMFD output is obtained due to an adjacent channel signal, the gating circuit remains disabled and the adjacent channel signal is rejected.

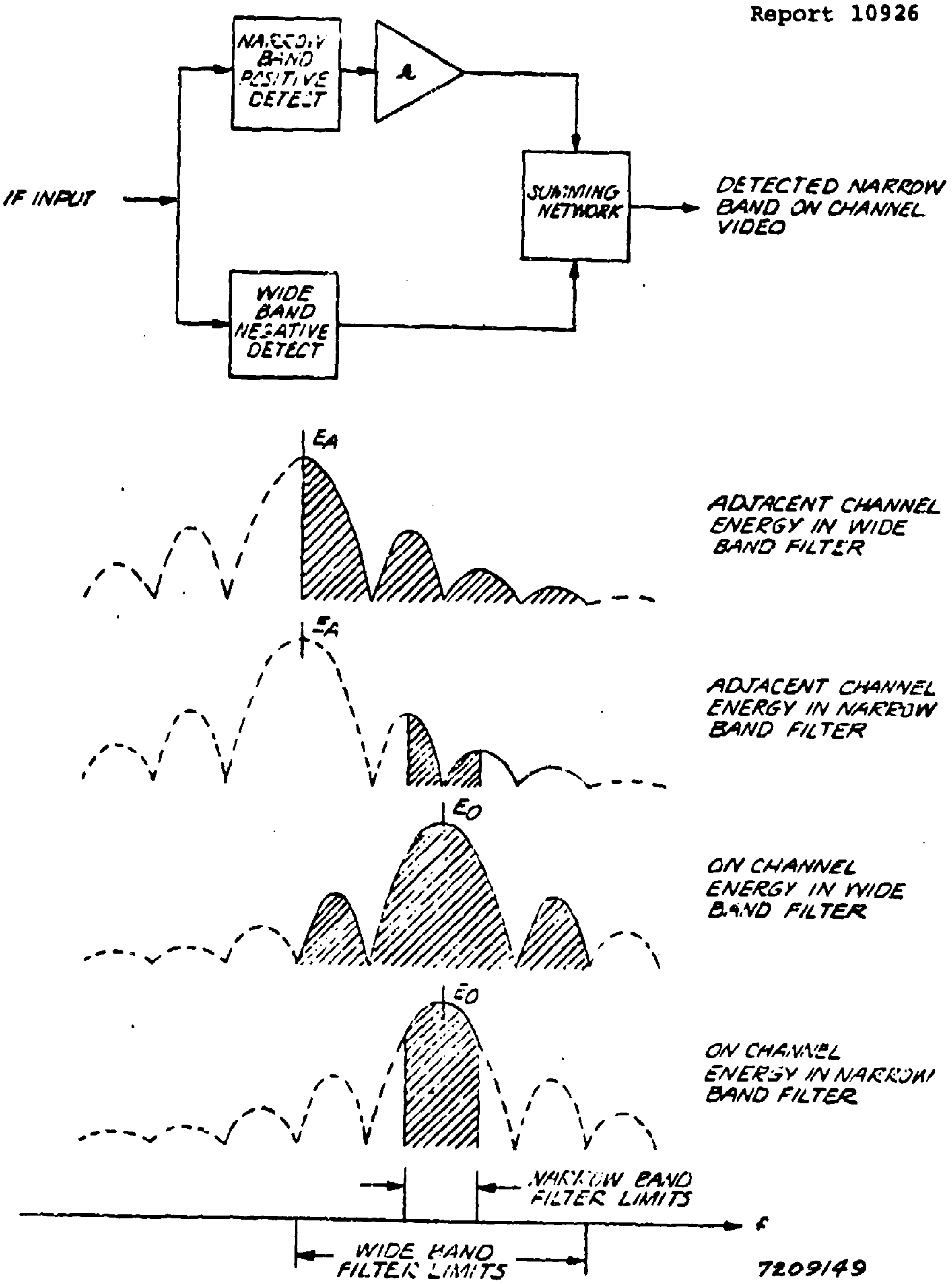


Figure 8-16. TMFD Block Diagram

Experiments were performed to verify that the TMFD will provide absolute rejection of an adjacent channel signal. The TMFD was designed with an adjustable narrow bandwidth and variable narrow band gain. These parameters were adjusted to provide optimum performance with respect to absolute rejection of adjacent channel signals (adjacent and on-channel signals not occurring simultaneously) and hole punching (adjacent and on-channel signal occurring simultaneously). The test setup used to make the measurements is shown in figure 8-17.

The bandpass (swept frequency) characteristics of the log IF amplifier and the TMFD summed output are shown in figure 8-18. The frequency characteristics for the log IF amplifier and TMFD were set as follows:

- o Center IF frequency = 61MHz
- o Log IF amplifier bandwidth = ±5MHz (3dB)
- o Narrow band TMFD filter center frequency = 61MHz
- o Narrow band TMFD bandwidth = ±0.75MHz
- o Wide band TMFD filter center frequency = 61MHz
- o Wide band TMFD bandwidth = ±2.5MHz

The on-channel signal generator was set to operate at 61MHz while the adjacent channel signal generator was set to operate at 58MHz. The characteristics of the pulse input to the IF bandpass filter are shown in figure 8-19 and are as follows:

- o Rise time = 0.1 microseconds
- o Pulse duration 0.67 microseconds

The pulse generators were set to provide an on-channel pulse pair, separated 10 microseconds, and a single adjacent channel pulse with variable delay such that it may be positioned to occur simultaneously with an on-channel pulse.

Figure 8-20 indicates the result of adjusting the TMFD narrow band gain below that required for adjacent channel balance. The TMFD output indicates a positive going signal for the on-channel signal

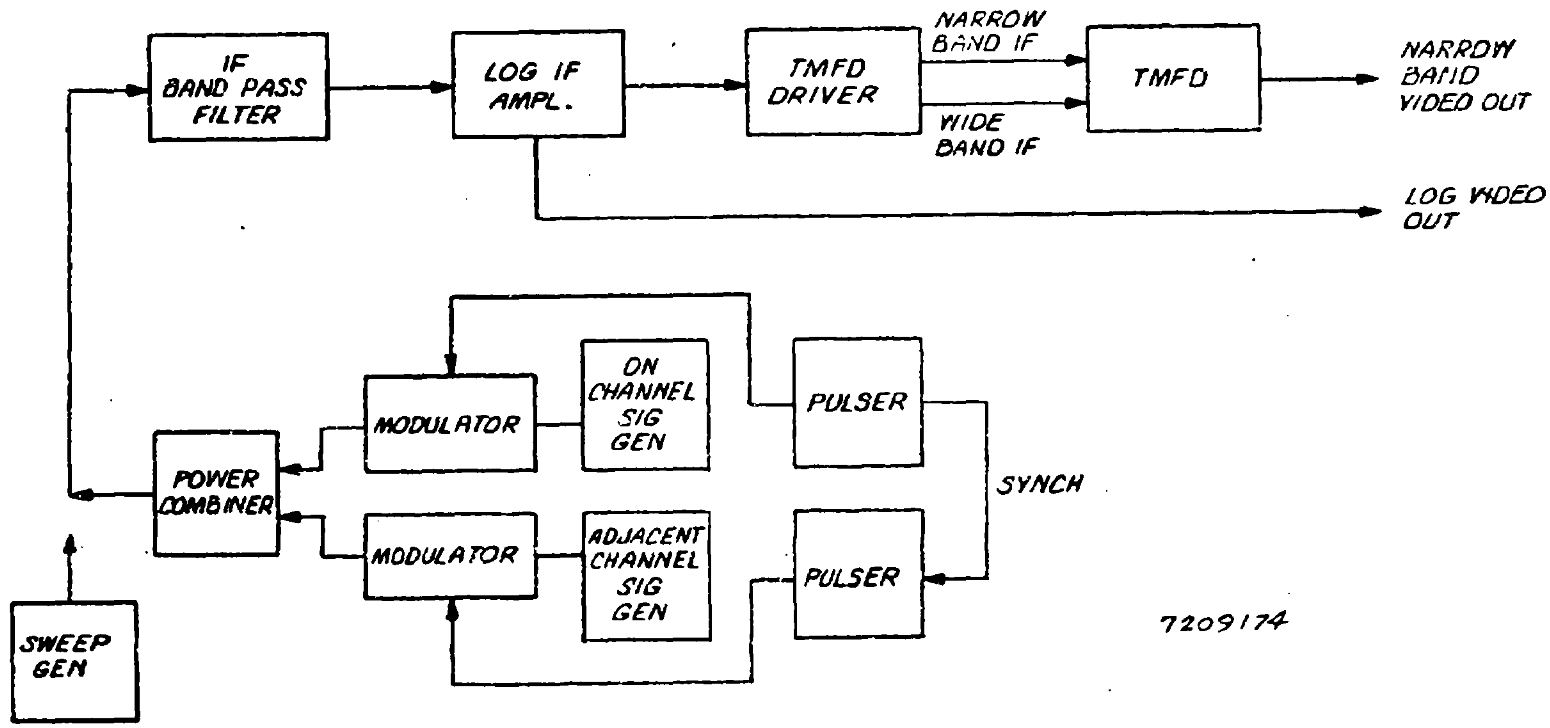


Figure 8-17. Test Setup for TMFD Evaluation

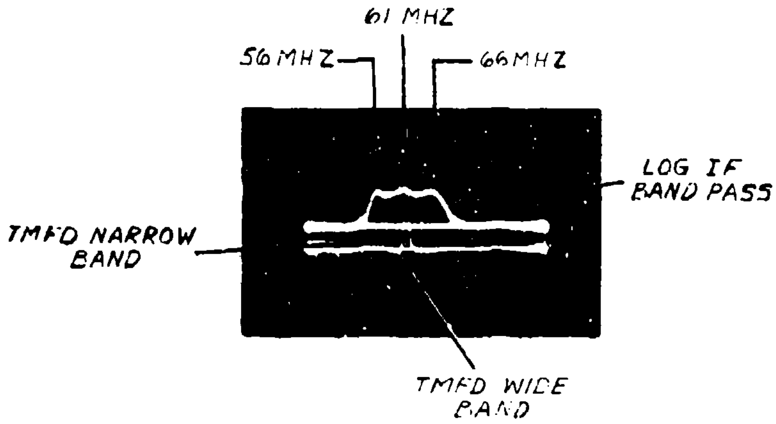


Figure 8-18. Bandpass Characteristics of Log IF Amp and TMFD Summed Output

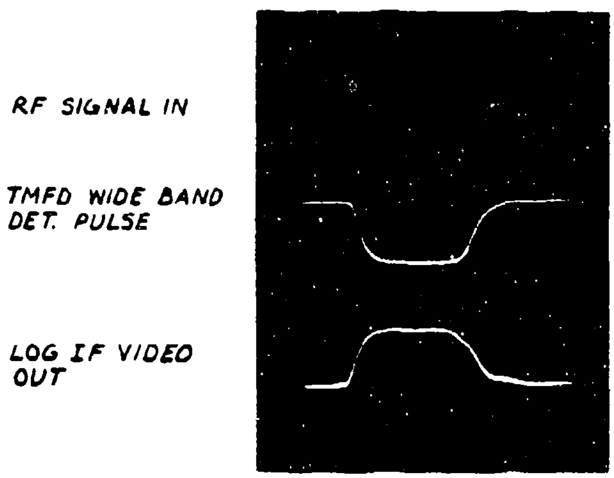


Figure 8-19. Comparison on Input RF Pulse and Detected Output Pulse (Log Video & Wide Band TMFD)

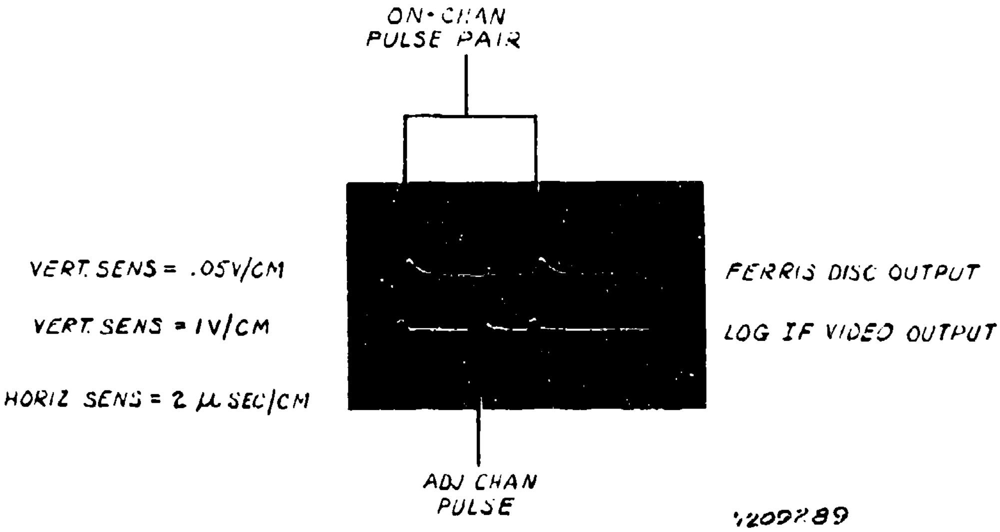


Figure 8-20. TMFD and Log Video
Output Pulses

and, a slightly negative signal for the adjacent channel signal. The positive TMFD output signal is used to enable a gate, allowing the wide band on-channel signal output of the log video (also shown in figure 8-20 for comparison) with a 0.2 microsecond rise time to pass through to the video processing circuits. The negative adjacent channel TMFD signal will not enable the gate thereby absolutely rejecting all adjacent channel signals.

The RF signal input levels used to give the results of figure 8-20 were as follows:

- o On-channel signal level = -55dbm
- o Adjacent channel signal level = -25dbm

Data was also obtained on the susceptability of the TMFD to hole-punching (on-channel and adjacent channel signals occur simultaneously). The results of this experiment are shown in the curves of figure 8-21. These curves were obtained by overlapping the on-channel and adjacent channel pulses. The RF input signal for the on-channel signal was maintained at a constant level while the adjacent channel signal was increased from a level below the on-channel signal to the level where the positive on-channel TMFD signal was reduced to zero (hole-punch). Several curves of on-channel TMFD output as a function of adjacent channel input signal level are plotted with constant on-channel input signal as a parameter.

Hole-punch susceptability is defined as the amount of adjacent channel signal power above that of the on-channel signal required to reduce the on-channel TMFD output to zero. The curves of figure 8-21 indicate that for the linear portion of the log IF characteristic, prior to limit level of the last IF stage, the hole-punch susceptability is at a minimum of 17db. As the on channel signal level is raised such that the last IF stage begins to limit, the hole-punch susceptability reaches a maximum of 10dB.

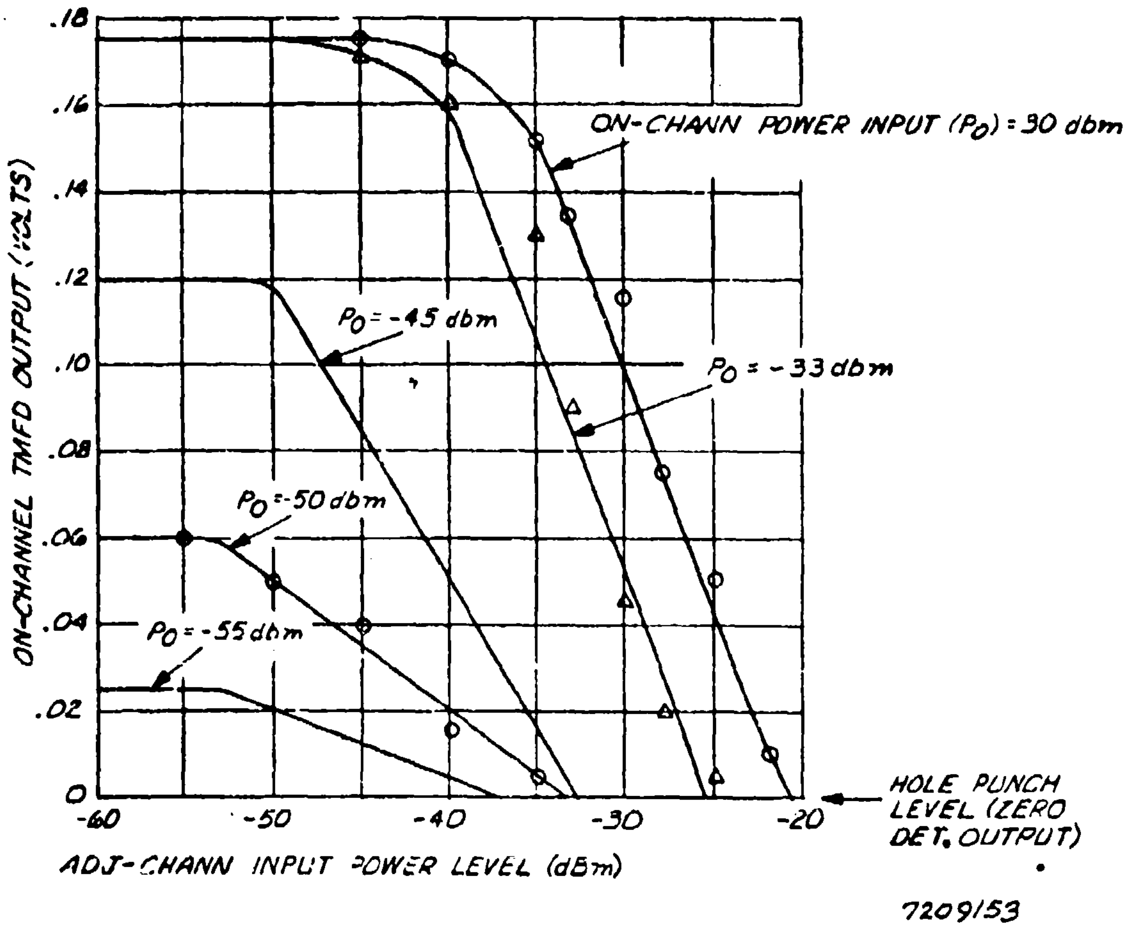


Figure 8-21. In Band TMFD Detected Output as a Function of Outband Input Power Level

The following conclusions were reached from the above experiments:

- The TMFD provides absolute rejection of adjacent channel signal (3MHz channel separation) while providing a signal to allow passage of the 5MHz bandwidth on channel signal.
- Susceptability to hole-punching, when on-channel and adjacent channel signals are simultaneously received, is not severe and can probably be tolerated.

(3) Echo Discriminator

A circuit that discriminates against echoes that are approximately 6db or greater below the main pulse was designed and tested. The discriminator operation is based on a variable reference voltage, proportional to the main pulse, supplied to a comparator circuit. A block diagram of the echo discriminator is shown in figure 8-22.

The first video pulse (main pulse) is simultaneously applied to the comparator and peak detector circuits. The peak detector charges a capacitor to the peak value of the main pulse and holds this value for the duration of the pulse pair. The detected peak voltage is then off-set by an amount corresponding to 6db times the slope of the transfer characteristic of the log IF amplifier. This DC signal is applied to the comparator and only pulses having a greater amplitude than this DC level are passed by the comparator. Thus, echoes 6db or greater below the main pulse are discriminated against. At the end of the pulse pair period, a transistor switch discharges the peak detecting capacitor and the circuit is reset for the following pulse pair. The transistor switch is controlled by a single-shot and differentiating network that is enabled by a signal from the Two Mode Ferris Discriminator.

Figure 8-23 shows the Echo Discriminator rejecting a pulse 7db below the main pulse. The figure also indicates the echo pulse being passed after the occurance of the second pulse of the pulse pair. The length of time during which discrimination takes place after the second pulse may be adjusted by increasing the length of the single shot pulse output.

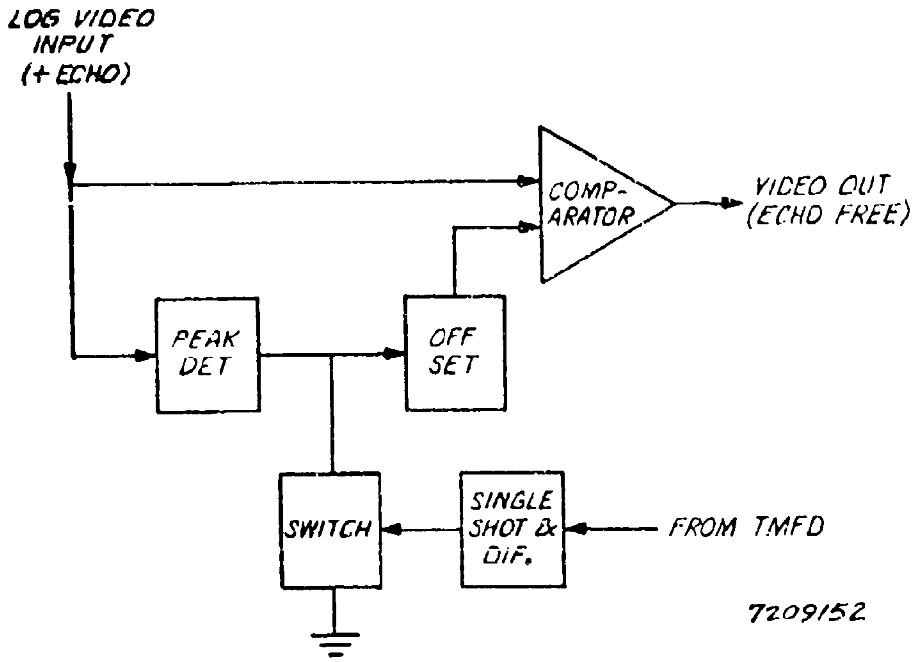


Figure 8-22. Echo Discriminator Block Diagram

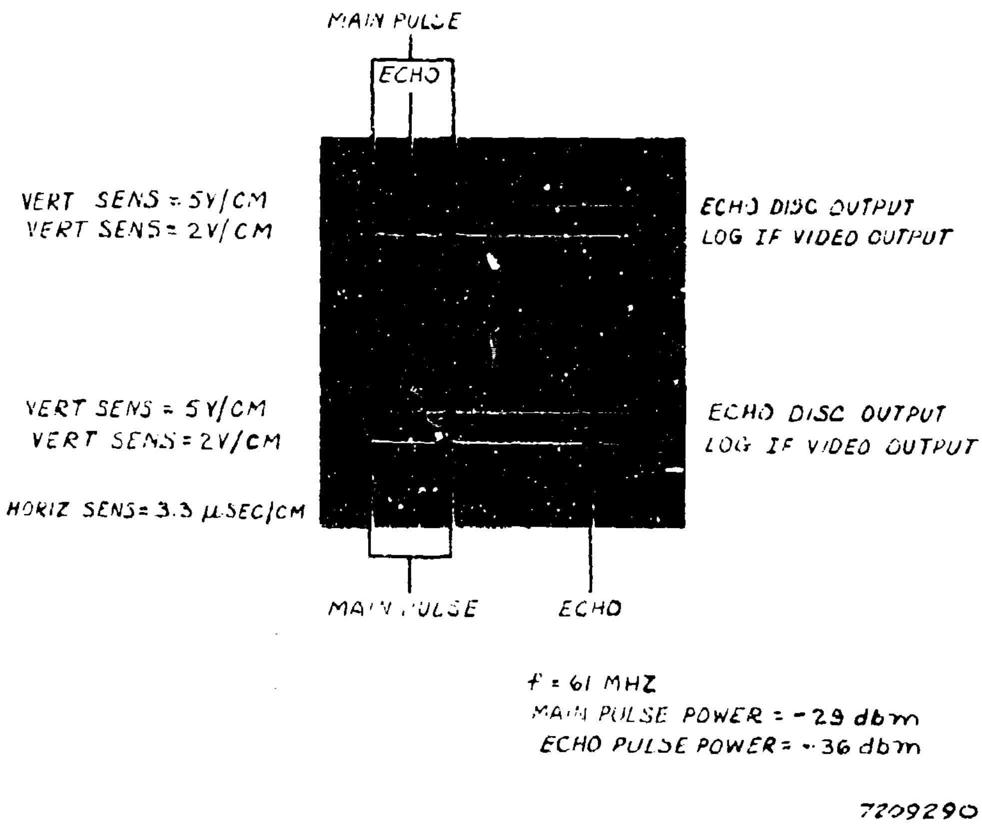


Figure 8-23. Echo Discriminator Rejection of Echo 7dB Below Main Pulse

(4) System Integration

The various subsystems described above were integrated and tests were performed to determine whether the objectives for video processing could be met. The overall block diagram of the system under test is shown in figure 8-24. Tests were performed using two separate IF signal generators and pulse generators. One combination of signal and pulse generator simulated the on-channel signal of 61MHz. The second combination was used to simulate the adjacent channel signal in tests to determine adjacent channel rejection and, as an echo generator in tests to determine echo rejection capability of the system.

Figure 8-25 indicates the system capability for absolutely rejecting an adjacent channel signal. The photographs were taken of oscilloscope presentations at test points 2 and 3. The input pulse, observed at test point 1, is also shown for reference. The adjacent channel signal input was set at -2dbm, 30db greater than the on-channel signal. The photographs were taken with the adjacent channel signal occuring during the on-channel pulse pair period and 20 sec after the on-channel pulse pair period. This was done to indicate that adjacent channel rejection is not influenced by the echo discriminator. The echo discriminator is set to recover approximately 10 μsec after the occurrence of the second pulse of the on-channel pulse pair.

Figure 8-26 indicates the systems resistance to "hole-punching". The adjacent-channel and on-channel pulses were made to occur simultaneously with the adjacent channel input set at -20dbm, 10db greater than the on-channel signal. The oscilloscope photograph taken of the system output at test point 3 indicates little degradation of the on-channel pulse pair. The log video pulse, taken at test point 1 is also shown for reference.

The system capability to reject echoes greater than 7db below the main pulse is indicated by the photograph of figure 8-27. Part A of this figure was taken with the echo set to occur within the main pulse pair period. The echo pulse signal level was set at

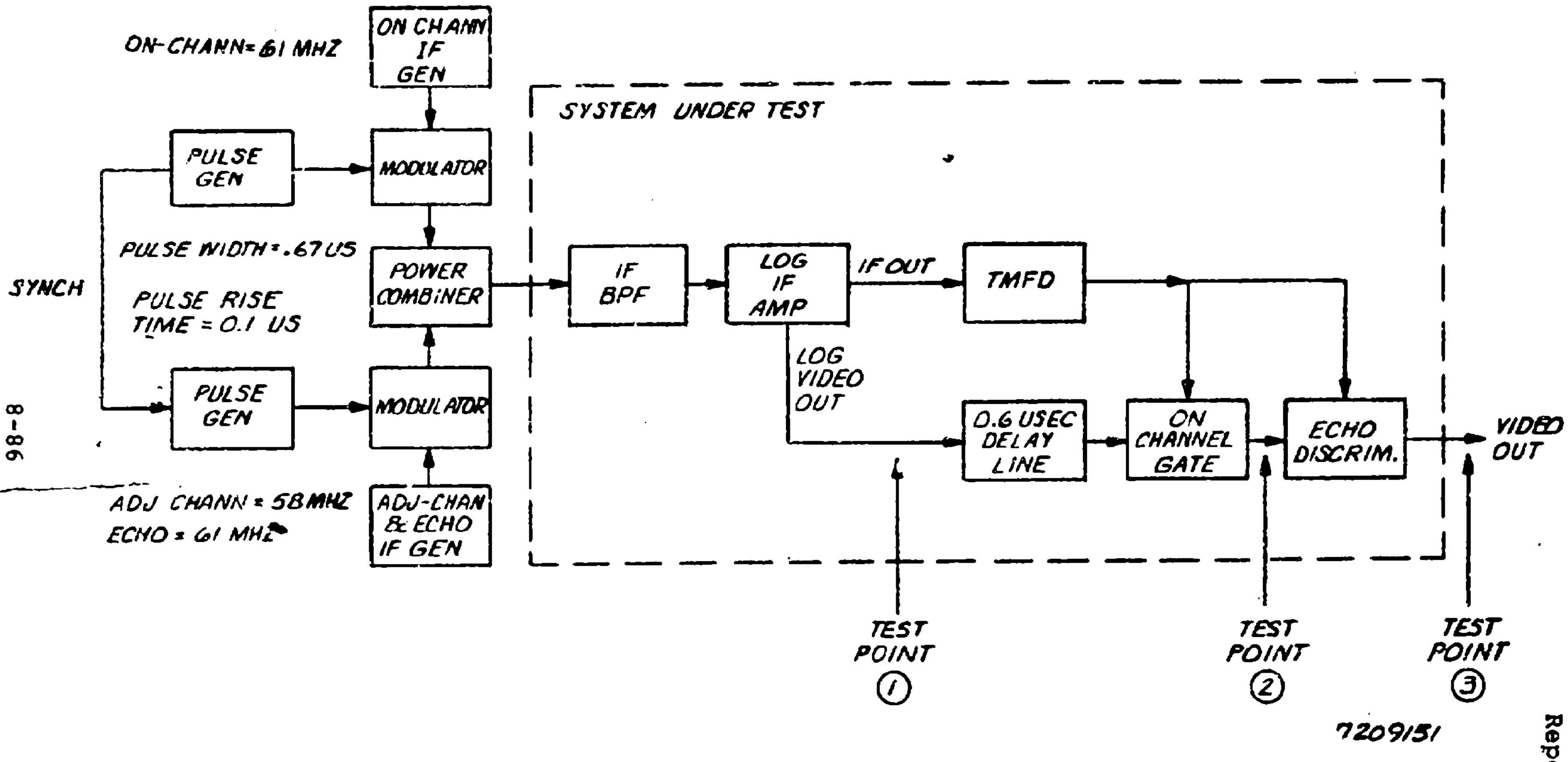


Figure 8-24. Block Diagram of System Test Set-Up

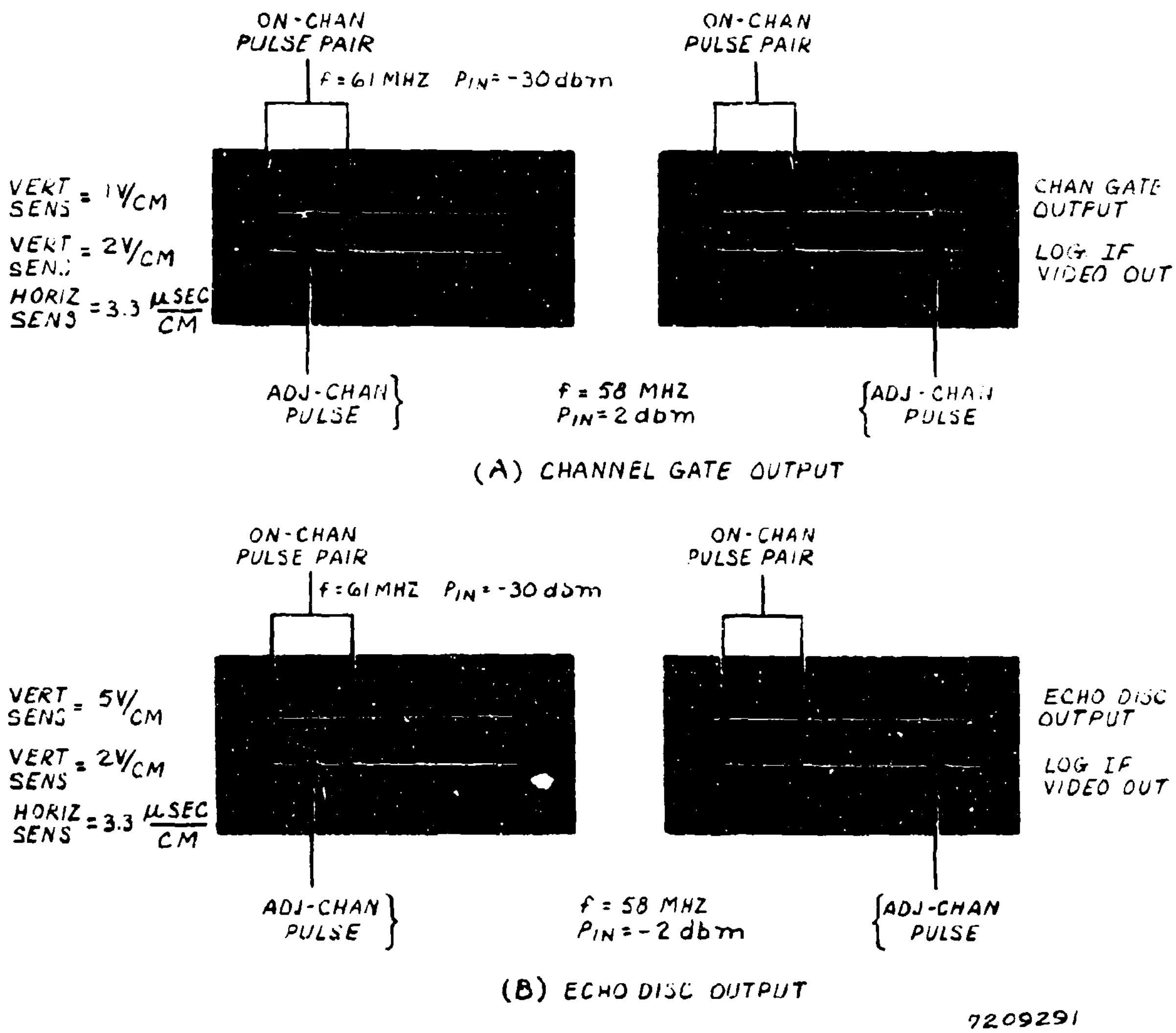


Figure 8-25. Non Synchronus Adjacent and On-Channel Signals

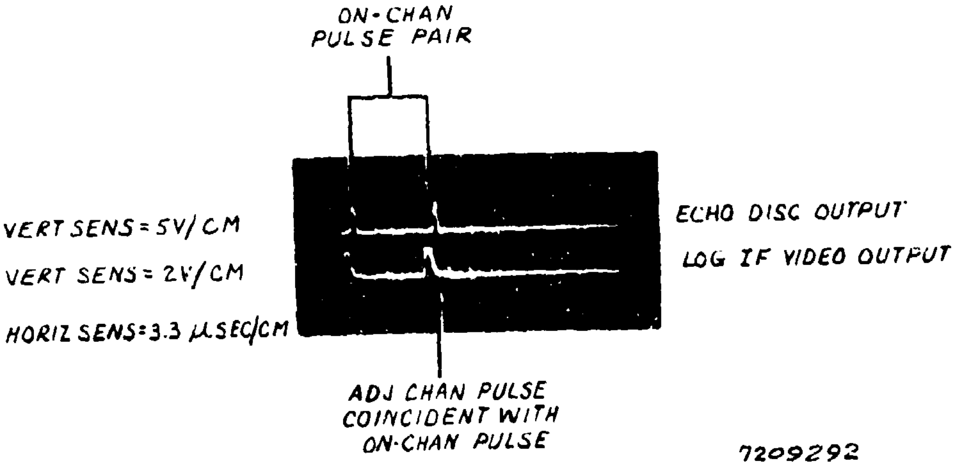


Figure 8-26. System "Hole-Punch" Resistance

SEE FIGURE 8-23

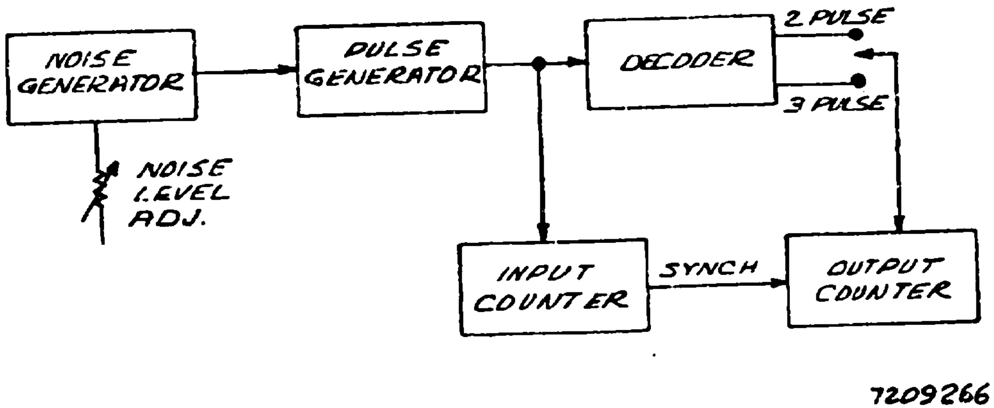
Figure 8-27. Echo Rejection

-36dbm, 7db below the main pulse. Part B was taken at the same input power levels but, the echo pulse has been moved out to occur at 20 seconds after the occurrence of the second pulse of the main pulse pair. The echo discriminator was set to recover approximately 10 μsec. after the occurrence of the second pulse of the pulse pair. These photographs were taken of the oscilloscope presentation of the output pulse at test point 3. The log video pulse, taken at test point 1 is shown for reference.

b. Investigation of 2-Pulse vs. 3-Pulse False Decode Susceptability

The number of false decodes per second for a 2-pulse code and a 3-pulse code has been analytically determined. The calculations are based on a system of 44 interrogators on each of 9 different code-multiplexed channels (in the same frequency channel) interrogating a transponder that is receptive to a different (10th) code. Results of the calculation show that a 2-pulse code system (32,000 p/sec) will elicit 1500 false decodes per second and, a 3-pulse code system (48,000 p/sec) will elicite 250 false decodes per second. An experiment was performed to check the validity of the calculation. A decoder tolerance of 1.5 μsec was used for both.

Figure 8-28 is a block diagram of the equipment used to perform the experiment. A high density interrogating environment was obtained using a noise source to trigger a single-shot pulse generator. The average triggering rate was adjusted by varying the RMS output of the noise source thereby varying the average rate of noise spikes with sufficient amplitude to trigger the single-shot pulse generator. The output pulse width of the single-shot was set at 0.67 microseconds, similar to that of the proposed DME. The random pulses were fed into the delay line driver of a modified UPA/39A Coder-Decoder. Delay line taps were selected at 0 microseconds and at 9.8 microseconds to simulate a 2-pulse decoder and, at 0 microseconds, 4.9 microseconds, and 9.8 microseconds to simulate the 3-pulse decoder. A second set of taps at twice the above delays was also selected to provide additional data for the



..e 8-28. Test Setup for Measurement of 2 VS 3 Pulse False Decode Susceptability

2-pulse code and the 3-pulse code. The decoding tolerance was adjusted to 1.6 microseconds in each case.

Two counters were used to simultaneously count the random pulses entering the decoder and the decoded output pulses. The counters were synchronized to insure that input and output counts were taken over the same time period. For each setting of the random pulse generator, a series of ten, 10 second, counts were taken for the 2-pulse code system and the 3-pulse code system. The data for the 2-pulse code is averaged and plotted in figure 8-29. Figure 8-30 is a similar plot for the 3-pulse code. These results clearly indicate the validity of the analytic calculation.

4. Hardware Approach

In this section, the avenues for resolution of the technical issues (as determined by study and verification) are translated into specific hardware approaches. All block diagrams and circuits presented are considered to be within the state-of-the-art and represent low risk developments in themselves. Demonstration that the integration of the hardware described will meet the coverage, accuracy, traffic handling, and integrity required of the MLS DME equipment is the mission of the Feasibility Demonstration Program.

a. Hardware Approach-Interrogator

(1) General

(a) Gain-Time-Control (GTC) vs. AGC

As a first try, we shall assume that the interrogator's receiver shall use GTC instead of Long Time Constant AGC. This is because Pulse-Multiplexing may produce 30-50% spurious decodable replies (See Section on Traffic Density) from other beacons than the one being interrogated. There may be times and places where these spurious signals are stronger than the desired signals. They may then takeover the agc and unduly reduce the sensitivity to the desired reply. Further tests and evaluation are desirable before making this decision final.

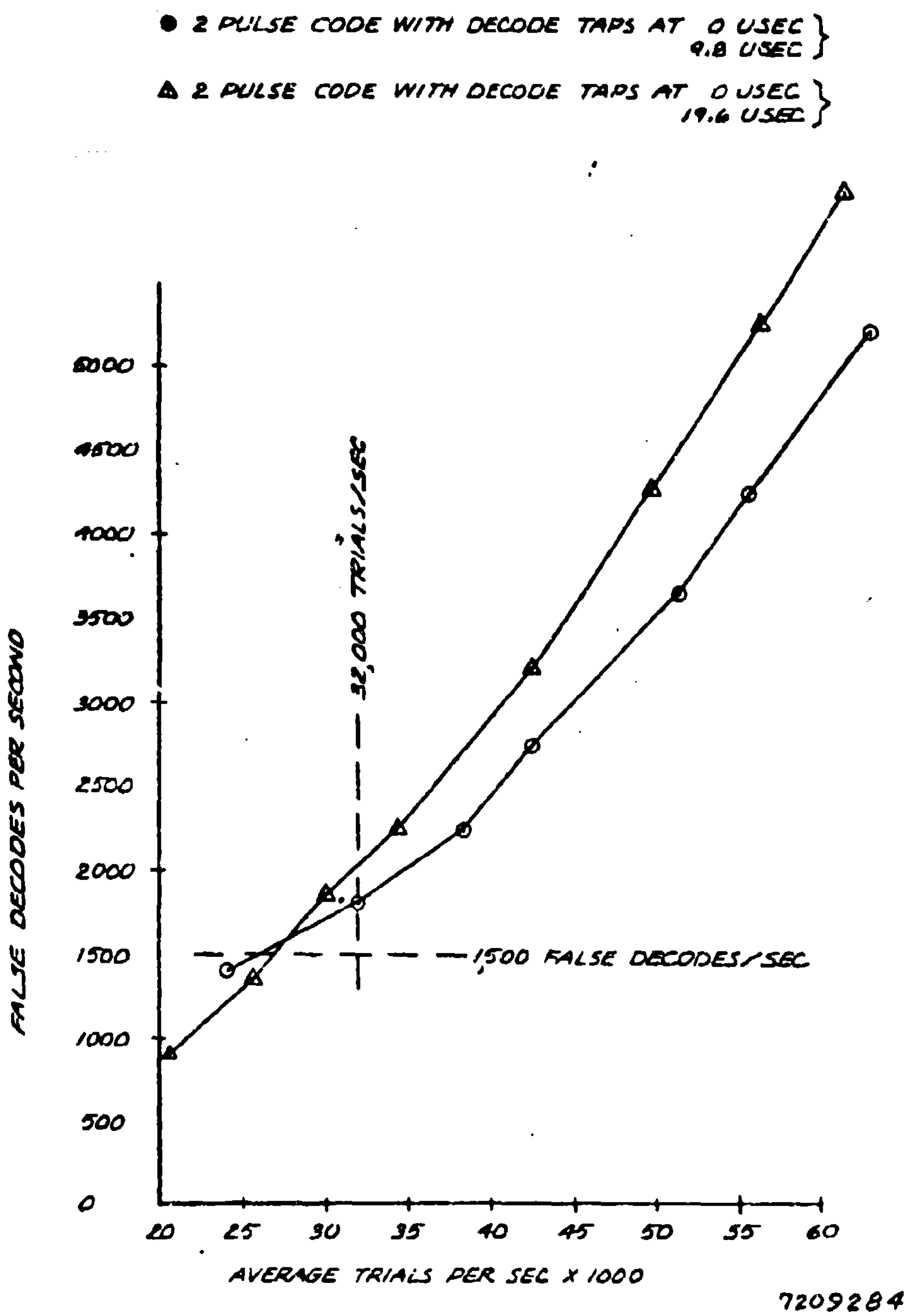


Figure 8-29. Two Pulse Code False Decodes As a Function of Average Trials

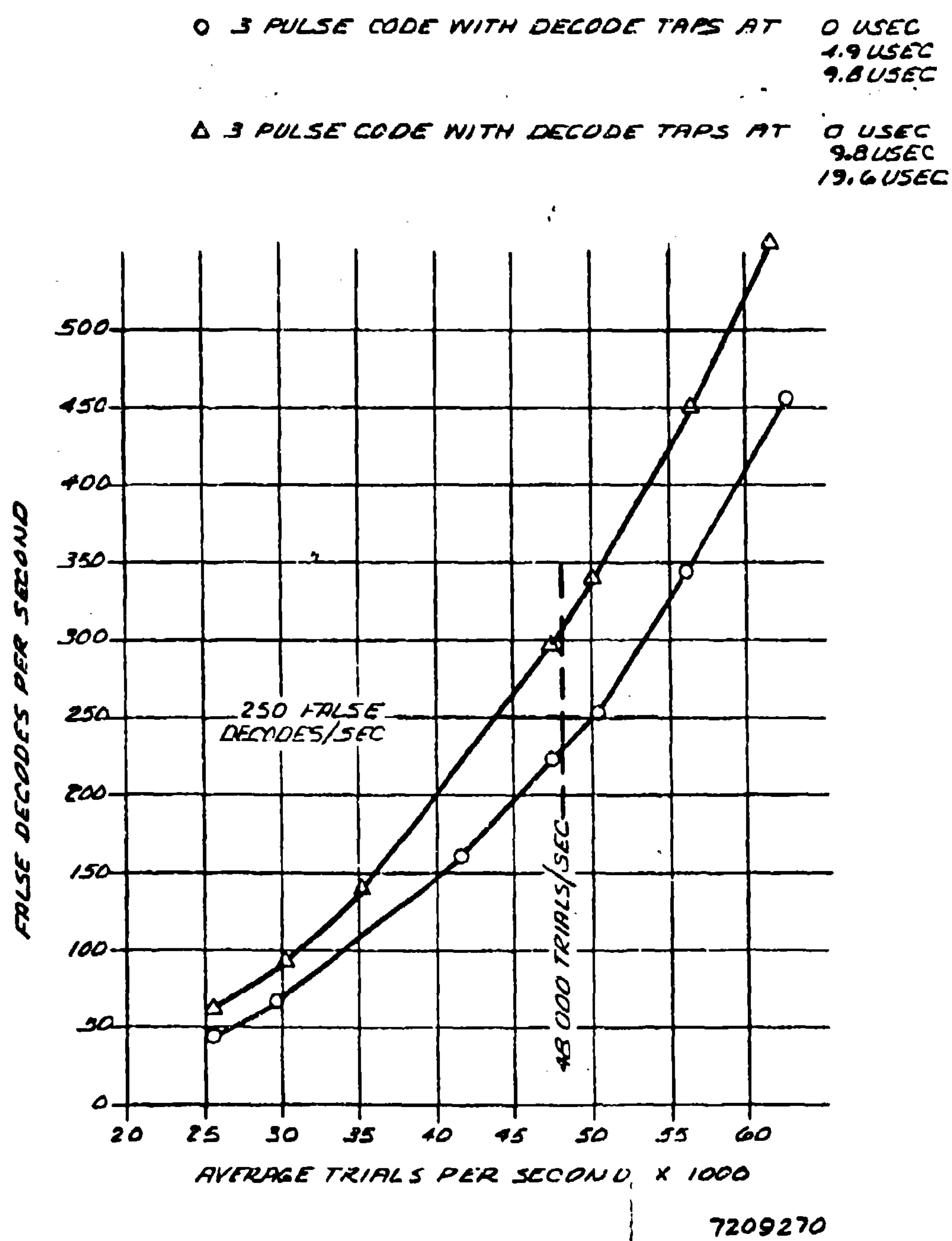


Figure 8-30. Three Pulse Code False Decodes As a Function of Average Trials

(b) GTC Description (Figure 8-31)

The signal voltage (e_r) received by the airborne receiver, as the a/c travels from 1,000 ft. to 180,000 ft. from the beacon, varies as

$$e_r = 180{,}000\ e_m/x \text{ volts}$$

where: e_m is the voltage received with the a/c 180,000' away

x is the distance of the a/c to the beacon in ft.

The GTC then varies the voltage gain (g) of the a/b receiver as

$$g = ax/180{,}000$$

so that the voltage at the output of the controlled amplifier is

$$ge_r = (ax/180{,}000)\ (180{,}000\ e_m/x) = ae_m$$

for all distances.

The S/N ratio is of course higher at the short ranges. To obtain the advantage of a steeper leading edge at short ranges, the video gain is modified by $g_v = (GTC)^{-1} = 180{,}000/x$. The video output is then

$$gae_m = 180{,}000\ a\ e_m/x$$

(c) Percent Amplitude Threshold

The receiver of the interrogator is equipped with a circuit which triggers a new pulse when the leading edge of the reply pulse reaches a fixed percentage of its peak value. The triggering time is then independent of the pulse amplitude. The pulse timing is usually defined when it reaches its 50% point. However, a stronger pulse having the same shape as a weaker pulse may have steeper leading edge at its 25% point than the weaker pulse at its 50% point. The earlier decision level at 25% of peak amplitude gives greater immunity to leading edge echoes than the 50% point.

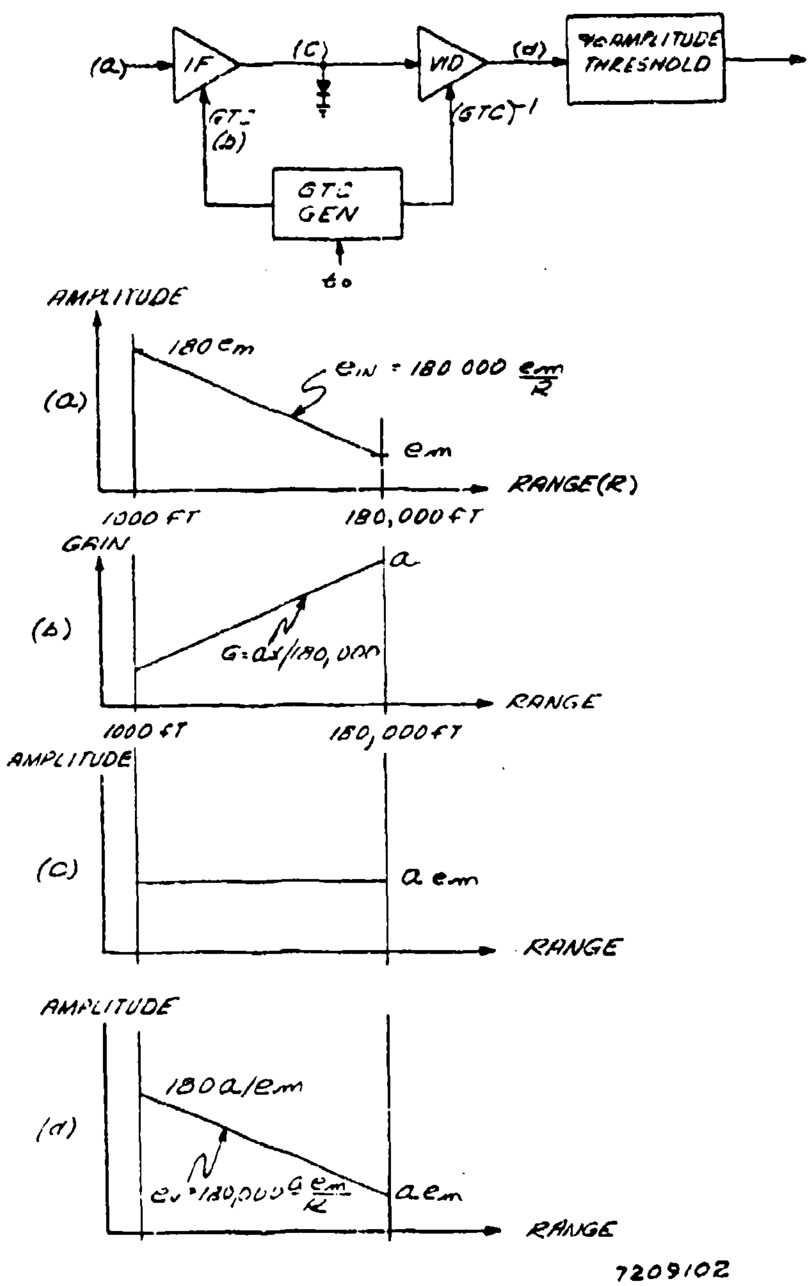


Figure 8-31. Gain-Time-Control in the Interrogator

The inverse GTC causes the received pulse to increase as the beacon is approached. When this pulse exceeds a given value, the decision level is changed from 50% to 25% (or less) of its peak value. The decision level at 25% of peak pulse amplitude leads that at 50% by a constant time (δ) which is independent of the pulse amplitude. For the standard pulse δ = 0.08 μs. This amount can be calibrated out of the final range measurement.

Circuits which recognize the 50% A. or 25% A. are well known in the art. See figure 8-32.

(d) Tracking Gate

Assume that an aircraft interrogates a beacon at the rate of q = 15/sec. while traveling at V = 600Kts = 1,000 ft/sec or 2μs/sec. The aircraft travels 1,000/15 = 67 or 2.0/15 = 0.13μs between interrogations. Let the reply be at the center of a 4.0μs gate (±2.0μs). The reply can then be lost for 2.0/2 = 1 sec before the reply travels outside the gate and is lost. This corresponds to 15 interrogations. If the signal is lost for longer periods, say 10 sec., velocity memory may be applied.

It may be desirable to increase the interrogation rate or widen the gate for supersonic aircraft.

If the timing clock emits pulses at the rate of 12.5MHz (a period of 0.08μs), a 4.0μs gate will contain 4.0/0.08 = 50 timing pulses and its center is 25 timing pulses from its edge.

(2) Interrogator Block Diagram (Figure 8-33)

The primary timing source is the Pulser which emits 40 pulses/sec when searching, and 15 ±0.3/sec (randomly jittered) when tracking. These timing pulses are impressed on the coder which generates pairs of pulses, spaced by 28 - 2(n-1)μs where (n) is the code-number. The output of the coder is then impressed on Modulator along with the selected C-band frequency (5,000-5,060MHz) to produce pulse-pairs of RF signals which are amplified by the RF amplifier. The RF amplifier will preferably consist of Trappatt Diodes, if the state of the art permits it. If not, the amplifier

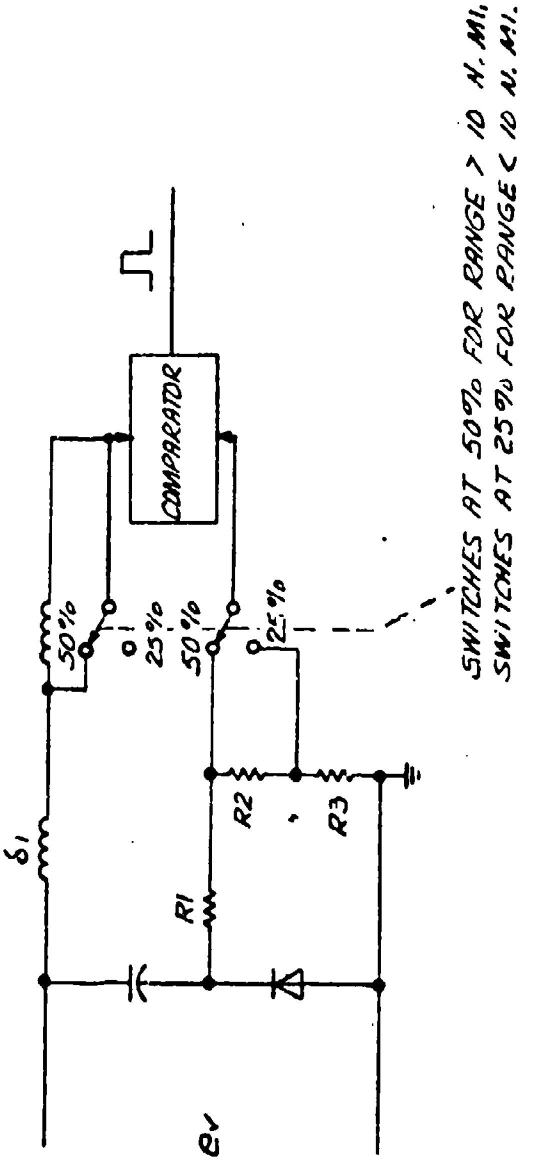


Figure 8-32. Typical Per Cent Amplitude Recognizer

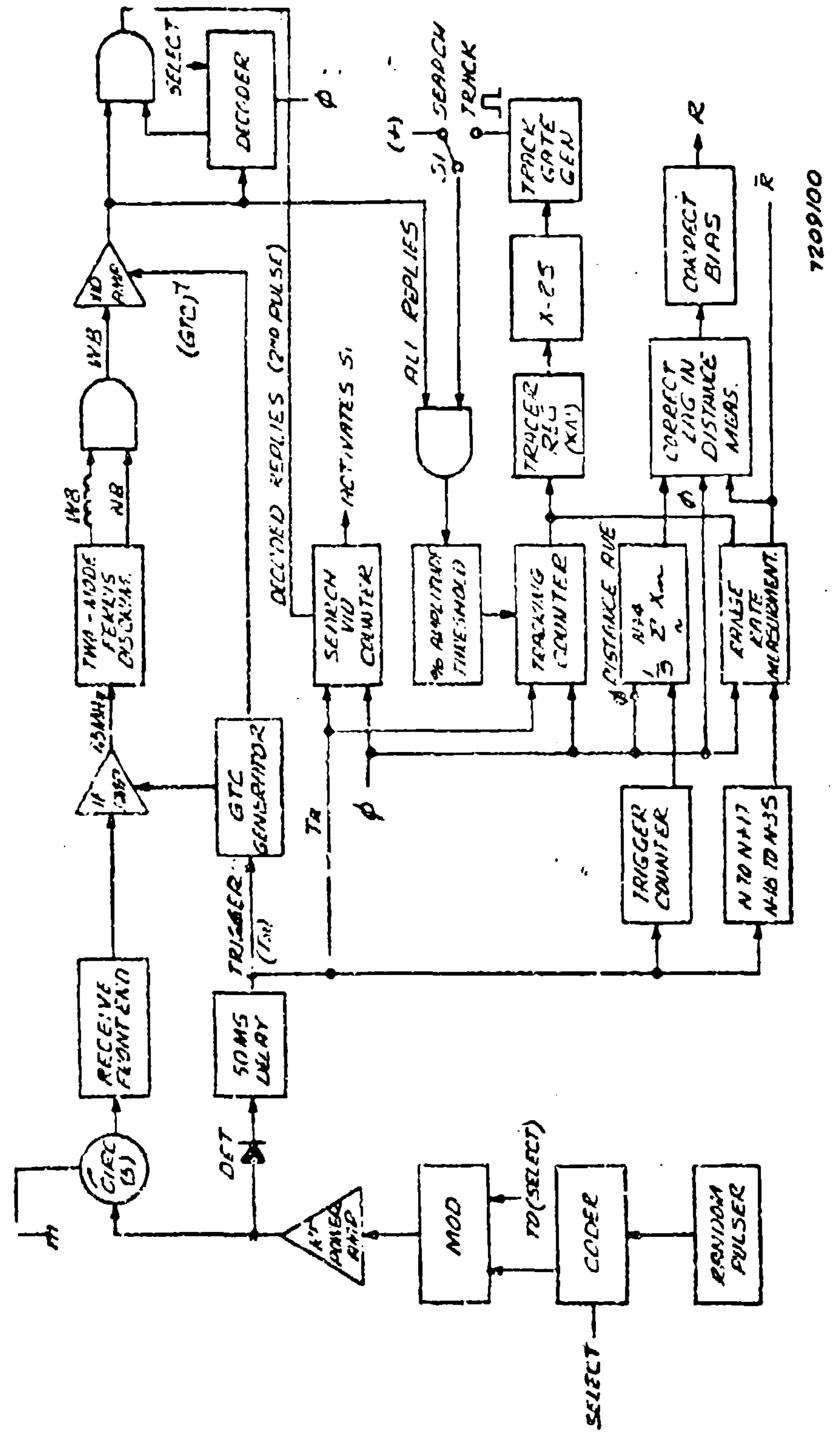


Figure 8-33. Interrogator Block Diagram

will consist of Planar Triodes operating well below ratings for reliability. The transmitted interrogation signal, at the desired power level, is applied to the antenna through the circulator.

The RF pulse-modulated signal is detected by a detector and a single trigger pulse(T_r) is generated by the 50μs delay generator. This trigger is delayed from the leading edge of the first interrogation pulse by 50μs to compensate for the "System-Delay" in the transponder. This trigger pulse is the main timing reference for the interrogator and establishes t = 0. It is the reference for:

- o The GTC and inverse GTC
- o Search and Tracking Process
- o Distance Measurement and Averaging
- o Velocity Measurement

The reply signal from the circulator is applied to the "Broad-Band Pre-Selector and Limiter" which is part of the angle receiver. For details of the front end see Section 1.1.1.1.D. For simplicity of explanation, the receiver front end output is applied to the "Linear IF amplifier" at 65 MHz with a bandwidth of 7.0 MHz. The gain of the IF amplifier is controlled by a "Gain-Time-Controlled" GTC wave-form from the GTC generator. The GTC wave-form biases the IF amplifier according to a function of time, beginning with t = 0, so as to produce essentially constant voltage signals for synchronous replies at all ranges.

The output of the GTC's amplifier is applied to a "Two-Mode Ferris-Discriminator". This device produces essentially "absolute selectivity" over a bandwidth of ±0.8 MHz, while providing a "Video Information Bandwidth of 3.5 MHz". The operation of this device is described in detail in Hazeltine Report 3-5252 "Technical Proposal for the Development of a Microwave Landing System" (Sept 21, 1971), and in section 1.1.1.1.G.3.a of this report.

The wideband output of the Ferris Discriminator is then applied to an amplifier with an inverse GTC control to allow close-in signals to be amplified by an amount permitted by the S/N.

The output of the Video Amplifier is decoded according to the selected code 10 +2 (n-1)μs. A second decoder detects signals coded according to 10.75 + 2(n-1). The output of the two decoders serve as logical-one and logical-zero for channel identification. (See previous discussion on identification coding - section 1.1.1.1.G.2.d.)

The decoders also provide a gating pulse to pass only the first reply pulse which is delayed by slightly more than the code spacing.

The output pulses of the video amplifier are then peak-detected and applied to a circuit which recognizes the instant (t) when it reaches 50%, 25% and 10% of its peak amplitude. If distance is calibrated at the 50% of peak-pulse amplitude, then detection at 25% and 10% introduces fixed distance-biases, which are known and are calibrated out. 50%, 25%, and 10% amplitude points are selected by the distance measurement circuits and produce early decision levels which provide high immunity to echoes (see text for circuit discussion and details). The output of the amplitude recognizer is a steep rise pulse delayed beyond the second pulse and gated by the decoder output.

The output reply of the % amplitude recognizer is then applied to the Search and Track circuits which locate and track the synchronous reply. This reply is isolated from all others by a "tracking gate" which centers itself about the reply.

The Search and Track circuits are shown in more detail in the text. Although a single Search-Track circuit could be used, the "Search-circuit" is so simple that the functions of "Search" and "Track" are separated to allow continued "Search" while "Tracking" and verify that the tracked reply is not an "echo" of the true reply.

The "Tracking Gate" is now located in time at the distance of the a/c from the beacon. Several, say 5, successive "distance-gates" may be averaged to produce a distance measurement with a very small random error ($\sigma \approx 9$ ft.) but with a known lag error, which is a function of velocity.

Velocity is measured by measuring the time required to cover a given distance.

A distance-correction is applied from the measured velocity to correct for the lag introduced by the distance averaging.

A bias correction will also be applied, either as a fixed correction or as a function of distance, to reduce the bias error introduced by the transponder to values < 20'.

(3) Search and Track Circuits

The "Search and Track" circuits are digital in operation and are similar in nature to those used in the latest generation of L-BAND DME interrogators (ARINC 568 and equivalent) now manufactured by RCA, KING, and COLLINS. The details of this operation will not be repeated here except where they differ from usual practice.

MLS requires a maximum range of only 30n.m. instead of 400n.m. as for the present L-BAND DME. This permits appreciable simplification in the "SEARCH" function. However, MLS requires very high accuracy for distance (±20') and velocity (±10'/sec) which necessitate special treatment.

(a) Search

The shorter range over which search takes place permits selection of the first received reply pulse as a valid reply, unless it is shown not to be in subsequent processing; in which the search gate is resumed from range 0n.m. outward, instead of proceeding outward from a reply that may be non synchronous, as is done presently. This greatly reduces the probability of missing the direct reply and locking on a later echo.

Search is ended tentatively on receiving two consecutive first replies at the same range. This positions the TRACKING-GATE. The next step is the "Acquisition Mode" which examines the content of the gate. If two or more replies fall in the gate for five interrogation, the reply is presumed valid and the "Track" mode is initiated. Once in the TRACK Mode, loss of signal in the gate results in continuous positioning of the gate based on memory of the last measurement plus velocity correction, for say 10 seconds. After this time, search is again resumed.

The SEARCH process is so simple that it is continued at a lower repetition rate even during the "TRACK" mode for verification that the gate is locked on the direct reply and not on an echo. A synchronous reply occurring before the one on which the gate is locked causes the gate to release and lock on the earlier reply.

(b) Statistics of Search

All distance measurements start with the RANGE-TRIGGER which occurs 50μs after the first interrogation pulse and which establishes $t = 0$. The distance is measured by counting "clock cycles" from $t = 0$ to the first reply. Two counts on consecutive interrogations which differ by less than a predetermined amount, establish the presumed validity of the reply and set-up the TRACKING-GATE so that its center is located at the counted value.

As an example, let an a/c be at 25n.m. (150,000 ft.) from the beacon toward which it travels at 2,400 Kts (4,000 ft/sec), to take an extreme case. Its DME searches when interrogating at the rate of $q = 40$/sec. The plane travels 4000/40 = 100' between interrogations.

UP/DOWN counters are used. The first count is from 0' to 150,000' (t=0 to 300μs). The second count is from 0 to (150,000-100). The result is 150,000 - 150,000 + 100 = 100 ft = 0.2μs. The correct range is presumed to be 150,000 ft (300μs). The gate, say 4μs in duration is started when the second count is 300.0 - 1.5 = 298.5μs.

Table 8-5 shows the following: the distance of the a/c from the beacon as (x) in feet-in Col (1a) and in elapsed time (T) in Col (1b); the average number of non-synchronous replies per interrogation which precede the valid reply at range (T) is mT, where (m) is the reply rate of the beacon. Including spurious replies received by the a/c, m = 2,700/sec. for a fully loaded system. mT is shown in Col (2); the probability that one or more non-synchronous replies precede the desired reply is P(+) obtained from the Poisson Summation and given in Col (3); the probability that no non-synchronous reply precedes the desired reply is P(o) = 1.0-P(1+), Col (4); the average number of desired replies per interrogation is equal to B, the beacon reply efficiency, Col (5); the probability that a desired reply (B) is not preceded by a non-synchronous signal is BP(o), Col (6); the probability that two successive desired replies are not preceded by a non-synchronous signal is $[B\,P(o)]^2$, Col (7); The number of interrogations necessary to obtain two valid 1st replies lies between

$$\left\{\frac{1}{[B\ P(o)]^2}+1\right\} \text{ and } \frac{2}{[B\ P(o)]^2}$$

as shown in Col (8) for the pessimistic case of

$$\frac{2}{[B\ P(o)]^2};$$

and the time required to complete search by finding two such consecutive replies when interrogating at the rate of q/sec is pessimistically $[2/(B\,P(o)]^2 q$, Col (9)

For a fully loaded system, the Search time is less than 0.10 sec at 5.0 n.m. and less than 0.45 sec at 30 n.m.

(c) Search Circuit (Fig. 8-34)

The search circuit consists of an UP/DOWN counter which counts the number of clock-pulses, at the rate 12.5 MHz, which occur between the trigger at t=0 and the reception of the first reply decoded 2nd pulse at t=x/500 μs (x in feet). In succession, one count is UP and the next count is down. Since we are searching for two consecutive counts at the same distance search is ended when the

Table 8-5. SEARCH TIME

(1a)	(1b)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
distance		Av. Spurious	P(1+)	P(o)	B	B P(o)	$[B\ P(o)]^2$	$\frac{2}{[B\ P(o)]^2}$	ts Search time
X(n.m.)	τ(μs)	mT		1 - P(1+)	0.90			no. of int.'s	q = 40/sec
30	360	1.00	0.64	0.36	0.90	0.32	0.11	18	< 0.45
15	180	0.50	0.40	0.60	0.90	0.54	0.29	7	< 0.18
5	60	0.17	0.15	0.85	0.90	0.77	0.59	4	< 0.10

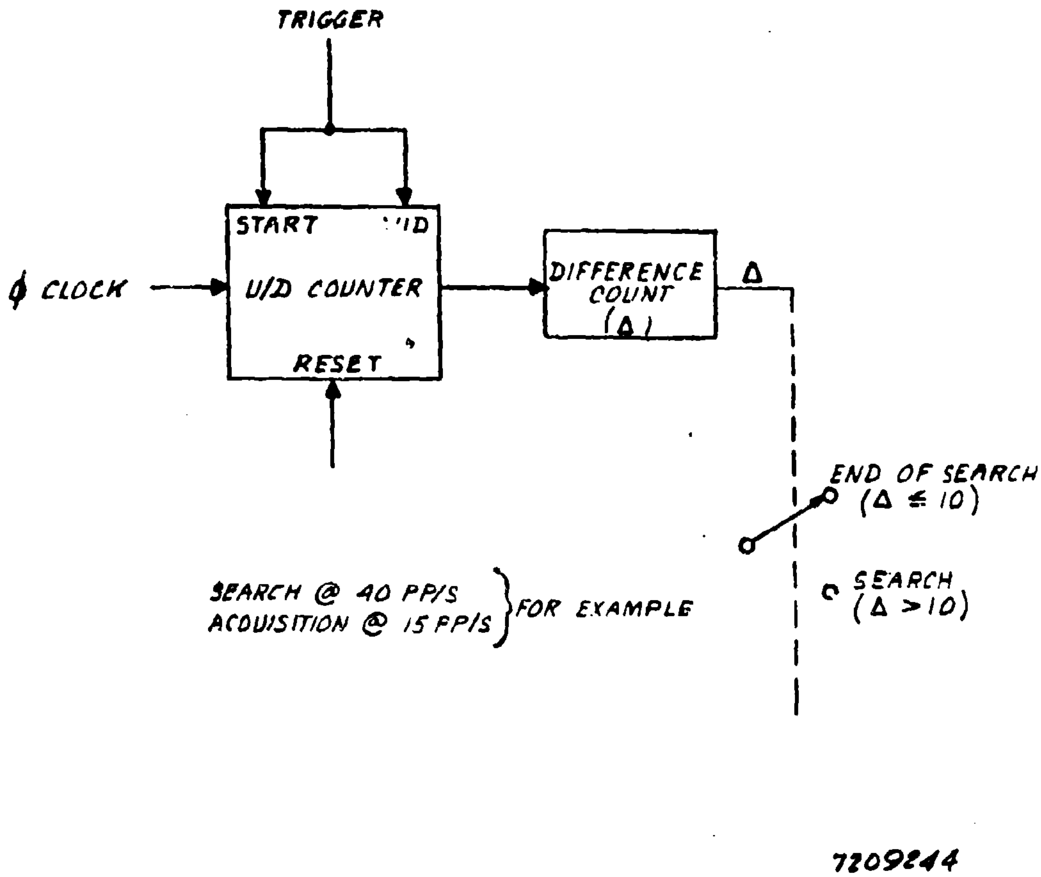


Figure 8-34. Search Circuit

UP count minus the down count ⩽10(400 ft). This low combination count results in throwing a switch to initiate the "acquisition" and the "track" modes in succession. In actuality, there will be two UP/DOWN counters so that each successive pulse will be part of a pair of pulses (either UP or DOWN), and the search time will be reduced substantially. (This is not shown here for simplicity of explanation.)

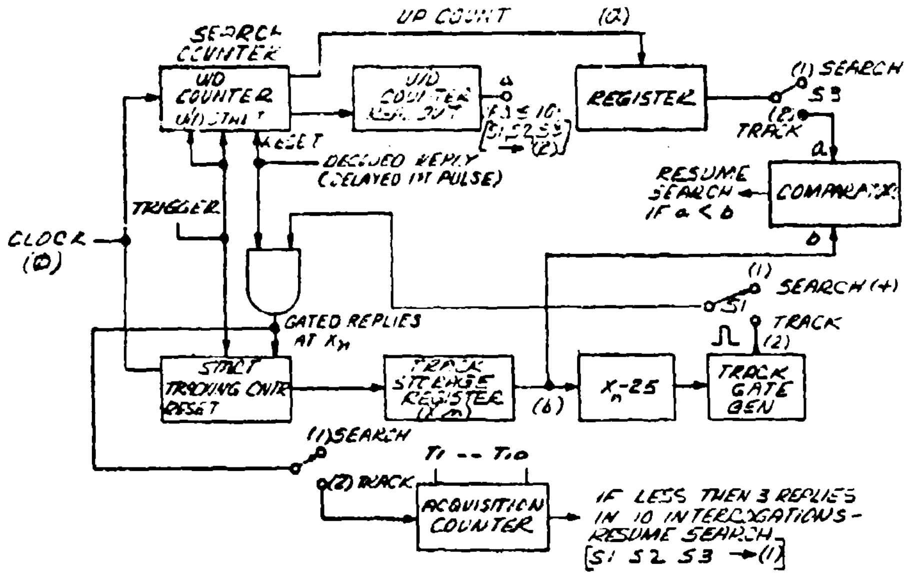
Acquisition, Tracking, and Verification

The "Tracking Gate", 3.0 to 5.0 μs in duration, tracks and isolates the true reply from all other replies. To make it "Track" the selected reply once it has been found by "Searching", two methods can be used as follows:

The gate is divided into an "early" and a "late" gate. A reply which falls in the "late gate" causes the gate to occur later in time (at a slightly greater distance) prior to receipt of the next reply. The converse applies to a reply in the "early gate". The resulting balance between the two "half gates" centers the whole gate on the desired reply. This method has been used essentially by all DME interrogators until the most recent generation.

Referring to figure 8-35, Clock-Pulses(Ø) at a high rate (say 12.5 MHz) are counted by the "Tracking-Counter" from the initiation of the count by the Trigger (T) until it is reset by a reply through the AND-GATE (after the %A recognizer). During "Search" the AND-GATE is in a receptive condition to pass all replies (r) by receiving a (+) signal through switch S-1 in the "Search" position. During "Track" the AND-GATE is actuated by the "tracking-gate pulse".

Each count from the Tracking-Counter is stored by the Track-Storage-register. When the second count exceeds the (Stored Count minus 25 counts) the "tracking-gate pulse" is generated which is applied to the AND-GATE when Switch S1 is in "Track" position. The next reply, if true, is then centered in the "tracking-gate pulse". The count for the position of the tracking gate is again stored in the (count-storage register).



SEARCH:

1) If output at Δ is ≤10 counts, then switches S1, S2, S3 are thrown to position (2) TRACK.

ACQUISITION:

2) After search is ended and switches S1, S2, S3 are in TRACK position (2):

If the acquisition counter counts less than 3 replies in 10 interrogations, switches are returned to SEARCH position.

FALSE LOCK-ON MONITOR:

While in TRACK, if the SEARCH up/down counter Δ ≤10 counts and the up count (a) is less than the current range reading in the TRACK register (b), which would indicate an earlier synchronous reply, the switches are thrown back to position (1) to resume SEARCH.

Figure 8-35. Search Acquisition Track Operation

Acquisition

This is a trial condition which verifies if the "Search" has truly ended on a proper reply. To do so, the number of "gated-replies" during 10 interrogations (Triggering) is counted. If there are at least (say 3) "gated replies" in ten interrogations, the "Tracking Conditiors" is confirmed.

During "Tracking", the "Search" circuit continues its search by counting up and down. One of the counts (a) is stored in the "Search" register. If the UP count equals the DOWN count, the stored count is compared with that of the "Tracking Counter" (b). If a < (b - code spacing), then "Search" is resumed.

Implementation to Achieve Accuracy

Random Errors

Random errors in the measurement of distance are discussed in section 1.1.1.1.G.2.b(5) and 1.1.1.1.G.6.c. Section 1.1.1.1.G.2.c discusses the means of achieving velocity accuracy. The basic means consist of averaging a number of successive measurements.

Velocity (Fig. 8-36)

Each Trigger (T) starts an "UP-count" which is stopped by the "Tracking-Gate-Pulse" to measure distance (X_n). 15 UP-counts are added (from T_1 through T_{14}) which are followed by 15 DOWN-counts (from T_{15} through T_{29}) when the counter is "reset".

After count #29, the final count is

$$\sum_{15}^{29} x_n - \sum_{1}^{14} x_n = vn^2T \pm \left[\sum_{n}^{2n-1} a^2\right]^{1/2} v(\Delta T) \pm \sqrt{2n}\, \sigma_X$$

where v is the velocity to be measured

n = 15 is the number of UP-measurements and DOWN measurements

T = Trigger period ≈ 1/15 sec

(ΔT) = Trigger jitter; $(\Delta T)/T \approx 0.02$

σ_X = Random distance error per measurement

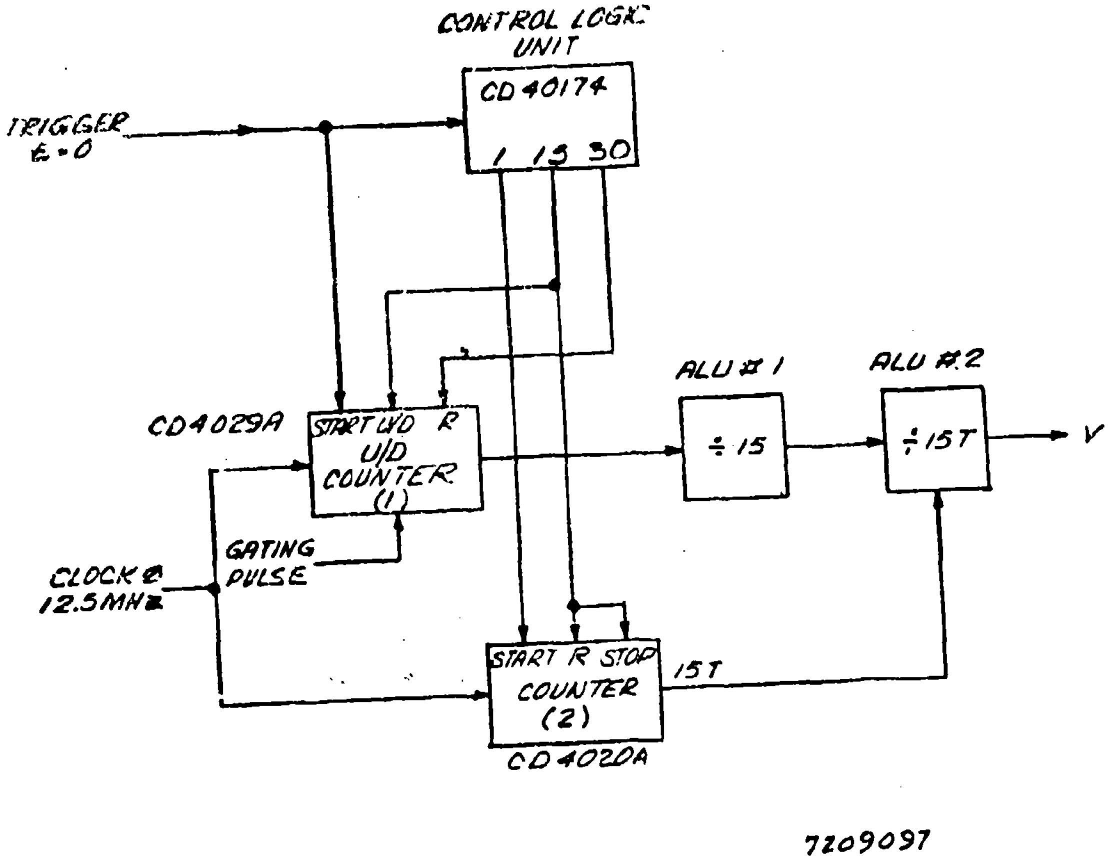


Figure 8-36. Velocity (Range-Rate) Measuring Circuit

The velocity V is then

$$\frac{1}{n^2T}\left[\sum_{15}^{29} x_n - \sum_{1}^{14} x_n\right] = V\left[1 \pm \left(\sum_{n}^{2n-1} a^2\right)^{\frac{1}{2}} (\Delta T)/n^2T\right] \pm \frac{\sqrt{2n}}{n^2T}\sigma x$$

The difference of the sums if first divided by n=15 by ALU#1 and then by nT=15T which is accurately measured by counter #2.

Substituting the above parameters gives

$$V = V\,[1 \pm .008] \pm 7.5 \text{ ft/sec}$$

The total measurement requires 30 interrogations or 30/15 = 2.0 sec. Since each component measurement of distance includes changes in velocity, the final result is a true measure of the average velocity over the previous two seconds (including acceleration).

Distance Averaging (Figure 8-37)

The basic trigger (T) at t=0 is applied to "Tracking counter" (1) (which is the same unit shown in Figure 8-35) to initiate the counting of clock-pulses (Ø) at the rate of 12.5 MHz. The counting is stopped after each Trigger by the "Tracking Gate Pulse" at distance (X_n). The counter is reset sometime after the reception of the "tracking-gate pulse".

The trigger is also applied to "Control Unit" (2) which counts one to 10 trigger pulses and then resets.

Five "adders" (A-1 to A-5) controlled by the "Control Unit" (2) add the counts from the "tracking-counter" (1) as follows:

Adder $A_1 - \sum_{n}^{n+4} x_n$

$A_2 - \sum_{n+1}^{n+5} x_n$

$A_3 - \sum_{n+2}^{n+6} x_n$

etc.

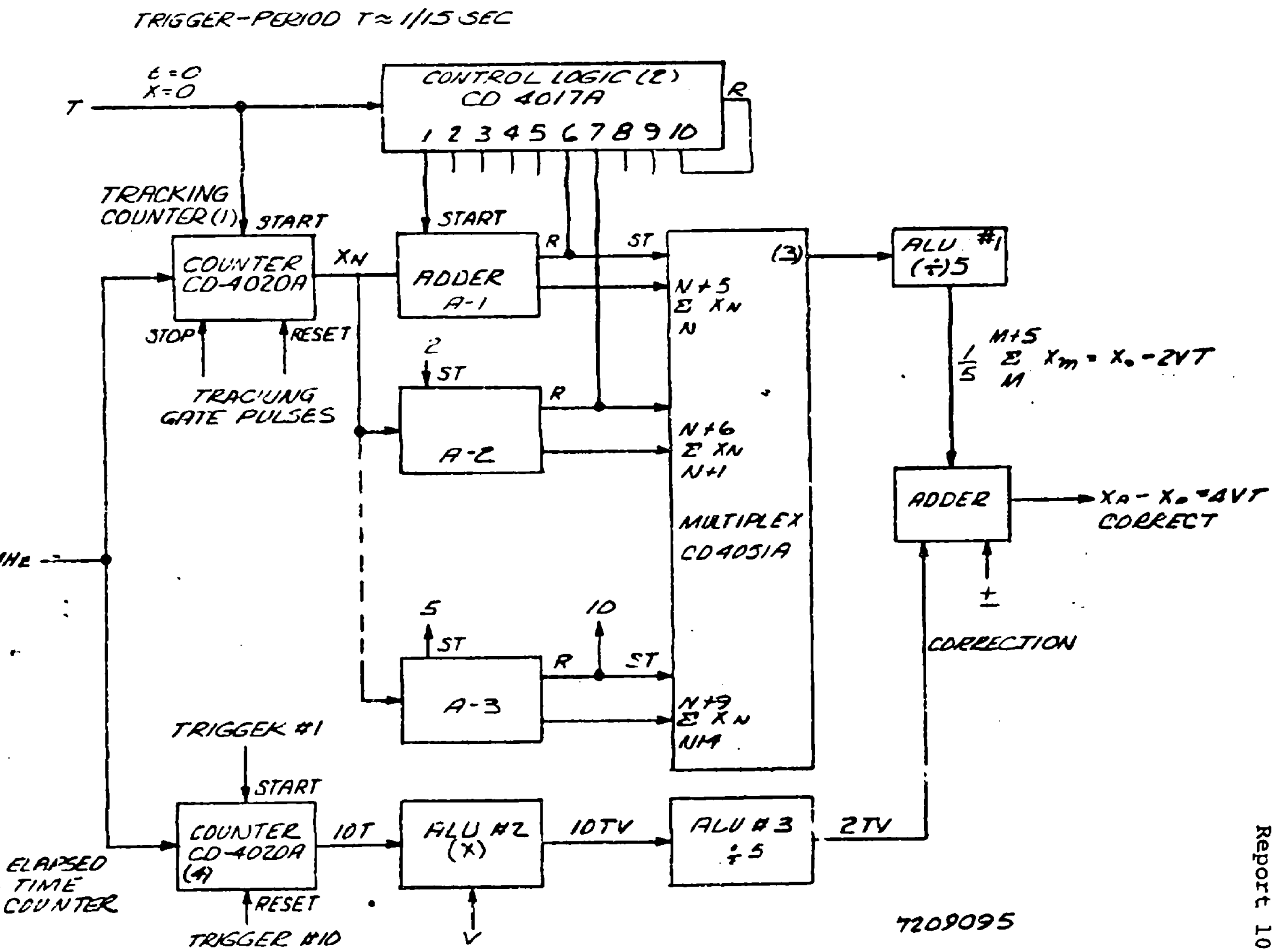


Figure 8-37. Distance Averaging Circuit

The outputs of the five adders are applied successively to Multiplexing Unit (3) after triggers (6), (7), (8), (9), (10), (1) etc.

The average of 5 distance measurements is obtained by ALU #1 which divides the output of (3) by (5) to give

$$\bar{x}_n = \frac{1}{5} \sum_{n}^{n+4} x_n = x_o - 2VT \pm \sigma_x / \sqrt{5}$$

However, this measurement is correct for two measurements ago. The correct value is

$$x_n = x_o - 4VT \pm \sigma_x / \sqrt{5}$$

The correction is applied by "elapsed-time" counter (4) which counts the time taken for 10 interrogations t=10T. The velocity (V) obtained from the circuit of figure VII-6 is multiplied by (10T) in ALU #2 to give 10VT. This value is then divided by (5) by ALU #3 to supply the correction (2TV) which is subtracted from x_o - 2VT to give the correct value of $x_n = x_o - 4VT \pm \sigma_x / \sqrt{5}$.

The polarity of the correction is established by the UP/DOWN counter in the velocity circuit depending on whether the velocity is + or -. The details of the polarity switch are not given.

Note - The number of clock pulses between the trigger and the reply is quantized and cannot be less than 1.0 pulse (0.08 μs = 40 ft for a 12.5 MHz clock). If the clock were started in the same phase by the trigger, the arrival of the reply would be in doubt by 0.08 μs. To obviate this, it is important that the phase of the clock pulse be completely random with respect to the trigger and therefore with respect to the reply. If the actual number m or m+1 is completely random and one is as likely as another, then the standard deviation for the actual count is σ = ±0.29 x 1.0 = ±0.29 pulse or = ±0.029 x 0.08 = ±0.0032 μs.

Bias Errors

The bias errors due to measurements, neglecting for the moment those due to equipment drift, are due to the following: (1) Close-in echoes which are unpredictable but can be almost eliminated by a steep leading edge and an early decision level; (2) Having the transponder use a fixed decision-level at low voltage. This provides the only reliable protection from echoes. The error is predictable and can be partly calibrated out as shown in section 1.1.1.1.G.2.b.(4); and (3) The error due to distance-averaging which can also be corrected completely.

Other bias errors due to equipment drift can be calibrated out by means of an automatic self-checker. This provides for a reply at a known distance. The indicator corrects itself if it indicates erroneously.

(4) DME Interrogator Receiver

A detailed block diagram of the DME interrogator receiver is shown in figure 8-38. The RF front end is part of the angle guidance receiver and is described in section 1.1.1.1.D of this report.

To insure effective image suppression, the receiver utilizes dual down conversion. Primary conversion takes place in the RF front end section where the received channels are converted to a first IF frequency of 451 MHz. The signal to noise ratio is established in the RF front end section and is based on having a 4.5 db noise figure at the input to the main portion of the interrogator receiver. This noise figure is achieved by using a 2N2857 amplifier at the 451 MHz frequency to drive the second down converter. The local oscillator for the second down conversion is obtained from a crystal controlled oscillator operating at 98.5 MHz. A quadrupler amplifier raises this frequency and power level to 386 MHz and 10 mw respectively, sufficient to produce the second down conversion to an IF frequency of 65 MHz.

Amplification at the second IF frequency is obtained using a four stage linear amplifier comprised of synchronously tuned 3N187 MOSFET's. At the threshold signal level, the IF amplifier provides 75 db gain. The expected dynamic range for this receiver is 50 db. In order to insure non-limited operation of the receiver and

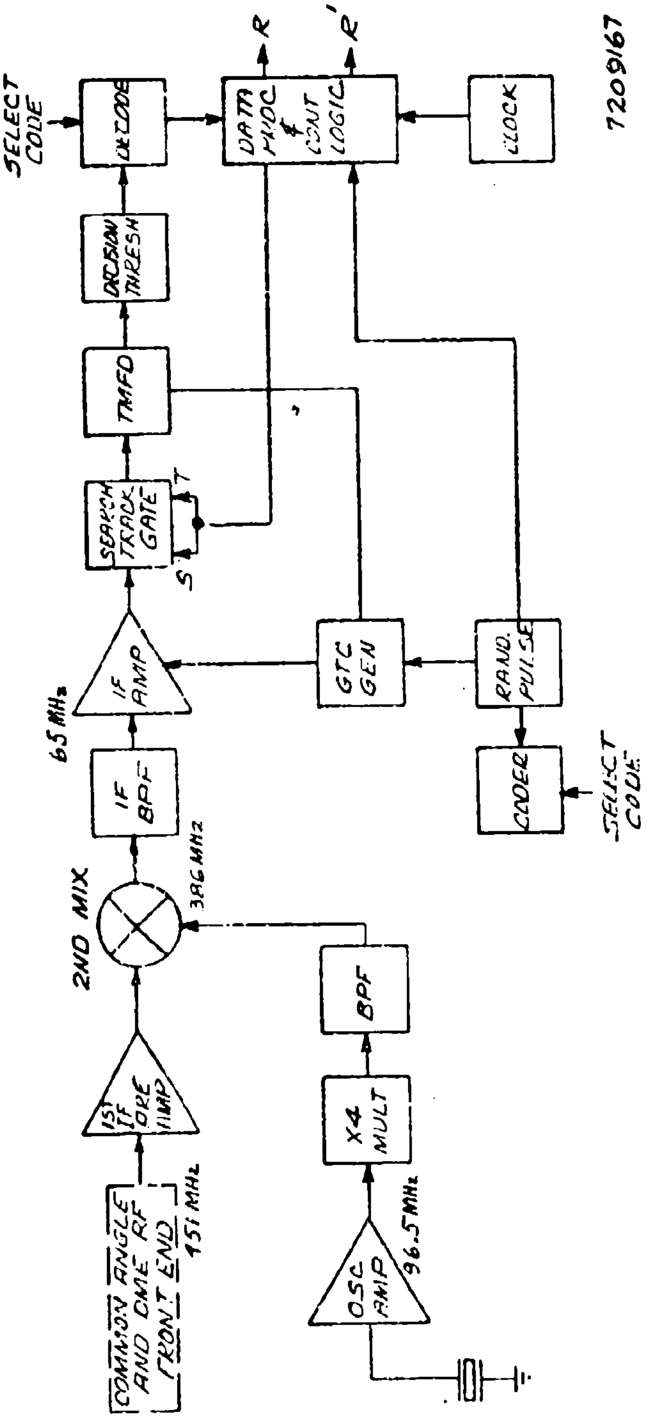


Figure 8-38. DME Interrogator Receiver

to maintain a constant detected pulse output, the IF amplifier is provided with Gain Time Control (GTC). Dual channel MOSFET's are particularly useful as gain controlled amplifiers since they can be controlled with no appreciable frequency detuning or variation in bandwidth. The 3N187 is capable of providing approximately 17 db gain reduction when the bias on gate 2 is varied from +4 volts to 0 volts with respect to the source terminal. The GTC signal is shaped in accordance with the gain characteristics of the 3N187 such that linear gain variation is achieved over the dynamic range of the receiver. Therefore, the requirement for prevention of limiting and maintaining a constant detected pulse output is achieved by providing GTC to the first three stages of the IF amplifier.

A search-track gate is employed at the output of the IF amplifier to minimize receiver susceptability to unwanted pulses. In the search mode, the gate is turned on for 30 n.mi with every interrogation in order to allow the receiver to search for legitimate transponder replies out to the maximum range of the interrogator. When a legitimate transponder reply is confirmed by the receiver logic, the gate is automatically switched to the track mode and is enabled only during the time period that a legitimate transponder reply is expected. See section 1.1.1.1.G.4.a.(3) for a full discussion of the search, acquisition, track gating sequence.

The search-track gate is followed by a Two Mode Ferris Discriminator, used to detect on-channel signal and to reject adjacent channel signals. Operation of the TMFD as a detector and adjacent channel discriminator is described in detail in section 1.1.1.1.G.3.a.(2) of this report.

The wideband output of the TMFD is fed to the decision threshold circuitry. This section contains several stages of video gain utilizing 3N187 MOSFET's. A reverse GTC signal is applied to gate 2 in order to restore the signal dynamic range. The pulse, with its restored dynamic range is fed to a threshold circuit that uses a percentage of the pulse amplitude as the threshold. The percentage will vary as a function of range to achieve maximum accuracy in a multipath environment as described in section 2.b.3. Distance is measured by stopping the clock count when the rise time crosses the threshold.

A random pulse generator is employed as the trigger/synchronizer to insure that the receiver does not lock onto transponder replies elicited by other aircraft interrogating the same transponder. Its function is to initiate the transmitter, the range measuring circuits, the control logic and the GTC signal generator.

(5) Interrogator Transmitter

Figure 8-39 is a simplified block diagram showing the design approach to be used in the feasibility model airborne DME interrogator transmitter. The transmitter is an all solid state design except for the final output amplifier. The peak power output requirements (100 watts peak) of the final output stage will be met with planar ceramic triodes. However, for the prototype units the use of solid state devices such as transistors or TRAPATT diodes for the output amplifier is a definite possibility. See section 5.a.

Figure 8-40 is a detailed block diagram of the transmitter. Frequency excitation is derived from a fifth overtone crystal controlled oscillator operating at 1/60 of the transmitter frequency. The oscillator is followed by a frequency tripler that will provide a minimum of 2 milliwatts CW power at the output. A class AB stage is used for the tripler in order to obtain good multiplication gain and stability. In addition, some padding is provided at the output of the tripler for increased stability and isolation.

The crystal controlled oscillator and tripler section is followed by a VHF amplifier section. This section accepts the 2 mw CW signal and provides a pulse-modulated 4 Watt peak power signal at its output. This section contains three stages of power gain, providing a minimum gain of 33 db. Each stage in this section is modulated in order to insure a maximum on-off ratio of the output

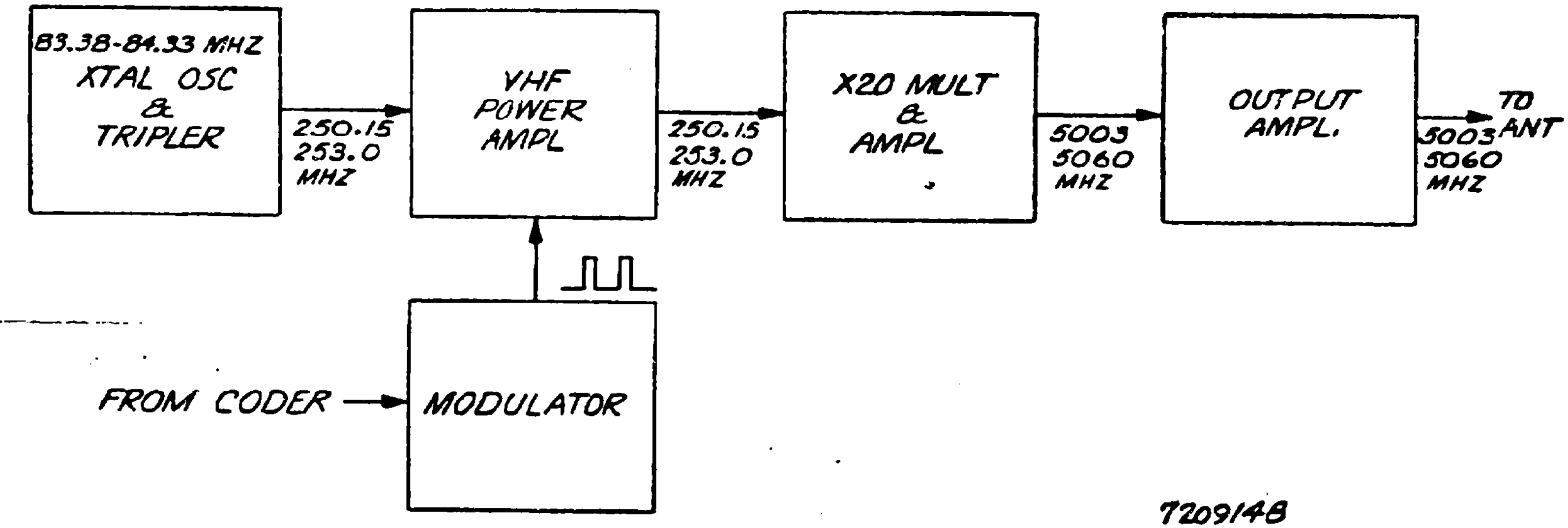


Figure 8-39. Interrogator Transmitter Simplified Block Diagram

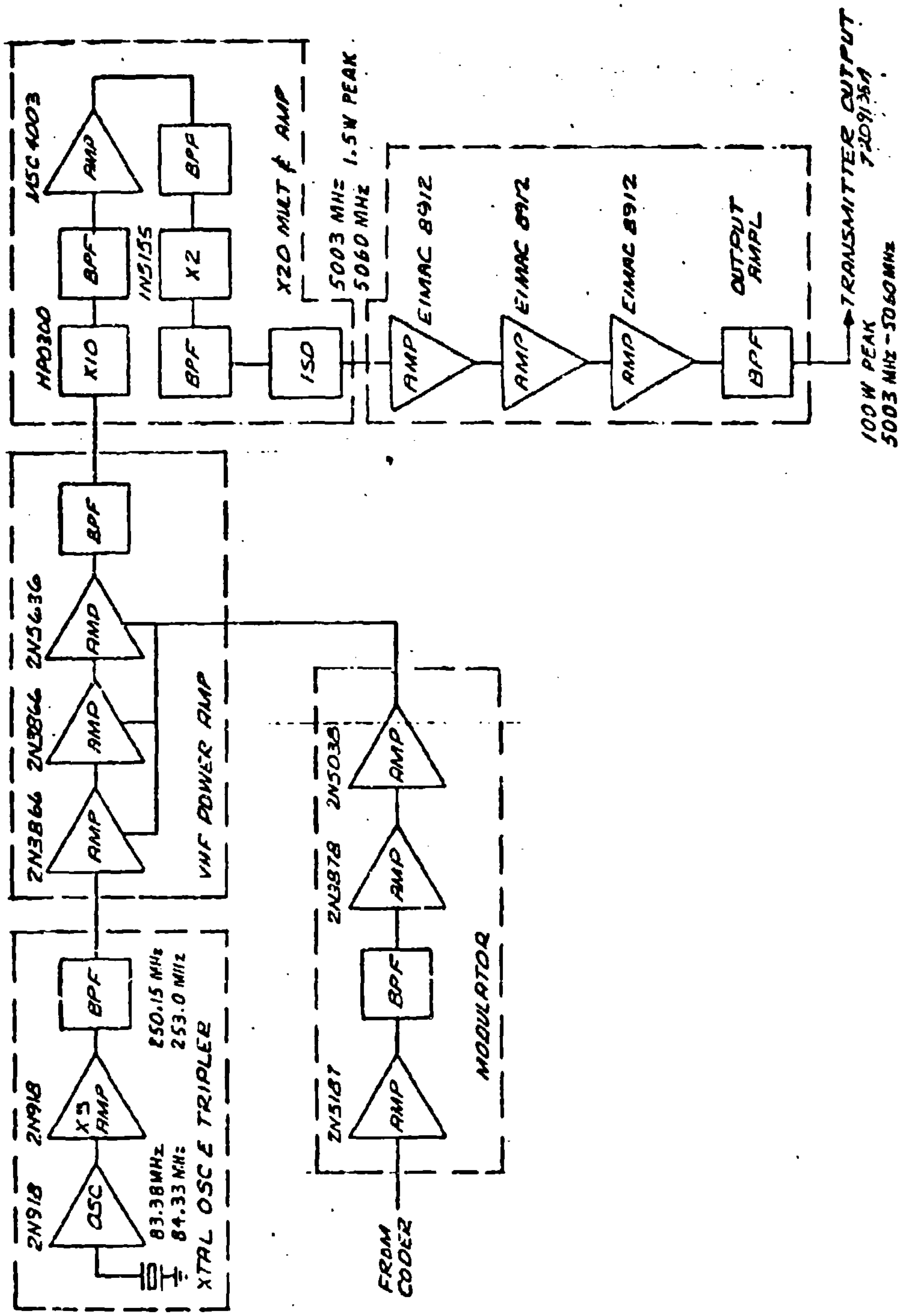


Figure 8-40. Transmitter Detailed Block Diagram

signal. The first and second stages are biased for class A and class AB operation respectively in order to preserve pulse linearity. The third stage is biased for class C operation.

Frequency multiplication up to the transmitter frequency is obtained in a 2 stage multiplier, separated by a stage of amplification. The amplifier is included between the multipliers to provide isolation and to make up for some of the losses due to the multipliers. The first multiplier is designed for a multiplication ratio of 10 and is achieved using a step recovery diode similar to the Hewelett Packard HP0300. The 4W peak input pulse is converted to a .5W peak output pulse at 1/2 the transmitter frequency. This stage will be followed by an MSC 4003 power transistor capable of amplifying the .5W input pulse to 3.5W peak at the output. This stage provides isolation between the 10 times multiplier and the output doubler stage.

The final frequency multiplier stage is designed as a doubler using a Motorola IN5155 abrupt junction diode. The output frequency of this stage will be the transmitter frequency. The IN5155 will provide a 1.5 Watts peak power at the transmitter frequency for the 3.5 Watts peak input power at 1/2 the transmitter frequency.

The final output amplifier is designed using Eimac 8912 planar ceramic triodes. Each triode stage is capable of providing a minimum of 6.5 db gain at the transmitter frequency thus, a 3 stage amplifier is used to provide a minimum of 100 Watts of peak power at the transmitter output.

The bandwidth of the transmitter is sufficiently broad (70 MHz at 1 db down) to accommodate all DME channels (including sufficient tolerance for a 0.1 μsec risetime pulse for the first and last channels) without the need for tuning. The sole requirement for changing channel frequency is to replace the crystal in the exciter crystal controlled oscillator.

Pulse modulation is performed at the medium power level of the VHF amplifier. The modulator receives pulses from the DME interrogator coder. The three stages are sufficient to provide ample drive to modulate the three VHF power stages in the transmitter.

b. DME Transponder

(1) General

The transponder portion of the DME system serves as the ground "reflector" of coded pulse pairs from the airborne interrogator. A simplified block diagram indicating the major subsections of the transponder is shown in figure 8-41. The receiver section provides the sensitivity and dynamic range necessary to amplify the received RF interrogations. The coded pulse pairs are passed into the video portion of the transponder where only the on-channel, properly coded pulses are accepted. Following the video processing and decoding, the pulses are encoded and transmitted as the interrogator "reflected" and delayed signal. Details are provided in the sections on the receiver, transmitter and video that follow.

(2) Transponder Receiver

The transponder receiver is designed to cover the full transponder receiver band (5003 MHz to 5060 MHz) without the need for tuning. However, the close proximity of this band to that of the transponder transmitter band (5068 MHz to 5125 MHz) requires the use of dual down conversion in order to insure maximum image rejection. In addition, local oscillator re-radiation will be reduced to acceptable levels through the use of double conversion.

Figure 8-42 is a block diagram of the receiver front end and first down converter. The receiver will utilize a low noise rf amplifier to achieve a low NF and reduce the peak power required in the airborne transmitter. Several approaches are available including Ga As FET's that have demonstrated 3 db NF beyond 5 GHz. The following discussion centers around the use of an available tunnel diode amplifier as is planned for Feasibility, but should not be construed as the final choice for future MLS DME. A tunnel diode

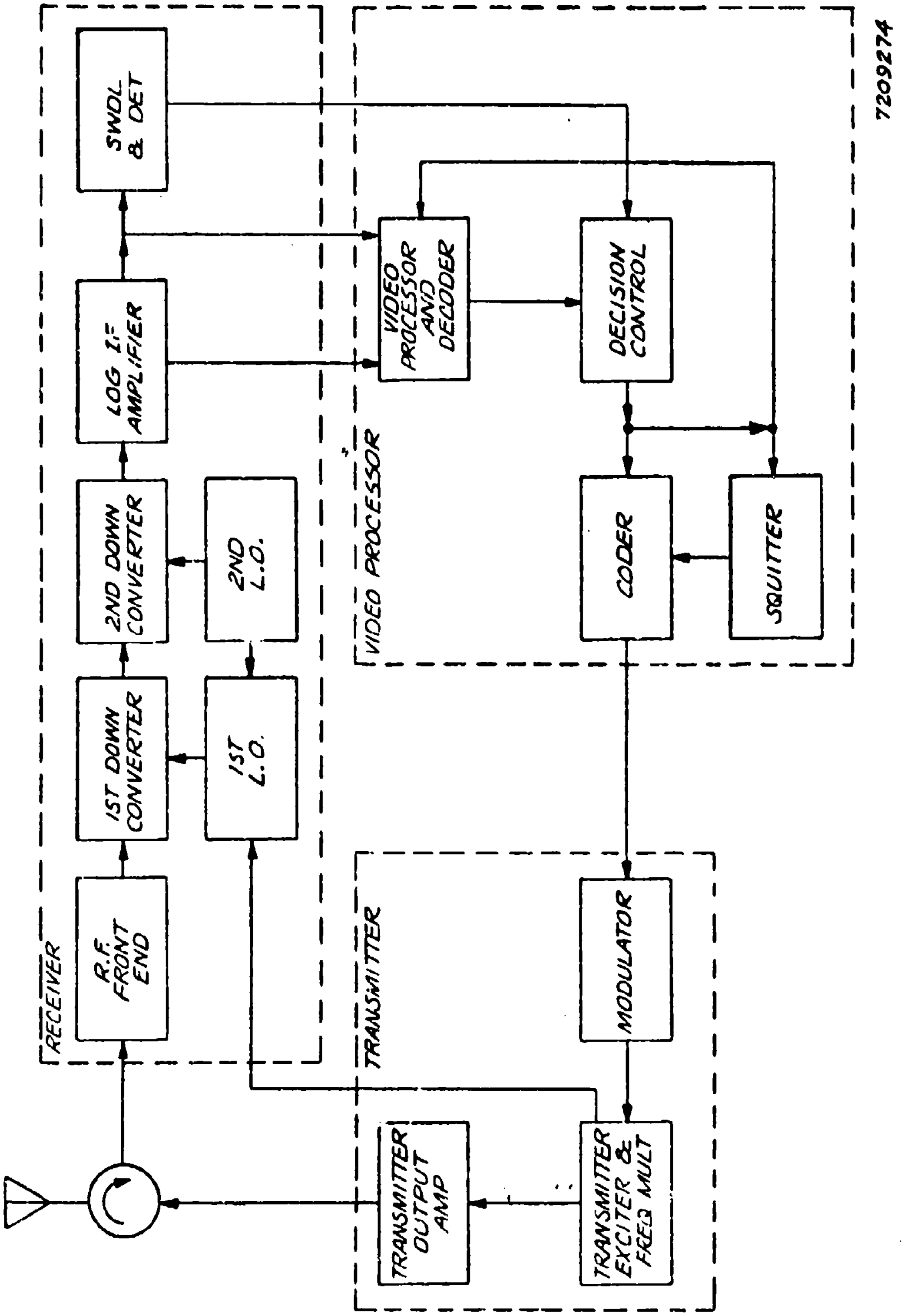


Figure 8-41. DME Transponder Simplified Block Diagram

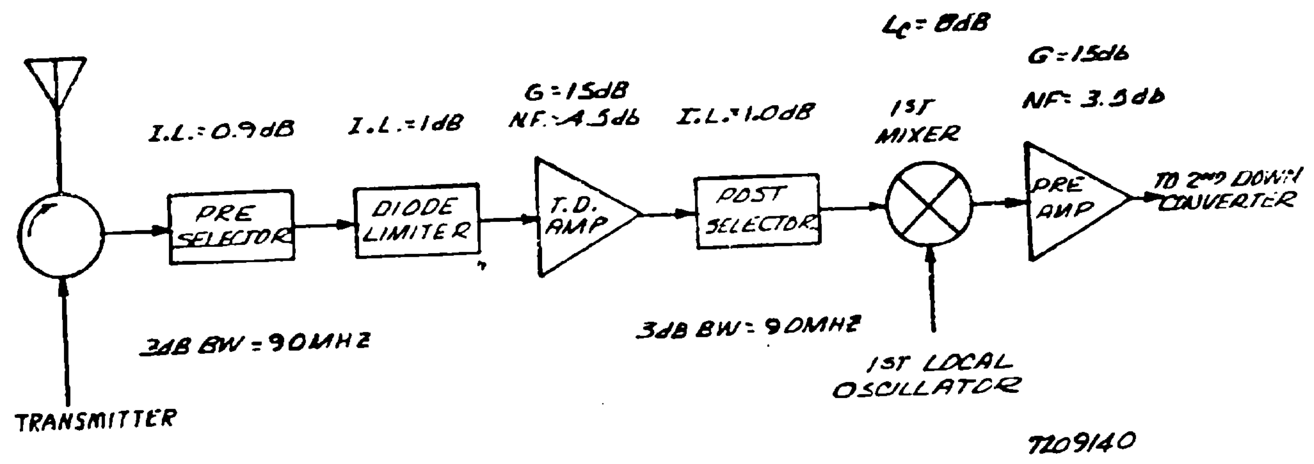


Figure 8-42. Transponder RF Front End and First Down Converter

amplifier, having a gain of 15 db and a noise figure of 4.5 db, determines the receiver noise figure in conjunction with the remaining portion of the receiver. The tunnel diode amplifier is followed by a post selector (insertion loss 1 db) and a balanced mixer-IF amplifier combination with a 12 db noise figure. The receiver noise ratio referred to the tunnel diode input terminals is therefore:

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1} = 2.8 + \frac{20-1}{31.5} = 3.4 \text{ (5.3 db)}$$

where:

F_{12} = overall receiver noise ratio
F_1 = noise ratio of tunnel diode amplifier
F_2 = combined noise ratio of post-selector and mixer
G_1 = gain ratio of tunnel diode amplifier

The insertion loss of the passive devices preceeding the tunnel diode amplifier is 2.2 db and is budgeted as follows:

diode limiter	= 1.0 db
signal pre-selector	= 0.9 db
transmit/receive circulator	= 0.3 db
Total	2.2 db

The receiver noise figure referred to the antenna terminals, is, therefore, 5.3 db + 2.2 db = 7.5 db + cable losses. If long cable runs are required, it may be preferable to install the front end at the antenna to minimize overall NF.

Signal preselection is required to prevent strong signals outside the receiver bandwidth from saturating the tunnel diode amplifier. Saturation of the tunnel diode amplifier occurs at an input signal level of -39 dbm. The amplifier is also protected from burn out during the transmitter pulse. As indicated in section 1.1.1.1.G.4.b, the transponder peak power output is 1 KW. Reverse attenuation of the transmitter/receiver circulator is 20 db and, therefore, a leakage of 10 Watts peak is expected in the receiver. The burn out level of the tunnel diode amplifier is 250 mw. A diode limiter with a peak power capability of 20 Watts and a leakage level of 75 mw is, therefore, included for tunnel diode amplifier protection.

The signal output of the tunnel diode amplifier is passed, through the post amplifier, to the first down converter. This signal, in conjunction with the first local oscillator, produces a first IF frequency of 235 MHz.

Figure 8-43 is a block diagram of the local oscillator section of the transponder receiver. The base frequency for the first local oscillator (253.4 MHz to 256.25 MHz) is obtained from the transponder transmitter described in section 1.1.1.1.G.4.b of this report. This CW signal is amplified, quadrupled and fed to an off-set mixer. The off-set signal (60 MHz) is obtained from the crystal controlled base oscillator of the second local oscillator. The lower sideband (953.6 MHz to 965.0 MHz) output of the off-set mixer is amplified and multiplied by five to obtain the first local oscillator frequency of 4768 MHz. The second local oscillator is obtained from the crystal controlled base oscillator at 60 MHz. A 5 times multiplier raises the 60 MHz up to 300 MHz, the local oscillator frequency required for the second down conversion.

Figure 8-44 is a block diagram of the second down converter and IF amplifier. The signal input (235 MHz) to the second down converter is combined with the second local oscillator (300 MHz) to obtain an IF frequency of 65 MHz. This signal is pre-amplified and passed to the log IF amplifier through a band limiting filter. The log IF amplifier, described in section 1.1.1.1.G.3.a of this report, provides linear amplification over the dynamic range of the received signal. A detected log Video pulse is supplied to the Video processing circuits by the log IF amplifier. In addition, the log IF amplifier provides wide band IF signals (both on-channel and adjacent-channel) to the TMFD for on-channel signal selection. The IF signal is also supplied to a surface wave delay line to provide system delay at IF frequencies.

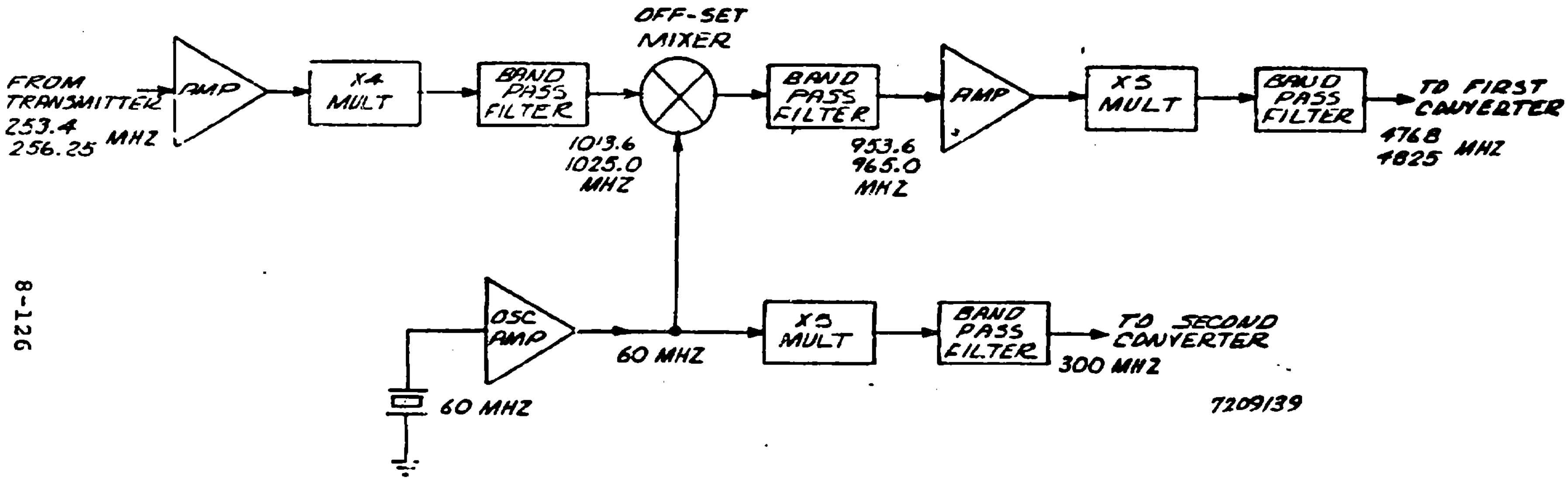


Figure 8-43. Transponder First and Second Local Oscillator Block Diagram

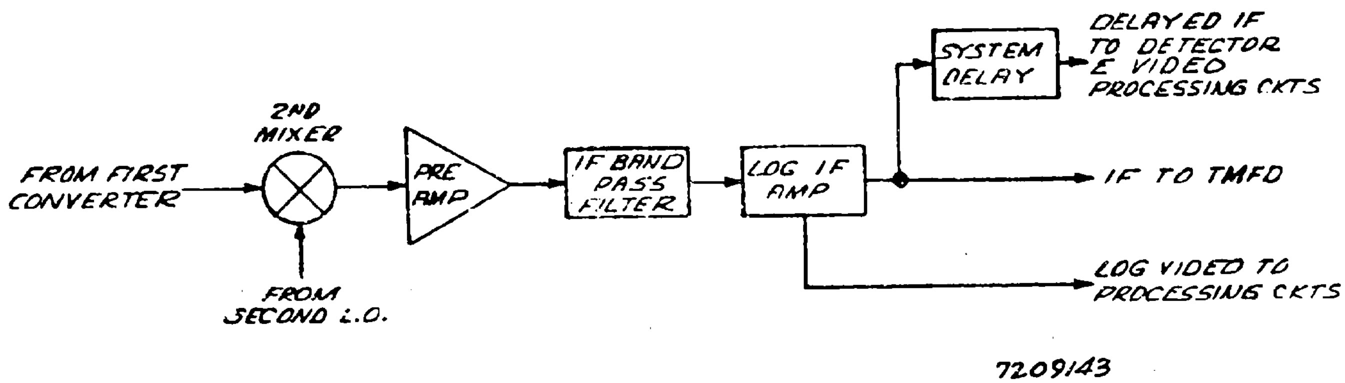


Figure 8-44. Block Diagram of 2nd Converter and IF Amplifier

The following basic parameters set the design of the adjustable surface wave delay line system.

Center Frequency	65 MHz
Delay Range	35 to 60 μs
Adjustment steps	within ±0.0155 μsec of nominal (± 1 cycle of 65 MHz).
Delay drift	± .01μs for all combinations of 5 to 100 percent humidity -30° to $70^{\circ}C$ temperature

ST-cut quartz is the only material known to have a low enough temperature coefficient for acoustic surface wave delay. The basic tapped delay line consists of an input and output interdigital transducer 4 wavelengths long. To achieve the delay adjustment, the input transducer is chosen from a group of 103 identical transducers spaced 16 wavelengths (.0305 inches) apart. Coarse delay adjustment consists of selecting one of these transducers.

The output transducer consists of two adjacent sections chosen from a group of 9 contiguous sections, each 2 wavelengths long. The eight choices provide fine delay steps of .031 μs.

Figure 8-45 shows the quartz piece with its electrode pattern mounted in a recess on a printed circuit board. The input transducers are spaced too close together to be accommodated by one array of connections on the P.C. board. The odd-numbered input transducers are wire-bonded to lands on one side while the even-numbered taps are bonded to lands on the other side. All lands are connected to a ground bus for shielding purposes. For field adjustment, the desired land is cut away from the ground bus and a wire jumper is soldered from the selected land to a hot bus conductor. The lands are spaced on .061 inch centers, so it is possible to do the soldering with a small pencil iron. If the adjustment is to be changed, the severed conductor can be bridged with a wire jumper, and a new land opened and connected to the hot bus.

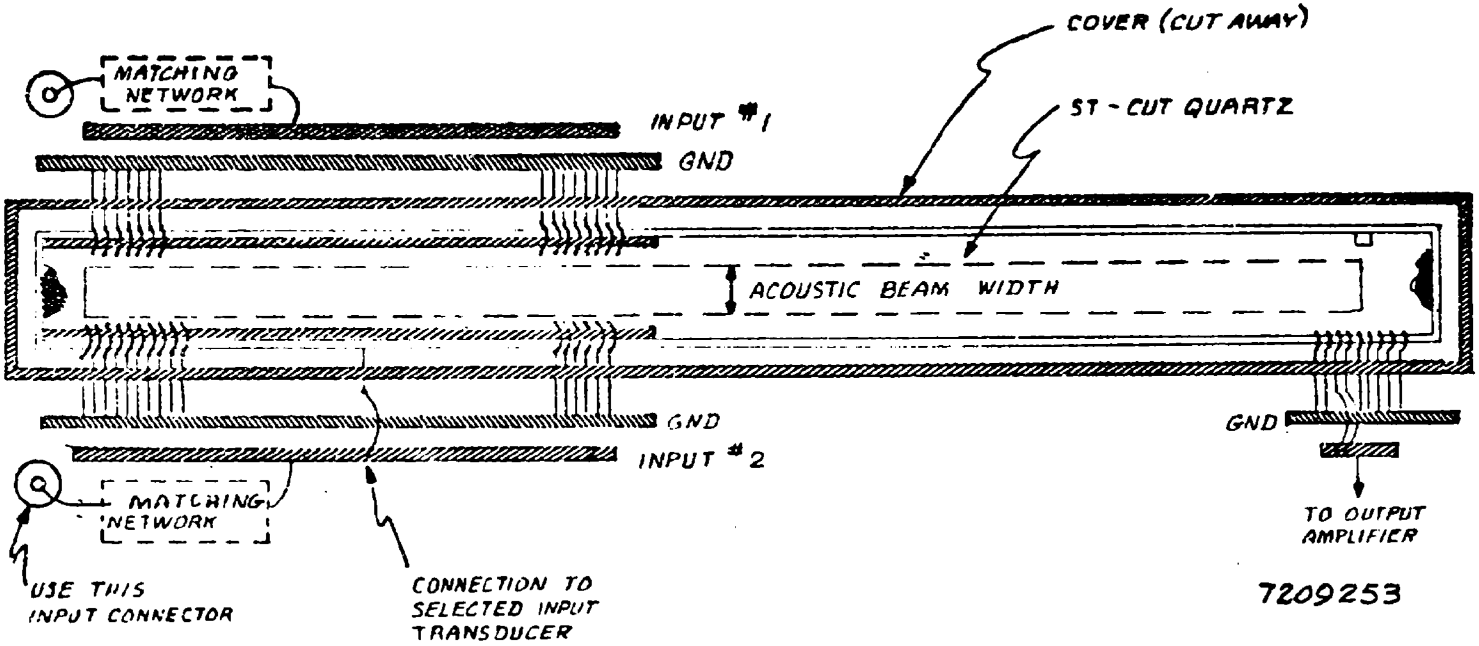


Figure 8-45. Sketch of Adjustable Acoustic Surface Wave Delay Line Showing Sample Connections on P.C. Board

The nine sections of the output transducer are spaced on .0038 inch centers. The connections are fanned out on the quartz plate to a row of nine bonding pads spaced .062 inch apart. These pads are wire bonded across to conductors on the P.C. board. All transducer sections are connected to a P.C. ground bus. For field setting, two of the ground connections are scratched out, and the selected transducer sections are wired to the output bus.

The optimisitic estimate of insertion loss (measured with 65 MHz C.W.) is 32 dB. Stray capacitance added by the P.C. connections and the associated amplifiers increase the loss to a maximum value of 42 dB. An output amplifier is incorporated in the package in order to allow operation at 1000 ohm impedance level rather than the customary 50 ohm level. This makes impedance matching easier, with the introduction of less stray C.

Hazeltine has 100% confidence in the acoustic surface wave design. The material, aperture dimension (.30 inch) and the path length (7.45 inches) are the same as those used in our 511 - bit tapped delay lines operating at 60 MHz, and 70 MHz. The path length attenuation is 2.7 dB and the diffraction (beam spreading) loss is 0.3 dB. These figures are included in the theoretical insertion loss of 32 dB.

Aluminum metallization will be used. The reflection coefficient for 1000 A°aluminum fingers has been measured. A 40 dB spurious response level can be met by using three fingers per wavelength in the transducers, a common practice at Hazeltine. (If A represents connection to the hot bus and B represents connection to the ground bus, the fingers are connected B A BB A BB A BB A B.) Distortion due to bulk wave coupling by the fingers is known to be negligable on quartz.

(3) Transponder Transmitter

The approach used in the design of the transponder transmitter is similar to that used for the interrogator transmitter described in section 1.1.1.1.G.4.a of this report. There are, however, several differences to be noted and only these differences will be described. They are as follows:

- o The output power of the transponder is 1 KW peak rather than 100 Watts peak.
- o The transponder transmitter chain provides the local oscillator signal for the first down conversion in the transponder receiver (see figure 8-46).
- o The output frequency is 65 MHz lower than the interrogator transmitter frequency.

The last of these differences is relatively minor and is accomodated by adjustment of the oscillator. The first difference, however, requires an additional stage of gain in the final output amplifier. This portion of the transponder transmitter will contain four Eimac 8912 planar triodes instead of the three required for the interrogator.

The local oscillator for the transponder receiver first down conversion is obtained from the transmitter frequency multiplier chain at the output of the oscillator tripler stage. The CW signal is fed to the receiver where it is multiplied, off-set and applied to the receiver first down converter. A detailed description of the local oscillator frequency multiplier is presented in section 1.1.1.1.G.4.b.

(4) Transponder Video

The transponder video section processes the received pulses to determine if they are legitimate interrogations. This function is performed by:

- o rejecting adjacent channel signals through the use of a Two Mode Ferris Discriminator.
- o rejecting echos of the on-channel pulses through the use of an echo discriminator.
- o insuring proper pulse spacing (code) through the use of a decoder.

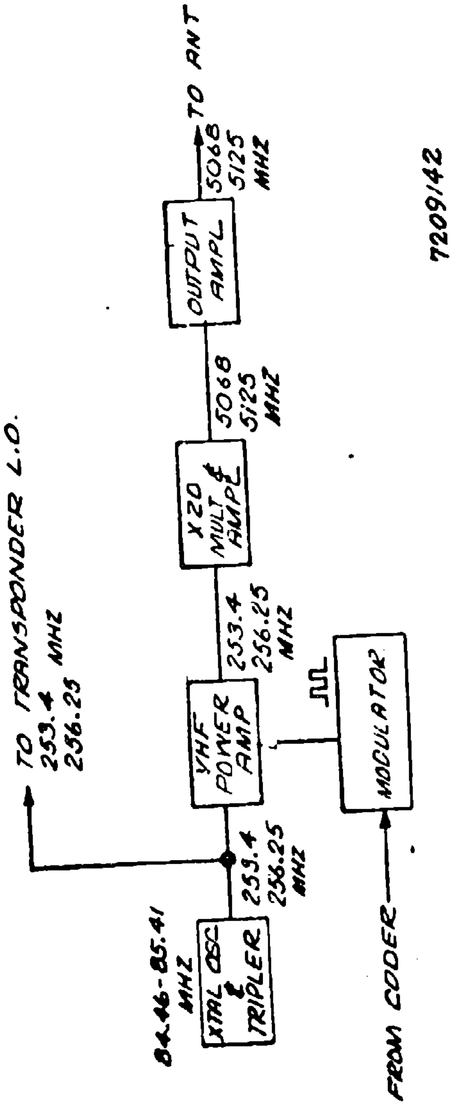


Figure 8-46. Transponder Transmitter Block Diagram

The video section also initiates the transponder reply by correlating the decoded pulses with the detected wide band pulse from the surface wave delay line.

Figure 8-47 is a block diagram of the transponder video section. The circuits up to the output of the echo discriminator are described in section 1.1.1.1.G.3. A sharply rising video pulse (0.2 sec. rise time), obtained from the log IF detected video output, is gated into the video processing circuits by virtue of channel selectivity offered by the TMFD. The requirement for a sharply rising pulse for an on-channel pulse pair in the video processing circuits is necessary for decoding purposes. The decoder is designed for a decoding tolerance of 0.5 μseconds. The on-channel echo-free output of the echo discriminator is applied to the decoder. Only those pulse pairs that match a code peculiar to an individual transponder will be allowed to pass through the decoder circuits. All other pulse codes, even though on channel, are rejected at this point. When a legitimate code is present, the decoder output turns on the reply gate and enables the detected wide band pulse output of the surface wave delay line to pass onto the decision threshold circuit.

The decision threshold circuit is functionally similar to that described in section 1.1.1.1.G.4.a of this report. However, this circuit uses a fixed threshold, set about 7 dB above the noise. When the threshold is crossed, the coder is initiated to supply a properly coded pulse pair to the modulator and transmitter. In addition, the decision threshold output is fed to the squitter killer, reply counter, and dead time generator.

In the absence of received interrogations, the squitter generator supplies random pulses, at a maximum average prf, to airborne interrogator receivers within the range of the transponder. As the traffic density increases, the reply counter adjusts the average prf of the squitter generator from a maximum at zero received

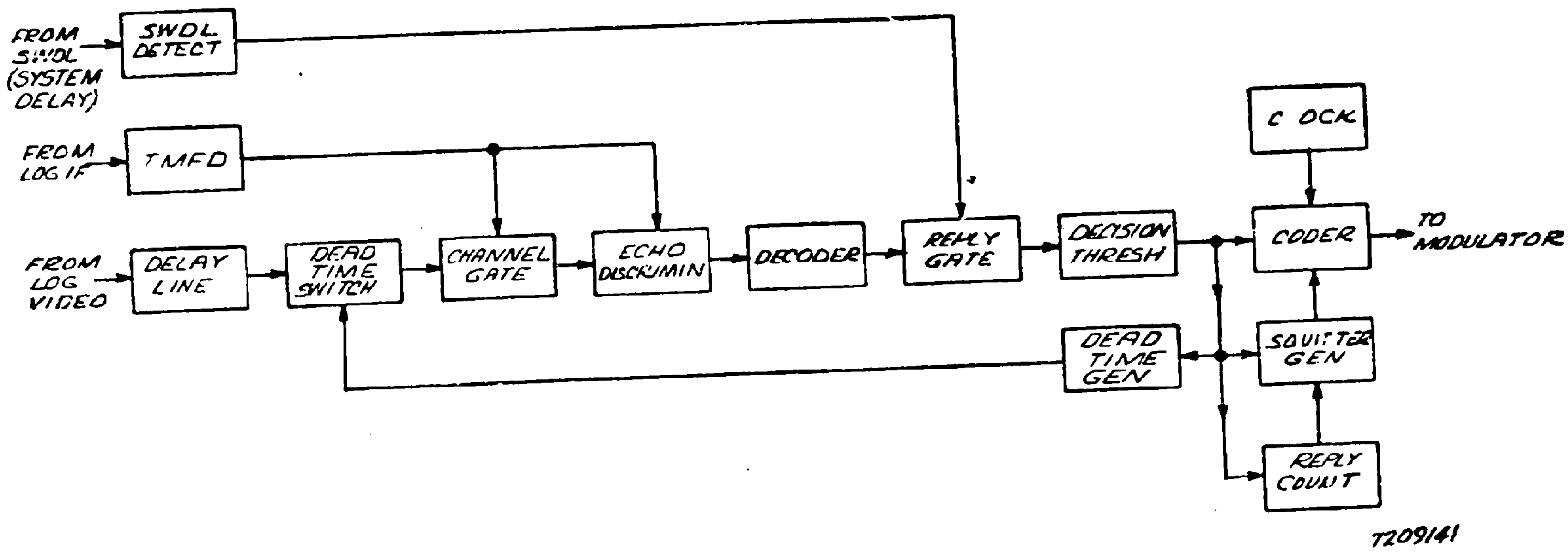


Figure 8-47. DME Transponder Video

interrogation, down to a minimum during periods of high traffic densities. The squitter killer also receives an input directly from the threshold decision circuit. This input stops the operation of the squitter generator during the time interval that a reply is being transmitted.

A dead time generator is employed to further reduce the possibility of false decode due to echos after the reception of a legitimate pulse pair. The dead time generator is initiated by the output of the decision threshold. The output of the dead time generator is used to disable the video processing ckts immediately following the reception of a legitimate pulse pair and, for a predetermined length of time following the second pulse of the pulse code.

5. Solid State Possibilities for DME Implementation

The hardware approach to the prototype model of the DME equipment will be different than that of the feasibility model in the areas of interrogator transmitter and transponder low noise front end. A possibility also exists that the transponder transmitter will be different for the prototype model.

a. Interrogator Transmitter

A minimum interrogator power of 50 watts peak output has been calculated to produce a signal-to-noise ratio of 13 dB at the transponder for a range of 30 nautical miles and a 10.0 db transponder noise figure. The calculation takes into account antenna gains and all losses due to circulators and cables in the interrogator-transponder system. The interrogator transmitter for the feasability model will be designed using planar ceramic triodes. Triode tube technology has advanced to a point where a peak power output of 1 KW is possible at frequencies up to 6 GHz. The operating life of these devices are, however, restricted to approximately 500 hours for a 1 KW amplifier operating at a 0.5 percent duty cycle. Increased operating life time, up to 1500 hours, is to be expected when the power output and duty cycle are reduced to 100 watts peak and 0.01 percent respectively. Power output specification for the feasibility interrogator transmitter is set at 100 W ±3dB peak output power. This excess power over the calculated minimum 50 watts peak power is required to handle contingencies such as reduced output due to early tube degradation, unanticipated losses, etc, that may occur during the feasibility tests. A more realistic specification for the prototype model, based on significantly increased life expectancy for solid state devices, will be 60 W ±1.5dB.

Two types of solid state transmitters, capable of generating 60W ±1.5dB peak power at a 0.01 percent duty cycle, are being considered for the prototype interrogator transmitter to replace the planar ceramic triodes. They are the transistorized output amplifier and the TRAPATT diode output amplifier.

The use of either approach represents a significant increase in the operating life and reliability over that of a planar ceramic triode. Microwave Semiconductor Corporation (MSC) is presently developing a transistor capable of providing a 10 watt peak power output with 6dB gain over the interrogator transmitter band. This transistor will be available during the last quarter of 1972 or the first quarter of 1973. Two sets of four of these transistors in parallel may be combined through a hybrid junction to provide the required peak power output. This approach has been successfully demonstrated by a Hazeltine in-house program designed to produce 500 watts of peak power at "L" band. Six MSC1100 transistors, each capable of 100 watts peak output power, were paralleled to produce a combined output of 500 watts peak power.

The second approach, TRAPATT diodes, is presently capable of providing 50 watts peak output power with 6dB gain. RCA has indicated that a TRAPATT amplifier capable of producing 100 watts peak output power with 10db gain can be available prior to the prototype phase. The state-of-the-art in these devices has progressed to the point where noise, jitter, and repeatability are no longer problems. The primary advantage of these amplifiers over transistor amplifiers are their ability to handle greater peak powers in a single device. This means greater circuit simplicity and therefore, ultimately lower cost.

b. Transponder Low Noise Front End Amplifier

The transponder receiver feasability model will employ a tunnel diode amplifier with a 4.5dB noise figure as the low noise front end amplifier. A low noise transponder front end approach was selected in order to reduce the required airborne transmitter power and hence, to reduce the cost and increase the reliability of the interrogator for the user. A further reduction in noise figure for the prototype transponder is anticiapted by taking advantage of recent developments in Gallium Arsenide field effect transistors (Refer to the April 1972 edition of "MICROWAVES").

Several companies have announced the development of Gallium Arsenide field effect transistor capable of noise figures with less than 3.5 db at 5GHz. Several companies, Hewlett Packard and Watkins Johnson, plan to introduce Gallium Arsenide FET's with less than 3db noise figure at 8GHz during 1973. Fairchild Corporation is presently marketing a device, MT9001, capable of providing a 3.5db noise figure with 9dB gain at 5GHz. Although these devices are presently expensive, it is anticipated that with demand the price will drop to a point where they will be highly competative with tunnel diode and parametric amplifiers.

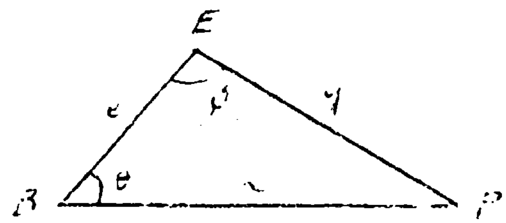
c. Transponder Transmitter

A minimum of 200 watts peak power has been calculated for the transponder transmitter in order to produce a 13 db signal to noise ratio at the interrogator receiver for a 30 nautical mile range. This calculation includes a 14.5db interrogator noise figure, cable and circulator losses and antenna gains. The approach for the feasibility model and, tentatively for the prototype model, is based on the use of planar ceramic triodes. However, the use of a TRAPATT amplifier will be thoroughly investigated during the feasibiility phase. Recent results in this field have indicated that TRAPATT diodes can be operated in a series stack (housed in a IN23 diode type cartridge) to obtain greater power output. An output power of 200 watts peak power does not represent the upper limit of these devices. It is therefore essential that this approach be investigated for possible use in the prototype since the operating life and reliability of the transponder transmitter would be greatly increased with a corresponding decrease in operating costs.

6. Additional DME Supporting Analyses

a. Variation in the Phase of Leading-Edge Echoes as the A/C Approaches the Landing Strip

The purpose of this Analysis is to show that the echoes that are received during the leading edge of the direct pulse do not vary sufficiently pulse-to-pulse to allow averaging to be utilized to reduce errors due to such echoes.



A plane (P) receives signals from beacon (B) at a distance (x). He also receives an echo from (E) at a distance (e) from B and an angle (θ) from the beacon. The echo travels a distance y + e and lags behind the desired signal by $\delta = y + e - x$, or

$$\delta = \left[x^2 + y^2 - 2xe \cos \theta \right]^{1/2} + e - x \qquad (1)$$

As the plane travels toward the beacon, the rate of change of (δ) with respect to (x) is:

$$\frac{d\delta}{dx} = \left[x - e \cos \theta \right] \left[x^2 + e^2 - 2xe \cos \theta \right]^{-1/2} - 1 \qquad (2)$$

The angle (θ) for which dδ/dx is a maximum is determined from

$$\frac{d}{d\theta} \left[\frac{d\delta}{dx} \right] = 0 \qquad (3)$$

$$\frac{d}{d\theta}\frac{d\delta}{dx} = e \sin\theta \left[x^2 + e^2 - 2xe\cos\theta\right]^{-\frac{1}{2}}$$

$$= -\tfrac{1}{2}\, 2xe \sin\theta \left[x - e\cos\theta\right]\left[x^2 + e^2 - 2xe\cos\theta\right]^{-3/2} = 0$$

factoring:

$$e \sin\theta\left[x^2 + e^2 - 2xe\cos\theta\right]^{\frac{1}{2}} \Big\{1 - x\left[x - e\cos\theta\right] \left[x^2 + e^2 - 2xe\cos\theta\right]^{-1} = 0$$

$$\frac{x^2 - xe\cos\theta}{x^2 + e^2 - 2xe\cos\theta} = 1.0 \qquad (4)$$

$$x^2 - xe\cos\theta = x^2 + e^2 - 2xe\cos\theta$$

$$\cos\theta = e/x$$

This means that the maximum rate of change occurs at a changing angle and that $\phi = 90°$ (see sketch 2 below).

Substitute $\cos\theta = e/x$ (4) in (2)

$$\frac{d\delta}{dx} = \left[x - e - e/x\right]\left[x^2 + e^2 - 2xe\,(e/x)\right]^{-\frac{1}{2}} - 1$$

$$= \frac{x^2 - e^2}{x}\left[x^2 - e^2\right]^{-\frac{1}{2}} - 1$$

$$= \frac{1}{x}\left[x^2 - e^2\right]^{\frac{1}{2}} - 1$$

$$= e/x\left[(x/e)^2 - 1\right]^{\frac{1}{2}} - 1$$

$$\approx e/x\left[\left(\frac{x}{e} - \frac{e}{2x}\right)^2\right]^{\frac{1}{2}} - 1 = e/x\left[\frac{x}{e} - \frac{e}{2x}\right] - 1$$

$$\approx 1 - \tfrac{1}{2}\,(e/x)^2 - 1 = -\tfrac{1}{2}\,(e/x)^2$$

$$d\delta = -\tfrac{1}{2}\,(e/x)^2\,dx \qquad (5)$$

Let dx be the distance covered between interrogations

$$dx = vt = v/q \quad ; \; q = \frac{1}{T} \qquad (6)$$

$$d = -\tfrac{1}{2}\left(\frac{e}{x}\right)^2 v/q$$

if v is in ft/sec; $\lambda = 0.2$ ft so that

$$d\lambda = \frac{d\delta}{0.2} = -\frac{1}{2} \quad (5)(e/x)^2 \frac{v}{q} = -2.5 \frac{v}{q} (e/x)^2 \qquad (7)$$

The maximum value of e is the distance travelled by the echo from the start of the pulse at t = 0 to the decision level say at $\frac{E}{2}$ at T/4; and T = 0.48μs or $e = \frac{0.48}{4} \times 1{,}000 = 120'$

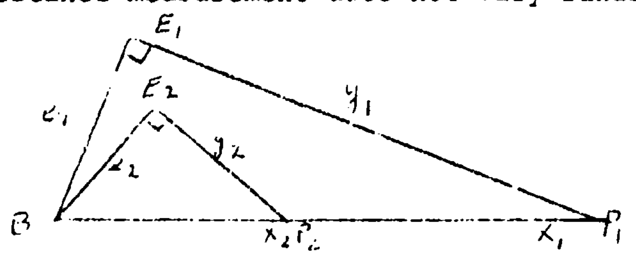
When landing, a plane travels at about 250'/sec; let q = 15, then

$$d\lambda = -2.5 \times \frac{250}{15} \times 120^2/x^2$$

$$= 6 \times 10^5/x^2$$

v(ft/s)	250	250	125
e(ft)	12υ	120	120
x(ft)	12,000	6,000	3,000
ε/x	0.01	0.02	0.04
θ (deg)	4	89°	87.5°
dλ (λ)	0.0042	0.017	0.033

We see from this that the phase difference between a direct signal and an echo does not vary significantly at normal landing distances and speeds. Therefore, the amplitude of the error it introduces in the distance measurement does not vary randomly.



The angle for maximum delay variation with x varies so that cos θ = e/x, which means that the ∠E = 90°.

i. Analysis of Error Sources in the Transponder

This Analysis derives the errors due to thermal noise, decision level uncertainty, and the leading edge/fixed threshold technique of measurement proposed for use in the Transponder.

(1) Let (E_p) be the detected peak video signal at the maximum distance of 30 n.mi. Its rms value is

$$E_s = \frac{\sqrt{2}}{2} E_p \tag{1}$$

The signal/noise voltage ratio is

$$\frac{E_s}{E_n} = \sqrt{S/N} \quad \text{, so that}$$

$$\frac{\sqrt{2}}{2} \times \frac{E_p}{E_n} = \sqrt{S/N}$$

$$\frac{E_p}{E_n} = \sqrt{2S/N}$$

$$E_n = \pm E_p \sqrt{N/2S} \tag{2}$$

(2) Let the "decision level" (E_d) be set at the fixed value $E_d = aE_p$ and let the instrumentation error be $\Delta E_d/E_d = \pm 0.1$, then $E_d = \pm 0.1E_d = \pm 0.1aE_p$ (3)

(3) Since E_n and ΔE_d are random and uncorrelated, the "effective noise-voltage" is:

$$\Delta n = \sqrt{(\Delta E_d)^2 + E_n^2} = E_p\sqrt{0.01a^2 + N/2S} \tag{4}$$

Let a = 0.5 and S/N (at 30 n.mi.) = 13db, N/2S = 0.025

$$\Delta n = \pm\sqrt{0.01 \times 0.25 + 0.025 = 0.0275} = \pm 0.17E_p \tag{5}$$

The effective $(S/N)_e$ is then obtained from:

$$E_n = \overline{\Delta n} = \sqrt{N/2S} \quad E_p$$

$$(S/N)_e = 12.6 \text{ db}$$

The leading-edge of the detected pulse is defined as:

$$\varepsilon_\ell = \frac{E_p}{2}\left[1 - \cos\frac{2\pi t}{T}\right] \text{ at 30 n.mi.} \tag{6}$$

at the distance (d) n.m. this becomes

$$\varepsilon_\ell = \frac{E_p}{2}\,\frac{30}{d}\left[1 - \cos 2\pi t/T\right] \tag{7}$$

(4) The slope of the leading edge is

$$S = \frac{d\varepsilon_\ell}{dT} = E_p\,\frac{15}{d}\,\frac{2\pi}{T}\sin 2\pi t/T$$

$$= \frac{30}{d}\,\frac{E_p\pi}{T}\sin 2\pi t/T \tag{8}$$

When t/T = 1/4, this is

$$S_{30} = \frac{30\pi}{dT}\,E_p = \frac{\pi E_p}{T} \text{ (at 30 n.mi.)} \tag{9}$$

At distance(d), the slope is

$$S_d = \frac{30\pi}{dT}\,E_p \sin(2\pi t/T)$$

$$\frac{S_d}{S_{30}} = \frac{30}{d}\sin(2\pi t/T) \tag{10}$$

The leading edge of e_ℓ reaches the decision level E_d at time t_d according to

$$\alpha E_p = E_d = \frac{15E_p}{dT}\left[1 - \cos 2\pi td/T\right]$$

$$\cos\frac{2\pi td}{T} = 1 - \frac{ad}{15}$$

from which:

$$\sin \frac{2\pi td}{T} = \pm\sqrt{\frac{ad}{15}\left(2 - \frac{ad}{15}\right)}$$

let a = 0.5:

$$\sin\left(\frac{2\pi td}{T}\right) = \sqrt{\frac{d}{30}\left(2 - \frac{d}{30}\right)}$$

so that

$$\frac{S_d}{S_{30}} = \frac{30}{d}\sqrt{\frac{d}{30}\left[2 - \frac{d}{30}\right]} = \sqrt{\frac{60}{d} - 1} \qquad (11)$$

(5) The total output of the receiver, including noise, is

$$\varepsilon = \frac{15}{d} E_p \left[1 - \cos \frac{2\pi t}{T}\right] \pm 0.17\, E_p$$

(6) e_1 reaches the decision-level $E_d = aE_p$ at $t = t_d$ according to:

$$E_d = \alpha E_p = \frac{15}{d} E_p \left[1 - \cos 2\pi t/T\right] \pm 0.17\, E_p$$

Cancelling the common factor (E_p) and rearranging

$$\theta = 2\pi td/T = \cos^{-1}\left[1 - (\alpha \pm 0.17)\frac{d}{15}\right]$$

$$t_d = \frac{T}{2\pi}\cos^{-1}\left[1 - (\alpha \pm 0.17)\frac{d}{15}\right] \mu s$$

$$= \frac{500T}{2\pi}\cos^{-1}\left[1 - (\alpha \pm 0.17)\frac{d}{15}\right] \text{ ft.}$$

The rf pulse rising in $t_o = 0.1\mu s$ is broadened to $0.14\mu s$ by a BW = 7.0 MHz.

Let a = 0.5, then

$$t_d = \frac{500T}{2\pi}\cos^{-1}\left[1 - (0.5 \pm 0.17)\frac{d}{15}\right] \text{ ft.}$$

Table 8-6 below lists the bias and random errors as a function of distance. Also listed is the bias error when a 40 foot correction is applied. Note that a simple bias correction is very effective.

The curves of figure 8-48 show the bias error as a function of (d) and for a ±6db variation in received power.

Note that as shown in part a of the figure.

If 40' is added to the reading, the bias error is < 20' from 0 to 15 nmi for the calibrated voltage E; from 0 to 7 nmi for -6db below the calibrated power, and for +6db the bias error never exceeds 20 ft.

And as shown in part b:

If the linear dynamic correction is applied for the nominal value of received voltage at 30 nmi then up to 15 nmi, a decrease of 6db will produce a bias error of < 20' and an increase of 6db will produce a bias error of < +12'.

Table 8-6. BIAS AND RANDOM ERRORS AS A FUNCTION OF DISTANCE

d (nmi)	bias error (ft)	noise error (ft)	bias error-40 ft (ft)
1.5	47.5	±2.0	+7.5 ft.
3.0	42.5	±3.0	+2.5
5.0	37.5	±4.0	-2.5
7.5	32.5	±5.0	-7.5
10.0	28.0	±6.2	-12.0
15.0	20.0	±7.5	-20.0
30.0	0.0	±15.0	-40.0

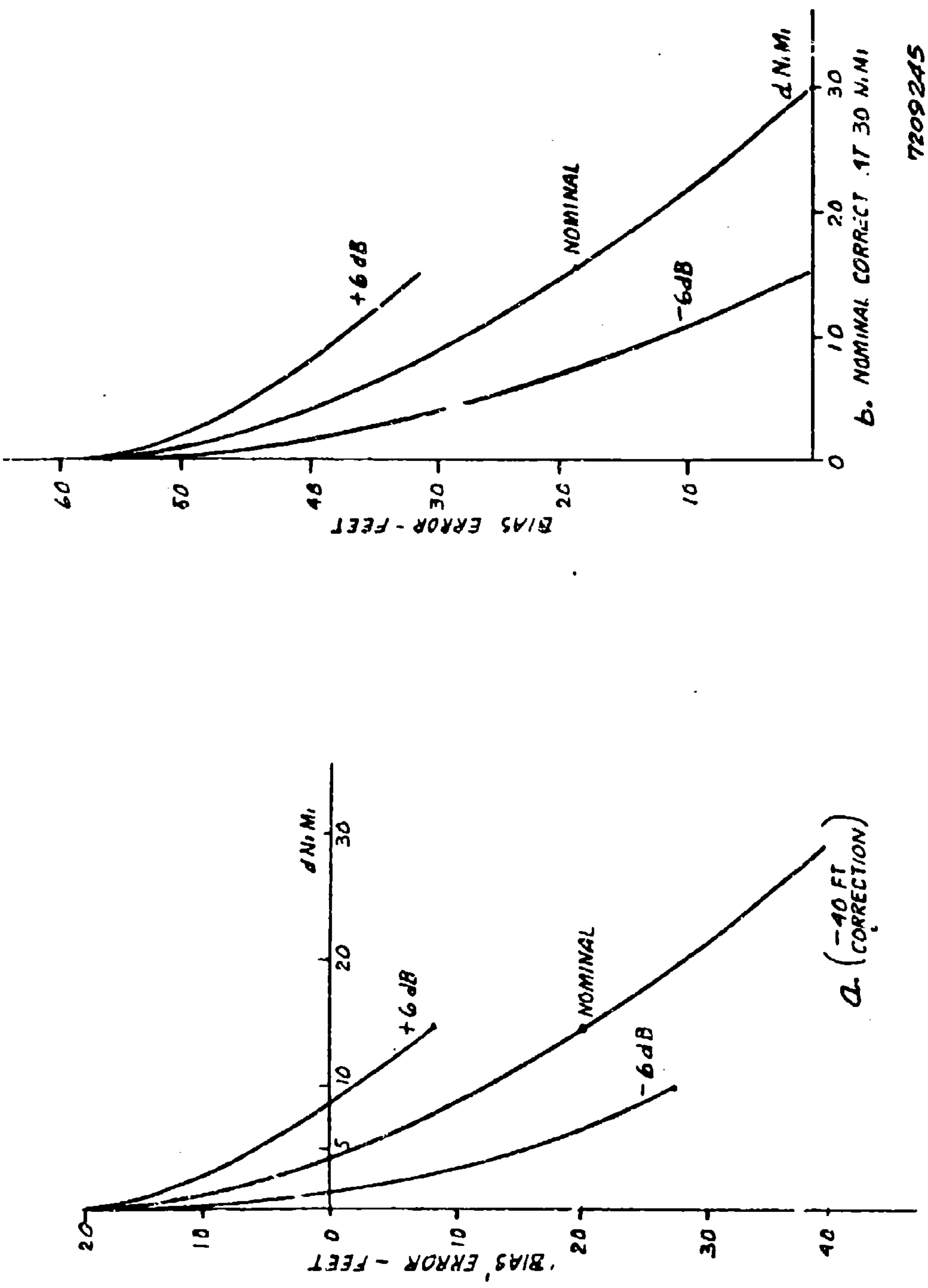


Figure 8-48. Plot of Bias Error vs d

c. Analysis of Noise-Jitter with Decision Level Set at Constant-Fraction of Peak Amplitude

The purpose of this analysis is to derive the errors due to noise for the case where the leading edge is applied to a threshold that is set at a fixed percentage of the peak amplitude of the received pulse. There are no bias errors in this type of range measurement except when echoes affect the pulse amplitude.

(1) The leading edge of the pulse is described by the video detected signal, as:

$$\epsilon_{\ell} = \frac{E_p}{2} \left[1 - \cos 2\pi t/T\right] \quad (1)$$

It is assumed that there is no distortion of the pulse during the amplification and detection process so that a decision level which is a constant fraction of the peak-level, no matter what the value of the peak, is reached at a constant time.

(2) The rms value of the signal is $E_s = \frac{\sqrt{2}}{2} E_p$

(3) The voltage "signal-to-noise" ratio is

$$\frac{E_s}{E_n} = S/N$$

The noise-voltage is then

$$E_n = \sqrt{N/S}\, E_s = \sqrt{N/2S}\, E_p \quad (2)$$

Let E_n be the noise at 30 n.mi. If agc is used, and E_p is nearly constant,

$$E_n = \pm \frac{d}{30} E_p \sqrt{N/2S} \text{ at d n.mi.} \quad (3)$$

Assume S/N = 13db = 20 at 30 n.mi.; then

$$E_p = \pm \frac{d}{30} E_p \sqrt{1/40} = \frac{0.16}{30} d\, E_p \approx \frac{1}{200} d\, E_p \quad (4)$$

(4) Let the decision-level be $E_d = aE_p$ and let the jitter in measuring the instant when E_d is reached by $\Delta E_d/E_d = \pm 0.1$, so that

$$\Delta E_d = \pm\, 0.1\, E_d = \pm\, 0.1\, \alpha E_p$$

(5) Since E_n and E_d are random and uncorrelated the "effective noise" is given by

$$\Delta n = \sqrt{(\Delta E_d)^2 + (E_n)^2}$$

$$= \sqrt{(0.1\alpha)^2 + \left(\frac{d}{200}\right)^2}\; E_p \tag{6}$$

$$= \pm\, 0.1\, E_p \sqrt{\alpha^2 + \left(\frac{d}{20}\right)^2} \tag{7}$$

The total output voltage is then

$$\epsilon_t = \frac{E_p}{2}\left[1 - \cos\frac{2\pi t}{T}\right] \pm \Delta n \tag{8}$$

e_t reaches the "decision-level" E_d at time t_d in accordance with

$$E_d = \alpha E_p = \frac{E_p}{2}\left[1 - \cos\frac{2\pi td}{T}\right] \pm 0.1\, E_p \sqrt{\alpha^2 + \left(\frac{d}{20}\right)^2} \tag{9}$$

cancelling E_p and rearranging:

$$t_d = \frac{T}{2\pi}\cos^{-1}\left[1 - 2\alpha \pm 0.2\sqrt{\alpha^2 + \left(\frac{d}{20}\right)^2}\right] \tag{10}$$

(6) Let a = 0.25; d = 30 n.mi.; then

$E_d = 0.25\, E_p$ and $\Delta n = 0.152\, E_p$, and $\frac{E_d}{\Delta n} = 1.64 = 4.3\text{db}$

(7) Table 8-7 gives the values of t_d in μs and ft. for different values of (d). The values in feet represent a fixed bias (x) ± a noise jitter (± Δx).

Table 8-7. BIAS AND RANDOM ERRORS AS A FUNCTION OF DISTANCE (CONSTANT FRACTION THRESHOLD)

$E_d = 0.25E_p$

d(n.mi.)	t ± Δt(λ)	x ± Δx(ft.)
30	0.080 ± 0.028	40.0 ± 14.0
20	0.080 ± 0.019	40.0 ± 9.5
10	0.080 ± 0.010	40.0 ± 5.0
5	0.080 ± 0.007	40.0 ± 3.5
4	0.080 ± 0.006	40.0 ± 3.0
2	0.080 ± 0.005	40.0 ± 2.5

(The fixed distance bias of 0.08μs = 40 ft.) can be calibrated out

d. Derivation of Maximum Accelerations

The purpose of this analysis is to derive the values of acceleration accompanying landing maneuvers.

The following accelerations are considered:

a. From touchdown to complete stop, or short take-off

b. At start of Standard-Rate turn

c. On Missed-Approach

(1) From Touchdown to Complete Stop

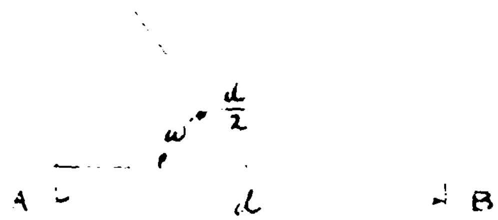
Modern a/c land at a maximum speed of 150 KTs = 250'/sec. In an emergency, they could stop in 3,000 ft.

The average velocity from touchdown to stop is (v) =250/2=125'/sec.

The time required to stop is 3,000/125 = 24 sec. The deceleration is then 250/24 = $\underline{10.4'/sec^2}$. The same applies for take-off.

(2) Standard-Rate Turn

A standard rate turn is done at an angular velocity of $\omega = 3°/sec = \pi/60$ rad/sec.



Referring to the diagram:

An a/c at A makes a SRT to B. Its linear velocity is $v = \omega d/2$.

When at A, the acceleration toward B is a maximum and is equal to

$$a = \frac{v^2}{d} = \frac{\omega^2 d}{4}$$

$\omega = \pi/60$ rad/sec, $\omega^2 = 0.00275$ rad^2/sec^4

d ft	v KTs	v ft/sec	a ft/sec^2
16,000	250*	420	12.4
32,000	500	835	22.0
64,000	1,000	1,667	44.0

*Maximum velocity below 10,000 ft.

(3) Missed Approach

$\alpha = v^2/h$, where h is the slant range to the a/c.

For v = 150 KTs = 250'/sec:

h	100 KTs	500'/sec,	1,000 ft.
α	625 KTs	125'/sec,	62.5 ft/sec^2

e. Averaging of Distance Measurements

The purpose of this analysis is to derive the effects of averaging of distance measurements on accuracy for an aircraft in motion, including accelerations.

At time (t_1) let an a/c be at a distance (x_o) from the beacon, which it approaches with a velocity (v) and a deceleration (a). Let the period between interrogations be (T). The measurement of distance is made with an error $\pm \sigma_x$:

The 1st measurement at t_1 results in: $x_1 = x_o - v\left|0T\right| + \frac{aT^2}{2}\left|0\right| \pm \sigma_1$

The 2nd measurement at t_1+T results in: $x_2 = x_o - v\left|1.0T\right| +$

$$\frac{aT^2}{2}\left|1\right|^2 \pm \sigma_2$$

The 3rd measurement at t_1+2T results in: $x_3 = x_o - v\left|2.0T\right| +$

$$\frac{aT^2}{2}\left|2\right|^2 \pm \sigma_3$$

The nth measurement at $t_1+(n-1)T$ results in: $x_n = x_o - v\left|(n-1)T\right| +$

$$\frac{aT^2}{2}\left|(n-1)^2\right| \pm \sigma_n$$

The sum of the (n) measurements is:

$$\sum_1^n x_n = nx_o - \frac{n(n-1)}{2} vt + \frac{aT^2}{2}\sum_{i=1}^{i=n-1} i^2 \pm \sqrt{n}\,\sigma_x$$

The average of the (n) measurements is:

$$\bar{x} = \frac{1}{n}\sum_1^n x_n = x_o - \frac{n-1}{2} vt + \frac{aT^2}{2n}\sum_{i=1}^{i=n-1} i^2 \pm \sigma_x/\sqrt{n}$$

The random error is descreased from $\pm \sigma_x$ to $\pm \sigma_x/\sqrt{n}$. However, a bias error is introduced because the average of the n measurements gives the range for the time of the $\frac{n-1}{2}$ measurement (neglecting acceleration effects) and not for the last (nth) measurement. To update the average of n measurements so that it corresponds to the range at the time of the nth measurement, we can identify the correction needed as follows:

True range at the nth measurement is: $x_o - v\,(n-1)\,T + \frac{\alpha T^2}{2}\,[n-1]^2$

Average value of x at the nth meas. is: $x_o - v\,\frac{(n-1)}{2}\,T + \frac{\alpha T^2}{2n} \sum_{i=1}^{n} i^2$

Corrections needed, Δx, $= -\frac{v(n-1)}{2}\,T + \frac{\alpha T^2}{2}\left[(n-1)^2 - \frac{1}{n}\sum_{i=1}^{n} i^2\right]$

Substituting Typical Values of corrections needed (see Section F.4 for values of acceleration (a):

(1) From Touchdown to Stop or Quick Take-Off

$v = 250'/\text{sec};\ a = 10'/\text{sec}^2;\ T = 1/15\ \text{sec};\ n = 5.0$

True R: $x_n = x_o - 250(5-1)/15 + \frac{10}{2x15^2}\,[5-1]^2 = x_o - 66.6 + 0.36$ ft.

Av. R: $\bar{x} = x_o - 250(5-1)/2x15 + \frac{10}{2x15^2}\left(\frac{55}{5}\right) = x_o - 33.3 + 0.24$ ft.

Correction needed, $\Delta x = -250\,\frac{(5-1)}{2x15} + \frac{10}{2x15^2}\left[(5-1)^2 - \frac{55}{5}\right] = -33.3$

$+ 0.12$ ft.

(2) Standard-Rate Turn

$v = 1{,}000$ KTs $= 1{,}667'/\text{sec},\ a = 45'/\text{sec}^2,\ T = 1/15\ \text{sec},\ n = 5$

$x_n = x_o - 1{,}667\,[5-1]/15 + \frac{45}{2x15^2}\,(5-1)^2 = x_o - 444 + 1.6$ ft.

$\bar{x} = x_o - 1{,}667\,[5-1]/2x15 + \frac{45}{2x15^2}\,\frac{30}{5} = x_o - 222 + 0.6$ ft.

$\Delta x = -1{,}667\,[5-1]\,/2x15 + \frac{10}{2x15^2}\,(5-1)^2 - 6 = -222 + 1.0$ ft.

(3) On Missed-Approach

(a) $v = 150$ KTs $= 250'/\text{sec}$, alt. $= 100'$,
$a = 625'/\text{sec}^2$

$T = 1/15$ sec, $n = 5$

$$x_n = x_o - 250\ (5-1)/15 + \frac{625}{2\text{x}15^2}\ (5-1)^2 = x_o - 66.6 + 22.2 \text{ ft.}$$

$$\bar{x} = x_o - 250\ (5-1)/2\text{x}15 + \frac{625}{2\text{x}15^2}\ \frac{30}{5} = x_o - 33.3 + 8.4 \text{ ft.}$$

$$\Delta x = 250\ (5-1)/2\text{x}15 + 625(16-6) = 33.3 + 13.8 \text{ ft.}$$

(b) $v = 150$ KTs $= 250'/\text{sec}$; $h = 500'$; $a = 125'/\text{sec}^2/$; $T = 1/15$s; $n = 5$

$$x_n = x_o - 250\ (5-1)/15 + \frac{125}{2\text{x}15^2}\ (5-1)^2 = x_o - 66.6 + 4.4 \text{ ft.}$$

$$\bar{x} = x_o - 33.3 + 1.7 \text{ ft.}$$

$$\Delta x = 33.3 + 2.7 \text{ ft.}$$

The effect of acceleration is in the last number of the values for x_n, x, and (Δx). We see that it is negligible, except perhaps for a low missed-approach at 150 KTs and only 100' above the beacon. In this worst case, neglecting the effect of acceleration in the range correction would introduce an error of 13.8' in 100'. For all other cases, we can safely neglect the acceleration in correcting for the bias error introduced by "averaging". This is because a fresh measurement is made at each interrogation and the acceleration affects only the measurement between interrogations.

(4) Correcting the Lag due to Averaging

Neglecting the effect of acceleration, the needed correction, is

$$\Delta x = -\ v \left[\frac{n-1}{2}\right] T$$

Section 1.1.1.1.G.2.C shows how velocity (v) can be measured to $\sigma_v = \pm 10'/\text{sec}$ in 1.8 sec with q = 15 int./sec. Multiplying the value of v by $\frac{n-1}{2}$ T to obtain the correction $\Delta x = -v \frac{(n-1)}{2} T \pm \frac{(n-1)}{2} T \sigma_v$,

the corrected range is

$$\bar{x} + \Delta x = x_n = x_o - v \left[\frac{n-1}{2}\right] T + \frac{\sigma_x}{\sqrt{n}} - \frac{v(n-1)}{2} T \pm \frac{(n-1)}{2} T \sigma_v$$

$$x_n = x_o - v\,(n-1)\,T \pm \sqrt{\frac{\sigma_x^2}{n} + \sigma_v^2 \left(\frac{n-1}{2}\right)^2 T^2}$$

Substituting 20.5 ft. for σ_x, 10 ft/sec for σ_v, 1/15 sec for T, and 5 for n:

$$x_n = x_o - v \left| n-1 \right| T \pm 9.3 \text{ ft.}$$

x is then the distance at the last measurement. It is in error by ± 9.3'.

In order not to increase graininess it is desirable that the successive averages are interlaced, as indicated below, rather than sequential. Interlaced averaging results in an averaged value being available for every interrogation.

Interlaced Averaging refers to the continuous availability of the average of the last 5 measurements:

$\frac{1+2+3+4+5}{5}$ (corrected for 5th meas.)

$\frac{2+3+4+5+6}{5}$ (corrected for 6th meas.)

$\frac{3+4+5+6+7}{5}$ (corrected for 7th meas.) etc.

Sequential Averaging refers to the availability of the average value every knth measurement (where k is a successive integer):

$\frac{1+2+3+4+5}{5}$ (corrected for 5th meas.) (k = 1)

$$\frac{6 + 7 + 8 + 9 - 10}{5}$$ (corrected for 10th meas.) (k = 2)

The advantage of interlaced averaging in reducing graininess and providing smoothness is obvious.

1.1.1.2 Functional Requirements and Signal Format Studies

A. Functional Requirements

1. Background

a. General

As part of its Five Year Plan, Hazeltine initiated during TACD a comprehensive review and refinement of the Functional Requirements for MLS. Using as a starting point the original SC-117 requirement, Hazeltine, with the assistance of expert subcontractors, reviewed and updated descriptions of user needs, operational requirements and the various elements of functional requirements (services, coverage, accuracy, etc), to which the MLS is to be designed. This section presents the approach, the analyses performed and the results as they stood at the end of TACD.

Development and specification of the MLS functional requirements is a complex problem because they are derived from operational requirements of the many different types and classes of anticipated aviation users and because they depend to some degree on the constraints resulting from the characteristics of possible guidance techniques.

It was recognized at the outset and confirmed by experience that on many of the issues explored, there was neither a consensus among the aviation community nor agreement on all the "facts." Furthermore, the user communities are planning to invest considerable effort in exploring and defining the ways in which future operations will be affected by newly available MLS technology. Hazeltine, therefore, envisions a continuing need to interact with user requirements, and to revise system design goals and features accordingly, and we plan to resume this work during Phase II as part of the Prototype Planning effort.

b. Scope of Effort

The SC-117-generated functional requirements (Reference 1) provided the basis for the analysis and refinement during TACD. The procedure for developing functional requirements followed by SC-117 (and subsequently, Hazeltine) was in summary:

(1) Identification of aviation needs in the terminal area (i.e., increased airport capacity, all-weather landing, etc) for all classes of users, and grouping these needs for convenient classification.

(2) Identification of required flight operations, or operational requirements, to meet the identified needs (curved path approaches, selectable glide slopes, etc).

(3) Identification of functional requirements to provide these operations for a number of airport "configurations" lettered B, D, E, F, G, I, K.

Work by Hazeltine concentrated in the following area:

- Areas, such as specified accuracy over the coverage volume, which were incompletely specified in SC-117.
- Areas in which there was need for further verification of requirements, such as data rate and noise specifications.
- User applications, such as Navy Carrier Landings and remote battlefield systems for which the SC-117 system (letter) designations fit rather loosely.
- Areas, such as the application of elevation guidance data to altimetry, which have significant impact on important overall system trades.
- Areas which serve to bound the capabilities required of the selected MLS techniques and which must be explored by experiment and analysis during TACD.

c. General Approach

The method used to derive the detailed functional requirements (and to be used in future MLS program phases to further refine these requirements) is as follows.

(1) Identify, list and classify: user needs, operations to meet needs, and functional requirements to provide indicated operations.

(2) Determine quantitative relationships between needs, operations and requirements by use of existing documentation and analyses (e.g., SC-117) and by further technical analysis.

(3) Identify factors which limit or control particular requirements to permit rapid and significant assessment of any proposed changes, clarification or definition.

(4) Maintain updated statement of functional requirements to serve as the basis for system and subsystem design, in a form convenient for referral and further refinement.

The terms aviation needs, operational requirements, and functional requirements are used with the following meanings: Aviation needs are the general needs of airports, aircraft, and ATC. Operational requirements define the operational and safety procedures, and operational configurations required to meet those needs. Functional requirements are the technical, for the most part quantified, parameters associated with meeting the operational requirements.

These consisted of:

- functional services required of the system
- system accuracy requirements
- noise and data rate requirements, which are interrelated
- required coverage volumes
- coordinate system

- requirements relating to system integrity, such as allowable outage time
- auxiliary data requirements

d. Participation by Subcontractors

Hazeltine was assisted very materially in its preparation of revised requirements by frequent consultation and review by technical and operational experts on the staff of our subcontractors. Areas of concentration of each of the participating subcontractors are indicated in Table 9-1.

2. Methodology

The overall methodology for the Phase I requirements study is indicated in figure 9-1. As shown in the figure, the process was an iterative one based on reviews by subcontractors in their respective field of expertise. The tasks are described briefly below. Detailed descriptions and results of study efforts are given in the sections that follow.

a. User Needs and Operational Requirements

Matrices of airport and aircraft needs and requirements were prepared along with descriptions of typical flight operations to be expected. The matrices included flight operation supported (terminal maneuvers and approaches), required integrity levels, typical environments, interface requirements and other special requirements. They served as a checkpoint both to assure that functional services met requirements, and to insure compatibility among the various avionics and ground equipment types being considered in the baseline and prototype design efforts. This matrix was based on information obtained from:

- existing requirements summaries
- information from subcontractors
- discussions with government agencies

TABLE 9-1

PARTICIPANTS IN HAZELTINE REQUIREMENTS STUDY

Subcontractor	Area of Concentration
1. Grumman Aerospace Company	Review of operational and functional requirements from the viewpoint of military needs and operations.
2. Plessey Radar	Review of functional requirements from the viewpoint of non-U.S. users and operators. Review with respect to ongoing work by the U.K. on MLS requirements.
3. Sperry Flight Systems	Review of functional requirements from the viewpoint of a supplier of commercial and military for navigation and guidance avionics. Assessment of accuracy requirements with respect to compatibility with flight control systems, pilot acceptability and operational requirements.
4. United Air Lines	Review of operational and functional requirements from the viewpoint of commercial airline operators and pilots.

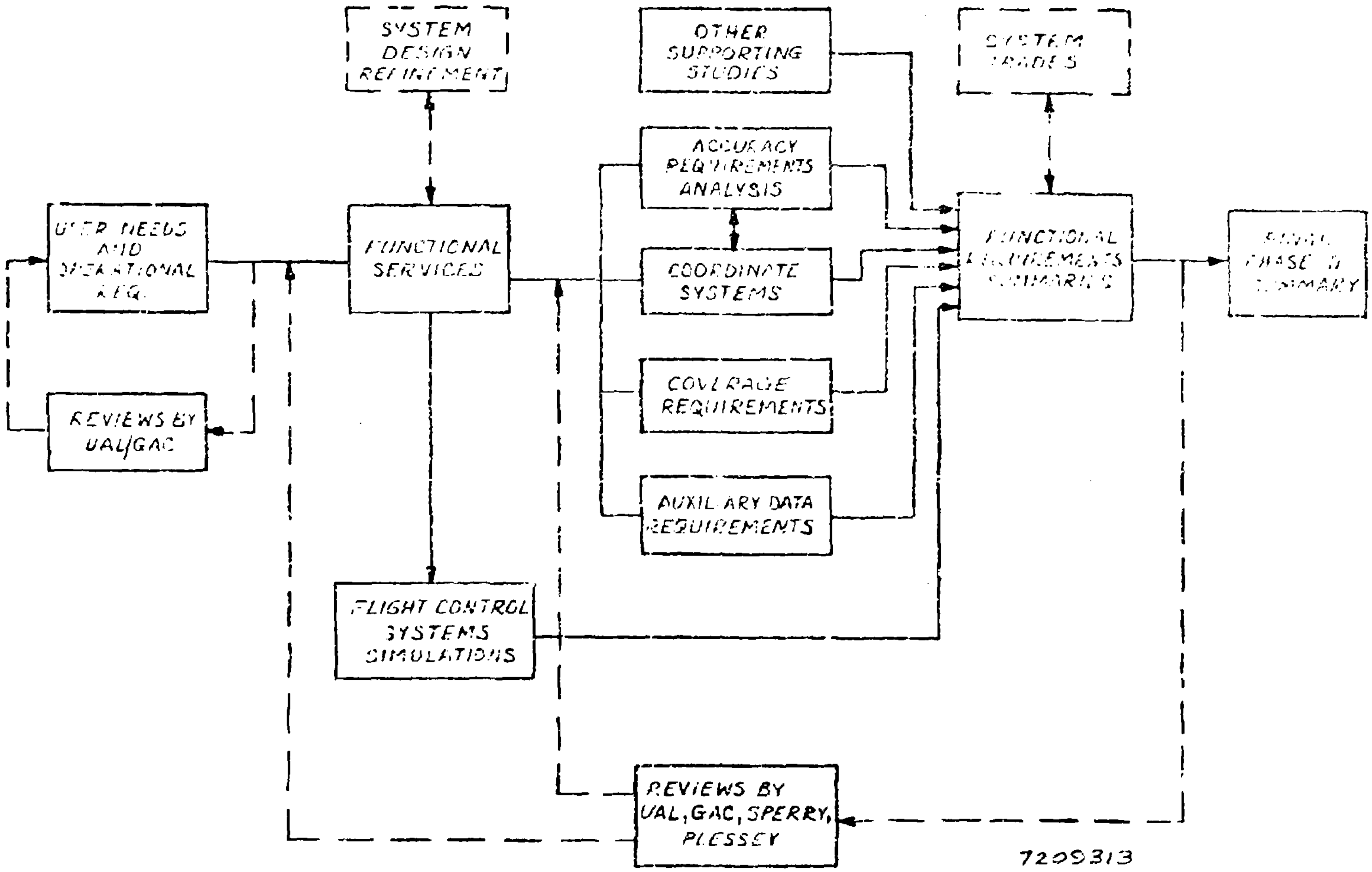


Figure 9-1. Functional Requirement Methodology

b. Functional Services Summary

Based on the operational requirements assumed, a summary description was prepared of the functional services to be expected of avionics systems of various levels of sophistication using MLS. This included:

- Path selection provisions
- Guidance output descriptions during the phases of approach, landing and rollout
- Identification, obstacle warning and malfunction warning provisions

The definition of functional services determined the levels of required sophistication for each user type for both ground and airborne equipments. They also assisted in defining the basic requirements for the study of quantitative requirements which followed.

c. Detailed Requirements Studies

Studies were performed of the detailed quantitative system and subsystem characteristics required to provide the respective functional services to all users. In each case, the SC-117 requirements (where existing) were reviewed for adequacy, and changes were recommended where there was an identifiable need for more stringent specifications or where it could be demonstrated that a function had been overspecified by SC-117 and a significant impact could be made on system cost effectiveness by relaxing the requirement. These latter decisions were influenced by the system tradeoff studies which are discussed in Section 1.1.2.

Studies of accuracy, data rate and granularity were based on:

- simulation of flight operations
- analysis of pilot reactions to simulated guidance systems using MLS
- paper analysis of the compatibility of flight operation with levels of accuracy
- comparison with existing systems (ILS) characteristics where applicable

Studies of coverage requirements were principally based on description of assumed flight operations which most severely taxed the system coverage capabilities. Special attention was paid to near runway coverage requirements that were not completely spelled out by SC-117.

The issue of alternative coordinate systems was treated as a critical technical area during TACD and is reported in detail in section 1.1.1.1, Part B. The study conducted did, however, utilize the existing descriptions of typical flight operations and took into account the overall system accuracy constraints that were determined from the requirements study.

Auxiliary data requirements were reviewed for completeness from the viewpoint of meeting all functional services. Re-allocation of data transmission requirements among the guidance elements was also performed.

Other studies which were conducted to complete the requirements survey and reported in the compatibility section were:

- a survey to validate the feasibility of retrofitting MLS into existing avionics systems, in order to assess required modifications (if any) and ways in which the MLS output characteristics might ease possible retrofit problems
- a survey of path selection and display features that should be incorporated in the avionics to suit the respective functional services requirements
- a preliminary definition of receiver processor output recommendations for compatibility with existing interface requirements.

3. Highlights of Study Results

The requirement study resulted in a number of major and minor additions and changes to the SC-117 specification. This subsection highlights those that are believed to be significant in terms of overall system concept and operational utility. A full description of the studies and results is given in the following subsections and complete summaries of operational and functional requirements are given in Section 1.1.4.

a. Functional Services and Operational Requirements

(1) Selectable glideslopes

A requirement was included to prevent the setting of a glideslope which is inappropriate (too low) for a given facility. This was based on consultant's advice that many commercial operators would discourage pilot selectable glideslopes because of possible human error.

After review of existing literature regarding safety aspects of category II landings at high glideslopes, it was recommended that the maximum permissible glideslope under Cat. II and III conditions should be limited to significantly less than the SC-117 figure of 15° (max).

(2) Coursewidth setting

After evaluation of several techniques for taking into account variable runway lengths in setting the angular sensitivity of the entire guidance system, it was recommended that azimuth coursewidth be automatically established in the receiver at each runway based on received auxiliary data.

b. Accuracy and Data Rate

(1) Angular Bias

A review of bias accuracy requirements in terms of allowable positional errors during various phases of approach and landing verified the adequacy of the SC-117 bias specification with few exceptions. For installations at very short runways, such as

STOL ports and military VTOL installations, the azimuth bias accuracy was relaxed. Also, as a result of landing simulations conducted by Sperry, it was concluded that adequate touchdown dispersions at K configurations would be achieved with slightly relaxed EL-2 bias. In addition angular accuracies were reviewed in terms of terminal area navigation requirements off-runway centerline. It was our conclusion that a relaxation of angular specifications in this region of coverage was tolerable on this basis.

(2) Angular Noise and Data Rate

Extensive investigation of coupled approaches and landings were conducted by analog simulation at Sperry Flight Systems. These studies explored the effects of sampling rate and noise on aircraft control systems behavior, pilot reactions and touchdown dispersions. In general, it was confirmed that coupled approaches and landings using MLS data and typical autopilots are feasible provided reasonable data quality requirements are met, and should be acceptable to pilots.

The study identified a technique of receiver output processing ("rate limiting") which tends to reduce significantly the affects of angular noise.

As a result of these investigations, data rate/noise tradeoffs were established and specific data rates and angular noise specifications were chosen for all systems. Generally, system data rates were increased; e.g., to 7 and 14 Hz for the K configuration and to 10 Hz for the D configuration. At the same time, noise specifications were slightly relaxed for all cases except (1) EL-2 noise, where susceptibility of the autopilot flare computations to noise required a tighter specification and (2) lower category facilities, where compatibility with flight control systems limited the extent to which noise could be allowed to differ from the K configuration.

(3) DME Accuracy

The SC-117 values for DME accuracy were validated by comparison to requirements for decision height computation, touchdown dispersion and other criteria. It was found that the specifications for the lowest grade (D) DME equipment should be upgraded from ±300 feet (1σ) as in SC-117 to ± 100 feet (1σ) in order to achieve acceptable decision height accuracy. For the R configuration, DME accuracy approximately the same as SC-117 was required, based on touchdown dispersions in the autoland mode. For T (shipboard) applications, a special problem was identified with respect to DME, caused by the peculiar geometry involved. Requirements here have been estimated as ±10 feet (1σ).

(4) EL-1 Altimetry

An evaluation of the applicability of elevation guidance for general altimetry purposes in the terminal area indicated that altimetry requirements at long ranges place an extreme burden on the accuracy required of the EL-1 guidance element. This was one input to the system trade study on methods of altimetry (Section 1.1.2); the conclusion of which was a recommendation that use of EL-1 be confined to the area immediately around the runway centerline (e.g., for final glideslope generation) and barometric altimetry be retained for general altimetry purposes.

c. Coverage

Major refinements in coverage requirements included the following:

(1) Reduction of azimuth coverage required of the EL guidance function by the retention of barometric altimetry data in the approach zone.

(2) Continuous coverage in the back course over the runway (with no "zone of silence") to provide takeoff guidance and, in the case of missed approach to permit back course AZ angle guidance validation before reliance on a new functional element.

(3) Provision of accurate proportional elevation guidance at D and F configurations so that glideslopes up to 7.5° can be supported.

(4) Refinement of EL-1 and EL-2 coverage requirements to adequately cover the volume of space over the runway and down to minimum guidance altitude.

(5) Definition of coverage requirements for special military applications, including variable azimuth and elevation coverage cutoffs for portable systems operating at unprepared sites.

(6) Formulation of a coverage requirement for Terminal Area Navigation encompassing 360° azimuth coverage for all guidance elements, to be included as a possible option for future system growth.

d. Coordinate System

As a result of an intensive study of alternative coordinate systems (Section 1.1.1.1, Part B) it was recommended that planar coordinates be retained (as in SC-117) for all applications and guidance elements except where contraindicated. The one remaining application for conical coordinates is in a portable VTOL system where selectable azimuth approaches appear to be required.

e. Auxiliary Data

In addition to the requirements identified by SC-117 and retained in the Hazeltine refinement, the following are now believed to be highly desirable.

(1) Time of day data to be used in future ATC metering and sequencing schemes.

(2) Local barometric settings to remove a major source of blunder error in present barometric altimetry.

(3) Minimum safe glideslope angle for added integrity in the glideslope select function.

(4) Runway length for coursewidth selection and rollout guidance.

Additionally for a carrier landing system in which the flight path computation is to be made on the aircraft, special requirements were identified for the transmission of pitch, roll, yaw, and heave corrections to permit translation of coordinate systems and ship's motion compensation during the final seconds of flight.

f. Organization of Section

The remainder of the section is organized around the main elements of the studies performed.

- User Needs and Operational Requirements
- Functional Service Description
- Signal Quality Investigations
- Coverage Requirements
- Auxiliary Data Requirements
- Coordinate Systems

4. User Needs and Operational Requirements

Review of user needs and operational requirements formed the first step in the requirements study during TACD. The needs and requirements descriptions were formulated based on a review of existing guidelines and other literature available (Reference 1 through 5). They were subsequently reviewed by experts at United Air Lines and Grumman, and amended accordingly. During the remainder of the program, additional information came to light as a result of discussions with government agencies (NASA on STOL, USAECOM on Army requirements) and other work in the requirements area; this information has been included in the recent version.

The discussion is divided into sections on (1) needs of airports, aircraft operators and air traffic control, and (2) the operational requirements envisioned to satisfy these needs.

a. User Needs

Three separate groups of "users" are identified as having sets of "needs" which presumably MLS, as a system itself and as an adjunct to other systems, is to fulfill. These are airports, aircraft and air traffic control. The codified needs presented here were used to guide the formulation of operational requirements and functional services descriptions which follow.

(1) Airport-Related Needs

Airport needs fall into the general areas of extending the efficiency, capacity, utilization of airport real estate, and insuring acceptability and adaptability with the environment. Relative importance of given needs over others is a function of airport type. Table 9-2, which is keyed to the following discussion, indicates our view of those requirements which may have higher priority for each of several possible airport applications.

Extended Airport Capacity - It is desired to maximize the number of flight operations per hour for a given size airport utilizing precision guidance provided by MLS, so that the remaining constraint is merely the aircraft runway occupancy time. This will be accomplished by

- automation and precision flying beyond that available with manual or present instrumentation, to reduce delays in arrival at runway threshold
- providing for aircraft speed-class sequencing patterns
- decreasing separation of runways to maximize utilization of airport real estate
- reducing runway occupancy time by employing high-speed turnoffs

TABLE 9-2. AIRPORT NEEDS

AIRPORT NEEDS	CIVIL AVIATION AIRPORTS					PRIVATE AVIATION AIRPORTS	MILITARY AIRPORTS					
	HIGH DENSITY (PRIMARY)	MEDIUM DENSITY (SECONDARY)	LOW DENSITY (FEEDER)	V/STOL	VTOL		MAIN OPERATING BASE	DISPERSED OPERATING BASE	FORWARD OPERATING BASE	COMBAT BASE	CARRIER	LHA
EXTEND AIRPORT CAPACITY	X	X		X			X				X	
EXTEND EFFICIENCY OF RUNWAY LENGTH				X			X	X	X			
DECREASE NOISE ENVIRONMENT	X	X	X	X	X		X					
DECREASE SUSCEPTIBILITY OF OPERATIONS TO WEATHER CONDITIONS	X	X	X	X	X	X	X	X	X	X	X	X
PROVIDE FLIGHT OPERATIONS IN HOSTILE AND UNPREPARED ENVIRONMENTS				X	X				X	X	X	X

Extended Efficiency of Runway Length - It is desired to minimize runway length required for takeoffs and landings, especially at military sites. This can be accomplished by reducing the threshold-to-touchdown for high performance aircraft with long flare paths, which in turn requires proper placement of guidance elements or special glide path computations.

Decreased Noise Environment Near Runways by Procedures - Both vertical and lateral maneuvers are indicated as measures to be considered. It has been noted by UAL that under severe weather conditions noise abatement requirements might concernably be relaxed in order to preserve flight safety when no visual cues are present.

Decreased Susceptibility to Weather Conditions - Primary in this area is the provision of Cat II (and III) MLS at runways where ILS has been unacceptable as a result of siting considerations. There is also a significant need for an inexpensive Cat I version of MLS for smaller airports.

Efficient Operations in Hostile and Unprepared Environments - These are needs relating to special situations.

- avoidance of "forbidden areas" populated by obstacles to flight and/or hostile forces (for military field installations).
- avoidance of the effects of interference from both passive (multipath) and active (EMI) sources
- operation with limited power sources (man-transportable systems)
- rapid installation and mobility (transportable systems)
- operation in confined quarters (shipboard installation)

(2) Aircraft-Related Needs

Aircraft needs relate to freedom of operations (subject to other constraints), adaptability to aircraft, type and preservation of integrity. The discussion is keyed to Table 9-3 which indicates our view of the higher-priority requirements for several aircraft types.

Reduction of the Effects of Weather on Mission Performance - Effects today consist of departure and arrival delays, rerouting of flights or cancellation of operations.

Improvement of the Economics of Operation - Flight operations under non-visual conditions and/or at high-density airports should have minimum constraints imposed on their ability to

- select optimum glidepaths for the individual aircraft and flight configuration
- execute efficient arrival and departure routes. This includes close-in intercepts to final approach especially for short-haul (STOL) aircraft where the percentage time lost in inefficient terminal maneuvers is the greatest.

Maximizing the Ability of Avionics - Aircraft with basic avionics should be able to obtain basic performance at even the most complex airport. Aircraft with sophisticated avionics should be able to obtain performance limited only by the complexity of the ground installations.

Ensuring Adaptability to Aircraft and Avionics - MLS avionics must be compatible with present avionics and aircraft capabilities and have sufficient performance characteristics to support improved capabilities envisioned for future aircrafts, including increased flight envelopes and new control systems and dynamics.

TABLE 9-3. AIRCRAFT NEEDS

	AIR CARRIER				MILITARY				
	PRESENT JET TRANSPORT	FUTURE AIRCRAFT	VTOL/ STOL	PRIVATE SMALL CTOL	HEAVY TRANSPORT	HI-PERF. A/C	STOL	VTOL	CARRIER A/C
REDUCE EFFECT OF WEATHER ON MISSION PERFORMANCE	X	X	X	X	X	X	X	X	X
IMPROVE ECONOMICS OF OPERATION	X	X	X		X	X			X
MAXIMIZE UTILITY OF AVIONICS	X	X	X	X	X	X	X	X	X
ADAPT TO FUTURE A/C DESIGN		X							
ADAPT TO PRESENT AVIONICS	X		X	X	X	X	X	X	X
FREEDOM TO EXECUTE MANEUVERS	X	X	X	X	X	X	X	X	X
PRESERVE INTEGRITY OF FLIGHT OPERATION	X	X	X	X	X	X	X	X	X

Insuring Freedom to Execute All (Otherwise-Safe) Maneuvers Required Within the Terminal Maneuver Area.

Preserving Integrity of Flight Operations - Use of MLS to extend capabilities into all weather conditions and to improve aspects of precision flying should not degrade the integrity of operations below that applicable to less stringent conditions. Specific needs are

- Provision of blunder-proof facility identification
- Simplicity of man machine interface requirements
- Compatibility with pilot operations, e.g., transition from instrument to visual flight
- Protection against system failures during critical maneuvers
- Provisions of warning and status-change indications upon equipment failure

(3) Air Traffic Control Needs

Needs of the ATC system fall into two categories: improving the efficient utilization of terminal airspace and, in so doing, preserving the integrity of ATC operations.

(a) Improving airspace efficiency. Basic MLS-related needs are:

- Flexibility of terminal routing, including speed-class segregation and departure control, should be unconstrained by MLS characteristics
- Aircraft and ATC displays and computational capabilities should be compatible so that improved three-dimensional routing to touchdown is practical
- MLS should support growth and evolution of ATC concepts, including future metering and spacing systems

(b) Preserving the integrity of operations. Key needs are:

- MLS operational status must be known at all times by controllers
- equipment downtime must be minimized, and unscheduled downtime at high-density facilities must be extremely remote
- remote control of equipment must be available for ATC to change runways or to cope with interference on a runway
- monitoring of aircraft path selection and progress is highly desirable and is essential in the carrier landing environment

b. Operational Requirements

The objective of the operational requirements analysis is to segment the users and their needs so that system configuration and performance requirements could be validated to show that MLS satisfies all needs. Categories of users (aircraft and airports) were chosen to point out differences in needs that might lead to different physical and functional design requirements. At the same time, duplication of essentially similar user classes was to be avoided.

A set of Operational Requirements matrices and associated descriptions were formulated which tie together aircraft, ground facilities and flight operations required to fulfill user needs. The resulting segmentation was not purposefully made to be in accordance with specific assignment of SC-117 configurations, but the full range of probable requirements is believed to be illustrated. Assignments to specific SC-117 configurations were made in connection with the Functional Services description which follows this section.

Significant results of the operational requirement analyses included:

- Identification, based on assumed missions between airports, of requirements for each aircraft avionics to be compatible with a number of airport configurations.
- Identification of probable level of equipment sophistication for a number of user types.
- Definition of issues concerning the utility of variable vertical and lateral approaches.
- Identification of the utility of multiple glide-slope capability at the lowest category airports.
- Definition of special operational requirements associated with military transportable and shipboard systems.

(1) Requirements Matrices

It was necessary to treat a four-dimensional relationship among users and requirements. The dimensions were:

- user aircraft
- airports
- aircraft requirements
- airport requirements (including, for convenience, ATC requirements)

The requirement therefore, evolved in the form of three matrices. The relationship between these matrices is illustrated schematically in figure 9-2. The individual matrices are depicted in Tables 9-4, 9-5 and 9-6.

The following discussion defines the airport, aircraft and requirement coordinates and gives the rationale for the matrix entries. Special requirements not covered in the matrices are also discussed.

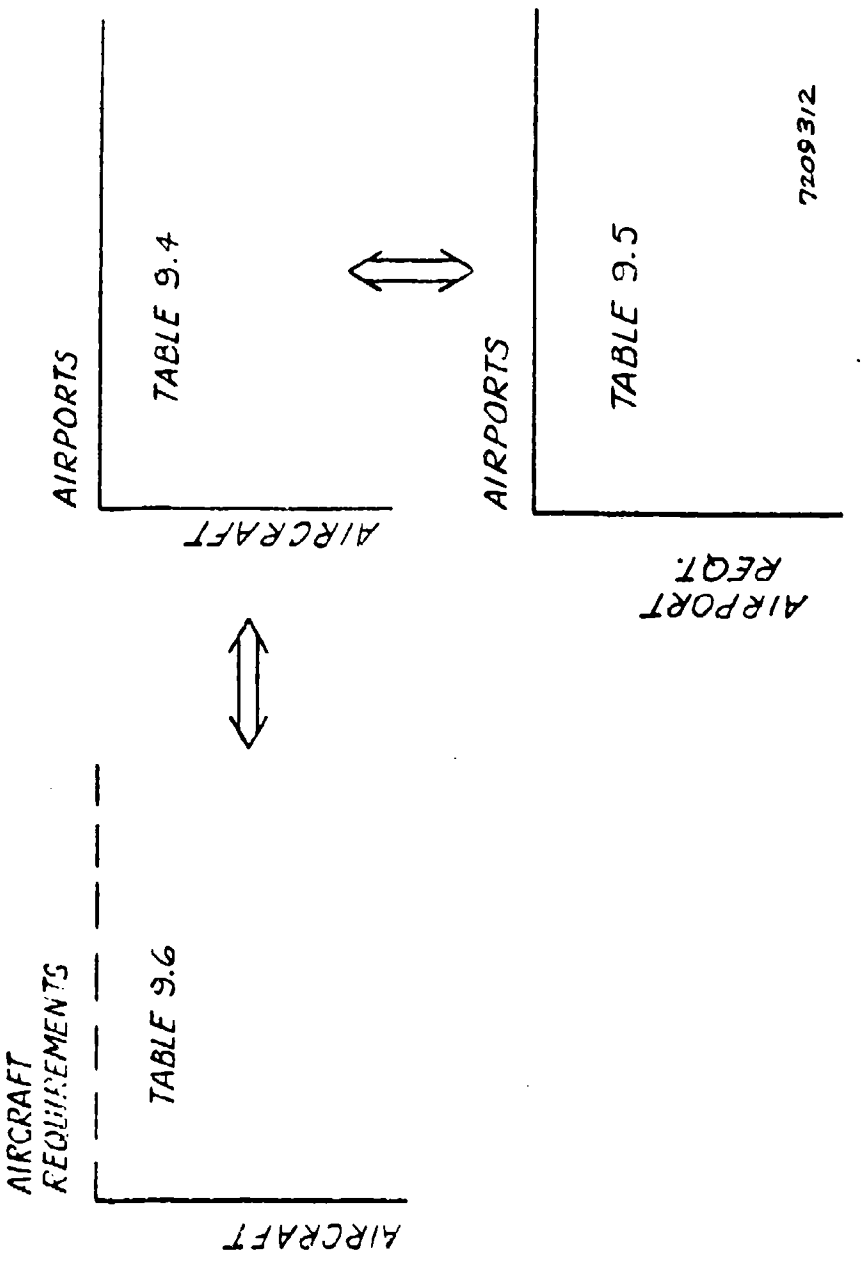


Figure 9-2. Relationship Among Tables of Operational Requirements

TABLE 9-4

AIRPORTS VS AIRCRAFT

Airports vs. Aircraft	Civil Aviation Airports						Military Airports					
Aircraft Type	High Density (Primary)	Medium Density (Secondary)	Low Density (Feeder)	V/STOL	VTOL	Private Aviation Airports	Main Operating Base	Dispersed Operating Base	Forward Operating Base	Combat Base	Carrier	LHA
Air Carrier												
SST	X	O					O					
Long Haul Jet	X	O					O					
Short Haul Jet	X	X	X				O					
Prop/Turbo Prop/Older Aircraft	X	X	X				O					
STOL	X	X	X	X								
VTOL	X	X	X	X	X							
Private												
JET	X	X	X			X						
CTOL	X	X	X	X		X						
VTOL	X	X	X	X	X	X						
Military												
Heavy Cargo Transport	O						X	X				
Light Cargo Transport	O	O	O				X	X	X		X	
High Performance CTOL	O	O					X	X	X			
STOL	O	O	O				X	X	X	X		
VTOL	O	O	O	O	O		X	X	X	X		
CTOL (SHIP)	O	O					X	X	X		X	
VTOL (SHIP)	O	O	O	O	O		X	X	X	X	X	X

NOTES: X = Routine Generation

O = Occasional Operation

TABLE 9-5
AIRPORT REQUIREMENTS

Airport Requirements	Civil Aviation Airports					Private Aviation Airports	Military Airports					
Airport Requirements	High Density (Primary)	Medium Density (Secondary)	Low Density (Feeder)	V/STOL	VTOL		Main Operating Base	Dispersed Operating Base	Forward Operating Base	Combat Base	Carrier	UHA
Runway Configuration	Parallel +Short +Pad	Single +Short	Single	Short	Pad	Single	Parallel + Short Pad	Single + Short	Single + Short	Short or Pad	Short	Pad
Aircraft Operations												
Single Approach	X	X	X	X	X	X	X	X	X	X	X	X
Multiple Vertical Approaches	X	O	X	X	X		X	X	X	X	O	X
Multiple Lateral Approaches	O	O	O	X	X		O	O	O	X	O	X
Curved/Complex Vertical Approaches	X	X		X	X		X	O			O	
Curved/Complex Lateral Approaches	X	O		X			X	O			O	X (?)
Autoland	X	X		X	X		X				X	
Rollout	X	O		X			X					
Missed Approach	X	O		X	X		X	O			X	
Guided Takeoff	X	O		X	X		X	O				
Acceptance Rate	120/hr. Desired	60/hr?	30-60/hr?	60/hr?	30-60/hr?		120/hr Desired	120/hr Desired	60/hr	60/hr	120/hr Desired	60/hr
Multipath Environment	Severe	Moderate	Moderate	Severe	Severe	Light	Severe	Moderate	Severe	Severe	Severe	Moderate
Weather Category (Max)	CAT III	CAT II/III	CAT I/II	CAT III	CAT II/III	CAT I	CAT III	CAT II	CAT II	CAT I/II	CAT III	CAT II
Rainfall Rate (mm/hr.)	50	50	15	25	25	15	50	50	15	15	50	50
Portability					O	O		X	X	X		
Remote Control	X	X	X	X	O		X	X	O		X	X
Remote Interface Req.	X	X	X	X	X		X	X			O	
Integrity Levels Failure Mode Flight Path Monitoring ESE Course Elimination ECM Capability	FAIL OP Desired Required	FAIL/SAFE Desired Required	FAIL/SAFE Desired Required	FAIL OP Desired Required	FAIL OP/SAFE Desired Required	FAIL SAFE Required	FAIL OP Desired Required Desirable	FAIL SAFE Desired Required Desirable	FAIL SAFE Desired Required Desirable	FAIL SAFE Required Desirable	FAIL OP Required Required Desirable	FAIL SAFE Required Required Desirable

NOTES: X = Routine or Required
O = Occasional or Optional

TABLE 9-6
AIRCRAFT REQUIREMENTS

Aircraft Type	Aircraft Operations									Weather Category Max	Airborne Integrity/ Reliability Level	ECM	EMI Environment
	Straight In	Multiple Vertical	Multiple Lateral	Curved/Complex Vertical	Curved/Complex Lateral	Autoland	Rollout	Missed Approach	Guided Takeoff				
Air Carrier													
SST	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP		Moderate
Long Haul Jet	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP		Moderate
Short Haul Jet	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP		Moderate
Prop/Turbo Prop/Older A/C	X	X	X	O	O				O	CAT I/II	FAIL SAFE		Moderate
STOL	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP		Severe
VTOL	X	X	X	X	X				X	CAT II	FAIL SAFE		Severe
Private													
JET	X	O	X					O	O	CAT II	FAIL SAFE		
CTOL	X		O							CAT I	FAIL SAFE		
VTOL	X	X	X						X	CAT I	FAIL SAFE		
Military													
Heavy Cargo Transport	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP	Desired	Severe
Light Cargo Transport	X	O/X	X	/X	O	/X	/X	X/X	X/X	CAT II/III	FAIL SAFE/OP	Desired	Severe
High-Performance CTOL	X	X	X					X	X	CAT II/III	FAIL SAFE	Desired	Severe
STOL	X	X	X	O	O			O	O	CAT II	FAIL SAFE	Desired	Severe
VTOL	X	X	X	O	O					CAT II	FAIL SAFE	Desired	Severe
CTOL (SHIP)	X		O	X	X	X		X		CAT III	FAIL OP	Desired	Severe
VTOL (SHIP)	X	X	O							CAT II	FAIL SAFE	Desired	Severe

NOTES: X = Routine Requirement

O = Option

(2) Airport Categories

Ideally, airports would be categorized according to the parameter that would largely determine the ground configuration to be used. Possible parameters are runway configuration, aircraft users, traffic density, and traffic patterns. It would be preferable to use airport classifications accepted by the users, but existing classifications are overlapping and not sufficiently defined to be used directly. Therefore, existing classifications were modified and elaborated as necessary to cover the scope of requirements. Referring to Table 9-5, possible runway configurations are given for each airport.

User groups (civil, private, military) were kept separate under the presumption that each user should see a set of requirements uniquely describing his situation.

Civil aviation airport categories were not defined in SC-117. Instead, only the possible ranges of parameters were identified. In the operational requirements analysis, the civil categories were adopted from a brief outline of the new National Airport System Plan (NASP) classifications found in Reference 6. This new classification is expected to offer "greater opportunity for systems analysis techniques in long range airport planning." Classifications will be based on "public service level" and level of aircraft operations. The categories in our summary are a simplification of the projected classification system in which general density levels and runway configurations are assumed to be correlated. V/STOL and VTOL classifications were added to indicate the near metropolitan, special purpose applications which are not explicitly identified in the NASP scheme so far. It will be useful to monitor the development of the NASP by FAA as a policy tool for developing each class of airports to specific capability levels.

"Private airports" represent that class requiring the simplest landing guidance function. More sophisticated private airports are presumed to be included in one or more civil aviation categories.

Military airport classifications were condensed from several over-lapping category descriptions presented in the MLS RFP Appendix (General Requirements) for USA, USMC, and USN, and in the NIAG requirements document (Reference 5). A listing of USAF airport types was also given in preliminary notes on Airport Environment by SC-117 without description.

"Main Operating Base" denotes a strategic, permanent or semi-permanent equivalent of a high density international civil airport. "Dispersed Operating Base" denotes a tactical deployable facility suitable for all aircraft but the largest transports. "Forward Operating Base" differs from the former category in the high degree of portability and rapid installation required, under forward area conditions, and includes the "Split-Site" category of USA, "Forward Area Airbases" of USMC, and "Forward Battle Landing Site" in the NIAG report. "Combat Base" denotes highly portable V/STOL facilities and includes the "Co-located" category of USA and the "Remote Area" category of USMC. The LHA designation does not appear in USN requirements as presently stated, but is presumed to be a requirement category which would include VTOL carriers (LHA's) and special pads on other vessels. With respect to the LHA designation, this requirement has not been explicitly stated in the MLS plan, but is considered a real one by Grumman consultants. While a version of the USMC "Remote Area" system may be adequate for this application, Hazeltine plans to review this requirement during Phase II after discussions with the Navy.

(3) Aircraft Categories

The aircraft were categorized in a way which would ultimately point up differences in avionics requirements.

- Users will most likely determine the level of sophistication of avionics based on capabilities of aircraft, importance of missions, availability of alternative routings, available space on board and crew size.
- Avionics requirements will also be determined by the frequency with which landings at high density terminals are made.

(4) Airports vs Aircraft

Table 9-4 indicates Hazeltine estimates of the regular and occasional use of airport facilities for each type of aircraft. This compatibility matrix is a key reason for the requirement of universality in the MLS concept. Hazeltine made use of this matrix in selecting the operating frequencies for various MLS ground configurations and avionics. Of particular note is the occasional cross-utilization of civil airfields by military aircraft (and to a lesser extent, the converse) which is a principal reason for the design of common civil/military signal formats.

(5) Airport Requirements

This section highlights some of the aspects of airport operational requirements indicated in Table 9-5.

(a) The capability for supporting multiple vertical approaches (glideslopes) is recommended at virtually all facilities for several reasons.

- Accommodation of aircraft with different preset glideslopes based on individual optimum flight configurations.

- Accommodation of jumbo jets (especially short haul jumbos which can use smaller airports) where wheel clearance at threshold is a special problem because of nose-to-rear-wheel geometry.
- Accommodation of higher glideslopes for noise abatement, which may be a requirement in the future even at low density airports.

(b) With reference to multiple vertical approaches, recent STOL experiments (Reference 7) indicate a maximum practical glideslope of 6° or $7\text{-}1/2^{\circ}$, well below the maximum glideslope of 15° in the SC-117 O.R. Even with some increase due to future technology, there remains some doubt that guidance at large airport runways needs to support glideslopes up to 15°.

(c) With the exception of VTOL operations at co-located facilities, it appears unlikely that off centerline azimuth approaches are likely to be used, principally because this involves flying towards the stop end of the runway, and requires a two-step maneuver to converge on final approach.

(d) Curved and complex vertical approaches will include:

- two-step vertical maneuvers for noise abatement.
- offset - GPIP glidepaths especially at military fields to shorten the runway length required for high performance aircraft. The objective is to match the

glidepaths flown under visual conditions in which the initial aiming point is considerably downwind from the elevation datum.

- turning and spiraling descents, especially at STOL ports, to minimize air space volume used. The objective is to avoid traffic to and from other airports and to avoid obstacles to flight in urban areas.

(e) Curved and complex lateral approaches will include:

- Routing for metering and spacing (M&S) systems, probably linear segments using RNAV procedures. However, as pointed out in the coverage requirements section below, only the final leg of the M&S route is likely to be in the MLS coverage areas.
- Curved and segmented paths for noise abatement. The SC-117 operational requirements showed "worst case" 1/2 mile radius turn converging on the runway centerline practically at threshold. However, it was the general view of Hazeltine's expert consultants that during Category II/III weather, pilots will require convergence and settling on a final centerline approach at least one minute before "decision height." This provides a stable "platform" from which to assess aircraft and control guidance system behavior prior to the decision to land. This view is supported in the literature (Reference 8).

- Special gradually curved paths for convergence on parallel runway approaches with minimum danger of overshoot.

(f) Missed approach and departure guidance was recommended for inclusion as an option at medium density airports to make maximum use of sophisticated MLS and RNAV equipments which will be carried by many user aircraft.

(g) Multipath environments were considered to be "severe" at high density airports because of the amount of air and ground traffic typically present. Also labeled "severe" were V/STOL and VTOL ports in metropolitan areas, tactical bases operating in unprepared terrain and carrier systems where deck reflections are significant.

(h) All Cat. III systems are labeled as fail-operational, meaning that the system will remain operational after any component or subsystem failure which is not remote. This is required to meet FAA requirements for probability of hazardous failure of signal during final approach and landing. All other systems are labeled fail-safe, meaning that any subsystem or component failure will result in an invalid state which cannot be confused with valid data.

(6) Aircraft Requirements

This section highlights some of the aspects of aircraft operational requirements indicated in Table 9-6.

(a) Requirement levels were based on long range operational requirements and not necessarily on first buys of equipment. For instance, UAL indicated that airlines are likely to fully equip their fleets with Cat. II avionics before a large conversion to Cat. III capability is initiated.

(b) With reference to variable glideslopes under Cat. II weather, STOL experiments at NAFEC (Reference 7) tend to support the view that breakout at 100 feet on a 6° or 7.5° glide-slope leaves insufficient time (as low as 6 seconds) for adjustment to visual conditions and runway alignment. Therefore, higher glideslopes may be restricted to Cat. I conditions.

(c) With respect to the category of equipment in high performance military CTOL aircraft, a potential problem was determined relative to the available space for the dual receiver installation that has been determined to be necessary in civil aircraft for Cat. III fail-operational integrity. Resolution of this issue will await further information on form factors of production avionics and the integrity philosophy relevant to Air Force operation.

(7) Special Military Requirements

This section indicates significant additional operational requirements peculiar to military situations.

(a) Remote VTOL/STOL facilities.

- adaptability to severe terrain blockage (by adjustment of coverage).
- adaptability to either landing ships or VTOL pad operation by co-located or split-site operation.
- capability for special power conservation (service demand mode) measures.
- ability to support landings on several azimuth courses simultaneously, without requiring special avionics equipment.

(b) Carrier Landing Facilities

A tentative design outline for a shipboard system accommodating the following requirements is presented in the prototype plan (Section 1.2.2.1).

- stabilization of the signal-in-space on a moving frame of reference
- provisions for flight path monitoring on ship and on board the aircraft. (Present SPN-41/42 system combination provides these capabilities and these are believed to be essential for all weather carrier landing operation.)

5. Functional Services

From the descriptions of user needs and operational requirements Hazeltine formated a comprehensive statement of functional services to be supplied to each user type from each of the ground configurations. This section gives the final description generated at the end of TACD and includes numerous comments by expert consultants and other explanatory material.

The functional services described are tabulated in Table 9-7 along with applicable users and ground facilities. The services are for the most part provided to the user in conjunction with other required equipment. Table 9-8 summarizes the assumed equipment complement for each user. Based on the user services descriptions, the required functional elements for each ground facility are indicated in Table 9-9.

a. Lateral Approach Guidance

(1) Basic Localizer Service

In this mode the receiver/processor provides outputs essentially equivalent to ILS. The output will be proportional to deviations from runway centerline, providing a proportional coursewidth equivalent to a 700-foot wide course at runway threshold. Outside this region, fly-right/fly-left logic outputs are provided. In ILS, the coursewidth is adjusted in the localizer ground equipment to compensate for runways of different length. The choice of implementation for this adjustment in MLS raises issues of compatibility, as discussed in Section 1.1.3.3. The method chosen was to provide automation coursewidth correction or course softening in the receiver. All receivers will be capable of decoding a coursewidth factor encoded in auxiliary data in order to do this.

(2) Wide-Angle Localizer Course

This is a pilot-selectable mode which takes advantage of the wide-angle output capability of proportional receivers when they are not

TABLE 9-7
FUNCTIONAL SERVICES SUMMARY

	USERS													AIRPORTS				
	CIVIL					MILITARY												
						USAF	USAF/ USA	USMC/ USA VTOL	USN						USAF	USA USAF	USMC USA VTOL	USN
Service	I/E	F/G	E	D	B	I	E	E/G	I	E	F/G	E	D	B	I	E	E	I
1. Lateral Approach Guidance																		
a. Basic Localizer Service	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
b. Wide Angle Localizer Service	X	X	X			X	X	X	X	X	X	X	X		X	X	X	X
c. Selectable Lateral Approaches	X	X	O			X	O	O	O	X	X	X	X		X	O	X	O
d. Area Navigation Approaches	X	X				X			(2)	X	X	X	X		X	X		O
2. Vertical Approach Guidance																		
a. Single Glide Slope	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X
b. Selectable Glide Slope	X	X	X	(1)		X	X	X	X	X	X	X	X		X	X	X	X
c. Offset and Two-Step Vertical Guidance	X	X	O			X	X			X	X	X	X		X	X		
d. Complex Vertical Flight Paths	X	X				O			(2)	X	X				O			
3. Longitudinal Guidance																		
a. Basic "Marker" Service				X	X					X	X	X	X	X	X	X	X	
b. Basic Continuous Service	X	X	X	O	O	X	X	X	X	X	X	X	X	O	X	X	X	X
c. Metering Service	X	X				X			O	X	X	O	O		X	O	O	O
4. Landing Guidance																		
a. Category I Guidance	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
b. Category II Guidance	X	X				X		/X		X	X				X		/X	
c. Category III (Flare) Guidance	X					X			(3)	X					X			(3)
d. Decrab	O					O				X					X			
5. Runway Guidance																		
a. Rollout	X					X				X					X			
b. Turnoff	X					X				X					X			

TABLE 9-7 (Continued)
FUNCTIONAL SERVICES SUMMARY

Service	USERS: CIVIL K	F/G	E	D	B	MILITARY: USAF I	USAF USA E	USMC/ USA VTOL E/G	USN I	AIRPORTS: K	F/G	E	D	B	USAF I	USA USAF E	USMC USA VTOL E	USN I
6. Takeoff/Missed Approach Guidance																		
a. Lateral Guidance	X	X	0	0		X			0	X	X				X			0
b. Vertical Guidance	(5)	(5)				(5)				(5)	(5)				(5)			
c. Longitudinal Guidance	X	X	0	0		X		0	0	X	X	0	0		X	0	X	0
7. Identification																		
a. Aural	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
b. Automatic	X	X	0	0		X	X	0	0	X	X	X	X	X	X	X	X	X
8. Obstacle Warning																		
a. Minimum Glide Slope Indication	X	X	X	X		X	X	X	X	(4)	(4)	(4)	(4)		(4)	X	X	X
9. Malfunction Indications																		
a. Basic Alarm			X	X	X		X	X		X	X	X	X	X	X	X	X	X
b. Malfunction Discrimination	X	X				X			X	X	X	X	X	X	X	X	X	X
10. Airport Condition Data	X	X				X		/X	X	X	X	0	0		X	0	/X	X
11. Services to ATC										X	X	X	X		X	X		X
12. Flight Path Monitoring									X									X

(1) Over narrow range.

(2) Straight flight path must be computed for Cat III landing

(3) Guidance to TD but no flare.

(4) Where required by terrain and siting.

(5) Growth option.

TABLE 9-8
AIRBORNE EQUIPMENT

	CIVIL				MILITARY			
	I/K	F/G	E	D	USAF I	USAF/ USA E	VTDL E/G	USN I
Category	III	II	I	I	III	I	I/II	III
Narrow Angle Decode				X				
Proportional Angle Decode	X	X	X		X	X	X	X
Ident Decode	X	X	X	X	X	X	X	X
Aux Data Decode	Full	Full	Part	Part	Full	Part	Part	Part
DME Range	X	X	X	0	X	X	0	X
Height Comp	X	X	X	0	X	X	0	X
Auto Pilot	X	X	X	0	X	X	0	X
Flare	X				X			
Selectable-Course Module		0	0					
RNAV/Curved Path Computer	RNAV	RNAV			LORAN	LORAN(?)		SPECIAL(?)

TABLE 9-9
REQUIRED FUNCTIONAL ELEMENTS FOR GROUND FACILITIES

	CIVIL					MILITARY			
	I/K	F/G	E	D	B	USAF I	USA USAF E2	USMC USA VTOL E2/G	USN I
Proportional AZ	X	X	X	X	X	X	X	X	X
Proportional EL1	X	X	X	X		X	X	X	X
Proportional EL2	X					X			(1)
DME	X	X	X	X	X	X	X	X	X
Back Course AZ	X	X				X			0
Back Course DME	X	X				X		0	0
Aux. Data	X	X	X	X	X	X	X	X	X
Flight Path Monitor									X
ATC Interface	X	X	X	X	X	X	X	0	X

(1) Guidance to touchdown required.

being used in more sophisticated ways (as below). When this mode is selected, a wide (±10°) azimuth course, centered in the runway centerline, is generated for display on course deviation instruments. When the AZ angle is reduced below a preset amount (say 2.5°) the receiver reverts to the normal coursewidth (as above).

- This wide-course option is envisioned as aiding normal convergence to the centerline course, especially at high azimuth intercept angles relatively close to threshold, and would tend to minimize overshoots. The autopilot would be coupled after the normal narrow-coursewidth mode is obtained.
- There was not a concensus on the desirability of a wide coursewidth for convergence on centerline. Further investigation is required to confirm possible advantages.

(3) Selectable Lateral Approaches

In this mode, a small number of highly standardized lateral approaches would be made available via a special "offset path" computer. Examples of programmed courses would be two-step lateral maneuvers (for parallel runway operation) and standardized wide-angle intercepts of the centerline approach. A possible set is Right (1), Right (2), Centerline, Left (1), Left (2). Nominally the "offset path computer" operates on MLS-only data.

- The advantages of a separate, MLS-only offset path computer seem to be dependent on it being much less expensive than an RNAV system. However, the consensus of our consultants is that (1) approaches which are both completely standardized and widely applicable may be impractical to implement, (2) RNAV Systems, utilizing multisensor data, will show superior performance in executing these maneuvers, and (3) most users who will have proportional receivers will probably have RNAV capability also. If so, then these maneuvers would become part of item d below. We intend to investigate the issue of offset-path computers further during Phase II.

- Flying radials to the azimuth guidance elements is practical and desirable for VTOL applications where guidance elements are co-located.

(4) Area Navigation Approaches

In this mode, range/bearing measurements from a proportional MLS receiver are used in conjunction with an area navigation (RNAV) computer to generate complex flight paths in the terminal area. A repertoire of approaches is stored in the area nav computer or imputed via magnetic "approach cards", magnetic tape or paper tape. Within the RNAV system guidance transitions automatically from VORTAC to MLS at the MLS coverage limits. Automatic MLS channel selection may be incorporated as an RNAV function. All maneuvers terminate in a runway centerline approach segment. Area nav is principally an autopilot mode, with flight director backup, and CDI or other displays to monitor the error from the desired flight path.

- RNAV display design has been identified by UAL and Sperry as a critical item in ensuring compatibility with the ATC function and in monitoring progress along curved and complex flight paths.
- Since most users of proportional guidance will be equipped with RNAV, compatibility with RNAV is a key functional requirement for proportional MLS service.

b. Vertical Approach Guidance

(1) Single Glideslope

In this mode the receiver provides outputs essentially equivalent to ILS. The output will be proportional to the deviation from glideslope. A "nominal" glideslope and coursewidth, optimized for the aircraft, will be wired in the receiver. The receiver will decode a word from the MLS auxiliary data corresponding to the minimum safe glideslope for the facility. If this is higher than the "preset" glideslope by a small amount, the receiver will automatically bias the receiver glideslope to the higher one. If the minimum safe glideslope should exceed the capability of the receiver, the deviation outputs will be suppressed and the indicator flags will not drop.

- This mode relates to receivers which nominally are "fixed" glideslope units, such as the "D" receiver. The glideslope bias feature was added to resolve a compatibility issue relative to those airports where, because of surrounding terrain or special siteing situations, the minimum standard glideslope (2.5 -3°) cannot safely be used. The feature permits the nominal receivable glideslope to be reasonably optimized for aircraft performance and yet allows these aircraft to use a maximum number of facilities.

(2) Selectable Glideslope

In this mode the operator selects, via the MLS mode select panel, one of a number of available discrete glideslopes. (For a CTOL aircraft, these might be 2° to 6° in 1/4° increments; for a STOL, these might be 3° to 9° in 1° increments). The selected angle must be displayed prominently to the operator during descent. Glideslope courswidth is automatically adjusted to be proportional to the glideslope angle chosen.

- Variable coursewidth is required to prevent the glideslope deviation output from being overly sensitive to aircraft activity during descent on a high glideslope. It is also useful to facilitate pushover onto high glideslops without overshoots (Ref. M.7).
- It was strongly recommended by Sperry that within the MLS controller, design provisions be made for stops which can be adjusted (at an aircraft shop level) to limit the angles which can be selected as a function of aircraft or airline operational procedures. In addition, UAL pilots showed considerable reluctance to accept the pilot selectable glideslope feature as a useful one, because of the possibility of human error. Therefore, two variants are to be considered: (1) RNAV selects the final glideslope as the last leg of vertical navigation as in d. below or (2) the receiver compares the glideslope selected with the minimum safe glideslope for the facility, which is encoded in the MLS auxiliary data; if the selected glideslope is lower, the pilot is notified via the mode select panel and the receiver outputs are suppressed.

(3) Offset and Two-Step Vertical Guidance

In this mode, the glidepath intercept point is artificially displaced downwind from the elevation guidance datum. An "offset path computer" is nominally used to generate this glide path, although RNAV may be used if available. Offset guidance is designated by glide angle and aiming point displacement. Two-step guidance is a combination of (1) an initial, step, displaced glidepath, intersecting (2) a shallower final glidepath aimed at the elevation datum, and is designated by initial slope, final slope and intercept height, In this mode, glideslope course width is automatically and gradually adjusted within the computer during the transition.

- The two-stop glideslope maneuver is a candidate for noise-abatement procedures which may ultimately be required for jet aircraft at most civil airports. Offset glidepaths are also desirable to shorten the runway length for high-performance aircraft landings at military installations.
- Sperry commented that, in general, the transition from initial to final glidepath is essentially an intercept from above, and is not a simple function. Errors can cause undershoots, which are to be avoided, especially at low transition altitudes, in which noise abatement is made most effective. Generation of transition cues, and programming the aircraft through the transition, are complex functions, involving aircraft type and configuration as well as approach angle, and the required interface with other sensors could be quite extensive. Therefore this function may be best incorporated as an RNAV function, as in recent two-step experiments. (Ref 9).
- Two-step vertical maneuvers may be required for noise-abatement procedures even at D configuration airports. "Noise" on an offset-glidepath guidance signal is found to be a combination of noise on the EL and DME channels.

This noise will be of higher amplitude at the D configuration than at, say, a K configuration. The complementary filtering of radio signal and onboard sensor inputs which is available in RNAV makes RNAV a very desirable method of generating two-step glidepaths.

(4) Complex Vertical Flight Paths

In this mode, MLS supplies vertical information for Vertical Navigation (VNAV) operation in an area navigation computer. This is an extension of "area navigation" lateral guidance mentioned above.

- As pointed out in the following discussion of accuracy, practically, achievable elevation guidance accuracy is probably not sufficient for VNAV throughout the MLS coverage range. The VNAV system will utilize MLS elevation only over a limited coverage volume as determined by DME and azimuth data. Outside this region barometric (or equivalent) altimetry will be utilized. To improve the integrity of the baro altimetry, the runway baro setting correction will be included on MLS data.

c. Longitudinal Guidance

DME is assumed available throughout the angle guidance coverage. Indicators driven may include ground speed, distance to go, area navigation computer, altitude and descent rate.

(1) Basic "Marker" Service

This service provides basic "marker beacon" type indications at one or more preset heights; for example, H = 1500 feet (Outer Marker) and H = 200 feet (Middle Marker).

- Consideration should be given to "D" users who may not wish to purchase DME. For these users, present marker beacons could be retained.

However, only one glideslope will give exactly the right height indications. For these receivers it may be necessary to fix the receiver glideslope at the high end of the range of present ILS glideslopes.

(2) Basic Continuous Service

Once on the centerline approach, MLS will provide ground speed, distance to threshold and altitude above runway.

(3) Metering Service

This service is available via the RNAV system, to provide precise time-of-arrival control. Depending on the speed-control concept utilized, outputs would be along-track error (in seconds, early/late), predicted time to threshold or special graphic display.

- Assuming, in a future system, that speed control is assumed by the aircraft, with ATC surveillance as a backup, then it is necessary to initialize the airborne system in real-time. For this purpose, the MLS auxiliary data will provide precise airport time to synchronize the airborne clock. The desired time-of-arrival at threshold would be provided via an ATC voice or data link.
- Longitudinal guidance via speed control is only one possible metering and spacing concept. Another concept is utilization of path stretching maneuvers to correct for time-of-arrival. This is a "lateral guidance" function generated either by ATC vectoring or in the onboard computer. MLS would then be utilized for lateral guidance as covered above.

d. Landing Guidance

(1) Category I Guidance

Precision Guidance signals are provided to at least 150 ft. above the runway level on the glidepath. A decision height indication is provided at 200 feet above runway level.

- As an option, a "fly-up" indication may be given if the aircraft deviation from the nominal flight path exceeds a preset "window".
- Precision guidance is provided to 50 feet below the decision height, as in ILS, as a safety margin to amount for pilot's reaction time after the decision height is past.

(2) Category II Guidance

Precision guidance signals are provided to at least 50 ft. above the runway level on the glidepath. A decision height indication is provided at 100 feet above runway level.

- Same comments apply as above

(3) Category III (Flare) Guidance

During the flare, MLS provides computed height information to the flare computer, which is normally incorporated in the autopilot. The transition from glidepath guidance to flare guidance is performed in the autopilot. The system must be in fail-operational status to proceed to flare initiation. In addition to other monitoring features, to assure system integrity, a pre-flare verification period of approximately one minute is provided for. During this period, the height is computed both from glidepath (EL-1) and flare (EL-2) guidance angle outputs and DME. The two height readings must agree within a preset tolerance in order for positive verification to be given to the pilot.

- It should be noted that the use of a radio altimeter flare is not considered part of the MLS system. However, category II and III

MLS systems will still be supplying AZ and EL-1 guidance to aircraft equipped with radio altimetry autoland systems, and should have sufficient guidance signal quality to do so.

(4) Decrab

The decrab function is assumed to be incorporated in the autopilot system, if required. The MLS auxiliary data will provide runway heading and crosswind data as necessary.

e. Runway Guidance

Runway length and exit positions will be provided on the MLS data link.

(1) Rollout

During rollout, localizer information is available on instruments or for automatic steering. Runway remaining (to the nearest 100 feet) is displayed, along with speed (to the nearest 10 mph) for controlled deceleration. Course softening may be required in azimuth to prevent over-sensitive lateral deviation indications as the stop end is approached.

(2) Turnoff

For service up to Cat III b conditions, an exit cue will be provided 3 to 5 seconds in advance of arrival at an exit.

For service up to Cat III C conditions, the existence of an independent support Surface Navigation System is assumed. This system would be acquired after touchdown, and verified by comparison to MLS while the aircraft is on the runway. The high-speed turnoff maneuver would then be executed under the control of the surface system. If the surface system is not validated, then the aircraft would proceed to the next exit, at which a low-speed turnoff would be executed.

- Little information was available on the required characteristics of a runway/taxiway guidance system for a zero visibility system.

The above description was envolved after discussions with United Air Lines. This area will be investigated further during Phase II; as of this writing, Hazeltine has recently started an analysis of an Airport Ground Traffic Control system for the DOT.

- The Cat III C concept was formulated under the assumption that MLS has the primary responsibility for guidance only while the aircraft remains on the runway. Alternatively MLS may assume primary responsibility out to some distance from the runway; say 500 feet. In the case of off-runway guidance, a new dimension of multipath and blocking effects is encountered. Site control will affect aircraft on runways and taxiways, buildings, other objects, and turnoff location and design. Also, guidance antenna requirements will be more severe. It appears unnecessary to so burden the system at this time. We also note that alternative surface guidance systems concepts utilizing direct microwave transmission tend to favor high vantage points for guidance transmitters in order to overcome these problems.

f. Takeoff/Missed-Approach Guidance

Departure and miss-approach guidance requires the extra cost of antenna diversity and is therefore considered optional for lower-grade users.

(1) Lateral Guidance

Guidance is provided around runway centerline to at least 10 nmi from the stop end. To avoid lapses in azimuth guidance on the order of 12 seconds during the flyover, the back course guidance element is to be located at the threshold end of the runway.

- Consultants at UAL indicated that a 12-second zone of silence might be tolerable during infrequent missed approaches, but would not be acceptable by airlines for use in takeoff procedures on a regular basis. Also, it was recommended that back-course guidance, to be useful to pilots during the departure procedure, should extend at least 10 nmi past stop end.
- Section IV of Appendix A discusses several problems associated with the transition from landing guidance to missed-approach guidance and the autopilot mechanization required to overcome them.
- The inclusion of this service (and DME as well) at all category II facilities were definitely recommended by UAL. This would increase the utility of those airborne systems which are equipped for this service for use at category III facilities.

(2) Vertical Guidance

This is recommended as a growth option.

- Sperry has indicated that attempting to fly to a vertical guidance beam during takeoff missed-approach can result in stalls. It was recommended that vertical course guidance should not be provided unless and until it can be utilized in conjunction with a sophisticated speed command system associated with energy management of the total aircraft. Without a guidance role for this service it was felt there was insufficient justification for the expense of the guidance generation equipment and its occupation of function time in the signal format.

(3) Longitudinal Guidance

Distance to stop end will be provided (in hundreds of feet) until stop end is overflown. Then distance from stop end will be provided (in miles).

g. Identification

(1) Aural Identification

In this identification a morse code identification signal is heard in earphones. Only airport identification is provided. For parallel runway airports, channel assignments (there are 200 MLS channels planned) should be made sufficiently different numerically so that selection of the wrong runway at the right airport will be very improbable.

Voice identification was preferred by some pilots interviewed but MLS signal structure requirements preclude this.

(2) Automatic Identification

Airport and runway automatically will be decoded and displayed on the MLS controller.

h. Obstacle Warning

A single service will be provided in conjunction with vertical approach guidance as indicated above. Included on the MLS auxiliary data will be the minimum safe glidepath for each facility. This will be decoded in all receivers and compared to the receiver glidepath setting. If the receiver setting is lower, the receiver will generate an "invalid" discrete and will provide no guidance information (so that the indicator flags will not drop).

- The need for obstacle warning appears to be preset for the lower-class users, since trunk airlines due to stringent procedures, including cockpit checklists, teaming, etc., have minimal problems of obstacle clearance on approach/departure. NTSB statistics show this area to be a major cause of accidents with the preponderance of cases being general aviation and supplemental air carriers.

i. Malfunction Indications

(1) Basic Alarm

A "Malf" indication will be given upon airborne equipment failure, or loss of signal, or unreliable signal.

(2) Malfunction Discrimination

For higher-class users, indications will discriminate as to the source of the failure: airborne or ground equipment. A built-in delay in the failure indications will "coast" over momentary signal outages.

- Maximum "coast" periods during final approaches and landing have been determined at Sperry by simulations. These are discussed under Integrity Features in Section 1.1.1.1, Part A.
- The significance of malfunction discrimination is (1) to assist in decisions as to what subsequent actions to take -- whether another instrument approach can be made, and (2) to avoid loss of pilot confidence in the system by informing him as to the source of failure: ground, receiver or autopilot. UAL maintenance reports pilot complaints of autopilot decoupling during ILS approaches where the pilot never knew whether the aircraft, the ILS or neither was at fault.

j. Airport Condition Data

The following MLS auxiliary data will be provided in support of Category II and III MLS users:

- Runway Visual Range
- Wind speed and direction

- Barometric setting
- MLS status (all-up or reduced operating category)

k. Services to ATC

In applicable facilities, operational status of all MLS guidance elements will be provided for the tower controllers. Optionally, this data will also be available for transmission to the common IFR facility. The MLS elements for each runway and direction will be operable remotely from the tower.

(1) Flight Path Monitoring

The need for independent flight path monitoring at Cat. II/III facilities has been discussed at length and it was the opinion of SC-117 that this service should be independent of MLS. Hazeltine proposes one exception to this. For carrier landing, it is believed required for any system to be a functional replacement for the SPN41/42 systems, that monitoring be provided both for the pilot and for shipboard personnel. This is discussed more fully in the Description of Prototype Systems, Section 1.2.2.1.

6. MLS Signal Quality Requirements

a. Introduction

This section presents a summary of the analysis and simulations performed by Hazeltine and its subcontractor, Sperry Flight Systems to review and further define the requirements for the "quality" of the MLS guidance signals. The parameters assessed were bias, noise, data rate, granularity and signal interruptions.

(1) Purpose of Review

In the initial formulation of the MLS accuracy requirements, SC-117 utilized the existing ICAO specifications for ILS as a basis for extrapolation. That further investigation of MLS accuracy requirements is needed is clear when certain differences between systems are considered.

- The ILS signal is continuous, while MLS is a sampled-data system.

- Because of the very different operating frequencies of MLS and the resultant interference patterns produced in space by multipath effects, the nature of the resultant MLS "noise" is significantly different tha.. ILS beam bends.
- MLS is required to provide services over a wider range of conditions, such as glidepath and coverage volumes.
- MLS incorporates additional guidance elements not present in ILS (DME, EL-2)
- Special considerations relative to non-standard operations and runways influence requirements.

In addition, other aspects of signal quality (e.g., granularity and signal interruptions) were not considered by SC-117.

The effort undertaken in Phase I of the MLS program was intended to:

- Review existing requirements to identify areas where an increase in accuracy was needed to meet operational requirements and ensure compatibility with flight control systems
- Identify areas where the extrapolation from ILS specifications may have resulted in an uneconomical overspecification for MLS.

(2) Elements of Signal Quality

The following elements of signal quality are discussed in this section:

Bias - Bias comprises those guidance signal errors which are essentially invariant over the typical response time of the aircraft position ("outer") loop, which is typically 10-30 seconds. These errors relate to aircraft positional deviations, and, if large, contribute to excessive touchdown dispersions and excessive deviations from the desired flight path, as compared to accepted practice. Bias errors also cause errors in height measurements in MLS.

Noise - Noise, or essentially random jitter in MLS output data, effects most significantly the performance of the aircraft under direct automatic flight control. Excessive noise causes excessive jitter in the control column and wheel and in the aircraft actuator and control surfaces. Sources of noise include

- Transmitter jitter
- Receiver thermal noise
- Multipath

In the case of multipath, the effect can either be essentially random, if caused by many small multipath sources, or sinusoidal in nature. These issues are addressed in Section 1.1.1.1, Part E on multipath effects. Fortunately it is believed that in instances of interest the multipath effect will most of the time be of short duration and noise-like in nature.

Data Rate - Increased data rates tend to increase the effects of noise, so that a noise/data rate tradeoff is required. It is believed the Doppler Technique is tolerant of comparatively high data rates, subject only to the desire to take maxim advantage of multiscan averaging, which is very effective in overcoming the effects of multipath. In the absence of noise, there is a lower limit of tolerable data rate based on path following, but this is believed to be academic in the face of real-world noise levels.

Granularity - Lack of smoothness in spatial coding (granularity) also effects the control system, as the aircraft transitions rough abrupt c nges in the guidance signal.

Interruptions - Interruptions in signal could be caused by momentary blockage of the transmitting elements or by equipment switchover following failure indications. This will affect the aircraft deviation from desired flight path, and control wheel/column motion when the signal is resumed. This is especially critical during the final moments of flight.

(3) Elements of Study

The major activities during this study will be identified below, along with key results.

Simulations - At Sperry Flight Systems, extensive flight control systems analog simulations were performed to assess the effect on control system dynamics of MLS signal quality. This study and detailed results are fully documented in Appendix A of this report. In this study, compatibility with existing flight control systems (AFCS) was considered of paramount importance. Also investigated were the implications of future AFCS designs wherein more optional use is made of the MLS signal. Key results of this study include:

- Establishment of noise and data rate values, producing acceptable AFCS performance, which are achievable in a practical system design.
- Identification of a technique for processing receiver output data to reduce the effects of receiver jitter.
- Identification of potential problems associated with attempting to divorce the AFCS from other sensors by coupling more closely to the MLS beam.
- Establishment of the effect of bias errors on touchdown performance.
- Establishment of tolerable levels of granularity
- Specifications of tolerable signal interruption durations before and during the flare maneuver.

Although the study was oriented towards the most stringent MLS application, Cat III CTOL and STOL operation, many results were extrapolated to derive tentative requirements for other facilities as well.

Multipath Evaluations - From the data base accumulated during the TACD multipath analysis, sample multipath "signatures" were described, and evaluated by Sperry for effects in AFCS performance. The conclusion was that multipath effects during final approach and landing will be tolerable at worst and will otherwise be essentially indistinguishable from random error.

Other Analysis - Accuracy specifications were also evaluated to ascertain that they will meet other operational requirements and functional services. These studies included consideration of

- decision height computation accuracy
- two-step glidepaths
- wide-area navigation
- metering and spacing
- Altimetry
- variable glideslopes
- parallel runway operation
- rollout

The results generally indicated that sufficient accuracy will be available for all operations with the possible exceptions of derivation of altimetry data throughout MLS coverage.

Also, values of DME accuracy were set as a result of the decision height measurement tradeoff.

Miliary requirements were also reviewed. This included review of existing specifications for Military tactical systems and estimation of carrier landing requirements. Additional analytical and simulation work relative to special requirements was identified for Phase II of the MLS program.

(4) Summary of Results

Key results relative to bias, noise and data rate are indicated in Table 9-˘0. These are the revised specifications as a result of our study. In each case, the corresponding SC-117 specification is also given for comparison, along with the method of validation. It should be noted that these are tentative specifications and are subject to extensive review and revision during Phase II. Qualitatively the following general conclusions are made:

- Allowable angular (AZ, EL-1, EL-2) bias errors are generally set by positional dispersions at the minimum guidance altitude (deviations from flight path or touchdown dispersions) as in ILS.
- In special situations, the angular bias is limited by the interface with other navigation systems (co-located case) or by deviations at "waveoff windows" (carrier landing).
- Where AFCS operation is applicable, this determines acceptable combinations of data rate and angular noise.
- The combination of DME and EL-1 errors are constraints by decision height computations.
- In the special case of aircraft carrier landing, because of peculiar geometry, the DME error is limited by touchdown dispersions.
- Multipath effects on final approach and landing will be tolerable and generally comparable to noise effects.

The study also identified the need for further requirements studies in the areas of:

- carrier landings
- high-performance military CTOL aircraft applications

TABLE 9-10
SUMMARY OF ACCURACY AND DATA RATE RESULTS

		B	D	E	F	G	I/K (CTOL)	K (STOL)	E MIL. COLOCATED	E MIL. SPLIT SITE	G MIL. SPLIT SITE	I CARRIER SYST "A"	I CARRIER SYST "B"
AZ	BIAS (2σ)	.275° (.275°) □	.275° (.275°) □	.275° (.275°) □	.066° (.141°) □	.066° (.141°) □	.043° (.043°) □	.20° ■	.26° ■	.26° ■	.26° ■	.034° ■	.15° △
	NOISE (2σ)	.12° (.14°) ○	.12° (.14°) ○	.12° (.14°) ○	.065° (.048°) ○	.065° (.048°) ○	.065° (.038°) ●	.084° ●	.3° △	.12° ○	.12° ○	.046° △	.15° △
	DATA RATE	10 Hz (5 Hz) ○	10 Hz (5 Hz) ○	10 Hz (5 Hz) ○	7 Hz (5 Hz) ○	7 Hz (5 Hz) ○	7 Hz (5 Hz) ●	7 Hz ●	10 Hz △	10 Hz ○	10 Hz ○	10 Hz △	5 Hz △
EL_1	BIAS (2σ)	N/A	.10° (.10°) □	.10° (.10°) □	.06° (.06°) □	.06° (.06°) □	.06° (.06°) □	.06° □	.17° ■	.10° □	.06° □	.034° ■	.07° △
	NOISE (2σ)		.12° (.12°) ○	.12° (.12°) ○	.08° (.07°) ○	.08° (.07°) ○	.03° (.07°) ●	.10° ●	.2° △	.12° ○	.12° ○	.046° △	.07° △
	DATA RATE		10 Hz (5 Hz) ○	10 Hz (5 Hz) ○	7 Hz (5 Hz) ○	7 Hz (5 Hz) ○	7 Hz (5 Hz) ●	7 Hz ●	10 Hz △	10 Hz ○	10 Hz ○	10 Hz △	5 Hz △
EL_2	BIAS (2σ)	N/A	N/A	N/A	N/A	N/A	.05° (.034°) ●	.09° ●	N/A	N/A	N/A	N/A	N/A
	NOISE (2σ)						.036° (.040°) ●	.036° ●					
	DATA RATE						14 Hz (10 Hz) ●	14 Hz ●					
DME	BIAS (1σ)	300' (300') ■	100' (300') ■	32' (100') ■	32' (100') ■	32' (20') ■	20' (20') ■	20' ■	32' ■	32' ■	20' ■	10' △	N/A
	NOISE (1σ)	100' ■	100' ■	32' ■	32' ■	20' ■	20' ■	20' ■	32' ■	32' ■	20' ■	10' △	
	DATA RATE	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	10 Hz △	

- ● SIMULATION DATA
- ○ EXTRAPOLATION OF SIMULATIONS
- ■ OTHER ANALYSES
- □ ICAO ILS SPECIFICATION
- △ OTHER SPECIFICATIONS

- VTOL coupled approaches
- further optimization of MLS output data processing

Work in these areas will be carried out by analysis and computer simulation during Phase II.

b. AFCS Simulation Study

(1) Introduction

The Phase I simulation study and analysis conducted by Sperry as part of the Phase I program had the following basic objectives:

- to determine the constraints on MLS signal quality requirements for compatibility with flight dynamics of typical CTOL and STOL transport aircraft
- to identify, if possible, opportunities for improved and simplified AFCS designs that might be provided by sufficiently-refined MLS characteristics.

The study is covered in detail in Appendix A. This section summarizes the study methodology and presents the major numerical results. It also contains interpretations and extrapolations of the configuration K results to other configuration specifications.

The following introductory material is excerpted from Appendix A.

Two types of aircraft, a conventional take-off and land (CTOL) and a short take-off and land (STOL), were chosen for the specific studies conducted for this phase of the MLS program. While study of these aircraft is not intended to provide representative specifications for all aircraft, it is representative at a spectrum of aircraft involved in the commercial transport field as it exists now and as it will develop in future years. The results obtained from this study will be applicable to commercial airline transports, light and heavy executive aircraft, to a lesser extent to small propeller driven aircraft, and to the commercial and military STOL vehicles. The specific vehicles simulated were the Boeing 747 aircraft, representative of current high performance commercial transports, and the deHavilland Buffalo C8-A, representative of the emerging class of medium STOL aircraft.

The CTOL aircraft, as it exists today, utilizes flight directors and automatic pilots configured to operate with current localizers and glide slopes with all the necessary compromises required to provide acceptable performance. Since the current generation of turbo jet aircraft will be utilized for a significant time after MLS entry into the market, these aircraft constitute a retrofit market for MLS equipment. On this basis, its capability to fit directly into these aircraft as a replacement for the VHF navigation receivers forms one constraint on definition of MLS parameters. Envisioning a time in the future in which sufficient MLS coverage is provided throughout the world to make it feasible to design flight guidance equipment based upon the use of MLS only, effort was expended to define a preliminary flight control system which was based solely upon the use of the Microwave Landing System. The primary objective of this approach is to offer cost, logistics, and maintenance advantages to the aircraft industry by reducing the need for peripheral subsystems such as radar altimeters body-mounted accelerometers, central air data computers, and inertial navigation systems. An additional benefit to be derived from this approach is an improvement in overall system reliability by concentrating effort upon fewer subsystems which are intimately involved with lower weather minimums in the implementation of automatic control. This factor will assume even greater importance as traffic density increases and the need for greater utilization of automatic landings becomes more prevalent.

To investigate problems involved with MLS application, an analog simulation of the aircraft equations of motion and the associated autopilot control laws was used. The preponderance of the study effort was accomplished by that method; wherever possible, however, mathematical analysis of specific problems was undertaken to define requirements. For the purpose of these studies, the small disturbance equations of motion were used; allowing separation of the aircraft simulation into 3 degree of freedom studies independently conducted for pitch and for roll axes. This method is conventionally used for approach studies.

Inasmuch as the MLS, for the purposes of automatic flight control, interfaces with the control system only during the approach phase of flight, attention was directed primarily to the centerline azimuth capture and track phases and the elevation capture, track and flare portions of the longitudinal control problem. The analog computer used was the Applied Dynamic AD4 computer. This computer is hybrid (analog/digital), facilitating analog simulation of the linear control laws while providing digital arithmetic, sensing, and logic functions. Computer outputs were recorded in continuous, real time displays using a X-Y plotter, where expansion of a particular phase of an approach was required (e.g. the flare), and 8 channel strip recorders. The recorders monitored pertinent aircraft and control parameters such as vehicle attitude, attitude rate, beam deviation, surface motion, etc.

The study showed that MLS will, if interfaced with a conventional autopilot in current usage, provide capture and track of both azimuth and elevation 1 beams with performance comparable to that provided by ILS, provided that a signal format of equal or more stringent accuracy than that in our recommendations is used. The use of elevation 2 and DME range to compute altitude and altitude rate for flare was investigated and found to be workable alternative to a radar altimeter referenced flare maneuver. The results of attempting to totally divorce the autopilot from external sensors and substitute beam rate as the only damping term during capture and track were disappointing. A rate coupled autopilot will require dependence on additional sensors, typical of what is in current usage, for the capture and initial track phase. As the aircraft descends to an altitude where good wind shear performance is required, the appropriate rate gain could be phased in and other damping terms phased out. This would allow an "MLS-only" final portion of the approach prior to the Category II window and flare while avoiding problems of control column and wheel activity during the capture and early track phase in the presence of reasonable levels of noise.

(2) Methodology

The acquisition of data during this program followed an orderly pattern which was repeated for each aircraft or control axis being studied. For each axis, e.g. pitch CTOL with a conventional autopilot, analog beam runs of capture, track and flare modes were made with no perturbations. Analog beam in this case is intended to indicate continuous signal inputs equivalent to current, ideal ILS beams. A "run" is defined as a single operating sequence on the analog computer in which generally only one parameter value is changed as a discrete input or initial condition from the previous studies. A set of analog beam control runs were then taken in which various wind conditions were introduced to provide a comparison base for subsequent parameter variations. Once control runs were obtained, parameters were varied one at a time throughout the range considered pertinent for any particular variable (noise, data rate, etc.). This technique provides the basis for assessing the effect of any one change on baseline performance. The obvious disadvantage to this technique, however, is the lack of any statistical base for combinations of effects. This is significant where considerations of turbulence and beam noise were involved. The tradeoff here in use of the completely analog system is that all normally encountered non-linearities could be and were simulated. Significant non-linearities which were included in this simulation, and incidentally greatly influenced the results, were ground effects for the aircraft and rate limiters in various portions of the combined autopilot aircraft system. Rate limiters were used on the input signal to non-linearly attenuate beam noise. Within the autopilot, roll rate and displacement limits which exist within virtually every autopilot were also simulated. One additional rate limit application involved simulation of the hydraulic actuator which significantly affected the response of the control column to disturbances associated with the beam.

In an attempt to achieve some dispersion data from the analog study, a computer run in which a significant parameter was being randomly varied was allowed to continue for a sufficient length of time, relative to the frequency content of the disturbance, so that the data obtained on the appropriate output could be considered as peak-to-peak or 6 sigma data. Consideration of these results on a 2 sigma basis then permitted combination of these results assuming that the random input had been gaussian in nature. This approach was used primarily with relation to the effects of white noise inputs.

The data utilized to arrive at the performance specifications were derived from the simulations of

- The conventional STOL autopilot evaluated for capture, track and transition to conventional radio-altimeter-derived autoland
- The conventional CTOL autopilot with MLS inputs replacing radio-altimeter height and height rate for flare.
- The projected STOL autopilot with MLS derived flare.

The result of the "rate-coupled" autopilot, with MLS-only control laws, generally tended to show the need for excessively stringent MLS noise performance, especially in EL, capture and both capture and track in AZ. These results were not used to set requirements.

Criteria used to set requirements are summarized in Table 9-11. It should be noted that additional analysis of DME/EL accuracy tradeoffs relative to decision height computations have been performed and are discussed in the following section.

TABLE 9-11
CRITERIA USED FOR RECOMMENDATIONS FOR CTOL AND STOL

	Elevation 1	Elevation 2	Azimuth	DME
Data Rate	Cooper Rating and Beam Noise			Airborne Calculations
Noise	Cooper Rating and Data Rate			
Granularity	Column Transients		Wheel Transients	
Angle Accuracy	Decision Height	Touchdown Performance		
Interruptions	Touchdown Performance			
Accuracy				CTOL - Radio Altimeter STOL - Touchdown Dispersion

(3) Noise/Data Rate Tradeoffs

Simulations - As previously mentioned, the principal effect of MLS noise, because of its high frequency content, appears to be on spurious AFCS control activity, most noticeable in control wheel/column activity. For the simulation efforts, the critical phases of flight were identified where noise on each MLS beam was expected to have the greatest effect on control activity. These were:

EL-1 - just before course softening starts (1500 ft. alt.)
EL-2 - during flare
AZ - during final portion of beam capture

For each guidance beam, control activity (inches or degrees displacement) was then measured by simulation, for a variety of data rates (e.g., 2.5 Hz to 20 Hz) and beam noise levels (in degrees).

Pilot Acceptability - To evaluate what was an "acceptable" amount of noise, it was necessary to relate control activity to pilot acceptability, under the assumption that pilot's feel of control activity would be a more sensitive measure than effects felt by passengers, and much more sensitive than aircraft deviations in space. No adequate quantitative data on pilot's reactions to control column/wheel motion was available for this assessment. To obtain this data base, a series of tests were conducted at the United Air Lines Training Facility in Denver, under contract to Sperry, in which random column and control wheel motion were introduced for a number of pilots to experience during simulated landing approaches. As a result of this study, it was possible to identify amplitudes of column/wheel motions with Cooper Ratings. These ratings indicate the pilot's estimates of the control system performance. This is summarized in Table 9-12.

TABLE 9-12
PILOT SENSITIVITY TO WHEEL AND COLUMN MOTION

Cooper Rating	Description	Pitch Axis Column Motion, Inches (25)	Row Axis Wheel Motion, Inches at Rim (28)
2	Good, pleasant to fly	.17	.22
3	Satisfactory, but with some mildly unpleasant characteristics	.27	.28

Rate Limiter Investigations - It was found that, without any special processing between MLS receiver and autopilot, only a very small amount of beam noise was tolerable in terms of acceptable control activity. This was especially true in the aircraft pitch axis. Several methods of processing the MLS signal at the receiver output were then investigated, in hopes of removing at least a portion of the objectional sample-to-sample jitter before injection into the autopilot. The most promising measure investigated was the incorporation of a rate limiter at the receiver output. Figure 9-3 illustrates the action of the rate limiter. It proved extremely effective at reducing the amount of control activity associated with a given beam noise level. The effectiveness of the rate limiter is, however, bounded by at least two factors:

- the rate limit must be able to pass beam rates corresponding to true aircraft motion
- in severe noise, the action of the limiter may tend to desensitize the small-signal response of the aircraft position loop.

The latter effect was not completely evaluated. However, the desensitization apparently was not observed in flare behavior in wind shear, where it might have been expected.

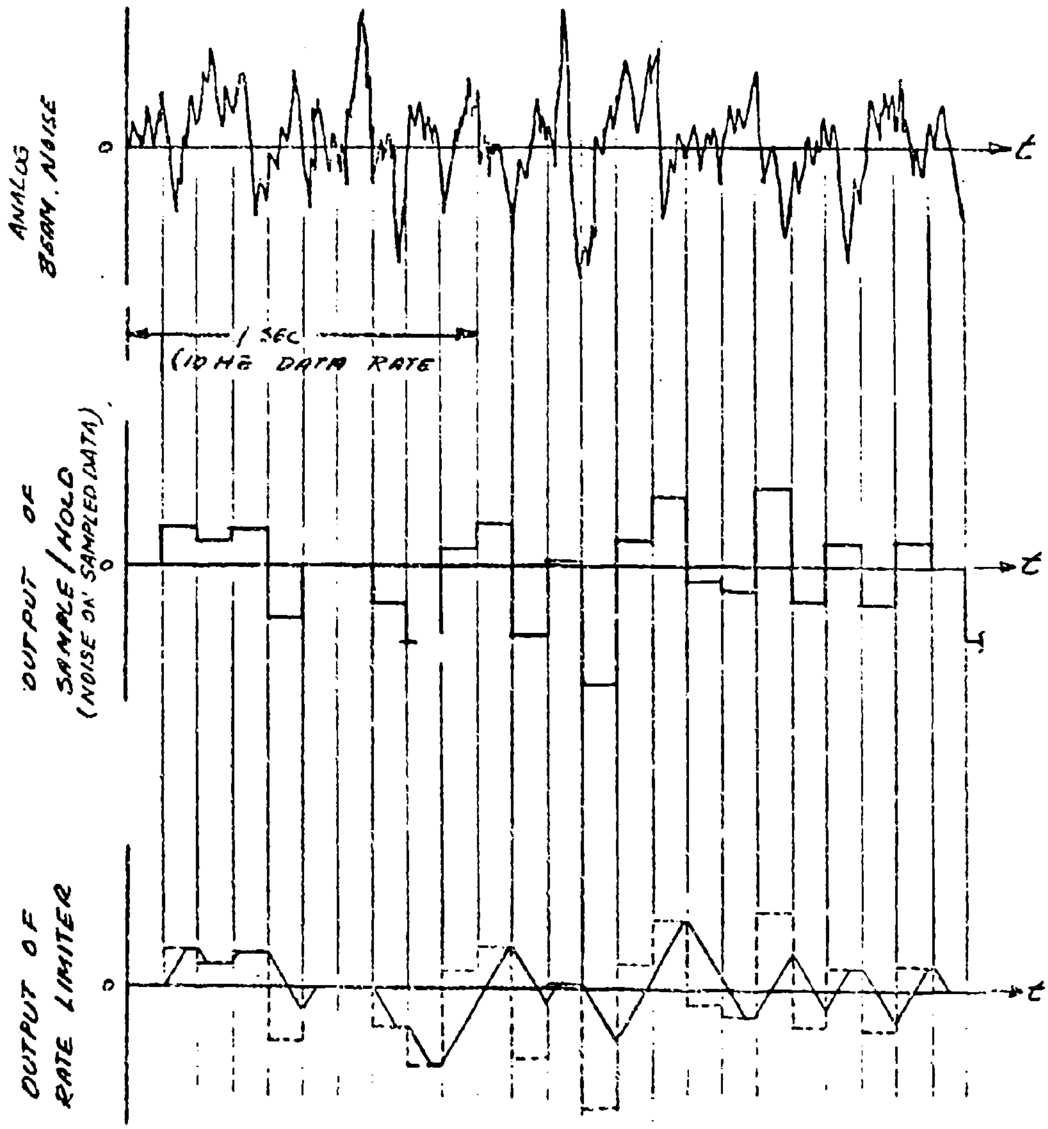


Figure 9-3. Effect of Rate Limit on Sample/Hold Output

The rate limiter (with properly set rate limits) was included in the simulation runs from which the specifications in this report were generated. We plan to continue our study of the rate limiter technique (and others, including time-domain filtering) during Phase II to identify an optimum method for sampled-data noise reduction.

Results - From the data in Appendix A, obtained by the method summarized above, the noise/data rate tradeoff curves in figures 9-4, 9-5, and 9-6 were generated. Each curve represents combinations of noise and data rate that is estimated to result in the same amount of control activity in the AFCS. The amount of control activity is indicated by a Cooper Rating as defined above. The objective in each case is to choose a combination of noise and data rate that will fall on, or above and to the left, of the curve corresponding to "Cooper #2", which describes a "good, pleasant to fly" condition. Many modern short- and medium-range transports can land at standard runways to be instrumented with any of the standard MLS configurations. Therefore, it is important that they, as well as K configurations, all have tolerable noise/data rate specifications as evaluated in the jet transport. This is especially appropriate for Cat II/III approaches; for Cat I a slight relaxation (say to Cooper 2-1/2) might be tolerable.

On the figures, the SC-117 Noise/Data Rate specifications for categories B through K are shown as open circles. It is clear that with the exception of Az, they are generally unacceptable. An infinite number of possibilities were open to adjust the specifications.

We choose to take advantage of the relatively high data-rate capability of the Doppler technique. The system data rates were adjusted as follows:

- For I/K, from 5/10 Hz (SC-117) to 7/14 Hz
- For F/G, from 5 Hz (SC-117) to 7 Hz
- For B/D/E, from 5 Hz (SC-117) to 10 Hz

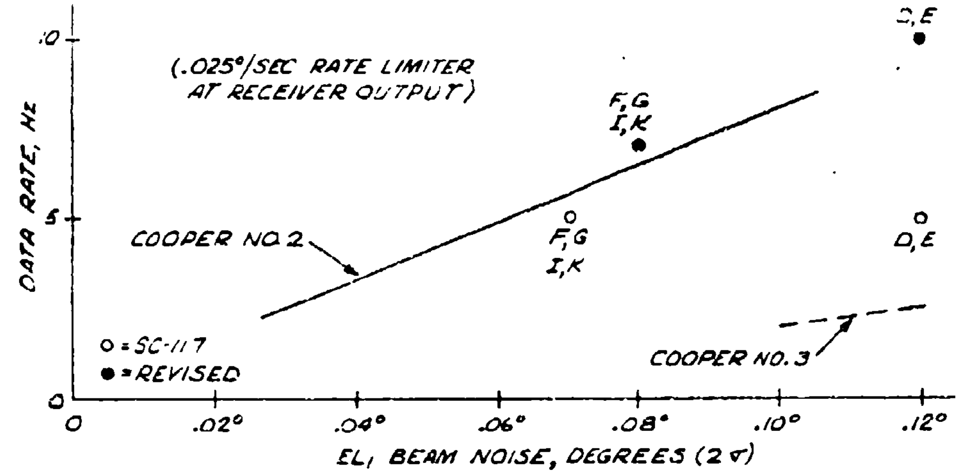


Figure 9-4. EL-1 Beam Noise vs Data Rate Tradeoff, CTOL Autopilot Pitch Axis

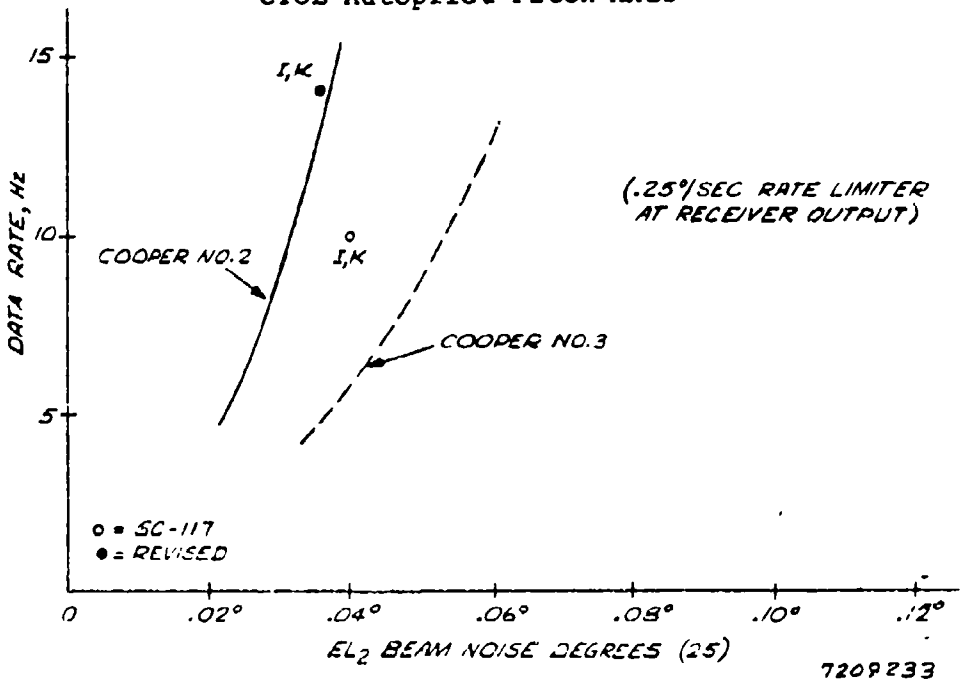


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Figure 9-5. EL-2 Beam Noise vs Data Rate Tradeoff, CTOL Autopilot Pitch Axis

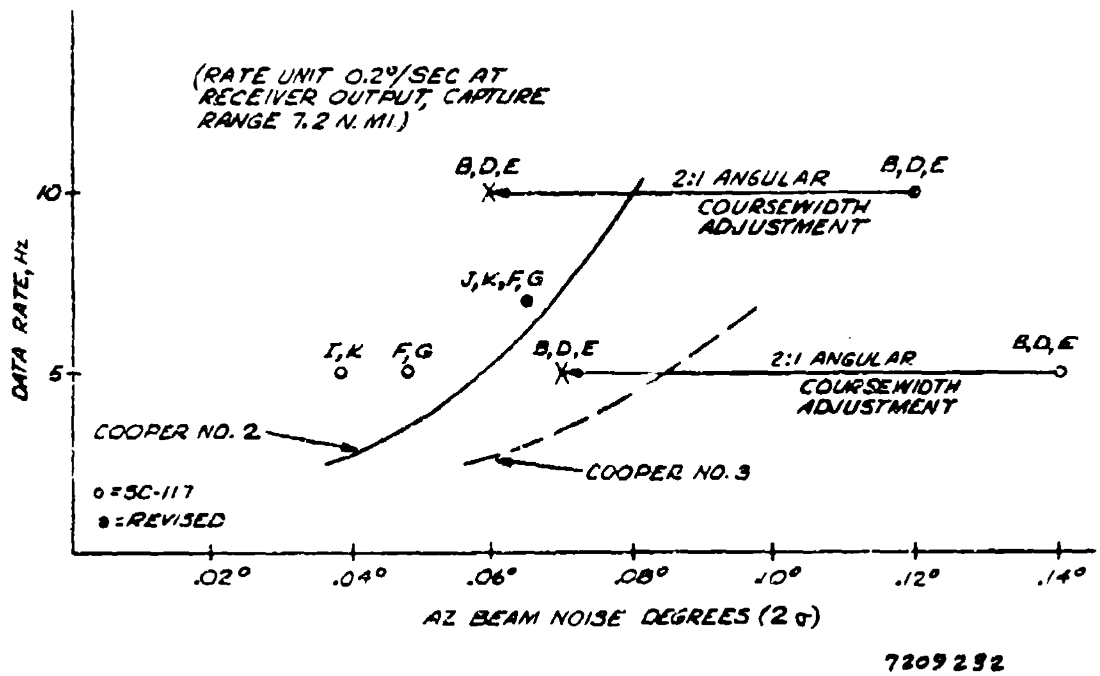

Figure 9-6. AZ Beam Noise vs Data Rate Tradeoff, CTOL Autopilot Roll Axis

For the latter category, the data rate adjustment was higher to allow slightly more noise on the beam and reduce equipment requirements. This was allowable especially since there are less guidance elements in the data format in these configurations.

At the new data rates the noise specifications were then adjusted to bring the specification points slightly above the Cooper 2 curve, as indicated by the solid circles on the figures.

With respect to B, D, and E configurations in Azimuth it will be noted that the raw angle output noise is still apparently much too large. However, it must be recalled that, unlike, ILS, the MLS system will have uniform azimuth angular coding for simplicity.

By our present plan, there will be no adjustment in the ground equipment to make the localizer coursewidth a constant (±350') at threshold as it is in ILS. This adjustment will be made automatically in the receiver (see functional services description) and is equivalent to a receiver output desensitization for shorter runways. For a 7000-foot runway (typical of B.D.E.) relative to a 14,000 foot one, the adjustment is approximately 2:1. This factor cuts the effective noise into the autopilot by 1/2, bringing the effective operating point well into the Cooper #2 curve, as illustrated in figure 9-6. However, the specifications have been adjusted so that a slightly smaller scale factor (corresponding to a larger runway) will still produce satisfactory results.

A similar set of tradeoffs were performed for K STOL (STOL-only airport) using simulated responses of the STOL aircraft. It is appropriate to use the STOL aircraft as the determining case here, since CTOL jet transports will not be utilizing the K STOL facility. For convenience the same data rates as the standard K were chosen.

The above results for CTOL and STOL facilities are entered in the summary Table 9-10 for all civil and standard military facilities. Special military considerations are covered in the following section.

(4) Granularity

Analog simulations were also used to define the tolerable limits of spatial granularity of coding. The spatial granularity is defined as follows: in a noise-free environment, a given receiver is moved slowly through the angularly-coded signal in space. If the receiver output response with angle is smooth, there is no granularity. If the receiver exhibits a "staircase" response with angle, the granularity is defined as the angle between adjacent steps. (The response may be caused either by the guidance signal generation technique or the receiver-decoder technique). It should be noted that a noisy environment can mask the granularity effect.

The effect of granularity was estimated by simulating the wheel/column response to traversing a granularity step in a noiseless environment. The response amplitudes were then related to the Cooper #2 value of allowable motion. The results are presented in Table 9-13. The K-CTOL results were then applied to all standard-size runway facilities, and the K STOL results to the STOL and VTOL facilities.

(5) Signal Interruptions

The effect on guidance of signal interruptions is most critical in Category III operations below 100 ft. The expected effect of interruptions is an increase in landing dispersions and a change in touchdown sink rate. Simulations and calculations were employed to determine the maximum tolerable signal interruption for each guidance element. The results are summarized in Table 9-14. These results pertain directly to Cat III facilities only. Other interruption limits are defined in Section 1.1.1.1, Part A on system integrity.

TABLE 9-13
GRANULARITY LIMITS

	CTOL AFCS at Configuration K CTOL	STOL AFCS at Configuration K STOL
AZ	.025	.03
EL	.01	.025
EL_2	.035	.05

TABLE 9-14
SIGNAL INTERRUPTION LIMITS FOR CAT III OPERATION

Guidance Signal	Where Evaluated	Tolerable Limits K CTOL (seconds)	Tolerable Limits K STOL (seconds)
EL-1	Just before flare initiation	3	3
EL-2	During Flare	0.5	0.5
AZ	Just before touchdown (in shear)	2	2
DME	During Flare	2	2

(6) Angular Bias

Angular bias (referred to as "angle accuracy" in Appendix A) was investigated by simulations to determine the effects on touchdown dispersions during Cat III operations. Utilizing budgeted amounts of the acceptable touchdown dispersions (±750 ft (2σ) longitudinally and ±27 ft. (2σ) laterally, per FAA specifications). The tolerable limits on angular bias were derived and are given in Table 9-15. It should be noted that the EL-1 bias figure at $\pm 0.2^\circ$ (2σ) is considerably larger than the SC-117 specification of $\pm .06^\circ$ (2σ). This occurs because the Cat III flare law is apparently very "forgiving" to EL-1 beam deviation at flare initiation. However, it is questionable whether this would be acceptable in terms of Cat II operation at 3° glideslope. In addition, the bias accuracy of EL-1 is also constrained by the requirement to compute decision height; this is covered in a following subsection.

(7) DME Error

Simulations showed that acceptable touchdown dispersions in CAT III operations were obtained with DME errors as follows:

±32.5 feet (1σ) for CTOL aircraft
±22 feet (1σ) for STOL aircraft

The difference between the two is attributable to different flare geometries.

It happens that DME may be further constrained by the computation of decision height. In fact, decision height is the only restriction at category I and II facilities. There is a discussion on decision height accuracy in a following subsection.

c. Other Accuracy Considerations

Hazeltine has reviewed a number of operational considerations relating to accuracy in addition to those directly associated with

TABLE 9-15

ANGLE ACCURACY REQUIREMENTS FROM DYNAMIC SIMULATIONS

	Criterion	Acceptable STOL (2σ)	Accuracy STOL (2σ)
EL-1	Touchdown Dispersion	±.2	±.2
	(Decision Height)	(±.06)	(.06)
EL-2	Touchdown Dispersion	±.05	±.09
AZ	Touchdown Dispersion	±.04	±.2

the Sperry simulation studies reported above. Discussed in this section are:

- A review of the adequacy of accuracy specification for phases of approach and landing not fully covered above:
  - navigation in the terminal area
  - performance in metering and sequencing systems
  - parallel runway operation
  - decision height computation
  - execution of two-step glidepaths
  - rollout guidance
- A review of special accuracy requirements relating to military applications:
  - co-located VTOL guidance system
  - shipboard landing system

The results of these studies can be related to the summary of Table 9-10.

(1) Terminal Area Navigation

Support of the terminal airspace area navigation capability by use of MLS is fundamental to the requirement for wide angular coverage and is therefore nominally applicable throughout MLS coverage (outside of 1-2 nmi radius around threshold).

Lateral Accuracy - If the MLS is utilized with an RNAV system within the terminal area, it should be capable of significantly better performance than VOR-based area navigation. A survey of minimum operational characteristics of RNAV systems (Ref 10) indicated the best VOR performance to be expected is ±1.1° (2σ) accuracy and DME aggregate error of ±0.2 nmi. Additionally, an area nav equipment error and pilotage errors of ±0.2 nmi are also given. In view of these errors in existing equipment, it is proposed that an MLS caused error of 0.1 nmi (2σ) would be a meaningful improvement, and probably a smaller error would not materially reduce the overall RNAV performance when combined in RSS with other errors. It is proposed to consider this accuracy figure at the limits of coverage (viz 25 nmi) at any azimuth. This corresponds to an angular specification of ±1/4° (2σ) or DME range accuracy of ±300 ft. (1σ). Referring to Table 10, these accuracies are approximated or bettered by the runway centerline accuracies of all configurations listed. In addition, the nature of the doppler technique is such that the azimuth and DME accuracies of the Cat. II/III configurations probably will not degrade sufficiently off-axis to approach the area navigation specification in any case. Therefore it is expected that an area navigation specification of approximately ±0.1 nmi (2σ) lateral error in flight path anywhere in MLS coverage is achievable.

Vertical Measurement Accuracy - Complete 3-dimensional area navigation would be provided with the inclusion of a sufficiently precise vertical measurement system. A key MLS issue is whether a practical vertical system can provide the required altimetry accuracy throughout the coverage volume.

The required accuracy is taken from the Minimum Operational Characteristics of VNAV systems (Ref. 11) as ±90 ft (3σ) during final approach (5000 ft. altitude and below) and ±200 ft. (3σ) during Terminal Area maneuvers (10,000 feet altitude and below).

The proposed EL-1 accuracy requirement for the K configuration based on other constraints, will be evaluated for compliance with required altimetry accuracy. The EL-1 accuracy requirement is (Table 9-10)

Bias $.06^\circ$ (2σ)
Noise $.08^\circ$ (2σ)

We assume for purpose of altimetry that the noise error is put through a 1-second filter. Bias plus filtered noise yields an RSS equivalent angular error of $.067^\circ$ (2σ). Figure 9-7 shows the relationship of height error to range for $.067^\circ$ elevation error and for an error twice that value, assuming degradation in accuracy off-centerline as allowed in the SC-117 specification (the contribution of DME error resolved into the vertical plane is relatively small and is neglected). The altimetry accuracy goals are also plotted. Assuming the terminal area goal were to be met everywhere, out to 25 nmi range, the required EL-1 error would have to be about 20% smaller and, more significantly, no off-axis degradations at all would be permitted. This could result in a more stringent requirement in the angle guidance equipment than would otherwise be necessary.

It has been asserted that barometric altimetry and MLS-derived altimetry are incompatible in the same airspace because changes in local pressure would result in changes in separation between aircraft on different systems. If this is so, then MLS-derived altimetry would be inapplicable over a wide volume unless all aircraft within the volume have MLS height computation compatibility and this is considered unlikely for the entire terminal airspace.

However, it is possible that a subvolume, e.g. STOL marshalling area at low altitudes might be reserved nearer to the runway for purposes of sequencing these aircraft into final approach. Such a volume would naturally be off-centerline and might lie within a 5-nmi radius of the airport, in which case MLS with the stated

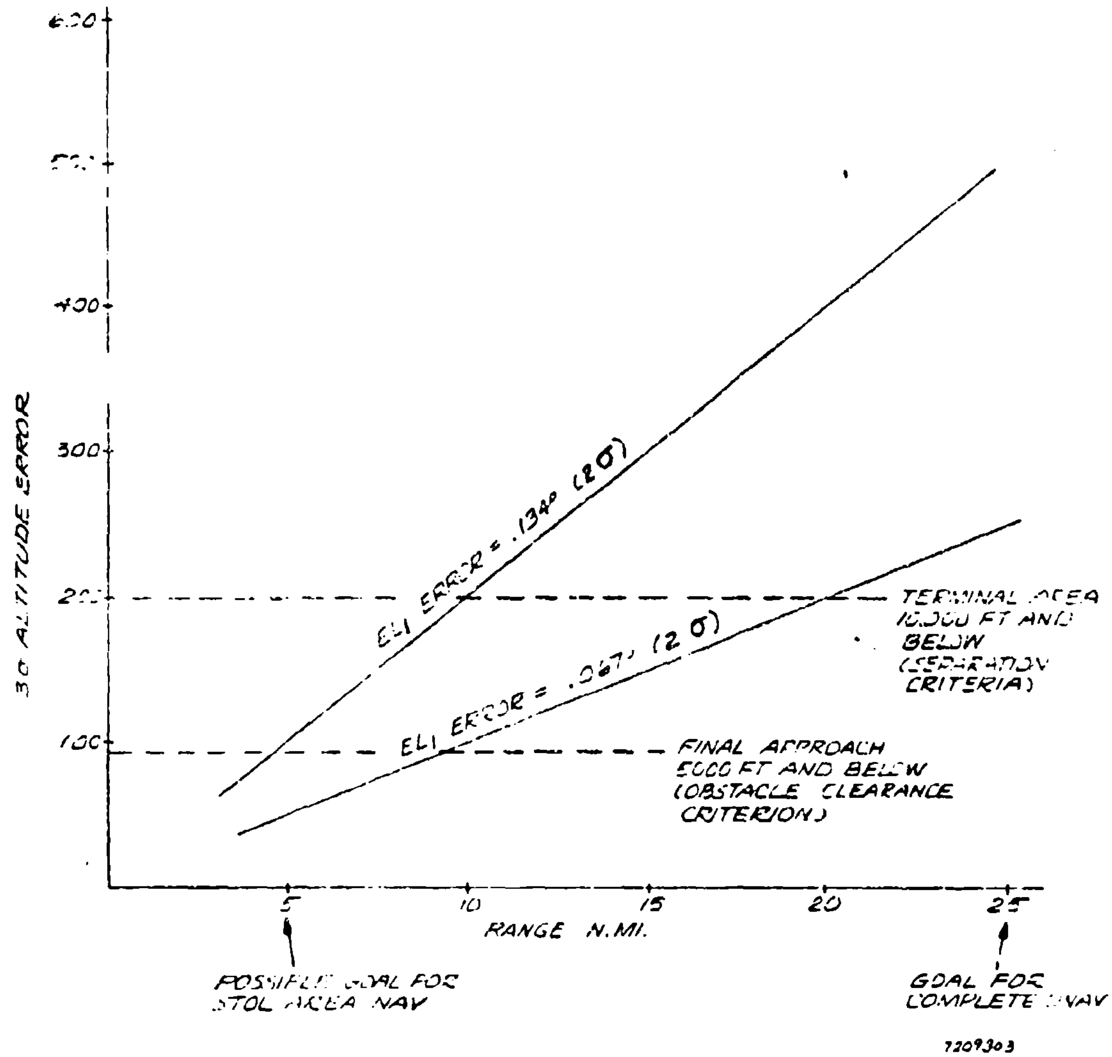

Figure 9-7. MLS Altitude Error as a Function of Range

accuracy might be satisfactory in a very limited way for altimetry. There are many issues concerning MLS-derived altimetry. These are discussed in the section on System Trades (1.1.2)

(2) Sequencing and Spacing

MLS must provide sufficient accuracy so that it will not be a constraint on airport capacity in the future. A typical metering and spacing concept will call for approach tracks on which each aircraft will make good (via ATC vectoring or on-board control) time of arrival at the approach gate by utilizing path stretching maneuvers, speed control, or both. In the case of onboard control, MLS may be used to generate corrective commands and therefore must be sufficiently accurate so as not to degrade time-of-arrival at the gate. The goal for arrival at the final approach gate is ±5 seconds (1σ). Typically this gate may be 5 miles from threshold. An aircraft may arrive at the approach gate from any direction relative to the runway heading.

Assuming an aircraft ground speed of 120 kts, an error in time corresponds to an along track position error of approximately 1000 ft. Comparing this positional error to the MLS measurement errors at 5 n.mi range, it is obvious that MLS errors will form a very small part of the overall along-track error. For a K CTOL configuration the along track error would be approximately ±30 ft. (1σ) regardless of whether the error is DME or azimuth-predominant. At a K STOL configuration, the error would be between ±30 ft. and ±55 ft. It is concluded that MLS accuracy is more than adequate for meeting gate arrival precision requirements.

(3) Parallel Runway Operation

Although not every K configuration may serve in a parallel runway environment, this will in some instances be an operational requirement, so that adequate MLS guidance accuracy is assured. An analysis in the ATCAC report (Ref. 12, p. 271) analyzes a control strategy involving aircraft in approaches to parallel runways with runway separation treated as a parameter, and a 500-ft wide buffer zone midway between runways which aircraft are never to enter.

Aircraft maintain course within a normal operating zone (NOZ) centered on each extended runway centerline. The width of the zone depends on onboard positioning accuracy. The ground-based Data Acquisition System (DAS) monitors aircraft about to leave the NOZ and relays corrective commands to them. Using this strategy, minimum allowable runway separation vs. DAS positioning error was plotted in the ATCAC report for various NOZ widths and is reproduced in figure 9-8.

The goal is to achieve simultaneous operations at 2500 ft. runway separation. DAS position errors are now approximately 380 ft. With improved DME and interrogator direction finding techniques, improvement to approximately 200 ft. can be expected in the DAS system. For the desired runway spacing, a NOZ width of 400 feet or ±200 ft. is needed, and this is assumed to correspond to a ±200 ft. (2σ) lateral aircraft position deviation while under MLS control. It is assumed that MLS control for this purpose is required starting at 10 nmi from threshold. A portion of the lateral aircraft deviation is attributed to MLS azimuth measurement accuracy. Only the bias term is considered, inasmuch as the aircraft position loop response filters out most of the noise. For a K CTOL configuration the AZ bias errors at 10 nmi from threshold produce a linear deviation of ±54 feet (2σ) which is approximately 7% of the allowable positional variance. Similarly, the configuration F azimuth accuracy will produce a ±83 ft. (2σ) deviation, which is 17% of the allowable positional variance. Therefore, either the Cat. II or Cat III CTOL system should have sufficient accuracy for parallel runway operation.

(4) Decision Height Computation

Most users will obtain decision height indications via height above runway as computed from EL-1 and DME measurements. It is necessary that the resultant error in decision height be acceptably small, i.e. no larger than allowable errors by today's

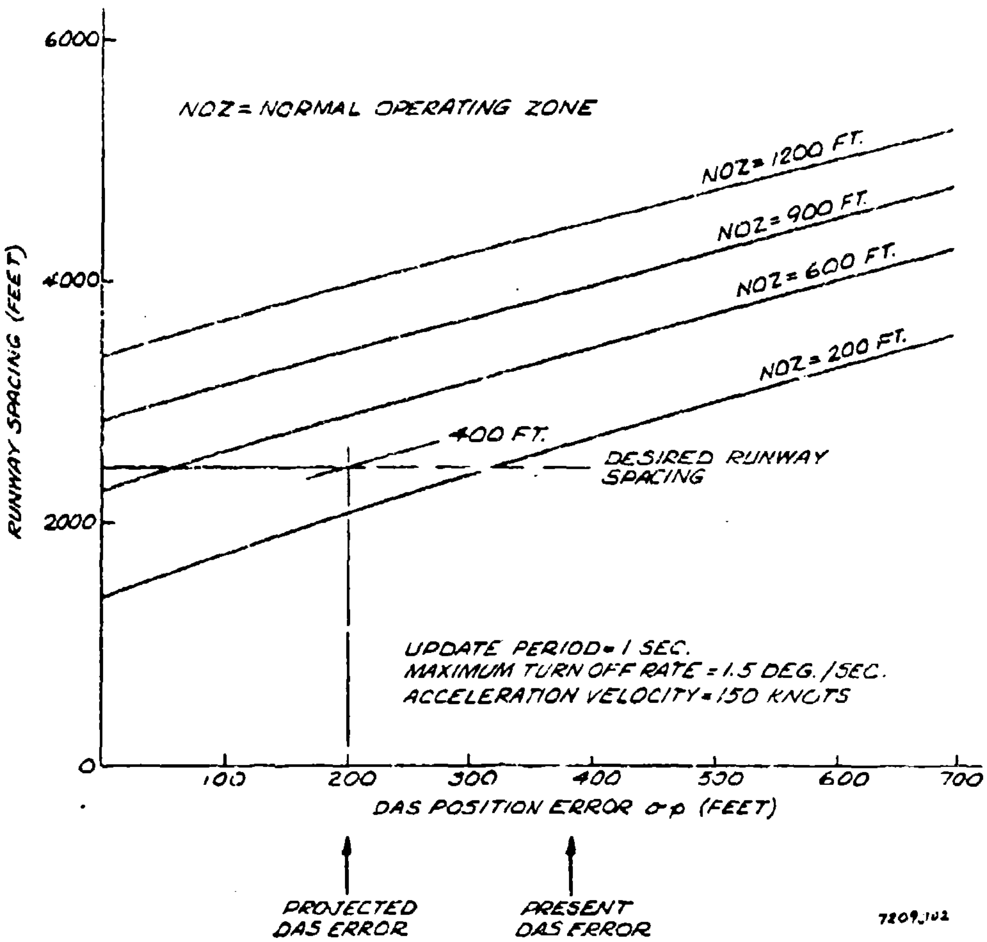

Figure 9-8. Parallel Runway Operation Requirements

standards. The principal difference between MLS and present practice is that decision height indications must be provided for a wide range of possible glideslopes.

The error in computed decision height is a combination of errors in EL-1 and DME. Figure 9-9 shows the composition of decision height error and the associated geometry. It is noted that the error contributed by DME increases with glideslope angle and that contributed by a constant EL-1 angular error decreases correspondingly. We make the assumption that at a given decision height (say, the Cat. II height, 100 feet) the same maximum decision height error requirements (in feet) applies regardless of glideslope. Then the lowest glideslope used at the facility will determine an EL-1 accuracy constraint, while the highest glideslope will determine a DME accuracy constraint. These constraints are naturally a function of the allowable decision height error assumed. A figure for acceptable decision height error must be determined. For Cat. II operations today, two methods are used for obtaining decision height: radar altimeter and inner marker. As indicated in Appendix A, the radar altimeter errors at low altitude (including indicator error) are typically ±5 ft. (2σ) assuming uniform terrain. The error associated with use of the inner marker is composed of (1) the error associated with measuring precisely when one is over the nominal marker beacon position and (2) the aircraft's vertical deviation from the desired glidepath. To obtain a conservative estimate of accuracy for this case, we ignore contribution (1) and use the FAA certification requirements for aircraft deviation of ±12 ft. (2σ).

Although it would be preferable to utilize the more stringent of these decision height accuracies, it happens that an unrealistically severe requirement on DME accuracy results if one wishes to support glideslopes above 6°. It is necessary to consider such glideslopes in view of possible future aircraft development. It is believed however, that the ±5 ft. requirement is overly stringent when compared with typical pilot/aircraft reaction

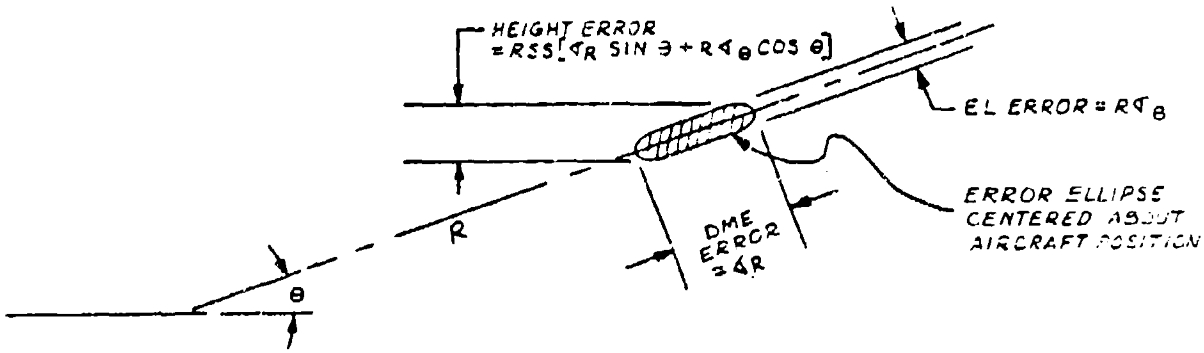

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Figure 9-9. Error in Computed Decision Height times during final descent. A ±12 foot (2σ) requirement would be equal to approximately ±1 second (2σ) at typical descent rate.

The situation for Cat. I is less clear, inasmuch as barometric altimetry is also permissible for decision height indications. Here a conservative figure of 30 feet (2σ) is assumed.

Tradeoff curves are presented in figure 9-10 which show acceptable combinations of EL-1 and DME error as a function of decision height and glideslope, using as a criteria the decision height accuracies discussed above. Also indicated are typical values of EL-1 angular error as given in Table 9-10. The resultant DME errors required are assumed to consist of equal parts of bias and noise. For the Cat. II/III systems to produce acceptable decision height accuracies of approximately 20' bias (1σ) and 20' noise (1σ) is required. However, Cat. II operations at such high glideslopes may not prove practical in the foreseeable future. If so, then a lower maximum glideslope may be chosen. If a 7.5° glideslope is used, the required DME accuracy is approximately 32 feet (1σ) bias and noise respectively. For Cat. II/III then, it is recommended that the overall system capability be available to generate acceptable decision heights for future glideslopes, but for those aircraft using glideslopes lower than 7.5°, a reduced DME capability is sufficient.

For a D configuration, the required DME accuracy to support decision height accuracy on a 6° glideslope is approximately 100' (1σ) bias and noise. These recommendations, and analogous ones for the other configurations were included in the summary Table 9-10.

(5) Glideslope Accuracy Considerations

It is instructive to determine the effect of relaxing the EL-1 accuracy requirements for higher glideslopes. As a possible approach, consider the implication of the SC-117 bias accuracy specifications. These were given in feet rather than in angular terms. A possible interpretation is that this linear accuracy is

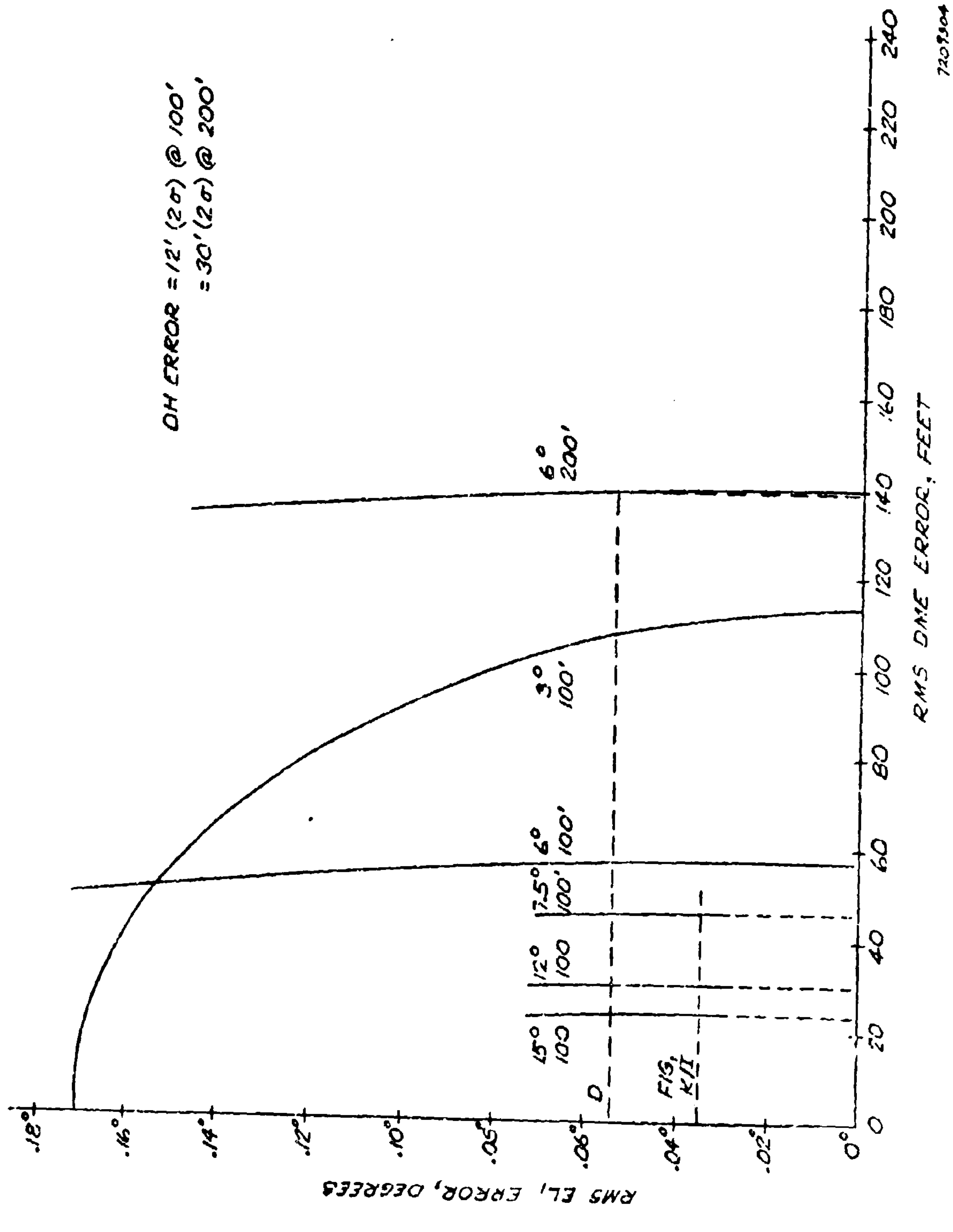

Figure 9-10. Accuracy Tradeoffs for Decision Height Computation

to be achieved at a given height (the minimum guidance altitude) for all glideslopes. Thus, a greater angular error would be tolerable at higher glideslopes. Consider the numerical examples:

Glideslope	EL-1 Error	Altitude	Altitude Error
3°	$\pm 0.06^{\circ}$	50'	±1'
6°	$\pm 0.06^{\circ}$	50'	±0.5'
6°	$\pm 0.12^{\circ}$	50'	±1'

An elevation system which provides minimum glideslopes of 6° need have only half the angular accuracy of one which provides minimum glideslopes of 3°, to achieve the same precision in vertical positioning at the minimum guidance altitude. The significance lies in the fact that there are two MLS configurations that need not supply guidance for 3° glideslopes: the military E (co-located) and the K-STOL. Both are estimated to require a minimum usable glideslope of 5°. Their EL-1 accuracies have been adjusted upwards by a factor of 5/3 over the corresponding standard K and E configurations. As a check on the accuracy of decision height computations, an examination of figure 9-10 will indicate that the accuracy tradeoff is very insensitive to increased angular errors in the region of interest. In addition, it will be recalled that the simulation study showed that touchdown dispersions are very insensitive to bias error in EL-1. Therefore, the relaxation in bias accuracy requirements for these facilities meets the three texts: linear deviation from glideslope decision height computation and touchdown dispersion.

(6) Two-Step and Offset Glide Paths

The ability to support a two-segment glide path (for noise abatement or other purposes) is recognized as a possible constraint on DME and EL-1 accuracy. A two-segment glide path is characterized by an initial, steep glidepath, transitioning at a specified height AGL to a final, shallower glidepath. To evaluate MLS requirements, it is necessary to consider practical limits for two-step maneuvers performed by fixed-wing aircraft near the ground, the positional accuracy required during maneuvers, and tradeoffs between DME and EL-1 measurement accuracies to achieve the required positional accuracy.

A basic assumption must be made concerning the allowable deviation from programmed flight path at various heights during the maneuver. On a simple 3° glidepath within 700 feet of ground level, category II ILS requires a maximum of $\pm 35\mu A$ (or ± 12 feet) 2σ deviation from nominal glidepath (Ref. 13). The $35\mu A$ constraint is an angular specification so that glidepath deviation in feet is proportional to aircraft height above runway level. Specifically, the rms allowable error comes out to approximately 3.4% of height above the runway level. Higher glideslopes will probably use proportionally wider elevation course widths than the 3° glideslope, implying also that the permissible deviation from glidepath will also be proportionally wider. If so, then the result is that the glidepath error will be a function of altitude and not the particular glidepath. Extrapolating to a two-step maneuver, we can define the permissible error at any given altitude as a constant fraction of that altitude. This concept is illustrated in Figure 9-11. The FAA rule stated above is used to define this fraction.

The present study has investigated the errors in maintaining initial glideslope during the moments before transition to final glideslope. The initial glideslope is really a path to an offset glidepath intercept point (GPIP), and is evaluated at the intercept height as illustrated in Figure 9-12. The MLS system is considered as a position measuring system in the vertical plane. The errors in EL-1 and DME measurements create an uncertainty in position measurement, shown as an error ellipse in the figure. The ellipse is a function of the measurement accuracy and the geometry of aircraft location relative to the guidance elements, and is not a function of the velocity vector. The ellipse is defined so that the projection of the ellipse perpendicular to any given flight path indicates the rms deviation in position measurement relative to that flight path. Whereas if the glidepath were not offset, EL error alone would determine the glidepath deviations, the offset glidepath error is a combination of

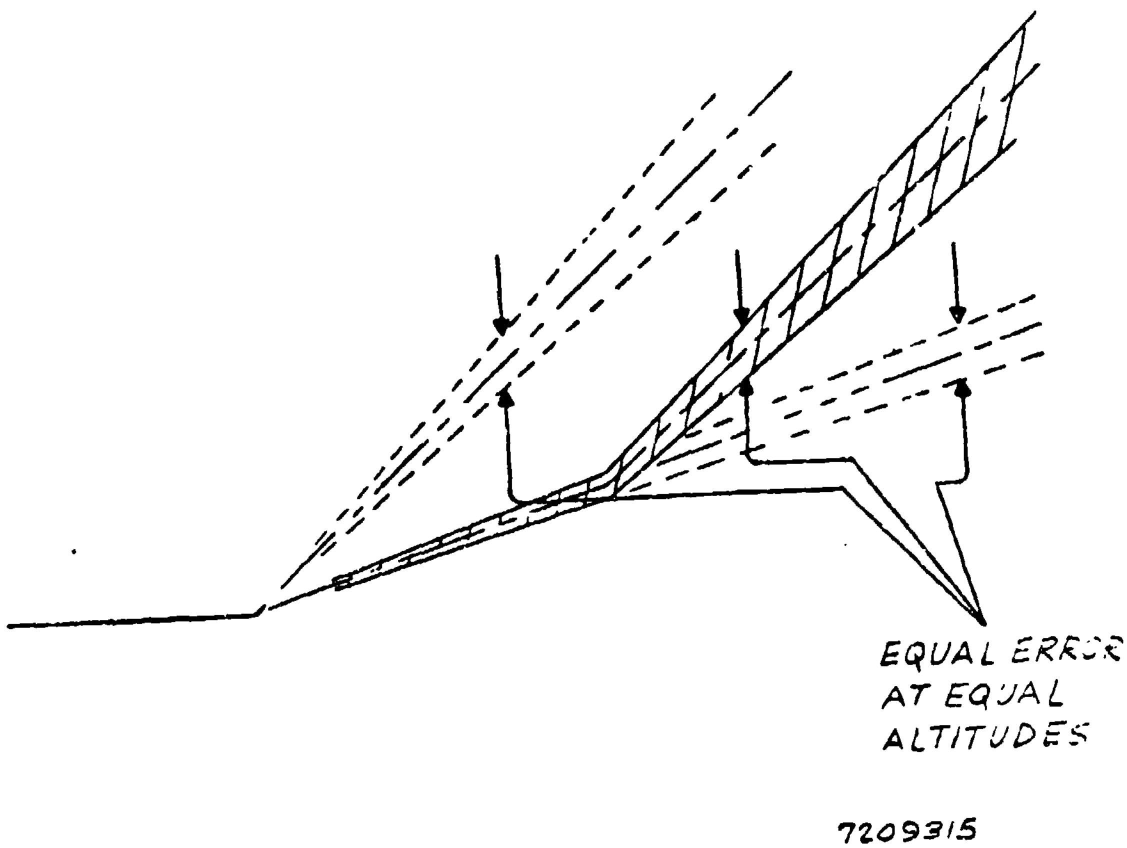

Figure 9-11. Vertical Deviation During Two-Step Glidepath:
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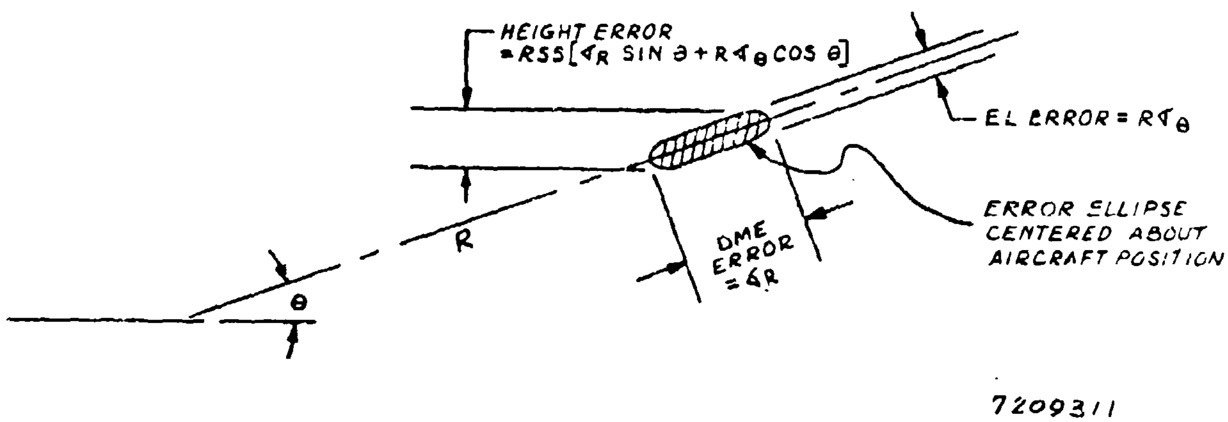


Figure 9-12. Composition of Offset Glidepath Error

contributions of both EL_1 and DME errors as shown. (There is negligible difference in results whether DME is co-located with EL-1 or located at runway stop end). The formula for the approximate error in offset glidepath has been derived by Hughes (Ref. 14) and is indicated on the figure.

Tradeoff curves of DME error vs EL angular error were prepared using the above formulas to illustrate what is required to support various two-step operations. Several such curves are plotted in figure 9-13. Each curve represents a constraint defined by initial glidepath, final glidepath and transition height. The position measurement accuracy constraint was chosen so that MLS contributes a 50% variance to tolerable aircraft deviations from initial glidepath at the transition height.

All points lying within a given constraint curve denote acceptable combinations of EL and DME errors for flying the maneuver associated with the curve. Points are indicated for Cat. I, II and III systems per the specifications in Table 9-10. It is concluded that Cat. II/III MLS accuracies will be sufficient to support a wide range of possible two-step maneuvers; probably a wider range than will prove necessary for sometime to come. Furthermore, Cat. I MLS bias accuracies are sufficient to support $6^\circ/3^\circ$ transition at approximately 400 feet altitude. This may be a practical maneuver to consider for all runway facilities.

(7) Rollout Guidance

Rollout guidance is primarily a Cat. III requirement. MLS is to supply AZ and DME guidance to steer the aircraft along the runway, generate turnoff areas, measure runway remaining and possibly steer the aircraft through the turnoff onto the taxiway. Precise requirements have not been spelled out with regard to rollout guidance, but some consideration has been given to the capability of MLS to perform adequately in this regard.

With respect to lateral guidance on the runway, it is presumed that the azimuth accuracy is sufficient if it already meets touch-

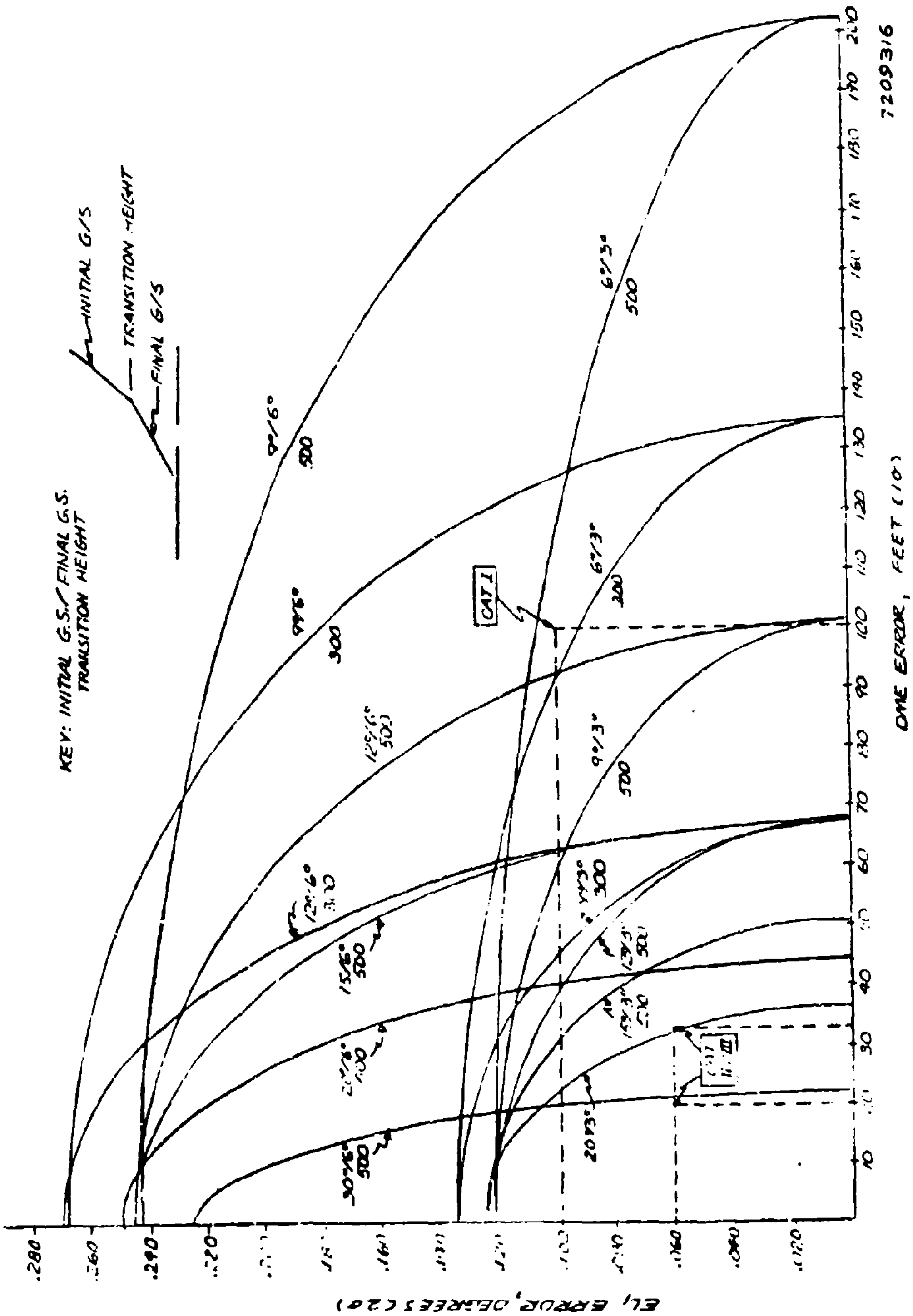


Figure 9-13. Accuracy Tradeoffs For Two-Step Approaches

With respect to distance and velocity measurements during rollout, an analysis in Section 1.1.1.1, Part G shows that the following performance is achievable with the DME baseline equipment design:

Condition: 10 ft/sec^2 deceleration

Results: velocity error = 10 mph
distance error = ±20 feet bias (1σ)
±20 feet noise (1σ)

A discussion with UAL consultants indicated that this performance appears adequate for manual control of aircraft speed during deceleration and for generation of exit cues.

With respect to the accuracies required for guidance on turnoffs and (taxiways, it has been shown (Ref. 15) that a very stringent DME accuracy (±3.6 ft. 1σ) may be required for rollout on a 75 foot wide taxiway. We believe this points up a need to define the high-speed turnoff configurations, taxiways, distance from runway to which guidance must be provided, typical steering errors and other significant determinants of performance before a requirement may be stated for this phase of airport guidance. Further, the question of whether the MLS system should be charged with primary responsibility for off-runway guidance is still to be determined.

(8) Military Transportable Systems Requirements

The findings of the simulation and analyses of signal quality were reviewed for applicability to the military transportable systems serving fixed and rotary-wing aircraft at short fields or helicopter pads.

Three configurations were considered:

- E co-located (primarily VTOL)
- E split-site (VTOL and CTOL)
- G split-site (VTOL and CTOL)

The tentative performance requirements are given in the summary Table 9-10. These were extrapolated from the similar civil systems evaluated with some exceptions. The following describes the general rationale used:

Bias - Elevation bias for the split-site configurations was made identical to that specified for the corresponding civil system since diversity of vertical profiles are presumed to apply.

For the co-located system, the MLS RFP appendix states that the minimum glideslope for this facility will be 5°. The bias error was adjusted upward to produce the same vertical deviation in feet that is produced on a 3° glideslope at a conventional D/E configuration.

Azimuth bias was reviewed for both deviations at runway threshold and for compatibility with other navigation systems. With respect to the latter criterion, the lateral error at maximum range (10 nmi) was set to be no greater than errors achievable from Loran, which is presently the most precise tactical radio navigation system. Loran accuracies were taken (optimistically) as 0.05 nmi or ±300 ft. (2σ). The equivalent azimuth angular bias error is $\pm 0.26^{\circ}$ (2σ). This error specification will also satisfy lateral deviation requirements at decision height for runways up to approximately 7000 feet in length.

Noise and Data Rate - The split-site systems presumably will serve fixed-wing aircraft making coupled approaches, and therefore the results of the simulation studies were used. The data rate for these systems was set at 10 Hz to take advantage of the fact that only two guidance functions are present on the signal format.

For the co-located system it is unclear as to whether it is planned for VTOL aircraft to perform only manual approaches or coupled approaches as well. (The tolerability of beam noise during a coupled VTOL approach was not assessed during Phase I, but it is planned in Phase II to conduct an initial VTOL simulation study to provide a data base in this area.)

Present systems serving only manual VTOL approaches have noise levels considerably above those allowable for coupled CTOL and STOL approaches (and, by extrapolation, probably coupled VTOL approaches as well). These systems utilize smaller antennas than would otherwise be required. Therefore, in order to facilitate the achievement of a highly portable system, it was assumed (subject to further review with users) that the co-located system will not be required to support coupled approaches.

It was then necessary to estimate a tolerable level of beam noise for a manual approach. It was assumed that the major effect of excessive noise is to produce a jitter in the deviation indicator that is annoying to the operator. A needle jitter of approximately 1/20 coursewidth is believed to be acceptable. A beam noise specification of 0.2° (2σ) in Elevation and 0.3° (2σ) in Azimuth were chosen to produce an acceptable needle jitter under the following assumptions:

data rate = 10 Hz
receiver output filter time constant = 0.5 sec
localizer course width = $\pm 2.75^{\circ}$
glideslope course width = $\pm 1.75^{\circ}$

Coursewidths were obtained from the U.S. Army Tactical Landing System (TLS) specification (Ref. 18) assuming a minimum glideslope of 5°, as indicated for the co-located system in the MLS RFP. When combined in RSS with bias errors for the E co-located system, the results compare favorably to total TLS accuracy specifications. The specification for this system will be thoroughly reviewed during Phase II based on:

review with users
new data available from the E feasibility model
results of VTOL flight simulations

(9) Carrier Landing System Requirements

The landing system concept being considered for carrier application is discussed in the prototype plan. This system is envisioned to perform the functions of both the SPN-42 and SPN-41 and consists of separate elements to be placed in each of their respective existing locations.

"System A" performs the all-weather landing function of the SPN-42. "System B" provides guidance to Category I ("Mode II") decision heights and also provides flight path monitoring for System A operation.

An examination of the factors involved in determining adequate landing system performance in the carrier situation indicated that special detailed analyses and possible simulation work was needed to provide an independent estimate of requirements.

Unique factors affecting performance are:

- carrier motion
- guidance element geometry
- control system stability: remote target tracking vs on-board flight path computation
- stabilization accuracy
- multipath effects

A detailed study of these problems is planned for Phase II.

In the interim, we are using as a baseline the existing specifications for the SPN-41 and SPN-42 (Refs. 19, 20, 21). These are:

SPN-42

Bias (both axes) = .3 milliradians (1σ)
= $.034^\circ$ (2σ)

Noise (both axes) = .4 milliradians (1σ)
= $.046^\circ$ (2σ)

Range Accuracy = 10 feet

SPN-41

Bias and Noise (Azimuth) = $\pm 0.2^\circ$ (2σ)
Bias and Noise (Elevation) = $\pm 0.1^\circ$ (2σ)

In the absence of specific information, the latter specifications were split evenly between bias and noise.

A brief examination of existing specifications in light of operational requirements was made to assess differences compared to other MLS configurations and to identify any areas of possible relaxation of requirements.

- Bias errors were evaluated in terms of their effect on positional deviations at critical points during the approach and landing. These are indicated in Table 9-16, and point up a possible relaxation at least in azimuth measurement accuracy.
- Range accuracy appears to be a critical determinant of lateral touchdown error and relates directly to DME error in the MLS system. Apparently the shipboard DME accuracy requirement will be significantly more stringent than for the other configurations.
- Noise accuracy requirements are somewhat tighter than those indicated as a result of the Phase 1 simulation studies on CTOL aircraft. Possible reasons were put forth for this difference:

  (1) Differences between the control system responses of high-performance fighter aircraft and those of the transports evaluated in the simulation.

  (2) Computation of flight path deviations and control commands external to the aircraft. The outer (position) control loop is then divorced from other on-board sensors. This was found, in the simulation study for transport aircraft, to require very stringent limits on acceptable beam noise.

Resolution of these issues is left to Phase II.

TABLE 9-16

COMPARISON OF SPN-42 MEASUREMENT ERRORS TO ALLOWABLE FLIGHT PATH DEVIATIONS

Phase of Flight	Allowable Deviation (Approx)	Contribution of SPN-42 Angular Bias Error (3 milliradian rms)	Contribution of SPN-42 Range Error (10 feet)	Percent of Allowable
Touchdown	± 20 feet longitudinal (1σ)	1.8 feet (1σ)		9%
	± 10 feet lateral (1σ)	.1 foot (1σ)	3-5 feet	1% 30%-50%
Automatic Wave-Off: Mode I 8000 feet to touchdown	± 40 feet vertical	2.4 feet (1σ)		6%
Automatic Wave-Off: Mode I 2400 feet to touchdown	± 22 feet, lateral	.7 feet (1σ)		3%

d. Assessment of Multipath Effects

In the SC-117 "noise" specification, no differentiation was made between multipath effects and other sources of jitter in the angle data. Multipath arising from many very small reflecting objects in the environment will appear very similar to a low-level random jitter normally associated with "noise". However, as pointed out in the section on multipath, a larger-amplitude multipath signal was a "signature" that is substantially different in nature from random jitter.

In order to assess the tolerability of multipath effects when operating with an automatic flight control system, sample multipath signatures were prepared, using the analytical tools previously developed, for review by Sperry Flight Systems. The signatures were typical of those that would be experienced on a standard centerline approach at a high-density terminal. Signatures were prepared for Az, EL-1, and EL-2 guidance beams. The characteristics of the signatures are given in table 9-17. Typcial signatures for the EL-1 multipath are plotted in figure 9-14.

The following facts were noted with respect to the multipath phenomena:

- Our analysis showed that high-amplitude phenomena will rarely be seen. These will exist concurrently with very large structures of very particular shape, construction and location with respect to approach paths.
- The phenomenon for any given major reflecting object happens once during a given approach; i.e., is non-repetitive.
- The least tolerable type of multipath effect would be a long-duration, highly sinusoidal phenomenon of moderate frequency (above 1 Hz) which the pilot would interpret as an instability in the AFCS.

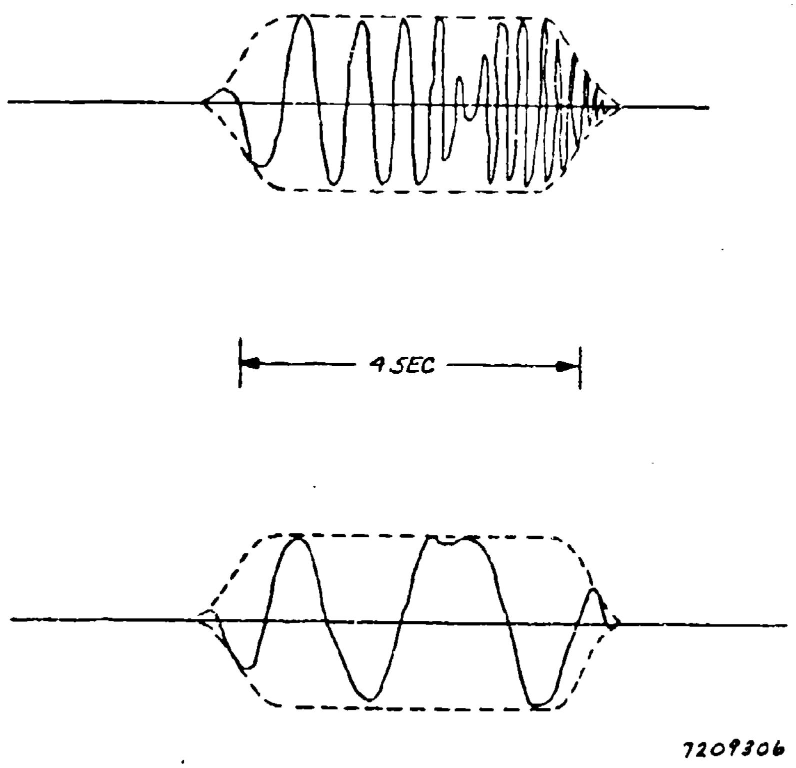


Figure 9-14. Multipath Signatures of Short Duration, Typical of EL-1

Table 9-17. MULTIPATH SIGNATURE CHARACTERISTICS

EL-1 Multipath

Location of Aircraft: 150 - 1500 feet height

Duration: 4 Seconds

Amplitude (Peak): .005 - .03

Frequency: Any frequency between 0 Hz and 3.5 Hz (½ data rate)

EL-2 Multipath

Location of Aircraft: Near Touchdown

Amplitude: Less than .01°

Az Multipath

Location of Aircraft: Near threshold

Duration: 3 seconds

Amplitude: .06°, upper bound, seen rarely (one data sample in several approaches)

.03°, infrequently seen (sample per second during signature)

.01°, continuous noise-like ripple, center frequency approximately ½ data rate (3.5 Hz).

It was Sperry's assessment that the most significant multipath was that for EL-1. For the signatures and amplitudes shown, if there are no special filters or rate limiting techniques applied at the output of the MLS receiver, column motions in excess of .4 inches may be observed. Although this amplitude is in excess of the tolerability limits derived during the UAL pilot survey, it was felt that the phenomenon might be acceptable, based on the following considerations:

- The frequency is changing throughout the duration of the interference and will not appear repetitious.
- Gain scheduling in the autopilot will reduce the magnitude of the noise as the aircraft proceeds towards touchdown.

- o The interference will constitute an isolated instance on any particular approach.

If however, a beam rate limiter is assumed to exist at the output of the MLS receiver, as dictated by noise studies of the CTOL autopilot, the effect of the interference is completely changed and is much less bothersome. Three areas of interest are apparent with the beam rate limiter installed.

For frequencies less than 1 radian per second, or .16 Hz, which are not modified by the rate limit, the disturbance would appear to a pilot more as a beam bend than noise. This is true since less than a full cycle of beam deviation would occur during the transient. This consideration is valid up to 0.25 Hz, assuming a 4-second multipath signal.

For frequencies greater than 0.25 Hz, the deviation signal to the autopilot drops rapidly as a result of limiter action. In the frequency range from .3 and on, the sinusoidal input to the autopilot will result in acceptable levels of attitude deviation (less than ±0.5° of pitch attitude).

When the multipath frequency exceeds 1 Hz, the short duration and low level of column activity should be tolerable. These conclusions are based upon studies of sinusoidal noise inputs made early in the program with both rate coupled and conventional autopilots similar to that used in the 747.

With respect to the EL-2 multipath, the amplitude was considered to be low enough so that it would not be noticeable in a typical noise environment.

With respect to the Azimuth Multipath, the following points were made:

- o The single pulse of amplitude .06 degrees should not produce any unacceptable aircraft response. This level is below that specified for noise to produce a Cooper Rating of two and the autopilot filtering, coupled with aircraft response, will tend to smooth the response. These considerations along with the fact that the multipath occurs only once in several approaches which will have the effect of making it appear as a gust, combine to make this level of multipath appear acceptable.

- The same rationale as quoted for the .06 degree level of noise is applicable to the .03 degree noise with the additional comment that the fact that three pulses will appear in a given approach, the effect on the airplane may appear similar to mild turbulence.
- The .01 degree continuous level of noise of 3 seconds duration with a center frequency of 3.5 hertz is well below the levels specified for noise and will in all probability not be detectable by the pilot or passengers.

The general conclusion of this investigation was that multipath phenomena which may occasionally be seen during a final approach will not create a tolerability problem with respect to the pilot/AFCS interface. The rate limiter (or other output data smoother) removes any possible EL-1 multipath problem and is required for noise effects in any event. Multipath effects off-runway centerline were not evaluated inasmuch as it is assumed that an RNAV or equivalent computer will be required to process the MLS guidance signals into AFCS commands. These computers contain complementary filters which are required to smooth VORTAC data and will remove any MLS multipath effects.

e. Summary and Conclusions

The results of the signal quality study are summarized in Table 9-18. They include the following new information:

- Revised bias and noise specifications
- Revised system data rates
- Granularity limits

		B	D	E	(4) F	(4) G	(4) I/K (CTOL)	(4) K (STOL)	E (MIL Colocated)	E (MIL SPLIT SITE)	C (MIL SPLIT SITE)	(4) I (Carrier) System "A"	System "B"
Az	Bias (2σ) (2)	.275°	.275°	.275°	.066°	.066°	.043°	.20°	.26°	.26°	.26°	.034°	.15°
	Noise (2σ) (3)	.12° [illegible]	.12° (10)	.12° (10)	.065°	.065°	.065°	.084°	.2° (6)	.12°	.12°	.046°	.15°
	Data Rate	10 Hz	10 Hz	10 Hz	7 Hz	7 Hz	7 Hz	7 Hz	10 Hz	10 Hz	10 Hz	10 Hz	5 Hz
	Granularity	.025°	.025°	.025°	.025°	.025°	.025°	.03	.05°	.025°	.025°	.025°	.025°
	Interruptions	5 sec	5 sec	5 sec	2 sec	2 sec	2 sec	2 sec	5 sec	5 sec	2 sec	2 sec	5 sec
EL_1 (5)	Bias (2σ) (2)	N/A	.10°	.10°	.06°	.06°	.6°	.06°	.17°	.10°	.66°	.034°	.07°
	Noise (2σ) (3)		.12°	.12°	.08°	.08°	.08°	.08°	.2° (6)	.12°	.12°	.046°	.07°
	Data Rate		10 Hz	10 Hz	7 Hz	7 Hz	7 Hz	7 Hz	10 Hz	10 Hz	10 Hz	10 Hz	5 Hz
	Granularity		.01°	.01°	.01°	.01°	.01°	.025°	.05°	.01°	.01°	.01°	.01°
	Interruptions		3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec
EL_2	Bias (2σ) (2)	N/A	N/A	N/A	N/A	N/A	.05°	.09°	N/A	N/A	N/A	N/A	N/A
	Noise (2σ) (3)						.036°	.036°					
	Data Rate						14 Hz	14 Hz					
	Granularity						.035°	.05°					
	Interruptions						.5 sec	.5 sec					
DME	Bias (1σ) (2)	300'	100'	32'	32' (7)	20' (7)	20' (7)	20' (7)	32'	32'	20'	10'	N/A
	Noise (1σ) (3)	100'	100'	32'	32'	20'	20'	20'	32'	32'	20'	10'	
	Data Rate	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	10 Hz	
	Interruptions	5 sec	5 sec	5 sec	2 sec	2 sec	2 sec	2 sec	5 sec	5 sec	2 sec	2 sec	5 sec
Min Guidance Altitude		150'	150'	150'	50'	50'	8'	8'	50'	50'	50'	3'	150'

Table 9-18. SIGNAL QUALITY SUMMARY

Notes to Table 9-18.

1. All values are for the total system, including ground and airborne equipment.

2. Bias-error which is constant over more than 20 seconds.

3. Noise includes all spatial and temporal effects.

4. Back Course guidance at these facilities has same accuracy requirements as first course guidance. Back course guidance at shipboard I configuration is optional.

5. EL-1 data is to be interpreted as the angular error at the minimum usable glidescope. At a given height within the coverage volume the angular error at a greater elevation angle shall not produce a linear equivalent error which exceeds that for the minimum glideslope.

6. Noise specification is based on support of manual approaches only.

7. Total system should have this capability. For aircraft using glideslopes 6° or under, the allowable DME error is 32'.

8. These accuracies apply at the centerline of the runway at the decision height.

9. The combination of DME and A error at maximum range should not exceed 0.1 nmi. circular error.

10. Assumes course width adjustment by varying receiver output scale factor.

- o Signal interruption limits
- o Specifications for military systems

All performance figures are necessarily tentative pending review of assumptions made and further investigation of special requirements, such as carrier landings, high performance military aircraft, and VTOL approaches. Hazeltine and our subcontractors ha planned considerable extension or our analytic and simulation work in these areas during MLS Phase II.

We are aware of other studies of signal quality requirements, most notably the work reported by the Transportation Systems Center on data rate and noise requirements for CTOL aircraft (Ref 22, 23). One of the conclusions of the TSC study was a recommendation that the role of MLS-only flare guyidance be reconsidered in light of the susceptibility of the AFCS to noisy data.

The results of the simulation study performed by Sperry for Hazeltine have pointed towards a means of achieving a satisfactory flare maneuver, using MLS-only data and non-linear output data processing. Preliminary simulation of performance in wind shear indicated that touchdown dispersion will be adequate; further verification will be provided in Phase II.

We realize that the conclusions of the Hazeltine-sponsored simulation study are not universal, having been limited in scope with respect to certain design philosophies, control systems evaluated, simulation techniques and sample sizes. While we plan to expand the scope of our studies during Phase II we strongly recommend to the Government that an effort be made among the various investigators in this field to come to a common ground with respect to critical assumptions that will otherwise create a diversity of conclusions that will be difficult to reconcile. Key assumptions are in the areas of:

- o diversity of aircraft/control systems to be evaluated.
- o simulations and other evaluation techniques, including consideration of systems nonlinearities (which we

believe to be quite important) and accumulation of statistically significant data bases.

o applicability of output data processing techniques

o integrity philosophy, including the use of non-ground referenced sensors and the use of non-MLS sensors in a primary or a backup role.

We believe an excellent time for such an effort would be at the inception of Phase II. At that time considerable information should be available as to the result of MLS contractors' efforts as well as the progress being made elsewhere. Results based on common viewpoint would then be available for refinement of systems techniques planned for MLS Prototype Phase.

7. Coverage Requirements

a. General

This subsection presents the results of the study of MLS coverage requirements performed during TACD. The study consisted of examining existing and projected operational requirements and existing system specifications to validate and extend the coverage requirements set forth by SC-117. The major issues addressed were as follows:

It was necessary to validate the existing SC-117 coverages with respect to the variety of operational requirements and functional services defined. The majority of SC-117 coverages appear satisfactory in light of available knowledge of requirements at this time. However, some are quite sensitive to requirements that as yet have not been fully defined (for example, terminal area route structures and altimetry sources) and so the revised performance specifications remain tentative and are subject to further review as more information becomes available. In the interim, we are recommending the following refinements to the requirements:

- proportional guidance should be available throughout the defined coverage region for all configurations.
- for all configurations, EL-1 coverage at long ranges is specified only to ±20° azimuth, under the assumption that barometric altimetry will be preferably for use away from the runway-centerline zone.

- a growth objective was defined to cover Terminal Area navigation over the full 360° in azimuth.
- the back-course azimuth guidance coverage was redefined to take advantage of antenna placement at the threshold end of the runway.

It was required to complete elements of the coverage definition which SC-117 left undefined:

- for elevation guidance elements, coverage requirements near the runway as a function of glideslope
- volumetric coverage of EL-2 guidance element
- coverage requirements for a typical STOL-port.

Military requirements were to be reflected in the coverage performance picture.

- transportable systems requirements were included per existing specifications and information in the MLS RFP.
- special coverage requirements for carrier landing systems were formulated.

The remainder of this subsection presents the detailed results of the study. The material is divided into sections on wide-area (volumetric) coverage, near-runway coverage, special military requirements and a revised coverage performance summary.

b. Wide-Area Coverage Requirements

The coverage requirements for configurations B through K as envisioned by SC-117 are summarized in table 9-19. These were segmented for review into two groups, based on the nature of the most stringent requirements involved:

- approach and landing - (all configurations) covering support of operations presently associated with landing guidance: final approach, flare and takeoff/missed approach.

Table 9-19. SC-117 COVERAGE REQUIREMENTS FOR MLS

GUIDANCE CHARACTERISTICS		CONFIG. B	CONFIG. D	CONFIG. E	CONFIG. F	CONFIG. G	CONFIG. I	CONFIG. K
COVERAGE								
(Elevation Guidance)	HORZ	NA	±20°	±20°	↑	↑	±40°	±60°
	VERT	NA	1°-8°	1°-20°			1°-20°	1°-20°
	RANGE	NA	20 nm	20 nm			20 nm	20 nm
(Azimuth Guidance)	HORZ	±20°	±20°	±20°			±40°	±60°
	VERT	1°-5°	1°-8°	1°-20°	SAME AS "D"	SAME AS "E"	0° to 20° 7/	0° to 20° 7/
	RANGE	20 nm	20 nm	20 nm			Stop end to 20 nm	Stop end to 20 nm
DME	HORZ	±20°	±20°	±20°			±40°	±60°
	VERT	1°-5°	1°-8°	1°-20°			0° to 20° 7/	0° to 20° 7/
	RANGE	20 nm	20 nm	20 nm	↓	↓	Stop end to 20 nm	Stop end to 20 nm
PATH LOCATION								
	EL.	NA	FIXED 2°-6°	2°-15° Air Select.	FIXED 2°-6°	2°-15° Air Select.	2°-15° Air Select.	2°-15° Air Select.
	AZ.	extended centerline	→	→	→	→	Air Select. ±40°	Air Select. ±90°

- terminal area navigation - (configurations I and K) supplying guidance for complex three-dimensional maneuvers throughout all or a portion of the terminal area.

The two areas are treated separately in the discussion that follows.

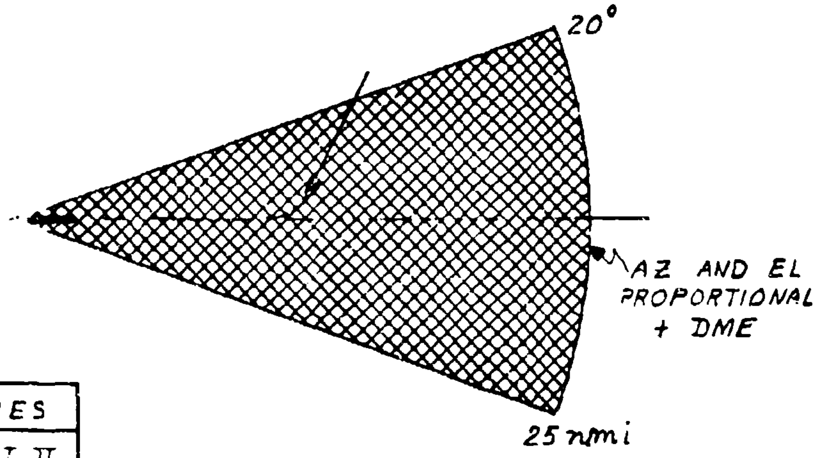
(1) Requirements for Approach and Landing

This section discusses the rationale for the coverages defined above in terms of meeting the requirements for approach and landing, which we define as: final turn, convergence on runway centerline, pitchover onto glideslope, flare, touchdown, and takeoff/missed approach. These are the principal services offered at configurations D, E, F and G and are encompassed within the borader services of the I and K configurations.

Figure 9-15 shows the refined coverage requirements for Azimuth, Elevation 1 and DME. The rationale is grouped by dimensional parameter: range, lateral and vertical. Separate discussions of flare and takeoff/missed approach are also given. Of the three guidance signals discussed, DME and azimuth coverage are always made identical, so that two-dimensional lateral position is always available for monitoring progress along flight path.

Range. Minimum requirements for all civil airports and other fixed-base installations are recommended at 25 nmi. The following factors have been considered:

- uniformity of operational procedures at all airports implies uniform maximum range
- coincidence of AZ, and EL and DME guidance range limits is convenient (but not essential) so that proper receiver operation on all signals can be checked out simultaneously.



	GLIDESLOPES	
	CAT. I	CAT. II
D	2°-7.5°	—
E	2°-15°	—
F	2°-7.5°	2°-7.5°
G	2°-15°	2°-12°

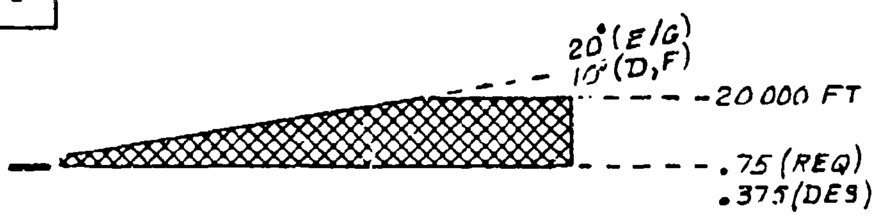


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Figure 9-15. Approach and Landing Coverage Requirements

- present maximum range of the ILS localizer is 25 nmi (nominal) and it is understood that use is occasionally made of the signal at this range.
- parallel runway operations, where runway separations are reduced to a fraction of a mile, may require near-maximum range. Transition from the enroute system, acquisition and validation of the MLS signal, convergence on azimuth course and settling to precision path following could use up 15 nmi at 180 kt. If followed by a 10-nmi parallel-runway approach this would require 25 mile coverage.
- elevation guidance should provide the opportunity for noise-abatement procedures as early as possible during the approach. Vertical noise-abatement maneuvers involve establishing high glidepaths as far out as possible. A 6° glidepath (assumed to be maximum for CTOL) can be intercepted at 15,000 feet at 25 nmi; this is believed to be more than adequate.

Lateral Coverage. There was a signficant decision to be made as to whether to provide fully proportional azimuth guidance or a narrow (±3° or 4°) region of proportional guidance plus "clearance" signals, as in ILS. Since the nominal mission of SC-117 configurations D through G is to provide centerline azimuth guidance only, an ILS-type of coding was possible. An evaluation of the required guidance-signal generating equipment for the ILS mode showed a potential cost savings over that required for full proportional coverage. Possible compatibility problems between a K-type receiver and an ILS-type coding were foreseen, however.

Full proportional coverage was chosen in order to derive the most benefit for the users with proportional receivers who will frequent these facilities. Benefits are believed to include the improved ability to converge on the runway centerline approach from wider (to 90°) intercept angles. This would be especially significant in performing centerline intercepts close to the runway threshold. For example, assume a 1-1/2° per second final turn to a centerline approach, for any aircraft speed between 60 and 180 kt, followed by at least 1 minute of azimuth course-following prior to reaching the decision height. This turn will lie entirely within a ±20° proportional coverage region. For manual intercept, it is planned to include in the proportional receivers a wide coursewidth (±10°) selection to assist in this maneuver. For users having RNAV/MLS capability, transision from VORTAC to MLS would occur at the ±20° coverage limit and a final course to intercept would be followed under MLS guidance.

Vertical Coverage. Vertical Coverage specifications include minimum angle, range of proportional guidance, maximum angle and maximum altitude. The following factors have been considered in defining the coverage limits:

- Minimum azimuth (and DME) coverage angle at all installations is in conformance with ICAO ILS specifications: reception at 2000 ft (1000 ft desired) at maximum range in level terrain. L coverage is not as useful at low altitudes and maximum range therefore the minimum angle for EL was retained at 1°.
- The proportional coverage region is defined to provide a range of glidepaths even at the simplest installations.
  - For the D and F configurations, the range of glidepaths provided was extended slightly (from the SC-117 figure of 6°) to 7.5°. This was done to accommodate the range of glidepaths for which the most satisfactory STOL experience has been accumulated. It should extend the utility of these configurations and only a very minor ground equipment cost is involved.

- For the G configurations, a maximum Category II glideslope of 12° is provided, as compared to the SC-117 figure of 15°. This small reduction in glideslope is believed to be reaslitic from the viewpoint of operational limitations of Category II approaches, and is significant from the viewpoint of practical antenna design and siting considerations. This topic is discussed further in the subsection on near-runway coverage below.

- Maximum elevation coverage was chosen to be at least one coursewidth above the maximum usable glidescope. For a 7-1/2° glideslope, a 2° coursewidth has been found acceptable during tests at NAFEC (Ref 7). Extrapolating to a 15° glideslope, 5° margin should be adequate.

- 20,000 feet maximum altitude per SC-117, is expected to be adequate, even with growth of terminal airspace. At a STOL port, 10,000 feet altitude is recommended as being adequate.

Flare Guidance Coverage. Coverage for the flair guidance element is shown in figure 9-15. This element operates at Ku-band and as such requires careful definition of coverage limits to conserve power requirements. Flare guidance will typically be used during the last 100 feet of descent. A minimum of one minute of reception will be required prior to that, for acquisition and validation. This establishes, the range of glidepaths covered, the maximum range of 3.5 nmi and height of 2000 feet. The elevation coverage limit of 10° is determined by the requirement to provide 1 minute of clear reception for an aircraft descending at 15° glideslope, as indicated in figure 9-17. Assuming that during the last minute of flight, the aircraft is stabilized on the runway centerline course, a nominal coverage width of ±10° is also specified. A lower limit of 1° on vertical coverage is provided for future high-V_{so} aircraft with longer and shallower

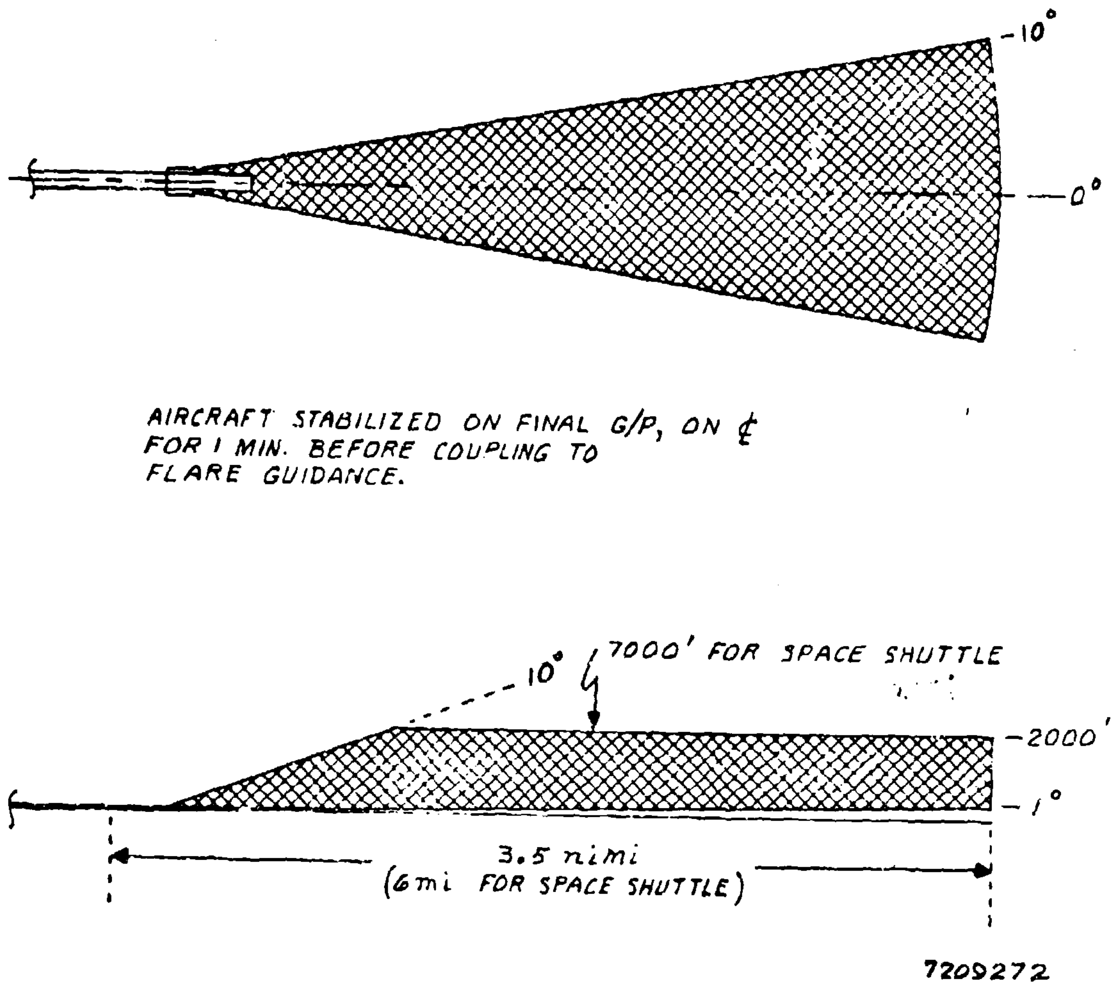

Figure 9-16. Flare Guidance Coverage

flare profiles. A flare guidance element designed for use with the U.S. space shuttle should have the extended coverage indicated on the figure, assuming an aircraft approach speed of 240 knots on an 11° glidepath, with a flare initiation approximately 1.5 miles from touchdown.

It should be pointed out that each additional mile of EL-2 coverage in 50 mm/hr rainfall requires approximately 10 db more transmitter power. Therefore we will continue to examine the requirement for EL-2 range with the following possibilities in mind:

- o tolerating a shorter validation period based on estimates of validation confidence levels to be performed during Phase II.
- o utilizing directive Ku-band airborne antennas

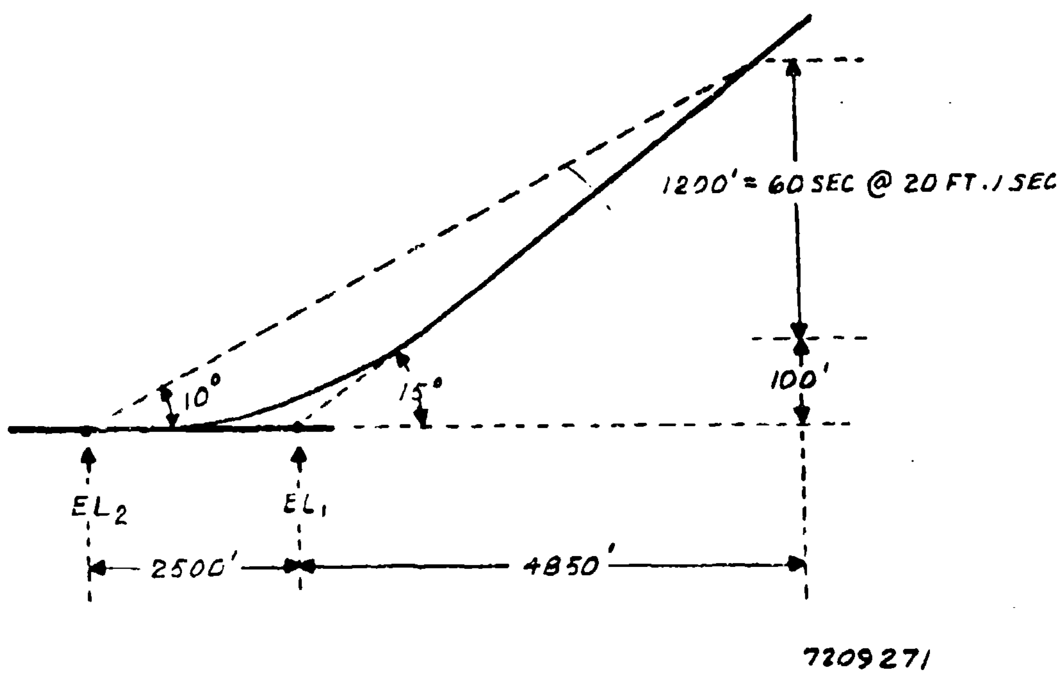

Figure 9-17. Computation of Maximum EL-2 Elevation Coverage Angle

Takeoff/Missed-Approach Guidance Coverage - The azimuth and DME guidance coverage requirement for this function is shown in figure 9-18. As described in the functional services section, we elected to include back-course azimuth/DME guidance in Cat II configurations as well as for Cat III, to increase the utility of those airborne equipments which will include a back-course guidance antenna/front end.

SC-117 described the missed approach guidance as originating at the stop end of the runway, so that the equipment could be colocated with the front-course azimuth and DME equipment. However, this produces a "cone of silence" as the stop end is overflown This cone of silence could be on the order of 12 seconds or greater duration, depending on aircraft speed, and altitude. It was the opinion of our consultants that while such an interruption might be tolerable on an occassional basis in connection with a missed approach, it might discourage regular use as a departure aid. Therefore we have modified the requirement to show guidance originating at the threshold end. Most often, this will not involve significant additional expense inasmuch as back-course guidance will be provided by the guideline elements for the reverse runway direction. The ICAO AWOP (Ref 4) has specified that missed-approach guidance should extend to 2000 feet altitude over the runway and 5000 feet altitude past the runway end, and provide guidance to 5 nmi. This latter figure was also used in SC-117. We were advised by UAL consultants that this coverage should extend to 10 mile in order to be worthwhile for regular use. Therefore this range was adopted and the maximum altitude was scaled upwards accordingly.

For a single-runway airport (e.g. F and G) lateral backcourse coverage of $\pm 20^{\circ}$ is believed to be sufficient to cover the initial turn to go-around or for departure. For high-density and/or parallel-runway applications (I and K) there may be a need for increased coverage for precision guidance during curved departures. There was insufficient information available on proposed departure procedures in this case, and we are therefore retaining the SC-117 coverage figure of $\pm 40^{\circ}$ for further validation during future phases.

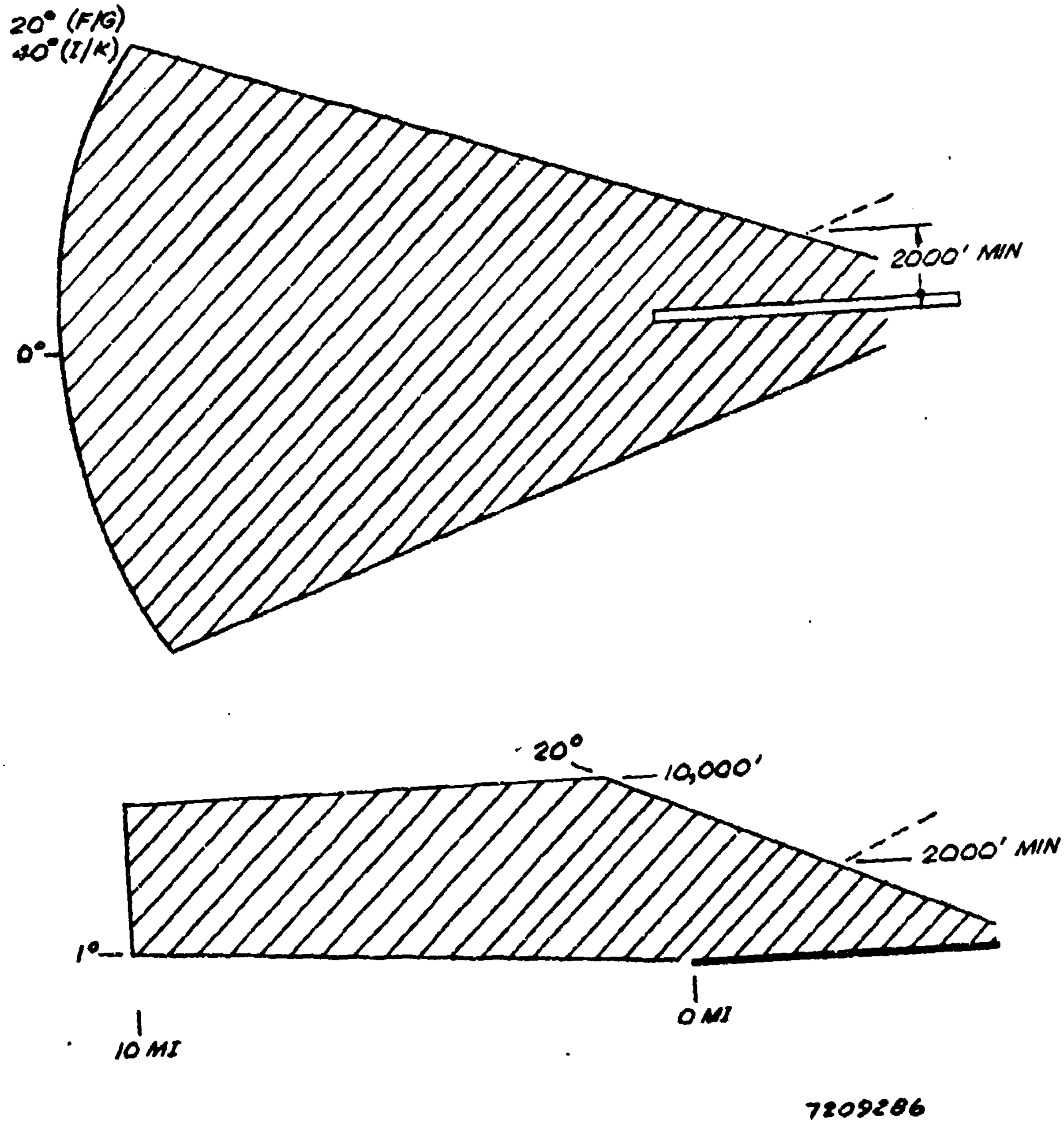

Figure 9-18. Takeoff/Missed Approach Coverage

(2) Requirements For Terminal Area Navigation

Curved and complex maneuvers associated with advanced ATC concepts for speed-class sequencing, precise time-of-arrival control, etc, have infinite possibilities in terms of flight paths. It appears that these more sophisticated maneuvers will ideally be performed in a manner analogous to area navigation today, under the control of an RNAV computer, with ATC surveillance and monitoring. We have therefore defined these operations as "Terminal Area Navigation" and include under this category the requirement to support all phases of flight outside the nominal "approach and landing" zone defined above.

Our motivation in discussing this requirement separately is that:

- o the MLS system design should consider a functional module satisfying this requirement to be installed at any airport with sufficient traffic-handling requirements.
- o the MLS system design should contemplate growth to provide full 360° coverage for this function.

Assessing the suitability of the azimuth coverage requirement for terminal area maneuvers is difficult because of the variety of routing schemes in use and planned for the future. Some illustrations are given in figures 9-19 thru 9-22.

Figure 9-19 (Ref 13 p-37) shows the noise-abatement approach paths ("Canarsie Approach") to JFK runways 31 R and 31 L. These curved approaches are made in visual conditions utilizing approach lights, but could be followed by users equipped with MLS and an appropriate path computer. They illustrate the fact that curved approaches which terminate very near the runway threshold may not lie comfortably within a $\pm 60^{\circ}$ coverage sector. Note that the approach to 31L begins very shortly after entering the coverage sector, leaving little time for signal acquisition and validation before the turn starts.

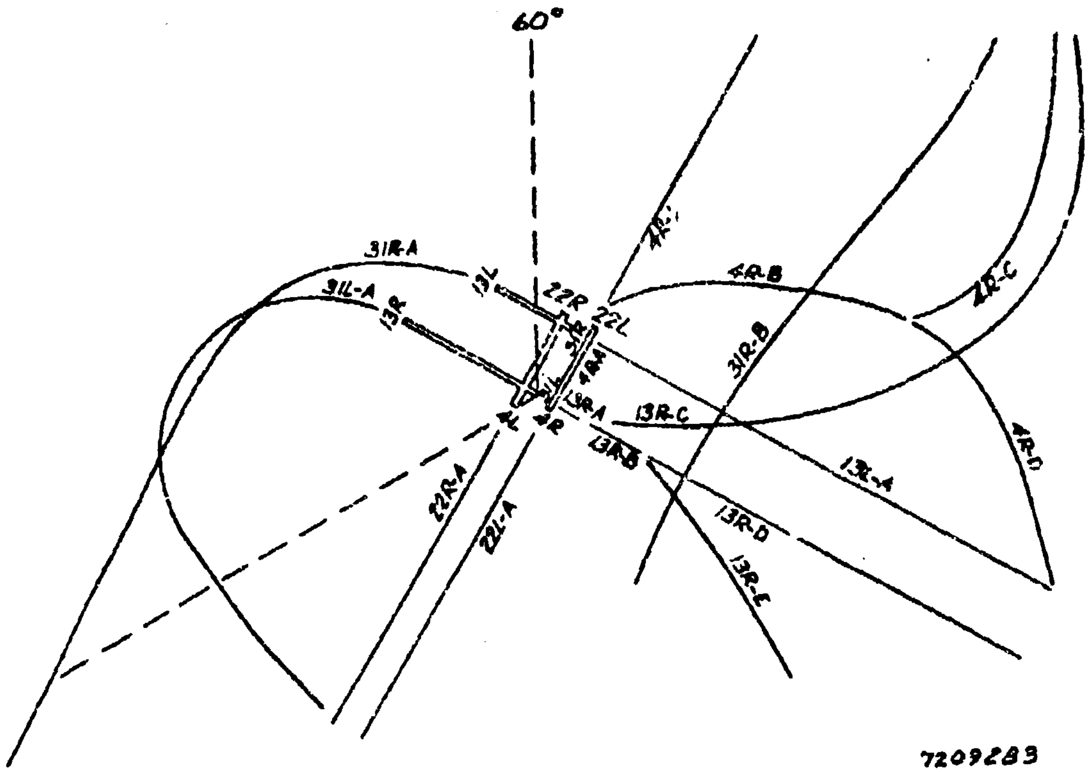

Figure 9-19. Major Flight Paths for JFK International Airport

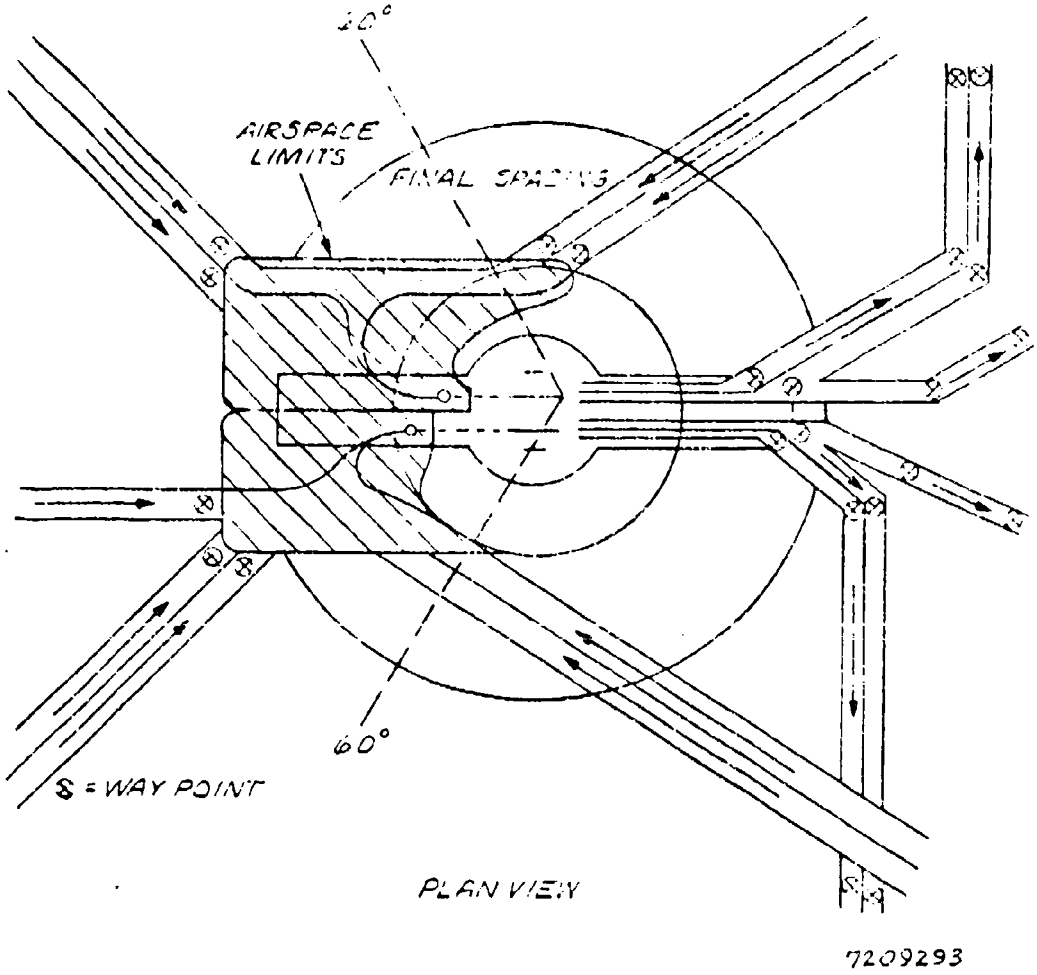

Figure 9-20. Schematic of High-Density Terminal Area Airspace

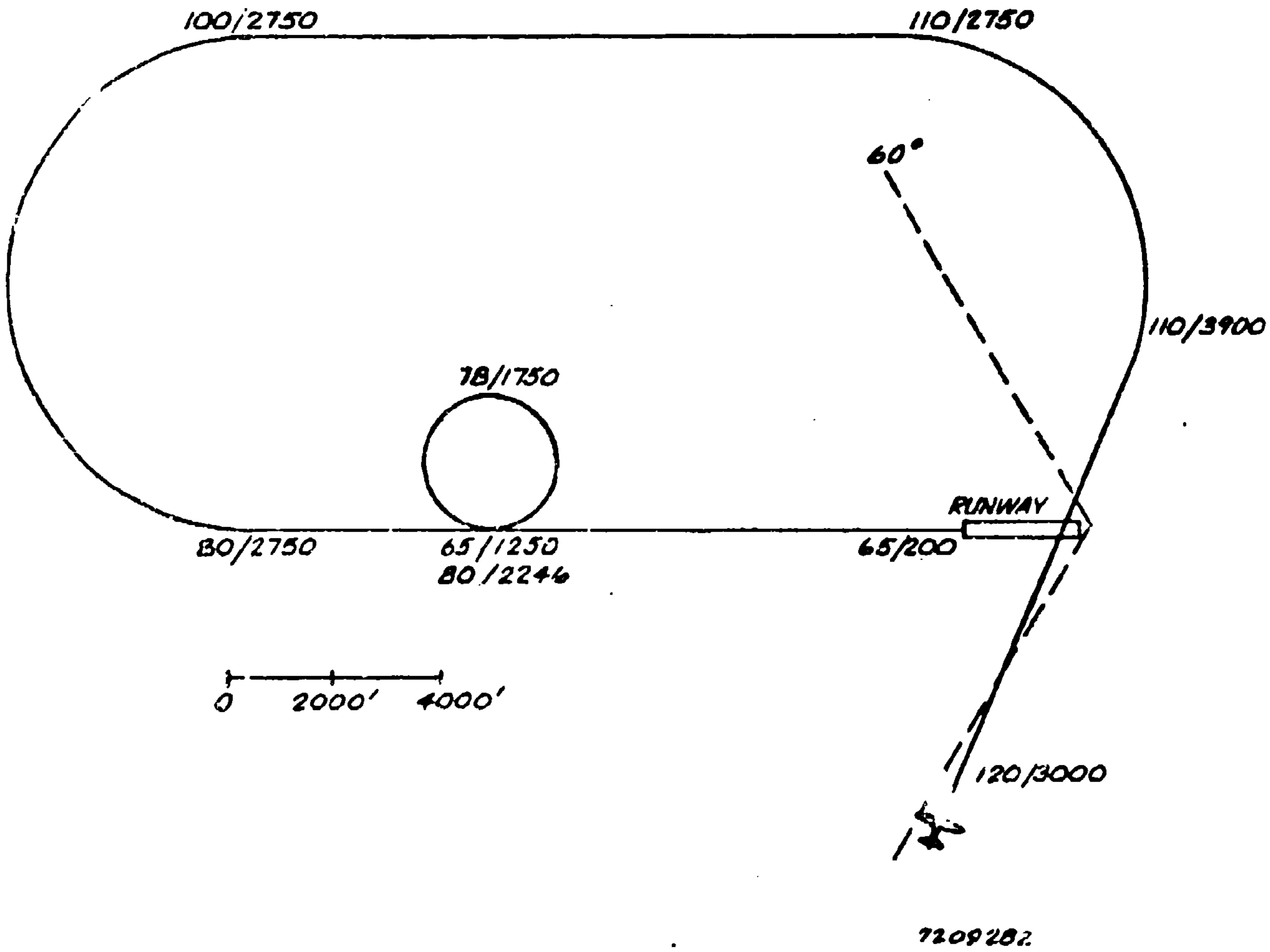

Figure 9-21. Possible Complex STOL Approach Path

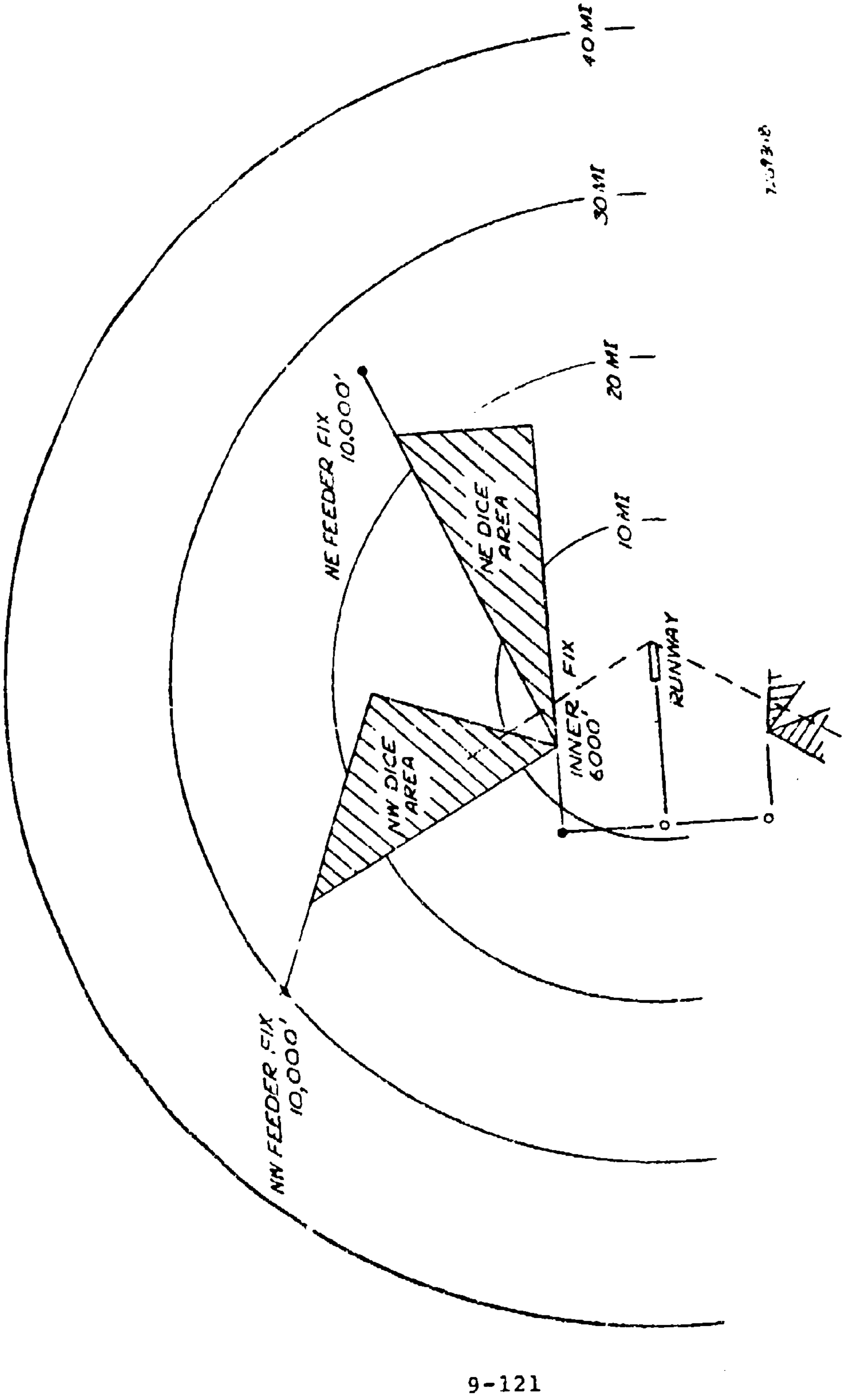

Figure 9-22. Typical Metering and Spacing Geometry

Figure 9-20 (Ref 12, p. 225) illustrates a schematic of a future high-density airspace concept for a multiple-parallel runway airport. The limits of high-density airspace, where MLS guidance is most critical, is principally within MLS coverage limit of $\pm 60^{\circ}$.

Figure 9-21 (Ref 16) illustrates a possible complex approach path to a STOL port. Here, even though a spiralling descent/ deceleration maneuver is made, the maneuver again lies entirely within the $\pm 60^{\circ}$ limits.

Figure 9-22 illustrates a possible metering and spacing concept which uses path stretching maneuvers to make good precise time of arrival at the runway approach gate. Intially this will be done by ATC vectoring but conceivably could be performed under MLS/RNAV control in the future. Typically 4 "feeder fixes" are disposed around the airport at approximately 30-40 nmi range. The corresponding path stretching areas are similarly distributed in azimuth and in general will not fall with the MLS coverage sector. However the final downwind leg is within precision time of arrival coverage and may be used for final adjustments.

A survey recently made by the FAA (Ref 17) estimated the proportion of aircraft within the busiest airspace sections associated with three high-density terminals. The results are tabulated in table 20. The conclusion is that most, but not all traffic at these facilities does lie within a wedge similar to the MLS coverage of $\pm 60^{\circ}$.

Table 9-20. PROPORTION OF AIRCRAFT IN THE BUSIEST AIRSPACE SECTORS OF THREE MAJOR AIRPORTS

AIRPORT	WIDTH OF BUSIEST SECTOR	PORTION OF TRAFFIC USING
JFK	120°	60° - 70°
ORD	140°	"MOST"
LAX	50°	97%

Our conclusion is that the $\pm60^\circ$ (40°I) coverage specification should be reaired until more definitive information is available as to the plans for airspace utilization at those busy terminals where the K configuration MSL will be installed. However, consideration should be given to future growth to a full 360° coverage in azimuth. At least two methods appear feasible to accomplish this. One is applicable at crossed runways where two or more orthogonal MLS configurations could be operated simultaneous on different channels, with overlapping coverages. However, this is not universally applicable and entails transitions between systems in the terminal area. Another approach is to provide a single MLS system with 360° azimuth coverage.

Figure 9-23 shows two levels of terminal area navigation coverage: A "required" coverage extending $\pm60^\circ$ in azimuth, as in SC-117, and a "desired" coverage providing 360° coverage.

The vertical profile of the coverage area is similar to that for the approach and landing requirement previously described. Maximum coverage height of 20,000 feet is considered adequate for future terminal area control. The specification of 20° maximum coverage angle is based on the following.

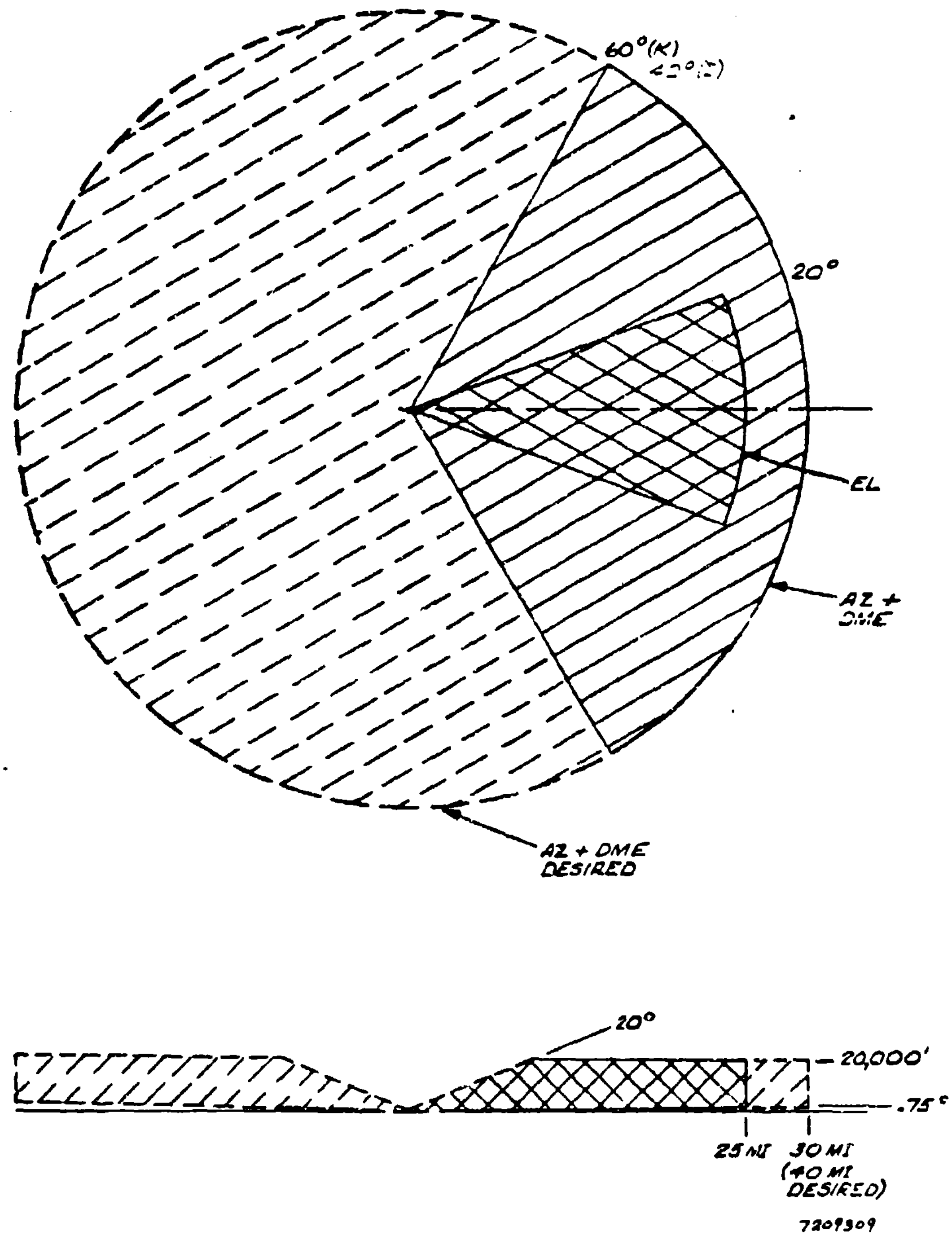

Figure 9-23. Terminal Area Navigation Requirement

- An aircraft executing down wind approaches parallel to and near the runway. A coverage angle of 20° would cover a (STOL) flight path at 2000 feet altitude parallel to and within one mile laterally of the runway.

- A metering and sequencing system (as above) wherein the inner fix is at an altitude of 6,000 feet and may be within 5 A. mi or less of the runway.

As mentioned above, investigations to date have not confirmed the need for MLS elevation data during terminal area navigation. This is covered in the section on system trades.

c. Near-Runway Coverage Requirements

Design of the MLS elevation guidance elements (EL-1 and EL-2) require careful definition of the coverage required near the runway surface. This requirement was not completely defined by SC-117.

The significance of this specification lies in the fact that the need to project on elevation guidance signal over the runway from an offset antenna sets the azimuth coverage requirement for that antenna. There is a practical limitation on planar elevation antennas of approximately 45° azimuth for signals of acceptable quality. It happens that for increasing glideslopes, the azimuth angle required to provide coverage over the runway to the minimum guidance altitude also increases. The following specifications provide adequate coverage of a wide range of glideslopes without requiring azimuth coverages above 34°, for reasonable antenna offsets. The issue of elevation antenna siting is covered in Section 1.1.3.2.

(1) El-1 Coverage

Figure 9-22 describes EL_1 coverage near the runway surface for Cat. I and Cat. II operation (Cat. III requirements with respect to EL_1 and identical to Cat. II).

With respect to Figure 9-24 (a), lower limits of coverage are set at 50' below the decision height, per SC-117 recommendations.

This provides a "safety margin" below the decision height for Category I/II approaches during which time the pilot can react to visual cues and take over manual control of the aircraft. Also, during Cat. III approaches it allows the auto-pilot to ride the EL-1 beam to approximately 65 feet, shortly before flare initiation.

The remainder of the coverage definition is based on four surfaces through the EL-1 element (GPIP) as indicated.

The range of glideslope supported for configurations D, K_{STOL} and K_{CTOL} are also indicated. Three deviations from SC-117 are noted:

- SC-117 Requirements indicated a maximum glideslope requirement of 15°, but it is unlikely that a STOL would land at greater than 9°-12° glideslope even under strong headwinds. Although VTOL aircraft could execute such maneuvers, it is unlikely that VTOL aircraft will land routinely on the same runway as fixed wing aircraft. Additionally, a VTOL aircraft could use a 12° (or lower) glideslope when such a landing is necessary.
- As mentioned previously, we are providing glideslopes up to 7.5° at D (and F) configurations. This could increase the utility of the facility for STOL noise-abatement approaches.

	①	②	③	④
D	1°	[illegible]°	6°	8°
K CTOL	1°	2°	12° RE[illegible] 15° RE[illegible]	20°
KSTOL	1°	5°	12° RES 15 DES	20°

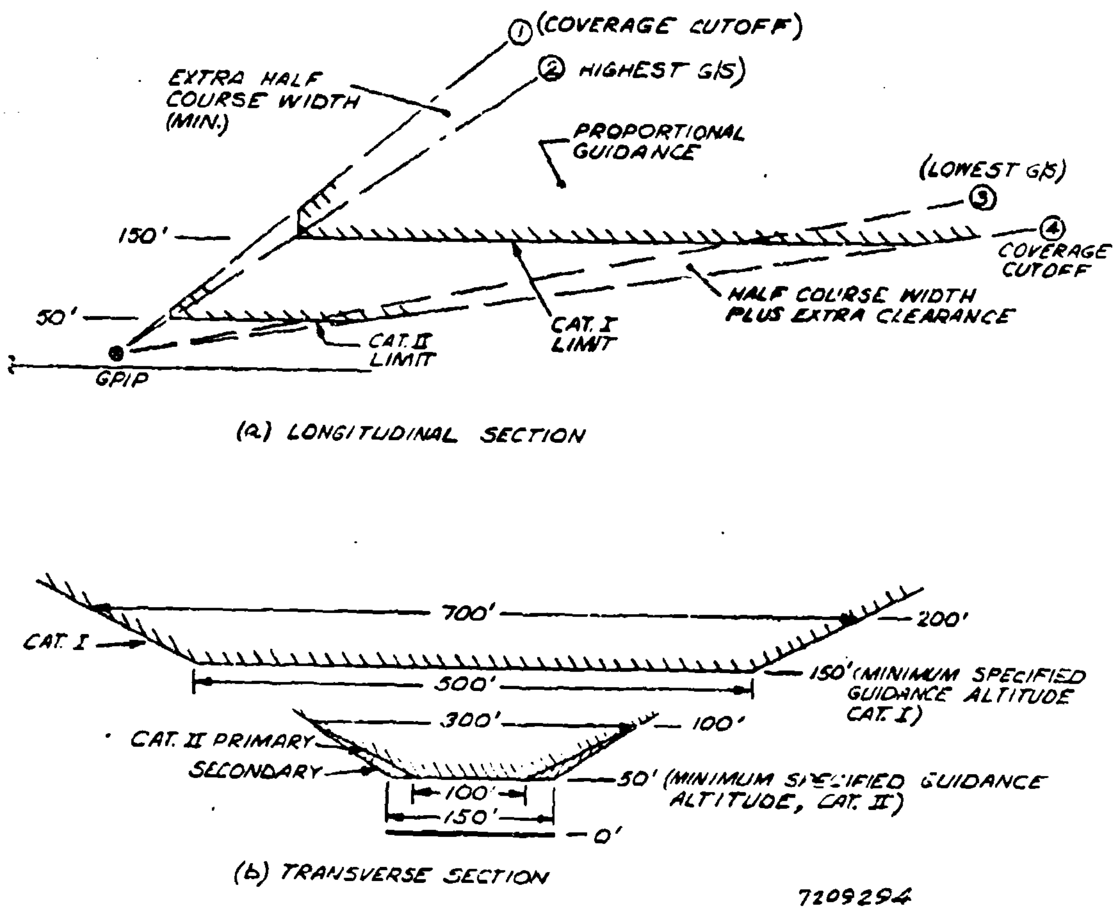

Figure 9-24. EL-1 Coverage Near Runway

- CTOL requirements indicate a minimum glidepath of 2^o which seems unnecessarily low for a STOL port. An inspection of planned FAA obstacle clearance surfaces for STOL ports confirms this. Minimum glideslope for STOL ports has therefore been estimated as 5^o. If further STOL port plans modify this estimate the coverage requirement will change accordingly.

A transverse section of the coverage volume is shown in figure 9-24(b). The rationale for setting the coverage limits was that the full guidance accuracy should not be limited to the runway centerline but should extend laterally over a region at least wide enough to cover all points from which a safe landing could be made from breakout altitude. (It should be noted that present ILS coning errors increase as one moves off runway centerline away from the glideslope transmitter.)

- For Cat. II, full accuracy will be available over a "primary" region equal to twice the runway width at 100 feet altitude. This is based on the FAS definition of a "successful landing" for CAT II (FAA AC-120-29) wherein the "cockpit must be within, and tracking so as to remain within, the lateral confines of the runway extended". A "secondary" buffer zone with slightly degraded accuracy serves to maintain glideslope track until (presumably) the landing is aborted.
- From the CAT I decision height, many aircraft possess sufficient maneuverability to correct for significant lateral displacements in time for a safe landing. A nominal 700' coverage width (equal to the localizer coursewidth) has been provided at this height.

(2) EL-2 (flare guidance) Coverage

Coverage for the flare guidance element was not completely defined in SC-117, and in any event requires separate definition for STOL runways. Definitions are given in figure 9-25 for CTOL and STOL runways. With respect to the side views of coverage, coverage extends down to 8' above the runway, for a distance along the runway estimated to correspond to the touchdown limits for the applicable range of final glideslopes. All final glideslopes are assumed referenced to the EL-1 (GPIP) location. With respect to the plan views, nominal coverage widths of twice the runway width provided. The rationale is that past the flare initiation height, excessive lateral deviation should not be compounded with a dropout of EL-2 guidance.

d. Coverage equipments for military systems.

The coverage requirements for the military transportable systems and carrier landing systems are unique because each reflects special operational requirements. The coverage requirements assumed are presented in this subsection. These are based on our best knowledge of user needs at this time and we plan to review these thoroughly with all users during Phase II.

(1) Military Transportable Systems.

A tentative set of performance requirements for the military transportable system is given in table 9-20. The special operational requirements which affect coverage performance of the military transportable systems are:

- o The need for portability; to achieve which, size is traded for maximum range via the selection of Ku band operation.
- o The terrain environment, which results in the requirement for adjustable coverage cutoffs.
- o In the case of the E colocated configuration, the restriction to VTOL aircraft only and the desire to perform multiple simultaneous landings on different azimuth courses.

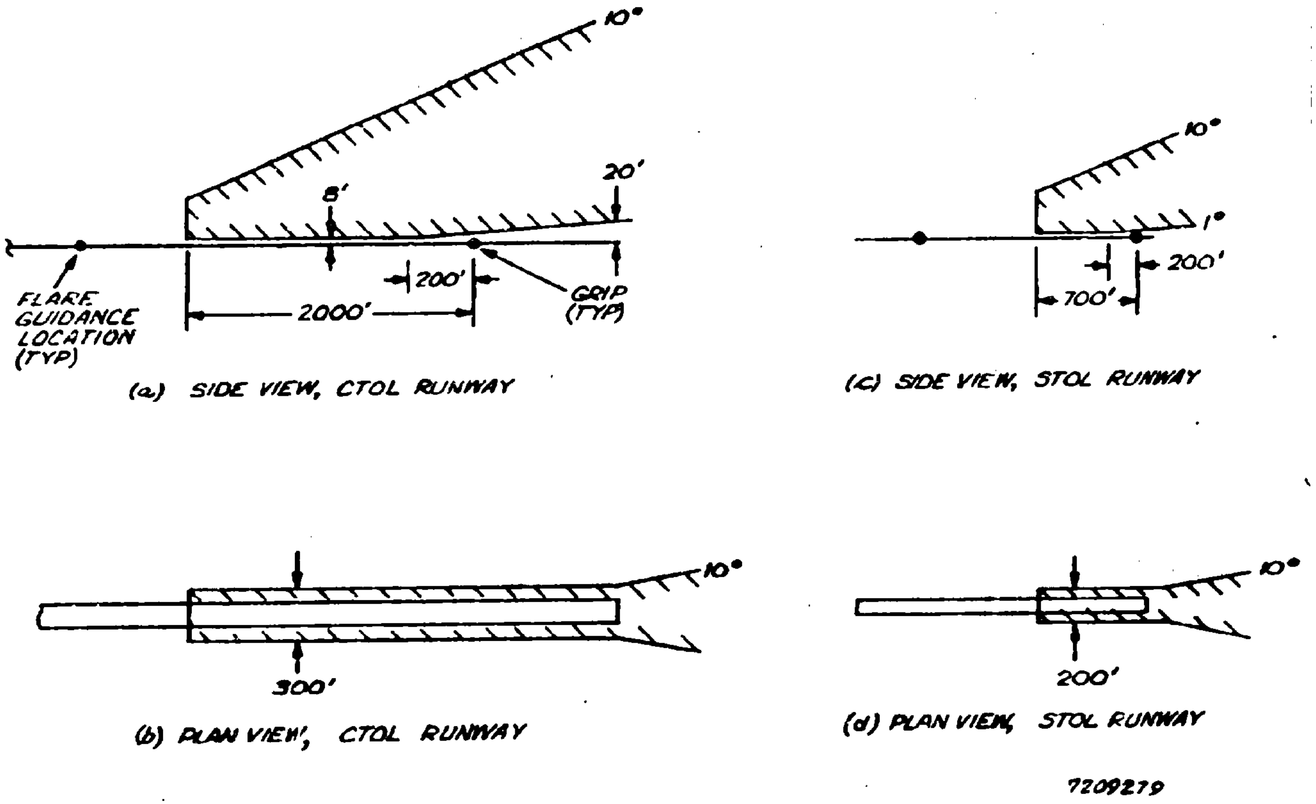

Figure 9-25. EL-2 (Flare Guidance) Near Runway

Table 9-21. COVERAGE REQUIREMENTS FOR MILITARY TRANSPORTABLE SYSTEMS

	SYSTEM SOURCE	US ARMY E COLOCATED MILS RFP	US ARMY E SPLIT MLS RFP	USMC G SPLIT MRAALS SPEC
	HORZ	± 60°	± 30°	± 20° 2
AZ	VERT	0° - 20° 1	0° - 20° 1	0° - 20° 1
	RANGE (miles)	10	10	10
	HORZ	± 60°	± 30°	± 20°
EL	VERT	0° - 20° 1	0° - 20° 1	0° - 20°
	RANGE (miles)	10	10	10
	HORZ	360°	± 30°	± 20°/360° 3
DME	VERT	0° - 20°	0° - 20°	0° - 20°
	RANGE (miles)	10	10	3/20 3
PATH	EL	5° - 15°	3° - 15°	3° - 15°
LOCATION	AZ	Air Selectable	Centerline	Centerline

Notes:
1. Lower cutoff adjustable up to 5° to compensate for terrain and other obstacles.
2. Right/left azimuth cutoff adjustable to compensate for terrain and other obstacles.
3. Coarse/fine DME

The sources for the requirements information were: for the US Army systems, the existing performance description in the MLS RFP and, for the USMC system, the specification for the interim MRAALS system.

It should be noted that the located E system planned for testing during feasibility will demonstrate full capability for coverage cutoff adjustment.

(2) Carrier Landing System Requirements

The system concept envisioned at this time for the carrier landing application involves two antenna systems: one on the superstructure for all-weather landing guidance (System "A") and one at the present SPN-41 locations (System "B") for backup and flight path monitoring. This system is outlined in the Prototype Systems Development Plan.

The coverage requirements of the System A antenna are quite unique because of its location and considerations of multipath. For this function, a Doppler MLS transmitter provides Ku-band radiation for separate frequency coding of AZ and EL angles in space. For this dual function, a single antenna is mounted on the superstructure at a height affording a clear view of the glide path. Figure 9-26 shows a view of the coverage sector including the approach glide path in space. It is a pictorial view from the transmitter antenna location 30 ft above the deck. The receiver antenna location is on the nose of the approaching aircraft, 8 ft. above the deck at touchdown. The glideslope is the flight path of the receiver antenna, where the angle coding is to be received.

The glideslope is to be illuminated with the frequency coding by the direct path from the transmitter. The glideslope image in the deck is not to be illuminated, by the indirect (reflection) path, because that would cause interference and would carry an erroneous coding in EL.

The nominal coverage cone, shown in figure 9-26 is 50° wide and $\pm 10^{\circ}$ from the horizon, It is to be illuminated selectively over the band A-A. The lower edge of this band has a sharp cutoff at the runway centerline (CL) for discriminating between the glideslope and its image in the deck. The upper edge of this band is 8 higher

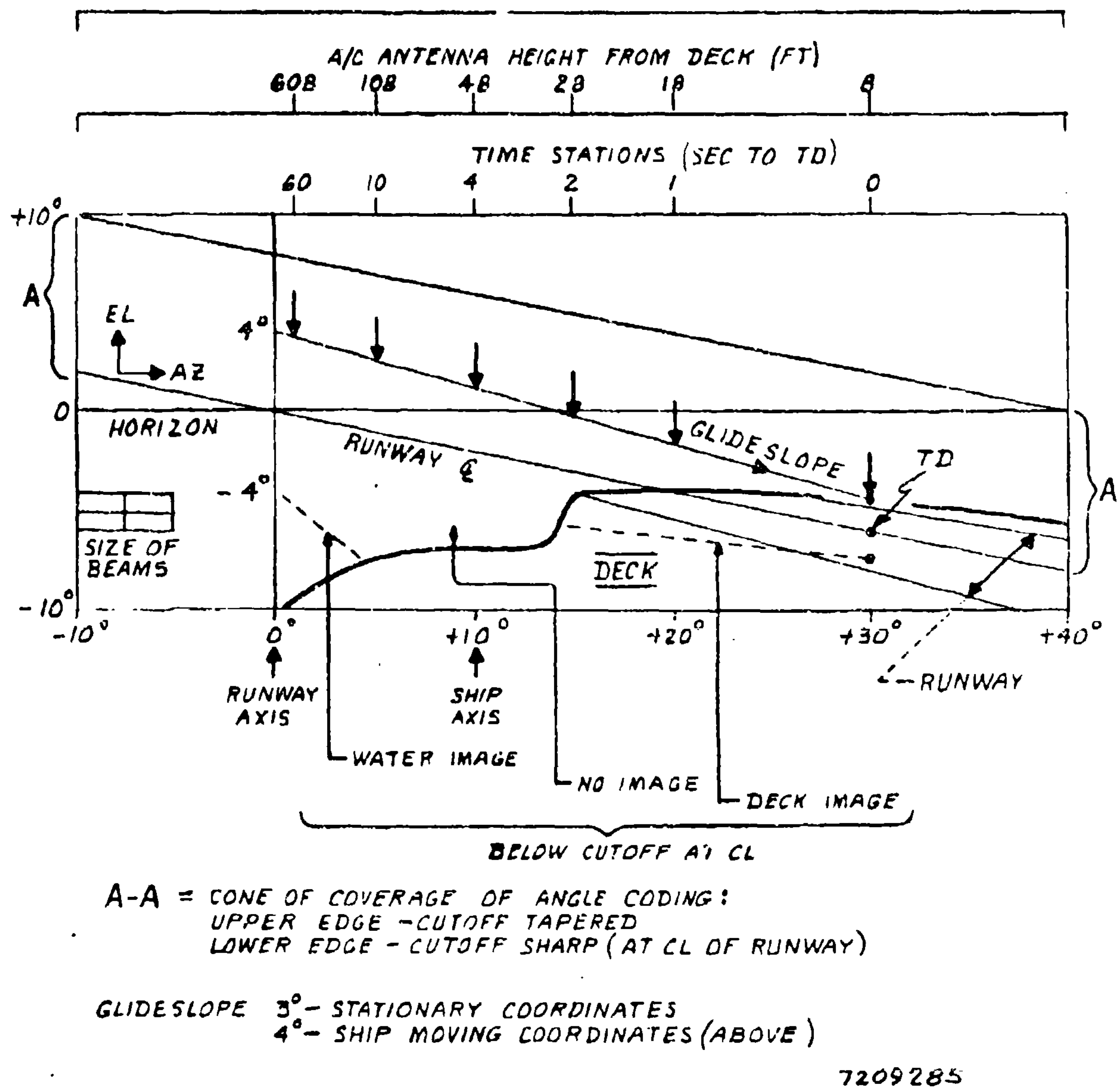

Figure 9-26. Aircraft as seen from antenna on superstructure for limits of coverage

and may have a tapered cutoff which is easier to accommodate. This bandwidth is twice as high as required to include the entire glide slope.

It should be noted that the stabilized Doppler guidance signal will be available simultaneously to all users anywhere within the coverage sector stated. An aircraft executing a go-around maneuver will enter the coverage sector between 30° and 40° from the ship's axis, and can use MLS guidance to complete the go-around and make good a precise time slot in the sequencing. Range coverage of System A, operating at Ku band, will be approximately 10 nmi.

System B is to be located at the position of the present SAN-41 antennas and will radiate a signal format which is compatible with the same airborne receiver needed for System A. The coverage is specified somewhat wider than the present SPN-41 coverage to allow acquisition sooner and to provide coverage as close to touchdown as feasible. These are:

	Az_B	EL_B
Horizontal Coverage	± 20°	-20° to + 30°
Vertical Coverage	0° - 30°	1° - 10°

The coverages for system B are illustrated in figure 9-27.

The range (assuming C-band operation) is to be approximately 25 nmi.

e. Summary

Table 9-22 summarizes the refined coverage requirements as they stood at the close of TACD. The major changes and additons are:

- o Definition of baak course requirements
- o Definition of extended azimuth coverage requirements for elevation antennas
- o Provision of additional elevation coverage at D and F faulties

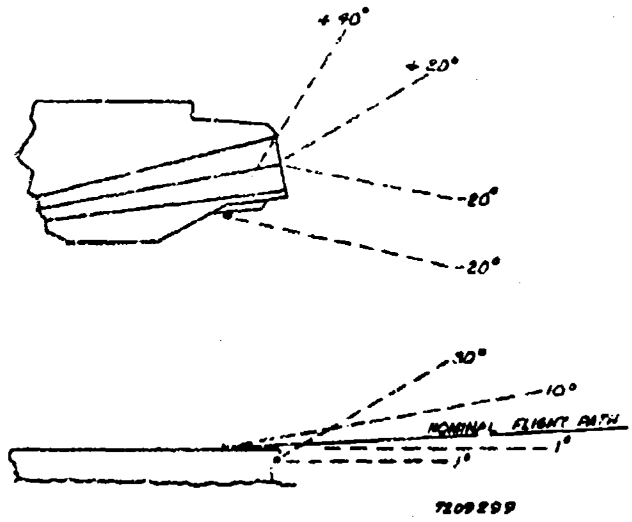

Figure 9-27. Coverage for Carrier Landing System

- o Inclusion of coverage requirements for special military requirements.

8. Auxiliary Data Requirements

As a result of the study of operational requirements, three new auxiliary data requirements were identified for inclusion in the auxiliary data format. They were:

- o Time-of-day - This was included to allow for possible future terminal control concepts in which a time-slot is assigned to a given aircraft for 4-dimensional navigation to threshold. Time-of-day permits automatic synchronization of the onboard control system with ATC and all other aircraft.

- o Barometric Setting - This was included to provide an alternative means for obtaining runway barometric setting. Present verbal communications permit interpretation

Coverage		C	D	E (1)	F	G	C/A 2 (CTOL)	K (STOL)	D (Col. Colocated)	E (Mil Split Site)	G (Mil Split Site)	I (Carrier) System A	I (Carrier) System B
Az	Horiz	120°	120°	120°	120°	120°	140°(1), 140°(1)	110°	160°	190°	120° (4)	-10° to +40°	120°
	Vert	.75° - 5°	.75° - 10°	.75° - 20°	.75° - 10°	.75° - 10°	.75° - 20°	.75° - 20°	0° - 20° (3)	0° - 20° (3)	0° - 20° (3)	110° (5)	1° - 10°
	Range	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	10 n.m.	10 n.m.	10 n.m.	10 n.m.	25 n.m.
El_1	Horiz (1)	N/A	-20° to +40°	-20° to +45°	-20° to +45°	-20° to +45°	-20° to +45°	-20° to +45°	165°	130°	-20° to +45°	-40° to +40°	-20° to +40°
	Vert		1° - 20°	1° - 20°	1° - 10°	1° - 20°	1° - 20°	1° - 20°	0° - 20° (3)	0° - 10° (3)	0° - 20° (3)	110°	1° - 10°
	Range		25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	10 n.m.	10 n.m.	10 n.m.	10 n.m.	25 n.m.
El_2	Horiz (1)	N/A	N/A	N/A	N/A	N/A	-10° to +30°	-10° to +30°	N/A	N/A	N/A	N/A	N/A
	Vert						0° - 10°	0° - 10°					
	Range						3.5 n.m.	3.5 n.m.					
BCAS/ECOM	Horiz	N/A	N/A	N/A	120°	120°	140°	140°	N/A	N/A	N/A		120°
	Vert				1° - 20°	1° - 20°	1° - 20°	1° - 20°					1° - 20° (6)
	Range				10 n.m.	10 n.m.	10 n.m.	10 n.m.					10 n.m.
DME	Horiz	120°	120°	120°	120°	120°	140°(1), 140°(1)	140°	160°	175°	120°	-20° to +30°	N/A
	Vert	.75° - 5°	.75° - 10°	.75° - 20°	.75° - 20°	.75° - 20°	.75° - 20°	.75° - 20°	0° - 20°	0° - 20°	0° - 20°	110°	
	Range	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	10 n.m.	10 n.m.	10 n.m.	10 n.m.	
Path Location													
	Azimuth	Extended Center Line (7)	Extended Center Line (7)	Extended Center Line (7)	Extended Center Line (7)	Extended Center Line (7)	140° I, 180° 2	140°	160°	Extended Center Line	Extended Center Line	Extended Center Line (8)	Extended Center Line
	El	N/A	2° - 7.5°	2° - 15°	2° - 7.5°	2° - 12° (CAT II) 2° - 15° (CAT I)	2° - 12° (CAT II) 2° - 15° (CAT I)	5° - 12° (CAT II) 5° - 15° (CAT I)	3° - 15°	2° - 15°	2° - 12° (CAT II) 2° - 15° (CAT I)	3° Nom. (6) (9)	3° Nom. (9)
Minimum Guidance Altitude		150'	150'	150'	50'	50'	0'	0'	150'	150'	50'	0'	150'
Rainfall, mm/hr		15	15	15	50	50	50	25	15	15	25	50	50

NOTES

1. The larger of the two coverage extremes is required to provide coverage to the minimum guidance altitude over the runway. At maximum range, coverage is plus or minus the smaller of the coverage angles given.
2. B and I include USAF requirements.
3. Elevation cutoff to be adjustable from 0° to 5° in approximately 10 steps.
4. Azimuth cutoff to be available to avoid obstacles in the terrain.
5. Special coverage shaping required.
6. Optional guidance element.
7. For higher-class [illegible], entire azimuth coverage region available for proportional guidance.
8. Flight path must be computed for blind landing.
9. Glideslope angles in still air. In practice, will be adjusted upwards to compensate for wind over deck.

Table 9-22. COVERAGE PERFORMANCE SUMMARY errors which would be avoided in this manner. Furthermore, if the barometric correction is automatically done from MLS data, the additional error source of incorrect manual setting entry would also be removed.

- Minimum Glideslope - As mentioned previously, it should not be possible for an operator to choose a glideslope setting below that which is appropriate with respect to obstacle clearance and threshold crossing height limitations at a particular facility. This feature would transmit to the receiver the minimum allowable glideslope at the facility. This will be decoded in all receivers and compared to the receiver glideslope setting. If the receiver setting is lower, the receiver will generate an "invalid" discrete and the indicator flags will stay up.

The revised summary of data requirements is given in table 9-23. It will be noted that Tones E and F are the only tones used, and that both AZ and EL channels are now used for data transmissions. These revisions and the time format adopted are covered in the section on Signal Format.

9. Coordinate Geometry

Coordinate geometry was treated by Hazeltine as a critical technical area, and is described in detail in that section. During TACD Hazeltine refined the data base required to choose an MLS coordinate system representing the best compromise between satisfaction of operational requirements, equipment cost and integrity. Coordinate schemes considered included conical-only, orthogonal conical systems for planar guidance, unitary planar guidance elements, and hybrid systems. The general conclusions were that:

- planar coordinates were definately required for EL-1 guidance along the runway center line especially in consideration of the diversity of siting requirements and the variety of glideslopes that may be used in the future.

Table 9-23. AUXILIARY DATA REQUIREMENTS

AUXILIARY DATA	MLS ELEMENT	TONE	REP. INTERVAL	# BITS
Morse Code Airport I.D.	AZ	E	1 Bit Per Function time (seconds)	15
Fixed Data				
o Runway Heading			10	10
o Distance EL_1 to DME			10	10
Time of Day	AZ	F	10	15
Barometric Setting			10	7
Growth			10	8
Runway I.D.			10	15
Minimum Glideslope	EL	E	10	30
Growth			10	
Facility Status			5	
Wind Shear	EL	E&F	5	15
Wind Vector at TD			5	
RVR			10	15
Runway Condition	EL	E&F	5	
Dist.EL_1/EL_2			10	15
Alt EL_1/EL_2			10	
Growth			10	15

- o Planar coordinates were preferable for azimuth guidance, but not essential. One problem with conical coordinates was coordinate system incompatibility with ATC. A potential solution not requiring orthogonal antennas was the employment of a correction computation involving DME range; however, it was not seen as a universal solution because of the extra cost of the computational element.

- o The EL-2 geometry under practical siting considerations, is essentially indifferent to the basic coordinate system type.

Meanwhile, studies and experiments in the area of guidance signal generation produced confidence in the ability to generate planar beams with a very simple antenna design. The decision could therefore be made to use all-planar guidance without suffering the cost and integrity penalties of the orthogonal-antenna approach. As a result the baseline coordinate philosphy was adopted: all-planar guidance except where otherwise indicated by operational requirements. At this time the only conical coordinate retained was for the military colocated "E" system for which wide azimuth coverage is provided to permit (among other uses) approaches on several different azimuth courses.

10. References

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B. SIGNAL FORMAT

The signals-in-space is the single factor that unites the Doppler MLS by establishing ground rules to which the ground and airborne systems can be designed. The resultant implications of the signal format on the cost effective design of ground and airborne equipment must be considered while maintaining the ability to satisfy the functional requirements. Although the SC-117 report provides considerable direction and guidelines is selecting a format, there still remained considerable room for optimizing system performance cost, etc. The signal format parameters were analyzed in detail during the TACD program to arrive at a compatible format for all users. A primary constraint placed on the format is that it must contain sufficient integrity features to permit autoland in CAT III weather conditions.

The signal format as conceived by SC-117 used time division multiplex (TDM) as a baseline for the Doppler format in order to make comparison between Doppler and conventional scanning beam systems possible. In the Hazeltine TACD proposal we adopted the TDM format, but made several refinements such as:

- new subcarrier location to 105 kHz
- odd number of tones for function identification to increase integrity
- number of scans per function time
- data rate

However, we also recognized the need to optimize the signal format based on consideration of alternate signal format techniques. As a result we identified several study areas in order to resolve many of the issues. Figure 9-28 indicates a flow chart for defining the format. As noted on the figure, several arrows are indicated. These represent the constraints placed on various elements of the format. For example, the constraints placed on the signal format itself are:

- o integrity consistent with autoland requirements
- o 600 KHz channel bandwidth
- o number of MLS functions to be transmitted

The individual studies performed in this section include a brief summary of our conclusions and are presented below in the following order

- o frequency (FDM) vs time division multiplex (TDM)
- o sequential dual scan (SEDS) vs simultaneous dual scan (SIDS)
- o frequency coding rationale
- o spectrum control requirements
- o timing relationship between parameters
- o power budget

Detailed discussions follow the summary in Part 2.

1. Summary of Signal Format Studies

a. Frequency-Time Division Multiplex Trade Off

TDM was proposed in the SC-117 format primarily for compatibility with conventional scanning beam formats. Since the Doppler technique as described by SC-117 required a small bandwidth for each function it was believed to possess a potential for FDM. Each guidance function would be assigned a separate frequency band within the 600 kHz angle guidance channel.

The major factors that effect the choice between TDM and FDM are the numbers of MLS functions to be transmitted, data rate required of each function, equipment cost and growth potential of MLS. We have identified five MLS functions to be transmitted; AZ, EL-1/H, EL-1/L, EL-2, and BC AZ with data rates corresponding to accuracy requirements as defined by Sperry Flight Systems considering present AFCS requirements.

Pure FDM of all functions is wasteful of bandwidth and requires many processors in the aircraft. Also, if the AZ and EL-1 functions are transmitted simultaneously then the frequency sidelobes of the EL-1 transmission would have to be at least 53 dB down in the AZ channel to avoid interference due to path difference of the aircraft and ground stations. A candidate for a hybrid FDM-TDM format, mentioned as a possibility by Cornell Aeronautical Laboratories (CAL), would be to use FDM for main and auxiliary array signals to provide the conical-to-planar beam corrections. Since the Hazeltine antenna approach is to generate planar beams from a single antenna the hybrid format as suggested by CAL is unnecessary. The TDM format of SC-117 was retained since it:

1) provides minimum co channel and ajacent channel interference
2) uses a single processor in the aircraft
3) provides adequate data rate for all functions with growth capability
4) permits independent testing of functions

b. Dual Scan - the selection of SEDS in preference to SIDS

The signal format of the Doppler MLS includes dual scan, which is available in two forms: sequential (SEDS) and simultaneous (SIDS). The former was proposed in the SC-117 report and the Hazeltine proposal. The latter was proposed by Hazeltine as an alternative offering the maximum in performance, and therefore deserving some consideration. The study reported in this section presents numerous considerations in choosing SEDS or SIDS.

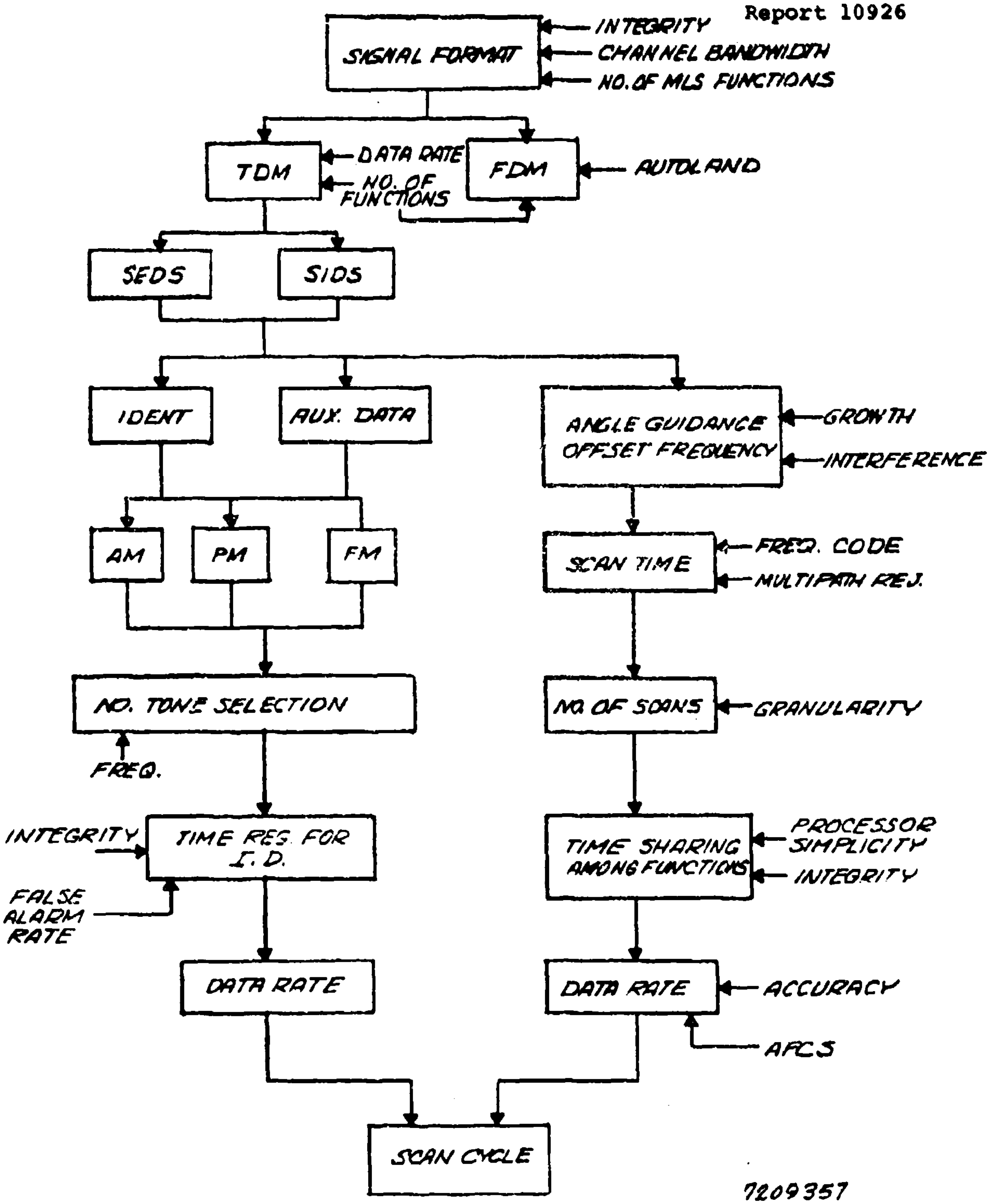


Figure 9-28. Parameter Trade Off

The ultimate in performance is obtainable from SIDS at some system cost. This includes a few refinements not possible in SEDS. One is 'chirp' cancellation to cope with a problem of antenna design and application. Another is related to multipath error reduction by multiscan motion averaging, the greatest benefit being realized by excluding one of the two sets of 'grating lobes'. Both of these refinements are in the 'luxury' class, not being essential to the basic performance of Doppler MLS.

On the other hand, all the essential features of performance are obtainable from SEDS with the simplest transmitter and an option of the ultimate simplicity in the receiver. For the present baseline system, the selection of SEDS is based on all considerations, with some weighing in favor of simplicity and economy.

c. Frequency Coding Rationale

In the interest of achieving high spectrum utilization, the frequency coding plan uses the entire available guidance spectrum for each function. This implies that the code or frequency per unit angle is different for AZ, EL-1, and EL-2 functions, although each individual function is identical at each airport configuration. The major factors effecting the choice involves MLS coverage requirements from each antenna and processor complications resulting from different codes. Since the AZ coverage requirements are 120 degrees with possible growth to 180 degrees, and since the EL-2 coverage requirements are only 10 degrees, a uniform code for all functions is extremely wasteful of bandwidth. Therefore, the receiver must accommodate several codes. In order to simplify, the translation from frequency to angle in the receiver, a harmonic relationship is required between functions. The following code meets this requirement and is chosen for the baseline in our format.

AZ: 333 1/3 Hz per degree
EL1: 1000 Hz per degree
EL2: 2000 Hz per degree

d. Spectrum Control Requirements

The Doppler MLS concept employs electronic scan techniques to generate the required Doppler signals in space. Three types of Doppler MLS scanners are identified and each technique involves switching or phase shifting RF signals which, of course, produce frequency sidelobes. In the TACD proposal we identified the required spectrum control mechanism (switching at low power levels) but did not define the requirements for the beamport or model scanners used in all EL and the configuration K AZ antennas respectively. The study in this section defines the Doppler MLS spectral control requirements to preclude adjacent and co-channel interference. The results of the study show that frequency sidelobes must be kept within the following bounds to preclude interference.

- first frequency sidelobe suppression should be at least 16 dB
- 73 kHz from angle band center the frequency sidelobes should be at least 20 dB
- 310 kHz from angle band center the frequency sidelobes should be at least 30 dB

The methods to achieve the spectrum control have been discussed in the antenna section 1.1.1.1., Part C and a complete RFI study is included in the receiver section 1.1.1.1., Part D.

e. Timing Relationship Between Parameters

The basic overall timing cycle is determined by the data rate selected based on an accuracy-data trade off study performed for Hazeltine by Sperry. The timing within each scan cycle is determined by a number of factors concerning:

- buffer times
- receiver AGC requirements
- receiver STALO requirements
- auxiliary data
- minimum number of scans per function time

- o relative timing between functions
- o integrity

As a result of the studies in this section, the scan cycle shown in figure 9-29 was developed. It consists of a start pulse and a multiscan pulse. During the first 300 microseconds of the start pulse, a reference carrier only signal is transmitted to facilitate receiver AGC and AFC operation. This period is followed by 1.7 ms of function ident and auxiliary data tones. Following the 2 ms start pulse, the auxiliary data tones are inhibited at the transmitter, (except tone G as used for sidelobe suppression) and the multiscan time is initiated by an upper sideband Doppler transmission. The multiscan duration for a specific function is fixed at all facilities. The minimum number of scans in a multiscan is defined as 16 times the effective Doppler beamwidth for granularity resolution.

In the TACD proposal, we indicated that phase cycling was difficult to achieve due to stringent implementation control requirements in order to realize the full benefit from phase cycling. Upon further analysis, we formulated an approach to include phase cycling and this concept is discussed fully in section 1.1.1.1, Part D. As a result of the phase cycling requirements, a harmonic relationship was needed between the scan time and the angle offset frequency. An angle offset frequency of 100 kHz satisfied this requirement and is used as a baseline.

f. Power Budget

The power budget was refined based on updated design concepts from the antenna, receiver, and propagation studies. The power budget tabulated below for configurations K and D reflect a conservative approach in that the angle and reference functions are integrated in each EL antenna (3 dB loss in power) and the Ryde-Ryde model was used for rain attenuation while satisfying the full range requirements in 50mm/m rain. It should be noted that the discussion in Section 1.1.1. Part F, allocates a 20 dB rain attenuation allowance for Ku band which is exceeded by 10 dB in the figures presented below. The power requirements for a maximum of 20 dB rain attenuation are given in parenthesis.

	CONFIG K					CONFIG. D	
	AZ	EL-1/L	EL-1/H	EL-2	BCAZ	AZ	EL-1/L
Power Reference	30	6.4	0.8	30 (3)	4	2	3
Sideband	14	1.6	0.20	9 (.9)	1.4	0.7	0.7

Note: All figures in watts

2. Detailed Discussion of Format Studies

a. Time vs. Frequency Division Multiplexing

The Hazeltine Doppler baseline system has retained the time division multiplex (TDM) approach after careful review of the alternative, frequency division multiplex (FDM). The FDM format is being considered by some workers in Doppler, especially in England. Their view, which is well taken, is that FDM offers advantages when primary emphasis is placed on the low-cost user. However, when the complete range of users and requirements are reviewed, it is Hazeltine's viewpoint that the TDM approach can better meet the needs of the wide spectrum of civil and military users, anticipated for MLS. This viewpoint has been derived from our studies of the two formats by considering:

- The number of separate MLS functions
- The number of angle processors
- Data rate and processing time
- Stability requirements
- Interference effects

The following discussion presents only a brief summary of our studies in this area. Although we have adopted TDM for our feasibility demonstration models, we plan to continue discussions on this subject with our team member, Plessey Radar of the UK, which is also carefully studying the two alternative approaches.

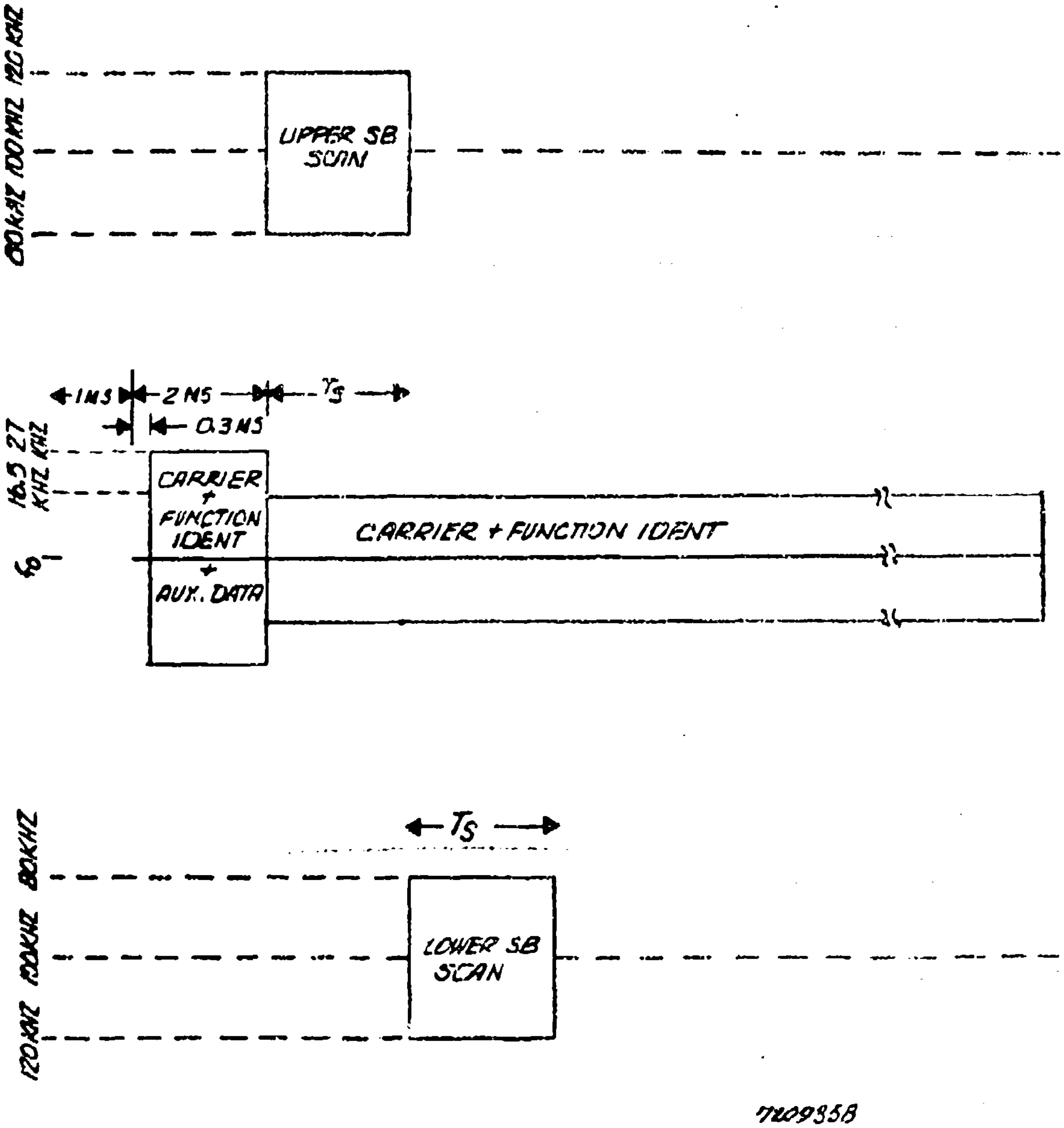


Figure 9-29. Function-Time Organization

Definitions:

Time division multiplexing (TDM) - transmits each MLS function in its own time slot. This approach avoids problems of simultaneous transmission.

Frequency division multiplex (FDM) - transmits each function in a separate frequency slot. This permits simultaneous and continuous transmission of each MLS function.

Hybrid multiplex - is a combination of the two approaches. There are two hybrid approaches that have been suggested. One by Cornell Aeronautical Laboratories applies FDM to the two crossed linear (conical) antennas for obtaining planar coordinates and TDM to all other functions. A second hybrid being considered by Plessey places AZ and EL-1 and data on separate frequency bands and all other functions on a separate time multiplexed band. The CAL hybrid is not applicable to the Hazeltine approach since we plan to provide planar coordinates from a single time slot.

The number of processors that are required in pure FDM is equal to the number of functions which is indicated to be a minimum of four. Since our estimates have indicated that the cost of the processor is one-quarter of the total cost of the angle avionics package, multiple processors could increase the cost substantially. However, there is the argument that, if each function is on continuously, there is a relatively long processing time available, a low-cost process approach can be designed. This approach counts through a long series of Doppler Scans and its implementation is believed to be of substantially lower cost. Therefore, the choice of FDM vs. TDM should not be based on cost factors alone, since considerable additional definition is required and definitive estimates must be made.

The primary advantages that one can state for the FDM is the longer processing time available compared to TDM for any given data rate. This might be a factor as much as about four times. This longer time permits the use of simple counters operating over the full time available presumtively with granularity errors reduced to tolerable levels. There is then the opportunity to design low-cost receivers, and, even though multiple processors would be required, for the general aviation user with only A2 and EL-1 required, there might be a resultant overall cost reduction.

However, there are a number of problems introduced by the FDM format, which are all associated with interference among the functions. The first is co-channel interference. Consider, a pure FDM format or the hybrid format where AZ and EL-1 are transmitted simultaneously and the geometry shown below.

Path Attenuation	:	-25 dB
Rain Attenuation	:	- 0.4 dB
Radiation Pattern	:	- 8 dB
Transmitter Power	:	- 3 dB
Acceptable S/I Ratio to satisfy CAT II Accuracy req	:	-16 dB
Total		-52.4 dB

In order to preclude interference from the EL-1 angle guidance signal in the AZ guidance band, the frequency sidelobes must be controlled to better than -52.4 dB. Even if the commutated array were used for EL-1 with electronic commutating at low level (corresponding to a $\cos^2$ pulse with 0.1 amplitude pedestal), the sidelobe control criteria would just barely be satisfied. Any variation in the pedestal to say 0.15 (85% MODULATION) precludes the use of FDM.

An additional interference problem exists for the FDM and Hybrid formats which is differential Doppler between the reference signal and angle sideband signal. The differential Doppler occurs because the reference signal is not colocated at each functional facility. Since two miles of runway typically separate the AZ and EL-1 stations, the differential Doppler may be in the order of several beamwidths.

There is also the problem of integrating KU band for EL-2 into the FDM format. Stability requirements are the same in absolute frequency, so stability expressed as a percentage is one-third that at C-band, or a more difficult problem.

Considering the stability, differential Doppler, interference effects leads one to the conclusion that excess bandwidth is required to accommodate these factors. Therefore, it is not considered that, at this time, the FDM approach has been sufficiently defined or techniques refined to the extent that it could be adopted to meet SC-117 requirements.

On the other hand, our studies of the verification of our Doppler approach utilizing TDM have treated each problem and arrived at acceptable solutions. A summary of these factors is presented in figure 9-29A.

	ADVANTAGES	DISADVANTAGES
TDM	o HIGH DATA RATE WHERE REQUIRED o SINGLE PROCESSOR o SIMPLE PROCESSOR STILL APPLICABLE TO RESOLVE GRANULARITY FOR MANUAL OPERATION o COLOCATED SITES CAN USE ONE TRANSMITTER o PERMITS PARALLEL TESTING OF MLS STATIONS (AZ, EL-1, ETC).	o UNISCAN COUNTER (TIC) TO RESOLVE GRANULARITY FOR AFCS o TIMING LINK REQUIRED ON GROUND o REQUIRES AFC OR STALO FOR HIGH QUALITY RECEIVERS
FDM	o HIGH DATA RATE POTENTIAL o PERMITS MULTISCAN COUNTING TO RESOLVE GRANULARITY o SIMPLE GROUND LINK BUT REQUIRES FREQUENCY LOCKED TRANSMITTERS. o MULTISCAN MULTIPATH AVERAGING	o WASTEFUL OF BANDWIDTH TO FDM 5 FUNCTIONS PLUS AUXILIARY DATA. o MULTIPLE PROCESSORS TO REALIZE HIGH DATA RATES o 3 TIMES Ku BAND STABILITY REQUIREMENTS o REQUIRES 52 dB EL-1 FREQUENCY SIDELOBE CONTROL o NO GROWTH POTENTIAL
HYBRID	o HIGH DATA RATE WHERE REQUIRED o PERMITS MULTISCAN COUNTING TO RESOLVE GRANULARITY o MULTISCAN MULTIPATH AVERAGING o LOWER POWER REQUIREMENTS	o MULTIPLE PROCESSOR TO REALIZE HIGH DATA RATES o 3 TIMES KU BAND STABILITY REQUIREMENTS o TIMING LINK REQUIRED ON GROUND o REQUIRES 52 dB EL1 FREQUENCY SIDELOBE CONTROL o REQUIRES AFC FOR ALL RECEIVERS o CROSSED LINEAR ARRAY NOT REQUIRED FOR PLANAR ANGLES CONVERSION IN HAZELTINE ANTENNAS

Figure 9-29A. Multiplex Tradeoff Summary

Table 9-24.
DUAL SCAN
(SEDS OR SIDS)

DESCRIPTION

BOTH SIDEBANDS WITH BIDIRECTIONAL SCAN (OR EQUIVALENT) SO EITHER SIDEBAND YIELDS SAME ANGLE TONE IN RECEIVER.

PURPOSE

STALO CAN BE USED IN RECEIVER AS A "CLEAN" CARRIER IN PLACE OF RECEIVED REFERENCE CARRIER.

SELECTION

CHOOSE BETWEEN:
SEDS FOR SIMPLICITY AND ECONOMY;
SIDS FOR MAXIMUM PERFORMANCE.

SEDS IS PRESENT RECOMMENDATION.

Table 9-25.

SIMULTANEOUS DUAL SCAN
(SIDS)

DESCRIPTION

MULTISCAN WITH DSB TRANSMISSION.

SIMULTANEOUS BIDIRECTIONAL SCAN (OR EQUIVALENT) CAN YIELD ANGLE TONE WITHOUT USING THE REFERENCE CARRIER.

TRANSMITTER REQUIRES DUPLICATION OF SOME FUNCTIONS, ALSO SOME CONSTRAINTS TO ENABLE RECEPTION OF ANGLE TONE WITH SIMPLE DETECTOR.

FEATURES

PERFORMANCE IS AVAILABLE WITH LEAST SUSCEPTIBILITY TO MULTIPATH AND OTHER ERRORS IN ANGLE DECODING.

CHIRP CAN BE CANCELLED AHEAD OF NARROWBAND FILTER AND LIMITER, SO LEAST BANDWIDTH CAN BE USED.

REFERENCE CARRIER (OR STALO) IS NOT NEEDED FOR DETECTION OF ANGLE TONE.

Table 9-26.

SEQUENTIAL DUAL SCAN

(SEDS)

DESCRIPTION

MULTISCAN WITH ALTERNATE SSB TRANSMISSION.

PHASE CYCLING CAN BE PROVIDED BY A SLIGHT SHIFT IN FREQUENCY OF REFERENCE CARRIER IN TRANSMITTER (OR RECEIVER) FOR REDUCING ERROR CAUSED BY INTERSCAN GRANULARITY IN MULTISCAN COUNTING.

RATIONALE FOR SELECTION OVER SIDS.

SIMPLER TRANSMITTER.

SIMPLEST RECEIVER CAN BE USED, OR REFINEMENTS TO YIELD NEARLY THE HIGHEST LEVEL OF PERFORMANCE (SIDS).

IF STALO IS USED, UNISCAN COUNTING AND TIMING WITH MULTISCAN AVERAGING YIELDS A HIGHER LEVEL OF PERFORMANCE.

b. Dual Scan - Sequential (SEDS) or Simultaneous (SIDS).

Purpose of this section. In the baseline system proposed in this report, a choice is made between two distinct forms of "dual scan". Dual scan in some form is expected to be used in any Doppler MLS, as described in the SC-117 report. The two forms of dual scan (denoted SEDS and SIDS) are to be described here in detail sufficient to form a basis for choosing one. The former (SEDS) is chosen. It is the one described in the SC-117 report, and it was the baseline form in the Hazeltine proposal. The choice is based mainly on some advantages relating to simplicity, reliability and economy in the equipment, especially in the airborne receiver.

Highlights. An outline of this topic was shown at the June review meeting and is reproduced here as tables 9-24, 9-25, and 9-26. It may be helpful in highlighting the considerations which are uppermost in this discussion.

Background. The MLS accomplishes frequency coding of angle in space by radiating at least one frequency component whose received frequency is related to the angle in space. Previous proposals, and the present "baseline" proposal, are based on the radiation of a strong reference carrier and somewhat weaker sidebands. The former is at a fixed frequency (f_c) and the latter at a frequency difference which provides the coding of the angle. This difference is unaffected by the Doppler shift of both components, caused by the radial speed of the aircraft carrying the receiver.

The Doppler-scan system. This system relies on the radiation of at least one component from a moving source on a linear aperture (or equivalent) so that the received frequency has a deviation related to the angle from the broadside direction. One such operation is termed one scan. In previous proposals, and in the baseline system herein, the reference carrier and one sideband frequency (f_c|f_o) are radiated at one time, the latter radiation being somewhat weaker (1/2 amplitude) and being scanned on the aperture to develop a Doppler shift (f_d) for angle coding. Therefore this one sideband carries the guidance information, with some handicap in being the weaker component.

Dual scan. The Doppler-scan system requires only one sideband, but dual scan using both sidebands has been proposed by Hazeltine and others for accomplishing some further objectives. The essentials of dual scan are here to be reviewed with reference to figure 9-30.

First, figure 9-30(a) shows the principle of Doppler scan for frequency coding of angle in space. The angle tone is transmitted as modulation at the difference frequency of two radiated components. Figure 9-20(b) shows the bandwidth for selection of the angle tone after detection in the receiver. The carrier and one sideband are sufficient for this operation, so it may be completed in one scan.

Sequential dual scan (SEDS). Figure 9-30(c) shows this form of dual scan, which utilizes sequential alternate transmission of upper and lower sidebands, each providing the angle-coding frequency of modulation. The feature of bidirectional scan on opposite sidebands provides the Doppler shift necessary for this result. Figure 9-30(d) shows one method of detection which is made possible by dual scan, and will be a subject of further discussion. The opposite sidebands are individually selected, then separately detected with the carrier in two product detectors. Instead of the carrier, a "clean" carrier may be substituted in the form of a stable local oscillator (STALO) at nearly the same frequency. A slight difference from the carrier frequency is tolerable because the average value of modulation frequency from both sidebands still has the correct value.

Simultaneous dual scan (SIDS). Figure 9-30(e) shows this form of dual scan, which utilizes simultaneious transmission of both sidebands. Then detection of the doubled modulation frequency can be accomplished without the carrier, by separating the sidebands as in (d) and applying them to a product detector. This offers some added advantages that will be discussed further on. Figure S.1 (f) shows the selection of the resulting angle tone after detection.

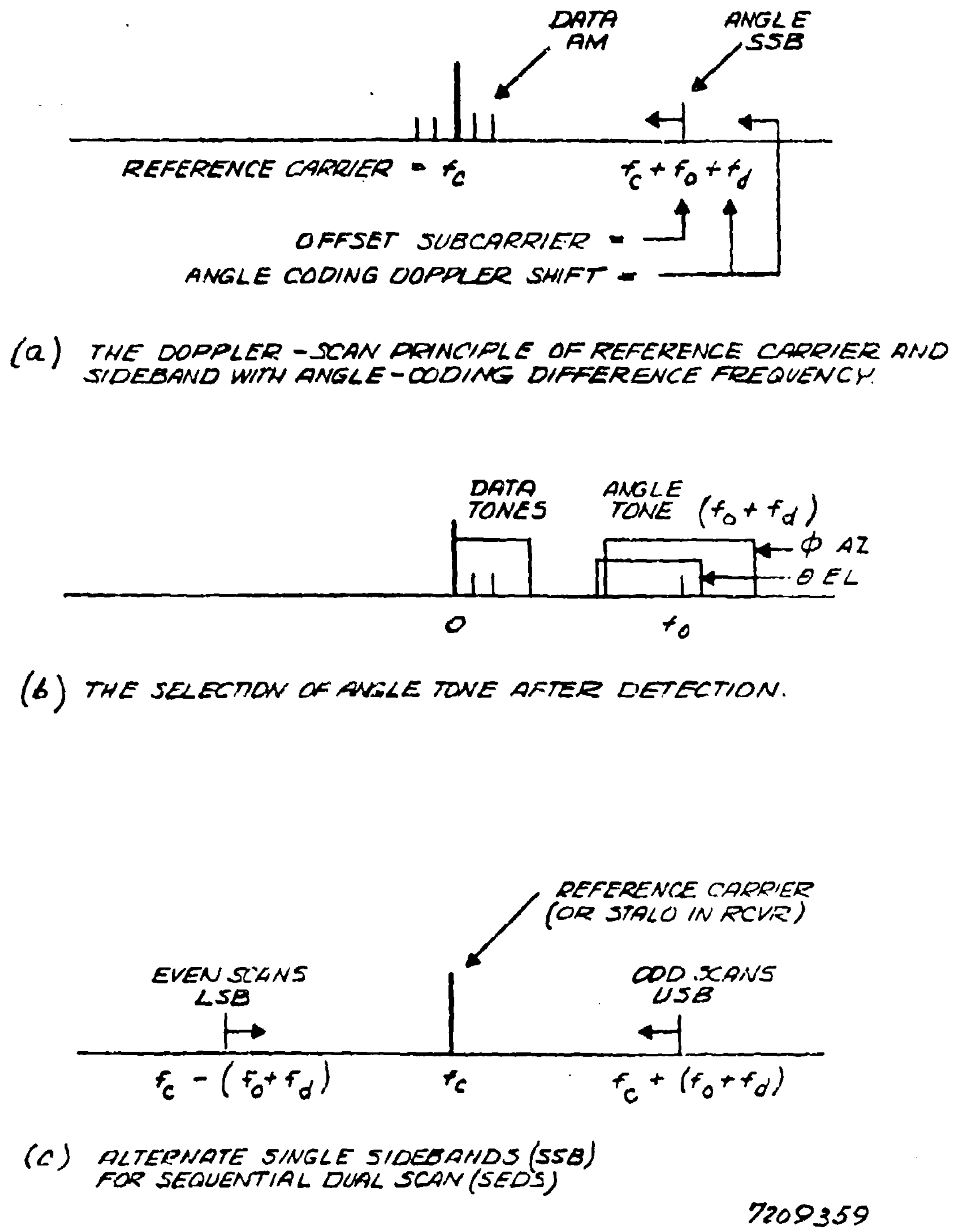
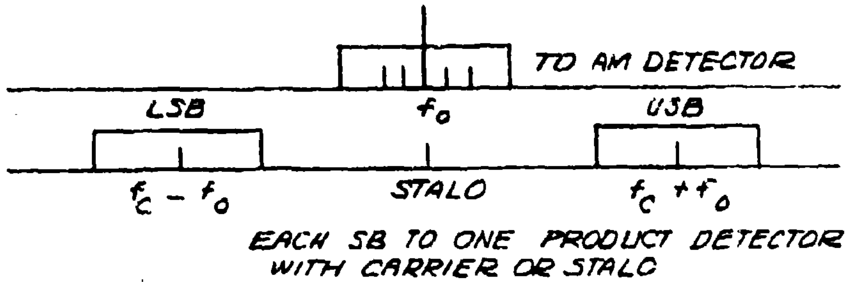
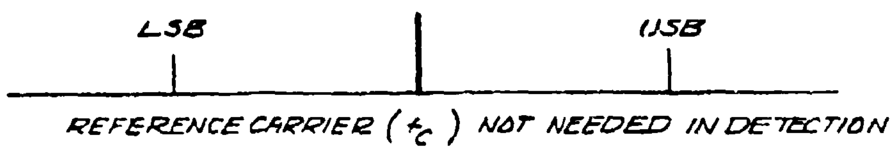


Figure 9-30. Dual Scan in Various Forms and its Detection in the Receiver. (Sheet 1)



(d.) OPTIONAL SEPARATE DETECTION OF LSB AND USB IN TWO PRODUCT DETECTORS.



(e.) DOUBLE SIDEBANDS (DSB) FOR SIMULTANEOUS DUAL SCAN (SIDS).

(f.) THE SELECTION OF DOUBLED ANGLE TONE AFTER DETECTION OF TWO SIDEBANDS IN PRODUCT DETECTOR.

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Figure 9-30. Dual Scan in Various Forms and its Detection in the Receiver. (Sheet 2)

The time-frequency diagram. Figure 9-31 shows the spectrum utilization of some signal formats, mapped on time-and-frequency coordinates. The basic concept of dual scan (a) is detailed further in (b) and (c) to show the difference between SIDS and SEDS in a multiscan format. It is noted that SIDS makes full use of the available spectrum capacity and SEDS only one-half, this being one of various factors in making a comparison.

A stable local oscillator (STALO) as a reference carrier for the angle decoder. The radiated reference carrier is limited in power and may suffer contamination in transmission to the receiver. In the receiver, a stable local oscillator (STALO) may be provided at nearly the same frequency, subject to automatic presetting or slow tracking. Then this oscillator is used as a "clean" reference carrier of any desired strength relative to the received sidebands. Any slight error in its frequency has opposite effects on the frequency decoding of opposite sidebands, so the average is free of such error and is used for angle decoding. The same applies to any Doppler shift caused by the radial speed of the aircraft. This feature of dual scan provides two benefits:

(a) It avoids any disturbance of the angle decoding that might be caused by contamination of the reference carrier.

(b) It enables detection of the difference frequency in a manner that ignores the data-tone sidebands close to the reference carrier.

The basis for comparison of SEDS and SIDS. Either of these offers some practical advantages related to performance, reliability, simplicity and economy. These are not clearly separable. In particular, their weighting is different for transmitter and receiver, and for different levels of compromise between performance and economy. For any signal format, there are numerous choices as to implementation in transmitter and receiver. The intention herein is to present the various considerations in a form that would be helpful in making a selection between SEDS and SIDS for the Doppler-scan MLS.

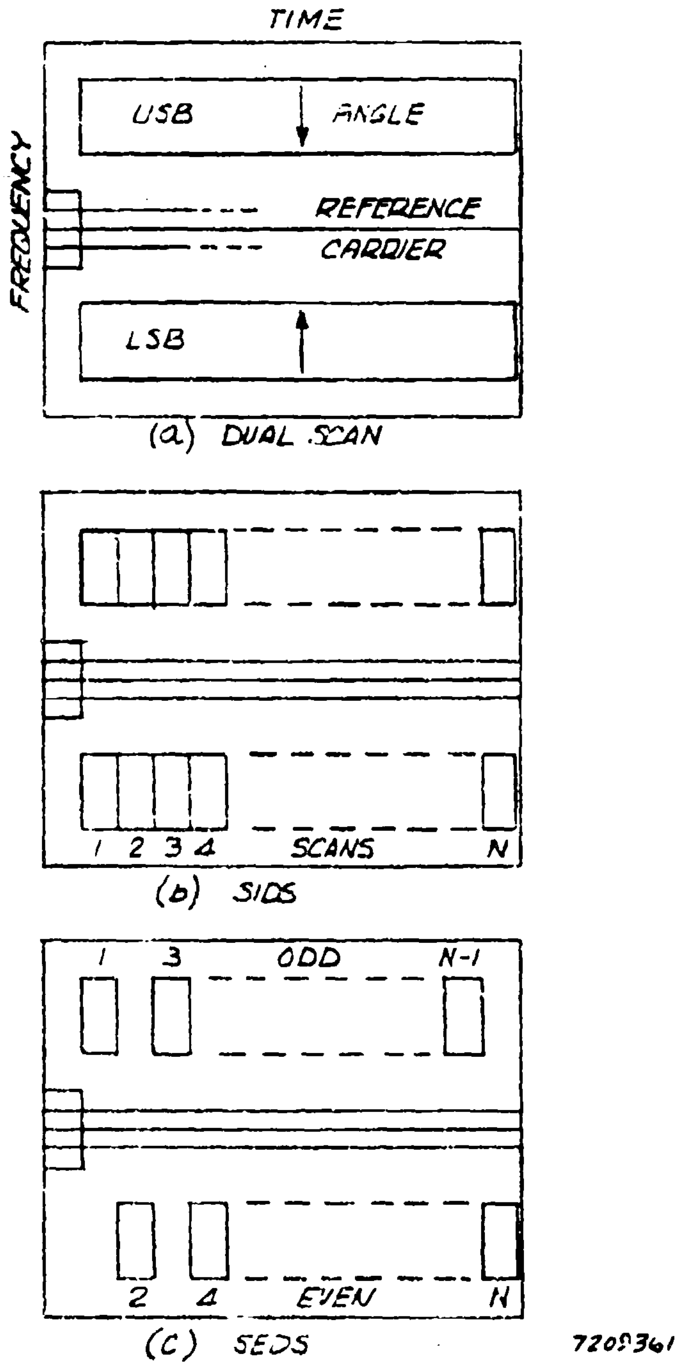

Figure 9-31. Dual Scan and Multiscan Frequency-Time Patterns.

The system. The signal format would be expected to include a clear choice of SEDS or SIDS. The latter, as will be seen, requires a choice as to phase relation between reference carrier and angle-coding sidebands. In the present discussion, there is not assumed any restriction on this phase relation, except where specified. Primary attention is given to implementation and evaluation that ignores this relation and therefore does not require such restriction.

The transmitter. The ground equipment generates and radiates the signal format for frequency coding of the directional angles from the centerline of a runway. There will first be stated the peculiarities of SEDS and SIDS in context of signal format, with reference to some problems of implementation in the transmitter. There will be little reference to the antenna because it is thought that it would not be a deciding factor in choosing between SEDS and SIDS.

Transmission of SEDS. This form of Doppler scan relies on time sharing for dual scan, radiating USB and LSB in alternate scans of a multiscan series. In one respect, this method is simplest because only one of the two sideband frequencies is radiated during one scan. It does require a SSB modulator to provide either sideband alone. It requires a multiscan format (with an even number), which however would be used for another reason, the utilization of the available time and frequency bandwidth.

Transmission of SIDS. This form of dual scan is complete in each scan, but however would likewise be used in a multiscan format for utilization of the available time and frequency bandwidth. If the antenna is made of aperture ports with Doppler scan by sequential switching, SIDS excitation requires doubling some or all of the circuits needed for SEDS excitation. The same is true if a beamport antenna is used with phasers for angle coding. On the other hand, if a beamport antenna is used and the angle-coding frequencies are developed from angle-tone low frequencies, a simple DSB modulator may be used at each beamport.

<u>Carrier modulation by SEDS</u>. In this form of dual scan, the reference carrier is said to have single-sideband (SSB) modulation or, more specifically, alternate SSB. This may be regarded as a combination of amplitude modulation (AM) and phase modulation (PM), and the difference frequency may be derived from either kind of detector. The simplest detector is the envelope detector which responds only to AM. It may be utilized in a simple receiver for recovering the angle-coding tone at the difference frequency.

<u>Carrier modulation by SIDS</u>. A simultaneous pair of sidebands (DSB) has phase coherence with the carrier. Therefore there are several significant cases of relative phase. In general, the relative phase determines whether the sidebands together correspond to AM or PM or a mixture of both.

(a) Equal-phase radiation of sidebands and carrier from a common phase center in the antenna. This is AM so it can be detected by a simple rectifier or envelope detector.

(b) Quadrature-phase radiation of sidebands and carrier from a common phase center in the antenna. The first-order effect is PM, which can be detected by a phase detector (or by a frequency discriminator).

(c) Accidential constant or slowly wandering phase difference. Which kind of DSB modulation happens to occur, cannot be relied on, so a SSB method of detection is chosen which ignores the phase. One detector receives only one sideband, which is compared with the carrier (or STALO) to derive the frequency difference. Two such detectors may be provided to utilize both sidebands separately, then the average difference frequency may be computed.

Radiation from a common phase center, as in (a) or (b), can be provided by using a common aperture or by locating a reference-carrier (smaller) radiator in the center of the aperture; the latter cannot be located at one side of the aperture.

Detection of SIDS without a carrier. As previously mentioned, the angle tone may be recovered as 1/2 the frequency difference between the pair of sidebands in SIDS. This avoids the question of phase relation to a carrier (or STALO) and requires separating the sidebands from the carrier if one is radiated. The pair of sidebands may be selected together and applied to an AM detector to derive their difference frequency. Preferably, they may be selected separately and applied to a product detector (balanced modulator). Such separation is necessary if each sideband is to be subject to a limiter before comparing the two sidebands. Either of these methods may be used for chirp cancellation in detection, yielding directly the angle tone doubled in frequency and free of chirp.

The receiver. The airborne receiver is the "customer" in the MLS. After being tuned to one runway, it senses the radiated signal and derives therefrom its directional angles measured from the centerline of this runway. The receiver will be used in large numbers and in a variety of designs. The receiver is required to derive from the radiated signal such information as may be needed for carrying out a plan. Special attention is given here to some receiver problems that might be different for SEDS and SIDS.

Simple detection for SEDS. From the discussion of carrier modulation by SEDS or SIDS, it appears that the former is naturally suited to the simple envelope detection of the entire signal in the receiver. The modulation by SIDS would require special control of carrier phase in the transmitter, or would require some selection of sidebands (from carrier or from each other) before detection in the receiver.

The need for chirp cancellation in a receiver. "Chirp" is frequency modulation of the angle-coding sideband, caused by departure from focus of the radiating aperture. It causes similar phase deviation, and hence frequency shift, in both sidebands. In SIDS, the direct comparison of the two sidebands offers chirp cancellation in the receiver. In some cases, the chirp may substantially increase the spectrum bandwidth of the Doppler-scan angle tone. The average frequency over one scan remains the same so there is not necessarily an error in angle decoding. Therefore chirp cancellation may offer an improvement only on cases such as the following:

(a) If there is a narrowband filter centered near the angle-tone frequency, it may be desirable to use the least bandwidth.

(b) If there is a wideband filter with sharp cutoff, the same may be true.

In the baseline system described herein, neither of these problems is expected to be severe. It remains that chirp cancellation does leave open some options in design of antenna and/or receiver for any particular signal format.

Grating lobes in motion averaging. Multipath reception may cause an error in the frequency measurement of the angle tone during one scan. Multiscan averaging during receiver motion may greatly reduce this error. Under certain conditions, the phenomenon called "grating lobes" (GL) may prevent motion averaging. Therefore it is desired to minimize this effect. It happens that there are two sets of GL in general, occurring when the path-difference motion frequency is an odd or even multiple of the coding-frequency difference corresponding to 1/2 beamwidth.

(a) In SIDS, because the scans are individually repetitive, only the even GL are present, so the maximum advantage of motion averaging is achieved.

(b) In SEDS, because the scans are repetitive in pairs, the odd GL are interspersed with the even.

In practical situations, the combined effect of both sets may be little more detrimental than that of the even set alone. The one condition likely to be persistent is near the zero GL, which is present in either SIDS or SEDS. Any other GL is likely to be a transient effect of less concern. Motion averaging in the receiver is inherent in the multiscan signal format, so only the difference in behavior is relevant to a choice between SIDS and SEDS.

The simplest receiver for SEDS. This opportunity is one of the principal advantages of SEDS, so it deserves most attention. By relying on the reference carrier and the simplicity of SSB modulation for angle coding, the envelope detection of the composite signal yields all data tones and the angle tone. This was proposed in the SC-117 report. There are strong arguments for leaving available this simplest receiver, at least as one option. This is true in spite of the fact that a higher level of performance, even with SEDS, requires a more complicated receiver and may be needed in some cases.

The maximum performance available in a receiver for SEDS. In considering the choice of SEDS, it is essential to perceive the maximum performance available in a receiver. To this end, the following features may be considered for the receiver.

(a) The STALO as a "clean" reference carrier.

(b) The individual selection of USB and LSB, and their detection in two separate circuits.

(c) A prefilter in each circuit to select a wide or narrow range of angle-tone coding in preference to multipath interference and noise. There is no interscan overlap in either circuit.

(d. Alternate-scan time gates for frequency measurement by counting and timing in each scan, then averaging over one multiscan.

(e) A self-tracking narrowband digital postfilter for further reduction of multipath error.

Item (d) provides that the receiver respond only to the active sidebandduring each scan, rejecting the noise in the inactive sideband and thereby realizing the maximum signal/noise ratio.

The extra performance available only in a receiver for SIDS. This is the range of performance that would become unavailable on choosing SEDS,

(a) Avoiding the "odd" GL.

(b) Chirp cancellation.

Comparison of SEDS and SIDS. There are a few areas where these two forms of dual scan can be clearly differentiated in respect to performance or implementation in some part of the system. Table 9-27 contains an outline of such a comparison. It is intended for reference in drawing conclusions and making a choice.

In table 9-27, item (1) requires some further interpretation. A receiver for SEDS, during each scan, may gate out the noise in the inactive sideband and thereby recover the maximum signal/noise ratio.

In choosing between SEDS and SIDS, these are the principal tests of the one to be chosen.

(a) Net advantage in typical applications, which may place comparable weight on performance and economy (a cost-effective compromise).

(b) The availability of nearly the highest performance at additional cost for the most demanding applications (autoland).

Table 9-27. Comparison of SEDS and SIDS

SEDS	SIDS
(1) The utilization of the spectrum channel capacity (the product of time and frequency bandwidth); full utilization is desired for tolerance of thermal noise relative to average power.	
Half utilization, because only one of two sidebands is radiated at one time.	Full utilization, because both sidebands are radiated.

Table 9-27. COMPARISON OF SEDS AND SIDS (Cont)

SEDS	SIDS
(2) In a transmitter using aperture ports with sequential switching.	
Simple.	Requires simultaneous excitation at LSB and USB frequencies with opposite directions of switching (crossing at one point in the aperture); requires two sets of switches.
(3) In a transmitter using beam ports with simultaneous frequency coding of angle.	
Requires alternate excitation of each port at LSB and USB frequencies.	Requires simultaneous excitation of each port at LSB and USB frequencies; may be provided by an amplitude modulator at each port.
(4) In the transmitter, relative phase control and a coincident phase center of radiation for the reference carrier and angle-coding sidebands.	
Not required for SSB, so a separate antenna may be used for the reference carrier.	Required if DSB is to be received as AM on the reference carrier.
(5) In the receiver, the simplest detection of the angle tone by use of the reference carrier.	
Common envelope detector for recovering data and angle tones; the angle tone is subject to any contamination of the reference carrier.	Common envelope detector can be used if the radiated signal has a phase relation between carrier and angle sidebands to assure amplitude modulation; detection is insensitive to contamination of reference carrier.

Table 9-27. COMPARISON OF SEDS AND SIDS (Cont)

SEDS	SIDS
(6) In the receiver, the use of multiscan motion averaging against multipath errors in angle decoding; such averaging fails at certain "grating lobe" frequencies of path-difference speed.	
"Even" and "odd" series of GL.	Only the "even" series of GL.
(7) In the receiver, a direct comparison of two sidebands; this avoids the need for a reference carrier or STALO; this gives instantaneous cancellation of chirp so the angle tone has minimum bandwidth.	
Not available.	Requires selection of the angle sidebands free of the carrier and data sidebands.

These tests apply differently to transmitter and receiver, as follows:

(c) In the transmitter, the emphasis may be directed to simplicity for reliability.

(d) In the receiver, the emphasis may be directed to the availability of design options for:

(i) Simplicity and economy:

(ii) Refinement at a price.

Here we shall state the few factors which seem to be most significant. The above tests appear to favor SEDS, which therefore is being chosen for the baseline system.

Advantages of SIDS.

(a) Detection by directly comparing the pair of sidebands, without reliance on the received reference carrier or a STALO; cancellation of chirp.

(b) In multiscan motion averaging, the "grating lobes" are minimized.

Advantages of SEDS.

(a) Ultimate simplicity available in the receiver, using the reference carrier with alternate sidebands in a simple detector to derive the data tones and angle tone.

(b) Simplicity in the transmitter, radiating only one sideband at a time. Avoids duplication of circuits in generating the angle-coding excitation of the antenna aperture.

(c) This form has received more attention and study, so it may be more familiar and more thoroughly understood.

Conclusion. From these considerations, the following summary may be stated.

(a) SIDS offers greatest potential in performance at any cost, while lacking some opportunities in simplicity and economy.

(b) SEDS offers the option of ultimate simplicity and economy, with other options in the receiver yielding nearly the maximum performance.

(c) Either SIDS or SEDS appears capable of providing a satisfactory system.

(d) SEDS is selected, as a practical compromise weighted in favor of simplicity and economy.

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c. Frequency Coding Rationale

In the interest of achieving high spectrum utilization, the frequency coding plan uses the entire available guidance spectrum for each function. This implies that the code or frequency per unit angle is different for AZ, EL1, and EL2 functions, although each individual function is identical at each airport configuration. The major factors effecting the choice involves MLS coverage requirements from each antenna, natural codes in space, and processor implications resulting from different codes.

Coverage. Since the AZ coverage requirements are 120 degrees (with growth potential to 180 degrees) and the EL-2 coverage requirements are only 10 degrees, a uniform code for all functions is extremely wasteful of bandwidth. Therefore, for a given bandwidth, the codes vary 12:1 from AZ to EL-2. In order to accommodate antennas that do not employ the beamport technique (such as the linear array described in SC-117), A 6:1 variation in code is used as a baseline.

Natural Codes In Space. By natural codes in space, we mean the code naturally produced by a given type of antenna. For example, a linear array (conical beam antenna) produces a code $f \propto \sin\theta$ and a circular array (planar beam antenna) produces a code $f \propto \theta$. The difference in the two codes is reflected in the "small angle" code when the entire bandwidth is used. These considerations are summarized in figure 9-32.

In AZ when the full 40 kHz bandwidth is used, then the conical array produces a 400 Hz per degree "small angle" coding and the planar coordinate array produces a 333 1/3 Hz per degree "small angle" coding. Obviously both antenna systems cannot be accommodated if full use is made of the available bandwidth unless separately identified. Since the Doppler MLS technique to produce planar coordinates can be accomplished in a single antenna, the 333 1/3 Hz per degree code is chosen for the AZ function (20 kHz divided by 60 degrees). Similar reasoning is used to establish a code for EL1 and EL2 of 1kHz per degree and 2kHz per degree respectively. However, if the same analysis is applied to BC AZ, then the BC AZ antenna code is 500 HZ per degree (only $\pm$40 degrees coverage required). In order to permit growth in the BC AZ function and to obtain compatibility with the AZ function a 333 1/3 Hz code is used.

Processor Implications. The implications of the different codes in the processor, is a scale factor adjustment. In a digital processor, where the measured frequency is determined by counting the number of cycles and dividing by the time interval, this normalization can be incorporated in or after the frequency measurement circuitry. The most cost effective approach is to incorporate

FUNCTION	BANDWIDTH (KHZ) AVAILABLE	BANDWIDTH (KHZ) USED	CODE (HZ/DEG) SMALL ANGLE	REMARKS
AZ (CONICAL)	40	40	.400	BASELINE CHOICE REQUIRED FOR RESOLUTION
AZ (PLANAR)	40	40	.333	
BC AZ	40	40	.500	NOT COMPATIBLE WITH AZ
	40	29	.400	COMPATIBLE WITH AZ SELECTION
	40	26.7	.333	
EL1	40	20	1.0	
ELC	40	19.6	1.0	
EL2	40	20	2.0	

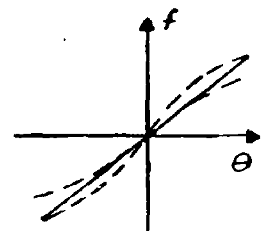

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Figure 9-32. Frequency Coding

the normalization in the counter by changing the effective time interval. This is accomplished by programming a clock frequency according to function identification.

In order to simplify, the normalization process, a harmonic relationship is required between function codes. For the alternative codes shown in figure 9-32, the codes tabulated below for each function satisfy this requirement and is chosen for the baseline in our format.

AZ: 333 1/3 Hz per degree
EL-1: 1000 Hz per degree
EL-2: 2000 Hz per degree
BC AZ: 333 1/3 Hz per degree

d. Spectrum Control Requirements:

The Doppler MLS concept employs electronic scan techniques to generate the required Doppler signals in space. Three types of Doppler MLS scanners are identified and each technique involves switching or phase shifting rf signals which of course produce frequency sidelobes. In the TACO proposal we identified the required spectrum control mechanism (switching at low power levels) but did not define the requirements for the beamport or model scanners used in all EL and the configuration K AZ antennas respectively. The study in this section defines the Doppler MLS spectral control requirements to preclude adjacent and co-channel interference. The results of the study are that frequency sidelobes must be kept within the following bounds to preclude interference.

first frequency sidelobe suppression should be at least 16B
73 kHz from angle band center the frequency sidelobes should be at least 20 dB
310kHz from angle band center the frequency sidelobes should be at least 30 dB

The methods to achieve the spectrum control have been discussed in the antenna section 1.1.1.1 Part C and a complete RFI study is included in the receiver section 1.1.1.1 Part D

Assumptions used in this analysis are:

(1) Transmitter stability = 5×10^{-6} (C-band(= 25 kHz); 1.5×10^{-6} Ku band (= 25 kHz)

(2) RCVR stability = 1.5×10^{-5} (C-band = 75 kHz; Ku band = 225 kHz)

(3) Geometry: See figure 9-33

(4) 200 channel capability includes adjacent channel locations within the range of one another.

(5) Cosecant shaped beams in elevation for EL and AZ antennas were used to develop interference model

(6) Function identification tone AM modulation = 25%

(7) Dynamic tone threshold circuit is used in the receiver

(8) Transmitter output power may vary ±1.5 dB between adjacent channels

(9) The MLS receiver outputs are used to couple to an AFCS at 10 nmi range. Hence degraded data rates can be tolerated at maximum range.

(10) Basic function time organization is shown in figure 2

Co-Channel Interference: The co-channel interference study encompasses interference caused by: (1) spurious signals generated in the tone band and its effect on angle guidance processing and tone guidance processing; and (2) spurious signals generated in the angle data band and its effect on angle guidance processing and tone guidance processing.

In the general aviation receiver (configuration D), the baseline receiver detects both angle guidance signals and tone signals in a common square law detector. The square law detector is used for angle and tone decoding since (1) Data tones are free of angle-tone contamination, although distorted slightly by their own harmonics and cross products, and (2) Angle tone free of harmonics and free of phase modulation by data tones.

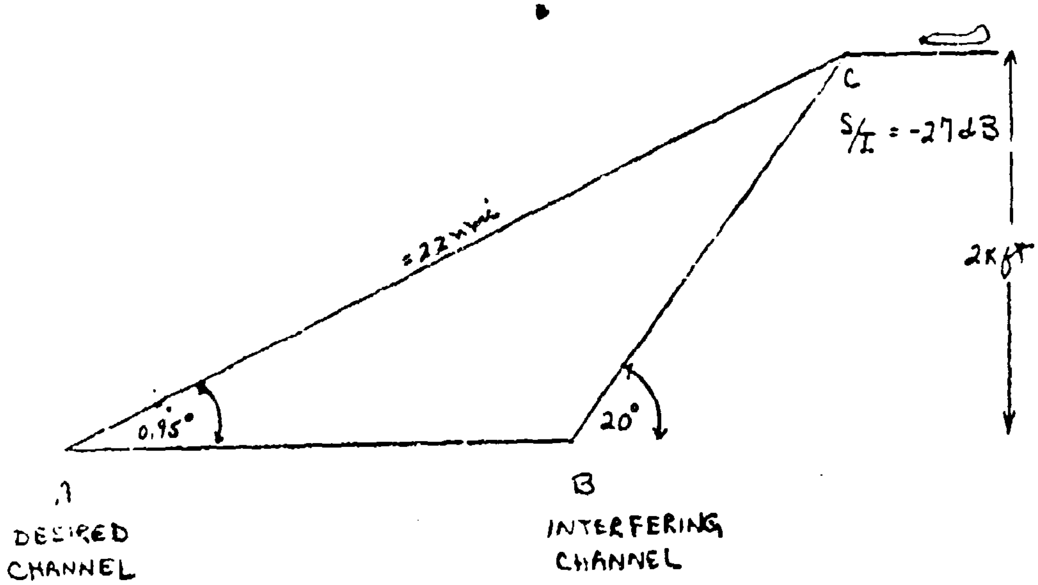


Figure 9-33. MLS Approach Geometry

Since the tone signals are AMed with low percentage of modulation, the harmonics and cross products are small (-3 dB below the carrier) in the angle signal band and can be neglected as long as the angle sideband signal is less than -10 dB below the carrier. The resultant error is 0.01 degrees.

In order to specify the frequency sidelobe control required in the angle signal generation, it is necessary to review the operation of the antenna scanners and the tone processor. In the aperture port scanner (commutated array), the frequency sidelobes are controlled by switching at low levels. However, the frequency sidelobes can occur at any frequency. In the beamport and modal scanners, the frequency sidelobes are harmonics of the effective Doppler beamwidth frequency and do not effect the phase when viewed for an entire scan. When viewed after a dual scan, measurement times less than a complete scan time, produce no angular efforts due to the averaging property of dual scan. Errors do occur when refocusing circuits are used and the beamport coding is deparated by full multiples of a beamwidth. A. 16 dB sidelobe separated by 1.1 beamwidths produces a maximum error of 0.01 degrees which is tolerable providing the refocusing is less than 0.1 beamwidths.

The tone processor detects the amplitude of the largest tone and use its amplitude (actually 6 dB below this amplitude) to establish the threshold for detecting the other tones.

During the first 2 ms of a function, no angle guidance is generated so co-channel interference is not a problem. In configurations requiring tone validation during a function, validation must occur for 50% of the function. The problem then is to define the level of frequency sidelobes that still permits validation during the multiscan. By defining function validation as complete when identification occurs for 50 percent of the multiscan, then the frequency sidelobes 4.5 dB below the threshold, produce a 10 percent probability of false alarm. In the three unused tone channels this results in a net 30 percent probability of false alarm. In addition, by accounting for a 1.5 dB tolerance in relative power stability between the angle data channel and the reference carrier, the frequency sidelobes must be controlled 12 db below the single sideband tone. The results from the above discussion are summarized in figure 9-34 where the angle guidance sideband amplitude is 6 dB below the carrier. For this case, the frequency sidelobes must be -21 dB at 73 kHz from the angle guidance band center.

Adjacent Channel Interference. Adjacent channel interference was calculated from the geometry of figure 9-33, antenna elevation pattern shapes, transmitter power variation and the frequency spectrum and stabilities as indicated in the list of assumptions. The adjacent channel problem is similar to that of multipath in the angle guidance band since the interfering channel may be viewed as one contributing to multipath. Adjacent channel interference into the tone band is also considered and is discussed separately.

Interference is considered by taking the worst case situation with regard to geometry, rain, and transmitter power levels. The difference in range between the two stations result in a 27 dB increase in power due to path attenuation, a 4.5 dB increase in power due to rain, and a 3 dB difference in transmitter power. The resultant difference is 34.5 dB in favor of the unwanted signal. The following four interference conditions are analyzed.

Interference into AZ_A from AZ_B

Interference into AZ_A from EL_B

Interference into EL_A from AZ_B

Interference into EL_A from EL_B

Interference into AZ_A from AZ_B: If a cosecant AZ antenna elevation pattern shaping is used then the net interference from the unwanted signal is 24.5 dB. The interference takes the form of a Doppler frequency and hence is subject to motion averaging. The averaging results in an improvement to the multipath signal of $1/\sqrt{N}$ where N is the number of scans in a multiscan. For a 10 dB S/I ratio and

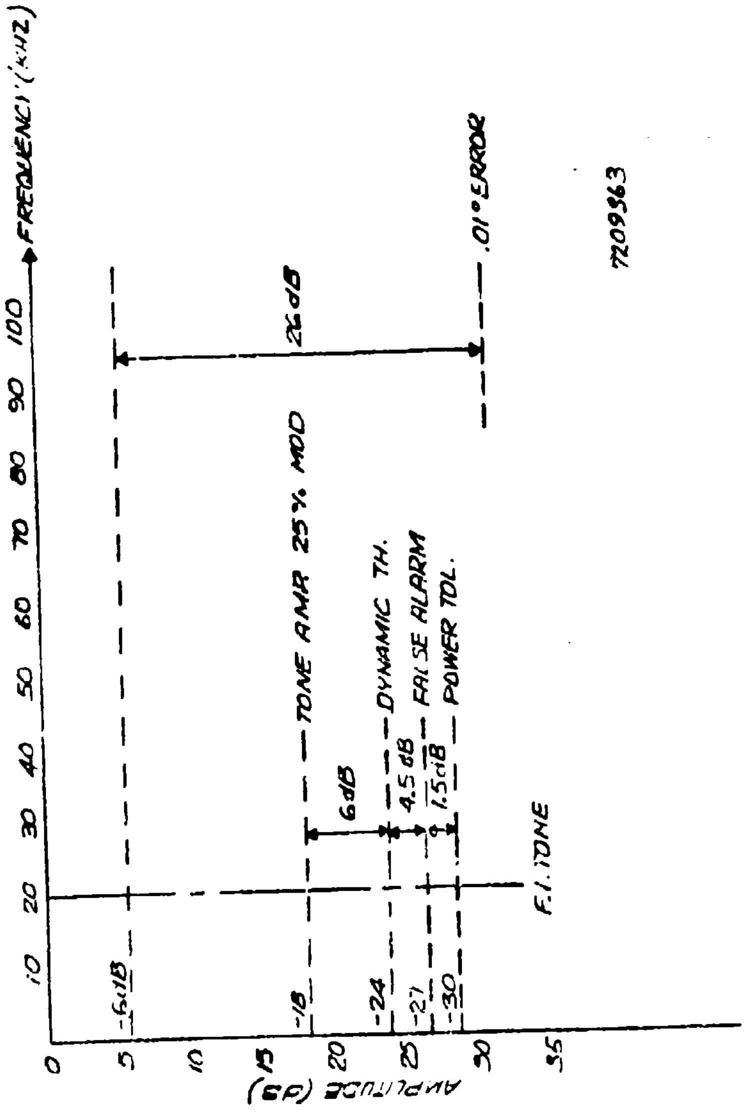


Figure 9-34. Co-Channel Interference

16 scans the resultant UB error is 0.025 degrees, and a 6 dB S/I ratio produces a 0.04 UB error. Since the aircraft is not coupled directly to the MLS beam (assumption #1) at maximum range, the 6 dB S/I ratio is acceptable since the 2 σ error is 0.02 degrees. Thus the frequency sidelobes in AZ_B must be controlled to 30.5 dB when 310 kHz from band center.

Interference into AZ_A from EL_B: This interference problem is treated in two parts; first the interfering station is EL-1, and second the interfering station is EL-1/H. When the interfering station is EL-1/L, then the range to the interfering station is doubled and the geometry only produces 21 dB increased power, but only 2 dB is obtained due to pattern shaping. The net result is that 2 dB more interference is experienced over case #1. However, since the EL station is transmitting for one third the time as the AZ station, the resultant UB error is 0.017 degrees per function time for a 4 dB S/I ratio and the 2 σ error is 0.0085 . This geometry is the limiting case for adjacent channel interference and is summarized pictorally in figure 9-35. Thus the frequency sidelobes in EL-1/L must be controlled to 30.5 dB when 3.0 kHz from band center,

When the interfering EL-1 station is EL-1/H, 10 dB is gained since the power radiated from the EL-1.H antenna is 10 dB less than EL-1/L. Thus the frequency sidelobes in EL-1/H must be controlled to 20.5 dB when 310 kHz from band center.

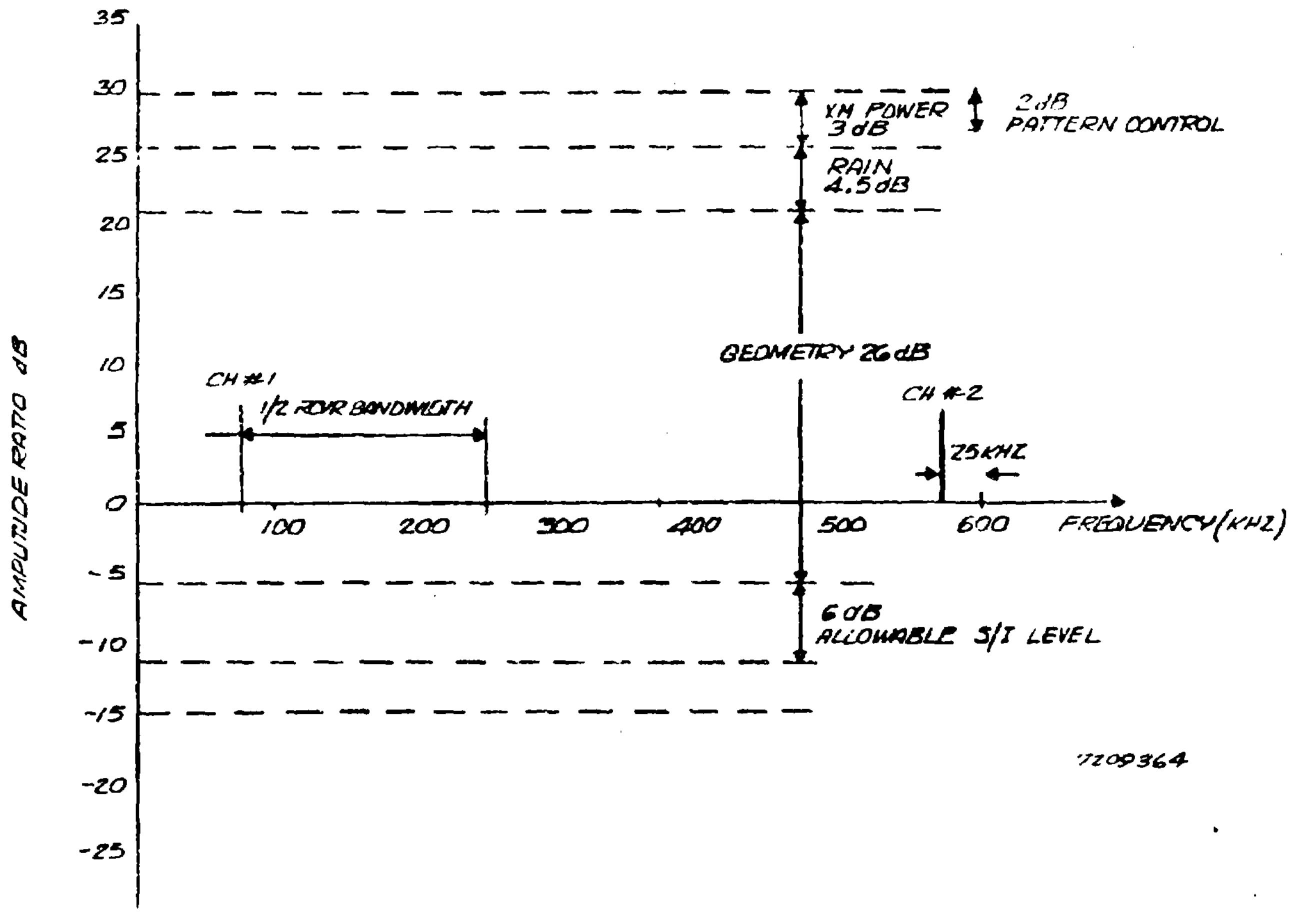


Figure 9-35. Adjacent Channel Interference Worst Case: AZ Desired, EL1 Interfering

(3) Interference into EL_A from AZ_B and (4) Interference into EL_A from EL_B:

The interference geometry for these conditions are similar to the interference into AZ_B. The one exception is that at low elevation angles and at maximum range, EL guidance is not used for path following; it is only used for receiver capture. Therefore, the AZ_B and EL_B sidelobes when controlled to 30.5 dB as discussed above, is slightly overspecified for this interference condition.

Tone Contamination. The second part of this problem involves the adjacent channel Doppler spurious signals being mistaken as a tone. In this case, the interference may take place during the initial tone detection process (first 2 msec) as well as during the validation period. In addition, the adjacent channel interference may interfere with the other auxiliary data being transmitted.

Adjacent channel interference can cause tone contamination. By defining function identification as complete when identification occurs on 90% of the functions, the frequency sidelobes must be 9.5 dB below the level of the correct tone. Noise will increase the false tone level to the tone and the 6 dB threshold will not reject it. The false tone being 9.5 dB below the true tone will have a probability of detection of 3%. Any one of these will have a detection probability of 10%. If both transmitters were of equal power level, the sidelobes 400 kHz from the angle guidance band edge should be 18.5 dB below the level of the angle guidance. Considering that the angle guidance is at -6 dB, the sideband should be at -24.5 dB. From geometry of 27 dB, rain attenuation of 4.5 dB, transmitter variation of 3 dB and -2 dB of pattern control, the frequency sidelobes would have to be controlled by 51 dB below the angle guidance level.

It should be noted that this type of interference does not produce any angular errors but causes function identification and auxiliary data tones to be misinterpreted with the result that the information is disregarded. From the approach geometry. shown in figure 1, this condition might last as much as 35 seconds during initial acquisition. However, during this time the interfering signal will be sequencing through the tones and as long as the angle guidance is not misinterpreted, high integrity is maintained.

Although this type of interference does not result in angular errors, it does result in a reduction in the effective range of the system. In order to preclude interference in the tone band, the frequency sidelobes would have to be controlled within 51.0 dB when 400 kHz from the angle guidance band edge. There are several alternative means to accommodate this frequency sidelobe control specification.

One alternative involves synchronizing the two channels so that angle guidance and tones are not radiated simultaneously. Secondly, the channel assignments can be adjusted such that adjacent channels cannot be located within the service volume of each other (25 nmi radius). Thirdly, the frequency sidelobes can be controlled at the transmitter or scanner and that the power in the tone band can be increased by raising the carrier signal level.

A fourth technique is to modify the tone format slightly such that the phase of the audio tone can be flipped by 180 degrees every millisecond. This technique permits us to gain about 16dB in tone processing gain. An additional gain of 5 dB is obtained since the reference carrier was increased that amount to maintain a reference carrier 6 dB above to angle sideband. A more complete examination of this approach will be performed. during the GAP period.

e. Timing Relationship Between Parameters

The basic overall timing cycle is determined by the data rate selected on an accuracy-data rate trade off study performed for Hazeltine by Sperry. The timing within each scan cycle is determined by a number of factors concerning;

- o buffer times
- o receiver AGC requirements
- o receiver STALO requirements
- o auxiliary data
- o minimum number of scans per function time
- o relative timing between functions
- o integrity

Buffer Times. In Doppler MLS the receiver AGC is not critical since angle measurements are made in the frequency domain but should be established within a few dB of the nominal level to reduce the linear amplifier dynamic range and reduce the number of false alarms due to noise firings when the function is received at levels 8-10 dB above minimum sensitivity. Since an instantaneous 37 dB change may be present in the TDM format when going from AZ to EL-1, the AGC amplifier has to slew 37 dB in a short time. For realistic AGC slewing requirements a 1 ms buffer time is introduced in the format at the end of each function time, to permit the receiver to reset the AGC to maximum gain.

AGC. The AGC amplifier is needed only when determining the threshold level for tone demodulation to limit the dynamic range in the tone decoder. It should, therefore, be set prior to acting on the function identification and auxiliary data tones. If the tones were transmitted during the entire "function start pulse", the AGC would have to accommodate a 6.5 kHz AM tone on the reference. The AGC time constant would then be in the order of 400 microseconds and three time constants (1.2 ms) would then be required to establish the AGC level. An alternative approach is to transmit a carrier only signal for a specified period of time prior to the AMed tones, which permits the AGC time constant to be reduced. As a baseline choice, a 300 microsecond period is used to transmit a carrier only signal. During this period the AGC level is set and held constant until the 1 msec buffer time is detected.

STALO. In the Doppler MLS approach, it is sometimes necessary to substitute a reference signal in the receiver in place of a multipath contaminated transmitted reference signal. The STALO will be placed to within a fraction of a beamwidth to permit both upper and lower sidebands to be detected and then applied to one prefilter. The exact frequency of the STALO is not critical, since the dual scan format averages adjacent scans. However, if the STALO were set too loose, then the prefilter bandwidth would have to be increased. AZ is the only function that requires a narrow or tracking prefilter, so the STALO will be set to within 100 Hz for minimum effect on the prefilter bandwidth.

In order to facilitate the setting of a STALO, all ground transmitters should be locked to a common frequency. This is done easily through a microwave or ground link which also contains the timing signals. In this way, the airborne oscillator could be locked on the received carrier frequency during the acquisition cycle, where the STALO (APC loop) in the receiver is updated at the start of each function time. Again use is made of the 300 microsecond period to update the APC loop, since no modulation is present on the carrier to distort the output of the filter when the signal is placed unsymmetrically about the carrier.

Auxiliary Data Timing. The auxiliary data format was refined from that suggested in SC-117 and the Hazeltine proposal. In SC-117, four tones were used to transmit auxiliary data, but all tones were transmitted from the AZ reference antenna. The refined format retains all the information in the SC-117 concept, but places two tones on AZ and two on EL-1. This approach permits the use of only two tones. When used in conjunction with the AZ and EL-1 ident signals, it performs the function of the original four tones.

The organization of the tone cycle is shown in figure 9-35. It consists of two basic formats; a Morse Code format and an Auxiliary data format. The Morse Code format is transmitted with an "I" letter start followed by the Morse Code one character (mark or space) per AZ function time by modulating tone E. The auxiliary data format is a constant word which consists of a 10 bit preamble followed by four 15 bit words. Each word contains 11 information bits and 4 bits for Hamming Code detection. Several key features are incorporated in this format organization and are described below.

On tone F-AZ, "time of day" and "barometric altitude set" data words are transmitted for use in terminal navigation. The "time of day" word uses 6 bits for minutes and 3 bits for seconds. The seconds are derived in the aircraft by decoding the preamble and using the fact that the preamble repeats every ten seconds. In this way, it takes at most ten seconds to synchronize to the "time of day" signal.

On the EL-1 function changing data, such as facility status, wind vector, and wind shear, are transmitted both on tones E and F. In this way, the data rate of these functions are increased to once per five seconds. This approach also has an integrity feature in that should the "E" tone generator fail, the information can still be derived from the tone F EL-1 signal.

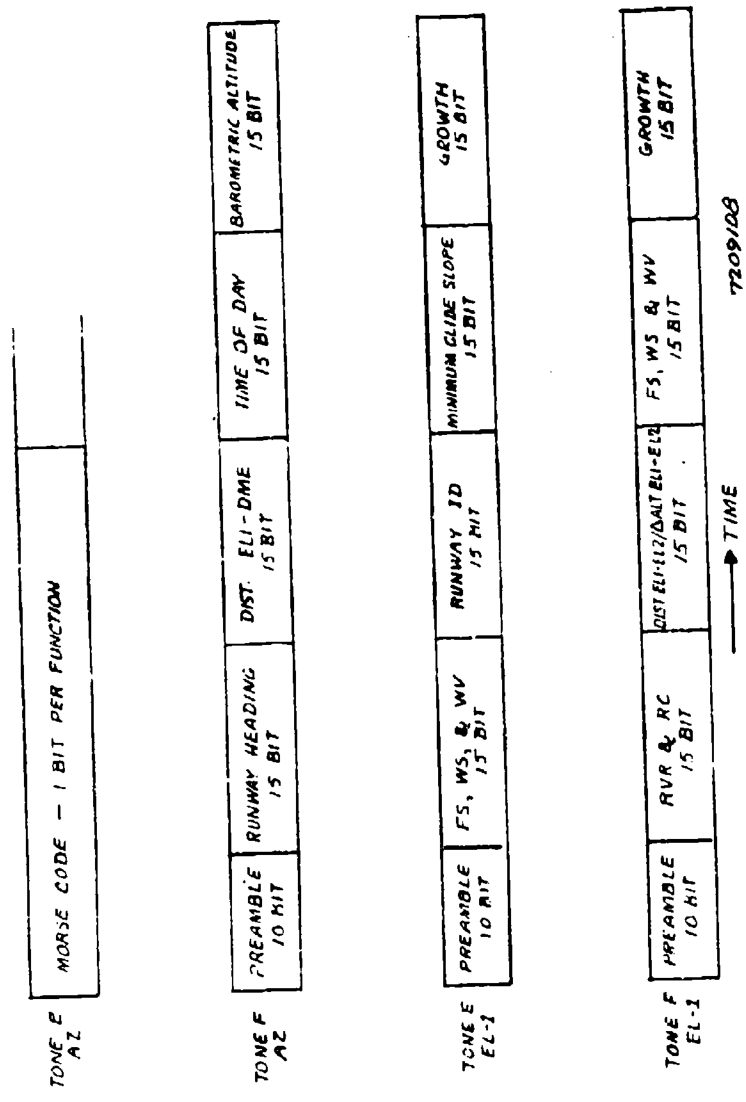


Figure 9-36. Auxiliary Data Format Organization

In addition, the format is organized such that tone F contains all the data relevant to computation requirements and tone E EL-1 contains information which can be used even in a low cost receiver. The tone E EL-1 feature is accommodated at little additional cost, since the tone E decoder is required anyway for Morse Code identification.

Minimum Number of Scans. The minimum number of scans per function time is related to the phase cycling granularity reduction and power requirements. By using two successive function times to resolve the granularity with phase cycling, a relationship 16 times the Doppler beamwidth (one over the scan time) is required to satisfy granularity requirements for manual control operations.

Relative Timing Between Functions. Relative timing between functions is chosen to establish a specific function length for each function (AZ, EL-1, etc.) at all facilities. This approach permits the receiver to establish its own time interval which reduces the complication in the division process. In addition, the receiver has a cross check on the function identification (additional integrity).

The primary mode of function identification is on tones A, B, C, D during the initial two milliseconds of each function time. If the receiver time interval is much different than the received time interval, the receiver can disregard the processed data.

f. Power Budget

The power budget for Doppler MLS, first defined in the TACD proposal, was refined based on updated design concepts from the receiver, propagation, and antenna studies, and the spectrum control requirements analysis. The new power budget is summarized in table 9-28. The receiver sensitivity calculations include loss figures based on state-of-the-art components, such as the following.

Table 9-28. POWER BUDGET SUMMARY

POWER BUDGET	CONFIGURATION K										CONFIGURATION D			
	AZ		ELI_L		ELI_H		EL2		BC AZ		AZ		ELI_L	
	TONES (dB)	SB (dB)	TONES (dB)	SB (dB)	TONES (dB)	SB (dB)	TONES (dB)	SB (dB)	TONES (dB)	SB (dB)	TONES (dB)	SB (dB)	TONES (dB)	SB (dB)
RECEIVER														
THERMAL NOISE Per Hz	-204	-204	-204	-204	-204	-204	-204	-204	-204	-204	-204	-204	-204	-204
THERMAL NOISE IN BP FILTER	33.5	50	33.5	47	33.5	47	33.5	47	33.5	50	33.3	50	33.5	47
RECEIVER NOISE FIGURE	11	11	11	11	11	11	13	13	11	11	11	11	11	11
SNR	11	10	11	10	11	10	11	10	11	10	11	10	11	10
ANTENNA	-4	-4	-4	-4	-4	-4	-9	-9	-4	-4	-4	-4	-4	-4
VSWR	1.0	1.0	1.0	1.0	1.0	1.0	0.7	0.7	1.0	1.0	1.0	1.0	1.0	1.0
CABLE	2.6	2.6	2.6	2.6	2.6	2.6	1.0	1.0	2.6	2.6	2.6	2.6	2.6	2.6
PRESELECTOR	1.6	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.6	1.6	1.6	1.6	1.6	1.6
LIMITER	1.2	1.2	1.2	1.2	1.2	1.2	-	-	1.2	1.2	1.2	1.2	1.2	1.2
COUPLER #1	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.2	0.4	0.4	0.4	0.4	0.4	0.4
COUPLER #2	0.4	0.4	0.4	0.4	0.4	0.4	-	-	0.4	0.4	0.4	0.4	0.4	0.4
CIRCULATOR	0.3	0.3	0.3	0.3	0.3	0.3	-	-	0.3	0.3	0.3	0.3	0.3	0.3
BP FILTER	1.0	1.0	1.0	1.0	1.0	1.0	-	-	1.0	1.0	1.0	1.0	1.0	1.0
SENSITIVITY	-144 (-114dBm)	-128.5 (-98.5dBm)	-144 (-114dBm)	-131.5 (-101.5dBm)	-144 (-114 dBm)	-131.5 (-101.5 dBm)	(-149.4) (-119.4 dBm)	(-135.9) (-105.9 dBm)	-144 (-114 dBm)	-128.5 (-98.5dBm)	-144 (-114dBm)	-128.5 (-98.5 dBm)	-144 (-114 dBm)	-131.5 (-101.5dBm)
PATH ATTENUATION														
RANGE FROM TOUCHDOWN														
25 nmi	-142	-142	-141	-141							-142	-142	-141	-141
10 nmi					-134	-134			-134	-134				
3.5 nmi							-131	-131						
(2 nmi)							-(130)*	-(130)*						
RAIN ATTENUATION	-5	-5	-5	-5	-2	-2	-30dB -(20dB)*	-30dB -(20dB)*	-2	-2	-2	-2	-2	-2
ANTENNA														
DIRECTIVITY	+15.9	+16.9	21.2	21.2	20.8	20.8	23.5	23.5	16.9	16.9	20.9	20.9	21.2	21.2
DISSIPATION, REFLECTION	-2	-5	-4	-4	-4	-4	-3.4	-3.4	-2	-3	-2	-4	-4	-4
LOPING, SPILLOVER	-2	-2	-1	-1	-1	-1	-1	-1	-2	-2	-2	-2	-1	-1
COUPLING			-3	-3	-3	-3	-3	-3					-3	-3
CABLE LOSS TO SHELTER	-2.6	-2.6	-1	-1	-2	-2	-1	-1	-2.6	-2.6	-2.6	-2.5	-1	-1
TRANSMITTER POWER REQUIREMENTS	-6.3	11.2	-10.2	2.3	-18.8	-6.3	-1.9(-12)*	10(1)*	-18.2	-1.8	-14.3	2.4	-13.2	-.7
REFERENCE	14		8.5		-.3dB		24(4)*		4		5.4		6	

NOTE: * PER RAIN BUDGET

- o An 11 dB NF in the C-band receiver
- o A 13 dB NF in the Ku-band receiver
- o 1 dB for VSWR loss, etc.

The propagation studies presented in section 1.1.1.1 Part F indicate a rationale for limiting the maximum rain attenuation at Ku band to 20 dB which reduces the range of the EL-2 antenna to 2 nmi. An aircraft landing at 140 KIAS and a 10 knot tailwind would then receive EL-2 guidance about 40 seconds before touchdown and about 30 seconds before flare initiation. At the most critical distance around 1 nmi from EL-2 where primary vertical guidance is "phased over" from EL-1 to EL-2, the 20 dB attenuation allowance is sufficient to permit outages less than 1.5 hours per year in the most severe climate (Asia). The power budget indicates two numbers for rain attenuation: one to meet the full range requirements of 3.5 nmi and the other to satisfy the rain attenuation budget of 20 dB.

It should be noted that the rationale for selecting the 3.5 nmi requirement was based on the reasoning that the aircraft requires corroboration of EL-2 signals one minute before touchdown. There are two areas for further investigation regarding these assumptions; reliability considerations (amount of time required to validate EL-2 data for autoland applications) and the accommodation of future aircraft with higher landing speeds. We plan to analyze the range requirement of EL-2 in more detail during the feasibility program.

The ground antenna studies resulted in an updated definition of doppler antenna gains. A conservative approach was taken in defining the EL-1 antenna characteristics, by designing an integrated angle and reference channel antenna. This approach results in a 3 dB loss in antenna but is included to provide phase centers for the reference and angle guidance signals for additional granularity reduction for EL-1.

In the receiver sensitivity calculations, it was noted that a 10 dB SNR is required for tone detection and that 11 dB SNR is required for angle guidance processing. These SNR's were based on a small false alarm rate and tolerable noise errors in the receiver at maximum range. When translated into receiver senstivities they are expressed as -114 dBm for the tones and -98.5 dBm for the angle guidance. Since the tone sidebands are 18 dB below the carrier, the carrier sensitivity is -96 dBm, (only 2.5 dB greater than the angle guidance sideband). For proper spectrum control and detection in a low cost receiver, the carrier should be as large as possible with respect to the sidebands. A 6 dB difference provides sufficient rejection due to difference frequencies in the detector, so the carrier power must be increased by 3.5 dB.

1.1.1.3 IDENTIFICATION AND RESOLUTION OF REMAINING TECHNICAL PROBLEMS

The TACD studies have addressed requirements, critical technical areas, system definition, and definition of Feasibility and Prototype Equipment. The studies have verified the fundamental soundness of the Doppler technique and the ability to implement it in cost-effective equipment. It is our belief that all major system problems for Doppler as a technique have been resolved, as indicated in the discussions of this report. There remain, however, a number of tasks to complete system definition from choices among alternatives and from the further definition of requirements, especially those associated with the military. In addition, there remain a number of problems common to any MLS technique which require additional effort for their resolution.

A. COMMON MLS PROBLEMS

1. Interface with Flight Control Systems

It has been described in Section 1.1.1.2 that MLS--being a sampled data system--presents a different format to AFCS and that is has been necessary to address the effect of this difference. Our studies to date have indicated the quality of the MLS signal output required to interface with the AFCS for several aircraft types in both CTOL and STOL categories. However, there remain questions in this area concerning other aircraft types. This problem is being addressed by various workers within the MLS contractors and in the Government.

Hazeltine has made specific plans to continue to address this problem. Sperry Flight Systems Division will conduct studies for VTOL, Carrier Landing and USAF High Performance Aircraft during the Feasibility Program.

2. Military Requirements

This area remains as a problem since definitive plans for incorporation of MLS have not yet been made available for all the military services. It is understood that the U.S. Army is planning to complete specifications for tactical landing systems and define transportability requirements. There is also information needed on U.S. Navy Carrier Landing plans. We understand that these plans will depend in part on the results of the TACD studies.

We plan to continue contact with the various military agencies to resolve requirements and system definition.

3. Multipath

Extensive studies of multipath and terrain effects have been made by Hazeltine during TACD (and earlier) and have resulted in several concrete results. A multipath model of the character of multipath return has been defined based on realistic descriptions of airport physical environments. Our Doppler MLS equipment has been designed to accommodate to the multipath signal characteristics. This has had its effect on ground guidance equipment as well as airborne equipment approaches. It is a task in Feasibility Demonstration to experimentally verify the characteristics of the multipath signal (see below for specific Doppler investigations).

Another aspect is siting on irregular terrain and runway humps. It is planned to simulate these conditions and evaluate their effects experimentally in Phase II.

4. Propagation at Ku-Band

The power that is required to be radiated for EL-2 and military systems is very dependent on the actual rain attenuation that will be encountered. It is planned to continue to review this problem and update attenuation and power specifications. However, it is also recommended as a backup that measurements be made under separately contracted effort or directly by the Government.

5. Compatibility with ATC

There are a number of new ATC procedures being considered such as RNAV and terminal area procedures including two-step glideslopes, metering and sequencing, etc. There is the general need for MLS workers to continue to be aware of studies and policies relating to these ATC areas, and it is part of Hazeltine's plan to continue this activity.

B. DOPPLER DEFINITION PROBLEMS

1. Multipath and Receiver Accommodation

As mentioned above in Item A3, our receivers have been designed to reject multipath signals using certain filtering approaches. These are planned to be evaluated by Field and Flight Tests during Phase II to select and define optimum approaches for various classes of users. It is planned to be able to select among fixed sector filters and tracking filters, as applied to various classes of users..

2. Frequency Measurement Approaches

We plan in the Feasibility Demonstration to evaluate several counting and analogue frequency measurement approaches. This evaluation will permit selection of optimum approaches among the various techniques including uniscan counting and multiscan counting.

3. Low-Cost Receiver

It has been a long-stated objective in the MLS Program to provide a low-cost MLS receiver for the general aviation user. This problem has been studied and receiver approaches have been defined during our TACD activities. However, a direct consideration of this problem is planned for Phase II. Sperry will have the task of designing a low-cost Doppler receiver for General Aviation application (i.e. Configuration "D").

4. Synthesizer

There is a need to fully define an optimum cost-effective design for this key component. We plan to specifically carry out this task in Phase II.

5. Acquisition and Reacquisition Timing

MLS will be operating in a multipath environment where large reflections can occur. We have configured approaches to select or acquire the direct or "true" signal and to reject multipath components. This includes data validation as well as reacquisition after momentary outages caused by signal blockage. There remains the detailed definition of the timing of these functions; it is planned as a specific task to determine optimum timing formats for these functions.

6. Monitoring

This topic has been discussed in detail in Section 1.1.1.1, Part A and monitoring approaches have been configured. Integrity has been evaluated for these approaches. There remain some questions concerning the exact location of near and far-field monitors and the effect of the airport environment on their performance. (It is also planned to employ extensive integral monitors as described.) These questions are to be fully evaluated in Phase II to define specific locations for Prototype Systems.

C. CONCLUSION

Of the remaining problem areas which have been discussed above, several are fully expected to be of a continuing nature until equipment is actually in the hands of the users. We plan to address these problems on a continuing basis during subsequent phases. For the other areas, we believe the results of the planned Phase II program will provide positive resolution which will permit the program to proceed without additional risk. In conclusion, we have a firm plan to address and resolve all the remaining technical problems that have been identified.

1.1.2 SYSTEM TRADES

This section reviews the decision process which was followed in selecting our baseline approach and the selection of hardware to demonstrate its feasibility. It will be organized, first under those factors or criteria which affect life-cycle costs. Our selections will then be delineated and any associated technical risks will be reviewed. Additional factors which entered into the overall process of system trades will be indicated.

There are two general types of system trades that were considered. The first is concerned with the definition of the most cost-effective approach which remains within the specific functional requirements as delineated in the report of the RTCA and as refined by Hazeltine. The second type of trade concerns departures from specific techniques in the SC-117 approach, but which meet the operational requirements and aviation needs, also delineated by SC-117. Each of these approaches is discussed in the material which follows.

The first approach has led to our baseline system and format described in Section 1.1.1.1, Part A and Section 1.1.5, Part B, respectively. The second approach has led to the recommendation of a number of viable system alternatives which can offer the solution to certain identified difficult technical problems and offer the potential for overall system cost reduction. For example, one of the problems identified for MLS, and not associated with any particular technique, is the signal blockage of very large hangars for wide azimuth angles in the coverage region. We will present the discussions relating to the baseline system first and follow with system alternatives.

1.1.2.1 LIFE-CYCLE COST IMPLICATIONS

Here we are concerned with the total cost to the aviation community. It concerns not only the initial acquisition and maintenance costs for ground equipment to be installed on airports, but also the costs to the far more numerous airborne users of the MLS. In both cases costs must be considered over the range of installations from the high performance configuration K for commercial air carrier and military user to the simpler service supplied for the general aviation user. An important consideration is the growth potential of the system.

A. BASIC APPROACH

It is our plan to determine full life-cycle costs for our system approach as it becomes defined in the necessary detail during our studies in Phase II concerning Prototype and Production equipments. During this TACD phase it had not been planned to carry out this detailed cost analysis for each alternative considered because of the magnitude of the task. It was decided to apply an approach based on more general criteria.

The criteria applied in our selection were based on fundamental considerations which permitted an expeditious evaluation of alternatives. These general criteria which relate to overall cost are:

- Simplicity of Design
- Fundamental Soundness of Design
- Independence of Design
- Available Modularity
- Flexibility of Approach

It must be recognized that the selection of a detailed baseline approach must be based also on additional criteria which were considered concurrently with cost factors and include:

- Ability to meet functional and operational requirements
- System Integrity
- Compatibility with Ground Environment
- Compatibility with Flight Operations
- Compatibility with ATC Operations
- Compatibility with Users/Airports

The remainder of this discussion will be divided into two parts. The first will review individual factors; the choices made will be based on the sets of criteria indicated. The various baseline candidate configurations which were considered during our studies are presented in figures 11-1 to 11-6.

B. INDIVIDUAL FACTORS

The following summarizes the factors to be considered in the definition of the baseline system

1. Doppler vs Scanning Beam MLS
2. Conical vs Planar Coordinates
3. Crossed vs Unitary Planar Coordinates
4. Aperture Port vs Beam Port Antennas
5. Ground vs Airborne Filter
6. Elevation No. 1 Antennas (EL-1)
7. Configuration D
8. Selection of Optimum Format Parameters
    a. Time division multiplex vs frequency division multiplex
    b. Sequential dual scan (SEDS) vs. simultaneous dual Scan (SIDS)
    c. Frequency coding
    d. Adoption of phase cycling
    e. Timing relationships

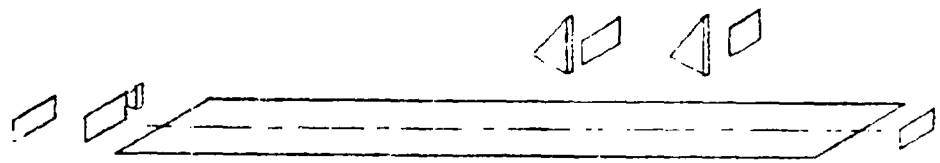
It should be noted that the above list refers to our baseline selection. The description and recommendation of overall system alternatives will be described in Part 4 of this section.

(PRELIMINARY WORK SHEET)

CONFIGURATION "K"

PLANAR COORDINATES (OPTIONAL CONICAL)

CROSSED LINEAR ANTENNAS



Antenna Function	Azimuth	Elevation 1	Elevation 2	Az Back Course
Antenna Type Main	Linear aperture port array 12' by 4'	Linear beamport pillbox 0.2' by 12'	Linear beamport pillbox 0.1' x 8'	Linear aperture port array 6' x 4'
Auxiliary	Linear beamport pillbox 0.2' by 4'	Linear aperture port array 6' x 4'	Linear aperture port array 1.5' x 4'	(None Required)
Coverage Azimuth Elevation Range	130° 0° to 20° 25 n.m.	[illegible]0° 1° to 20° 25 n.m.	[illegible]0° (-10° to +50°) 0° to 10° 3.5 n.m.	80° 1° to 20° 10 n.m.
Airborne Computation for Planar Coordinates	Required	Required	Required	Required

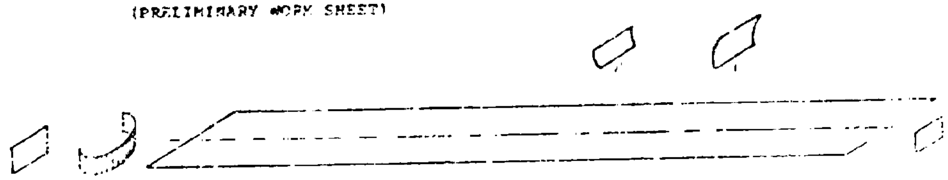
Figure 11-1. Baseline Candidate Number 1-K

(PRELIMINARY WORK SHEET)

CONFIGURATION "F"

PLANAR COORDINATES

UNITARY PLANAR ANTENNAS



Antenna Function	Azimuth	Elevation 1	Elevation 2	Azimuth Back Course
Antenna Type	Circular Cylinder array: diameter: 15½' height: 4'	Circular Cylinder reflector: width: 24' height: 16'	Parabolic Cylinder reflector: width: 7' height: 8'	Linear aperture port width: 6' height: 4' height: 4'
Coverage Azimuth Elevation Range	 120° 0° to 20° 25 n.m.	 120° 1° to 20° 25 n.m.	 60° (-10°, +50°) 0° to 10° 3.5 n.m.	 80° 1° to 20° 10 n.m.
Airborne Computation for Planar Coordinates	None	None	None	None

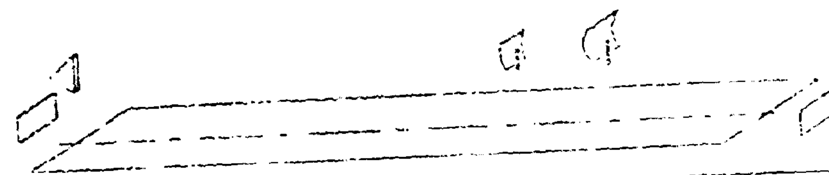
Figure 11-2. Baseline Candidate Number 2-F

(PRELIMINARY WORK SHEET)

CONFIGURATION "K"

HYBRID PLANAR - CONICAL
COORDINATES:
OPTIONAL CONICAL FOR AZIMUTH
CONICAL FOR WIDE ANGLE EL-1
PLANAR FOR NARROW ANGLE EL-1

COMBINATION OF UNITARY PLANAR AND
CROSSED LINEAR ANTENNAS



Antenna Function	Azimuth	Elevation 1	Elevation 2	Az Back Course
Antenna Type Main	Linear aperture array 12' by 4'	[1]Located at Az site linear beamport pillbox 0.2' by 12'		Linear aperture port array 6' by 4'
Auxiliary	Linear beamport pillbox 0.3' x 12'			
Unitary Planar		[2]Circular cylinder reflector: width: 12' height: 16'	Parabolic cylinder reflector: width: 7' height: 8'	
Coverage Azimuth Elevation Range	120° 0° to 20° 25 n.m.	1: 120°, 1° to 20°, 25 n.m. 2: 40°, 1° to 20°, 25 n.m.	60° (-10° to +50°) 0° to 10° 3.5 n.m.	80° 1° to 20° 10 n.m.
Airborne Computation for Planar Coordinates	Required	None	None	None

Figure 11-3. Baseline Candidate Number 3-K

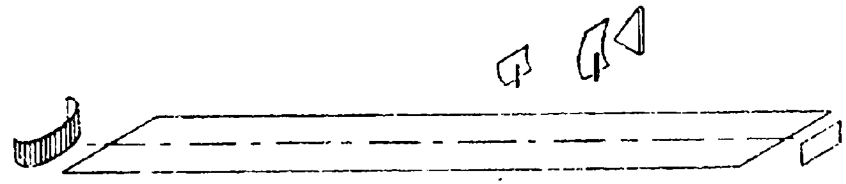
(PRELIMINARY WORK SHEET)

CONFIGURATION "K"

HYBRID PLANAR - CONICAL

COORDINATES:
CONICAL FOR WIDE ANGLE EL-1
PLANAR FOR ALL OTHER FUNCTIONS
INCLUDING ₵ EL-1

ADDITION OF LINEAR EL-1 TO ALL
PLANAR SYSTEM



Antenna Function	Azimuth	Elevation 1	Elevation 2	Azimuth Back Course
Antenna Type Unitary Planar	Circular Cylinder Array: dia: 15½' height: 4'	1 Circular or Parabolic Cylinder Reflector height: 16' width: 12'	Parabolic Cylinder Reflector: height: 7' width: 8'	1 ∆ Circular cylinder array
Main		2 * Linear beamport pillbox: height: 12' width: 0.2'		2 Linear aperture port array: width: 6' height: 4'
Coverage Azimuth Elevation Range	120° 0° to 20° 25 n.m.	1 40° 1° to 20° 25 n.m. 2 120° 1° to 20° 25 n.m.	60° (-10° to + 50°) 0° to 10° 3.5 n.m.	80° 1° to 20° 10 n.m.
Airborne Computation for Planar Coordinates	None	None	None	None

* - Used to provide elevation guidance during vertical maneuvers in approach zone

∆ - Used when circular cylinder available from Az antenna system for approach from opposite side of runway

Figure 11-4. Baseline Candidate Number 4-K

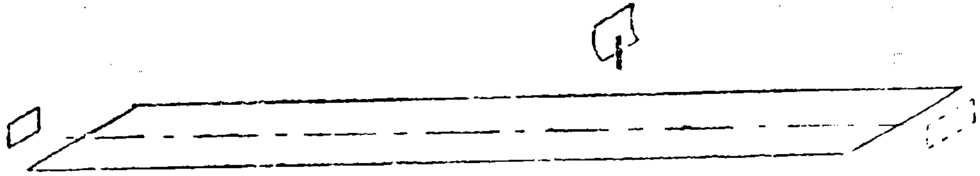
(PRELIMINARY WORK SHEET)

CONFIGURATION "D"

PLANAR COORDINATES

LINEAR ANTENNAS

FULL PROPORTIONAL COVERAGE



Antenna Function	Azimuth	Elevation 1	Elevation 2	Azimuth Back Course
Antenna Tape	linear aperture part array 6' by 4'	Parabolic cylinder		Optional linear aperture port array 4' x 4'
Coverage Azimuth Elevation Range	 40^{o} 0.7^{o} to 8^{o} 25 n.m.	 40^{o} 1^{o} to 8^{o} 25 n.m.		 40^{o} 1^{o} to 8^{o} 10 n.m.
Airborne Computation for Planar Coordinates	None	None		None

Figure 11-5. Baseline Candidate Number 1-D

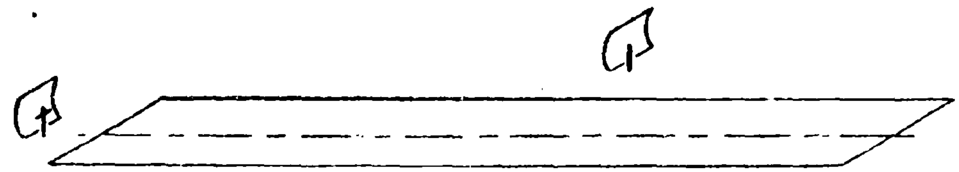
(PRELIMINARY WORK SHEET)

CONFIGURATION "D"

"ILS REPLACEMENT"

PLANAR COORDINATES

LIMITED PROPORTIONAL COVERAGE



Antenna Coverage	Azimuth	Elevation 1	Elevation 2	Az Back Course
Antenna Type	Beamport Width: 6' Height: 2'	Beamport Width: 4' Height: 6'		Optional
Coverage				
Azimuth proportional	$\pm 3.5^o$			
Azimuth deviation	$\pm 35^o$			
Elevation proportional		1^o to 8^o		
Elevation deviation		0 to 12^o		
Range	25 n.m. ($\pm 10^o$) 17 n.m. ($\pm 35^o$)	20 n.m. ($\pm 10^o$) 3 n.m. ($\pm 20^o$)		
Airborne Computation for Planar Coordinates	None	None		

Figure 11-6. Baseline Candidate Number 2-D

C. DISCUSSION OF TRADES

1. Doppler vs Scanning Beam

This very fundamental question was not considered at this time because of the approach that we have adopted during TACD. Our original decision to pursue the study and development of the Doppler technique had been based on recognized advantages in both fundamental performance of the Doppler system and in anticipated simplification of the required implementation. Our TACD approach has been to bring the Doppler technique to the stage of development by detailed technique analysis and equipment design development so that comparison and evaluation of alternative techniques may be made with Doppler "at its best".

Our studies and experiements to date have reaffirmed our original decision to pursue the Doppler technique. We believe that the designs and approaches developed have verified Doppler's ability to meet operational and functional requirements with higher levels of performance and lower co s than may be possible with other techniques. One aspect will be pointed out which is the experimental demonstration of the planar beam-port ground guidance system. In this case we have achieved anticipated performance of planar beams, low-angle cutoff and smooth frequency coding in a very simple cost-effective structure. It has provided additional confidence that Doppler potentialities can be realized in practice.

2. Conical vs Planar Coordinates

This has been a fundamental consideration since the inception of organized MLS activity. SC-117 has adopted planar coordinates for all elements, but this viewpoint has been challenged abroad, as well as within the U. S. During TACD this question was reviewed and several conclusions can be stated here, since they have far reaching cost implications. First, there should be a statement of an identification of the optimum set of coordinates for MLS. With these in mind the discussion can be clarified.

We would like to define an optimum as the coordinate required for "direct use" - This coordinate set would be the most useful for the simplest airborne implementation with the minimum of computational facility available. These "direct-use" coordinates are:

- Planar azimuth which means that it is independent of height or elevation angle.
- Planar elevation along runway centerline intersecting the runway at the GPIP.
- Conical elevation at wide azimuth angles for height determination, especially if colocated with DME.

It is our analysis that "direct-use" coordinates will provide for the least cost in airborne equipment computations, provide coordinates directly applicable to the general aviation aircraft, and provide maximum integrity at decision height and touchdown regions. It is our conclusion that these coordinates should be adopted.

The one departure of these coordinates from SC-117 is the conical elevation at wide azimuth angles. It is believed that, as long as centerline guidance is planar in elevation, there will be greater system simplicity with resulting lower overall cost with conical wide azimuth angle elevation. Also, conical elevation permits 360° coverage in the azimuth dimension; planar does not.

3. Crossed vs Unity Planar Antennas

There are two ways which have been identified to achieve planar coordinates with the Doppler technique. One was described in the SC-117 report and required two orthogonal conical coordinate arrays with a simple airborne coordinate converter. This approach operates sequentially in two time slots. A second approach was presented in the Hazeltine TACD proposal to be a single antenna structure, operating in a single time slot. Moreover, simple implementations for these antennas were described. At Hazeltine a selection has been made of the unitary planar antenna for three basic cost-related reasons.

- o The airborne receiving and decoding equipment will be simpler with resulting lower cost.
- o The unitary approach will require simpler monitoring on ground and in airborne equipment to insure the proper operation. There would be a need for monitoring both antennas of the crossed approach with corresponding flag indications in the receiver for each of the two antennas.
- o The dual or crossed systems are considered less reliable for Cat II/Cat III operations with computations in the aircraft required. It is anticipated that this would result in additional missed approaches introducing an additional burden and therefore cost on overall system operation.
- o The cylinder array has a growth potential to 360° and as such can increase the life cycle with attendant overall lower cost.

4. Aperture Port vs Beam Port Antennas for Elevation

The original suggestion in SC-117 for Doppler elevation antennas is a linear array of many elements, possibly exceeding 150 elements in a high performance configuration. This type is called an "Aperture Port" antenna in the Hazeltine proposal. It was recognized early and it was presented in the proposal that where coverage angle is limited to 10 or 20 degrees, a saving in the number of active components could be achieved (see Section 1.1.1.1, Part C), by the use of a "Beam Port" antenna. Also, it was recognized that the Beam-Port approach could provide planar coordinates when configured with a cylindrical parabolic reflector. Therefore, Beam-Port approach has been adopted for basic simplicity as well as other technological reasons. The smaller number of active elements is anticipated to result in lower direct costs and lower operating and maintenance costs as well as simpler associated monitoring circuits.

5. Ground vs Airborne Filter

In the Doppler elevation antennas as envisioned by SC-117, there is radiation toward the airport surface which is reradiated and received at the airborne receiver decoder at characteristic frequencies. This component must be eliminated from the decoding process or intolerable guidance errors result. It was proposed to eliminate this component by the use of a sharp cutoff filter in the airborne receiver, but there are two problems associated with this approach. One is the complexity of the sharp cutoff circuit design and the second is the distortion of the angle guidance calibration at very low angles because the signal is very near the sharp cutoff of the filter. Also, there must be a filter in every airborne receiver. As an alternative to this approach, a Doppler antenna which limits the radiation and resulting reradiation from the ground to levels which do not require an airborne filter, has been devised. It is a characteristic of the beam port antenna previously described. The sharp cutoff characteristic which eliminates the ground reflection directly and avoids the need for the airborne filter has been selected in our baseline approach.

6. Elevation No. 1 Antennas (EL-1)

There is a complicated situation regarding elevation antenna selection which involves a number of constraints. These are:

- Wide azimuth elevation guidance "direct-use" coordinates are conical (Item 2).
- Planar elevation coordinates are required along the centerline as low as 50 ft. above the runway for Category II landings.
- EL-1 antennas must be sited opposite the GPIP or require an offset GPIP computation.
- Very high glideslopes, up to 15°, with 20° coverage have been postulated as being required for potential future operations.

- o High glideslopes, low decision heights and EL-1 siting locations require wide azimuth coverage to include runway centerline plus anticipated tolerances.
- o It becomes increasingly costly to provide planar coordinates at very high glideslope angles at the very wide azimuth angles corresponding to very low decision heights (see Section 1.1.1.2, Part A).

Based on an extensive review of these factors and the consideration of many alternatives a baseline approach has been selected tentatively for on-going planning (figure 11-7), and several viable options have been identified, Also, there is suggested that careful review of requirements be continued to carefully set limits to provide what is actually needed, so that costly unessential performance can be avoided.

The baseline selection provides for a modular approach to EL-1, separating elevation coverage into two regions, one for CTOL and one for STOL. EL-1L provides coverage in planar coordinates from 1° to 10°; EL-1H provides it from 4° to 20°. Each antenna operates in a separate time slot, so they can be used individually or in combination as requirements dictate. Planar guidance is provided to 50 ft. below Cat II decision heights. One option permits the beams to be shaped in azimuth to avoid illumination of largest sources of multipath error. Wide angle elevation information to determine altitude is not provided by this approach for the reasons which will be discussed below. It is recommended that altitude in in wide angle regions only be determined by barometric altimeters for cost and technical reasons. It is believed that the most cost-effective way to reliably meet the operational requirements is provided by this recommended approach.

It is to be noted that our Doppler approach is fundamentally capable of providing the full coverage elevation performance, either by a conical coordinate antenna or by a larger planar coordinate antenna, such as described in the Hazeltine TACD proposal. We have adopted

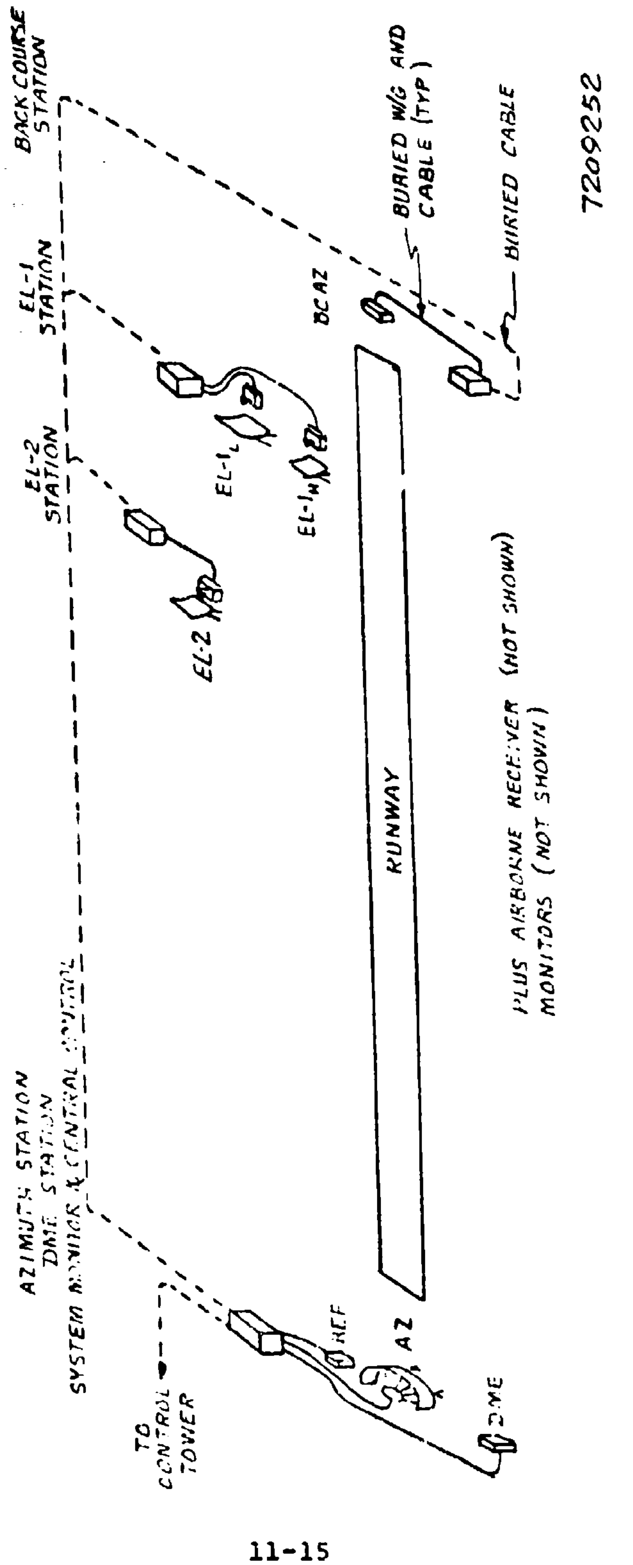


Figure 11-7. K Configuration System

the baseline approach because it results in what we believe is the most practical way to compatibly integrate MLS into the National Aviation System and meet MLS operational requirements.

The rationale for this selection is based on the recognition of several practical and compatibility factors which must be carefully weighed and judged before adopting a particular approach. These include:

- The maximum glideslope required for STOL and even VTOL may not require angles as steep as 15° and may only require 7° to 8°.
- The decision heights (and therefore the lowest guidance angle) for the highest glideslope paths may not be as low as the current 100 ft.
- There is potential incompatibility with determining altitude by the combination of EL-1 and DME with users operating on baro-altitude.

If either or both of the first two items are realized, then it will be possible to use a single EL-1 antenna and meet all planar coordinate and accuracy requirements. This would avoid the two antennas and result in a further cost reduction. Over 95 percent of current airport installations would require only one antenna.

The last item is concerned with height determination by MLS (EL-1 combined with DME) at wide angles. The first concern with this approach is that should planar coordinates be utilized, azimuth angle would also be required for the height computation. Also the location of DME, whether at the AZ or EL-1 site presents another parameter in the computation. The second concern is the accuracy for height determination at the maximum range. In the worst case at wide azimuth angles and 25 n mi range three sigma errors of up to 500 ft could be present (Section 1.1.1.2, Part A). There is also the fact that an EL-1 angle coordinate reference is a plane tangent to the earth at its location, while baro-altitude is above mean sea level. Since the ATC system is operated with reference to mean sea level, there exists a basic incompatibility in a trivial way because of the altitude of the EL-1 antenna, but in a significant way because of the earth's curvature. While this could probably be corrected or calibrated out, it represents a complication. An error or incompatibility which may not be resolved, however, is the MLS height determined from two different EL-1 antennas which are separated by a substantial amount on a large airport. For a spacing between EL-1 antennas of 5 miles and a range of 20 miles, there would be an error of 150'. It would require considerable computation to remove this bias.

Therefore, while it would have been possible to provide wide-angle elevation angle coverage for the general baseline K configuration, we are recommending that height be determined by baro-altitude at wide angles only so as to be compatible with ATC and avoid the errors described in the paragraph above. It should be made very clear, however, that centerline altitude in the final approach will be provided by MLS. When maximum usable glideslopes and decision heights are set, we visualize a K configuration airport with a single planar azimuth system, an EL-2 system for touchdown guidance, a single planar EL-1 system for required centerline guidance on the approach path and landing regions and a back course system as a very cost-effective approach to MLS.

It should be noted that special requirements may have to be satisfied for military operations where side-angle elevation may be required. Our military system provides elevation guidance to ±60° azimuth angle (Section 1.1.1.1, Part C).

7. Configuration D

For configuration D there were two basic alternatives which were considered. One would provide proportional azimuth coverage to ±20° and the second to ±3°, with left-right indication to ±20°. Our choice of baseline, as shown in figure 11-8 has been to provide the full proportional coverage, but the reduced requirement D system does provide an attractive low-cost alternative. It would be an "ILS Replacement" and may be attractive to some general aviation users.

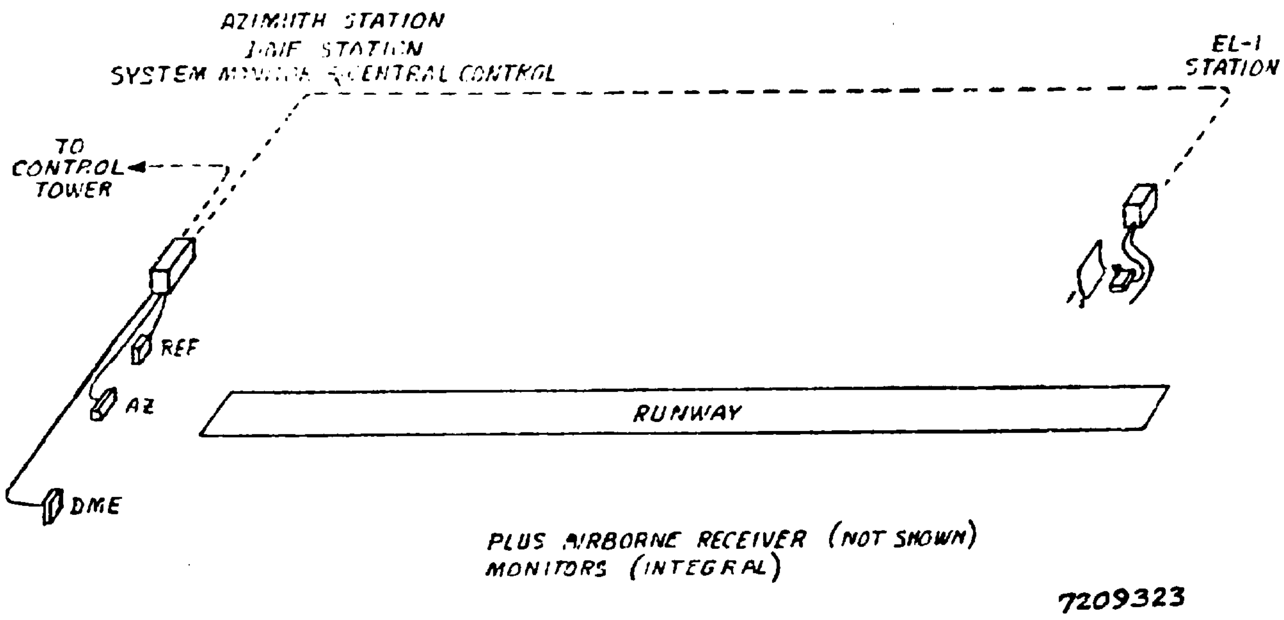


Figure 11-8. Baseline D Configuration

8. Selection of Optimum Format Parameters

Detailed signal format studies have been performed as reported in Section 1.1.1.2, Part B. It was required that a large number of choices be made in the format with criteria established with technical and cost-related factors. The detailed discussions will not be repeated here and the reader is referred to that Section. However, a very brief summary is included here to indicate the factors reviewed and conclusions reached.

- o Time Division Multiplex (TDM) has been selected over the alternative Frequency Division Multiplex (FDM), primarily because FDM requires multiple processors and because of the bandwidth economy of the TDM approach while retaining adequately high data rate and reasonable transmitted power levels.
- o Sequential Dual Scan (SEDS) has been retained over Simultaneous Dual Scan (SIDS) as a means of retaining simplified airborne receiver approaches.
- o A Frequency coding has been selected with a harmonic relation among functions to simplify receiver angle normalization implementation.
- o Phase cycling in the transmitter has been adopted to permit application of multiscan counting for low-cost general aviation receiver design.
- o A number of timing relationships have been chosen to simplify receiver design. These include
  - o 300 μ-second pure carrier to simplify AGC and AFC
  - o 1 ms buffer time to reset AGC
  - o fixed function time length
- o A test signal is planned to be radiated from the ground systems in function "dead" times to provide a check of the airborne receiver.

- o AM tone modulation is planned for simple receiver detection.
- o Ground systems will be frequency locked to permit simple AFC in airborne receiver.

D. SYSTEM ALTERNATIVES

There are two major alternatives which have been considered to provide an overall cost reduction. They are presented here for consideration, but are not recommended for adoption at this time. One is the "Common-Format Micronavigation" approach and the other is the "ILS Replacement," which was discussed earlier.

Common-Format Micronavigation/Landing System. In the TACD effort we analyzed the MLS concept as defined by SC-117 and stressed the combined landing system guidance capabilities and limited terminal navigation capabilities of the system. However, microwave propogation studies affecting wide-angle coverage around major airport terminals highlighted the problem of blockage. Sectors 3°EL x 5°AZ may be blocked due to the large fixed airport structures, such as the large hangar complex along runway 31R at JFK. One solution to this problem is to separate the landing and terminal navigation equipments. If we provide a wide-angle accurate and blockage free system for terminal navigation, then a narrow-angle highly-accurate system can be placed on each runway for landing guidance.

The system would operate using one airborne receiver in the following manner. A 360° AZ navigation system referenced to magnetic north would transmit on one MLS channel and a landing system would transmit on another channel, but both systems would use the Doppler MLS format. Only one navigation system would be required per airport and it would be elevated or suitably located to reduce blockage. If an option were adopted to reduce the wide-angle coverage of the landing guidance system, a simplified and lower cost landing guidance system could be placed on each runway requiring MLS.

The micronavigation approach would permit interfacing with ATC systems outside the terminal area, included proposed 4th generation satellite systems. It is interesting to note that a 4th generation airborne navigation package could then consist of only a general navigation receiver (e.g., a satellite L band transceiver) and a C band MLS receiver.

The antenna configurations chosen for this common format system are identical to those used in the baseline system description. A more definite position will be taken during the feasibility program regarding the separation of the two functions (wide angle navigation and final approach) after a more complete analysis is made. However, the concept of separating the landing and navigation aspects of MLS is introduced here to indicate the growth potential of the Doppler MLS.

1.1.2.2 Technical Risk Implications

In Section 1.1.2.1 the selection process for our baseline system was described, based on a number of technical and cost-related factors. Having made this selection, the question then remains concerning the degree of technical risk associated with these choices. It is our belief (Section 1.1.1.3) that our studies have verified the fundamental soundness of the Doppler approach and that all major system problems have been resolved. In that section there was, however, indicated the need for further detailed system definition to meet the needs of all users, and work on certain common problems associated with MLS techniques in general. Although additional verifications were recommended for final resolution and optimization, in each case there had been sufficient study performed to indicate to us that no significant risk remains.

In this section we will briefly list the major choices and the degree of technical risk which remains in the development program associated with each. The individual factors considered are:

1. Doppler vs Scanning Beam
2. Conical vs Planar Coordinates
3. Crossed vs Unitary Planar Antennas
4. Aperture Port vs Beam Port Antennas for Elevation
5. Ground vs Airborne Filter
6. Elevation No. 1 Antennas
7. Configuration D
8. Selection of Optimum Format Parameters

The technical risk associated with each of these factors is summarized in table 11-1. A review of this table indicates that we believe that our chosen approach has achieved a very low technical risk for further development and feasibility demonstration because of the extensive and complete analytic and verification studies and experiements carried out during the TACD phase.

Table 11-1. SELECTED PARAMETERS VS TECHNICAL RISK

Baseline System Selection Feature	Technical Risk Implication
1. Doppler over Scanning Beam	Our studies have indicated fundamental advantages for the Doppler approach and verification that Doppler can be implemented to meet requirements in a cost-effective manner - low technical risk.
2. Planar over Conical Coordinates	It has long been recognized that planar coordinates, if obtainable, represent a lower cost and higher integrity approach. Our definition of straight-forward antennas to achieve planar coordinates and their verification by analysis and experimentation have reduced technical risk to a very low value.
3. Unitary Planar over Cross Conical Antennas	The ability to obtain planar coordinates in a unitary structure reduces technical risk in system integrity and reliability. We have already demonstrated the unitary antennas (see Item 2) and therefore assign a low technical risk to this selection.
4. Beam Port Antennas over Aperture Port Antennas for Elevation Guidance	The aperture port or "commutated" array spills energy into the ground so as to require filtering of unwanted reflection components in the airborne receiver by a sophisticated sharp cutoff filter. The elimination of the ground reflection and the need for the airborne filter by our beam port approach has removed the high risk filter and has resulted in lower technical risk for the system.

Table 11-1. SELECTED PARAMETERS VS TECHNICAL RISK (Cont)

Baseline System Selection Feature	Technical Risk Implication
5. Ground over Airborne Filter	This has been discussed in Item 4 to indicate that the beam port antenna provides the same function as the airborne filter. The analytic and experimental verification of the beam port antenna has reduced the technical risk for this decision to a low value.
6. Modular Elevation No. 1 Antennas	The decision to separate the coverages in a modular form for EL-1 was based in part on lowering the cost and technical risk in antenna design. The studies indicate a low risk for system operation; however, this approach will continue to be assessed for impact on overall system design.
7. Configuration D with Proportional Coverage; Option of Simpler, Limited Proportional Coverage for "ILS Replacement"	The choice of full proportional D coverage with identified approaches does not represent a risk, nor does the option available for minimum cost "ILS Replacement" usage.
8. Selection of Optimum Format Parameters	These parameters were all chosen to minimize system complexity and any resulting technical risk (see 1.1.2.1).

1.1.3 System Compatibility

1.1.3.1 - Colocation with Existing Approach and Landing Aids

The following three areas are considered in this section: (1) colocation of the AZ antenna with the ILS Localizer antenna, (2) colocation of the EL-1 antennas with the ILS Glide Slope antenna, and (3) colocation of the AZ antenna with the Approach Lighting System.

A. SUMMARY

1. Colocation of AZ with Localizer

The MLS AZ antenna should be placed on the runway centerline beyond the stop end of the runway. However,there may be an ILS Localizer antenna already in operation in this location. It is important that neither antenna degrade the performance of the other.

It is recommended that for most runways the AZ antenna be located in front of the Localizer antenna, within obstruction clearance limits. Because the AZ antenna is small compared with the Localizer, and because the AZ antenna is usually close to the ground where the Localizer field is relatively weak, the effect of the AZ antenna on the Localizer radiation will usually be small. Furthermore, only the slope of the Localizer ddm pattern will be affected; the "on-course" or null direction of the Localizer pattern will be essentially unchanged because of the symmetrical location of the AZ antenna on the Localizer centerline. With the Localizer behind the AZ antenna, the Localizer will not affect AZ performance.

Figure 12-1 indicates three typical configurations. In the first, an AZ antenna for configuration K is shown located 75 feet in front of a V-Ring Localizer. The top of the AZ antenna is assumed to be 6 feet above flat ground. (A 6-foot-height AZ antenna can be placed in front of a 7.5-foot-height V-Ring Localizer without

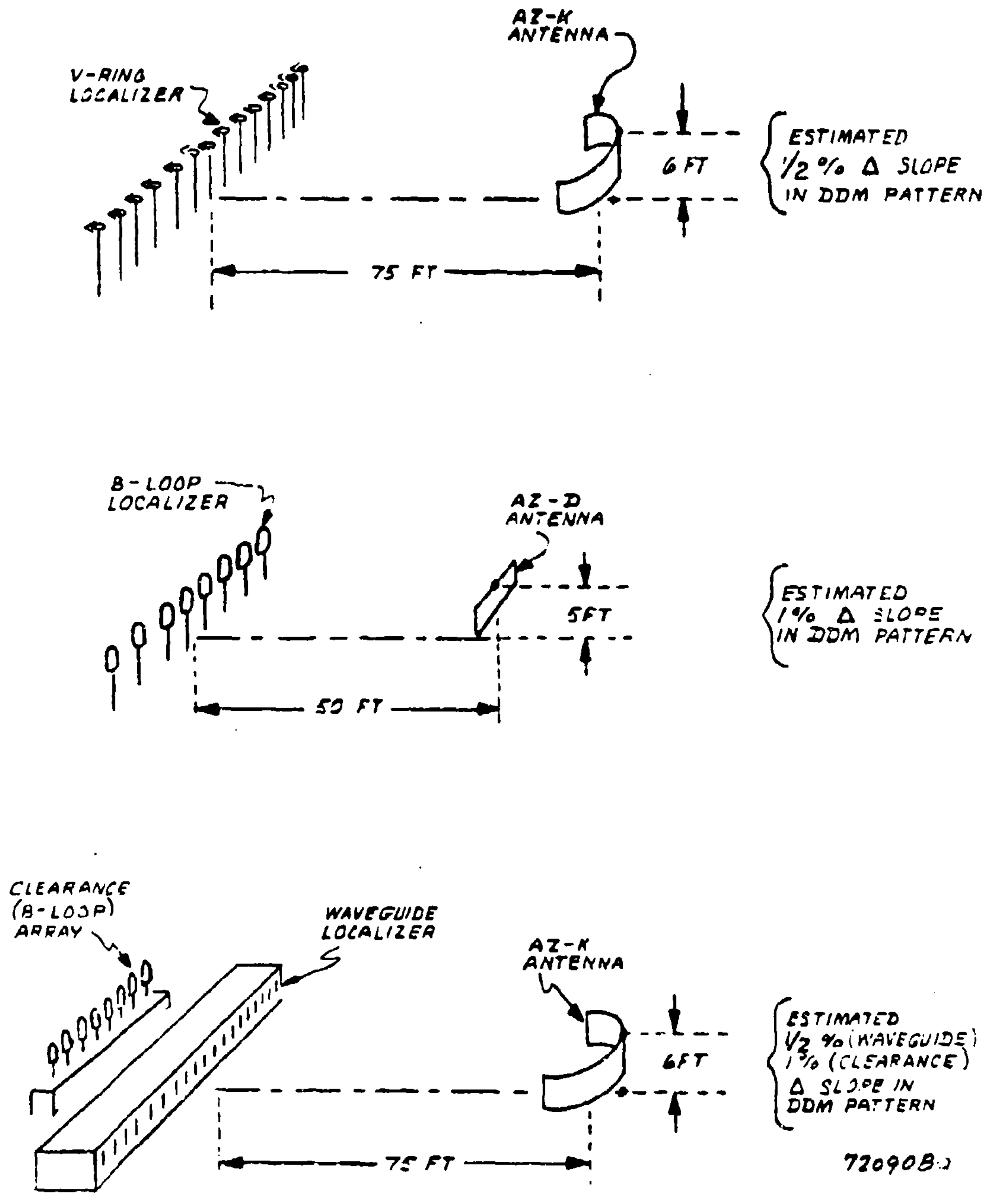


Figure 12-1. Typical Configurations with AZ Antenna in Front of Localizers

affecting the normal 50/1 clearance limit.) With these these dimensions, the change in slope of the Localizer ddm pattern is estimated to be only 0.5%. This is believed to introduce a negligible change in Localizer system operation.

A second configuration shown in Figure 12-1 is an AZ antenna for configuration D located 50 feet in front of an 8-Loop Localizer. A change of ddm pattern slope of 1% is estimated for this case. A third configuration shown in Figure 12-1 is an AZ antenna for configuration K located 75 feet in front of a Waveguide Localizer with a Clearance (8-loop) Array. A change of ddm pattern slope of 0.5% for the Waveguide antenna and 1% for the Clearance antenna is estimated for this case. All of these effects are believed to introduce negligible changes in Localizer system operation.

In certain runway environments, the simple approach described above may be inadequate. For example, an AZ antenna may have to be located high above the ground in a valley between the Localizer and the runway. This could result in a significant effect on Localizer performance because the AZ antenna would no longer be in a region of weak field near the ground. In this case an "invisible" AZ antenna could be used, as indicated in Figure 12-2 (top). This antenna would be designed to prevent a continuous horizontal conducting path for current induced by the Localizer radiation (which is horizontally polarized and has a 9-foot wavelength), and the antenna would appear invisible at 110 MHz. It is estimated that the effect of the AZ antenna could be reduced by 20 dB with an "invisible" design.

An alternate approach is indicated in Figure 12-2 (bottom), utilizing a double AZ antenna, with one antenna placed on each side of the Localizer where the Localizer radiation is usually weak. In this system, successive Doppler scans are radiated

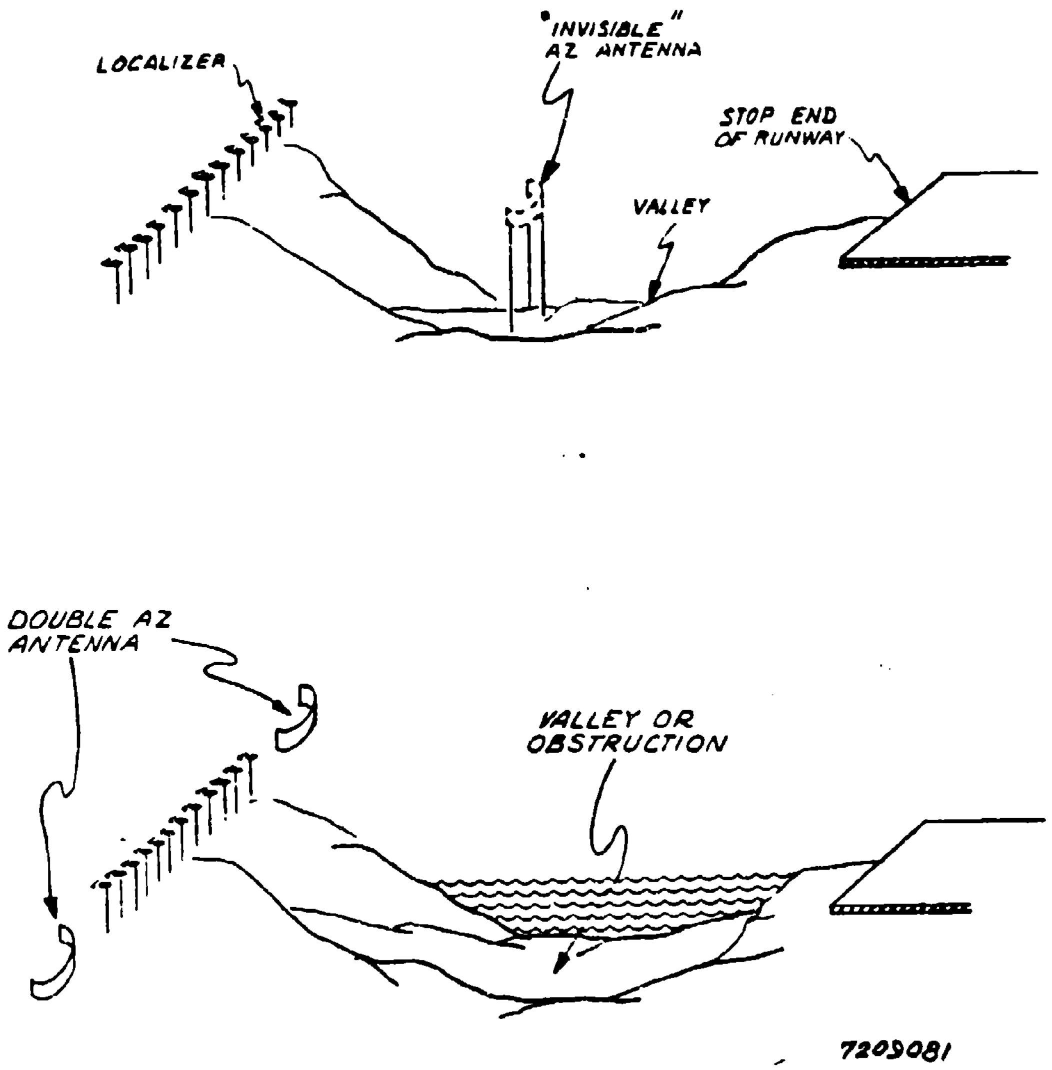


Figure 12-2. Special AZ Antennas for Difficult Colocation Situations

alternately by each of the two antennas. In the aircraft receiver, the two different received frequencies are automatically averaged over the many scans in each function time, giving the same result as if there was a single AZ antenna on the runway centerline.

In addition to being a possible solution to the colocation problem, the double AZ antenna can also be considered for those runways where there is no room for any antenna, including the Localizer, beyond the end of the runway. The ability to use a double AZ antenna where necessary is a significant feature of the Doppler-scan system.

A limitation of the double AZ antenna system is that as the aircraft approaches the stop end of the runway the two received frequencies can separate beyond the bandwidth of the narrowband (or "centerline") filter that may be in use in the receiver. For a 150 foot separation of the AZ antennas and a $\pm$3.5 degree angular limit permitted by the filter bandwidth, an aircraft at the edge of a 150 foot wide runway would to bypass the filter in order to receive signals from both antennas at ranges less than about 3,000 feet. The system can be arranged so that this can be done automatically in the receiver for those runways using a double AZ antenna. The need for a narrowband filter decreases markedly as the aircraft approaches the stop end of the runway.

In conclusion, a simple AZ antenna located in front of the Localizer is recommended as a solution to the colocation problem for most runways. For special circumstances, an "invisible" antenna or a double antenna system may be necessary. Testing is recommended to be performed following the Feasibility Demonstration Phase to demonstrate the immunity of Localizer performance to this proposed A2 location.

2. Colocation of EL-1 with Glide Slope.

The EL-1 antennas should be placed alongside the runway opposite the GPIP. There may be an ILS Glide Slope antenna already in operation in this location. It is important that neither antenna degrade the performance of the other.

The El-1 antenna closest to the Glide Slope antenna is the larger of the two proposed EL-1 antennas and is used for the lower coverage angles. Figure 12-3 indicates this antenna placed alongside the Glide Slope antenna, about 50 feet closer to the runway. It is estimated that the effect of this antenna on the Glide Slope angle accuracy will be less than 0.01 degrees. This is believed to introduce a negligible change in the Glide Slope system operation. The effect of the other EL-1 antenna, which is smaller and further away, would be even smaller. The Glide Slope antenna will have a negligible effect on EL-1 performance. Testing of this location of the EL-1 antenna is recommended to demonstrate the immunity of Glide Slope performance.

3. Colocation of AZ with Approach Lighting System.

Certain runways are equipped with an Approach Lighting System (ALS). This system of lights occupies the region beyond the end of the runway in which an AZ antenna would be placed. The effect of each system on the other is of interest. Figure 12-4 (top) indicates an AZ antenna located above the plane of the lights and just inside one row of lights. For an aircraft approaching the runway along the glide slope, one of the ALS lights may be obscured by the AZ antenna until the aircraft reaches a point where the light appears over the top of the AZ antenna. In many cases, this would occur when the aircraft is outside the middle marker. At the present time, based on discussion with United Air Lines, this effect does not seem to be a significant handicap to the pilot.

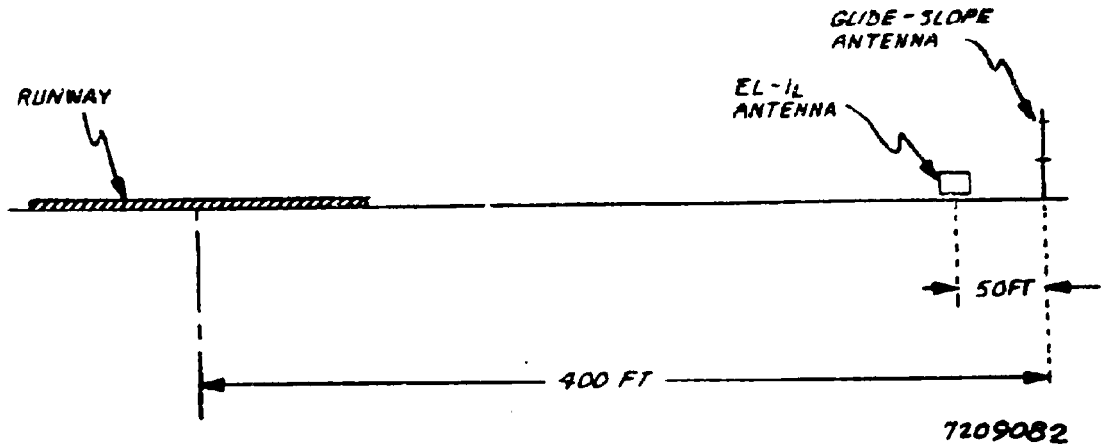


Figure 12-3. Typical Colocation of EL-1 and Glide Slope Antenna

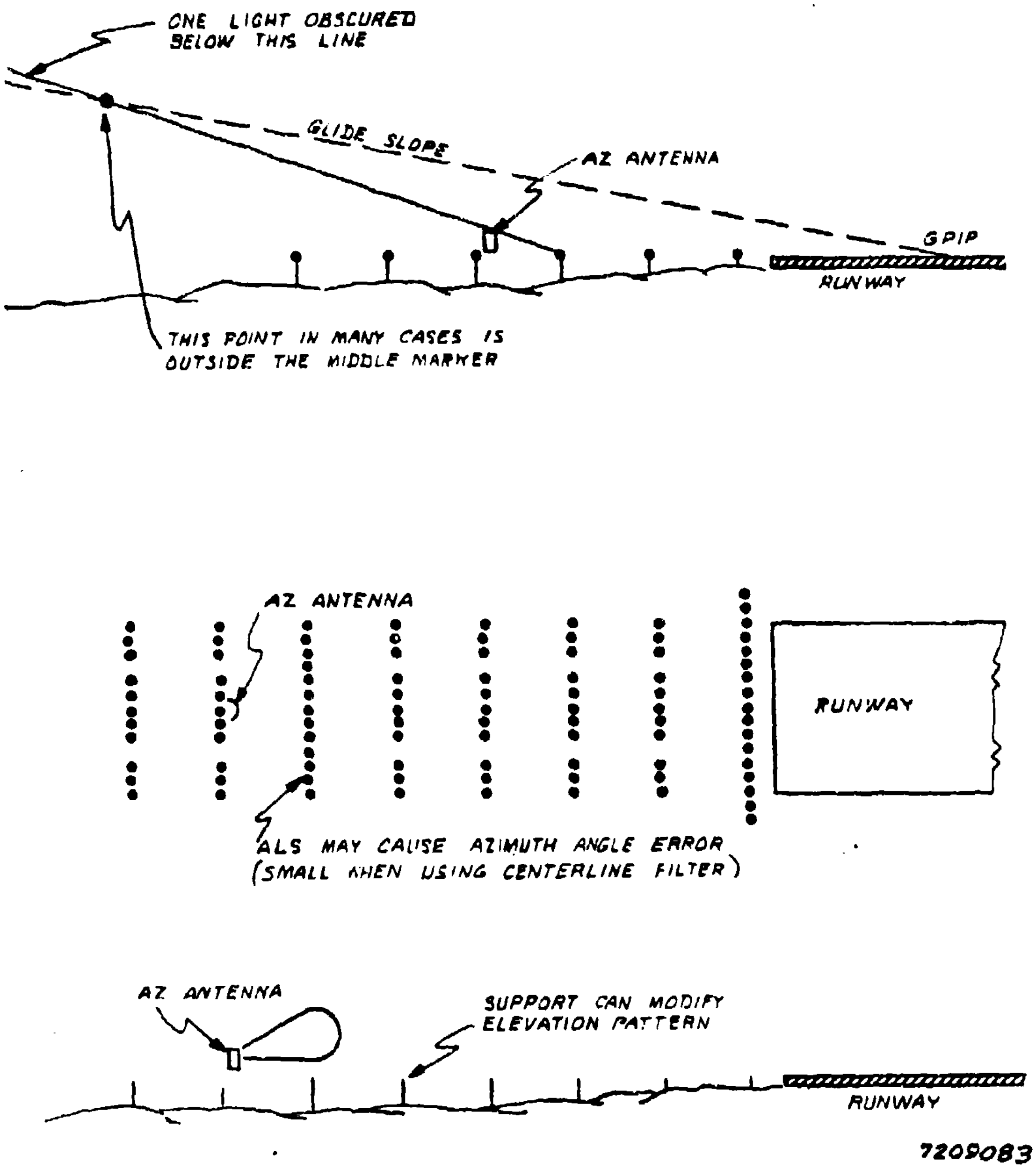


Figure 12-4. AZ Antenna and Approach Lighting System

As indicated in Figure 12-4 (bottom), the presence of the ALS above the ground between the AZ antenna and the runway can have some effect on the antenna performance. The ALS structure can cause an azimuth angle error; this error becomes small when the aircraft receiver is using the "centerline" narrowband filter. The support structure for the lights can modify the elevation pattern in a manner somewhat different from the normal modification caused by the ground. All of these effects decrease as the vertical aperture of the AZ antenna is increased and as the distance between the bottom of the antenna and the plane of the lights is increased. When the lights are well below the bottom of an AZ antenna with a large vertical aperture, the effect on AZ performance is expected to be negligible.

B. DETAILED DISCUSSION

1. Discussion of AZ Colocation with Localizer.

Four possible locations for the AZ antenna were studied: these are indicated in Figure 12-5.

The first location, with the AZ antenna together with the Localizer does not appear to be attractive. For the V-Ring and 8-Loop Localizers, locating an AZ antenna close to the radiating elements will affect the Localizer patterns. Even an "invisible" AZ antenna will have some effect when it is close to these Localizer elements. For the Waveguide Localizer, an AZ location just above the front of the waveguide roof is possible, but the AZ vertical aperture would usually have to be larger, and there remains the problem of affecting the patterns of the Localizer Clearance antenna which is located to the rear. In any case, it would seem that attempting to integrate the AZ antenna with an existing Localizer antenna would be a major nuisance.

A possible exception is the special case of a Localizer antenna which has been installed on a platform sufficiently high above the runway to permit an AZ antenna to be properly located

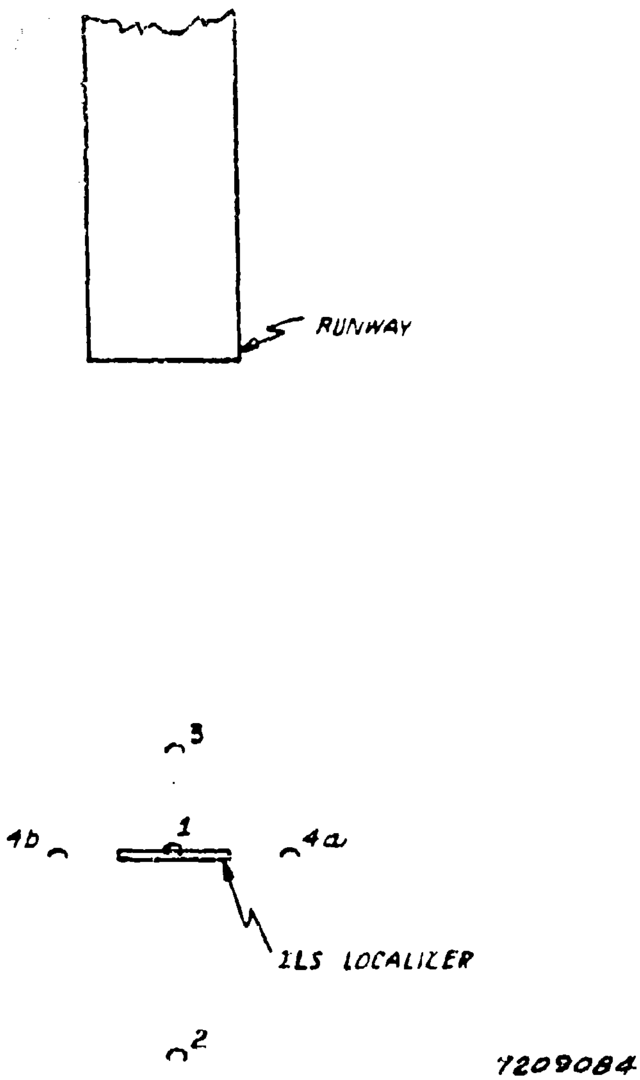


Figure 12-5. Locations Considered for AZ Antenna

underneath the platform. If the platform supports can be arranged to avoid blocking the AZ antenna radiation, the underneath location may be acceptable for this case.

The second location, with the AZ antenna behind the Localizer, cannot be guaranteed to provide the required MLS performance unless the AZ antenna is located (a) very far behind the Localizer, or (b) above and just behind the Localizer. The far-behind location is not generally available, and the above-behind location is likely to have an obstruction clearance problem as well as requiring a larger vertical aperture for the AZ antenna.

It is estimated that with the V-Ring Localizer, a close-behind location of the AZ antenna may give adequate MLS performance when a "centerline" narrowband filter is used in the receiver to remove most of the spurious signals caused by reflection from the V-Rings and their supports. It is also possible that an AZ antenna for configuration D placed close behind the 8-Loop Localizer and offset from the centerline to radiate between the wider-spaced loops would yield adequate MLS performance. However, it should be recognized that both the V-Ring and 8-Loop Localizers radiate substantial power to the rear, so with the rear AZ location there would be an effect on ILS performance comparable with that with the front location. In general, the rear location for the AZ antenna is not considered attractive.

The third location, with the AZ antenna in front of the Localizer is recommended for most runways. When both the runway and the ground between the Localizer and the AZ antenna are substantially flat, the AZ antenna is likely to be located close to the ground. Since the Localizer radiation has a null along the ground, an AZ antenna close to the ground will be in a region of weak field and will have a much smaller effect than would otherwise be the case. Also, the AZ antenna is shorter than the Localizer, and intercepts only a fraction of the Localizer radiated power, as well as re-radiating this power in a broad, low-gain pattern. Both the weak-field effect and the intercepted-power-fraction effect are dependent on distance between the two antennas; the greater the distance the less is the effect of the AZ antenna.

An analysis has been made of the effect of the AZ antenna for various antenna combinations as a function of distance between the two antennas and of height of the top of the AZ antenna above ground, for the case of a flat ground. These results are plotted in terms of the ratio of the signal reradiated from the AZ antenna relative to the direct Localizer signal, as both signals are received by an aircraft near the runway centerline. The results are essentially independent of Localizer height above ground when this height is not unusually large, and are essentially independent of aircraft elevation angle for angles near the glide slope.

Figure 12-6 presents the results for the case of a V-Ring or a Waveguide Localizer and an AZ antenna for configuration K (a 15-foot diameter circular array was assumed, but a 12-foot long linear array yields about the same result). The solid curve marked h = 6 ft. is for the case of a 6-foot height of the top of the AZ antenna above ground (corresponding, for example, to a 4-foot vertical aperture and a 2-foot clearance from the ground). For a 75-foot distance between the AZ antenna and the Localizer, the ratio of reradiated to direct signal is calculated to be about -46 dB near the runway centerline.

The reradiated signal occurs only in the "carrier and sideband" signal that is radiated on the "sum" pattern of the Localizer. This is because the "sideband only" signal is radiated on the "difference" pattern of the Localizer which has a null along the centerline of the Localizer. Assuming that the AZ antenna is located on the Localizer centerline, there is essentially no "sideband only" field at the AZ antenna. As a result, the AZ antenna will affect the slope of the ddm pattern of the Localizer system, but will not affect the ddm null location or the "on-course" direction.

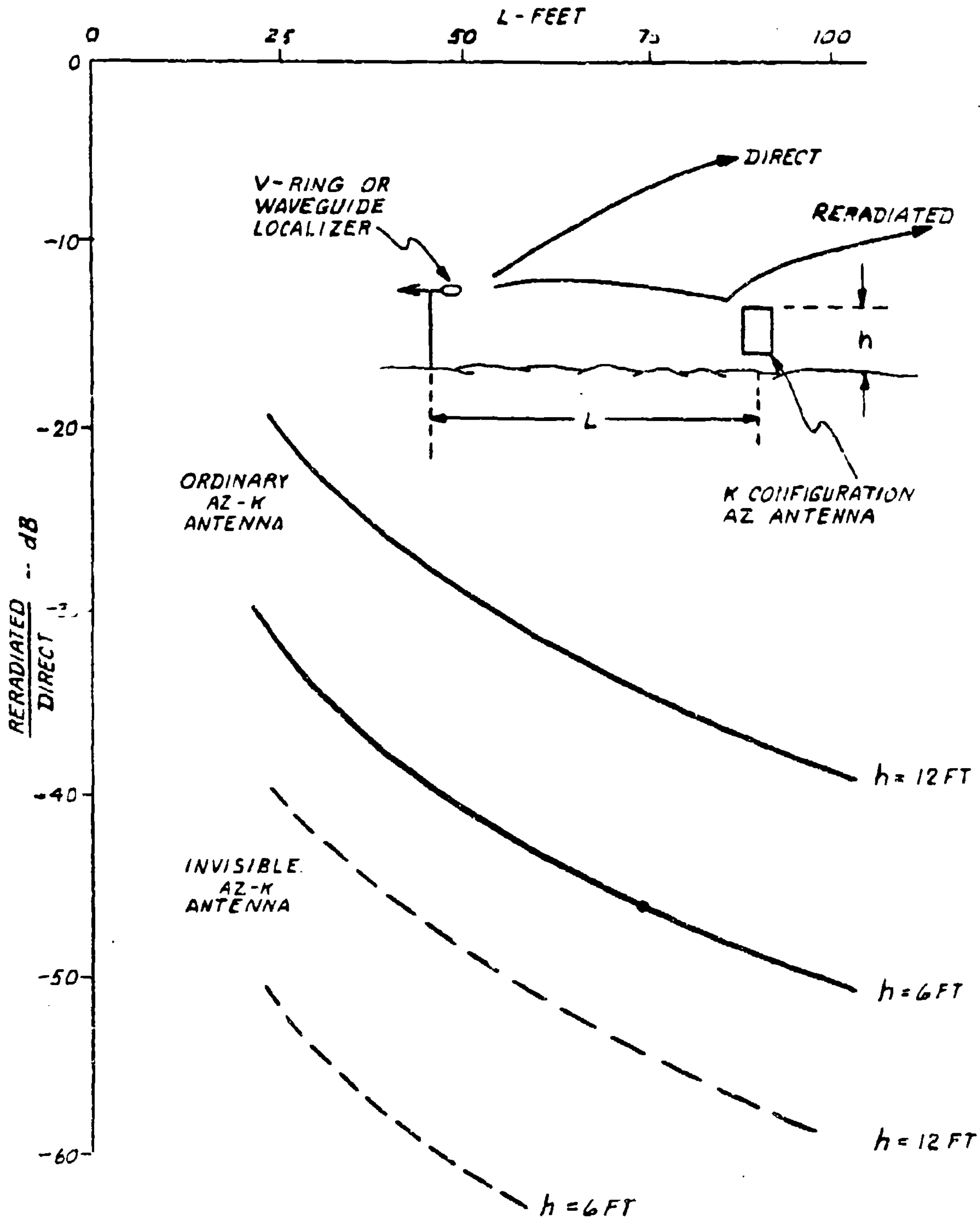


Figure 12-6. Reradiated Signal from AZ-K Antenna in Front of V-Ring or Waveguide Localizer

For a reradiated "carrier and sideband" signal 46 dB weaker than the direct signal, the maximum change in ddm slope would be 0.5%. This is believed to introduce a negligible change in Localizer system operation. If the AZ antenna is only 50 feet in front of the Localizer instead of 75 feet, the signal ratio becomes about 40 dB yielding a maximum change in ddm slope of about 1%. This is also believed to be a negligible effect in the Localizer system. However, a reduction of distance to 25 feet would correspond to about 30 dB or 3% which may be large enough to be noticeable in Localizer system operation.

Nominally the Localizer is placed 1000 feet or more from the stop end of the runway. For these cases a 6-foot-height AZ antenna could be located 500 feet in front of the Localizer without interfering with the 50/1 clearance surface that begins 200 feet from the end of the runway. However, there are a significant number of runways where the Localizer is substantially closer; for example, two of the six Localizers at JFK are less than 500 feet from the end of their runways. Localizers such as these are likely to penetrate the clearance surface and therefore require a waiver for their installation. For such cases the AZ antenna would probably also penetrate the clearance surface and require a waiver, but the amount of penetration can typically be made no greater than that of the Localizer. For example, a 6-foot-height AZ antenna placed 75 feet in front of a 7.5-foot-height V-Ring Localizer would penetrate the 50/1 slope by the same amount. If placed only 50 feet in front, this AZ antenna would penetrate the 50/1 slope 1/2 foot less than the Localizer.

The solid curve marked h = 12 ft. is for the case of a 12-foot height of the AZ antenna above flat ground. Such a height might be needed with a runway that is high in the middle or with a ground that slopes off beyond the stop end of the runway. With this height becoming twice the previous height the reradiated signal becomes essentially 12 dB stronger than the previous value. For example, at a distance of 75 feet the ratio of reradiated signal to direct signal is about -34 dB, yielding a maximum change in ddm slope of about 2%.

For greater heights or shorter distances, the reradiated signal can become stronger than a level considered acceptable. For such cases a design is available for the AZ antenna that is "invisible" to the Localizer radiation. Figure 12-7 indicates the principle of the "invisible" antenna design. The basic AZ antenna we propose for configuration K comprises a series of slotted vertical waveguides placed side-by-side. In the ordinary design, these metal waveguides would be in electrical contact with each other and an incident wave from the horizontally polarized Localizer would induce a horizontal current flowing across the AZ antenna which would reradiate. In the "invisible" design, the waveguides would be separated from each other by an air gap or other non-conducting material, so that a horizontal conduction current could not flow across the antenna. As a result, the reradiation of the AZ antenna would be reduced.

For an air gap between the waveguides equal to one-quarter of the waveguide spacing, it is estimated that the reradiation amplitude would be reduced to about 0.2 of its original value. This residual effect is caused by the capacitance across the air gaps, which permits a small capacitive current to flow across the antenna. The capacitive current can be considerably reduced by a few small coils attached between some of the waveguides; this tuning process can include the capacitive effect of a radome covering the slotted waveguides. It is estimated that the resulting reradiation amplitude would be reliably less than 0.1 or -20 dB compared with the original antenna. This result is indicated by the dashed curves Figure 12-6.

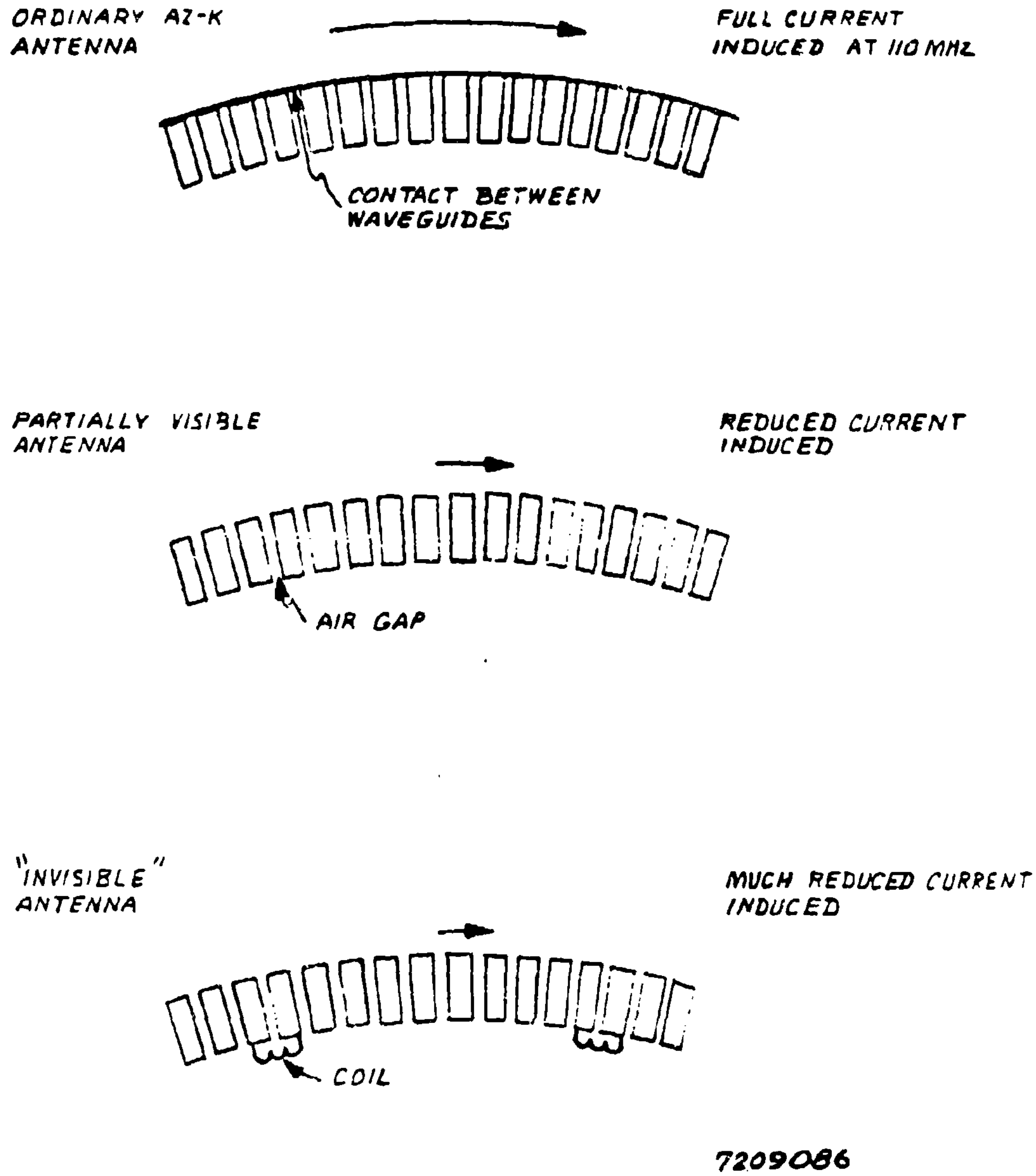


Figure 12-7. Principle of "Invisible" Antenna

The "invisible" type of antenna would require some additional effort during the design of the AZ antenna. It would also be a little more expensive than the ordinary antenna to construct. The installation of an "invisible" antenna would have to be carefully controlled to ensure that the desired result was achieved; for example, the cables leading down from the waveguide columns should be kept apart until they are near the ground. The tower on which such an antenna might be mounted should be designed so that its horizontal lateral members are non-conductors and not too thick. The "invisible" antenna is recommended only where it is needed at a particular runway.

Figure 12-8 presents results of an analysis for the case of an 8-Loop Localizer and an AZ antenna for configuration D. It is believed that on a runway equipped with an 8-Loop Localizer it is likely that a D rather than a K configuration AZ antenna would be used. The D antenna has a smaller vertical aperture, and its top is assumed to be at a 5-foot height above ground (corresponding, for example, to a 3-foot vertical aperture and a 2-foot clearance from the ground). This, together with the smaller length of the antenna (6 feet), overcomes the effect of the smaller length of the Localizer to yield reradiated-to-direct signal ratios similar to those for the configurations given in Figure 12-6. Placing the AZ-D antenna 50 feet in front of the 8-Loop Localizer yields a 1% maximum change in ddm slope, which is believed to be a negligible effect in the Localizer system.

Along with the Waveguide Localizer there is a Clearance antenna consisting of an 8-Loop Array. When an AZ antenna for configuration K is located in front of this Localizer system it will affect the Clearance antenna performance as well as the Waveguide antenna performance. Since the Clearance antenna is smaller than the Waveguide antenna the AZ antenna will have a greater effect on the Clearance antenna performance. It is estimated that with the Clearance antenna an AZ antenna for configuration K will yield reradiated-to-direct signal ratios about 8 dB greater than those for the configurations given in

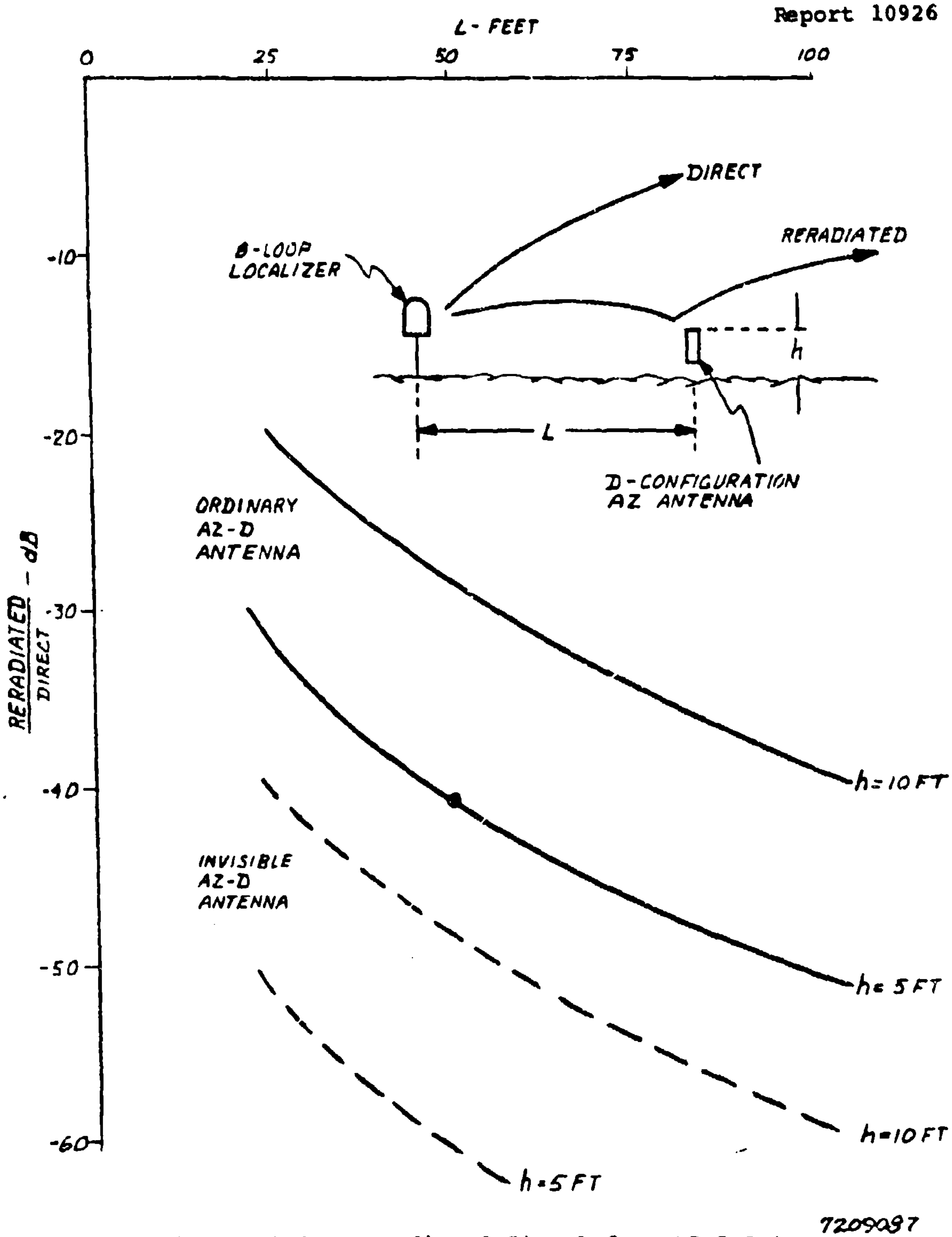


Figure 12-8. Reradiated Signal from AZ-D Antenna in Front of 8-Loop Localizer

Figure 12-6. For a 75-foot distance the maximum change in ddm slope is about 1% which is believed negligible, particularly since the Clearance antenna is intended to provide only "fly left-fly right" information.

Various other types of Localizer antennas can be considered. The amplitude of the effect of an AZ antenna in front of any Localizer is essentially inversely proportional to the length of the Localizer. The new Alford Localizer antennas with traveling-wave elements are available with several lengths ranging from 32 feet to 140 feet. The Plessey STAN-7 and STAN-37 Localizer course antennas range from 85 feet to 165 feet in length. The Thomson-CSF Localizer course antenna is about 100 feet long. For those Localizers about 40 feet long the effect of an AZ antenna in front will be about the same as that for the 8-Loop Localizer, and for those Localizers about 100 feet long the effect will be about the same as that for the V-Ring Localizer.

It has been assumed in the analysis so far that the AZ antenna is located exactly on the Localizer centerline, so that no change in the "on-course" direction would occur. If the AZ antenna is not exactly on the Localizer centerline because of siting tolerances, AZ antenna asymmetry, or a small intentional steering of the Localizer beam direction from its original direction, there would be a small "sideband only" signal reradiated from the AZ antenna resulting in a small error in the Localizer "on-course" direction. Assuming a 1-foot offset of an AZ antenna 75 feet in front of the Localizer and assuming a -40 dB ratio of reradiated to direct signal, the error in the Localizer "on-course" direction is calculated to be less than 0.01 degrees. This is believed to be a negligible error. It therefore appears that reasonable tolerances on symmetry and alignment of the two antennas will be adequate.

Another question concerns the possible effect of the AZ antenna on the signals received by the Localizer monitor antennas. If the monitors are far from the AZ antenna they receive essentially the same ratio of reradiated to direct signals that the aircraft receives. However, if the distance between the monitor antenna and the AZ antenna is small compared with the distance between the monitor antenna and the Localizer, the ratio will be greater and the monitor antenna signal may be changed significantly.

The V-Ring and the Waveguide Localizers employ two aperture monitor antennas located about 12 feet in front of the Localizer antenna. For an AZ antenna 75 feet in front of these Localizers, the change in the monitor signals would be quite negligible. The 8-Loop Localizer employs two field monitor antennas 150 feet from the Localizer. For a D-configuration AZ antenna having a 5-foot height above ground and located 75 feet in front of this Localizer, a change of less than 0.2 dB in the monitor signals is estimated; this is believed to be also negligible. An AZ location 50 feet in front of this Localizer will yield a similar result.

The near-field monitor antennas for the Stan 37 Localizer are located about 78 feet and 250 feet from the Localizer. An AZ antenna at 75 feet would be too close to one of the monitors. However, an AZ antenna located about 200 feet from this Localizer is estimated to yield a change of less than 0.3 dB in the signals of these monitor antennas, for a K configuration AZ antenna having a 6-foot height above ground. With these Localizers, which are typically 18 feet or 12 feet high, an AZ antenna 200 feet in front would not affect the 50/1 takeoff clearance limit.

There are probably some Localizer situations where an AZ antenna could not be reasonably located without substantially affecting the signal in a monitor antenna. For such cases, it would be necessary to adjust the monitor system for the modified signal that is received in the presence of the AZ antenna. Alternatives to this adjustment would be the use of an "invisible" AZ antenna or a double AZ antenna.

The estimates presented here of the effect on Localizer performance of the AZ antenna located in front of the Localizer are considered to be sufficiently reliable to indicate feasibility of the concept and to proceed with the planning of system configurations. However, it is recognized that before the completion of the five-year MLS program, it would be desirable to demonstrate the immunity of Localizer performance to the proposed AZ location. It is therefore recommended that experimental evaluation be performed in one of the following suggested approaches:

- Following the Feasibility Demonstration Phase, Hazeltine will supply the AZ cylindrical array antenna to the government for installation on an ILS runway for test and evaluation

- Hazeltine supply equivalent electrical mockups of both the AZ antenna and the "invisible" antenna for installation, test, and evaluation. These tests could be run concurrently with the feasibility demonstration.

Such measurements would be desirable for any system (not only Doppler scan) that proposes to locate the AZ antenna in front of the Localizer.

It is recommended that the ddm slope and the "on-course" direction of an existing Localizer be measured in an aircraft for several cases. One case should be without any AZ antenna. Another case should be with an AZ antenna located in its nominal position close to the ground. A third case should be with an AZ antenna high enough above its nominal position to obtain a clearly measurable effect, so as to permit interpolation for lower heights.

For these measurements, the AZ antenna need not be the actual antenna. A simple piece of sheet metal having the same overall dimensions would yield the same result. This would allow the "antenna" to be raised and lowered easily for rapid comparative tests. It also would allow the tests to be made independent of the availability of the actual AZ antenna.

The last of the four locations studied utilizes a double AZ antenna, with one antenna placed on each side of the Localizer. This approach is available for difficult situations where the other approaches may be inadequate. One such situation is where an obstacle exists between the Localizer and the runway which would either prevent installation of an AZ antenna or would substantially degrade its performance. Another situation is the special case of a Localizer placed so close to the stop end of the runway that an AZ antenna in front of the Localizer would not be permitted.

In general, each of the two AZ antennas should be placed near the line of the Localizer array because a more forward location would usually increase the effect on Localizer performance and a location more to the rear would be likely to cause an effect on AZ performance. The effects of the AZ antennas on the performance of the various Localizers have not been analyzed quantitatively for the AZ location to the side of the Localizer but it is believed likely that the effects would not be greater than those with the AZ antenna in front of the Localizer. All types of Localizers have weaker radiation toward the side than toward the front; the V-Ring Localizer in particular has an element pattern with a minimum value near the sideward direction. (It may be noted that the transmitter building for a Localizer is permitted to be located as close as 200 feet from the center of the Localizer array.) It is recommended that the two AZ antennas be symmetrically located relative to the Localizer centerline, thereby guaranteeing essentially no change in the "on-course" or null direction of the Localizer "sideband only" pattern. It is also recommended that measurements similar to those described earlier be made to demonstrate that AZ antennas can be placed on each side of the several types of Localizers without significantly degrading Localizer performance.

In the double AZ antenna system, successive Doppler scans are radiated alternately by each of the two antennas. When the aircraft is far away, it receives the same frequency from both antennas. As the aircraft comes closer its azimuth angle to the two antennas differs and two different frequencies are received, one on one scan and the other on the next scan. However, in the receiver the two frequencies are automatically averaged over the many scans in each function time, giving the same result as if there was a single AZ antenna on the runway centerline.

A limitation of the double AZ antenna system is that as the aircraft continues to approach the AZ antennas the two received frequencies can separate beyond the bandwidth of the narrowband (or "centerline") filter that may be in use in the receiver. This would typically occur after touchdown as the aircraft approaches the stop end of the runway. Figure 12-9 shows a graph of range from the AZ antennas to the aircraft vs. the maximum angle of the aircraft relative to one of the AZ antennas for an assumed 200-foot separation of the AZ antennas. For this case three curves are given: one for an aircraft on the runway centerline, one for an aircraft at the edge of a 150-foot-wide runway, and one for an aircraft at the edge of a 250-foot-wide runway. An additional set of three dashed curves is given for the case of a single AZ antenna on the runway centerline.

As an example, consider a receiver with our baseline centerline filter having a bandwidth equivalent to ± 4.5 degrees from the centerline. With a K-configuration AZ antenna having a Doppler beamwidth of 1 degree, the maximum azimuth angle for accurate use of the filter would be about 3.5 degrees. For a 150-foot-wide runway, the minimum range permitting use of the filter would be about 2900 feet from the double AZ antenna. This range would have been about 1200 feet with a single AZ antenna.

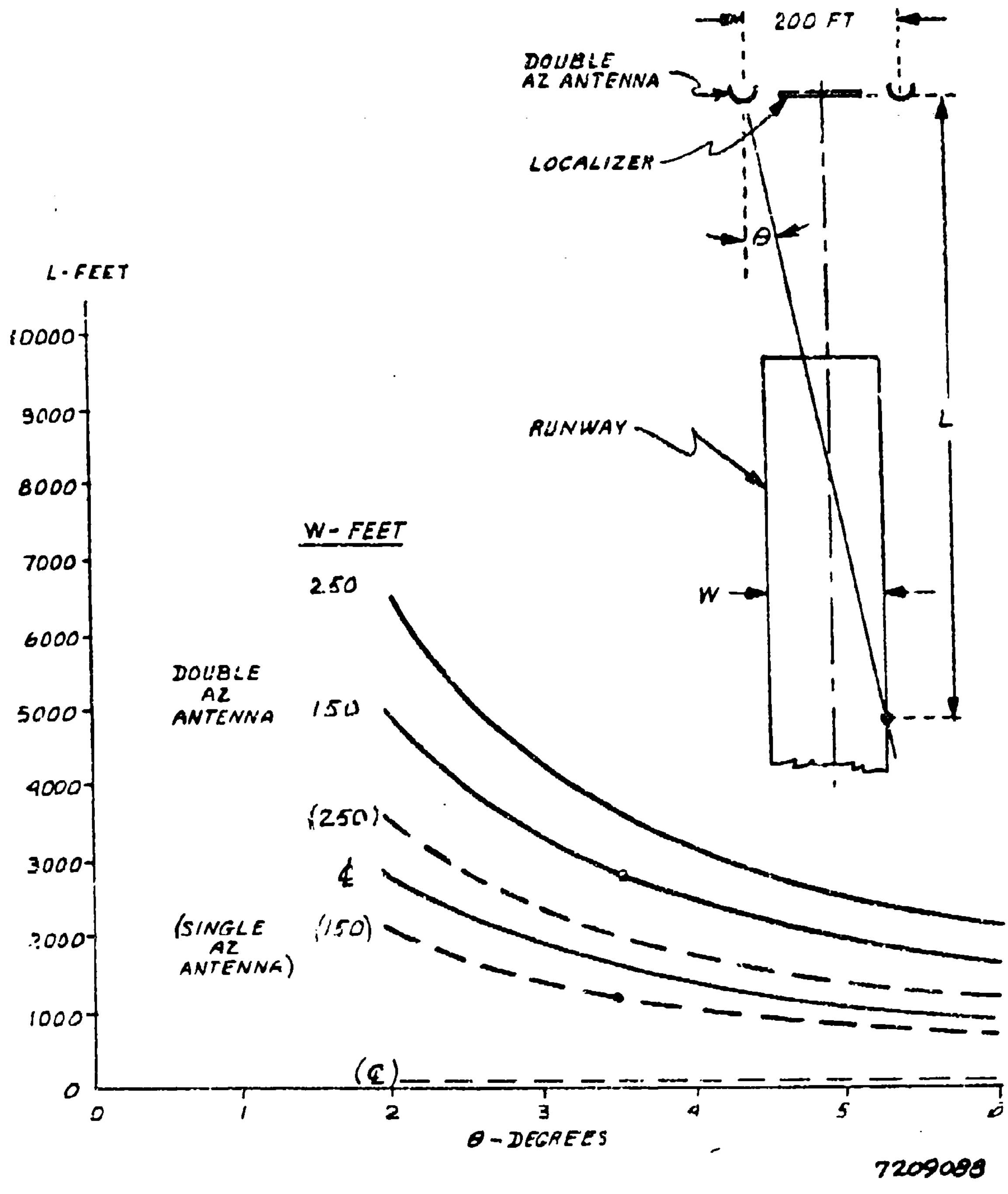


Figure 12-9. Range vs. Maximum Angle for Double Antenna with 200-foot Separation

For those aircraft desiring AZ guidance to the stop end of the runway, the system can be arranged so that the centerline filter is automatically bypassed at short ranges when the aircraft is on a runway having a double AZ antenna. The need for a narrow-band filter decreases markedly as the aircraft approaches the stop end of the runway because (1) the multipath signal from reflections to the side of the runway follows a longer and lower path than the direct signal and is likely to be weak compared with the direct signal, and (2) a relaxation of azimuth angle accuracy required by the aircraft occurs because both range and velocity are decreasing. It is planned to include in the data transmission to the aircraft one bit that notifies the receiver that the runway has a double AZ antenna. In those aircraft desiring AZ guidance to the stop end of the runway, the receiver will then automatically bypass the filter at an appropriate point as the aircraft rolls down the runway, based on DME information.

The double AZ antenna is available as a solution to difficult special problems of colocation with the ILS Localizer. The double AZ antenna can also be considered for those runways where there is not enough room for any antenna, including the Localizer, beyond the end of the runway. An example of this situation occurs at Logan Airport in Boston where at least three of the runways have only about 300 feet between their stop ends and the water of Boston Harbor. It is unlikely that an AZ antenna would be permitted this close to the end of the runway on the runway centerline. However, a double AZ antenna, close to the end of the runway but with the antenna separation greater than the runway width, might be permitted in such cases. An example of a structure in this location is the transmitter building for the Localizer, which can be offset as little as 200 feet from the runway centerline and is sometimes placed close to the end of the runway.

Figure 12-10 shows a graph similar to the previous one but for an assumed 400-foot separation of the AZ antennas. It is evident that with the greater separation, the minimum range for use of the narrowband filter is greater. For example, with a filter bandwidth equivalent to $\pm 4.5^{\circ}$, an AZ antenna with 1 degree Doppler beamwidth, and a 150-foot-wide runway, the minimum range permitting use of the filter would be about 4500 feet. For the shorter runways this would require bypass of the narrowband filter soon after the touchdown if the aircraft was using AZ guidance at this time. However, runways having little clear land beyond the stop end are not likely to be certified above Category II; therefore, the aircraft would not be using AZ guidance at the close ranges where filter bypass would be necessary. Thus, it appears that for such runways, the double AZ antenna with wide (about 400 foot) spacing is of interest.

With any of the double AZ antenna systems it is expected that each of the two AZ antennas would have its own reference antenna. This would allow phase cycling to operate properly where it is needed for those aircraft receivers utilizing multiscan counting.

2. Discussion of EL-1 Colocation with Glide Slope

The EL-1L antenna is assumed to be located alongside the Glide Slope antenna, about 50 feet closer to the runway. The elements of the Glide Slope antenna radiate only weakly toward the side where the EL-1 antenna would be placed. In addition, this sideward radiation is unlikely to be coherently redirected toward the forward direction by the EL-1 antenna.

As a result of these factors, an EL-1L antenna 50 feet to the side of a Glide Slope antenna is estimated to affect the Glide Slope angle accuracy by less than 0.01 degrees. This is believed to introduce a negligible change in Glide Slope system operation. The effect of an EL-1H antenna, which is smaller and further away, should be even smaller.

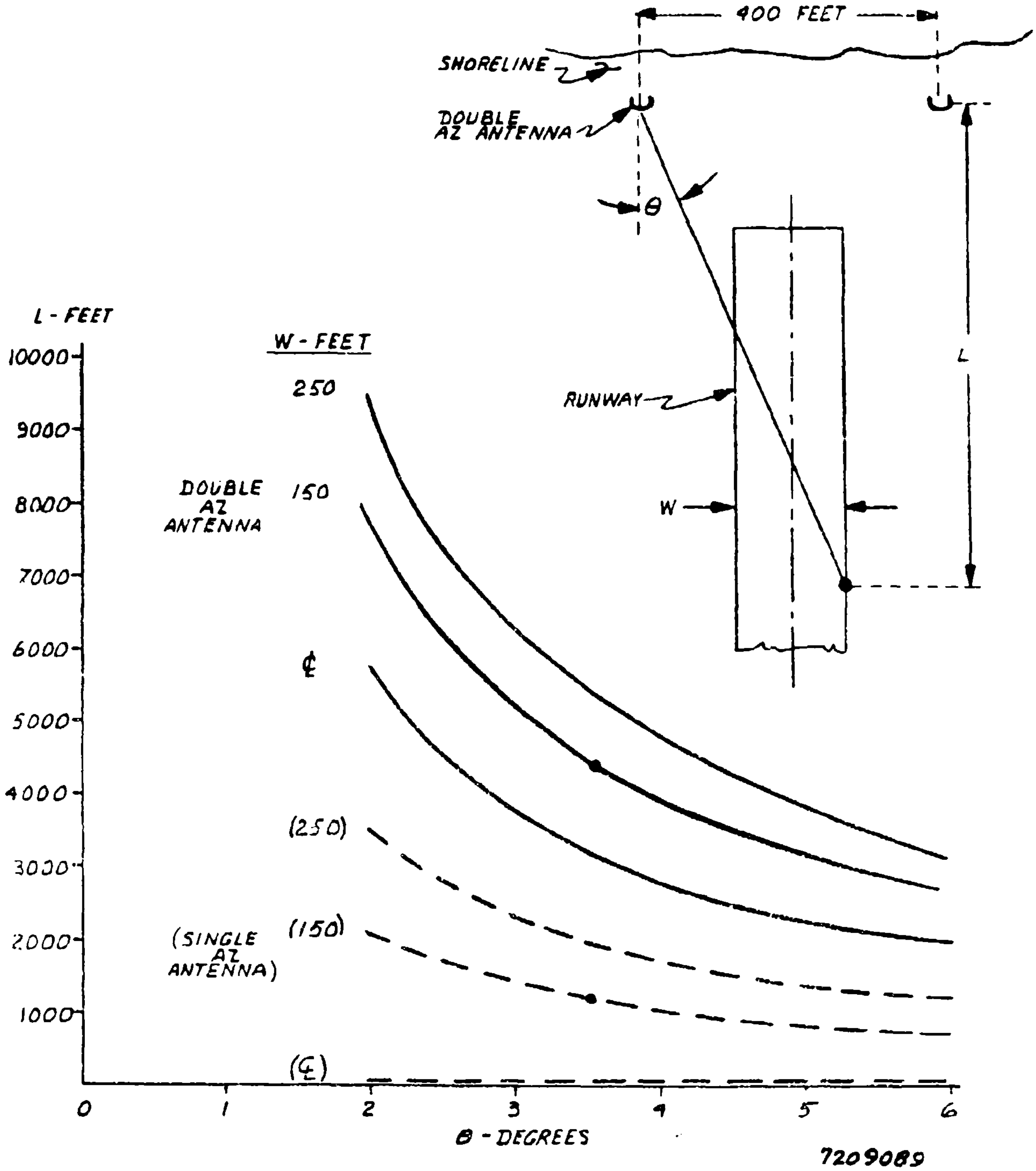


Figure 12-10. Range vs. Maximum Angle for Double Antenna with 400-foot Separation

In order to conclusively demonstrate the feasibility of colocation of an EL-1 antenna with the Glide Slope antenna, an experimental demonstration similar to that recommended for the AZ-Localizer case is believed desirable. Because of the very small effect expected, it may be necessary to move the EL-1 antenna closer than 50 feet from the Glide Slope antenna during the experimental demonstration in order to observe a measurable result. It should be noted that increasing the height of the EL-1 antenna does not necessarily increase the reradiation because the Glide Slope elevation pattern can have several vertical lobes across the vertical dimension of the EL-1 antenna. For the experimental demonstration the structure used to represent the EL-1 antenna should be reasonably similar to that of the actual antenna.

3. Discussion of AZ Colocation with Approach Lighting System

Certain runways are equipped with an Approach Lighting System (ALS) beyond the end of the runway. The AZ antenna would typically be located above the plane of the lights. In order to minimize the number of lights obscured by the antenna, it is desirable to place the antenna just inside (ie., nearer to the runway than) one row of lights. For an aircraft approaching the runway along the glide slope, one of the lights in the next row may be obscured by the AZ antenna until the aircraft reaches a point where the light appears over the top of the AZ antenna.

Figure 12-11 indicates some typical cases for three glide slopes and four antenna heights above the obscured light. For most of the cases shown, the obscured light appears before the aircraft reaches the middle marker. At the present time, based on discussion with United Air Lines, this effect does not seem to be a significant handicap to the pilot.

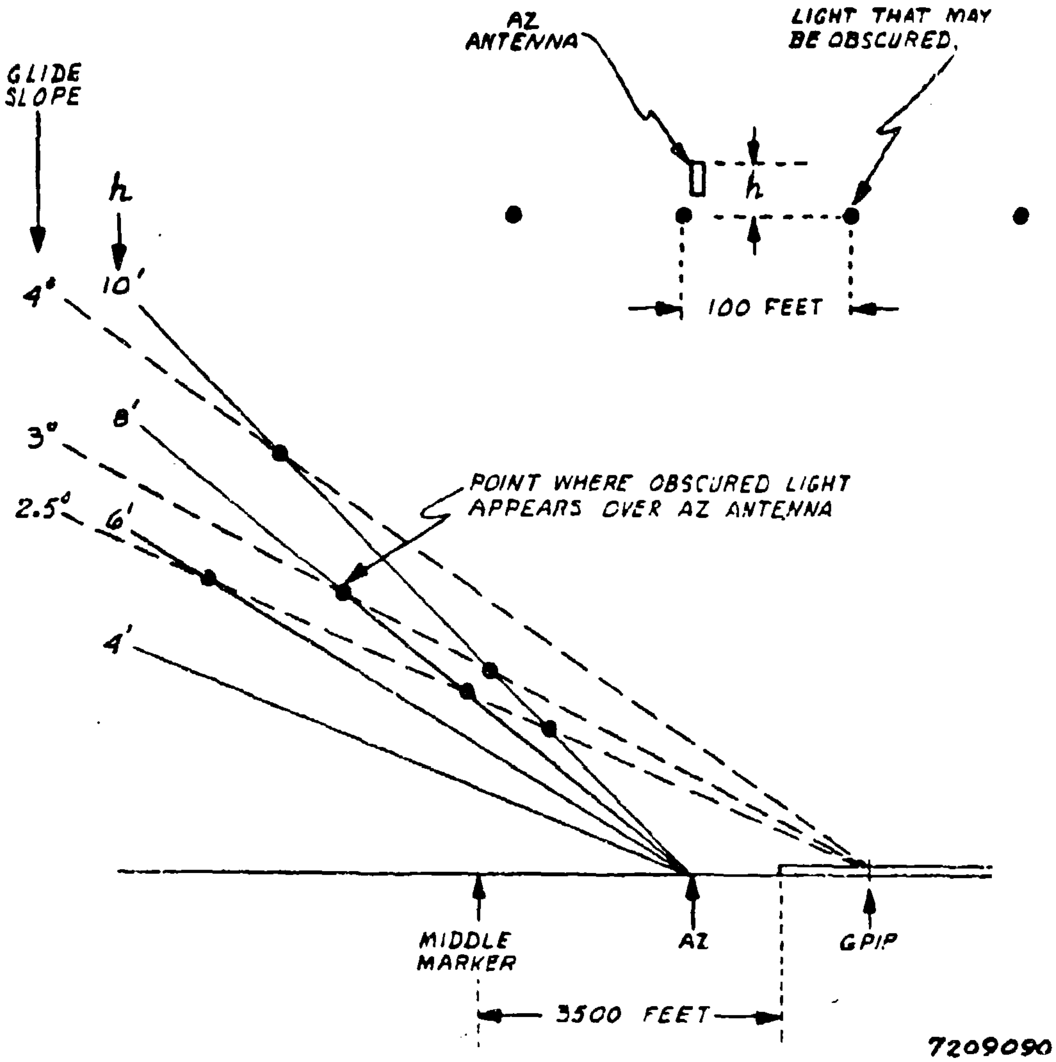


Figure 12-11. Typical Appearance Points of ALS Light Obscured by AZ Antenna

The presence of the ALS above the ground between the AZ antenna and the runway can affect the antenna performance to some extent. As indicated in Figure 12-12, the beam radiated by the AZ antenna gradually diverges downward toward the ground, where it would reflect and modify the basic antenna radiation in the usual manner. When the ALS is present there would be some reradiation from the structure supporting the lights that would further modify the basic antenna radiation.

Since the ALS is nominally symmetrical about the runway centerline, it nominally would not cause an azimuth angle error for an aircraft on the runway centerline. However, asymmetries in the ALS structures can create an error for an aircraft on the centerline, and even a perfectly symmetrical structure can cause an error for an aircraft off the centerline. Both of these errors are substantially reduced when a centerline filter is used in the receiver of an aircraft on, or close to, the centerline. It is believed that for most situations the resulting azimuth angle error would be small.

The ALS structure can cause a significant change in the elevation pattern of the antenna. Because of the regular (100 foot) spacing of the rows of lights, the reradiation from several rows will combine coherently at particular low elevation angles and cause a vertical-lobing effect in the elevation pattern. While this would not directly cause an azimuth angle error, it would reduce the signal strength and may increase the errors caused by multipath.

The amount of the effect of the ALS structures depends on the fraction of power they intercept from the AZ antenna radiation. The intercepted power decreases as the antenna vertical aperture is increased and as the bottom of the antenna and its beam of radiation is raised above the plane of the lights. The intercepted power is also less where the height of the ALS above ground is small because the AZ field strength is weak close to the ground. The number of rows of lights in front of the antenna,

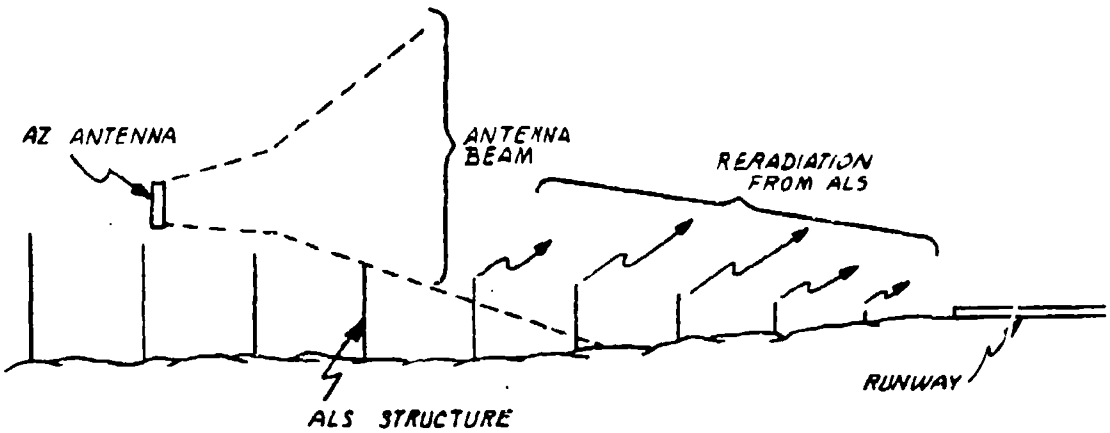


Figure 12-12. Reradiation from ALS Structure Illuminated by AZ Antenna

and the configuration of their supporting structure, also affect the amount of intercepted power. It is suggested that each runway having an ALS should be considered individually for AZ antenna installation in view of the above factors.

There may be some runways where the ALS is such that an AZ antenna cannot be located on the runway centerline without its performance being seriously affected. In such cases the double AZ antenna is available as a solution to the problem.

1.1.3.2 - Siting Considerations

This section presents the ground rules and basic considerations for siting of specific Doppler MLS antennas at various airport configurations. The constraints employed were derived from the following documents which specify the protection surface requirements at civil CTOL and STOL airports.

- FAA Advisory circular AC 120-29
- FAA Advisory circular AC 150/5300-8
- FAR volume XI part 77

In addition, physical constraints have been considered such as airport boundary limitiations and colocation with ILS and approach lighting systems. As a result of these constraints low-profile antennas were designed for the Doppler MLS application. Figure 12-13 tabulates the Doppler antenna physical characteristics currently visualized for the D and K configurations. The nominal Doppler MLS siting plan is indicated in figure 12-14 the rationale for siting each antenna type is presented in the paragraphs in this section. Basically we satisfy the requirements listed in the documents with respect to AZ and BC AZ antenna siting, but we exceed the protection surfaces either side of the runway for some of the elevation antennas. The rationale permitting this approach centers around the small physical size of the MLS antennas and the ability to site these antennas closer to the runway without decreasing safety standards.

Antenna Type	K Configuration Width by Height in feet	D Configuration Width by Height in feet
AZ	15' by 4'	6' by 3'
$EL1_L$	15' by 12'	3' by 6'
$EL1_H$	9' by 6'	
EL2	8' by 6'	
BCAZ	6' by 3'	
DME	1.5' by 4'	1.5' by 3'

Figure 12-13. Doppler Antenna Physical Characteristics

AIRPORT TYPE	a	b	c	d	e	f	g	h	l
	Dimensions in Feet								
CTOL - K Config.	1K	1K	2.8K	1K	0.2K	0.3K			12K
CTOL - D Config.	-	1K	-	1K	-	0.33K			8K
STOL - K Config.	1K	0 (1)	1.5K	1K	0.2K	0.3K			1.8K
V/STOL-Elevated, Floating	-	0 (1)	-	-	-	-	0 (1)	.2K	1.8K
VTOL - PAD	-	0	-	0.5K	-	-		-	0.5K
Ship Board-I-Config.	-	-	?	-	-	-	.38K	.18K	.7K

(1) Siting in Violation of AC 150/5300-8 But Consistent with Recent Studies

Figure 12-14. Nominal Doppler MLS Siting Plans

A. AZ AND DME SITING

The AZ and DME systems are colocated for all airport types with the antennas generally along the extended runway centerline and equipment shelters 200 feet offset from centerline. The antenna systems are small and kept below the required protection surfaces. However, at some V/STOL ports (E configuration), we plan to colocate the AZ, E11/H, and DME systems opposite the GPIP at runway threshold. FAA has experimented with this siting configuration and received favorable operational results.

B. BC AZ SITING

The baseline selection for BC AZ siting is at the approach end of the runway, below the protective surfaces which is a refinement from the SC117 location. This siting was chosen based on integrity, reliability, and safety considerations. Since the BC AZ antenna does not radiate in the front course, the only way the aircraft receiver can validate reception is when it enters the coverage of the BC AZ antenna. If it were located back-to-back with the AZ antenna, guidance is not provided for some thirty seconds over the runway and then the aircraft is still not sure that any back course guidance is available in the departure zone. In addition, we concur with comments received from United Air Lines in that the major function of the BC AZ system should be to provide departure guidance and that missed approach requirements should be infrequent.

C. EL-1L SITING

The baseline siting selection of EL-1L is opposite the GPIP and 350 feet offset from the runway centerline. Although this siting arrangement exceeds the protection surfaces specified in AC 120-29, the ILS glide slope antenna which is four times as high as our Doppler MLS antenna is permitted to be sited 400 feet offset from runway centerline. In order to colocate MLS with the ILS glide slope, the EL antenna should be located at least 50 feet to the side. Compliance with the protection surfaces places an otherwise unwarranted strain and cost on the equipment design both in the aircraft and on the ground. Besides, the physical dimensions of this antenna are small as compared to the ILS glide slope and is capable of being sited as close as 300 feet offset from runway centerline. However, it is only planned to use the 300 foot siting at configuration F, I, and K airports supporting 6^{o} descent angles to 50 foot minimum guidance altitude. Otherwise the 350 foot centerline offset siting is planned.

D. EL-1H SITING

The same rationale as presented above permits the siting of the EL1H antenna to be located 200 feet offset from runway centerline. This location is greater than the 100 foot offset tentatively indicated by FAA in AC 150/5300-8. It is assumed that this location was based on a Ku band system and that a C band system requires additional safety constraints due to its increased size. However, this antenna is sufficiently small to minimize the degradation in safety at 200 foot offset. For example, the antenna is smaller than current ILS localizer equipment shelters which are permitted to be located 200 feet offset from runway centerline.

E. EL-2 SITING

With regard to runway offset siting of the EL2 antenna, the same rationale is adopted as that presented above for EL1L siting. In this paragraph we discuss the rationale for siting the EL2 antenna at a different distance beyond the GPIP for CTOL and STOL airports. The alternative siting considerations are (a) to locate EL-2 a fixed distance from GPIP so that the altitude and descent rate computations can incorporate a fixed siting constant; or (b) to locate EL2 at different distances from GPIP, sufficient to meet coverage requirements, but requiring that the EL2 siting coordinates be transmitted for use in the flare computation. The latter alternative is chosen to permit the possibility of designing a smaller EL-2 antenna for the V/STOL airport applications.

1.1.3.3 AIRCRAFT TYPES, MISSIONS AND CONTROL DYNAMICS

This section summarizes the ways in which the TACD baseline system design and the definition of performance requirements were influenced by considerations of compatibility with aircraft types, missions and control dynamices. These considerations have influenced the TACD results in many areas including:

- Definitions of functional service
- Signal quality specifications
- Auxiliary data requirements
- Signal format
- Operating frequency
- Angle processor design
- Airborne antennas

The details of the design decisions made in these areas can be found in their respective report sections This section will present an overview of the compatibility issues and resolution. Table 12-1 summarizes the issues, compatibility factors and conclusions reached by the end of TACD. In some areas these conclusions are not final and are subject to revision based on new information.

A. AIRBORNE ANTENNA COVERAGE AND LOCATION

Section 1.1.1.1.D discusses the rationale for the selection of antenna types and locations for various aircraft. It is believed that (with the possible exception of small military jets) the most significant compatibility issues arise in the case of the large jet transports. The typical range of maneuvers and possible flight paths within the terminal area due to ATC consideration result in the requirement for 360° azimuth coverage around the aircraft horizon. Constraints such as available location, airframe effect, coverage during flare, wheel blockage and height of antennas above the ground resulted in the decision to use a two antenna diversity system with one antenna mounted above the nose and one below the tail.

ISSUE	AIRCRAFT TYPE	MISSION	CONTROL DYNAMICS	CONCLUSIONS
Airborne Antenna Coverange and Locations	o availability of location	o need for 3-d maneuvers or final approach guidance only	o effect of nose location on flare guidance	o antenna coverage specified per maximum maneuver limits
		o Category of operation -need for flare guidance -antenna height above runway	o front/back azimuth switchover during missed approach	o antenna diversity scheme formulated
				o two locations chosen for large transport: above nose and below tail
				o effects in flare computation to be evaluated
				o use of roll acceleration limit during switchover procedure recommended
Operating Frequency	o Inexpensive avionics desired, especially for Cat I/II users	o missions between STOL port and standard runway		o all Cat I/II civil aviation guidance at C-band; dual frequency required for Cat III
		o missions from transportable installation to fixed bases		o dual-frequency avionics required for some military users (subject to review in Phase II) -all Cat III users (including carrier aircraft) -most users of transportable ground stations
		o missions shipboard to shore		

Table 12-1. Compatibility Factors

ISSUE	AIRCRAFT TYPE	MISSION	CONTROL DYNAMICS	CONCLUSIONS
Airborne Angle Processor (uniscan or multiscan) (analog or digital)	o Inexpensive avionics desired	o multipath environment at STOL ports and military field installations o single course, selectable course or proportional output required o rapid changes in angle for carrier landing	o coupled approaches demand low-noise outputs and low granularity	o prefiltering chosen according to type of approaches o tracking prefilter used for high multipath, proportional output o analog multiscan for D user o digital multiscan for proportional output with greater granularity tolerance o digital uniscan for highest grade users
Signal format		o aircraft use wide variety of facilities		o functions identified unambiguously in receiver o decoders accept range of format parameters; (scan time, function time, place in format)
Interface compatibility with instruments and AFCS	o Minimum retrofit problems desired			o Filtering/processing in MLS receiver specified in accordance with signal quality studies o trial specifications for output characteristics written. (See Appendix B) o outputs included for old and new AFCS

Table 12-1. Compatibility Factors (Cont.)

ISSUE	AIRCRAFT TYPE	MISSION	CONTROL DYNAMICS	CONCLUSIONS
System Signal quality	o all types of aircraft must be satisfied	o lowest grade airport facility should provide adequate signal quality for K receiver with AFCS	o control activity must be tolerable o multipath effects must be tolerable o touchdowns within limits	o noise/granularity levels estimated for CTOL, STOL, with AFCS o multipath effects analyzed, are tolerable o bias accuracy limits estimated o doppler beamwidths chosen to meet accuracy and multipath o Phase II plans include further investigation of VTOL, carrier landing, high-performance aircraft, etc.
Missed-Approach Elevation Guidance			o Maintenance of stall margin with speed command/autothrottle operation	o Not recommending flying to vertical course; Back-Course elevation is a future growth option
Course Desensitization	o low-cost D receiver desired for CTOL aircraft	o aircraft using runways of different lengths	o maintenance of receiver sensitivity (coursewidth) at threshold	o For D receiver course width automatically selected from auxiliary data o For K receiver, course softening from DME available o Angle coding variations rejected (Complex D receiver)

Table 12-1. Compatibility Factors (Cont.)

ISSUE	AIRCRAFT TYPE	MISSION	CONTROL DYNAMICS	CONCLUSIONS
Minimum Glide-slope Angle	o aircraft with fixed or selectable glideslopes	o aircraft uses some airports with high minimum glideslope		o minimum glideslope angle encoded on auxiliary data; receiver prevents guidance on glideslope lower than the minimum
Decision Height Implementation	o low-cost user may not have DME	o airports have marker beacons; locations not standardized		o fixed glideslope receiver biased relatively high; decodes minimum glideslope as as check

Table 12-1. Compatibility Factors (Cont.)

The diversity design addressed the possible problem of how to choose which antenna to use without leaving open the possibility of rapid switching between the two. The mecahnization chosen maintains reception from the forward antenna as long as signal strength is 3 dB above receiver threshold. If not, then the stronger signal of the forward/rear pair is chosen. Two problems remained with regard to the flight control system. The nose antenna location for flare puts the antenna at the end of a lever arm with respect to the main gear. The gear now maintains a track in space that is below the actual glidepath beam. At some airports this can become a problem in the light of obstacle clearance requirements at the approach end of the runway. Simulations showed the touchdown point moved approximately 550 feet towards threshold, when the antenna was moved from the gear to the nose, for a given flare law. An effect on sink rate at touchdown is also predicted. It is planned during Phase II to utilize a more complete simulation of these parameters including the effects on shadowing and flight performance for alternative locations and to define corrective measures associated with compensation in the receiver.

The other compatibility area remaining has to do with the front/back antenna combinations used during a switchover to back course azimuth guidance during a missed approach. In a maximum crosswind of 15 knots, a 747 aircraft at its landing speed will assume a 9° crab angle. At the switchover, the receiver will sense a beam error equal in feet to the length of the aircraft times the sine of the crab angle. Computer studies indicated a roll altitude transient of 3° could be observed, with a significant roll rate/acceleration transient. Sperry recommended that a roll acceleration limit be switched in at beam switchover to reduce the transient to inconsequential levels.

B. OPERATING FREQUENCY

In the choice of operating frequency for the various ground configurations, it was of paramount importance to provide (where not otherwise constrained) single frequency operation to the greatest number of users, especially Cat. I/II users with relatively inexpensive avionics. Based on investigations of accuracy requirements, antenna design and siting considerations, we concluded that it was feasible to utilize C-band antennas at a STOL port so that all C-band operation is possible for civil Cat. I/II users. It remains impractical to place a sufficiently precise C-band flare guidance antenna near the runway; therefore Cat. III users require dual frequency receivers.

With respect to military installations, the situation remains complex. Frequency choice is constrained by:

- o Portability requirements for battle area installations
- o Desire of nominal (20-25 mile) operating range at main bases
- o The size restrictions which prevail on board ship.

If all military installations were made Ku band, there would be a significant decrease in the range of operations at busy Main Operating Bases, and the airborne units would not be compatible with civil installations. If DME operation remained at C-band, dual frequency operation would still be necessary. If all Cat. I/II facilities were made C-band, battle area installations could still probably be made transportable, but not manpack transportable. Also, carrier aircraft would still need a dual-band system for compatibility with shore-based systems. The conslusion was to provide Ku band angle guidance operation for military transportable systems and the carrier based Cat. III system. Combat aircraft using these facilities will carry dual frequency antennas/front ends for operation with DME and compatibility with other facilities. If the manpack requirement is deleted, the frequency choice for battle area installation can be revised to bring the military situation closer to all C-band operation.

C. AIRBORNE ANGLE PROCESSOR

In the receiver studies we have indicated two basic types of processors capable of deriving MLS angle data outputs;

- o Multiscan processor
- o Uniscan processor

The multiscan processor determines the position or deviation from a fixed course by measuring the Doppler frequency throughout the multiscan (i.e., 16 Doppler scans within one function time) period. In the uniscan processor the frequency is measured on each individual scan.

The choice of processing techniques is primarily effected by the required output granularity for coupled approaches; the uniscan processor is required for autocoupled approaches and the multiscan processor is acceptable to AZ beam coupling but not to the EL1 beam. There are several variations of each type of processor depending upon the type prefilter selected to eliminate multipath effects, and each prefilter can be used in conjunction with both types of processors. There prefilter types are:

- o Tracking prefilter to permit navigation in multipath environments such as STOL ports and tactical military applications
- o Sector prefilter to permit navigation at wide as well as centerline approach angles at a primary airport with large multipath obstacles
- o Wideband/narrowband prefilter to permit centerline approaches as provided by ILS today

The prefilter itself is a separate module in the processor unit and therefore each airborne set can update the capability of a given processor by replacing the prefilter module. The following prefilter processor combinations were selected for each user category.

o The TRACKING PREFILTER/MULTISCAN PROCESSOR is chosen for STOL and tactical military aircraft to support manual operations and coupled approaches in AZ at all facilities. EL1 coupled approaches can be accommodated at STOL port and tactical airfields but are not applicable to the configuration K airports. The multiscan processor chosen for this user is a digital type to permit a wide range of angle outputs and to interface with R-NAV systems.

- o The TRACKING PREFILTER/UNISCAN PROCESSOR is chosen for STOL and tactical military aircraft to support EL1 coupled approaches at all airfields

- o The SECTOR PREFILTER/UNISCAN PROCESSOR is selected for CTOL (civil and military) and carrier based aircraft to support wide angle navigation and coupled approaches

- o The WIDEBAND-NARROWBAND PREFILTER/MULTISCAN PROCESSOR is selected for the general aviation user to support centerline approaches. The multiscan processor for this user is selected as an analog type for low cost potential.

The basic types of prefilter/processors described above will be demonstrated in the feasibility program where a complete cost/performance tradeoff analysis will be performed. As a result, the specific processor types will be used for prototype development. However, all the prefilter/processor combinations are designed as modular components such that a specific user can select the unit to satisfy specific intended requirements.

D. SIGNAL FORMAT

The signal format is configured within the TDM concept to be rigid for some parameters and flexible for others to satisfy the needs of all users. The signal format parameters are shown in figures 12-15 and 12-16 to indicate both these features as applied to the ground and airborne equipment. The rigid parameters in the signal format are identical at each facility and include:

- o Channel stability
- o Angle code fixed for each MLS function (AZ, EL1, etc.)
- o Function ident transmitted before and during each multiscan
- o Function times fixed for each MLS function (AZ, EL1, etc.)

	SIGNAL FORMAT									
Ground Eqpt.	Scan Times (ms)	Function Time (ms)	Aux Data	Function Ident	Angle Code (Hz Per Deg.)	Coordinates	Chirp (Unitary) (Planar) (Ant.)	Channel Stability	Data Rate (Hz)	Time Multiplex
Az	0.9 → 3.0	51	X	X	333 1/3	Planar	0 → 2 kHz	5×10^{-6}	7/10	X
EL 1	0.3 → 1	19	X	X	1000	Planar/ Conical	0 → 1 kHz	5×10^{-6}	7/10	X
EL 2	0.5 → 1.0	12	X	X	2000	Planar	0 → 1 kHz	1.5×10^{-6}	14	X
BCAS	1 → 2	21	O	X	333 1/3	Planar	0 → 2 kHz	5×10^{-6}	7/10	X

NOTES:

1. "X" = Required
2. "O" = Optional

Figure 12-15. Ground Equipment Compatibility

	SIGNAL FORMAT										
	Scan Times (ms)	Function Time (ms)	Aux Data	Function Ident	Angle Code	Coordinates	Chirp (Unitary) (Planar) (Ant.)	Channel Stability	Data Rate (Hz)	Time Multiplex	Growth
Air Carrier o Large Transport o Short Haul/Bus.	0.3 → 3	Fixed	X	X	Common	Planar/ Conical EL Optional	0 → 2 kHz	1.5×10^{-5}	7/10/14	X	Empty Time Slot
Private	0.3 → 3	Fixed	O	X	Common	Planar	0 → 1 kHz	1.5×10^{-5}	7/10/14	X	Empty Time Slot
Military o Large Transport o High Performance	0.3 → 3	Fixed	X	X	Common	Planar/ Conical EL Optional	0 → 2 kHz	1.5×10^{-5}	7/10/74	X	Empty Time Slot
V/STOL	0.3 → 3	Fixed	X	X	Common	Planar/ Conical EL Optional	0 → 2 kHz	1.5×10^{-5}	7/10/14	X	Empty Time Slot

NOTES:

1. "X" = Required
2. "O" = Optional

Figure 12-16. Avionics Compatibility

- o Planar coordinates for all functions except an EL1 conical
- o Auxiliary data format

The flexible parameters are intended to permit the selection of a ground configuration to provide service to all intended users. These parameters include as ground based options:

- o Antenna aperture selected for multipath rejection capability is accommodated by corresponding scan time selection
- o Data rate selected to permit a specified noise allowance with constraint that maximum data rate at a configuration K facility is 7 Hz for AZ and BC AZ.
- o Unused time slot in all configurations for growth capability
- o Unused "bits" in auxiliary data format for growth capability

In the aircraft, the processor has the capability of operating with all the signal format parameters without requiring any adjustments. For example, the prefilter bandwidth was specified to include the smallest antenna beamwidth and corresponding smallest scan time.

E. COMPATIBILITY WITH AFCS AND INSTRUMENT INTERFACES

One of the first markets for MLS avionics will probably be retrofit application where aircraft instrument and AFCS interfaces have been designed around existing sensors such as ILS and radio altimeters. Based on studies of conventional CTOL applications, Sperry concluded that there are no modifications required to either flight directors or automatic flight control systems in order to work satisfactorily with Microwave Landing System equipment. This conclusion has been reached based upon the assumption that the following features will be incorporated in the MLS design:

1. MLS outputs for both glideslope and localizer should be of the same scale factors as provided by current ILS equipment. The form factor should be a plus or minus DC current and should provide proportional guidance signals in the range of at least $\pm 2.5^{\circ}$ of localizer and $\pm .7^{\circ}$ of G/S with a 2.75° nominal glideslope beam.

2. The receiver output may provide the equivalent to a first order lag filter. The time constant of this filter, however, should not exceed 0.1 second. This requirement is based on providing satisfactory performance with guidance couplers designed to operate with the existing time constants in receivers built to meet ARINC 547 and 578 characteristic specifications. In addition, the receiver output impedance should be approximately the same as in existing receivers.

3. Output signal rate limiters must be provided within the receiver to assure acceptable levels of control system activity in the presence of currently defined noise levels. The rate limits, whose magnitudes will require further investigation to define, should vary as a function of range to provide a decreasing rate limit as range increases. In addition, consideration should be given to enable a scale factor change in the rate limit as a function of receiving a logic level signal (either 28 vdc or ground) from the flight control equipment. This feature may be required to provide separate capture and track rate limits for autopilots.

4. Annunication of the selected glideslope angle can be provided as part of the tuning head assembly or controller if this component is mounted in a prominent location. If the tuning head is to be located in the pedestal, consideration should be given to a separate form of glideslope angle annunciation located in a more prominent place. Individual airline operators will probably dictate the actual location such as glare shield, panel, overhead, etc.

A typical interface for both new and retrofit AFCS installations is shown in figure 12-17. The basic receiver/decoder outputs are shown at left. The altitude computation shown using EL-1 and DME is necessary for decision height computations and for course softening in retrofit systems where the radio altimeter has been removed. DME information feeding both axes of the autopilot would be used in new autopilot designs which utilize DME course softening in lieu of altitude gain programming. The altitude computation shown, using elevation 2 and DME, is for the flare computation.

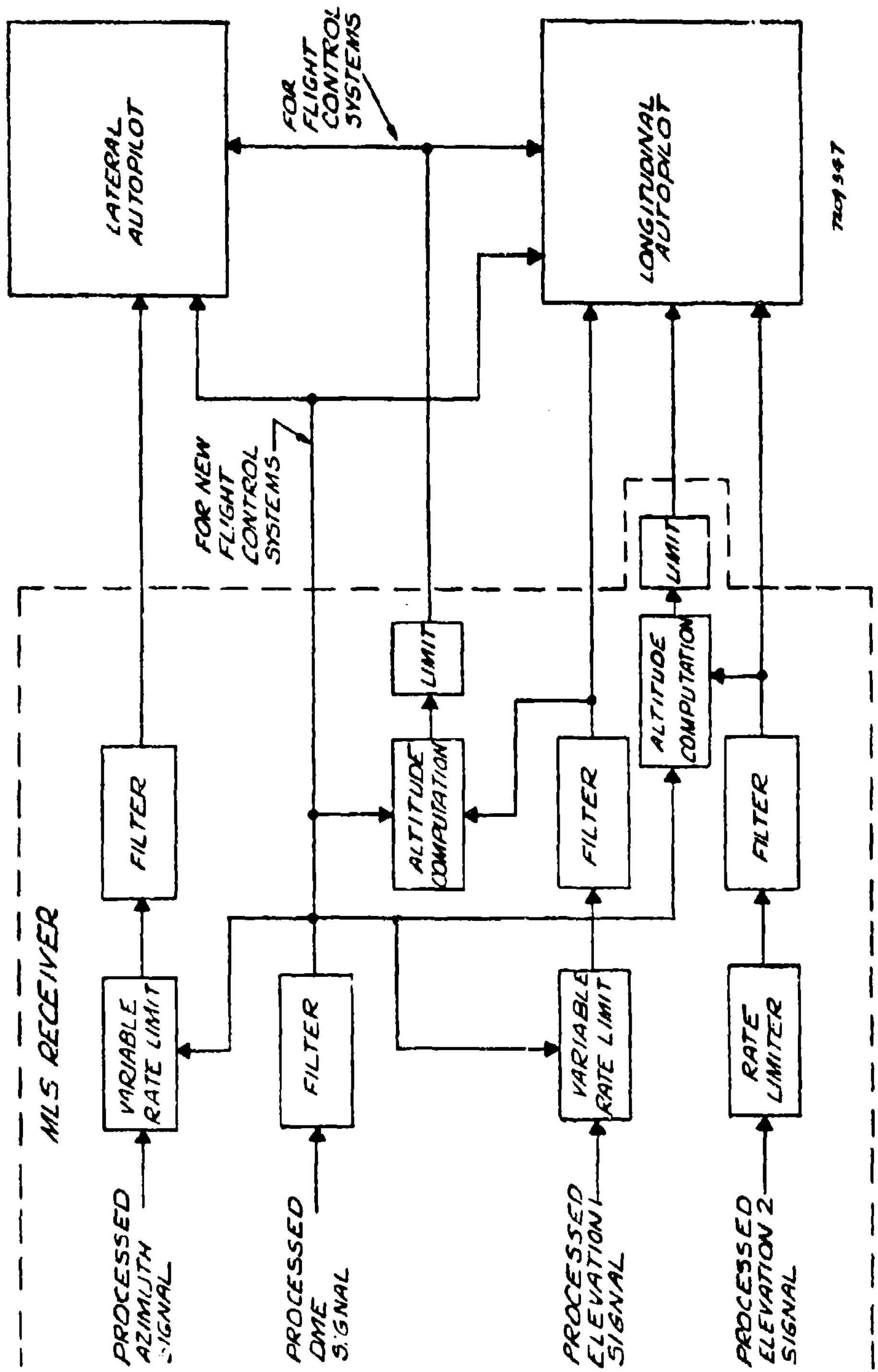


Figure 12-17. Typical MS/AFCS Interface

Sperry also prepared a preliminary set of output signal level/ gradient specifications for an MLS receiver based on the current ARINC characteristics as pertains to ILS/Navigation outputs. These will be utilized as guidelines where appropriate in preparation of feasibility and prototype specifications.

F. MLS SIGNAL QUALITY

As detailed in Section 1.1.1.2A, MLS signal quality parameters - bias accuracy, noise, data rate, granularity, and interruptions were assessed to assure compatibility with all aspects of flight operations. Among the most significant determinants of signal quality requirements was suitability to automatic flight control systems. Suitability was assessed based on touchdown dispersions for Cat. III operation and spurious control system activity during final approach. As a result of simulations and analyses, a complete set of requirements was formulated for K CTOL and K STOL configurations. These results were extrapolated to a number of other configurations under the assumption that aircraft with K type receivers and AFCS should perform satisfactorily at all facilities, limited only by the operational capability of the facility.

The effects of multipath on AFCS performance were also assessed, based on typical multipath "signatures" predicted by an extensive multipath modeling effort. The conclusion was that with nominal receiver output processing, multipath effects during approach should be quite tolerable. Multipath levels were in turn determined by proper selection of the doppler beamwidths for the various facilities (see Section 1.1.1.2).

The simulations conducted at Sperry on AFCS compatibility were restricted to a typical CTOL and a possible STOL AFCS implementation. These studies will be expended in Phase II to include VTOL high performance military aircraft, and carrier based aircraft.

G. MISSED APPROACH ELEVATION GUIDANCE

The transitions which take place in the case of a missed approach involve changing the rate of descent to zero or climb and selecting a heading on which to go around. In currently certified aircraft, the highly recommended pitch go-around technique is the use of a speed command/auto-throttle system to provide the pitch command and thrust change. A major problem in any automatic go around system is that it is difficult to arrive at a fixed path in space and guarantee that for every aircraft configuration, e.g., velocity, flap setting, center of gravity, gross weight; a stall situation will not exist. A speed command system computes a flight trajectory to provide a constant stall margin for a given aircraft configuration, but in so doing, produces different flight paths in space. For the foregoing reasons, it is recommended that any attempt to fly a fixed MLS elevation angle for a missed approach to be made only through a speed command system.

A second method used for pitch axis go-around is to command fixed pitch attitude consistent with safe stall margin. A fixed pitch attitude is safer than an inertial path in space since an aircraft may fly a variety of paths in space for a particular pitch altitude depending on gross weight, e.g., etc. In either case, the aircraft does not fly to a vertical course because an adequate stall margin could not be guaranteed.

For these reasons it was recommended by Sperry that flying to a specific path in space only be considered when and if a relatively sophisticated speed command system, associated with energy management of the total aircraft is available. We therefore are treating vertical guidance during missed approach and departure as a possible future growth item.

H. COURSE DESENSITIZATION

A significant compatibility issue was encountered relative to the method to be used to compensate lateral guidance sensitivity for different runway lengths.

Nominally, the lateral course width at runway threshold should be approximately 700 feet wide to provide good control to the beam without oversensitivity to random noise in the system.

In ILS this adjustment is performed in the localizer and affects sensitivity of the outputs both to the AFCS and to the indicators. In MLS with nominally uniform angular coding at all stations, the sensitivity of the signal at threshold is different for different runway lengths, as illustrated in figure 12-18.

The course width adjustment can be made either (1) in the aircraft or (2) by adjusting the coding in space. If the latter is done, it relieves the low cost D airborne receiver of a function, but the proportional receiver must still recognize the coding adjustment factor and compensate for it. In addition, at a short runway, the beam is desensitized at long ranges for all users. In addition, the angular granularity of the D receiver output now comes into question because of the expanded spatial coding at short runways.

Two methods were investigated for adjusting the coursewidth in the receiver:

1. Continuous linear course softening can be used as a function of range. This will be applicable to new MLS oriented autopilots. However, some autopilots do not have that function today, and the rest utilize an altitude input for course softening. This also requires DME as part of the airborne equipment, which might not otherwise be required for some low-level users.

2. Utilization of a discrete coursewidth adjustment applicable to each runway. This might be provided on an approach plate but this is not considered of sufficient integrity in the overall system. Instead, the coursewidth adjustment can be made automatically in the receiver by decoding the most significant bits of the runway length as transmitted on the auxiliary data. It is believed that this can be implemented rather simply in all receivers.

The second of these methods was chosen as a baseline. However, continuous course softening will continue to be available for new avionics.

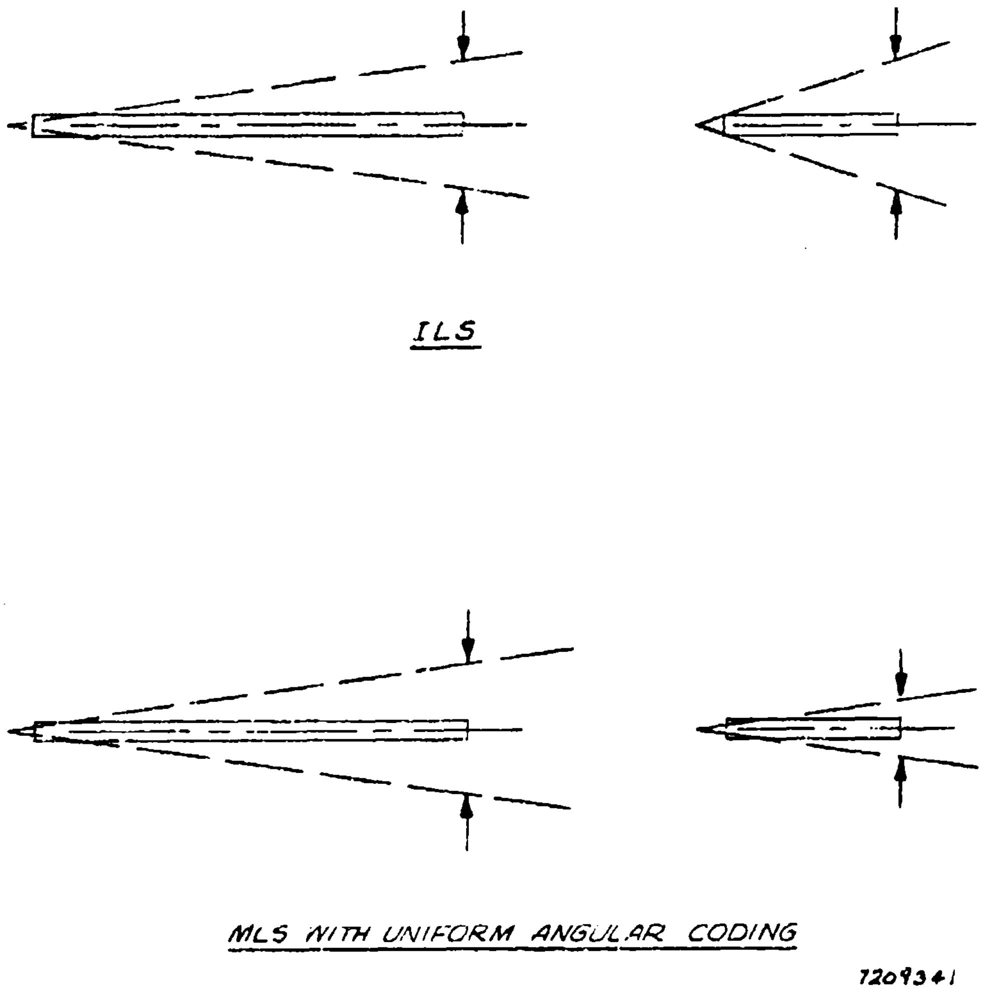


Figure 12-18. Lateral Course Width Comparison

I. MINIMUM GLIDESLOPE ANGLE

An issue arises in connection with the possibility that a receiver may be set to a glideslope that is incompatible with the minimum safe approach to a given runway. This might occur for a receiver with selectable glidescopes where an inappropriate selection is made, or for a fixed glideslope receiver being used at a runway with a relatively high minimum glideslope due to terrain or siting problems. Possible solutions are:

- Limit the minimum glideslopes in all receivers to the worst case airport
- Radiate an obstacle warning signal at angles below the minimum for the facility
- Include on MLS auxiliary data the minimum for the facility.

The first solution is clearly impractical at it would prevent the use of the lower (2^{o} - 3^{o}) range of glideslopes which are optimal in many instances.

The second method can be implemented by changing the coding in space below the minimum glideslope. However, the obstacle warning signal must not disturb the coding in the adjacent useable angles. It is difficult to provide this coding within a small fraction of a degree of the minimum usable glideslope. The second method may also be implemented by transmitting a unique auxiliary data message at angles below the minimum. This will be explored further during Phase II.

The third method is believed to be the most straightforward and is the baseline approach. All receivers will decode the minimum glideslope. A selectable glideslope receiver will not provide valid signals if set below the decoded glideslope. A "fixed" glideslope receiver will actually have a small range of adjustment in the discriminator characteristics which will be automatically biased upwards to the minimum angle. If the minimum angle is above the adjustment range, the receiver will not provide guidance outputs.

J. DECISION HEIGHT IMPLEMENTATION

In the ILS, marker beacons are used to intersect the glidepath at specified decision heights above the runway. The aircraft then receives an aural and visual indication for each decision height provided the aircraft is on the glidepath. In addition, the marker beacon system is qualified to provide decision height information to Cat. II weather minimums in a low cost manner. Since the MLS permits glidepaths ranging from 2 degrees to 15 degrees, the range from GPIP for a specified decision height is different for each glidepath. In addition, the decision height computation places one of the constraints on EL1 and DME accuracies. In order to resolve this incompatibility we propose to retain the marker beacon system as a temporary system, with eventual phase over to an all MLS system as marker beacon maintenance and land acquisition costs increase.

The MLS only system is based on DME and EL1 guidance but is slightly different for each user class.

- A V/STOL aircraft requires DME, EL1, and siting data (range from DME to EL1) to accuractely compute its decision height at all facilities.

- For CTOL aircraft using fixed descent angles below 6 degrees at all CTOL runways, this feature can be derived from the DME function alone.

- For the low cost general aviation type user, we configured a low cost DME approach to obtain decision height information. The technique uses, a low power (under five watts peak power) DME transmitter with fixed range gates in the DME processor (as opposed to range and range rate tracking) and low speed processing techniques. The low power DME transmitter will operate from 7 nmi (outer marker maximum range) to threshold and the decision heights will be based on the DME readout with slight modification due to minimum glideslope angles if greater than three degrees.

1.1.3.4 AIR TRAFFIC CONTROL AND NAVIGATION SYSTEM INTERFACE

The interfaces between the MLS system and existing/planned ATC and navigation systems were treated from the viewpoint of compatibility on the operational, functional and physical levels.

- The functional services and performance levels of the MLS were evaluated as to its ability to provide guidance for present and future ATC operations.
- The ability of MLS to interface with modern airborne navigation equipments was reviewed to identify whether these equipments can make use of MLS guidance data.
- The problem of coexistence with MLS of existing ATC and navigation equipment on the airport property was evaluated.

It is concluded that no incompatibility has been identified that would seriously inhibit the ATC function from delivering aircraft at the maximum runway acceptance rate. Also, several opportunities were pointed out for further exploration to utilize onboard RNAV and other radio navigation systems for generating complex flight paths in the terminal area.

A. COMPATIBILITY WITH ATC NEEDS AND OPERATIONS

Compatibility with ATC operations was treated from the viewpoints of interference effects, accuracy, coverage, data transmissions and display requirements.

1. Multipath and Shadowing

The airport environment contains numerous fixed and moving objects which can block and reflect the MLS signal. This provides a limitation to ATC capability if:

- Significant regions of space are permanently shadowed and are unusable for MLS guidance
- Reflections and shadowing by one aircraft effect the signal received by another so as to limit the freedom of ATC to route aircraft or limit the acceptance rate at the runway.

A detailed study of multipath and shadowing was performed to assess the potential effects on the quality of signal that will be received by aircraft under these conditions. This study is reported in Section 1.1.1.1.E. The general conclusions were:

- Buildings on or near the airport property block MLS coverage in narrow, low-lying sectors of space. The blockage cannot be avoided but generally lies lower than a typical flight path
- Shadowing of one aircraft by another (overflying AZ or on the runway near AZ) creates a drop in received signal. During AZ overflight, it may last one second, and will have little effect on the operation
- Diffraction effects, separate from shadowing and reflections appear to be small
- Reflection is the principal cause of multipath signals. The strongest reflectors are:
  - the metal doors of a large hangar
  - the tail fin of a large aircraft, the reflection being much reduced by the convex curvature of the face

Several features within the proposed doppler technique were also identified that would further reduce multipath effects. A "coast" feature in the receiver overcomes momentary blockages.

It is concluded that with the exception of those regions of space where large structures block the radiation from the MLS transmitters, there will not be significant limitations on the freedom of ATC routing.

2. Metering and Spacing Systems

During the functional requirements study reported in Section 1.1.1.2A, the ability of MLS to provide guidance for ATC metering and spacing (M&S) was assessed. Sperry Flight Systems, who is active in evaluating M&S concepts, provided consultation in this area. The principal problems associated with completely fulfilling this function were in coverage. The ARTS-III M&S concept calls for several path stretching areas located anywhere in azimuth with respect to the runway. Furthermore, the initial feeder fixes which provide entry into the M&S area are located between 30 and 40 miles from the runway. It was concluded that an MLS with azimuth coverage of $\pm 60^{\circ}$ would not provide guidance for the entire M&S layout. However, the final downwind leg and turn to final approach would be within MLS coverage. It was also shown that the MLS positioning accuracy will be sufficient so that it will contribute negligible error to the time of arrival at the approach gate. VOR/DME accuracy is expected to be adequate elsewhere in the M&S volume.

The ARTS-III M&S system is an evolutionary system which operates under direct control of ATC. Future revolutionary M&S systems were also considered in which the aircraft is assigned a time of arrival at threshold and controls its own flight path and/or speed to make good the assigned arrival time. To insure compatibility with such a system, time-of-day has been added on the MLS auxiliary data format so that each aircraft's clock will be automatically synchronized with airport time.

3. Micronavigation System

As a result of the above (and other) considerations of limited MLS coverage, it was realized that the MLS services should be separated conceptually into those serving the final approach/landing function and those serving a terminal Area Navigation function. The terminal area navigation need was seen as eventually growing to require services throughout 360° in azimuth. A system growth requirement for MLS was postulated to fulfill this need.

Such a system was envisioned as a VORTAC-like "Micronavigation" system of extremely high precision utilizing the same doppler signal format, compatible with MLS receivers. A 360° AZ navigation system referenced to magnetic north would transmit on one channel and a landing system would transmit on another channel. Only one of the micronavigation systems would be needed per airport and would be sited in an elevated location to avoid most of the building blockage problems mentioned above. The interface with the enroute system would then be at the perimeter of the terminal area. A future integrated navigation system for 4th generation ATC might consist of a satellite system for enroute use interfacing with a single-format terminal area navigation and landing system. We intend to investigate the potential utility of this growth feature during the next phases of the MLS program.

4. Parallel Runway Operations

It is planned to install closely spaced (2500 ft) parallel runways at high-density airports to make more efficient use of airport property. Lateral path-following during final approach must be very precise in order to maintain safe separations between traffic to and from adjacent runways. An accuracy analysis made during the functional requirements study showed that for a K configuration the azimuth accuracy is sufficient to produce only 7% of the allowable positional variance, and therefore was judged acceptable.

5. Noise Abatement Procedures

Both two-step glidepaths and curved approaches for noise abatement were also considered in the functional requirements review. It was concluded that MLS will be capable of supporting both types of approaches from the viewpoint of accuracy and coverage requirements. Some curved approaches, however, apparently are a very close fit inside of ±60 azimuth MLS coverage. These are the type of curves that terminate right at threshold. One example is the "Carnarsie approach" to JFK which is flown in visual conditions using approach lights. Some doubt was raised, however, if curved-path flying will terminate so close to threshold in Cat. II or Cat. III weather.

6. Display Requirements

It has been pointed out by our consultants that there are some very unique display requirements associated with some of the maneuvers associated with future terminal ATC. These have to do with utilizing MLS in an "area nav" mode and in curved path flying.

In the former case, there is a definite need for a similar display of information to the pilot and controller to ease communications problems. This is visualized as a graphic display (e.g., EADI) of position, desired route and predicted flight path. In the case of curved path flying, we are advised that at present there is no effective means of assessing adherence to the programmed flight path. This is in contrast to normal area nav or other course-following techniques where identifiable vertical and lateral deviation are meaningful. It is believed that a pictorial display is one potential answer to this requirement also. Recommendations will be formulated in Phase II for display techniques to demonstrate curved path flying during the Prototype phases.

B. COMPATIBILITY WITH AIRBORNE NAVIGATION SYSTEMS

1. RNAV Compatibility

During the time frame for the implementation of MLS, it is likely that area navigation (RNAV) techniques will be gaining wide acceptance. RNAV equipment in the high and intermediate user configuration will have the capability of performing the computations required for the more sophisticated approach paths. The development of offset glideslopes for 2-step approaches is considered to be within the province of the area navigation computer and display. Advantages include:

- The ability to automatically transition from enroute navigation to terminal area navigation to final approach, all within a pre-programmed route description
- The utilization of complementary filtering to smooth high-frequency noise on an MLS beam or DME output
- Common planar-angle and range format as used for VORTAC

The MLS receiver should be capable of supplying the range and angular signals to the RNAV in a serial digital format similar to that specified in ARINC characteristics 568 (DME) and 579 (VOR). Sperry has prepared a short preliminary summary of the required output signals, signal levels and gradients as envisioned for an MLS receiver where operating with an RNAV system. This is presented in Appendix B. Hazeltine will use these as a guideline for Prototype specifications.

2. Compatibility with Other Airborne Navigation Systems

In a manner similar to RNAV above, a new and sophisticated set of airborne Loran navigation equipments is being developed and will probably be in use when MLS is operationally available. These equipments will contain sophisticated computer capability which should be highly adaptable to the computations required for MLS-based navigation and guidance. Hazeltine plans to investigate in Phase II the practicality of utilizing a Loran-type avionics to generate MLS-derived flight paths during the Prototype test and evaluation phase.

C. PHYSICAL COMPATIBILITY WITH AIRPORT ATC AND NAVIGATION TRANSMITTERS

The issue of electromagnetic capability with ground-based radiators in the airport was addressed in the design of the Doppler MLS receiver decoder.

The selection of the local oscillator frequencies and IF frequencies are based on obtaining a high degree of integrity for the MLS when operating in a dense signal environment. A high first IF was selected to simply preclude the effects of level dependent spurious signals such as the 2 x 2 and 3 x 3 responses from effecting the system integrity. Image rejection of greater than 85 dB is obtained in both C and Ku bands.

The 3 x 3 response has greater rejection than the 2 x 2 response so the 2 x 2 response is the more critical and given here. In C band,, the 2 x 2 rejection is 105 dB and in Ku band it is 67 dB. These levels consider the signal to be a CW signal and their effect will be to give a false tone. The tone interference was chosen since it is the most sensitive channel in the receiver-decoder. Pulse signals at the 2 x 2 frequencies have greater rejection since the spectrum will be broader than the tone filter width and less energy will be transmitted in the tone filter bandwidth. In Ku band the

2 x 2 rejection can be increased to 75 dB with an increase in LO power but 67 dB should be sufficient. The 67 dB rejection requires a cw 2.5 mW EPP at 10 nmi to have a signal equal to the tone level. A pulse type signal would nominally be at the tone noise level due to spectrum spreading in the narrow filter used in the tone channel.

A 7-pole preselector and 5-pole preselector is used, respectively, in C and Ku bands to reduce the near band signals from saturating the front ends. In C-band a limiter is included prior to the mixer to prevent mixer burnout due to high level signals that may occur from on-board equipment or tracking radars.

A limiter is not used in Ku band since known levels will not cause burn-out of the mixer. A limiter can be included if desired with a nominal insertion loss of 2.0 dB. The peak power rating is 100 watts for both bands and recovery time is about 20 ns. The 2 dB insertion can be made up by an additional 2 dB in transmitter power.

1.1.4 SYSTEM PERFORMANCE SUMMARY

This section summarizes the results of the studies of Operational and Functional Requirements conducted during TACD. The results are organized as follows:

Section 1.1.4.1 Operational Requirements

Section 1.1.4.2 Functional Requirements

A. Functional Services

B. Signal Quality Performance

C. Coverage Performance

D. Auxiliary Data Requirements

E. Coordinate Geometry

The results are presented in chart form. In each case a full description of the study performed and further explanation of the material is included in a subsection of Section 1.1.1.2.A.

Further revisions and refinements of these results are expected during the following phases of the MLS program.

1.1.4.1 UPDATED CIVIL/MILITARY OPERATIONAL REQUIREMENTS

Tables 13-1, 13-2, and 13-3 summarizes the requirements for civil and military users. The relationships between users, airports, user requirements and airport requirements are indicated.

Aircraft types chosen are representative but not all inclusive. Airport definitions were adapted from existing definitions. The LHA designation was included for further study at a later date.

The operational requirements were used to define functional services and performance level which are summarized in the following section.

1.1.4.2 FUNCTIONAL REQUIREMENTS SUMMARY

This section tabulates the MLS functional requirements for both civil and military users, as updated during TACD. The section

Table 13-1. AIRPORTS VS. AIRCRAFT

Aircraft Type	Civil Aviation Airports						Military Airports					
	High Density (Primary)	Medium Density (Secondary)	Low Density (Feeder)	V/STOL	VTOL	Private Aviation Airports	Main Operating Base	Dispersed Operating Base	Forward Operating Base	Combat Base	Carrier	LHA
Air Carrier												
SST	X	O					O					
Long Haul Jet	X	O					O					
Short Haul Jet	X	X	X				O					
Prop/Turbo Prop/Older Aircraft	X	X	X				O					
STOL	X	X	X	X								
VTOL	X	X	X	X	X							
Private												
JET	X	X	X			X						
CTOL	X	X	X	X		X						
VTOL	X	X	X	X	X	X						
Military												
Heavy Cargo Transport	O						X	X				
Light Cargo Transport	O	O	O				X	X	X		X	
High Performance CTOL	O	O					X	X	X			
STOL	O	O	O				X	X	X	X		
VTOL	O	O	O	O	O		X	X	X	X		
CTOL (SHIP)	O	O					X	X	X		X	
VTOL (SHIP)	O	O	O	O	O		X	X	X	X	X	X

NOTES: X = Routine Ceneration

O = Occasional Operation

Table 13-2. AIRPORT REQUIREMENTS

	Civil Aviation Airports						Military Airports					
Airport Requirements	High Density (Primary)	Medium Density (Secondary)	Low Density (Feeder)	V/STOL	VTOL	Private Aviation Airports	Main Operating Base	Dispersed Operating Base	Forward Operating Base	Combat Base	Carrier	LHA
Runway Configuration	Parallel +Short +Pad	Single +Short	Single	Short	Pad	Single	Parallel + Short Pad	Single + Short	Single + Short	Short or Pad	Short	Pad
Aircraft Operations												
Single Approach	X	X	X	X	X	X	X	X	X	X	X	X
Multiple Vertical Approaches	X	O	X	X	X		X	X	X	X	O	X
Multiple Lateral Approaches	O	O	O	X	X		O	O	O	X	O	X
Curved/Complex Vertical Approaches	X	X		X	X		X	O			O	
Curved/Complex Lateral Approaches	X	O		X			X	O			O	
Autoland	X	X		X	X		X				X	X (?)
Rollout	X	O		X			X					
Missed Approach	X	O		X	X		X	O			X	
Guided Takeoff	X	O		X	X		X	O				
Acceptance Rate	120/hr. Desired	60/hr?	30-60/hr?	60/hr?	30-60/hr?		120/hr Desired	120/hr Desired	60/hr	60/hr	120/hr Desired	60/hr
Multipath Environment	Severe	Moderate	Moderate	Severe	Severe	Light	Severe	Moderate	Severe	Severe	Severe	Moderate
Weather Category (Max)	CAT III	CAT II/III	CAT I/II	CAT III	CAT II/III	CAT I	CAT III	CAT II	CAT II	CAT I/II	CAT III	CAT II
Rainfall Rate (mm/hr.)	50	50	15	25	25	15	50	50	15	15	50	50
Portability					O	O		X	X	X		
Remote Control	X	X	X	X	O		X	X	O		X	X
Remote Interface Req.	X	X	X	X	X		X	X			O	
Integrity Levels												
Failure Mode	FAIL OP	FAIL/SAFE	FAIL/SAFE	FAIL OP	FAIL OP/SAFE	FAIL SAFE	FAIL OP	FAIL SAFE	FAIL SAFE	FAIL SAFE	FAIL OP	FAIL SAFE
Flight Path Monitoring	Desired	Desired	Desired	Desired	Desired		Desired	Desired	Desired		Required	Required
ESC Course Elimination	Required	Required	Required	Required	Required	Required	Required	Required	Required	Required	Required	Required
ECM Capability							Desirable	Desirable	Desirable	Desirable	Desirable	Desirable

NOTES: X = Routine or Required

O = Occasional or Optional

Table 13-3. AIRCRAFT REQUIREMENTS

Aircraft Type	Aircraft Operations									Weather Category Max	Airborne Integrity/ Reliability Level	ECM	EMI Environment
	Straight In	Multiple Vertical	Multiple Lateral	Curved/Complex Vertical	Curved/Complex Lateral	Autoland	Rollout	Missed Approach	Guided Takeoff				
Air Carrier													
SST	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP		Moderate
Long Haul Jet	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP		Moderate
Short Haul Jet	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP		Moderate
Prop/Turbo Prop/Older A/C	X	X	X	O	O				O	CAT I/II	FAIL SAFE		Moderate
STOL	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP		Severe
VTOL	X	X	X	X	X				X	CAT II	FAIL SAFE		Severe
Private													
JET	X	O	X					O	O	CAT II	FAIL SAFE		
CTOL	X		O							CAT I	FAIL SAFE		
VTOL	X	X	X						X	CAT I	FAIL SAFE		
Military													
Heavy Cargo Transport	X	X	X	X	X	X	X	X	X	CAT III	FAIL OP	Desired	Severe
Light Cargo Transport	X	O/X	X	/X	O	/X	/X	X/X	X/X	CAT II/III	FAIL SAFE/OP	Desired	Severe
High-Performance CTOL	X	X	X					X	X	CAT II/III	FAIL SAFE	Desired	Severe
STOL	X	X	X	O	O			O	O	CAT II	FAIL SAFE	Desired	Severe
VTOL	X	X	X	O	O					CAT II	FAIL SAFE	Desired	Severe
CTOL (SHIP)	X		O	X	X	X		X		CAT III	FAIL OP	Desired	Severe
VTOL (SHIP)	X	X	O							CAT II	FAIL SAFE	Desired	Severe

NOTES: X = Routine Requirement

O = Option

covers functional services , signal quality, coverage, auxiliary data and coordinate geometry.

A. FUNCTIONAL SERVICES

Tables 13.4 and 13.5 summarize the services that MLS, in conjunction with other user equipment, will provide to user types at each airport. In addition to angular and range guidance services, the system provides:

- aural and displayable identification
- obstacle warning indications via minimum safe glideslope transmitted on auxiliary data
- airborne and ground based malfunction indications
- facility status data

Services for special users includes flightpath monitoring for carrier landing systems.

All services are fully defined in Section 1.1.1.2.A.

B. SIGNAL QUALITY PERFORMANCE

Table 13.6 summarizes the required signal qualities for civil and military systems. The following parameters are given.

1. Bias, or long term errors associated with drifts and alignment errors.

2. Noise, or rapidly fluctuating random errors in angle measurements. These are caused by transmitter and receiver effects, thermal noise and very small contributions from many multipath sources. Large contributions from a single source of multipath causing highly sinusoidal inputs to the flight control system of amplitude comparable to the noise specification are not comparable.

3. Data Rate which is set along with noise to produce acceptable AFCS behavior.

4. Granularity, which is described by discrete discontinuities in the receiver response in the absence of noise to changing angle,

Table 13-4. FUNCTIONAL SERVICES SUMMARY

Service	USERS CIVIL I/K	F/G	E	D	B	MILITARY USAF I	USAF/USA E	USMC/USA VTOL F/G	USN I	AIRPORTS K	F/C	E	D	B	USAF I	USA USAF E	USMC USA VTOL E	USN I
1. Lateral Approach Guidance																		
a. Basic Localizer Service	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
b. Wide Angle Localizer Service	X	X	X			X	X	X	X	X	X	X	X		X	X	X	X
c. Selectable Lateral Approaches	X	X	0			X	C	0	0	X	X	X	X		X	0	X	0
d. Area Navigation Approaches	X	X				X			(2)	X	X	X	X		X	X		0
2. Vertical Approach Guidance																		
a. Single Glide Slope	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X
b. Selectable Glide Slope	X	X	X	(1)		X	X	X	X	X	X	X	X		X	X	X	X
c. Offset and Two-Step Vertical Guidance	X	X	0			X	X			X	X	X	X		X	X		
d. Complex Vertical Flight Paths	X	X				0			(2)	X	X				0			
3. Longitudinal Guidance																		
a. Basic "Marker" Service				X	X					X	X	X	X	X	X	X	X	
b. Basic Continuous Service	X	X	X	0	0	X	X	X	X	X	X	X	X	0	X	X	X	X
c. Metering Service	X	X				X			0	X	X	C	0		X	0	0	0
4. Landing Guidance																		
a. Category I Guidance	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
b. Category II Guidance	X	X				X		/X		X	X				X		/X	
c. Category III (Flare) Guidance	X					X			(3)	X					X			(3)
d. Decrab	0					0				X					X			
5. Runway Guidance																		
a. Rollout	X					X				X					X			
b. Turnoff	X					X				X					X			

Table 13-4. FUNCTIONAL SERVICES SUMMARY (Continued)

Service	USERS CIVIL					USERS MILITARY USAF	USAF USA	USMC/ USA VTOL	USN	AIRPORTS					USAF	USA USAF	USMC USA VTOL	USN
	X	F/G	E	D	B	I	E	F/G	I	X	F/G	E	D	B	I	D	E	I
6. Takeoff/Missed Approach Guidance																		
a. Lateral Guidance	X	X	0	0		X			0	X	X				X			0
b. Vertical Guidance	(5)	(5)				(5)				(5)	(5)				(5)			
c. Longitudinal Guidance	X	X	0	0		X		0	0	X	X	0	0		X	0	X	0
7. Identification																		
a. Aural	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
b. Automatic	X	X	0	0		X	X	0	0	X	X	X	X	X	X	X	X	X
8. Obstacle Warning																		
a. Minimum Glide Slope Indication	X	X	X	X		X	X	X	X	(4)	(4)	(4)	(4)		(4)	X	X	X
9. Malfunction Indications																		
a. Basic Alarm			X	X	X		X	X		X	X	X	X	X	X	X	X	X
b. Malfunction Discrimination	X	X				X			X	X	X	X	X	X	X	X	X	X
10. Airport Condition Data	X	X				X		/X	X	X	X	0	0		X	0	/X	X
11. Services to ATC										X	X	X	X		X	X		X
12. Flight Path Monitoring									X									X

(1) Over narrow range.

(2) Straight flight path must be computed for Cat III landing

(3) Guidance to TD but no flare.

(4) Where required by terrain and siting.

(5) Growth option.

Table 13-5. REQUIRED FUNCTIONAL ELEMENTS FOR GROUND FACILITIES

	CIVIL					MILITARY			
	K	F/G	F	D	B	USAF I	USA USAF E	USMC USA VTOL E/G	USN I
Proportional AZ	X	X	X	X	X	X	X	X	X
Proportional EL1	X	X	X	X		X	X	X	X
Proportional EL2	X					X			1
DME	X	X	X	X	X	X	X	X	X
Back Course AZ	X	X				X			0
Back Course DME	X	X				X		0	0
Aux. Data	X	X	X	X	X	X	X	X	X
Flight Path Monitor									X
ATC Interface	X	X	X	X	X	X	X	0	X

1. Guidance to touchdown required.

Table 13-6. SIGNAL QUALITY PERFORMANCE SUMMARY

		B	D	E	(4) F	(4) C	(4) I/K (CTOL)	(4) K (STOL)	E (MIL Colocated)	F (MIL SPLIT SITE)	G (MIL SPLIT SITE)	(4) I (Carrier) System "A"	System "B"
Az	Bias (2σ) (2)	.275°	.275°	.275°	.066°	.066°	.043°	.20°	.26°	.26°	.26°	.034°	.15°
	Noise (2σ) (3)	.12° (19)	.12° (19)	.12° (19)	.065°	.065°	.065°	.084°	.3° (6)	.12°	.12°	.046°	.15°
	Data Rate	10 Hz	10 Hz	10 Hz	7 Hz	7 Hz	7 Hz	7 Hz	10 Hz	10 Hz	10 Hz	10 Hz	5 Hz
	Granularity	.025°	.025°	.025°	.025°	.025°	.025°	.03	.05°	.025°	.025°	.025°	.025°
	Interruptions	5 sec	5 sec	5 sec	2 sec	2 sec	2 sec	2 sec	5 sec	5 sec	2 sec	2 sec	5 sec
SL_1 (5)	Bias (2σ) (2)	N/A	.10°	.10°	.06°	.06°	.6°	.06°	.17°	.10°	.06°	.034°	.07°
	Noise (2σ) (3)		.12°	.12°	.08°	.08°	.08°	.08°	.2° (6)	.12°	.12°	.046°	.07°
	Data Rate		10 Hz	10 Hz	7 Hz	7 Hz	7 Hz	7 Hz	10 Hz	10 Hz	10 Hz	10 Hz	5 Hz
	Granularity		.01°	.01°	.01°	.01°	.01°	.025°	.05°	.01°	.01°	.01°	.01°
	Interruptions		3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec	3 sec
EL_2	Bias (2σ) (2)	N/A	N/A	N/A	N/A	N/A	.05°	.09°	N/A	N/A	N/A	N/A	N/A
	Noise (2σ) (3)						.036°	.036°					
	Data Rate						14 Hz	14 Hz					
	Granularity						.035°	.05°					
	Interruptions						.5 sec	.5 sec					
DME	Bias (1σ) (2)	300'	100'	32'	32' (7)	20' (7)	20' (7)	20' (7)	32'	32'	20'	10'	N/A
	Noise (1σ) (3)	100'	100'	32'	32'	20'	20'	20'	32'	32'	20'	10'	
	Data Rate	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	5 Hz	10 Hz	
	Interruptions	5 sec	5 sec	5 sec	2 sec	2 sec	2 sec	2 sec	5 sec	5 sec	2 sec	2 sec	5 sec
Min Guidance Altitude		150'	150'	150'	50'	50'	8'	8'	50'	50'	50'	8'	150'

Notes to Table 13-6

1. All values are for the total system, including ground and airborne equipment.
2. Bias-error which is constant over more than 20 seconds.
3. Noise includes all spatial and temporal effects.
4. Back Course guidance at these facilities has same accuracy requirements as front course guidance. Back course guidance at shipboard I configuration is optional.
5. EL-1 data is to be interpreted as the angular error at the minimum usable glideslope At a given height within the coverage volume the angular error at a greater elevation angle shall not produce a linear equivalent error which exceeds that for the minimum glideslope.
6. Noise specification is based on support of manual approaches only.
7. Total system should have this capability. For aircraft using glideslopes 6° or under, the allowable DME error is 32' 1 sigma
8. These accuracies apply at the centerline of the runway at the decision height.
9. The combination of DME and AZ error at maximum range should not exceed 0.1 nmi. circular error.
10. Assumes course width adjustment by varying receiver output scale factor.

and is caused by characteristics of the signal in space, the receiver processing, or both. The granularity specification assumes operation with a K receiving at all civil facilities.

5. Signal interruptions, defined as maximum tolerable length of signal interruption acceptable for continuing the revision.

6. Minimum guidance altitude, the minimumaltitude on the glideslope for which the specified accuracy must be met. The accuracy must be met over a lateral coverage region extending either side of runway centerline. This region is defined in the coverage summary below.

C. COVERAGE PERFORMANCE

Table 13-7 summarizes the required angular coverage for each civil and military facility. The following significant changes were made to the SC-117 coverage.

1. Maximum glideslope at D and F facilities was raised from 6° to 7.5° by providing additional elevation coverage.

2. A K STOL requirement was also defined.

3. Coverage estimates for military facilities were also included.

4. EL1 azimuth coverage at K/I configuration was reduced in accordance with our recommendation to retain barometric altimetry for guidance off-centerline.

Detailed coverage requirements near the runway for EL1 and EL2 guidance elements are given in figures 13-1 and 13-2.

D. AUXILIARY DATA REQUIREMENT

Table 13-8 gives the updated requirements for transmission of auxialiary data on the MLS signal format. New requirements defined are:

o Time of day for automatic synchronization of all user aircraft to facilitate future metering and spacing operations.

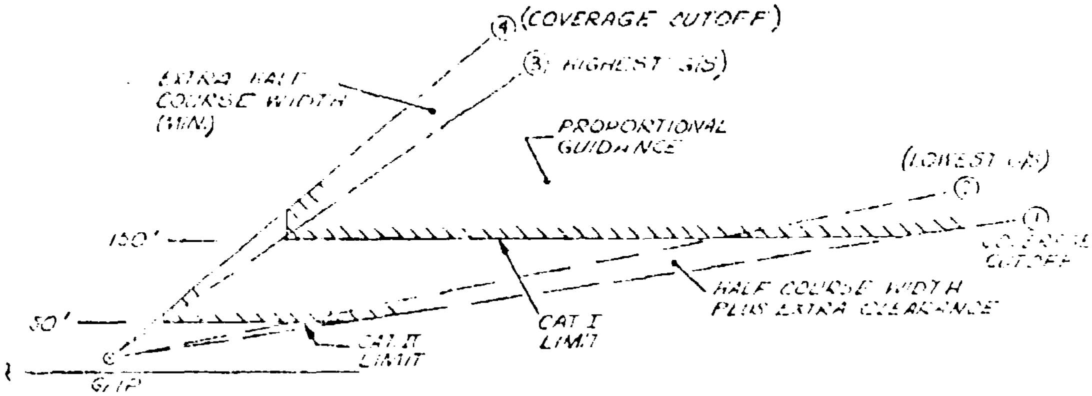
Table 13-7. COVERAGE PERFORMANCE SUMMARY

Coverage		B	D	E (2)	F	G	I/F 2 (CTOL)	K (STOL)	G (MIL Colocated)	E (MIL SPLIT SITE)	G (MIL SPLIT SITE)	I (Carrier) System A	I (Carrier) System B
Az	Horiz	±20°	±20°	±20°	±20°	±20°	±60° K, ±40° I	±60°	±60°	±10°	±20° (4)	-10° to +40°	±20°
	Vert	.75° - 5°	.75° - 10°	.75° - 20°	.75° - 10°	.75° - 20°	.75° - 20°	.75° - 20°	0° - 20° (3)	0° - 20° (3)	0° - 20° (3)	±10° (5)	1° - 10°
	Range	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	10 n.m.	10 n.m.	10 n.m.	10 n.m.	25 n.m.
El_1	Horiz (1)	N/A	-20° to +40°	-20° to +45°	-20° to +45°	-20° to +45°	-20° to +45°	-20° to +45°	±60°	±10°	-20° to +45°	-10° to +40°	-20° to +40°
	Vert		1° - 20°	1° - 20°	1° - 10°	1° - 20°	1° - 20°	1° - 20°	0° - 20° (3)	0° - 20° (3)	0° - 20° (3)	±10°	1° - 10°
	Range		25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	10 n.m.	10 n.m.	10 n.m.	10 n.m.	25 n.m.
El_2	Horiz (1)	N/A	N/A	N/A	N/A	N/A	-10° to +30°	-10° to +30°	N/A	N/A	N/A	N/A	N/A
	Vert						0° - 10°	0° - 10°					
	Range						2.5 n.m.	3.5 n.m.					
BCAs & DME	Horiz	N/A	N/A	N/A	±20°	±20°	±40°	±45°	N/A	N/A	N/A		±20°
	Vert				1° - 20°	1° - 20°	1° - 20°	1° - 20°					1° - 20° (5)
	Range				10 n.m.	10 n.m.	10 n.m.	10 n.m.					10 n.m.
DME	Horiz	±20°	±20°	±20°	±20°	±20°	±60° (K), ±40° (I)	±60°	±60°	±10°	±20°	-10° to +40°	N/A
	Vert	.75° - 5°	.75° - 10°	.75° - 20°	.75° - 10°	.75° - 20°	.75° - 20°	.75° - 20°	0° - 20°	0° - 20°	0° - 20°	±10°	
	Range	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	25 n.m.	10 n.m.	10 n.m.	10 n.m.	10 n.m.	
Path Location													
	Azimuth	Extended Center Line (7)	Extended Center Line (7)	Extended Center Line (7)	Extended Center Line (7)	Extended Center Line (7)	±40° I, ±60° K	±60°	±60°	Extended Center Line	Extended Center Line	Extended Center Line (8)	Extended Center Line
	El	N/A	2° - 7.5°	2° - 15°	2° - 7.5°	2° - 12° (CAT II) 2° - 15° (CAT I)	2° - 12° (CAT II) 2° - 15° (CAT I)	5° - 12° (CAT II) 5° - 15° (CAT I)	5° - 15°	2° - 15°	2° - 12° (CAT II) 2° - 15° (CAT I)	3° Nom. (8) (9)	3° Nom. (9)
Minimum Guidance Altitude		150'	150'	150'	50'	50'	8'	8'	150'	150'	50'	8'	150'
Rainfall, mm/hr		15	15	15	50	50	50	25	15	15	25	50	50

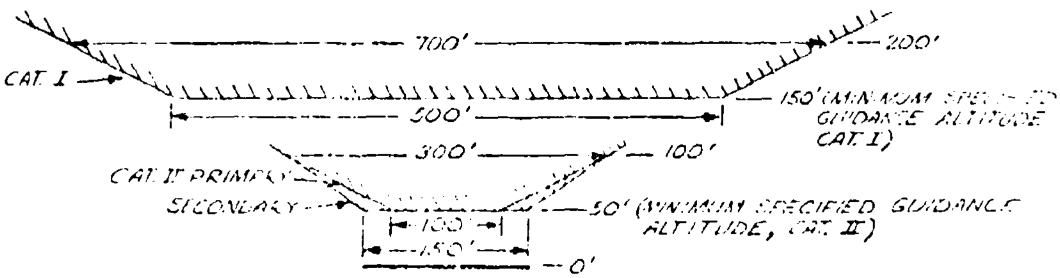
NOTES

1. The larger of the two coverage extremes is required to provide coverage to the minimum guidance altitude over the runway. At maximum range, coverage is plus or minus the smaller of the coverage angles given.
2. E and I include USAF requirements.
3. Elevation cutoff to be adjustable from 0° to 5° in approximately 10 steps.
4. Azimuth cutoff to be available to avoid obstacles in the terrain.
5. Special coverage shaping required.
6. Optional guidance element.
7. For higher-class users, entire azimuth coverage region available for proportional guidance.
8. Flight path must be computed for blind landing.
9. Glidescope refers to still air. In practice, will be adjusted upwards to compensate for wind over deck.

	①	②	③	④
D	1°	2°	6°	8°
KC10L	1°	2°	12° REQ 15° DES	20°
KS10L	1°	5°	12° REQ 15° DES	20°



(a) LONGITUDINAL SECTION



(b) TRANSVERSE SECTION

7209294

Figure 13-1. El Coverage Near Runway

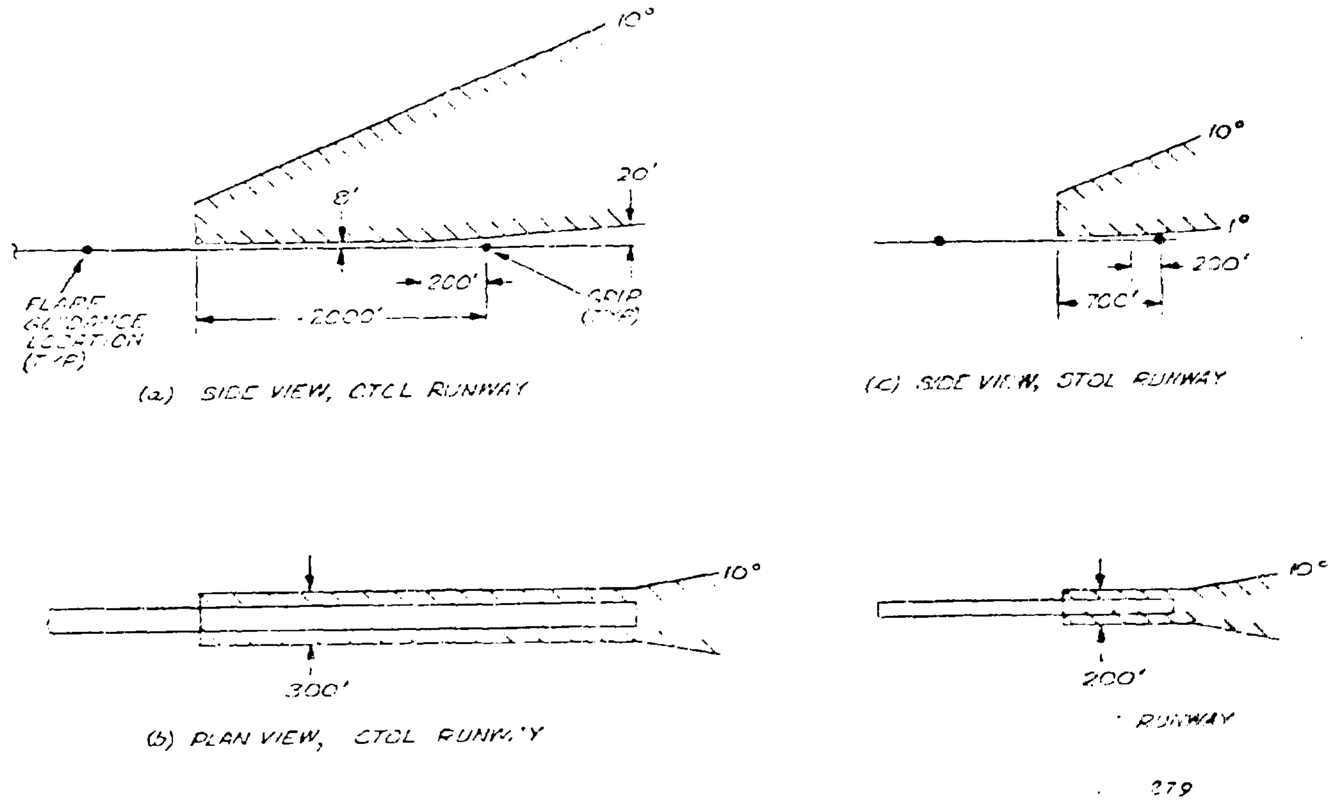


Figure 13-2. El -2 (Flare Guidance) Near Runway

Table 13-8. Auxiliary Data Requirements

Auxiliary Data	MLS Element	Tone	Rep. Interval	# Bits
Morse Code Airport I.D.	AZ	E	1 Bit Per Function Time (seconds)	15
Fixed Data				
θ Runway Heading			10	10
θ Distance EL_1 to DME			10	10
Time of Day	AZ	F	10	15
Barometric Setting			10	7
Growth			10	9
Runway I.D.			10	15
Min Glideslope	EL	E	10	30
Growth			10	
Facility Status			5	
Wind Shear	EL	E&F	5	15
Wind Vector at TD			5	
RVR			10	
Runway Condition			5	15
Dist. EL_1/EL_2	EL	E&F	10	
Alt EL_1/EL_2			10	15
Growth			10	15

- Local barometric setting to improve integrity of the present altimetry system.
- Minimum glideslope for the facility, to be used in selection or modification of receiver glideslope.

Growth capability is also provided for future ATC communications.

E. COORDINATE GEOMETRY

All radiated guidance signal coordinates shall be planar. One exception is included for the co-located E man-transportable system (USA) where selectable azimuth approaches are desirable. Here elevation guidance is conical.

F. OTHER TECHNICAL PARAMETERS

1. Monitors and Flag Alarms

Ground-based monitors shall be provided which automatically detect and respond to significant degradation or loss of any transmitted guidance signal. Monitor tolerances and adjustability shall ensure compliance with system accuracy specifications and with any safety criteria peculiar to each installation. Airborne flag alarm signals shall be provided which respond to signal losses from any cause, to unreliably weak signals, and to inconsistencies in signal format tending to result in false data. Separate alarm signals shall be available for azimuth, elevation and distance data. Flag alarm response times shall not exceed one second. The system monitoring philosophy is covered in section 1.1.1.1.A(Systems Concept and Integration)

2. Installation Factors

The locations of surface guidance facilities relative to each other and to the landing zone shall be sufficiently flexible to avoid conflicts with existing surface features such as taxiways and structures. Manual adjustments to the airborne equipment in compensation for such variations in installation geometry shall not be permissible. Siting considerations are covered in Section 1.1.3.2.

3. Co-Location with Existing Facilities

The instrument landing system provided shall be designed such that its normal performance characteristics fall within prescribed tolerances when co-located with an existing conventional instrument landing system or other such systems. Co-location shall be interpreted as being physically located so as to serve the same runway with azimuth, elevation and distance guidance, and with no degradation in performance characteristics of the existing system. Co-location is covered in detail in section 1.1.3.1.

4. Electromagnetic Compatibility (EMC)

The system and its equipment elements shall neither produce nor be vulnerable to radio interference to such a degree that standard electromagnetic control methods would be ineffective. Misleading indications due to accidental interference shall be prevented. Positive safeguards against hostile jamming are desirable options for military applications. Initial considerations of EMC are covered in section 1.1.3.4. Further considerations of EMC as well as ECCM are planned for Phase II.

1.1.5 SIGNAL FORMAT SUMMARY

The signal format summary is provided in two sections; the signal format description and the indication of growth potential. The signal format is described in section 1.1.5.1 and the indication of growth capability is given in section 1.1.5.2.

1.1.5.1 SIGNAL FORMAT DESCRIPTION

A baseline signal format for the Doppler Scan technique was developed at Hazeltine based on the format described in SC-117 and as refined by Hazeltine during the TACD proposal, and the signal format studies performed in Section 1.1.1.2 Part B of this report. The key parameters of the signal format include the elements listed below.

- Channel Plan
- Time Division Multiplex Format
- Data Rate
- Angle Data Signal
- Frequency Code
- Auxiliary Data Format
- Scan Cycle Description
- DME
- Integrity Features

The major features of each parameter are summarized in figures 14-1. The features with an asterisk (*) indicate the refinements made by Hazeltine. A brief description of these features are included in this section for quick reference to the Hazeltine signal format.

Channel Plan:

The MLS frequency channel plan (shown in figure 14-2) is identical to the SC-117 plan. It has a capacity for 200 ground-to-air angle data (AZ-EL frequencies with 0.6 MHz spacing) and a corresponding 200 ground-to-air and air-to-ground DME channels, each function in

CHANNEL PLAN

- ° 200 Channel Assignment per SC-117
- *° Common frequency reference for each facility
- *° 5×10^{-6} ground frequency stability C-band
- *° 1.5×10^{-6} ground frequency stability Ku-band
- ° 1.5×10^{-5} airborne frequency stability

TIME DIVISION MULTIPLEX

- ° Five angle functions in K configuration
- ° Two angle functions in D configuration
- *° Growth time slot
- *° Ground test signal in growth time slot

DATA RATE

- *° 7 Hz for AZ, EL-1/L, $EL1_H$, BCAZ in K configuration
- *° 14 Hz for EL2 in K configuration
- *° 10 Hz for AZ, EL-1/L in D configuration
- *° 1 Hz for ground test signal
- *° 0.10 Hz for not changing auxiliary data
- *° 0.2 Hz for changing auxiliary data

Figure 14-1. Signal Format Parameters (Sheet 1 of 4)

ANGLE DATA SIGNAL

- ° Sequential Dual Scan
- ° Phase cycling in transmitter
- *° Angle sideband subcarrier at 100 kHz with 10^{-5} stability
- *° Planar coordinates in single time slot
- *° Sidelobe control

  First sidelobe in angle guidance band -16 dB

  Sidelobe -24 dB 73 kHz from angle sideband

  Sidelobe -30 dB 310 kHz from angle sideband

FREQUENCY CODE

- *° Multiple of whole numbers

  333.3 Hz/deg for AZ, BC AZ

  1 kHz/deg for EL-1/L, EL-1/H

  2 kHz/deg for EL-2

AUXILIARY DATA FORMAT

- *° Auxiliary Data Signal

  First two milliseconds of AZ and EL1 functions
  300μs period of reference carrier only; 1.7 ms period of F.1. + one bit of tones E and F
  Tone frequency stability ±100 Hz
  Two tones used for Auxiliary Data

- *° Function Identification

  Four tones - one each for AZ, EL-1, EL-1/H, EL-2

  Odd number of tones

Figure 14-1. Signal Format Parameters (Sheet 2 of 4)

SCAN CYCLE

*° Auxiliary Data Format

*° Number of Scans
16 times the Doppler beamwidth on AZ and EL1 stations

° Scan Time
Function of Doppler beamwidth

*° Constant Function Times at All Facilities

AZ 51 ms
EL-1/L 19 ms
EL-2 13 ms
EL-1/H 19 ms
BC AZ 21 ms

DME

° Pulse characteristics
0.66 ±0.1μs Duration
0.1 +0.02μs Rise Time
0.3 +0.1μs −0.04μs Fall Time

° Code Characteristics
10μs Shortest Spacing
28μs Longest Spacing
Two Pulse Code on down link
Two Pulse Code on up link

*° Interrogation Rate
40 per sec during Search
20 per sec during Track
5 per sec during Test

Figure 14-1. Signal Format Parameters (Sheet 3 of 4)

INTEGRITY FEATURES

*° Function identification using odd number of tones and transmitted during entire function time

*° Ground Test Signal

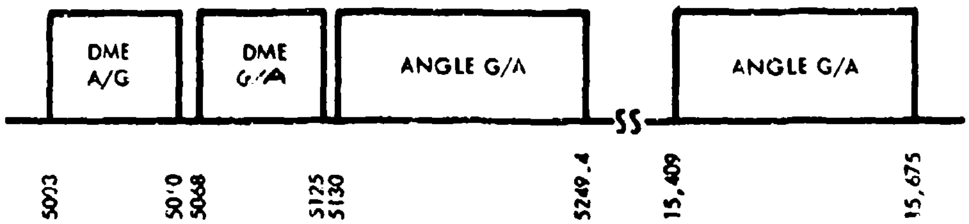
3 tones same as AZ, EL1, EL2 + fourth tone at 99 kHz

1 Hz data rate

*° 1 ms buffer time after each multiscan

*° Sidelobe suppression signal

Figure 14-1. Signal Format Parameters (Sheet 4 of 4)



CHANNEL	DME A/G	DME G/A	ANGLE C-BAND	ANGLE Ku-BAND
1	5003	5068	5130.0	15,409.0
2	5003	5068	5130.6	15,409.9
5	5003	5068	5132.4	15,412.6
6	5003	5068	5190.0	15,413.5
7	5003	5068	5190.6	15,414.4
10	5003	5068	5192.4	15,417.1
11	5006	5071	5133.0	15,418.0
15	5006	5071	5135.4	15,421.6
16	5006	5071	5193.0	15,422.5
181	5057	5122	5184.0	15,571.0
191	5060	5125	5187.0	15,580.0
195	5060	5125	5189.4	15,583.6
196	5060	5125	5247.0	15,584.5
200	5060	5125	5249.4	15,588.1

Figure 14-2. Doppler MLS Frequency Allocation Plan

a separate portion of C-band. 200 Elevation No. 2 Ku-band channels are spaced 0.9 MHz rather than 0.6 MHz used in C-band This arrangement permits use of the same frequency tolerance and synthesizer for C and Ku-bands, in the airborne unit. The angle data transmission will use separate frequency assignments for each channel. Twenty air-to-ground DME interrogating frequencies with a 3.0 MHz spacing and an equal number of ground-to-air reply frequencies will be used, each using 10 pulse-pair spacing identity codes.

All C-band ground stations are frequency locked with a stability of $5X10^{-6}$ (25 kHZ). The ground frequency stability at Ku-band is $1.5X10^{-6}$ (22.5 kHZ).

Time Division Multiplex (TDM) Time multiplexing is utilized in the SC-117 signal format and was retained by Hazeltine after considering the possibility of frequency multiplexing and hybrid formats. In frequency multiplexing scheme or hybrid format the angle functions would be separated by subcarrier frequency placement to permit simultaneous transmission of angle functions. The advantages of this technique are:

- permits longer smoothing time
- high data rates if parallel processors are used
- permits best smoothing of multipath
- high integrity
- lower peak transmitter power

The technical disadvantages of the frequency multiplex signal formate are:

- Severe spectrum control requirements for the EL-1 station for the geometry of an aircraft near runway threshold and attempting to derive AZ data.
- The carrier undergoes a differential Doppler shift in the receiver due to the aircraft motion for the split site location of the ground stations.

For reason of difficult spectrum control and the need for many parallel processors, we chose the TDM format as a baseline.

In this format different slot numbers are assigned to various Doppler MLS functions depending on the specific functions to be transmitted from a given ground configuration. In addition, a growth time slot is maintained in all configurations. A part of the growth time slot is however used at a 1 Hz rate to transmit a test signal from the ground to permit calibration in the aircraft.

Data Rate. The data rates chosen for the Doppler MLS were derived from simulations performed by Sperry Flight Systems. These simulations involved recording control activity as a function of beam noise and data rate, in order to determine pilot acceptability criteria for the control activity. In order to permit smooth coupling to the Doppler MLS, several alternative refinements to the SC-117 data rates were available. The 7 Hz data rate for AZ, EL-1, and BC AZ and a 14 HZ data rate for EL-2 were chosen as the best compromise among all factors.

Angle Data Signal. The angle guidance ground station consists of unitary planar beam antennas that radiate a signal offset from the reference in a dual scan format. The upper and lower sideband ($f_R \pm f_O$) are radiated alternately in successive scans (odd and even numbered) and the simulated moving source is bidirectional on alternate scans; moving away from positive angles in odd scans or toward such angles in even scans. The offset frequency (f_O) is chosen to be 100 kHz such that a harmonic relationship is available between the scan time and the offset frequency in order to control the repetition of function times required for phase cycling. The phase cycling is implemented to provide 180 degrees of phase shift during one function time.

Frequency Code. The frequency codes have been chosen so that each function (AZ and EL) utilizes the full available angle bandwidth recommended by SC-117 for the maximum required coverage angle. THis is 40 kHz in azimuth and only 20 kHz in elevation, since one half the elevation spectrum represents negative angles into the ground which are not used. This procedure results in different codes for AZ, EL-1 and EL-2, but each utilizes the maximum bandwidth available to provide guidance accuracy and, of course, each individual function has the same code at all airport configurations. The frequency codes were chosen such that a multiple of whole numbers can be used in going from one code to another. This requirement is added to simplify the normalization procedure in the airborne processors. These codes are:

Az:	333-1/3 Hz per degree
BC Az:	333-1/3 Hz per degree
EL-1:	1000 Hz per degree
EL-2	2000 Hz per degree

Tone Data Format. The auxiliary data format includes a functional identification scheme and an auxiliary data signal format. Both signals are transmitted as amplitude modulation on a reference carrier by multiple tone codes, and the modulation depths of the individual tones are 25 percent. The characteristics of the auxiliary data signal is such that during the first 300 microseconds a reference carrier only signal is transmitted followed by 1.7 ms of all applicable AM tones. However, during the angle guidance transmission only the function identification AM tones are transmitted.

We have adopted a different function identification coding scheme than was presented by SC-117. The purpose of the change is to increase the integrity of the function identification tones. The Coding scheme adopted has two salient features that increase integrity: (1) identification is made always using an odd number of tones A. B. C. & D; and (2) two tones are changed when identifying a new function. This coding scheme is summarized in figure 14-3.

The auxiliary data signal format was refined from that suggested in SC-117 and the Hazeltine proposal. In SC-117, four tones were used to transmit auxiliary data, but all tones were transmitted from the AZ reference antenna. The refined format retains all the information in the SC-117 concept but places two tones on AZ and two on EL-1. This approach permits the use of only two tones. When used in conjunction with the AZ and EL-1 ident signals, it performs the function of the original four tones.

The orgainziation of the tone cycle is shown in figure 14-4. It consists of two basic formats; a Morse Code format and an Auxiliary data format. The Morse Code Format is transmitted with an "I" letter start followed by the Morse Code one character (mark or space) per AZ function time by modulating tone E. The auxliary data format is a constant word which consists of a 10 bit preamble followed by four 15 bit words. Each word contains 11 information bits and 4 bits for Hamming Code detection.

On the EL-1 function changing data, such as facility status, wind vector, and wind shear, are transmitted both on tones E and F. In this way, the data rate of these functions are increased to once per five seconds. This approach also has an integrity feature in that should the "E" tone generator fail, the information can still be derived from the tone F EL-1 signal.

ANGLE DATA CODE		100 KHz TO 120 KHz
TONE A	FUNCTION IDENTIFICATION	6 KHz
TONE B		9.5 KHz
TONE C		13 KHz
TONE D		16.5 KHz
* TONE E	MORSE IDENT / RUNWAY IDENT / AUXILIARY DATA	20 KHz
* TONE F		23.5 KHz
TONE G	CLEARANCE AZ	27.0 KHz

NOTE:
* TONES E AND F ARE NOT TRANSMITTED DURING MULTISCAN

FUNCTION	IDENTIFICATION TONES A	B	C	D	E	F	G
AZ	0	0	0	1	M1	F_1	–
EL #1_L	1	0	0	0	R1	F_2	–
EL #1_H	0	1	0	0	–	–	–
EL # 2	0	0	1	0	–	–	–
BC AZ	1	1	●	1	–	–	–
TEST	1	0	1	1	–	–	–
SUPPRESSION	0	0	0	1	–	–	1

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Figure 14-3. Tone Data Identification

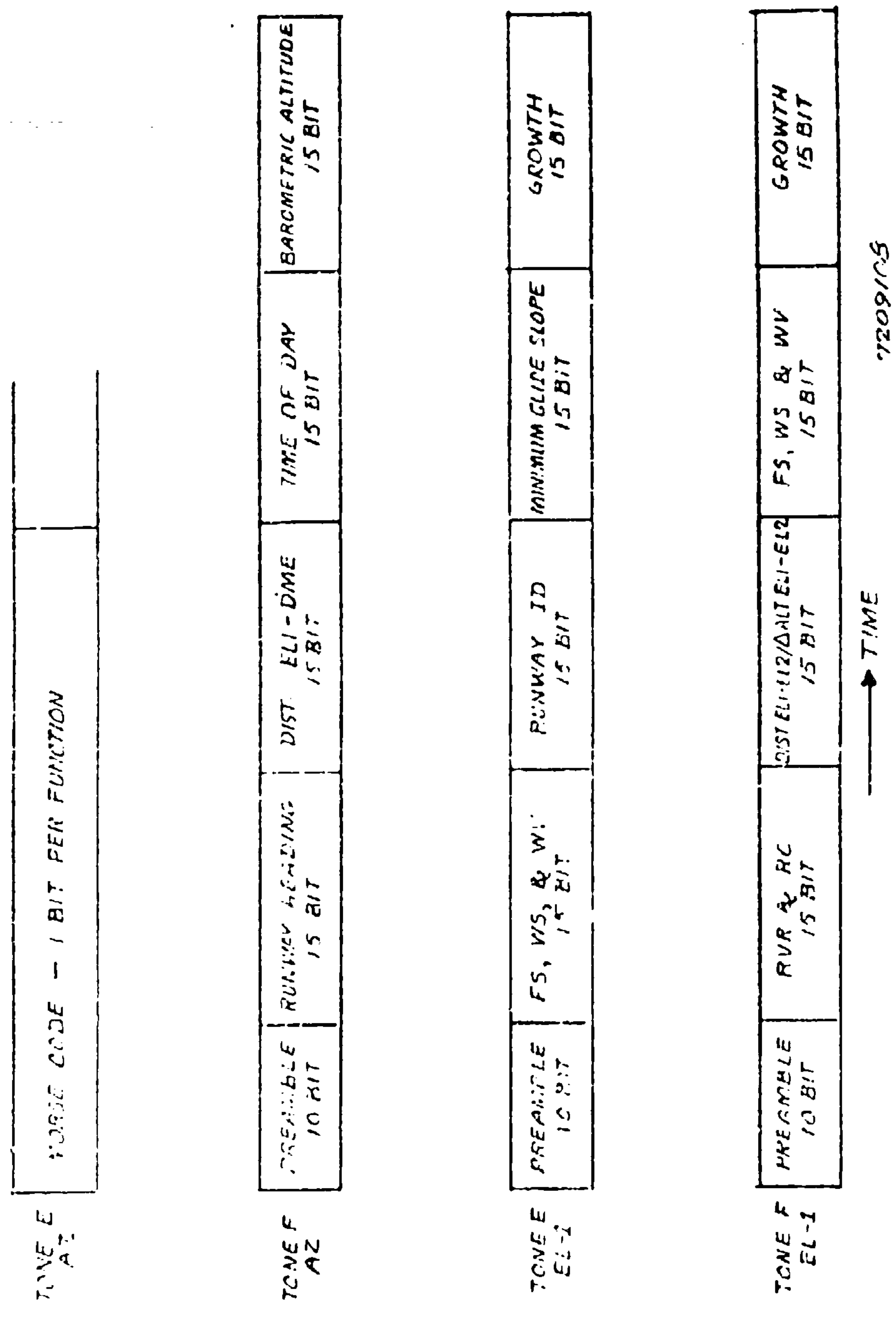

Figure 14-4. Auxiliary Data Format Organization

Scan Cycle. The scan cycle consists of several time multiplexed slots. Each slot contains format followed by a number of dual scan pairs of the angle guidance frequency (multiscan) and a 1 msecond buffer period. This total period is called a function time and the number of different function times make up the scan cycle.

The minimum number of scans per function time is related to the phase cycling granularity reduction and power requirements. By using two successive function times to resolve the granularity with phase cycling, a relationship 16 times the Doppler beam-width (one over the scan time) is required to satisfy granularity requirements for manual control operations.

Relative timing between functions is chosen to establish a specific function length for each function (AZ, EL-1, etc.) at all facilities. This approach permits the receiver to establish its own time interval which reduces the complication in the division process. In addition, the receiver has a cross check on the function identification (additional integrity). The baseline function times are indicated in figure 14-1.

DME. The signal format for DME is virtually unchanged from that described in SC-117. The only refinement was in the interrogation rate requirements as a result of the studies conducted during the TACD program. The refined interrogation rates are 40 PPS during search and 20 PPS during track.

Integrity. The major integrity features incorporated in the signal format have been indicated in figure 14-1. They include a ground test signal transmission, odd tones for function identification, a one millisecond buffer time after each multiscan, and a sidelobe suppression (SLS) signal. The first three features were mentioned in the previous paragraphs so only the SLS signal is discussed here. This signal is an AMed signal containing the AZ function identification and tone G and is transmitted on a separate antenna during the same time slot as the AZ function. The antenna pattern of the SLS antenna is a cardiod with a null in the front course. Upon detection of this combination of signals the AZ data is not processed. Confusion in the front AZ course does not exist since the SLS signal is less than the AZ signal in this region and the dynamic tone detection threshold in the receiver would discriminate against this tone G signal.

Summary. The above discussion can be summarized in a time-frequency diagram which indicates the spectrum utilized for each element of the scan cycle. Figure 14-5 shows the baseline format for configuration D ground stations and figure 14-6 shows the baseline format for a configuration K ground station.

1.1.5.2 FORMAT GROWTH POTENTIAL

The major areas in which growth is envisioned for MLS are:

- o to provide larger antenna apertures
- o to provide 360 degree AZ coverage
- o to provide additional auxiliary data words and
- o to permit additional functions to be added to the TDM scan cycle.

Features for each of the above growth areas are included in the signal format and are summarized in figure 14-7. Larger antennas require longer scan times which reduces the number of scans per multiscan. At first glance it appears as though the granularity is increased. However, since granularity is related to the Doppler beamwidth (one over the scan time), as the aperture size increases the Doppler beamwidth decreases so granularity is not increased.

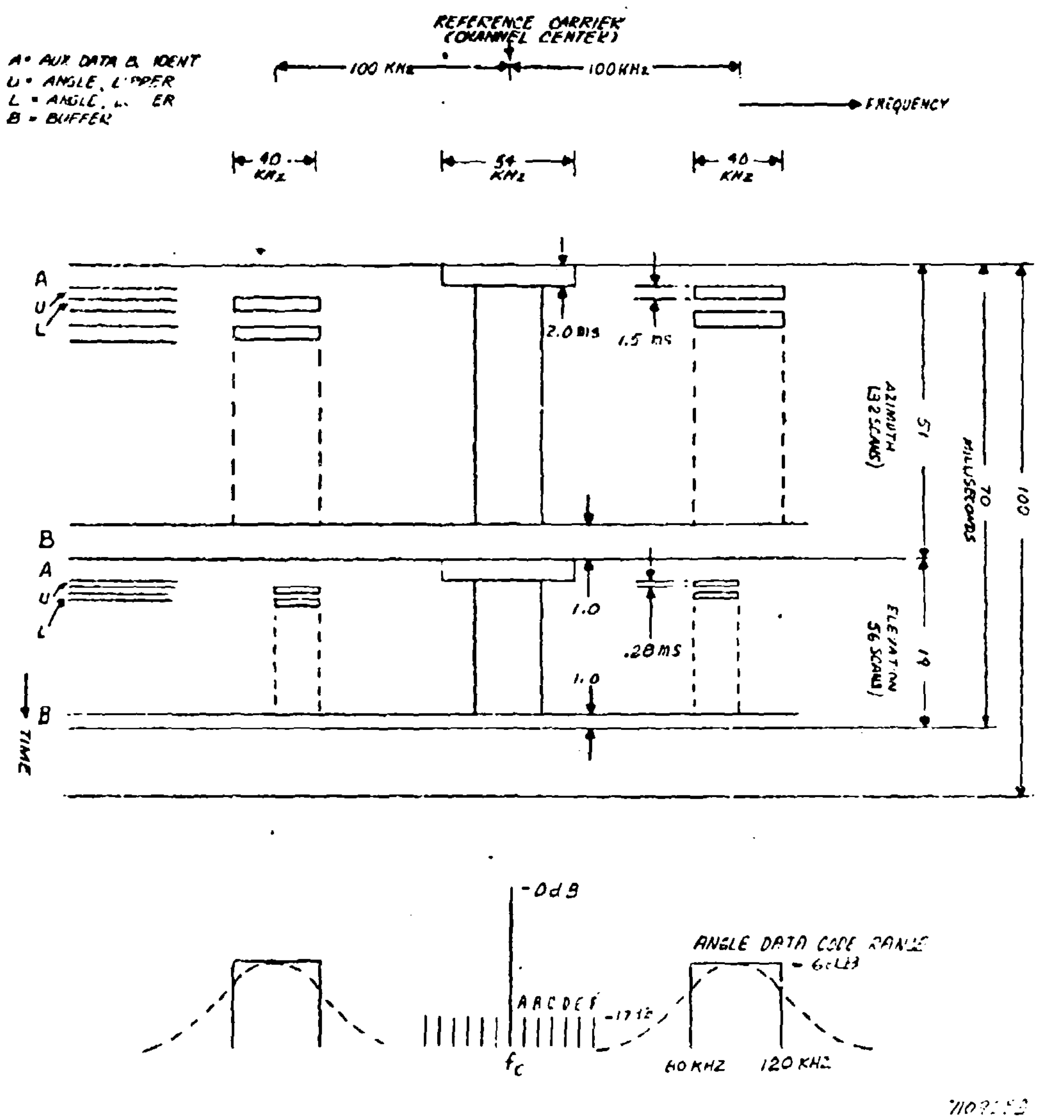

Figure 14-5. Configuration D Signal Format

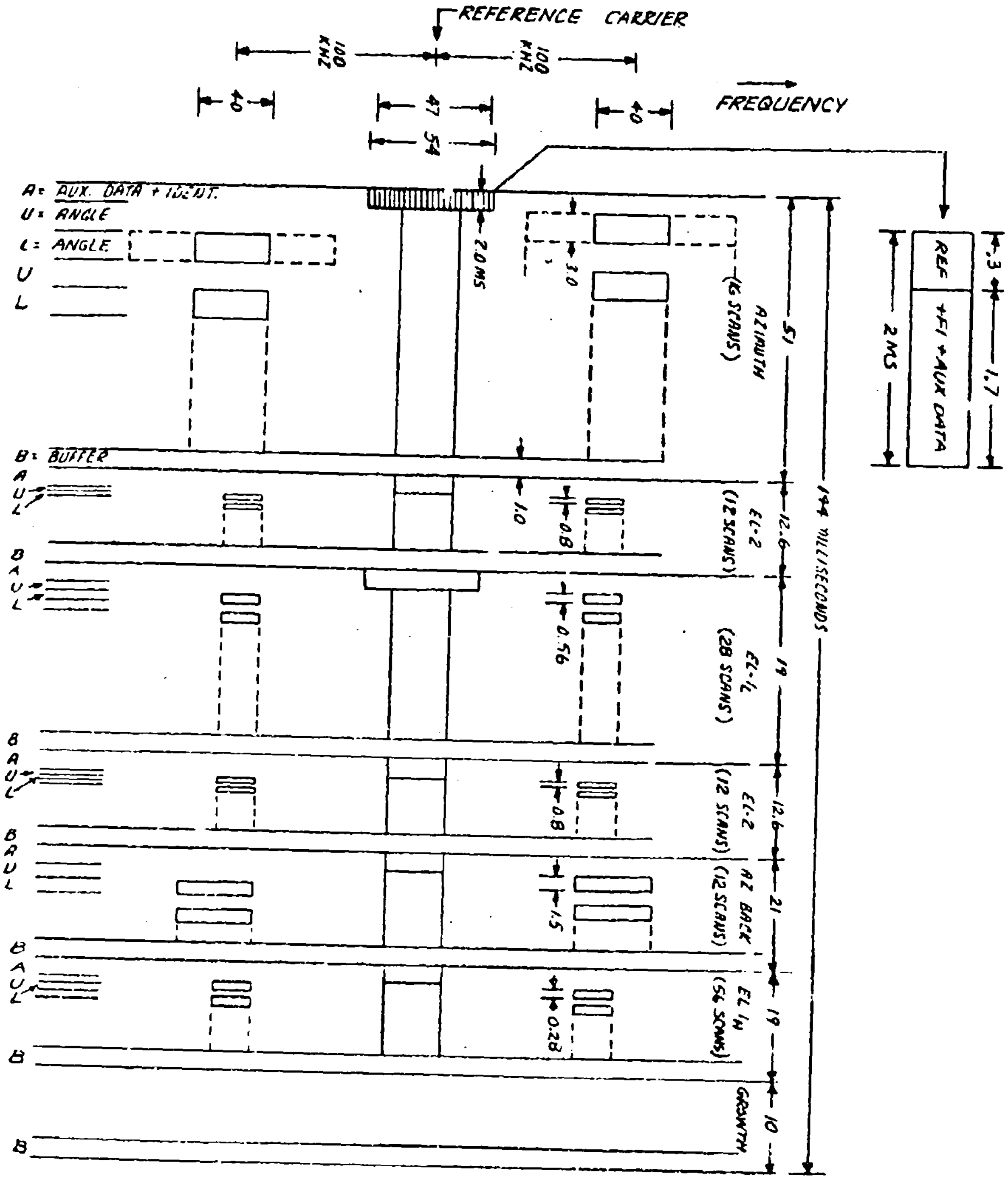

Figure 14-6. Configuration K Signal Format

SIGNAL FORMAT GROWTH FEATURES

- LONGER SCAN TIMES (larger Antennas) FOR INCREASED MULTIPATH REJECTION
- 360 COVERAGE IN AZ
  - LOCATION OF ANGLE SIDEBAND AT 100 kHz
- ABILITY TC SEND MORE AUXILIARY DATA
  - Provision on Tones E and F
  - Provision on Tones E and F on EL-1/H or EL-2
- GROWTH TIME SLOT AVAILABLE IN ALL FORMATS
  - CAN BE USED FOR ONE WAY DME OR TCRS

Figure 14-7. Signal Format Growth Features

360 degrees coverage in AZ is accommodated by locating the angle sideband frequency at 100 kHz (this reduces spectral control requirements when considering tone contamination) and scanning half of a 360 circular array in one time slot (AZ) and the other half of the array in another time slot (BC AZ). In this way angle coding and the corresponding angle frequency bandwidth need only cover ±90 degrees during any one transmission.

The ability to send more auxiliary data is provided on tones E and F where a 30 bit growth word can be accommodated. In addition, users that require EL-1/H and EL-2 angle guidance can have special auxliary data words added to the EL-1/H and EL-2 reference antennas and decode these words in the receiver. This technique does not interfere with other messages, since the receiver must decode the function before determining what the auxiliary word represents.

In addition to the above features, a time slot is left vacant in the scan cycle at all facilities for growth potential. One possible use for this time slot is one way DME growth potential and antoher is to permit a Time Ordered Ranging System (TORS).