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FINAL REPORT

Contract No. FA-WA-4514

Project No. 114-22R

**ANALYSIS OF TECHNIQUES
FOR AIRCRAFT GROUND GUIDANCE
AT AIRPORTS**

APRIL 1965

This Report has been approved for availability within
the U. S. Government.

Prepared for
FEDERAL AVIATION AGENCY
Systems Research & Development Service

by

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CATALOGED BY: DDC

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Final Report, Contract No. FA-WA-4514

ANALYSIS OF TECHNIQUES FOR AIRCRAFT
GROUND GUIDANCE AT AIRPORTS

APRIL 1965

Project 114-22R

Report No. RD-65-34

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ABSTRACT

Assuming future use of runway approach and flareout guidance in extremely low visibility, this report describes an investigation of suggested techniques for aircraft guidance during landing and takeoff roll and taxiing in poor visibilities down to zero-zero conditions.

The techniques examined are: ILS localizers (including DME); gyro compasses and inertial systems; infrared; magnetic cables; aircraft radar; light and line patterns from conventional light sources including lasers and radioactive materials; and miscellaneous techniques including wheel tracks.

These systems are judged relative to the operational requirements and considerations, including some economic analysis.

It is concluded that, for landing and takeoff ground operations, improved ILS localizer plus DME offers the best solution. For taxiing operations, magnetic leader cables show the most promise. Research programs are indicated as being necessary for both ILS/DME and leader cables.

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I. INTRODUCTION

With the impending improvement in all-weather landing, it is possible that, in a few years, aircraft will operate under weather conditions that will make normal ground operations difficult. This situation will occur when the quality of control and guidance provided during the airborne portions of a flight exceeds the pilot's ability to see during poor visibilities. In anticipation of this situation, the Research Division of the Systems Research and Development Service, Federal Aviation Agency (FAA) authorized this study of possible means of guiding aircraft on the ground during extremely poor visibility.

This study has been confined to the following six possible solutions to the ground-guidance problem:

1. ILS localizer techniques,
2. Aircraft directional-gyro systems,
3. Infrared detection,
4. Magnetic fields,
5. Aircraft radar,
6. Lines and/or line patterns.

Since these techniques represent somewhat different technical disciplines, the study was organized into six separate investigations, each of which was guided by the common operational requirements for ground guidance formulated for this study. These operational requirements are explained in detail in Section V of the report.

Section II summarizes each of the separate investigations preceded by a summary of the operational requirements and presents the most significant conclusions. Sections III and IV are the conclusions and recommendations of the overall study. Sections VI through XI contain detailed discussions and supporting material for each investigation.

Appendix A describes some actual taxiing operations at John F. Kennedy International Airport when the visibility was reported as zero. The opportunity to examine these operations only occurred after the main portion of the report had been completed. Therefore, there is no specific reference to the Appendix in any of the other sections. However, it is suggested that it be read in conjunction with Sections IIA and V.

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The authors wish to acknowledge the assistance of the following individuals and agencies: Captain J. Carroll of Trans-World Airlines; Captain F. J. Quinn of United Airlines; Harry Diamond Laboratory; C. Douglas of National Bureau of Standards; The Boeing Company; Sperry Gyroscope Company; Port of New York Authority; Department of Aviation, City of Chicago; and the Assistant Civil Air Attaché of the British Embassy.

In addition, the assistance and advice of the FAA project manager, Mr. C. Santora, and the deputy project Manager, Major C. Lindell and also Mr. N. Proferes are greatly appreciated.

II. SUMMARY

A. OPERATIONAL CONSIDERATIONS

Techniques for airport ground guidance must be judged in relation to the operational environment. Therefore, the requirements for each of the three phases of guidance (takeoff, landing, and taxiing) must be stated.

Throughout the report the terms "navigation" and "guidance" are used either to define the pilot's task or to refer to a specific use of a piece of equipment. These terms are defined in the following paragraphs.

Navigation means the ability to know where the aircraft was, is now, and where it is going considering the airport as a whole.

Guidance means the ability to steer the aircraft so that it remains safely on the taxiway or runway regardless of where the aircraft is on the airport.

For example, it is one thing to provide guidance along each taxiway or runway but it is not much help if the pilot does not know the correct path to take because the navigational information is insufficient.

1. TAKEOFF

During takeoff, the pilot's main task is to maintain a safe track over the runway surface, not necessarily maintaining the centerline. The takeoff must begin from a known starting position and direction. Once rolling from this point, deviations from the runway centerline can be caused by crosswinds, water, slush, or snow on the runway; some small deviations may also be caused by the pilot. An analysis of all these factors indicates that it is often safe to continue parallel to the runway centerline. Under some circumstances, an increasing lateral deviation from centerline may be acceptable provided that the deviation is not large enough to cause the aircraft to run off the runway or to exceed specified limits.

The takeoff should be considered as using the entire runway length because there are occasions when a pilot must abort because of some mechanical failure even though the actual distance to lift-off is much shorter.

In defining the lateral accuracy of a satisfactory ground guidance system, an error no greater than +30 feet from centerline should be permitted as a normal practice. Errors of +50 feet could occur, but this figure should be regarded as the limit.

After considerable study of the pilot's visual cues and taking into account the published matter on runway operations in poor visibility, 600-foot visibility is considered to be the minimum for

visual takeoffs with good runway centerline and edge lighting, assuming no other aids are available.

2. LANDING

Ideally, the same guidance used for runway approach and flareout would be used for the beginning of the landing roll. There are enough aerodynamic problems during flareout and touchdown without switching to another form of guidance at this point. Once the aircraft has touched down on the runway and is stabilized, the landing roll is similar to the aborted takeoff case. Therefore, the same accuracy required of the guidance system for the aborted takeoff is necessary for the landing roll, and good lighting systems will permit visual reference down to visibilities of 600 feet during landing roll.

Runway turnoff will be critical and it is doubtful that high-speed exits will be made at 60 mph even if the design of the turnoffs permitted such practices.

Before summarizing the taxiing requirements, the following runway guidance requirements must be stated:

1. Known starting position (laterally and longitudinally) and direction,
2. Position relative to the runway centerline and/or runway edge,
3. Rate of change of lateral position,
4. Distance to go along the runway,
5. Aircraft speed.

In some respects, there is little economic justification for insisting that runway guidance be provided for zero-zero visibility. However, since 600-foot visibility cannot be guaranteed just because the average runway visibility is reported as 600 feet from several observation points near the runway, safety considerations demand a runway guidance that can operate in zero-zero visibility.

3. TAXIING

Guidance alone cannot meet all of the taxiing requirements. The ability to navigate around the airport is just as important as guidance--that is, the pilot must know which taxiway to use as well as being able to steer the aircraft safely along a taxiway. Therefore, the ideal taxiway-guidance system should combine the navigation function with a pure guidance function.

It is considered that the use of Airport Surface Detection Equipment (ASDE) plus pilot navigation using suitable charts and good signposts will meet most of the navigational requirements; however, these provisions may not be adequate in low visibilities around 300 feet.

Good taxiway centerline lighting is essential, and it has already been established that some modification of taxiway layouts is

necessary to accommodate large aircraft during turns. The main problem is to provide guidance that permits the steerable nosewheel to follow a smooth nonoscillatory path and the main gear to stay on the taxiway.

An analysis of the available literature together with the results of some studies conducted by AIL have led to the conclusion that good taxiway lighting will permit visual taxiing in visibilities as poor as 300 feet at reduced speeds. An economic analysis of the effects of airport closure (below 300-foot visibilities) and slow-speed taxiing in fog seem to indicate that speed in taxiing is important and may be more important than providing a truly blind taxiing capability. The main reason for this is that the incidence of fog, where the visibility is less than 300 feet, is very low in this country and the airlines may consider it impractical to accommodate these rare cases.

However, it must be noted that the runway turnoff is very critical and is of primary importance. It is probable that a truly zero-zero weather capability is needed to at least clear the aircraft off the runway onto the beginning of the taxiway system. This is a very necessary safety requirement rather than an economic justification.

B. ILS LOCALIZER TECHNIQUES

The techniques associated with lateral guidance for instrument landing systems (ILS localizers) are only applicable to those portions of this study dealing with rolling on the runway. Any localizer technique used for rollout and takeoff roll should either be the same technique that is used for landing or one with smaller errors. The latter reason is important because of the limited range of allowable error within the width of runway. This portion of the study depends, to some extent, on decisions and acceptances still to be made in the field of instrument landing, and, therefore, the objective of this discussion is to reach conclusions that will guide future activity, regardless of the status of instrument landing.

The following localizer techniques merit consideration because they are likely to be adopted in the foreseeable future:

1. ICAO standard VHF localizer,
2. K-band scanning-beam type of localizer (currently being developed by the FAA).

Both of these establish a position in terms of an angle whose apex is at a localizer site beyond the stop end of the runway; the runway centerline is one side of the angle. Errors from this system can be analyzed in terms of angular errors. The results can be applied to either type of localizer if the proper angular error is used.

The angular position established by the localizer system has limitations for runway guidance because of the convergence of the lines of position. This convergence, which depends in part on the aperture of the localizer, can be shown to be so predominant in the

region of the runway that angular guidance, of itself, does not appear to be acceptable for rollout or takeoff roll. This situation is true if judged from the viewpoint that it is better to follow a track close to, and parallel to, the centerline than to attempt, in all cases, to bring the aircraft back to the centerline regardless of the magnitude of the error. Therefore, the angular system does not appear to be the best approach. In order to provide a rectangular-coordinate guidance system, it is necessary to include, with the localizer technique, a means of determining the linear distance from the apex of the angular coordinate system. With this distance information, the guidance information can be presented as a linear measurement from the centerline, which is consistent considering the rectangular shape of the runway surface.

Runway distance information is another important input to the runway guidance system and is essential if the pilot is to be able to judge deceleration and acceleration. These two parameters must be known to ensure stops before the end of the runway, to anticipate turn-offs, and to monitor takeoff performance.

It has been concluded that the best form of guidance along the runway is controlling the linear displacement from the centerline and its rate of change. The following types of guidance were also considered during this study (Section VI) but were rejected because of various shortcomings:

1. Localizer angular displacement alone,
2. Angular displacement and its rate of change,
3. Angular displacement and heading error,
4. Linear displacement from runway centerline.

The choice of linear displacement and its rate of change as the basis for a guidance system arises from the well-established need to provide an asymptotic return to track and to avoid oscillatory overshoots and undershoots.

Distance information can be obtained by using a Distance-Measuring-Equipment (DME) technique. Such questions as the best location of the DME ground site and the methods of distinguishing between distance-to-go-to-touchdown and distance-to-go-to-stop-end (if the DME is used for landing as well as rollout) must be resolved.

When all-weather operations are achieved, the most critical period of flight will be during the few seconds before and after touchdown. During this period, the guidance signals must be smooth, accurate, and unambiguous. Considering the swiftness of the transition from the landing phase to the rollout phase, it is very desirable to use the same control signals and methods. Providing a different guidance method before the aircraft is brought completely under the control of nosewheel steering and the velocity has been reduced is only practical if that method can provide superior characteristics. Therefore, the overall compatibility of the landing-guidance technique must be con-

sidered. (Any technique that is adequate for rollout will probably also be adaptable to takeoff roll.)

The detailed investigations of the use of an ILS localizer technique for runway rollout and takeoff roll have been based primarily upon the current ICAO-standard VHF localizer-signal characteristics and the accuracy that can be achieved with that system. This system was chosen as the starting point because it is well-defined and performance data is available from various sources. However, because there will probably be a need for a localizer system that will be more accurate, have wider angular coverage with a linear response, and be less subject to reflections and other forms of interference, the FAA is developing an advanced instrument landing system that is a localizer based on scanning-beam techniques and operating in K-band. Because this system is expected to be more accurate and less subject to site reflections, the signals provided to the aircraft will be better for the runway guidance function than those obtained from the most advanced standard VHF localizer. Therefore, this analysis uses the current system only as a reference point. The overall function will be improved if the advanced localizer system is adopted.

The total linear displacement error from centerline is made up of two components--one due to the angle error and the other due to DME error. The error geometry and derivation are contained in Section VI. The application of this analysis to any angle and distance-measuring techniques depends upon the errors assumed for these two variables.

An error analysis of the data available from the various VHF localizers is described in Section VI. The data that pertains only to the region of the runway has been used. It indicates that, with the best currently available localizer practice--that is, with wide-aperture localizer antennas--an angular error of 0.1 degree is reasonable. It must be assumed that, if a rollout guidance system is needed, only the best localizer techniques will have been provided in order to achieve successful landing. Although DME errors are currently specified as about 0.5 nm in the region of interest, there is considerable evidence that a 600-foot error with the current standard DME may be achievable in practice. On this basis, the combined error from the two sources has been plotted in Figure 2-1 to indicate the maximum-error performance that may be achieved using the current standard ILS and DME systems.

Figure 2-1 also includes the error curves that indicate the performance that can be achieved with a K-band scanning-beam localizer and the precision DME that will be included in that system. These curves are based on an angular error of 0.05 degree and a distance error of 100 feet. These values were taken from the FAA specification for the development of the equipment. The dashed line in Figure 2-1 shows the error for a 20-foot displacement with a highly improved localizer/DME and assumes an angular error of 0.075 degree and a DME error of 350 feet.

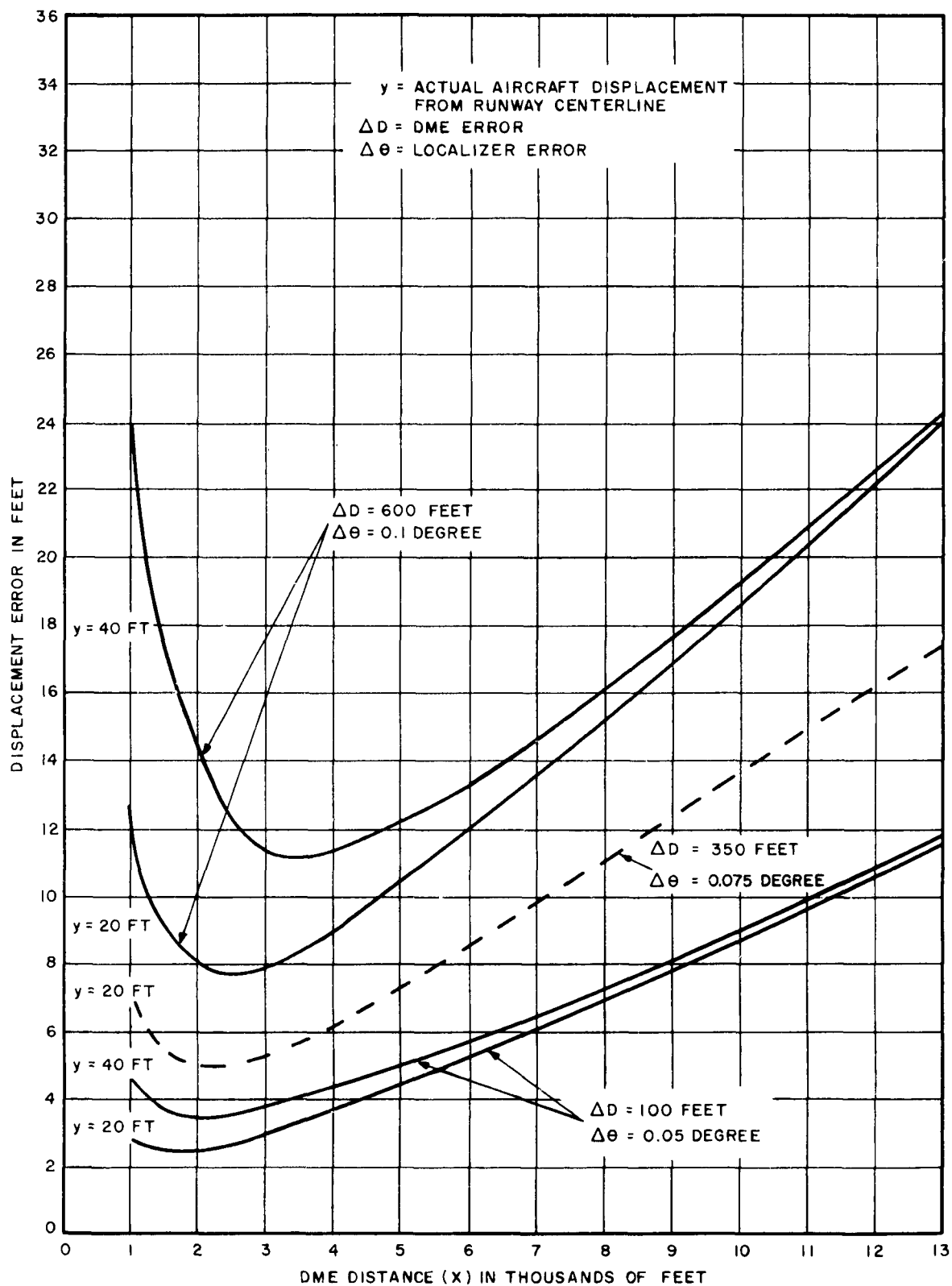


FIGURE 2-1. LATERAL DISPLACEMENT ERRORS FOR VHF AND K-BAND LOCALIZERS

In summarizing these calculations, it must be remembered that actual measurement data of performance on the runway under a wide variety of reflection and interference conditions are not available. Unless both the performance of the current VHF ILS and standard DME is improved, they will be marginal for providing runway guidance. On the other hand, these shortcomings would limit their effectiveness for the all-weather landing that is a prerequisite for runway guidance. Therefore, these systems are undergoing further experimentation to make the VHF localizer better for the Category III landing operation.

The K-band systems, though still under development, appear to be capable of providing the quality of guidance signals required for rollout and takeoff roll.

C. SELF-CONTAINED SYSTEMS (GYRO-COMPASS, INERTIAL)

No gyro-compass can be considered as a primary technique for taxiway guidance because of the complexity of taxiways and the maneuvers required in turns. However, for takeoff and landing, the gyro-compass does offer some desirable features. An analysis of cross-wind effects shows that the track of an aircraft over the runway surface does not necessarily correspond to the aircraft heading. The reasons for this phenomenon are somewhat complex, but they are based on the fact that all aircraft tends to weathercock into the wind and, though the pilot opposes this force, the aircraft tires allow side-slipping to occur. Thus, a yaw angle is introduced and, for a given aircraft type, the magnitude of the yaw depends primarily upon the aircraft's gross weight and the strength of the cross-wind component.

For example, a Boeing 707 with a gross weight of 200,000 pounds can deviate 25 feet from the runway centerline after 4500 feet of takeoff run in a 10-knot cross wind.

Figure 2-2 shows angular error from runway centerline at the threshold as a function of distance along the runway and lateral error from centerline. In the previous example, the 25-foot error at 4500 feet is an angular error of about 0.3 degree--that is, if the pilot maintains an exact runway heading on the gyro-compass without visual reference, the yaw angle (or apparent compass error) can be 0.3 degree.

In addition to cross winds, yaw angles of many degrees can occur because of tire hydroplaning when an aircraft is landing or taking off from wet or slush-covered runways. Therefore, no matter how accurate the compass system is, these unpredictable and excessive yaw angles require that lateral acceleration be measured and added to the system as primary information.

To account for the yaw-angle input to the system, two types of gyro-inertial systems are considered. The first, a "strap-down" system, consists of accelerometers rigidly attached to the airframe. For the small angles of pitch, roll, and yaw typical of normal cross-wind ground-roll conditions, a relatively simple computation would

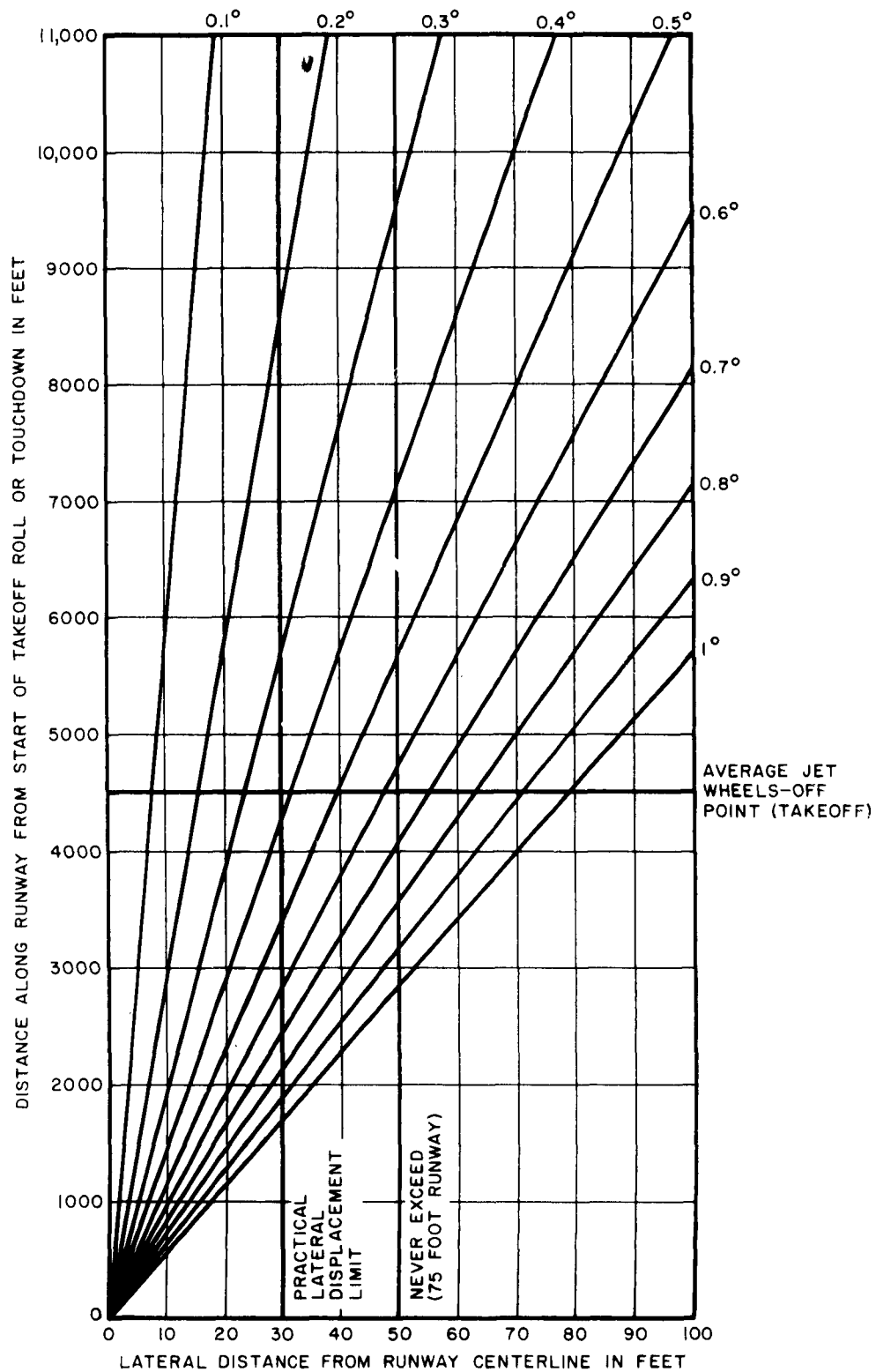


FIGURE 2-2. RUNWAY ANGULAR ERRORS

indicate lateral deviations from the runway centerline. However, normal commercial gyros are not accurate enough for this system. The most critical item is the vertical gyro since a small error in vertical sensing imparts an appreciable error to the lateral and longitudinal acceleration measurements.

The strap-down system appears to be worthy of consideration only as an inexpensive secondary system unless the small angle restrictions are removed by using the full and complex equations of coordinate transformation. The complicated circuitry to compute these transforms and the lack of experience throughout the industry with such systems have led to the investigation of stable-platform inertial systems.

Advertised accuracies of stable-platform inertial systems are high, and the angular errors relative to runway centerline should be as low as 0.1 degree. Referring to Figure 2-2, this is obviously acceptable. In addition, future aircraft such as the supersonic transport (SST) will probably use stable platforms as part of their basic instrumentation package, and, therefore, in these aircraft, little extra equipment will be needed to implement the guidance function.

Operationally, gyro-inertial systems suffer from certain disadvantages. Future runway approach aids will probably be ground-based and some form of localizer in VHF or K-band will form the basis of the system. Using inertial systems for the landing roll will require switching during the landing maneuver and probably updating the inertial system during the approach before touchdown. For take-off, the inertial system will require a good runway centerline check before the roll.

Since the SST will probably carry some form of inertial system, inertial systems for runway guidance may be useful if the updating technique can be resolved. However, it must not be forgotten that all-weather operations of present jet aircraft and the DC-9 and BAC III are just as important, and it is doubtful that all these aircraft will carry inertial systems.

D. INFRARED DETECTION

The infrared range extends from the longest visible-light wavelength (0.7 micron) to the beginning of the millimeter radio band (1000 microns). If this energy band is to provide worthwhile guidance during periods of extremely bad visibility, it must be shown that either:

1. Greater amounts of energy can penetrate fog at infrared wavelengths than at visible-light wavelengths for equal ranges, or
2. Detectors of greater sensitivity than the human eye can be used in a practical way.

A study of theoretical systems using infrared energy would be worthwhile only if these preconditions could be satisfied.

The ability of high-frequency energy such as visible or infrared light to penetrate the atmosphere during low-visibility conditions depends on the nature of the particles in the atmosphere. Since fog is considered to be the most important cause of poor visibility, this study was confined to considering fog, which generally is highly unstable and nonhomogeneous.

Three types of attenuation of electromagnetic energy can occur in the atmosphere: Rayleigh scattering, absorption, and Mie scattering. It can be shown that Rayleigh scattering is not important at infrared wavelengths and that absorption is subject to "windows" in the atmosphere in certain regions of the infrared spectrum. For this study, it was assumed that any system could be made to operate in a window and that, therefore, the most important consideration would be Mie scattering caused by aerosol particles such as fog droplets, smog, dust, and condensation products.

The discussion and mathematical presentation of the laws governing Mie scattering are described in Section VIII. In general, however, the energy (E) detectable at a receiving source is a function of Allard's law--that is,

$$E = \frac{IT^R}{R^2}$$

where

I = energy of source,

T = transmissivity of atmosphere,

R = range.

The transmissivity of the atmosphere can also be expressed as an optical density per unit distance (d) as $T = 10^{-d}$. With this transformation, curves such as those shown in Section VIII can be drawn. These curves show that the received energy, relative to a reference (E_0) at 1 meter, falls off with range from the source for atmosphere with different optical densities. Using these curves, it is possible to compare the ranges at which equal energy is received if the optical densities at two frequencies are known.

Experimental and theoretical evidence is presented in Section VIII to demonstrate that, in general, the lower optical densities in fog occur in the region of 10 microns as compared with visible and near-infrared wavelengths and that the best improvement that can be expected is about 2 to 1 in optical density at visibilities of less than 1/8 mile. Using the previously mentioned curves, it can be seen that a reduction of 2 to 1 in optical density results in a less than 1 to 2 increase in range.

To take advantage of this apparent increase in atmospheric transmissivity during fog, it must be possible to use a source of energy at 10 microns that is almost as good or better than one in the visible-light spectrum. Section VIII shows that this is not possible; all simple sources of radiant energy are not monochromatic, but release a spectrum of energy. The nature of the spectrum depends on the temperature of the radiating element.

The interesting feature of these curves is that a source at 3000°K, which peaks at about 1 micron, emits more energy at all wavelengths than any cooler source, no matter where the cooler source peaks. Thus, a 3000°K source has about 100 times as much energy at 10 microns as a 300°K source that peaks in the region of 10 microns, but it has over 1000 times more energy at 1 micron than it does at 10 microns.

It has been concluded that the advantages gained by the possible improvement in transmissivity at 10 microns is more than lost by the greater amount of energy that can be emitted in the visible-light range. Therefore, greater amounts of energy can be made to penetrate fog at the visible-light range than in the infrared spectrum. The remaining question is whether detectors operating at any wavelength can be found that are superior to the human eye.

It is difficult to compare artificial detectors with the human eye. All the available evidence seems to indicate that the eye is a better detector than any reasonably practical artificial device, and is at least as sensitive to visible light as are known artificial devices in either the visible or infrared range, though this does not completely rule out the possibilities of artificially enhancing human capabilities.

When coupled with the interpretive ability of the pilot it appears that visible-light systems are better than artificial systems at either visible or infrared wavelengths, even under severe fog conditions.

E. GUIDANCE USING MAGNETIC FIELDS

A considerable amount of research has been expended on applying the magnetic field generated around an electric wire to aircraft, automotive vehicles, ship guidance, and many variations of wire installations and detector systems have been tried.

Several items were considered important as a result of our analysis:

1. The leader-cable technique is a system that could provide both runway and taxiway guidance consistent with the operational requirements.
2. Many experimental systems have been installed in sterile environments--that is, free from the interference caused by adjacent power cables, telephone lines, etc. It was noted that, when such cables and lines were present, the interference caused dis-

tortion in the magnetic field around the leader cable, which, in turn, gave erroneous displacement indications. Furthermore, the signals in the leader cable can be coupled into communications circuits causing interference. The actual magnitude of such problems can only be determined by actual field tests.

3. All of the experimental installations have had fairly simple layouts. However, runway and taxiway layouts are very complex. Even if only the minimum number of routes are considered, a considerable number of intersections and junctions result. These factors will necessitate the use of frequency-selected leader cables along specified routes. Furthermore, because interference problems would probably be severe at the junctions of twin cables, we believe that the single-wire system is best.
4. It is believed that single-wire systems will be cheaper and easier to install than the two-wire type, especially where turns are involved, since the dimensions are critical and the wiring must be kept on the runway or taxiway surface.
5. The navigation requirement must be met so that in addition to the frequency-selected guidance system, it is possible that voice loops can be used. A selective communications capability, dependent upon aircraft position, would then be possible. Thus, the pilot of an aircraft approaching an intersection would receive a message instructing him to change cable frequency as required. Such messages could be taped in advance and could contain other useful route or positional information. These voice loops have not been tested in an operational airport environment, but it is known that their signals can be induced into nearby conductors (for example, power cables) and reradiated elsewhere. However, the principle is attractive for airport use even if leader cables are not installed for guidance, and the technique seems to be worthy of investigation.

F. AIRCRAFT RADAR

Of all the techniques examined for taxiway ground guidance (and airport navigation), aircraft radar is theoretically the most ideal. It could be used at any airport, would not rely on complex ground installations, and could present to the pilot a visual display of the actual airport or taxiways on a small scale.

Remembering that navigation refers to the location of the aircraft on the airport and guidance refers to the position of the aircraft on a given taxiway, some provisional specifications for an aircraft-mounted radar can be stated:

	<u>Airport Navigation</u>	<u>Guidance</u>
Range	2 to 3 miles	600 to 1000 feet
Pulse width	0.5 μ sec	20 nsec (0.02 μ sec)
Beamwidth	0.9 degree	4 degrees
Minimum range	200 feet	20 feet
Bearing accuracy	5 degrees	1 degree
Minimum display size	5 inches	8 inches
Antenna height	Unknown (probably at least 20 feet)	At least 5 feet
Field of view	<u>+125</u> degrees	<u>+125</u> degrees

Whichever system is considered, the location of the antenna on the aircraft is a problem because the dish required would be larger than 20 inches in diameter.

For the guidance radar, the nose of the aircraft may be feasible, but this position is now occupied by the weather radar. Present weather radars are not suitable for the guidance function because of certain requirements, especially pulse length and minimum range. K_u -band is considered to be the minimum frequency for the guidance system and present weather radars operate in X- or C-band.

The only possibility, therefore, is to consider either a dual-function K_u -band weather/ground-guidance radar or a hybrid system of X- or C-band radar for weather and a separate K_u -band radar using the same antenna with a special feed for ground guidance.

Even after accepting either of these solutions, it is doubtful that an antenna in the nose would be high enough to ensure adequate returns from a 2 or 3 mile range (for the navigational requirement) over possible undulations of the airport surface. It might also be desirable for the antenna to "see" over small buildings. The vertical tail surface is the only location that is high enough for this requirement, but the scanner radome would induce severe aerodynamic drag. To reduce the antenna size necessitates an increase in frequency and a consequent increase in cost.

For guidance, the scanner location in the nose may be feasible but, as yet, the extremely short pulse widths cannot be produced economically at the present time.

Any program to develop this technique will be long and costly, and there is no certainty that the final display would be adequate for the guidance function because the "looking" angles of the radar would be low, undoubtedly resulting in a "dirty" scope picture.

G. MISCELLANEOUS TECHNIQUES

1. LINES AND PATTERNS

a. PAINTED MARKINGS

Operationally, painted markings are required on runways and taxiways for pilot visual reference regardless of the eventual techniques used for ground guidance. However, they cannot be considered as a primary aid because:

1. They are obscured in snow and are difficult to detect through water, ice, or slush,
2. Precise and adequate coverage of runways and taxiways would involve large-scale painting, which would be expensive and cause excessive down-time,
3. Maintenance would be severe because areas that are used heavily become coated with rubber in a few days.

b. RADIOACTIVE GUIDE LINES

Gamma-ray emitters, particularly Cobalt 60, are operationally feasible. Runway or taxiway installations would consist of a centerline strip of Cobalt 60 paint. Two sensors would be located in the aircraft. The accuracy of the system would depend on integration time in the detectors, which, in turn, depends on the radioactive source strength.

The source strength required would probably be moderate, but health precautions would be necessary, especially around the terminal area.

c. LIGHT PATTERNS

As in the case of painted markings, light patterns also will be required for pilot visual reference regardless of future guidance techniques.

As a primary technique, line sources are considered more desirable than point sources because point sources require complex detection schemes and computations to provide suitable guidance.

Line sources, such as electroluminescent panels, have low brightness levels, which degrade rapidly as viewing range is increased. They are not visible in daylight. In addition, a considerable number of coded or modulated line patterns would be required. Installation and maintenance would be expensive. Water, slush, snow,

or ice would further reduce the brightness and cause backscattering of light, which would complicate the detection and resolution of the pattern.

d. LASERS

Lasers are point sources of light that offer certain advantages over normal light sources. The light emitted by a laser is:

1. Monochromatic (known and stable frequency),
2. Collimated (narrow beamwidth),
3. Coherent (stable phase).

Laser light is attenuated through the atmosphere at the same fractional rate as conventional coherent light. Thus, watt for watt in a given beamwidth, there is no advantage in the use of a laser for fog penetration. However, the property of collimation results in higher intensity within a narrow beam, but this could be an operational disadvantage for airport guidance if the laser is thought of as replacing ordinary light sources. It is not sufficient to produce a narrow beam of light down a runway centerline if the aircraft cannot be controlled within the width of the beam.

However, if ground speed and aircraft yaw angle are considered to be useful inputs to a runway guidance computer and that such inputs could be derived from a laser-doppler system carried on the aircraft, the laser principle can be used to its best advantage.

Two lasers could provide ground speed and aircraft yaw angle data accurately over aircraft speeds ranging from 0 to 150 knots. However, to use them for actual runway ground guidance requires that distance-to-go and lateral-error-from-runway-centerline information be computed from a known starting position and direction. This referencing requires accurate position and direction information from K-band ILS plus DME and an accurate gyro-compass in the aircraft.

2. MECHANICAL TRACKS

Single, centerline, flush-mounted steel tracks have been suggested for runway and taxiway guidance. To guide the aircraft along the track, a rigid boom is mounted on the aircraft's nosewheel, at the other end is mounted a spring-loaded blade that slips into the track.

After some study of this proposal, it has been concluded that this particular technique is not suitable for runway guidance since an excessive boom length (16 feet) is required in addition to an excessively large runway track installation.

There may be some advantages in using a flexible rather than a rigid boom. If the boom were telescopic, the length of the boom at any given moment would be a measure of the distance from the centerline track if an angular pickoff were mounted at the aircraft attachment point. This would still require a long boom but it may be easier to install on an aircraft since it would not be subject to the stresses of a rigid boom, and it would also be retractable.

For taxiways, either technique could only be accepted if some suitable way for switching tracks at taxiway junctions could be developed. In addition, the tracks at taxiway curves could cause problems because of expansion and contraction of the track when the temperature changes.

Without further field tests, the only foreseeable application for this technique is in guiding aircraft near the loading gates at the airport terminal.

3. TELEVISION TRANSMISSION OF ASDE PICTURE

Although it may be possible to transmit the ASDE radar-scope picture to the aircraft on the airport, there are several problems that make this method impracticable from an operational standpoint.

It is doubtful whether the accuracy or the picture-repetition rate is sufficient for accurate taxiway guidance in turns, even assuming no definition loss in the television transmission.

In considering runway guidance or taxiway navigation (as opposed to taxiway guidance), we believe that unless the cockpit picture can be referenced to the heading of the aircraft and unless the identity of the aircraft can be retained at all times by centering the display at the aircraft's position, the proposed technique would be of doubtful value.

Meeting these requirements would require a very lengthy and costly development program.

III. CONCLUSIONS

1. Runway guidance for the landing and takeoff roll will be required, and must be accurate enough to allow operations down to zero-zero visibility.

2. Runway guidance can best be obtained from the same signal sources that provide approach and landing guidance. To correct for divergence of the lines of position from localizer angular systems, distance information is also required to calculate the linear lateral displacement from the runway centerline.

3. To ensure accurate guidance within a tolerable lateral distance from the runway centerline, angular accuracy must be better than 0.1 degree and distance accuracy better than 600 feet. For pure distance-to-go information for the pilot, the accuracy should be of the order of 300 feet, assuming suitable guidance is provided for runway turnoff.

4. For taxiway guidance under zero-zero visibility conditions, the single-wire magnetic leader cable offers the best solution. However, this technique must be field tested to determine interference from power cables, etc., in an actual airport environment.

5. For safety reasons, it is almost certain that a taxiway guidance capability in zero-zero conditions will be required for runway turnoffs after a landing or an aborted takeoff. For all other taxiing, good centerline taxiway lighting should provide adequate pilot visual guidance down to a minimum of 200 to 300 feet visibility.

6. Economic and operations studies indicate that within the United States the incidence of thick fog (visibility less than 300 feet) is so rare that it may not justify a zero-zero weather taxiing capability other than for runway turnoffs.

7. Airport taxiing operations including vehicular traffic even in visibilities greater than 300 feet will require careful traffic control.

8. Aircraft taxiing speed is very important and all efforts should be made to encourage maximum safe taxiing speeds. It may be necessary to indicate speed within the aircraft as an integral part of the guidance function. Navigational procedures based on ASDE radar will also be needed in poor visibility.

9. In considering future development work on any taxiway guidance system, parallel work must be conducted in such important areas as airport-traffic control and navigation techniques during low-visibility operations.

10. Since interference problems are known to exist with leader cable installations, the radioactive-line marking system offers the best potential as an alternative to the leader-cable technique.

11. None of these runway or taxiway guidance techniques obviate the need for good lighting systems and adequately painted markings. Centerline lights are necessary as a visual reference under all weather conditions.

IV. RECOMMENDATIONS

1. As soon as the improved ICAO-standard wide-aperture ILS localizer and DME have been installed together, a series of tests should be conducted to determine:

- a. Operational accuracy of the system under all landing and takeoff conditions,
- b. Sensitivity requirement and localizer reflection errors and their effects at slow speed,
- c. Pilot display requirements.

2. An experimental installation of a single-wire leader cable system should be made in an airport environment. The environment should include centerline taxiway lighting. In addition, junctions requiring two sets of cables operating at separate frequencies should be installed and tests should be conducted to determine:

- a. Accuracy, particularly in turns and at junctions,
- b. Pilot display requirements, including whether speed indication can be derived from a nose-wheel sensor.

V. OPERATIONAL CONSIDERATIONS

Before describing proposed techniques for airport ground guidance, operating techniques and procedures of the pilot against which the technical characteristics of the guidance systems can be evaluated must be discussed.

Airport ground guidance can be divided into these phases: (1) takeoff, (2) landing, and (3) taxiing.

Throughout the report the terms "navigation" and "guidance" are used either to define the pilot's task or to refer to a specific use of a piece of equipment. These terms are defined in the following paragraphs.

Navigation means the ability to know where the aircraft was, is now, and where it is going considering the airport as a whole.

Guidance means the ability to steer the aircraft so that it remains safely on the taxiway or runway regardless of where the aircraft is on the airport.

For example, it is one thing to provide guidance along each taxiway or runway but it is not much help if the pilot does not know the correct path to take because the navigational information is insufficient.

A. TAKEOFF

This phase begins when the aircraft is positioned on, or very close to, the runway centerline at the threshold before takeoff roll. It is presumed that the aircraft has arrived at this point in such a way that it is pointing down the runway. The takeoff can be considered as completed when the aircraft has left the runway surface and is beginning its initial climb.

Operationally, the pilot has the following tasks to perform during the takeoff:

1. Maintain a track along the runway so that the aircraft will remain on the runway during the entire maneuver at a safe distance from either edge and avoid abrupt changes in tracking.
2. Check aircraft speed and acceleration closely relative to the remaining runway distance to ensure that aircraft performance is satisfactory to complete the takeoff. If speed and acceleration are not satisfactory, the takeoff must be abandoned below a certain specified speed (V_1 , critical engine failure speed).

The basic elements of runway guidance during takeoff are:

1. Known starting position and direction,
2. Position relative to the runway centerline and/or edges,
3. Rate of change of lateral position on the runway,
4. Distance-to-go along the runway,
5. Speed along the runway.

The aircraft is steered with the rudder and nosewheel. The nosewheel is controlled by a wheel in the cockpit and used from the beginning of the takeoff roll up to about 80 knots on present-day jet aircraft. Nosewheel steering is effective and positive. The rudder is used throughout the entire maneuver. At slow speeds up to about 60 knots, it is rather ineffective but, above this speed, it becomes the primary steering control until, at about 80 knots, it is used exclusively.

Cross winds, and water, snow, or slush on the runway affect the pilot's ability to steering accurately. Most modern airliners have a large fin area and, in a cross wind, the aircraft tends to weathercock into the wind. This can be countered by rudder and nosewheel steering but, since the rudder is ineffective at slow speed, it involves a great deal of physical effort by the pilot and the aircraft response is slow. If the nosewheel is used in an attempt to hold the runway centerline under such conditions, "scrubbing" will occur because the aircraft is side slipping. This is neither comfortable nor conducive to long tire life. Cross winds also lift the up-wind wing, which cannot be checked by aileron control since this actuates the spoilers on modern jet aircraft. Again, holding a centerline is complicated by the fact that steering back to the centerline tends to increase the lift affecting the up-wind wing still further.

If the runway surface is slippery, the aircraft will not necessarily track in the direction that it is pointed--that is, the aircraft tends to skid. Under such conditions, abrupt changes in aircraft heading should be avoided.

Further discussion of cross wind effects and runway surface conditions are contained in Section VII of this report.

The pilot's main steering task is to maintain a safe track over the runway surface. However maintaining the centerline of the runway, need not be the safest nor the smoothest way of taking off. A pilot can permit a lateral error from runway centerline, even an increasing lateral error, if he is satisfied that the aircraft will not run off the runway. Obviously, there are limits to both the lateral error and the rate of change of lateral error that can be permitted. Furthermore, there is a relationship between the two in that the larger the lateral error, the less acceptable the rate of change in the same direction.

This task is also affected by the longitudinal position of the aircraft with reference to the point of takeoff or, if the takeoff is aborted, the end of the runway. If the aircraft is at the beginning of the takeoff

roll but has a large displacement error, little or no increase in lateral error can be permitted. However, the aircraft may have the same lateral error until, for example, 5 seconds before lift-off when a large increase in lateral error may occur. This increase is permissible provided that the aircraft does not come too close to the runway edge.

Most ILS-equipped runways are 150 feet wide (75 feet on either side of the centerline), and this width is expected to remain standard. In defining aircraft lateral position, the centerline of the aircraft is usually considered as the datum point for measurements. This tends to reduce the usable width of the runway since the track of the main wheels must be considered. Most modern jet aircraft have a track of between 20 and 25 feet. Some larger propeller driven airliners have tracks of 30 to 35 feet. The track is the distance between the main gear; measured from the aircraft centerline they should be divided by two. Therefore, about 25 feet of runway width at either edge must be considered as unusable in order to allow for the main gear and a margin of safety. Thus, the aircraft has +50 feet in which to maneuver on the runway. However, although a displacement limit of +50 feet from centerline is acceptable from a theoretical viewpoint, the pilot confidence in any guidance system must be high for any system to gain acceptance. On a practical operational basis, 50 feet from runway centerline is a large error. At this distance, the outboard engine pods on most jets would be over the edge of the runway. Psychologically, it is doubtful that pilots would accept such errors except as a rare occurrence.

Therefore, any guidance system having a normal distribution of errors should be planned on the basis of a three- or four-sigma error of +30 feet from runway centerline, and this should be the basis for any final evaluation.

The length of runway required is a function of the following variables:

1. Aircraft type,
2. Aircraft weight,
3. Air temperature,
4. Airport elevation,
5. Runway gradient,
6. Runway surface conditions,
7. Wind speed and direction.

In flight planning, a pilot accounts for most of these factors to decide whether he can use the available runways at any particular airport. If the runway length required exceeds what is available, the aircraft weight must be reduced. The runway lengths computed in this discussion are for total length to allow for adequate braking in the event of engine failure on the runway and for obstacle clearance once airborne. The pilot is not directly concerned with the runway distance at which the aircraft lifts off. However, during the takeoff roll, the acceleration

time to speed V_1 can give the pilot an indication of aircraft performance-- V_1 being the speed above which the aircraft is committed to takeoff in the event of engine failure. After this point, the next significant event is rotation speed (V_R). At this point, the pilot moves the elevators so that the aircraft pitches upward, rotating about the main gear. The aircraft usually lifts off about 3 to 8 seconds after rotation.

No actual distance measurement is required by the procedures established by the airlines, but obviously, in good weather conditions, the pilot monitors his performance visually relative to the end of the runway. If a takeoff is aborted, he is vitally concerned about the distance to go even though he is braking as hard as possible. The present lack of distance measurement should not be taken as meaning that this information is not desirable.

For scheduled aircraft operations, the lowest-visibility run currently allowed for takeoff is 1/4 mile (1320 feet). Once the runway visibility drops below this value, takeoffs are not legally permitted. With runway edge lights spaced every 200 feet, six lights are visible on either side of the runway ahead of the pilot and these, together with the concrete expansion joints and painted markings on the runway surface, provide sufficient guidance for the pilot.

Future lowering of visual minimums for both landing and takeoff will require flush lights in the runway surface as well as runway centerline lights. From reference 1 and general analyses of our own, it appears that, with good centerline and edge lights and well-maintained line patterns, the pilot will be able to safely take off in visibilities greater than 1/8 mile (660 feet). However, it is most probable that, at such visibilities, the pilot's need for distance information will become acute. There seems little doubt that, at visibilities less than 1/8 mile, some form of guidance will be required in addition to lights and markings.

Many forms of takeoff performance monitors have been proposed that measure actual aircraft performance and automatically check against certain parameters so that the pilot always has a current indication of performance. These monitors are not installed in civil jet aircraft at the present time, and there are no plans as yet for their installation in the future. However, they may be absolutely necessary when instrument takeoffs become a reality--that is, when visibility is less than 1/8 mile.

In addition, there is much to be said for the pilot's ability to use all the visual aids available to him even when the visibility is very low. This is a valid argument in favor of a "heads-up" display in which the required guidance instrumentation is arranged in the area of the pilot's windshield so that the transition from contact to instrument flying is achieved with a minimum of effort. In addition to the steering and distance-to-go/speed requirements, there is a need for aircraft pitch information at the rotation point (V_R), which occurs while the aircraft is still on the runway. These factors are not of direct concern in this study but indicate that, in any future flight testing or simulated runway guidance systems, the final result of any proposed system will then

depend largely on the success or failure in achieving a good display for the pilot. Monitoring aircraft performance is vital in the takeoff phase and an excellent guidance system is not the only requirement that must be met for all-weather takeoffs. Thus, all required information must be carefully displayed for the pilot.

B. LANDING

The start of landing roll is somewhat more difficult to define than the start of the takeoff roll. For this study, we have assumed that the aircraft has arrived at the runway threshold by means of the instrument approach or landing system. This means that the aircraft is close to (or on) the runway centerline, is tracking in approximately the right direction, is within 50 feet or less of the runway surface, and is descending. Whether the aircraft is being landed manually or automatically (by autopilot), the sequence of events is essentially the same from this point on.

The rate of descent is reduced through the flare until the aircraft contacts the runway at about 2 feet per second. The lateral position of the aircraft will remain close to (or on) the runway centerline. However, due to wind and slight heading changes to counter lateral errors, the aircraft heading may be different from the runway heading. Landing at a speed of 130 knots with a cross-wind component of 10 knots gives a drift angle (angular difference between ground track and aircraft heading) of 4 to 5 degrees. If the aircraft were permitted to land with this angle, the stresses on the landing gear would be severe and the aircraft would deviate rapidly from the runway centerline.

Therefore, this angle must be predictable so that, just before touchdown, the aircraft heading can be changed to coincide with the runway heading. If this "decrab" maneuver is done at too great an altitude, the aircraft will be blown downwind or laterally across the runway. If it is initiated too late, the drift angle may not be eliminated at touchdown. Furthermore, it should be noted that if the drift angle is incorrectly sensed, the consequences will be similar to those where the aircraft touches down with the drift angle present.

These circumstances suggest either of the following solutions:

1. The same guidance should be used at the beginning of landing roll (after touchdown) as is used during the approach phase. In other words, there are enough aerodynamic problems during flareout without changing to another form of guidance at this point.
2. If some form of guidance is to be provided for takeoffs on similar runways and if this guidance is to start at the runway threshold, there is some substance to the argument that, if the guidance for landing roll is to be different from that used during the approach, the switch to rollout guidance should be made at, or near, the runway threshold before the final stages of the flareout.

Using the same guidance is the most attractive because traditionally (and for the most obvious reasons) airline companies hesitate to install new equipment when existing equipment does as good a job. There is also a built-in safety factor in that to approach the runway in bad weather, some guidance equipment must be provided and, if this equipment has proved satisfactory before the runway, there is good reason for the pilot to have confidence in its use after touchdown. In addition, changing the basic nature of the guidance is complicated by the fact that sensitivities may be different among different equipment.

The most obvious solution is that, since the landing roll is similar to the aborted takeoff once touchdown is made and the aircraft is stabilized, the same guidance can be used for approach, landing, and takeoff.

Once the main wheels of the aircraft are on the runway surface, the guidance requirements are identical to those listed for takeoff:

1. Known starting position and direction,
2. Position relative to the runway centerline and/or edges,
3. Rate of change of runway lateral position,
4. Distance-to-go along the runway,
5. Speed along the runway.

Pilot technique will differ from takeoff but only in the sense that the aircraft is decelerating and not accelerating. Steering is performed mainly with the rudder down to about 60 knots, below which the nosewheel becomes the primary steering control.

Cross winds and runway surface affect the accuracy of steering and, though cross-wind effects may be slightly less of a problem once the wheels are on the runway, the fact that the wheels are being braked at a high-speed complicates the skidding problem. Thus, it is not always desirable to maintain or strive to regain the runway centerline. Therefore, a stabilized safe track within ± 30 feet of the centerline is the most desirable condition.

The runway length required to stop the aircraft is known in advance and is a function of:

1. Aircraft type,
2. Aircraft weight,
3. Airport elevation,
4. Runway gradient,
5. Runway surface conditions,
6. Wing speed and direction.

Distance information is much more critical because the touchdown position is far less precise than for the start of takeoff. Also

the application of brakes and reverse thrust or pitch is much less measurable than the application of a known takeoff power.

It is true that once the aircraft nosewheel is on the ground, the pilot will endeavor to apply maximum safe braking regardless of the distance to go, but, for safety and to reduce tire and brake wear, he will reduce braking if he knows that there is ample runway length ahead.

Another consideration of braking and distance-to-go is the selection of the runway exit to be used. In this case, there is a double requirement since the pilot must exit from the runway as quickly as possible to allow it to be used by following landings or takeoffs. At the same time, he must plan his deceleration to avoid harsh braking; thus, distance-to-go to the runway exit is important.

For scheduled aircraft operations, the lowest visibility minima presently allowed for approach are between $1/2$ and 1 mile (2640 and 5280 feet), the $1/2$ -mile minimum being the ICAO Category 1 definition for approach/landing (reference 2). With improved localizer and glide-slope facilities plus runway centerline lights, Category 2 will be reached; this will permit approaches $1/2$ to $1/4$ mile (1320 feet) visibility. From all indications, there is no doubt that visual references will be adequate for steering during the rollout once the aircraft is on the runway (references 1, 3, and 4). It also seems probable that distance information will be desirable, but not absolutely essential, in such visibilities. The final step beyond Category 2 is operation in the $1/4$ mile to "zero-zero," this range being Category 3.

It should be realized that the categories are based on the assumption that certain aids will be necessary for approach and flareout in the visibility conditions stated and that these aids will permit "operation down to and along the surface of the runway unrestricted by cloud base and visibility conditions with a high probability of landing success" (reference 2). From an examination of references 1, 3, and 4, it appears that the runway lights required for Category 2 operation will provide adequate steering guidance for visibilities down to $1/8$ mile (660 feet). Below this limit, there is no doubt that visual aids must be supplemented by additional forms of steering and distance guidance.

The landing roll can be considered as over when the aircraft has decelerated to a speed that permits the pilot to turn the aircraft off the runway at a suitable exit. For runways having normal right-angle exits, this speed is about 10 to 15 mph. High-speed turnoffs, however, are designed to permit the turn off the runway to be made at speeds up to 60 mph.

There should be no serious problems in taxiing during visibilities as low as $1/16$ mile (330 feet) with centerline lighting, provided that aircraft speeds do not exceed about 30 mph. Therefore, landing with a Category 3 instrument system in visibilities of $1/8$ mile or greater, the pilot should be able to visually complete his landing roll and turn off the runway. However, even if it were desired to use the high-speed turnoffs, it is doubtful that such turns would be made at 60 miles per hour in $1/8$ -mile visibility. In fact, it is questionable as to whether pilots would

accept high-speed turnoffs in poor visibility even if the most perfect guidance system were available. With no data on this subject, therefore, it has been assumed that 30 mph represents the highest speed that can be accepted in turning off a runway in visibilities less than 1/8 mile.

Therefore, the landing phase ends when the aircraft is on (or close to) the runway centerline at a speed that permits the runway turnoff to begin.

Pilot display considerations are as important to the landing roll as they are to the takeoff roll. In addition, aircraft pitch angle must be considered because the nosewheel of the aircraft does not contact the runway until about 10 to 20 knots below the speed at which the main gear touches down. This pitch-down angle can be as high as 10 degrees and is difficult to judge. The display of runway landing guidance will probably combine these additional items, thereby contributing to greater safety and greater accuracy in rolling out correctly.

C. TAXIING

In some respects, taxiing is a more complex operation than landing and takeoff. In landing or taking off, the main problems are keeping the aircraft within a safe lateral distance based on a straight-line track (the runway centerline) and ensuring that the aircraft does not run off the end of the runway. Within this context, all runways look alike. This is obviously not so with taxiways. Figure 5-1 shows a typical layout for John F. Kennedy International Airport.

Pilots get lost at airports on many occasions even in good weather. This is no reflection on pilot's skill and the fact that it happens is not always dangerous; however, it does complicate the guidance problem in low visibility because guidance alone does not ensure that the correct path is being used. In addition, there is the ever-present possibility during bad visibility of a collision with another aircraft or ground vehicles.

In good weather, airport navigation (as opposed to guidance) and collision avoidance is achieved visually by the pilot and tower ground controllers. If the visibility drops, the controllers must either rely on pilot position reports, or, if Airport Surface Detection Equipment (ASDE) radar is available, they can monitor aircraft movements provided that they have some knowledge of aircraft identity.

Therefore, it is obvious that as aircraft begin to operate in lower weather minima than at present, the use of ASDE will become mandatory for the control of taxiing aircraft. However, the use of ASDE will require careful surveillance by the ground controllers because of the number of aircraft involved and the fact that the aircraft identity must be maintained constantly. Because of the nature of the scope picture on the ASDE radar, it is not always easy to identify quickly a stopped aircraft unless its position is accurately known or it is being continually monitored. Some successful tests have been performed (reference 5) in the past in which aircraft have been continuously followed around taxiways and, in some cases, given actual guidance directions.

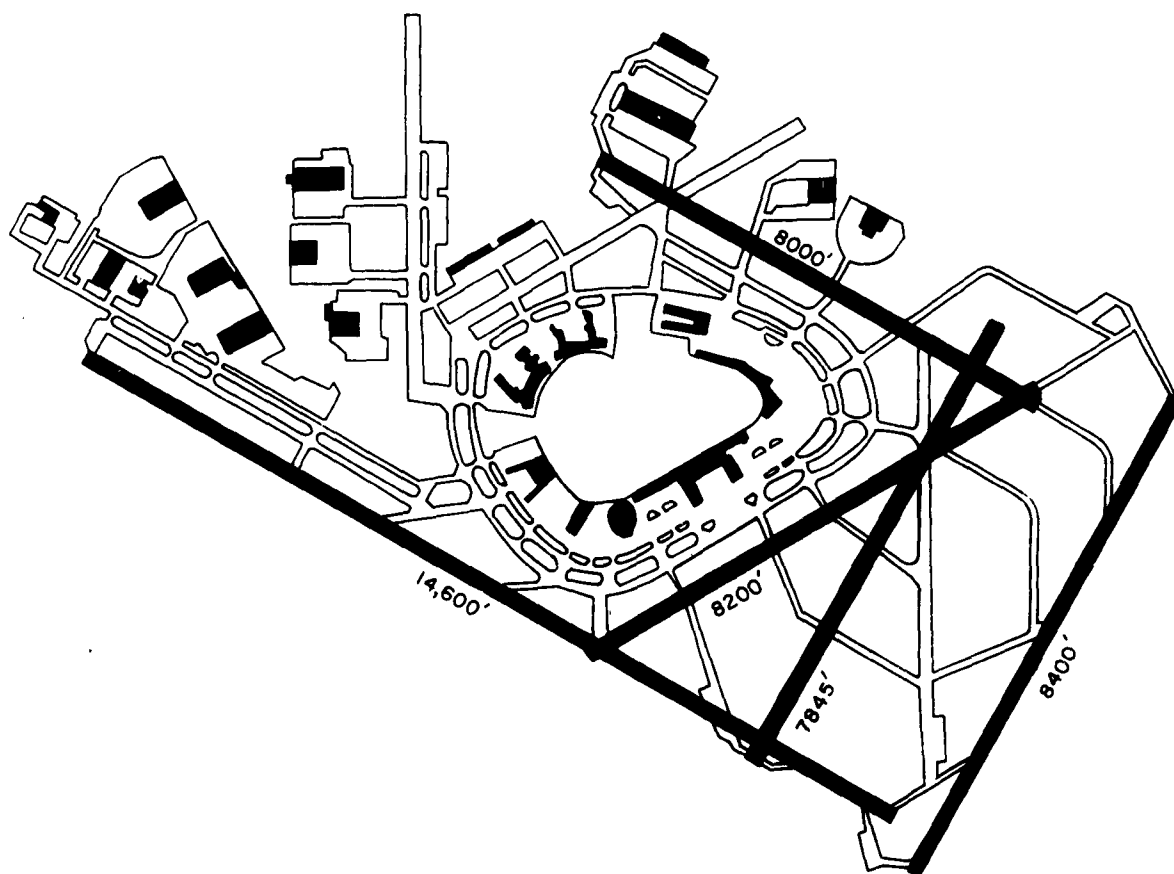


FIGURE 5-1. TAXIWAYS AND RUNWAYS AT J. F. KENNEDY INTERNATIONAL AIRPORT

These tests, however, were carried out at a small- to medium-size airport with a fairly simple taxiway layout and only one or two small aircraft were involved. It is expected that operations on a larger more complex airport, where as many as 10 to 20 large jet aircraft may be taxiing at any given moment, will introduce the problem of giving enough navigational and collision-avoidance information at the right moment.

To offset these problems in poor visibility, the pilots themselves will undoubtedly go through a self-education process in navigating themselves around airports using existing signboards and airport maps. It should be mentioned that, in some cases, airport signboards (indicating directions to ramps and runways) are somewhat inadequate in size and visibility, and present airport maps are not always suitable for navigation.

As a result of these findings, the desirable features of any taxiway guidance system is that it should also function as a navigational aid and, if possible, provide for collision avoidance or warning. If we cannot provide these features within the guidance system, we must rely on a separate system. If the separate system consists of ASDE and the pilot's eyes, we must expect some difficulties in the lower visibilities. In fact, if the visibility is less than the distance from the pilot to the taxiway edge (normally 37 1/2 feet with the aircraft on the taxiway centerline), the pilot is not going to see signboards, and controller instructions derived from ASDE position will not be of any value. Therefore, operations during true zero-zero conditions will demand a navigation capability within any proposed guidance system.

In good visibility, pilots should be able to taxi at speeds up to 42 mph on straight runways, the average speed being 25 to 30 mph (reference 6). As the visibility drops, the aircraft taxi speeds will decrease as pilots become cautious. They become cautious because taxiing is a maneuver that requires forewarning of future events. To avoid collisions (with other aircraft and service vehicles), the pilot must have adequate warning time (depending on his speed) to stop. As he approaches an intersection, he must know if there is a runway ahead at which he may be required to stop. If the intersection is another taxiway, he must have some idea of whether he will have to turn and, if so, through what angle he must turn (a tight turn requires a slower speed than a shallow one).

Speed is an important factor. At some of the larger airports, it can take as long as 20 minutes to taxi from the runway exit to the terminal gate. If fog reduces the average taxi speed by one-half, then the taxi time will increase to 40 minutes. One foreign carrier stated that on one occasion in thick fog, it took one aircraft an hour to taxi from the runway to the terminal (reference 4). With the operating costs of present-day jet aircraft up to \$1000 per hour, such long taxiway times can cause severe economic penalties.

Another interesting aspect of taxiing speed arose out of the tests carried out by the British using the BLEU leader-cable system

(reference 7). The pilot taxied "blind" using only the left-right indications received from a single cable along the taxiway centerline. It was found that, with no speed indication around a taxiway turn, the aircraft could come to a complete stop without the pilot being aware of it. This certainly indicates the need for speed information not only to ensure that taxiing time is kept to a minimum but also as an integral part of taxiing guidance in zero-zero conditions.

In summary, the preliminary considerations of taxiway guidance are as follows:

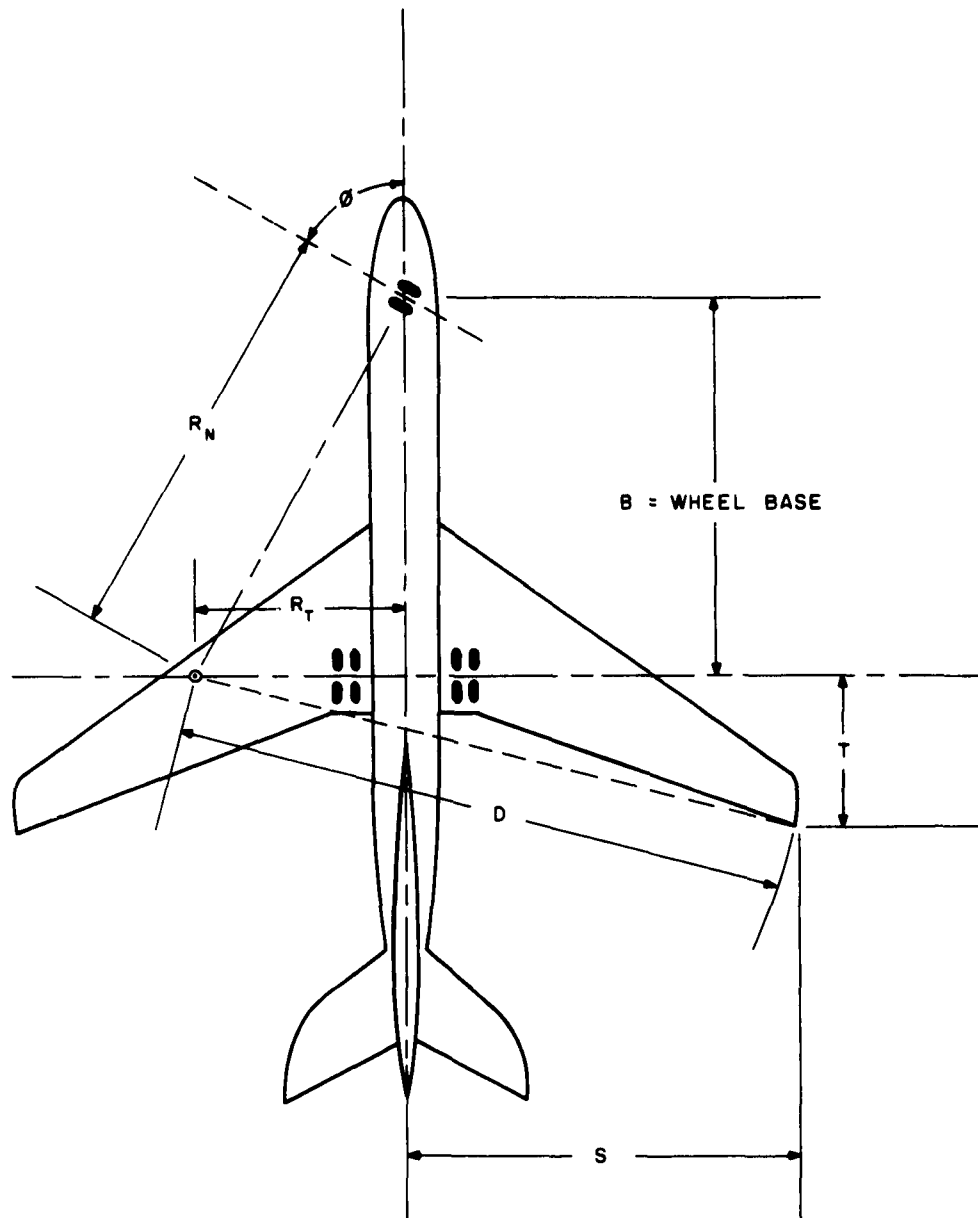
1. With the proper use of ASDE radar and pilot navigation, aircraft can be expected to find their way around airports in low visibility, but the lowest limits are not known.
2. Aircraft speeds must be kept at a reasonable level or economic penalties will result. It is doubtful if ASDE and pilot navigation will permit high taxi speeds.
3. Airport navigation and guidance require knowledge of the speed of the aircraft and the path ahead of the aircraft.

D. GUIDANCE

Assuming that the pilot of an aircraft knows his position and his route across the airport, he must then keep the aircraft on the taxiway while moving forward at a reasonable speed. This is a steering maneuver. The difficulty of this task is usually a function of the size of the aircraft and the design of the taxiway. To be more specific, it depends on:

1. Wheel-base length between the main gear and the nosewheel,
2. Distance between the pilot and the main gear and between the pilot and the nosewheel,
3. Nosewheel steering angles and limitations,
4. Cockpit visibility and height above ground,
5. Taxiway turn radii and size of taxiway fillets,
6. Design of taxiway markings and lighting facilities.

The pilot's task in reasonable visibility will be described first. Figure 5-2, a plan view of an aircraft, shows the nosewheel and main gear. The aircraft is steered by changing the nosewheel angle (θ), by turning a wheel in the cockpit. In a turn, the aircraft pivots about a point (θ). On a taxiway clear of all buildings and vehicles, the pilot must keep the nosewheel and the main gear on the taxiway. If he is turning the aircraft, he must, in the ideal case, steer the nosewheel at such an angle



S = SEMISPAN

Ø = NOSEWHEEL STEERING ANGLE

⊙ = POINT OF PIVOT

$$R_N = \frac{S}{\sin \varnothing}$$

$$R_T = \frac{B}{\tan \varnothing}$$

$$D = \sqrt{[S + (B \cot \varnothing)]^2 + T^2}$$

FIGURE 5-2. AIRCRAFT STEERING PARAMETERS

that the distance R_T (Figure 5-2) is the same as the taxiway radius measured at the taxiway centerline. Since $R_T = \frac{B}{\tan \phi}$ it can be seen that for aircraft having a long wheel base (B), a larger nosewheel angle must be used in a turn than for aircraft with a shorter wheel base. A sharp turn requires skillful judgment by a pilot because, in the larger aircraft, the pilot is ahead of the nosewheel and cannot normally see the main gear. When turning, he must ensure that the distance R_N is not so large that the nosewheel runs off the taxiway, and that aircraft speed is low enough to avoid tire scrubbing and skidding but high enough to overcome turning drag.

Figure 5-3 shows a taxiway intersection that requires aircraft to make a turn through 150 degrees. Both taxiways are 75 feet wide and there is a small fillet at the junction. For example, the aircraft type is a Vickers Super VC-10 with a wheel base of 86 feet.

If the pilot must maneuver his aircraft so that the aircraft's main gear tracks the centerline of the curve, he must take the nosewheel well beyond the desired centerline and then begin the turn when the main gear is on the beginning of the centerline curve. (The centerline is the dashed line in Figure 5-3A.) About halfway through the turn, the nosewheel will run off the edge of the taxiway.

If the aircraft's nosewheel must track the centerline of the curve (dashed line), it can be seen that at a point about 1/3 of the way through the turn, the nosewheel on this aircraft has reached its maximum angle of 63 degrees and, therefore, cannot continue to track the centerline (Figure 5-3B). In addition, the main gear runs off the taxiway close to the junction point.

If the requirements are changed and the pilot is permitted to turn in any way he desires to keep the nosewheel and main gear on the taxiway, the aircraft will follow a complex path (Figure 5-3C).

None of these situations are desirable if instrumentation is to be used for taxiway guidance. The first two result in the aircraft coming off the taxiway, and the third is a complicated maneuvering problem.

As mentioned previously, visual aids in the form of lights and painted markings are very useful to the pilot even in bad fog. Reference 7 states that both taxiway centerline marking and lights "should provide adequate clearance between the main wheels of all aircraft using the taxiway system and the edges of the taxiway pavement when the lights (markings) are followed so that the cockpit remains over the lights (markings)."

To implement this requirement, which is similar to that shown in Figure 5-3B, some large fillets must be added at taxiway junctions. Figure 5-3D shows the filleted junction. The turn must also have a larger radius in order to avoid the maximum nosewheel angle limitation.

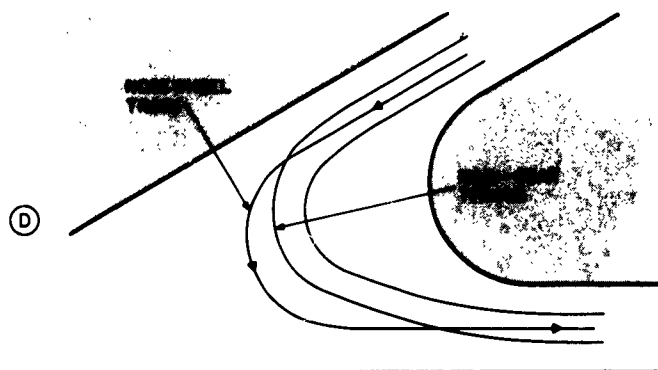
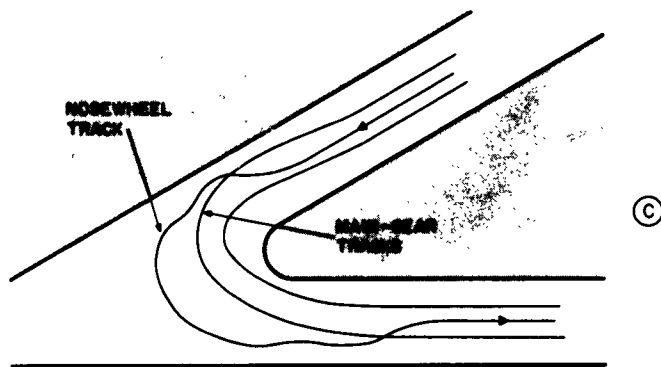
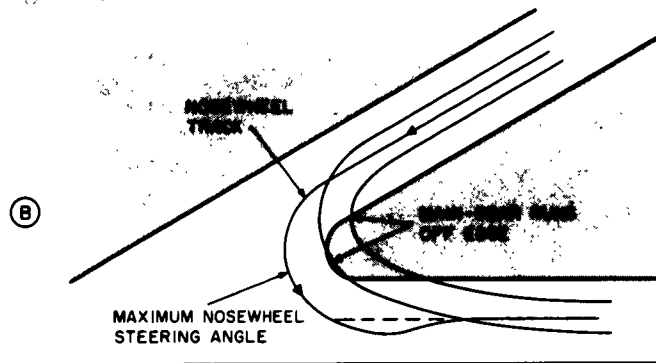
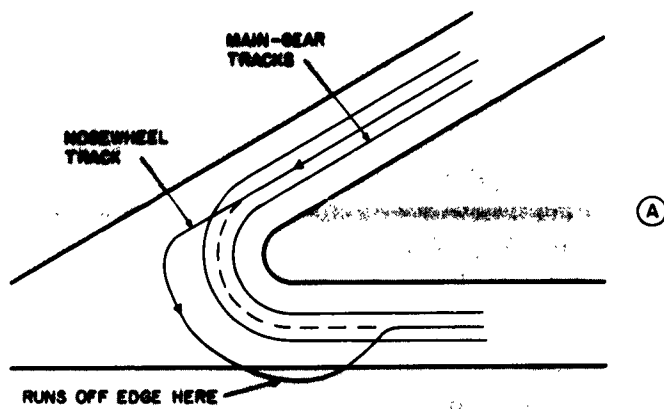


FIGURE 5-3. TAXIWAY TURNS

With the turn modified, as shown in Figure 5-3D, the aircraft can maneuver so that the nosewheel follows a smooth constant-radius turn and the main gear is safely within the taxiway edges at all times.

These examples have been picked to show extreme situations--that is, a large aircraft making a sharp turn--in order to demonstrate the type of problems that exist.

Figure 5-4 shows four airline-type aircraft and their significant dimensions. On the Anglo-French SST, the nosewheel is about 40 feet behind the cockpit, which is 91 feet ahead of the main gear. At this time, the only drawings available for comparison with the American SST showed that the North American design had a wheel base of about 122 feet.

Considering airport operations in fog conditions, it is unlikely that every taxiway on an airport will be used. Figure 5-5 shows Chicago O'Hare Airport; the taxiways most likely to be used in poor visibility are indicated. The most complicated network of taxiways is around the terminal area. Although it is possible to institute one-way traffic on nearly all of the taxiways, it is impossible to avoid 90-degree turns and intermixing of departing and arriving aircraft at some intersections.

During fog, airline gate allocation will probably become a problem as some flights are delayed in leaving and incoming flights are off schedule. These aircraft must be "stored" until gates are vacant; these storage areas are shown in Figure 5-5.

Furthermore, airlines cannot operate without a considerable amount of vehicle traffic (servicing trucks, baggage trailers, etc.) and this type of activity is concentrated around the terminal, particularly near the gates. Some ASDE film has been analyzed and, during one 5-minute period at Kennedy Airport taken in an average peak-hour operation, 137 vehicle movements were counted.

Even though the vehicles do not always use the same taxiways as aircraft, they constitute a problem at the gate areas and when they must cross active aircraft taxiways.

From a study of all available literature, we have concluded that, apart from the navigation problem, pilots of present-day jet transports can taxi in visibilities down to 300 feet (1/16 mile) provided that good centerline lighting and markings are available. The addition of fillets at taxiway junctions will make such operations much easier and may allow the visibility limit to be reduced to 200 feet.

Taxiing during visibilities less than 200 feet will undoubtedly require some instrumentation. The greatest problems will arise in the terminal area because the taxi paths are complicated by the number of gates and the fact that incoming and outgoing aircraft must cross each other's path. In addition, wingtip, nose, and tail clearances become critical near the buildings. Although it is still possible to define a

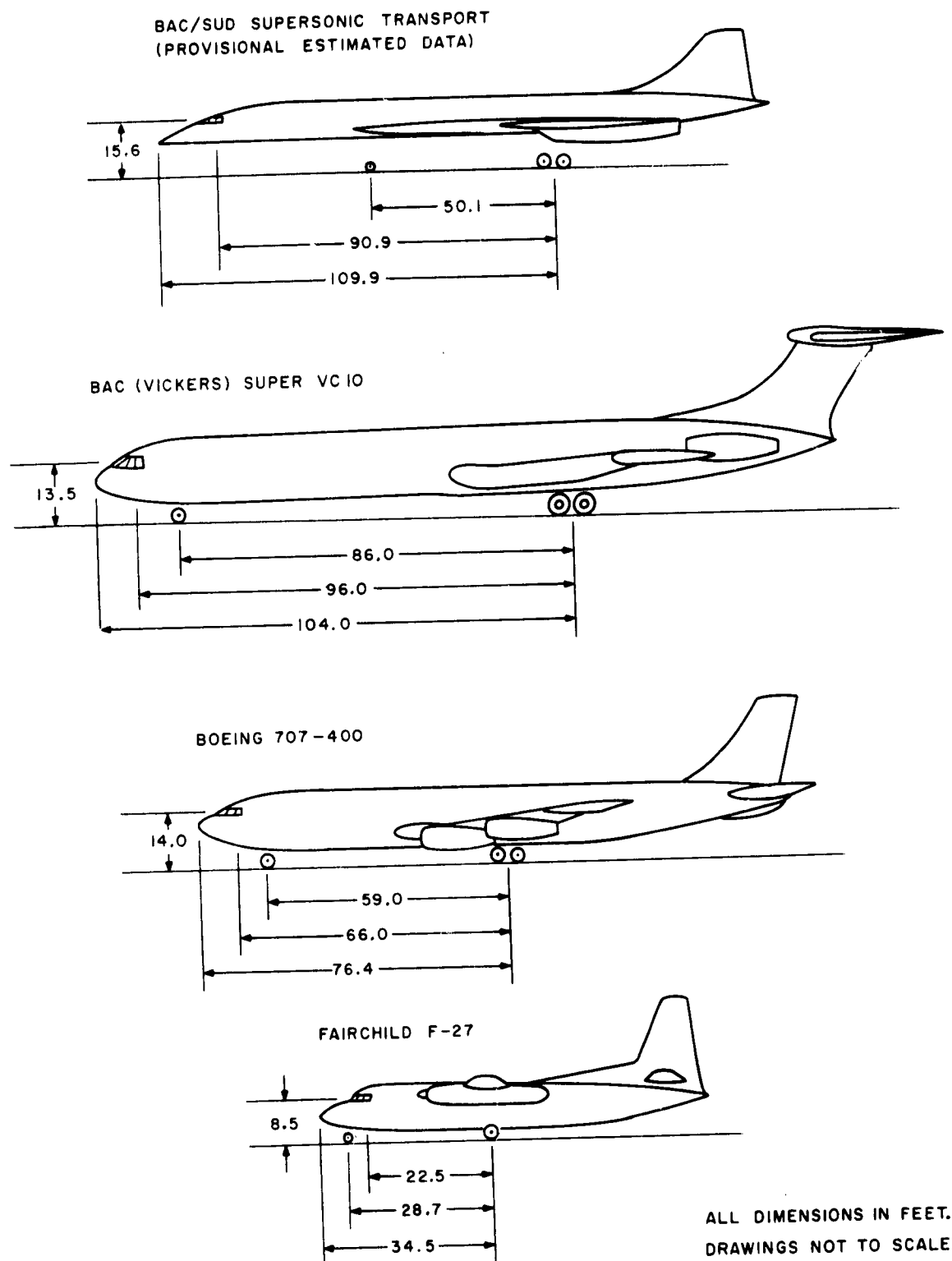


FIGURE 5-4. SIGNIFICANT DIMENSIONS OF FOUR AIRLINE TRANSPORT AIRCRAFT

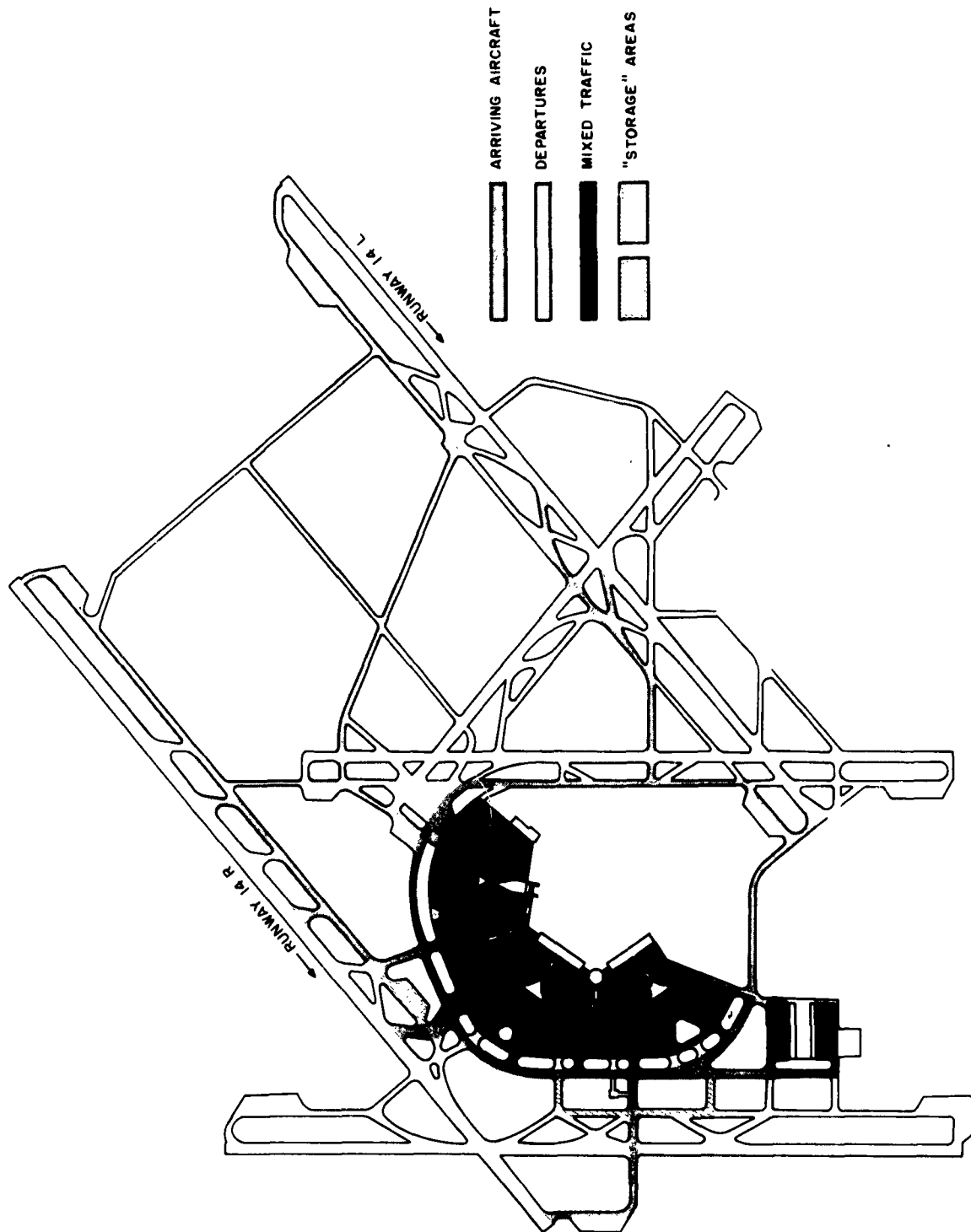


FIGURE 5-5. CHICAGO O'HARE AIRPORT MASTER PLAN BAD-WEATHER TAXI ROUTES

maneuvering path for the nosewheel, the path will not necessarily be simple because buildings cannot be moved in the same way that fillets are added to taxiways. Since airline gates are often used for more than one type of aircraft and the gates are close together, taxiing paths are complex in the terminal area. This fact, combined with the vehicle problem, will undoubtedly cause the greatest difficulties to ground guidance in thick fogs.

E. MEASUREMENT AND INCIDENCE OF FOG

Visibility in fog is difficult to measure. Almost every type of fog encountered is nonhomogeneous and, to a stationary observer, the visibility through a fog can vary with time and direction of observation. Variations can occur at sunset and sunrise. During the day, the position of the sun can cause extreme variations. At night, the visibility of lights is normally much greater than in daylight--assuming a homogeneous fog.

Minimum visibility values under which visual cues are sufficient for landing, takeoff, and taxiing have been used throughout this report. To a certain extent, they are academic because of the tremendous variations in fog. A pilot can be given a visibility of 600 feet and, while taking off, encounter a patch where the visibility is only 200 feet. If the pilot is relying on visual aids, he may become disoriented; in this case, the safety of the aircraft may be jeopardized. Such incidents have occurred when approaching to land visually in bad weather. They rarely happen on the ground because landing and takeoff minimums are currently high enough to permit visual rollout and safe taxiing.

To consider airport ground operations in bad visibilities down to true zero-zero conditions, several problems must be explored:

1. DEFINITION OF VISIBILITY

Visibility along runways can be measured by a transmissometer--a device that measures the amount of light penetration (from a source with a known intensity) through the atmosphere along a known baseline length--usually parallel to the instrument runway. At the present time, most baselines are 700 feet long. An examination of transmissometer records in bad visibility shows that, over short time periods, the visibility can vary significantly.

For operations in weather down to zero-zero visibility, transmissometer baselines must be shortened and the short term variations must be closely monitored so that visual guidance can be relied on down to certain minimums.

Visibility across the entire airport surface is difficult to define at the lower limits. Transmissometers at strategic points may be of assistance but will not necessarily give a complete picture.

At the present time, apart from runway-visual-range measurements by transmissometer, all visibilities are measured by eye relative to known objects or lights. When the visibility is less than 4 miles, these

observations are taken from the airport tower unless the fog is below the level of the tower.

2. OPERATIONS IN FOG

As previously stated, runway operations can probably be continued down to visibilities of 600 feet if approach and flareout systems are available. Taxiway operations can probably continue down to visibilities of 200 to 300 feet.

Therefore, the runway is the most important of the two areas. Although visual techniques may be adequate down to 600-foot visibility, there is no guarantee that a measurement of 600 feet ensures no lower levels of visibility. Therefore, it is logical to assume that the instrument developed must be capable of providing guidance in all visibilities.

In taxiing, there is a great advantage in that, if the pilot is in doubt, he can stop, thereby avoiding dangerous situations. For example, if the visibility is reported as 300 feet and a pilot encounters a patch of fog where it is 30 feet, he should wait and, in most cases, the heavy fog will roll out of his field of view.

However, one point must not be overlooked. The aircraft must clear the runways as quickly as possible after landing so that it does not constitute a collision risk or cause subsequent landings to be waved off. Since the runway turnoff maneuver is considered as taxiing, this movement must be possible as long as landings and takeoffs are permitted, thus emphasizing the need for a nonvisual method of turning off runways. This will be a serious limitation on the overall guidance system if it cannot be provided.

3. INCIDENCE OF FOG

If it is accepted that runway operations including turnoff should be possible in all visibilities, the incidence of fog where the visibility is 600 feet (1/8 mile) or less should be examined to determine the economic effects if taxiing is contingent upon only visual techniques.

Visibility data obtained from the United States Weather Bureau for John F. Kennedy, LaGuardia, and Newark airports for the period 1958 to 1962 and a summary for London Airport, England, for the period 1949 to 1958 are listed below:

<u>Airport</u>	<u>Average Hours per Year</u>		
	<u>$\geq$ Zero < 1/16 mile</u>	<u>$>1/16$ mile, $\leq 1/8$ mile</u>	<u>$\geq 1/8$ mile, < 3/16 mile</u>
John F. Kennedy International	8	16	28
Newark	10	5	14
LaGuardia	2	12	12
London	119	67	38

The airports in the New York area appear to have about as much fog as Chicago and Los Angeles so that they can be considered as representative for the continental United States. The figures for London are startling by comparison.

Since periods of poor visibility seldom last long in this country, the figures show that, if airport operations had to cease when the visibility dropped below $1/16$ mile, the economic repercussions would probably not be severe. However, at London Airport, the economic aspects would undoubtedly be very severe and, since both London and John F. Kennedy Airports are international, aircraft wishing to leave Kennedy Airport for London would be delayed during periods of fog at London.

However, even if airport operations were independent of thick fog, passengers may not be able to leave or get to the airport terminals because other transportation would not be able to operate in such conditions.

It is generally agreed that good centerline taxiway lighting is required for Category 3 ($1/4$ mile to zero visibility) weather conditions. This lighting is expensive but, as explained, should be sufficient for taxiing in visibilities down to 300 feet. If the airlines consider it to be uneconomic to operate for 8 hours a year when the visibility is less than 300 feet at a particular airport or airports, it would not be worthwhile installing expensive taxiing guidance, in addition to all the lighting, which is essential.

To investigate these economic aspects, aircraft operating costs and cost figures for cancellations and diversions for the types of aircraft operating into John F. Kennedy International Airport as forecast for 1965 were examined (reference 8). Assuming that the weather for 1965 would be similar to that of 1961 when there were 14 hours of 0- to $1/16$ -mile visibility, the airline costs were calculated.

Of the 14 hours of severe fog, it was assumed that 7 hours would consist of true zero-zero conditions and aircraft would have to be diverted or departing flights would be cancelled. For 1965 average hourly traffic, this is 203 aircraft (in 7 hours) for a cost of \$185,484. In the other 7 hours, aircraft could still land and taxi but at reduced speeds, taking 20 minutes longer than normal. The aggregate is \$56,712 in direct aircraft operating costs.

Still assuming "1961-type" weather, there were 26 hours when the visibility was from $1/16$ to $1/8$ mile. This was assumed to cause 15 minutes longer taxi time for a total cost of \$157,626. Visibilities of $1/8$ to $3/16$ mile for 38 hours were assumed to cause an 8-minute taxi-time increase for a cost of \$22,598.

Finally, 23 hours of $3/16$ to $1/4$ -mile visibility were assumed to cause 5 minutes longer for a cost of \$46,704.

Thus, the total cost of not being able to taxi in zero-zero weather and the increased taxi times due to reduced speed in visibilities of less than $1/4$ mile is \$569,124.

The interesting point about this economic analysis is that if a "blind-taxiing" aid is assumed to exist at the airport permitting slow-speed taxiing (taking 20 minutes longer than normal) in zero-zero conditions, the annual cost of taxi delays only drops to \$440, 000.

It is not claimed that these cost figures or the extra times assumed are precise. The point is that from an economic standpoint speed of taxiing is important and may be more important than providing a blind-taxiing capability.

VI. GROUND GUIDANCE BY LOCALIZER TECHNIQUES

A. SYSTEM DISCUSSION

The localizer is the runway approach radio aid that shows the pilot his left-right displacement from the extended runway centerline. In the history of localizer development, localizers have been designed in many forms but, in order to keep the scope of this description within reasonable bounds, only those localizer techniques that currently have a good chance of being used are analyzed in substantial detail. Thus, the discussion is centered around compatible VHF localizers and the new K-band all-weather landing system being developed for the FAA.

Historically, there were many localizer developments that are not considered because they were never generally accepted. They did not satisfy the requirements for a new localizer technique mainly because of operational requirements involving either the airport equipment or the airborne equipment. However, the operational requirements would probably have been changed to incorporate a new localizer if one of the innovations demonstrated significant progress in improving the technical characteristics of the localizer technique.

At this point in the history of localizer development, there is practically no movement to resurrect any of the old designs at C-, S-, L-, or X-band, the split-site localizer, or the phase comparison localizer. These concepts can be dismissed simply by pointing out that the accuracy and stability of measuring displacement from the runway centerline on the current improved VHF localizers are as good as the best results that were demonstrated by the old projects and that no introduction of new localizer techniques is seriously contemplated in the foreseeable future until the K-band localizer is ready for testing. What makes the K-band localizer different is that it uses sector scanning of an extremely narrow azimuth beamwidth whereas all the previous developments used a stationary pattern of radiation over a relatively wide azimuth beamwidth.

Even limiting the discussion to compatible VHF localizers encompasses several different localizer techniques, but the differences are relatively minor. All localizers are now single-site installations, but may be antenna arrays or waveguide antennas of various lengths. They may or may not have a back course and may or may not provide all-around coverage. Of particular interest to ground guidance in which localizer service is considered for runway rollout after touchdown and for runway speed-up before takeoff, an important localizer characteristic is that localizers are primarily designed to provide service for runway approach rather than guidance along or over the runway surface.

The question naturally arises about whether localizer techniques should be considered for ground guidance in view of the fact that ground guidance is a secondary concern in localizer design. The answer is that the runway centerline is the reference for runway rollout and takeoff, just as it is for the approach alignment and, therefore, the localizer can provide a guidance technique with continuity. This continuity is highly desirable especially in the landing maneuver to enhance the reliability and safety of the overall system.

The guidance rules for in-flight localizer guidance and for runway localizer guidance are the same--that is, to establish a condition in which the displacement from the runway centerline is safely within tolerable limits and to prevent the displacement from increasing.

Passenger reaction and pilot confidence must be taken into consideration in instrument approach and landing; unusual or unnecessary changes in control must be kept to a minimum at low altitudes. In localizer guidance, a satisfactory situation is defined as a tolerable small angular displacement from centerline with no increase in angular displacement. Experience shows that, when the aircraft is airborne, the displacement seldom remains zero and that a small stable displacement is preferable to an oscillatory decreasing displacement. A perfectly satisfactory track, next best to the centerline extension, is one that is displaced from the centerline by a displacement distance that is small compared with the runway width.

Inherent in the prevailing use of the localizer for lateral guidance is the assumption that distance information is of minor importance in the in-flight region. In fact, at typical localizers, the distance is measured only approximately and discontinuously--once at the outer marker, once at the middle marker, and all along by occasionally relating the reading of the altimeter to the glide-slope angle. A DME readout would be more direct and more accurate, but not absolutely necessary for reaching the runway threshold in a safe condition for switching to visual references.

In a situation where runway guidance must be obtained from localizer information, it must be assumed that accurate distance information is required in order to determine runway distance to go and ground speed for a safely controlled stop. With accurate distance information available, the pilot would also find it useful in making the decision whether to land or to go around and on the takeoff run, whether to continue or to stop if an emergency is indicated on the power, air-speed, or attitude references.

In the absence of DME, the localizer signal would directly show only angular displacement on the cross-pointer situation display. This signal could be combined with radio rate (rate of change of angular displacement) or with heading relative to the runway heading on the flight director.

Considering only the problem of runway surface guidance during rollout, steering action must be postponed until the nosewheel is

down and the speed has decreased to about one-half of the landing speed about half-way down the length of the runway. Since the only lateral correction that is tolerated at low altitude is the decrab maneuver, the localizer display will probably show some deviation when steering becomes effective. Thus, the problem is to determine the kind of lateral guidance data that would be most useful for steering.

The following major types of lateral guidance data are considered on subsequent pages.

1. Localizer angular displacement only,
 2. Angular displacement and its rate of change,
 3. Angular displacement and heading,
 4. Lateral displacement from runway centerline,
 5. Lateral displacement and its rate of change.
1. LOCALIZER ANGULAR DISPLACEMENT ONLY

The trouble with using only angular displacement for guidance is that the display cannot remain centered unless the track settles down exactly on centerline (assuming a perfect radio system). Smooth closure toward centerline, as opposed to overshoot and bracketing, can only be obtained by the pilot mentally interpreting the rate of movement of the deviation needle. For example, in a typical situation, a deviation current of $8.6 \mu\text{a}$ represents 20 feet off centerline at threshold; the same current half-way down the runway represents only 10 feet; and the same current three-fourths of the way down the runway represents only 5 feet. This changing lateral sensitivity along the runway makes it even more difficult to establish a stabilized track exactly along the centerline.

Of course, some localizers, particularly of the large wave-guide antenna type, have constant signal contours that look more like hyperbolas near the stop end of the runway.

2. ANGULAR DISPLACEMENT AND RATE OF CHANGE

The combination of angular displacement and its rate of change makes it easier to approach the centerline with asymptotic closure, even though the sensitivity is still changing with distance. This is because the flight director can be centered on a track where the angular displacement is decreasing exponentially with time and, therefore, exponentially with distance traveled from the start of the initial conditions. In theory, assuming perfect data and perfect command tracking, the rate of change of angular displacement remains proportional to the angular displacement and, therefore, both the angle and its rate will decrease together as the centerline is approached.

3. ANGULAR DISPLACEMENT AND HEADING

The combination of angular displacement and heading makes it easier to continue the rollout without necessarily tracking along the centerline, while keeping the steering needle on the flight director centered. This assumes that the heading error relative to the runway heading is equal to the angle between the direction of the track and the center-

line direction, which is strictly true only when all the landing wheels are going in the same direction. Under these conditions, the flight director can be centered on a track that represents an approximate constant angular displacement, which approaches the centerline at a rate proportional only to ground speed.

4. LATERAL DISPLACEMENT FROM RUNWAY CENTERLINE

The three guidance techniques previously outlined are perfectly feasible for application to runway guidance, and none is too difficult to implement. However, they have one common defect: none permits the use of a track that is parallel to the runway centerline.

Since the alignment maneuver is performed with respect to a rectangle representing the runway surface and since the decrab maneuver theoretically is designed to start the rollout parallel to the centerline, it is reasonable to permit the situation of a parallel-to-centerline track to be maintained. It could even be claimed that, if a parallel-to-centerline track (safely distant from the side of the runway) already exists, it would be preferable to hold that track because unnecessary steering maneuvers are undesirable.

Guidance based on lateral displacement is required in order to permit parallel-to-centerline tracks. This implies the need for DME and is compatible with the implied need for DME for determining runway distance ahead and rollout speed.

The conceptual implications of linear displacement and runway distance ahead are almost alike. The safety provisions involved in having a situation display showing distance from the sides of the runway are very similar to the safety and confidence that are derived from knowing the length of concrete surface ahead; the interpretation of lateral drift in feet per second is just as useful to lateral-displacement guidance as ground speed is to distance-to-go guidance.

Lateral guidance based on linear displacement is the most flexible among the techniques listed for runway guidance. To steer directly to the centerline (as required for angular displacement alone), only the deviation situation display showing linear displacement from centerline is necessary, with the significant advantage that the steering demand sensitivity (in μ a per foot) remains constant while the distance is changing. In computing this deviation the special characteristic of waveguide-antenna localizers must be considered.

5. LATERAL DISPLACEMENT AND RATE OF CHANGE

To obtain a track that closes asymptotically toward the centerline by exponential decay of displacement, only the linear displacement from centerline need be combined with its rate of change on the flight director. The steering demand sensitivity remains constant since it is independent of distance.

To obtain a track parallel to the runway centerline starting from wherever the steering command becomes effective, the rate of change of lateral displacement in combination with the time integral of the rate of change need be displayed on the flight director.

As in common localizer usage, when a flight director is used as the primary guidance display, a situation display showing linear displacement from centerline should always be within the pilot's view for reference.

The transformation in emphasis from angular-displacement guidance to linear-displacement guidance is recognized in several familiar concepts. In its most rigorous form, it is recognized as the transformation from polar coordinates of position (ρ, θ) to rectilinear coordinates (x, y). In ILS parlance this is recognized as course-softening in which the angular-displacement signal is modified (that is, multiplied) by distance, so that the effective displacement is proportional to distance, becoming less in amplitude (that is, less sensitive or softened) as the course progresses inbound and the distance-to-go decreases.

The transformation from polar to rectangular coordinates for course-softening, or for computing linear displacement mean that the angular-displacement data and the distance data measured from the localizer site are processed in a computer whose output is (rigorously) the product of the ground-projected slant-range distance and the sine of the azimuth displacement angle. In the runway region, the computer can form the product of the slant-range distance and the angular-displacement angle without trigonometric functions, but with attention to a constant scale factor that relates the dimensions of distance and angle. The characteristics of waveguide-antenna localizers can be compensated for with nonlinear potentiometers.

Computers of the required type are readily available in small packages, generally as analog multipliers of two voltages, one proportional to distance and the other proportional to azimuth angle.

This discussion generally assumes that the localizer is located near the stop end of the runway, which is the standard case. One organization in Great Britain has proposed a localizer located in the approach region using a front course for approach and a back course for landing. There are many complications: conforming to ICAO standards of course width, providing service in the region over the localizer, sense reversal between front and back course, real-estate availability, remoteness of equipment, and just plain unorthodoxy. The purpose of this unusual site is evidently to reverse the pattern of changing sensitivity with distance by making the distance change by a smaller ratio from one end of the runway to the other. In the absence of DME, this too represents a guidance technique that does not permit parallel-to-centerline tracks in a direct manner though, indirectly, it could approximate this type of track; the angular displacement would have to decrease by the same ratio that the distance from the localizer site increases. If DME is considered in connection with such a site, the basic reason for using it disappears. It is expected that the idea of placing a localizer in

the approach region will probably not be accepted, and the normal localizer site at the stop end of the runway will remain the accepted standard.

In fact, this discussion is limited to the front course of the localizer even for the normal sites.

Any discussion of using DME for runway guidance naturally assumes that the DME readout is relative to the localizer site. Although no standard for ILS/DME has been adopted, the Airline Electronic Engineering Committee, Aeronautical Radio Inc. (AEEC of ARINC) has recommended locating the DME at the glide-slope site in order to make the ILS reference point at zero distance. Only one ILS/DME site exists under FAA cognizance: at Miami, Florida under experimental evaluation by Pan American personnel. The purpose of this Pan American project is to provide experience with using angular-displacement and distance-to-go information. The DME was supposed to have been moved from the glide-slope site to the localizer site in November 1963.

Although it is theoretically possible to compute linear displacement using distance from the glide-slope site, it is a much more complicated computation and not universally applicable unless the localizer to-glide-slope distance is standardized (which is, of course, out of the question). Furthermore, runway-distance-ahead information is most usefully measured relative to the localizer site.

It should also be pointed out that distance information measured from the glide-slope site provides a measure of distance to the ILS reference point that becomes less accurate with decreasing distance unless the glide-slope offset from the centerline is taken into account in a computing operation. If further argument is needed, it is finally pointed out that the whole problem of using DME for runway guidance was studied in the Advanced Instrument Landing System (K-band) under development for the FAA, and, in that system, the DME station is located at the localizer site.

Putting the DME station at the glide-slope site precludes the use of DME for distance-ahead and linear-displacement rollout guidance, whereas putting the DME station at the localizer site permits these forms of guidance to be feasible, even if the feasibility is obtained at the cost of some inconvenience. The following conflict still remains--there are at least four possibilities for the reference point of direct-distance readout: (1) the runway threshold, (2) the glide-slope (ILS) reference point, (3) the stop end of the runway, and (4) the localizer site. Considering these in order, the threshold point was never proposed as a serious contender in relation to the others; the ILS reference point is the current ARINC recommendation; the stop end of the runway is useful for direct determination of runway distance ahead; the localizer site is the logical point for computing linear displacement.

The conflict arises from the fact that, according to present procedures, the only published quantity relating these points is the distance between the threshold and the stop end of the runway, the site locations for the glide slope and the localizer being unknown quantities as far as the approach charts are concerned.

Another source of difficulty is that the requirement for referring to a chart and making related adjustments on the cockpit readouts is commonly regarded as an undesirable inconvenience to the pilot. If this inconvenience must be avoided, then only one of the four possible references can be selected for direct DME readout, and the others become merely approximations.

Since a good case can be made for justifying the need for at least two types of accurate DME readout, it becomes apparent that some pilots may accept the procedure for setting in a fixed-distance bias by reference to a chart early during the approach. A reasonable compromise may be to adjust the system time delay of the DME so that zero output is obtained at a standardized reference--for example, at the ILS reference point--and to permit the DME output to become negative past the zero point. Then, by adding a positive voltage of appropriate value scaled according to published distance from the zero point, any pilot could establish another zero-distance point anywhere else--for example, at the stop end for rollout distance and/or at the localizer site for computing lateral displacement.

The K-band Advanced Instrument Landing System has a system time delay of 80 μ sec and the capability to obtain negative DME readout for 12,000 feet past the ILS reference point, which should be adequate. The standard DME has a system time delay of 50 μ sec (second pulse to second pulse) and is theoretically capable of providing negative distance for about 9000 feet past the ILS reference point on the 12- μ sec code spacing. Unfortunately, the new DME code spacings of 30 and 36 μ sec preclude negative-distance readout with a 50- μ sec system time delay.

The best solution of all on theoretical grounds would be for everyone to regard the localizer site as the zero-distance readout reference and to look up and set in the airport constants for the ILS reference point and the ends of the runway, thus avoiding the confusion and the complication of negative distances while making maximum use of the DME facility.

As far as this study is concerned, the assumption will be made that the DME station is located at the localizer site and the direct-distance readout has a zero-reference at the localizer. This assumption is made only because linear-displacement computation is motivated by the operational requirements of runway guidance; the problem of satisfying all DME users will be left for the standards committees to solve when the time comes.

B. MATHEMATICAL TREATMENT

The discussion uses the coordinate system shown in Figure 6-1. Linear displacement from centerline is:

$$y = x \sin \theta \approx x \theta / 57.3 \quad (\theta \text{ in degrees}) \quad (6-1)$$

The assumption for sine proportional to angle is convenient and of practical accuracy within the sector of interest. The worst effect of this assumption is equivalent to an error of less than 0.1 percent in the computation of y within the limits of useful localizer coverage.

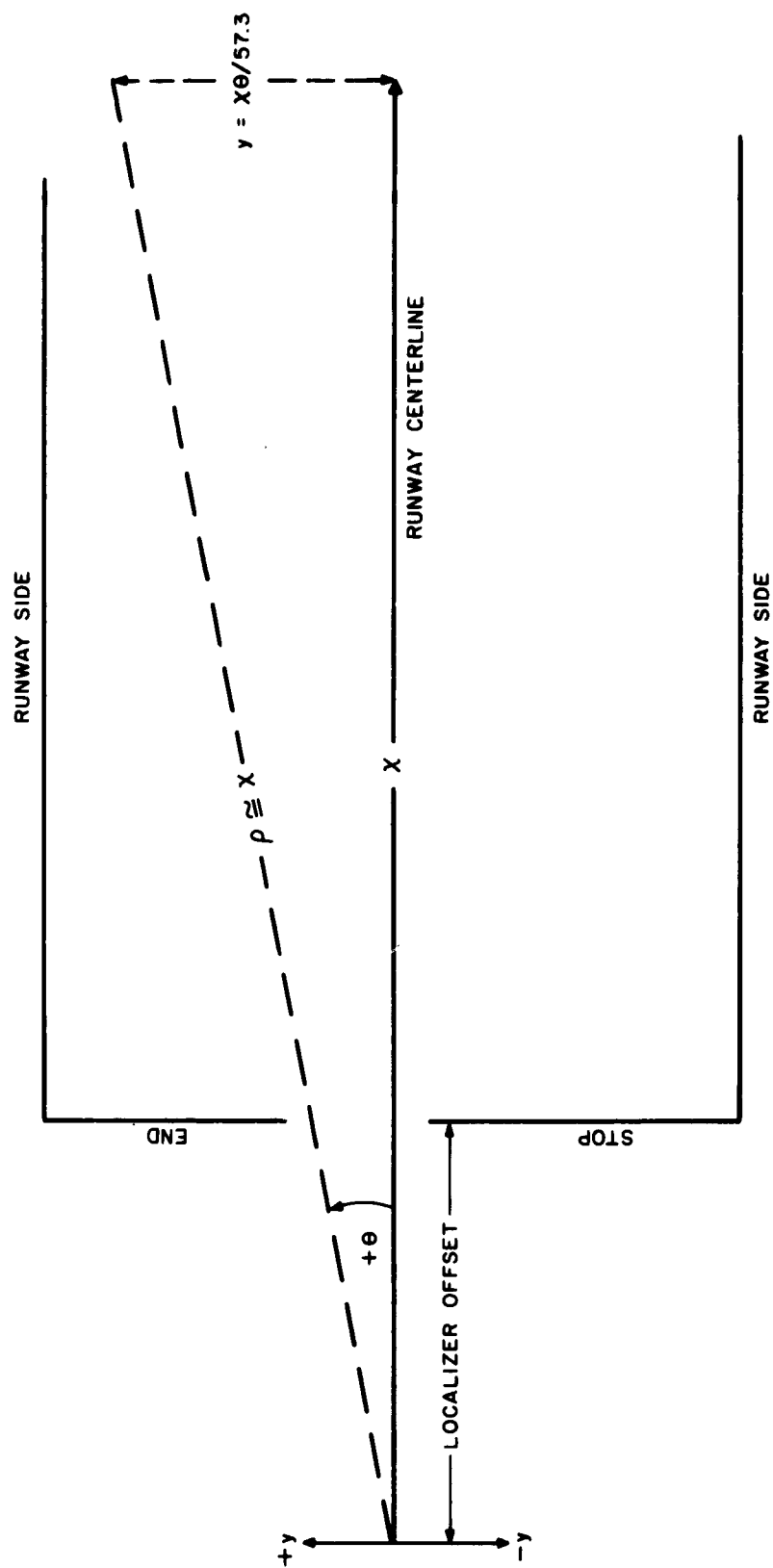


FIGURE 6-1. LOCALIZER/DME COORDINATES

Localizers that are adjusted in accordance with ICAO standards* have proportional relationships among angle, difference in depth of modulation (DDM), deviation current, and linear displacement. These are summarized as follows:

1. DDM is linearly proportional with angles up to +4 degrees with full-scale deviation (150 μ a) defining the course width for DDM = 15.5 per cent.
2. Course width is 700 feet (+350 feet) at 50-foot altitude on the glide slope. In practice, this is considered to be near the runway threshold.

These standards make the localizer sensitivity 43 μ a per 100 feet of linear displacement at the runway threshold. Figure 6-2 shows the standard relations on the ordinates, the dashed vertical ordinate being located at the runway threshold. The abscissa shows distance as x/x_0 , where x_0 represents the distance from the localizer site to the runway threshold. The value of x_0 varies from site to site, generally within the limits of 7000 and 13,000 feet; x_0 is the sum of the runway length plus the offset distance of the localizer from the stop end of the runway.

The localizer deviation current, proportional to azimuth angle ($\theta = 57.3 y/x$), is given by

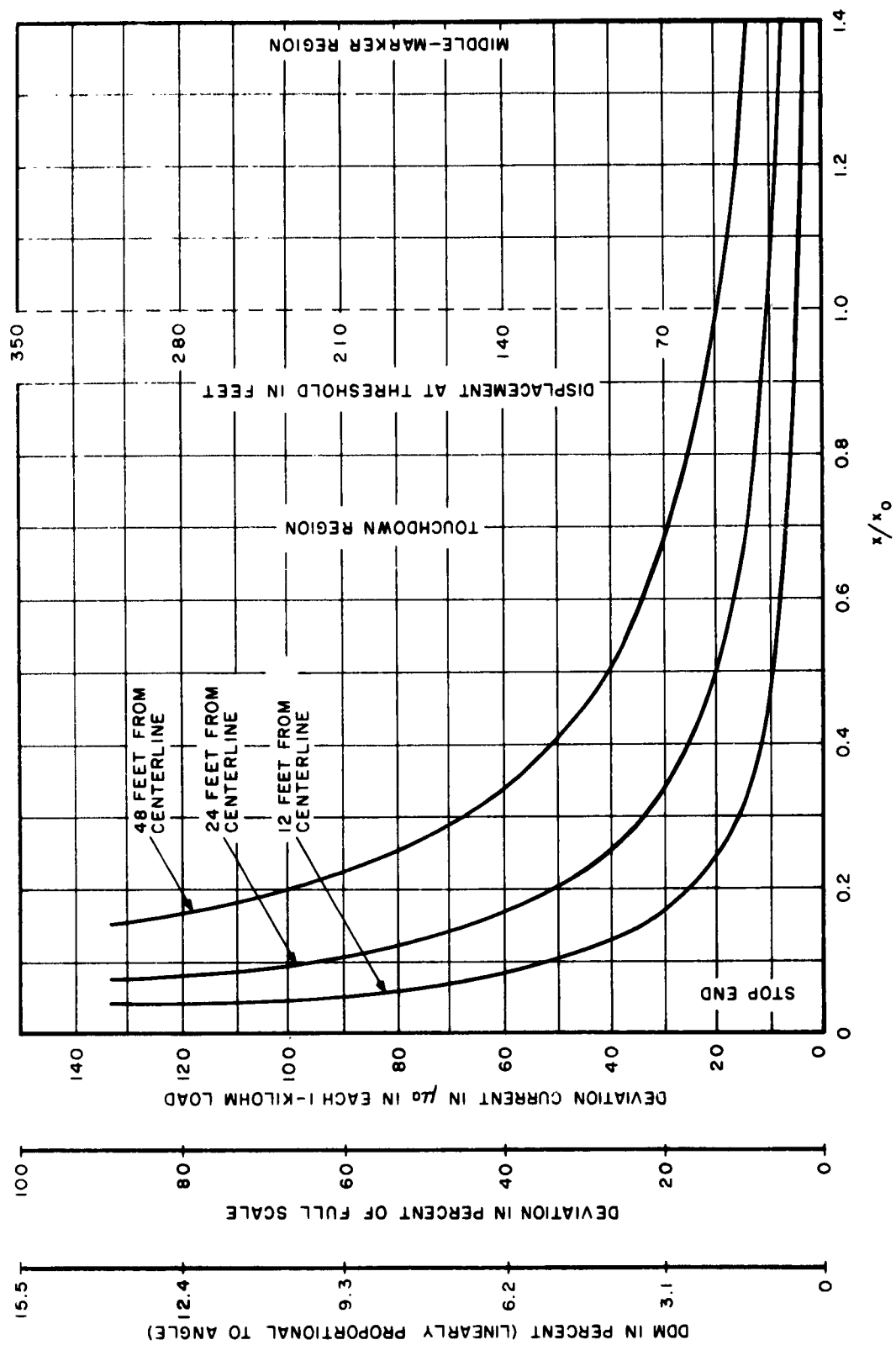
$$I_{\mu a} = \frac{0.43y}{x/x_0} \quad (6-2)$$

where x and y are the rectilinear coordinates (Figure 6-1) and 0.43 is the sensitivity of 0.43 μ a per foot of y at x_0 .

The curves in Figure 6-2 were computed for constant linear displacements of 12, 24, and 48 feet, using equation 6-2. They show that the deviation current increases and accelerates as the track progresses inbound toward the localizer when the displacement is constant. For distances greater than the runway threshold, the change in sensitivity (μ a per foot) is small enough to be tolerable, but this situation rapidly deteriorates when the distance is less than runway threshold.

In using linear displacement for guidance, the deviation current, which is ordinarily proportional to localizer angular displacement (θ), must become proportional to linear displacement (y). In this sub-

* ICAO, "International Standards and Recommended Practices Aeronautical Telecommunications Annex 10 to the Convention on International Civil Aviation," Seventh Edition, August 1963.



x_0 = DISTANCE FROM LOCALIZER TO THRESHOLD

FIGURE 6-2. STANDARD LOCALIZER RELATIONS

stitution, the same left-right sensing that is used for angular displacement would be retained--from Figure 6-1, positive y is on the fly-left side and negative y is on the fly-right side of centerline.

Theoretically, it would be desirable to avoid any mode switching in applying the signal for deviation current to the localizer displays, but this is not practical. In the runway guidance region, the course width (+ full-scale deviation) is measured in dimensions of the order of hundreds of feet, whereas in the region of the localizer intercept, the course width is measured in dimensions of the order of thousands of feet in order to permit a turn-on starting outside the outer marker and ending in stabilized alignment before reaching the outer marker. It would be impossible to start the intercept when the needle left the full-scale end and roll out onto the course line with only several hundred feet of course width. On the other hand, it would be undesirable to operate with such low sensitivity at threshold that the width of the runway would represent only about 10 percent of full-scale deviation current. Accordingly, it is concluded that the localizer will continue to be used in the normal angular-displacement manner for most of the approach, and that a mode switchover must occur in order to obtain linear-displacement deviation near the runway threshold.

Two requirements exist for the mode switchover to be acceptable: (1) it must be automatic, and (2) it must introduce no transient deflection on the localizer needle.

The switchover should occur at the distance from the localizer site where the angular-displacement deviation current is standardized in terms of μa per foot, thus eliminating the possibility of introducing a transient deflection. According to ICAO standards, the course-width standardization distance is required to be the distance where the glide-slope altitude is 15 meters (about 50 feet). The ICAO recommendation was made to interpret this distance to be near the runway threshold (for a 2.5-degree glide slope and an ILS reference point 1150 feet past threshold, this would be a good approximation). For automatic switchover purposes, these definitions, for a course-width standardization distance, are not directly useful because the airborne equipment can not sense threshold directly and because it would probably be preferable to effect switchover in terms of DME readout than in terms of altimeter readout, in the absence of a special marker beacon.

Since DME readout from the localizer site is assumed for the purposes of this discussion, the mode switchover from θ guidance to y guidance could take place at any course-width standardization distance providing that the distance is greater than the threshold distance and that the resulting course width is within reasonable limits. The longest threshold-to-localizer distance is about 13,000 feet, and the course width should be between 3 and 6 degrees for $2\theta w/2$ where $\theta w/2$ is the half-course width on either side of the runway centerline.

Retaining the standard sensitivity of full-scale deviation for +350 feet linear displacement at the course-width standardization dis-

tance (x_1), where x_1 is distance to the localizer site, the course width ($\pm\theta_w/2$) is

$$\pm\theta_w/2 \text{ (degrees)} = 57.3 \frac{350}{x_1} = \frac{20,000}{x_1 \text{ (feet)}} \quad (6-3)$$

For localizers modulated 20 percent, which is the nominal case, the maximum DDM is 40 percent, which must be obtained at an azimuth angle of at least 4 degrees. Taking the course width as the angle between DDM +15.5 percent, the minimum course width $\theta_w/2 = +1.55$ degrees. According to equation 6-3, this limits the value of x_1 to 13,000 feet. These results show that there is enough latitude in the prevailing localizer standards to permit automatic switchover from angular-to-linear-displacement deviation current at sites with the longest runways and the largest localizer-offset distances that are encountered in practice.

A good set of standards would use a course-width standardization distance of 13,000 feet from the localizer, where the course width would be +350 feet (+1.55 degrees). The total sector of the course width is 3.1 degrees (full-scale to full-scale, left and right) and, starting when the DME readout becomes less than 13,000 feet, the deviation sensitivity becomes 43 μ a per 100 feet.

With DME available, localizer designers would be tempted to provide course-softening of the localizer angular-displacement deviation current in the approach region, especially inside the middle marker. Such course-softening techniques are consistent with the standards previously recommended, permitting any law of course-softening that may be desired by localizer designers and users at large values of distances, providing only that the sensitivity of 43 μ a per 100 feet be matched at the course-width standardization distance of 13,000 feet. In accordance with these standards, the automatic switchover from localizer guidance (course-softened or not) to linear-displacement (y) guidance is actuated by the DME readout corresponding to 13,000 feet. In accordance with these standards, the automatic switchover from localizer guidance (course-softened or not) to linear-displacement (y) guidance is actuated by the DME readout corresponding to 13,000 feet. No transient deflection would result from the switchover actuation, and, at distances of less than 13,000 feet from the localizer, the deviation sensitivity would remain 43 μ a per 100 feet over the region of runway-surface guidance.

The practical effect of the present ICAO standards on sensitivity is to make 10 percent of full-scale deviation equivalent to 35 feet of linear displacement from centerline at the threshold of the runway. The practical effect of the recommendations for switchover to linear displacement described in this report is to make 10 percent of full-scale deflection equivalent to 35 feet of linear displacement over the entire runway surface within the sector of proportional localizer DDM, which limits the useful range of angular displacement (θ) to values between

$\pm\theta_{\max}$ where $\theta_{\max}$ is the $\theta_{\max}$ angular displacement beyond which the DDM is no longer proportional to angle.

Figure 6-3 shows the ICAO standards for difference in depth of modulation (DDM) on the side where the 90-cps side-band signal predominates. The reference (carrier) pattern is modulated 20 percent with 90-cps and 150-cps signals; the side-band pattern adds 90-cps signals to the reference and subtracts 150-cps signals from the reference. The addition and subtraction resultants are shown as 90-cps total and 150-cps total, and the DDM is the difference between the two totals. The angular displacement $\theta_w/2$ corresponds to DDM = 15.5 percent and the angular displacement $\theta_{\max}$ corresponds to DDM = 40 percent.

In the lower part of Figure 6-3, the values of $\theta_w/2$ and $\theta_{\max}$ are shown in degrees, according to equation 6-3, for various values of x_1 . The values in degrees correspond to a linear displacement of 350 feet at x_1 for DDM = 15.5 percent (at $\theta_w/2$).

The recommended x_1 standard of 13,000 feet, for automatic switchover to linear displacement, gives $\theta_w/2 = 1.55$ (course-width total = 3.1 degrees). For this case, $\theta_{\max} = 4.0$ degrees, this being the maximum angular displacement for which the localizer deviation current is proportional to angular displacement.

The displacement of $\theta_{\max}$ is encountered at some maximum linear displacement ($y_{\max}$) in relation to some minimum distance from the localizer ($x_{\min}$). Extending equation 6-3 linearly to DDM = 40 percent, the maximum ratio becomes

$$\frac{y_{\max}}{x_{\min}} = \frac{350}{x_1} \frac{40}{15.5} = \frac{900}{x_1} \quad (6-4)$$

For $x_1 = 13,000$ feet, $y_{\max} = 0.07 x_{\min}$, which shows that the limit of $\theta_{\max}$ is not exceeded for linear displacement of less than 70 feet at distances of more than 1000 feet from the localizer. Taking into account that the localizer offset distance is usually more than 200 feet and often more than 500 feet and the fact that runway guidance would not be needed within the last 500 feet of runway surface, it is estimated that linear displacement could be computed over the practically useful region of the runway surface under the present ICAO standards of localizer sensitivity.

The K-band localizer of the Advanced Instrument Landing System will provide deviation current proportional to azimuth angle within the limits of $\theta_{\max} = \pm 5$ degrees, regardless of the standards adopted for the deviation displays. This value of $\theta_{\max}$ is sufficiently close to the ICAO standards for the same quantitative analysis to apply in a general way. In any case, the sector of angle with proportional signal is sufficient to cover the requirements for localizer intercept, high sensitivity of linear runway displacement, and adequate proportional coverage near the stop end of the runway.

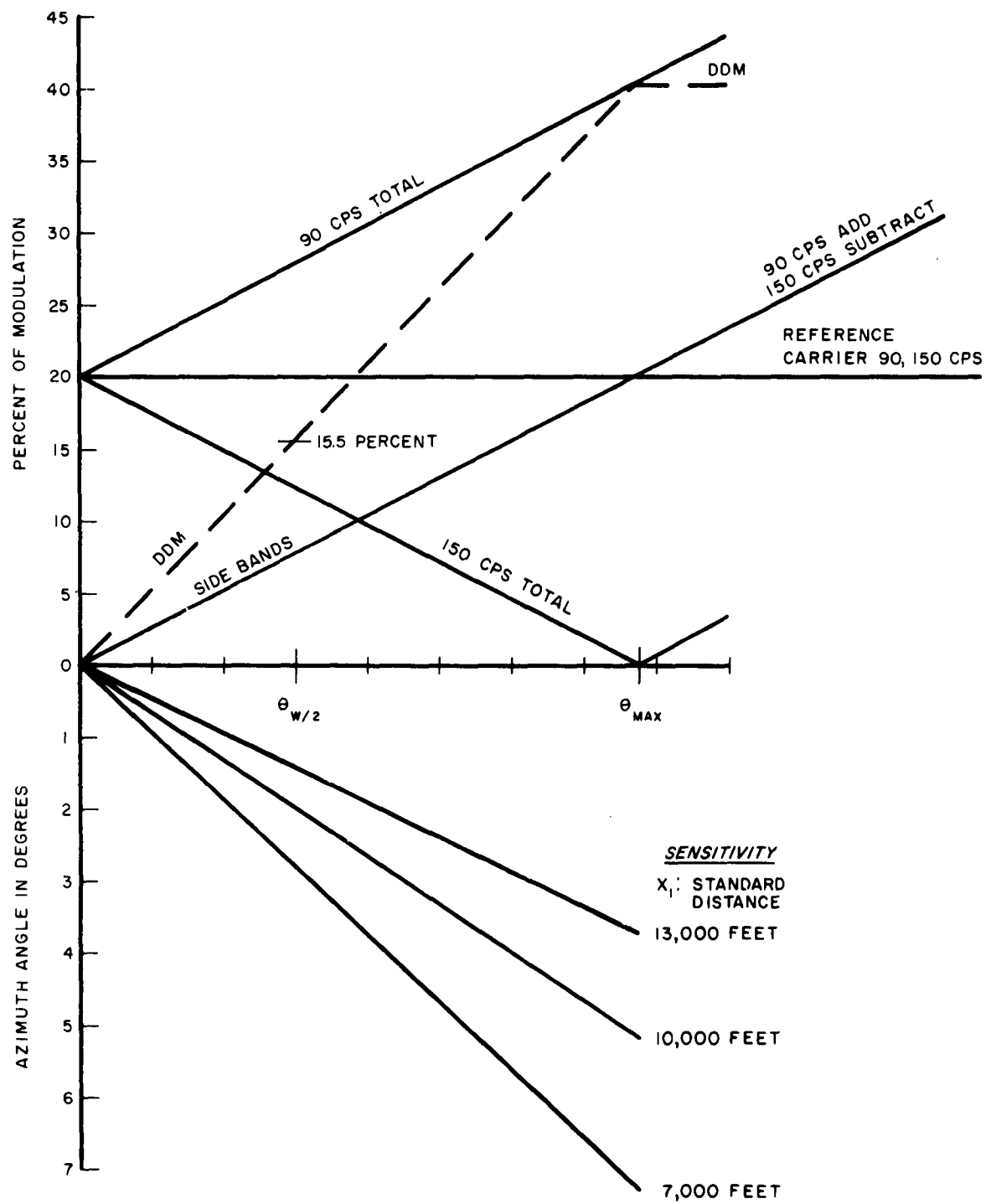


FIGURE 6-3. SENSITIVITY STANDARDS

C. ERROR ANALYSIS

Two sources of error apart from any piloting errors are present in the computation of $y = x \theta / 57.3$ --the angular error and the distance error. A great deal more is known about the angular error than about the distance error because angular data is currently the only type that is used in landing and because high-precision standards like theodolites are more useful for localizer checks than for DME checks on accuracy without going to extremes (like pairing theodolites and setting up tracking stations out where the DME is normally used).

The subject of accuracy is complicated by definitions, standards, availability of evidence, and statistical concepts. One can only arrive at a reasonably believable estimate of accuracy, even on a well-known system like the localizer by hoping that the exceptional cases will seldom combine in the most unfortunate manner.

The best available evidence consists of the difference between Category I localizer recordings and theodolite recordings on flights at typical sites. The next best available evidence consists of histories of equipment measurements over a long period of time at one site and for a large sample of airborne-type equipments under static tests.

The on-course (zero-deviation) point at runway threshold is found within +10 feet of centerline 90 percent of the time for a conventional localizer. The corresponding angle is ± 0.08 degree.

Although the minimum-performance standard for receiver centering error is $+9 \mu a$, most receivers can be maintained to stay within $\pm 5 \mu a$ (± 0.08 degree for a 5-degree course width).

Over 1000 alignment checks on the waveguide localizer over a two-year period, at a point on the runway 2000 feet from the localizer, fell within 0.08 degree of centerline for 95 percent of the checks. During the last 8 months of this period, the alignment was never off more than 0.1 degree. A flight test of this same localizer, where the reading is corrected by theodolite, shows a bias of $5 \mu a$ (0.08 degree) with practically no change in error over the runway.

A similar waveguide localizer at NAFEC was flight-tested and showed a bias of $12 \mu a$ (0.2 degree), but still with negligible change in error over the runway.

A dipole-array directional localizer was flight-tested and showed perfect alignment along the runway and only $\pm 4 \mu a$ (± 0.07 degree) noise on the runway.

Theodolite-corrected localizer recordings are available for 16 commissioned localizers; the recordings include at least the first several thousand feet of the runway, where the aircraft made approaches that leveled out at 50 feet. Of these 16, the results on 5 were about as good as could be expected (bias and noise both less than $5 \mu a$ or 0.08 degree), 7 others were almost as good (bias and noise both less than $12 \mu a$ or 0.2 degree), and the remaining 4 had both bias and noise less than $24 \mu a$ (0.4 degree).

The following table shows the results for theodolite-corrected localizer recordings where they are available for low flights over the runway surface.

<u>Facility</u>	<u>Average (μa)</u>	<u>Deviation from Average (μa), 95 Percent of Run</u>
Fort Worth (Meacham)	-5	<u>+1</u>
NAFEC	+12	<u>+2</u>
Duluth	+2	<u>+4</u>
Baltimore (Friendship)	+3	<u>+3</u>
New York (Kennedy)	+2	<u>+4</u>
New Orleans (Moisant)	+5	<u>+5</u>
Chicago (O'Hare)	-3	<u>+9</u>
St. Louis (Lambert)	-3	<u>+9</u>
Miami	+3	<u>+9</u>
Cleveland (Hopkins)	-5	<u>+10</u>
Detroit (Metropolitan)	-10	<u>+5</u>
Minneapolis (St. Paul International)	+8	<u>+7</u>
Ontario (International)	+16	<u>+10</u>
Los Angeles (International)	-7	<u>+23</u>
Washington (National)	+11	<u>+20</u>
Dallas (Love)	-6	<u>+18</u>

These results were obtained by analyzing the over-the-runway segments read off every 200 feet from localizer recordings made by the FAA and published in Radio Technical Commission for Aeronautics (RTCA) Paper 31-63/DO-118, March 1963. The remainder of the recordings (not included in the published version) were examined at Teterboro, New Jersey and were found to show localizer results over the rest of the runway not significantly different from the over-the-runway segments in the published version.

Taking all this evidence into account, it can be estimated that, most of the time, a good localizer system can provide angular accuracy of between 0.1 and 0.2 degree in the over-the-runway region. Given good maintenance on a directional localizer, the best estimate is that the angular error is very near 0.1 degree.

The effect of this angular error is to place the actual position of the aircraft either to the left or to the right of the value that is computed as the linear displacement ($y = x \theta / 57.3$). The values of x and θ in this equation are the measured coordinate values or the coordinates of position that are represented by the equipment measurements. An angular error introduces an additional term $\Delta\theta$ to the measured angular coordinate in estimating the actual position. It is operationally significant to determine whether the actual position is safely within the bounds of the runway. In this respect, the angular error toward the side of the runway is more important than the angular error toward the centerline--that is, the operational significance of the angular error is best observed by adding $+\Delta\theta$ to the magnitude of θ . Confusion between positive and negative is avoided and no loss of analytic validity results from taking only positive values of $\theta + \Delta\theta$ in the error analysis to determine whether the actual displacement is safe when the computed displacement is interpreted as being safe.

At this point, it is convenient to introduce a distance error Δx , which can also be positive or negative. The effect of this distance error is to place the actual position of the aircraft either closer to the localizer (negative Δx) or further from the localizer (positive Δx) than the distance represented by the measured x -coordinate. However disconcerting a negative Δx might be in estimating distance to go, as far as linear displacement is concerned, a negative Δx puts the actual position of the aircraft closer to the centerline no matter what the actual angular position is (except the unique case of being exactly on centerline). The operational significance of Δx is best observed by taking only positive Δx in determining whether the actual displacement is safely within runway bounds.

The combined effect of $\Delta\theta$ and Δx is then given by taking measured coordinates (x, θ) and finding the actual displacement error, which is:

$$(x + \Delta x)(\theta + \Delta\theta)/57.3 - x\theta/57.3 = \frac{1}{57.3} (\Delta\theta \Delta x + x \Delta\theta + \theta \Delta x) \quad (6-5)$$

According to equation 6-5, three components involved in the error of linear displacement are due to angular error ($\Delta\theta$) and distance error (Δx). The three components are shown in Figure 6-4; the errors have purposely been exaggerated in this figure for clarity. The smallest component is $\Delta\theta \Delta x$ (where $\Delta\theta$ is in radians) or $\Delta\theta \Delta x / 57.3$ (where $\Delta\theta$ is in degrees). For $\Delta\theta = 0.1$ degree and $\Delta x = 600$ feet, the value of the component $\Delta\theta \Delta x$ is about 1 foot.

In computing $\Delta\theta \Delta x$, it is assumed that both Δx and $\Delta\theta$ are invariant with respect to distance from the localizer. This assumption of constant error is probably more nearly true for Δx than for $\Delta\theta$ because the Δx error is most likely due to a time-interval error of about $1 \mu\text{sec}$ in the distance readout. However, there is good reason to estimate that the error $\Delta\theta$ is a function of θ and, thus, indirectly a function of distance for a constant value of linear displacement.

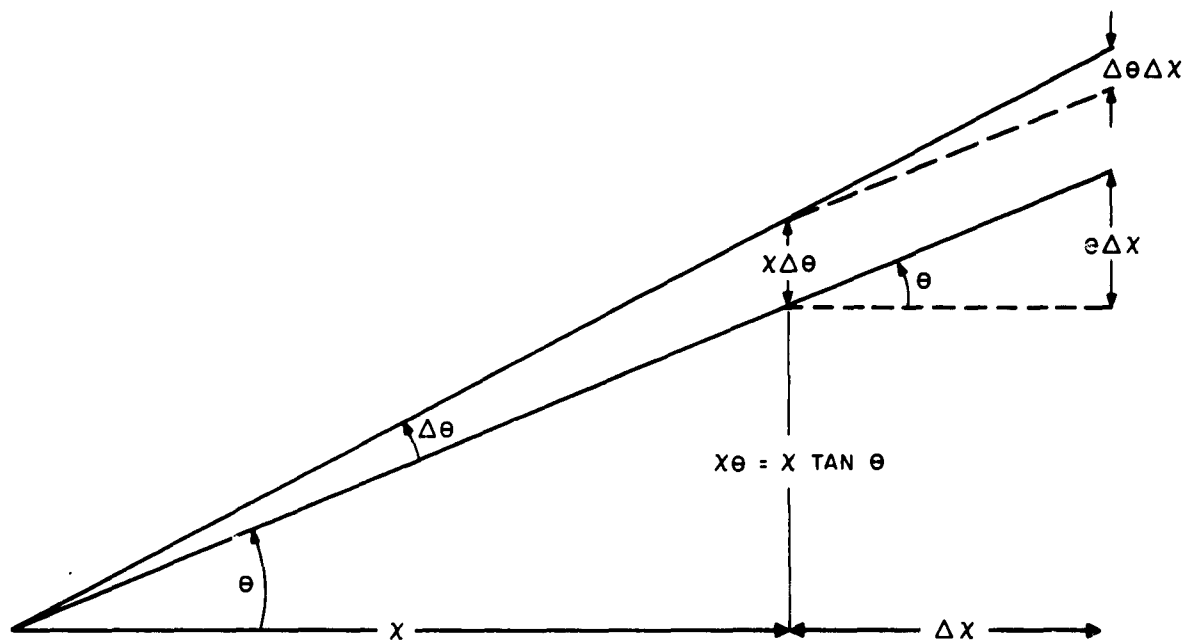


FIGURE 6-4. LINEAR-DISPLACEMENT ERRORS

The dependence of $\Delta\theta$ on θ is related to the fact that the localizer-station course-width instability affects the angular-displacement error off-course but not on-course. It is also related to the fact that the localizer receiver generally has an off-course error due to an error in tracking between the readout (in μa) and the difference in depth of modulation (DDM) over the sector between zero and the full-scale localizer deviation signal (150 μa).

In evaluating the dependence of $\Delta\theta$ on θ , account is first taken of the ground-station course-width stability. The localizer is supposed to be monitored to alarm for a course-width change of +20 percent according to ICAO standards. In practice, this tolerance can be tightened. Course-width measurements made by FAA flight-check aircraft on an improved directional localizer revealed that 90 percent of all checks were found to be within 10 percent of the nominal course-width. Taking an optimistic view of the improvement that could come from further experience with directional localizers, it is estimated that the course width could be maintained within +8 percent of the nominal course width more than 90 percent of the time.

The tracking accuracy of the airborne equipment is supposed to be within 10 percent according to the performance standards in RTCA Paper 20/63/DO-115. An optimistic view of this specification can be taken by regarding the tracking results obtained by Collins Radio on the new solid-state ILS receiver. For the limited environment believed to represent operating conditions realistically in a landing situation using modern commercial aircraft, the off-course tracking error was found to be 6 percent almost all the time.

The off-course tracking capability of the Collins Radio 51RV-1 receiver results from the improved design of the detector and audio-circuit linearity at high modulation levels. Substantial improvement has been achieved by optimum use of solid-state techniques, rigid component standards, and careful consideration of the sources of error. Standard statistical methods were used in evaluating the results. These statistical methods had minor variations on the methods recommended by RTCA Special Committee 98 for computing localizer-receiver errors.

Systematically, the composite off-course error is taken as the root sum square of the station error (8 percent) and the receiver error (6 percent) for a total of 10 percent. This represents an estimate of the best that can be obtained with improved equipments, careful maintenance, and high standards for personnel, procedures, and test equipment.

In order to combine the errors of 0.1 degree and 10 percent of θ , several simplifying assumptions will be made:

1. Total mean error is zero.
2. Values of 0.1 degree and 10 percent of θ represent 3 standard deviations (3- σ values), which will not be exceeded more than 0.3 percent of the time.

3. Errors are normal distributions of independent random variables whose total variance is the sum of the individual variances.

Under these assumptions, the combined error is:

$$\Delta\theta = \left[(0.1)^2 + (0.1 \theta)^2 \right]^{\frac{1}{2}} = 0.1 (1 + \theta^2)^{\frac{1}{2}} \quad (6-6)$$

where $\Delta\theta$ and θ are in degrees.

The value θ in equation 6-6 represents the localizer deviation = current readout of the angular coordinate of position. The value $\Delta\theta$ represents the extra deviation current that should be included if the actual displacement is larger than is represented by the θ readout. The value of $\Delta\theta$ would be a constant representing 0.1 degree if the deviation current remained zero, but this condition is seldom realized in practice. Even an autopilot-coupler combination with a noiseless beam is not expected to track localizer zero within less than 10 μ a under wind-shear conditions--for example, 4 knots change in cross wind per 100-foot change in altitude (RTCA Paper 31-63/DO-118). Adding the fact that a noiseless beam is fictional, it must be expected that θ will have a finite value that will vary with distance and with displacement. Working inversely from $y = x \theta / 57.3$, θ can be expressed as $\theta = (y/x)(57.3)$, where x is the DME readout and y is the computed linear displacement. Substituting this value of θ into equation 6-6 and combining the first two linear-displacement-error terms in equation 6-5, the combined error involving $\Delta\theta$ becomes

$$\frac{1}{57.3} (\Delta x \Delta\theta + x \Delta\theta) = \left[\left(\frac{x}{57.3} \right)^2 + \left(\frac{y}{10} \right)^2 \right]^{\frac{1}{2}} \left(1 + \frac{\Delta x}{x} \right) \quad (6-7)$$

which will be shown in terms of the variables x and y after examining the third error term ($\theta \Delta x / 57.3$).

The term for Δx is the DME error, which could be a subject of considerable discussion. The original specifications permitted a DME system error of about 0.5 nautical mile (nm) but improvements over this value are currently realized. The Pan American ILS/DME project at Miami, Florida claims a DME accuracy of 0.1 nm, and this figure is being recommended as the specification for a new ARINC DME characteristic (AEEC Letter No. 62-1-61). Although no good information is yet available for determining the effect of tracking accuracy in the speed range used for approach and landing, the maximum error of 0.1 nm (600 feet) is based on the best possible changes and improvements that can be accomplished without a basic change in the standard DME system. Some of the improvement can be achieved by using a pulse rise time as short as 1.0 μ sec instead of the specified maximum of 3.0 μ sec, and

provision is made within the airborne equipment to adjust the precise zero setting and minimizing the distance error spread. In fact, the FAA is working toward improving the accuracy of DME for ILS applications.

For the error analysis in this project of ground guidance, the best estimate of DME error to use with standard localizer is +600 feet, independent of distance. The third error term of equation 6-5, expressing θ in terms of y/x , becomes

$$\frac{\theta \Delta x}{57.3} = \frac{y}{x} \Delta x = \frac{y}{x} (600 \text{ feet}) \quad (6-8)$$

The computed values for linear-displacement error, based on equations 6-7 and 6-8, are shown in Figure 6-5. The curves for $y = 20, 40$, and 60 feet that decrease with decreasing distance are for equation 6-7 (due to angle error). The curves for $y = 20, 40$, and 60 feet that increase with decreasing distance are for equation 6-8 (due to DME error).

Figure 6-5 shows that the displacement error due to angle error is dominant in the region of the threshold and that the displacement error due to DME error is dominant in the region of the stop end of the runway. It can also be seen that the combined displacement error, adding the values from the two sets of curves, is less than 30 feet even for the large displacement value of 60 feet until the distance becomes less than 2000 feet from the localizer/DME site. By the time this occurs in a rollout, the speed would be substantially reduced so that steering toward centerline would probably reduce the indicated displacement to less than 40 feet, keeping the combined error below 30 feet to $x = 1000$ feet. On takeoff, the initial displacement error would be small and would probably not build up to a large value before rotation occurs.

From Figure 6-5, it can be estimated that for the assumed localizer and DME errors (0.1 degree, 10 percent of angle, and 0.1 nm), the displacement error would remain less than 30 feet over the useful section of the runway surface providing that localizer offset distance was at least 500 feet so that the minimum DME distance from the localizer remained more than 1000 feet.

It appears that an improved directional VHF localizer and an improved DME would provide data with sufficient accuracy to permit the computation of linear displacement with a maximum error of about 30 feet. In addition to computing linear displacement, it would be desirable in the determination of runway distance ahead to have a distance accuracy better than 600 feet. The FAA has a project that intends to obtain a DME accuracy of 350 feet, which represents an optimistic view of what can be done with the standard type of DME by research and development on improved DME techniques.

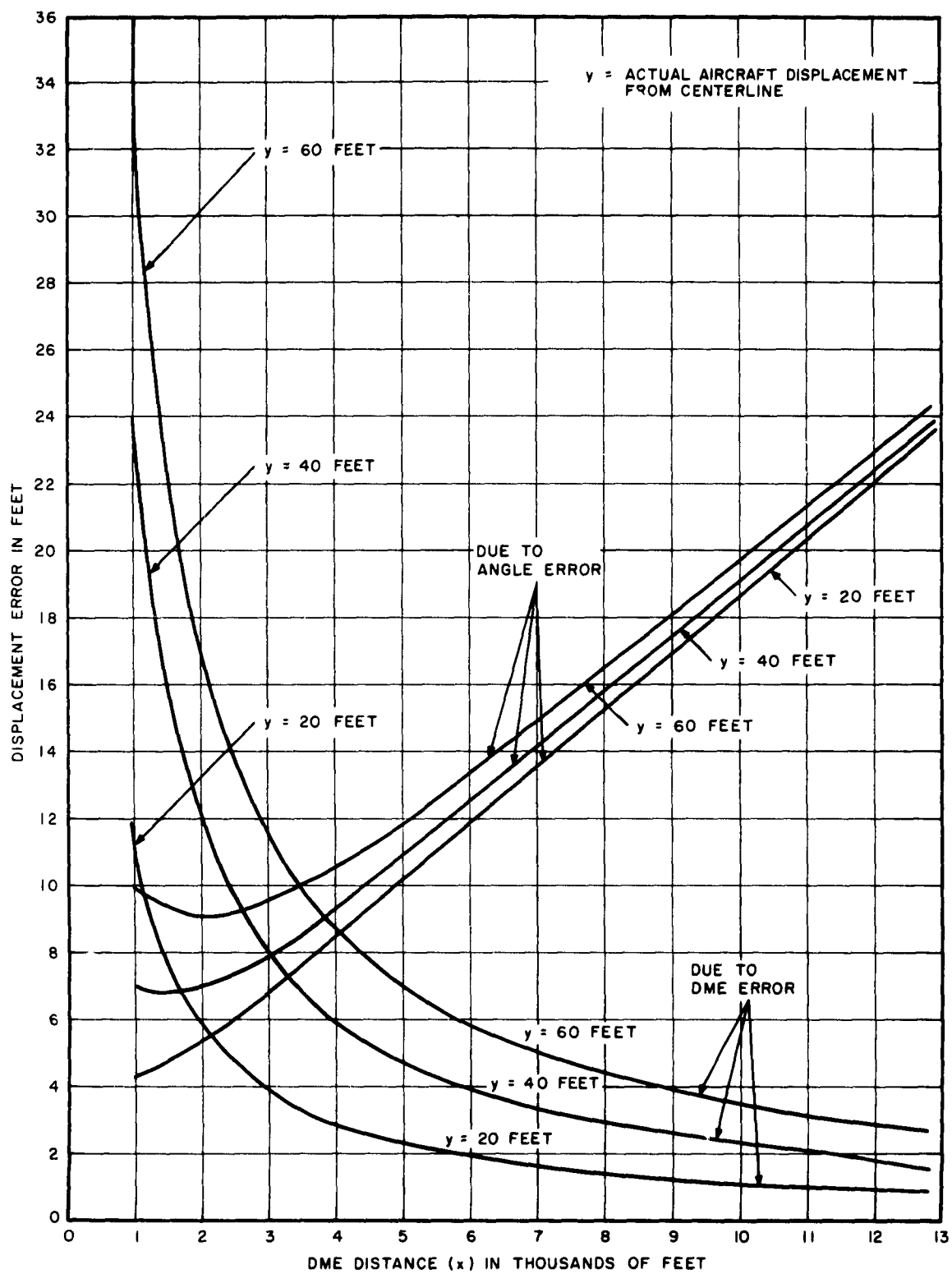


FIGURE 6-5. MAGNITUDE OF DISPLACEMENT ERRORS

Even greater improvements are promised by the K-band All-Weather Landing System development program. The DME accuracy of this system is specified to be 100 feet and the angular displacement accuracy is proposed to be 0.03 degree. Based on the experience of the measurements made on the FLARESCAN project, which has been under evaluation for about 2 years, these accuracy figures can be obtained using the K-band All-Weather Landing System.

The effect of this improved angular accuracy would be to reduce the slope of the curves due to angle error to about one-third the slope shown in Figure 6-5. The effect of the improved distance accuracy would be to reduce the ordinate values of the three curves for $\theta \Delta x$ to one-sixth of the values shown in Figure 6-5. The overall effect would be to obtain a linear-displacement error of less than 10 feet over the length of the runway, instead of the estimated 30-foot error for the VHF/L-band system. In addition, the value of runway ahead would be measured to an accuracy of 100 feet, instead of 600 feet (or 350 feet for the proposed improved L-band DME).

All these foreseeable improvements with the K-band system are worthwhile, but will not become available for about 2 years, even in a development model. However, a system consisting of an improved VHF localizer and an improved L-band DME will be available much sooner, and the accuracy implied by Figure 6-5 would certainly be a worthwhile improvement over the present operating system.

The guidance rules for in-flight localizer guidance and for runway localizer guidance are the same--that is, to establish a condition in which the displacement from the runway centerline is safely within tolerable limits and to prevent the displacement from increasing.

Passenger reaction and pilot confidence must be taken into consideration in instrument approach and landing; unusual or unnecessary changes in control must be kept to a minimum at low altitude. In localizer guidance, a satisfactory situation is defined as a tolerable small angular displacement from centerline, with no increase in angular displacement. Experience shows that, when the aircraft is airborne, the displacement seldom remains zero and that a small stable displacement is preferable to an oscillatory decreasing displacement. A perfectly satisfactory track, next best to the centerline extension, is one that is displaced from the centerline by a displacement distance that is small compared with the runway width.

Inherent in the prevailing use of the localizer for lateral guidance is the assumption that distance information is of minor importance in the in-flight region. In fact, at typical localizers, the distance is measured only approximately and discontinuously--once at the outer marker, once at the middle marker, and all along by occasionally relating the reading of the altimeter to the glide-slope angle. A DME readout would be more direct and more accurate, but not absolutely necessary for reaching the runway threshold in a safe condition for switching to visual references.

In a situation where runway guidance must be obtained from localizer information, it must be assumed that accurate distance information is required in order to determine runway distance to go and ground speed for a safely controlled stop. With accurate distance information available, the pilot would also find it useful in making the decision whether to land or to go around, and on the takeoff run, whether to continue or to stop if an emergency is indicated on the power, air-speed, or attitude references.

In the absence of DME, the localizer signal would directly show only angular displacement on the cross-pointer situation display. This signal could be combined with radio rate (rate of change of angular displacement) or with heading relative to the runway heading on the flight director.

Considering only the problem of runway surface guidance during rollout, steering action must be postponed until the nosewheel is down and the speed has decreased to about one-half of the landing speed about half-way down the length of the runway. Since the only lateral correction that is tolerated at low altitude is the decrab maneuver, the localizer display will probably show some deviation when steering becomes effective. Thus, the problem is to determine the kind of lateral guidance data that would be most useful for steering.

VII. SELF-CONTAINED GUIDANCE SYSTEMS

A. TAXI AND TAKEOFF

Ground guidance from the airport terminal until climbout includes the taxiing phase, initial location and alignment at or near the runway centerline; steering information during the takeoff run (such as heading, lateral displacement, runway remaining), and initial climbout heading.

In theory, a directional gyro, in combination with supplementary DME, could probably be designed to provide taxi guidance, but it is obviously an impractical approach because of the complexity of the maneuvers and the accuracy required, especially for precise tuning maneuvers at intersections.

A gyro system is also unable to define the initial centerline location at the start of the takeoff roll and some supplementary system is required, this function being provided by the taxiway guidance system. Except in the most severe weather, a visual method of locating the centerline can serve the purpose. The directional gyro is ideally suited to provide the initial alignment of the airplane along the direction of the runway and will probably be used for this purpose regardless of the final scheme adopted to provide takeoff guidance.

Only partial steering information can be provided by a gyro system during the takeoff roll. It appears that the heading information provided by a directional gyro would be directly usable as steering information with limited supplementary inertial devices--for example, a single lateral accelerometer--or kinematic information to keep track of lateral displacement from the runway centerline and the amount of runway remaining. This would be true if the airplane did not have to contend with the effects of cross winds. It will be shown that the side load on the airplane induced by a cross wind causes elastic deflection of the tires and they assume a yaw angle. Furthermore, structural deflections occur that tend to cause further deviation between the direction of the airplane velocity vector and the gyro heading indication. In essence then, cross winds during ground roll can introduce unknown angular deflections on the aircraft with magnitudes approaching the desired accuracy of the directional gyros in a ground-guidance system, and a reliable system must be based on the accurate determination of lateral acceleration. With an accurate measure of lateral acceleration, successive integrations provide lateral velocity and displacement. For consistency, runway remaining can be determined with a longitudinal accelerometer, though other on-board systems are possible (such as an odometer scheme).

B. LANDING

It would be preferable to have the same guidance system for the approach and landing roll, or at least to switch to rollout guidance at the final stages of the flareout. Neither alternative appears feasible with a purely inertial system (cross winds eliminate the consideration of a gyro system that depends on heading information alone); however, further consideration is warranted based on the attractiveness of the inertial system as a supporting system.

The directional gyro can supply aircraft heading and, if the required ground track is known (runway heading), the drift angle of the aircraft can be computed. As explained in Section V the drift angle must be eliminated by this decrab maneuver just prior to touchdown. For this reason, the directional gyro as part of the basic aircraft compass system is likely to be used for the solution of decrab, regardless of the guidance system finally chosen.

Initial lateral displacement before touchdown is best established with the aid of the localizer. A computer will be required to combine localizer and inertial information to establish the position of the airplane with respect to the runway centerline at the time of touchdown.

Runway remaining at the time of touchdown can be handled by means of a longitudinal accelerometer and some accurate reference point such as the localizer inner marker or a scheme set up particularly for this purpose.

In summary, a gyro-inertial ground-guidance system is only satisfactory during the landing ground roll. Other systems are required during the approach and turnoff phases of landing guidance.

C. SYSTEM DESIGN CONSIDERATIONS

A ground-directional-guidance system incorporating a directional gyro can take any one of several forms:

1. Directional gyro can be used alone for heading information during the ground roll.
2. Supplementary instrumentation can be incorporated in a system with the directional gyro as one of the primary sources of information. The two examples applicable are:
 - a. The "strap-down" inertial system, where accelerometers are rigidly attached to the airframe. Gyros are used to resolve the required acceleration vectors.
 - b. The "stable-platform" inertial system where the accelerometers are rigidly attached to a platform that is stabilized independently of the airframe by gyros.

3. Directional gyro (and possibly some supplementary instruments) can be used as a support system for cross-checking the primary system or providing alternative guidance in case of primary system failure.

1. DIRECTIONAL GYRO

Heading information alone supplied by a directional gyro can be used for ground directional guidance under certain conditions. One condition, which is common to any guidance system that depends primarily on inertial instruments, is providing an accurate method of locating the aircraft with respect to the centerline of the runway before the takeoff ground roll begins--that is, an initial point of reference is required. For landings, the initial alignment problem is more complex, and possible methods of providing the required initial lateral position reference for takeoff and landing has already been mentioned. It is worthwhile to note that, if an external lateral position reference system is used for landing, it will have to extend over a large portion of the runway length available in order to cover delayed touchdowns (overshoots). For runways commonly used in both directions, this could mean that the entire length would have to be instrumented. In this event, the lateral-position reference system could serve as the primary guidance system since it will define aircraft displacement from the center over the entire length of the runway, and gyro guidance would become secondary.

The use of a directional gyro in a takeoff and landing guidance system is complicated by the effects of cross winds, which produce a side load on the airplane and cause the longitudinal axis to deviate from the direction of motion--that is, the aircraft moves forward with a yaw angle. This effect is familiar when an airplane is airborne, but it is also present to some extent when the airplane is rolling along the runway because of the manner in which tires behave under the influence of a side load. Under normal circumstances, the yaw angles are negligible and probably not even noticeable to the pilot. However, if a 4000 to 5000 foot ground roll is assumed, the ground track must be true to within at least 0.5 degree and preferably 0.25 degree and, therefore, even a small angular error can be significant.

The magnitude of the yaw angle possible during ground roll in a cross wind has been evaluated using aerodynamic and tire characteristics corresponding to a Boeing 707 or 720 since these data were readily available. The analysis is simplified because only a result typical of a jet aircraft is desired.

The aerodynamic forces on an airplane rolling down a runway in a cross wind are determined by the basic airplane configuration and by the control inputs of the pilot. If the aerodynamic forces are not in equilibrium, the landing gears supply a ground-reaction force. In addition, the effects of engine thrust and aircraft inertia must be taken into account. Stability derivatives were used to derive

the aerodynamic forces on the airplane and these are only valid up to about a 10-degree maximum deviation of the flow from the symmetrical or zero-reference condition. This is a standard situation since the aerodynamic forces are usually nonlinear beyond these angles, and the motion of the aircraft in flight rarely exceeds these conditions. The flow angle of interest is the side-slip angle and, assuming a maximum cross-wind component of 15 knots (about 25 fps), the calculations were restricted to forward-velocity components greater than 85 knots (144 fps).

The following simplifying assumptions were made concerning the loading on the airplane:

1. Rolling moments due to side-slip are canceled by pilot lateral-control input.
2. Yawing moment due to engine side force is negligible compared with the other moments considered.
3. Yawing moments due to side-slip are canceled by rudder input. Above 80 knots, this is a valid assumption since nosewheel steering is not used at high speeds.
4. Nosewheels do not resist side forces above 80 knots but rather act like freely castering wheels.
5. Pitching moments on the airplane have only a second-order influence on the main landing-gear loads.
6. Magnitude of the side-force aerodynamic coefficients are approximately correct despite the proximity of the airplane to the ground.
7. Ground path of the airplane remains parallel to the centerline of the runway. In order to accomplish this in the presence of side forces, the nose of the airplane must point slightly into the cross wind.
8. All components that transmit the ground reaction loads to the airplane are perfectly rigid except for the tires. This is a conservative assumption since structural flexibility would increase the yaw angle.
9. Tire-cornering power is constant with speed. Reference 9 indicates that this is probably a valid assumption within the accuracy of these calculations.

The loading on the landing gears (Figure 7-1) can be determined from the following equations:

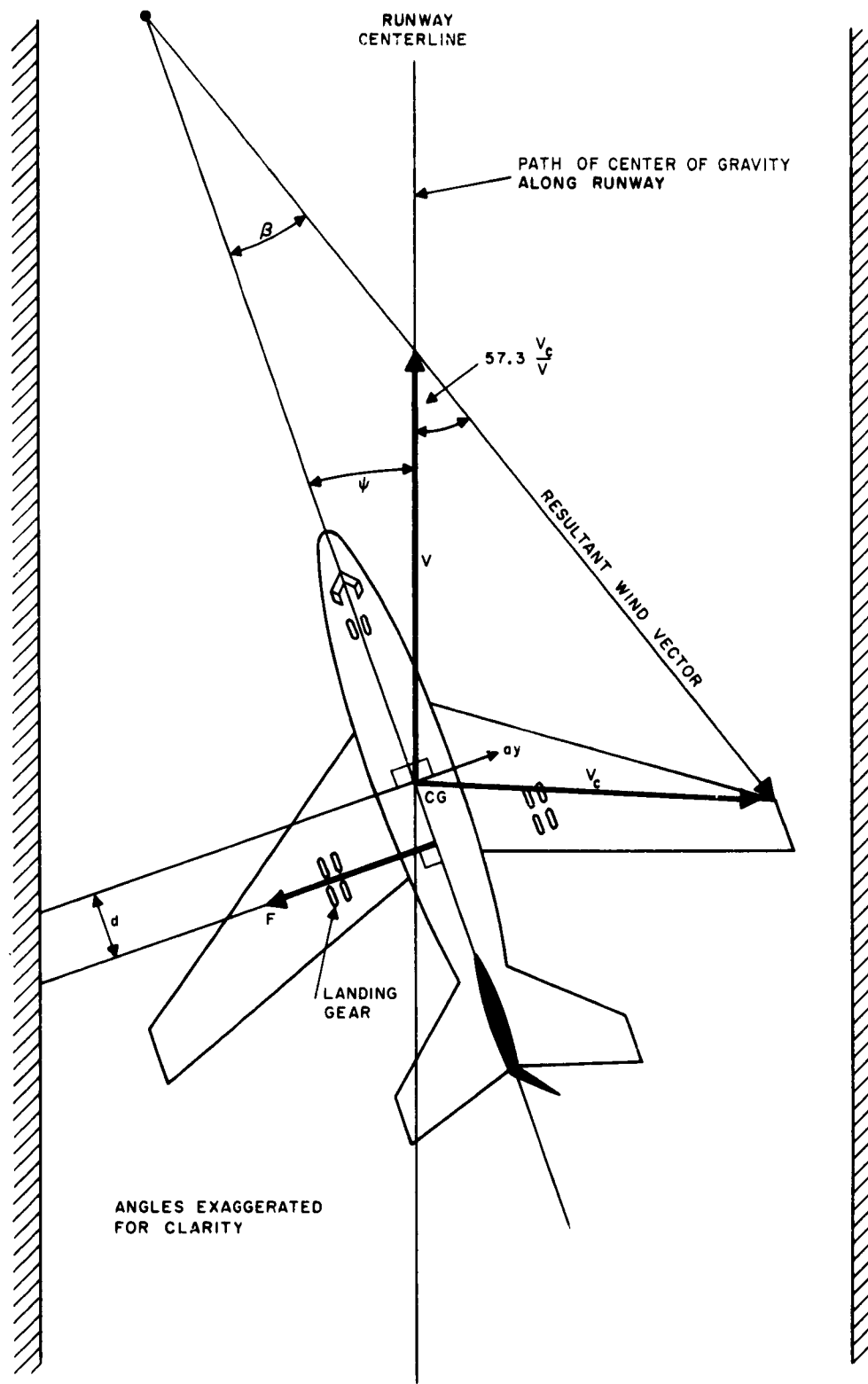


FIGURE 7-1. YAWED AIRCRAFT ROLLING DOWN RUNWAY

Side Load:

$$\frac{W_a}{g} \frac{V\beta}{57.3} + Y_\beta \beta - Y_{\delta_r} \delta_r - 2F = \frac{W}{g} a_y \quad (7-1)$$

Yawing Moment:

$$N_\beta \beta - N_{\delta_r} \delta_r - 2Fd = 0 \quad (7-2)$$

Vertical Load:

$$L - W + 2G = 0 \quad (7-3)$$

Side-Slip Angle:

$$\beta = \left(\frac{V_c}{V} \times 57.3 - \psi \right) \quad (7-4)$$

Accelerations:

$$a_y = a_x \tan \psi \quad (7-5)$$

Tire Side-Force:

$$F = K\psi \quad (7-6)$$

where

W_a = air flowing through all engines in pounds/second,

Y_β = side force per degree of side-slip,

β = side-slip angle in degrees,

Y_{δ_r} = side force per degree of rudder,

δ_r = rudder angle,
 F = side-force reaction on each main landing gear,
 W = airplane gross weight,
 $g = 32.2 \text{ ft/sec}^2$,
 a_y = lateral acceleration,
 N_β = yawing moment per degree of side-slip,
 N_{δ_r} = yawing moment per degree of rudder,
 d = longitudinal distance from the resultant main-landing gear side force to the center of gravity,
 L = lift force,
 G = vertical force reaction on each main landing gear,
 V_c = cross-wind velocity,
 V = forward velocity of airplane along runway,
 a_x = longitudinal acceleration,
 ψ = yaw angle,
 K = cornering power.

Combining the preceding equations, it can be shown that the yaw angle ψ can be defined as follows:

$$\psi = \frac{57.3 \frac{V_c}{V} q s \left[C_{y\beta} - C_{y\delta_r} \frac{C_{N\beta}}{C_{N\delta_r}} \right] + \frac{W_a}{g} V_c}{q s \left[C_{y\beta} - C_{y\delta_r} \frac{C_{N\beta}}{C_{N\delta_r}} \right] + 2K \left[1 - \frac{C_{y\delta_r}}{C_{N\delta_r}} \frac{d}{b} \right] + \frac{W}{g} \frac{a_x}{57.3} + \frac{W_a}{57.3g} V}$$

where

q = dynamic pressure,
 s = wing area,
 b = wing span.

Using Boeing data, typical low-speed values of the stability derivatives are:

$$\begin{aligned}C_{y\beta} &= 0.0135 \text{ per degree (30-degree flaps, gear down),} \\C_{y\delta_r} &= 0.00395 \text{ per degree,} \\C_{N\beta} &= 0.002 \text{ per degree (30-degree flaps, gear down),} \\C_{N\delta_r} &= 0.0017 \text{ per degree.}\end{aligned}$$

A typical value of d is 4 feet, the longitudinal acceleration (a_x) for takeoff is chosen as $1/4$ g, and engine airflow (typical of a fan jet) is assumed to be constant at 470 pounds/sec.

The value of the cornering power must be estimated. Information from an aircraft tire supplier to the airlines indicated that the Boeing 720 uses a Type VII, 40×14 , 24-ply, nylon-rib tire with a rated pressure of 160 psi. The Boeing 707 uses a Type VII, 46×16 , nylon-rib tire. However, one airline uses a 20-ply tire with a rated pressure of 145 psi and another uses a 24-ply tire with 170-psi rated pressure. The cornering power was calculated with the aid of equations 23 and 82 of reference 9 and equation 7-3 of this section. The equations to be solved, assuming the tires are operated at rated pressure, are:

$$\frac{W - C_L q s}{8 \times 1.08 P w \sqrt{w D}} = 2.4 \left[(\delta/W) - 0.03 \right] \text{ for } \delta/W \geq 0.1 \quad (7-8)$$

$$\frac{K(\text{force/degree})}{1.44 P w^2} = 1.2 (\delta/D) - 8.8 (\delta/D)^2 \text{ for } \delta/D \leq 0.0875 \quad (7-9)$$

where

- C_L = lift coefficient,
- P = tire pressure,
- w = width of tire,
- D = diameter of unloaded tire,
- δ = vertical tire deflection.

Table VII-1 summarizes the cornering-power capabilities of the several tires in use at a vertical loading corresponding to a 200,000-pound airplane at 100 knots at sea level with 30-degree flaps.

TABLE VII-1
CORNERING POWER (K) FOR VARIOUS TIRES

<u>Tire Size and Ply Rating</u>	<u>Rated Pressure (psi)</u>	<u>K per Tire (pounds)</u>	<u>K for four Main Wheels (pounds)</u>
40 x 14, 24 ply	160	1790	7160
46 x 16, 20 ply	145	2020	8080
46 x 16, 24 ply	170	2240	8960

The yaw angle can now be calculated. A value of 2000 pounds/degree is chosen for K (per tire) since it is close to an average value for the three tires. For a gross weight of 200,000 pounds and a velocity of 100 knots at sea level during takeoff (30-degree flaps) in a 15-knot cross wind, $\psi = 0.47$ degree. A similar calculation for 130 knots yields a yaw angle of $\psi = 0.60$ degree. These two calculations showed that the value of the denominator in equation 7-7 is reasonably constant during the high-speed portion of the takeoff ground roll since the cornering-power term dominates the denominator and the small changes that occur in this term are partially compensated for by a change in the first term of the denominator. As a consequence, in a constant cross wind during takeoff, the variation of yaw angle with forward speed (above the nosewheel steering speed) is approximately linear. The exact variation, taking the changes in all the terms of equation 7-7 into account, is shown in Figure 7-2. At the nosewheel-steering termination speed of 80 knots, the value of ψ is about 0.38 degree. Although no reliable estimate is possible of the yaw angles below about 80 knots, an estimate of the total lateral deviation from the runway centerline during a 4500-foot takeoff ground roll can be made assuming that the pilot tries to maintain a constant gyro-compass reading. (The side loads and yaw angles on the airplane are almost identical to the conditions calculated previously. The slight differences would be due to the fact that, for the previous calculations, the airplane was assumed to be traveling in a straight line down the runway, whereas, in the following, the airplane travels a path that curves slightly down wind relative to the cross wind.) The approximately linear variation of yaw angle with forward velocity is assumed valid over the entire takeoff run. Although this seems to be a rough assumption in light of the lack of information below 80 knots, it should introduce only a relatively small amount of error since small yaw angles are involved and only about 1/3 of the takeoff distance occurs up to 80 knots. Furthermore, it is likely that this variation underestimates the true situation at low speeds and overestimates it at somewhat higher speeds, which tends to cancel some of the error. The assumption is also made that the forward acceleration is constant throughout the takeoff. Therefore,

$$\psi = K_1 V + K_2 \text{ (radians)} \quad (7-10)$$

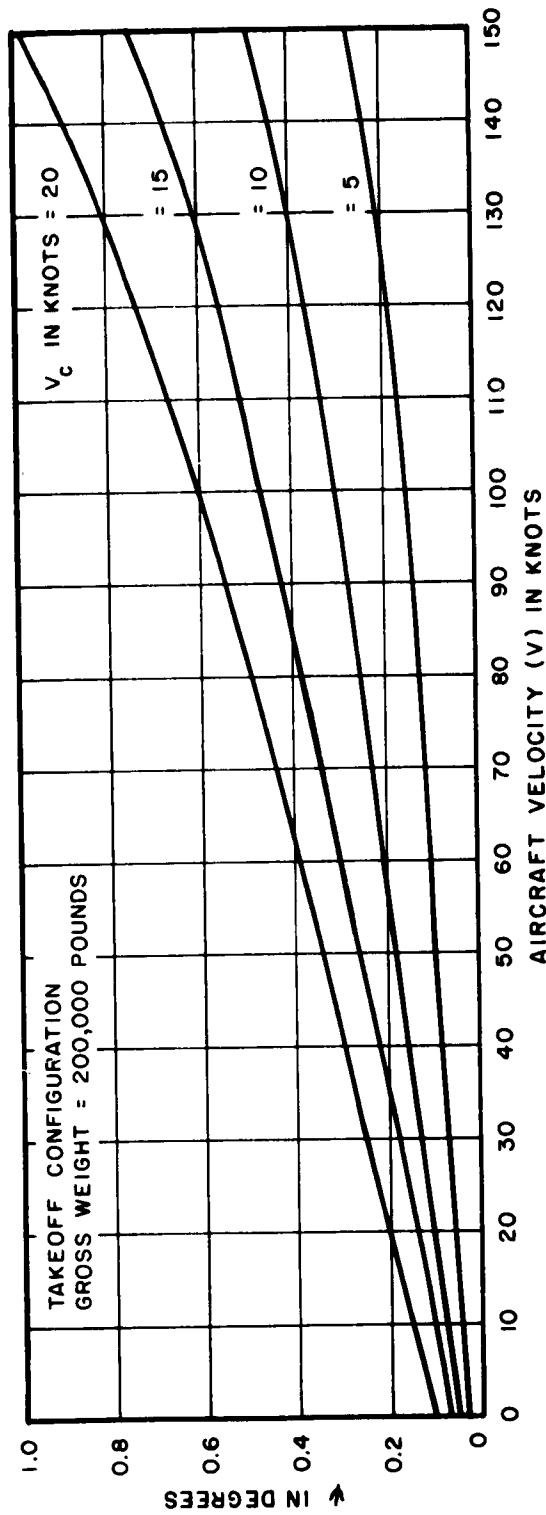


FIGURE 7-2. YAW ANGLE DUE TO SIDE-LOAD ON TIRES DURING CROSS-WIND CONDITIONS DURING TAKEOFF

$$V = at \quad (7-11)$$

$$S = \int_0^t V \psi dt \quad (7-12)$$

where

K_1 = constant of proportionality in rad/fps,

K_2 = constant due to engine side force,

a = longitudinal acceleration in ft/sec²,

S = lateral deviation from runway centerline in feet,

t = time from $V = 0$ in seconds.

Substituting equations 7-8 and 7-9 into equation 7-12 yields

$$S = \frac{2}{3} K_1 VR + K_2 R \quad (7-13)$$

where R is the runway distance from $V = 0$ in feet.

This variation of lateral displacement with runway distance is plotted in Figure 7-3 for several cross-wind components and final velocities for a gross weight of 200,000 pounds. For 4500 feet of runway used and 135 knots in a 15-knot cross wind, the lateral displacement is about 34 feet. For longer used runway lengths, the lateral deviation increases proportionally. If this figure can be considered as typical, the error due to side loads on the airplane during normal takeoffs in cross-wind conditions is seen to be appreciable especially when it is realized that on a standard runway the Boeing 707 main gear would go off the edge at about 64 feet from the centerline. For the emergency condition of an aborted takeoff, where runway distances of about 8000 feet would not be inconceivable, Figure 7-3 indicates that about 15 knots of cross wind would bring the 707 to the edge of the runway. During known cross winds, the airplane could be started with an initial offset relative to the centerline of the runway and thereby cancel the major portion of this effect. However, the wind usually occurs in gusts, and, if its velocity happens to drop off to a few knots during the last several seconds of the takeoff run, the offset would represent a loss in useful runway width.

Figure 7-4 illustrates the variability of the yaw angle. In the landing configuration, assuming the flaps are held at full deflection and the gross weight is 175,000 pounds, the yaw angle tends to build up rapidly at the higher airspeeds and cross-wind velocities. This is the effect of reduced vertical load on the main wheels due to high wing lift and low gross weight. It is apparent then, that airplane configurations that reduce the vertical load on the main wheels tend to increase the lateral deviation.

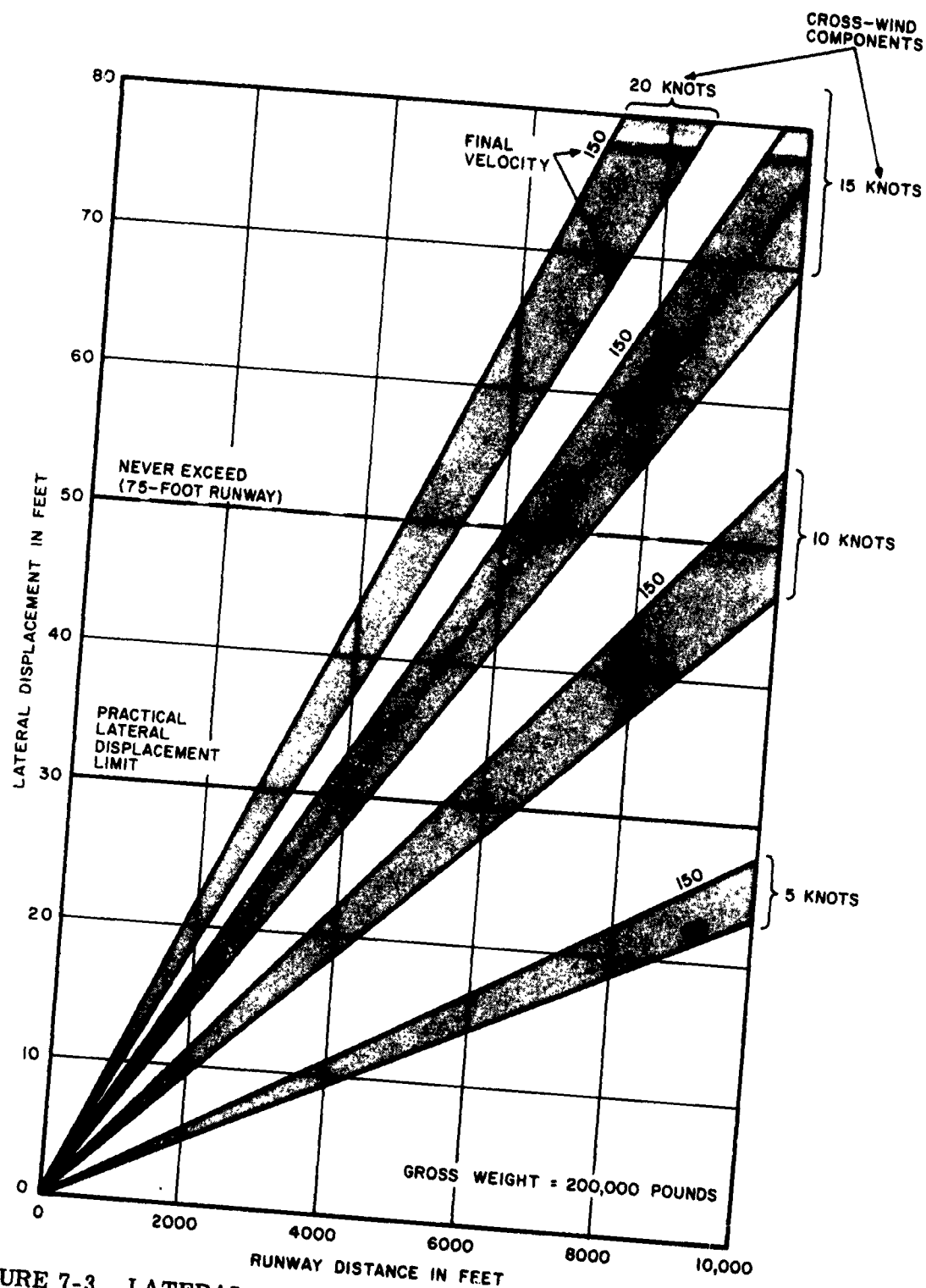


FIGURE 7-3. LATERAL DISPLACEMENT OF AIRPLANE FROM RUNWAY CENTERLINE DURING TAKEOFF DUE TO CROSS WIND

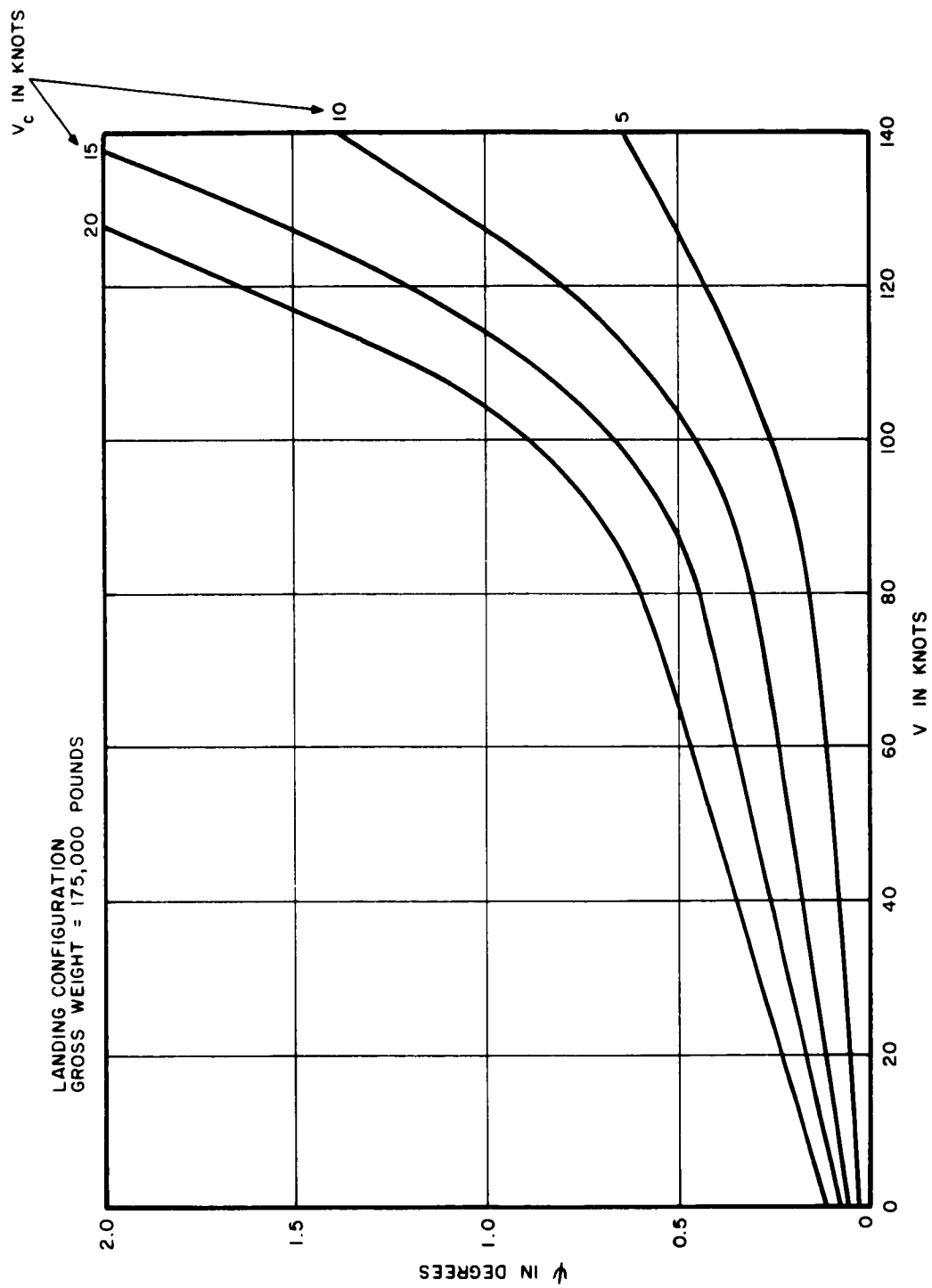


FIGURE 7-4. YAW ANGLE DUE TO SIDE LOAD ON TIRES DURING CROSS-WIND CONDITIONS DURING LANDING

Another factor should be considered. Poor visibility on the ground is often associated with moderate winds during rain or snow, and the maximum coefficient of friction (μ) between the tires and the runway is not as high as for dry conditions. The variation of tire side force with yaw angle consists of a linear variation that eventually tends asymptotically to a maximum value determined by the maximum friction force. Typical curves, calculated from Figure 46 of reference 9, are presented in Figure 7-5. The curve for $\mu = 0.75$ is for a dry concrete runway for the airplane under consideration. The curve for $\mu = 0.1$ may be considered to represent a dry ice surface (well below freezing). For side forces of about 1000 pounds per tire, which corresponds to a 15-knot cross wind and the conditions shown in Figure 7-5, the tires are still operating in the linear range of the side-force yaw-angle characteristic curve. Any appreciable increase in forward speed and cross-wind velocity or decrease in the maximum friction coefficient will disproportionately increase the yaw angle. Under certain conditions, extremely low friction coefficients can be encountered with wet surfaces (references 10 and 11), and the tire, in effect, hydroplanes on a layer of water. In such a situation, the airplane is essentially out of contact with the ground and asymmetric thrust or aerodynamic forces must be used to control the path of the airplane. The proper heading needed to accomplish a straight path down the runway can deviate by many degrees from the runway azimuth during landing or takeoff. In such an emergency, a gyro heading indication by itself provides grossly inadequate information.

2. DIRECTIONAL GYRO AND SUPPLEMENTARY INERTIAL INSTRUMENTATION

A more versatile, self-contained, ground-guidance system consists of a directional gyro for heading information and additional inertial instrumentation for defining airplane attitude and linear acceleration. The instrumentation can be packaged in many different ways that generally can be classified as either strap-down systems or stable-platform systems.

A strap-down system is worthy of investigation since it could theoretically use the directional and vertical gyros already in the airplane as part of its system, with consequent savings in cost and weight. The stable platform is a fairly complex and expensive equipment, but it also warrants consideration because it may be useful as an enroute navigation aid or as basic instrumentation on future aircraft and would therefore be available. Regardless of the type of system used, additional inertial instrumentation beyond the directional gyro provides accurate ground-roll guidance information despite the presence of cross winds.

a. STRAP-DOWN SYSTEM

The strap-down system, as its name implies, has all its components rigidly attached to the airframe and an analytical transformation of the aircraft-fixed measurements to an earth-fixed coordinate system is required. The acceleration components can be expressed as (reference 12):

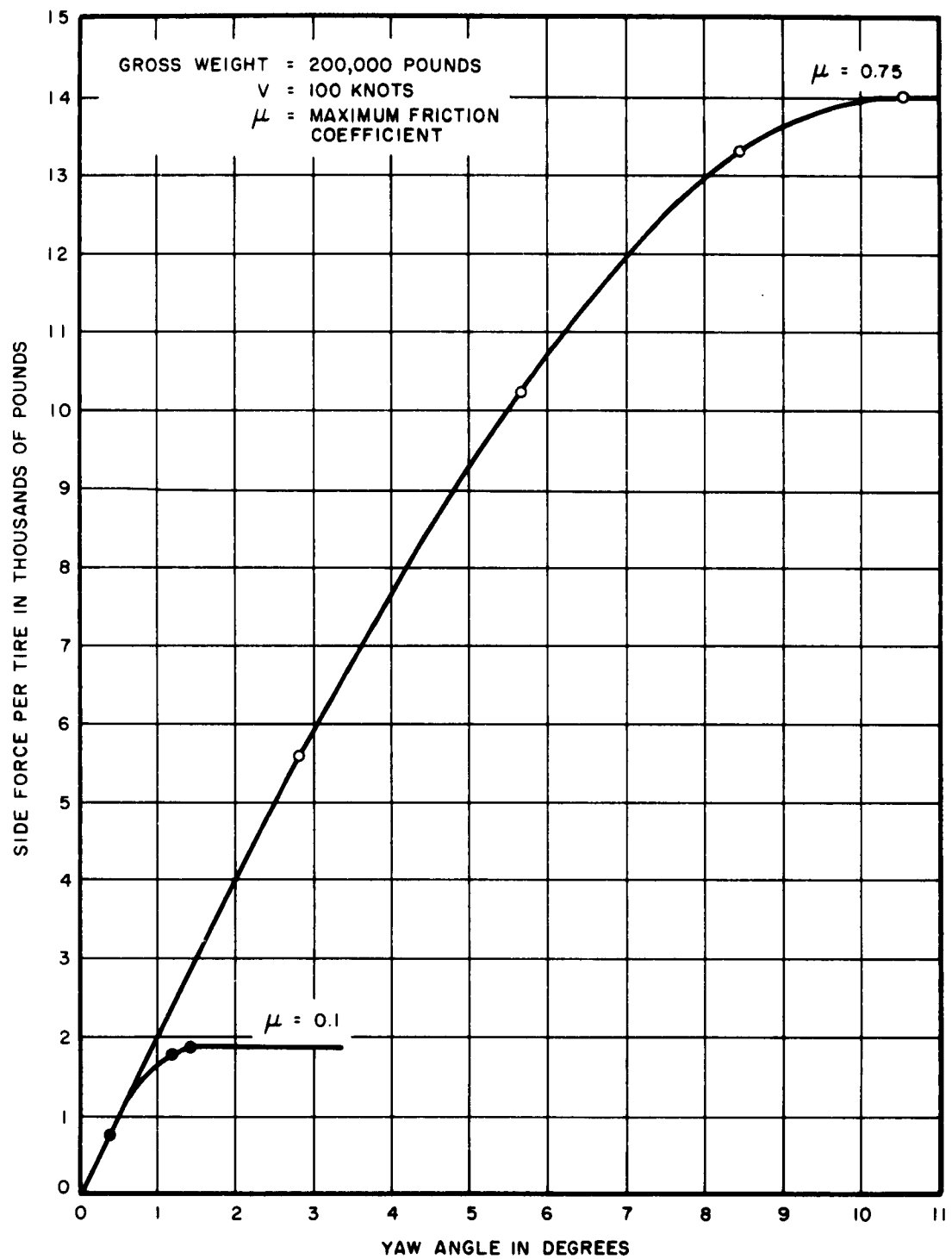


FIGURE 7-5. YAWED ROLLING CHARACTERISTICS FOR VARIOUS FRICTION COEFFICIENTS

$$A_X = a_X \cos \theta \cos \psi + a_Y (\sin \emptyset \sin \theta \cos \psi + \cos \emptyset \sin \psi) \quad (7-14)$$

$$+ a_Z (\cos \emptyset \sin \theta \cos \psi - \sin \emptyset \sin \psi)$$

$$A_Y = -a_X \cos \theta \sin \psi + a_Y (-\sin \emptyset \sin \theta \sin \psi + \cos \emptyset \cos \psi) \quad (7-15)$$

$$+ a_Z (-\cos \emptyset \sin \theta \sin \psi - \sin \emptyset \cos \psi)$$

$$A_Z = -a_X \sin \theta + a_Y \sin \emptyset \cos \theta + a_Z \cos \emptyset \cos \theta + 1 \quad (7-16)$$

where

A_X, A_Y, A_Z = longitudinal, lateral, and vertical components of acceleration in earth-fixed axes,

a_X, a_Y, a_Z = longitudinal, lateral, and vertical components of acceleration in airplane-fixed axes including the effect of gravity,

$\emptyset, \theta, \psi$ = roll, pitch, and yaw angle of airplane axes relative to earth-fixed axes. (The ψ convention used in this report is opposite to that used in reference 12.)

These expressions are involved, and a complicated computational system would be required to cover the full operational range of all the parameters. During a normal cross-wind ground roll, some simplification of the equations is possible since, for this case, the angles are all small and it is a good approximation to consider the cosine of the angle equal to 1.0 and the sine of the angle equal to the angle in radians. The following approximate relationships of A_Y and A_X are obtained:

$$A_Y \approx -a_X \psi + a_Y - a_Z (\emptyset + \theta \psi) \quad (7-17)$$

$$A_X \approx a_X + a_Z \theta \quad (7-18)$$

These expressions help to clarify the transformation equations by pointing out the most important components of runway lateral and longitudinal displacement and provide the means for a first-order estimate of the accuracies required of the inertial instrumentation. The most important component is the lateral acceleration. This component requires a knowledge of airplane acceleration and attitude angle about all three axes. Longitudinal acceleration (earth-reference)

requires knowledge of airplane vertical acceleration and pitch angle in addition to longitudinal acceleration. In a cross-wind situation during the ground roll, a yaw, pitch, and roll angle will usually be present.

It is of interest to determine the loss in accuracy in A_y involved in making a small-angle assumption. Figures 7-6, 7-7, and 7-8 present the results of calculations using typical values of the various parameters under cross-wind takeoff conditions. The value of A_y in equation 7-17 was held constant at 0.002 g, a_x was set equal to 0.2, a_z was set equal to 1.0, and a_y was allowed to assume values consistent with the chosen values of θ , ϕ , and ψ and the above assumption of A_y equal to 0.002 g. The exact value of A_y was then computed. The error was determined and expressed as a percentage of the true value. For small angles of pitch and roll during takeoff (2 degrees or less), which is the usual situation, it can be seen from the curves that a yaw angle of 7 degrees results in 10-percent error or less. All the angles can go to about 4 degrees without exceeding the 10-percent error. This error is such that equation 7-17 indicates too high a value of lateral acceleration and is, therefore, conservative. The positive values of the angles ϕ , θ , and ψ correspond to the windward wing raised and the nose of the airplane up and pointed into the wind.

If the instrumentation were connected to solve the equation for A_y , the output would have to be successively integrated to obtain lateral velocity and the displacement relative to the initial lateral position. It is apparent that high instrument accuracy and sensitivity would be required since the equation to be solved involves small differences of relatively large numbers. The approximate magnitudes of A_x and A_y can be estimated for a typical takeoff ground roll by assuming a takeoff distance of 4500 feet, constant longitudinal acceleration, a takeoff speed of 135 knots, and an available runway width of 65 feet. The takeoff distance of 4500 feet and the available runway width of 65 feet are somewhat optimistic since we have shown that the entire runway length should be considered for aborted takeoffs and that the maximum usable runway width is only 50 feet (Section V). The figures used here are therefore intended as a basis for calculation and not as a final operational requirement.

Assuming constant longitudinal acceleration

$$A_x = \frac{V^2}{2R} = \frac{(135 \times 1.69)^2}{2 \times 4500} = 5.78 \text{ ft/sec}^2 = 0.18 \text{ g}$$

The average value of lateral acceleration that just brings the airplane to the edge of the runway during the 4500-foot ground roll can be computed from:

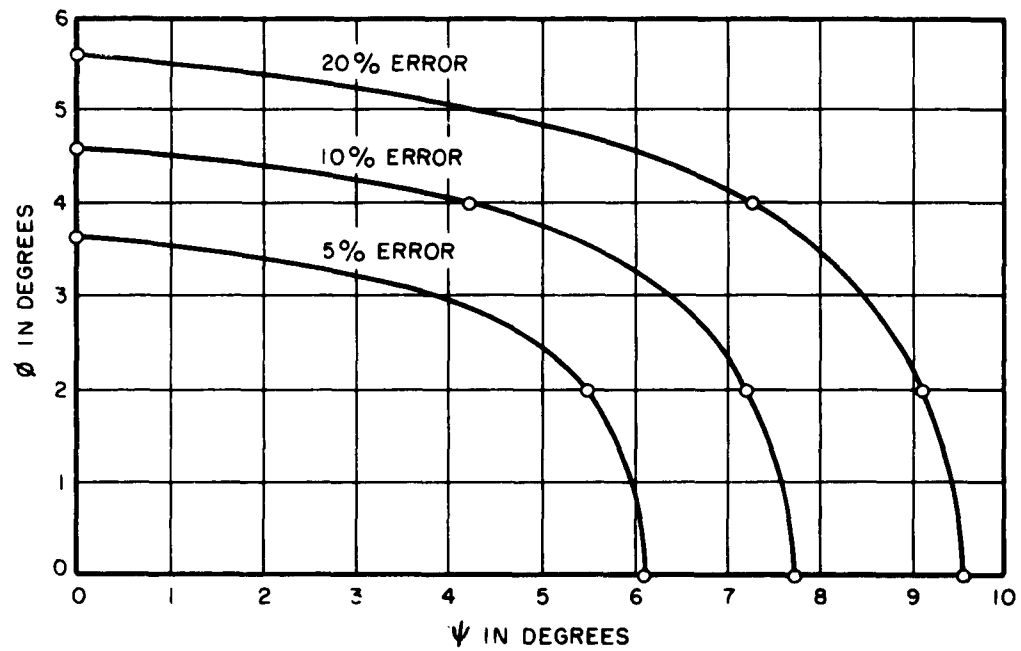


FIGURE 7-6. ERROR IN LATERAL ACCELERATION DUE TO SMALL-ANGLE ASSUMPTION: $\theta = 0$ DEGREE

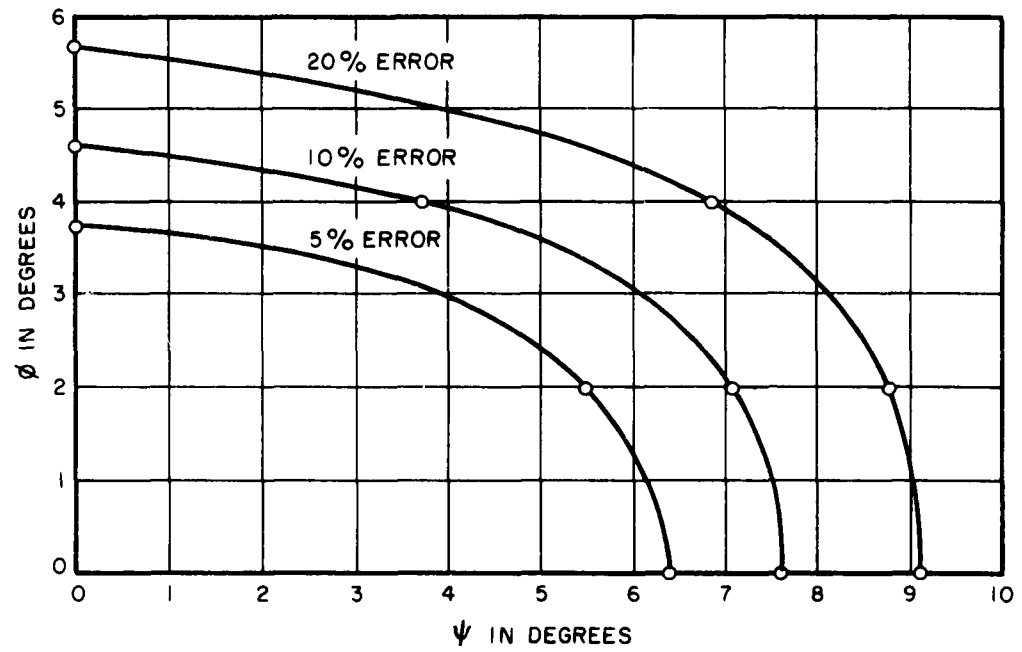


FIGURE 7-7. ERROR IN LATERAL ACCELERATION DUE TO SMALL-ANGLE ASSUMPTION: $\theta = 2$ DEGREES

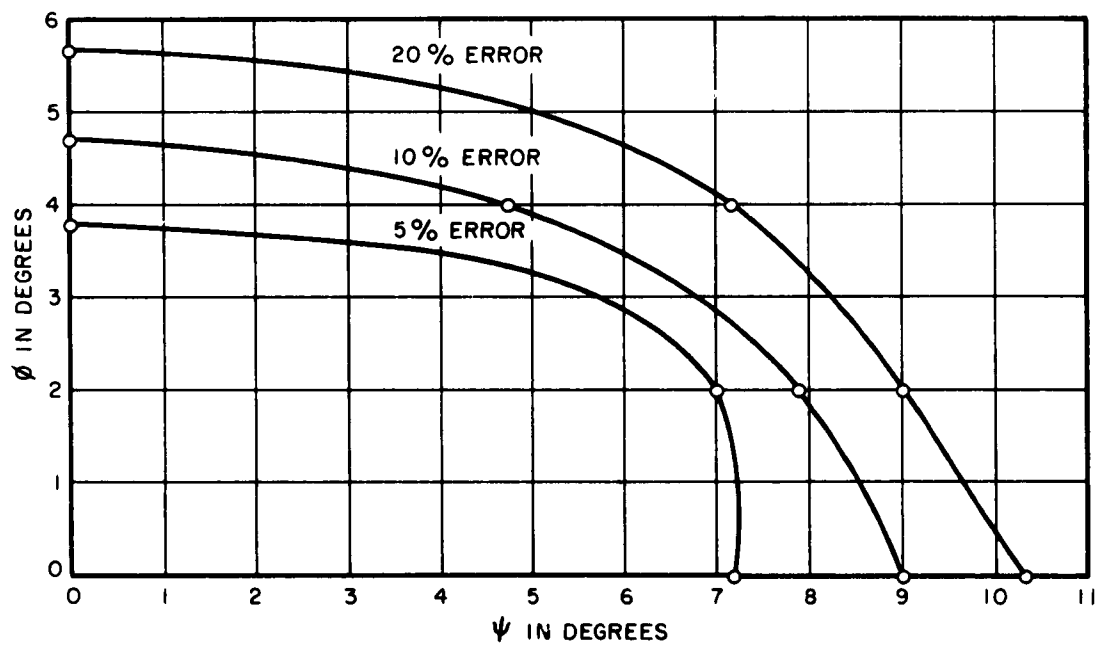


FIGURE 7-8. ERROR IN LATERAL ACCELERATION DUE TO SMALL-ANGLE ASSUMPTION: $\theta = 6$ DEGREES

$$\begin{aligned}
 A_Y &= 2S \left(\frac{A_X}{V} \right)^2 \\
 &= 2 \times 65 \times \left(\frac{5.78}{135 \times 1.69} \right)^2 \\
 &= 0.0832 \text{ ft/sec}^2 \approx 0.0026 \text{ g}
 \end{aligned}$$

Assuming that ψ rarely exceeds about 1.5 degrees (as justified earlier), the roll angle does not exceed about 5 degrees due to ground-clearance problems and the pitch angle does not exceed 2 degrees, the average value of a_y is a maximum of about

$$0.0026 + 0.18 \times \frac{1.5}{57.3} + \frac{2 \times 1.5}{(57.3)^2} = 0.0955 \text{ g} \approx 0.1 \text{ g}$$

The total error in solution of the equation for A_Y should not be allowed to exceed 0.0026 g since this carries the airplane to the edge of the runway. In order to provide some margin of time for the pilot to react, errors in the initial determination of lateral position and small-angle approximations, it will be assumed that the overall maximum error should not exceed $3/4 \times 0.0026 \text{ g}$ or 0.002 g.

The accuracy requirement is easily met for the lateral accelerometer. For example, reference 11 presents the characteristics of typical pendulum accelerometers. The Kearfott Type C70 2401 005 accelerometer, which is a typical force-balance type using an inverted pendulous mass in conjunction with a flexure type of suspension, weighs only 4 ounces, has a linearity within $5 \times 10^{-6} \text{ g/g}^2$, a threshold of $2 \times 10^{-7} \text{ g}$, and a zero stability of $1 \times 10^{-5} \text{ g}$. Similar specifications apply to the Kearfott Type 425093-1 accelerometer, which weighs 2 pounds, has a linearity within 0.02 percent of applied acceleration, a threshold of less than $5 \times 10^{-7} \text{ g}$, and zero stability (over a continuous time interval) of $\pm 2 \times 10^{-5} \text{ g}$. These instrument capabilities are far enough beyond the levels of accuracy and sensitivity required for acceleration measurement to place the burden on the measurement accuracy of the attitude angles.

In order to assess the possibility of using the most common type of directional gyro systems in commercial use today, an estimate of the yaw-angle measurement accuracy required has been made assuming that the roll-angle measurement is exact and that the accelerometers contribute no error. Then, the maximum error in the directional gyro reading should not exceed $3/4 \times \frac{65}{4500} \times 57.3 = 0.62 \text{ degree}$. Gyro-magnetic systems use earth magnetic-reference information, such as

from a flux-gate transmitter, to provide a continuous azimuth torquing signal. The random errors inherent in this system are (references 11 and 13):

1. Drift errors. --Directional gyros tend to drift in a random manner within certain limits depending on the design and condition of the instrument. Reference 11 indicates a free drift rate as low as 0.25 degree per hour for the Kearfott Type C70 2204 001 and as high as 4 degrees per hour for Kearfott Type C70 2215 002.
2. Detector errors. --The magnetic detector can reasonably be assumed to have an accuracy of ± 20 minutes.
3. Resolver and gearing errors. --30 minutes of error is assumed as a tolerance.
4. Synchro errors. --14 minutes of error per synchro is assumed with two synchros contributing to the error.
5. Swinging errors. --A typical recording accuracy of calibration is $1/4$ degree, but 0.1 degree is assumed.

Since it is unrealistic to directly add all these figures, a root-mean-square error has been estimated. References 11, 13, and 14 indicate that gyros exhibit random errors distributed about a mean zero in a pattern that is approximately normal. References 12 and 13 assume a truncated normal distribution with a standard deviation that is half of the maximum value; the same assumption is applied in this report. On this basis, the maximum possible error, neglecting drift error, is $0.33 + 0.5 + 0.47 + 0.1 = 1.40$ degrees. On an rms basis, $\sigma = 0.34$ degree, and the error would always be less than 1.40 degree, and less than 0.62 degree on 93 percent of all occasions. A maximum error of 1.4 degrees is not satisfactory accuracy and the error is large enough to indicate that either a great improvement must be made in the components comprising the compass loop or the magnetic information should be bypassed and dependence placed entirely on the inertial properties of the gyroscope for directional information.

The only terms in equation 7-17 that have not been discussed are the roll angle and the pitch angle. The roll angle is the more critical parameter requiring high measurement accuracy and will generally be nonzero, especially during cross-wind conditions. Since a_z is almost equal to 1.0 during the periods of interest to the ground-guidance problem, the magnitude of the roll-angle error should be appreciably smaller than 0.002 radian (which is equivalent to 0.12 degree) if the total error in A_y is to be held to within 0.002 g. This stringent requirement can only be satisfied with the highest-quality gyros. For instance, a typical Kearfott vertical gyro with good performance characteristics can be set to vertical within ± 3 minutes of arc and has a free drift rate of 1.5 degrees per 5 minutes. Assuming

a time of 30 seconds for takeoff, a total maximum vertical-angle error of $3/60 + 1/10 \times 1.5 = 0.20$ degree can occur during takeoff--a value well beyond that allowable (0.12 degree). Actually, it is more reasonable to assume a half hour for random drift since very accurate vertical referencing is best done with the airplane at rest prior to taxiing. Furthermore, delays will be common in bad weather. For delays of this length, the error is intolerable.

Therefore, it appears that a strap-down system is not practical using the standard vertical and directional gyro in present-day aircraft. Higher-performance gyros would be required, particularly for definition of the vertical. Appreciable expense is involved in the purchase of these units and the system would be restricted to small angles unless the full transformation equations are solved. This could be done with the use of complex circuitry that could compute the vector components and correct for gravity, but this technique has not yet reached the sophistication and reliability desirable in a commercial unit.

b. STABLE PLATFORM

With a stable platform, the transformation equations need not be solved since the accelerometers are, in effect, decoupled from the aircraft. It is assumed that the platform will not be put aboard for the exclusive purpose of providing ground directional guidance and that it will have another, probably primary, function. This function will probably determine the type of platform configuration--that is:

1. Geometric. --Gyros fixed in space and accelerometers follow local vertical,
2. Semianalytic. --Gyros and accelerometers follow local vertical,
3. Analytic. --Gyros and accelerometers are fixed in space with no attempt to orient them with local vertical.

All of the systems can be satisfactorily applied to the ground-guidance problem. The systems that automatically orient themselves with the local vertical eliminate the need for computing corrections for earth rotation; however, all of the systems require a correction for Coriolis acceleration. Coriolis is expressed in Ferrel's law, which can be simply stated as any freely moving body traveling at a constant speed above the earth is subject to an apparent force caused by the earth's rotation which deflects its path (to the right in the Northern hemisphere). This deflection can be significant even for the low velocities involved during the ground roll.

The accuracy of a stable platform is exemplified by the Kearfott miniature stable element C70 2664 001, which uses floating rate-integrating gyro and high-accuracy synchro resolvers for gimbal-output readout. Kearfott claims a readout accuracy of +1 minute of arc over +15 degrees and a drift rate of 0.003 degree/hour for the roll axis and 0.015 degree/hour with the same readout accuracy for the

azimuth axis. Including the accelerometers, this unit weighs about 14.3 pounds. The maximum error in roll angle with these specifications one-half hour after referencing the unit is $\frac{1}{60} + \frac{1}{2} \times 0.003 \approx 0.018$ degree. This is approximately equivalent to $\frac{0.018}{57.3} = 0.00031$ g lateral acceleration error, or an angular error of about 0.1 degree--within the desired accuracy.

Azimuth accuracy is within the level required, as far as ground guidance is concerned, and this is also true of pitch-attitude accuracy.

So far, only typical takeoff conditions have been considered. It is important to consider the emergency case of aborted takeoff. If the runway length used in this emergency can be assumed to be a maximum of twice the typical runway used, then the total allowable error in lateral acceleration is reduced to about 0.001 g. The lateral acceleration error of a stable platform is still within this requirement.

It is interesting to note that the quantities required for accurate ground guidance are lateral acceleration and its derivatives, lateral velocity and lateral displacement, rather than heading. The azimuth output can be used to provide initial steering information before the velocity components are large enough to be reliable, but then the linear acceleration information must be displayed to the pilot.

3. DIRECTIONAL-GYRO SUPPORT SYSTEM

Any system chosen for the ground-guidance task would have to be very reliable before it would be adopted by the airlines or used by the pilots. Reliability can be achieved by redundancy--that is, by using multiple identical systems or parts of systems--or by providing a separate monitoring system. Multiple redundancy is usually an expensive proposition from the standpoints of economics and additional weight. A gyro-inertial system for ground guidance may be useful for the monitoring function and for emergency guidance if another system is used for primary guidance. If the inertial instrumentation is already on board for other purposes, adding the ground guidance function may be the least-expensive way to achieve the desired reliability.

D. MANUAL DISPLAY

The information gathered by the ground-guidance system can be presented to the pilot or incorporated into an automatic control system.

The output information should be presented in a form that is easily digested--that is, it should be pictorial or be presented a familiar type of instrument such as an ILS display. If possible, all the cues should be incorporated into one instrument. Reference 15 suggests an interesting instrument design that is based on the Sperry R-1 Pictorial Deviation Indicator. The instrument face displays a plan

view of the airplane fixed to the glass cover of the instrument case and a "movable runway" (below the glass) that is controlled by the guidance system inputs. The runway can rotate to represent a pointing error, and it can translate to represent lateral deviation. The visual cues required for steering can be listed as follows:

1. Yaw rate,
2. Lateral displacement,
3. Lateral displacement rate,
4. Ground track,
5. Heading.

A gyro-inertial system can easily supply the inputs corresponding to these five cues. However, the ground track information should not be based on the directional gyro, which can supply heading information only.

E. AUTOMATIC SYSTEMS

It is considered unlikely that pilots will accept an automatic ground-guidance system that they cannot monitor closely and override instantly, if required. Therefore, despite the provision of an automatic steering system, a manual display of the type previously discussed would still be required. An automatic system would only be incorporated under these circumstances if it could perform with better response and accuracy than the pilot. It is not within the scope of this study to discuss the design of an automatic steering system; however, it is noted that a gyro-inertial system provides at least two usable error signals--heading and lateral-position error. The heading and lateral-position rates are also easily derived. If integral feedback is desired, the total lateral deviation from the runway centerline could provide this input.

VIII. INFRARED TECHNIQUES

Low-visibility meteorological conditions can occur during driving rains or blowing snow; haze and smog are rarely a serious problem. However, the most consequential weather limitation affecting aircraft operation is fog. Therefore, this discussion will emphasize the investigation of any improvement afforded in the penetration of fog using infrared radiation.

Meteorologists define fog as a visible aggregate of minute water droplets in the atmosphere near the earth's surface, which, according to international definition, reduces visibility to below one kilometer (3281 feet). Fog differs from cloud only in that the base of fog is at the earth's surface, whereas clouds are above the surface. Although fogs are further defined by the meteorological phenomena that create the condition, this section will refer to fog by its statistical stability and density because the latter characteristics are more meaningful to aircraft operation. Relatively little is known about the physical parameters and behavior of fog from a quantitative aspect. In general, fog is highly unstable and nonhomogeneous.

Several investigators in the photometric field have experimented and theorized on the performance of infrared radiation, and they have concluded that the difference in performance between infrared radiation and visible light is inconsequential. This section re-examines the experimental results of these photometric studies with a view toward guidance and navigation of aircraft on the surface of an airport.

Rather than attempting to invent or design an infrared system, we have evaluated fundamental system parameters (such as atmospheric attenuation, detectors, infrared radiation sources, and backgrounds) to ascertain the potential of infrared radiation. The performance is computed relative to visible light with the human observer as the detector. Two cases are considered:

1. Variation of wavelength to reduce atmospheric attenuation,
2. Variation of wavelength to maximize radiant emittance or transmitted power.

The evaluation is based on experimental results and theory.

Infrared radiation is loosely defined as that portion of the electromagnetic spectrum between light and microwaves. Light is the band between 0.4 and 0.7 micron (1 micron = 10^{-6} meters). The infrared region is further subdivided as follows:

- 0.7 to 1.5 microns -- near
- 1.5 to 10 microns -- intermediate
- 10 to 1000 microns (1 millimeter) -- far

These subdivisions are not rigidly defined but follow general custom.

A. ATMOSPHERIC ATTENUATION

There are three sources of atmospheric attenuation-- Rayleigh scattering, absorption, and Mie scattering.

Rayleigh scattering, which is due to molecular reflection, is not significant in the infrared region because the wavelengths are large compared with the size of a molecule.

Absorption occurs when the radiated signal supplies sufficient energy to electrons in the atoms of the transmitting media to change the quantum level of the electrons. This phenomenon is a complicated function of many variables (such as atmospheric pressure, water-vapor density, and gas density) and varies as a function of wavelength. Fortunately, there are "windows" in the infrared spectrum where the atmosphere is relatively free from absorption. (No equivalent window exists for scattering.) A typical transmission spectrum is shown in Figure 8-1. Only water vapor and carbon dioxide are of consequence at the lower atmosphere. It will be assumed that the "system" is operating in a window in the lower atmosphere so that absorption can be neglected. This is a reasonable simplification.

Hence, the remaining and most significant attenuation source is Mie scattering, which is caused by aerosol particles such as fog droplets, smog, dust, and condensation products.

A collimated beam of monochromatic light having a flux F at a distance R from a convenient origin will scatter out of the beam an amount of flux proportional to F so that

$$dF = bFdR$$

where b is the scattering coefficient. This integrates to

$$F = F_0 e^{-bR}$$

A similar expression can be found for absorption so that

$$F = F_0 e^{-(b+k)R} = F_0 e^{-\sigma R}$$

where k is the absorption coefficient and σ is the extinction or attenuation coefficient. (In this report $\sigma = b$ since $k = 0$.) The transmissivity per unit distance ($R = 1$) is $F/F_0 = T$. Photometrists often prefer to use 10^{-d} rather than $e^{-\sigma}$ where d is the optical density per unit distance. Hence, $T = e^{-\sigma} = 10^{-d}$.

Allard's law governing the transmission of radiant energy is

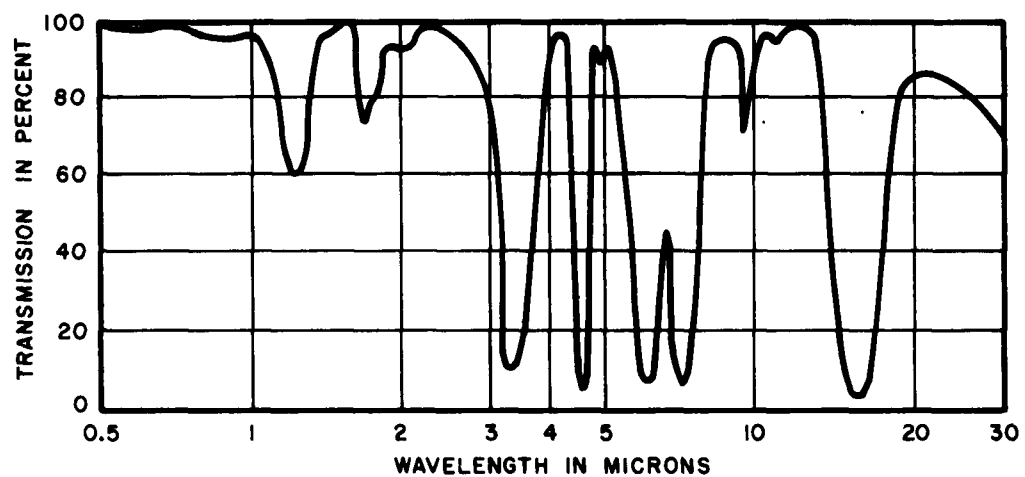


FIGURE 8-1. TYPICAL INFRARED TRANSMISSION IN THE ATMOSPHERE

$$E = \frac{IT^R}{R^2}$$

where E is the illuminance in lumens/meter and I is the luminous intensity in candles. This equation is a combination of the familiar inverse square law and the attenuation factor.

Figure 8-2 is a plot of Allard's Law for ranges from 10 to 1000 meters as a function of optical density (d)--that is, $T = 10^{-d}$. E is expressed in db below E_0 , where E_0 is the illuminance at a distance of one meter from the source (I). The solution for the ratio of improvement between two optical densities is a transcendental function. Hence, a graphical solution is offered. The plot assumes a constant E/I ratio as d varies. For example, assume that the optical density in the visible region is 60 per kilometer and the threshold of visibility is 100 meters (328 feet). Furthermore, suppose that the optical density is reduced to 30 per kilometer by operating at 10 microns. Thus, Figure 8-2B is entered at 100 meters until the curve for $d = 60$ is intersected. Proceeding along a line of constant E until $d = 30$ is intersected yields a new threshold range of 187 meters. All other factors being equal, there is a range improvement of 87 meters (285 feet). Subsequent portions of this section will demonstrate the effect of varying other factors.

Optical density can be computed by determining the Mie scattering coefficient from

$$b = \frac{\pi D^2 n}{2}$$

where D is the droplet diameter and n is the particle density in droplets per unit volume. Fog droplets range from about 6 microns to 120 microns in diameter with densities from 1 to 50 per cubic centimeter. The wide range of scattering coefficients is shown in Figure 8-3. Good correlation for density and diameter in natural aerosols is obtained with the expression

$$n(D) = K_1 D^{-K_2}$$

where K_1 and K_2 are empirically derived constants.

Theoretical considerations are offered for completeness. However, experimental data is more acceptable in a study of this nature because of the lack of homogeneity and stability of fog.

Arnulf and his associates (reference 16) have performed extensive tests in diffusing media. They have found that haze penetra-

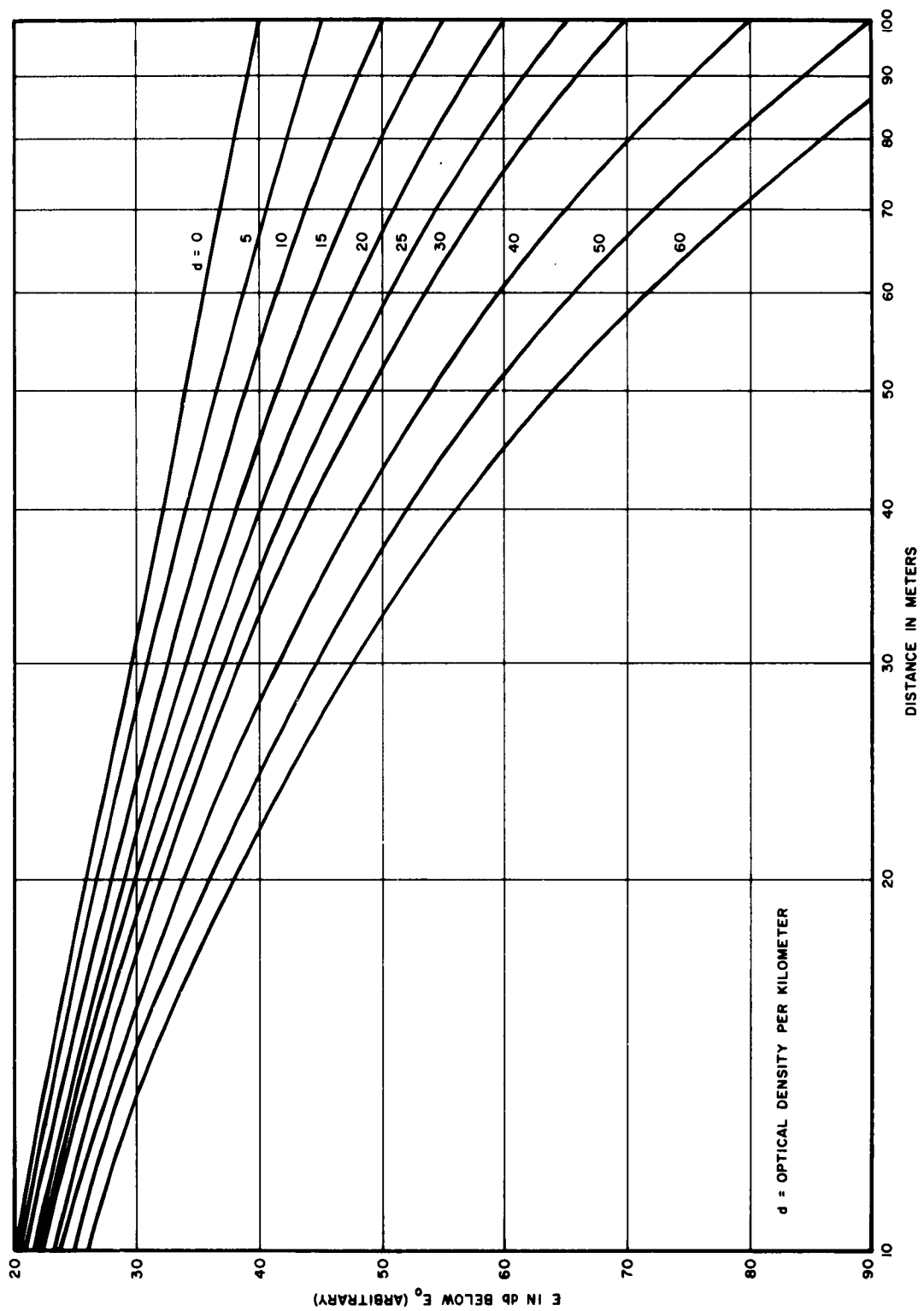
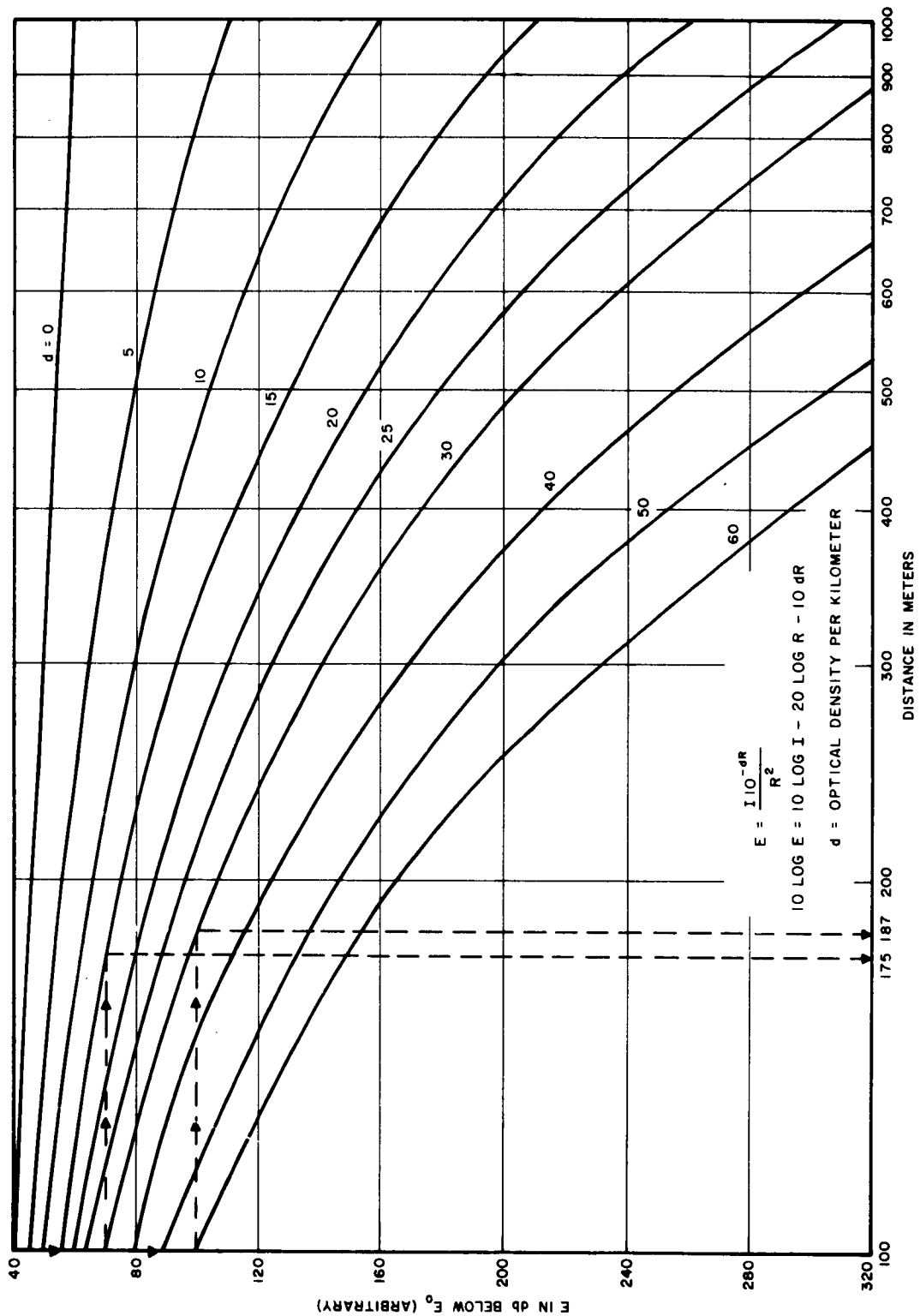


FIGURE 8-2. ILLUMINANCE VS DISTANCE AS A FUNCTION OF OPTICAL DENSITY (SHEET 1 OF 2)

A. 20 TO 90 db BELOW E_0



B. 40 TO 320 db BELOW E_0

FIGURE 8-2
(SHEET 2 OF 2)

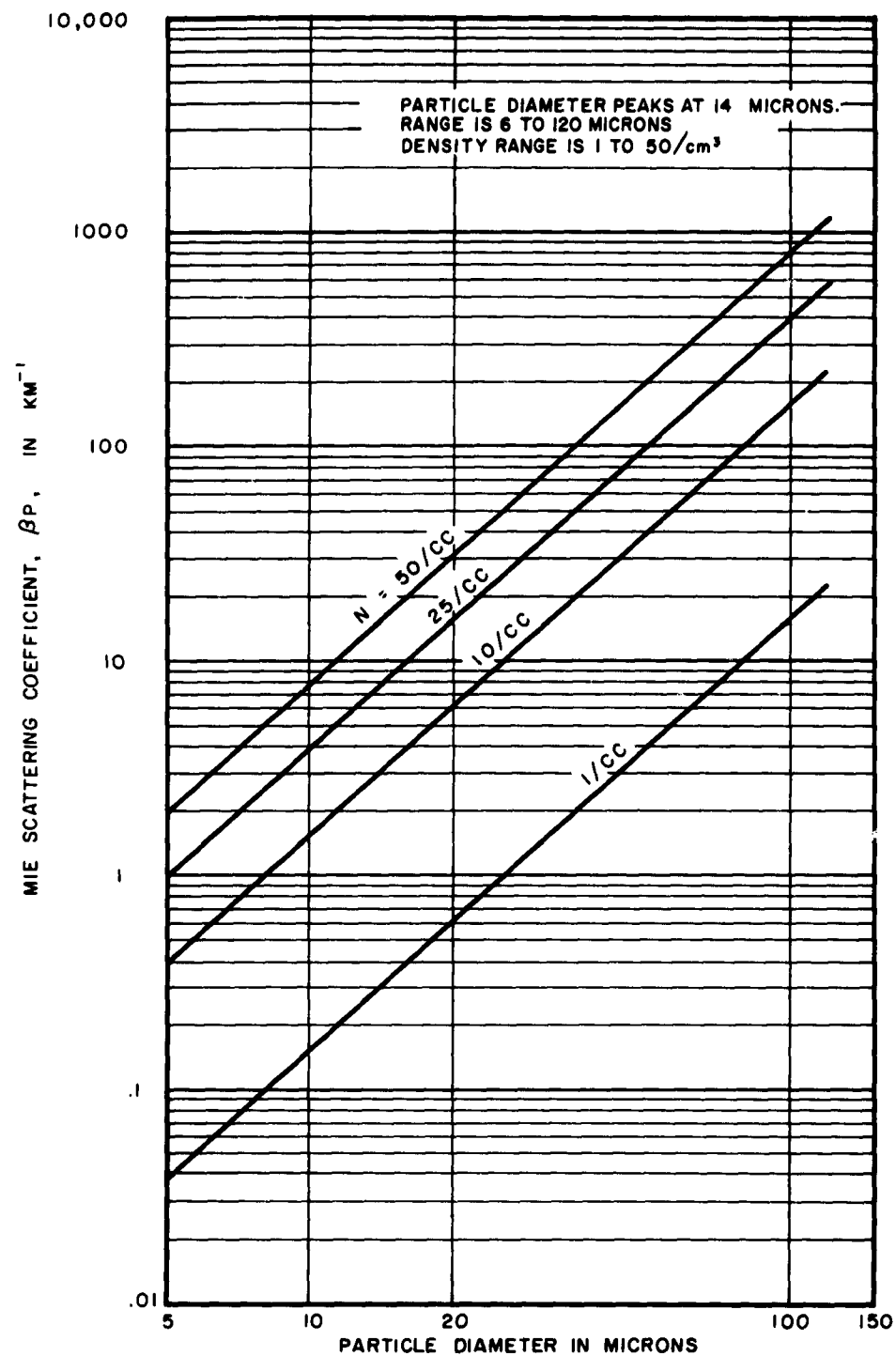


FIGURE 8-3. MIE SCATTERING COEFFICIENT AS A FUNCTION OF PARTICLE DIAMETER AND DENSITY

tion improves rapidly with wavelength. Optical density is 10 to 100 times smaller at 10 microns than in the visible region.

Two classes of small-drop stable fogs were found. The first class has good transmission at 10 microns with d approximating zero per kilometer; corresponding optical densities in the visible range are between 2 and 8 per kilometer. Thus, the range of visibility at 10 microns is improved by a factor of about two to three at 100 meters (Figure 8-2B). A second class of this type of fog is less selective, with a maximum density of 15 to 30 per kilometer in the visible spectral region and a density at 10 microns that is a little less than one-half the maximum. Range improvement is somewhat less than double at 10 microns compared to light. These fogs are rare and were found in the vicinity of Paris only.

As fog evolves from haze or the reverse, the densities shift up and down with the evaporation or condensation process, but the ratio of densities between the visible range and 10 microns does not improve, in general, by more than two to one.

A stable fog is one in which the shape of the density-wave-length curve is constant. The actual density varies considerably. Again, density reduction is seldom better than one-half.

Arnulf and his associates have concluded that transmission through haze at 10 microns is of interest, but the reverse is true of fog. Transmission in the infrared region is not generally higher than that in the visible and ultraviolet regions; it is often lower except at 10 microns. Furthermore, the improvement in the distance corresponding to the limit of perception, using the 10 micron wavelength, is too small to be of practical interest.

Kurnick (reference 17) presents transmission data over optical path lengths of 600 feet taken throughout the duration of two fogs. Data from the first fog begins at 10:15 a. m. A marked improvement, almost 10:1 between 10 and 1 microns, is noted between the hours of 10:15 a. m. and 2:30 p. m. However, the improvement ratio begins to degrade rapidly at 2:35 p. m. when the visibility is about $1/4$ mile, and, at 3:10 p. m., when the visibility is reduced to about $1/8$ mile, the ratio approaches 1:1. At 3:25 p. m., a fine rain begins and the fog thins.

The data during the second fog was taken between 9:25 a. m. and 2:30 p. m. when the visibilities were between $1/8$ and $5/8$ mile. Improvement during the lower visibility is seldom better than 2:1.

These results tend to further substantiate the results of Arnulf and his associates. No substantial improvement is noted at the longer wavelengths for the low-visibility conditions of interest.

Experiments in Japan (reference 18) lead to the following conclusions:

1. Attenuation of infrared rays is less than that of light through smoke or light haze,
2. Both attenuate similarly through fog or rain.

Still another experimental study (reference 19) in Germany shows about 2:1 improvement between visible and near-infrared wavelengths in the range of 0.9 to 2.0 microns, as received by an electronic receiver. The conclusion is reached that fog particles at the test location must have been relatively small.

H. P. Leet (reference 20) has experimented with infrared transmission in fog between a 15- and 35-micron wavelength. It was concluded that there is significant transmission over a 50-foot path length, but a higher power source and a more sensitive detector would be required for longer path lengths. The data are extensive and include meteorological visibilities down to zero-zero. Unfortunately, the data are not compared with transmission in the visible portion of the spectrum.

From the large number of references which we have studied, we can summarize by stating that, in the lower visibilities of interest (below 1/8 mile), the experimental data show that the range of fog penetration is improved by about 2:1 at wavelengths of 10 microns or more (relative to the visible wavelengths), all other factors being equal.

No account has been taken of such special situations as industrial environment where sulphur-dioxide fumes are converted to sulphur trioxide when exposed to ultraviolet radiation and then to sulphuric acid. This action creates larger condensation nuclei and leads to atmospheres of greater opacity.

B. RADIANT EMITTANCE

The radiant emittance of a source is the power density per unit area and is a measure of the intensity of a source. The radiant emittance of a blackbody source is related to temperature and spectral distribution of the source by Planck's law:

$$W_{\lambda} = \frac{C_1}{\lambda^5} \left(e^{\frac{C_2}{\lambda T}} - 1 \right)^{-1}$$

where

W = spectral radiant emittance from a black body per unit surface area per unit wavelength interval into a hemisphere at wavelength λ ,

T = temperature of the black body in degrees Kelvin,

λ = wavelength in centimeters,

$C_1 = 3.7405 \times 10^{-12}$ watt cm²,

$C_2 = 1.43879$ cm degree K.

Figure 8-4 is a plot of Planck's law. Differentiating W_λ with respect to λ and setting the derivative equal to zero determines the wavelength corresponding to maximum W_λ . That is,

$$\lambda_m T = K$$

and $K = 2897$ micron degrees if λ_m is measured in microns. This is Wien's displacement law. Substitution of Wien's displacement law into Planck's law yields the maximum spectral radiant emittance.

$$W_{\lambda_m} = 1.3 T^5 \times 10^{-15}$$

The Stefan-Boltzmann law is derived from Planck's law by integrating over the total spectrum to obtain the total radiant emittance.

$$W = \sigma T^4$$

where $\sigma = 5.6697 \times 10^{-12}$ watts/(cm²)(deg⁴)

These laws are all for blackbodies. Corrections are usually made by applying a factor called emissivity. Use of this factor is not necessary in this report.

Runway and taxiway lights are at operating temperatures of about 3000°K and, therefore, from Figure 8-4 or Wien's law, peak at about 1 micron, whereas a source that peaks for 10 microns is approximately at room temperature (300°K). Planck's law clearly demonstrates that the spectral radiant emittance of a blackbody at the wavelength of the peak is always less than that available at the same wavelength from a higher-temperature blackbody.

The spectral radiant emittance (of 3000°K source) at the center of the visible spectrum (0.55 micron) can be compared with that at 10 microns where the latter affords a 2:1 range improvement in fog penetration. Intensity per unit area of the source in the visible part of the spectrum is about one hundred or more times greater than at 10 microns. Thus, range capability is improved by a factor of 10 for visible light relative to range capability at 10 microns in the absence of attenuation. This is based on the power density being an inverse square function of range. The important conclusion is that the improvement in fog penetration when operating at 10 microns is more than offset by the loss of intensity.

The 3000°K source peaks in the near-infrared range at about 1 micron. It is of interest to determine the increase in intensity at the peak of the source relative to the visible spectrum. Figure 8-4 shows that the power density is higher by 2:1 for 1 micron. This corresponds to a 40-percent increase in range, which is hardly significant.

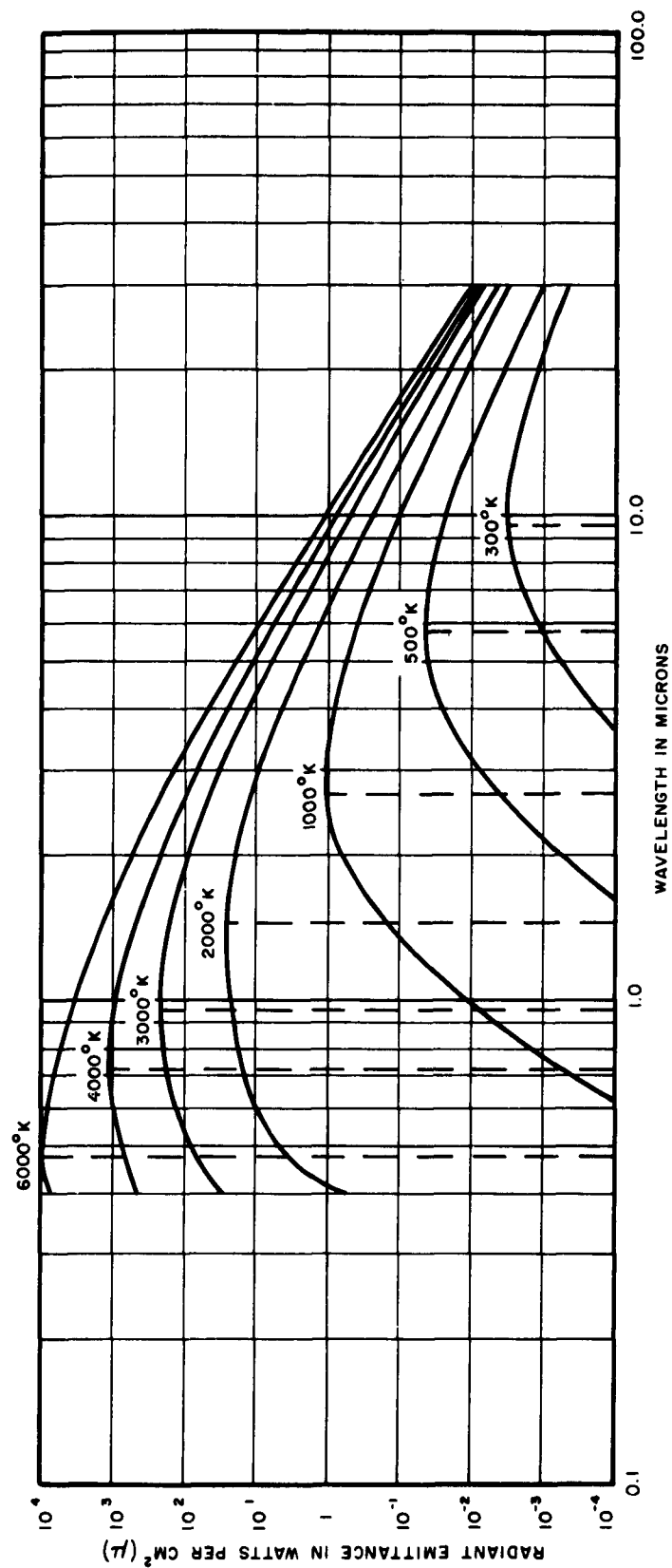


FIGURE 8-4. BLACKBODY RADIATION FOR TEMPERATURES BETWEEN 300 AND 6000°K

C. RECEIVING SYSTEM

1. DETECTORS

Detectors can be classified in many ways. Perhaps the broadest classification is according to whether the physical phenomenon is thermal or photoconductive. A detailed classification is by figure of merit. This report defines the detector class in a manner that tends to be more related to the infrared spectrum (reference 21).

Type I: Photoelectric cells, including photoemissive, some photoconductive, and photovoltaic cells; dielectric cells and thalofide cells; photographic plates; phosphorus and phosphor cells. Image-conversion tubes.

This type exhibits superior responsitivity in the visible and near-infrared spectral regions; large-signal amplification is possible in photomultiplier cells.

Type II: Photoconductive cells that are more responsive to lower-temperature sources; superior detecting in intermediate-infrared spectral region; faster time constants than Type III, but not always faster than Type I; faster recovery from transients; can be directly coupled to preamplifiers.

Type III: Thermal detectors, more responsive to low-temperature sources; responsive over wide wavelength bands, in the far-infrared spectral region detect greater fraction of the total infrared radiation than photocells; mechanical chopping often not required; cooling of detector to low temperatures generally not required.

A fourth type, and the one belonging to the reference system in this comparative study, is the human eye. We will compare the infrared to the visible spectral regions with regard to major system parameters. Thus far, atmospherics and power have been considered. It is difficult to compare the human observer with material technology because of the psychophysical characteristics of the former.

As commonly defined for aviation purposes, the nighttime threshold of the eye is 2 lumens per square mile. Minimum perceptible illuminance for the dark-adapted eye is about 1/1000 of this value (a star of magnitude six), but this figure is not practical for aviator activity.

At night, the area of the pupil of the eye is about 40 mm² since the diameter of the pupil is about 7 mm. An area of 40 mm² is equal to 1.5×10^{-11} square miles. Thus, about 3×10^{-11} lumen enters the eye for an illuminance of 2 lumens per square mile.

The maximum theoretical conversion factor (at a wavelength of 0.55 micron) is 680 lumens per watt. This factor is applicable to cone vision. For red vision, the factor is much greater. Thus, at this

wavelength, the working threshold is about 4.5×10^{-14} watts. The conversion factor for the light from incandescent lamps is usually in the range of 10 to 30 lumens per watt. However, the wavelength giving maximum sensitivity should be used when comparing the eye with other detectors since that is done with other detectors.

Detectors are most often characterized by their noise equivalent power (NEP), which is the radiation that will produce an electrical output equal to the rms electrical noise. Minimum detectable input is usually about five times NEP. NEP varies from about 10^{-9} to 10^{-11} watts (reference 22) assuming the signal is chopped. It is noteworthy that physical systems can be narrow-banded by correlating a chopped signal whereas the eye must remain a broad-band device. However, each receptor of the eye has a small field of view. Moreover, the eye is supported by an excellent filter--the brain.

Factors contributing to noise are: shot noise, Johnson noise, temperature noise, photon noise, current noise, and flicker noise.

In general, it appears that the human eye is equal to, or more sensitive than, other detectors. Some improvement is afforded by other detectors when they are cooled, but this is an added complexity. Furthermore, the eye automatically includes the brain, which is a very suitable adaptive computer for the application.

Another factor of interest is that illumination decreases very rapidly with increasing range regardless of whether the detector is the human or a physical device. For example, from Allard's law the illumination at 1 mile in a moderate fog with a transmissivity of 0.04 per mile is 0.04 I lumens per mile² (I is the candlepower of the source), whereas the illumination at 2 miles is 0.0004 I at 2 miles. Thus, a large increase in candlepower will not increase the system range in thick fog.

2. PROTECTIVE MATERIALS

Optical and radome materials are difficult to obtain in the infrared spectrum. Materials lack uniformity or matching to particular desired spectrums.

The literature contains voluminous material regarding materials and their limitations. Thus, this small section is merely included to indicate an additional source of power loss and mechanical limitation in design.

D. BACKGROUND RADIATION

A hazard to any infrared system is a background that radiates like the source or loads the detector beyond its linear range. Anomalous sources can usually be eliminated by chopping the desired source. However, the design and configuration of runway and taxiway light sources can preclude the elimination of ambiguous sources on adjacent runways or taxiways. Variation of the chopping rate may alleviate this problem.

In clear daylight weather, in the visible and near-infrared spectrums, the principal source of sky background energy is that caused by Rayleigh scattering of sunlight and reflection of sunlight by clouds. Beyond 3 microns, the amount of sun radiation becomes exceedingly low due to the reduction of sun energy in the band and to the fall-off of Rayleigh scattering. The principal source of radiation becomes the thermal radiation of gases and water vapor of the atmosphere.

Background radiation in fog is a relative unknown. Presumably, the problem is one of thermal radiation whose magnitude is a function of the type of fog and the meteorological conditions before and during the development of the fog. If sun irradiation penetrates into a fog, a large portion of radiation in the infrared spectrum will also be scattered.

Background radiation degrades signal-to-noise ratio and mitigates any improvement that may be afforded by infrared techniques.

E. CONCLUSIONS

The results of this cursory study indicate that improvement in fog penetration by infrared techniques is obtained at longer wavelengths (for example, 2:1 at 10 microns at a visibility of 1/8 mile). However, power radiation is insufficient at the longer wavelengths to realize any of these atmospheric gains (Figure 8-4). Furthermore, special materials for radomes, etc., are needed at these longer wavelengths, thereby further complicating the problem.

The approach herein has been to examine basic system parameters without consideration of the handicaps of actual system design. For example, the sensors require suitable radomes if the equipment is mounted in the fuselage. Alternatively, the radome can possibly be foregone if the sensor is mounted on the main-wheel strut. In any event, the mechanical problem is great because of such factors as vibration, temperature, alignment, and field of view.

No mention has been made of the display and processing system. This is a difficult problem with all types of sensors. It is evident that the processing and display system of the pilot is superior to that produced by human ingenuity for this application.

It is concluded that the net benefit to be derived from the application of infrared techniques in low-visibility conditions is equal to or less than that of visible light and the human observer. Therefore, the application of infrared techniques to ground guidance is not promising.

IX. GUIDANCE USING MAGNETIC FIELDS

A. GENERAL DESCRIPTION

There are many possible ways of using the magnetic fields that exist around current-carrying wires for guidance. Many of these techniques have been investigated and feasibility demonstrations and tests have been conducted. The possible uses have been:

1. Missile guidance,
2. Ship channel guidance,
3. Automobile guidance,
4. Aircraft landing guidance,
5. Aircraft taxiing guidance,
6. Arctic trail marking.

Developments have been pursued in each of these areas.

The systems that have been developed can be classified either as one- or two-wire systems. The two-wire systems can either be excited as a loop or separately at different frequencies. The leader cable used in the British (BLEU) landing system development and installed in the runway approach area uses two wires carrying equal currents at different frequencies. A spinning loop was used to detect the maximum field from each cable and these maxima were compared to measure distance off the runway centerline. Of more importance to this study were the tests carried out by BLEU investigating the use of a single leader cable for taxiing (reference 7). This system used three detector loops in the aircraft, two for sensing displacement and the third to provide aircraft heading. In this particular case, the aircraft heading was that required to achieve a smooth ground track to avoid overshooting turns and ease the pilot's task in following the cable centerline.

The General Mills Trailmarking system developed for the United States Army used a loop configuration with equal currents in both wires. Two orthogonally crossed loops were used to determine distance and direction off centerline. A third loop provided an indication of heading. These two-wire systems will not be considered further for the ground guidance problem because of the added complexity of a two-wire installation and the problems posed by junction fields where taxiways join runways. A further problem is that on-course sensitivity is low when the detector height is small compared with the wire spacing in a single-frequency system.

Two general methods have been considered for single-wire guidance. The first uses crossed orthogonal loops in a manner similar

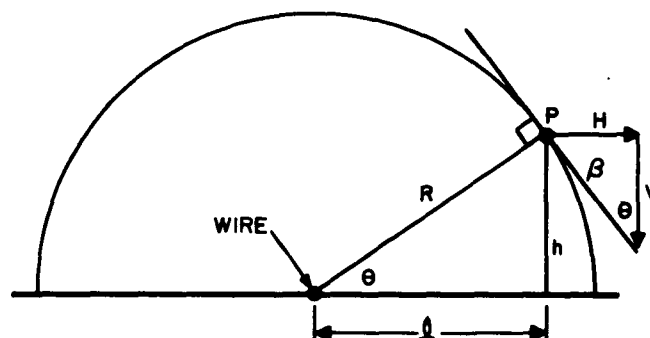
to the two-wire system and the second uses two loops separated in space to provide a course null signal. It is important to examine the field about the single conductor. Figures 9-1 and 9-2 are normalized curves of the horizontal and vertical fields about a current-carrying conductor that produces a unity magnetic field at a distance of one unit. The field is only shown in one quadrant. In ground-guidance, fields below the ground are of no concern. The horizontal component does not reverse sign between the right and left side of the wire. The vertical component does reverse sign. It can be seen that the vertical component is zero above the axis of the wire, and the phase angle changes with respect to the horizontal on the right and left sides of the wire. Hence, the information necessary for guidance is present in the vertical and horizontal components. However, the range of proportional guidance is only equal to twice the height of the detector and the amplitude of the error signal falls off outside of this range.

A similar characteristic is shown in Figure 9-3 for the difference between the horizontal field components at various horizontal spacings between detectors. This is the gradient or change in magnetic field over the spacing. However, the range of proportional guidance is again limited; in this case, to about the spacing of the detectors.

It is desirable to increase the range of proportional guidance considerably. A means of accomplishing this aim has been determined and will be described.

The range of proportional guidance desired may be much larger than the feasible height of the sensor.

If the ratio of the vertical component (V) to the horizontal component (H) is taken, the ratio (V/H) is directly and linearly proportional to displacement from the vertical plane passing through the wire.



In the sketch, the field B at point P is proportional to some unit radius B_0 , therefore:

$$B = \frac{B_0}{R}$$

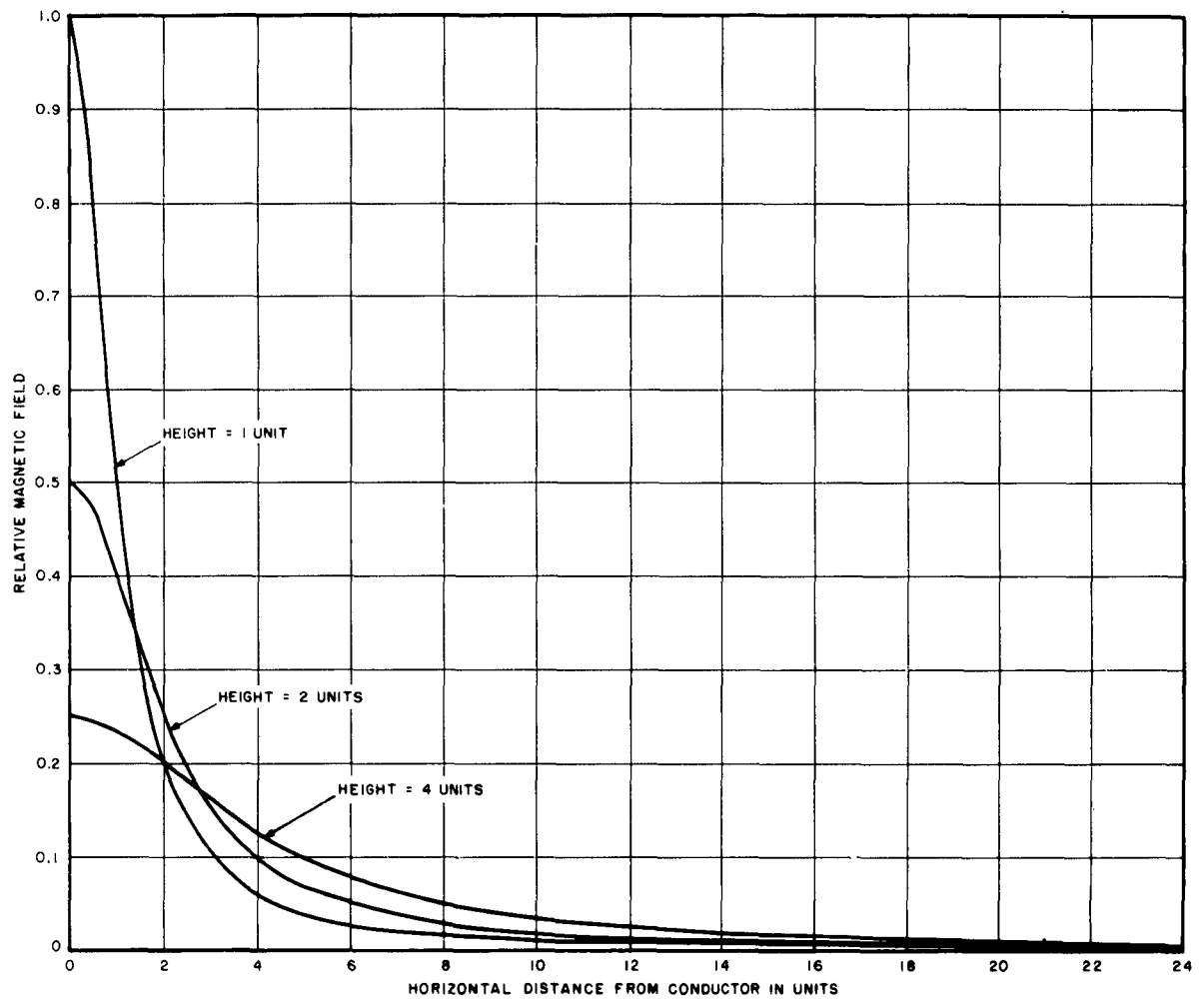
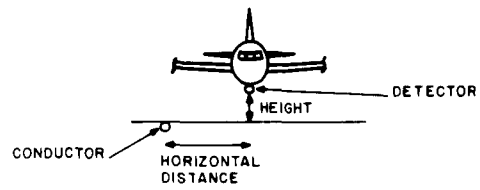


FIGURE 9-1. HORIZONTAL COMPONENT OF MAGNETIC FIELD ABOUT SINGLE CONDUCTOR

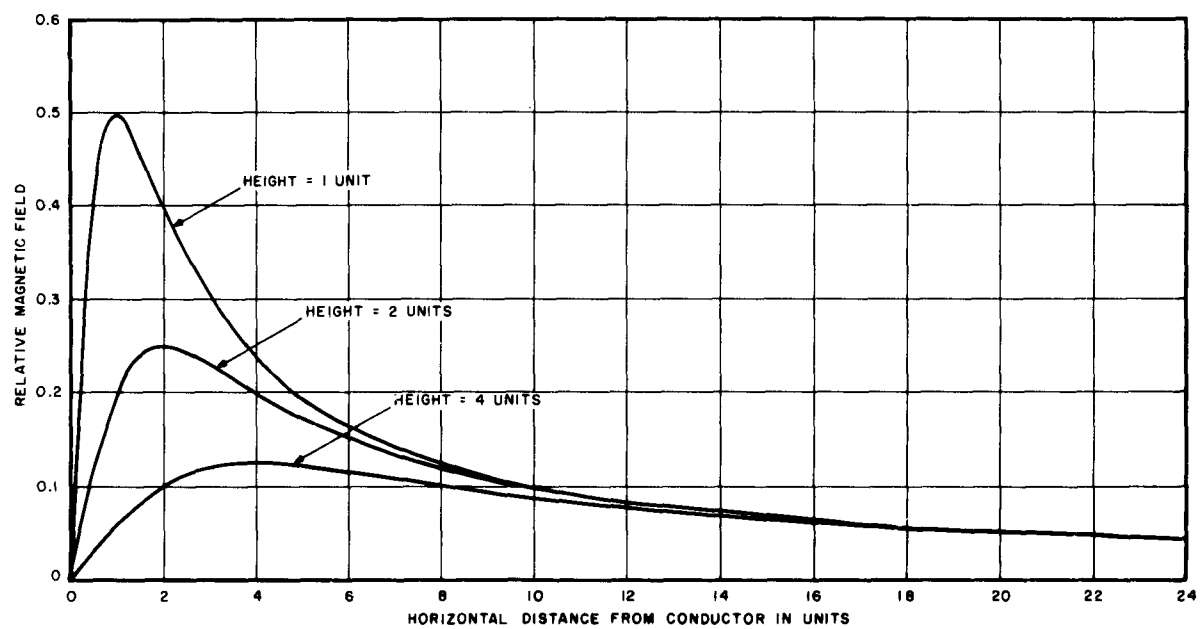
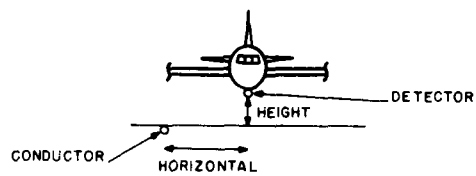


FIGURE 9-2. VERTICAL COMPONENT OF MAGNETIC FIELD ABOUT SINGLE CONDUCTOR

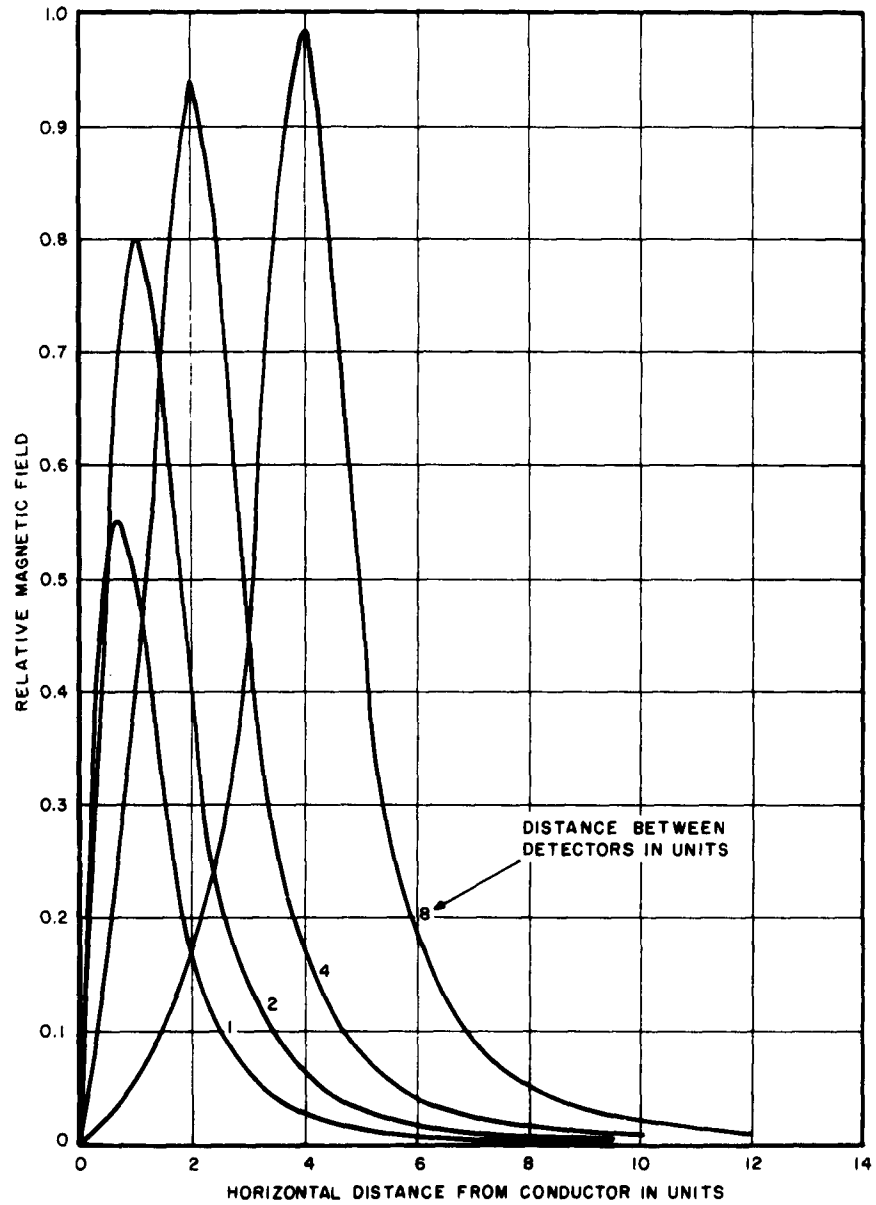
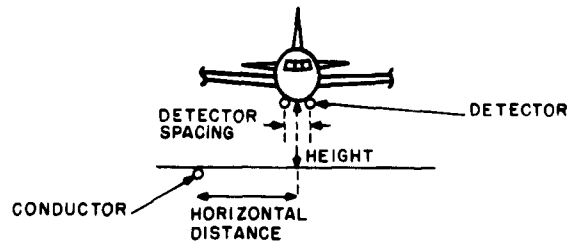


FIGURE 9-3. HORIZONTAL GRADIENT AS A FUNCTION OF DETECTOR SPACING

The vertical component (V) of the field at point P is

$$V = \frac{B_0 \cos \theta}{R}$$

The horizontal component (H) of the field at point P is

$$H = \frac{B_0 \sin \theta}{R}$$

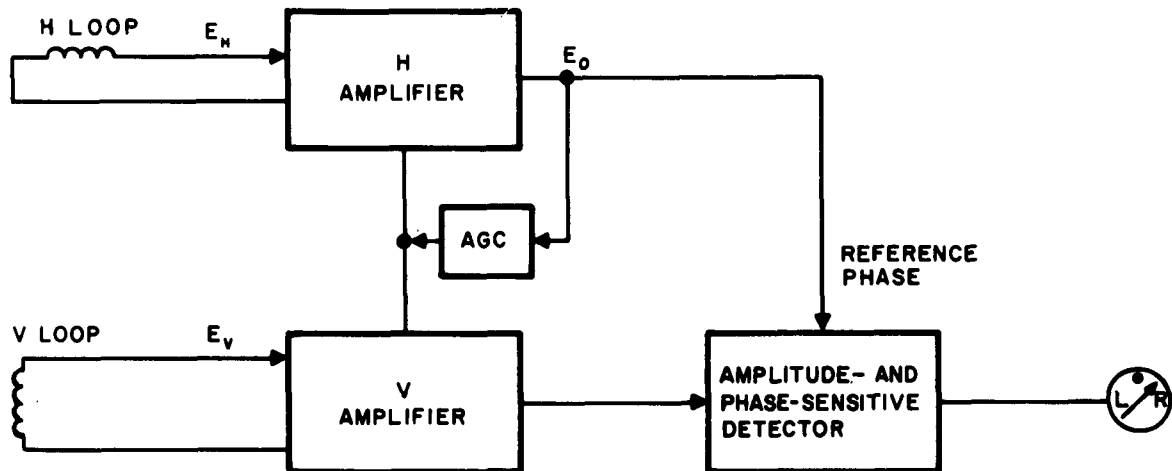
Therefore,

$$\frac{V}{H} = \frac{\cos \theta}{\sin \theta} = \frac{1}{\tan \theta} = \frac{\ell}{h}$$

If the height of the detector is constant, as it would be in a vehicle such as a car, bus, or airplane rolling on the ground,

$$\frac{V}{H} \propto \ell$$

A technique for implementing this expanded proportional guidance is shown in the following block diagram.



The automatic-gain-control (AGC) circuit maintains a constant output (E_O) from the H-amplifier. The gain of the H-amplifier is, therefore,

$$G_H = \frac{E_O}{E_H}$$

The V-amplifier is a duplicate of the H-amplifier and has the same gain control voltage applied to it from the AGC circuit. Therefore,

$$G_V = \frac{E_O}{E_H}$$

and the output of the V amplifier is

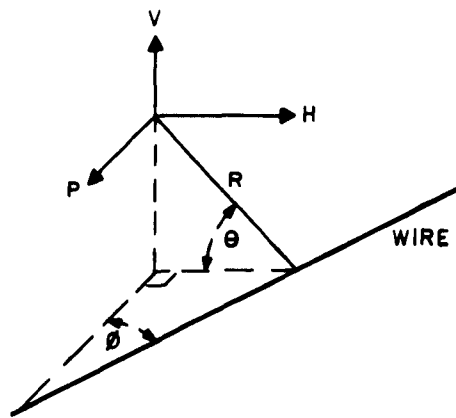
$$E_V G_V = E_V \times \frac{E_O}{E_H} = E_O \times \frac{E_V}{E_H}$$

The output of the phase-sensitive detector is a voltage whose amplitude is proportional to the input from the V-amplifier and whose polarity depends on the phase of the V and H inputs.

The range of proportional guidance is not proportional to sensor height but is proportional to the current in the wire. When the current in the wire is decreased, the range (at which noise becomes a limiting factor) is decreased.

The distance off centerline indication is a function of height. Hence, if a single wire is laid on the runway and into the approach zone, a landing aircraft flying a path parallel to the centerline but offset will receive an indication that the offset is increasing because of the decreasing height. If aircraft height is available, the indication can be corrected. For example, if the reference voltage E_O is made proportional to height above the leader cable, the offset indication will be correct at all heights. The height from a flareout radio altimeter could be used to set E_O down to touchdown. However, since the leader cable is only used for rollout guidance in this application, this is somewhat of an academic point for a given aircraft.

If a third loop is used at right angles to the V and H loops, heading information can be derived. If the H loop is rotated through an angle (θ), its output is reduced by the factor cosine θ . The third loop or P-loop has no voltage induced in it when it is perpendicular to the wire. The voltages in the H and P loops are given by



$$E_H = \frac{B_0 \cos \theta \cos \phi}{R}$$

$$E_P = \frac{B_0 \cos \theta \sin \phi}{R}$$

and $E_P/E_H = \tan \phi$.

The ratio of the voltage in the P-loop to that in the H-loop is a measure of aircraft heading. This is considered to be a desirable feature in any runway or taxiway-guidance system.

It would be possible to use two pairs of crossed loops--one located at the nosewheel for guidance, and the other between the tracks of the main gear to provide an indication of the position of the main gear on the taxiway. This would result in some additional equipment complexity, but may prove worthwhile. The need for main-gear position information should be carefully examined before including it as final system requirement.

A current of about 4 amperes has given adequate service in the BLEU twin-wire system. Frequencies of about 1 to 2 kc have been found to be optimum. A number of different frequencies can be used in this band. The number is limited on the basis of the cost of narrow-band filters for the aircraft. However, the optimum band is broad and frequencies outside of the optimum band can be used to provide additional operating frequencies without increasing filter costs excessively. Four to six operating frequencies can be easily obtained.

The requirements for ground guidance indicate that lateral guidance may not be sufficient. Longitudinal displacement and speed should also be indicated. It is probably unnecessary to provide longitudinal displacement information continuously except as may be required to determine speed. It should be sufficient to indicate longitudinal displacement at discrete points such as turns or junctions.

Speed can be obtained from a two-wire guidance system by laying the two wires in a series of loops as shown.



The discontinuities in the field at the crossover points can be detected. The rate of crossing these discontinuities is a function of speed. While a discontinuity scheme could conceivably be applied to a single-wire system, there is no obvious practical way to achieve both speed and guidance together. Apart from these considerations, the speed determined from rate of change of longitudinal displacement may not be sufficient to satisfy all requirements. For example, when the aircraft is in a tight turn, the velocity along the taxiway centerline may be small, and yet certain portions of the aircraft are moving rapidly. It may be desirable with any system of ground guidance to derive speed information from the rate of rotation of the nosewheel.

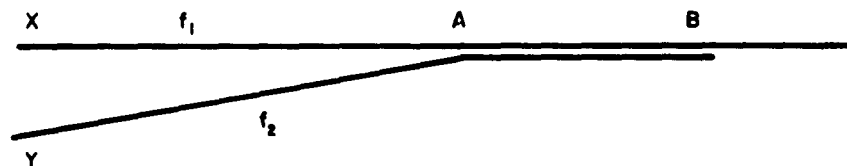
B. LAYOUT PROBLEMS

We have described a technique for providing guidance by a single wire along a taxiway or a series of taxiways with no intersections or turnoffs. Such systems have been demonstrated for many purposes with excellent results. A ground-guidance system for aircraft on an airport cannot be limited to consideration of a single route. We will now explore various problem situations and propose solutions.

1. JUNCTIONS

Figure 9-4 shows two leader cables spreading out from junction A. It is assumed that these cables are excited with in-phase currents of equal amplitudes. (Currents flow in the same direction from A.) The ground-guidance receiver is designed to give an expanded range of proportional coverage. The dotted lines show the indicated position of the detector as it approaches A. It can be seen that aircraft approaching A from either taxiway X or taxiway Y will deviate slightly from the taxiway centerline if they show an on-centerline reading. This deviation is toward the inside of the junction where there is more paved taxiway for maneuvering. The guidance-signal variation is less on the inside of the junction and there is more tendency to err in that direction. It appears possible to use the same frequency on the two cables in a converging junction. The two cables could be excited by two phase-locked generators or as a balanced parallel circuit from one generator.

The situation is considerably different for an aircraft at A that desires to proceed on taxiway X from the junction at A. If the two wires are excited with the same frequency, there is no information present that will enable him to choose positively taxiway X rather than taxiway Y. It appears that two frequencies will be required for the two taxiways. Information must also be provided to indicate that a frequency change must be made. Figure 9-4 is redrawn in simplified form.



NUMBER = INDICATED DISTANCE FROM CABLE CENTERLINE
 LETTER = LEFT OR RIGHT INDICATION

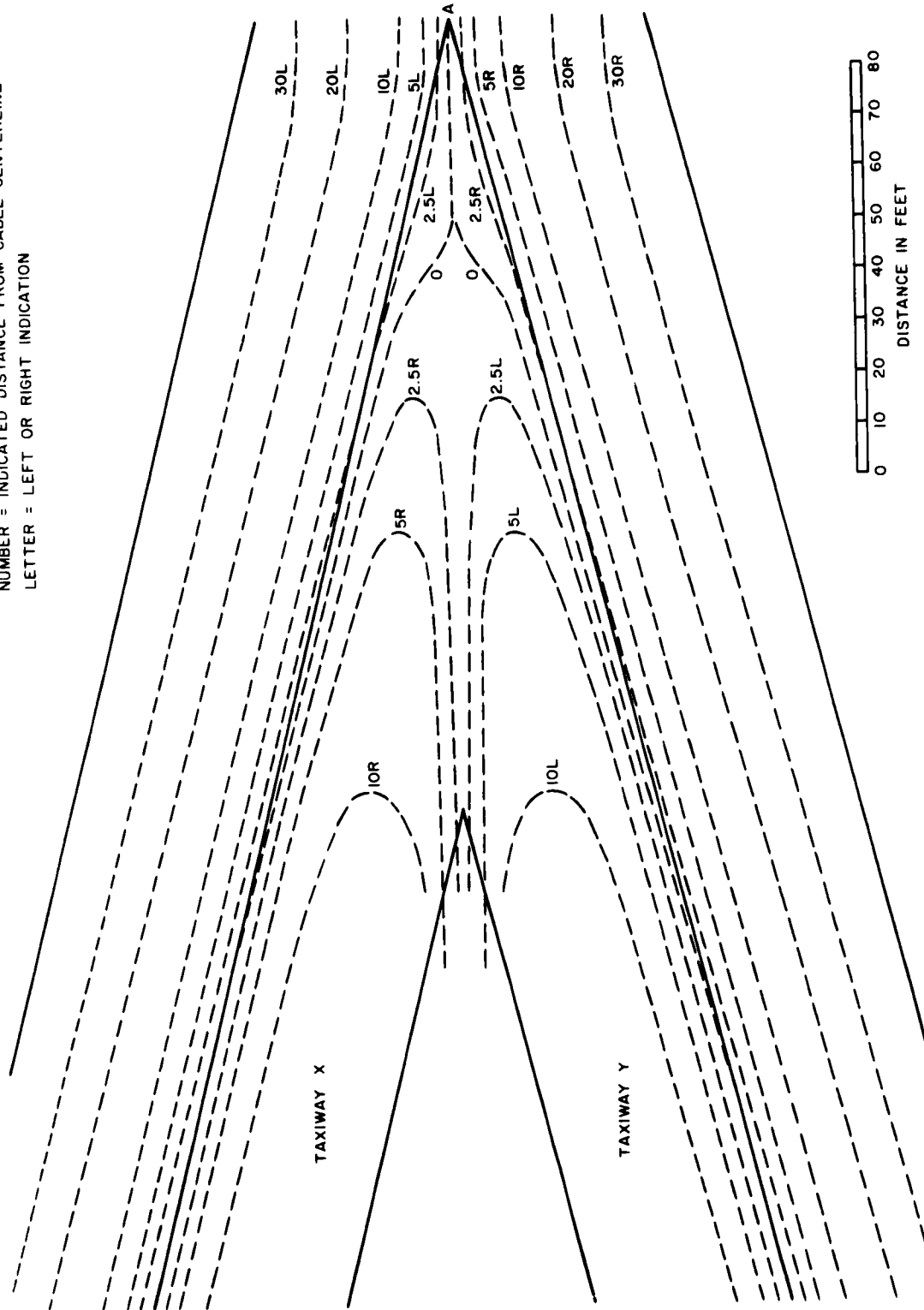


FIGURE 9-4. SINGLE INDICATIONS AT A JUNCTION OF TWO LEADER CABLES

The wire XAB would be excited with frequency f_1 , and the wire YAB with frequency f_2 . An aircraft approaching point B from the right would be tuned to frequency f_1 for guidance. At point B, his receiver would start receiving frequency f_2 and a light could be turned on as an indicator. If the pilot desired to taxi down taxiway Y, he would shift frequency to f_2 for guidance. If not, he would remain on frequency f_1 . An alternative scheme would be to energize wire YAB with a voice transmission as well as the guidance signal f_2 . The output of the receiver would be coupled to the pilot's headset, and any specific instructions such as identity of the junction and destination of f_2 guidance could be given to the pilot. If this voice transmission were undesirable over the entire length of the f_2 wire, a short third wire could be laid in the region AB to provide the same information. The output of the horizontal receiver would provide the voice reception. The use of inductive loops for voice communication will be discussed further.

2. CROSSING

A crossing situation must be handled by a two-frequency operation. The vertical fields from two crossed wires will combine and introduce errors unless they are separable in frequency. It is not believed that this is a serious limitation since there will be a natural tendency to have separate frequencies at crossings for other reasons such as positive separation of inbound and outbound traffic.

3. GENERAL

As indicated previously, it is believed desirable to have inbound and outbound traffic separated in frequency. It is also advisable to restrict the crossing or merging of such traffic as much as possible.

The capability of taxiing without visual guidance is required for only a small percentage of the time. Since the alternative of diversion to another airport is so costly, it probably is not necessary to provide this capability over all taxiway segments. For example, a runway turnoff near the approach end of the runway might only be used by an aircraft that is too small to warrant either a blind landing or taxiway capability, and this turnoff would not need to be implemented. Furthermore, sharp turns (greater than 90 degrees) will probably be difficult to negotiate safely in very low visibility, and the blind taxi system should be laid out to eliminate them as far as possible. In summary, a simplified taxi system should be considered for blind taxi conditions.

It is not necessarily desirable to lay the leader cable on the existing taxiway centerline at turns. Since guidance will be provided at the nosewheel, proper nosewheel paths must be provided at turns. If sharp turns are eliminated, it is believed that one nosewheel track can be provided that will be satisfactory for all using aircraft.

C. TYPICAL LAYOUT

Figure 9-5 shows a suggested layout of leader cables and generators at Chicago-O'Hare Airport. Runways 14R and 14L are being used for takeoffs and landings. Four different frequencies are in use.

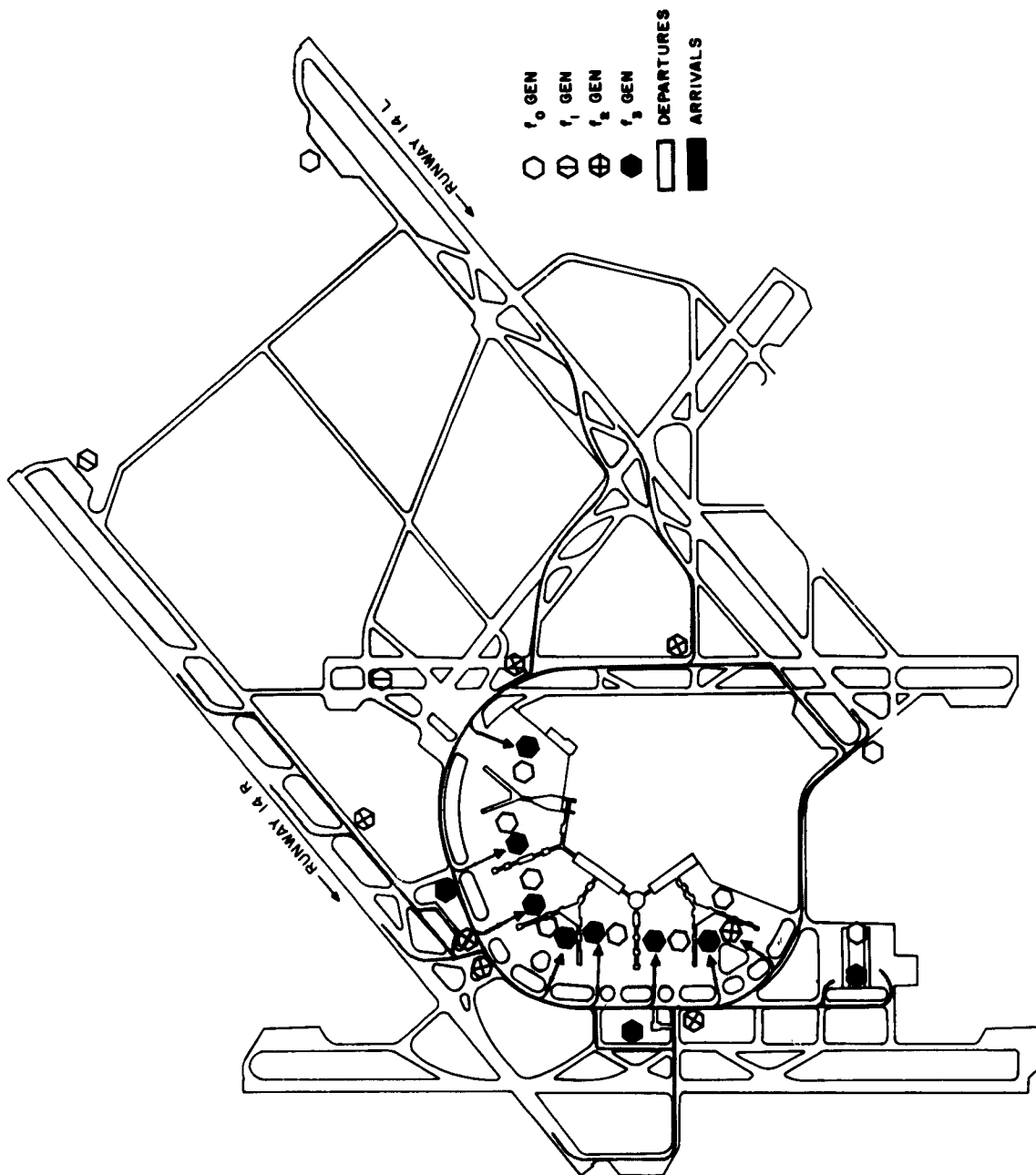


FIGURE 9-5. CHICAGO O'HARE AIRPORT MASTER PLAN
SUGGESTED LAYOUT OF LEADER-CABLE INSTALLATION

Frequency f_0 is principally used for takeoffs and frequency f_2 , for landings though there is some common use of frequency f_0 . Frequency f_0 also supplies an inner loop and f_2 an outer loop around the terminal. Separate phase-locked generators are used at converging junctions because there are as many as three branches off of one line. The division of current in parallel circuits would require excessive current (8 times normal) at the input. Ten generators are required at f_0 , two at f_1 , seven at f_2 , and ten at f_3 . About 80,000 feet of wire would be required. If No. 12 wire driven with 4 amperes of current were used, about 2.5 kilowatts of power would be dissipated in the wires. An additional power loss would occur in the ground return path. These figures may vary considerably in an actual layout and are only intended to give an idea of the magnitude of installation required.

D. INSTALLATION

The leader cable can be installed by cutting a groove down the center of the runway, laying the wire in the groove, wedging the wire in place, and filling the groove with an epoxy cement filler. Experience in the TRACE program indicates that a 1/4-inch wide by 5/8-inch deep slot can be cut with a diamond saw at the rate of 5 feet per minute in Portland cement and 12 feet per minute in bituminous concrete. The wire loops in the TRACE system were installed in the slot at a rate of about 320 feet per hour using two men. Installation of the long straight runs required in a leader cable should be much faster. Two men could pour sealant at the rate of about 200 feet per hour. Improved methods should increase this rate considerably.

E. INTERFERENCE PROBLEMS

Most of the systems using leader cable for guidance have been tested and used in a "sterile" environment--that is, devoid of other conductors that might cause interference. For example, the trail-marking system was tested in Greenland in an area where there were no other conductors present. A similar situation applies to the case of automobile guidance on an isolated test track.

It is known that some difficulties were experienced with the two-wire BLEU system due to interference from other wiring along the runway and approach zone. The currents in the leader cable induce currents in nearby conductors and cause a distortion of the magnetic field. Similarly, in the Bliss two-wire system for taxi guidance on an aircraft carrier, the induced currents in the steel carrier deck almost completely canceled the effect of the normal current in the cables. This problem was solved by proper shielding between the cables and the deck.

The basic layout of the runway and taxiway edge-lighting causes an interference problem with a two-wire leader-cable system (reference 7). Feeder cables for edge lighting exists and will probably continue to exist along the sides of the runways and taxiways. The situation is not as clear as with the single-wire leader cable. Centerline lighting will probably be mandatory for bad-weather operations. In

some cases, the feeder cable for this lighting runs down the center of the runway. In other cases, it runs down the edge and shorter feeder lines run out to the lighting fixtures on the runway. The centerline feed would be an inherent source of trouble since fiberglass ducts are used that provide no shielding. The short lateral feeds would not be a problem since they are at right angles to the leader cable and would have no induced current.

Operational tests should be conducted to determine the extent of the interference problem both in the distortion of the leader cable field and the coupling into communications circuits that may be nearby. These tests should be conducted with a single leader cable and with various combinations of lighting and power-cable installations. An analytical prediction of interference currents and fields becomes extremely complex when multiple conductors are present. Only field testing will provide adequate data.

F. VOICE COMMUNICATIONS USING INDUCTIVE LOOPS

Regardless of whether the magnetic leader cables are used for guidance, it may still be desirable to provide controlled voice communications on the airport surface for navigational purposes. Although normal ground control instructions will come from the airport tower and will be of vital importance to airport navigation, there would be very great advantages if, in addition, each aircraft could be assured of discrete information on cable frequencies, exact position, or warning of turns.

A voice communication system known as "Hy-Com" has been developed by the Delco Radio Division of the General Motors Corporation. This system, developed primarily for highway use, uses the induction field from a loop of wire.

The system is a single-side-band suppressed-carrier system with a carrier frequency of about 9 kc. The loop is laid alongside the highway and is long enough to provide about 6 seconds of reception in a vehicle passing at a maximum speed. The loop length of 500 feet is required at a speed of 65 mph. The 6 seconds of reception ensures complete reception from start to finish of a 3-second message. Aircraft taxi speeds would permit a shorter loop of about 250 feet.

The Hy-Com system uses a second loop with a special signal to enable the receiver in the vehicle to be used. This loop is placed at the end of the voice loop in the direction from which desired traffic will come. In this way, reception is constrained to vehicles moving in one direction past the voice loop. This feature might not be necessary in a ground-guidance system.

The induction field is confined to a strip at right angles to the loop and about equal in width to the length of the loop. The signal falls off rapidly with displacement from the loop and the signal level is predictable. A threshold setting in the receiver will limit the range of reception.

The strength of the signal is also a function of the width of the loop or separation between wires. The greater the separation, the greater the signal strength will be at a given distance.

A 250-foot loop would provide about 6 seconds of transmission time at a speed of 30 mph. The power required to provide a signal strength of 10^{-3} amperes per meter as a function of loop separation and distance from the closest wire has been computed and is plotted in Figure 9-6. The power required is predicted on the requirement for a 2.5-kc bandwidth at a carrier frequency of 9 kc. It can be seen that power levels are nominal, providing that adequate separation between the wires is possible.

Although the primary field from the loop is controllable and predictable, considerable care must be exercised to ensure that a signal is not induced in other conductors and radiated over long distances. The Hy-Com signal has been picked up in a railroad rail and transmitted and detected at long distances along the rail. Operational tests should be conducted to evaluate this problem on an airport surface.

Tests of the General Mills Trailmarking System have demonstrated that it is possible to transmit voice over leader cables concurrently with guidance signals. The range of the voice information was limited to a few hundred feet. Hence, a selective communications capability is available in such a system.

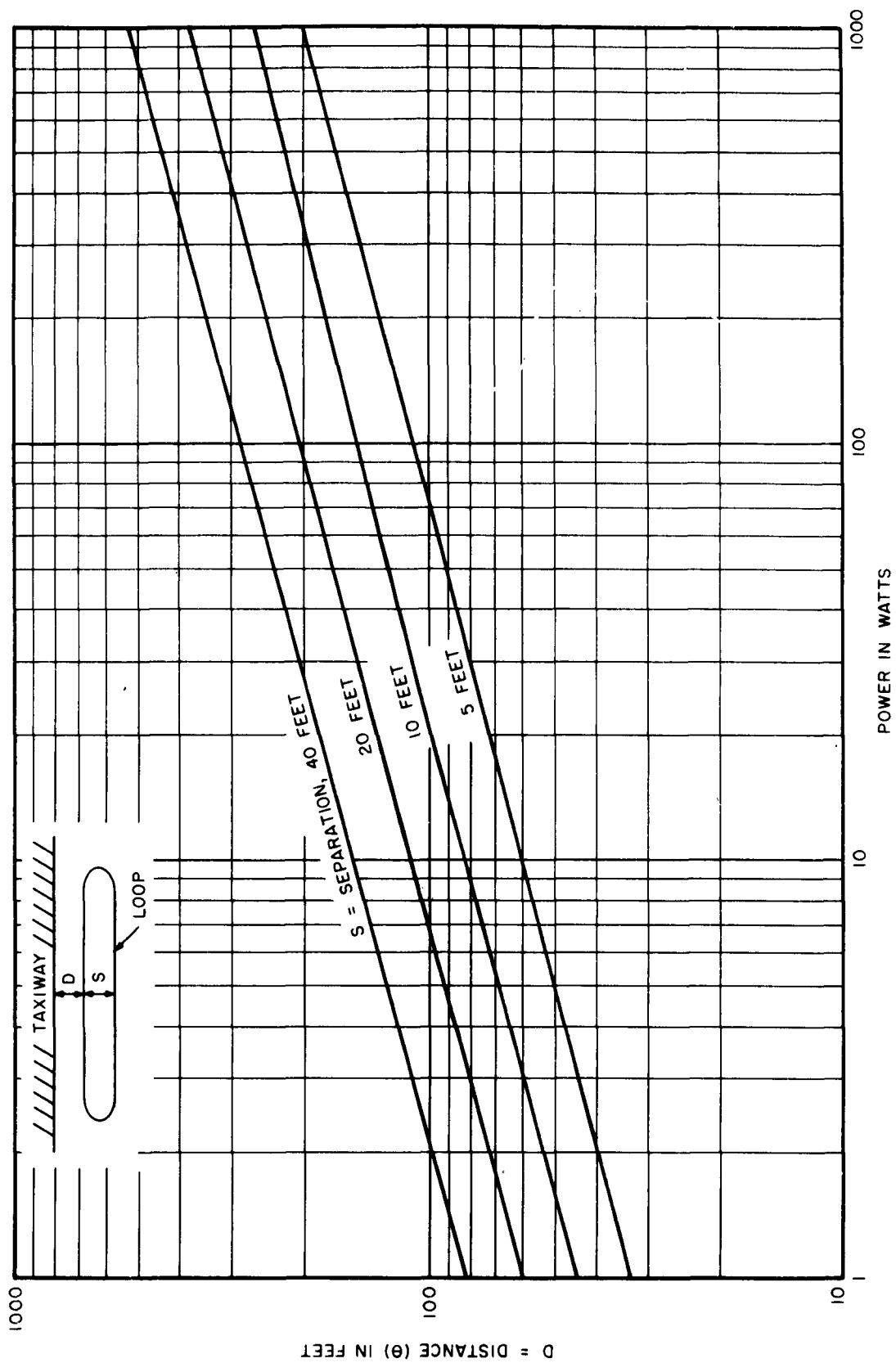


FIGURE 9-6. POWER VS DISTANCE FOR VOICE LOOP

X. AIRCRAFT RADAR FOR GROUND GUIDANCE

It would appear that a radar in the aircraft would be useful in ground guidance. An ideal radar would be able to present a picture of the airport surface that would duplicate, on a small scale, the normal visual appearance of the airport. The system would be self-contained and would not rely on cooperation from the ground or other aircraft. Hence, the system would not have to await the development, production, and installation of ground equipment and could be used at any airport. It would provide lateral and longitudinal position information, heading information, and collision-avoidance information.

Such an ideal radar is not obtainable. Compromises of cost, weight, size, and complexity result in degradations of the radar picture. This section is concerned with the effects of these compromises and the practical limitations on a radar system for ground guidance.

The two possible uses for radar in ground guidance are:

1. To provide general area navigation. The radar would provide information about the general location of the aircraft on the airport but with insufficient accuracy for actual guidance.
2. For actual guidance.

The estimated parameters of these two radars are:

	<u>Airport Navigation</u>	<u>Guidance</u>
Range	2 to 3 miles	600 to 1000 feet
Pulse width	0.5 μ sec	20 nsec (0.02 μ sec)
Beamwidth	0.9 degree	4 degrees
Minimum range	200 feet	20 feet
Bearing accuracy	5 degrees	1 degree
Minimum display size	5 inches	8 inches
Antenna height	Unknown (probably at least 20 feet)	At least 5 feet
Field of view	+125 degrees from aircraft heading	+125 degrees from aircraft heading

These estimated parameters should be considered tentative at this time. Operational experience may indicate that some parameters can be relaxed whereas others may need to be made more stringent. For example, the beamwidth of the navigation radar is specified as less than 0.9 degree. This ensures resolutions of a 75-foot taxiway at a range of 1 mile. If the airport surface between taxiways does not give a noticeable return, it would not be necessary to resolve the sides of the taxiway in order to recognize the taxiway on the display. The requirement is that the taxiway be recognizable from the background on the display. High resolution will ensure recognition, but may not be necessary.

Figure 10-1 shows a portion of the taxiway system at John F. Kennedy International Airport with an aircraft positioned on a taxiway. It is assumed that the aircraft has a radar in the nose capable of providing a picture in the cockpit. Beamwidth is assumed to be 2 degrees (+1 degree) and the pulse width is equivalent to 15 feet of range. (This is based on a 30-inch scanner dish operating at K-band and a 25-nsec pulse width.) It is further assumed that there is a corner reflector mounted at each taxiway light fixture.

If perfect radar returns and no clutter are assumed, Figure 10-2 shows the idealized scope picture. For this illustration, the range shown is 2000 feet. For either the navigational or guidance function, it would probably be necessary to use a logarithmic range scale so that greater accuracy could be obtained from the picture of taxiway edges close to the aircraft. This type of presentation has been used in Figure 10-2.

In practice, the actual radar picture would be degraded from that shown here but this figure is not intended to show all the extraneous clutter that would undoubtedly be present, nor is it suggested that this type of display is the best. It is by no means certain that pilots could use such a display for guidance purposes.

The ideal situation from a cost standpoint would be to use the existing airborne weather radar for the ground-guidance function. The characteristics of two typical airborne weather radars are:

	<u>AVQ-10</u>	<u>RDR-1</u>
Frequency (Mc)	5400	9375
Pulse width (μ sec)	1.8	1.5
Beamwidth (degrees)	7	3.8 or 2.9
Antenna scan rate (rpm)	15	15
Estimated minimum range (feet)	1400	1250
Display size (inches)	5	5

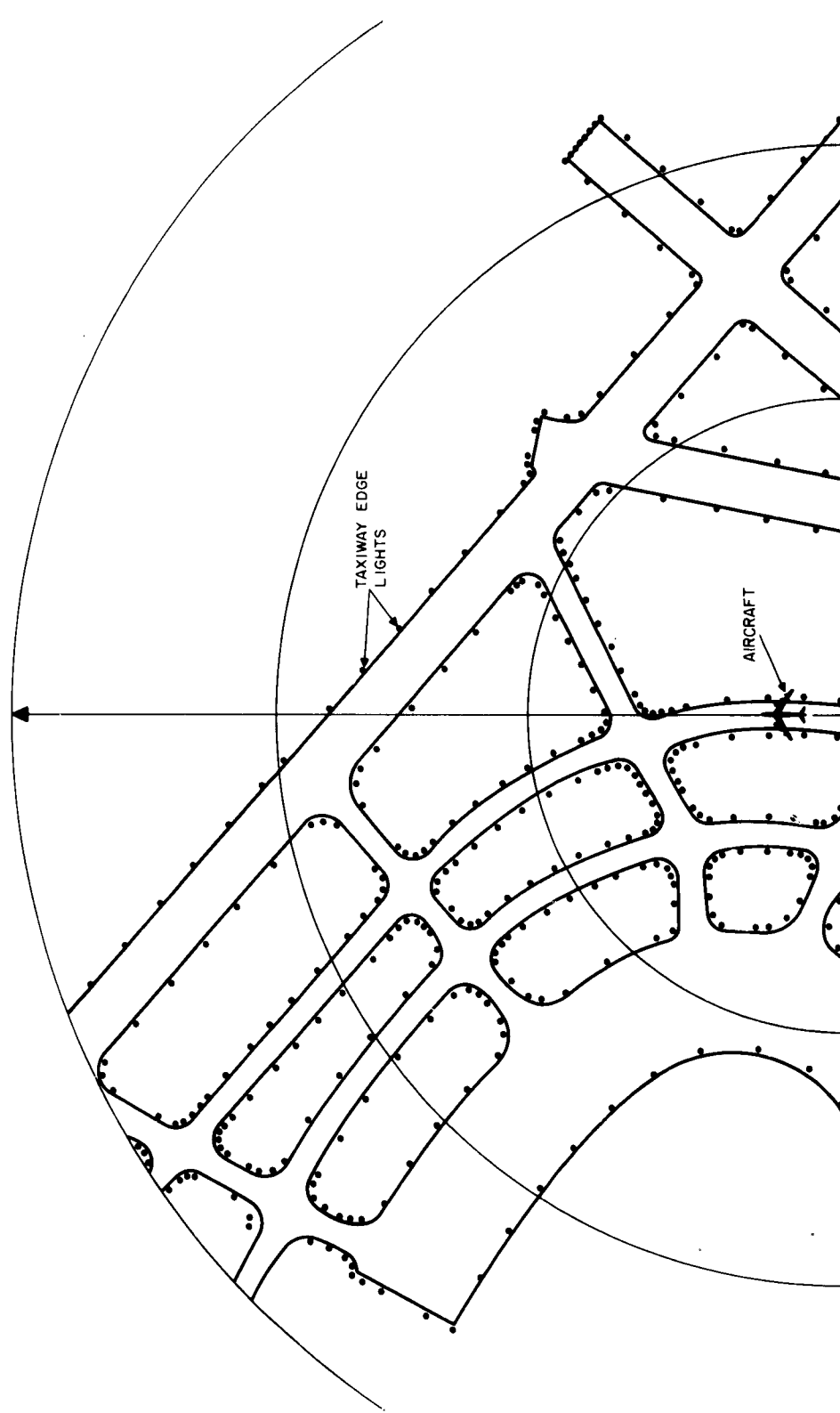


FIGURE 10-1. PORTION OF TAXIWAYS AT J. F. KENNEDY
INTERNATIONAL AIRPORT

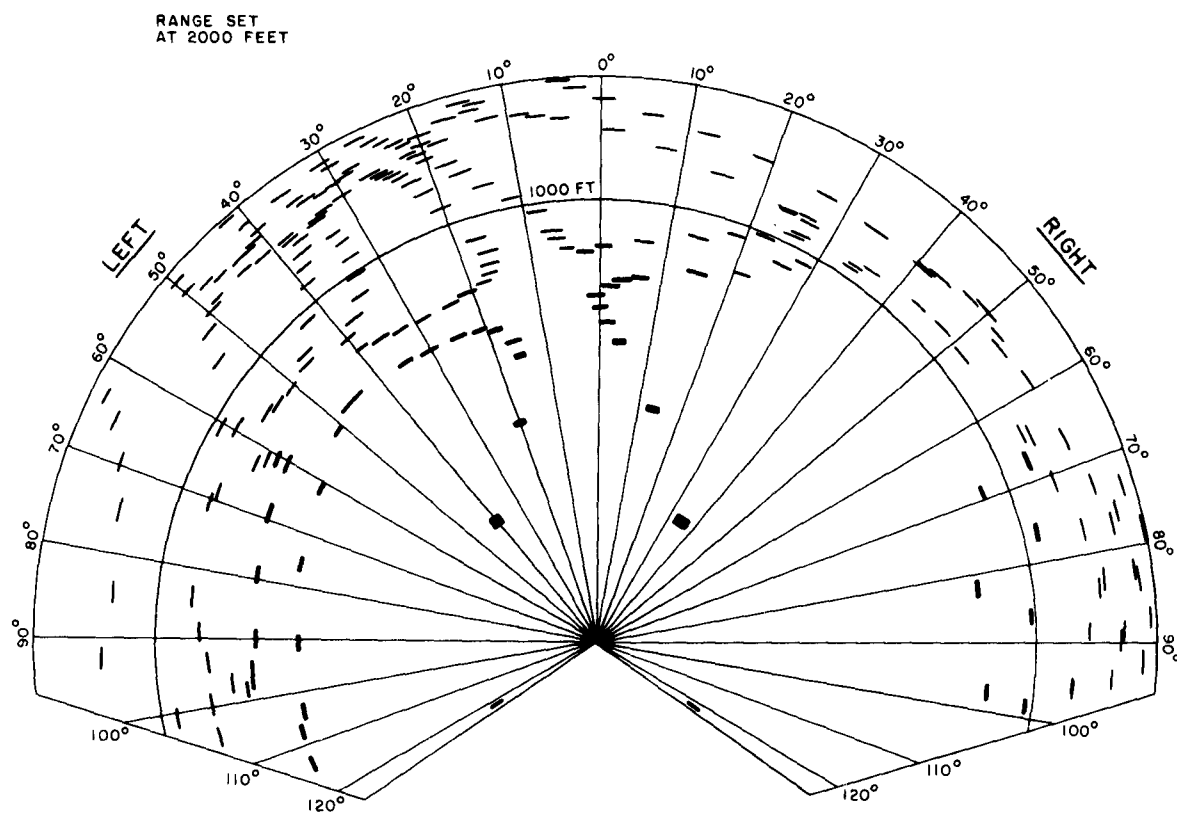


FIGURE 10-2. IDEALIZED RADAR SCOPE PICTURE OF TAXIWAYS

It can be seen that most of these characteristics are completely unsuitable for either navigation or guidance for a ground-guidance system.

The C-band version, which has had more widespread implementation, is even more unsuitable. In order to achieve the desired angular beamwidth and resolution, it would be necessary to operate at a higher frequency, which would be unsuitable for the weather-radar function. The size of the aperture is limited by the dimensions of the aircraft and can be considered as a fixed size. Hence, on the basis of azimuthal resolution and range performance, two radars are required to perform the ground-guidance and weather-radar functions. A frequency of about 42 Gc (Q-band) would be required to give a 0.9-degree beamwidth with a 22-inch dish.

It would be attractive to consider the use of common components for such units in the two radars in order to reduce costs. The following subunits will be considered:

1. Modulator,
2. Transmitter,
3. Receiver,
4. Display,
5. Servosystem,
6. Antenna,
7. Antenna feed.

The pulses required for adequate range resolution in the guidance radar are so much shorter than the normal pulses used in the weather radar that a completely new modulator would be required. The transmitter frequency is also sufficiently different that two transmitter tubes would be required.

The wide frequency difference would also require that two local oscillators be used in the receiver. The bandwidth requirements would almost undoubtedly dictate two IF amplifiers. Video circuits in the existing receiver would need to be replaced to broaden the video bandwidth to handle the shorter pulses.

The present 5-inch display may be sufficient for the ground-navigation function but probably not for the guidance function. However, the present display would require a hood for observation in all ambient lighting conditions. A bright display would certainly be desirable if not mandatory. The sweep circuits would have to be modified to provide the short-range displays required.

The bearing accuracy of the existing weather radars is not available. The RTCA minimum-performance requirements specify an accuracy of only +5 degrees. Such a bearing accuracy may be acceptable for the navigational function but not for the guidance function. The more stringent requirements of the guidance function may require an improved servosystem and associated gearing.

It appears feasible to use a common antenna for the ground-guidance radar and the weather radar. It is not certain that the existing dish could be used at a much higher frequency since the tolerances on the existing dish are not known. Tests may show that a new dish is required.

Since two frequencies are required, a completely new feed system is needed. A dual-channel rotating joint must be provided, and optimum compromise locations of the two feed horns determined. The ground-guidance radar must have an extremely rapid recovery time in order to achieve the necessary minimum range. The use of a ferrite isolator to lower the power at the transmitter/receiver (TR) tube is indicated. The required recovery time for the guidance function is barely possible with the existing state of the art in TR devices. The navigation requirement is definitely feasible.

Another alternative is that, if it is possible to raise the frequency of the weather radar into K_u -band and still retain adequate weather coverage, the need for dual feeds will be eliminated.

The Raytheon Company has proposed a K_u -band airborne weather radar--the Model LP-900--that more closely approaches the airport navigational requirement. It has a 37 to 42 inch dish antenna to produce a beamwidth of 1.3 to 1.5 degrees. The pulse width is 0.1 μ sec. Such a large antenna would probably not be capable of being retrofitted to existing aircraft and any compromise would widen the beamwidth, which is undesirable.

Radar guidance can be summarized as follows:

1. For guidance, a picture free from clutter with a narrow pulse width and a small minimum range is needed. Although it is possible to get the narrow pulses required together with small minimum range, it is expensive. In addition, the location of the antenna is problematical because, mounted in the nose of an aircraft, the looking angles across the airfield are low and it is difficult to predict the quality of the scope picture.
2. For navigational purposes, a narrow beam is required and this is a simple tradeoff between frequency and antenna size. Since airports are not perfectly flat and some buildings must be overlooked to obtain a map presentation, the antenna height is critical. It is doubtful whether large radome on top of the tail unit can be justified solely for taxiway navigation radar. If a higher frequency is used, it merely reduces the antenna size for the greater cost of the high-frequency components. Even so, the many unknowns as to picture quality are present.

All indications are that, to develop this technique would require a lengthy and costly development program, and the installation of production units would be difficult because of antenna limitations.

XI. MISCELLANEOUS TECHNIQUES, INCLUDING LINES AND PATTERNS AND LASERS

This study program required us to examine the use of lines and patterns. Various other techniques for providing ground guidance have been suggested or have been discovered during the course of the project and will be examined in summary form in this section.

A. LINES AND PATTERNS

1. PAINTED MARKINGS

There is no doubt that painted markings on runways and taxiways (when they are maintained in good condition, are of suitable pattern design, and can be seen by the pilot) are very valuable aids.

Reference 1 stated, "The visual guidance in fog conditions by day comes mainly from the painted center line (of the runway) and from the lines formed by the joints in the concrete blocks that form the runway surface."

There is no doubt that, whatever landing, takeoff, or taxiing aid is used in the future, well-designed and maintained runway and taxiway markings are very important aids to pilots. However, it is doubtful that a guidance system could be based on this technique as the primary aid during adverse weather conditions.

In conditions of snow, ice, slush, or any appreciable water coverage, markings will be either covered or indistinct, especially when, at night, they would have to be illuminated by lights from the aircraft.

To give adequate coverage of the entire runway and taxiway system, the problems of suitable pattern codes (to give left/right or distance information) would be difficult and would result in an extensive painting program at a large airport. This would be expensive and would cause excessive down-time on the instrument runways.

In addition, maintenance problems would be severe. Figure 11-1 shows the threshold of one of the main instrument runways at J. F. Kennedy International Airport. After repainting, runway markings and those in constant use on taxiways become coated with rubber in a matter of days. Although a cleaning solvent might be found, there is still the question of constant maintenance and runway closure.

2. RADIOACTIVE GUIDE LINES

Various types of radioactive emitters were examined for this application and, for reasons of safety, radioactive life, cost, and range required, gamma-ray emitters were found to be the only practical forms.



**FIGURE 11-1. TOUCHDOWN AREA OF INSTRUMENT RUNWAY 4R,
J. F. KENNEDY INTERNATIONAL AIRPORT**

Of these, the following are of interest:

<u>Source</u>	<u>Half-Life</u>	<u>Energy Range (Mev)</u>	<u>Basic Cost per 1000* Feet to give 50-Foot Detection Range (\$)</u>
Cesium 144	290 days	0.07 to 0.14	0.20
Cesium 134	2.3 years	0.56 to 0.60	100.00
Cesium 137	2.7 years	0.63 to 0.68	0.20
Cobalt 60	5.3 years	1.1 to 1.4	0.10

* Basic raw material not including costs of solubles for paint mixture, etc.

It is necessary to consider various sources because discrimination between adjoining taxiway routes or at intersections is necessary. Of all the sources, Cobalt 60 has the most desirable features. If it is assumed that the radiation must be detectable at distances up to 50 feet, it is possible to estimate the source strength.

Two detectors would probably be required for left/right sensing. The detectors could either be separated by distance (about 10 feet would be required) or positioned side-by-side with shielding in between. It is assumed that a 5-inch scintillation detector with 50-percent efficiency (reference 24) is used.

The runway or taxiway center line is to be painted with a Cobalt 60 paint. The accuracy required is +5 feet, 99 percent of the time. A count-rate meter with a 1-second integration time is used.

Taking the source as an infinite line, the signal strength is proportional to $1/r$ rather than $1/r^2$, and attenuation in 50 feet of air could be expected to be about 10 percent. Attenuation in the aircraft structure may have to be considered later, but it is ignored at this stage.

The accuracy of distance measurement is controlled by statistical fluctuations in the count rate. Since the mean count rate is large in this case, the true count distribution, which is binomial, is approximated by a Gaussian rather than a Poisson distribution (reference 23). The standard deviation is equal to the square root of the average value.

The accuracy assumed requires that a 10-percent deviation correspond to three standard deviations--that is:

$$3\sqrt{C} = 0.1 C; C = 900$$

where C is the average number of counts in 1 second. C is given in terms of the source strength by:

$$C = \frac{eLA}{2\pi r} \quad (11-1)$$

where

e = counter efficiency (1/2),

L = gammas emitted per second per unit length of source,

A = counter area (130 cm²),

r = distance from source (50 feet = 1500 cm).

Evaluating equation 11-1, we find $L = 1.3 \times 10^5$ gammas/cm-sec. The total emission rate in 9000 feet of runway is about 3.5×10^{10} gammas/sec. Since Cobalt 60 emits two gammas per disintegration, the total activity is about 1/2 curie--a modest amount.

a. HEALTH HAZARD

The flux at 1 foot from the source is about 650 gammas/cm² sec, or about 1.4 mr/hr. The maximum permissible exposure is 2.5 mr/hr for a 40-hour week (reference 25). Thus, it seems that the health hazard is not severe enough to prohibit use of this method.

b. NATURAL BACKGROUND

Thus far, the natural background radiation has been ignored. The total gamma background in some places can reach 0.1 mr/hr; the signal flux assumed at 50 feet is only about one third of this value. Cobalt 60, however, has a sharp line spectrum (two gamma rays, at 1.17 and 1.33 Mev), and the scintillation detector assumed can discriminate in energy. By using one or two single-channel analyzers, for example 0.03 Mev in width, it is believed that the effective background can be reduced by a factor of 50. In this case, its effect is negligible.

c. OPERATIONAL CONSIDERATIONS

Like all painted markings, the source must be stable under weather and wheel usage. Because the paint does not have to be visible, it could be coated with some sort of plastic material. This would also ensure that the radioactivity would not be carried around the airport on tires that had been contaminated.

Health precautions would be necessary on some scale, and film badges would be required for many personnel. Also, a health physicist may be needed at each airport.

To get the necessary system accuracy, a 1-second integration time was assumed. For landing and takeoff, this is probably too long when it is considered that at 120 mph, 176 feet of distance is covered in 1 second. To reduce the integration time would require correspondingly higher amounts of source material, thus increasing the health hazard.

For taxiing, the integration time is satisfactory for straight sections of taxiway, but it is possible that, at turns, the time might be too great even at slow speed. As described in Section V, the taxiing turn is a precise maneuver.

Furthermore, to offset absorption by water, slush, etc., it may be necessary to raise the source strength by another factor of two.

Therefore, the overall exposure rate could be increased by a factor of four to 5.6 mr/hr. This may not be too serious a hazard on runways and most taxiways but, around the terminal area, it would require careful monitoring.

3. LIGHT PATTERNS

As discussed in Section V, light patterns such as runway and taxiway center line lights and runway touchdown patterns will be essential for pilot visual guidance at all times.

It was shown that such lights will be useful down to visibilities of 300 to 600 feet and, even in thick fogs, one or two lights can still be of some use. In considering light patterns as a primary guidance for low-visibility conditions, we must now consider some form of detector mounted on the undersurface of the aircraft looking at a light pattern just underneath the aircraft.

It is doubtful whether point sources of light would be suitable for this purpose. Because detecting devices would probably operate with a two-dimensional field of view, a pattern of point sources may be ambiguous in the region of turns and around curves. To provide smooth tracking the speed of the aircraft would also figure in any integrating process required to bridge the gap between sources. Consequently any system using point sources would, at best, be relatively complex to provide reliable detection and worthwhile guidance. In addition, the computational problems in vector analysis of angle and range of each source would undoubtedly be very complex.

Therefore, we will consider line sources. Such a source is the electroluminescent panel. At the present time, these panels are not capable of very high brightness levels, and no examples were found that were visible in daylight. Even if they were only considered for use under nighttime conditions, the brightness varies as a function of the cosine of the looking angle. Thus, a detector mounted 5 feet above the ground (on the underside of the fuselage) 20 feet from an electroluminescent center line would only see $1/4$ of the light level emitted by each panel. Therefore, a considerable number of coded or modulated line patterns would be required for any given runway or taxiway. This would prove expensive for both installation and maintenance.

In addition, any water, slush, etc., would further reduce brightness and resolution in addition to causing the backscattering of light, which would complicate the pattern detection and resolution.

4. LASERS AS LIGHT SOURCES

Lasers have three significant advantages over common light sources:

1. They are monochromatic, thus emitting light at a known and stable frequency,
2. The light emitted is collimated and beamwidths are of the order of minutes and seconds,
3. Their light is time-coherent, and therefore the phase-angle relationship of the light waveform is fixed in relation to a particular reference.

There are two basic types of lasers--pulse and continuous wave (CW). Pulse lasers have very high power in the megawatt range for microsecond pulses. CW lasers have powers between 0.01 and 1 watt, depending on the type.

Laser light is attenuated through the atmosphere at the same fractional rate as conventional incoherent light. Thus, watt for watt in a given beamwidth, there is no advantage in the use of a laser for fog penetration.

For a laser to be considered over conventional light sources, it must be shown that the advantages of a laser are required for the particular application.

The monochromatic properties are useful where there is a problem in discriminating light sources one from another. This would be useful in taxiway guidance at intersections if lasers were considered as capable of providing the required light pattern.

Collimation of the light, in addition to allowing very narrow beamwidths that increase the power per unit area, would prove beneficial if the aircraft could be tightly controlled to maintain its position within the light beam. However, as pointed out in Section V, this is not operationally desirable. In taxiway applications, the collimation would be a severe disadvantage since it is necessary to define curvature of the taxiway center lines and the curvature must be known in advance. It appears that no laser installation would meet this operational requirement.

Time coherence would prove useful in ranging applications if fog penetration were high.

We are, therefore, faced with two basic difficulties in considering the laser for ground guidance. If the laser is considered as a source of light outside the aircraft, its fog penetration is limited and its collimating properties are, in fact, a disadvantage.

However, if laser or lasers mounted in the aircraft are considered, there is one particular application that would make full use of all the advantages described. A doppler laser installation of two units could provide ground-speed and yaw angle information.

Two lasers mounted in the nose of the aircraft would provide two narrow light beams, each shining forward of the aircraft at a fixed angle in both the vertical angle and in azimuth either side of the aircraft center line. The doppler frequency shift of each beam due to aircraft velocity is compared with the transmitted frequency of the lasers. In a fixed installation, the addition of the two received frequencies compared with the reference frequency provides the aircraft speed. The difference between the two received frequencies is proportional to the aircraft yaw angle. The ground-speed readout would be useful for both runway and taxiway applications, though of course ground-speed alone does not provide guidance.

With the addition of a computer referenced to a known starting position and direction on the runway, it would then be possible to indicate distance-to-go along the runway and lateral deviation from the center line.

Final system accuracy depends largely on the accuracy of setting the starting point and direction in the computer and the aircraft heading reference supplied to the computer. It is expected that the starting point must be known accurately to within +5 feet of runway center line and probably less than 50 feet in longitudinal distance. Furthermore, an aircraft heading reference to within ± 0.1 degree will be required.

Such a computer will therefore demand an outside reference system at least as good as a K-band localizer together with DME and a highly accurate aircraft gyro-compass.

Another difficulty that would have to be considered would be the reflective properties of water-covered runways where most of the transmitted light would be reflected away from the aircraft.

B. MECHANICAL TRACKS

The All-American Engineering Company has proposed that runway and taxiway center line guide tracks be used for guidance. A rigid boom would be fixed to the aircraft nosewheel strut. A blade at the other end of the boom would be spring-loaded to make contact with a mechanical track mounted flush in the pavement surface.

The length of the guide boom required depends on the angle between the nosewheel heading, the orientation of the track at initial pickup, and aircraft speed. Because it cannot be guaranteed that the aircraft will enter either the runway or the taxiway exactly on center line, a number of angled entry tracks are required feeding into the center line track.

It has been calculated by All-American that for runway tracks suitable for landing aircraft, a nosewheel boom of up to 16 feet in length would be required for present-day jet transports. This requirement, together with the operational characteristics of aircraft detailed in Section V and the probable high cost of installation and maintenance, would prohibit any runway application.

Taxiway applications might, however, be more feasible in some respects. The nosewheel boom would probably not be of excessive length, though whether it could be retracted with the nose-wheel and yet retain the required rigidity when extended would have to be determined.

There may be some advantages in using a flexible rather than a rigid boom. If the boom were telescopic, the length of the boom at any given moment would be a measure of the distance from the center line track if an angular pickoff were mounted at the aircraft attachment point. This would still require a long boom but it may be easier to install on an aircraft since it would not be subject to the stresses of a rigid boom, and it would also be retractable. In either system, the installation of taxiway tracks would require that the taxiway be closed for some time but, on straight sections, it would probably not be excessive.

Taxiway curves would probably present some difficulty in installation. In addition, expansion and contraction of such curved tracks under various weather conditions may cause maintenance problems.

If field tests indicated that curved tracks similar to those required for taxiway turns were operationally feasible and involved no maintenance difficulties, the technique must have some possible application.

The actual use of tracks would then depend on the boom attachment. If it were possible to carry the boom as a retractable item, the technique could be used for all taxiing applications, provided that the operational tests showed that, at taxiway junctions and intersections, the desired track can be selected by the pilot.

At a junction of tracks, it would be necessary to force the boom or the tracking blade to one side of the track to pick up the new track on that side leading from the original track. If the aircraft had a slight displacement error at that point in the opposite direction, this action would result in tire scrubbing and twisting of the nosewheel strut.

However, if a limited application of the technique to the terminal area in the close vicinity of the loading gates is considered, it may be possible to avoid track junctions and the boom could be installed by the ground personnel as the aircraft approached its terminal.

C. TELEVISION TRANSMISSION OF ASDE PICTURE

It has been suggested that television transmission of the ASDE radar picture to the aircraft might meet both the airport navigation and guidance requirements.

The picture definition in the aircraft should be of the highest quality. Therefore, additional television bandwidth is required. Studies have shown that about a 1000-line system is required. This would require

special transmitters, receivers, and scan converters and would involve the expenditure of time and money in development. Alternatively, it would appear possible to use multiple pickups and transmitters to reduce the number of lines required and simplify the system. For example, four 500-line scan-conversion systems, each converting one-fourth of the ASDE display could be used. The output of each scan converter would be coupled to a separate transmitter. The aircraft could receive the appropriate portion of the ASDE display by selecting the proper channel. Standard scan converters, transmitters, and receivers could be used. The antenna on the aircraft would require some special considerations.

Apart from these aspects, there are two other considerations. The existing ASDE radar was designed as a monitor for airport ground operations. It is doubtful whether it has the required accuracy for ground guidance or sufficient picture repetition rate for accurate turns to be made.

However, for airport navigation and runway guidance, these disadvantages would not be serious.

One fundamental problem remains. For a picture to be really useful to a pilot for navigational or guidance purposes, it would have to be oriented to the aircraft heading. In addition, the center of the scope should be the aircraft's position. This would complicate the data-processing and demand that aircraft identity be known and preserved throughout the system.

Therefore, although such a system is theoretically possible, it is doubtful whether the operational problems could be sufficiently overcome at reasonable cost.

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APPENDIX A
ACTUAL LOW-VISIBILITY OPERATIONS AT
JOHN F. KENNEDY AIRPORT, NEW YORK

Since the main portion of the report was written, we have had an opportunity to study some airport operations at John F. Kennedy International Airport under visibility conditions reported as "Zero Visibility." As pointed out in Section V of the report, the number of such hours at this airport are somewhat rare. Therefore, it was felt that this particular event was worth recording and commenting upon. It is very easy to theorize about a certain situation and then, when the situation actually occurs, to report only those facts that fit the theories. However, in this case, it was quite remarkable how closely the actual operations followed the ideas expressed in Section V.

Since we could only study the actual operation after the event, the following information was obtained from the airport tower tape-recordings of the ground-control radio transmissions and from the personal experiences of one of the pilots who was involved.

Narrative

Date: 23 April 1964

Airport: John F. Kennedy International

Fog started forming at about 0600 hours (local time) when visibility was 1/16 mile. Between 0636 and 0651 it reduced to zero as reported by both the airport tower and the Weather Bureau. At 0734, the tower was still reporting zero and the Weather Bureau, 1/4 mile. By 0805, the visibility had improved to 3 miles.

The fog was very low-lying so that the tower was above the top of the layer. Visibility on the ground was extremely variable throughout the whole period according to tower and pilot conversations at the time. One runway had a visibility of 1/8 mile (660 feet) at the same time as 1000 feet was recorded on another runway and at least

one pilot could not see the wing-tips of his aircraft (Boeing 720) which would mean a visibility of less than 95 feet. This very clearly illustrates the extreme variability of fog visibilities.

The main time period of interest is from 0645 to 0745 hours. During this period, the visibility was reported as zero until at about 0734 runway 31L cleared enough (runway visual range 2500 feet) to permit takeoffs starting at 0745 hours.

During this time period, there were 30 aircraft movements on the airport. At least 10 of these were towing or taxiing movements from the airline hangars to the terminal gates. This shows the importance of considering a large number of taxi routes rather than the oversimplification of a single route around the airport.

The remaining 20 movements were all from the airline gates out to the departure runway, 31L. Pilots preferred to leave their gates and get in a position in sequence so that, when the fog lifted, they could get on their way with a minimum of delay.

From listening to the conversations, it was quite apparent that airport navigation was the main pilot problem but was eased by the fact that the ground controller was using the ASDE radar to give directions and advance warnings of turns. There was only one occasion during the hour when a pilot called that he did not know where he was. The controller located his aircraft on the ASDE scope and the pilot could resume taxiing.

It was evident that the controller had two main problems. The first was maintaining identity of each aircraft when they were scattered about the airport, though this problem was alleviated by the fact that pilots were asked for position reports at specific locations.

The second problem was that the controller seemed to have some difficulty in orienting himself to the aircraft so that he would often give instruction for a "right turn" and then quickly correct himself and give a left-turn instruction. It is considered that this difficulty would probably be overcome as controllers gain more experience in using ASDE during bad-weather conditions.

The problem of identity is common to most congested radar situations. At no time during this period did it seem to be a serious handicap but it did result in the use of a lot of communication time. Although the technical problems are somewhat severe, the advantages of a horizontal daylight viewing scope would be of value since identity tags could be moved about the scope.

One obvious value of the radar was in avoiding collisions and the psychological advantages for the pilots because of this. The pilot who related his experiences said it was comforting to be told to stop at a certain point because of an aircraft ahead he could not see, and then as the fog rolled away to see the aircraft in question just ahead. Also, this pilot mentioned the tremendous advantage in being given advance warning of when and in which direction to turn.

In view of the fact that there is no taxiway centerline lighting (only white painted centerlines) and visibilities were as low as 95 feet, it is quite remarkable that 30 aircraft moved about the airport as well as they did. It should also be realized that, in 707 and DC-8 type aircraft, there is a blind area ahead of the pilot because of the aircraft's nose. This blind area extends out to 50 feet ahead of the pilot. These facts tend to emphasize that taxiing by visual references may not be a severe problem even when the visibility is less than 300 feet, providing the navigational requirement is met.

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