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STUDY OF CAPTURE-EFFECT
GLIDE-SLOPE MONITOR TECHNIQUES

October 1963

Project No. 3182-1

Report No. RD-64-17

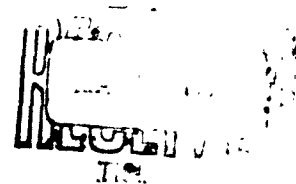
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FEDERAL AVIATION AGENCY
SYSTEMS RESEARCH AND DEVELOPMENT SERVICE

By

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Deer Park, Long Island, New York



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AIRBORNE INSTRUMENTS LABORATORY
A DIVISION OF CUTLER-HAMMER, INC.

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TABLE OF CONTENTS

	<u>Page</u>
Abstract	v
I. Introduction	1
II. System Description	3
A. Outline of Capture-Effect System	3
B. Elevation Patterns	5
C. Application of Capture Effect	6
D. Relation Among Antenna Heights	9
III. On-Course Monitor Techniques	11
A. General Discussion	11
B. Location of On-Course Monitor	13
C. Detection of On-Course Variations	14
D. Effect of Snow	16
E. Variation in Coefficient of Reflection	17
IV. Monitor Techniques Off Course	19
A. General Discussion	19
B. Location of Course-Width Monitor	20
C. Mast Location of Course-Width Monitor	21
D. Detection of Course-Width Variations	23
E. Phase-Adjustment Procedure	25
F. Effect of Coefficient of Reflection	26
G. Effect of Snow on Course-Width Monitor	27
V. Conclusions and Recommendations	29
A. On-Course Monitor	29
B. Course-Width Monitor	29
Appendix A--Snow Effect	A-1
Appendix B--Effect of Coefficient of Reflection	B-1

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Signal Patterns for Capture-Effect Glide Slope	7

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Glide-Slope Projector Summary	8
II	Capture-Effect Projector Phase Relations	12

Airborne Instruments Laboratory, A Division of Cutler-Hammer, Inc., Deer Park, Long Island, New York
STUDY OF CAPTURE-EFFECT GLIDE-SLOPE MONITOR TECHNIQUES by
A. Tatz, October 1963
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ABSTRACT

The capture-effect glide-slope system is explained by comparison with a standard null-reference system, and the relative advantages of the glide-slope system are analyzed. A general exposition of monitor techniques leads to an analysis of capture-effect monitor problems; solutions for the particular capture-effect monitor problems are presented and logically justified.

The recommended solution for the on-course monitor is recognized as the monitor-detector location for the first null of the middle-antenna resultant where the top- and bottom-antenna resultants exactly cancel at the 360-degree dephase point for top and bottom antennas.

The recommended solution for the course-width monitor-detector location is found on the antenna mast midway between the middle and bottom glide-slope antennas. An alternative solution for the course-width monitor is recognized as the monitor-detector location for the second null of the top-antenna resultant, where the middle- and bottom-antenna resultants are in phase opposition at the 180-degree dephase point for middle and bottom antennas.

Analyses are given for the monitor effects of changes in amplitude and phase of the signals in the capture-effect glide-slope circuits, and of changes in coefficient of reflection and depth of snow in the monitor region.

The recommended solutions were successfully demonstrated at a brief field trial and are currently being evaluated at an operating site. A noteworthy outcome of the project is the feasibility of operating a course-width monitor system that does not deteriorate because of the accumulation of snow near the glide-slope station.

I. INTRODUCTION

The Capture-Effect Glide-Slope Projector was developed during 1962 by the Federal Aviation Agency as a new type of station that provides service that is compatible with standard glide-slope receivers, while providing improvement relative to the standard null-reference station at sites where the terrain in the approach region includes a hill. It has been demonstrated, at several sites, that where the energy reflected from the hill caused deterioration of service on a null-reference system, the airborne service was improved by substituting a capture-effect system.

Although the capture-effect system is compatible with standard airborne receivers, it is not directly compatible with the monitor techniques that are used for the null-reference system. The early attempts to adapt the null-reference monitor techniques to the capture-effect system were unsuccessful, resulting in numerous alarms when, in fact, the system was performing satisfactorily.

The purpose of this report is to state the results of a study of the capture-effect system leading to the recommendation of new monitor techniques that promise to be more satisfactory. The newly recommended techniques resulting from this study have been subjected to a brief trial at one typical capture-effect glide-slope site, and the results have been encouraging. Further corroboration of the success of the new techniques will be determined by the Federal Aviation Agency at other capture-effect stations during the next several months.

II. SYSTEM DESCRIPTION

A. OUTLINE OF CAPTURE-EFFECT SYSTEM

The explanation of the capture-effect system is conveniently started by making a comparison with the standard null-reference system, which it resembles to a large extent.

The null-reference glide-slope projector has two radiating antennas, one above the other, with the bottom antenna installed at one-half the height above ground of the higher antenna. A UHF reference signal, modulated equally with an audio-frequency signal of the fly-up sense and an audio-frequency signal of the fly-down sense, is radiated from the bottom antenna. Additional sideband energy, about 11 db below the reference, is radiated from the higher antenna. Taking into account the energy reflected from the ground plane (assuming specular reflection), the energy of the additional sidebands is zero at the nulls of the higher antenna. The glide angle is selected at the first null above the ground plane, and the course width is confined to the region near this null. The additional sidebands are phased with respect to the reference sidebands so that in the half-course width below the null, the fly-up sidebands add, and the fly-down sidebands subtract; in the half-course width above the null, the fly-down sidebands add, and the fly-up sidebands subtract.

Building from the null-reference system, the following additions are made to construct a capture-effect glide slope:

1. A third antenna is added above the lower two, making the former upper antenna of the null-reference system the middle antenna of the capture-effect system.

2. The reference-signal energy is split so that the power fed to the bottom antenna is four times the power fed to the middle antenna. The splitting circuit is phased so that the middle-antenna reference energy subtracts from the bottom-antenna reference energy. This subtractive condition prevails below the null of the middle antenna; however, above this null, the two reference energies are in additive phase.

3. The additional sideband energy is split among all three antennas. The power fed to the middle antenna is four times the power fed to the bottom antenna, and the bottom-antenna power is equal to the top-antenna power, as far as additional sidebands are concerned.

4. The ratio between the reference sidebands fed to the bottom antenna and the additional sidebands of the middle antenna is maintained at about 11 db, just as in the null-reference system; furthermore, the relative phasing between middle-antenna additional sidebands and bottom-antenna reference sidebands is the same as the phasing for the null-reference system.

5. The additional sidebands fed to both the top and bottom antennas are in opposite phase from the middle-antenna additional sidebands. The net effect of this phasing, taking the lobing caused by ground reflection into account, is that over the region of the course width the bottom-antenna additional sidebands have fly down adding to (fly up subtracting from) the reference sidebands, whereas the top-antenna additional sidebands have fly up adding to (fly down subtracting from) the reference sidebands. It turns out that the amplitudes of the top- and bottom-antenna additional sideband patterns are equal at the middle-antenna null, so that the difference in degree of modulation measured by the airborne receiver is zero on course.

In fact, the difference in degree of modulation (ddm) over the entire course width, taking all signals into account in the capture-effect glide-slope projector, is precisely the same as the ddm for the null-reference system, and therein lies the compatibility attribute of the capture-effect system.

6. An additional transmitter is obtained, using either the standby glide-slope transmitter or an additional unit. The primary transmitter is tuned offset about 4 kc from the assigned channel frequency, and the additional (clearance) transmitter is tuned offset about 4 kc on the other side of the assigned channel frequency. The clearance transmitter is 90-percent amplitude modulated by the audio-frequency signal of the fly-up sense (150 cps only).

7. The clearance power is split so that equal amounts are fed to the top and bottom antennas. The ratio between the reference-sideband energy and the clearance energy in the bottom antenna is about 14 db (nominally 4 watts to 0.16 watt).

The purpose in adding reference sidebands to the middle antenna is to create a net reference-sideband pattern in elevation that is relatively weaker below course than above course.

The purpose in feeding additional sidebands to the top and bottom antennas is to create a net additional sideband pattern in elevation that maintains the same ddm over the course width that would prevail if a null-reference system were used.

The purpose in adding a clearance transmitter is to make up for the deficiency of the low-powered portion of the primary system in the region below course. The clearance energy provides adequate signal of the fly-up sense to maintain a large ddm exceeding full-scale meter deflection at low angle and long distance from the station.

The contribution of the clearance energy to the meter deflection is negligible in the region of the course width and on the useful fly down side of the system above the nominal course width.

B. ELEVATION PATTERNS

An explanation of the advantage of the capture-effect system in reducing the interference of hill-type reflection is necessarily based on numerical ratio and, therefore, a set of numerical quantities typical for the system must be assumed for the purpose of discussion.

Taking as a numerical base the value +1.00 for the amplitude of the reference signal fed to the bottom antenna, it follows that the reference signal fed to the middle antenna has an amplitude of -0.50 (paragraph A2).

The amplitude of the additional sideband (up/down) signal is stated (paragraph A5) to be related to +1.00 by a factor of about -11 db, or an amplitude of 0.28. Justification for this number depends on making assumptions relating to percent of modulation and course width. In a theoretical derivation of ddm as proportional to the ratio between additional (up/down) resultant pattern and reference resultant pattern, it can be shown that:

$$\frac{\text{up/down meter deflection}}{\text{full-scale deflection}} = \frac{0.92}{0.175} (0.28)^2 \sin \frac{W}{\alpha_0} \frac{\pi}{4} \quad (1)$$

where

W = course width between 150 μ a fly-up to 150 μ a fly-down deflection,

α_0 = glide-slope angle, 0.92 is the total percent of modulation,

0.175 = standard number for aligning glide-slope receivers in terms of ddm.

Taking the course width as $(4/9) \alpha_0$, the number 0.28 is chosen to make the right-hand side of equation 1 equal unity.

Of course, slight variations can be made in the choice of the modulation percentage and course width, whereupon slight changes would be made from 0.28. The numbers selected above are typical, because the total modulation is maintained

between 91 and 94 percent in practice, and $W = 4/3$ degree ($2/3$ degree each side of the glide-slope angle) is a reasonable value for a glide-slope angle of 3 degrees.

According to the paragraphs A5 and A6, the relative amplitudes for the additional sideband (up/down) signals are +0.28 for the middle antenna, and -0.14 for the top and bottom antennas.

Table I shows a summary of the amplitudes of the resultants for all signals in the capture-effect system, and Figure 1(A) shows a plot of the resultants for the reference signal and the clearance signal; also shown for comparison (as the dashed line) is the lower portion of the reference-signal pattern for a null-reference system.

The pattern for the clearance signal in Figure 1(A) is based on paragraph A9. Note that the clearance signal is stronger than the reference signal only in the region below about one-half the glide-slope angle. (The exact location of the crossover depends on the power ratio that is used and is shown for the power ratio of 4 watts reference to 0.16 watt clearance in the bottom antenna.)

C. APPLICATION OF CAPTURE EFFECT

An analytic demonstration of the advantage of the capture effect depends on assuming that a major reflecting object such as a hill, protruding to a significant elevation angle, exists in the approach region.

The explanation is facilitated by the use of Figure 1(A). The highest reasonable estimate for a hill in the approach region is at 2 degrees--for example at Reno, Nevada. Comparing the amplitude of the reference signal at $2/3$ the glide-slope angle with the on-course amplitude, Figure 1(A) shows that for a null-reference system the energy striking the hill would be only 1.4 db below the on-course amplitude; whereas for a capture-effect system, the energy striking the hill would be 7 db below the on-course amplitude. The advantage has come about by generating a sharper elevation pattern for the reference signal below course, and the role of the clearance energy enters indirectly by permitting the use of a steeper reference-signal pattern without sacrificing low-angle fly-up signal.

At the elevation angle of $2/3 \alpha_0$ (and above), the direct role of the clearance signal is negligible. For example at $2/3 \alpha_0$, the clearance signal is 8.2 db weaker than the reference signal, and its detected output is relatively much weaker because of the capture effect.

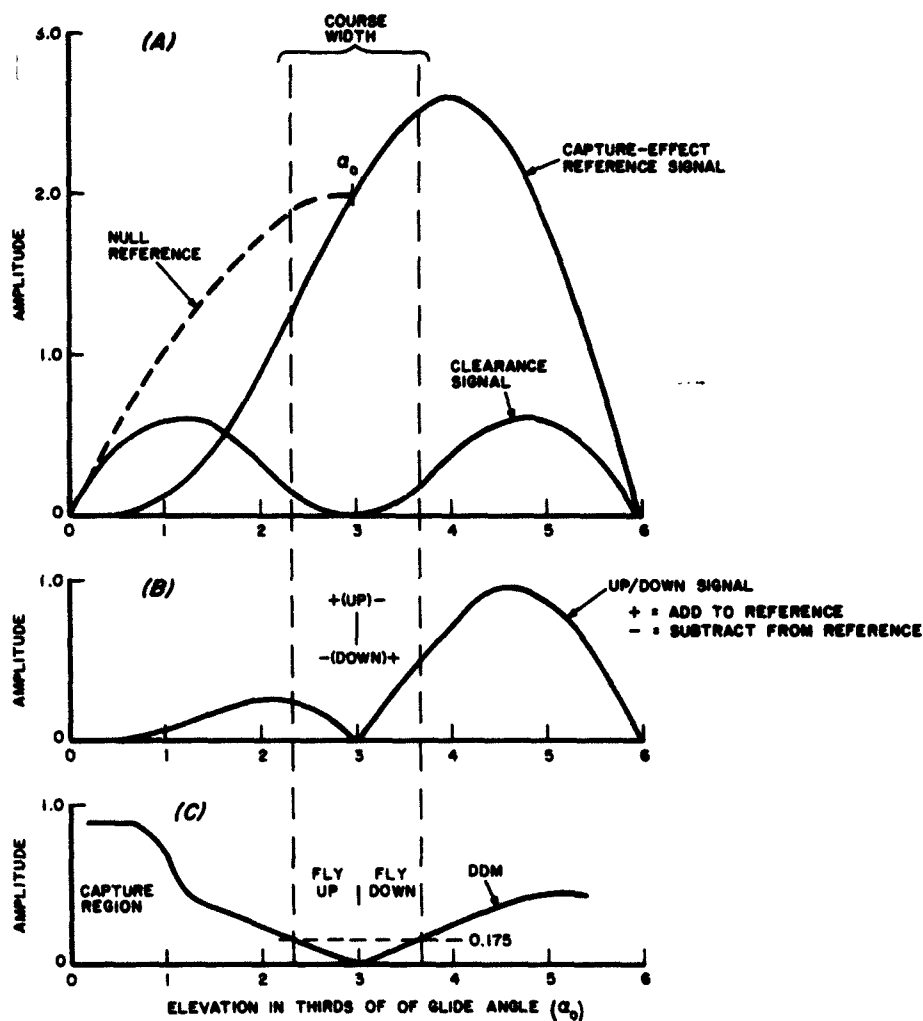


FIGURE 1. SIGNAL PATTERNS FOR CAPTURE-EFFECT GLIDE SLOPE

TABLE I. GLIDE-SLOPE PROJECTOR SUMMARY

Antenna	Null Reference	Signal Amplitude Capture Effect	Remarks on Phasing	Resultant with Image at Long Distance
Top $h_{top} = 3h_b$	none	up/down = -0.14 clearance = +0.20	Up/down signal becomes (+) between $(2/3)$ and $(4/3) \alpha_0$ (between nulls).	up/down = -0.28 sin 3β clearance = +0.40 sin 3β $\beta = (\alpha/\alpha_0)(\pi/2)$
Middle $h_{mid} = 2h_b$	up/down = +0.28	up/down = +0.28 reference = -0.50	Null at α_0 . Up/down becomes (-) and reference becomes (+) between α_0 and $2\alpha_0$.	up/down = +0.56 sin 2β reference = -1.00 sin 2β
Bottom $h_b = \lambda/(4 \tan \alpha_0)$	reference = +1.00	up/down = -0.14 clearance = +0.20 reference = +1.00	Up/down (-) means that up signal subtracts from reference (down adds). Up/down (+) vice versa.	up/down = -0.14 sin β clearance = +0.40 sin β reference = +2.00 sin β

Total reference = $2 \sin \beta - \sin 2\beta$

up/down = $+0.56 \sin 2\beta - 0.28 (\sin \beta + \sin 3\beta)$

clearance = $+0.40 (\sin \beta + \sin 3\beta)$

The capture effect is defined in Radio Engineers' Handbook by F. E. Terman (page 577) where it is shown that when two different amplitude-modulated carriers with significantly different amplitude levels are detected by a linear detector, the weaker signal is attenuated by the signal ratio and by an extra 6 db. This approximation sufficiently describes the capture effect for signal ratios above 6 db, and the attenuation of the stronger signal can be considered negligible.

Accordingly, where the clearance signal is 8.2 db weaker than the reference signal, as it is at $2/3 \alpha_0$ in Figure 1(A), the actual effect of the clearance signal is attenuated by 14.2 db; this makes the effective clearance signal 22.4 db below the effective on-course reference signal, and therefore negligible.

If a hill exists at $1/3 \alpha_0$ (about 1 degree), which is a case found more often, the reference signal striking the hill for a null-reference system would be 6 db below the on-course reference amplitude. On the other hand, for a capture-effect glide-slope system, the reference signal striking the hills is 22.5 db below the on-course reference amplitude. At this angle the clearance energy is nearly maximum, but still 10.5 db weaker than the on-course amplitude. Taking into account the capture effect, the clearance-signal detector output is attenuated 16.5 db, making the effective clearance signal 27 db below the effective on-course reference signal, and therefore negligible.

In both cases, for a hill at $1/3 \alpha_0$ and at $2/3 \alpha_0$, the energy striking the hill would cause much less interference on course for a capture-effect system than for a null-reference system.

D. RELATION AMONG ANTENNA HEIGHTS

The height of the antenna in a glide-slope system is related to the glide-slope angle by theoretical considerations that assume a flat perfectly conducting ground plane and the absence of phase relations involving distance. For horizontally polarized UHF, it is theoretically valid to assume that a mirror image of opposite polarity and of equal amplitude to the real antenna is located below the ground plane, with both antennas equidistant from the ground. The resultant radiation forms a pattern in elevation angle that depends on the phase between the two sources (real and image) that is directly related to difference in the length of the path of propagation.

A convenient distance reference for computing path differences is the distance from the receiver to the ground point between the real and image antennas. For small eleva-

tion angle α , the direct radiation from the real antenna leads the distance reference by phase angle $(2\pi/\lambda) h\alpha$, where h is the antenna height; the image radiation lags the distance reference by the same phase angle. The resultant pattern thus formed by two equal-amplitude vectors of opposite polarities with equal and opposite phase angles is given by $2 \sin [(2\pi/\lambda)(h\alpha)]$.

The on-course glide-slope angle α_0 is characterized by a zero value for the additional sidebands (up/down) signal. The middle-antenna resultant pattern is zero when

$$\sin [(2\pi/\lambda)(h_{\text{mid}} \alpha_0)] = \sin \pi$$

$$h_{\text{mid}} = \lambda/(2\alpha_0)$$

Thus, for a 2.87-degree glide slope ($\alpha_0 = 1/20$), the height of the middle antenna is 5λ (about 15 feet). This solution is identical with the solution applicable to the null-reference system.

It is further required in the capture-effect system that the resultant pattern of the top antenna combine with the resultant pattern of the bottom antenna to yield a net up/down signal of zero. Since the amplitudes of these two resultants are equal, it is required that $\sin [(2\pi/\lambda)(h_{\text{top}} \alpha_0)] + \sin [(2\pi/\lambda)(h_{\text{b}} \alpha_0)] = 0$, which is satisfied for $h_{\text{top}} - h_{\text{b}} = \lambda/(2\alpha_0)$.

It is thus shown that an ideal capture-effect system is based on the arrangement where the distance between the top and bottom antennas is equal to the height of the middle antenna from the ground.

The FAA has found that it is satisfactory to install the bottom antenna at $0.5 h_{\text{mid}}$ and the top antenna at $1.5 h_{\text{mid}}$, making a symmetrical system configuration. The relations shown in Table I for resultant patterns are based on the standard installation of three equally spaced antennas on a vertical mast.

III. ON-COURSE MONITOR TECHNIQUES

A. GENERAL DISCUSSION

The critical characteristics of a glide-slope system are the location of the on-course glide-slope angle and the extent of the course width.

Concerning the monitor problem, it is assumed that the airborne receivers are properly balanced and adjusted for full-scale deflection according to established performance standards, and that the location of the on-course glide-slope angle and the course width are characteristics that are determined solely by the ground-station environment.

Since a glide-slope station is generally not attended by operating personnel, the monitor equipment must turn the station off if established monitor criteria are violated continuously.

The established monitor-alarm criteria are generally accepted as the changes in ddm that can theoretically be associated with an on-course angle change of 0.2 degree or a course-width change of 0.4 degree. In practical terms, this means that the alarm is actuated when the ddm changes by 0.05 from the values expected on course and at the course-width boundary (assuming a course width of 1.4 degrees between ± 150 μ amp deflection).

It is common practice to monitor the modulation level and the ddm at an on-course location and to monitor the ddm at an off-course location. Automatic equipment to transfer or turn off the transmitters, at alarm levels adjusted in terms of ddm tolerance limits, are included in standard FAA glide-slope installations.

The on-course location and the extent of the course width are best measured by flight test, but must obviously be monitored at fixed points near the station. In practice, we assume that if the monitor alarms, the on-course angle or the course width have changed in the aircraft space. For this reason, it is highly desirable to actuate the monitor alarms only for the conditions that similarly affect the aircraft space.

When the aircraft-space conditions for on-course angle and course width are analyzed, it is found that these conditions are satisfied only at several choice locations.

Table II shows why only choice locations will work; it shows that phase angle involves not only elevation angle,

TABLE II. CAPTURE-EFFECT PROJECTOR PHASE RELATIONS

$$\begin{aligned}
 \text{Total phase angle} &= (2\pi/\lambda)(R_0 - R_A) & R_0 &= [D^2 + (aD)^2]^{1/2} \approx D(1 + a^2/2) \\
 \text{Distance} &= D, \text{ altitude} = D \tan \alpha \approx aD & R_A &= [D^2 + (h \mp aD)^2]^{1/2} \approx D(1 + a^2/2) \mp ha + h^2/2D \\
 & & & (2\pi/\lambda)(R_0 - R_A) = \pm(2\pi/\lambda) ha - (\pi/\lambda)(h^2/D)
 \end{aligned}$$

Vector	Phase Involving α $+(2\pi/\lambda)(ha)$	Phase Involving Distance D $-(\pi/\lambda)(h^2/D)$	Cosine/Sine Vector Components	
Top	-0.14	both $-(\pi/\lambda)(9h_0^2/D)$	$[\cos 3\beta - \cos(-3\beta)] = 0$	
Image	+0.14		$-0.14 [\sin 3\beta - \sin(-3\beta)] = -0.28 \sin 3\beta < -(\pi/\lambda)(9h_0^2/D)$	
Mid	-0.50 +0.28	both $-(\pi/\lambda)(4h_0^2/D)$	$[\cos 2\beta - \cos(-2\beta)] = 0$	
Image	+0.50 -0.28		$-0.50 [\sin 2\beta - \sin(-2\beta)] =$ or +0.28 $-1.00 \sin 2\beta < -(\pi/\lambda)(4h_0^2/D)$ or +0.56	
Bottom	+1.00 -0.14	both $-(\pi/\lambda)(h_0^2/D)$	$[\cos \beta - \cos(-\beta)] = 0$	
Image	-1.00 +0.14		$+1.00 [\sin \beta - \sin(-\beta)] =$ or -0.14 $+2.00 \sin \beta < -(\pi/\lambda)(h_0^2/D)$ or -0.28	

$$\text{Total reference} = 2 \sin \beta < -(\pi/\lambda)(h_0^2/D) - \sin 2\beta < -(\pi/\lambda)(4h_0^2/D)$$

$$\text{Total up/down} = +0.56 \sin 2\beta < -(\pi/\lambda)(4h_0^2/D) - 0.28 \sin \beta < -(\pi/\lambda)(h_0^2/D) - 0.28 \sin 3\beta < -(\pi/\lambda)(9h_0^2/D)$$

$$\beta = (\alpha/a_0)(\pi/2)$$

but also distance from the station. This proximity phase contribution is negligible at the large distances, or on the runway centerline (or extension), but is significant in the proximity monitor region.

For monitor locations on a line parallel to the runway centerline, the lateral offset among antennas on the mast has no effect, and all phase angles are related directly to elevation angle and forward distance.

For deriving the resultant patterns in Section II-D, it will be recalled that a reference distance from the receiver to the ground point of the antenna mast was used for comparing vectors of real and image radiation. Regarding the square root for R_0 and R_A (Table II) the simple relation for phase angle of $\pm h\alpha$ is seen to involve the assumption that for very large values of D only the first term of the binomial series for the square root is important. When the distance value D is smaller, but large enough to permit all but the first two terms of the series to be neglected, a phase lag of $(\pi/\lambda)(h^2/D)$ is associated with each resultant pattern.

The phase angle involving distance is the principal feature that separates the monitor analysis from the aircraft space analysis and makes the monitor analysis a matter of choice locations.

B. LOCATION OF ON-COURSE MONITOR

The theoretical basis for an on-course monitor location is that the total up/down additional sideband signal is zero. The three terms involved in the total up/down signal are shown at the bottom of Table II, taking $\beta = \pi/2$ for $\alpha = \alpha_0$. There are three vectors involved, only two of which can possibly be parallel at a given distance. Evidently, the two vectors to be made parallel are the final two vectors in the bottom equation of Table II, so that $\sin 2\beta = 0$, $\sin \beta = +1$ and $\sin 3\beta = -1$, and the positive and negative magnitudes cancel to zero.

The on-course monitor location is then given by the elevation angle α_0 (the null of the middle-antenna resultant) and the distance where the top-antenna resultant lags the bottom-antenna resultant by $n(2\pi)$, where n is integral.

$$\frac{\pi}{\lambda} \left(\frac{9h_b^2}{D_0} - \frac{h_b^2}{D_0} \right) = n(2\pi) \text{ and } \alpha_0 = \lambda/(4h_b)$$

$$D_0 = 4h_b^2/(n\lambda) \quad \text{altitude} = h_b/n$$

where h_b is the height of the bottom antenna.

The smaller the value of n , the larger the values of D_0 and altitude. It is desirable to use the largest feasible value of D_0 to minimize the angle of incidence for the reflected energy from the top antenna, thus providing less variation in the coefficient of reflection for different ground conditions and less difference among the coefficients of reflection for the three antennas. Therefore, letting $n = 1$, $D_0 = 4h_b^2/\lambda$, and altitude = h_b are the coordinates for the on-course monitor point.

Theoretically, the location of D_0 for a 3-degree (α_0) glide-slope angle can be computed as $\lambda/4 \tan^2 \alpha_0 = 91.25\lambda \approx 270$ feet, and the monitor altitude is theoretically $4.78\lambda \approx 14.2$ feet. Numbers such as these permit locating the monitor closely, but not exactly, because of the assumptions made in a theoretical analysis. In practice, the procedure for locating the on-course monitor would be:

1. Locate the monitor detector near the theoretically computed coordinates,
2. Adjust the distance to obtain minimum ddm in the portable detector meter after feeding the normal input for the middle antenna into a dummy load,
3. Adjust the altitude of the detector antenna to obtain zero ddm on the portable detector meter after restoring energy to the middle antenna.

C. DETECTION OF ON-COURSE VARIATIONS

In the absence of snow or reasons to cause a shift in the null angle of the resultant energy from the middle antenna, the significant equipment variations that introduce a measure of ddm at the on-course monitor are associated with the additional sideband energy radiated from the top and bottom antennas.

Figure 1(B) shows the ideal patterns for the up/down additional sideband signals, and Figure 1(C) shows the ideal pattern for ddm. Theoretically, the ddm pattern is the ratio of up/down signal to reference signal [Figure 1(A)] multiplied by the total modulation percentage--for example, 92 percent.

Regarding the possibilities that: (1) the bottom-antenna amplitude could be attenuated ($A_b \leq 1.0$), (2) the top-antenna amplitude could be attenuated ($A_{top} \leq 1.0$), or (3) the top-antenna resultant could drift in phase with respect to the bottom-antenna resultant ($\phi_{top} \neq 0$), the relative signals (from Figure 1 and Table I) are:

$$\text{Reference} = +2.00 A_b$$

$$\text{Up/down} = +0.28 \left[(A_{\text{top}} < \phi_{\text{top}}) - A_b \right]$$

For $\phi_{\text{top}} = 0$ (in-phase condition) the up/down modulations are:

$$m_{150} = \left[1 + 0.14 \left(\frac{A_{\text{top}}}{A_b} - 1 \right) \right] (0.46)$$

$$m_{90} = \left[1 - 0.14 \left(\frac{A_{\text{top}}}{A_b} - 1 \right) \right] (0.46)$$

$$\text{ddm} = 0.13 \left(\frac{A_{\text{top}}}{A_b} - 1 \right)$$

Ascribing a change in ddm of 0.05 to a course-angle shift of 0.2 degree, the ratio A_{top}/A_b must remain between the values of 0.6 and 1.4; in other words, the on-course alarm for a course shift of 0.2 degree is equivalent to either an attenuation of top-antenna energy to 0.6 of nominal or an attenuation of bottom-antenna energy to 0.7 of nominal.

If a phase shift ϕ_{top} exists without attenuation, the reference and additional sideband signals must be added vectorially instead of algebraically, m_{150} being proportional to the vector sum, and m_{90} being proportional to the vector difference. It is found that a phase shift ϕ_{top} of up to 50 degrees can occur before the ddm becomes greater than 0.05.

Phase shift either leading or lagging causes the fly-down signal to predominate; the fly-down signal also prevails for top-antenna attenuation, but bottom-antenna attenuation tends toward the fly-up sense.

The sense of the change in ddm is not practically significant; in practice, the monitor alarm is adjusted to be actuated for a course shift of +0.2 degree (+0.05 in ddm) and is usually caused by a large phase shift or by an appreciable attenuation in the top or bottom antenna systems.

It is important to point out that a phase shift or attenuation that is calculated to cause a monitor alarm is a system variation or combination of variations that is also calculated to cause the glide-slope angle to change by +0.2 degree in the aircraft space.

D. EFFECT OF SNOW

If the monitor alarm is actuated by a ddm change resulting from snow covering the ground in the monitor region, there is no direct correlation between the alarm and the shift in course position in the aircraft space. The snow introduces monitor effects, relating to phase involving distance, that do not occur in the aircraft space. In particular, if the depth of snow in the monitor region is higher than the depth of snow covering the ground plane for the aircraft space, the shift in the null of the middle antenna resultant is exaggerated at the monitor. The phase lag of 2π between the top-antenna resultant and the bottom-antenna resultant no longer holds at the on-course monitor location, destroying the precise up/down signal null at the choice location. The picture is further complicated by the fact that the middle-antenna resultant, no longer a null, is retarded in phase with respect to the bottom-antenna energy by the peculiar angle of less than 135 degrees (depending on snow depth).

Appendix A contains a mathematical discussion of the effect of snow on the on-course monitor reading. One result of the discussion is that a snow depth of $0.05 h_b$ (about 9 inches) is sufficient to generate a fly-down signal ddm of -0.05 , which is the alarm limit.

If the on-course monitor alarm is not actuated by snow, it is evident that the original phase relations, on which the alarms for attenuation and phase shift are based, no longer exist in the presence of snow, even for about 6 inches. These conditions cause an extraordinarily tight monitor-tolerance situation that is estimated to be undesirable.

The derogatory effects of snow on the monitor could be obviated if a monitor point is found without dominant ground-reflection effects. Such a monitor point may be sought on the antenna mast itself; it would require locating a point where the middle-antenna contribution was negligible, and where the top- and bottom-antenna energies were equal in amplitude and opposite in phase.

Such an approach is attractive to contemplate because (anticipating a later discussion in this report) a course-width monitor point on the antenna mast was found and tested with satisfactory results.

Although points were found on the antenna mast where the ddm was practically zero, these locations could not be interpreted directly as cases for a middle-antenna-resultant null and a top/bottom antenna null of equal magnitude and opposite phase. On the other hand, it is easy to make a direct correlation between the conditions for an on-course angle in aircraft space and for the monitor located at $D_o = 4h_b^2/\lambda$.

At sites where the snow is not expected to become extremely deep, it is recommended that a wide-mesh screen counterpoise be erected between the antenna mast and the monitor detector antenna. A counterpoise of this type is being erected at Duluth, Minnesota and will be evaluated with a capture-effect glide-slope system during the winter of 1963-1964. The counterpoise will provide a reflecting surface of constant height regardless of snow height.

Another solution is to install an asphalt or concrete driveway over the monitor region (with metal screen imbedded below the surface). Such a driveway could be cleared of snow by the same equipment that clears the runways of snow.

E. VARIATION IN COEFFICIENT OF REFLECTION

For horizontally polarized UHF radiation at typical monitor sites, the coefficient of reflection (r) is expected to be at least 0.6, increasing with water, without a significant change in phase angle due to differences in coefficient of reflection.

The principal contribution of a non-unity coefficient of reflection is the generation of a minimum middle-antenna resultant that is not zero, as assumed by theory.

Other less-significant effects are also created: (1) the reference signal at the on-course monitor point has an amplitude of $(1 + r)$ instead of 2.0 and (2) the peculiar phase angle of 135 degrees lag between middle-antenna resultant and bottom-antenna resultant at the monitor point must be considered. The effect of $r < 1.0$ is evaluated in Appendix B, where ddm is computed to be 0.05 for $r = 0.6$. It is concluded that with reasonable care in the monitor region, the coefficient of reflection (for the angles of incidence involved) is expected to be more than 0.7, increasing toward 1.00 when the ground becomes wet. The reasonable care consists of using the steel mats that are available for covering the ground surface in a long narrow rectangle between the antenna mast and the monitor.

IV. MONITOR TECHNIQUES OFF COURSE

A. GENERAL DISCUSSION

The standard FAA monitor installation consists of two ddm monitor channels, one for on-course position shift and one for measuring the change in course width.

The technique for monitoring the change in course width is to monitor the standard value of ddm at a selected point either above or below course. It is assumed that the ddm pattern is linearly related to elevation angle [Figure 1(C)] so that a standard value of ddm anywhere off course in the linear region can be directly related to the course width, assuming zero ddm on course. Therefore, it is not required to monitor the ddm value precisely at the elevation angles corresponding to the boundary limits of the course width.

In monitoring the ddm for course width, it is required that the changes in ddm at the course-width monitor point be directly proportional to the changes in ddm in the aircraft space. The changes in ddm usually result from changes in relative amplitude and/or phase angle among the resultant radiation patterns from the three-antenna system, or from a change in the amplitude of the additional sidebands in all three antennas relative to the reference-signal amplitude.

Since the three resultant patterns in the aircraft space represent parallel vectors, it is desired to locate the course-width monitor where the corresponding resultants are also parallel vectors. This cannot be done with the three antenna resultants in the capture-effect glide slope in the proximity monitor region because of the phase angles involving distance. The next best solution is to monitor the ddm at one location where two vectors are parallel and the third is a null and at a second location where two different vectors are parallel and the third is a null.

One of these monitor locations is already used, as described in Section III of this report--namely, at the on-course monitor, where the vectors for the top- and bottom-antenna resultants are parallel and the middle-antenna resultant is a null. The choice location for the course-width monitor should therefore be a point where the middle- and bottom-antenna resultants are parallel vectors and the top-antenna resultant is a null.

Points in the monitor region that satisfy the requirement for top-antenna nulls are on the elevation angle of $(2/3) \alpha_0$ or the elevation angle of $(4/3) \alpha_0$. These points are beyond the boundary limits of the normal course width, but are still in the linear region of the ddm pattern, as shown in Figure 1(C).

It is recalled that the on-course monitor measures the effect on ddm of amplitude and phase variations between the top- and bottom-antenna resultant vectors. The monitor on $(2/3) \alpha_0$ or $(4/3) \alpha_0$ measures the effect on ddm of amplitude and phase variations between the middle- and bottom-antenna resultant vectors.

Since only one monitor channel is available in the standard installation for monitoring course width, a choice must be made between $(2/3) \alpha_0$ and $(4/3) \alpha_0$. If the phase and amplitude variations between the middle- and bottom-antenna resultants reacted identically at $(2/3) \alpha_0$ and at $(4/3) \alpha_0$, the choice would be academic; however, in the capture-effect glide slope, there is a significant difference between ddm reactions above and below the on-course glide-slope angle in the aircraft space when amplitude and phase variations are considered. The difference arises because the middle- and bottom-antenna resultants are vectors that add above path and subtract below path. For example, attenuation of the middle- or the bottom-antenna amplitude to 0.9 of normal value causes a change in ddm of 37 percent of normal below path, but only 4 percent of normal above path. The course-width changes are much more sensitive to equipment variation below path than above path.

From the viewpoint of practical usage of the glide-slope system, it can be argued that course-width changes below path are more important than course-width changes above path. It can also be argued that course-width widening is more important to monitor than course-width narrowing, within reasonable limits. This kind of logic is not implemented in standard monitor-alarm circuitry. Under these circumstances, it seems prudent to monitor the most sensitive condition--the middle- and bottom-antenna resultant vectors are parallel and opposite in direction.

B. LOCATION OF COURSE-WIDTH MONITOR

Reference is again made to the bottom equation in Table II. The last term in that equation represents the top-antenna resultant, which is a null for $(2/3) \alpha_0$ or $(4/3) \alpha_0$. For the first two terms to represent vectors that are parallel and opposite in direction, it is required that

$$\frac{\pi}{\lambda} \left(\frac{4h_b^2}{D_w} - \frac{h_b^2}{D_w} \right) = n\pi$$

where n is an even integer for $(2/3) \alpha_0$ and an odd integer for $(4/3) \alpha_0$.

$$D_w = 3h_b^2/(n\lambda) \quad (\text{altitude} = h_b/2n \text{ for } n \text{ even})$$

$$(\text{altitude} = h_b/n \text{ for } n \text{ odd})$$

As stated in the derivation of the location for the on-course monitor, it is preferable to stabilize the coefficient of reflection, especially for the middle-antenna radiation, by using the smallest value of n . The smallest even value of n is 2.0, and the smallest odd value of n is 1.0; and $n = 1$ is better than $n = 2$ in this respect, by an incidence angle ratio of about $2/3$ for a 3-degree glide-slope angle. Accordingly for $n = 1$, the elevation angle is $(4/3) \alpha_0$, $D_w = 3h_b^2/\lambda$, and altitude = h_b (precisely the same altitude derived for the on-course monitor).

Theoretically, the location of D_w for a 3-degree (α_0) glide-slope angle can be computed as $3\lambda/(16 \tan^2 \alpha_0) = 68.5\lambda \approx 200$ feet or $3/4$ the distance of the on-course monitor point; the monitor altitude is theoretically $4.78\lambda \approx 14.2$ feet. Numbers such as these permit locating the monitor closely, but not exactly, because of the assumptions that are made in a theoretical analysis. In practice, the procedure for locating the course-width monitor would be:

1. Locate the monitor detector near the theoretically computed coordinates,
2. Adjust the distance to obtain minimum RF level on the portable detector meter while feeding the additional sideband signal into a dummy load and turning off the clearance transmitter.
3. Adjust the altitude of the detector antenna for an RF null on the portable detector meter while feeding reference signal only into the top antenna.

C. MAST LOCATION OF COURSE-WIDTH MONITOR

By reviewing the effects of snow on the on-course monitor and expecting similar effects at the distance D_w and the altitude h_b , we can predict that snow will have a serious effect on the proximity-region course-width monitor.

As snow falls, the critical parallel phase relation between the middle- and bottom-antenna resultants starts deteriorating because the coordinates for the monitor were found by adjusting distance and altitude when the antenna heights were simply h_b , $2h_b$, and $3h_b$, a relationship that no longer holds when snow raises the reflection plane. In addition, the amplitude ratio between middle- and bottom-antenna patterns changes when antenna heights change, and the magnitude of the top-antenna resultant becomes non-zero. The total effect of increasing snow depth is to decrease the value of ddm measured at the fair weather $(4/3) \alpha_0$ monitor point; it does not require much snow to make a ddm change sufficient to actuate the alarm.

Appendix A contains a more precise evaluation of the snow effect.

Possible solutions for removing the snow effect include the two that were mentioned with regard to the on-course monitor--namely, a wide-mesh counterpoise or a snow-cleared driveway. In addition to these two solutions, a mast-located course-width monitor point does exist; the ddm at this point has been found to react in a manner similar to the ddm changes at the $(4/3) \alpha_0$ monitor point, and for the same reasons stemming from equipment variations. In fact, the amplitude and phase relations among the three antenna resultants at the $(4/3) \alpha_0$ monitor point are practically obtained at the mast-located monitor point. In review, the three antenna-pattern resultants at the $(4/3) \alpha_0$ monitor point have the following relations:

1. The top-antenna energy vector is at a null, so that its phase relation to the other two vectors does not matter,
2. The vectors for the middle- and bottom-antenna resultants are parallel and opposite to each other, just as they exist in the feedpoints to the antenna elements,
3. The absolute magnitudes for the middle- and bottom-antenna resultants bear a 2 to 1 ratio, just as they exist in the feedpoints to the antenna elements.

Evidently, a point half way between the middle and bottom antennas would satisfy the second two requirements if the ground-reflected energy is considered negligible; the first requirement is approximately satisfied since the top antenna is three times as far from the middle-bottom midpoint as the distance to either of the other two antennas.

The important feature of the middle-bottom midpoint on the mast that prevents the harmful effects of snow is that the amplitude and phase relations at the monitor point on the antenna mast are independent of snow.

A field trial for the course-width monitor location on the antenna mast was experimentally investigated at the capture-effect glide slope site at Duluth, Minnesota, and was found to be satisfactory, but not perfect. The monitor location was found by installing a detector antenna at the midpoint and then adjusting its position slightly up or down until minimum RF level was detected while feeding only reference-signal energy only to the middle and bottom antennas.

The main difficulty with the monitor installation was found to be that when personnel or vehicles were located near the base of the antenna mast the measured value of ddm was found to vary widely, often beyond the alarm limits. No serious difficulty of this type was encountered when the ground area was undisturbed.

Admittedly, more experimental work should be done in connection with the mast monitor. The limited time of this project and the restrictions connected with working at a commissioned station temporarily shut down did not permit a complete investigation of optimum techniques. One major source of trouble is that the detector antenna being used for the monitor has a large forward gain in the approach direction toward the monitor region, whereas the principal regions of interest for the course-width monitor on the mast are the region directly above (for the middle-antenna output) and the region directly below (for the bottom-antenna output). It would be more desirable to have an experimental capture-effect glide-slope station convenient to work on and a program to develop a monitor detector antenna appropriately designed for the specific purpose of seeing up and down but not straight ahead. The experimental program would include the necessary relative attenuation of the ground-reflected energy, and attenuation of direct energy from the top antenna.

In principle, an investigation of mast-located monitors could be expanded to include a study of mast location of the on-course monitor, which would also be immune to the snow effects described in Section III.

D. DETECTION OF COURSE-WIDTH VARIATIONS

In the absence of snow or other reasons for changing the relative heights of the antennas on the mast, the significant equipment variations that introduce a change in ddm at the course-width monitor are changes in the relative amplitude and phase angle between the middle- and bottom-antenna resultants.

Regarding the possibilities that (1) the bottom-antenna amplitude could be attenuated ($A_b < 1.0$), (2) the middle-antenna amplitude could be attenuated ($A_{mid} < 1.0$), or (3) the middle-antenna output could drift in phase relative to the bottom-antenna output ($\phi_{mid} \neq 0$), the relative signals at the course-width monitor (from Figure 1 and Table I) are:

$$\text{Reference} = \left[2A_b - |A_{mid} < \phi_{mid}| \right] (\sqrt{3}/2)$$

$$\text{Up/down} = 0.28 \left[|2A_{mid} < \phi_{mid}| - A_b \right] (\sqrt{3}/2)$$

where $\sqrt{3}/2$ applies to the (4/3) α_0 monitor location, but is absent for the mast-located monitor.

In the absence of any phase error ($\phi_{mid} = 0$), the ddm is:

$$\text{ddm} = 0.26 \frac{2A_{mid} - A_b}{2A_b - A_{mid}}$$

where 0.26 is the product of 0.28 and 0.92.

A course-width change that is nominally 0.4 degree is equivalent to a change of 0.2 degree in the lower half of the course, or about 1/3 of the nominal width of the lower half of the course. Accordingly, the course-width monitor alarm would be set for a ddm change that is +1/3 of the value that is obtained under ideal conditions. A change of +1/3 in the ddm relation stated above is obtained for $A_{mid} = 0.88$ (for a decrease in ddm of 1/3) or $A_b = 0.91$ (for an increase in ddm of 1/3).

In practice, the course-width alarm could be set to be actuated by a change of 1/3 in the normal amount of additional sideband energy that is established by the sideband-amplitude control. The same result would then be achieved by attenuation to about 90 percent of normal in either the middle- or bottom-antenna outputs.

In the absence of any attenuation ($A_{mid} = A_b = 1.0$); in the presence of a phase error ($\phi_{mid} \neq 0$), the ddm is:

$$\begin{aligned} \text{ddm} &= m_{150} - m_{90} \\ m_{150} &= \frac{|1.72 - 0.44 < \phi_{mid}|}{|2 - 1.0 < \phi_{mid}|} (0.46) \end{aligned}$$

$$m_{90} = \frac{|2.28 - 1.56 < \phi_{mid}|}{|2 - 1.0 < \phi_{mid}|} (0.46)$$

The value of ddm decreases to a value that is 2/3 of normal for $\phi_{mid} = \pm 15$ degrees.

It is therefore concluded that if the course-width alarm is adjusted to be actuated for a ddm change of $\pm 1/3$ of the normal value, the alarm would be actuated by: (1) a 1/3 decrease in sideband amplitude, (2) a 10-percent attenuation in middle- or bottom-antenna amplitude, or (3) a relative phase drift of 15 degrees between the middle- and bottom-antenna outputs.

E. PHASE-ADJUSTMENT PROCEDURE

The normal procedure for adjusting relative phase between the sideband and reference antennas in the null-reference glide-slope system is to fly inbound beyond the outer marker at low elevation angle and to determine that the course width becomes indeterminate for a phase error of 90 degrees. This so-called "quadrature method" of phase adjustment does not work for the capture-effect glide slope.

The presence of the clearance transmitter energy would prevent obtaining zero ddm. If the clearance transmitter were turned off, the additional sideband energy from the top antenna would still prevent obtaining zero ddm; if the top antenna output were turned off, it would be found that the resultant reference and additional sideband vectors from the middle and bottom antennas would be in quadrature for a phase error of 37 degrees instead of 90 degrees.

The net effect of all these peculiarities of the capture-effect glide-slope system with regard to the quadrature method has been to abandon the entire airborne phasing procedure and to substitute a method based on measuring field strength on the ground at the site of the middle marker. The new phasing procedure is summarized as follows:

1. Adjust the relative phase between reference and additional sidebands at the monitor by reading minimum 150 cps output as detected in the middle-antenna transmission line,
2. Adjust the relative phase at a second phase-adjustment unit between reference and additional sidebands at the monitor by reading minimum 150 cps output as detected in the bottom-antenna transmission line,

3. Adjust a third phasing unit (in the bottom-antenna line) for minimum field strength detected at the middle-marker site, feeding only reference signal to the middle and bottom antennas,
4. Adjust a fourth phasing unit (in the top-antenna feed line) for minimum field strength detected at the middle-marker site, feeding only reference signal to all three antennas (via the additional-sideband feed line).

The last two steps of the preceding procedure can be performed anywhere on the extension of the runway centerline, which is the locus of points where the phase error involving distance is negligible because of the lateral offset of the middle- and top-antenna elements toward the runway. The middle-marker site is convenient for working on the runway centerline.

F. EFFECT OF COEFFICIENT OF REFLECTION

A discussion of the coefficient of reflection (or of the effect of snow) pertains to a course-width monitor at $(4/3) \alpha_0$ in the monitor region (derived in Section IV-B); for the course-width monitor located on the antenna mast (derived in Section IV-C), the coefficient of reflection and the depth of snow are not involved.

Appendix B contains a computation of the effect of the non-unity coefficient of reflection. The mathematics are tedious because the resultant vector for each of the three antennas is a complex variable, even without the phase lags involving distance, and none of the vectors add algebraically. However, when the computation is carefully performed, it is found that the ddm is at least 80 percent of the value of ddm for unity coefficient of reflection for $r > 0.6$. Since the alarm limit for the course-width monitor is nominally set for a ddm change of $1/3$ of normal, it is concluded that changes in the coefficient of reflection between 0.6 and 1.0 will not by themselves actuate the alarm.

The non-unity coefficient of reflection decreases the measured value of ddm at the $(4/3) \alpha_0$ monitor point; this could be hypothetically combined with a further decrease in ddm resulting from phase drift between middle- and bottom-antenna output, or attenuation in the middle-antenna output. It would therefore be advisable to use the metal-screen reflector mats in the monitor region to stabilize the coefficient of reflection, but this point is academic because the mats would be required to stabilize the reflection region of the on-course monitor in any case.

G. EFFECT OF SNOW ON COURSE-WIDTH MONITOR

Appendix A contains computations for the effect of snow on the reading of ddm at $(4/3) \alpha_0$ for a course-width monitor. The results are discouraging; the chances for a course-width monitor reading at $(4/3) \alpha_0$ surviving the alarm limit for any appreciable depth of snow appear rather dim. As the snow falls, the elevation angle of the on-course condition near the monitor rises, and since the monitor is installed above the normal on-course position, the measured value of ddm decreases significantly.

Here again, the solution lies in using either a counterpoise or a snow-cleared driveway (Section III, in connection with the effect of snow on the on-course monitor). Fortunately, a good alternative exists: to use the course-width monitor on the mast instead of at $(4/3) \alpha_0$.

The normal procedure at standard FAA glide-slope sites is to install the on-course monitor and the course-width monitor detectors in the proximity region. This procedure need not be changed at capture-effect glide-slope sites where snow is not usually encountered; however, at sites where snow tends to accumulate and is not cleared from the monitor region (or kept under a counterpoise), the course-width monitor on the antenna mast is preferred.

V. CONCLUSIONS AND RECOMMENDATIONS

A. ON-COURSE MONITOR

It is recommended that the on-course monitor for the capture-effect glide slope be located on a line from the antenna mast parallel to the runway centerline at a distance from the mast that corresponds to the proximity dephase angle of 360 degrees between the top and bottom antennas.

This distance is found by first locating the detector at a distance calculated to be $4h_b^2/\lambda$, where h_b is the height of the bottom antenna and λ is the wavelength. In a typical installation, the distance is found more precisely by setting the height of the detector antenna nearly level with the height of the bottom antenna on the mast, and by adjusting the distance until a zero ddm reading is obtained on the portable detector unit with the middle-antenna output turned off.

In a typical installation, the altitude of the monitor detector is found more precisely (after the distance has been established) by adjusting the height of the detector antenna until a zero ddm reading is obtained on the portable detector with the middle antenna turned on.

The only difficulty anticipated with the on-course monitor is that if it is installed over clear ground, it will become unreliable when snow covers the ground to a depth of about 9 inches. Snow depths between 5 and 9 inches will cause marginal performance; below 5 inches, performance should be tolerable.

At sites where heavy snowfalls are expected, it is recommended that the monitor region be paved and cleared of snow. Where this is impossible, it is recommended that a counterpoise be erected above the expected maximum level of the snow. Where this is not possible, the course-width monitor should not be installed at $(4/3) x_0$; instead, it should be installed on the antenna mast and the station should not be shut off the air in deep snow unless the course-width mast monitor also alarms.

B. COURSE-WIDTH MONITOR

It is recommended that the course-width monitor for the capture-effect glide slope be located on the antenna mast midway between the middle and bottom antennas. The precise location is found by adjusting the monitor detector antenna height until minimum RF level is detected while feeding only a reference signal to the middle and bottom antennas.

It is further recommended that a project be established to develop a course-width monitor antenna that is more suitable for location on the antenna mast than the antenna that was developed for other purposes. Particular attention should be paid to obtaining relative attenuation of reflected and top-antenna energy relative to energy received directly from the top and bottom antennas.

If a project is established to develop a new course-width monitor antenna, it should include a study of techniques to develop an on-course monitor antenna mounted on the mast. The specifications for this study should principally be that the energy from the top and bottom antennas should be detected with equal gains and opposite polarities, and that the reflected energy and the middle-antenna energy should be detected with relatively negligible amplitude.

If the site is usually clear of snow and it is desired to use a course-width monitor in the fashion similar to standard FAA practice, the course-width monitor for the capture-effect glide slope should be located on a line from the antenna mast parallel to the runway centerline at a distance from the mast that corresponds to the proximity dephase angle of 180 degrees between the middle and bottom antennas.

This distance is found by first locating the detector at a distance calculated to be $3h_b^2/\lambda$, where h_b is the height of the bottom antenna and λ is the wavelength. In a typical installation, the distance is found more precisely by setting the height of the detector antenna nearly level with the height of the bottom antenna on the mast, and by adjusting the distance until a minimum RF is detected on the portable detector with the additional sideband energy turned off.

In a typical installation, the altitude of the course-width monitor detector is found more precisely (after the distance has been established) by finding the RF null while radiating the reference signal from the top antenna.

If the monitors cannot be located on the line parallel to the runway centerline, they can be offset laterally from this line, either toward the runway or away from it. If they are offset laterally, the theoretically calculated distance is increased (away from the runway) or decreased (toward the runway) by a factor that is about equal to the ratio between the offset distance and the distance from the glide-slope mast to the runway centerline.

The field strength at the alternate width monitor location (i.e., the $4/3a_0$ point) is relatively weak compared to that obtained at the proposed mast location. For this reason, a receiver-type monitor which provides linear DDM

indications at low signal levels (and hence would show the capture effect better) must be utilized if the $4/3\alpha_0$ point is chosen for the width monitor.

APPENDIX A SNOW EFFECT

1. ON-COURSE MONITOR

The basic assumptions are that the clear-ground antenna heights for a capture-effect system are h_0 , $2h_0$, and $3h_0$ and that the monitor detector is located at a distance $D_0 = 4 h_0^2 / \lambda$ and altitude h_0 above clear ground.

Assume a snow depth of $s h_0$. The antenna heights above snow become

$$h_b = (1-s) h_0$$

$$h_{mid} = (2-s) h_0$$

$$h_{top} = (3-s) h_0$$

$$\text{Monitor altitude} = (1-s) h_0 = (\text{altitude above snow level})$$

$$\text{Monitor elevation angle} = (\lambda/4 h_0) (1-s) = (\text{angle above snow level})$$

The phase lag of the middle-antenna resultant vector with respect to the bottom-antenna resultant vector is

$$\phi_{MB} = -\frac{\pi}{\lambda} \left[\frac{(2-s)^2 - (1-s)^2}{4/\lambda} \right] = -\frac{3\pi}{4} + s \frac{\pi}{2}$$

The phase lag of the top-antenna resultant vector with respect to the bottom-antenna resultant vector is

$$\phi_{TB} = -\frac{\pi}{\lambda} \left[\frac{(3-s)^2 - (1-s)^2}{4/\lambda} \right] = -2\pi + s\pi$$

The reference signal is given by

$$\text{Ref} = 2 \sin \left[\frac{2\pi}{\lambda} h_b \frac{\lambda(1-s)}{4 h_o} \right] - \sin \left[\frac{2\pi}{\lambda} h_{\text{mid}} \frac{\lambda(1-s)}{4 h_o} \right] < -\frac{3\pi}{4} + s \frac{\pi}{2}$$

$$\text{Ref} = 2 \sin \left[(1-s)^2 \frac{\pi}{2} \right] - \sin \left[(2-s)(1-s) \frac{\pi}{2} \right] < -\frac{3\pi}{4} + s \frac{\pi}{2}$$

The additional sideband signal is given by

$$\begin{aligned} \text{SB} = & -0.28 \sin \left[(1-s)^2 \frac{\pi}{2} \right] + 0.56 \sin \left[(2-s)(1-s) \frac{\pi}{2} \right] < -\frac{3\pi}{4} \\ & + s \frac{\pi}{2} \\ & -0.28 \sin \left[(3-s)(1-s) \frac{\pi}{2} \right] < s\pi \end{aligned}$$

Express each angle in terms of cosine and sine components, so that

$$< a = \cos a + j \sin a$$

Express each of the values of the angles in degrees

$$\begin{aligned} \text{Ref} = & 2 \sin \left[(1-s)^2 90 \right] - \sin \left[(2-s)(1-s) 90 \right] \left[\cos (-135 \right. \\ & \left. + s 90) + j \sin (-135 + s 90) \right] \end{aligned}$$

$$\begin{aligned} \text{SB} = & -0.28 \left[(1-s)^2 90 \right] + 0.56 \sin \left[(2-s)(1-s) 90 \right] \left[\cos (-135 \right. \\ & \left. + s 90) + j \sin (-135 + s 90) \right] - 0.28 \sin \left[(3-s)(1-s) 90 \right] \\ & \left[\cos s 180 + j \sin s 180 \right] \end{aligned}$$

Let $s = 0.05$ for a snow depth of $h_0/20 \approx 9$ inches

$$\text{Ref} = 2 \sin 81 - \sin 167 \left[\cos (-130.5) + j \sin (-130.5) \right]$$

$$\text{Ref} = 2.12 + j 0.17$$

$$\begin{aligned} \text{SB} = & -0.28 \sin 81 + 0.56 \sin 167 \left[\cos (-130.5) \right. \\ & \left. + j \sin (-130.5) \right] - 0.28 \sin 252 \left[\cos 9 + j \sin 9 \right] \end{aligned}$$

$$\text{SB} = -0.10 - j 0.05$$

$$m_{150} = \frac{|2.02 + j 0.12|}{|2.12 + j 0.17|} (0.46) = 0.43$$

$$m_{90} = \frac{|2.22 + j 0.22|}{|2.12 + j 0.17|} (0.46) = 0.48$$

$$\text{ddm} = -0.05$$

It is thus shown that a snow depth of about 9 inches would introduce a fly-down signal equivalent to about the alarm limit for the on-course monitor.

Repeating the calculation for $s = 0.025$ (for a snow depth of about 4.5 inches)

$$\text{Ref} = 2 \sin 85.5 - \sin 173 \left[\cos (-133) + j \sin (-133) \right]$$

$$\text{Ref} = 2.08 + j 0.09$$

$$\begin{aligned} \text{SB} = & -0.28 \sin 85.5 + 0.56 \sin 173 \left[\cos (-133) \right. \\ & \left. + j \sin (-133) \right] - 0.28 \sin 261 \left[\cos 4.5 + j \sin 4.5 \right] \end{aligned}$$

$$\text{SB} = -0.05 - j 0.05$$

$$m_{150} = \frac{|2.03 + j 0.04|}{|2.08 + j 0.09|} (0.46) = 0.45$$

$$m_{90} = \frac{|2.13 + j 0.14|}{|2.08 + j 0.09|} (0.46) = 0.47$$

$$ddm = -0.02$$

It is thus shown that a snow depth of about 4.5 inches would introduce a fly-down signal equivalent to about 40 percent of the alarm limit set for the on-course monitor.

It is therefore concluded that a depth of snow exceeding about 5 inches would tend to make the on-course monitor dangerously sensitive to alarm.

2. COURSE-WIDTH MONITOR

The basic assumptions are that the clear-ground antenna heights are h_0 , $2 h_0$, and $3 h_0$, and that the monitor detector is located at a distance $D_W = 3 h_0^2 / \lambda$ and altitude h_0 above clear ground.

$$h_b = (1-s) h_0$$

$$h_{mid} = (2-s) h_0$$

$$h_{top} = (3-s) h_0$$

$$\text{Monitor altitude} = (1-s) h_0$$

$$\text{Monitor elevation angle} = (\lambda / 3 h_0)(1-s)$$

The phase lag of the middle-antenna resultant vector with respect to the bottom-antenna resultant vector is

$$\phi_{MB} = \frac{\pi}{\lambda} \left[\frac{(2-s)^2 - (1-s)^2}{3/\lambda} \right] = -\pi + \frac{2s}{3} \pi$$

The phase lag of the top-antenna resultant vector with respect to the bottom-antenna resultant vector is

$$\phi_{TB} = -\frac{\pi}{\lambda} \left[\frac{(3-s)^2 - (1-s)^2}{3/\lambda} \right] = -\frac{8\pi}{3} + \frac{4s}{3} \pi$$

The reference signal is given by

$$\text{Ref} = 2 \sin \left[(1-s)^2 120 \right] + \sin \left[(2-s)(1-s) 120 \right] \left[\cos (120s) + j \sin (120s) \right]$$

The additional sideband signal is given by

$$\text{SB} = -0.28 \sin \left[(1-s)^2 120 \right] - 0.56 \sin \left[(2-s)(1-s) 120 \right] \left[\cos 120s + j \sin 120s \right] - 0.28 \sin \left[(3-s)(1-s) 120 \right] \left\{ \cos \left[(-120)(1-2s) \right] + j \sin \left[-120 (1-2s) \right] \right\}$$

Let $s = 0.025$ for a snow depth of about 4.5 inches

$$\text{Ref} = 2 \sin 114 + \sin 231 (\cos 3 + j \sin 3)$$

$$\text{Ref} = 1.05$$

$$\text{SB} = -0.28 \sin 114 - 0.56 \sin 231 (\cos 3 + j \sin 3) - 0.28 \sin 348 \left[\cos (-114) + j \sin (-114) \right]$$

$$\text{SB} = 0.155 - j 0.05$$

$$m_{150} = \frac{1.21}{1.05} (0.46) = 0.54$$

$$m_{90} = \frac{0.90}{1.05} (0.46) = 0.38$$

$$\text{ddm} = +0.16$$

For the no-snow ($s = 0$) condition, the normal value of ddm at the course-width monitor would be +0.26. It is thus seen that a snow depth of about 4.5 inches would decrease the monitor reading at the $(4/3) \alpha_0$ point by more than $1/3$ the normal value; since the course-width alarm is adjusted to be actuated for a change in ddm of $1/3$, it must be concluded that only about 4 inches of snow would be sufficient to make the course-width alarm practically useless in monitoring relative amplitude and phase between the middle- and bottom-antenna outputs.

APPENDIX B

EFFECT OF COEFFICIENT OF REFLECTION

1. ON-COURSE MONITOR

At the on-course monitor, it is assumed that the top- and bottom-resultants for the additional side-band energy are in-phase as far as the phase angle involving distance is concerned; the phase lag for any residual middle-antenna energy is 135 degrees.

Let the coefficient of reflection be negative with a magnitude of r , and assume that no phase error is introduced by the non-unity coefficient of reflection.

The equations for reference energy and additional sideband energy are variations from those given in Tables I and II for the case where $\beta = \pi/2$, $2\beta = \pi$, and $3\beta = 3\pi/2$.

The reference signal is given by:

$$\text{Ref} = 1 + r + 0.5 (1-r) \left[\cos (-135) + j \sin (-135) \right]$$

$$\text{Ref} = 0.65 + 1.35r - j 0.35 (1-r)$$

The additional sideband is given by

$$\text{SB} = -0.28 (1-r) \left[\cos (-135) + j \sin (-135) \right]$$

$$\text{SB} = +0.20 (1-r)(1+j)$$

$$m_{150} = \frac{|0.85 + 1.15r - j 0.15 (1-r)|}{|0.65 + 1.35r - j 0.35 (1-r)|} \quad (0.46)$$

$$m_{90} = \frac{|0.45 + 1.55r - j 0.55 (1-r)|}{|0.65 + 1.35r - j 0.35 (1-r)|} \quad (0.46)$$

For $r = 1.0$

$$m_{150} = m_{90} = 0.46 \text{ and } \text{ddm} = 0$$

For $r = 0.6$

$$m_{150} = \frac{1.55}{1.47} (0.46) = 0.49$$

$$m_{90} = \frac{1.40}{1.47} (0.46) = 0.44$$

$$ddm = +0.05$$

It is thus shown that a variation in coefficient between $r = 0.6$ and $r = 1.0$ is equivalent to a full change in ddm within the limits of the on-course alarm. If the on-course monitor is installed and adjusted when the ground is dry and the coefficient of reflection is as low as 0.6, it will not be possible to obtain zero ddm as a monitor reading; however, a minimum value will be obtained as the normal condition. When the ground becomes wet, the coefficient of reflection will increase toward unity, and a smaller reading of ddm will be measured.

This does not seem to indicate a dangerous situation, but it would be preferable to limit the variation of coefficient of reflection to values as close to unity as possible. The steel mats that are available for covering the monitor-region ground surface have the effect of maintaining a more stable reflection coefficient between conditions of dry and wet ground.

2. COURSE-WIDTH MONITOR

At the course-width monitor ($4/3$) α_0 , it is assumed that the phase lag due to distance is 180 degrees for the middle-antenna resultant and 480 degrees for the top-antenna resultant, both being expressed with respect to the resultant vector of the bottom-antenna energy.

The equations for reference energy and additional sideband energy are variations from those given in Tables I and II for the case where $\beta = \frac{4}{3} \pi = 120$, $2\beta = 240$, and $3\beta = 360$ degrees.

The reference signal is given by

$$\begin{aligned} \text{Ref} = & +1 (\cos 120 + j \sin 120) - r \left[\cos (-120) + j \sin (-120) \right] \\ & - 0.5 \left[\cos (240-180) + j \sin 60 \right] + 0.5r \left[\cos (240-180) \right. \\ & \left. + j \sin (-60) \right] \end{aligned}$$

$$\text{Ref} = -0.5 (1-r) + j (\sqrt{3}/2)(1+r) - 0.25 (1-r) - j 0.5 (\sqrt{3}/2)(1+r)$$

$$\text{Ref} = -0.75 (1-r) + j 0.5 (\sqrt{3}/2)(1+r)$$

The additional sideband signal is given by

$$\begin{aligned} \frac{\text{SB}}{0.28} = & -0.5 \left[\cos 120 + j \sin 120 \right] + r 0.5 \left[\cos (-120) \right. \\ & \left. + j \sin (-120) \right] + 1.0 \left[\cos 60 + j \sin 60 \right] \\ & - r \left[\cos (-60) + j \sin (-60) \right] - 0.5 \left[\cos (360-480) \right. \\ & \left. + j \sin (-120) \right] + r 0.5 \left[\cos (-120) + j \sin (-120) \right] \end{aligned}$$

$$\text{SB} = 0.28 (1-r) + j (\sqrt{3}/2)(0.28)$$

$$m_{150} = \frac{|-0.47 (1-r) + j (\sqrt{3}/2)(0.78+0.5r)|}{|-0.75 (1-r) + j 0.5 (\sqrt{3}/2)(1+r)|} (0.46)$$

$$m_{90} = \frac{|-1.03 (1-r) + j (\sqrt{3}/2)(0.22+0.5r)|}{|-0.75 (1-r) + j 0.5 (\sqrt{3}/2)(1+r)|} (0.46)$$

For $r = 1.0$

$$m_{150} = \frac{1.28}{1} (0.46) = 0.59$$

$$m_{90} = \frac{0.72}{1} (0.46) = 0.33$$

$$\text{ddm} = +0.26$$

For $r = 0.6$

$$m_{150} = \frac{|0.19 + j(\sqrt{3}/2)(1.08)|}{|-0.3 + j(\sqrt{3}/2)(0.8)|} (0.46) = 0.59$$

$$m_{90} = \frac{|-0.41 + j(\sqrt{3}/2)(0.52)|}{|-0.3 + j(\sqrt{3}/2)(0.8)|} (0.46) = 0.37$$

$$ddm = +0.22$$

The value for $r = 0.6$ is 85 percent of the normal value of 0.26 (for $r = 1$). It is thus shown that a variation in the coefficient of reflection between $r = 0.6$ and $r = 1.0$ is equivalent to a variation in ddm that is within the limits of the course-width alarm ($\pm 1/3$).

It is concluded that if steel mats are used to stabilize the coefficient of reflection in the monitor region, the alarm should not be actuated solely because the ground conditions change between wet and dry.

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 STUDY OF CAPTURE-EFFECT GLIDE-SLOPE MONITOR TECHNIQUES
 I. Title, A. No. WA-4395
 II. Contract No. 3182-1
 III. Project No. 3182-1
 IV. Report No. RD-64-17
 Descriptors

The capture-effect glide-slope system is explained by comparison with a standard null-reference system, and the relative advantages of the glide-slope system are analyzed. A general examination of monitor techniques leads to an analysis of capture-effect monitor problems. Solutions for the particular capture-effect monitor problems are presented and logically justified. The recommended solution for the on-line capture-effect monitor problem is presented and justified. The first null of the midline-antenna resultant where the top and bottom-antenna resultant exactly cancel at the recommended solution for the course-width monitor-detector location is found on the antenna mast midway between the midline and bottom glide-slope antennas. An alternative monitor-detector location for the second null of the top-antenna resultant, where the midline and bottom-antenna resultant exactly cancel, is also given. Analyses are given for the monitor effects of changes in amplitude and phase of the signals in the capture-effect glide-slope circuits, and of changes in coefficient of reflection and depth of snow in the monitor region. The recommended solutions were successfully demonstrated at a brief field trial and are currently being evaluated at an operating site. A noteworthy outcome of the project is the feasibility of operating a course-width monitor system that does not deteriorate because of the accumulation of snow near the glide-slope station.

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