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DABS Link Performance Considerations

G.J. Schlieckert

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Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

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16. Abstract

The DABS link performance is computed using the present values for the system operating parameters and the available models that describe environmental and aircraft antenna effects. The various fade mechanisms are described, and a statistical determination of performance is proposed. The performance is computed for various sets of conditions including different ground antennas, aircraft maneuvers, antenna pedestal heights, ground reflection coefficients and reduced power. Also discussed are the effects of obstructions and the performance when aircraft are in the cone of silence.

The DABS link is found to have very good overall performance with only small regions of reduced reliability that are at low angles or due to maneuvers. Those missed replies due to maneuvers are found to be sporadic from scan to scan.

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1.0 INTRODUCTION

The Discrete Address Beacon System (DABS) provides a highly reliable surveillance and data communication link between ground stations and transponder equipped aircraft. The probability of successful communication in either direction depends on the signal power reaching the designated receiver. Under ideal free space conditions the received power for either uplink or downlink communication varies in a predictable fashion depending only on the range between the aircraft and ground station and the position of the aircraft within the ground station antenna pattern. Various fade mechanisms introduce departures from ideal free space conditions and result in a diminished received signal that reduces the likelihood of successful communication.

In this report, the combined effects of the various fade mechanisms on DABS link performance are examined. The performance of the sensor is presented graphically by plotting the probability of successful communication over the airspace around the sensor. This is done for various parameter choices that affect the fade mechanisms.

2.0 CALCULATION OF PERFORMANCE

2.1 Ideal Free Space Conditions

For a specified set of system parameters the communication success or failure is determined by the signal power level at the receiver, i.e., whether or not the receiver threshold for correct message decoding is exceeded. The excess signal power over the receiver threshold level is defined as the link "margin." For ideal free space conditions this factor is given by the expression:

$$M_{fs} = P_t + G_g + G_a + C_\lambda - L - 20 \log_{10} R - MUSL \qquad (1)$$

where

- M_{fs} = free space margin (dB)
- P_t = transmitted power (dBm)
- $G_g(\epsilon, \eta)$ = free space ground antenna gain at elevation angle ϵ above horizon and azimuth angle η from boresight (dBi)
- $G_a(\theta, \varphi)$ = aircraft antenna gain at aspect angles θ, φ in aircraft coordinate system (dBi)
- C_λ = 20 log $(\lambda/4\pi)$ (λ = wavelength in nautical miles)
- L = fixed system losses other than mismatch losses at the antenna (dB)
- R = range in nautical miles
- MUSL = minimum usable signal level for correct message decoding (dBm)

The values for the transmitted power, system losses, C_λ, and required signal level at the receiver are generally fixed and can be combined into a single constant. In addition, if the aircraft antenna is assumed isotropic ($G_a = \hat{G}_a = 0$ dBi) and the aircraft is on the peak of the ground antenna pattern ($G_g = \hat{G}_g = \max_\epsilon G_g(\epsilon, \eta = 0)$), the free space margin can be expressed as a function of range:

$$M_{fs} = \Sigma_1 - 20 \log_{10} R \qquad (2)$$

where

$$\Sigma_1 = P_t + \hat{G}_g + \hat{G}_a + C_\lambda - L - MUSL .$$

This margin must be sufficient to overcome the various types of fades that can degrade the link. Note that by this definition the margin is only a function of aircraft range. Normally the shape of the ground antenna pattern $G_g(\epsilon, \eta=0)$ would be included instead of $\hat{G}_g$, the peak gain, but in this report the shape effects are also considered a type of fade.

2.2 Fade Mechanisms

There are several fade mechanisms that combine to reduce the received signal power. The resultant total link fade may be expressed as a sum of these fades:

$$F_{total} = F_1(\epsilon, h, \alpha(\epsilon), d, \rho(\epsilon)) + F_2(R) + F_3(r, x, y) + F_4(\eta) + F_5(l_1, l_2) + F_6(\theta, \varphi) \quad . \qquad (3)$$

The following subsections describe the individual terms in this equation. Cited references should be examined for a detailed treatment of each subject and the modeling techniques employed.

2.2.1 Vertical Lobing

The effective gain of the ground sensor antenna is usually different from the peak gain included in Σ_1. This difference is caused by two effects: (1) The free space ground antenna gain is not a constant at all elevation angles, and (2) the received signal is made up of direct and reflected signals that may combine constructively or destructively at the receiving station. The reflected signals travel a longer path than the direct path signal and therefore arrive at the antenna with a different phase. They also intersect the ground antenna pattern at a different elevation angle but are not resolvable on the basis of their time displacement from the direct path signal. The total radiation field at the antenna is the vector sum of all the signals and results in a lobing pattern of peaks and nulls due to the constructive and destructive interference among these signals. This interference effect exists equally for uplink and downlink communications.

The first term in Equation 3, $F_1(\epsilon, h, \alpha(\epsilon), d, \rho(\epsilon))$, expresses the difference between the ground antenna peak gain, $\hat{G}_g$, and the effective antenna gain at an elevation angle ϵ. The ground antenna is mounted on a pedestal of height, h, and has an elevation gain pattern $\alpha(\epsilon)$ expressed in dB relative to the peak gain $\hat{G}_g$. The ground conditions around the sensor are described as "flat"* to a distant d, and as having a reflection coefficient of $\rho(\epsilon)$ within

*Differentiating flat from nonflat terrain is somewhat arbitrary in an actual situation and no definition of a flatness criterion is attempted here. The ideal extremes are assumed in the model employed.

the flat region and zero beyond. These parameters are sufficient to compute the gain variations due to multipath interference from ground reflected signals using Fresnel theory. The pedestal height influences the locations of the low gain nulls while the other parameters affect the severity of the gain reduction. Only specular multipath in the vertical plane is considered in this study, and for conditions of no multipath, F_1 would describe the free space gain variations of the antenna.

The magnitude of F_1 may be significant depending on the geometry between the ground sensor and aircraft, and the terrain conditions around the ground sensor. It is a very important contribution to the total fade because the magnitude is generally greatest at low elevation angles (i. e., below 2°) where a large fraction of the aircraft under surveillance are located, see Fig. 1. Some of the siting and environment parameters that influence F_1 vary from site to site as well as from azimuth angle to azimuth angle. These site characteristics make it difficult to do a complete parametric study of F_1. In calculating performance, some of these parameters are varied, however, to show their individual effects on the coverage region around the sensor. The model of terrain effects was obtained from Ref. 2.

2.2.2 Propagation Anomalies

A wave propagating through the troposphere is affected by the refraction and absorption properties of the media. The refractive index of the atmosphere causes ray bending which modifies the apparent elevation angle and range. This effect is not expressed as a fade, but is accounted for in the calculation of the range and elevation angle. The usual procedure is to modify the earth radius

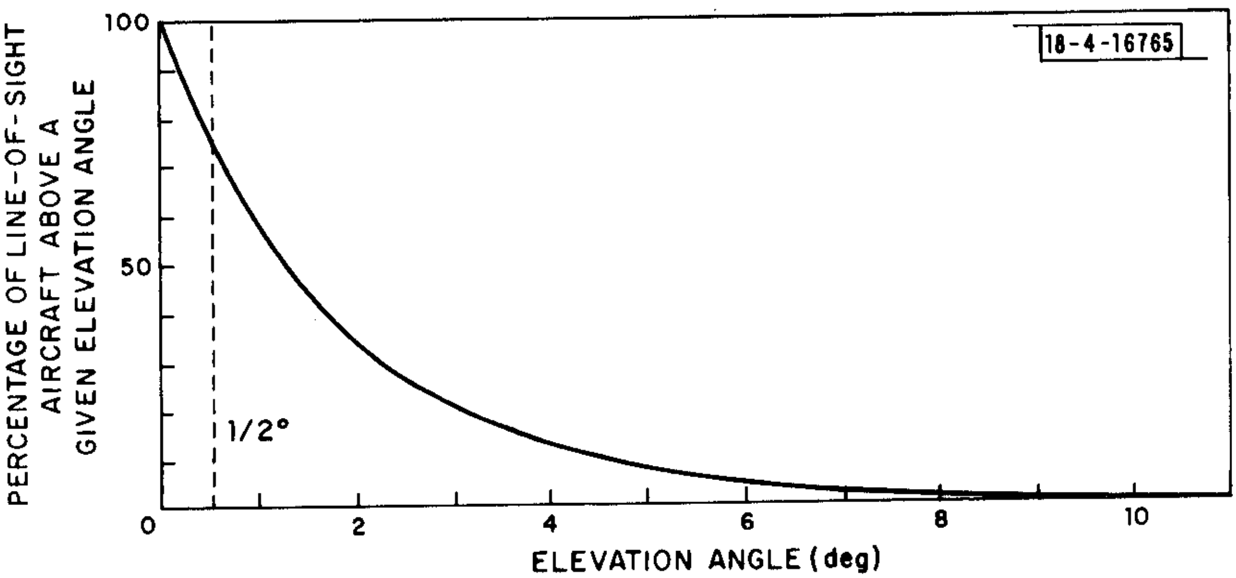

Fig. 1. Percent of aircraft above a given elevation angle (from Ref. 1).

by an appropriate factor k. The value of this factor can vary with weather and other atmospheric effects that change the refractive index. A value of 4/3 is considered the standard correction factor and is used throughout this performance study.

The second term in F_{total}, $F_2(R)$, is the loss due to absorption effects. This loss is modeled as linear in range. A reasonable value for L-band vertically polarized waves is 0.0093 dB per nautical mile and comes from Ref. 3.

2.2.3 Obstructions

The ground environment often includes man-made structures that prevent the direct path signal from reaching the receiving antenna. The receiving antenna is in the shadow region of the structure and the received signal is the result of diffraction around the obstruction. The magnitude of the signal can be calculated using Fresnel theory and is described in Ref. 4.

The third term, $F_3(r, x, y)$, is the loss of signal power due to obstruction effects. The obstruction is located at a ground range of r and has cross-range dimensions of x and y.

Since the combinations of structure height and width dimensions are unlimited and each is a special case, no particular obstructions are modeled in this performance study. The effects of obstructions must be examined on a site-by-site basis and often only affect the performance at very low elevation angles and over limited azimuth angles. If certain obstructions are particularly bad, siting tradeoffs must be considered. A qualitative discussion is presented later, but for the present F_3 is assumed to be zero.

2.2.4 Off Azimuth Effects

DABS schedules interrogations so they will be received when the aircraft for which they are intended is within the mainbeam of the sensor antenna. The mainbeam is defined by the 3-dB points (one way) of the antenna azimuth pattern. In cases when multiple interrogations are transmitted the interrogations cannot all occur when the target aircraft is on the boresight of the azimuth beam. The fade term $F_4(\eta)$ accounts for these off azimuth effects. For multiple equally spaced interrogations using a rotating antenna, F_4 is slightly over 1 dB. For an electronically scanned antenna, F_4 will be nonzero only when the track of the aircraft includes an azimuth error. In this study F_4 is assumed to be a constant 1 dB.

2.2.5 Antenna Mismatch

When an antenna is attached to a transmitter/receiver system, generally there is an impedance mismatch that reduces the signal level as the signal is passed between the antenna and the microwave subsystems. The mismatch losses at each antenna have been assumed to be constant values, l_1 and l_2, for the ground station and aircraft respectively, and the F_5 term is the total of such losses. The values of l_1 and l_2 will vary from ground station to ground station and aircraft to aircraft depending on the antenna used and installation techniques. In this study a value of 1 dB for F_5 has been assumed.

2.2.6 Aircraft Antenna Lobing

Finally, the sixth term in the equation for the total link fade represents the discrepancy between the ideal (isotropic) aircraft antenna pattern and the actual aircraft antenna pattern. The lobing structure of an aircraft antenna pattern is very complicated and depends on the viewing aspect angles, θ and φ.

The values of θ and φ depend on the aircraft attitude angles that relate the line-of-sight vector between the ground antenna and the aircraft to the position in space of the principal axes of the aircraft. This relationship is described in detail in Ref. 5. In addition, the value of F_6 depends on the aircraft type and the antenna location of the fuselage. The aircraft antenna is usually a simple quarter-wavelength dipole located on the bottom surface of the aircraft fuselage, and its pattern depends on the exact position along the fuselage. Just as the ground antenna gain is modified by the presence of signals reflected from the ground, the simple free space dipole pattern is modified by reflections from various parts of the aircraft structure. In addition, there are shadowing effects at some aspect angles where diffraction becomes important.

It would be unreasonable to attempt to express the DABS sensor performance for each possible combination of θ, φ, aircraft type and antenna location; consequently a statistical methodology is used as described in Section 3. The given result is in terms of a probability that the fade is less than any designated value.

2.3 Total Link Performance

If the free space margin, M_{fs}, and the total link fade, F_{total}, are combined, the link signal-to-threshold level is:

$$(S/T)_{dB} = M_{fs} - F_{total} \tag{4}$$

and the probability of successful communication, P(S), is the probability that S/T is greater than zero. The validity of this simplification is discussed in Ref. 6.

$$P(S) = P(S/T > 0 \text{ dB}) \ . \tag{5}$$

Combining Equations 2, 3, 4, and 5 and substituting the constant or linearly varying values described for F_2 through F_5, one obtains:

$$\begin{aligned} P(S) &= P(\Sigma_2 - 20 \log_{10} R - 0.0093 R - F_1 - F_6 > 0 \text{ dB}) \\ P(S) &= P(F_6 < \Sigma_2 - 20 \log_{10} R - 0.0093 R - F_1) \end{aligned} \tag{6}$$

where

$$\Sigma_2 = \Sigma_1 - F_3 - F_4 - F_5 .$$

Since F_1 has a determinant value at a point in airspace, the probability of successful communication between the ground stations and the aircraft at that point in airspace is the probability that the aircraft antenna fade does not exceed the margin remaining after accounting for all other causes of fades. The value on the right of the inequality in Equation 6 is called the isotropic margin, M_I, since it would be the extra power in the link if the aircraft were equipped with an isotropic antenna.

$$M_I = \Sigma_2 - 20 \log_{10} R - 0.0093 R - F_1(\epsilon, h, \alpha(\epsilon), d, \rho(\epsilon)). \tag{7}$$

Contours of constant values of M_I can be computed and plotted in range versus altitude for fixed choices of h, $\alpha(\epsilon)$, d and $\rho(\epsilon)$. With only small changes as a function of elevation angle, these constant margin contours correspond to constant probability contours according to Equation 6 if the inequality is changed to an equality. It is these proability contours that are used in this report to exhibit the performance of the DABS single sensor link. An example of constant M_I contours is given in Fig. 2. The parameter values used in this example are discussed later in this report.

3.0 AIRCRAFT ANTENNA STATISTICS

The probability of successful communication is thus equivalent to the probability that the aircraft antenna gain in the direction of interest is greater than a certain level. For a specific relative geometry between the ground station antenna and the airborne antenna, the probability would be zero or unity. Since there may be several unpredictable specific combinations of aircraft heading, roll, and pitch angles that fail to provide sufficient antenna gain for communication, the overall interrogator-transponder system performance must be examined statistically. The likelihood of sufficient gain under varying flight conditions provides a measure of system performance that does not exclude failures, but rather weighs those failures in a manner that more closely resembles actual ATC operations. For example, if a communication failure occurs when a Cessna 150 is banked 30° and is at some particular heading relative to the ground station antenna beam, one would not expect to see all Cessna 150s at exactly that bank angle and exactly that relative heading. That one particular set of conditions should not totally characterize the performance at that point in airspace.

The three attitude angles mentioned above were randomized by considering them uniformly distributed over different bands of values. Since aircraft are free to fly in any possible direction relative to the ground antenna azimuth boresight axis, the heading angle was considered uniformly random over all

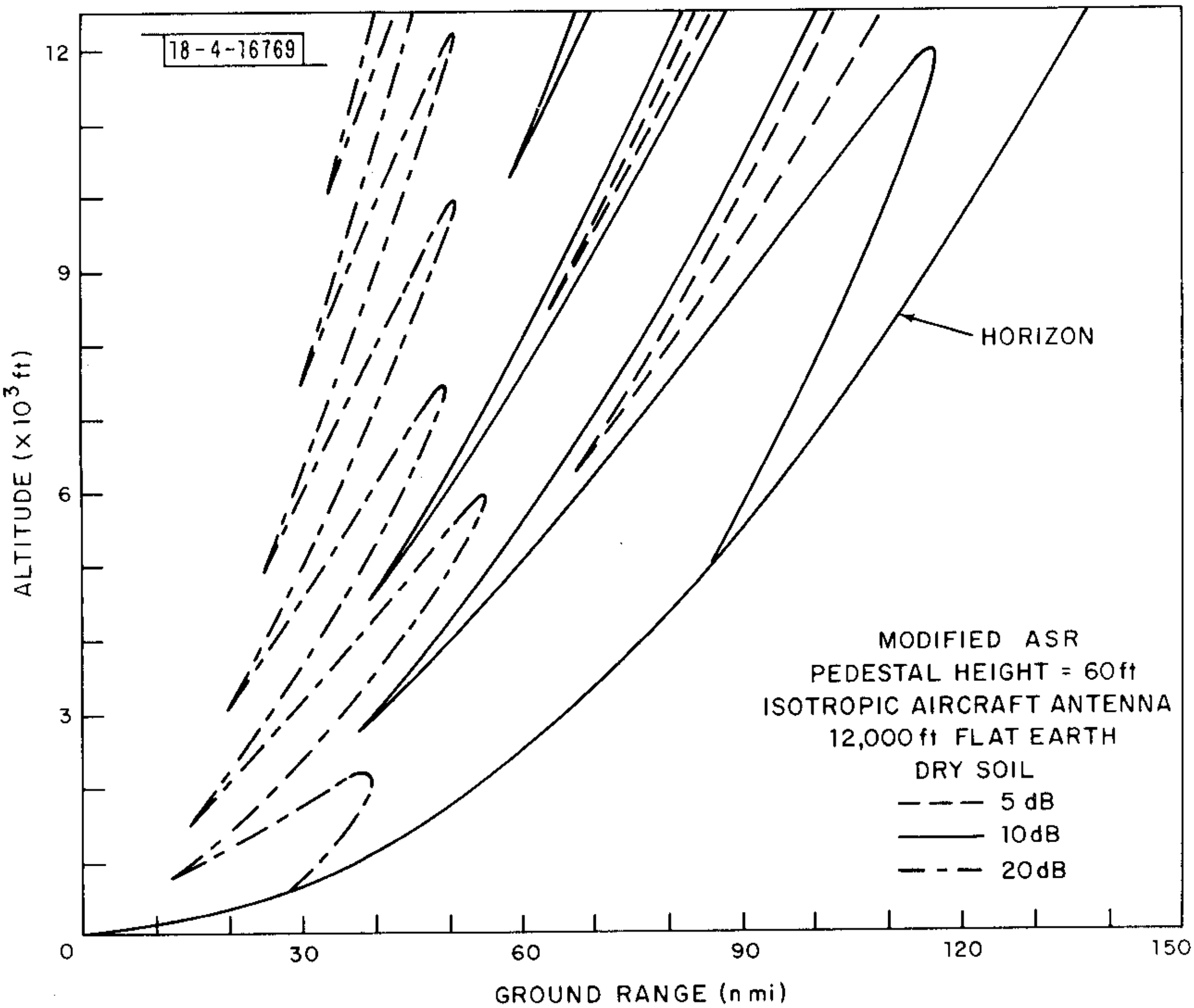

Fig. 2. Constant isotropic margin contours for standard parameter values.

relative headings from 0° to 360°. The roll and pitch angles were limited to bands of values on either side of zero, such as would occur during various categories of flight conditions. These categories and the corresponding bands are listed in Table 1. Even the "level flight" conditions include a span of values in either or both variables. This is done to account for normal variation in aircraft attitude due to winds, vertical air drafts, and pilot steering corrections.

Within each band of angles defining each flight condition or combination of conditions, the attitude angles were varied in two-degree increments. This corresponds to the angular quantization of the aircraft antenna pattern data. For each combination of the heading, roll and pitch angles, the appropriate antenna gain was determined using the measured pattern and correcting for cross-polarization effects. A histogram of gain values was thus determined which, when normalized by the number of attitude angle combinations, resulted in a density function of aircraft gain for the maneuver considered. A cumulative distribution was also computed that showed the fraction of attitude angle geometries providing less gain than any chosen level. This same technique was used in Ref. 5 to analyze the relative quality of antennas on different aircraft and under different flight conditions. Figures 3 and 4 give examples of density and distribution functions, respectively, for a Cessna 150 in a moderate roll. These functions vary slowly with the elevation angle to the aircraft, and this effect is accounted for in the results of this report.

The cumulative distribution function is the curve needed to determine system performance if the axes are redefined. Since the margin, M_I, at the aircraft is defined for an isotropic antenna and the aircraft antenna gain is

TABLE 1

DEFINITIONS OF MANEUVER CATEGORIES

Category of Maneuver	Limits of Maneuver	
	Roll	Pitch
Level	-3° to $+3^\circ$	-3° to $+3^\circ$
Shallow	-15° to $+15^\circ$	———
Moderate	-30° to -15° $+15^\circ$ to $+30^\circ$	-15° to $+15^\circ$
Steep	-45° to -30° $+30^\circ$ to $+45^\circ$	-30° to -15° $+15^\circ$ to $+30^\circ$
Very steep	-60° to -45° $+45^\circ$ to $+60^\circ$	———

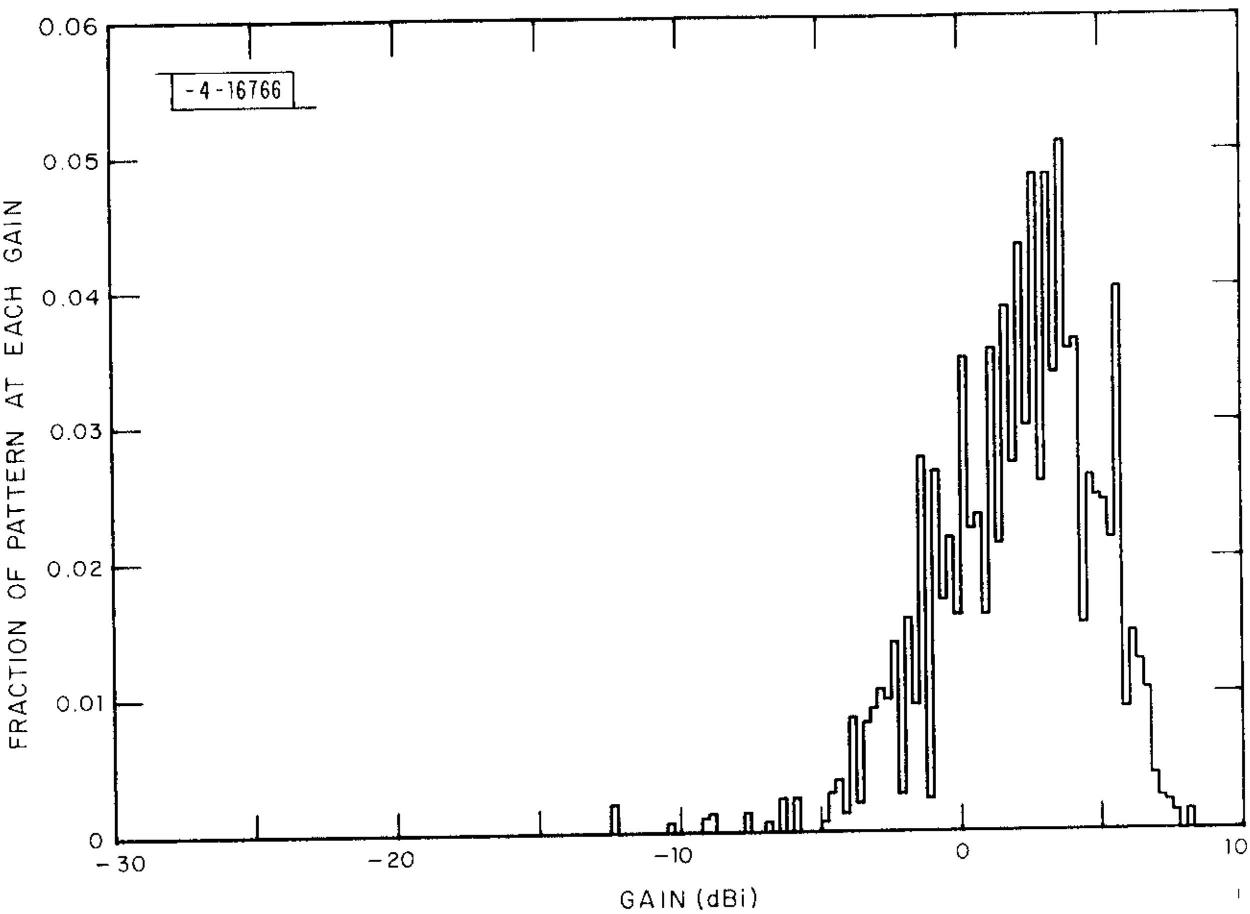

Fig. 3. Example of gain density function.

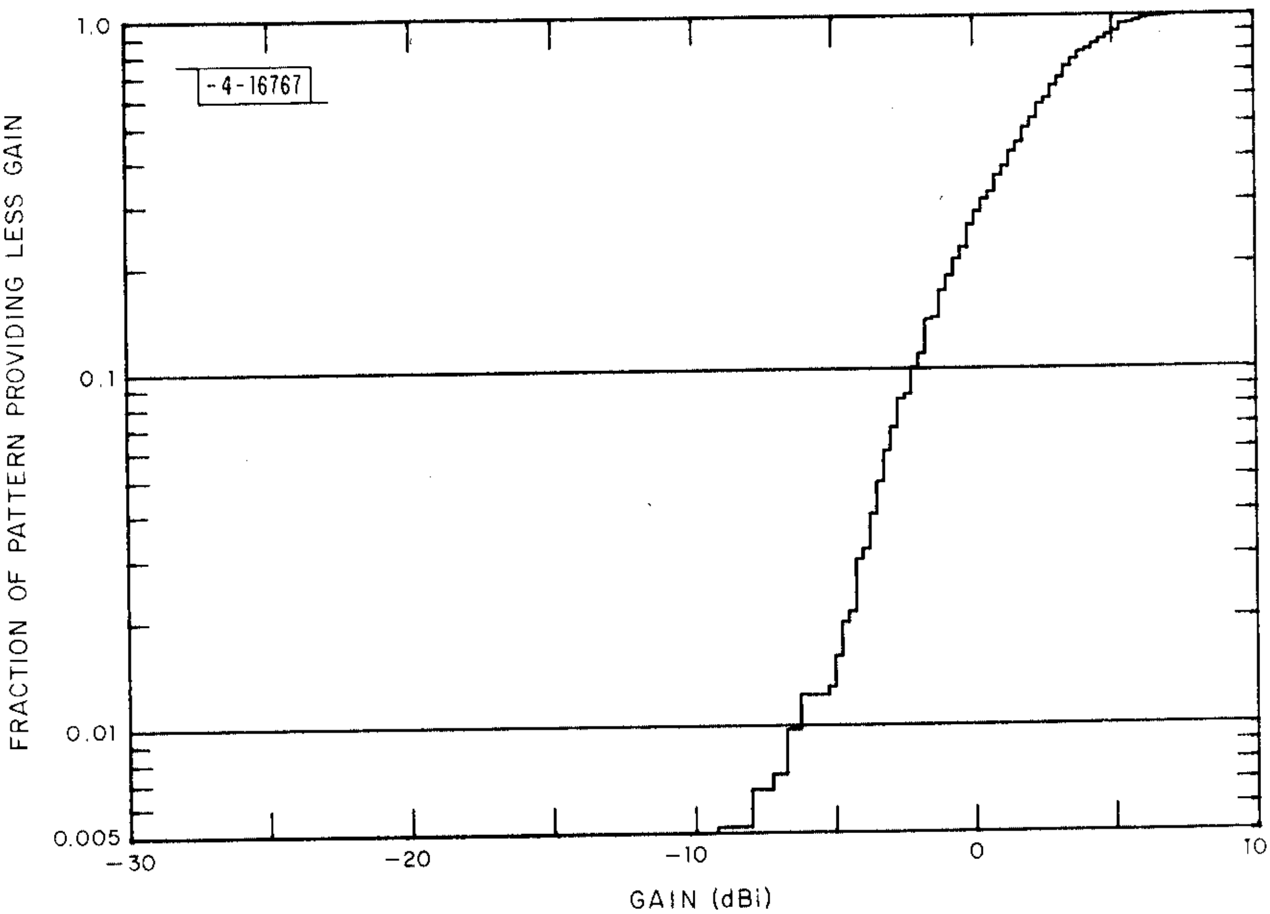

Fig. 4. Example of gain distribution function.

normalized to an isotropic antenna gain, the horizontal "gain" scale can be redefined as the "isotropic margin" scale if the values are multiplied by -1. Also, the vertical scale can be relabeled as the probability that the fade is less than the isotropic margin, $P(F < M_I)$.

4.0 SYSTEM PARAMETERS

This section describes the parameters used in the performance calculations presented in the next section. As one variable is altered, the others must, of course, remain fixed in order to make fair comparisons. These fixed or standard values are clearly defined in the text. Table 2 gives a summary of the parameter values tested.

4.1 Ground Antenna Pattern

There are a number of free space antenna patterns being considered for the DABS sensor. The proposed modification to the present airport surveillance radar (ASR), which provides a combination radar and DABS antenna (common reflector), is considered a reasonable choice for study since the evolution from ATCRBS to DABS would benefit from the use of antennas that already exist at the time. This new ASR/beacon antenna also has two desirable beacon features: (1) a moderate gain slope at the horizon to reduce fades due to ground reflected multipath, and (2) a cosecant squared gain characteristic at high elevation angles that leads to higher gains at low elevation angles where the majority of the traffic is located. Figure 5 shows the elevation gain pattern used in this model based on preliminary measurements of the modified ASR antenna. This antenna pattern is used as the standard when varying other parameters.

TABLE 2

PARAMETER VALUES USED IN THE PERFORMANCE STUDY

Parameter	Variable	Standard Value	Alternate Value
Ground antenna pattern* ($\hat{G}_g$)	$\alpha(\epsilon)$	Modified ASR (25 dBi)	4-ft Open array (22 dBi), Modified DABSEF, (30 dBi)
Antenna pedestal height	H	60 ft	30 ft, 180 ft
Extent of flat earth	D	12, 000 ft	–
Earth surface condition	$\rho(\epsilon)$	Dry soil	Snow
Aircraft type, antenna No.†	A/c, n	Cessna 150, #3	Piper Cherokee Arrow, #3 and Boeing 727, #2
Aircraft attitude angles	h, r, p	Level flight	Moderate roll
Antenna mismatch losses	F_5	1 dB	–
Off azimuth boresight losses	F_4	1 dB	–
Obstruction losses	F_3	0 dB	–
Atmospheric absorption losses	F_2	0.0093 dB/nmi	–
Transmit power‡	P_t	59 dBm(800 watts)	49 dBm(80 watts)
Receiver threshold for successful message decoding‡	MUSL	-71 dBm	–
Frequency, wavelength	γ, λ,	1, 031 mHz, 0.9 ft	–
Fixed system losses	L	0 dB	–
Resulting constants	Σ_1	$54.4\ dB_{ASR}$	51.4 dB Array 59.4 dB DABSEF
–	Σ_2	$52.4\ dB_{ASR}$	49.4 dB Array 57.4 DABSEF

* Optimum tilt angle used in each case

† Antenna location is best choice available for each aircraft type (see Ref. 5 for analysis and exact location information).

‡ Based on DABS uplink; downlink performance equivalent to using standard values and assuming a worst case transponder power level.

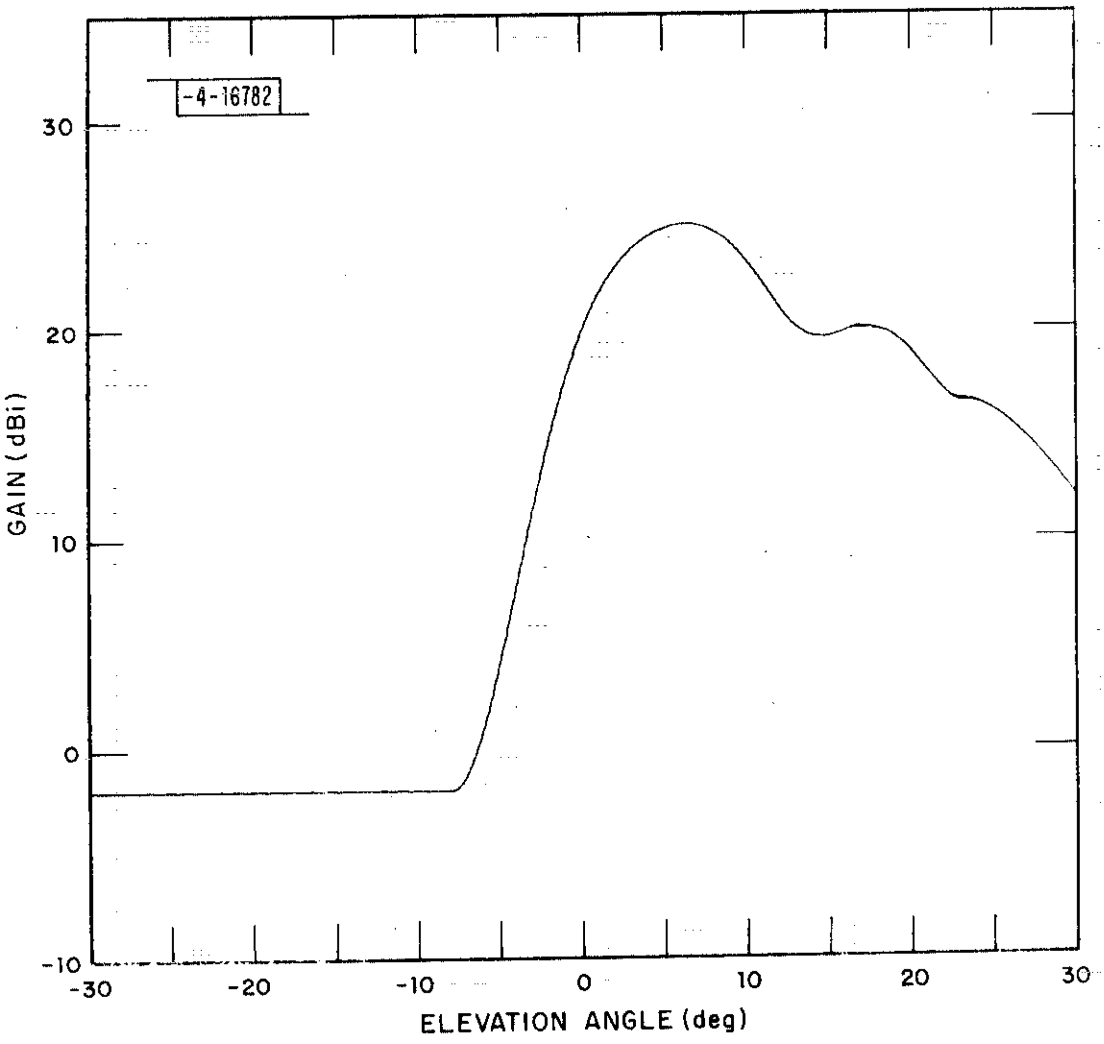

Fig. 5. Modified ASR, free space gain as a function of elevation angle.

Two other free space antenna patterns were used for comparison. The first was a proposed replacement for the present ATCRBS antenna, a 28-foot wide and 4-foot high array. Its elevation pattern is shown in Fig. 6. This pattern does not have as steep a slope at the horizon as the modified ASR and consequently, should have a more limited performance. Because the gain of this pattern is high over only a sector of elevation angle and falls sharply to its sidelobe level, a cone of silence problem may exist above the sensor. Because the shapes of all the antenna patterns in this report are uncertain at these high elevation angles, performance calculations above thirty degrees in elevation are excluded. The cone of silence issue is discussed briefly in a later section of this report.

The second antenna compared to the modified ASR was an idealization incorporating three desirable features. This antenna is an approximation of the rotating planar array installed at the Lincoln Laboratory DABS Experimental Facility (DABSEF) and is therefore designated as the "Modified DABSEF Antenna." This antenna embodies a sharp gain slope at the horizon similar to the present DABSEF antenna. However, this incorporated the desirable cosecant squared shape at high elevation angles. Finally, the cosecant squared falloff in gain is limited to a level 13 dB below the peak gain and remains constant for all higher elevation angles. This limit on the falloff reduces the cone of silence problem, as will be shown in the data presented later. Figure 7 shows this idealized antenna pattern.

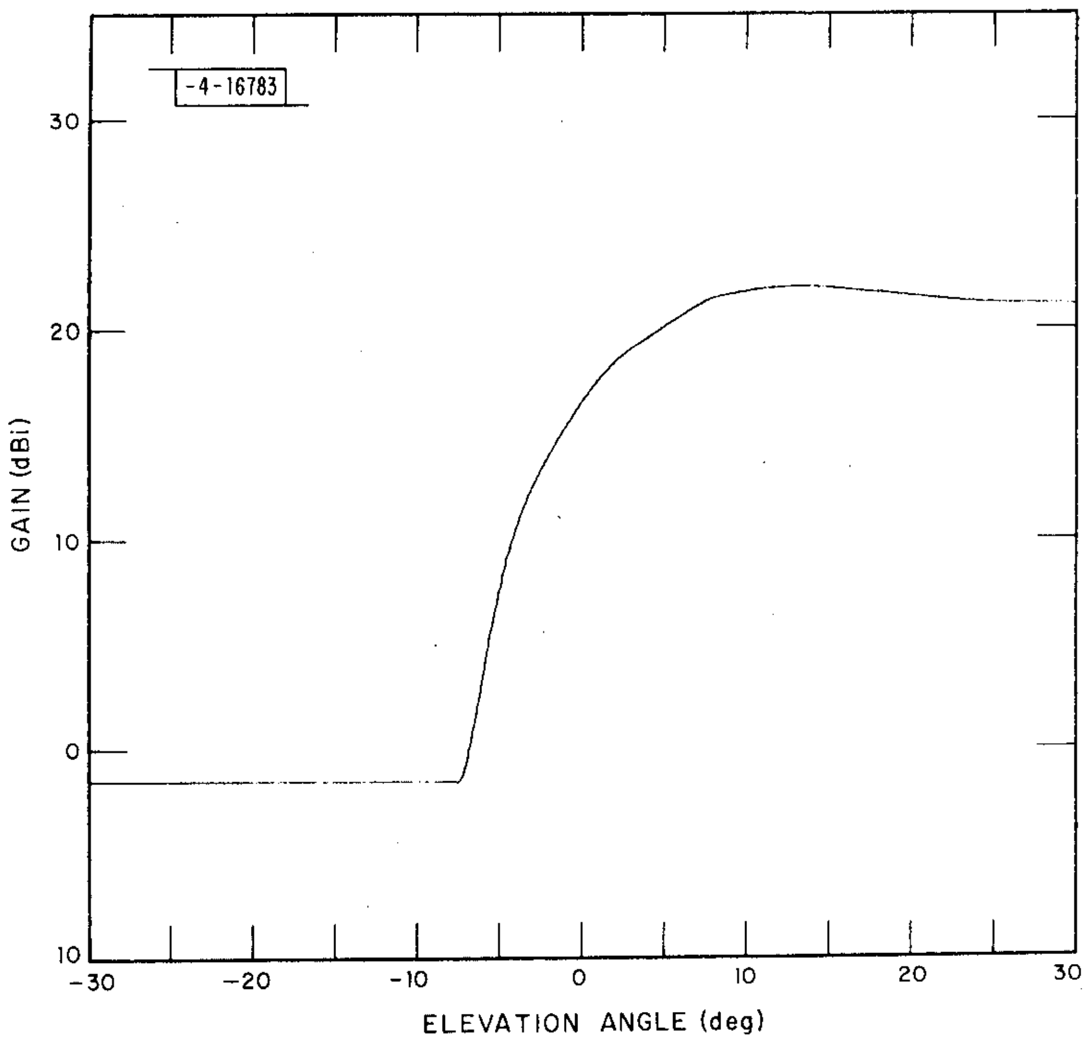

Fig. 6. Four-ft open array, free space gain as a function of elevation angle.

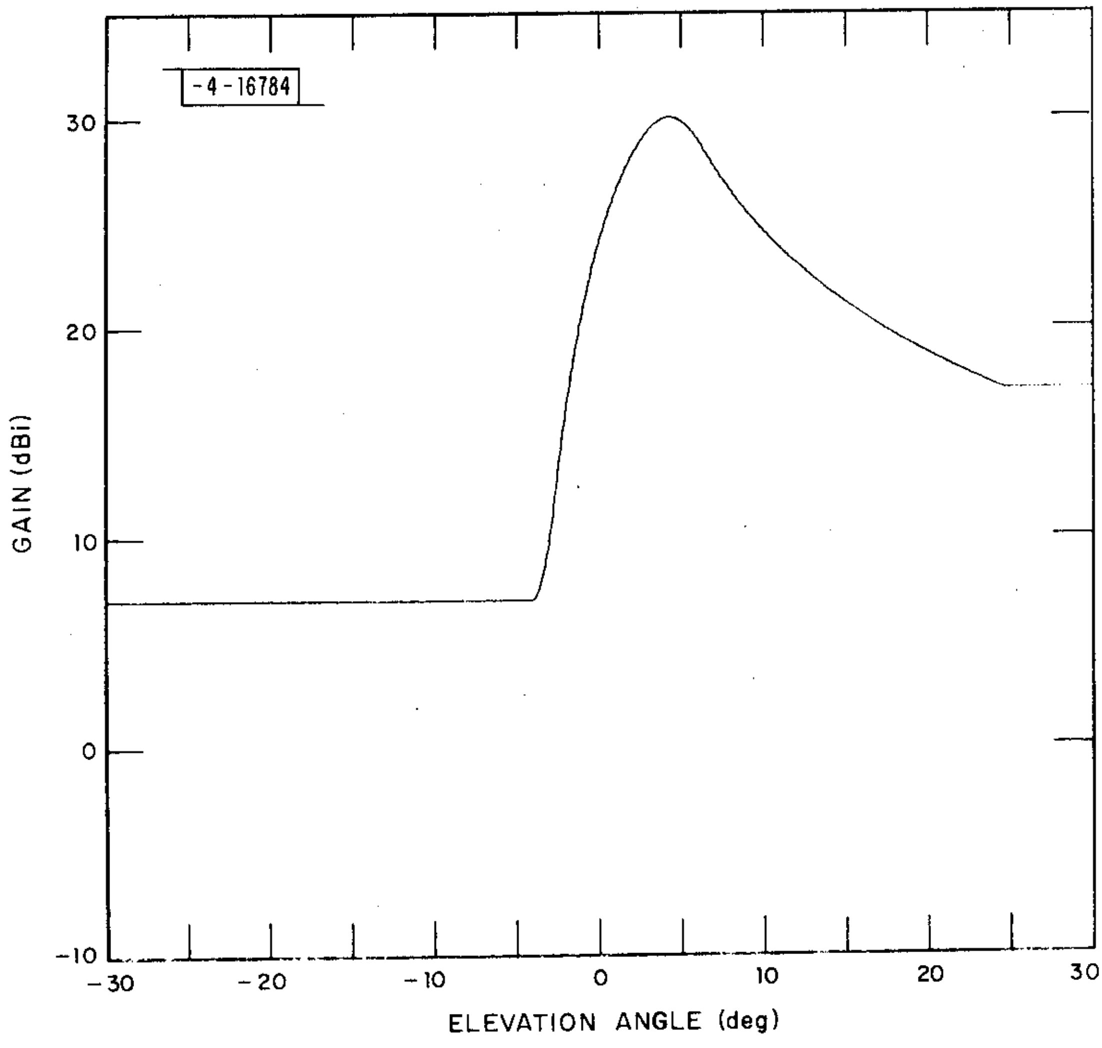

Fig. 7. Modified DABSEF, free space gain as a function of elevation angle.

4.2 Ground Antenna Site Conditions

The parameters, which describe the ground station site, also influence the performance calculation. The siting conditions determine the location and severity of any fades resulting from ground reflected signals destructively interfering with the direct path signal. Four siting parameters influence these multipath fades: antenna pedestal height, antenna elevation angle tilt, reflection characteristics of the ground, and the radial distance over which the ground surface is flat. The first parameter determines the elevation angle locations of the fades, while the remaining three parameters influence the degree of fade.

The definition of "flat" conditions is related to the coherence of the reflected signals over a spatial extent comparable to the dimensions of the first few Fresnel zones. Figure 8 shows a situation where some of the Fresnel zones are in the "flat" region and some in the "rough" region. It was assumed that the reflections from the "rough" region were random and, in total, contribute nothing to the reflected signal received at the antenna. At lower elevation angles more of the zones extend into the "rough" region, and less signal is reflected to cause interference with the direct path signal. This is the opposite result from having an unlimited ideally smooth earth when the reflection coefficient is large at small angles. The effect of limiting the extent of smooth, flat earth conditions is accounted for by the correction factor applied to the reflection coefficient amplitude and phase. An example of this correction for amplitude is shown in Fig. 9. The oscillatory nature of the curve is the result of a greater number of Fresnel zones contributing to

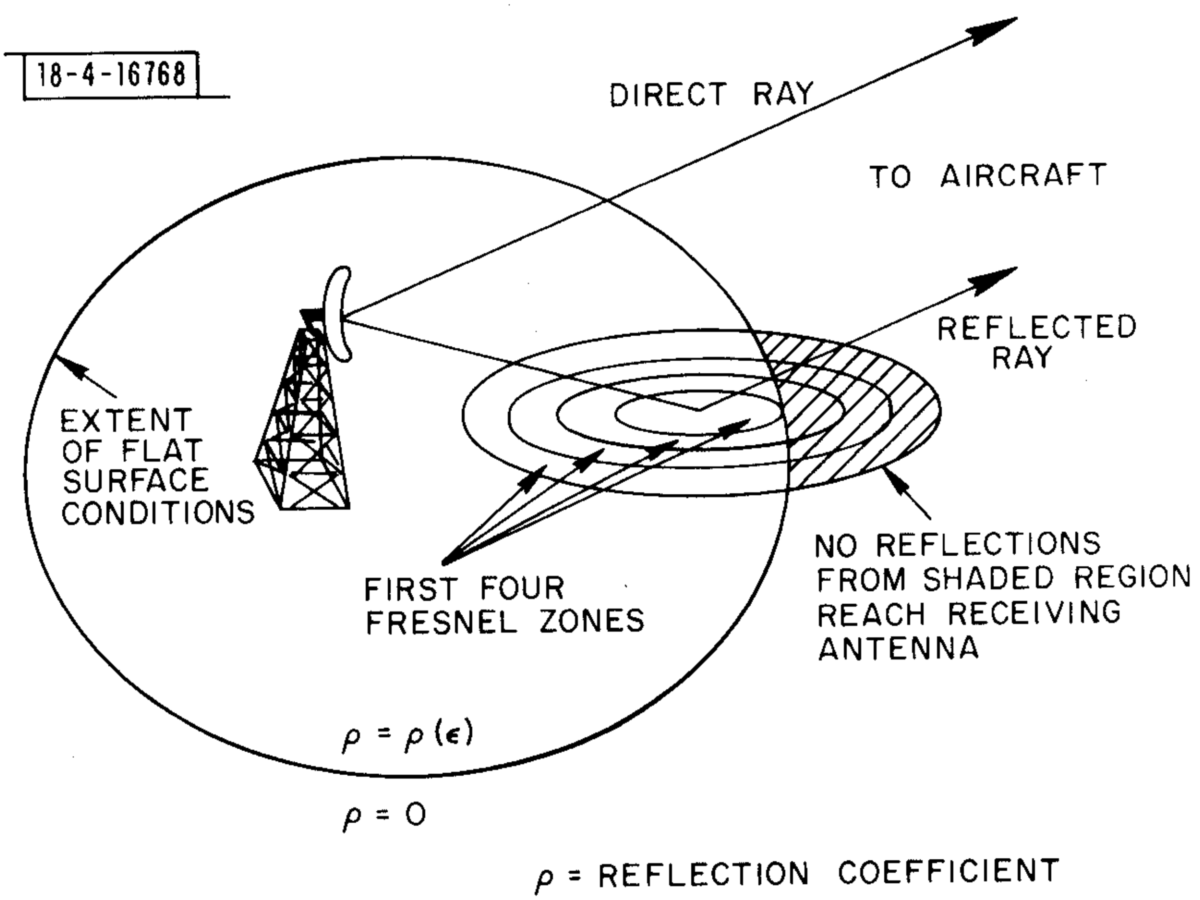

Fig. 8. Example of multipath Fresnel zones extending across flat and rough surfaces.

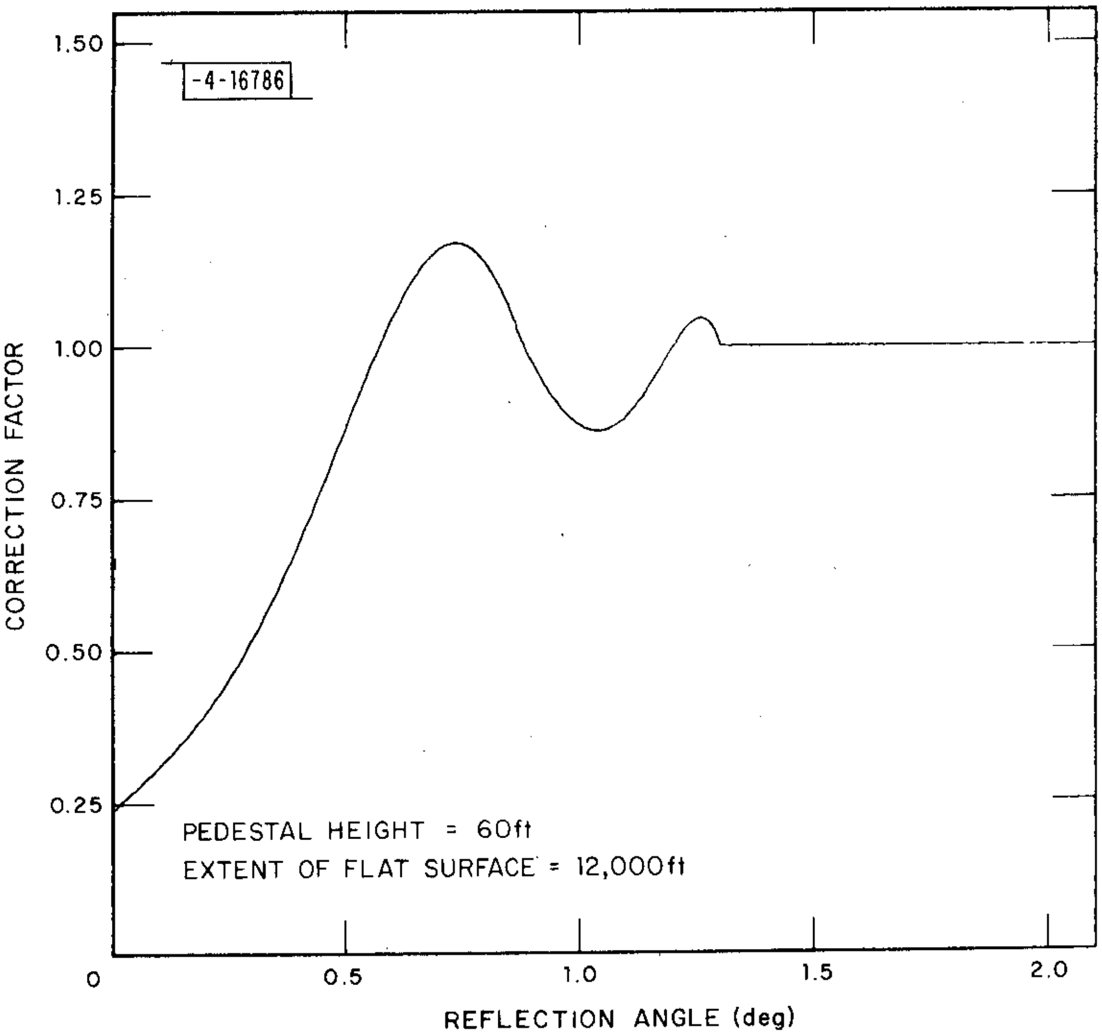

Fig. 9. Example of correction to reflection coefficient for limited flat surface.

the total reflected signal. As the elevation angle increases, zones move closer to the ground station while the zones also reduce in size. The oscillations tend to diminish rapidly since the first few zones contribute most of the reflected signal power. Despite the fact that the extent of flat ground generally varies with azimuth, the flat earth conditions are assumed to exist out to twelve thousand feet around the ground sensor in all azimuth positions. This parameter is not varied and one should consult Ref. 2 for the effects of this parameter.

A dry soil surface was generally assumed for the region around the ground station and is certainly a reasonable choice for most terminal sensors. This parameter also can vary with azimuth angle but was held constant in this study. Because fresh snow represents a "worst case" situation, the DABS performance was also evaluated for this reflecting surface condition as a limiting case. The reflection coefficients for these two types of surfaces are shown in Fig. 10.

The choice of elevation tilt angle affects the multipath fades by determining the ratio of the antenna gains applicable to the direct and reflected signals. The optimal tilt angle was obtained from Ref. 2 and was used here for each ground antenna examined. Figures 5 through 7 are drawn with the optimal tilt angle in effect.

As already mentioned, the pedestal height determines the locations of the fades for the assumed limited flat earth. The choice of pedestal height depends on several issues including cost, size and location of nearby obstacles, availability of present suitable structures, and safety. The present study used a sixty-foot pedestal height for most cases, but comparisons using a lower

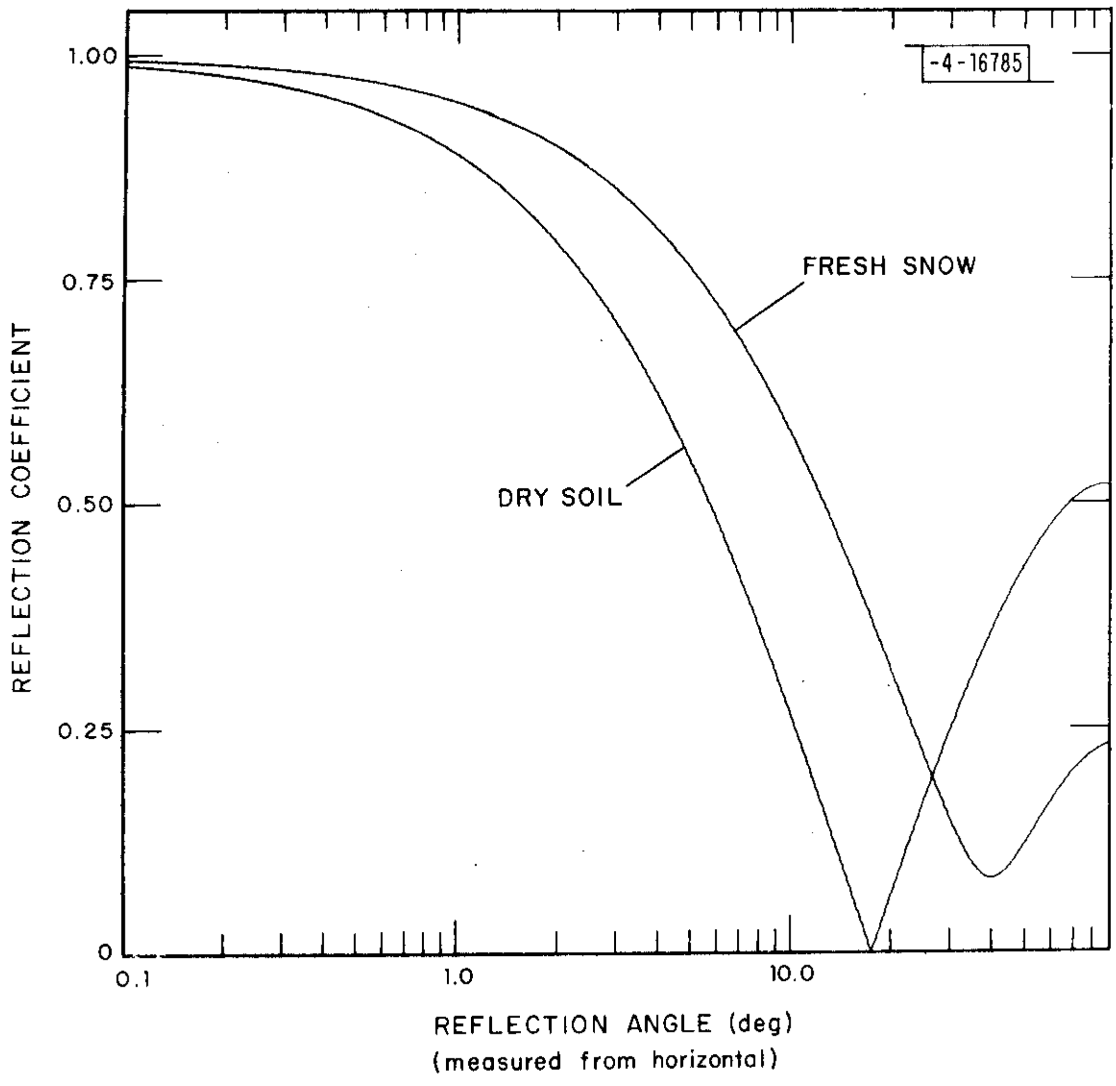

Fig. 10. Reflection coefficients (amplitude only) for snow covered and dry soil surfaces.

(30-foot) and much higher (180-foot) pedestal are also presented. Multipath fades, F_1, can occur at unusual elevation angles for sloping ground surfaces, but such ground conditions are unique characteristics of individual sites while most airport located sensors have large flat areas in the immediate vicinity. It is the performance in such an airport environment that is examined in this report and is represented by the above parameter value selections.

4.3 Transmitter and Receiver Characteristics

4.3.1 Downlink

The DABS transponder transmitted power is nominally specified as 54 dBm (250 watts) $\pm$ 3 dBm. In this performance study, the lowest power value was assumed in order to examine the worst case condition within specifications. This power is defined at the output from the transponder and includes the cable losses but not the possible mismatch losses when an antenna is attached.

The ground station receiver sensitivity or minimum usable signal level (MUSL) was chosen at -79 dBm at the antenna end of the cable to the receiver. The response of the receiver was considered a pass-fail type of system with -79 dBm as the threshold.

Various design factors in DABS permit operation at such a low signal level and assumption of such a pass-fail manner. The type of signal modulation, the use of error correctable coding (downlink only) and the dynamic reinterrogation capability all help cope with the interference and fruit problems anticipated for the future air traffic environments. The combined effects of these design factors are described in Ref. 6 and lead to the values of MUSL for correct message decoding in the downlink and uplink modes.

4.3.2 Uplink

A transponder receiver sensitivity of -71 dBm was assumed and also is defined at the input to the transmitting antenna. This sensitivity is again based on the results published in Ref. 6.

The interrogator transmitted power is nominally chosen as 80 watts, and 800 watts in the low power and high power modes, respectively. With the previously listed receiver sensitivities and transponder transmitter power level, the high power uplink power budget is identical to the fixed downlink power budget. Thus the calculated downlink performance is the same as the high power uplink performance, and only the low power uplink performance need be studied separately.

4.4 Aircraft Antenna Patterns

There are a number of parameters that affect the aircraft antenna pattern including the type of aircraft, the landing gear and flap status, and the location of the antenna on the aircraft. In addition, the actual value of the gain in a link calculation depends on the attitude angles describing the aircraft orientation. All these parameters have been examined previously; only a limited number of aircraft antenna parameter variations are presented in this report. The patterns were all measured on scale model aircraft as described in Ref. 5.

The types of aircraft used represent different popular categories: a high wing, single-engine, general aviation aircraft (Cessna 150), a low wing, single-engine, general aviation aircraft (Piper Cherokee Arrow), and a commercial airliner (Boeing 727). All patterns are for an aircraft in an enroute condition with flaps up and landing gear retracted except the Cessna 150 which does not have retractable landing gear. The antenna location is optimized as best as possible by the criteria used in Ref. 5.

5.0 RESULTS AND DISCUSSION

In this report the performance of the DABS link is characterized by the probability of successful communication within the surrounding airspace and is illustrated by contours of constant probability plotted in altitude vs ground range. Constant isotropic margin contours, as computed using Equation 7, were shown in Fig. 2, and an example of an aircraft antenna gain distribution function was given in Fig. 4. Combining these results yields the appropriate probability contours (Fig. 11), which indicate the performance of DABS, for parameter values listed in Table 2 and referred to in this report as the "standard" values. When these parameters are varied, one at a time, their effect on DABS performance is reflected in altered constant probability contours. These effects are described in the following paragraphs by comparing the new contours to the contours for the standard value conditions. The figure numbers for the contour plots under each of the parameter changes are listed in Table 3. Also listed are the ground range and altitude of the nearest region of airspace with less than 0.99 probability of success.

5.1 Ground Station Parameters

5.1.1 Antenna Type

The type of ground antenna affects DABS performance by the degree of ground multipath interference that reduces (or enhances) the received signal level. Even without multipath, the beam shape and peak gain differences among the antennas lead to different probability contours. Figure 12 shows the performance for the proposed four-foot open planar array under development

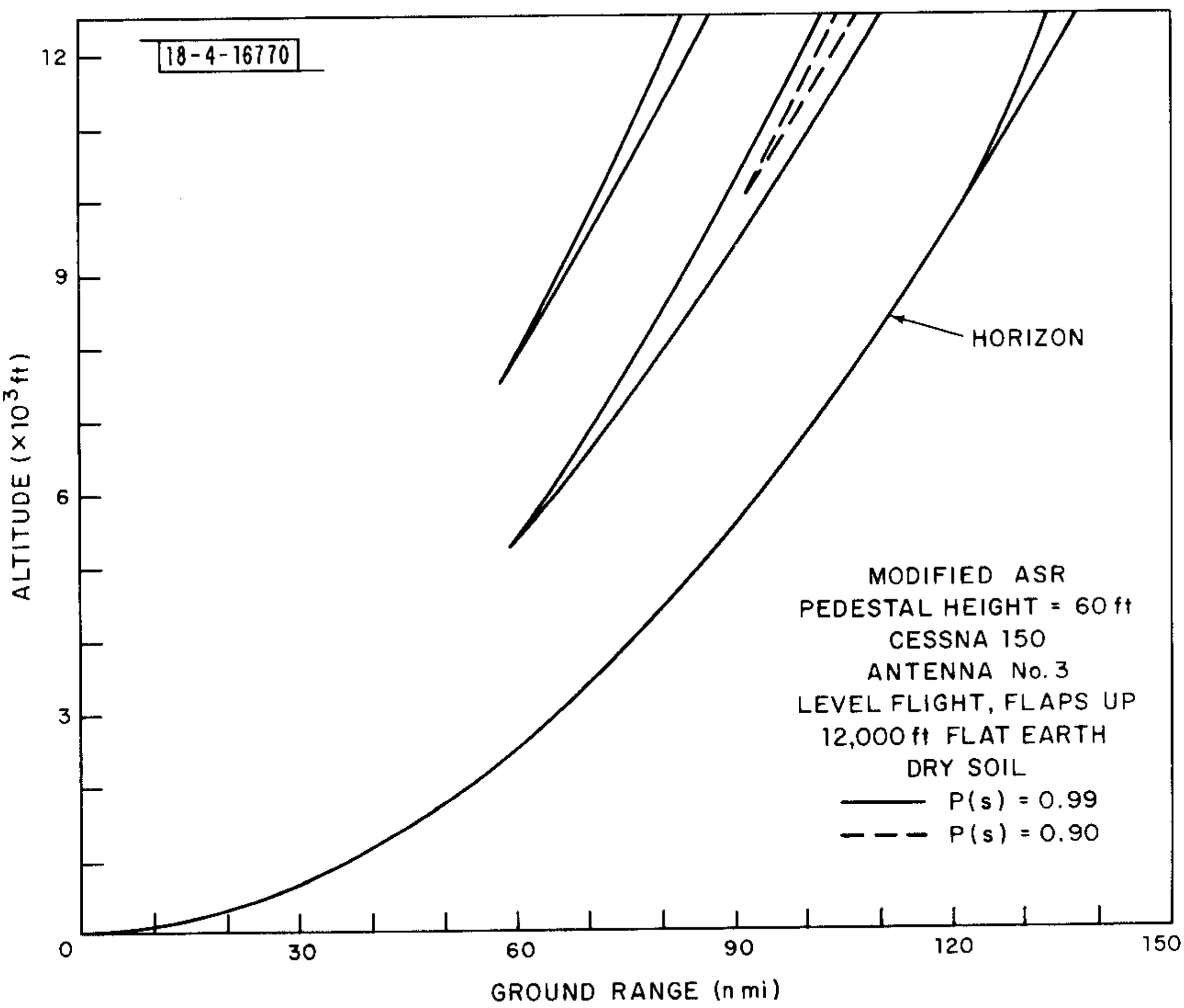

Fig. 11. Constant probability of success contours for standard conditions.

TABLE 3

INDEX OF FIGURES WITH VARIOUS PARAMETER CHANGES

Figure Number	Value of Changed Parameter	Ground Range/Altitude of First Airspace With P(S)<0.99 (nmi/ft)
11	Standard values	58/7,500
12	Ground antenna: 1. 4-ft open array	25/2,750
	2. Modified DABSEF	
None	a. Normal 30-dBi peak gain	-
13	b. 25-dBi peak gain	63/5,750
	Pedestal height:	
14	1. 30 ft	70/9,750
15	2. 180 ft	115/10,500
	Reflecting surface:	
16	Fresh snow	53/6,750
	Reduced power:	
17	-10 dB	20/1,250
	Other aircraft, level flight:	
18	1. Piper Cherokee	72/10,000
19	2. Boeing 727	113/19,000
	Maneuvers, moderate roll:	
20	1. Cessna 150	35/2,500
21	2. Piper Cherokee	9/600
22	3. Boeing 727	38/3,000

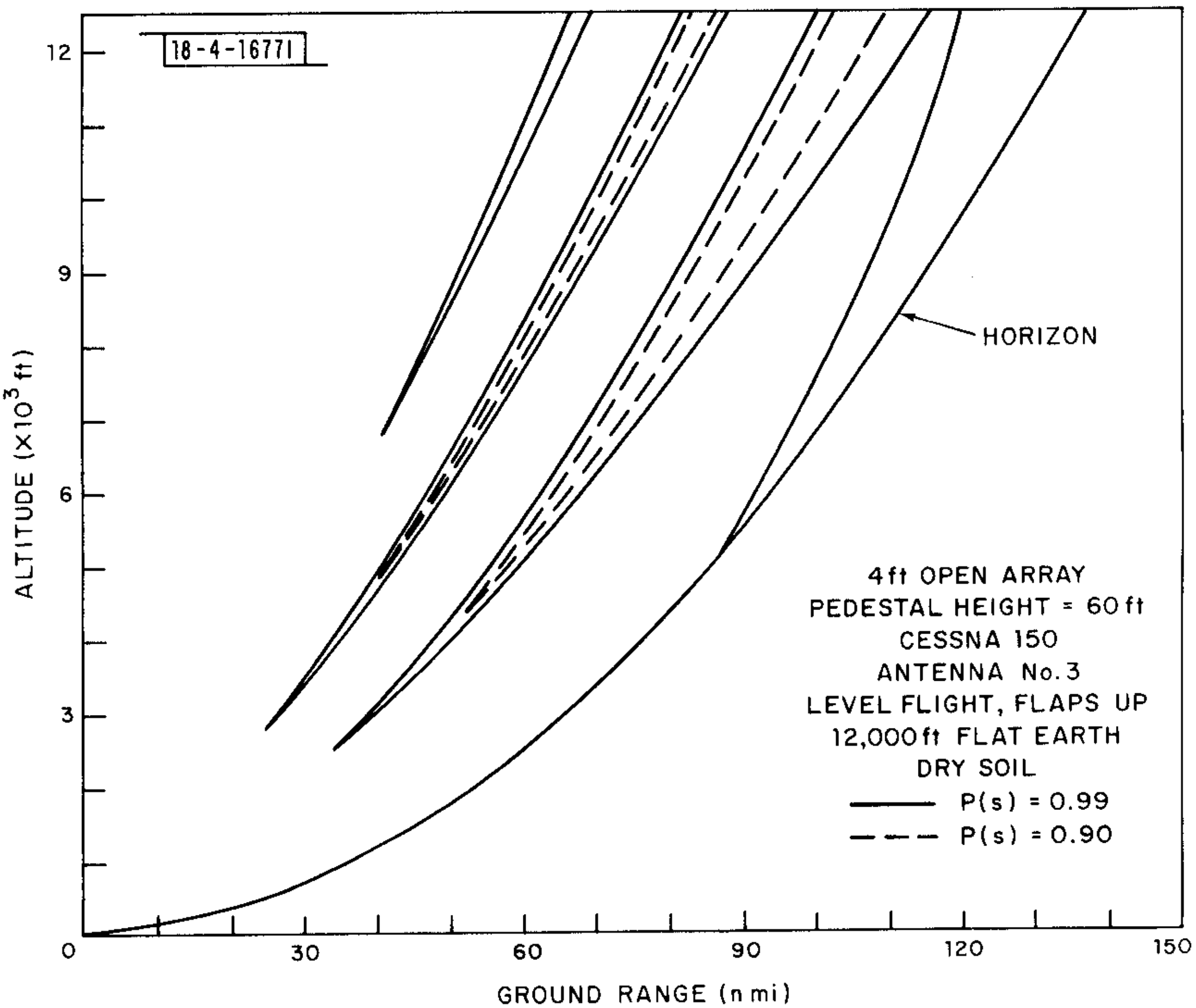

Fig. 12. Constant probability of success contours for 4-ft open array.

by Hazeline Corporation. As can be seen, there is a deeper intrusion of reduced performance regions for the four-foot array antenna than occurred for the modified ASR. This results from the lower gain of the four-foot array and the slope of the elevation pattern around the zero-degree point.

In contrast, if the modified DABSEF antenna described earlier is used, the performance is superior to the standard antenna case. No figure is included in this report to show the constant probability curves for this case because they do not extend into the airspace below 12, 500 feet. For this antenna the peak gain and the slope of elevation pattern around zero degrees are both greater than for the standard antenna used in Fig. 11.

If the peak gain of the modified DABSEF antenna is forced to equal the standard antenna peak gain, then the performance is as designated in Fig. 13. When the three regions of airspace with less than 0. 99 success probability are compared, the lowest elevation angle region, bounded by the line of sight horizon, is larger for the new antenna; the middle region is comparable in extent, and the highest region is smaller. These results are due to the slope difference between the antennas. The sharper slope reduces multipath interference but only as one moves above the zero-elevation angle. Very near zero elevation, the absolute gain level dominates and the sharper cutoff DABSEF antenna now has a lower absolute gain at the horizon.

5.1.2 Pedestal Height

Figures 14 and 15 show the performance using lower and higher pedestals, respectively. The lower pedestal leads to fewer but wider lobes in the multipath induced pattern. The dimensions of the Fresnel zones are

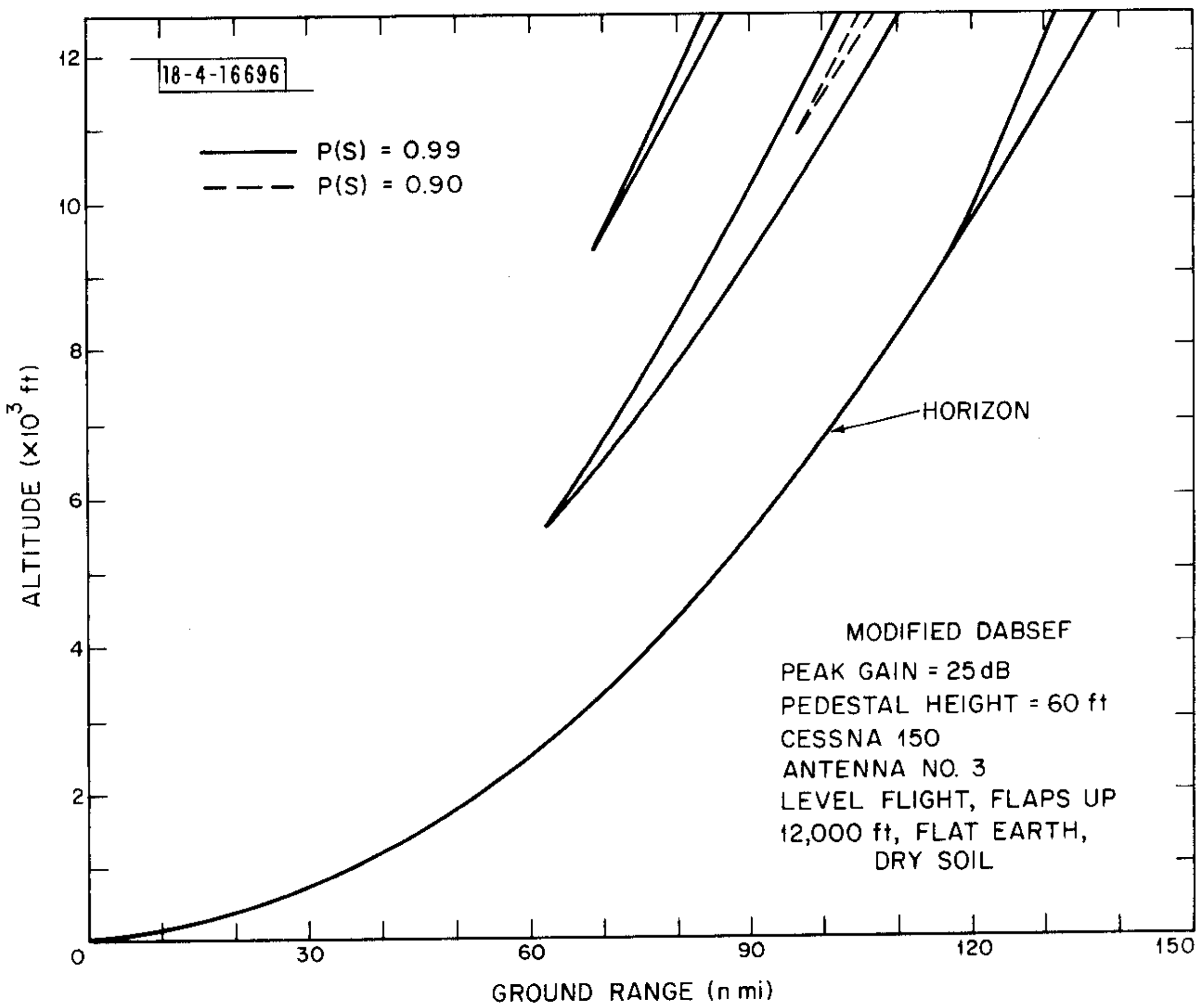

Fig. 13. Constant probability of success contours for modified DABSEF with peak gain of 25 dBi.

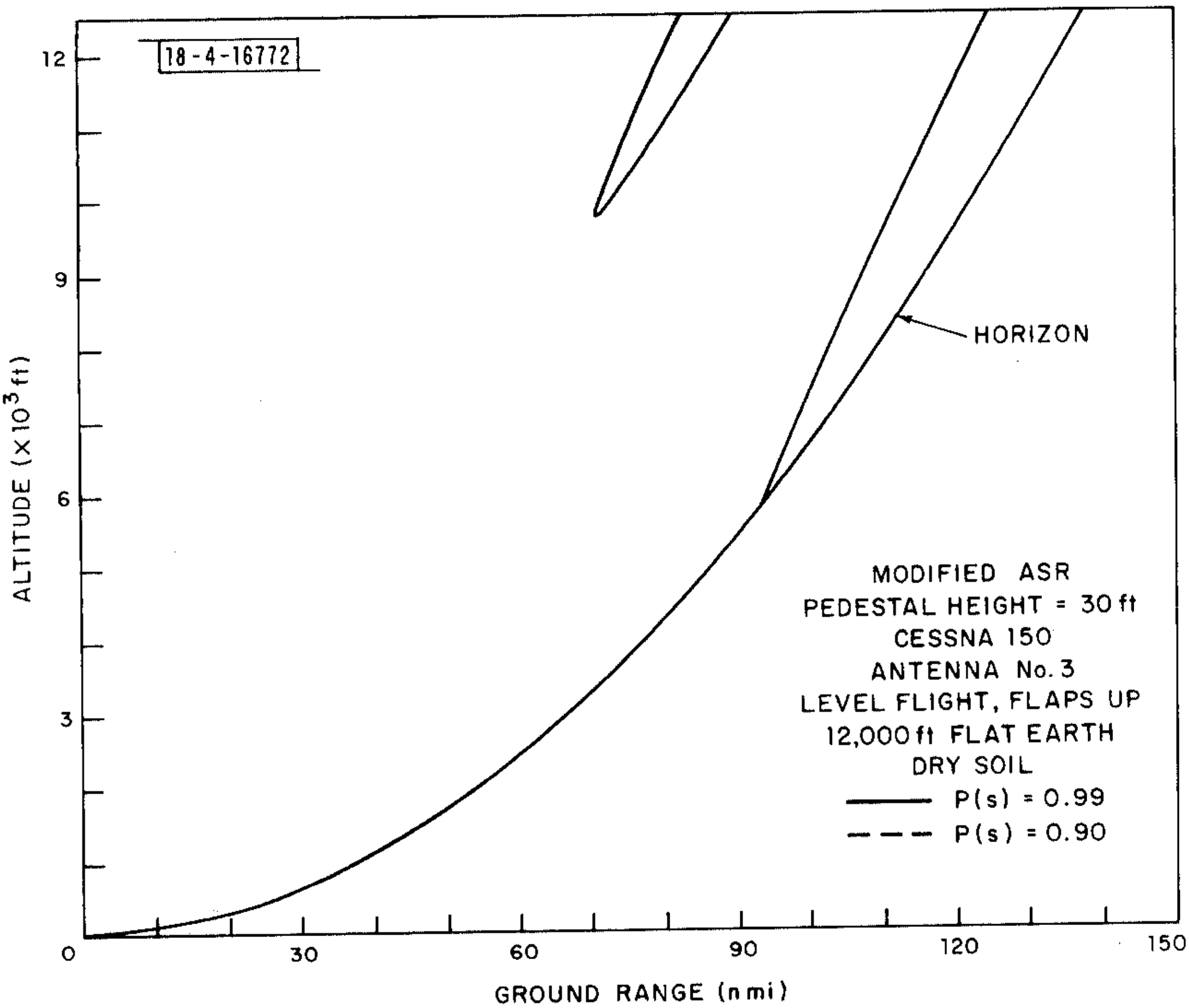

Fig. 14. Constant probability of success contours using a 30-ft pedestal.

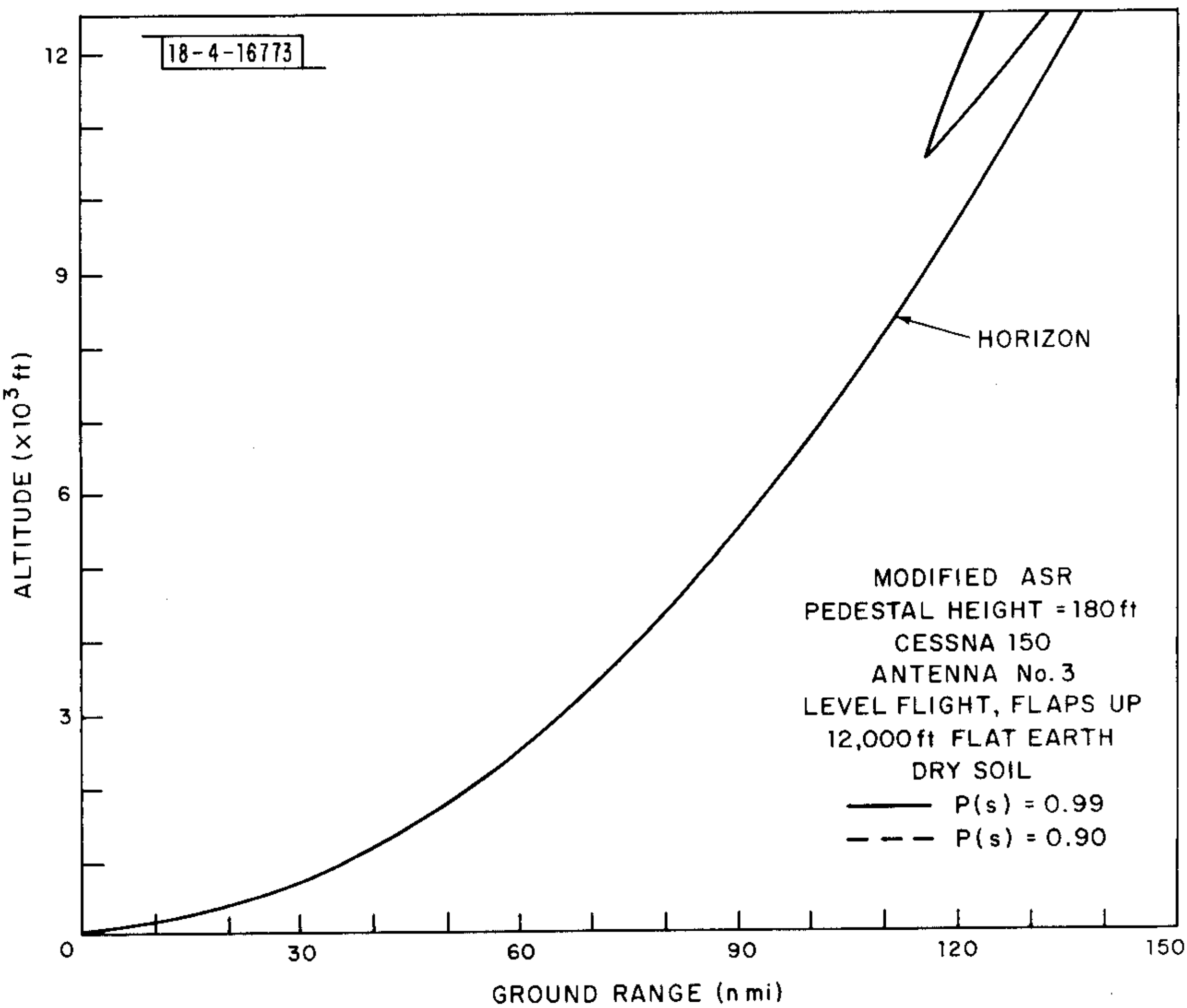

Fig. 15. Constant probability of success contours using a 180-ft pedestal.

such that the reduced performance region along the horizon extends deeper into the airspace while the other region does not extend as deep as in the standard pedestal case. The overall effect of this lower pedestal height is a greater range to the nearest point having less than 0.99 success probability.

For the higher pedestal the performance also improves. In this case most of the Fresnel zones are beyond the limit of the flat earth region over which specular reflections occur.

Although the region of good performance is enlarged in both of these alternative pedestal height cases, the use of either of these two pedestal heights does introduce other problems. The higher pedestal increases construction costs, while the lower pedestal results in the beam encountering more obstructions at low angles. The selection of pedestal height should properly be made on a site by site basis.

5.1.3 Surface Conditions

The standard set of parameters includes the assumption of dry, flat earth out to 12,000 feet. This is considered a reasonable choice for a terminal site, but there will be times and locations with different conditions. If, for example, there is a snow cover, the reflection coefficient of the ground is increased and the performance should degrade. At the critical low elevation angles, however, the calculated performance, as shown in Fig. 16, is changed very little because the effect of having a flat reflection surface out to only 12,000 feet around the sensor is the dominant feature.

For dry earth and for snow the reflection coefficients as a function of grazing angle were given by Fig. 10. Having a limited flat surface out to

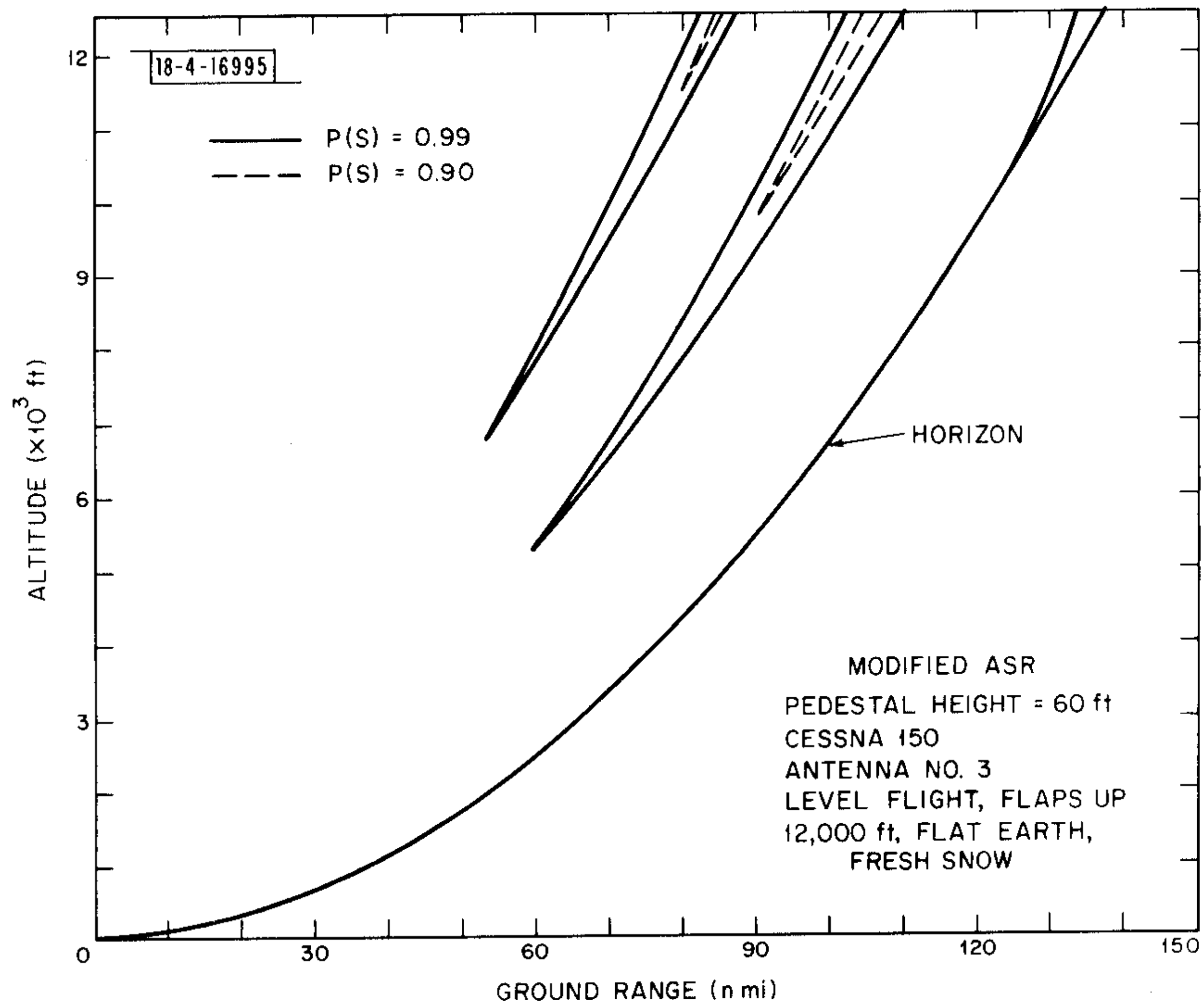

Fig. 16. Constant probability of success contours for a fresh snow reflecting surface.

12, 000 feet modifies the reflection coefficients by a multiplicative factor such as the one shown in Fig. 9 for a 60-foot pedestal height. This factor is only shown for the crucial low angle values, and as the elevation angle to the aircraft increases, the factor goes through small oscillations about unity. For low angles this factor tends to reduce the differences between the two surfaces. If the extent of flat earth were greater, one would expect a greater difference in performance at low angles as additional Fresnel zones were included in the flat region and the multiplicative factor became less dominant.

5.2 Reduced Power

The power budget used thus far was for the high power uplink and normal downlink modes. Normally DABS ground stations will transmit at a 10-dB lower power to reduce the interference at the aircraft antenna. The high power mode will be employed only if the low power attempt fails to elicit a reply. The performance for the low power mode is shown in Fig. 17 and, as expected, is significantly poorer at long ranges. In fact, there are even regions with less than 0.01 probability of success for a single scan. The small distance between the 0.90 and 0.01 curves at some locations shows how quickly the probability decreases and why one should not consider the regions of less than 0.90 probability on other figures as being "near" 0.90. While the results in this low power case may at first seem poor, there will be a significant number of aircraft successfully reached in this low power mode, and interference will be reduced.

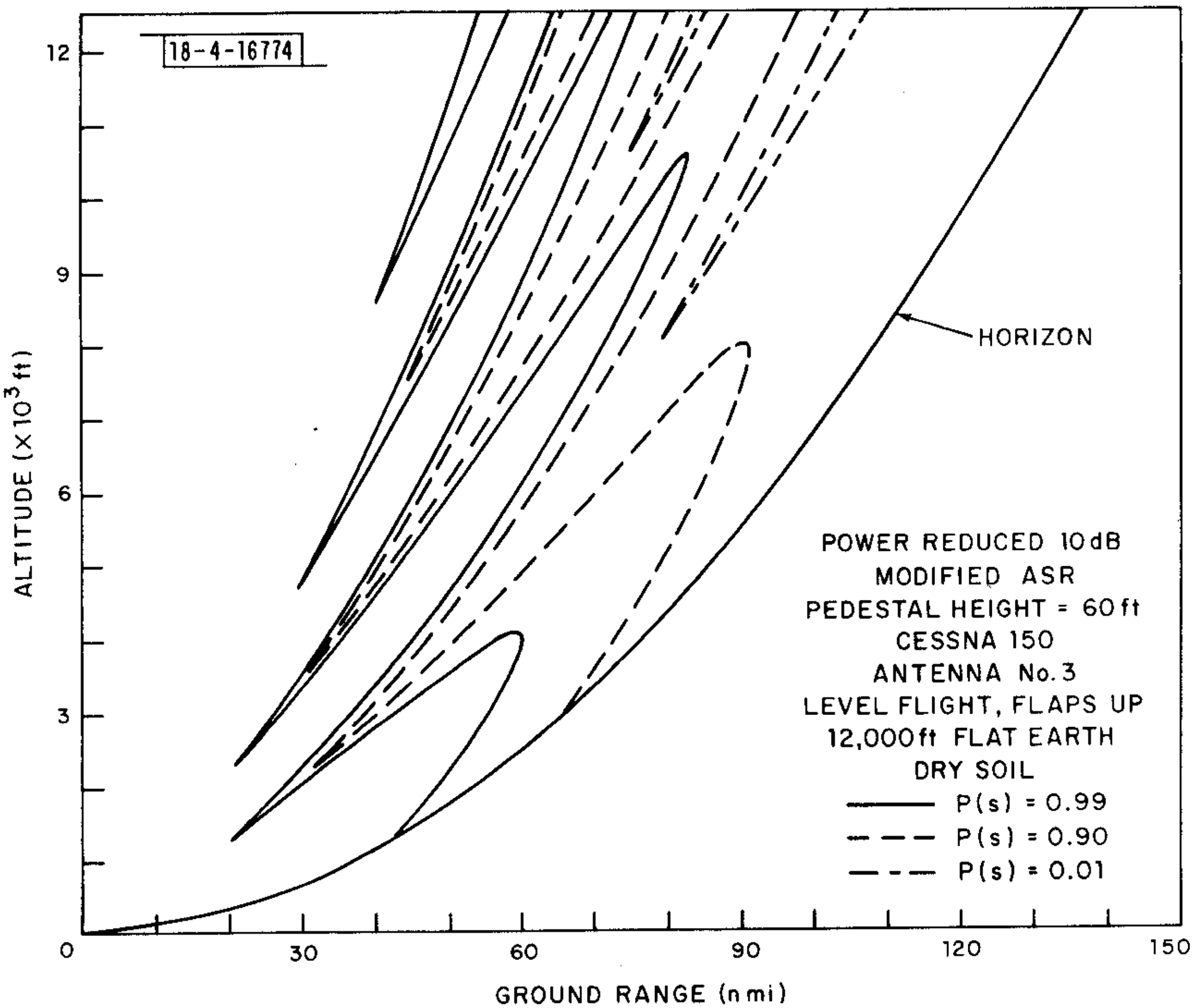

Fig. 17. Constant probability of success contours for 10-dB less power.

5.3 Aircraft Parameters

5.3.1 Type

The performance of the DABS link as affected by aircraft type is demonstrated by considering two other example aircraft. Whereas the Cessna 150 is a good example of popular high wing, general aviation aircraft, the Piper Cherokee Arrow is an example of a popular low wing, general aviation aircraft, and the Boeing 727 is a popular commercial airliner. Under level flight conditions the performance curves for these two additional aircraft are shown in Figs. 18 and 19. The Boeing 727 has a much higher flight ceiling, consequently the performance is presented for altitudes up to 40,000 feet and out to 200 nautical miles. In both cases the performance of the system is improved. This is due to the presence of landing gear on the Cessna 150 which cannot be retracted as it is for the other two aircraft. These effects are described more completely in Ref. 5.

5.3.2 Maneuvers

The other aircraft parameter that is examined in this report is the effect of aircraft maneuvers on performance. As an alternative to level flight, the example maneuver is a moderate roll that is defined as a bank between 16° and 30° in either direction. Figures 20, 21, and 22 show the performance of the Cessna 150, Piper Cherokee Arrow, and Boeing 727 for a moderate roll condition. In each case the performance degrades substantially, with the Piper aircraft having a point of less than 0.99 success probability as close as 9 nautical miles from the ground station and less than 0.90 at 30

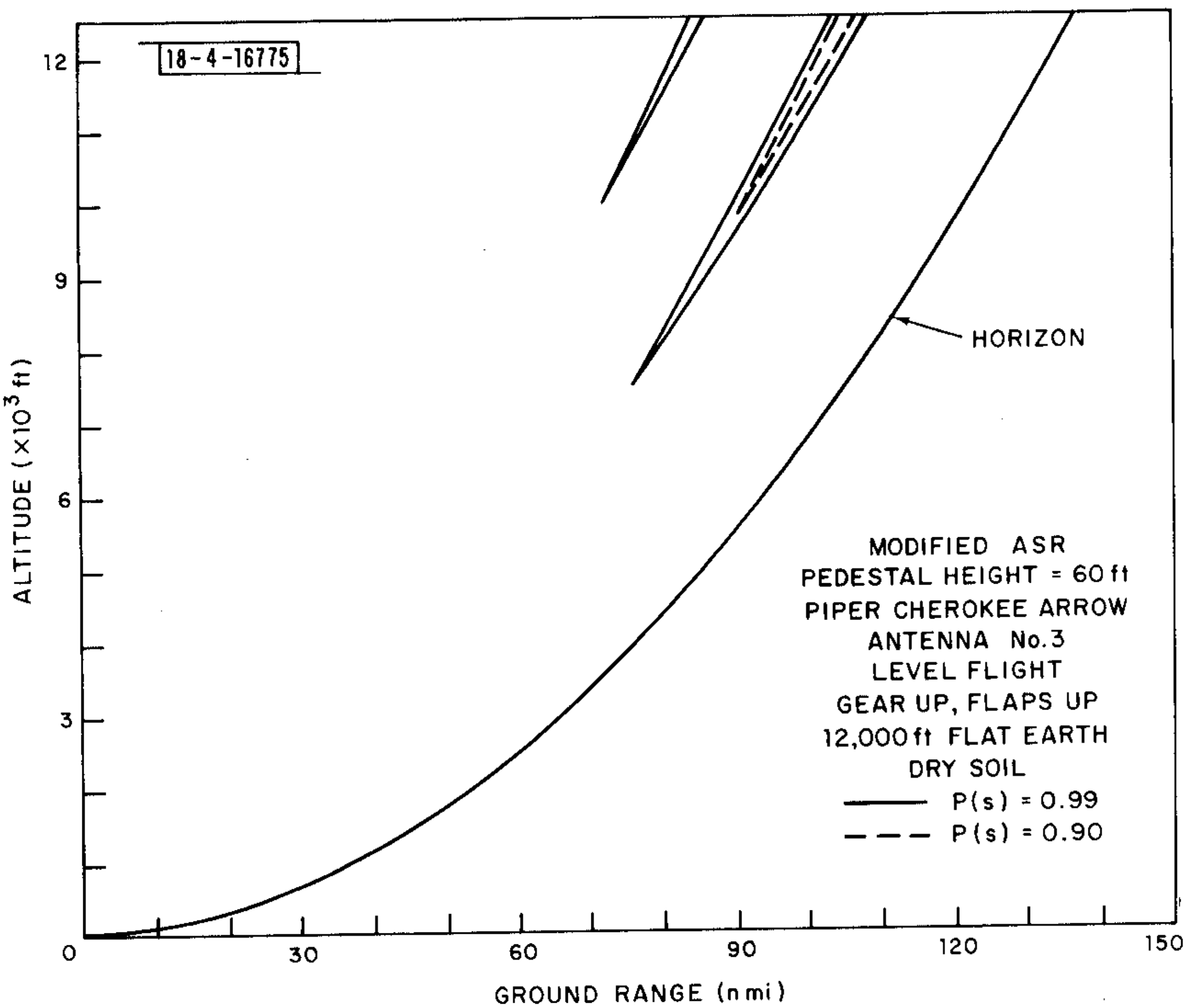

Fig. 18. Constant probability of success contours for a Piper Cherokee (level flight).

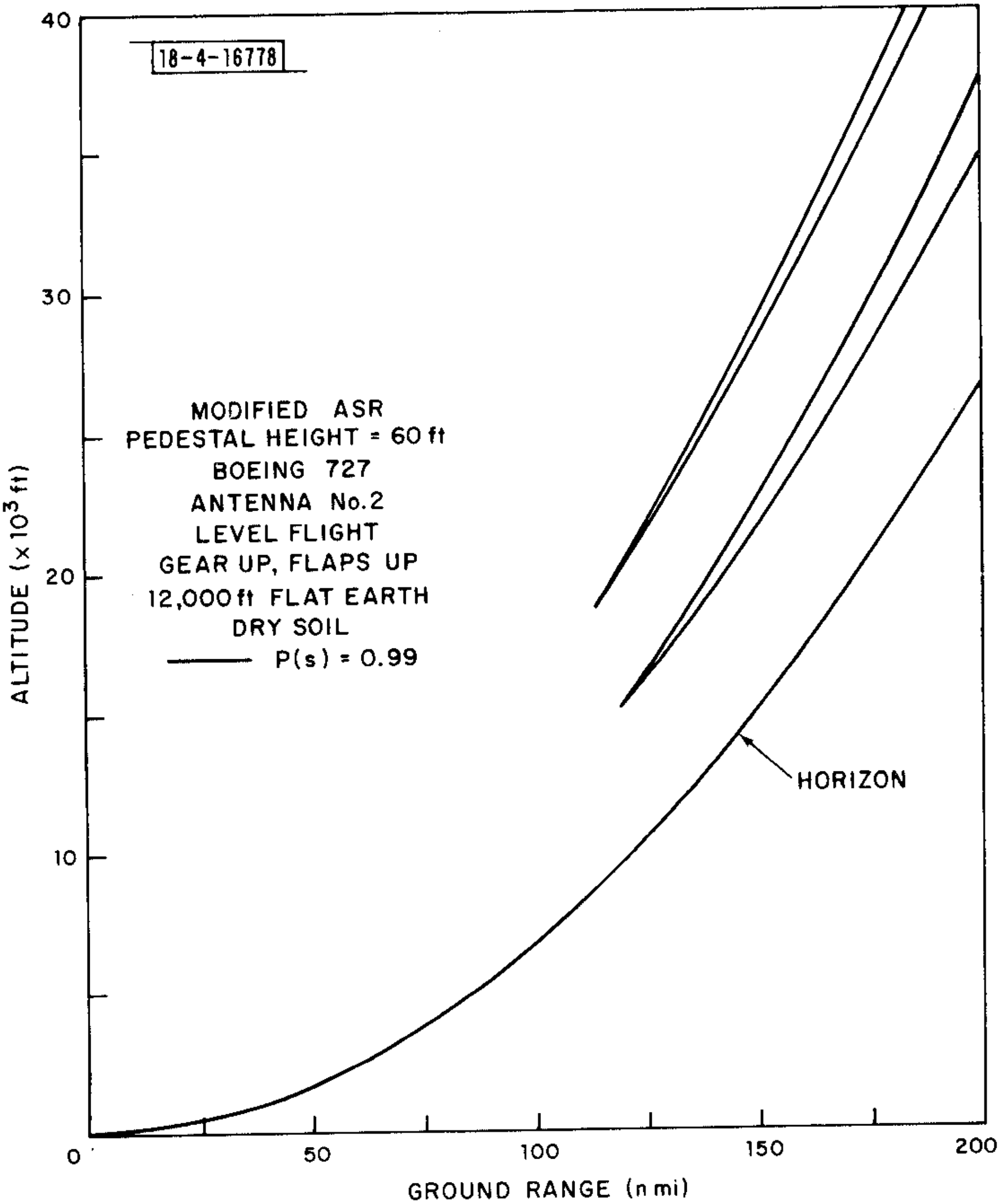

Fig. 19. Constant probability of success contours for a Boeing 727 (level flight).

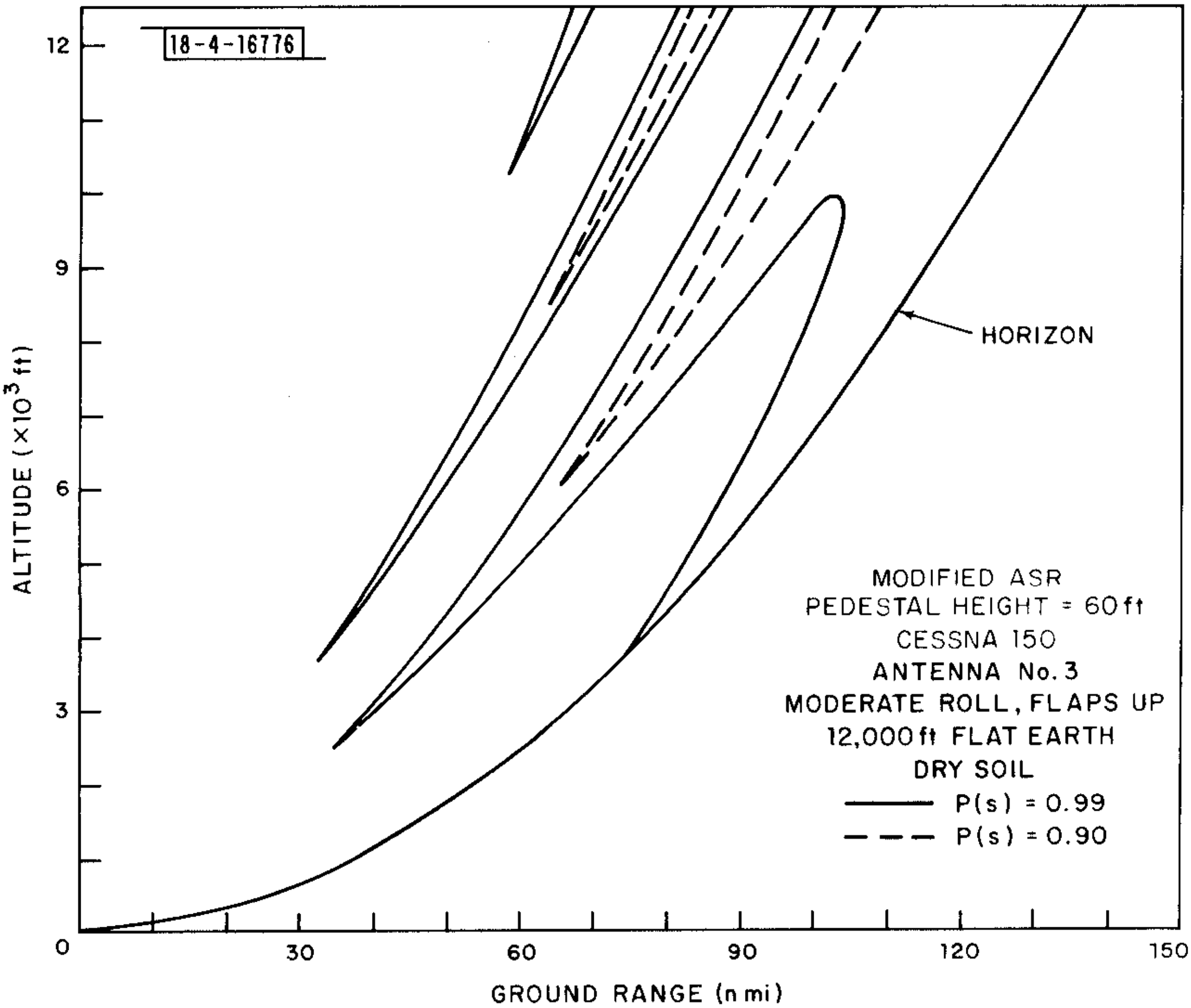

Fig. 20. Constant probability of success contours for a Cessna 150 in a moderate roll.

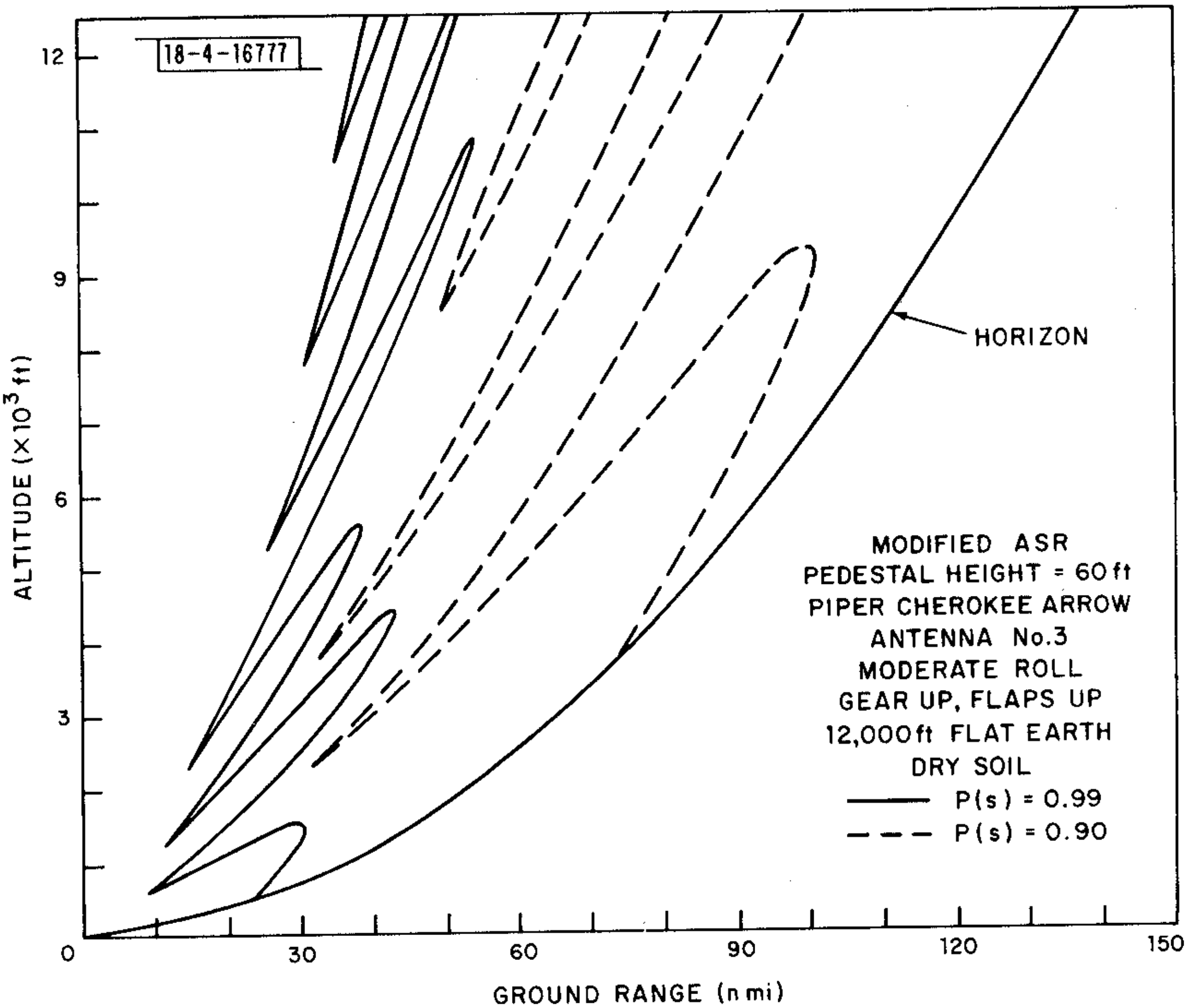

Fig. 21. Constant probability of success contours for a Piper Cherokee in a moderate roll.

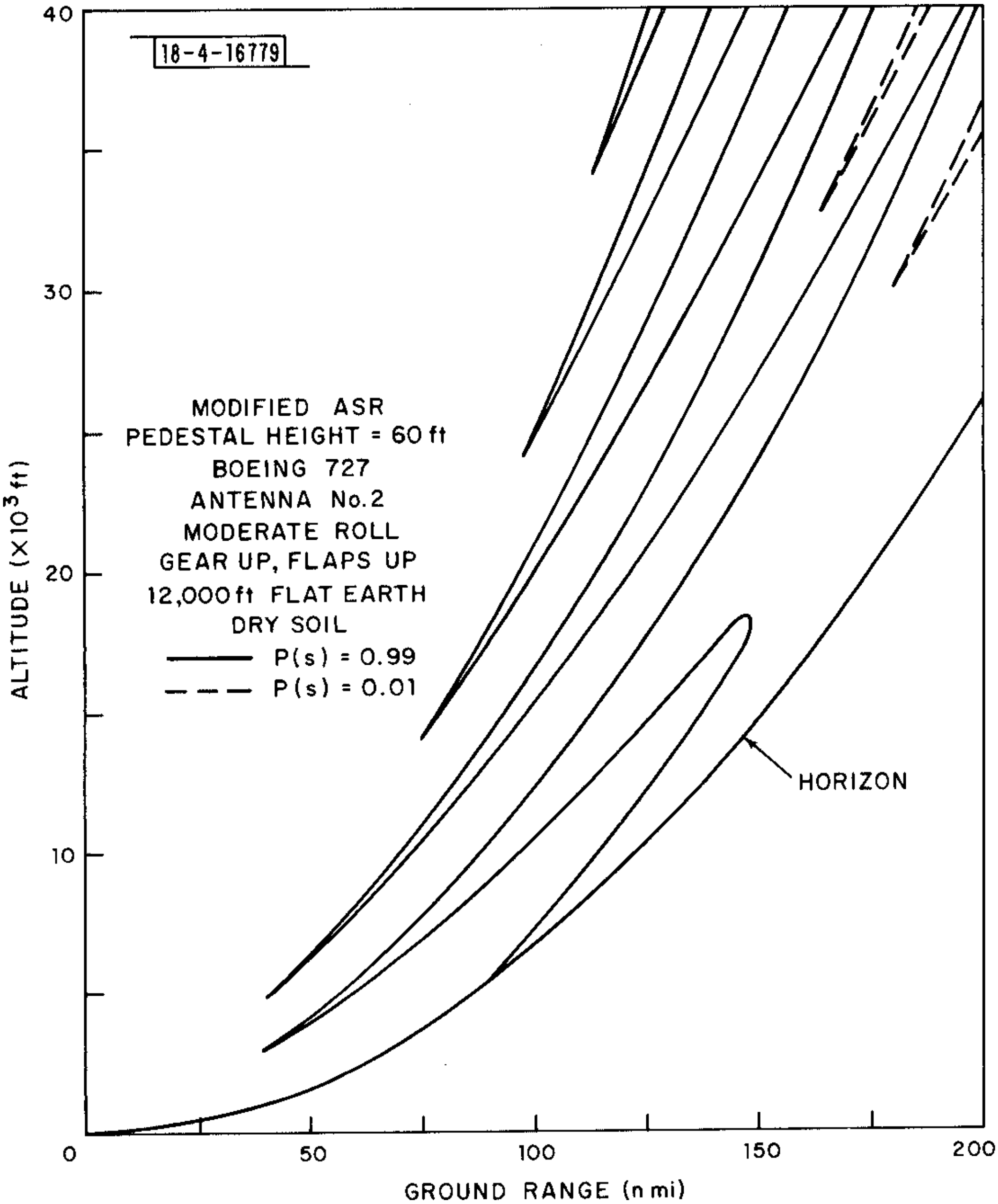

Fig. 22. Constant probability of success contours for a Boeing 727 in a moderate roll.

nautical miles. If one requires a 0.99 probability of success, this type of maneuver severely reduces the coverage domain of a ground station. The results are consistent with the antenna shielding effects described in Ref. 5 and other types of aircraft will show similar results.

While the performance for maneuvering aircraft looks bad initially when only a single scan is considered, scans occur every four seconds. A miss on one scan does not necessarily mean a miss will occur on the next scan. In other words, the aircraft orientation changes in a prescribed way for each maneuver, and the low gain regions of the aircraft antenna pattern may be uncorrelated over that orientation change. As an example of this phenomenon, Fig. 23 shows the constant probability curves for successful communication when two scans are permitted and the Piper aircraft is in a moderate roll. The 0.99 probability curve is now pushed out to be no nearer than 26 nautical miles from the ground station. This is almost a factor of 3 better than for the one-scan case. The use of multiple scans, however, may impact other DABS functions, but that is not within the scope of this report.

5.4 Other Effects

5.4.1 Obstructions

As mentioned earlier, the presence of natural or man-made obstructions will limit the minimum elevation angle at which a DABS ground station can observe aircraft, and this limit will vary with azimuth angle. Since the lower performance airspace regions are also at low angles, the obstruction limit may supersede the problems introduced by ground multipath. For the

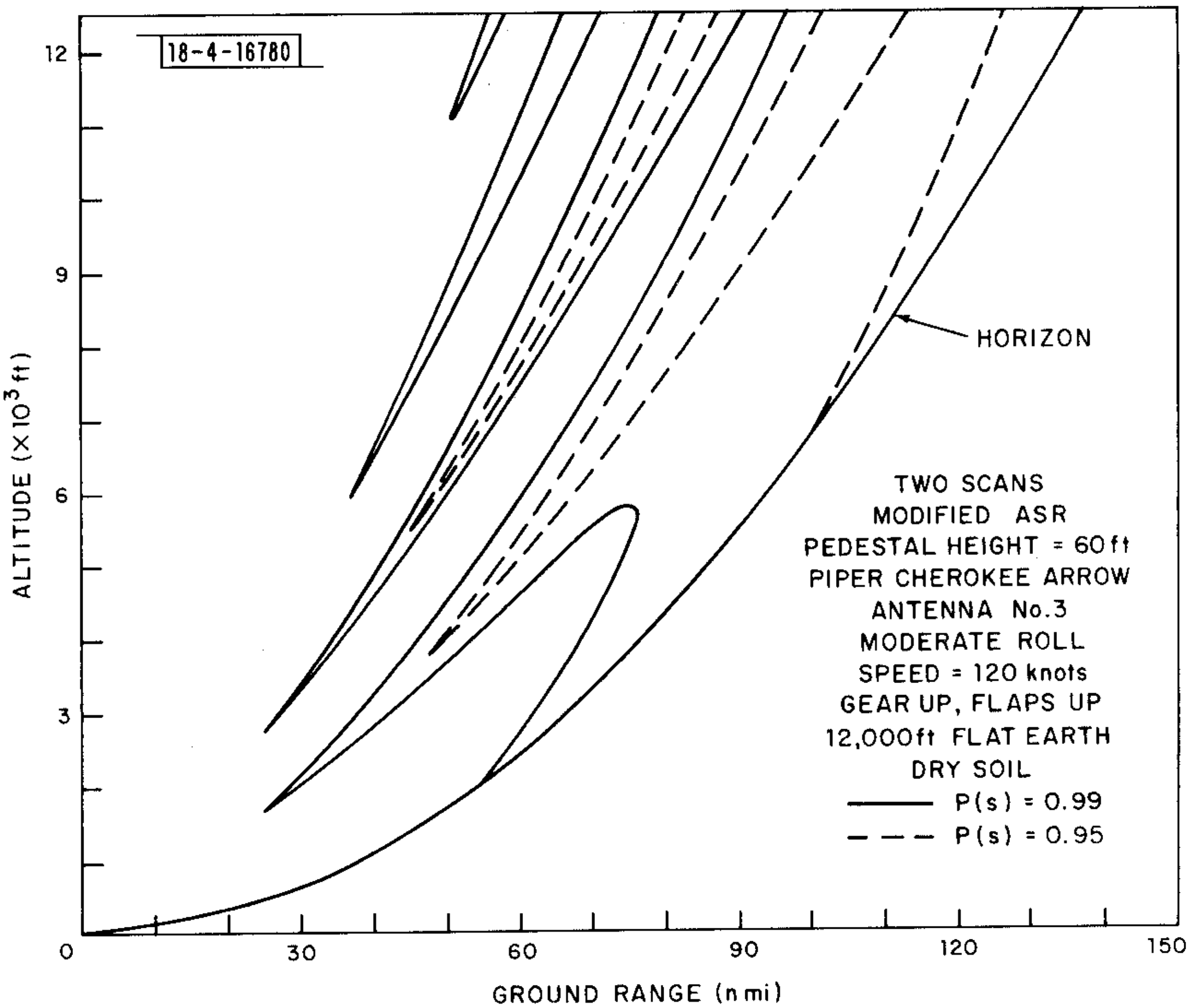

Fig. 23. Constant probability of success contours for a Piper Cherokee in a moderate roll (two scans).

example pedestal height of 60 feet, the points where destructive interference occurs are approximately 0.45 degree apart. Figure 24 shows curves of constant elevation overlaying the probability contours for the standard parameter values. If the presence of obstructions leads to a 1° minimum elevation angle capability, then multipath effects no longer reduce the performance below a 0.99 success probability level within the remaining airspace. Because the obstructions introduce diffraction effects, the performance at elevation angles below or slightly above the top of the obstruction is quite complicated. Reference 4 gives a more complete discussion of these effects.

Obstructions limit the minimum elevation angle when they are higher than the pedestal height of the ground station. Figure 25 shows the minimum elevation angle that occurs when an obstruction Δh feet higher than the antenna pedestal is situated at a distance d from the antenna. At a metropolitan terminal the airport structures and surrounding community buildings can easily produce minimum elevation greater than 0.25 degree. Careful siting can help minimize these effects and must be considered on a site by site basis. The obstruction effects, the extent of flat earth, and the cost and safety aspects of choosing a pedestal height all need consideration when selecting a site for the ground station.

5.4.2 Cone of Silence

High antenna gain is generally not available at either the ground station or the aircraft when the aircraft is at high elevation angles. As stated previously the exact shape of the proposed ground antenna patterns above 30° is

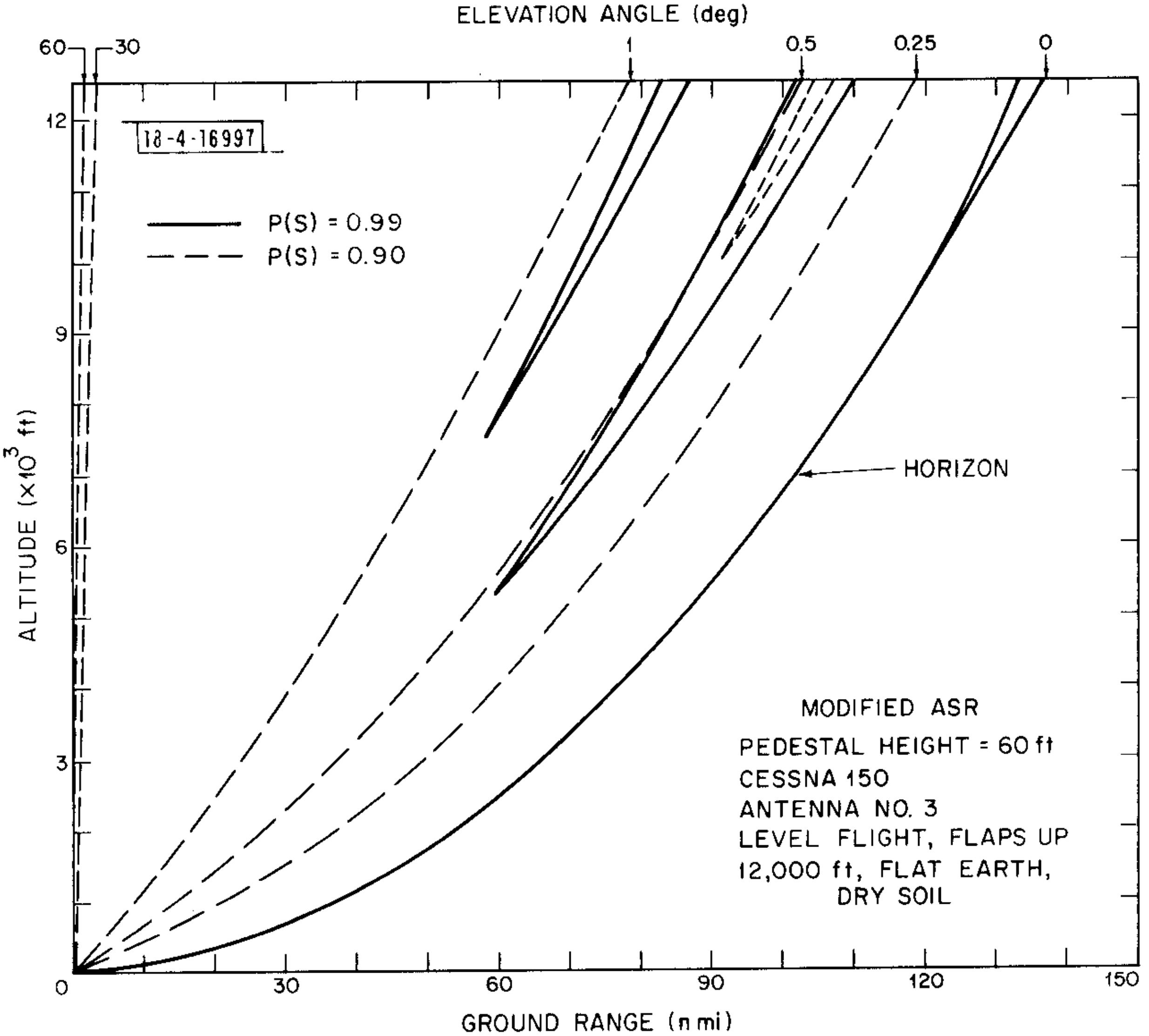

Fig. 24. Location of constant probability contours relative to elevation angle from the ground station (standard conditions).

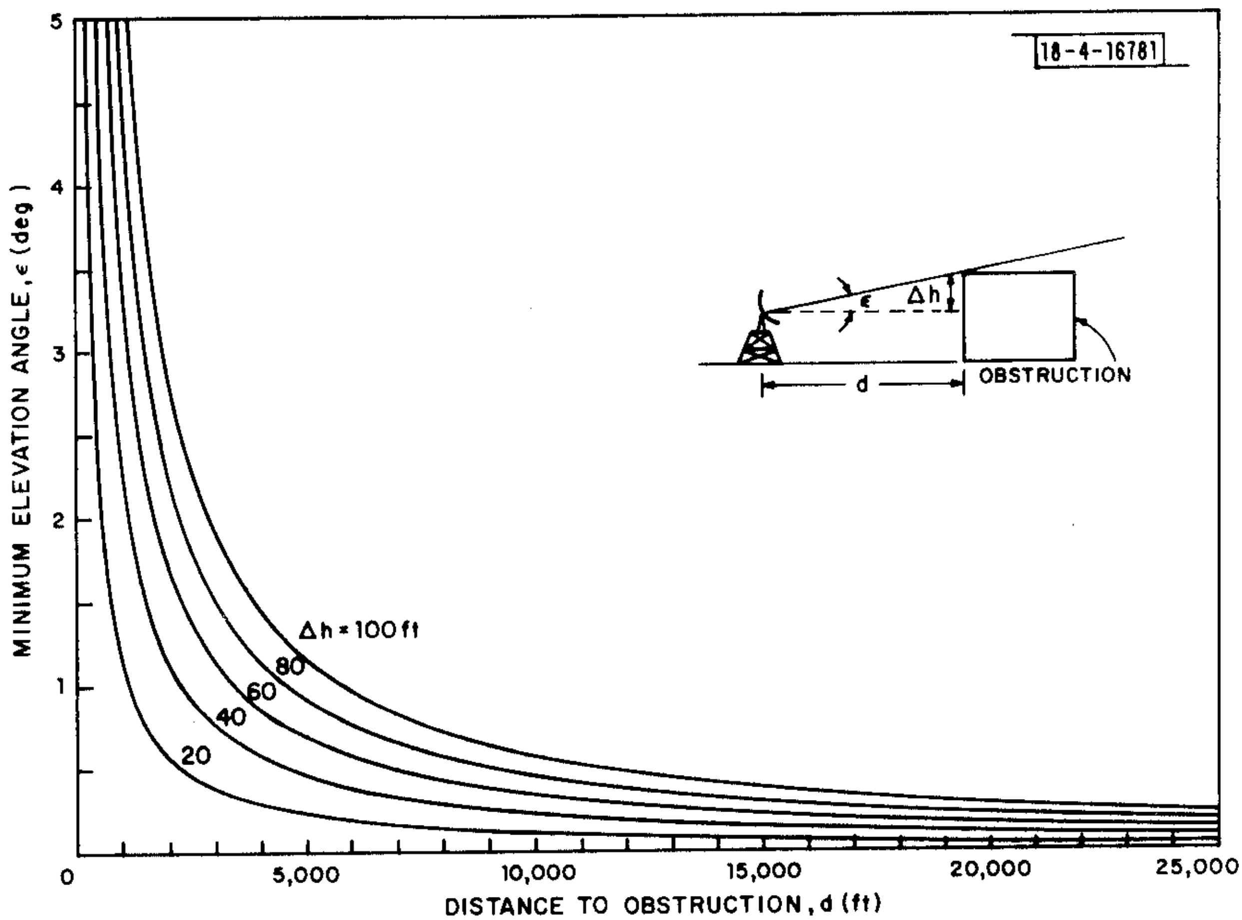

Fig. 25. Elevation angle limit due to obstructions around the ground station.

not well known, but the gain can often be given a lower bound that can be used in a simple performance calculation. Figure 24, used in the previous discussion, also shows an elevation angle of 60°. Up to 60° the modified ASR is not expected to have a gain less than +5 dBi. Aircraft antenna patterns for bottom mounted antennas are not shielded during maneuvers when viewed from the ground at such an elevation angle, and the antenna gain only drops to very low values for very nearly end-on views of the antenna. In examining aircraft antenna patterns, very few gains below -20 dBi are observed for the lower half of the antenna pattern. If the multipath effects are assumed negligible because of very low gains in the direction of the reflected signal, the signal to threshold can be calculated easily. For an aircraft six miles above the ground station and for the standard system parameters used in previous calculations, the signal to threshold level from Equations 1, 3, and 4 is:

$$S/T = P_t + \hat{G}_g + \hat{G}_a + C_\lambda - L - MUSL - 20\log_{10} R - F_1 - F_2 - F_3 - F_4 - F_5 - F_6$$

$$= P_t + (\hat{G}_g - F_1) + (\hat{G}_a - F_6) + C_\lambda - L - MUSL - 20\log_{10} R - F_2 - F_3 - F_4 - F_5$$

$$= 59 \text{ dBm} + (5 \text{ dBi}) + (-20 \text{ dBi}) + (-98 \text{ dB}) - 0 \text{ dB} - (-79 \text{ dBm}) - 20\log(6 \text{ nmi}) - (0.0093 \text{ dB/nmi})(6 \text{ nmi}) - 0 \text{ dB} - 1 \text{ dB} - 1 \text{ dB}$$

$$= +7 \text{ dB}$$

Thus, even at the very low antenna gains, which have been assumed in the traditional "cone-of-silence" region, there is still enough signal to communicate. It is important to bear in mind, however, that many ground antenna designs do not have the cosecant squared pattern shape at high elevation angles, and aircraft antenna gains of less than -20 dBi do occur when viewing the antenna nearly end-on. The portion of the pattern with less than -20 dBi is difficult to estimate accurately because the lobing structure is very complex at very high θ aspect angles, and the 2° measurement increments limited the detail that could be recorded from the aircraft models.

6.0 CONCLUSION

This report has attempted to give the reader an understanding of how various system parameters and operating conditions affect the overall performance of the DABS link. The quantitative results must, of course, be used cautiously since they strictly depend on the validity of the various models employed, and the models are only intended to approximate real conditions. There will be many actual cases when the DABS link performs much better than indicated in these results and some cases when it performs much worse, but it is the general conclusion of this report that the DABS link performs very well ($P(S) \geq 0.99$) over most airspace and for reasonable environmental and flight conditions. The system must cope with an occasional missed reply from aircraft at low angles or during certain maneuvers, but these misses should be sporadic or predictable and handled by the system in other ways.

Although this report examined only aircraft with a single bottom mounted antenna, for certain aircraft with unusually poor performance qualities during maneuvers, the use of dual antennas (one top mounted and one bottom mounted) should be considered. Also unusual terrain conditions may impair performance in only certain directions, and the use of additional ground stations may be necessary to obtain the desired performance level. In either situation the need for and benefits of each type of diversity should be examined on a case by case basis.

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