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MULTIPATH PROPAGATION STUDY FOR L-BAND, OVER-OCEAN, SATELLITE-AIRCRAFT COMMUNICATION LINK

JOSEPH H. DEAL

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ABSTRACT

This report presents the results of a study of multipath propagation between an aeronautical relay satellite in synchronous earth orbit and an aircraft flying over the ocean. An analytical model for the reflected power is developed and the results of a computer solution are compared with an approximate solution obtained through integration by the method of steepest descent. The computer solution is shown to differ considerably from the approximate solution. Both methods are compared with the limited experimental results available.

MULTIPATH PROPAGATION STUDY FOR L-BAND, OVER-OCEAN, SATELLITE-AIRCRAFT COMMUNICATION LINK

I. INTRODUCTION

Currently, there is a great deal of interest in the use of synchronous satellites for the relay of communications to aircraft operating over oceanic routes, such as, commercial transoceanic jet aircraft. Aeronautical L-band (1.54-1.66 GHz) is used because of low natural noise and low radio-frequency interference (RFI). A satellite relay system has the obvious advantage of greatly extended line-of-sight coverage; however, the elevation of the terminal antenna introduces multipath propagation due to reflections from the ocean's surface. The purpose of this report is to present the results of a study of L-band multipath propagation between an aeronautical relay satellite, in synchronous earth orbit, and an aircraft flying over the ocean. An analysis is performed for a CW-test signal for both vertical (v) and horizontal (h) polarizations.

The multipath power reflected from the ocean is a function of the path geometry, the antenna pattern, the polarization of the satellite and aircraft terminals, and the reflecting surface characteristics. For a very rough surface the entire surface area, within line-of-sight of the aircraft, contributes significantly to the reflected multipath power. The path geometrical relationships are shown in Figure 1. From the geometrical relationships, the specific communication link is characterized as follows:

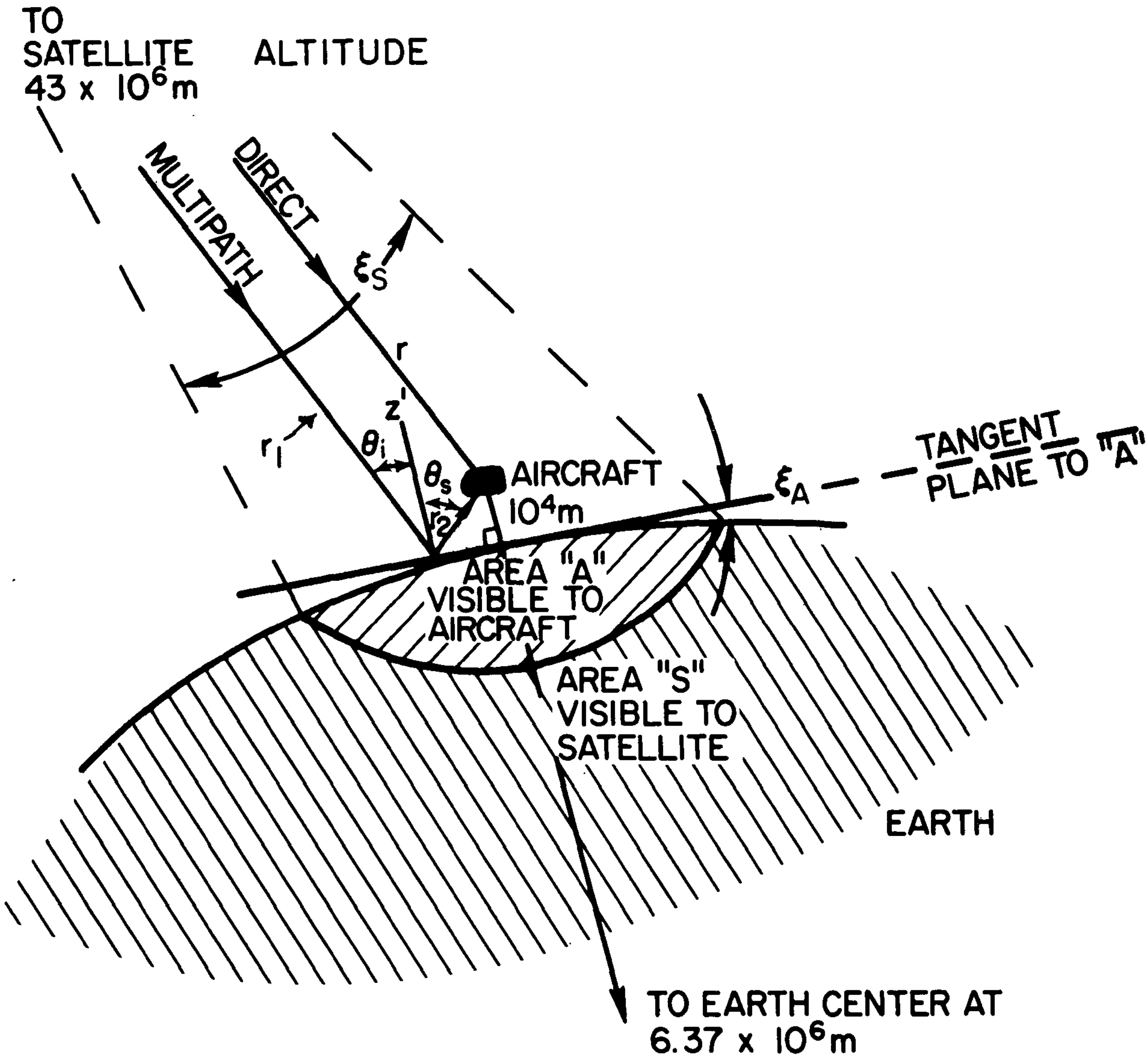


Figure 1. Satellite-to-Aircraft Path Geometry

(a) Radiation from the satellite can be considered a plane parallel wave within the region visible to the aircraft terminal (area A) and hence, the incidence angle θ_i is assumed constant over this region. This condition follows from the fact that the solid angle, ξ_s, is small, being less than one degree for the satellite and aircraft altitude shown in Figure 1.

(b) Direct-path range from aircraft-to-satellite, r, shown in Figure 1, can be considered approximately equal to the multipath range (indirect path) to the reflection point within the area, A.

(c) Ocean surface visible to aircraft may be modeled as a surface with the mean height describing a plane. This condition implies that the only effect introduced by the curvature of the earth's surface, within the region A, is a corresponding small variation in θ_i over area A. The maximum angular variation introduced by the spherical earth, upon angle ξ_A in Figure 1, is less than 3 degrees for aircraft altitudes less than 10 km. This variation is neglected in the multipath computations presented in this report.

(d) Area visible to the aircraft is also visible to the satellite. This is a primary condition for the satellite relay-aircraft, communication link.

The terminal antenna pattern and polarization characteristics also influence the amount and nature of the multipath interference. In this report, the satellite antenna is assumed to have a uniformly illuminated radiation pattern over the region of interest, and typical results are presented for a 90-degree, 3 dB beamwidth, low-gain, aircraft antenna. Horizontal and vertical polarizations are investigated.

The modeling of multipath reflections from the ocean reqiures a knowledge of surface roughness. Two surface areas separated in height by a distance, h, will reflect waves which differ in phase by an amount

$$\Delta_{phase} = \frac{4 \pi h \cos \theta_i}{\lambda} \tag{1}$$

where θ_i is the angle of incidence and λ, the wavelength of the incident radiation. The Rayleigh criterion[1] for surface roughness states that the surface is smooth if the phase difference between the reflected waves is less than 90 degrees. In terms of height variation, this criterion may be expressed as

$$h < \frac{\lambda}{8 \cos \theta_i} \tag{2}$$

For a surface with random height variations, as the ocean, we may use the same criterion and define "h" as the ocean wave rms height variation. It follows that a rough surface is defined as one where the rms surface height variation exceeds the Rayleigh criterion.

Table I presents the Beaufort sea state scale[2] and related wind speed, wave rms surface height variation and wave rms slope for an ocean surface. The wave rms slope has been related to the wind speed by Cox and Munk[3] through measurement. From a graph of their data the empirical relationship is

$$s^2 = 0.0055 W \tag{3}$$

where W is the wind speed in meters/sec and s^2 is the mean-square surface slope. The slope is related to the rms height of an ocean wave by the expression

$$s = \frac{2h}{\ell} \tag{4}$$

Table I

Oceanographic Data

Wind Speed Knots	Beaufort Sea State	RMS Wave Height h Meters	RMS Wave Slope s
1-3	1	.02	.07
4-6	2	.10	.12
7-10	3	.30	.16
11-16	4	.90	.27
17-21	5	2.00	.33
22-27	6	4.00	.38
28-33	7	7.00	.42
34-40	8	11.00	.45
41-47	9	17.00	.49
48-55	10	25.00	.53
56-63	11	35.00	.57

where ℓ is defined as the surface correlation length. Cox and Munk[4] also confirm through measurements that to a first approximation the large-scale ocean surface variations may be considered isotropic and random with a Gaussian distribution.

Figure 2 is a graph of the roughness criterion (Equation 2) versus the angle of incidence θ_i; all of the sea states, with the exception of sea state 1, the calmest, fall into the rough-surface region for incidence angles less than 75 degrees. The nominal rms sea height, i. e., $h \simeq 1.5$ meters, is well within the rough-surface region for the entire range of incidence angles, except near grazing angle incidence.

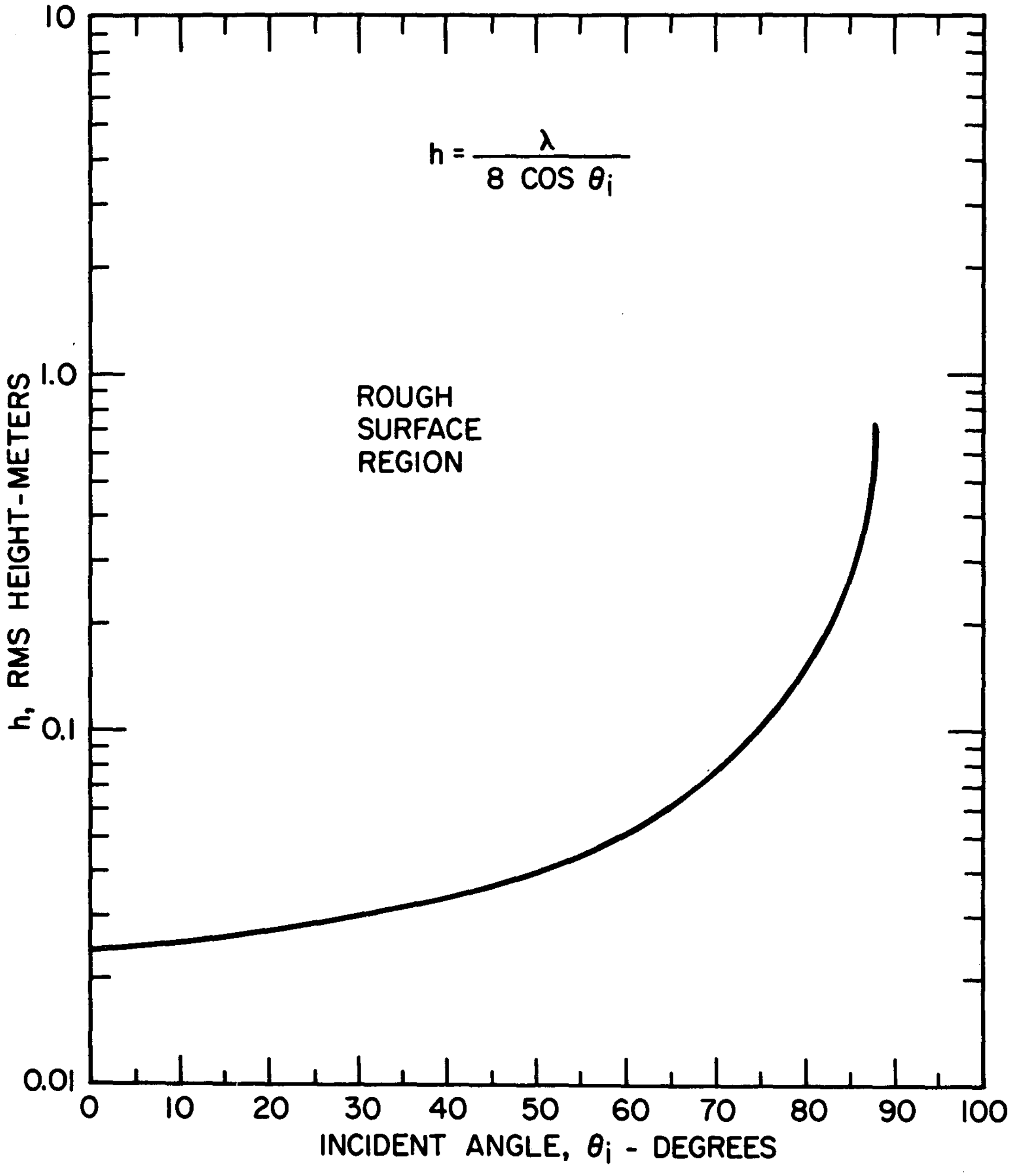


Figure 2. Rayleigh Roughness Criterion for $\lambda = 0.2$ meters (1.5 GHz)

For a smooth surface, the reflected power comes from within the first Fresnel zone,[5] concentrated within a single area on the surface near the specular point. When only this single area contributes to the reflected power, the multipath reflection is coherent. As the surface becomes rough, however, significant reflections also come from areas outside the first Fresnel zone, and the entire surface within line-of-sight of the aircraft receiving antenna becomes a potential source of multipath interference. In this case, a large number of independent areas of the surface contribute to the reflected multipath signal and the reflected power can be assumed incoherent. For a CW source illuminating the surface, the resulting multipath envelope has a Rayleigh distribution.[6] Smooth-surface reflection of a coherent nature is called specular reflection in the literature, and incoherent rough-surface reflections are called diffuse. The possibility also exists for the simultaneous occurrence of both specular and diffuse multipath magnitudes which are approximately equal. In this case, with a CW illuminating source, the multipath will have a Rician distribution.[7]

Several investigators have made measurements of multipath propagation for over-the-ocean satellite-aircraft communication links.[8,9] In these measurements the nature of the multipath reflection is determined from the distribution of the multipath signal envelope. It follows from the previous discussion that for diffuse reflection the envelope is Rayleigh distributed. Jordon[10] has observed this in experiments at 230 MHz. Tests conducted for the Federal Aviation Administration[11] also indicate that the sea-reflected signal is predominantly diffuse for a satellite-aircraft, L-band link. This is not conclusive proof that L-band sea reflections will always be diffuse; to the contrary, as previously pointed out, the exact nature of the multipath reflection will depend to a great extent upon sea state and angle of incidence. It is, however, assumed that, except for unusual circumstances, the over-ocean, L-band multipath is predominately diffuse, and we therefore limit the analysis in this study to the diffuse multipath case.

This work differs from earlier studies in this area by Durrani and Staras[12] and Staras[13] in a number of ways. As noted previously, diffuse reflections will dominate for a rough surface L-band link. In the range of rough surfaces considered in this study, the approximate solutions employed in the references cited above are not applicable and one must resort to a computer solution. In the presentation of results of this study, it is shown how the computer solution differs from the referenced studies, and also how the computer solution compares with the limited experimental results available.

No attempt has been made in this study to assess the effect of the multipath on the quality of communication. The degradation due to multipath is greatly dependent on the particular modulation method used to convey the link information, and is considered outside the scope of this study.

II. DIFFUSE MULTIPATH

The reflection of electromagnetic radiation from a surface satisfying the roughness criterion, $h > \lambda/(8 \cos \theta_i)$, has been investigated by many authors using several techniques. In general, the tangent plane, or physical optics approach, is the applicable technique for solution; however, Kodis[14] has shown that the correct results may also be obtained for a rough surface using geometric optics. Isokovich[15] was perhaps one of the first to formulate rough-surface scattering using the Kirchoff-Helmholtz theory.[16] This theory has also been extended by Semenov,[17] Davies[18], and Beckmann and Spizzichino.[19] The formulation of rough-surface reflection has also proceeded from the exact Chu-Stratton integral equation.[20] Practitioners of this technique include: Semenov,[21] Hagfors,[22] Kodis,[23] Stogrys[24] and most recently by Sancer.[25] In addition, a third heuristic approach has been taken by Muhleman[26] which leads to the same result. In fact, all of the various approaches and formulations cited can and do agree in the high-frequency limit.

The analytical result for rough-surface scattering can be expressed in terms of the scattering coefficient. Following the definition of Peake,[27] the differential scattering coefficient per unit area is defined as

$$\sigma = \lim_{S \to \infty} \left\{ \lim_{r_2 \to \infty} \frac{4 \pi r_2^2 \, |E_s|^2}{S \, |E_0|^2} \right\} \tag{5}$$

where $|E_0|^2$ is proportional to the incidence power, and $|E_s|^2$ the scattered power. The quantities S, the surface area, and r_2, the range, are shown in Figure 3. In the analysis that follows we assume that the radiation from the satellite is a plane wave so that θ_i, the angle of incidence, is constant over the

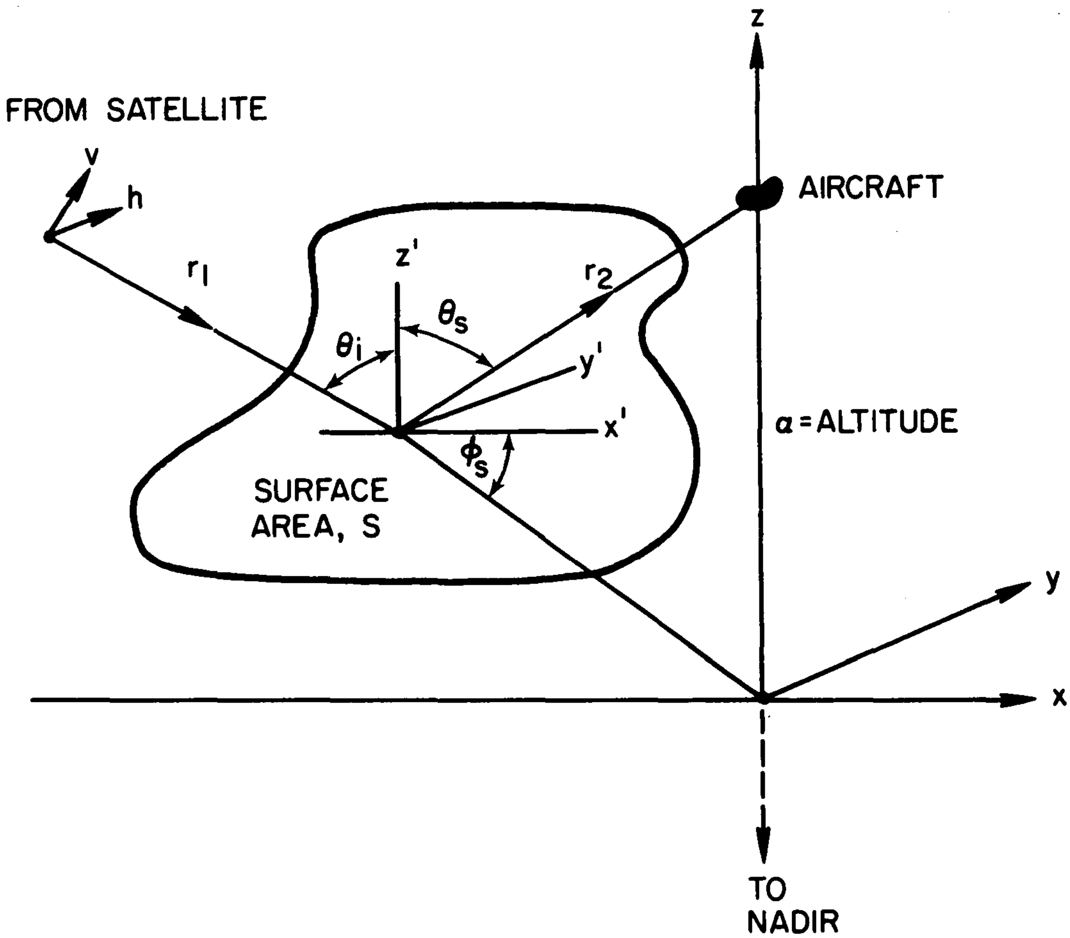


Figure 3. Rough-Surface Scattering Geometry

scattering area. Also, the coordinate system is oriented so that radiation from the satellite is in the positive-x direction. This simplification of the problem is possible if we assume that the rough surface is isotropic. We further define the vertical (v) and horizontal (h) polarization directions as shown in Figure 3 with "v" in the x-z plane and "h" in the "y" direction.

Using the above definitions and qualifications, the relative, reflected multipath power can be expressed by a surface integral over the reflecting surface as

$$\left.\frac{P_R}{P_D}\right|_{a,b} = \frac{1}{4\pi} \int_S \left[\frac{r}{r_1 r_2}\right]^2 G(S)\, \sigma(S)\, |R_{ab}(S)|^2\, dS. \tag{6}$$

The subscripts a, b refer to the polarization of the incident and reflected radiation, respectively, (a and b can be v or h), and $P_R/P_D|_{a,b}$ is the ratio of the power reflected from the ocean surface to the aircraft, P_R, with polarization direction "b", to the direct-path power to the aircraft, P_R, with polarization direction "a". The quantities r_1, r_2 and r, defined previously, are shown in Figure 1. In eq. (6), G represents the aircraft antenna pattern gain function, where G = 1 for an omnidirectional (isotropic) antenna. The quanitiy, R_{ab}, is the reflection coefficient for a tangent plane at the point of reflection and the integration is over the entire surface area within line-of-sight of the aircraft.

Expressions for the reflection coefficient R_{ab}, have been derived by Mitzner[28] for a dielectric surface. These expressions may be written as:

$$R_{hh} = -\frac{a_1 R_v + a_2 a_3 R_H}{a_4},$$

$$R_{vh} = \sin\phi_s \frac{a_2 \sin\theta_s R_V - a_3 \sin\theta_i R_H}{a_4},$$

$$R_{hv} = \sin\phi_s \frac{a_2 \sin\theta_s R_H - a_3 \sin\theta_i R_V}{a_4},$$

and

$$R_{vv} = \frac{a_1 R_H + a_2 a_3 R_V}{a_4} \tag{7}$$

where

$$a_1 = \sin\theta_i \sin\theta_s \sin^2\phi_s,$$

$$a_2 = \cos\theta_i \sin\theta_s + \sin\theta_i \cos\theta_s \cos\phi_s,$$

$$a_3 = \sin\theta_i \cos\theta_s + \cos\theta_i \sin\theta_s \cos\phi_s,$$

and

$$a_4 = 4 \sin^2 i \cos^2 i. \tag{8}$$

The quantities R_V and R_H are the Fresnel reflection coefficients for the local surface.

In the analysis and calculations that follow, the ocean surface will be assumed electrically homogeneous with a relative dielectric constant $\epsilon_r = 80$ and a conductivity of $\sigma_c = 4$ mhos/meter. The Fresnel reflection coefficients are given by Kerr[29] as

$$R_V = \frac{\epsilon_{rc} \cos i - \sqrt{\epsilon_{rc} - \sin^2 i}}{\epsilon_{rc} \cos i + \sqrt{\epsilon_{rc} - \sin^2 i}}$$

and

$$R_H = \frac{\cos i - \sqrt{\epsilon_{rc} - \sin^2 i}}{\cos i + \sqrt{\epsilon_{rc} - \sin^2 i}} \quad (9)$$

where ϵ_{rc} is the complex dielectric constant, and for an ocean surface, ϵ_{rc} = 80-j48 at L-band ($\lambda = 0.2$m). In these equations "i" is the local angle of incidence at the reflecting point. It is easily shown (Figure 4) that

$$\cos i = [1/2\,(1 - \sin\theta_i \, \sin\theta_s \, \cos\phi_s + \cos\theta_i \, \cos\theta_s)]^{1/2} \quad (10)$$

The scattering coefficient, σ, depends, in general, upon the statistics of the surface; it has been shown by Kodis[30] to be given as

$$\sigma = \pi \, \overline{n} \, (\overline{r_1 \, r_2}) \quad (11)$$

where we can interpret the quantities in eq. (11) in the geometric optics sense. The quantity $\overline{n}$ is the average number of specular points per unit area. This quantity is the average number of tangent planes on the surface that are positioned favorably so that the local angle of incidence and the local angle of reflection are equal, and the reflected ray is directed toward the aircraft. The second quantity on the right side of eq. (11) is the average of the product of the principal radii of curvature at the reflection point. As pointed out by Barrick,[31] eq. (11) could be arrived at from geometrical considerations directly since the scattering cross-section of a single point is π time the principal radii of curvature at that point.

In order to evaluate the expression for the scattering cross-section we must make assumptions concerning the statistical nature of the surface. Since

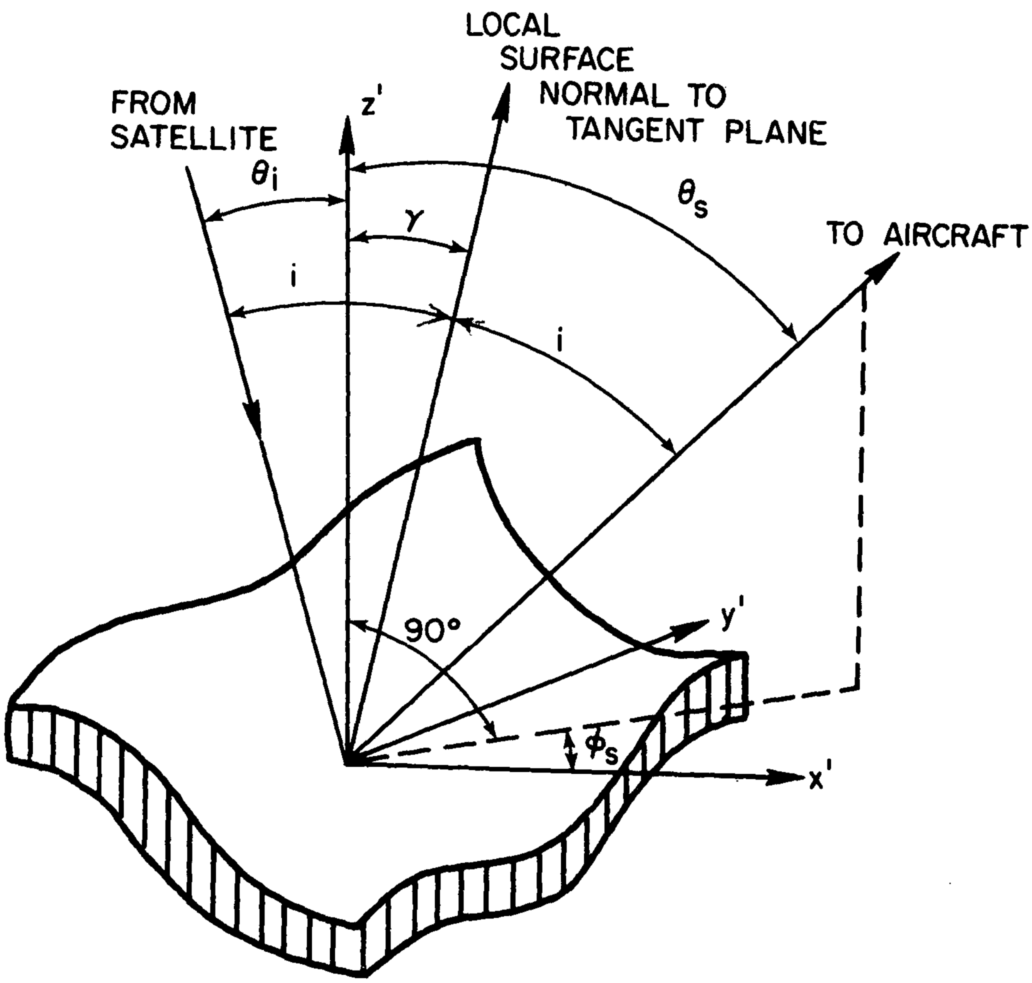


Figure 4. Rough-Surface Tangent Plane: Description of Angles

we are concerned with modeling the ocean surface, we assume that the height variation of the surface is isotropic and Gaussian distributed with zero mean. The probability density function for such a surface is given as

$$f(z) = \frac{1}{\sqrt{2\pi h^2}} \exp\{-z^2/2h^2\} \tag{12}$$

where h is the rms surface height variation. We must also make assumptions concerning the nature of the lateral variation of the rough surface. In this respect we assume, as is common practice in dealing with the ocean, that the surface is described by an autocorrelation function of the form

$$C(r) = e^{-d^2/\ell^2} \tag{13}$$

where d is the distance along the surface mean plane and ℓ is the correlation distance.

Based on the statistical relationships described above, the scattering coefficient of the rough surface has been shown by Barrick[32] to be

$$\sigma = \frac{\sec^4\gamma}{s^2} \exp\left\{\frac{-\tan^2\gamma}{s^2}\right\} \tag{14}$$

where s, defined previously, is the rms slope of the surface and γ, the angle between the z-axis and the local tangent-plane normal as shown in Figure 4. This angle is expressed in terms of the angles shown in Figures 3 and 4 as

$$\tan\gamma = \frac{(\sin^2\theta_i - 2\sin\theta_i \sin\theta_s \cos\phi_s + \sin^2\theta_s)^{1/2}}{\cos\theta_i \cos\theta_s} \tag{15}$$

Figure 5 is a plot of the scattering coefficient (eq. 14), in dB, versus γ, which shows that as the rms wave slope, s increases a larger range of tangent-plane-tilt angles contribute significantly to the scattered power. This may be interpreted as meaning that as the surface becomes rougher, a larger area of the illuminated surface contributes significantly to the total reflected multipath power directed toward the aircraft.

The analytical solution for the reflected, diffuse, multipath power, as presented from the geometric optics point-of-view, is generally valid at radio frequencies if at least one of the following conditions is satisfied (Strogryn [33]):

(a) Radius-of-curvature is everywhere on the surface much greater than a wavelength. This implies that diffraction effects are negligible.

(b) Surface is very rough, i. e. $h > \lambda/8 \cos \theta_i$.

The next section presents the results of a computer solution to the rough-surface multipath problem.

III. COMPUTER SOLUTION

A computer program was written to determine the diffuse-multipath power reflected from the ocean surface, relative to the direct-path signal for an L-band, satellite-aircraft, communication link. The program performs a numerical integration of the surface integral defined by eq. (6). The terms appearing in eq. (6) were defined earlier. The remainder of this section describes the computer solution and the results.

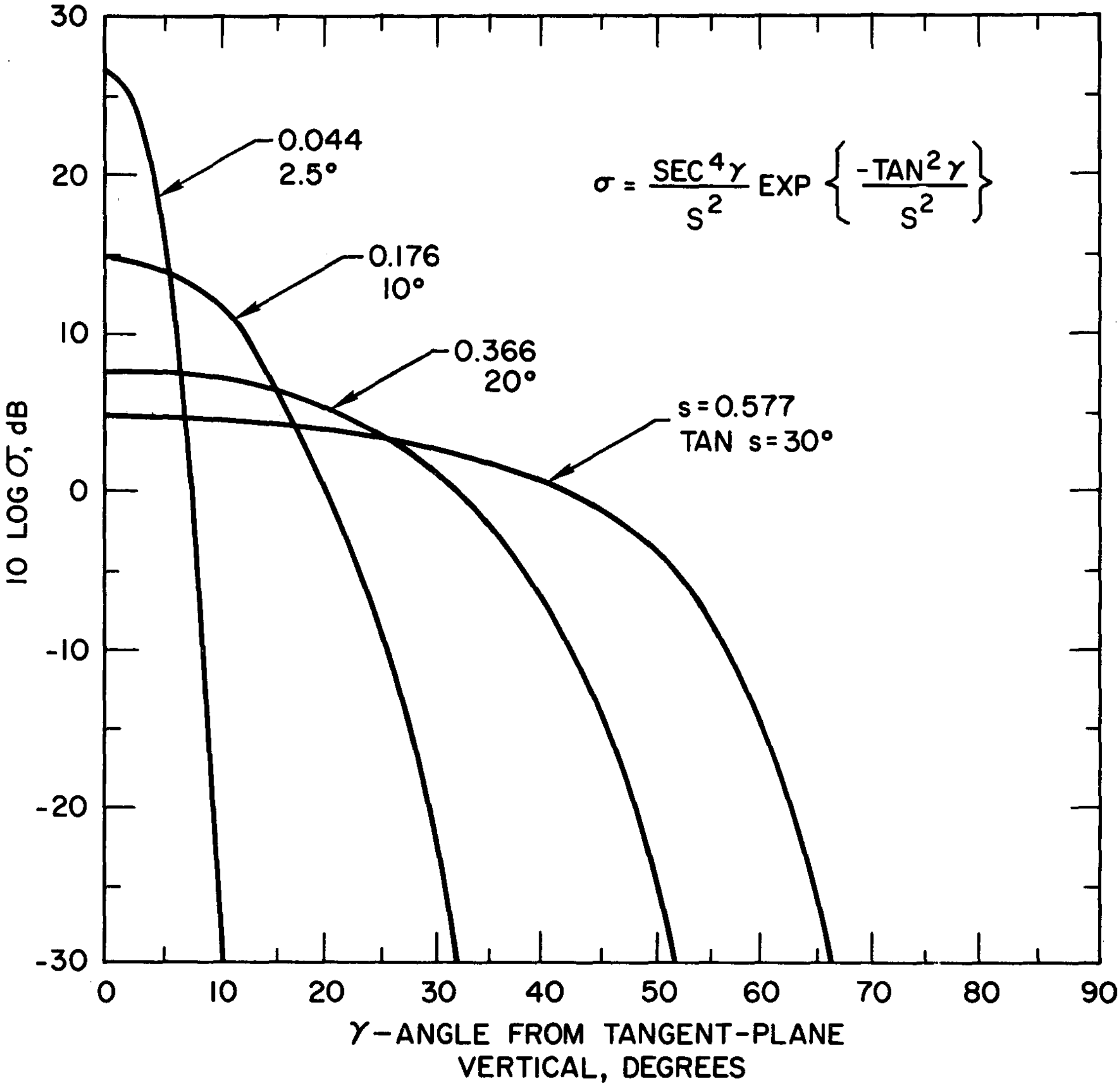


Figure 5. Scattering Coefficient, σ, Versus Tangent Angle, γ

Restating eq. (6) as

$$\frac{P_R}{P_D}\bigg|_{a,b} = \frac{1}{4\pi}\int_{\alpha=0}^{<90^\circ}\int_{\beta=0}^{2\pi}\frac{1}{r_2^2(\alpha,\beta)}\, G(\alpha,\beta)\,|R_{ab}(\alpha,\beta)|^2\,\sigma(\alpha,\beta)\,d\beta\, d\alpha. \quad (16)$$

$G(\alpha, \beta)$ = antenna gain function

$R_{ab}(\alpha, \beta)$ = reflection coefficient, as defined by eq. (7),

$\sigma(\alpha, \beta)$ = scattering coefficient function, eq. (14) based on the link geometrical approximation: $[r/r_1\ r_2]^2 \simeq 1/r_2^2$.

The diffuse-multipath power reflected from the rough-ocean surface was determined from the computer solution by summing together the contributions from segments of annular rings, as shown in Figure 6, from eq. (16). The aircraft "look" angles α and β describe the incremental areas, and the summation is performed for equal increments of α and β for the entire surface out to the aircraft's local horizon. The scattering coefficient, σ, described in the previous section, is a sensitive function of α and β and dominates in determining the contribution from a particular incremental area. To account for the aircraft antenna pattern, the contributions from different segments, determined by α and β, are weighted according to the antenna gain, G, in that direction.

Another phenomena which influences the reflection of electromagnetic radiation from a rough surface is shadowing. The peaks of a rough surface

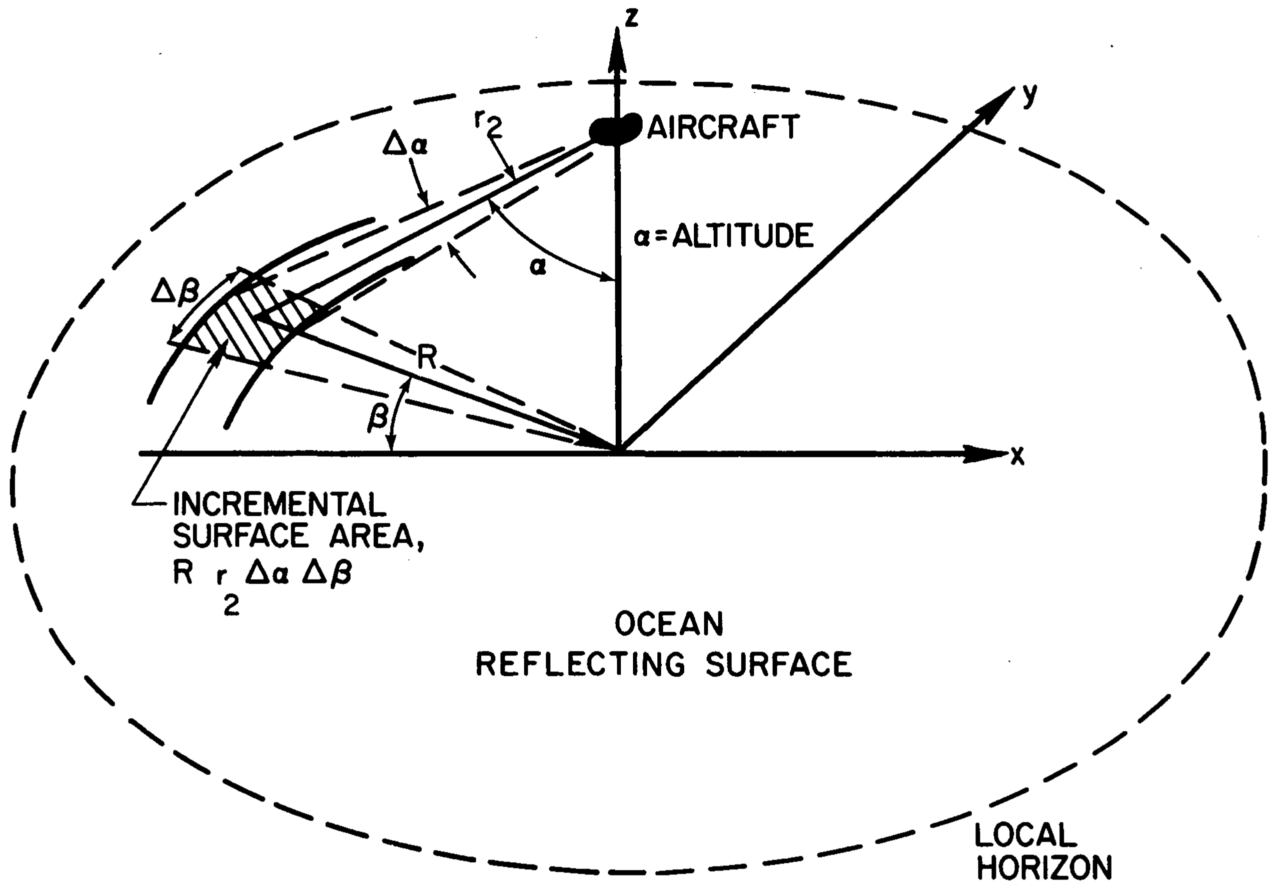


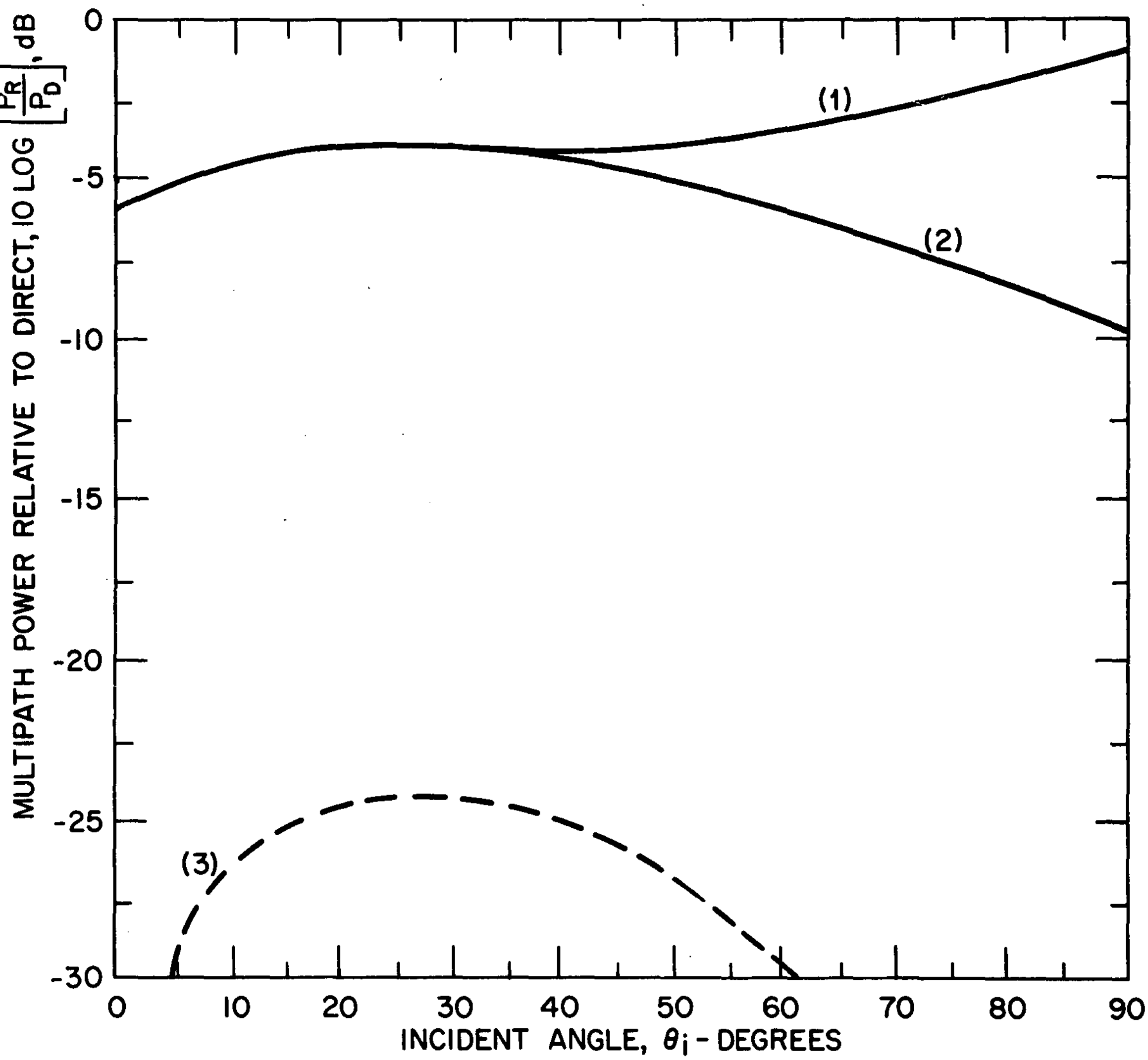
Figure 6. Reflecting-Surface Geometry and Incremental-Surface Area

block the high-frequency radiation from reaching adjacent valleys particularly at incidence angles approaching grazing incidence. Rough-surface shadowing has been studied by several investigators,[34, 35, 36] in effect , the shadowing of a rough surface causes the surface to appear rougher, and to account for its effect properly, one must modify the surface-probability distribution accordingly (Ref. 37). Since shadowing only has a significant effect near grazing incidence, and since we are not primarily concerned with operation in this region, we omit the shadowing effect from the computer solution.

We also omit accounting for the curvature of the earth surface is a separate divergence term as is customary in the smooth-surface solution. The divergence of the reflected radiation due to the curvature of the individual tangent planes is accounted for in the scattering coefficient as pointed out in the previous section. The increase in curvature of the individual tangent planes, due to the earth's curvature, is insignificant.

The computed rough-surface, relative, reflected power for a typical low-gain-pattern aircraft antenna is shown plotted versus incidence angle in Figure 7. Results are presented for both reflections polarized in the plane-of-polarization of the incident radiation (curves 1 and 2), and for crosspolarized reflections (curve 3). The satellite and the aircraft altitude, for the computations (Figure 7) is 43,000 kilometers (km) and 10 km, respectively.

A few comments on the nature of the computer solution are appropriate at this point:



(1) HORIZONTAL → HORIZONTAL
(2) VERTICAL → VERTICAL
(3) CROSSPOLARIZED REFLECTIONS

Figure 7. Rough-Surface Multipath: Typical Computer Solution for Low-Gain, Linearly Polarized, Aircraft Antenna

First, both the vertical and horizontal in-plane polarized reflections are within a few decibels of the direct-path power over a wide range of incidence angles; the horizontally-polarized reflected power increases as grazing incidence is approached, whereas the vertically-polarized power decreases. This is characteristic of Beckmann and Spizzichino's[39] smooth-surface solution where the reflected power is determined by the Fresnel reflection coefficient.

Second, the maximum occurring in the range of "high" incidence angles (e. g., $\theta_i \simeq 20°$) and the minimum at the origin are not characteristic of the smooth-surface solution. The location of the maximum has been found to vary with surface rms roughness, occurring approximately at an incidence angle corresponding to the rms slope angle ($\tan^{-1}$ s).

Third, crossed-polarized reflections (curve 3 in Figure 7) are predicted by the computer solution.

Several investigators have studied the rough-surface reflection problem for a satellite communication link. The work of Durrani and Staras[40] and Staras[41], previously referenced, concerns primarily the case where both communication link terminals are considered in the far field of the earth reflections, in which case, the expression for the relative reflected power (eqs. 6 and 16) can be integrated using the method of steepest descent, which is and approximate solution. Figure 8 shows a comparison of the computer solution and the results obtained by the method of steepest descent. Also, plotted in Figure 8 is Boeing's[42] experimental data for an over-ocean, L-band,

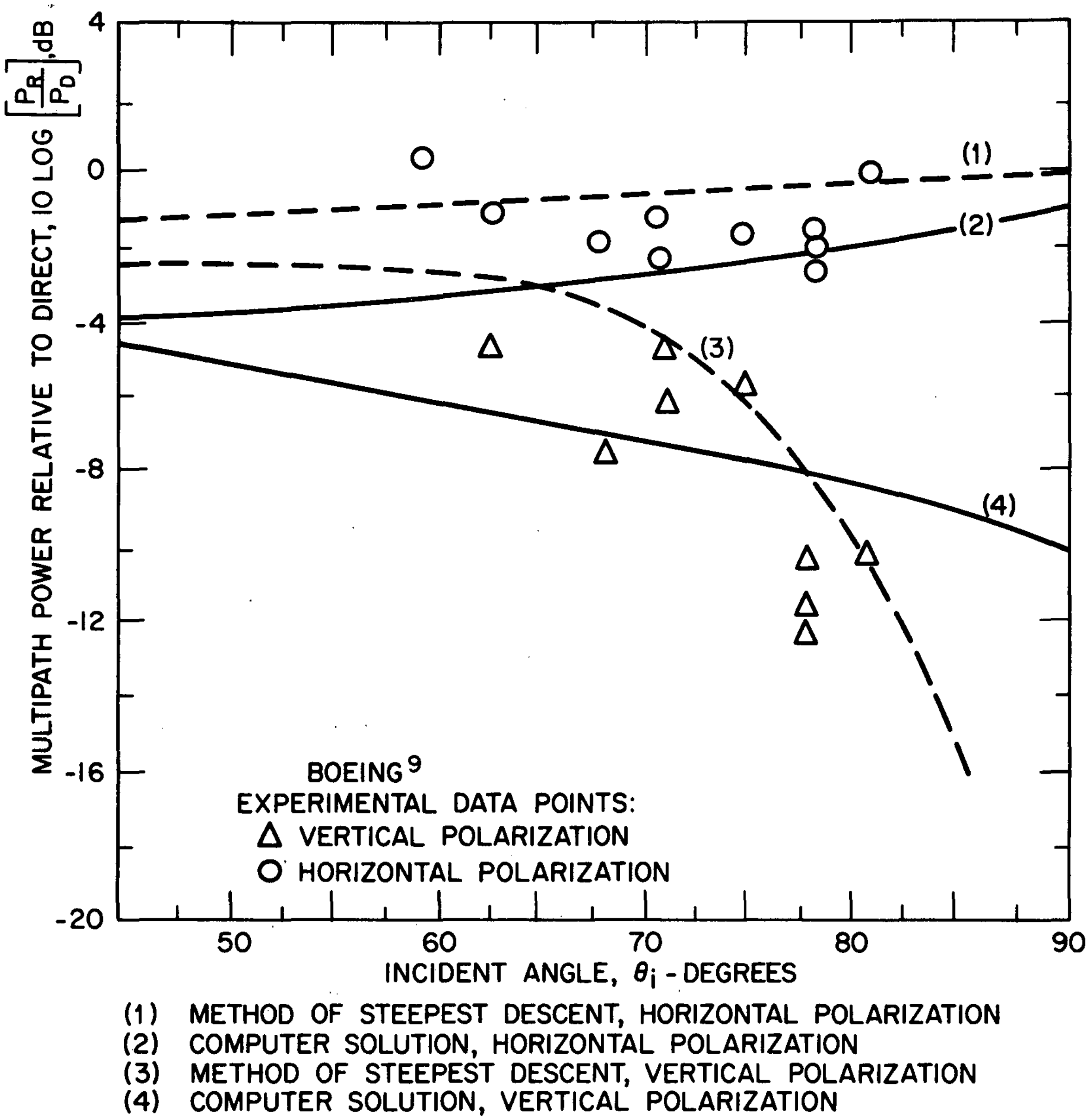


Figure 8. Comparison of Computer Solution with Approximate Solution by Method of Steepest Descent and Experimental Data

satellite-aircraft, communication link. The Boeing tests were conducted by transmitting a CW signal from the NASA/Rosman, North Carolina (U.S.A.) ground station to a KC-135 airplane, via the ATS-5 satellite, wherein a CW-test signal at 1551.7 MHz was received on the airplane. It is noted that sea-state information is not available for the Boeing results, and that the computer solution approaches the results by the method of steepest descent as the rms roughness parameter is decreased.

IV. CONCLUSION

This study presents in some detail the results of a theoretical analysis of multipath reflections from the ocean's surface at L-band. The results are particularly applicable to a communication link between a synchronous satellite and an aircraft. It is shown that L-band multipath reflections should be predominantly diffuse, with the entire surface area, within line-of-sight of the aircraft, being significant in determining the total reflected power. The results of the computer solution show a significant departure from the approximate solution obtained through integration by the method of steepest descent however, the limited experimental data available is insufficient to verify the computer solution.

Several general observations concerning the computer solution follow:

(a) Both the horizontally and vertically polarized reflections in the plane of polarization of the incident radiation are within a few decibels of the direct path signal for low incident angles. As grazing incidence is approached, the horizontally-polarized reflections increase and the vertically polarized reflections decrease. This is characteristic of the smooth-surface solution; however, the decrease in the vertically polarized reflections is much less pronounced.

(b) A maximum in the multipath reflections occurs in the range of high incidence angles approximately where $\theta_i = \tan^{-1} s$.

(c) The predicted crossed polarized reflections are attenuated considerably below (> 20 dB) the in-plane polarized reflections for an aircraft antenna such as a dipole. The cross-polarized reflections also exhibit a peak approximately where $\theta_i = \tan^{-1} s$. This suggests a method of measuring the sea state based upon the magnitude of the cross-polarized component.

The above conclusions are based primarily upon the behavior of the computer solution model. As more experimental results become available, they can be compared with this model.

ACKNOWLEDGMENT

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