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A REVIEW OF THE ROLE OF SURFACE REFLECTION IN MULTIPATH PROPAGATION
OVER TERRESTRIAL MICROWAVE LINKS

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SUMMARY

It has long been recognized that surface reflection on overwater microwave radio relay paths plays an important role in causing frequency selective multipath fading. However, there has been a tendency among many radio scientists and engineers to assume that similar but less prevalent fading on most overland paths arose mainly from multiple paths through the atmosphere. With the introduction of wide-band digital radio into microwave relay networks, the origin of selective fading has been investigated with renewed interest because of the damaging effects of distortion. There is mounting experimental and theoretical evidence that ground reflection and scattering has an important role in producing much of the selective multipath propagation effects on overland links. This paper reviews both old and new evidence, providing some new insights into the complex mixture of mechanisms involved. Some resulting implications for the design of digital radio links are also discussed.

1. INTRODUCTION

Much of the severe fading on terrestrial line-of-sight microwave links has long been recognized to be due to multipath propagation. Its potential to cause thermal noise outages in analog radio systems was discovered early and taken into account in system design. The less significant effect of intermodulation noise resulting from the often frequency selective nature of the most severe fading was more-or-less tolerated, even with increased system bandwidths (Hubbard, 1984). Then with the design and testing of the first wide-band digital radio systems, it was gradually recognized that the distortion resulting from the frequency selective nature of the fading was a more serious source of outage than thermal noise. This resulted in a simultaneous effort by engineers to design radios more immune to this distortion and by propagation researchers to determine more precisely its source and quantify its effect.

It has been known for many years that surface reflection on overwater microwave paths causes deep frequency selective fading. The potential adverse effects on relatively flat overland paths was also recognized and experiments conducted to determine effective reflection coefficients (e.g., Matsuo et al., 1953; Bullington, 1954). However, it appears that deep interference fading on the longer rougher overland paths was usually attributed almost entirely to atmospheric mechanisms, in particular to atmospheric multipath. It is now possible to find many papers in the scientific literature that treat most interference fading on overland links in general as resulting from atmospheric multipath. As late as 1982, even the CCIR (1982) left the impression that the effects of ground reflection were insignificant for the majority of overland paths.

Now with the renewed interest in the effects of multipath propagation on digital radio systems, there is mounting experimental and theoretical evidence that ground reflection and scattering has an important role in producing much of the selective fading on overland paths. Associated with this is the equally important evidence that atmospheric effects, and particularly defocussing, are responsible for reducing the direct signal to a level where the ground reflected signal can interfere destructively with it. The aim of this paper is to review the evidence.

In reviewing the evidence, the authors wish to avoid leaving the impression that the importance of ground reflection on overland paths has been almost totally ignored. There have indeed been a number of works, including those of Beckmann and Spizzichino (1963) and Dougherty (1968), in which its importance has not been overlooked. Fortunately there is now considerably more information from which to make a new assessment. To more quickly advance future investigation, some speculation (possibly incorrect) is included in this assessment.

The various atmospheric and surface mechanisms that have been considered responsible for fading on terrestrial microwave paths are summarized in section 2. The experimental and theoretical results that the authors consider to be evidence for the importance of terrain reflection are then considered in turn in section 3. Section 4 presents some new implications resulting from the importance of terrain reflection, and section 5 presents conclusions.

2. PHYSICAL MECHANISMS OF INTEREST

A number of clear-air fading mechanisms on terrestrial microwave paths have been proposed and investigated over about the last four decades. These will be summarized first before presenting the evidence for the important combination of atmospheric fading and surface reflection. Since most of them have been suggested and reviewed previously (Beckmann and Spizzichino, 1963; Dougherty, 1968), the authors will not try to cite all the originators.

Perhaps the most useful classification for the purposes of this paper is the division into atmospheric fading mechanisms, and combined atmospheric and surface mechanisms. Other classifications such as "K-type" fading (earth diffraction fading due to subrefractive bending, or interference fading associated with ground reflection) and "duct type" fading (defocussing and atmospheric multipath fading) (Matsuo et al., 1953), or "power fading" and multipath fading (Dougherty, 1968) have been employed previously. The early one of these seems particularly unfortunate since it does not recognize the combinations that subsequent observations have shown to exist.

2.1 Atmospheric fading mechanisms

Several atmospheric fading mechanisms have been investigated:

- (a) **Defocussing.** This mechanism, which has been variously termed "divergence", "space-wave fadeout" (Bean, 1954) and "diffraction" (Dougherty, 1968), is assumed to be caused by the divergence of waves due to the presence of abnormal refractive layers (usually ducts) in proximity to the path. The fades are often of long duration (several hours), and relatively non-frequency selective. The fading is also fairly non-selective in space, the large zones where it occurs often being termed "shadow regions" or "radio holes". As discussed in section 3, defocussing is considered to be the most prevalent severe atmospheric fading mechanism.

Although as discussed in section 3, regular horizontal ducts either below the path or intermediate between the antenna heights on an inclined path can cause defocussing, another type of defocussing with a finer spatial scale has also been considered. This defocussing could originate from an undulating (wavy) abnormal refractive layer between the terminals on an inclined path (Strickland, 1980). It is particularly indicated from the measurements of severe fading on low elevation angle earth-space paths (Strickland et al., 1977). Further investigation of this likely faster varying type of defocussing is required.

- (b) **Atmospheric multipath.** This mechanism in which the transmitted wave follows two or more discrete paths is also usually assumed to be due to a duct in proximity to the path. The additional paths are usually assumed to result from gradual refractive bending, but reflection from an elevated layer or a layer below the path have been considered. More generally, other types of abnormal layers can also cause atmospheric multipath fading (Dougherty and Dutton, 1981; Segal, 1985). This mechanism is also discussed in more detail in section 3.
- (c) **Antenna decoupling.** As a result of abnormal refractivity gradients, the beam can be bent off the axes of the antennas, resulting in non-frequency-selective attenuation. It can be particularly severe for links in which the antennas are mispointed or have beamwidths that are too narrow. Although the levels of this fading can be estimated, given the antenna beamwidths and information on the distribution of angle-of-arrival (Webster, 1982), the uncertainty in antenna pointing accuracy makes its prevalence difficult to assess. It is noteworthy, however, that Webster (1983) has shown that large angles-of-arrival are associated with defocussing layers below the path. Thus, there may be some antenna decoupling loss in many defocussing situations. Again, further investigation is required.
- (d) **Scintillation.** This very fast frequency selective fading is due to scattering from many small turbulent irregularities in the atmosphere. It is always present to some degree superimposed on the slower deeper fades arising from the other mechanisms. Since its magnitude increases with increasing frequency, it has made the identification of other fast fading mechanisms difficult.

As noted, mechanisms (a) and (b) are usually assumed to arise as a result of ducts in proximity to the path. A detailed review of the meteorological mechanisms that produce ducts is beyond the scope of this paper. It may be noted, however, that surface ducts are caused by advection, evaporation, frontal processes, and radiation, and elevated ducts by advection, subsidence, and advective intrusion. Surface and elevated subrefractive layers that are sometimes involved are caused by some of these and other processes. More detailed information is given elsewhere (Ikegami et al., 1966; Dougherty and Dutton, 1981).

2.2 Combined atmospheric and surface fading mechanisms

Several combined atmospheric and surface mechanisms have been considered and investigated to varying degrees:

- (a) **Defocussing plus reflection.** This would seem to be the most likely mechanism producing the many observed instances of fast frequency selective fading superimposed on slow non-selective fading (see section 3). The combination of the fine-scale type of defocussing noted in the previous sub-section and surface reflection could explain the very severe fading on very low angle earth space paths.
- (b) **Atmospheric multipath plus surface reflection.** Here the atmospheric multipath is expected to produce relative non-selective ("quasi-flat") fades across the system bandwidths normally in use. As discussed further in section 3, the authors contend that the surface multipath should not be significantly more selective than the interfering atmospheric multipath. The resulting fades, however, can be very deep.

- (c) **Antenna decoupling plus surface reflection.** On most paths, this mechanism may be more important associated with mechanism (a) than it is on its own.
- (d) **Scintillation plus surface reflection.** Again this mechanism is most likely when associated with mechanism (a) (see section 3). To be significant on its own, the effective surface reflection coefficient would need to approach unity, a not unlikely situation on overwater paths.
- (e) **Earth diffraction resulting from subrefraction.** Here a subrefractive layer below the antennas causes the direct wave to intercept the earth ("earth bulge"), with the resulting relatively non-selective diffractive attenuation. The occurrence of significant diffractive attenuation is minimal on well-designed paths with adequate surface clearance.

In mechanisms (a) to (d), the degree to which the surface reflection is "specular" or "diffuse" will depend on many factors (Beckmann and Spizzichino, 1963), which are not all yet well understood, particularly for the relatively long microwave paths of interest here. Some initial consideration to this question is given in section 3.

3. EXPERIMENTAL AND THEORETICAL EVIDENCE

There is much experimental and theoretical evidence that surface reflection is an important factor in causing selective fading on terrestrial microwave links. It comes not so much from one or a limited number of investigations, even though some of these have been very productive, as from a synthesis of the results of many. To best make this synthesis, it seems useful to classify the evidence and consider it in some suitable order. Thus, in this section the multitude of observations of fast selective fading superimposed on slow quasi-flat fading are first reviewed. Following this the most likely atmospheric mechanisms (defocussing and atmospheric multipath) that could produce the slow quasi-flat fading are considered. Then to demonstrate that reflection from terrain is sufficiently strong to interfere destructively with these atmospheric fading mechanisms, measurements and calculations of effective ground reflection coefficients are discussed. Finally, to indicate that the fast highly selective interference fading most likely originates from the ground reflected component, the relative delays of atmospheric and surface reflected rays are compared. Following these main sub-sections, two other groups of supporting evidence are discussed (results of correlation and multiple regression calculations on large data bases, and multipath depolarization observations) along with miscellaneous supporting evidence.

Since it is believed that experimental results from overwater paths help clarify those from overland paths, these are considered along with the latter. The main differences between overwater and overland paths are believed to be the more frequent and severe defocussing on overwater paths, the more stable and higher level specular reflection, and lesser amount of diffuse reflection. While combined slow and fast fading events are more frequent on overwater paths they are not greatly different in overall character than those on overland paths.

3.1 Observations of selective fading superimposed on quasi-flat fading

Among the most important evidence that ground reflection and scattering interacts with atmospheric fading mechanisms are the many observations of rapid deep fading superimposed on shallower much slower fading. The slow fading, often referred to as "median depression" or "mean depression", has usually been assumed to result from atmospheric defocussing. The rapid fading has usually been assumed to be interference fading of atmospheric origin, either scintillation or multipath. Among these many experiments have been a few using sophisticated channel probing techniques in which the slow fading component was recognized as relatively non frequency selective (quasi-flat) and the rapid fading as selective.

Crawford and Jakes (1952) in their pioneering swept-frequency experiment were perhaps the first to measure a rapid frequency selective component superimposed on a slow non-selective component (see also Friis (1948)). They noted in fact that reflection from the small water portion of their path was a source of fading in abnormal circumstances, and that it would be desirable to avoid paths with significant ground reflections. However, they seem to have concluded from their associated angle-of-arrival measurements that atmospheric multipath was the most frequent cause of severe fading. Unfortunately as they indicated, the minimum angle-of-arrival in their scan (-0.8°) was not sufficiently low that they could be always certain that the surface reflected ray was in range.

Using frequency-sweep equipment similar to that of Crawford and Jakes, Kaylor (1953) produced the first statistics of amplitude selectivity as a function of fade depth (Fig. 1). He noted that no deep interference fading occurred on his 49 km overland path unless the signal was already depressed 10 dB or so across the entire 400 MHz band observed. He concluded that this depression was most likely due to interfering atmospheric rays of slight relative delay, but noted that it could also be due to non-selective attenuation of the direct signal. It is interesting that Kaylor demonstrated that small amplitude components (e.g., levels of -32 dB and -34 dB relative to direct signal level) could have a marked effect on notch shapes, while simultaneously implying that a much larger estimated ground reflection level for his path (< -20 dB) could be ignored. Crawford and Jakes (1952) also arrived at the same seemingly contradictory conclusion in their earlier work.

In their early paper on multipath distortion, Omori and Sato (1958) implicitly recognized from their swept-frequency measurements the superposition of selective and non-selective components, and described a novel technique for measuring the non-selective component. In attempting to explain the three-frequency measurements of Ugai (1961) in which the superposition of selective and non-selective fading was recognized, Ikegami (1967) suggested the possibility of ground reflected waves among others. Unfortunately, as noted previously by Segal (1985), the possibility of a significant ground reflection component in his own pioneering measurements (Ikegami, 1959, 1967; Ikegami et al., 1966) was not considered.

More recent swept- or multi-frequency measurements (e.g., Babler, 1972; Rummier, 1979; Sandberg, 1980; Webster and Ueno, 1980; Stephansen, 1981; Liniger, 1982, 1983; Martin, 1982a, 1984; Sakagami and Hosoya, 1982; Bundrock and Murphy, 1984; Hubbard, 1984; Valentin and Metzger, 1984; Lam and Webster, 1985; Lammers and Marr, 1985) have shed further light on the underlying fading mechanisms and provided more quantitative information on the selective and non-selective signal components. Although he did not consider in detail the possible physical mechanisms involved in his measurements, Rummier (1979) devised a practical channel model that incorporated quasi-flat and selective fading parameters describing his data. Using fairly narrow-band measurements (60 MHz), Sakagami and Hosoya (1982) were nonetheless very successful in proving that their results were due to the combination of a quasi-flat atmospheric signal and a surface reflected signal. They were further able to identify both specular and diffuse components in the reflected signal.

On the basis of wide-band (400 MHz) swept-frequency amplitude and group-delay measurements, one of the authors (Martin, 1982a) concluded for his particular 50 km, 11.5 GHz path that deep selective fading always occurred superimposed on a quasi-flat component. This is illustrated statistically in Fig. 2, which displays three levels of the conditional distribution of peak-to-peak amplitude variation within the band (DA, in dB) as functions of the peak fade depth (A_x , in dB). These measurements are discussed further in sub-sections 3.2, 3.3, and 3.4.

Bundrock and Murphy (1984) described the initial results of wide-band (1000 MHz) swept-frequency amplitude and group delay measurements on an overland path specifically chosen to facilitate observation of the effect of ground reflection. They showed the increase in selectivity with increasing fade depth in terms of the amplitude slope statistics within the band, a particularly useful approach for application to digital radio systems. More importantly for this review, they attributed their results to the combination of atmospheric defocussing of the direct signal and ground reflection. They noted, furthermore, an apparent increase in the effective ground reflection coefficient simultaneously with the defocussing of the direct signal (see sub-section 3.3).

Many investigators of overwater paths have had little difficulty in ascribing the superposition of slow, shallow and fast, deep fading to the interaction of an atmospheric mechanism and surface reflection. The conclusion that these are non-selective and selective, and derive respectively from the atmosphere (defocussing) and the sea surface (specular reflection), was particularly clear in the wide-band (1000 MHz) amplitude and angle-of-arrival measurements of Lam and Webster (1985). Interpretation of the mechanisms involved was made difficult, however, by the obstacles partially blocking the surface reflected ray on the two paths investigated. The distributions of direct and reflected signal amplitudes and relative delay for one of the paths, presented in Fig. 3, are discussed further in sub-sections 3.2 and 3.4.

While some investigators using sophisticated channel probing techniques have continued to clarify the propagation mechanisms responsible for combined non-selective and selective fading, others have been constructing models that include the two effects. Pearson (1965) noted the frequent occurrence of median depression associated with multipath fading and partially accounted for it in his model for the single frequency fading distribution. Barnett (1972) described the same phenomenon and tried to account for it in his model by employing a climate-dependent multipath probability occurrence factor. The degree to which the earlier model of Morita (1970) (see also Morita and Kakita, 1958) includes the effect of median depression is unclear, since Morita later introduced a modification (Morita, 1972) designed to take this into account. (In the same paper Morita illustrated the potential importance of including the effect of ground reflection and presented a method designed to do it.) More recently, the combined effect of selective fading superimposed on non-selective fading has been taken into account in channel distortion models (e.g., Rummier, 1978; Martin, 1982a,b; Sakagami and Hosoya, 1982; Sylvain and Lavergnat, 1985; Lavergnat and Sylvain, 1985a).

It is noteworthy that Beckmann and Spizzichino (1963) in their earlier review (Chapter 16) recognized the possibility of very severe fading (40 - 45 dB) when both slow and fast fading are present simultaneously, although they were uncertain as to the cause of the fast fading. They cite, for example, diffuse scattering from the earth or atmosphere. However, they noted the very important result common to this now large body of observations: "the lower the mean (non-selective) level, the greater the amplitude of the rapid (frequency selective) fluctuations".

3.2 Atmospheric multipath and defocussing: mechanisms and fade depths

Although mechanisms causing quasi-flat fading have been introduced in section 2, and further background information given in sub-section 3.1, the main mechanisms of defocussing and atmospheric multipath require further consideration. Concerning the mechanisms themselves, the major points of interest are the atmospheric structure under which they occur, their relative frequency of occurrence, and the possibility of simultaneous occurrence. Of course the fading levels attained are also important because this will partially determine the possibility of destructive interference with the ground reflected and scattered waves.

Mechanisms. The possible physical bases of defocussing and atmospheric multipath have been a subject of investigation for over four decades. Although an extensive review is beyond the scope of this paper, the important early work of several investigators (Sharpless, 1946; Price, 1948; Doherty, 1952; Crawford and Jakes, 1952; Rivet, 1956; Ikegami, 1959; Dutton, 1961) should be noted. For this paper, the work of Ikegami (1959, 1966, 1967) and more recently Webster (1983) is particularly germane.

A useful illustration of the remarkable work of Ikegami is presented in Figs. 5(a) and 5(b). These show the relationship between fading on two adjacent 55 km, 4 GHz paths (one horizontal and one inclined) and the heights of single and multiple ducts. Fig. 5(a) gives 5-minute mean received power, and Fig. 5(b), the 5-minute fading range (difference between the 10% and 90% levels of the distribution) as functions of height.

On the oblique path, a considerable mean depression and apparently superimposed fast fading is seen to occur when the duct exists near the height of the lower terminal. This occurs on the horizontal path when the duct is near the level of the path. Some fading occurred for duct heights above the paths, and between the terminals on the inclined path, but it was obviously much less severe. On the basis of ray theory, Ikegami explained the depression as due to the divergence of rays, or defocussing that occurs within a large shadow region. He explained the fast fading as due to destructive interference that he felt occurred between two groups of rays within a small "interference region" (see Figs. 6 and 7). Unfortunately, he did not explain for his own data why the mean depression and the faster fading occurred simultaneously, in spite of the fact that his shadow zones and interference zones were not coincident. Explaining this superposition of slow and fast fading in other data (Ugai, 1961), he noted the possibility of a ground reflected signal, as well as the seemingly impossible superposition of zones (Ikegami, 1967).

Fig. 8 displays some of the clarifying ray-tracing results of Webster (1983). Shown for a 50 km horizontal path (100 m antenna heights) are the ray amplitudes, relative delays, and angles-of-arrival as functions of the height of a 100 m thick duct of -20 Nu intensity. As evident, when the duct center is below a height just above the path, only a defocussed direct ray exists. The greatest defocussing occurs at about, or just above, the path height. (Since the angle-of-arrival is also greatest at this height, the greatest amount of antenna decoupling would occur simultaneously, the amount depending on the antenna beamwidths and pointing accuracy.) Over a range of greater heights, three-ray atmospheric multipath occurs. (The relative delays associated with the additional paths are discussed in sub-section 3.4.) For the particular "interference region" he investigated, Webster demonstrated that the lower antenna height is critical for inclined paths (i.e., defocussing of the single direct ray occurs below this height). He did not consider the effect of ground reflection although he noted the possibility.

A comparison of these results confirms Ikegami's conclusion that the large mean depression for a layer below the lower terminal height was due to defocussing. It also suggests that the less prevalent and less severe fading for higher duct heights was due to atmospheric multipath. It is interesting to note that in an earlier study similar to the later one of Ikegami, Matsuo et al. (1953) indicated that fading for ducts above the path was of the rapid interference type. Nevertheless, neither Webster's nor Ikegami's theoretical results seem to adequately explain the apparent simultaneous mean depression and faster fading in Ikegami's data. The best explanation would seem to be the presence of a significant ground reflected component. The likelihood of focussing-enhanced ground reflection is discussed in sub-section 3.3.

On the basis primarily of these and other results it is possible to speculate on the relative frequency of occurrence of defocussing and atmospheric multipath. From Fig. 8 it is apparent that significant defocussing should exist over a much greater duct height range than destructive atmospheric multipath. Even though atmospheric multipath occurs over a sizable duct height range, the main two rays would not be in phase opposition except for a small number of discrete heights (e.g., nine at 4 GHz). A similar conclusion seems possible from Ikegami's theoretical results that show his "interference" regions to be much smaller and at greater distances than shadow (defocussing) regions (see also Dutton, 1961). Furthermore, as implied by Ikegami (1959, 1967), it is only for a small portion of these interference regions (next to the shadow region boundary) that significant atmospheric multipath fading would be possible. (The possibility of signal enhancements caused by the presence of one of these interference regions at the receiving antenna seems more likely.)

The presence of Ikegami's small interference regions for duct heights below the path implies that Webster missed this possibility in his ray-tracing investigation. Ikegami (1967) also noted the possibility of interference regions arising from a subrefractive layer, and Segal (1985) confirmed this. Segal further noted the possibility of atmospheric multipath occurring as a result of a superrefractive layer. Nevertheless, it is important to emphasize that these theoretical results indicate that the regions of the atmosphere where multipath is possible are much less likely to be present at the receiving antenna than the defocussing-inducing shadow zones. The available observations seem to confirm this. Further analysis for multi-layer situations would be desirable.

Atmospheric multipath fading levels. Since the presence of atmospheric multipath implies the possibility of destructive interference at microwave frequencies, a wide range of fade levels are obviously possible given rays of approximately equal amplitude. This appears to be confirmed from the small number of observations available that indicate the presence of multipath without median depression. However, it is recognized that likely simultaneous occurrence of atmospheric and surface multipath itself make atmospheric multipath levels difficult to determine from simple measurements. A close scrutiny of swept-frequency amplitude measurements for the presence of rapidly changing quasi-flat fades should make this possible. In any case, it is not difficult to imagine the possibility of atmospheric multipath fades sufficiently deep to cause further destructive interference with the significant surface reflected wave apparently present on many paths (see sub-section 3.3).

Defocussing fade levels. Because of the slowly varying nature of defocussing attenuation and probably because of the greater size of shadow regions, measurements of fade depth are more readily available. These are available in three main forms: (i) direct measurements of slow fading, (ii) median depression estimates from data with superimposed slow and fast fading, and (iii) median depression estimates from swept-frequency measurements.

A number of direct measurements of defocussing levels have been made (e.g., Bean, 1954; Barsis and Johnson, 1962; Barsis et al., 1963; Hautefeuille et al., 1980). In the best of these, the use of multiple frequencies aided the interpretation that these slow fades were relatively non-selective. Estimates of defocussing levels are also available from combined slow and fast fading data obtained over many paths (e.g., Pearson, 1965; Barnett, 1972; Morita, 1972). These all indicate that typical paths in temperate climates can suffer fades of 20 dB for a significant fraction of time. Pearson (1965) noted furthermore that fades of greater than 30 dB had been observed on paths in coastal areas for periods of a few hours. Perhaps the most severe well-documented observations of extreme defocussing levels in tropical regions are

those of Hautefeuille et al. (1980) in Senegal, where 50 dB fades lasting several hours were not considered unusual. The fact that the ground-reflected signal was not observed under these conditions suggests that a shadow region extended over a large portion of the path surface as well.

One of the authors (Martin, 1982a) has estimated median depression statistics for his 50 km, 11.5 GHz path from swept-frequency amplitude and group delay measurements. These are illustrated in Fig. 4 in conditional form versus the relative delay between the two dominant rays (see sub-section 3.4 for further discussion). As evident for this somewhat inclined path, median depressions were of the order of 20 dB during disturbed conditions (i.e., fading greater than 12 dB). The swept-frequency measurements of Lam and Webster (1985) (Fig. 3a) indicate defocussing fades approaching 30 dB during disturbed conditions on their 80 km coastal path. (It is recognized that these statistics may include some incidence of atmospheric multipath.)

3.3 Measurements and calculations of effective ground reflection coefficients

Another source of evidence for the importance of ground reflection on overland paths is the literature on specular and diffuse reflection from terrain. Unfortunately, little progress appears to have been made in the treatment of microwave reflection and scattering from irregular terrain since the major work by Beckmann and Spizzichino (1963). Although some useful information can be gained from calculations of specular and diffuse reflection parameters at these frequencies, measurements on the type of paths involved would still appear to provide the most reliable evidence.

Calculation of specular reflection parameters. In principle, the effective specular reflection coefficient R_s over a terrestrial microwave path can be estimated from the well-known relation (Beckmann and Spizzichino, 1963; Hall, 1979; Boithias, 1983)

$$R_s = g_T g_R D R_0 \rho_s \quad (1)$$

where g_T and g_R are the directivity reduction factors of the transmitting and receiving antennas in the direction of the specular reflection point, D is the divergence factor for the earth's surface, R_0 is the Fresnel reflection coefficient, and the scattering coefficient ρ_s is a reduction factor designed to take into account the terrain roughness. Strictly, the factors in eq. (1) should also be multiplied by another factor that accounts for the amount of surface area reflecting specularly (Hall, 1979; Boithias, 1983). For example, if the specularly reflecting surface were exactly coincident with the first Fresnel zone, R_s would become a factor of two larger. Unfortunately, accurate estimation of this factor is difficult in practical situations involving real terrain.

In order to clarify the results of correlation and multiple regression analyses of a large 47-link fading data base discussed in a companion paper (Tjelta et al., 1986), some investigation was made of the dependence of R_s on the various variables involved. From the large amount of information available on the Fresnel reflection coefficient (CCIR, 1986a), it is clear that $R_0=1$ in the frequency range of interest, except in the rare cases of vertical polarization at grazing angles greater than about 1° . Over the test group of 47 links, $|20\log(D)|$ is typically less than 3 dB under the assumption of a spherical reflecting surface having a $4/3$ -earth radius of curvature.

The directivity reduction factors g_T and g_R in the direction of the specular reflection point were calculated using the Gaussian beam approximation

$$g_{T,R} = \exp(-c_{T,R} \theta^2) \quad (2)$$

with the constants $c_{T,R}$ obtained from the known half-power beamwidths. The overall reduction factor $g_T g_R$ is a complicated function of several variables including antenna beamwidth, path inclination, path clearance, and path length. Of the 47 links, only three relatively steep ones have reductions $|20\log(g_T g_R)|$ greater than 10 dB; half have reductions less than 0.9 dB. Thus, in most cases the specularly reflecting surface is well illuminated by the antenna beams.

Normally the most important overall variable in eq. (1) is the terrain roughness factor ρ_s . It has commonly been estimated using the Gaussian random surface approximation (Beckmann and Spizzichino, 1963)

$$\rho_s = \exp(-g^2/2) \quad (3)$$

where

$$g = 4\pi f s_h \sin\phi / c \quad (4)$$

with s_h the standard deviation of surface height about the local mean value within the first Fresnel zone, ϕ the grazing angle, f the frequency, and c the speed of light. A more recent derivation of ρ_s for sea surfaces (Miller et al., 1984) suggests that a better estimate providing agreement with experimental data can be obtained from

$$\rho_s = \exp(-g^2/2) I_0(g^2/2) \quad (5)$$

where I_0 is the modified Bessel function of zero order. It is likely that (5) is also more accurate than (3) for terrain.

As seen from (4) and (5), ρ_s and thus R_s would appear to be strongly dependent on the grazing angle ϕ , the surface roughness s_h within the first Fresnel zone, and the frequency f . However, there is a complex, somewhat path dependent relationship between s_h and f . Since s_h tends to decrease on

average as the size of the first Fresnel zone decreases, and this size decreases with increasing frequency, the actual average dependence of ρ_s on frequency should be different than at first glance.

At UHF, ρ_s can be estimated with some accuracy. Here the roughness s_h is dependent mainly on terrain surface variations. However, at SHF where the size of the first Fresnel zone is much smaller, s_h decreases to the point where it is difficult to estimate accurately from a single path terrain profile. For example, out of the 47 test links, the ratio of the first Fresnel zone length to the terrain profile correlation distance is less than three for 27 of them. Under such conditions, it is apparent that trees and other small terrain features would become relatively more important than at lower frequencies.

Another difficulty in accurately estimating ρ_s at SHF is that, with the reduced first Fresnel zone size, the specular reflection point and hence the grazing angle can no longer be as accurately determined from the antenna heights above the average terrain height. Furthermore, there may be more than one specular reflection zone on the path profile. Despite these various difficulties, effective specular reflection levels $20\log R_s$ have been estimated for a sample of the smoothest paths among the test group, employing the roughness parameter s_3 (Tjelta et al., 1986) calculated for the entire path (normally an upper bound for the roughness within the first Fresnel zone). The highest of these are in the range -10 dB to -20 dB and correlate well with the group experiencing the worst fading. More tangible statistical evidence that specular ground reflection is important within the overall group of 47 links is presented in a companion paper (Tjelta et al., 1986). Calculations are continuing with more accurate estimates for the surface roughness within the first Fresnel zone.

Calculation of diffuse scattering parameters. Beckmann and Spizzichino (1963) considered two cases relevant to terrestrial microwave links: (i) "glistening surface" (i.e., surface causing diffuse reflection) defined by the ground irregularities, and (ii) glistening surface defined by the antenna beams. To verify that the latter case is the most common with the narrow antenna beams employed at SHF, the parameters K_β and K_α corresponding to each of these two cases were calculated for the test sample of 47 links. These parameters are defined

$$K_\beta = \frac{h_T + h_R}{d \tan \beta_0}, \quad K_\alpha = \frac{1}{d} \left[\frac{h_R^2}{\alpha_T^2} + \frac{h_T^2}{\alpha_R^2} \right]^{1/2} \quad (7)$$

where h_T and h_R are the heights of the antennas above the average terrain height, α_T and α_R are the antenna half-beamwidths (i.e., half the half-power beamwidths), and d the path length. The factor $\tan \beta_0$ represents a mean-square value of the terrain slope irregularities given by

$$\tan \beta_0 = 2\sigma/d_c \quad (8)$$

where σ is the standard deviation and d_c the correlation distance of terrain heights. For the calculations it was deemed best to calculate σ and d_c with respect to the mean terrain profiles as determined by least squares fits to the terrain heights (i.e., $\sigma = s_3$, as employed by Tjelta et al., 1986).

From the calculations, the inequality (Beckmann and Spizzichino, 1963)

$$K_\alpha < K_\beta / 2\sqrt{2} \quad (9)$$

held for only six links. This is indeed an indication that the glistening surface is normally defined by the antenna beams. Since even for these six, $K_\beta > 1$ for two and $K_\beta > 0.5$ for the remainder, the glistening surface is close to the specular reflection point as in case (ii). For case (i), Beckmann and Spizzichino calculated that diffuse reflection coefficients can range between 0.25 and 1, although they noted that measurements ranged between 0.2 and 0.5.

Of the 41 links for which the glistening surface is limited by the antenna beams (case (ii)), $0.1 < K_\alpha < 0.5$ for 26 and $K_\alpha > 0.5$ for the remainder of which most are inclined paths. A few estimates for the most important first group of 26 suggest that significant diffuse reflection must be considered as a distinct possibility. Unfortunately, the theory for case (ii) does not yet appear to have been validated by measurements. Early correlation calculations on the 47-link test sample using the various diffuse reflection parameters are presented in the companion paper (Tjelta et al., 1986) (see also sub-section 3.5).

Measurements of effective specular and diffuse reflection coefficients. Because of the uncertainty in the accuracy of calculations of the effective reflection coefficients for irregular terrain at microwave frequencies, measurements for typical paths may still provide the best evidence for the importance of terrain reflection and scattering. Even though most measurements have been carried out under controlled conditions involving short paths, a few exist for longer paths.

The 4 GHz measurements of Bullington (1954) on many paths over cultivated terrain were classified by Beckmann and Spizzichino (1963) as describing diffuse reflection under conditions when the glistening surface is not defined by the antenna beams, as were the 1 GHz measurements of McGavin and Maloney (1959) over desert terrain. Most of the reflection coefficients measured ranged between about 0.2 and 0.5. Barton (1974) has questioned the validity of this conclusion, and the authors' own calculations for 16 paths at 2 and 4 GHz indicate that only two of them can be considered to have sufficiently non-directional antennas that the glistening surface is defined by the terrain itself. Barton (1974) also appears to question the conclusion that Bullington's measurements did not contain significant specular reflection contributions.

Since the measurements of Bullington (1954) and McGavin and Maloney (1959) were for paths that were expected to pose some reflection problems, it is helpful to observe the results for the rougher ($s_3 = 33$ m) relatively steep (0.3°) path between Roc Tredudon and Lannion in France. Fig. 9 displays the reflection coefficient estimates of Martin (1982a) based on amplitude and group delay measurements in a 400 MHz bandwidth (see also sub-sections 3.1, 3.2, and 3.4). Here, $R_s = GR$ (expressed in dB), corresponding to $R_s = ab$ in the well-known model of Rummier (1979). These frequency-sweep measurements are equivalent to the earlier spatial measurements along a vertical or horizontal line, although the specular and diffuse contributions cannot be separated. Unlike the earlier measurements, they were all obtained during disturbed conditions. Nevertheless, they provide two important pieces of information that the previous measurements do not. They show that the effective reflection coefficient is highly variable, with peak magnitudes more than 10 dB higher than the median value of about -25 dB, and that it decreases slightly with increasing delay of the reflected wave. The large variation in the effective reflection coefficient was apparently also observed by Bundrock and Murphy (1984), and thirty years earlier by Matsuo et al. (1953). Although some of the large variation may be due to the two-ray assumption involved (the spatial measurements also contain this assumption), it seems unlikely that departures from this assumption could cause most of this variation.

The fact that the effective reflection coefficient can increase significantly above its median value during disturbed conditions is a very important result. It implies that a rough path can behave like a smoother path for a significant fraction of time. The fact that these enhancements of the reflected signal are sometimes coupled with attenuation of the direct signal, as illustrated by Martin's measurements (see Martin, 1982a) of their relative levels (i.e., the parameter R , equivalent to b in the model of Rummier (1979)), illustrates why severe surface multipath fading is so prevalent even on rough paths.

It seems most likely that the significant enhancements in the effective reflection coefficient result from a focussing of incident-wave energy on the reflecting ground surface, and possibly a further focussing of the reflected wave itself. As evident from Fig. 7, the presence of a duct below the path could cause this if the region of dense rays adjacent to the lower apex of the "interference region" coincided with the reflecting surface of the path. Indeed, observation of the calculations of Dutton (1961) of "shadow zone" sizes and "interference region" location, and their ranges of variation, gives heed to the argument that the reflected wave can sometimes undergo a net focussing while the direct wave is simultaneously being defocussed. Since the areas of enhanced surface reflection would move along the path, the proportion of diffusely reflected power with respect to specularly reflected power can be expected to vary considerably. In addition to such large-scale focussing and defocussing, uncorrelated focussing and defocussing (scintillation) due to small scale irregularities could play some role, particularly at higher frequencies.

Regardless of the uncertainties in the average proportion of specular and diffuse reflection involved, the various measurements indicate that terrain reflection and scattering is of sufficiently high amplitude to interfere destructively with faded atmospheric waves for a significant fraction of time. The approximately -6 dB to -14 dB range of ground reflected signals during undisturbed conditions on the highly reflecting paths of Bullington (1954), and McGavin and Maloney (1959), would be sufficient. So also would the approximately -10 dB to -30 dB range during disturbed conditions of the rougher Roc Tredudon - Lannion path ($s_3 = 33$ m), as observed from the measurements. It might be noted that overall path surface roughnesses in the 47-link sample discussed previously range between $s_3 = 3$ m and $s_3 = 62$ m in 42 of these.

3.4 Measurements and calculations of relative path delays

Considerable evidence as to the usual role of surface reflection in selective fading is also available from a comparison of relative path delay measurements and calculations. A brief introduction to some relative delay measurements associated with fading measurements has already been made. Table 1 provides a more complete list of experiments reported, with relative delay and associated amplitude information in summary form.

Calculations of atmospheric delays. The information in Table 1 indicates that relative delays as large as several nanoseconds have been observed from most experiments, even on overland paths. Although most of the experimenters on overland paths have assumed these to result from atmospheric multipath, and some erroneous calculations available (e.g., Ruthroff, 1971) appeared to support this, recent calculations suggest that relative atmospheric multipath delays are normally fairly small. (In fact, even some early calculations by Omori and Sato (1958) seem to suggest this.)

The two most relevant and comprehensive works would appear to be those of Webster (1983) and Parl (1983). The ray tracing study of Webster has already been introduced in sub-section 3.2. Referring to the center graph of Fig. 8, it is clear that even for a 50 km path and a layer (100m thickness) with a total refractivity change as large as 20 Nu, the largest relative delays between the two dominant rays (1 and 2) are less than about 1 ns. The relative delay of the third ray is even less since it travels in a height interval where the refractivity is less.

Using a three-layer discrete gradient model, Parl (1983) has analytically derived an expression for the maximum relative delay between atmospheric rays. The solid curves in Fig. 10 display his results as functions of path length for ducts having a -50 Nu intensity and various refractivity gradients. Although the largest refractivity gradients give fairly long delays, it must be emphasized that such large gradients are extremely rare (Bean et al., 1966; Segal and Barrington, 1977; Dougherty and Dutton, 1981). As discussed in the following sub-section, it is more likely that long-delayed rays result from ground reflection.

As demonstrated by Parl, the maximum relative delay varies as d^3 for short path lengths (up to about 30 km) and as d for longer paths. Earlier workers (Ruthroff, 1971; Sasaki and Akiyama, 1979) had concluded that the dependence was as d^3 for all path lengths. This resulted in very pessimistic early estimates of digital radio performance, as noted by Hubbard (1984).

TABLE 1. RELATIVE DELAY MEASUREMENTS

Investigators	Path Location	Path Length (km)	Frequency (GHz)	Technique	Delay Information	Remarks	
Crawford and Jakes (1952)	Murray Hill - Holmdel, NJ	36	3.7 - 4.2	Frequency sweep	Delays up to 10 ns estimated with analog simulator	Associated angle-of-arrival measurements. See text.	
	Southard Hill, NJ, USA	27	"				
DeLange (1952)	Murray Hill - Holmdel, NJ USA	36	4	Pulse transmission	Delays up to 7 ns measured. Usually <3ns	Same path as Crawford and Jakes (1952)	
Meadows et al. (1966)	Widley - Green Hailey, U.K.	55	3.6 - 4.1	Frequency sweep	Delay of 2nd ray between 2 and 10 ns	Single event only. See text.	
Dougherty and Hartman (1977)	Haswell, CO, USA	23	13.3 , 14.9	Pseudo random noise	0.5 ns between 2 paths	Single event only. Associated meteorological measurements.	
Sasaki and Akiyama (1979)	Shiroyama - Kosuzume, Japan	36	18 - 22	Frequency sweep	4 ns maximum	Two-ray model assumed for all paths	
	Kawagoe - Musashino, Japan	23	18 - 22	"	0.3 ns maximum		
	Warusawa - Mt. Kano, Japan	79	5.65 - 6.42	"	6.7 ns max. (0.002%)		Exponential distribution estimated
	Mt. Hiei - Ohnogi, Japan	62	"	"	0.13 ns max.		
	Kawaguchi - Itsukaichi, Japan	48	3.7 - 4.2	"	2.3 ns max. (0.05%)		Exponential distribution estimated
M. Sandberg (1980)	Copenhagen, Denmark	75	13.5 - 15.0	Frequency sweep	<1 ns delay of second ray. Up to 6 ns delay of third small amplitude ray	Second ray comparable in amplitude to first. Single event only.	
Martin (1982a)	Roc Tredudon - Lannion, France	50	11.25 - 11.65	Frequency sweep	Delay distribution, with delays of 5 ns (0.01%), 8 ns (0.001%)	See text	
Hubbard (1984)	Miscellaneous	40 - 160	8.6	Pseudo random noise	Delays up to 18 ns	See text	
Lam and Webster (1985)	Otter Lake - Aylesford, N.S., Canada	80	9.5 - 10.5	Frequency sweep	Delays up to 5 ns (0.01%) in distribution	See text	
	Otter Lake - Nictaux S., N.S., Canada	"	"	"	Delays up to 14 ns (0.01%) in distribution	See text	
Lammers and Marr (1985)	Saddle back Mt. - Prospect Hill, MA, USA	73	16 GHz	Pseudo random noise	Estimated delays up to 4 ns	Two events only. Associated angle-of-arrival measurements	

The major difference between the single layer models of Webster and of Parl is that Webster assumed a smooth transition whereas Parl did not. The advantage of Parl's approach is that the ray equations can be solved analytically, allowing equations to be obtained for the maximum relative delay and other useful quantities. The maximum relative delay calculations of Parl, however, would seem to be comparable to those of Webster, if perhaps slightly less. Parl also showed that higher order rays which crisscross the layer lower boundary are theoretically possible (see also Dougherty, 1981). It is clear from his analysis, however, that any additional relative delay of these higher order rays is negligible by comparison with the results of Fig. 10. Further detailed comparisons between the various models, including those of Webster and Parl, would be useful.

Webster (1983) also calculated the relative delay that would result from total reflection by an elevated subsidence layer in which an abrupt change in refractivity occurs within a very small height interval. The results are displayed in Fig. 11, along with the observations of Meadows et al. (1966). Such an explanation for the results of Meadows et al. seems plausible, particularly in view of the associated refractivity profiles that they presented. It should be noted, however, that this was a single isolated event during a one-year period. The bulk of the fading that Meadows et al. observed on their very rough path was flat fading indicative of defocussing.

Hubbard (1984) also discussed some relative delay measurements and associated refractivity profiles that from his calculations seemed indicative of reflection by an elevated ducting layer well above his path. He also noted other measurements on the same day that appeared to be due to ground reflection. The relative frequency of both types of event would be of interest.

Calculation of surface multipath delays. Various investigators have assumed that the relative delay of ground reflected rays is quite small. Meadows et al. (1966), for example, calculated a relative ground delay of 2 ns for their experimental path. Such a calculation assumes, however, that the refractivity profile below the path is normal or near normal (i.e., 4/3-earth profile with gradient of -40 Nu/km). If a layer with an abnormally high negative gradient exists below the path, the situation can be quite different.

This is illustrated beautifully in the ray-tracing curves of Lam and Webster (1985) corresponding to their most elevated 80 km overwater path (Fig. 12b). When the duct (-40 Nu intensity and 100m thickness) is at the surface (the center of the duct that eventually becomes elevated, in this case), the direct ray, and for the most part the surface reflected ray, travel in an atmosphere with normal gradient. The relative delay calculated is almost exactly equal to that obtained for a normal atmosphere (4.4 ns), shown by the cross added to the graph of Lam and Webster. As the duct rises, an increasing portion of the path travelled by the surface reflected ray is in the much higher refractivity region below the duct. As evident, the relative delay increases almost linearly as the duct rises. Once the duct rises above the path and the direct ray no longer travels in a less "dense" medium above, the relative delay drops quickly back to the value for a normal atmosphere. As also illustrated in Fig. 12b, the relative delays of the atmospheric rays that arise once the duct is above the path (6 ns maximum) are considerably smaller than the maximum value for the surface ray occurring when the duct is just below the path (12 ns maximum).

Unlike the calculation of maximum relative delays of atmospheric multipaths, which appear to require a rigorous analysis such as that of Webster (1983) or Parl (1983), an approximate estimate of the maximum relative delay of the surface reflected ray can be obtained more simply. Under the assumption that a defocussing layer is just below the path, then the relative delay can be calculated as the sum of two contributions. The contribution $\Delta\tau_1$ from the region of constant gradient below the layer can be estimated in the normal way from the equation (Boithias, 1983)

$$\Delta\tau_1 = \frac{2d_T d_R}{c d^3} (h_T + h_R)^2 [1 - m(1 + b^2)] \quad (10)$$

where d_T and d_R are the distances from the transmitting and receiving terminals to the specular reflection point, and m and b are coefficients in a third-order equation. The contribution resulting from the fact that the direct wave travels in the lower refractivity region above the layer can be estimated from

$$\Delta\tau_2 = (|\Delta N| \times 10^{-6}) d/c \quad (11)$$

where ΔN is the duct intensity. The total relative delay, $\Delta\tau_m = \Delta\tau_1 + \Delta\tau_2$, of course assumes that the layer is infinitely thin.

The accuracy of this simple procedure is illustrated in Fig. 12b. As already noted, the value $\Delta\tau_1 = 4.4$ ns for a normal refractivity gradient is virtually identical to the ray tracing calculation for a ground-based layer half the thickness of the elevated layer. The value of $\Delta\tau_2 = 10.7$ ns for the -40 Nu layer gives a total relative delay of 15.1 ns. This is the approximate value that would be obtained if the approximately linear curve in Fig. 12b were extrapolated to the average path height. The 20% lower finite duct thickness. Lam (1983) showed the variation of maximum delay for finite duct thickness on his Bay-of-Fundy path as a function of duct intensity ΔN . From his delay statistics, he estimated that maximum $|\Delta N|$ values for his path seldom exceed 40 Nu.

The contribution $\Delta\tau_1$ to the maximum relative delay is usually much smaller than the additional contribution $\Delta\tau_2$ during the presence of fairly extreme ducts (e.g., $\Delta N = -40$ Nu). For the test sample of 47 links discussed earlier, $\Delta\tau_1$ ranges between 0.2 ns and 5.5 ns for 44; for the steepest path, $\Delta\tau_1 = 11$ ns. However, for 35 links this contribution is less than 2 ns.

Eq. (11) therefore provides a good approximate upper bound to the maximum delay under the worst-case condition that the layer is just below the path. The curve based on eq. (11) with $\Delta N = -50$ Nu is superimposed on the atmospheric multipath delay graph of Parl in Fig. 10. As evident, it gives larger relative delays than occur under worst-case conditions where the same layer is above the path, even in the case of very extreme gradients. For more normal relatively extreme gradients in temperate climates (e.g., -400 Nu/km), the difference is quite large. As for atmospheric multipath at longer path lengths, the maximum delay is approximately linear in d .

As evident from this analysis, the maximum relative delay depends much more on the layer characteristics, in particular the intensity ΔN , than on the path height above the reflecting surface. The approximate distribution of $\Delta\tau$ could be estimated, given the distributions of ΔN and abnormal layer heights. For horizontal paths, and layer heights h less than the mid-path height h_p , eq. (11) can be generalized to

$$\Delta\tau_2 = (|\Delta N| \times 10^{-6}) dh / h_p c \quad (12)$$

For inclined paths, little error would be introduced by employing the height at path center also, particularly since abnormal layers tend to be inclined with the average terrain slope (e.g., Lammers and Marr, 1985). Eq. (12) could be multiplied by some suitable factor (e.g., 0.8) to allow for the fact that it assumes infinitely thin layers.

Discussion. As evident from the calculations of surface multipath delays, (e.g., Fig. 12a,b) the greatest delays occur along with the greatest amount of defocussing attenuation of the direct signal. This is confirmed by the results of Martin (1982a) displayed in Fig. 4, and also by the observations of Lam and Webster (1985), described in more detail by Lam (1983). It is significant that the maximum defocussing loss in Fig. 12a (25 dB) and the maximum relative delay in Fig. 12b (12 ns) were both exceeded for the same percentage of time (about 0.3%) in the experimental measurements of Lam and Webster shown in Fig. 3. Thus, the single uniform layer model used to obtain the results of Fig. 12 would seem to be an excellent one, at least statistically. As indicated previously, the observations of Lam and Webster were complicated by the presence of a ridge partially obstructing the surface reflection path. Also displayed in Fig. 12a is the estimated amplitude of the surface reflected wave without the additional diffraction loss (Lam, 1983). It is noteworthy that, for this particular path geometry and layer characteristics, there is some indication of focussing of the reflected wave associated with the defocussing of the direct wave.

Of the main two main mechanisms causing significant median depression, defocussing and "refractive" atmospheric multipath, it is evident that the largest relative delays will be associated with defocussing layers just below the path. This is also the situation for which the greatest frequency selectivity of the deep fades will occur. The large relative delays occurring in this manner for both specular and diffuse ground reflection should have approximately the same value, except when the propagation distances for these two components are very different (e.g., the path of Sakagami and Hosoya, 1982). When refractive atmospheric multipath due to a layer above the path is the mechanism causing median depression, the relative delays of surface multipath will be comparable to those during undisturbed conditions (i.e., $\Delta\tau_1$). These are of approximately the same magnitude as the maximum relative delays due to refractive atmospheric multipath.

No information appears to be available for refractive atmospheric multipath delays associated with abnormal layers below the path (i.e., the interference regions of Ikegami (1959)). In view of the geometry of this situation, however, these are considered unlikely to be larger than those for layers just above the path. A similar speculative conclusion might be made for refractive atmospheric multipath arising from a subrefractive layer below the path. Further investigation is needed for these and various multi-layer situations.

The sole atmospheric multipath situation that would seem to produce relative delays comparably large to those for surface multipath is that of an elevated duct from which a reflection occurs (i.e., "reflective" atmospheric multipath, Fig. 11). All available observations, however, suggest that this highly frequency selective fading situation without median depression is extremely rare.

3.5 Correlation and multiple regression analyses

Usually the statistical analyses of large fading data bases are not considered to provide much information on the underlying clear-air mechanisms. Nevertheless, the type of detailed correlation and multiple regression analyses of many variables, discussed in a companion paper (Tjelta et al., 1986), has begun to do this.

The clearest indication that specular ground reflection is important in the 47-link test sample is that the grazing angle ϕ has emerged as one of the most significant variables in the asymptotic multiple regression equation for the large fade depth range of the fading distribution. The negative regression coefficient obtained for ϕ is in general agreement with eqs. (1) to (5) which give a specular reflection coefficient increasing with decreasing ϕ . It is fairly clear from the results of Tjelta et al. (1986) that earlier indications of the importance of path clearance in asymptotic models for the fading distribution (Crombie, 1983; Olsen et al., 1986) were an imperfect indication of the importance of grazing angle, and hence of specular reflection.

A clear indication of the importance of diffuse reflection is not as easily obtained from the analysis. Perhaps the most tangible indication is that the surface roughness parameter s_2 involving the terrain elemental slopes also emerged as a significant regression variable, and particularly that s_2 values for a path profile interval of 100 m produced the best results. The positive regression coefficient for s_2 indicates in effect that the greater the roughness, the greater the amount of diffuse reflection. This result is in agreement with results observed for diffusely reflecting water surfaces in the lowest range of surface roughnesses (CCIR, 1986a). The high correlation between the diffuse

reflection parameter K_α and the reference tail fade depth $A_{0.01}$ may also be an indication of diffuse reflection, as may the weaker correlations with the other two diffuse reflection parameters $\tan \beta_0$ and α/β_0^2 . It is evident, however, that there is a functional similarity between eq. (7) for K_α and the expression (Boithias, 1983) for the grazing angle ϕ (i.e., both K_α and ϕ are approximately proportional to the path clearance and inversely proportional to the path length). Thus, the correlation between K_α and $A_{0.01}$ may be more an imperfect indication of the importance of specular reflection. Further analysis is required.

The strong relationship between fade depth (or probability of exceeding a given fade depth) in the tail range of the distribution and path length, also evident in previous analyses (Morita and Kakita, 1958; Pearson, 1965; Morita, 1970; Barnett, 1972; Boithias, 1979, 1981; Martin et al., 1985; Olsen et al., 1986), is believed to be due to the fact that several mechanisms, including specular and diffuse reflection, are dependent on path length in mutually enhancing ways. Perhaps most importantly on the atmospheric side, as path length increases, the amount of flat fading due to defocussing would tend to increase. However, so also would the likelihood of refractive atmospheric multipath (Webster, 1983), and therefore the probability of exceeding a given atmospheric multipath fade depth. On the terrain side, the relative strengths of both specular and diffuse reflections from the ground tend to increase with increasing path length. Finally, on both atmospheric and terrain sides, the uncorrelated components of atmospheric fade depth and ground reflected signal enhancement due to scintillation tend to increase with increasing path length. The degree to which the importance of path length in the analysis is a measure of the importance of each of these mechanisms is as yet unclear. It is clear, however, that path length alone cannot describe the fading contributions of each mechanism nearly as well as combinations of variables that account for other aspects of these mechanisms also.

The importance of path inclination in the analysis of Tjelta et al. is believed to indicate the importance primarily of the atmospheric contribution to the fading. In particular, defocussing attenuation of the atmospheric signal component would tend to increase with increasing path inclination. (So also would atmospheric multipath fading, as indicated by the work of Webster (1983) and of Parl (1983).) An effect not unimportant on the terrain side, however, is the fact that an increasing path inclination will tend to cause a decreasing effective specular reflection coefficient as a result of the decreasing antenna directivity product (see sub-section 3.3).

The overall increase in fading with increasing frequency evident in the overland-path analyses of Tjelta et al. and others is believed to be another indication primarily of the importance of terrain reflection. The positive regression coefficient, however, would suggest that the strength of the specular reflection tends to increase with increasing frequency, the opposite of what would be expected at first glance from eqs. (4), (5), and (1). One reason may be that on most paths the surface roughness within the first Fresnel zone decreases sufficiently quickly with increasing frequency (because the size of this zone decreases with increasing frequency, reducing the proportion of large surface irregularities - see sub-section 3.3) to outweigh the normal decrease in the effective specular reflection coefficient with increasing frequency. Another not unrelated reason may be the fact that finite terrain reflecting elements can reflect more energy as the frequency is increased (e.g., Hall, 1979; Boithias, 1983). Recently, Lavergnat and Sylvain (1985b) have cited another possible reason associated with the constant phase shifts of the various multipath components. It does not appear that the 180° phase shift associated with at least specular reflection, however, would produce a significant frequency variation.

At microwave frequencies, the decrease in fade levels with increased surface roughness has been commonly attributed to the lessened probability of stable atmospheric layering over rough terrain (e.g., Vigants, 1975). The results of Tjelta et al. might be taken to suggest that the importance of large scale surface roughness parameters (such as s_1) in previous analyses (Pearson, 1965; Morita, 1970; Barnett, 1972; Vigants, 1975; Olsen et al., 1986) was an imperfect indication of the importance of path inclination (which is fairly highly correlated with surface roughness), since path inclination appears to be a better predictor variable. However, an effect of surface roughness on layer stability might be sufficiently well described by a variable such as path inclination that accounts for other effects as well. Some small effect of surface roughness may also be included in the geoclimatic factors determined by Tjelta et al., because of somewhat different distributions of surface roughness from one geoclimatic region to another. The whole question of surface roughness effects on both atmospheric and surface mechanisms is a complex one, and requires further investigation.

It is well known that single-frequency fading distributions have a tail region of 10 dB/decade slope that normally begins at fade depths of about 10 or 15 dB (CCIR, 1986b). The results of this and previous sub-sections suggest that this tail region arises mainly from the complex interaction of atmospheric fading and surface reflection that begins at about these fade depths.

3.6 Depolarization theory and measurements

It is fairly well established that deterioration in cross polarization discrimination (XPD) on dual polarized links results primarily from a combination of fading of the copolarized signal and multipath coupling into the crosspolarized patterns of the antennas (Morita, 1971; Martin and Casanova, 1974; Rooryck and Martin, 1977; Morita et al., 1979; Olsen, 1981; CCIR, 1986c). While the different effect of the copolar and crosspolar antenna patterns on the multipath signals poses a problem for operating radio systems, it provides another source of information on the multipath mechanisms involved.

The results of several clear-air crosspolarization experiments have shown that conditional XPD statistics XPD_c (mean, median, rms, or equiprobable value) can be related to the copolar attenuation (CPA) in the deep fading range by the empirical relation (Olsen, 1981; CCIR, 1986c)

$$XPD_c = -CPA + C \quad (\text{dB}) \quad (13)$$

Here, C is a parameter for each path and frequency that has virtually always been observed to be greater than XPD_0 , the value of XPD_C during undisturbed conditions (i.e., when $CPA = 0$), sometimes by more than 20 dB. This has been expressed as (Morita et al., 1979)

$$C = XPD_0 + Q \quad (\text{dB}) \quad (14)$$

where Q is an "improvement factor" that determines at what value of CPA the relation (13) begins to apply. Thus, Q has virtually always been observed to be positive, with values ranging beyond 20 dB.

One of the authors (Olsen, 1985) has theoretically verified eq. (13) and developed expressions for the parameter C for each of two of the combined fading mechanisms introduced in sub-section 2.2:

(a) atmospheric defocussing plus surface reflection;

(b) atmospheric multipath plus surface reflection.

These are the only copolar fading mechanisms for which eq. (13) would appear to apply. For mechanism (a) and the conditional mean statistic \overline{XPD} , C is of the approximate form

$$C = \overline{XPD}_s + \bar{A}_s \quad (\text{dB}) \quad (15)$$

where \overline{XPD}_s is the mean relative crosspolar response of the two antennas to the dominant surface reflected wave and \bar{A}_s is its mean relative fade depth for a conditional value of CPA . Similarly, for mechanism (b),

$$C = \overline{XPD}_a + \bar{A}_a \quad (\text{dB}) \quad (16)$$

where \overline{XPD}_a is the mean relative crosspolar response of the two antennas to the dominant atmospheric ray (not including the direct ray), and \bar{A}_a is its mean relative fade depth for a conditional value of CPA . Both \overline{XPD}_s and \overline{XPD}_a depend on the crosspolar patterns of the antennas and the distributions of ray angles-of-arrival and launch. For most crosspolar patterns used experimentally in which there is a notch on or near the axis and higher sidelobes off axis, $\overline{XPD}_s < XPD_0$ and $\overline{XPD}_a < XPD_0$. This just expresses the fact that the XPD of the antennas usually degrades off axis.

The value of Q for combined mechanism (a) is therefore

$$Q_s = \overline{XPD}_s - \overline{XPD}_0 + \bar{A}_s \quad (17)$$

Since $\overline{XPD}_s < XPD_0$, \bar{A}_s must be positive (i.e., the amplitude of the reflected wave must be less than that of the direct wave) and greater than this difference. This is the normal situation, and the lower the mean level of the reflected signal, the larger is Q_s .

In combined mechanism (b), in order that CPA be sufficiently large for eq. (13) to apply, the atmospheric ray and the direct ray must be of approximately the same amplitude so that they interfere destructively. Thus $\bar{A}_a = 0$, and

$$Q_a = \overline{XPD}_a - XPD_0 \quad (18)$$

For the crosspolar patterns usually applicable experimentally, Q_a would be negative or approximately equal to zero. Hence, the crosspolar performance of the link would tend to be much worse during atmospheric multipath and surface reflection than it would during defocussing and surface reflection. This just expresses the physically understandable fact that large amplitude atmospheric rays arriving off axis cause the link XPD to degrade more than do normally much lower amplitude surface reflected rays.

As discussed previously, mechanisms (a) and (b) both occur for some fraction of the time. Measured values of Q will reflect the relative occurrence. The fact that measured values are virtually always positive is a further indication that defocussing plus surface reflection is the dominant mechanism on most paths.

3.7 Other miscellaneous evidence

There are a number of other miscellaneous pieces of evidence that surface reflection is a component of multipath fading superimposed on a quasi-flat median depression. One is the observation that tilting the antennas slightly upwards reduces the severity of deep fading (e.g., Hartman and Smith, 1977; Liniger, 1982). In the experiment of Liniger (1982), the degree of frequency selectivity was also seen to reduce accordingly. Quarta (1966) in his earlier experiment essentially demonstrated the same effect, but using two antennas of different beamwidth. In the experiments of both Quarta and Liniger, the interpretation that the severity of the fading depended on the strength of the surface reflected signal was easily made because the reflecting surface was water.

Quarta's observation that horizontal polarization produced worse fading than vertical polarization was another demonstration of the same effect, made easy by the nature of his path. Again, Liniger (1984) demonstrated that the degree of selectivity of the horizontally polarized signal was greater than that of the vertically polarized signal, but this time on an overland path. He noted, furthermore, that the "notch" frequencies for the two polarizations were slightly displaced. However, he did not interpret these polarization differences for his overland path as due to the effects of ground reflection.

In a more recent experiment, Gardina and Lin (1985) demonstrated that horizontally spaced antennas with different beamwidths could provide a significant diversity improvement factor against distortion in their digital radio link. They interpreted this very important result as due to the different gain reductions of the two antennas to long-delayed atmospheric multipath signals arriving at large positive angles. In view of the large amount of evidence presented in this paper, it seems more likely that the long-delayed signals observed were from the ground, and that the median depression was caused not by two atmospheric signals of slight delay, but by defocussing of the direct signal.

It is believed that the collective multitude of all the space and frequency diversity experiments that have been carried out on overland paths provides another major source of evidence that ground reflection remains important on these paths. Such an interpretation has been made difficult, however, by several factors: the high degree of spatial correlation associated with defocussing coupled with the low degree of correlation associated with surface reflection, the differences in the relative phase and amplitudes of the specularly and diffusely reflected waves at different antenna positions, and probably by the fact that different parts of the ground reflect differently at different times as layer-focussed energy is directed at one point and then another.

A. SOME IMPLICATIONS OF THE EVIDENCE

An extensive discussion of the practical implications of these findings is beyond the scope of this paper. Many of them have already been known for years, since highly reflecting paths were avoided where possible, and diversity or other techniques normally applied otherwise. Some discussion is warranted, however, particularly with respect to recent attempts to obtain better models of wide-band propagation channel behaviour.

It is apparent that even on links having approximately the same path length, frequency, and path inclination, the statistics of the propagation channel transfer function will be quite variable because of the variation in ground reflection characteristics from one path to another. These statistics include the probability of significant fading (such as associated with single-frequency fading distributions, as discussed by Tjelta et al. (1986)), and the conditional distribution of transfer function shape variables (e.g., Lavergnat and Sylvain, 1985a). Associated with this, the proportion of minimum phase and non-minimum phase fading, a subject of speculation by systems engineers, will as a result vary somewhat from one path to another.

Several investigators have considered it necessary to employ three-phasor (usually assumed to correspond to three physical paths) models for the channel transfer function in wide-band studies (e.g., Martin, 1980; Sakagami and Hosoya, 1982; Lee and Lin, 1985; Shafi and Taylor, 1986). The utility of such models has been demonstrated by Lee and Lin (1985) and Shafi (1986a) in recent Monte Carlo simulations of frequency diversity performance of digital radios. These investigators used a model realization corresponding to two strong atmospheric rays of small relative delay and a third small amplitude ray of large delay (explicitly corresponding to a ground reflected ray in the study of Shafi). Unfortunately, as discussed in preceding sections, this approximate physical situation for realizing median depression seems to be far less prevalent than that involving defocussing attenuation of the direct wave. The importance of slight variations in the small atmospheric delay noted by Shafi and Taylor (1966) seems to be a consequence of this particular model realization, and the fact that insufficiently large bandwidths were considered to see the full effect of the large surface-reflected signal delay. More recently, Shafi (1986b) has obtained initial simulation results corresponding to a flat fade of the direct wave and two ground reflected waves.

As a consequence of the evidence presented in this paper and the results of these various early analyses, in wide-band applications there would seem to be a need for three-phasor ("simplified four-phasor") models of the form

$$H(j\omega) = a_0 + a_1 e^{j(\omega\tau_1 + \phi_1)} + a_2 e^{j(\omega\tau_2 + \phi_2)} \quad (19)$$

or

$$H(j\omega) = a_0 \left[1 - b_1 e^{j(\omega\tau_1 + \phi_1)} - b_2 e^{j(\omega\tau_2 + \phi_2)} \right] \quad (20)$$

in which there are five variables as follows:

- (i) a_0 is the amplitude of the quasi-flat atmospheric attenuation resulting from defocussing, atmospheric multipath, or antenna decoupling,
- (ii) a_1 and τ_1 are the amplitude and relative delay of the surface specularly-reflected wave,
- (iii) a_2 and τ_2 are the amplitude and relative delay of the surface diffusely-reflected wave.

The phase shifts ϕ_1 and ϕ_2 are the physically real but essentially frequency independent quantities associated with the surface reflection. Lavergnat and Sylvain (1985b) have recently discussed their physical necessity in general. Rummier (1979) in effect employed a phase shift ϕ_1 in his simplified three-ray model, although he let it vary and fixed the delay, a mathematically justifiable approach.

The explicit separation into specular and diffuse reflection contributions in (19) and (20) would seem to be necessary for at least space diversity applications, because of the great variability of the diffuse contribution with spatial variation. Unfortunately, suitable distributions for the ray amplitudes, relative delays, and their corresponding means and standard deviations, remain uncertain because of the lack of both experimental results and theoretical calculations. The small amount of evidence suggests that a_0 is lognormally distributed (e.g., Rummier, 1979; Lam and Webster, 1985), and τ_1 Gaussian distributed (e.g., Lam and Webster, 1985). The data of Martin (1982a) indicate that the

distribution of $20\log(a_1)$ is at least symmetric. The results of many controlled experiments in undisturbed conditions discussed by Beckmann and Spizzichino (1963) indicate that a_2 is Rayleigh distributed. However, with the apparent atmospheric-focussing enhancements in both a_1 and a_2 occurring during disturbed conditions, these are more likely to be approximately lognormally distributed.

Simulations have so far been based on the assumption of statistical independence between the various ray amplitudes and phases. However, the investigations discussed in section 3 have shown that there is some correlation between a_0 and τ_1 , a_0 and a_1 , and τ_1 and τ_2 . The effect of such correlations on the several applications of the simulation results needs to be investigated. In general, care must be taken to avoid models that are physically fairly realistic but impractical.

Finally, although ground reflection might be considered as a problem to be minimized as much as possible, there is some indication that its presence may help avoid outages when in rare instances the atmospheric signal fades beyond the flat fade margin of a system.

5. DISCUSSION AND CONCLUSIONS

This paper has attempted to classify and present the diverse evidence for the important role of terrain reflection at SHF in a systematic way such that the conclusion is clear. At the same time, it has tried to show that defocussing, and not atmospheric multipath, is the most prevalent mechanism reducing the atmospheric signal to a level where it can interfere destructively with the terrain-reflected signal. The authors do not claim that this combined atmospheric/surface mechanism is the only one responsible for the observed frequency selectivity of fading - only that it is the most frequently occurring one.

Much further research needs to be done in order to improve the understanding of the complex mixture of mechanisms interacting in the clear-air propagation channel. Both "microscopic" and "macroscopic" approaches in this research are required. Detailed microscopic investigations should include:

- (i) the conduct of more sophisticated channel probing experiments, along with simultaneous in-situ atmospheric measurements. There is a dearth of information on individual ray amplitudes (both polarizations), relative delays, and angles-of-arrival. There is even less such information in association with overall fade levels, group delays, and XPD's. Simultaneous meteorological measurements from which to interpret such transmission measurements are similarly lacking, although the availability of modern instrumentation and data processing equipment is encouraging (Segal, 1985). More attention needs to be paid to the terrain in controlled experiments.
- (ii) more ray-tracing calculations, and full-wave analyses where necessary. These must include rays reflected from the ground, and even real path profiles in some instances. Statistical ensembles of refractivity profiles should be used where possible (e.g., Costa, 1986). Ray amplitudes, delays, and angles-of-arrival need to be calculated in addition to ray paths. Subrefractive, superrefractive, and multi-layer situations require consideration.

More macroscopic investigations should include:

- (iii) further statistical analyses of large single-frequency fading and associated meteorological data bases (e.g., Schiavone, 1986; Tjelta et al., 1986; Martin et al., 1986), and wide-band data bases as they become available (e.g., Lavernat and Sylvain, 1985a);
- (iv) further Monte Carlo and associated theoretical analyses of the consequences of various channel models on amplitude slope distributions, diversity improvement factors, etc. (e.g., Lee and Lin, 1985; Shafi and Taylor, 1986; Shafi, 1986a,b).

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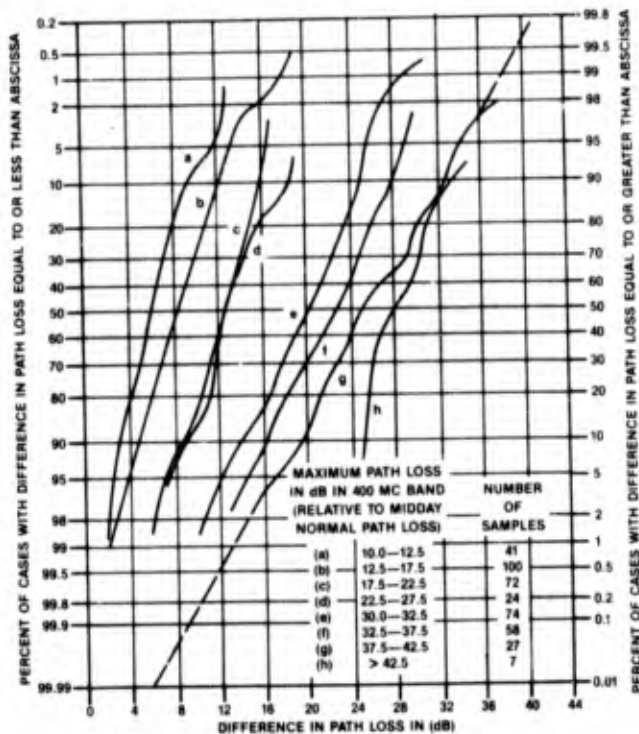


Fig. 1. Statistical distribution of differences between maximum and minimum fade depth in 400 MHz bandwidth. 49 km, 4 GHz path in Iowa, U.S.A., July and August, 1950. [reproduced from Kaylor (1953), Copyright, American Telephone and Telegraph Company, Reprinted by permission]

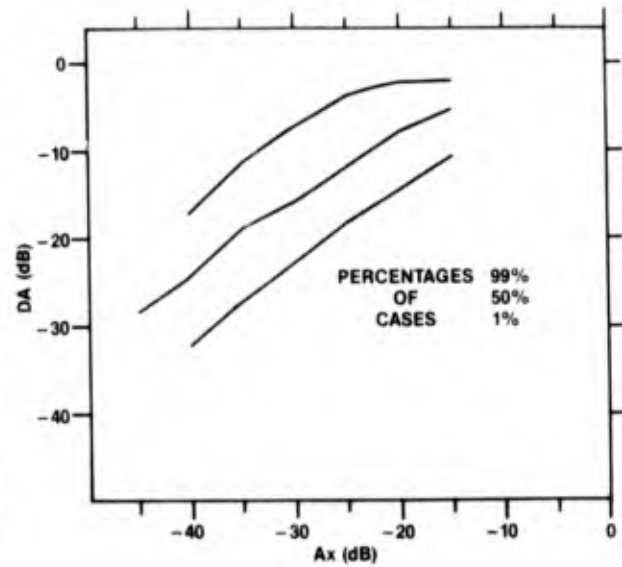


Fig. 2. Variation of 99%, 50%, and 1% levels of conditional distribution of maximum fade depth differences (DA) in 400 MHz bandwidth with maximum fade depth (A_x). 50 km, 11.5 GHz path in France, July 1979. [reproduced from Martin (1982a)]

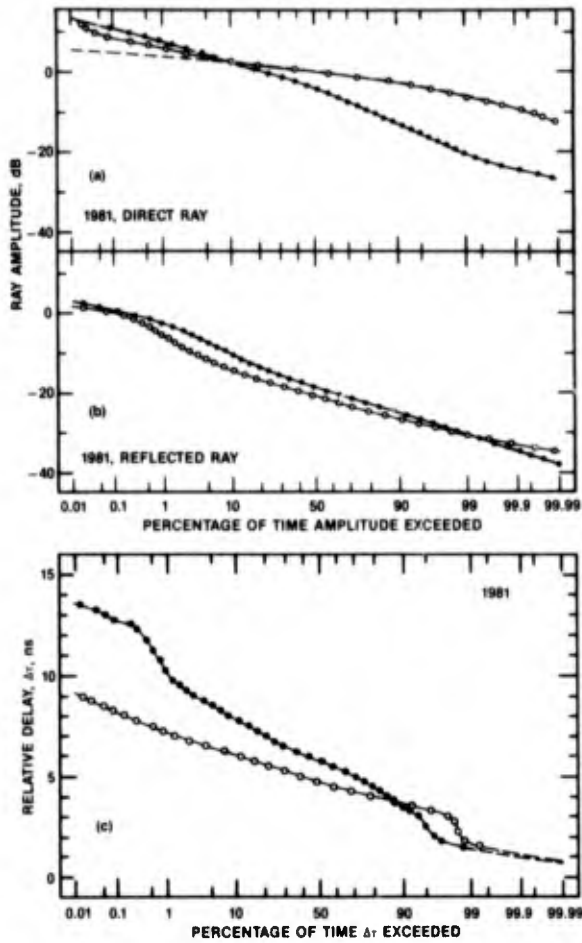


Fig. 3. Distributions of (a) direct ray amplitude, (b) reflected ray amplitude, and (c) relative delay, for quiet (-o-o) and disturbed (-●-●) periods. 80 km path (9.5-10.5 GHz) in Canada, July and August, 1981. [reproduced from Lam and Webster (1985)]

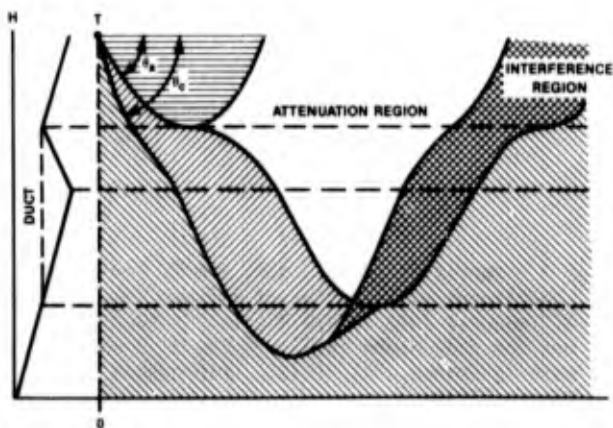


Fig. 6. "Attenuation" and "interference" regions for transmitter situated above a duct (shown by M-profile). [reproduced from Ikegami (1967)]

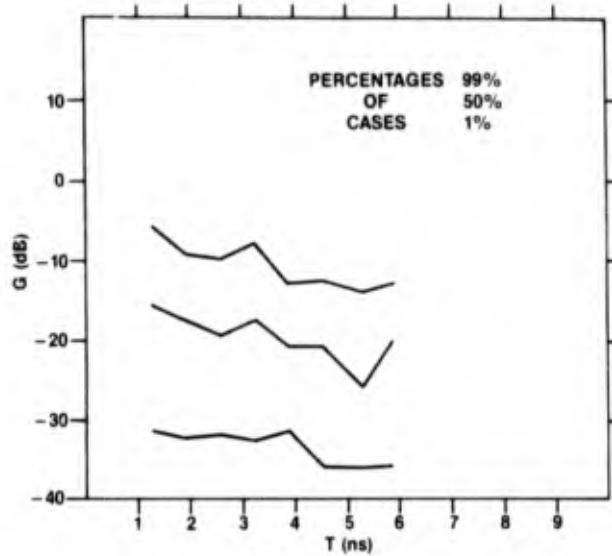
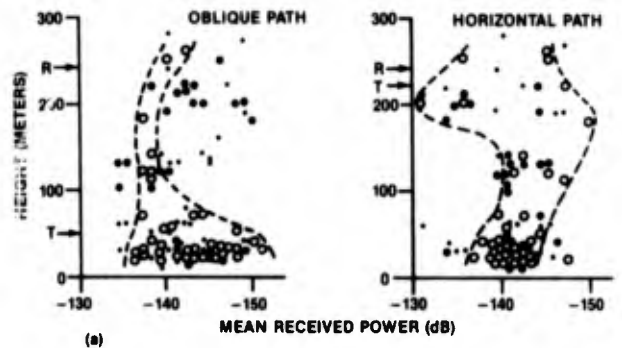
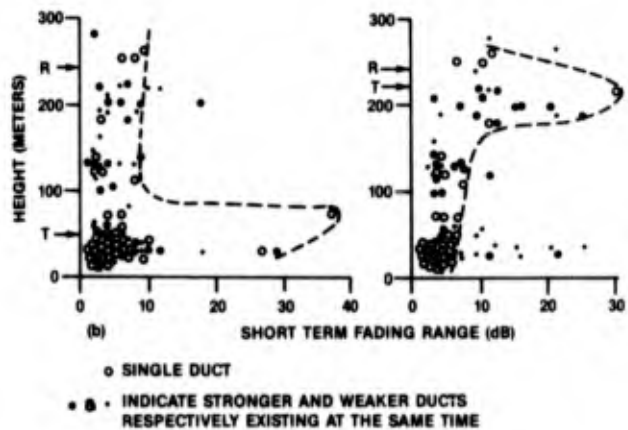


Fig. 4. Variation of 99%, 50%, and 1% levels of conditional distribution of quasi-fade depth (G) in 400 MHz bandwidth with relative delay (T) between direct and dominant secondary rays. 50 km, 11.5 GHz path in France, January 1980. [reproduced from Martin (1982a)]



(a)



(b)

Fig. 5. Comparison of (a) 5-minute mean received power, and (b) 5-minute fading range, with duct height. 55 km, 4 GHz co-located horizontal and inclined paths in Japan, 1-15 November 1954. [reproduced from Ikegami (1959)]

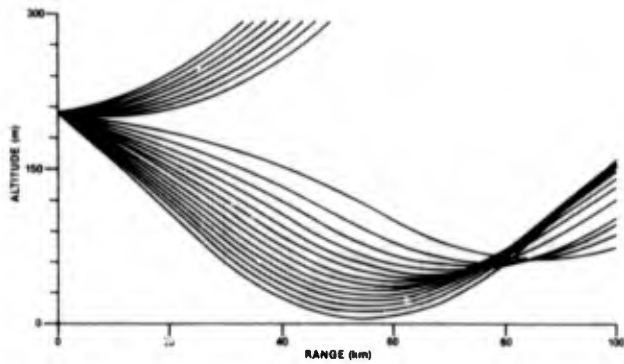


Fig. 7. Example of ray paths for transmitting antenna situated above a duct. [after Segal (1985)]

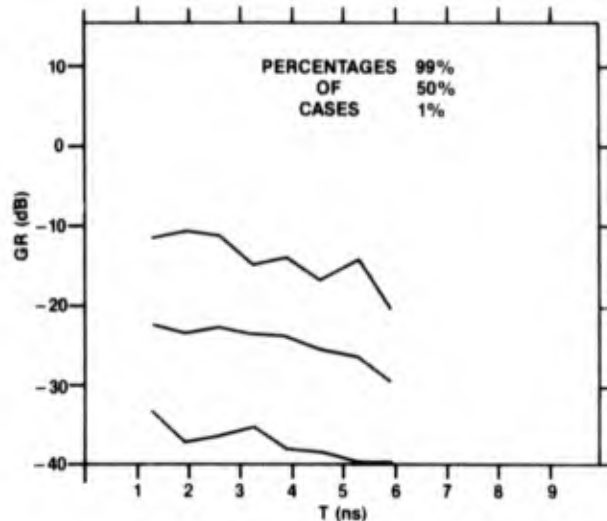


Fig. 9. Variation of 99%, 50%, and 1% levels of conditional distribution of effective reflection coefficient (G·R) with relative delay (T) between direct and dominant secondary rays. 50 km, 11.5 GHz path in France, January 1980. [reproduced from Martin (1982a)]

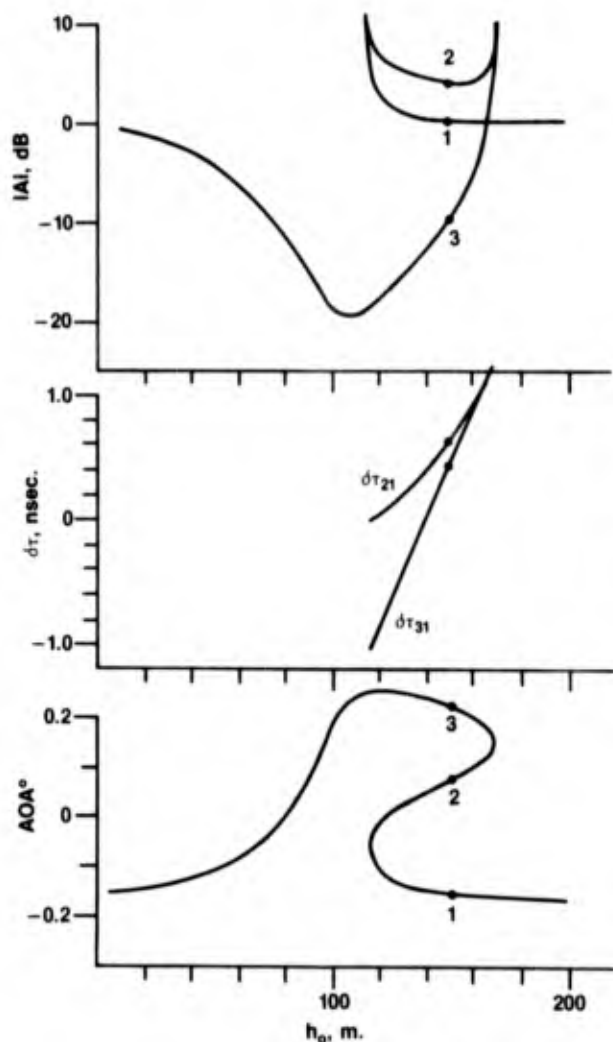


Fig. 8. Variation of ray amplitude $|A|$, relative delay δT , and angle-of-arrival AOA, with anomalous layer (-20 Nu intensity, 100 m thickness) height h_0 . 50 km path length, 100 m antenna heights, -40 Nu/km refractivity gradient outside layer. [reproduced from Webster (1983)]

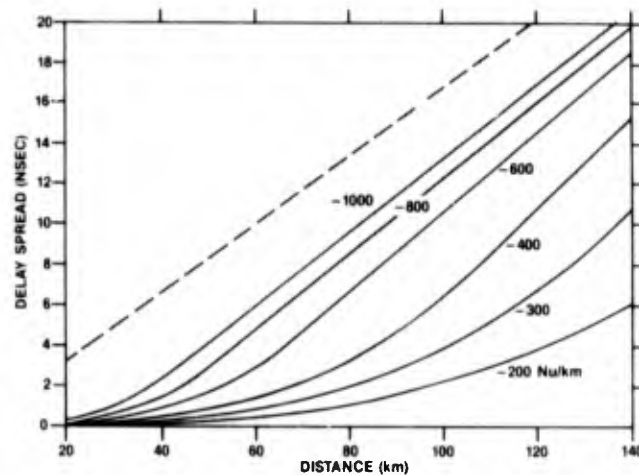


Fig. 10. "Maximum" atmospheric (—) and surface (---) multipath relative delays ("delay spread") versus path length for a duct of intensity $\Delta N \sim -50$ Nu. Refractivity gradient of -40 Nu/km outside the duct. Various duct refractivity gradients for atmospheric multipath. [partially reproduced from Parl (1983)]

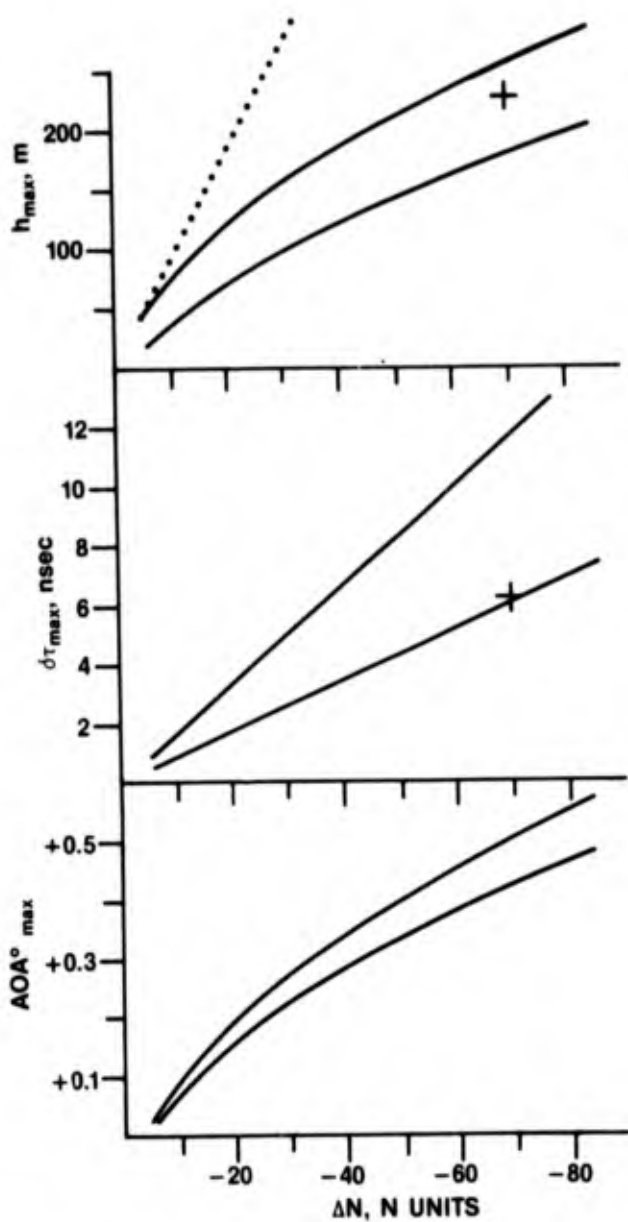


Fig. 11. The maximum anomalous layer height (h_{max}), associated relative delay ($\delta\tau_{\text{max}}$), and angle-of-arrival (AOA_{max}) versus intensity (ΔN) for "reflective" multipath. 50 km path, 100 m antenna heights, -40 NU/km refractivity gradient outside layer. Lower curve - layer thickness $\Delta h=100$ m; upper curve - $\Delta h=0$; dotted curve - maximum height for layer to support strong reflection. The crosses represent the values quoted by Meadows et al. (1966). [reproduced from Webster (1983)]

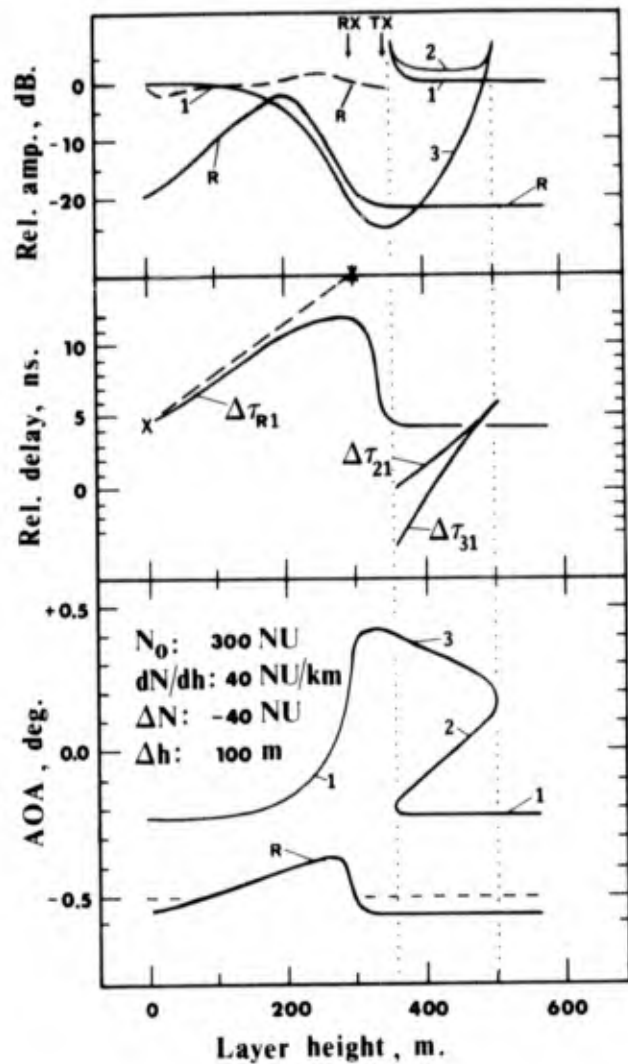


Fig. 12. Variation of ray (a) relative amplitude, (b) relative delay, and (c) angle-of-arrival with height of a single anomalous layer (characteristics indicated on Fig. 12c). Subscripts: 1 main ray; 2,3 - additional atmospheric rays; R - reflected ray with (—) and without (---) obstacle diffraction. [reproduced from Lam and Webster (1985), and Lam (1983)]

DISCUSSION

L.Felsen

You have made the statement that experiments for propagation loss and fading are more reliable than theory. If that is true, what is missing from the theoretical models? Are the experiments sufficiently controlled to isolate the various effects which you designated as being important? If not, then the data are the result of so many interacting parameters that systematic modeling for prediction is well nigh impossible.

Author's Reply

My statement was really that experimental results for the specular and diffuse reflection coefficients from terrain are more reliable than theoretical results. I hope the reasons for this given in sub-section 3.3 of the paper are sufficiently clear. To answer your more general question, fading models at the moment are fairly highly empirical and I don't see any prospect of this changing significantly even in the long term. On the other hand, I believe that experiments have been sufficiently well controlled that systematic modelling is possible, even if the empirical component is fairly high (e.g., Tjelta et al., 1986).

L.Boithias

Le phénomène de "trou radioélectrique" (RADAR) et le phénomène de baisse du niveau moyen (liaison point à point) sont liés. Ils correspondent au cas où le récepteur (ou la cible) est situé du côté de la caustique où, d'après la théorie des rayons, aucun rayon venant de l'émetteur ne peut passer. Le concept de caustique serait donc préférable aux concepts de focalisation et de défocalisation qui sont plutôt obscurs et non clairement définis.

Author's Reply

In some respects I prefer the terms "divergence" and "convergence" to "defocussing" and "focussing", because I think they are a little more physically descriptive. However, I have used the latter because they are more entrenched in the literature, and they are also somewhat descriptive of the physical situation. The fact that a stratified medium is causing the focussing and defocussing, rather than a lens-like medium should present no insurmountable difficulty. I find that the mathematical term "caustic" does not immediately convey enough physical meaning to qualify as part of a term for the type of loss involved, but to each his own preference.

T.E.Doble

Your work indicates that there should be some correlation between multipath delay and flat fade depth. Lam and Webster found this to be so on an overwater path, but has this been supported on a wider basis?

Author's Reply

As far as I know, Martin (1982 a) is the only one to have analyzed wide-band data in a way that gives an explicit statistical relationship between the median depression depth and the relative delay between the main two rays. Lam and Webster (1985) found a correlation also but did not present a statistical relationship in their paper. However, their associated ray-tracing calculations show a clear relationship between the defocussing attenuation resulting from a duct below the path and the corresponding relative delay between the direct and surface-reflected waves.

