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PROPAGATION DEGRADATION FOR MOBILE SATELLITE SYSTEMS

Land mobile satellite systems are being designed to provide communications to operators of moving vehicles throughout the United States and Canada. Major potential difficulties facing such systems are signal attenuation caused by roadside trees that intercept the line-of-sight signal path and multipath fading caused by multiply reflected signals in hilly and mountainous terrain. This article describes the results of a series of four propagation tests carried out jointly by APL and the University of Texas at Austin during 1985–86. The tests used remotely piloted vehicles and helicopters to simulate a transmitter satellite source platform. The first test was designed to measure the signal degradation by individual trees at the NASA Wallops Flight Facility, Wallops Island, Va. During the second and third tests, the emphasis was on attenuation caused by roadside trees when the vehicle was moving. The fourth test examined multipath effects in the hilly and mountainous terrain around Boulder, Colo. The first three tests were performed at UHF (870 MHz); the test in the Boulder region was performed at both UHF (870 MHz) and L band (1500 MHz). A major conclusion reached from the tests is that attenuation by roadside trees is the dominant cause of signal fading; the signal degradation may amount to 7 dB or more for 10% of the traveling time along tree-lined roads, and attenuations of 15 dB or more may be exceeded 1% of the time. Although multipath effects may give rise to severe fades over small time intervals, the signal degradation caused by this mechanism amounted to only about 2 dB for 10% of the time and 9 dB for 1% of the time.

INTRODUCTION

Background

Although "cellular" land-based vehicular communication exists, the technology is available only in urban regions with repeaters relatively close to the mobile unit. There exists no reliable civilian telephone communication for vehicles traveling in rural or remote areas. This is a particular problem for the United States and Canada, which have vast regions of low-density populations where cellular systems are nonexistent and economically unfeasible. Land mobile satellite systems will eventually complement existing land-based mobile systems by extending the range of communications to an area encompassing all of the United States and Canada.

Telephone communication links between geostationary satellites and land mobile vehicles operating at approximately 1.5 GHz are being planned in a cooperative effort between NASA and industry.[1] This system, the Mobile Satellite System, will make possible mobile line-of-sight telephone communications over vast geographic regions.[2] Until recently, carrier frequencies under strong consideration by the FCC were in the UHF band (800 to 900 MHz) and at L band (1500 MHz). In 1987, the World Administrative Radio Conference for Mobile Services allocated frequencies on a worldwide basis for planned land mobile satellite systems. In particular, the agreed uplink and downlink bands are (1) 1631.5 to 1634.5 MHz and 1530 to 1533 MHz, respectively, and (2) 1656.5 to 1660.5 MHz and 1555 to 1559 MHz, respectively.[3] The first set of bands must be shared with the maritime mobile satellite service.

Networking

A typical communications scheme shown in Fig. 1[4] consists of the following entities, each of which transmits and receives satellite signals directly:

1. A Network Management Center—monitors and controls the network operation.
2. Mobile terminals—trailers or automobiles that use the system.
3. Base stations—fixed locations that receive the satellite signals directly and that may interface with the mobile units.
4. Gateways—units that represent the public switched telephone network.

Propagation Problems

Two propagation parameters that should be established early are the required transmitter power and the receiver sensitivities associated with the mobile and satellite entities. These design requirements must be well understood because of the signal degradation caused by attenuation and multipath effects from trees and terrain in the ambient environment of the vehicle. For example, vehicles traveling along tree-lined roads may encounter persistent

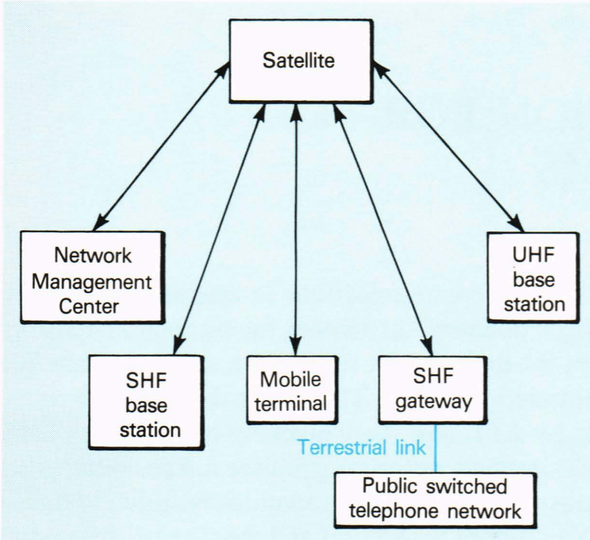

Figure 1—A typical networking scheme for a planned mobile satellite system. SHF = superhigh frequency.

shadowing of the line-of-sight propagation path. This gives rise to absorption and scattering phenomena caused by the tree trunks, branches, and foliage. Signal degradation may also result from multipath phenomena. For example, a vehicle traveling in mountainous terrain may experience signal attenuation caused by destructive interference because the line-of-sight signal (satellite to vehicle) is received out of phase with signals reflected from nearby rocks, canyon walls, or trees.

Experimental Efforts

Important questions that must be answered are "What are the attenuation levels caused by roadside trees and nearby mountainous terrain?" and "What percentage of the time might one expect a loss of communications when traveling along various types of roads?" Since 1985, APL and the University of Texas at Austin have carried out joint experiments to address these questions. The experiments involved remotely piloted aircraft and helicopters, representing the transmitter platforms (simulating the geostationary satellite), and a stationary or mobile van representing the receiving terminal. The aircraft were used in lieu of a satellite platform, which was not available. Field tests emphasizing the signal degradation caused by roadside and individual trees were performed in central Maryland in June and October 1985 and in March 1986[5,6] using both stationary and mobile vans. In August 1986, a helicopter field test in north central Colorado, in and around Boulder,[7] was directed toward measuring signal fading caused by multipath effects in mountainous and canyon terrain.

Before the ruling that L band be used in planned land mobile satellite systems, a frequency under serious consideration was in the UHF band near 870 MHz. The first three field tests (before August 1986) were performed at 870 MHz, and the Boulder-region test (after the ruling) was implemented at both UHF (870 MHz) and L band (1500 MHz). An additional field test was performed in central Maryland in June 1987 to replicate the previous tests, except that both UHF and L band were used. Unlike earlier measurements in this area, the test was performed during a season in which the trees contained maximum moisture. The data from this test showed the UHF results to be consistent with those derived previously. The L-band decibel fades were observed to be larger than the UHF values by a factor of 1.35 with an rms uncertainty of ± 0.1.[8]

SINGLE-TREE ATTENUATION MEASUREMENTS

Remotely Piloted Aircraft and Vehicle Configuration

The attenuation characteristics of individual trees were measured during the June 1985 tests[5] using a remotely piloted aircraft developed at APL.[9] The transmitting antenna was a microstrip right-circularly polarized system that was strapped to the fuselage. The antenna had a nominal beamwidth of 60°. The nominal wingspan and fuselage length were 2.5 and 2 m, respectively. The aircraft with fuel weighed 10 kg and carried a nominal payload of approximately 5 kg. The receiving antenna was mounted on the roof of a van containing the receiver and the data-acquisition equipment. The receiving antenna had a relatively flat elevation pattern function with nominal half-power beamwidths within the interval 75 to 15° (relative to the horizon).

The received signals were measured for a configuration in which the aircraft flew a straight-line path on the side of the tree opposite the van. Maximum shadowing occurred when the aircraft, tree, and vehicle were approximately aligned during a flyby; no shadowing occurred near the beginning and end of the trajectory. Path attenuations were obtained by comparing the shadowing and no-shadowing cases and by using an algorithm in which the line-of-sight received-power level (no shadowing) was compared with the maximum-shadowing power level. During flyby configurations in which the van was located on the same side as the aircraft (no tree blockage), the received signal levels replicated the pattern of the antenna on the aircraft to within a few tenths of a decibel. The dimensions of the tree were measured, and the receiving antenna's height and locations relative to those of the transmitting antenna were noted. In this way, the elevation angle relative to the receiving antenna was obtained for each run. In addition, the path length through the tree was calculated by means of simplified geometry, as shown in Fig. 2.

Similar measurements of individual trees were made in the Patapsco Valley State Park, central Maryland, in October 1985 and March 1986, using the helicopter as the source platform. Since the results of the later tests were consistent with those using the remotely piloted aircraft, the following paragraphs represent an elaboration of the June 1985 results.

Attenuation Caused by Individual Trees

For 47 aircraft flybys, the path elevation angle relative to the receiving antenna location was in the interval 10

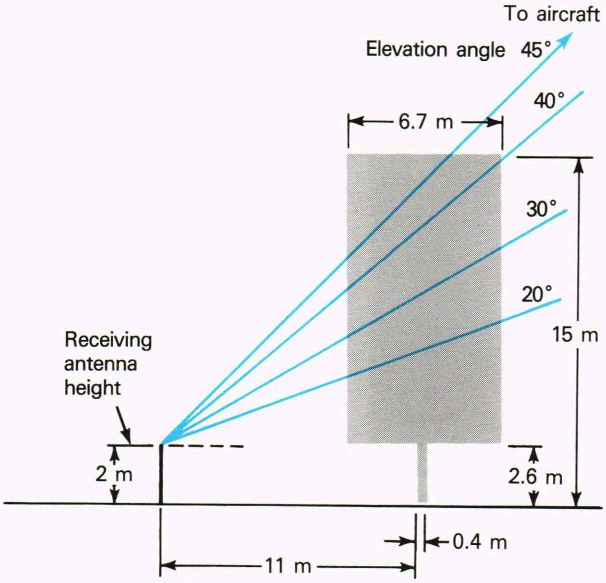

Figure 2—Simplified geometry depicting a white pine tree and the receiving antenna locations relative to remotely piloted aircraft positions for various elevation angles. The boxed area represents the region containing foliage and branches of the white pine.

Tree type	Height (m)
Holly	14
White pine	15
Burr oak	28
Pin oak	25

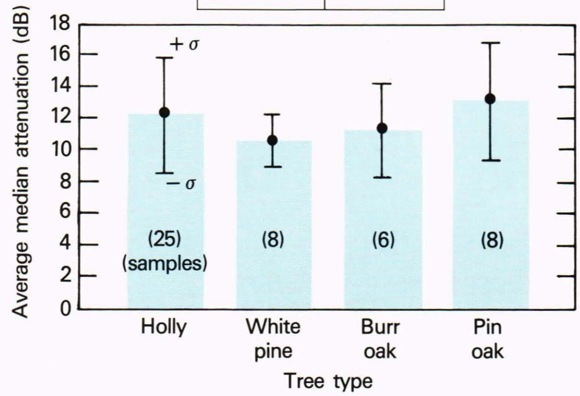

Figure 3—A comparison of median attenuations caused by different tree types for measurements made during June 1985 at the NASA Wallops Flight Facility.[5] The numbers in parentheses denote the sample size for each tree; each sample corresponds to one flyby.

to 40°. The upper angle limit was selected so that the path through each tree intersected the foliage box below the angle at which the path length decreased with increasing elevation angle. Figure 3 shows the average of the individual sampled median attenuations for the four tree types examined: holly, white pine, burr oak, and pin oak. Each median attenuation was obtained by examining 1024 measurements obtained at a rate of 1 kHz (i.e., 1.024 s per median). The average attenuations range from 10.6 dB for the white pine to 13.1 dB for the pin oak.

Table 1 summarizes the attenuation results for single trees. The second and third columns give the peak of the median attenuations and the average of the median attenuations. The fourth and fifth columns give the corresponding estimated attenuation coefficients. The peak attenuation coefficient values were generated by selecting the peak median attenuation value for the given flyby and dividing by the estimated path length through the foliage for that particular geometry. The average median attenuation coefficient values were obtained by dividing the average median attenuations by the average path length through the foliage.

Table 1—Summary of measured attenuations and derived attenuation coefficients obtained for individual tree measurements.[5]

	Attenuation (dB)		*Attenuation Coefficient (dB/m)*	
Tree Type	*Peak*	*Median*	*Peak*	*Median*
Holly	19.9	12.1	2.3	1.2
White pine	12.1	10.6	1.5	1.2
Burr oak	13.9	11.1	1.0	0.8
Pin oak	18.4	13.1	1.85	1.3
Average	16.1	11.7	1.7	1.1

ROADSIDE-TREE ATTENUATION MEASUREMENTS

Helicopter and Vehicle Configurations

A Bell Jet Ranger helicopter (single engine with front and rear seats) was used for roadside-tree measurements. During the tests in October 1985 and March 1986, a single helical antenna (60° beamwidth), transmitting an 870-MHz right-circularly polarized signal, was mounted on the helicopter so that the geometric axis pointed at a depression angle of 45° relative to the horizontal. The received signal levels were measured for the configuration shown in Fig. 4. Attenuation measurements were obtained while the van moved along typical roads in central Maryland and the helicopter flew approximately parallel paths at predesignated elevation angles and fixed heights (nominally 300 m). The attenuations when the propagation path was shadowed were normalized by comparison with those when the path was unshadowed, such as at a clearing. In large part, the configuration for the March 1986 tests replicated that for the October 1985 tests. The major difference was that in the fall the deciduous trees were covered with about 80% of full foliage, whereas they were bare during the March tests.[6] As mentioned, in June 1987, measurements along the same roads were replicated at both UHF (870 MHz) and L band (1500 MHz). The trees then were also in full foliage, having the highest moisture content relative to the previous seasonal test periods.[8]

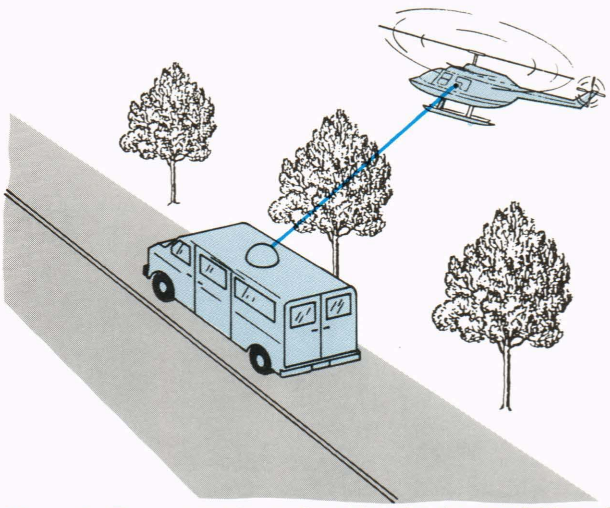

Figure 4—The geometric configuration for the acquisition of roadside-tree attenuation statistics. The helicopter is flying in the same direction as the van and parallel to it, so that the propagation path is perpendicular to the line of trees.

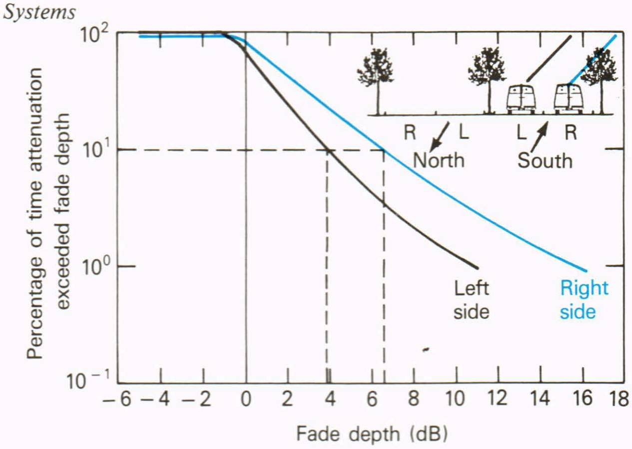

Figure 5—Cumulative fade distributions along Route 295 (south) for left- and right-side driving, October 1985. The helicopter is to the right of the van. The percentage of optical shadowing is 75%.

Cumulative Fade Distributions

The test results were analyzed in the form of cumulative distributions describing the percentage of time various fade depths (attenuation levels) were exceeded. Since the van was traveling at nominally fixed speeds (e.g., 55 mph along typical highways), the results could also be interpreted as being the percentage of the road traveled in which the attenuation exceeded given fade depths. Examples of the cumulative fade distributions caused by roadside trees are given in Fig. 5. The curves show the signal attenuation effects of right-lane versus left-lane driving for October 1985. The results were obtained from measurements made during two runs during which the van was traveling south on Route 295, and the elevation angle was 45°.

The stretch of road was about 24 km long (southerly direction between Routes 175 and 450) and was traveled in about 16 to 20 min. Route 295, the Baltimore-Washington Parkway, is a popular four-lane highway where pairs of lanes carry traffic in opposite directions. A wide median containing trees and separating the pairs of lanes narrows to a grassy strip at interchanges.

Percentage of Optical Shadowing

To assess the extent to which trees populate the roadside and cause attenuation, a quantity called percentage of optical shadowing was defined. It is the shadowing caused by the roadside trees at a path angle of 45° for driving on the right side of the road, where the path is to the right of the driver. The value was obtained by traveling at relatively constant speed, measuring the angle with an optical gauge, and noting the time shadowed with a stopwatch. For Route 295, it was about 75%.

Fade Distributions for Left Side versus Right Side of Road

We note from Fig. 5 that for 10% of the time the fade depth exceeds 6.7 and 3.8 dB for driving on the right and left sides of the road, respectively. The comparative values are consistent with the fact that left-side driving provides a configuration that is less likely to cause shadowing.

Effect of Tree Attenuation on Elevation Angle

Figure 6 shows the effects of a variable elevation angle from the van to the simulated satellite (helicopter). The curves were generated for driving on the left side of the road on Route 295 (south) at 30, 45, and 60° elevation angles for tests performed in October 1985. Fixed elevation angles were maintained by positioning the helicopter in range and altitude. The cumulative fade distributions depend critically on the path elevation angle, since at the smaller angles the frequency of tree intersection increases, as does the average path length through one or more trees. Ten percent of the time, 8.4, 3.8, and 2.7 dB are exceeded for 30, 45, and 60°, respectively.

Tree Fading Effects for Different Roads

Figure 7 shows the cumulative fade distributions for three roads traveled for the indicated geometry and for a 45° path angle during the October 1985 field tests in central Maryland. Route 108 is a well-traveled, relatively narrow, two-lane secondary road (between Routes 32 and 97, a distance of 15 km) lined with utility poles and trees along significant stretches. The percentage of optical shadowing was 55%. Route 32 (between Routes 108 and 70, a distance of 15 km) is a two-lane secondary road lined on both sides with trees that are less densely spaced and located farther from the road edges than the trees along Route 108. The percentage of optical shadowing for this road was 30%. For the three roads indicated, the trees range in height from about 5 to 30 m. The cumulative distributions for Routes 295 and 108 practically overlap, whereas the Route 32 fade values for the same percentages are considerably less. For example, the 10% levels show approximately 7 and 3 dB, respectively.

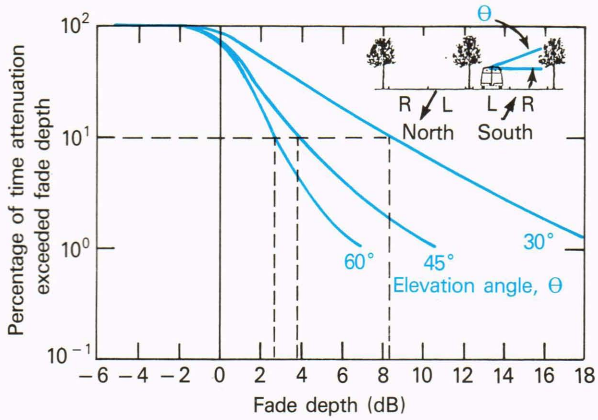

Figure 6—Cumulative fade distributions for different path elevation angles along Route 295 (south) for left-lane driving, October 1985.

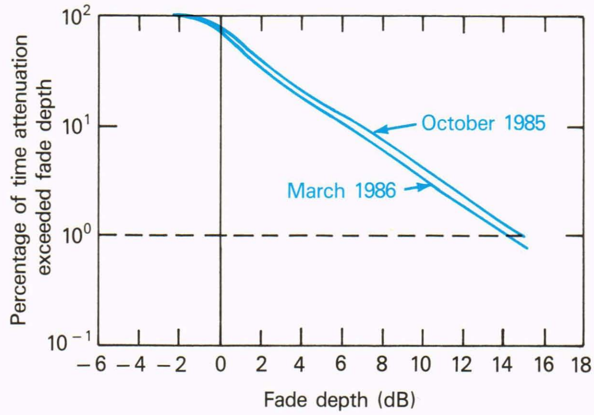

Figure 8—A comparison of cumulative distributions for March 1986 and October 1985 along Route 108 (southwest). The helicopter is to the left and the path angle is 45°. The percentage of optical shadowing is 55%.

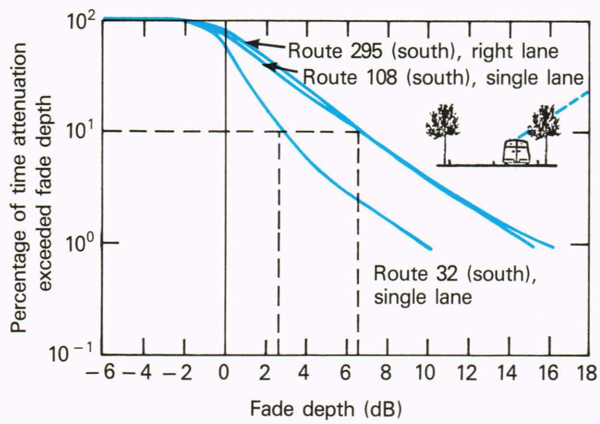

Figure 7—A comparison of the cumulative fade distributions along different roads for a path angle of 45° and for the relative geometry shown in the sketch, October 1985. The percentages of optical shadowing for Routes 295, 108, and 32 are 75, 55, and 30%, respectively.

Effects of Leaves on Signal Attenuation

As previously mentioned, during the October 1985 tests in central Maryland the deciduous trees contained about 80% of full foliage, whereas the same trees were bare during the March 1986 tests. A comparison of the fade distributions derived for the two cases gives a measure of the additional contribution caused by leaves. Figure 8 compares the cumulative distributions, demonstrating the effects of leaves for Route 108 at the 45° path angle. The attenuation increases caused by leaves are 11 and 6%, corresponding to 10 and 1% of the time, respectively. For the example given, this amounts to an addition of approximately 1 dB or less caused by leaves. Other comparisons of fade distributions (leaves versus no leaves) showed fade enhancements of less than 25% at the 1 and 10% probability levels. A caveat must be kept in mind when making the above comparisons: about 80% of full foliage was present in the fall, the leaves were dry, and the branches contained minimum moisture. As already mentioned, the measurements were repeated in June 1987, during a full foliage period when the leaves and branches contained maximum moisture. Analysis of these data showed that the foliage increased the fade by approximately 20% for 1% of the time.[8] Comparisons of the attenuations caused by individual trees (as measured in June 1985 using a remotely piloted vehicle)[5] with single-tree measurements in October 1985 and June 1986[7] also corroborate the contention that most of the attenuation is due to the branches and trunks of trees and that minimal effects are caused by the leaves.

MULTIPATH FADING IN HILLY AND MOUNTAINOUS TERRAIN

Background

A typical multipath situation that may exist for a mobile satellite system is one in which direct (unshadowed) signals are received by the antenna system along with scattered paths (multipaths) from the sides of cliffs and/or nearby trees. The received signals may add up either constructively or destructively and may result in signal enhancement or fade. Implicit in the resultant signals are the scattering cross sections of the multipath reflectors, their distances to the antenna, and the filter characteristics of the receiving antenna pattern.

Polarization rotations of the signal vectors caused by the ionosphere at L band and UHF are expected to be 22 and 66°.[10] For this reason, circular polarization has been chosen for the planned mobile satellite system because it is not sensitive to polarization rotation. Tropospheric effects are not expected to be important except at near-grazing angles (less than 5° elevation angles), where refraction effects and subsequent fading may occur.

The experimental configuration for the August 1986 canyon tests in the Boulder region consisted of a helicopter as the source platform that maintained a relatively fixed geometry with a mobile van containing the receiver and the data-acquisition system. An unobstructed line of sight between the radiating sources and the receiving van was, for the most part, maintained. In this way, the dominant mechanism causing signal fading (or enhancement) resulted from multipath effects. A major consideration addressed in this effort was the relative seriousness of the multipath problem, compared with roadside-tree shadowing, in assessing required fade margins for planned land mobile satellite systems. Both UHF (870 MHz) and L band (1500 MHz) were considered. The canyon passes were selected because they were believed to represent worst-case environments for multipath effects in a non-urban environment.

Experimental Features

For this test, the UHF antenna had a microstrip configuration, and the L band antenna was a helix. Both were right-hand circularly polarized and had beamwidths of approximately 60°. The two antennas were located below the aircraft on a steerable mount whose pointing was controlled by an observer inside the helicopter. Also on the steerable mount was a video camera with a field of view about half the beamwidth of the antennas. The experimenter inside the aircraft was able to observe and center the scene viewed by the camera as it appeared on a television screen. In this way, the geometric pointing axes of the antennas were kept nearly coincident with the direction to the van. The pilot, using a barometer/altimeter system, maintained a nominal height of 300 m above the van. The depression angle relative to the horizontal (elevation angle to the van) was kept fixed by means of an angle gauge with a digital readout, also appearing on the television screen. With the height and the depression angle kept constant through pilot maneuvering of the aircraft, the range to the van was also kept fixed (i.e., at about 430 m for the 45° depression angle).

Geographic Characteristics

The tests were performed within three canyons: Boulder Canyon (Route 119, west of Boulder), Big Thompson Canyon (Route 34, 40 km north of Boulder in the Loveland area), and Poudre Canyon (Route 14, 70 km north of Boulder in the Fort Collins area). Along each of these canyon roads, the walls were highly variable in slope, height, foliage overlay, and distance from the road. At many locations, the walls consisted of randomly oriented rock facets and patches of trees, and the roads made many twists and turns, offering highly variable aspects to the multipath illumination scene. With the helicopter height of 300 m and the antenna beamwidth of 60°, the illuminated ground area was elliptical, the shortest axes exceeding 300 m. Twelve runs were made in the three canyons. The elevation angles were either 30 or 45°; the helicopter followed the van in 11 of these runs, maintaining predominantly unobstructed line-of-sight propagation. Because the scenic aspects were different when the van traveled into and out of a canyon, those cases represent independent runs and are referred to as "up" and "down" cases, respectively, in the following paragraphs.

Comparison of Multipath Effects at UHF and L Band

At the smaller percentages of time in the cumulative fade distributions (higher fades), the L-band fades generally exceeded slightly the UHF values; the maximum difference at the 1% level was only 1.3 dB. The cumulative fade distributions depicting this result are shown in Fig. 9 for Big Thompson-down. Figure 10 is a plot of the average ratio of the L-band fade to the UHF fade versus the percentage of time the particular fade is exceeded. The averages (data points in Fig. 10) were obtained from the individual ratios of the L-band fade, $A(L)$, to the UHF fade, $A(U)$, for the different cases pertaining to all the canyon runs (an average of 12 ratios). The solid curve represents the associated best-fit line. Ratios above 10% were statistically noisy since the fades were very close in value, and therefore were not considered. The ratios of fades are approximately within the interval 1.01 to 1.14, corrresponding to the 10 and 1% levels, respectively. The best-fit line in the percentage range may be expressed by

$$R_f = \alpha + \beta \cdot P , \quad (1)$$

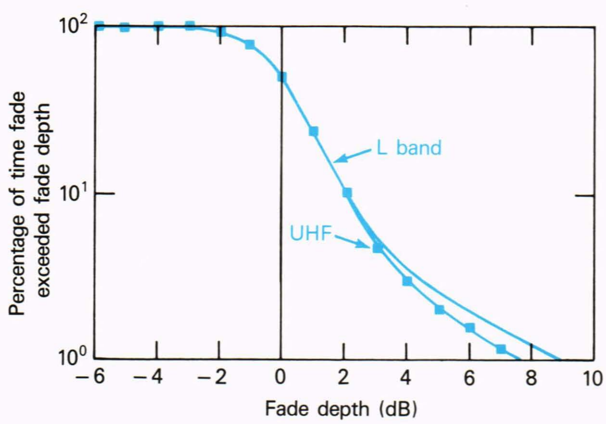

Figure 9—Cumulative fade distributions at UHF and L band through Big Thompson-down at 30° elevation angle (run 2).

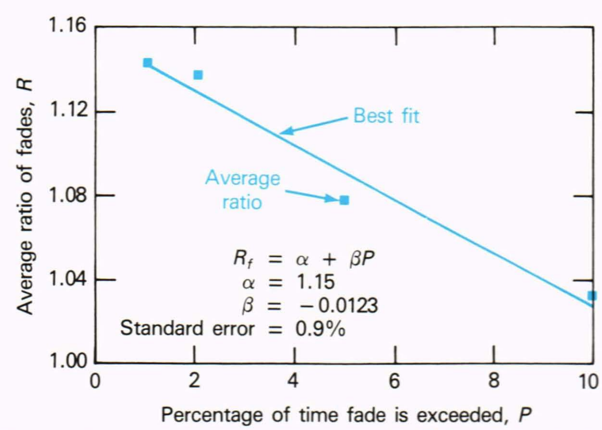

Figure 10—Average ratio for L-band to UHF fades versus the percentage of time the fade is exceeded.

where

$$R_f = \frac{A(L)}{A(U)} , \quad (2)$$

$$\alpha = 1.15 , \quad \beta = -0.0123 , \quad (3)$$

and $A(L)$ and $A(U)$ correspond to the average L-band and UHF fades at the corresponding percentage, P, respectively. In arriving at R_f, the ratios at the 45° elevation were combined with those at the 30° elevation. These ratios were relatively insensitive to path angle (e.g., 1% differences on the average).

A small amount of tree fading may have been present, and may have contributed to the larger fades at L band relative to UHF near the 1% level. If tree fading were present, L band would be slightly more attenuating than UHF. Although attempts were made to position the helicopter so that the direct energy was unshadowed, there may have been some time intervals when the winding roads and complex terrain did not allow this.

Dependence of Multipath Effects on Elevation Angle

Figure 11 shows typical distributions of the dependence of multipath fading on elevation angle. The larger fades occur at the smaller angles (e.g., 30°). For the case shown (Big Thompson-up), the 30° distribution exhibits approximately 4 dB more fade at the 1% level than does the 45° distribution.

Figure 12 plots the average ratios, R_a, of the 30° fade, $A(30°)$, to the 45° fade, $A(45°)$, for both L band and UHF, versus the percentage of time either the L-band or the UHF fade is exceeded. The ratios were computed from the data of eight runs corresponding to tests at Big Thompson and Boulder Canyon. Also plotted in Fig. 12 are the least-squares-fit power curves having the form

$$R_a = \alpha P^{\beta} , \quad (4)$$

where

$$R_a = \frac{A(30°)}{A(45°)} . \quad (5)$$

At UHF

$$\alpha = 1.62 , \quad \beta = -0.135 , \quad (6)$$

and at L band

$$\alpha = 1.55 , \quad \beta = -0.139 . \quad (7)$$

The enhanced fades at the 30° elevation angle relative to those at 45° may be attributed to several causes.

1. The direct signal is weighted by the antenna pattern, which peaks in gain nominally at 45° and is down slightly at 30°. The reduced direct signal combines with the multipath signals that are received by the antenna at all elevation angles. One might expect, then, that the interfering signals would have greater weight when combined with the direct energy received at the smaller elevation angles.
2. Tree-shadowing phenomena may arise at the smaller elevation angles, since in that configuration the energy is more likely to be shadowed by the foliage and branches some of the time.
3. Illuminated surfaces that dominate the multipath effects may be at heights closer to the vehicle antenna height. For example, assuming vertically reflecting facets, a vehicle antenna 2.4 m high and 4.5 m from the canyon wall will have a specular reflection point at a height of 5 m for 30° and at 7 m for 45°. The facets at the lower heights will dominate if there are more of them with the proper orientation.

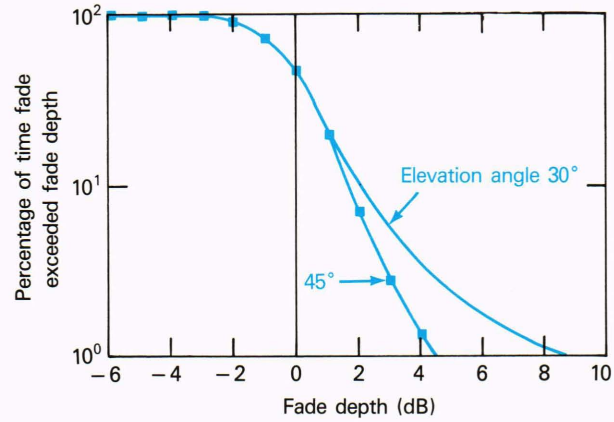

Figure 11—Cumulative fade distributions for L band at 30 and 45° elevation angles through Big Thompson-up.

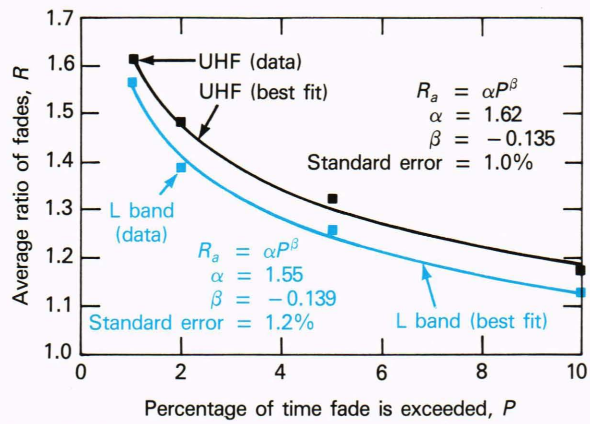

Figure 12—The average ratio of 30 to 45° fades versus percentage of time the fades are exceeded.

Comparison of Multipath Fading Results with Findings of Other Investigations

In arriving at the cumulative distributions caused by multipath fading, the direct ray was maintained in an unshadowed state. A fundamental question that arises is how the multipath-dominated distributions compare with those in which shadowing from roadside trees is the major cause of fading. Figure 13 compares the worst-case (greatest fades) multipath distribution at UHF (Big Thompson-down at 30° elevation angle) with a distribution, obtained by the authors for the same frequency and a path angle of 45°,[6,7] dominated by roadside-tree shadowing. The two distributions are dramatically different. At the 1 and 5% levels, roadside-tree attenuation exceeds multipath fades by 8 and 6 dB, respectively.

In Fig. 14 we compare the UHF fade distributions for four experimental investigations.[6,7,11,12] The vertical scale represents the signal level in decibels, where negative and positive values denote signal fades and enhancements, respectively. This designation is the opposite of the previous notation. The abscissa, which has a Gaussian scale, represents the percentage of time the received signal levels exceeded the ordinate values. It may be noted that the multipath distribution (curve H, Big Thompson-down at 30°) lies between curves E and F for signal levels smaller than −1 dB. Distributions E and F were obtained from measurements by Vogel and Torrence,[11] who located their UHF source on a stratospheric balloon and received the signal levels while the van moved along roads in east Texas and Louisiana. Their distributions correspond to path angles flanking 25 to 35°, demonstrating consistency with the canyon measurements, which were taken at 30°.

The similarity between the canyon multipath distribution (curve H) and the balloon results of Vogel and Torrence (curves E and F) may be attributed, in part, to the similar path elevation angles for the three curves (e.g., 30°). At the higher elevation angles of Vogel and Torrence, line-of-sight propagation was the dominant mode for which multipath effects gave rise to the corresponding fading. The fade part of the distributions was therefore dictated for the most part by similar levels of destructive interference caused by multipath propagation. The proximity of curves E and F to curve H is considered fortuitous; the enhanced-signal portions of the canyon curve (constructive interference) caused by multipath effects closely agree with those of Butterworth and Matt[12] (curves A and B). Distributions A and B were obtained from measurements performed in a 35% wooded region west of Ottawa. Also shown in Fig. 14 is the distribution for roadside-tree attenuation, curve G, which is flanked by curves A and B.

SUMMARY AND CONCLUSIONS

The major objectives of this work were to determine signal attenuation characteristics caused by roadside trees and hilly terrain at UHF and L band. Such information is vital to establish fade margin requirements in the design of a planned mobile satellite system. Since the planned satellite system is to be geostationary, a knowledge of realistic fade margin levels is essential in establishing satellite antenna size and transponder power levels. Other objectives of the experimental efforts were to explore methods by which signal attenuation may be mitigated.

Single-tree attenuation data acquired using a remotely piloted aircraft at Wallops Island and a helicopter in central Maryland have demonstrated that the nominal median attenuation at 870 MHz is 12 dB. Measured average attenuation coefficients corresponding to repeated measurements of the attenuation caused by canopies of

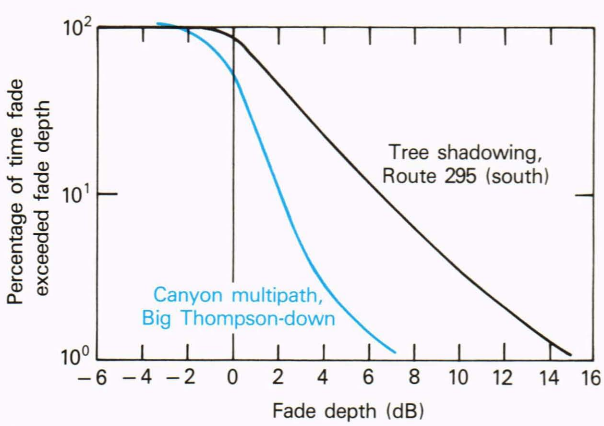

Figure 13—A comparison of cumulative fade distributions for roadside-tree shadowing and canyon multipath effects at UHF. The canyon data are for a 30° elevation angle down (worst case) and the tree-shadowing curve is for an elevation angle of 45°.

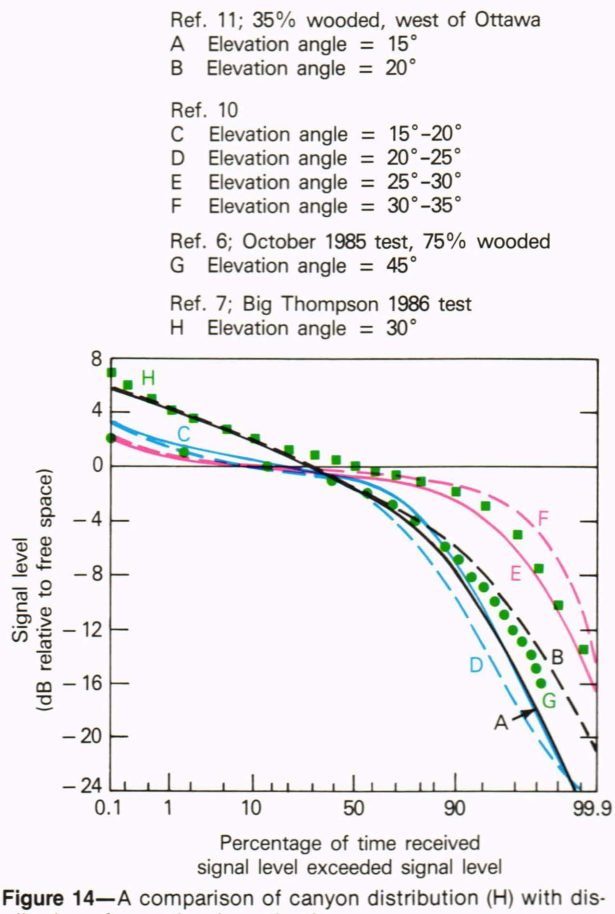

Figure 14—A comparison of canyon distribution (H) with distributions from other investigations.

single trees ranged from 0.8 to 1.3 dB/m for different tree types, with an overall average of 1.1 dB/m.

Roadside-tree attenuation statistics have demonstrated several important features:

1. Significant reductions in fade may be achieved by driving on the side of the road corresponding to minimum shadowing. For example, Fig. 8 demonstrates that for the percentage of time corresponding to a 10-dB fade, representing the worst side (right side), 4 dB may be saved by switching lanes.
2. The elevation angle to the satellite is expected to play an important role in establishing the fade levels for roadside-tree attenuation. Higher elevation angles mitigated the signal fading considerably (Fig. 6). Similar comments may be made for the multipath effects (Fig. 11). Figure 6 shows, for example, that for 10% of the time approximately a 6-dB difference exists between the distributions corresponding to 30 and 60° elevation angles. These results suggest that we should select satellite locations so that higher elevation angles are achieved for critical geographic regions.
3. Roadside trees along four-lane highways may contribute as much attenuation as those along two-lane highways, or even more (Fig. 7). The frequency of tree interception, the path length through the trees, and the density of branches and foliage dictate the extent of fading.

Where multipath effects constitute the dominant fading mechanism, the average fades at the 1 and 5% levels were, respectively, 5.5 and 2.6 dB at L band and 4.8 and 2.4 dB at UHF. Roadside-tree attenuations may exceed those produced by multipath effects by at least 8 and 5 dB at the 1 and 5% levels, respectively, demonstrating that tree attenuation is the deciding factor in determining fade margins for a future mobile satellite system.

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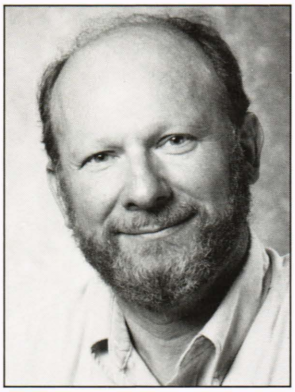

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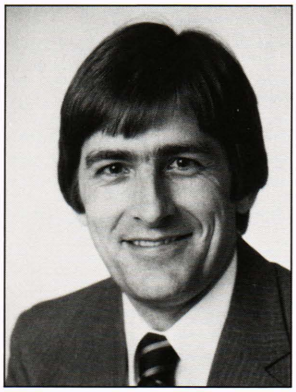

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