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MOBILE SATELLITE PROPAGATION MEASUREMENTS AND MODELING: A REVIEW OF RESULTS FOR SYSTEMS ENGINEERS

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ABSTRACT

This overview of Mobile Satellite System (MSS) propagation measurements and modeling is intended as a summary of current results. While such research is on going, the simple models presented here should be useful to system engineers. A complete summary of MSS propagation experiments with literature references is also included.

INTRODUCTION

This paper is a collective effort by a group of researchers in the U. S. and Canada in the area of Land Mobile Satellite propagation. It concerns the propagation effects of the natural environment as encountered under highway conditions at UHF and L-Band frequencies. It presents results, experimental and theoretical, that are applicable to future operational Mobile Satellite Systems (MSS). Our understanding of MSS propagation is by no means complete. Much needs to be done both in measurement and in theory. This review is essentially a summary of the current state of knowledge.

This paper emphasizes results, not the details of how experiments were performed or the theoretical background of the models developed. A comprehensive list of MSS related propagation experiments is presented (see Table 1); literature references for these experiments as well as for key theory and modeling works are given.

CHARACTERISTICS OF MSS PROPAGATION EFFECTS

MSS communications system design presents new problems. Mobile terminals do not have the fixed-terminal advantage of placing antennas with a clear line of sight view to the satellite. Instead, a mobile with a roof mounted antenna will encounter several propagation effects that will influence the system margin, reliability, and modulation format selection. These may be classified as follows:

(a) Tree shadowing of the direct wave
(b) Blockage from natural terrain and structures like overpasses
(c) Multipath scattering from terrain, and from simple scatterers like utility poles

Specular reflection is not significant above 15 degrees elevation with circularly polarized antennas [5] and therefore, we have not listed it as a propagation problem. Blockage from structures such as overpasses has been noted by Vogel during his balloon experiments [9]. They are obviously serious short term blockage problems but are not statistically significant. This paper does not include structure blockage effects, but concentrates on vegetative blockage and multipath scattering.

MSS PROPAGATION RESEARCH LITERATURE

Overview

The MSS propagation problem is attacked on three fronts: experimental, basic EM theory, and modeling. The most important of these is the establishment of an experimental data base. Satellite, helicopter, balloon, remotely piloted aircraft and tower platforms have been used, and most results appear to be applicable to satellite-to-earth mobile systems. This data base serves two purposes. First, it may be used for system planning if data of the proper frequency, elevation angle, etc. are available or can be scaled. Second, experimental data are used in verifying theoretical models and to drive software simulators.

Complete analytical solutions from electromagnetic theory are not available due to the complexity of the propagation environment, but partial analytical and empirical statistical models of MSS propagation have been developed [14, 20, 21, 22]. These offer considerable insight into the physics of slant path propagation.

The mobile aspect of MSS propagation complicates the problem. Theoretical models do not provide complete information on the variation of the parameters in terms of highway and system constraints. Simple empirical models can be developed to give fade statistics for simple relationships with the highway and system parameters as inputs.

Experiments

Mobile satellite propagation experiments have been conducted since 1978. Table 1 presents a chronology of slant path propagation experiments in the UHF and L-bands. Most of the experiments produced fade depth and duration statistics for various mobile travel conditions. Some results from these are given in following sections.

Some experiments also collected phase data. The peak-to-peak variations of the phase, Φ , as a function of peak-to-peak signal level fluctuations in dB, L, can be expressed by [14]

$$\Phi = c * L \quad \text{[degrees]} \qquad (1)$$

where

c =	6.0	analytical value	for unshadowed multipath
	7.6	90th percentile }	measured, includes
	3.9	median }	shadowing for fades up
	2.1	10th percentile }	to about 15 dB

The signal arriving at an MSS receiver has two components: a direct path component which can experience shadowing, and a diffuse component that is the sum of signals reflected from nearby objects. Campbell has performed experiments focusing on characterization of the diffuse component, which is quantified by the power level relative to the unattenuated direct signal power, $\overline{K}$, and the spatial distribution of arrival angles for the diffuse power. The measurements were made at 1300 MHz at several elevation angles near 10 degrees along a section of a hardwood tree lined road in upper Michigan. The average total diffuse signal power is 17 dB below the unattenuated direct path signal. The diffuse signal has a rather even angular distribution, except for trees within about 100 m of the receiver which have significant contributions. The diffuse component is relatively unaffected by instantaneous blockage of the direct component; therefore, during deep fading the diffuse component will dominate.

FADE DISTRIBUTIONS

Form Of The Fade Distribution

Both experimental observations and basic theory indicate that the fade statistics measured over a large distance become Rician at low fade levels because of the dominant multipath effects. For high fade levels a number of experiments indicate that they become lognormal when vegetative shadowing dominates. Thus, MSS fading is modeled by a Rician distribution, described by the carrier-to-multipath ratio K, to predict fading when there is no blockage of the signal. When tree blockage is present, the fading is modeled by the sum of a lognormal distribution, described by the mean, μ, and standard deviation, σ, and a Rayleigh distribution, described by $\overline{K}$, the carrier-to-multipath ratio. Bradley and Stutzman [20] showed how these distributions can be combined for an arbitrary percentage of shadowing along the travel route; apparently Lutz et al. [11] found this independently.

Experimental Results

Representative experimental results are plotted in Fig. 1. Shown are cumulative fade distributions over typically tens of km of road distance [18]. The distributions depend strongly on the elevation angle when shadowing by roadside trees dominates. A four-lane divided freeway lined with trees (Fig. 1a) can produce larger fades than a two-lane road lined with utility poles and trees (Fig. 1b). In comparison, a road with a wider cleared easement, even though tree lined (RT. 32), will have smaller probabilities. Measurements obtained at UHF on a road for various growing seasons (Leafless, March 1986; Fall Foliage, October 1985; Full Blossom, June 1986) show only a small increase in attenuation due to leaves (Fig. 1c).

To scale UHF data to L-Band, the relationship

$$F_L = (1.35 + 0.1)*F_U \quad (3)$$

can be used where F_L and F_U are the L-Band and UHF fades in dB, respectively [18]. A comparison of distributions obtained in differing geographic areas (Fig. 1d) emphasizes the dependence of the distribution on the dominating environmental parameters, from heavy tree shadowing (Curve A) to pure multipath (Curve G).

<u>Simple Model</u>

A simple model for predicting the probability that the fades will be less than a certain amount F is given by [23]

$$C(F) = C_u(F)*(1-s) + C_s(F)*s \quad (2)$$

where

F = fade level with respect to LOS in dB
s = fraction of time vegetative shadowing occurs along travel route

and where

$$C_u(F) = e^{-(F+U_1)/U_2}$$

= fade distribution for an unshadowed signal

$$U1 = 0.01*K^2 - .378*K + 53.98$$
$$U2 = 331.25*K^{-2.29}$$
K = carrier-to-multipath ratio [dB]

and where

$$C_s(F) = [(50-F)/V_1]^{V_2}$$

$$V1 = -0.275*\bar{K} + 0.723*\mu + 0.336*\sigma + 56.153$$
$$V2 = [-0.006*\bar{K} - 0.008*\mu + 0.013*\sigma + 0.103]^{-1}$$
$\bar{K}$ = carrier-to-multipath ratio [dB]
μ = mean of lognormal signal [dB]

σ = standard deviation of lognormal signal [dB]

The percent time that the fade F is exceeded is then found from (2) simply as P=100*C(F).

This simple model is valid for typical ranges of the propagation parameters. Typical values for each of the parameters are as follows:

$$13 \text{ dB} < \underline{K} < 22 \text{ dB}$$
$$12 \text{ dB} < \overline{K} < 18 \text{ dB}$$
$$-1 \text{ dB} < \mu < -10 \text{ dB}$$
$$0.5 \text{ dB} < \sigma < 3.5 \text{ dB}$$

Behavior Of Statistical Parameters With Time

Cumulative fade distributions give information about the average link performance for a large number of transmissions for particular environmental conditions. A typical telephone call has a shorter duration (about 90 seconds) and therefore covers a shorter distance than the one on which Fig. 1 is based. When cumulative fade distributions are determined for successive 90 second intervals, they will vary, depending upon the short term variation of the shadowing parameter statistics. At percentage levels of main interest, from 1% to 20%, the 10th, 50th and 90th percentiles of the 90 second fade levels have been calculated and are given in Fig. 2 for elevation angles of 30, 45 and 60 degrees. The curve labeled median represents the median cumulative fade distribution and the upper and lower curves give the bounds into which 80% of the measured distributions fall. The curves can be fit by the relationship:

$$F(n,P) = A(n)*\ln(P) + B(n) \tag{4}$$

where

F(n,P) = Fade at nth percentile for P percent of time fade is exceeded
A(n), B(n) = fit coefficients (see Table 2)

Hence, these experimental results indicate that over the limited percentage interval a simple logarithmic relationship holds.

FADE DURATIONS

Measured fade durations for a 5 dB threshold are given in Fig. 3. The curves correspond to the combined results of repeated runs along several roads at the indicated elevation angles, both under predominantly shadowing or under multipath conditions. Two sets of statistics are provided, "fade durations": the duration the signal is below the threshold and "nonfade durations": the duration the signal is greater than the threshold. The duration is expressed as spatial variable in wavelengths (0.2m) to gain independence from the vehicle speed. The durations are seen to systematically depend upon the elevation angle for the shadowing data. The lower the elevation, the longer the fades and the shorter the nonfades. Multipath durations are independent of the elevation angle, having very short fades and long nonfades.

The distribution of fade durations cannot in general be predicted analytically. Schmier and Bostian have reported a software simulator [24] which they claim will accurately predict the fade duration statistics of a signal whose cumulative fade distribution is known. The simulator operation is based on scaling values from a universal data set. Its predictions of the total number of fades exceeding specified thresholds agree well with experiment, but unpublished work by Barts indicates that it may not predict average fade durations well. Barts' work indicates that Schmier and Bostian's simulator works correctly, but its universal data set may have been incorrectly derived. Each side can make an effective case for the correctness of its results, and at the time this paper was written the issue was still unsettled.

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CUMULATIVE DISTRIBUTIONS FOR ROUTE 295 SOUTH (RHS)
COMPARISON FOR DIFFERENT ELEVATION ANGLES AT L-BAND

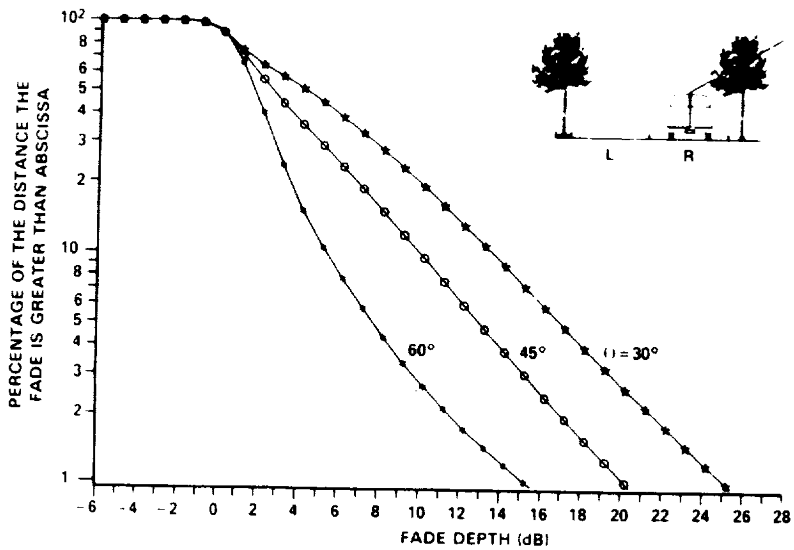


Figure 1a

COMPARISON OF CUMULATIVE FADE DISTRIBUTIONS
FOR VARIOUS ROADS AT AN ELEVATION ANGLE OF
45° FOR L-BAND

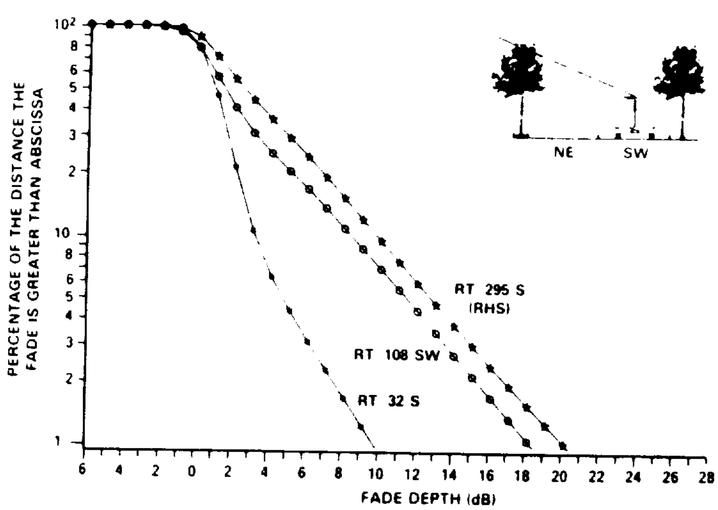


Figure 1b

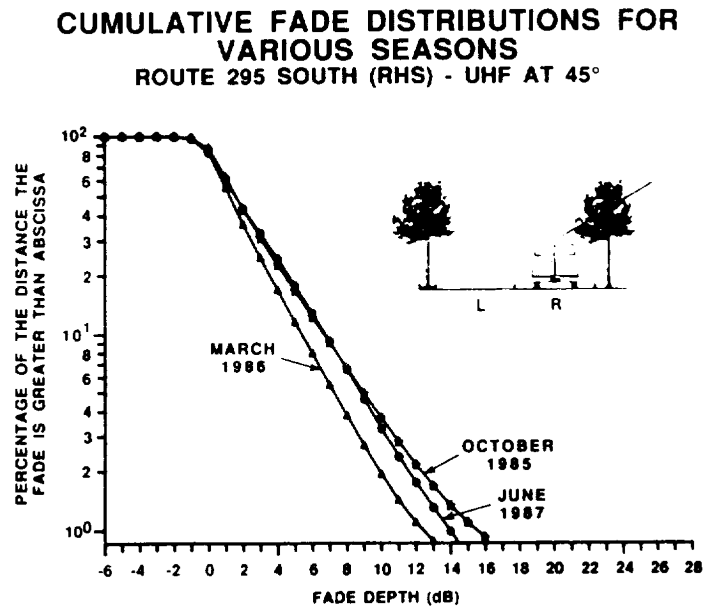


Figure 1c

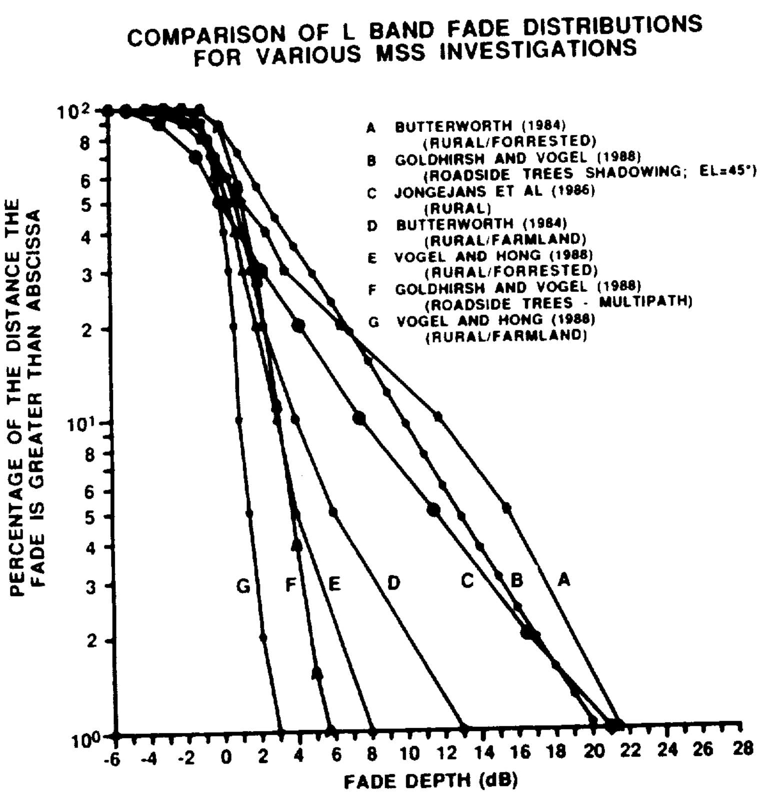


Figure 1d

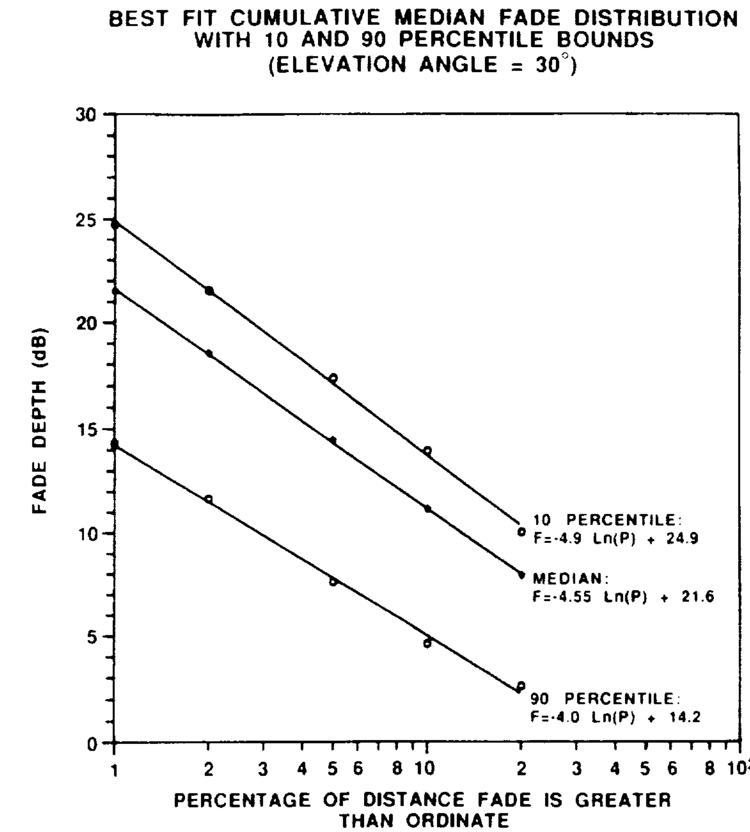
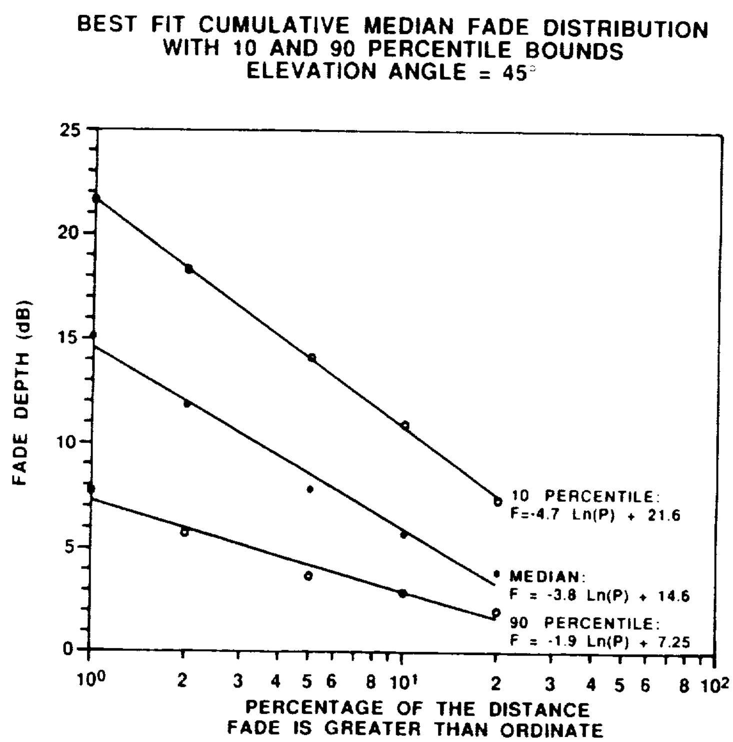


Figure 2a



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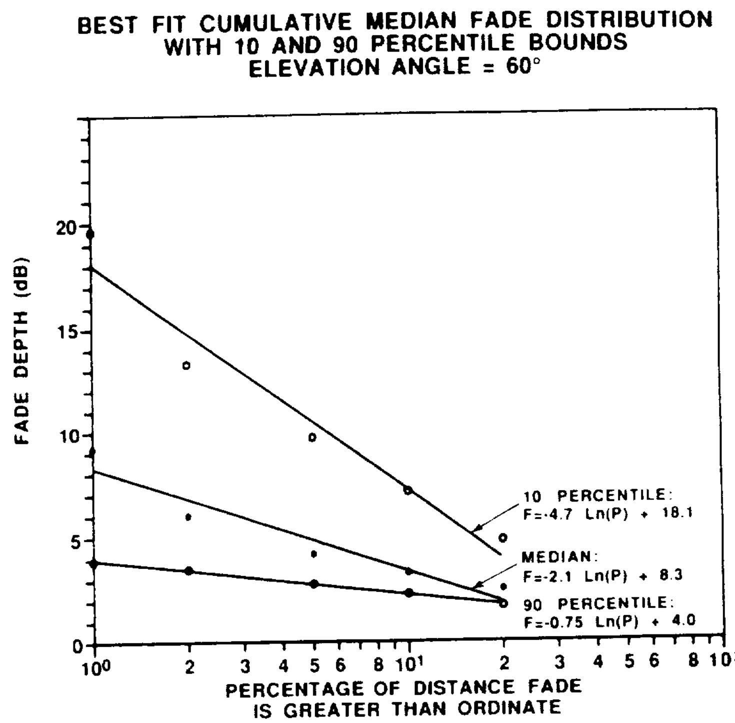

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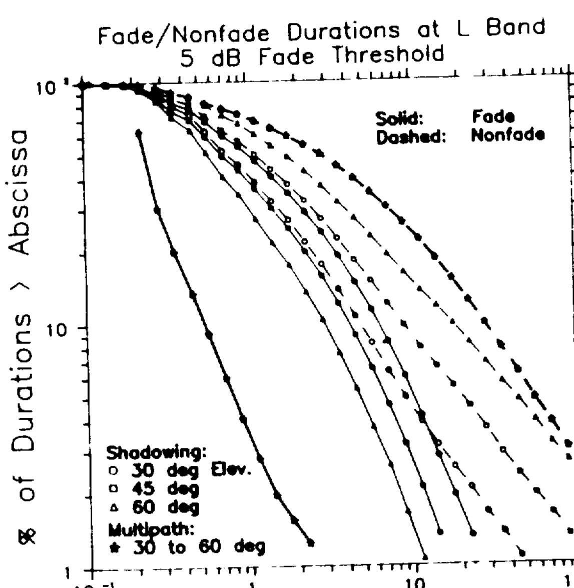

Figure 3

Table 1

Summary of Slant Path UHF/L-Band Land Mobile Propagation Experiments

Entry No.	Investigators	Date	Source	Freq (MHz)	Comments
1	Hess[1,2] (Motorola)	3/78	ATS-6	860 1550	Mostly cities: Chicago to San Francisco; whip antenna for receive; found shadowing more important than multipath
2	Anderson[3,4] (GE)	78	ATS-6	1550	Voice to trucks; CP; low elevation angles; concluded works well in non-urban areas but vegetation causes dropouts; multipath not a problem
3	Butterworth[5] (CRC)	4-11/81	Tower	840	Static tests
4	" [5]	82	Tethered Balloon	840	
5	" [5]	9/82	Helicopter	870	15o elevation
6	" [6]	6/83	Helicopter	870	5o,15o,20o elevation
7	" [7]	11/82	MARECS A	1542	19o elevation, no leaves
8	" [6]	6/83	MARECS A	1542	19o elevation, with leaves
9	Vogel[8] (Univ. Texas)	10/83 1/84	Balloon	869	Pooled; 10 to 35o elevation; also processed by elevation angle interval; frequent tree shadowing
10	Vogel[9]	11/84	Balloon	869 1501	
11	Bultitude[10] (CRC)	85	Tower	800 900	Spread spectrum measurements
12	Lutz, et al.[11] (DFVLR)	83-84	MARECS	1540	Germany measurements
13	Jongejans, et al.[25] (ESTEC)	1/84-7/84	MARECS	1540	Measurements made in Europe
14	Vogel/Goldhirsh[12]	6/85	RPV	869	Single trees; Wallops Island; van stationary
15	Goldhirsh/Vogel[13]	10/85 3/86	Helicopter	870	80% leaf shadowing No leaves
16	Vogel/Hong[14]	7/86	Balloon	870 1502	Open land; 20 to 59o el, 35o el typical; 2 to 8 o'clock azimuth; 9% level= 3 dB
17	Vogel/Goldhirsh[15]	8/86	Helicopter	870 1502	Canyons and mountains in CO; multipath
18	PiFex[16,17] (JPL)	3/87	Tower	870	No propagation data avail.
19	Goldhirsh/Vogel[18]	6/87	Helicopter	870 1502	Full leaf; 30o,45o,60o fixed elevation runs
20	Vogel/Goldhirsh[19]	12/87	MARECS A	1541	21o elevation angle

Table 2

Fit Coefficients for Equation (4)

nth Percentile	Elevation Angle (deg) 30		45		60	
	A(n)	B(n)	A(n)	B(n)	A(n)	B(n)
10	-4.9	24.9	-4.7	21.6	-4.7	18.1
50	-4.6	21.6	-3.8	14.6	-2.1	8.3
90	-4.0	14.2	-1.9	7.3	-.8	4.0