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Extended Empirical Roadside Shadowing Model from ACTS Mobile Measurements

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Abstract

Employing multiple data bases derived from land-mobile satellite measurements using the Advanced Communications Technology Satellite (ACTS) at 20 GHz, MARECS B-2 at 1.5 GHz, and helicopter measurements at 870 MHz and 1.5 GHz, the Empirical Road Side Shadowing Model (ERS) has been extended. The new model (Extended Empirical Roadside Shadowing Model, EERS) may now be employed at frequencies from UHF to 20 GHz, at elevation angles from 7° to 60° and at percentages from 1% to 80% (0 dB fade). The EERS distributions are validated against measured ones and fade deviations associated with the model are assessed. A model is also presented for estimating the effects of foliage (or non-foliage) on 20 GHz distributions, given distributions from deciduous trees devoid of leaves (or in full foliage).

1.0 Background

The Empirical Roadside Shadowing (ERS) is a formulation which describes the probability of exceeding Earth-satellite signal attenuation at frequencies between UHF (870 MHz) and S-Band (2.7 GHz) due to roadside trees for mobile scenarios [1,2]. This model was derived from systematic helicopter-mobile and satellite-mobile measurements over approximately 600 km of driving in central Maryland employing transmitters on helicopter and satellite platforms [2–4]. It corresponds to the median of a set of distributions (at fixed elevation angles) which describe roadside tree attenuation for highway and rural road scenarios with optical tree shadowing (at 45°) ranging between 55% to 75%; implying tree populations of at least this amount over the stretches driven. It corresponds to a worst case vehicle-satellite pointing aspect; namely, that in which the Earth-satellite path is orthogonal to the line of roadside trees. It also represents an overall average of various driving scenarios encompassing right and left lane driving, and opposite directions of travel along tree-lined highways and rural roads. In the acquisition of the data base, the dominant cause of attenuation was tree canopy shadowing where multipath fading played only a minimal role. The validity limitations of the model are enumerated as follows: (1) The probability range is from 1% to 20%. (2) The frequency interval is from 0.87 - 2.7 GHz. (3) The elevation

angle range is from 20°–60°. (4) The population of trees along the road is at least 55% of the distance driven. (5) The aspect of the Earth-satellite path is such that it cuts the line of roadside trees approximately orthogonal. An extended EERS model (EERS) is presented here which expands the first three of the above validity ranges as follows: (1) The probability interval ranges from 1% to 80%. (2) The frequency interval is from 0.87–20 GHz. (3) The path elevation angle ranges from 7° to 60°.

In deriving the EERS model, use was made of the original previously developed body of data at UHF and L-Band in central Maryland as well as more recently developed data bases. The more recent data bases correspond to mobile L-Band measurements of transmissions from MARECS B-2 in western United States [5], static K-Band measurements in Austin, Texas [6], and mobile K-Band measurements employing transmissions from the Advanced Communications Technology Satellite (ACTS) [7–9]. These latter measurements were performed during the first six months of 1994 during which a series of four 20 GHz mobile-ACTS campaigns were executed. The campaigns were performed in central Maryland (March, elevation = 39°), Austin, Texas (February and May, elevation = 55°), and Fairbanks, Alaska and environs (June, elevation = 8°) [7–9]. The mobile measurements in Austin, Texas during February and May enabled a determination of fading probability distributions for non-foliage and foliage conditions, respectively.

2.0 Review of Empirical Roadside Shadowing Model

The ERS model alluded to above, which also is a recommendation of the International Telecommunication Union, Radio Communication Study Groups (ITU-R) [10], is mathematically formulated as follows:

$$A(P,\theta) = -M(\theta)\ \ln P + N(\theta) \tag{1}$$

where

$$M(\theta) = a + b\,\theta + c\,\theta^2 \tag{2}$$

$$N(\theta) = d\,\theta + e \tag{3}$$

and where

$$\begin{aligned} a &= 3.44 \\ b &= 0.0975 \\ c &= -0.002 \\ d &= -0.443 \\ e &= 34.76 \end{aligned} \tag{4}$$

In (1), A(P,θ) is the L-Band (f = 1.5 GHz) fade (dB) exceeded at the percentage of driving distance P for an Earth-satellite elevation angle θ (deg). The fade is defined relative to non-shadowed and negligible multipath conditions. The equation had been previously validated in the elevation angle range between 20° to 60° over the percentage interval 1% to 20%.

Equation (1) had also been extended to include the frequency range between 870 MHz

(UHF) to 2.7 GHz (S-Band) employing the scaling relation

$$A(f_2) = A(f_L)\sqrt{\left(\frac{f_2}{f_L}\right)} \tag{5}$$

where $A(f_2)$ is the attenuation (dB) at a different frequency f_2 (GHz) valid between 0.87 to 2.7 GHz, $A(f_L)$ is the L-Band attenuation given by (1), and f_L is the L-Band frequency (1.5 GHz).

3.0 Extended Empirical Roadside Shadowing Model (EERS)

3.1 Extending ERS to Larger Percentages

In examining the original set of distributions at L-Band and UHF with the ERS model, it was found that the model may be conveniently extended to higher percentages employing a natural logarithmic fit which is continuous at the previously limiting 20% level and reaches 0 dB at P = 80%. That is, over the range of P from 20% to 80%, the model has been extended as follows:

$$A(P,\theta) = \frac{A(20°,\theta)}{\ln 4}\ln\left(\frac{80}{P}\right) \tag{6}$$

The rationale for selecting a logarithmic fit in the 20% to 80% range was based on the observation that most of the distributions similarly followed this variation. Furthermore, the distributions reached 0 dB fade in the 70% to 90% interval. Hence 80% was selected as the mid-level. Since the distributions coalesce in this interval, the exact value of probability (between 70% and 90%) at 0 dB fade plays an insignificant role. In employing the above fit, it was observed that the modeled distribution continued to maintain its median characteristic vis-a-vis the other measured distributions.

In Figures 1 through 4 are shown previously derived sets of distributions in central Maryland at 21° (MARECS B-2), and at 30°, 45°, and 60° (helicopter measurements) [2, 3]. These are compared with the extended ERS distribution (alternately referred to here as EERS model) at L-Band (thick solid curve) over the percentage range from 80% to 1%. We note that over the percentage range between 20% to 80%, the fade differences between the ERS model and the other distributions monotonically reduce, and the ERS distributions generally maintains its median characteristic. It should be emphasized that for the realm of percentages greater than 20% (fades < 3 dB), multipath effects play an important role.

3.2 Extending the ERS Model to 20 GHz

In Figure 5 are shown probability distributions derived from static measurements of attenuation due to the canopy of a Pecan tree in Austin, Texas at L-Band (1.6 GHz) and K-Band (20 GHz) [6]. In the determination of these distributions, measurements were made from a transmitter on a tower placed on one side of the tree canopy and a receiver was placed on the opposite side. The vertical scale in Figure 5 represents the percentage of locations for which the attenuation exceeds the abscissa value. In deriving these curves, the receiver was placed at different locations such that the transmitter-receiver path cut different parts

of the tree canopy, where at all receiver measurement aspects the tree optically shadowed the transmitter. An equal-probability frequency scaling function estimating the fade at the 10% probability at these two frequencies was developed given by

$$A(f_2) = A(f_1)\ \exp\left\{b \cdot \left[\frac{1}{f_1^{0.5}} - \frac{1}{f_2^{0.5}}\right]\right\} \tag{7}$$

where

$$b = 1.5 \tag{8}$$

and where $A(f_1)$ and $A(f_2)$ are the attenuations in dB at frequencies f_1 and f_2 (expressed in GHz). The above formulation shows a fade predictability for the static case (1.6 GHz to 19.6 GHz, and conversely) to within 0.2 dB at the 10% probability (see circled and triangular points in Figure 5).

We extend the ERS model to frequencies as high as K-Band (20 GHz) and as low as L-Band (1.6 GHz) employing (7) where

$$A(f_L) = A(f_2) \tag{9}$$

and where $A(f_L)$ is given by the left hand side of (1).

In Figure 6 is shown the K-Band distribution (elevation angle = 55° for a 10 km run along an evergreen tree-lined road in Bastrop, Texas. The Earth-satellite path generally cut the line of roadside trees on average at an angle of 57°. The population of trees were in excess of 55%, where there were considerable segments of road where the trees formed a tunnel of foliage overhead. Also shown plotted is the EERS model (dashed curve). We note that the EERS model underestimates the fade by at most 5 dB for probabilities between 1% and 20%. This deviation is within the variabilities expected in comparing the EERS model with measured distributions as exemplified in Figures 1–4 for the ERS model. The underestimation of the EERS model in Figure 6 at the smaller probabilities is caused by the prevalence of foliage tunnels giving a greater likelihood of fading at the higher elevation angles. Further validation examples related to extending the ERS model to 20 GHz is given in Section 3.4.

3.3 Extending the ERS Model to Low Elevation Angles

Extending ERS to elevation angles smaller than 20° is a complex task for the following reasons: (1) The ERS model tacitly assumes that the canopies of single tree shadows the Earth-satellite path. At lower angles, there is a greater likelihood that the path may cut the canopies of multiple trees or multiple tree trunks. (2) At smaller angles there is a greater likelihood that the terrain itself may block the Earth-satellite path creating high attenuation. (3) Ground multipath may be a factor. Based upon empirical experience for cases where the above caveats do not arise, it has been found that with good approximation, the ERS model at 20° elevation gives similar results to that at 7° or 8°. The rationale for this is that at 20° elevation the Earth-satellite path is already passing through the lower part of the tree canopies. Reducing the path elevation angle is likely to result in attenuation caused by tree

trunks which may tend to mitigate the path attenuation. On the other hand, attenuation effects may increase because of fading from those tree canopies which are further offset from the road (as was the case in Alaska). The combination of these two effects may result in the median fade statistics to be relatively invariant to angles below 20°, although larger deviations about the median are expected because of the breakdown of the aforementioned underlying assumptions.

In Figure 7 is shown an L-Band (1.5 GHz) cumulative fade distribution corresponding to a tree-lined road along an approximate 16 km stretch of road in Washington State (elevation angle = 7°), where the satellite path was orthogonal to the line of trees [5]. Also plotted (dashed curve) is the EERS model employing the assumption that the 20° fade is the same as that at 7°. The EERS distribution agrees with the measured distribution to within 2 dB for percentages smaller than 10% and larger than 50%, and is within 5 dB for the other percentage levels. The above deviations are comparable to those obtained when comparing the ERS model with L-Band distributions from multiple runs in central Maryland (Figures 1–4).

In Figure 8 are shown a set of K-Band distributions (elevation = 8°) derived from ACTS measurements in Alaska corresponding to different roads in which the Earth-satellite path was orthogonal to the line of roadside trees. Also shown is the EERS model. We note that the EERS model maintains its median characteristic, although the variability about the median is large. The low angle distributions are shown to vary considerably because of the reasons enumerated above, with the high probability fades caused by terrain blockage and multiple trees along the Earth-satellite path.

3.4 Validating the EERS Model in Central Maryland at K-Band

The difficulty in validating the EERS model in central Maryland employing the ACTS mobile measurements is that this data base was obtained during March when the deciduous trees were without foliage. A quasi-validation may however be made by converting a non-foliage run to a foliage case using a foliage conversion model described in the following paragraphs.

3.4.1 Modeling the Effects of Foliage at 20 GHz

In Figure 9 is shown a cumulative fade distribution (dashed curve) for an approximate 1 km segment of road driven in Austin, Texas during February when the trees (primarily Pecan trees) were devoid of leaves. Also shown is a distribution (solid curve) derived from a mobile run during May when the trees were in full foliage. The direction of travel for these run was approximately orthogonal to the satellite pointing direction, which represents a worst case fading situation. Furthermore, the optical blockage to the satellite during the full foliage period was estimated to be in excess of 55%.

Performing a least square fit associated with equal probability levels of the attenuations

for the two curves in Figure 9, the following relation was determined:

$$A(\text{Foliage}) = a + b \cdot A(\text{NoFoliage})^c \tag{10}$$

where

$$\begin{aligned} a &= 0.351 \\ b &= 6.8253 \\ c &= .5776 \end{aligned} \tag{11}$$

and where

$$1 \leq A(\text{NoFoliage}) \leq 15 \text{ dB} \tag{12}$$

and

$$8 \leq A(\text{Foliage}) \leq 32 \text{ dB} \tag{13}$$

Plots of the above mathematical fit at the equal probability levels show agreement to within 0.1 dB when compared to the measured distributions in Figure 9. Figure 10 represents an independent validation of the above foliage formulation. The solid curves represent the foliage and non-foliage static distributions at 19.6 GHz for the Pecan measurements alluded to previously relative to Figure 5. The dashed curves represent the predicted levels using the formulation given by (10). That is, the dashed curve on the right is the predicted level of A(Foliage) where equal probabilities of A(No Foliage) as given by the left solid curve was injected into (10). The left dashed curve represents the predicted levels of the A(No Foliage), where the measured levels of A(Foliage) as given by the right solid curve values were injected into (10). The formulation (10) generally produces agreement to within 1 dB or smaller over most of the probability range.

3.4.2 Comparison of EERS Model with K-Band Measurements in Central Maryland

In Figure 11 is shown a plot of a K-Band mobile measurements employing transmission from ACTS in March 1994 for Route 108 (traveling south-west). The solid curve to the left (with circled points) represents the actual measured distribution for the case in which the deciduous trees were without leaves. For this case, the satellite was on the left and the Earth-satellite path frequently cut the line of roadside trees at near orthogonal angles. Shown also is the right solid line distribution derived by applying the foliage formulation (10). This adjusted distribution thus represents a predictor of the full foliage case. Also shown is the EERS distribution at K-Band (dashed curve). We observe that the EERS distribution deviates from the adjusted measured distribution to within 5 dB and less.

The dot-dashed curve in Figure 11 was derived from previous L-Band helicopter measurements in June 1987 [3] employing the following procedures: (1) Distributions were examined which corresponded to the same scenario as for the K-Band measurements; namely, the vehicle was traveling in the southwest direction and the helicopter was on the left. (2) A resultant 39° distribution was derived by interpolating the 45° and the 30° distributions at L-Band. (3) The L-Band distribution was extended to K-Band employing (7). We note that relatively close agreement exists between the adjusted distribution (based on helicopter measurements), the adjusted ACTS distribution, and the EERS model.

4.0 Summary and Conclusions

A revised empirical roadside shadowing model has been derived which extends the previous ERS model such that it is now applicable to frequencies as high as 20 GHz and as low as 870 MHz. This model, now referred to as the extended empirical roadside shadowing model (EERS), may be applied to percentages from 1% to 80% and to elevation angles ranging from 7° to 60°. The model is representative of a median distribution of measured data which deviates from measured distributions generally to within ±5 dB at elevation angles above 20° (Figures 1–4, 6,7,11). At low elevation angles (Figure 8), terrain blockage and multiple tree attenuation may be prevalent and hence the deviation relative to the EERS model may be substantially larger.

To validate the EERS model in central Maryland, an empirical formulation was developed relating equal probability fades associated with distributions corresponding to foliage and non-foliage cases (equation (10)). This formulation was independently validated when applied to distributions for foliage and non-foliage scenarios associated with a Pecan tree employing static measurements at 20 GHz (Figure 10).

The EERS may be applied as follows: [1] We start with equation (1) which is the appropriate distribution model at L-Band in combination with (6), which extends the model from 20% to 80% over the elevation angle range between 20° and 60°. [2] To estimate distributions between the elevation angles of 7° and 20°, assume the value of A(P,θ) at 20°. [3] To extend the distribution to higher frequencies, apply the formulation (7), where $A(f_1) = A(f_L) = A(P,\theta)$, and where A(P,$\theta$) is given by (1). [4] To extend the L-Band distribution to lower frequencies (e.g., 870 MHz), greater accuracy may be achieved using (2) and the formulation (5).

5.0 Acknowledgements

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[10] International Telecommunication Union, Radio Communications Study Groups, "Propagation Data Required for the Design of Earth-Space Land Mobile Telecommunication Systems," *ITU-R Document 5/BL/42-E*, 15 March 1994.

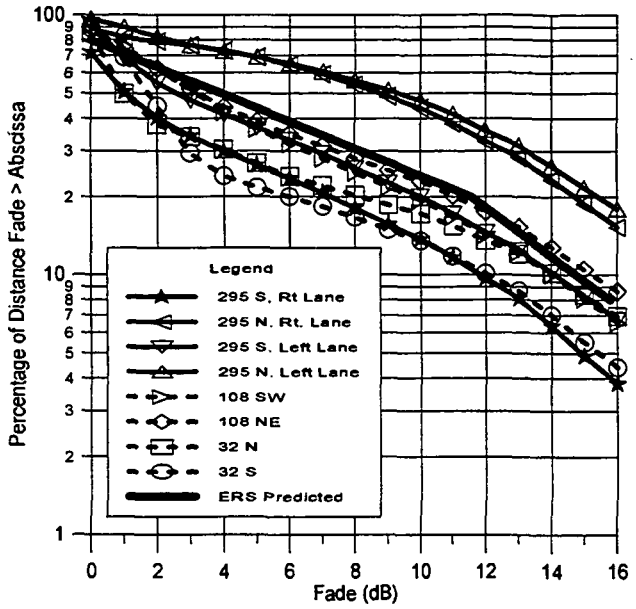

Figure 1: MARECS B2-mobile fade distributions at L-Band in central Maryland (elevation = 21.2°) and comparison with EERS model (thick solid curve).

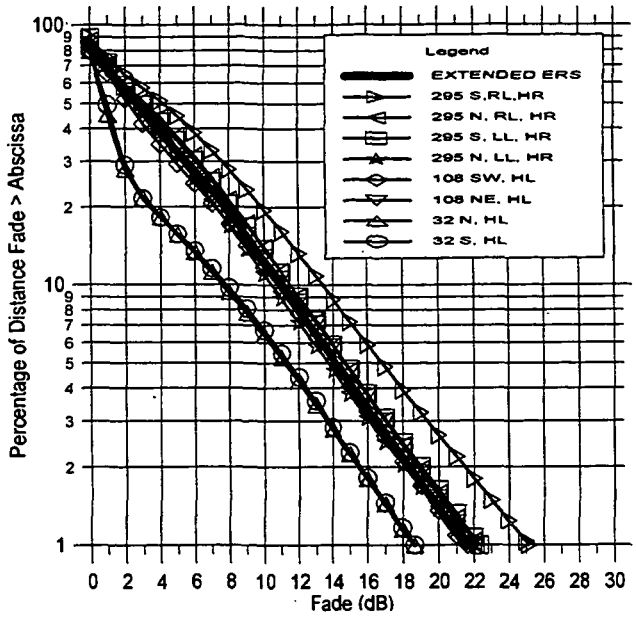

Figure 2: Helicopter-mobile fade distributions at L-Band in central Maryland (elevation = 30°) and comparison with EERS model (thick solid curve).

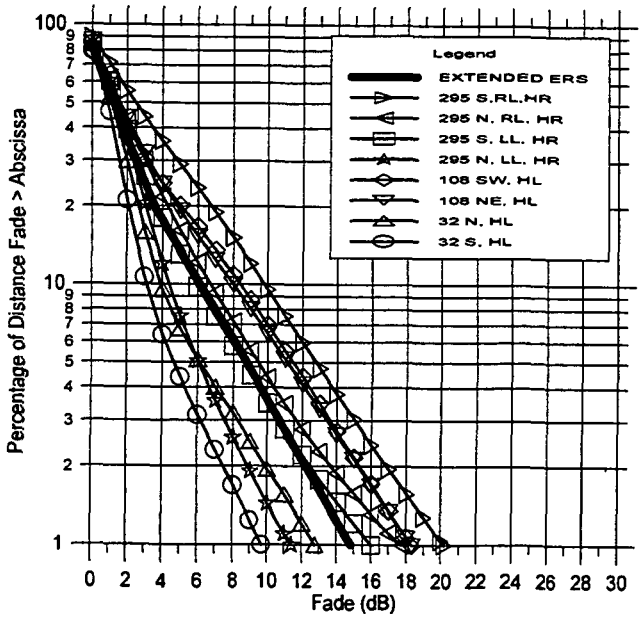

Figure 3: Helicopter-mobile fade distributions at L-Band in central Maryland (elevation = 45°) and comparison with EERS model (thick solid curve).

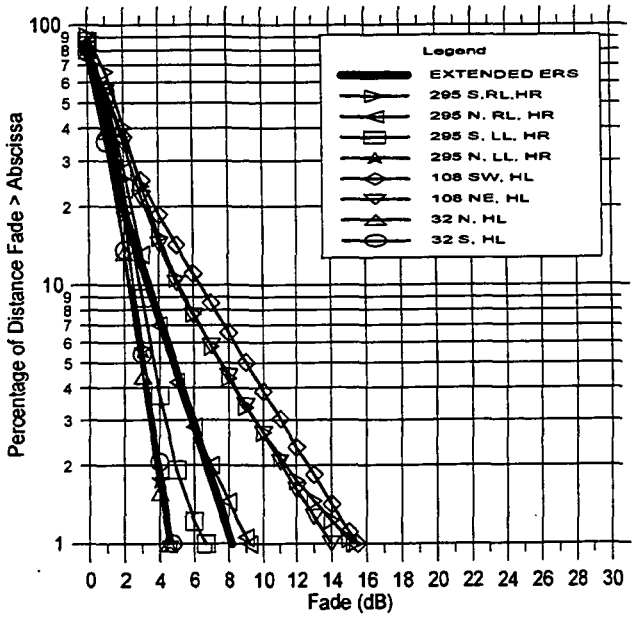

Figure 4: Helicopter-mobile fade distributions at L-Band in central Maryland (elevation = 60°) and comparison with EERS model (thick solid curve).

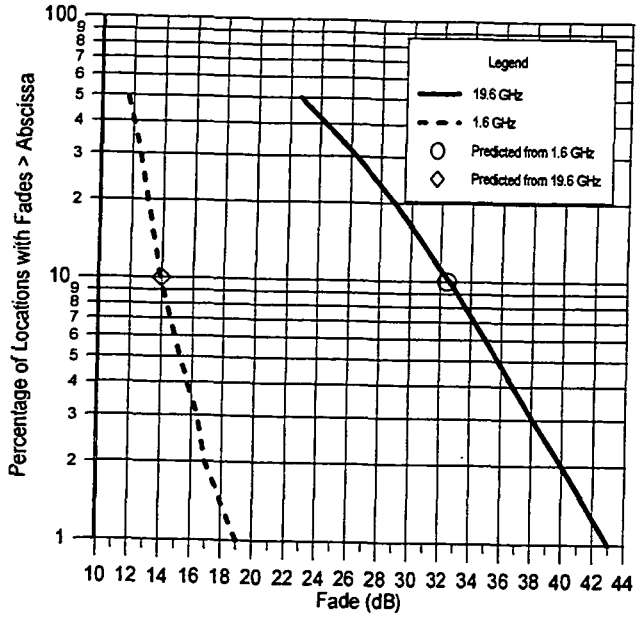

Figure 5: Fade distributions derived from static measurements of canopy attenuation of a Pecan tree at 19.6 and 1.6 GHz in Austin, Texas [6]. Circled and triangular points show prediction at the 10% probability using the formulation (7).

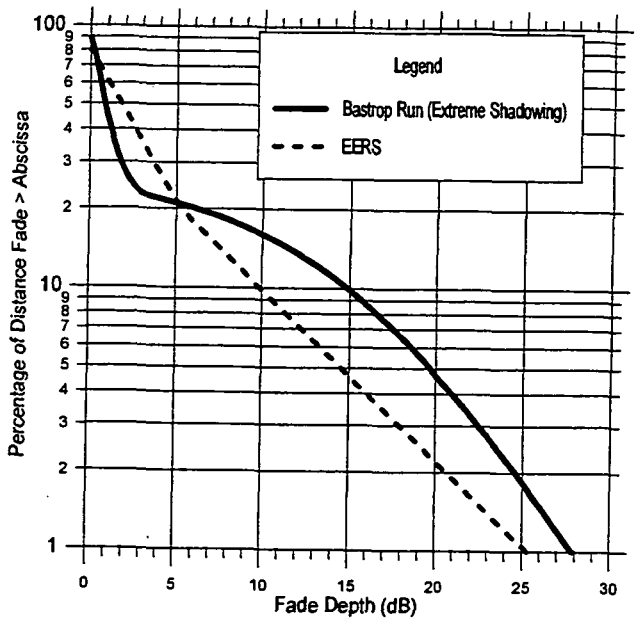

Figure 6: ACTS-mobile fade distribution at an elevation angle of 55° (solid curve) at 20 GHz for a 10 km tree-lined stretch of road in Bastrop, Maryland. Dashed curve is EERS predicted distribution.

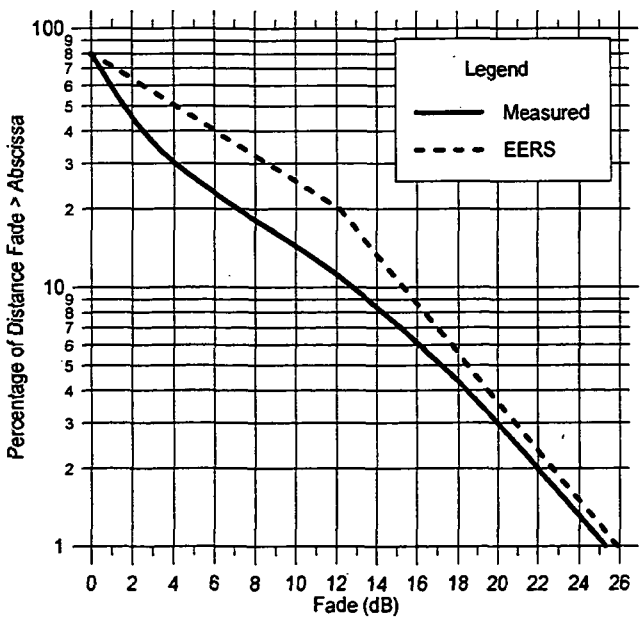

Figure 7: MARECS B2-mobile fade distribution at 1.5 GHz at elevation angle of 7° in Washington State over a 16 km tree-lined stretch (solid curve) [5]. Dashed curve is EERS predicted distribution.

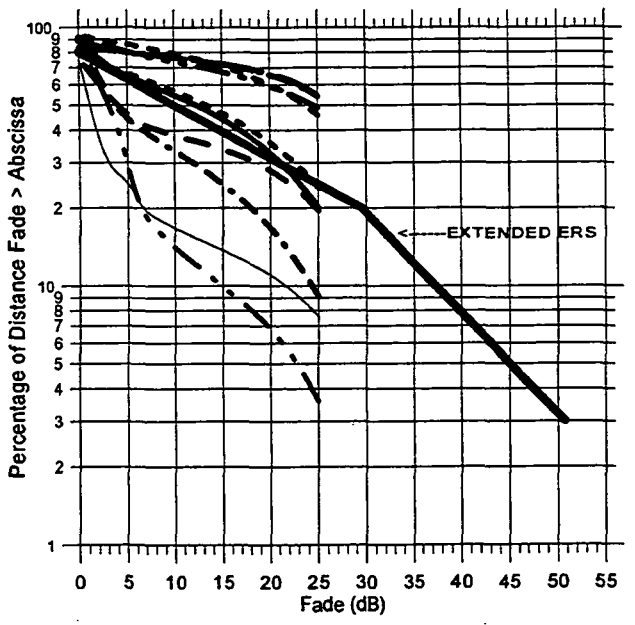

Figure 8: ACTS-mobile fade distributions in and around Fairbanks, Alaska (elevation angle = 8°) [7,9]. Thick sold curve is EERS predicted distribution.

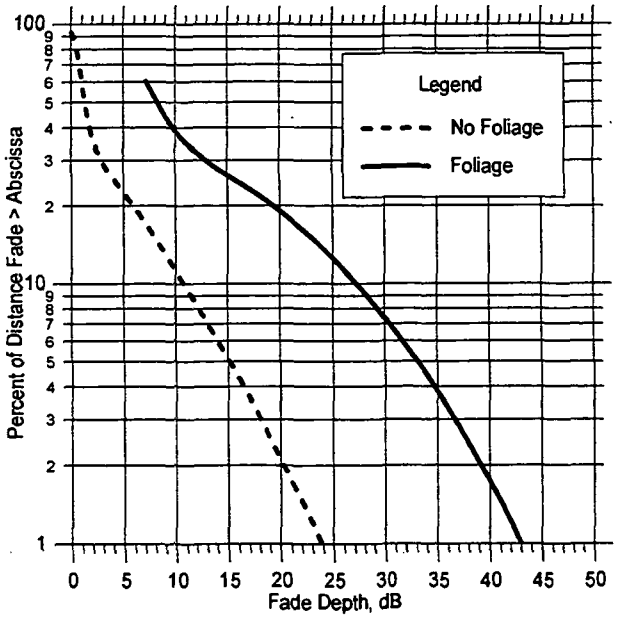

Figure 9: ACTS-mobile fade distributions at 20 GHz (elevation angle = 55°) in Austin, Texas with foliage (solid curve) and without foliage (dashed curve) for a 1 km stretch of a tree lined street.

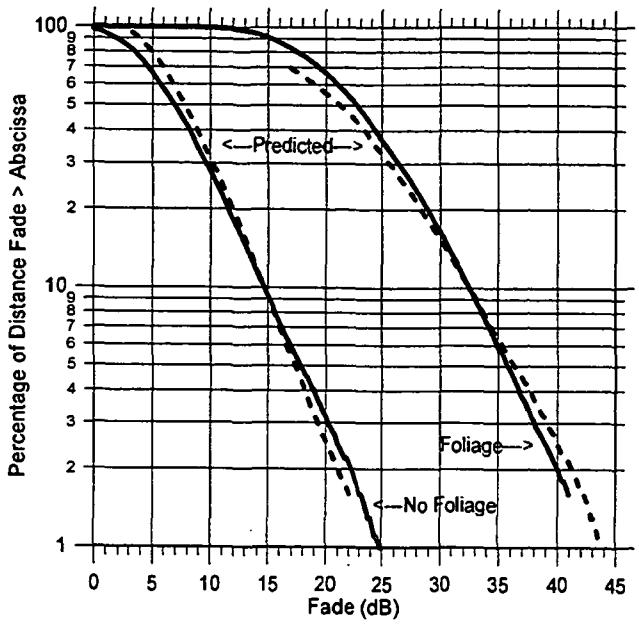

Figure 10: Fade distributions at 19.6 GHz derived from static measurements of a Pecan tree in Austin, Texas for foliage (right solid curve) and non-foliage (left solid curve) scenarios. Dashed curves are predicted distributions using the formulation (10).

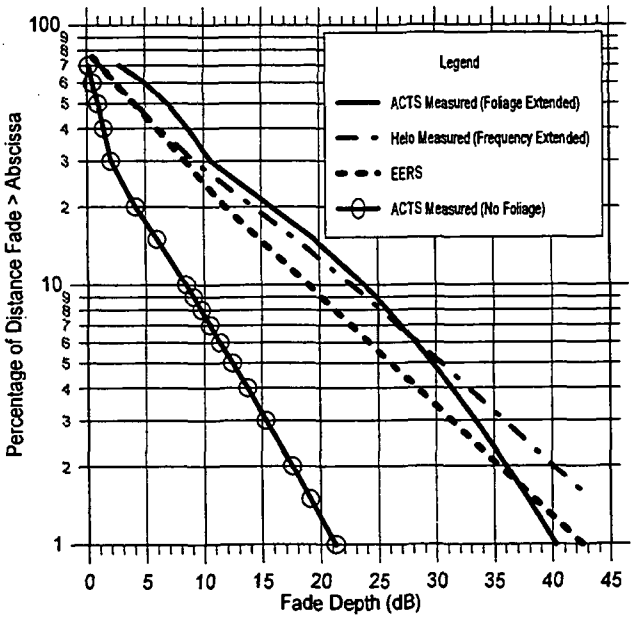

Figure 11: [1] The left solid curve with circled points represents the 20 GHz ACTS-mobile fade distributions for Route 108 (traveling S-W) during period in which trees were without leaves. [2] The right solid curve is the corresponding distribution when adjusted for foliage using (10). [3] The dot-dashed curve is the 20 GHz distribution obtained by frequency extending the helicopter L-Band distribution using (7). [4] The dashed curve is the predicted EERS distribution.