A UNIFIED LOW ELEVATION ANGLE SCINTILLATION MODEL

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Abstract— Enabling communications at very low elevation can lengthen the pass duration between a satellite and a ground station, which in turn can increase the amount of data return and possibly reduce the number of required supporting ground stations. Link performance, especially at very low angles and high frequencies, depends heavily on terrain, atmosphere, and weather, etc. Among the different crucial attenuations, scintillation fading plays a significant role and can greatly impair the performance of the link. It is therefore necessary to model correctly the overall impacts to the link due to scintillation fading. The current International Telecommunication Union Recommendation ITU-R P.618-10 describes three scintillation loss models as a function of elevation angles and percentage of time for which the loss exceeds certain threshold. Implementation of the recommendation resulted in many issues. Particularly, it was identified that (i) iterative solutions to an implicit nonlinear exponential model cannot be found in some cases, (ii) there is a discontinuity in fading values, (iii) scintillations at lower elevation angles from a model are unrealistically lower, (iv) for elevation angle between four and five degrees, there are two applicable scintillation models which yield conflicting values. In this article, we develop a new approach to unify the different fading models within the current ITU recommendation and remove the discrepancies completely. We further validated our models using the ITU-adopted scintillation data measured at Goonhilly, Great Britain and several recent NASA’s Space Shuttle launches. This improved model has been provisionally approved in the ITU International Meeting in Italy, November 2010, and is being evaluated by the ITU members for adoption into the next version ITU Recommendation ITU-R P.618-10.

Keywords—tropospheric scintillation; fading; multipath effects; low elevation.

I. INTRODUCTION

Scintillation is one of the many effects the Earth’s atmosphere may have on a propagating microwave signal. The small-scale turbulence in the atmosphere creates non-homogeneities in the refractive index and as a microwave signal propagates over the Earth’s atmosphere, it could scatter and defocus due to the changes of the dielectric values in the medium. Both the amplitude and the phase of the received signal can be affected by these rapid temporal fluctuations. The impacts are more significant at higher transmitting frequencies and small receiving aperture. It is evident that the Earth-satellite link goes through more atmosphere at the elevation angle decreases and thus the communication performance is further impaired. However, at very low elevation angle, tropospheric scintillation is not the only main cause of impairment. The multipath effects can significantly severe the link performance. To provide the necessary formulations for the prediction of tropospheric scintillation and fading losses, the current International Telecommunication Union Recommendation ITU-R P.618-10 [1] suggests three models depending on the elevation angles and percentage of time. For elevation angles four degrees and higher, the Karasawa scintillation model [2] is recommended. This model calculates the monthly and long-term statistics of the amplitude of the scintillation. When the elevation angles are five degrees or lower, the calculation of the scintillation fade becomes increasingly complicated. Namely, the fading is decomposed into two parts; the deep fading and the shallow fading. When patched together, they form a graph of scintillation fade depth as function exceedance percentage. The models are pieced together in the following approach. The profile starts with the deep fading model that is valid only for a loss of 25 dB or above. As a result, one can find the smallest exceedence percentage for which the scintillation loss is at 25 dB. Such exceedence percentage serves as the transition point between the deep fading model and the shallow fading model. The shallow model is constructed using highly complicated nonlinear model that interpolates the deep fading model and the beam spreading model over the exceedance percentage space. The beam spreading loss model is, however, very crude, which is a function of elevation angle and is independent of any meteorological or communications parameters. Besides, the beam spreading loss value is assumed to be scintillation loss by convenience at the exceedance percentage of 63%, or $1 - 1/e$. When implementing the current ITU-R P.618-10 recommendation, several issues have been identified. Specifically, because solutions to the existing shallow fade model are found iteratively, for certain parameters, the iterative solutions fail to converge, especially near the deep fading transition point. Also, when tracking over the elevation angle space, there is a discontinuity in fading value. Namely, the scintillation losses from the normal model and the low-elevation angle model do not match. As mention earlier, the existing shallow model assigns simple beam spreading loss model to be the scintillation value at the exceedance percentage of 63%, its predictions could produce non-physical scintillation losses. Especially, the loss computed using the current shallow model at a lower elevation is smaller than that from the normal model. Lastly, when the elevation angle is between 4 and 5 degrees, there are two applicable models in the recommendation. As a result, there are two conflicting scintillation fading values.

In this article, we develop a new approach to unify the different fading models within the current Recommendation ITU-R P.618-10. This work was initiated when we observed the anomaly exhibited by the current ITU scintillation model in a study to characterize the launch and ascent links between the Orion spacecraft and the Wallops Flight Facility ground antenna [3]. The proposed shallow fading model is constructed by unifying the deep fade model for low elevation angles and the Karasawa scintillation model for elevation angles five degrees and higher. Namely, the shallow model should be the transition between the deep fading model and the Karasawa model, instead of the beam spreading model. The resulting model is a cubic exponential function of elevation angles, whose coefficients are found explicitly from the values and the
derivatives of the deep fading and the Karasawa models at the interfaces. The differentiation process for the deep fading model and the Karasawa model is cumbersome, and symbolic computation is implemented to avoid arithmetic errors and simplify the mathematical expressions. The solution profile for the proposed unified model is smooth in both the exceedance percentage and the elevation angle spaces. Since the Karasawa model includes meteorological parameters along with ground station antenna parameters, which have not been taken into account in the existing beam spreading loss model, the resulting unified model can reflect more closely to measured data.

The proposed unified model was compared with the measured scintillation data sets acquired at Goonhilly, Great Britain, and at NASA Wallops Flight Facility, USA. The results indicate the proposed model agree well with the data set.

II. TROPOSPHERIC SCINTILLATION MODELS

Due to the page limit, the readers are referred to reference [1] on the detailed descriptions of the Karasawa fading model, the shallow fading model (which we propose to replace), and the deep fading model in the current ITU Recommendation ITU-R 618-10. The rest of this section discusses the new shallow fading model, which is the link between the deep fading model and the Karasawa model.

Besides being widely accepted and used, the Karasawa model involves extensively the various climatic and communications parameters. Its formulations enable us to perform interpolations over the elevation angle space; rendering the smooth and continuous fade transition from very low elevation angles to moderate elevation angles. The newly proposed shallow model will not only remove the discrepancy at the interface with the deep fading model, but also ensure the existence of the solution. That is, the formulations are given explicitly rather than iteratively. In addition, the fading values as well as the rates of change of the fading new shallow model will match those of the deep and the Karasawa models. Indeed, one is guaranteed a smooth profile in both the exceedance percentage as well as the elevation angle.

Following the formulation in [1] the shallow fading model is for losses that are less than 25 dB and apparent elevation angles less than 5 degrees. For a given exceedance percentage $p$, the proposed shallow fading model is interpolated over the apparent elevation angles $\theta_o$ in milli-radians. The apparent elevation angles $\theta_o$ is bounded on the left by the ending point of the deep fading model $\theta_1$ and on the right by the starting point of the Karasawa model $\theta_2$. Thus $\theta_1$ is the apparent elevation angle for which the deep fade model in equation (40) of [1] is equal to 25 dB. Let $A_1 = 25 \text{ dB}$, then

$$A_p = A_{\text{deep}}(p, \theta_1)$$

and the resulting angle in milli-radians is defined as,

Let $\hat{\theta}_2 = 5^\circ$ be the true elevation angle and $\theta_2$ be its corresponding apparent elevation angle in radians. Keep in mind that at 5 degrees, the true and apparent elevation angles are essentially identical and thus one can simply assume $\theta_2 \equiv \hat{\theta}_2$. However, for high-fidelity calculations, a simple angle conversion can be employed using equation (12) of the Recommendation ITU-R P.834. Evaluate the scintillation from the Karasawa model in equation (33) of [1] and denote the result by

$$A_2 = A_{\text{Kar}}(p, \hat{\theta}_2)$$

To require the fading profile to match the shapes of the deep and the Karasawa models at the interfaces, we differentiate the deep fade model in equation (40) of [1] with respect to the apparent elevation angle $\theta_o$ to get,

$$\frac{\partial A_{\text{deep}}}{\partial \theta_o} = \begin{cases} 
-55 \log(e) & \text{worst month} \\
-59.5 \log(e) & \text{average year}
\end{cases}$$

$$\frac{\partial A_{\text{deep}}}{\partial \theta_o} \text{ dB/mrad.}$$

Evaluating the result with $\theta_o = \theta_1(p)$, we define

$$A'_p = \frac{\partial A_{\text{deep}}}{\partial \theta_o} \bigg|_{\theta_o=\theta_1(p)}$$

Similarly, we differentiate (3) with respect to the elevation angle $\theta$ to get

$$\frac{\partial A_{\text{Kar}}}{\partial \theta} = A_{\text{Kar}}(p, \theta) \times \left[ \frac{g'(x)}{g(x)} \frac{dx}{d\theta} - \frac{1.2}{\tan \theta} \right]$$

where

$$g'(x) = 1770(x^2 + 1) + 2123x^{10}(x^2 + 1)^{11/12} \left[ \cos \xi - x \sin \xi \right]$$

$$\frac{dx}{d\theta} = \frac{1.22 D_{eff}^2 f}{2h} \frac{\sin \theta}{\sqrt{\sin^2 \theta + 2.35 \times 10^{-4}}} + 1 \cos \theta$$

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with $x$, $h_L$, and $D_{ef}$ are defined in equations (28)-(30) of [1], and $\xi$ denotes $\frac{11}{6} \arctan \frac{1}{x}$. Define the rate of change of fade with respect to the elevation angle at $\theta = \hat{\theta}_2$ in milli-radians as

$$A'_2 = \frac{\partial A_2}{\partial \theta} |_{\theta = \hat{\theta}_2} + 1000 \text{ , dB/mrad.} \tag{8}$$

Construct the shallow fades by interpolating the points $(\theta_1, A_1, A'_1)$ and $(\theta_2, A_2, A'_2)$ using the following cubic exponential model

$$A_{shal}(p, \theta_0) = A_1 \exp(\alpha(p)(\theta_0 - \theta_1) + \beta(p)(\theta_0 - \theta_1)^2 + \gamma(p)(\theta_0 - \theta_1)^2(\theta_0 - 1000 \times \theta_2)) \tag{9}$$

where the apparent elevation angle $\theta_0$ in mrad is bounded between $\theta_1$ and $\theta_2$, and the coefficients are defined as

$$\alpha(p) = \frac{A'_2}{A_1}$$

$$\beta(p) = \frac{\ln(A_2 / A_1) - \alpha \delta}{\delta^2}$$

$$\gamma(p) = \frac{A'_2 - A_2(\alpha + 2 \beta \delta)}{A_2 \delta^2}$$

$$\delta = (1000 \times \theta_2 - \theta_1). \tag{10}$$

Remarks: Weather parameters such as the water vapor pressure, ambient temperature, and local humidity can be chosen so that the higher-elevation angle fade model in equation (33) of [1] can be used for the worst month or the average year scenario. In addition, this particular model is valid for time percentage between 0% and 50%.

As shown in Figure 1, our proposed enhancement secures the existence of solution to the shallow fading model, removes the discontinuity between the models in the existing recommendations, and ensures that fading diminishes as the elevation angle gets higher. Notably, the unified fading model transits smoothly from the deep fading model at very low elevation angle to the Karasawa model for scintillation at moderate elevation angles.

Figure 1: Unified fadings with the deep, proposed shallow, and the Karasawa models
III. SUMMARY

A new unified method for fading prediction at low elevation angles was proposed. The current ITU-R P.618-10 Recommendation suggests a shallow fading model which interpolates the deep fading model and the beam spreading model over the exceedance percentage space. Several issues associated with the current ITU Recommendation have been found. Particularly, solution to this shallow model is determined iteratively, and, in many instances, does not converge, especially near the deep fading interface. In addition, because the beam spreading loss model, depends solely on the elevation angle, is quite simplistic, predictions from the ITU shallow fading model are independent of climatic and communications parameters. Therefore, its predictions provide unrealistic non-physical values; for example, the losses, produced using the current shallow model at a lower elevation, are smaller than those computed using the Karasawa model at higher elevation angles. Moreover, as the elevation angle increases, the scintillation prediction profile using the current ITU Recommendation contradicts that of the Karasawa model and results in a discontinuation in scintillation values. In the proposed model, the shallow fading model is constructed by unifying the deep fade model for low elevation angles and the Karasawa scintillation model for elevation angles five degrees and higher. The resulting model is a cubic exponential function of elevation angles, whose coefficients are derived from the values and the derivatives of the deep fading and the Karasawa models at the interfaces. Solution to the unified model is found directly (no iteration) and its profile is smooth in both the exceedance percentage and the elevation angles. Since the Karasawa model includes meteorological parameters along with ground station antenna parameters, which have not been taken into account in the existing beam spreading loss model, the scintillation from the proposed shallow fading model can reflect more closely to measured data. Tropospheric scintillations measured from Goonhilly, Great Britain and NASA’s Space Shuttle Launches have been shown and seem to agree well with for the newly proposed model. An expanded version of this paper that includes the detailed derivations of the unified model and the comparisons with the measured scintillation data from Goonhilly and Wallops can be found in [4].

ACKNOWLEDGMENTS

The authors would like to thank the ITU-R US Study Group 3 (Radiowave Propagation), especially Harvey Berger, Fatim Haidara, and Paul McKenna for supporting numerous group meetings and the suggestions, correction, and completion of the ITU Annexes.

The authors also appreciate the feedback from Selahattin Kayalar at JPL and the Shuttle data from Rob Tye and Ed Richards at the Wallops Flight Facility.

This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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REFERENCES


