

Analysis of Empirical Rain Attenuation Models for Satellite Communications At Q to W Band Frequencies

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Abstract— This paper examined the use of existing empirical rain attenuation models for earth-space paths links for frequencies at Q band and greater. Extrapolation of these models that are based on low frequency (< 20 GHz) data results in significant spread in attenuation predictions at 50 GHz and higher. Extrapolation of models based on the $p = 0.01\%$ rainfall rate to higher frequencies is limited due to the power law dependence of rain attenuation. Models that use the full rainfall rate to map attenuation to the corresponding rainfall rate distribution are subject to inaccuracies due to the artificial mapping of all sources of attenuation to a single rainfall rate. Comparison of the ITU-R P.618 attenuation model to available Q/V band data suggests limitations on the useful frequency range and highlights the importance of attenuation combining methodology.

Keywords—attenuation; radio propagation

I. INTRODUCTION

The growing interest in satellite communications at Q(33-50 GHz), V(50-75 GHz) and W(75-110 GHz) band frequencies coupled with the high atmospheric attenuation at these frequencies underscores the need for reliable attenuation prediction models. Empirical models relate measured attenuation statistics to the measured point rainfall rate statistics:

$$A_p = k R_p^\alpha \cdot L_S \cdot AF \quad (1)$$

where k and α are the frequency dependent parameters for specific rain attenuation, L_S is the slant path length through the rain, and AF is the adjustment factor whose parameters are determined by regression analysis. The functional form of AF varies with the empirical model. There are two basic empirical modelling approaches: (1) The R_{01} approach used by the ITU[1], is based on the observation of similarities in distribution functions. It calculates the attenuation distribution for all percentages from the $p = 0.01\%$ values. (2) The R_p approach uses the full rainfall rate distribution and calculates the attenuation for all p to according to equation (1). The regression parameters for the ITU-R P.618-10[1] and other empirical rain attenuation models[2-7] were derived from the

available data, which is dominated by low frequency ($f < 20$ GHz) measurements. Empirical models are useful for conditions similar to those within the database used. Extrapolation to other conditions needs to be assessed.

Based on the data used to determine the fitting parameters the authors of the ITU model gave the frequency range of applicability as 4 – 35 GHz.[2] The International Telecommunication Union (ITU) has since recommended that the range of applicability extends to 55 GHz. This paper examines the validity of this recommendation and more generally, the extrapolation of empirical models to these higher frequencies.

II. ANALYSIS

The question of the reliability of extrapolating the empirical models to higher frequency is illustrated in Figure 1. The attenuation predictions for six different empirical models at different frequencies are shown for Rome, NY, with elevation angle of 30° . The ITU[1] and the China-05[3] models use the R_{01} method and the UK-03 [4], China-08 [5], Brazil-08[6], and the China-10[7] models use the R_p approach. There is significant spread in the model predictions at the higher frequencies.

To further examine the extrapolation of the empirical rain attenuation models to the higher frequencies we first consider the scaling of the various attenuation sources from lower to higher frequency. Scaling of clouds[8], melting layer[9], and water vapor[10] included as they are present in the data, and therefore empirical models are not determined by rain only. Furthermore, these effects will be relevant for Q-W bands due to the high atmospheric attenuation at these frequencies. Figure 2 shows the scaling factors for scaling from 20 GHz to higher frequencies, plotted as a function of rainfall rate. As a reference, for Rome, NY $R_{01} = 39.4$, $R_{0.1} = 10.2$, and $R_{0.01} = 2.1$ mm/hr. The sharp increase in scaling factor for rain at low rain rates is a consequence of the nonlinear power law relation of the rain specific attenuation and the frequency dependence of α . [11] The net scaling factor then depends on the relative contributions of the various attenuation sources. A measure of the relative contribution of cloud attenuation is shown in Figure 3 where we plot the ratio of zenith cloud attenuation to

zenith rain attenuation for different frequencies. Here the cloud attenuation is due to the cloud liquid water content at percentage p that corresponds to rainfall rate distribution percentage. The cloud attenuation is significant for rainfall rates less than about 5 mm/hr ($p > .3 \%$), depending on frequency.

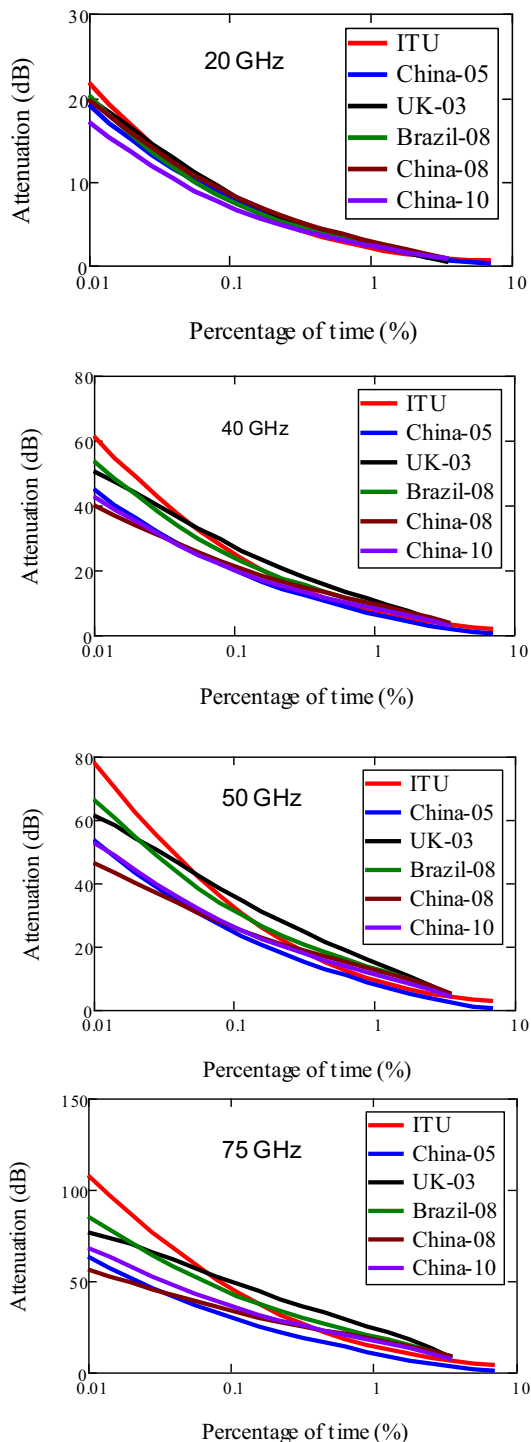


Figure 1 Attenuation predictions of empirical models for different frequencies.

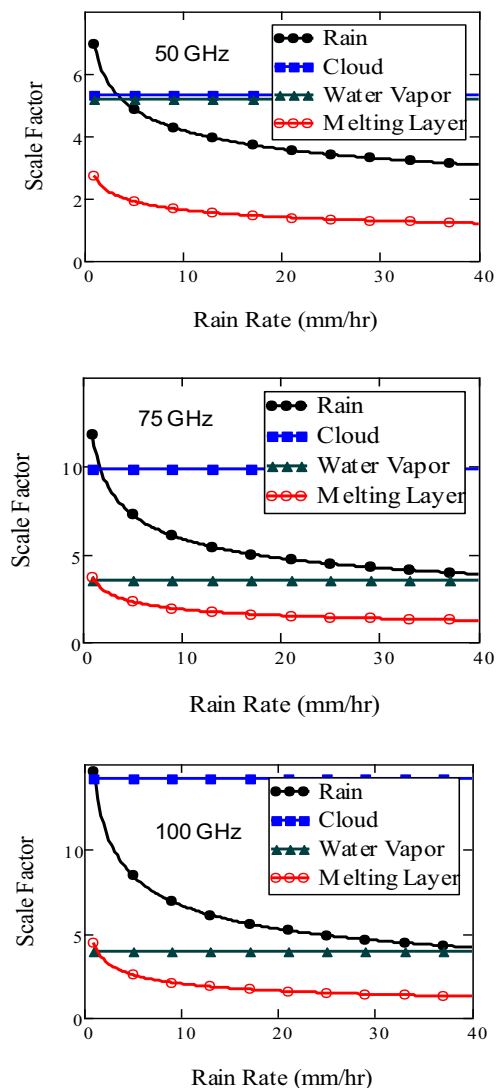


Figure 2. Scaling factors from 20 GHz to higher frequencies.

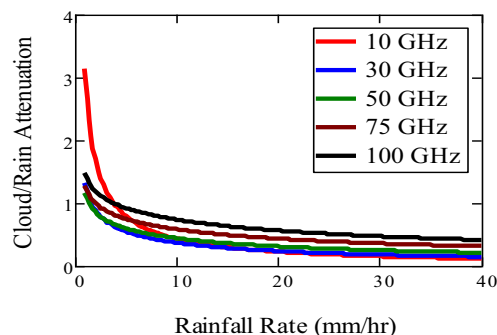


Figure 3. Ratio of cloud to rain zenith attenuation

The issue we want to examine here is how the different modeling approaches scale with frequency. In the R_{01} model approach all attenuation is scaled based on the scaling factor for rain at the R_{01} rain rate, which is typically greater than 30 mm/hr. This will tend to cause an under-estimation of the rain attenuation at higher exceedance probabilities/lower rainfall rates, as it does not account for the power law dependence of the specific attenuation. It will also act to under-estimate the cloud attenuation contribution. The R_p approach is an artificial mapping in the sense that it treats all attenuation at percentage time p as if it were caused by only rain at the rain rate corresponding to that percentage time. Since the actual distribution of rainfall rates contributing to attenuation at some value p includes rainfall rates greater than R_p , this mapping will tend to over-estimate the rain attenuation when extrapolating to higher frequencies. The cloud attenuation contribution estimation errors will be frequency and p dependent, but generally underestimated except at the higher exceedance probabilities.

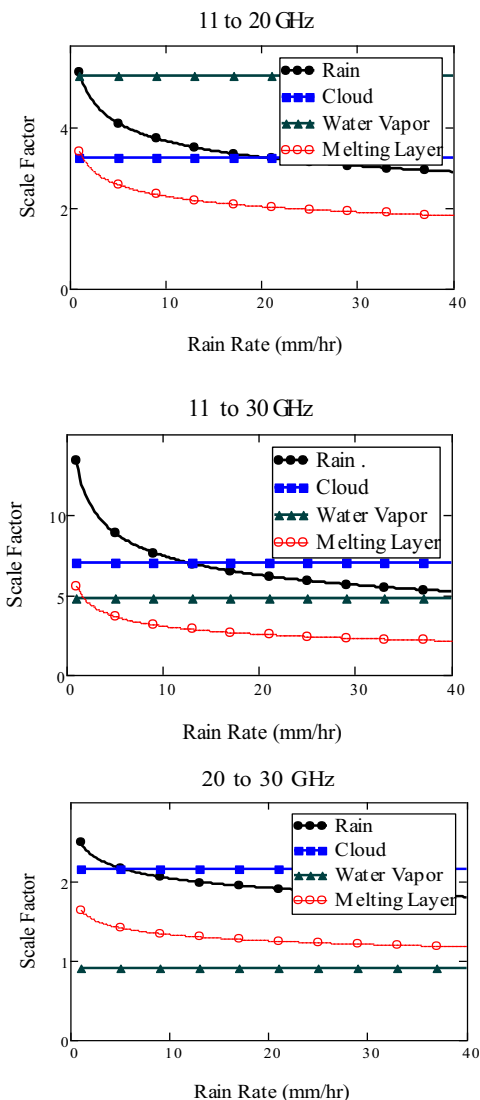


Figure 4 Scaling factors for different frequencies.

The other issue associated with empirical models is the expectation that the attenuation maps to rainfall rate even at the higher exceedance probabilities where cloud attenuation is significant. The validity of this approach is questionable because cloud liquid water distribution is only weakly correlated with rainfall rate distribution. Consequently R_p is not a good predictor of cloud attenuation.

The data used for the empirical models is not from a single frequency, but rather from a range of frequencies. The ITU database of slant path attenuation measurements is dominated by data over the frequency range of 11 to 30 GHz, with most of the data less than 20 GHz. Some of the corresponding scaling factors are shown in Figure 4. In Figure 5 we plot the scale factor per GHz for different frequency ranges. These plots indicate that the data used in the model regression analysis exhibits the general frequency and probability dependent trends expected for extrapolation to higher frequency, but not the correct magnitude.

We can conclude that the empirical models do not inherently extrapolate accurately to higher frequencies, particularly if derived from a single frequency, and especially for R_{01} approaches. However, the available data for model development does span a range of frequencies. To the extent that the model can capture the frequency trends it might provide some level of reliable extrapolation. Of the four R_p models examined, only the China-10 model has an explicit frequency dependence, although it is related to the slant path-length. The UK-03 adjustment factor has no frequency dependence. The China-08 and Brazil-08 models both exhibit frequency dependence through the dependence on the specific attenuation parameters k and α , but only the China-08 model has regression coefficients specifically associated with these parameters. The ITU and China-05 R_{01} models have a frequency dependence in the $p=0.01\%$ adjustment factor, but only the China-05 model has an explicit frequency dependence in the fitting function.

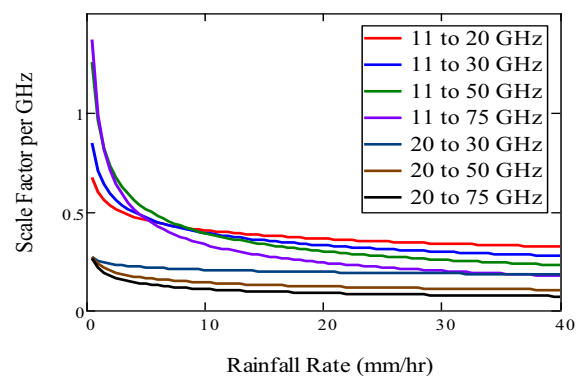


Figure 5. Rain attenuation scale factor per GHz for different frequencies.

III. ANALYSIS OF THE ITU-R P.618-10 MODEL

We now focus on the ITU-R P.618-10 Model and its frequency dependence. Referring to Figure 1, it is seen that the ITU model predicts significantly larger attenuation at $p = 0.01\%$ than the other models. This is due to the frequency dependence of the adjustment factor which is shown in Figure 6 for all six models at $p = 0.01\%$. While some frequency dependence of AF is expected, the ITU model has a significant increase of AF with frequency, resulting in a much larger value of A_{01} compared to the other models. This likely over-estimation of A_{01} in turn compensates the under-estimation expected from the analysis given above. Thus the ITU model may have some values of p for which the attenuation predictions are accurate, but this is the result of the two offsetting frequency dependencies.

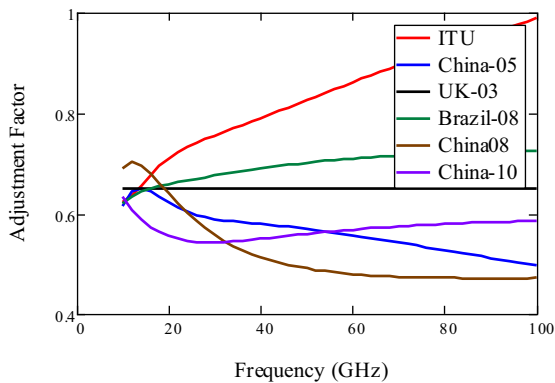


Figure 6. Adjustment Factor for $p = 0.01\%$.

In Figures 7 and 8 we compare ITU-R P.618-10 model predictions for total attenuation with 39.6 and 49.5 GHz data obtained from the ITALSAT beacon. This data was taken at Sparsholt, UK, and at Spino d'Adda, Italy. Details of the measurements are given by Ventouras *et al.* [12] and Riva [13]. In these figures we show two ITU model predictions. The first curve (red) shows the prediction using the ITU rain rate and cloud liquid water databases that were in use at the time of these publications. The second curve (blue) shows the ITU predictions using the current rain rate and cloud data bases. While the earlier model shows good agreement with the measured data, the current model clearly over-estimates the attenuation, particularly for Sparsholt. These differences are due to changes in the attenuation model databases that resulted in increased R_{01} and cloud liquid water content.

There are three issues here. The first is the accuracy of the extrapolation of the empirical model to higher frequencies beyond those used to derive the model parameters. The second issue is the accuracy of the non-rain attenuation models. The third issue is the methodology of how the different sources of attenuation are combined to obtain the total attenuation prediction. This is particularly important for these higher

frequencies where cloud attenuation is greater and outage times are limited to higher percentages where cloud is a significant percentage of the attenuation.

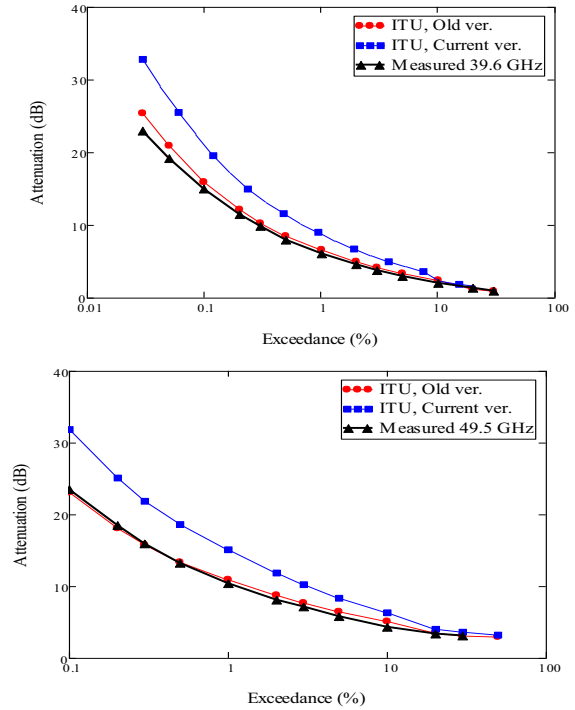


Figure 7. Comparison of ITU models with measured data at 39.6 and 49.5 GHz, Sparsholt, UK.

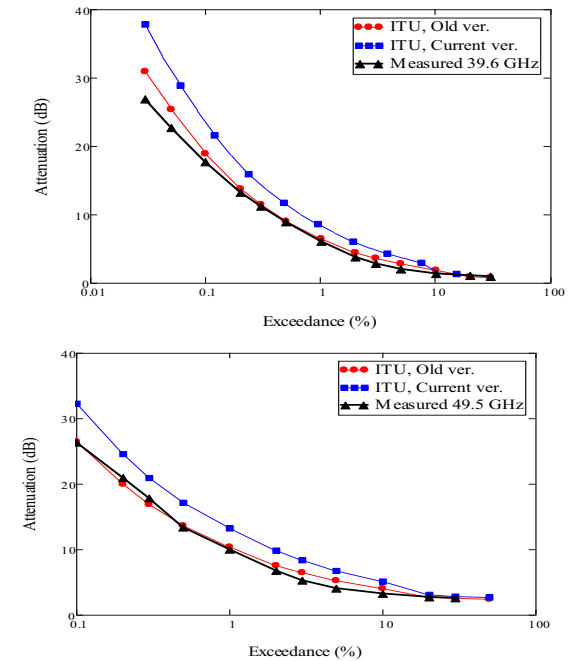


Figure 8 Comparison of ITU models with measured data at 39.6 and 49.5 GHz, Spino d'Adda, Italy.

The ITU approach to combining attenuations is effectively an equal probability summing of rain and cloud attenuations. For $1\% < p < 5\%$ the ITU approach effectively doubles the cloud attenuation, once in the empirical “rain” attenuation model and once in the cloud attenuation model. For $p < 1\%$, the $p = 1\%$ values of the cloud and gaseous attenuations are added to the rain attenuation.

This methodology is a departure from the combination approach proposed by Dissanayake *et al.*[2]. The DAH method does not add any cloud attenuation for $p < 1\%$, and only a graduated cloud attenuation for $p > 1\%$. Recalling that the DAH and ITU rain attenuation models are the same, the combination method makes a difference especially at the higher frequencies where cloud attenuation can be significant. This is shown in Figure 9 where we compare the DAH method with the ITU method for the 49.5 GHz frequency data.

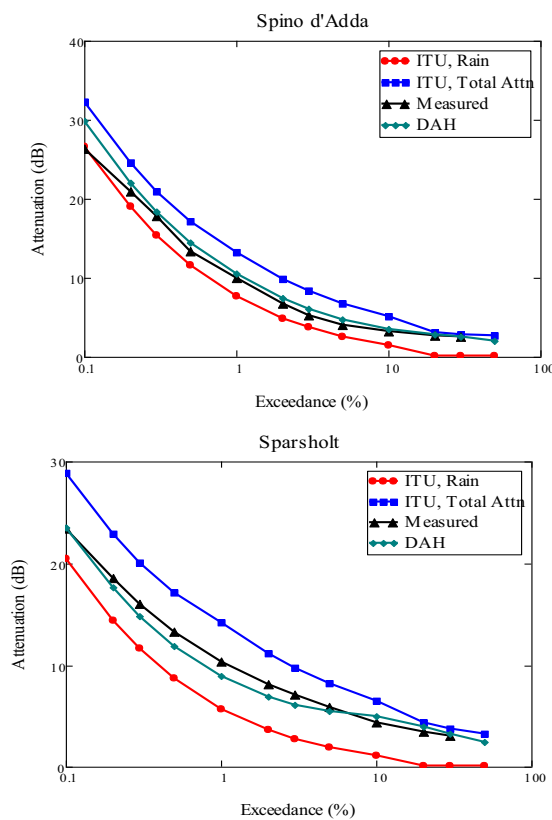


Figure 9 Comparison of ITU and DAH total attenuation methods with measured data at 49.5 GHz.

IV. SUMMARY AND CONCLUSIONS

We have examined the extrapolation of empirical rain attenuation prediction models to frequencies at Q band and above. Models such as the ITU model that calculate the attenuation based on the $p = 0.01\%$ values cannot properly extrapolate to higher frequencies since they do not account for the power law relation of rain specific attenuation. This effect

will act to under-estimate the attenuation. The frequency dependence of the ITU model adjustment factor likely causes an over-estimation of attenuation at $p = 0.01\%$. This in turn minimizes the under-estimation at higher exceedance probabilities. The R_p type models extrapolate in a way that will tend to over-estimate the attenuation since they scale all sources of attenuation as a single rainfall rate. These tendencies are further modulated by frequency dependencies in the adjustment factor. As a whole, the current empirical models may provide upper and lower bounds, but with significant spread.

The problem of attenuation prediction at the higher frequencies is also complicated by the need to consider cloud and other sources of attenuation and the methodology by which the total attenuation is calculated. The frequency range of the ITU-R P.618 attenuation model is brought into question, as the apparent good fit to the ITALSAT data at 39.6 and 49.5 GHz no longer exists when up dated rainfall rate and cloud liquid water data are used.

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