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applicable only for probability levels of < 0.4 (i.e. for rain rates above 20mm/h). For higher probability levels (> 0.4) the melting layer height obtained from the S-band Doppler radar can be used.

Conclusions: The 0°C isotherm height in Singapore displays a seasonal and rainfall type dependence. During the pre-Southwest monsoon period the 0°C isotherm height is ~1800m whereas during the rest of the year it is ~4800m. On rainy days, the 0°C isotherm height falls by ~100m. The melting layer height as detected by the S-band Doppler radar are in agreement with the expected values. For stratiform precipitation, it may be appropriate to consider the melting layer height as the effective rain height. For exceedance probability levels of < 0.4, the effective rain height statistics obtained through radiometric measurements are recommended.

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References
1 ITU-R Recommendations, P.618-5, 1997

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M.M.J.L. van de Kamp

The theory that tropospheric scintillation is associated with turbulence in clouds leads to an asymmetrical distribution of signal level fluctuations (see below), in contrast to the community modelled model. The asymmetry in measured signal fluctuations from Spino d'Adda is evaluated and it is found that the measured short-term distribution is in good agreement with the asymmetrical model.

Introduction: Tropospheric scintillation, which is a fast fluctuation of amplitude and phase on millimetre-wave links caused by atmospheric turbulence, significantly impairs low fade margin systems operating at high frequencies and low elevation angles. Prediction models of the effects of tropospheric scintillation have been developed semi-empirically by various researchers, by combining theoretical relations and experimentally observed dependencies. It is generally assumed that the signal level fluctuations due to turbulence on a short-term basis (up to several minutes) are Gaussian distributed, when expressed in decibels. However, it has been found that for large signal intensities, the short-term distribution is not as symmetrical as the Gaussian. The negative signal deviation, or "edge", is on average larger than the positive, or "enhancement", especially for large signal fluctuations.

Asymmetrical short-term distribution model: Van de Kamp [1] pointed out that, if scintillation is caused by a thin turbulent layer relatively far from the receiver, the distortion will result from multipath rather than multiple scattering. The interfering components of the field were scattered by different layers in the layer. In this case, the received electric field strength amplitude will in the short term be Rice-Neckang distributed. The signal level y in decibels will have the following asymmetrical distribution:

\[ p(y) = \frac{1}{\sigma y} e^{-\frac{y^2}{2\sigma^2}} \left( \frac{y}{\sigma} \right) \Phi(\frac{y}{\sigma}) + \frac{1}{\sigma y} e^{-\frac{y^2}{2\sigma^2}} \left( -\frac{y}{\sigma} \right) \Phi(-\frac{y}{\sigma}) \]

where \( \Phi(x) \) is the cumulative distribution function of a standard normal distribution, and \( \sigma \) is a parameter. The factor \( \sigma \) is a measure of the intensity of the scintillation and \( \left( \frac{y}{\sigma} \right) \) is the expected value of the parameter \( \sigma \). This figure clearly shows that as \( \sigma \) increases, not only the spread increases, but also the skewness of the distribution. Even though this asymmetry has often been observed (e.g. [2]), the short-term signal level distribution \( p(y) \) is still modelled as Gaussian.

To obtain the long-term signal level distribution, the distribution \( p(y) \) can be combined with a long-term distribution of the short-term standard deviation of \( y \). This results in another asymmetrical distribution [1]. Van de Kamp, Tervonen, Salonen and Polaveno Baptista [3] compared this result to measured long-term distributions of signal level, and found a good qualitative agreement. Quantitatively however, the agreement depends on the assumed shape of the long-term distribution of the standard deviation. In this letter, the distribution \( p(y) \) of eqn. 1 is verified using measurements of the short-term signal level distributions. This comparison is independent of the distribution of the standard deviation.

Experimental verification: The asymmetrical scintillation distribution model was verified using measurements of three beacon signals from the satellite Telsat, at 18.69, 39.39, and 49.49 GHz, which were received at Spino d'Adda using a 3.5m Cassegrain antenna and analysed at Politecnico di Milano. The local elevation angle of the link was 37.8°. Measurements were performed between 1994 and 1997. The signal level was measured with a time resolution of 1Hz.

A data selection was made of 30 days of measurements in 1995. Each month of the year, at least one day was selected. Since the asymmetry is especially pronounced for strong scintillation, most of the days selected were in the summer months, during which scintillation was strongest. None of the days contained any significant rain attenuation events. Even though rain events had been excluded, the data were high-pass filtered with a cutoff frequency of 20mHz to remove any remaining slowly varying attenuation components. Next, the standard deviation and the short-term signal level distribution around the mean were calculated over every minute of the data set.
The 1 min distributions were classified by the value of the standard deviation (with a resolution of 0.01 dB), and all distributions with the same standard deviation were grouped together. This resulted in a set of 101 short-term signal level distributions, each conditional for a standard deviation value between 0 and 1 dB. Fig. 2 shows an example of this: the cumulative distributions of fade and enhancement conditional for $\sigma = 0.26$ dB, measured at 40 GHz and compared to the new distribution model of eqn. 1.

![Fig. 2 Cumulative distributions of signal fade and enhancement, conditional for $\sigma = 0.26$ dB](image)

In this figure, the asymmetry, seen here as the difference between the fade and enhancement distributions, clearly appears from the measurements. In this particular case, the asymmetry is slightly larger than predicted by the asymmetrical model.

To evaluate the measured asymmetry for all values of the standard deviation, the asymmetry parameter $A$ could be used:

$$A = \frac{\langle y \rangle - \langle x \rangle}{\sigma_y}$$

where $\langle x \rangle$ is the average, $\langle y \rangle$ the median and $\sigma_y$ the standard deviation of $y$. However, this parameter, when calculated from the measured distributions, was severely distorted by quantisation. An alternative asymmetry parameter was therefore defined as follows:

$$A_2 = \frac{y(1\%) + y(99\%)}{\sigma_y}$$

where $y(x)$ is the signal level exceeded for position $x$ of the time, $A_2$ is defined by eqn. 3 on the condition that the distribution has zero mean, i.e., asymmetrical distribution $y(1\%)$ and $y(99\%)$ are equal in size with opposite sign, so $A_2 > 0$. For the asymmetry model of eqn. 1, negative signal levels are larger in absolute value than positive ones exceeded for the same probabilities, so $A_2$ is negative.

$A_2$ was calculated for all distributions at all frequencies; the result is shown in Fig. 3. Also $A_2$ is distorted by quantisation, but because the sum of the 1% and 99% levels is larger than the difference between the mean and the median, the distortion is less severe than that of $A$. In Fig. 3, the dependence of $A_2$ on $\sigma_y$ can be clearly observed. At 19 and 40 GHz, $A_2$ is well in agreement with the theoretically expected values using eqn. 1. These results indicate that the asymmetry of signal level fluctuations at 19 and 40 GHz in Spino d'Adda is in agreement with that of the theoretical model distribution of eqn. 1, so that this model is a better representation of the signal level deviations than a Gaussian model.

At 50 GHz, the asymmetry is even larger than predicted; this might be explained by angle-of-arrival fluctuations. At 50 GHz, the antenna at Spino d'Adda has a very high directivity, so fluctuations in the angle of arrival of the main received ray may cause fast fluctuating fade, but no enhancement, of the signal [8]. This would increase the asymmetry of the measured signal level distribution.

To check if some of the measured asymmetry was caused by rain attenuation fluctuations which were not completely removed, the same analysis as above was also performed after highpass fil-

![Fig. 3 Asymmetry parameter $A_2$ against $\sigma_y$ for measured distributions and model](image)

Conclusions. The theoretical asymmetrical signal level distribution of scintillation has been experimentally verified using measurements from Spino d'Adda. The measured short-term signal level distributions show an asymmetry which is in agreement with the theory, at 19 and 40 GHz. This confirms the theory of scintillation caused by a thin turbulent layer far from the receiver. At 50 GHz, the asymmetry is even larger, which may be explained by the influence of angle-of-arrival variations.

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