A COMPARISON OF MEASURED RAIN ATTENUATION, RAIN RATES AND DROP SIZE DISTRIBUTIONS

Walther Åsen[1], Chris Gibbins[2] , Terje Tjelta[3]

[1] Norwegian Defence Research Establishment, Box 25
2007 Kjeller, Norway
Tel: +47 63807259, Fax: +47 63807212, Email: walther.asen@ffi.no

[2] Rutherford Appleton Laboratory, Radio Communications Research Unit
Chilton, Didcot, Oxfordshire
OX11 0QX, UK
Tel: +44 1235 446584, Fax: +44 1235 446140, Email: c.j.gibbins@rl.ac.uk

[3] Telenor R&D, 1331 Fornebu, Norway
Email: terje.tjelta@telenor.com

ABSTRACT

This paper summarises a study of millimetre wave propagation models of precipitation in the atmosphere. Measurements of drop size distributions (DSDs), rain rates and millimetre wave attenuation have formed the key input to the analyses. In addition 20-30 years of rainfall from 3 sites in Norway have been investigated. The work includes physical and empirical modelling, and development of a method for administering DSDs, including averaging and statistical analysis of DSDs. Wind has a clear effect on the stability of rain rate measurements, and a method for correcting for some of the influence of wind is proposed.

INTRODUCTION

All radio frequencies above about 10 GHz suffer from attenuation due to precipitation. The need for employing higher frequencies, especially in new broadband services, has therefore encouraged research into precipitation caused attenuation.

In later years many some experiments have been conducted where DSDs for rain have been measured in connection with radar or millimetre wave attenuation experiments. The measured DSDs are important, since they can be used indirectly to predict the relationship between rain rate and radio wave attenuation for any frequency of interest. These calculations rely on assumptions regarding the size dependent attenuation from single raindrops and the terminal fall velocity of raindrops.

The different climates around the world will influence both the rain rate distributions and DSDs observed. It is therefore interesting to study observed data and fitted parametric distributions in order to predict what the specific attenuation at a given frequency is likely to be at a chosen location for a given percentage of time.

PHYSICS OF MILLIMETRE WAVE ATTENUATION

The importance of frequency comes clear when looking at interactions of the radio waves with single particles. For millimetre wave rain attenuation the wavelengths are comparable to the size of the raindrops. The variation of the number of raindrops of each particular size the electromagnetic waves encounter on their way from emitter to receiver are therefore important and may cause variable attenuation even though the rainfall rate is the same. It is therefore essential to establish the drop size distributions (DSD) and the resulting specific attenuation, for different rainfall rates. Early work in establishing a DSD was done by Laws and Parsons [1] and Marshall and Palmer [2], who proposed an exponential distribution, and others have later on proposed and tested more complex models such as shifted log normal, gamma and Weibull distributions.

Once the distributions of rain drops are measured and/or calculated, and the effects of interactions between millimetre waves and raindrops are described, one may combine the information in order to establish the theoretical relationship between rainfall rate and attenuation. Olsen, Rodgers and Hodge [3] verified the theoretical basis of a simple, but already established formula, used to calculate radio wave attenuation due to rain:

$$\gamma_R = kR^{\alpha} \qquad \text{(dB/ km)} \tag{1}$$

where $[k] = (\text{dB/km})/(\text{mm/hr})^{\alpha}$, and $[R]$ = mm/hr, and k and α are frequency, polarisation and drop canting angle dependent coefficients.

The background for a more basic and physical model is summarised in [4]. This model explains how the attenuation is proportional to a sum of products of the number of raindrops of a certain diameter and their extinction coefficient. This means that extinction and DSDs are equally important when calculating the specific attenuation. There are different models to choose from when calculating the single raindrop extinction. Mie theory is the simplest of the models that take the relationship between the size of raindrops and the wavelength into account. The restrictions on the Mie theory are mainly that the raindrops are spherical. We know that this is not true for raindrops falling through the atmosphere, since there will be a drag force acting on them as they fall. However, the simplicity of the Mie theory makes it attractive for easy calculation and comparison, without making assumptions about the detailed shape of the raindrops. Mie theory predicts that attenuation increases sharply from 8 GHz up to about 90 GHz, for typical raindrop diameters in the interval 0.1 – 5.5 mm. The attenuation stays at a nearly constant level for frequencies above 90 GHz.

Reference [5] discusses the variations of DSDs, and proposes other parameters of the DSD than rain rate to be important in modelling attenuation. Observed multi- modal (two or more peaks) behaviour of DSDs was initially the motivation for looking at the new parameters. The new parameters could possibly help in explaining or modelling the effect of the multiple peaks. Therefore the mode, mean and median drop sizes are chosen as parameters or candidate classes for placing individual 10-second measurements in different categories. Classifying DSDs according to mean, median or mode drop size resulted in similar distributions, and therefore a model based on median drop size categories was chosen. This new method, which depends on look up tables and a log-linear relationship between rain rate and median drop size was found to have smaller mean errors than other standard methods, such as the ITU method, at least for the seven event series that were investigated.

Reference [4] explains how single particle extinction is generalised into macro scale rain attenuation. On the macro scale it is common to refer to the fade due to rain as attenuation, although it includes a scattering component as well as a loss component. In [4] the analysis published in [5] is extended from 7 to 28 events (each event is a time series, of duration ranging from minutes to hours). The same method for constructing category dependent DSDs (as in [5]) is employed: Rain rate, median of drop size and mode of drop size are used for classification of DSDs. An average DSD is then established as a function of rain rate alone. Similarly an average DSD is established as a function of mean drop size alone, and another average DSD as a function of mode drop size alone. Each of the averaged DSDs are then treated separately. They are used to calculate the rain rate and the corresponding attenuation, using Mie theory. This results in pairs of attenuation and rain rate for each of the chosen ranges of the classification parameter. Logarithmic regression is then applied to equation (1), in order to establish estimates of k and α. Thus three estimates of k and α are made, corresponding to the three average DSDs.

These ways of establishing k and α are new, and we have therefore compared their success in predicting attenuation. If the difference in k and α is insignificant when using different classifiers, one of them may suffice to give a good estimate. It may well be that one of the classifiers is the better one in a particular region. In [4] the difference in k and α when using different classifiers was small, especially when taking horizontal wind effects into account, which is discussed later.

A paper by McFarqquhar and List [6] from 1993 points out that multiple peaks observed in Joss distrometers could be due to a calibration that ignores the fine details. A smooth, for instance Gaussian shaped, DSD in the interval 0.5 – 3 mm will result in three peaks in the drop density distribution due to the inaccurate calibration. When applying this new, more accurate calibration on measured DSDs from Chilbolton, Singapore and Kjeller, a tendency towards removal of the multiple peaks is found in almost all cases. Several references, for instance by the same authors List and McFarqquahar, but from 1990 [7] have tried to explain physically the formation of multiple peaks. The calibration effect is discussed in more detail in [8].

A large under prediction of the attenuation is generally found, at all but the lowest rain rates. There may be several reasons for this. One of the most obvious reasons is that the Joss distrometer is not sensitive to drops of diameter less than about 0.35 mm. However, an estimate of the contribution to the total attenuation of raindrops of diameter less than 0.35 mm can be made assuming the exponential distribution by Marshall and Palmer [2], and applying Mie theory. According to this calculation, at 40 and at 60 GHz, the raindrops not counted by the distrometer account for less than 2 % of the total attenuation at a rain rate of 1 mm/ hr or higher. At higher rain rates the contribution of these small raindrops is lower than this, less than 0.4 % already at 10 mm/hr rain rate or higher. Therefore it is not likely that the large deviations (up to 20 %) found in our measurements are caused by this effect alone. One other effect contributing to discrepancy between measured attenuation and the attenuation models would be updrafts and downdrafts, particularly effecting small raindrops. Again we may use the Marshall and Palmer distribution and Mie theory and this time calculate the contribution to attenuation of raindrops of diameter less than 0.7 mm at 40 and 60 GHz. Even this contribution is less than 5 % for rain rates above 10 mm/hr. The uncertainty in this contribution is therefore probably much less than 5%.

In [4] we suggest another effect to be more important: Horizontal wind. The input to all of our methods is rain rate, even though in the categorisation process different parameters are used to establish k and α. When wind is present the differently sized raindrops will fall with an angle relative to a normal to the ground and the rain gauge, given by the wind speed and their drop diameter dependent terminal velocity. This is equivalent to considering vertical rain onto a tilted distrometer of a tilt angle that depends on drop size. One understands that the tilting of the distrometer relative to the incoming flux of rain reduces the count of drops, since the effective area of the distrometer is reduced. Since wind velocity is measured, and we know the terminal fall velocity of each drop size, the effect can be accounted for. This method is used in the analysis described in [4], and then we get a much closer agreement between all of the models and the measured attenuation levels. After wind adjustment there is still a difference between the models, but this is relatively small, and within the error of the DSDs that they are calculated from.

In [8] all of the analysis is concentrated on using rain rate as the classifier, basically using the same methods as in [4] and [5]. The data analysed in this paper is from Chilbolton, England, and from Singapore. In [4] and [5] prediction methods are compared with attenuation measurements at 40 and 60 GHz from Kjeller, Norway, while in [8] prediction methods are compared with 57, 97, 135 and 210 GHz attenuation measurements from Chilbolton, England. Focus in [8] is on establishing k and α relationships for Chilbolton and Singapore and compare these with the ITU-recommendations on specific attenuation [9]. In addition DSDs are fitted to rain rate dependent mathematical distribution functions for Chilbolton and Singapore. The comparison of measured attenuation data with theoretical calculation of attenuation from measured DSDs shows the same underestimate of modelled attenuation at Chilbolton as for Kjeller, something which might have been different if the same 'wind corrections' had been applied to the measured rain rates. The fitting of distributions to gamma, shifted log-normal and Weibull distributions have shown which distribution performs most effectively for Chilbolton and Singapore in modelling the measured distributions for attenuation modelling purposes, at most rain rate and frequency combinations. Even though the distributions are very different for Chilbolton and Singapore, a shifted log normal distribution function is found in both cases to model distributions better than a Gamma or Weibull distribution. The distributions result in more predicted attenuation in Singapore than Chilbolton at high rain rates (>>10 mm/hr), while the opposite is true for low rain rates (about 10 mm/hr).

CHARACTERISTICS OF RAINFALL RATE

In [10] the input to all of the attenuation models, namely long-term rain rate data, is studied. The Norwegian Meteorological Institute has supplied data collected over 20 to 30 years from three different sites, which have been studied for this purpose. Two main aspects are addressed in the work of this paper: distribution and duration of rainfall rates. One should have in mind that the data available are excluding winter precipitation (dry snow), and that the resolution is rather coarse (12 mm/hr).

The distribution of measured rainfall rates are in good agreement with the model ITU-R recommended model for rainfall [11] at the inland site of Lillehammer, and at the dry coastal site of Oslo (no surrounding mountains). At the wet coastal site of Ålesund (surrounded by very high mountains) one has measured about half the rain rate compared to that predicted by the ITU-R model, when looking at very high rain rates that occur between 0.01 % and 0.001 % of the total time. Other researchers have reported similar results when studying wet coastal sites. One reason for the discrepancies is possibly that the high mountains force the atmosphere to release water in a continuous, low intensity manner. Another reason could again be the effect of horizontal winds, which will cause a decrease of the effective measurement surface of the rain gauge. The lower rain rate measurements is a very important result for planning of new millimetre wave radio services along the long coast of Norway, especially if these findings are confirmed by studies of other coastal sites. A closed rain rate dependent expression for rainfall duration is fitted to the three sites in Norway and compared. There is obviously a significant difference in rainfall duration for different sites and it is not easy to find a simple explanation to relate the differences between the sites.

CONCLUSIONS

Measured drop size distributions (DSDs) from three different sites (Singapore, Chilbolton and Kjeller) have been analysed. Using parameters of the distributions to categorise measured values, a significant difference in distributions between the sites has been noted. A more detailed calibration of the Joss distrometer than the manufacturers' calibration was employed. This effectively changes the translation from DSD to drop size density, and the tendency for multiple peaks disappears. Using data from Kjeller, three different candidate classification parameters of DSDs, namely rain rate and median and mode drop size, was investigated. Using these three parameters three new methods for prediction of attenuation was established. If no correction is made for the reduced collection area of the distrometer during windy conditions, these methods all under predict the attenuation. However, the difference between measured attenuation and any of the models is small when horizontal wind is corrected for. The methodology developed when analysing the DSD data from Kjeller can be applied to other climates.

20-30 years of rain rate data from three sites in Norway have been investigated in order to find how much one can trust the rain rate input to the propagation models, comparing with the standard ITU model for rain distribution at these sites. An important result is that the rain intensity at the wet coastal site in Ålesund has been measured to be significantly less than that predicted by the ITU-R P.837-2 model, for between 0.01% and 0.001 % of the time, i e for high rain rates. The inland dry site (Lillehammer) and coastal dry site (Oslo) measured rain rates more in agreement with the ITU model. One should do more investigations on some of the other 67 measurement sites before drawing definite conclusions about rain rate conditions in Norway.

REFERENCES

[1] J. O. Laws and D. A. Parsons, "The relation of raindrop-size to intensity", *Eos Trans. AGU*, *24*, 1943, pp 452 – 460

[2] J. S. Marshall and W. McK Palmer, "The distribution of raindrops with size", *Journal of Meteorology*, August 1948, pp 165-166

[3] Roderic L. Olsen, David V. Rogers and Daniel B. Hodge, "The aR^b Relation in the Calculation of Rain Attenuation", *IEEE Transactions on Antennas and Preopagation*, Vol. AP-26, No. 2, March 1978, pp 318-329

[4] W. Aasen and T. Tjelta, "A novel method for predicting site dependent specific attenuation of millimeter radio waves", unpublished

[5] W. Aasen and T. Tjelta, "Application of Measured Drop Size Distributions to Millimetrewave Rain Attenuation Modelling – A Study of Some Events", *Proceedings of the 8th URSI Commission F Triennial Open Symposium: Wave Propagation and Remote Sensing, Aveiro, Portugal, 22-25 September 1998, ISBN 972-8021-65-8,* pp 67-70

[6] Greg McFarqquhar and Roland List, "The Effect of Curve Fits for the Disdrometer Calibration on Raindrop Spectra, rainfall Rate, and Radar reflectivity", *Journal of Applied Meteorology,* Vol. 145, Issue 3, 1993, pp. 180-185

[7] Roland List and Greg M. McFarquhar, 1990: "The Role of Breakup and Coalescence in the Three-Peak Equilibrium Distribution of Raindrops", *Journal of the Atmospheric Sciences,*1990,Vol.47, No. 19,pp. 2274-2292

[8] W. Aasen and Chris Gibbins, "A Comparison of Rain Attenuation and Drop Size Distributions Measured in Chilbolton and Singapore", in press

[9] ITU-R Recommendation P.838-1, "Specific attenuation model for rain for use in prediction methods", *The Radiocommunications Agency of The International Telecommunications Union* ,1992-1999

[10] W. Aasen, "Analysis of three decades of rainfall rate data from dry inland and dry and wet coastal ares in Norway", *Eleventh International Conference on Antennas and Propagation, UMIST, Manchester, 17-20 April 2001, IEE Conference Publication No 480, IEE 2001,*vol. 2, pp 835-838

[11] ITU-R Recommendation P.837-2, "Characteristics of Precipitation for Propagation Modelling", *The Radiocommunications Agency of The International Telecommunications Unio* , 1999