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MILLIMETERWAVE ATTENUATION MODELS AND THEIR COMPARISON WITH EXPERIMENTAL RESULTS

7.1. Introduction :

With significant reduction in mm-wave system cost, use of millimeterwave systems are increasing by leaps and bounds and many other new application areas are being opened up. Besides frequency, mm-wave attenuation is a function of atmospheric pressure, temperature and humidity which varies with time and location. Millimeterwave signal is vulnerable to various atmospheric gases, in particular, oxygen and water vapour leading to considerable attenuation to the transmitted signal. To set up an efficient mm-wave LOS link for a location, attenuation under wide range of climatic changes at the site should be studied throughout the year before deciding on the fade margin to ensure a predetermined level of reliability. It is essential for uninterrupted operation of the link. All these need a good mm-wave attenuation model which should predict attenuation with reasonable accuracy. Extensive research in this direction have yielded some models which are given below,

1. Water's model
2. Liebe's model
3. Gibbins's model
4. CCIR's model.

All models are good in the prediction of attenuation at the absorption peaks but their predictions are different at the windows. The reason of this may be due to the inaccurate line shape function and also due to the contribution from thousands of wings of absorption lines. There may be some sources of attenuation which is yet to be known. The absorption at the window is too low to predict it accurately. All these observations have promoted us to study the accuracy of prediction of various models and compared them with experimental values. Thus a suitable model may be identified for use.

7.2. Background :

Atmospheric water vapour and oxygen are two main gases which causes attenuation to the radiowave above 10 GHz since they have strong absorption lines in the band. The attenuation changes primarily with water vapour concentration along the path since oxygen concentration remains the same. The attenuation is a function of frequency and dependent largely on humidity and to some extent on the atmospheric pressure, temperature. Attenuation at different frequencies are dependent on line shape function which is derived from line width parameter.

The oxygen has a magnetic dipole moment with a cluster of resonances near a wavelength of 5 mm (60 GHz) and a single resonance at 2.53 mm (118.75 GHz). Even though about more than 30 lines near a wavelength of 5 mm are resolvable at low pressures, they appear as a single pressure-broadened line near sea-level due to large number of molecular collisions. In addition, there are higher frequency absorption lines at 367 GHz and above and at sea level pressures collision-induced nitrogen absorption becomes significant at frequencies above 150 GHz. Owing to the fact that oxygen concentration and distribution throughout the atmosphere is stable with respect to time and location and therefore it is easy to predict.

Water vapour molecules have electric dipole moments with three major absorption lines at 22.235 , 183.3 and 325 GHz. At submillimeter and infra-red band it has a very large number of lines, some of which are very intense. The sum of the wings of these lines contributes substantially to the absorption at centimeter and millimeter wave bands. With unstable concentration and distribution of water vapour in the earth's atmosphere and it's variation with time and location leaves a real challenge to the model makers to predict absorption due to water vapour.

Hydrometeors in the atmosphere may cause significant attenuation to the propagating radiowave at mm-wavelength by scattering. Rain attenuates signal heavily which is dependent on rain rate and drop size distribution, temperature and terminal velocity and shape of the rain drops. Using series of expansion solutions of Mie scattering theory, rain attenuation can be deduced using the models of *Laws and Parsons* [1843], *Marshall and Palmer* [1948], *Joss et al.* [1968]. The dependence of rain attenuation on the details of drop size distribution has been confirmed by *Manabe et al.* [1983]. Estimate of attenuation for a given rain rate are subject to considerable uncertainty since the devices used to obtain raindrop size distribution data are inclined to underestimate the number of small drops which provide a significant attenuation. Because of the non-spherical shape of the raindrops which was initially thought of spherical, horizontally polarized waves suffers more attenuation than vertically polarized waves. [*Morita et al*, 1974, *Chu*, 1974]. Specific attenuation for vertical and horizontal polarization may be obtained from *Oguchi and Hosaya* [1974] and *Oguchi* [1977] that takes account of non-spherical raindrops and valid upto 100 GHz. For practical applications a simple power-law equation is given by *Olsen et al.* [1978].

Other effects of precipitation include polarization, rapid amplitude and phase fluctuations known as scintillation, antenna gain degradation and bandwidth coherence reduction. Several different models have come up which takes propagation affecting parameters into consideration. Different models are discussed below.

7.2.1. Water's model :

Water's model uses the kinetic line shape model of Zhevakin-Naumov-Gross line shape to fit the 22.2435 GHz line and an empirical term to account far wing absorption. This model is good for frequency below 100 GHz. This is explained in Chapter 3 in great detail. A computer program was also developed for computation of surface absorption coefficient and zenith absorption which is given in the last section of Chapter 6.

7.2.2. Liebe's model :

A practical millimeterwave attenuation prediction model was formulated [Liebe, 1985] to predict attenuation , delay, noise properties of moist air for frequencies upto 1000 GHz. About 450 parameters of spectroscopic data for H_2O and O_2 absorption lines were considered to derive continuum spectra for dry air, water vapour and hydrosols. Later in 1985, Liebe upgraded the previous model with complex refractivity and the new model [*Liebe*, 1989] that can predict propagation loss and delays upto 100 GHz. Contribution from dry air, water vapour suspended water droplets such as haze, fog, cloud etc. were taken into account.

Based on large refractivity data *Bean and Dutton* [1966] gave refractivity gradient of the atmosphere. Later *Liebe* developed the complex refractivity for dry air and water vapour, which includes 44 oxygen absorption lines and 30 water vapour lines, together with small correction for non-resonant refractivity of air due to the Debye spectrum of oxygen and pressure-induced nitrogen absorption, and an empirical non-resonant water vapour continuum. Cloud attenuations were determined using Rayleigh approximation to Mie scattering theory (since the size of water droplets in clouds is considerably smaller than the wavelength the employed by the radiometer) together with a double Debye model for the dielectric permittivity of water (*Liebe,* 1989).

7.2.3. Gibbin's model :

This method accounts for the discrepancy of theoretical and experimental results with incorporating an empirical, nonresonant, correction term which depends the square of the water vapour density. The origin of this difference is not fully known, however, hydrogen bonding of water molecules to form dimers may be one of the reasons.. Gibbin's model [*Gibbins*, 1986] is based on the millimeter-wave propagation model of *Liebe* (1985). It takes care of 48 oxygen lines and 30 water vapour lines, together with nonresonant contributions which account for pressure-induced nitrogen absorption The model is valid between 1 to 350 GHz. The model is based on the line by line calculation of attenuation employing most recent spectroscopic data. As a matter of fact the Gibbin's model is an improvement of CCIR model [CCIR Report, 719-1, 1984], since it accounts for high frequency rotational transitions in oxygen, pressure-induced nitrogen absorption and a quadratic dependence on water vapour density.

Gibbin's model is derived by comparison with line-by-line computations, from 1- 350 GHz, at 1 GHz interval gives better accuracy. Non-linear least square regression technique is used to find the coefficients in the algorithm. The algorithm is valid for surface parameters i.e. P=1013 mb and temperature at 15^0 C the oxygen attenuation for $1 < F < 57$ is,

$$\gamma_o = \left[7.19 \times 10^{-3} + \frac{6.09}{f^2 + 0.227} + \frac{4.81}{\left(f^2 - 57\right)^2 + 1.50} \cdot f^2 10^{-3} \right] \quad \text{dB/km} \qquad (7.1)$$

the oxygen attenuation for $63 < F < 350$

$$\gamma_o = \left[3.97 \times 10^{-7} f + \frac{0.265}{(f - 63)^2 + 1.59} + \frac{0.028}{(f - 118)^2 + 1.47} \cdot (f + 198)^2 10^{-3} \right] \text{dB/km} \qquad (7.2)$$

For water vapour attenuation non-linear least-square regression method has also been used and the resultant algorithm is valid between 1 to 12 gm/m^3 and constant atmospheric pressure, P=1013 mb and temperature at 15^0 C,

$$\gamma_w = \left[0.050 + 0.0021\rho + \frac{3.6}{(f-22.2)^2 + 8.5} + \frac{10.6}{(f-183.3)^2 + 9.0} \right.$$

$$\gamma_w = \left. + \frac{8.9}{(f-325.4)^2 + 26.3} \right] f^2 \times \rho \times 10^{-4} \text{ dB/km} \quad (7.3)$$

where is the water vapour density in g/m^3

Gibbin's model can not be used for estimation of zenith absorption since the model has been developed considering sea level temperature and pressure.

7.2.4. CCIR model :

In, general, calculation of specific attenuation through above discussed models are highly computational intensive task and very often they are impractical in the field. The International Radio Consultative Committee (CCIR) has developed a simpler algorithm, in the interest of computational efficiency and which is to some extent better than line-by-line calculation. The model found to be in error in certain range of frequency bands especially at high water vapour densities, because a linear dependence of attenuation with water vapour density is considered. [CCIR Report 721-1, 1984; CCIR Report, 721-2,1986; CCIR, 1986].

7.3. Comparison of experimental results with models :

Theoretical values of surface absorption coefficient have been calculated by four models, viz., (1) Water's model (2) Gibbin's model (3) Liebe's model and (4) CCIR model. Since radiometric values were only available at 22.235 GHz and 31.4 GHz, attenuation's with the models were calculated at these two frequencies with varying surface water vapour densities. Fig.7.1(a) displays the absorption results at 22.235 GHz and Fig.7.1(b) gives similar variation at 31.4 GHz. It has been found that all predicted values through four models are higher than the experimental curve. Since water vapour along the vertical path is not highly correlated with surface absolute humidity, it is understandable that the correlation of the absorption with the surface absolute humidity would be moderate. It would appear, however, that the surface absolute humidity should be an unbiased estimator of the water vapour aloft, i.e., there is no point to believe that the surface absolute humidity should consistently underestimate or overestimate the amount of water vapour aloft. So, the correlation of absorption with surface absolute humidity is meaningful.

The theoretical zenith absorption of Liebe and Water's model are in good agreement at both 22.235 and 31.4 GHz as shown in Fig.7.2(a) and Fig.7.2(b). The CCIR results are significantly higher for the higher humidities. The experimental zenith absorption agree very well with those of Liebe and Water at 22.235 GHz and 31.4 GHz., the agreement is poorer for higher humidities.

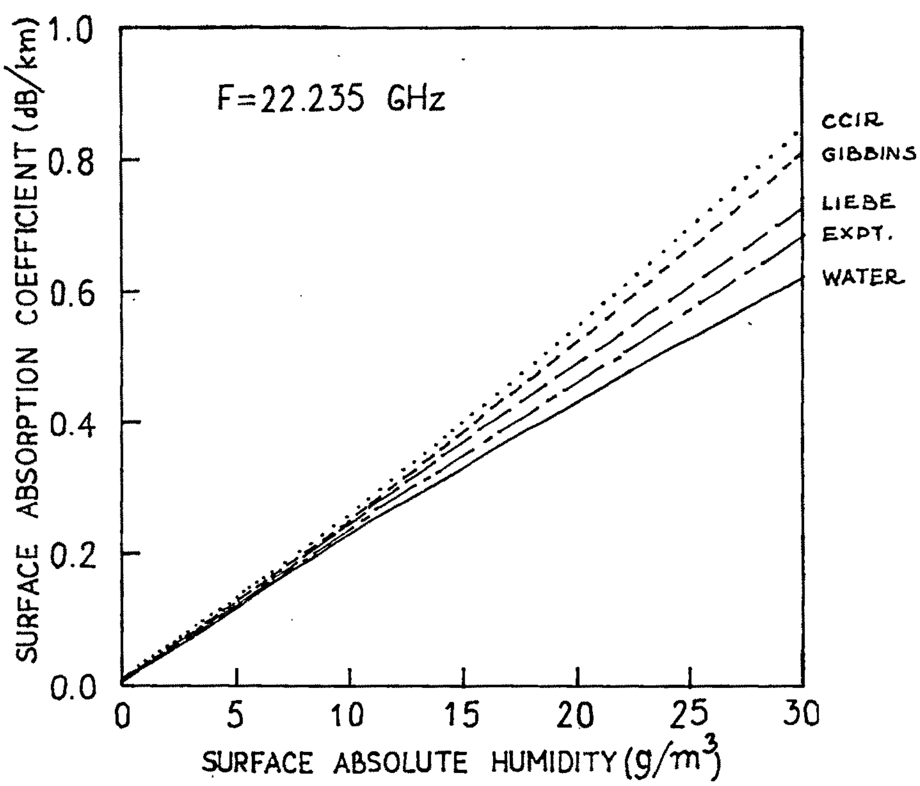

Fig.7.1(a)

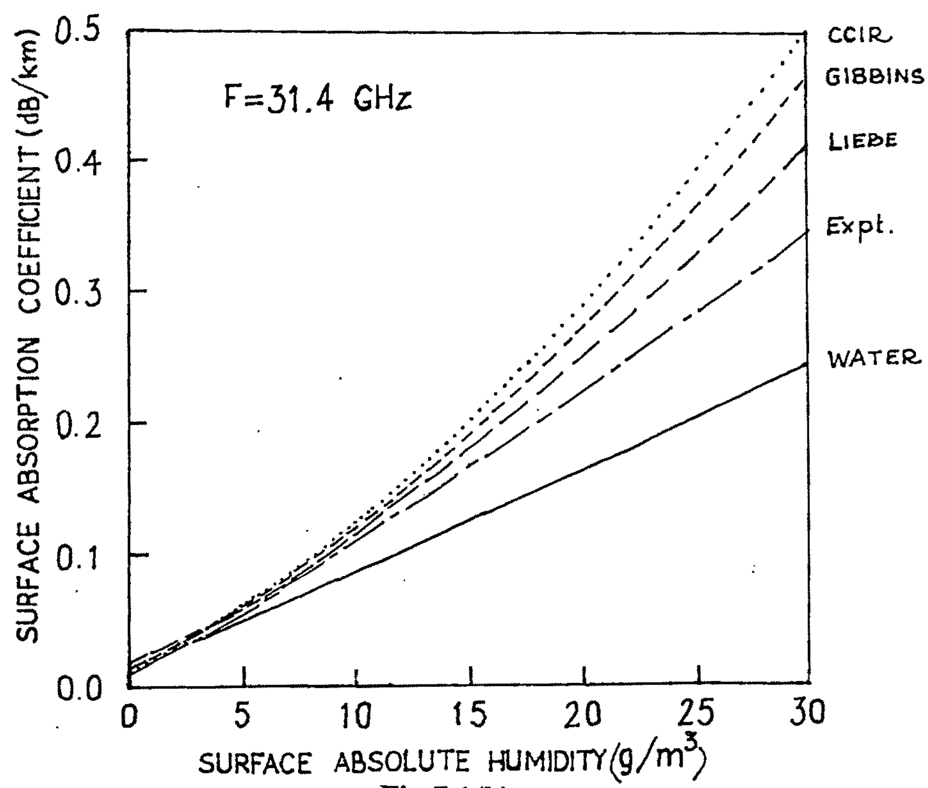

Fig.7.1(b)

Comparison of the estimated values of surface absorption coefficient (dB/km) with different models and experimental values

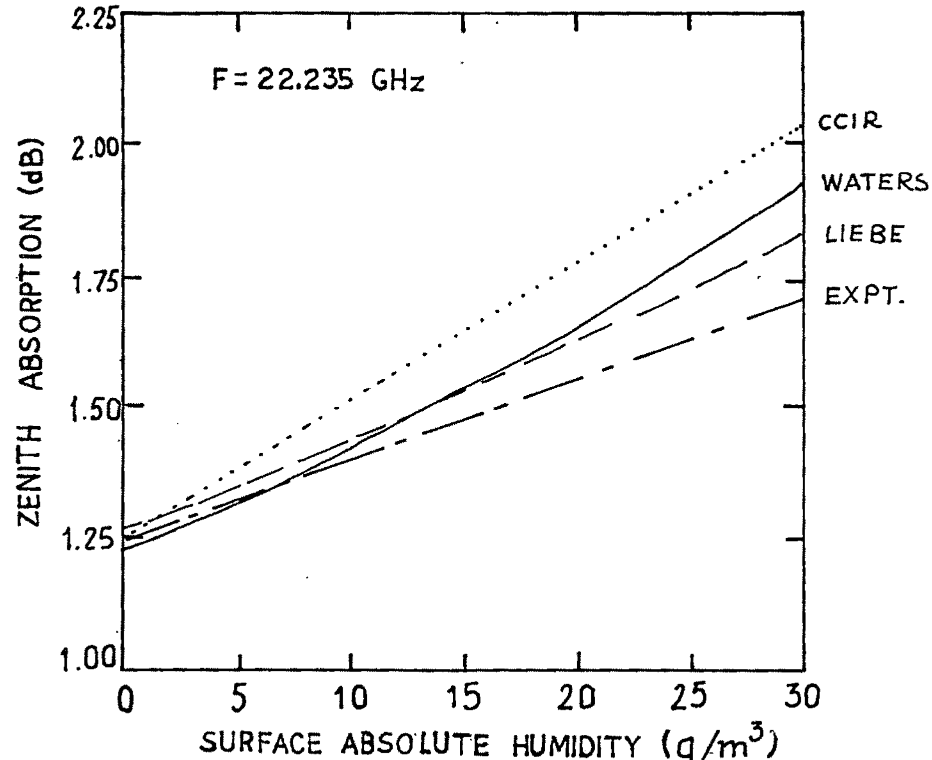

Fig.7.2(a)

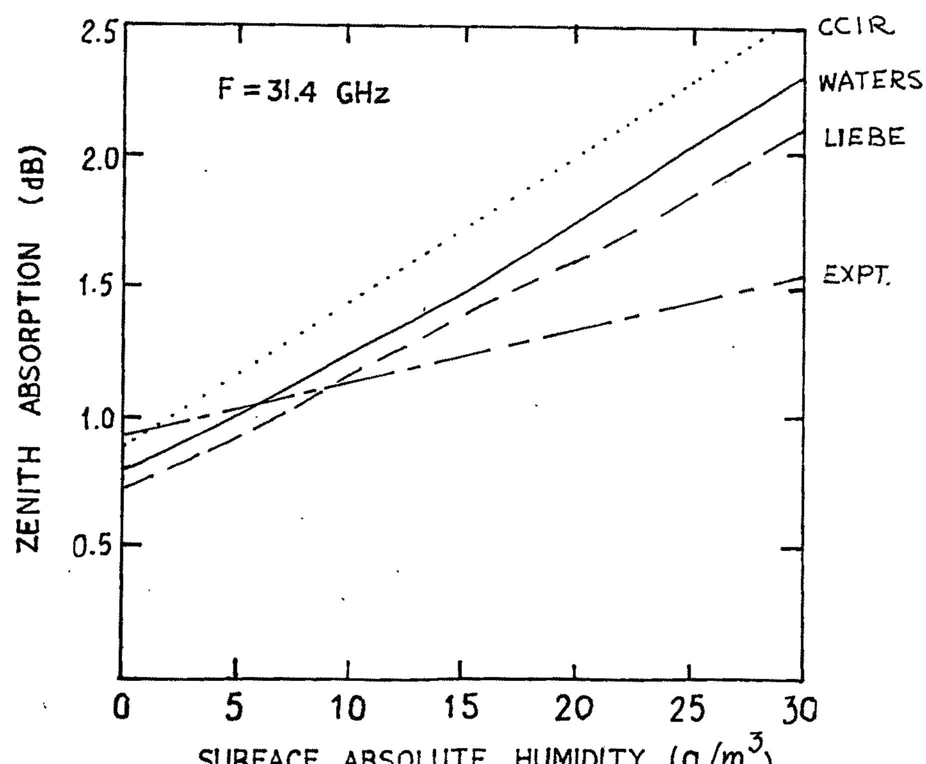

Fig.7.2(b)

Comparison of the estimated values of zenith absorption (dB) with different models and experimental values

Calculated surface absorption coefficient as a function of surface absolute humidity show good agreement at both frequencies Gibbin's values are slightly higher than the others. The experimental surface absorption coefficients are consistently lower than the theoretical value.

In general, the experimental and theoretical zenith absorptions are in good agreement; the experimental surface absorption coefficient on the other hand, are consistently lower than the calculated values. An explanation for this behaviour is not available at this time. Further experiments of absorption as a function of meteorological parameters may be useful to identify the cause.

7.4. Discussion :

In the comparison, the water's model showed significantly less rms difference than that of Liebe's model for both 22.235 and 31.4 GHz. The differences at 22.235 GHz, in particular, are due to modelling of the resonant line contributions. At 31.4 GHz and to the higher frequencies, the Liebe model is much more representative of the measured data. At the latter frequency most of the contribution to the absorption comes from the continuum and/or nonresonant terms which are modelled completely differently by two algorithms. Several authors have developed empirical corrections e.g. *Gaut and Reifenstein* [1971]; *Zammit and Ade* [1981]; *Burch* and *Gryvnak* [1980]; *Liebe* [1985]. It is important to note that the empirical terms are derived from the difference between theoretical and experimental results. Care should be taken in the use of these terms in the calculations.

It should be mentioned that there are over 1800 water vapour lines in the mm-wave/infrared spectrum, 26 of which are at wavelengths above 0.3 mm. Because wings of these lines contribute to the absorption in the window regions, very small errors in the line shape can significantly affect the overall absorption. In addition to the uncertainty of the absorption coefficient of water vapour, there is also the problem of water vapour concentration. The amount of concentration in the lower atmosphere is highly variable and has surface densities ranging from a fraction to 30 g/m^3.

A model was proposed by *Clough et al.* [1980] which also gives much error in the calculation of line shape and lacks the ability to explain the observed attenuation. Therefore, it is not discussed here.

As has been found that all the model have poor accuracy in prediction of attenuation at higher humidities of the atmosphere. The line shape function derived through the models differs from the actual line shape function and there may be some unknown influences which may affect line shape function as well. The characteristics of water vapour spectrum and its contribution is still not totally understood. partially known. However, some empirical values may reduce the modelling error, but through understanding of the continuum absorption is very much essential. The large difference between experimental value and predicted value of attenuation prompts us that the scope for developing new models still exists.