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Radio visibility at microwave frequencies

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Radio visibility through water vapour has been studied over Calcutta at microwave/ millimetre wave frequencies. Due to large abundance of water vapour over Calcutta, the integrated water vapour content restricts the radio visibility approximately up to 5 km at different microwave/millimetre wave frequencies. The present study has been restricted to only the total absorption (dB) part of the propagation parameters of radio waves. The vertical layers of atmosphere have been divided into 10 m slabs with the assumption that the meteorological parameters remain unchanged quantitatively within any of these slabs. The height at which the variation of total absorption (dB) is less than or equal to 1% of that of the immediate preceding height (which is one slab thickness less), is, here, defined as 1% height limit. It has been found that beyond this height the radio receivers at microwave/millimetre wave frequency suffer no appreciable change in the total absorption.

1 Introduction

Theoretical estimates of clear air attenuation due to atmospheric gases indicate that the attenuation rate (dB/km), also called the specific attenuation, exhibits minima[1] at around 30, 94, 140 and 220 GHz. In between these windows there exist the maxima of attenuation mainly due to water vapour and oxygen molecules of the atmosphere[2]. The maxima due to water vapour occur around 22, 183 and 325 GHz in the millimetre wave band[3] of electromagnetic wave spectrum.

The oxygen molecule possesses a permanent magnetic dipole moment, which arises from the pairing of two electron spins in the ground state. Around 60 GHz, a band of hyperfine transition is generated due to changes in the orientation of combined electronic spin relative to the orientation of rotational angular momentum vector. On the other hand, water vapour molecule considered to be an asymmetric top molecule, possesses a large electric dipole moment, exhibiting a spectral rotational line at 22.235 GHz [6_{16}-5_{23}] and much stronger lines at 183.31 GHz [3_{13}-2_{20}] and at 325.15 GHz [5_{15}-4_{22}] extending up to the far-infrared region of the electromagnetic wave spectrum[3].

For clarity, the absorption spectra up to 200 GHz over Calcutta, on a typical rain-free day in monsoon months, has been presented in Fig.1 using millimetre wave propagation model (MPM) as described by Liebe[4]. At 22.235 GHz the specific attenuation is 0.5 dB/km, as evident from Fig. 1, which is predominantly high due to large absorption by water vapour. In fact, from 1990 onward, the ITU-R has adopted Liebe's MPM model, in somewhat truncated form, to describe absorption behaviour of mm-wave during atmospheric propagation, where atmospheric temperature, pressure and humidity were used as input parameters to determine the specific attenuation profile of atmospheric propagation of millimetre waves[5]. This is also supported by Karmakar *et al.*[6] by exploiting 22.235 GHz ground based zenith-looking radiometric study at Calcutta. They[6], assumed that the radiometer possessed the radio visibility extended up to infinity along the zenith. But, this may not be the case in a place where the water vapour seems to be a key factor in contributing towards absorption in the millimetre wave band. The present study explores the possibility of quantification of the radio visibility in the zenith direction at some important microwave frequencies, over Calcutta. For this purpose, the radiosonde data over Calcutta obtained from the India Meteorological Department (IMD) were analysed.

2 Theoretical background

We consider a certain volume of the atmosphere which is considered to be an absorbing medium and attains a temperature, T_m, by absorbing incident microwave energy from outside. This, in turn, re-radiates isotropically. The extent of such absorption or emission of energy depends on fractional transmissivity, σ, of the atmospheric medium. Thus, the radiated energy from the atmosphere is a noise which enhances the thermal noise temperature by an amount $(1-\sigma)T_m$. Now, if such increase in thermal noise temperature is represented by T_a, then

$$T_a = (1-\sigma)\, T_m \text{ (in K)} \qquad \ldots (1)$$

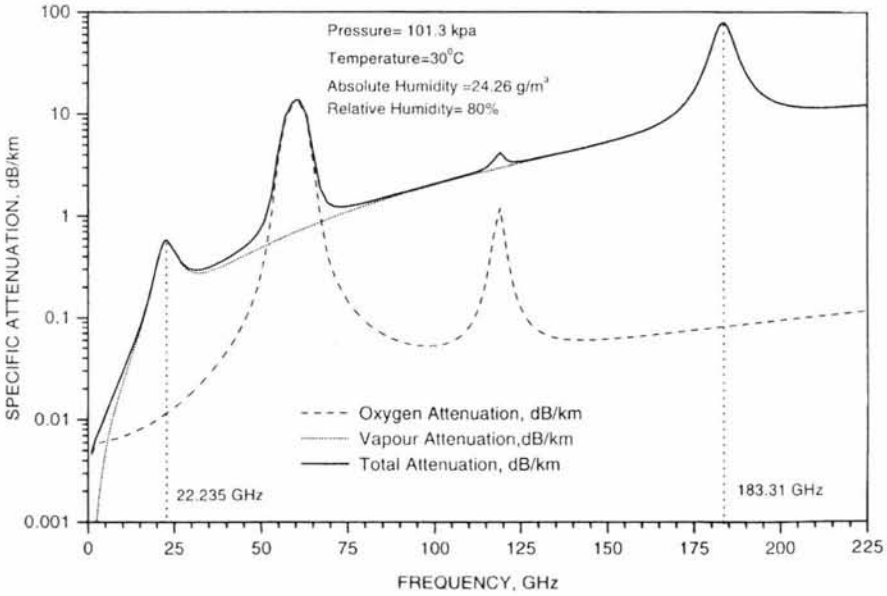

Fig. 1—Electromagnetic wave attenuation profile due to water vapour and oxygen as a function of frequency in the millimetre wave band

Again, by definition, the excess attenuation A(dB) is related to σ by $A = 10 \log_{10} (1/\sigma)$ dB, which, according to Allnutt[7], is given by

$$A = 10 \log_{10} \frac{T_m - T_c}{T_m - T_a} \quad \ldots (2)$$

where, T_c is the cosmic background temperature, which is 2.7 K in the microwave band.

It is to be noted here that T_m is the function of frequency with a significant variation in microwave and millimetre wave bands. According to Altshuler[8], the empirical relation for T_m (in K) involving ground temperature T_s is given as:

$$T_m = 1.12\, T_s - 50 \quad \ldots (3)$$

As we are interested in the frequency band 22-140 GHz, we shall make use of a linear relation between T_m, which is a function of frequency, and surface temperature T_s, for different microwave frequencies[9]. This is expressed as:

$$T_m = C\, T_s + D \quad \ldots (4)$$

for which the values of constants C and D are again reproduced in Table 1 from Mitra *et al.*[9], for the sake of completeness. For this purpose, we have used the following well known theoretical relations[10-12] to determine the water vapour density.

Table 1—Best fit linear regression coefficients for $T_m = C\, T_s + D$

Frequency GHz	Slope (C) K/°C	Intercept (D) K	Correlation coefficient (r)
22.235	0.823	267.383	0.986
31.4	0.857	267.354	0.985
53.75	0.819	269.045	0.982
67.8	0.864	266.800	0.987
76.0	0.911	266.691	0.983
94.0	0.928	268.246	0.988
118.75	0.966	266.975	0.982
120.1	1.004	265.570	0.979
125.0	0.998	267.288	0.985

$$\rho(\mathrm{g/m^3}) = \frac{216.7e}{T_d} \quad \ldots (5)$$

where, T_d is the dew point temperature in Kelvin and e is the partial vapour pressure in hectopascal, which is given by:

$$e = 6.1078 \times \exp\left[5369\left(\frac{1}{273} - \frac{1}{T_d}\right)\right] \quad \ldots (6)$$

3 Results and discussion

The radiosonde data over Calcutta were used to find out the integrated water vapour content (kg/m^2), which is defined as the amount of water vapour present in a cylindrical coloumn of infinitely extended vertical height with a base area of 1 metre square. Using Eqs (5) and (6) and the Liebe's MPM model [4], specific attenuation (α) in dB/km, at different altitudes corresponding to radiosonde data for atmospheric pressure, temperature and dew point temperature for Calcutta, were computed. With the assumption that the atmospheric parameters obtained from radiosonde observation remain unaltered within any vertical extent of 10 m thickness, the integration for specific attenuations, for a height up to 10 km over Calcutta, was carried out to get integrated attenuation in dB. Further, it is assumed that beyond 10 km of height there is too little trace of water vapour to affect the radio signal in the microwave/millimetre wave band in the earth-space path. A plot of integrated water vapour content over Calcutta is presented in Fig. 2. It is interesting to note that the vapour content over Calcutta attains a peak during the months of July through August. Moreover, beyond 7-8 km, the vapour content shows no appreciable change. This also supports the idea of Evans[13].

Also, from the quantitative estimation of the water vapour content in the atmosphere over Calcutta, the absorption coefficients (dB/km) are determined by using the same propagation model as proposed by Liebe[4], at different microwave frequencies. The specific attenuation (dB/km) at different heights up to 8 km for the month of August 1991 has been presented in Fig. 3.

A line-by-line summation has then been adopted to find the integrated attenuation (dB) considering atmospheric slab of 10 m width, at 22.235, 31.4, 53.5, 60, 94 and 183.31 GHz. The corresponding results of water vapour attenuation have been presented in Fig. 4, which shows a definite trend of saturation for attenuation values (dB) beyond 8 km.

With a view to furthering the numerical analyses we have calculated the percentage change of attenuation between two immediate successive levels (10 m each) of the atmosphere from ground up to a height of 8 km. This process has been continued till the limit of 1% change of attenuation is attained for a definite height limit for a given frequency of propagation. From the result so obtained, it has been found that for 22.235 GHz , on an average, the height limit is 4.7 km and those for 31 GHz and 94 GHz are 4.1 km and 3.7 km, respectively, while the maximum height limit attained by 183.31 GHz is 4.8 km. Monthly variations of 1% height limit at the selected frequencies are presented in Fig. 5. Here, it is to be

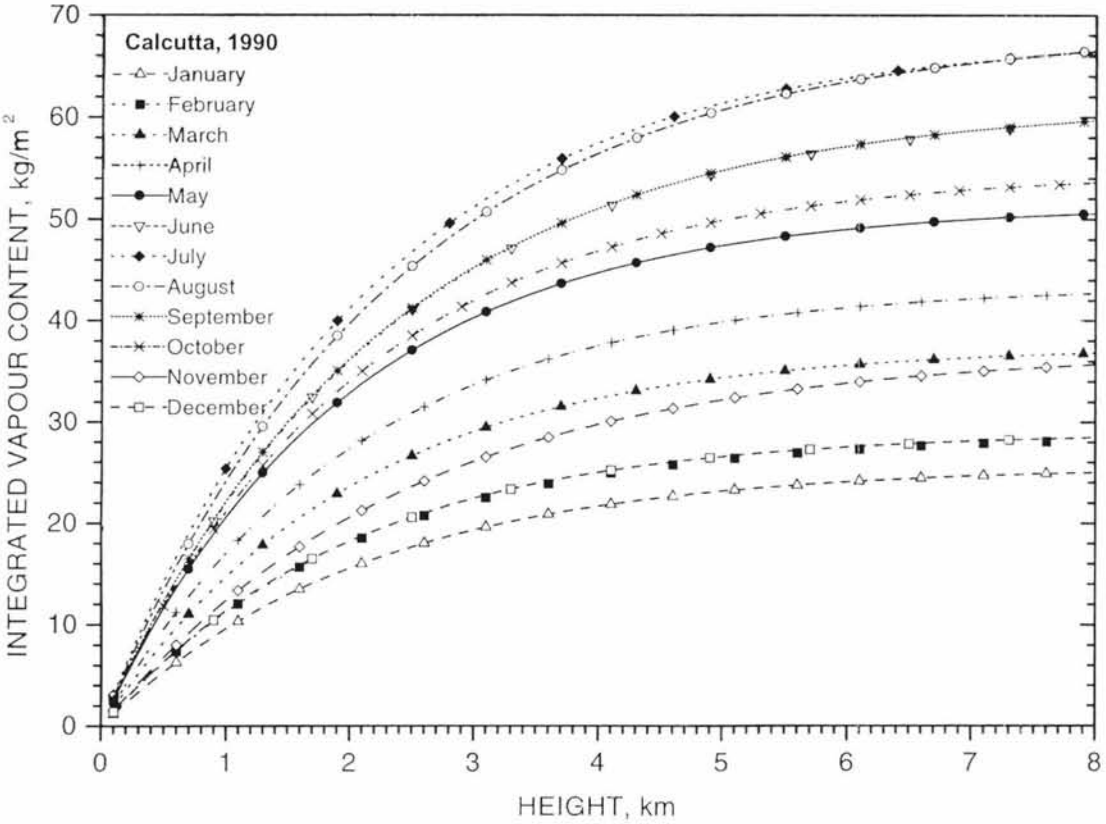

Fig. 2—Variation of integrated water vapour content of the atmosphere as a function of height at Calcutta

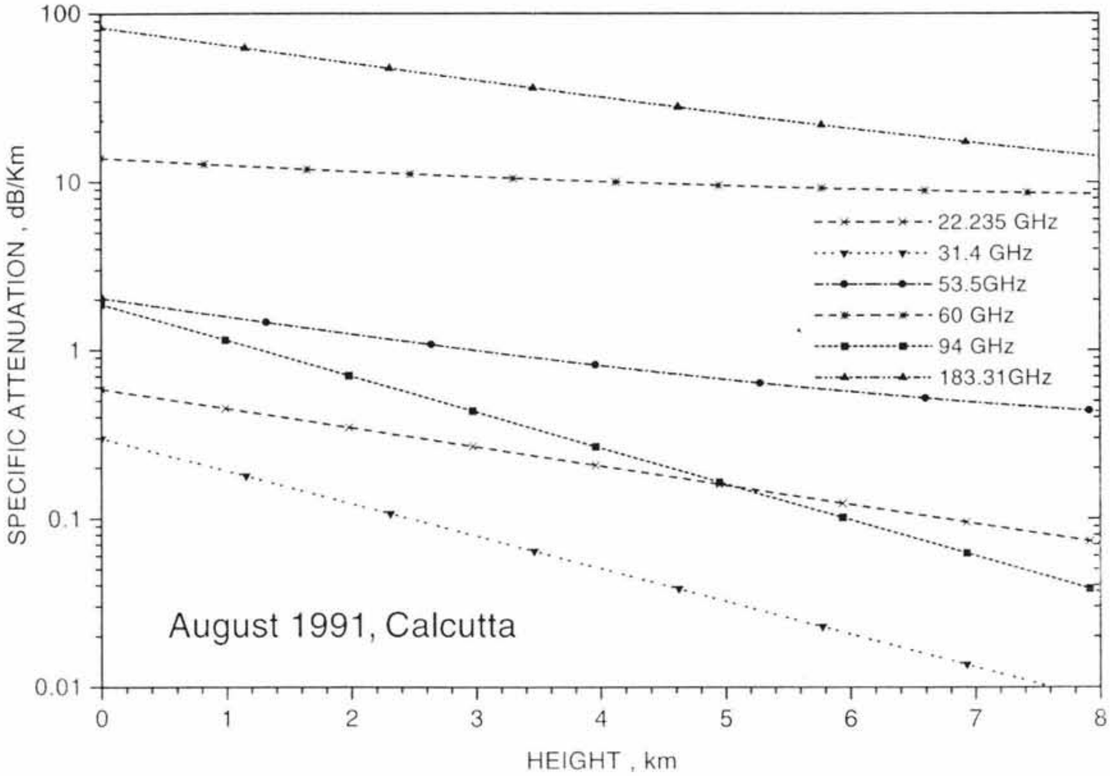

Fig. 3—Variation of specific attenuation with height at few selected frequencies in the millimetre wave band

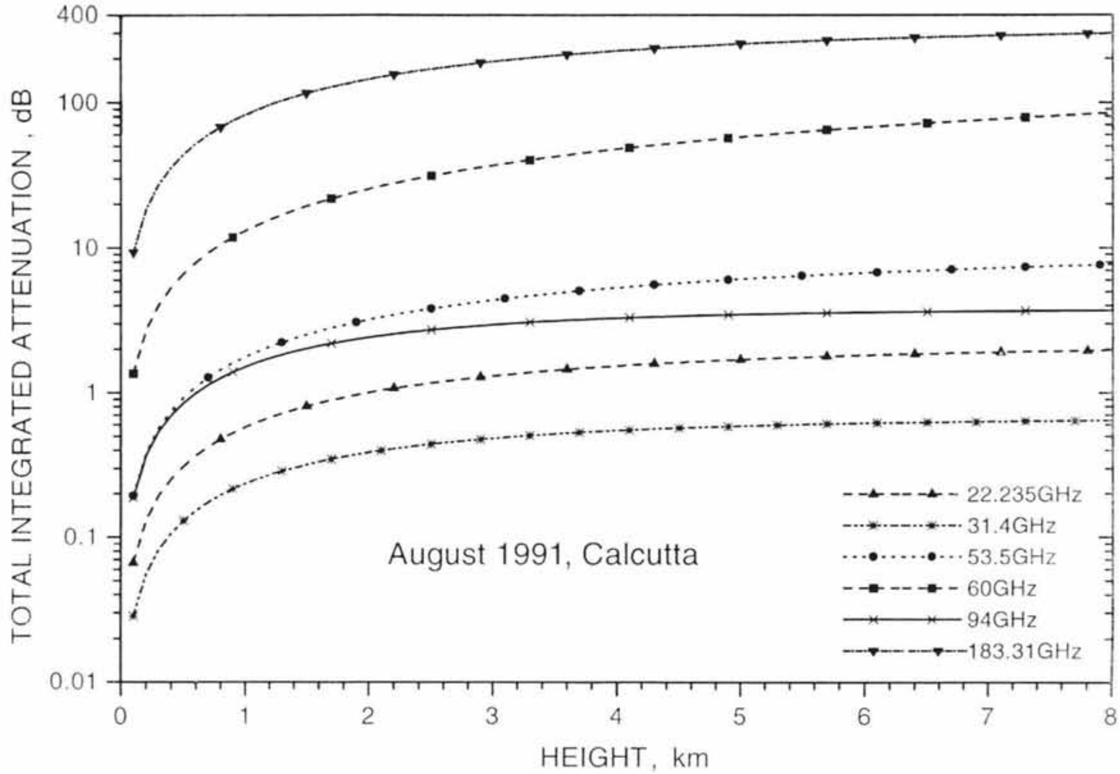

Fig. 4—Variation of total integrated attenuation with height at few selected frequencies in the millimetre wave band

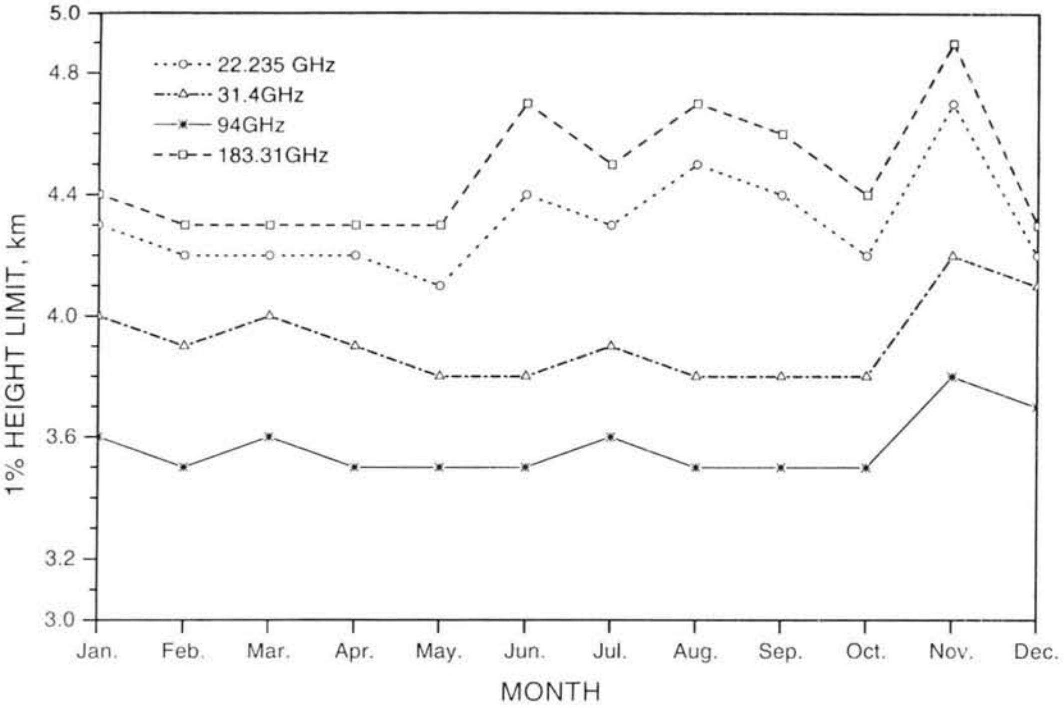

Fig. 5—Monthly variation of 1% height limit at different microwave/millimetre wave frequencies

mentioned that we have restricted the study to 1% height limit of absorption, because 1% value of attenuation has, as such, no significance with respect to the total attenuation at different microwave frequencies. So, beyond this 1% height limit of absorption, the radio receivers at microwave frequencies would not be able to have their appreciable radio-vision. In other words it may be concluded that the aforesaid microwave frequencies posses 99% radio visibility at their corresponding height limits. These are presented in Fig. 5.

During the numerical analyses, it is assumed that the radio receivers are located at the ground and they are all in the zenith-looking mode. So, essentially we have confined ourselves within the troposphere although the integration or summation procedure has been adopted up to infinity to look into any height limit beyond the troposphere.

Moreover, this numerical technique may be applied to any stratospheric height for which data may be obtained from any balloon or air-borne experiments. Murgatroyd *et al.*[14] found, on deploying aircraft experiment at 22.235 GHz, that the stratosphere bears a very dry mixing ratio (≈ 2 mg/kg) at 12-15 km altitude. But in contrast, the balloon experiment showed that the mixing ratio was very high[15] at about 18-20 km. Later, Murcray *et al.*[16] and Mastenbrook[17] solved this anomaly of the mixing ratio.

So, it is suggested to put the radio-receiver in an aircraft in zenith-looking mode in order to estimate 99% radio-visibility height.

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