4

INTEGRATED WATER VAPOUR MEASUREMENT WITH 22.235 GHz RADIOMETER AT CALCUTTA AND ANTARCTICA

4.1. Introduction :

Water vapour is one of the most important atmospheric constituents that imposes serious limitations to the millimeterwave propagation. Besides the effect on radiowave propagation, it can also influence thermodynamic balance, photochemistry of the atmosphere, sun-weather relationship and the bio-sphere. Measurement of vertical and horizontal distribution of water vapour with respect to seasonal and diurnal changes are essential for probing deeper into the mysteries of several effects. The water vapour molecule has an electric dipole moment with resonance at wavelengths of 13.49, 1.64 and 0.92 mm (22.235, 183.31 and 325.5 GHz). Of the various emission lines the 22.235 line is the weakest and therefore, a radiometer at that frequency can see through greater altitudes of the atmosphere and can collect information about the entire troposphere. The radiometer, in fact, works as a fast response ground based remote sensing tool. Conventionally, radiosonde data is used to determine meteorological parameters at different altitudes, but it has the following drawbacks;

- Radiosonde values are available at particular times of the day and it is unsuitable for continuous measurement
- Height resolution and time response of the sensors are often inadequate. Precision instruments can not be carried into balloon due to cost and their operation requires human interaction.
- Radiosonde has poor accuracy in relative humidity measurement at higher altitudes.
- Cloud liquid water information can not be obtained
- Radiosonde path can not be controlled through the atmosphere as balloon gets drifted from the site of release
- Slant path profiling is not possible
- Radiosonde can not provide instantaneous height profile, as it takes considerable time to ascend

The radiometric observation, in contrast, has the following advantages;

- Continuous unattended measurement is possible which may give dynamic variation of the parameter of interest
- Providing instantaneous height profile
- Sensitivity and measurement accuracy is far better than radiosonde
- It can sense cloud liquid water content
- Slant path profiling is possible
- Limb sounding by radiometers may provide accurate information about the minor constituents of the atmosphere, which often plays a major role in atmospheric photochemistry, ozone depletion and green house effect.

A microwave radiometer tuned at the thermal emission line of water vapour at 22.235 GHz is capable of detecting and measuring even minute traces of water vapour in the atmosphere from ground based observation. Such a radiometer developed as a part of Indian Middle Atmospheric Programme (IMAP) in collaboration with Space Application Centre, Indian Space Research Organisation (ISRO) has been in operation for about last 7 years at the Institute of Radiophysics and Electronics, University of Calcutta, under a collaborative IMAP (Indian Middle Atmospheric Programme) project. The same radiometer was taken to Antarctica, the world's driest continent, and was put into continuous measurement of atmospheric water vapour during polar summer. Both measurements were compared with corresponding radiosonde values to examine the superiority of 22.235 GHz radiometer in the measurement of water vapour at the two locations with extremely low and high humidities.

4.2. Theoretical background :

For ground based observations of the troposphere during non-precipitating conditions, the following analysis is based on the scalar radiative transfer equation that neglects scattering and polarisation. Polarisation effects are important for stratospheric and mesospheric observations in which Zeeman splitting, due to the Earth's magnetic field, is important [*Westwater et al.* 1990]. This may be reflected for tropospheric observations during nonprecipitating conditions. Scattering is also negligible during nonprecipitating conditions at the wavelength of interest.

The antenna temperature T_a measured by the radiometer is equal to the emission noise temperature $T(\theta, \varphi)$ of the atmosphere when $T(\theta, \varphi)$ is a slowly varying function of θ and φ, the antenna temperature is given by,

$$T_a = T(\theta, \varphi)$$

Also, the attenuation can be derived from the equation

$$T_a = T_{sk}\, exp\left[-\int_0^l \alpha(x)dx\right] + \int_0^l \alpha(x) T_{at}(x) dx . exp\left(-\int_0^l \alpha(x)dx\right)$$

where, T_a = antenna temperature, T_{at} = temperature of the atmosphere, α = absorption coefficient of the atmosphere in Nepers/meter and l=length of the raypath through the atmosphere from the antenna. For emission mode measurements T_{sk} is due to the galactic radio noise and it is only about 2.7K [For f>10 GHz, *Ulaby*, 1986]. Often, it is neglected and the above equation may be modified as

$$T_a = \int_0^l \alpha(x) T_{at}(x) dx . exp\left(-\int_0^l \alpha(x)dx\right)$$

If the height distribution of atmospheric temperature T_{at} is replaced by an equivalent mean atmospheric temperature T_m extending between zero and upto the limit l of the atmosphere, it can be taken outside the integral. The antenna temperature in this case is given by a much simpler expression,

$$T_a = (1 - e^{-\alpha l}) T_m$$

the total Zenith attenuation γ can be derived from [*Allnutt*, 1976],

$$\gamma = \alpha l = 10 log_{10} \frac{T_m}{T_m - T_a} \quad (4.1)$$

The mean temperature of the atmosphere is a function of the location, season, day and time of the day. Usually, the value of T_m is assumed to be around 275 K for temperate latitudes while for tropical latitudes like India we assume a value of T_m= 280 K for fair weather conditions. It may be mentioned here, that the mean temperature may increase during rain due to rain scatter [*Zhang and Li,* 1985]. By comparing total Zenith attenuation γ derived from Eqn.(4.1), using the measured emission noise temperature T_a with that measured directly by the absorption mode and using the Sun as the source, one can easily find out the value of T_m.

For the theoretical estimates of the attenuation coefficient *Barrett and Chung* [1962] gave the following expression for the water vapour absorption line at 22.235 GHz, based on monomer model.

$$\gamma_{1.35} = 1.05 \times 10^{-28} \frac{Nf^2 e^{-644/T}}{T^{5/2}} \left[\frac{\Delta f}{(f - f_o)^2 + \Delta f^2} + \frac{\Delta f}{(f + f_o)^2 + \Delta f^2} \right] + 1.52 \times 10^{-52} \frac{Nf^2 \Delta f}{T^{3/2}} \text{ cm}^{-1} \quad (4.2)$$

where pressure broadened line halfwidth parameter Δf is given by

$$\Delta f = 2.62 \times 10^9 \frac{(P / 760)}{(T / 318)^{0.625}} (1 + 0.0046\rho \ ) \sec^{-1} \quad (4.3)$$

here P = total atmospheric pressure in mm Hg, ρ = water vapour density in gm/m^3, N = the number of water molecules/cm^3 = 3.35×10^{16} molecules/cm^3,

T = Kinetic temperature in K, f = the frequency in Hz, f_o = 22.235×10^9 Hz. The above equation was later modified by *Staelin* [1966] for 6_{16}-5_{23} transition of water vapour and given as

$$\gamma_{1.35} = 3.24 \times 10^{-4} \frac{Pf^2 \rho e^{-644/T}}{T^{3.125}} \left(1 + 0.0147 \frac{\rho T}{P}\right)$$

$$\times \left[\frac{\Delta f}{(f - 22.235)^2 + \Delta f^2} + \frac{\Delta f}{(f + 22.235)^2 + \Delta f^2} \right] + 2.55 \times 10^{-8} \frac{\upsilon f^2 \Delta f}{T^{3/2}} \quad (4.4)$$

and

$$\Delta f = 2.58 \times 10^{-3} \frac{P}{(T/318)^{0.625}} (1 + 0.0147 \frac{\rho T}{P}) \quad (4.5)$$

From Eqn.(4.4) and Eqn.(4.5), after simplification, we get,

$$\gamma_{1.35} = 17.92 \times \frac{\rho e^{-644/T}}{PT^{1.875}} \times \left(1 + 0.0147 \frac{\rho T}{P}\right)^{-1}$$

$$+ 11.91 \times 10^{-7} \frac{P}{T^{2.125}} (1 + 0.0147 \frac{\rho_v T}{P}) \quad (4.6)$$

In Eqn.(4.6), the first term represents a resonance term and the second term is the non-resonance term. Now considering the typical surface parameters for Calcutta, P = 1000 mb; T_o = 300K ; ρ_o = 25 gm/m^3, we find that the non-resonance part is of the order of 1 percent of the resonance part. So this non-resonance part may be neglected.

$$\gamma_{1.35} = 17.92 \times \frac{\rho e^{-644/T}}{PT^{1.875}} \times \left(1 + 0.0147 \frac{\rho T}{P}\right)^{-1} \quad (4.7)$$

In addition to this, using the same data we find that the term $0.0147\rho T/P$ is much less than 1 and hence may also be neglected. Converting the Eqn.(4.7) into dB/km, we get,

$$\gamma_{1.35} = 17.92 \times \frac{\rho e^{-644/T}}{PT^{1.875}} \times log_{10}\,\rho \times 10^6 \quad \text{dB/km}$$

$$\gamma_{1.35} = 7.78 \times 10^6 \times \frac{\rho e^{-644/T}}{PT^{1.875}} \quad \text{dB/km}$$

$$\gamma_{1.35} = 7.78 \times 10^6 \times \rho \times F(T)\frac{T^{0.52699}}{P} \quad \text{dB/km} \qquad (4.8)$$

where, $F(T)$ is a implicit function of T and may be given as,

$$F(T) = \exp(-644/T)T^{2.40199}$$

The range of values of T is chosen in such a way that $F(T)$ may be considered as a slowly varying function within the range. It is found that a range of T from 230K to 310K makes $F(T)$ a slowly varying function of values of $F(T)$ over this range and is given by 1.3×10^{-7}. So Eqn.(4.8) reduces to

$$\gamma_{1.35} = 7.78 \times 10^6 \times \rho \times 1.3 \times 10^{-7} \times \frac{T^{0.52699}}{P} \quad \text{dB/km}$$

$$\gamma_{1.35} = 1.0114 \times \frac{\rho T^{0.52699}}{P} \quad \text{dB/km}$$

Total water vapour absorption (Zenith attenuation) at 22.235 GHz,

$$\gamma = 1.0114 \int_o^{\infty} \frac{\rho T^{0.52699}}{P} dh \quad \text{dB} \qquad (4.9)$$

According to *Hess* [1959] and *Brunt* [1947] the atmosphere is assumed to be of constant lapse rate. Then the relation between temperature (T) and pressure (P) is given by Poisson's equation as,

$$T = T_o \left[\frac{P}{P_o} \right]^{\frac{R\beta}{g}} \qquad (4.10)$$

Where, R = gas constant, β = lapse rate,

$$P = P_o e^{-\frac{h}{H_P}} \qquad (4.11)$$

$$\rho = \rho_o e^{-\frac{h}{H_\rho}} \qquad (4.12)$$

Where, T_o = surface temperature, P_o = surface pressure, ρ_o = surface water-vapour density, H_P = Pressure scale height, H_ρ = water vapour scale height.

$$\gamma = 1.0114 \times \frac{\rho_0 T_0^{0.52699}}{P_0} \int_o^\infty exp(-H_1 h)dh$$

$$\gamma = 1.0114 \times \frac{\rho_0 T_0^{0.52699}}{P_0 H_1}$$

where,

$$H_1 = \frac{1}{H} - \frac{1-(0.52699 R\beta / g)}{H_P}$$

For Calcutta, β = 0.7509 K/100 m (as obtained from Civil Aviation Department, Calcutta Airport, for 1.5 km to 7 km) R = 2.9 ergs °C^{-1} mole^{-1}; H_P = 8 km

Now using Eqns. (4.11) and (4.12) and substituting the values of β, R and H_P, we have

$$\frac{P_o\gamma}{H_\rho} = 1.0114 \times \rho_o \times T_o^{0.52609} + 0.1103\gamma \times P_o$$

then, water vapour scale height [*Sen et al.* 1990] over Calcutta,

$$H_\rho = \frac{P_o\gamma}{1.0114T_o^{0.52609}\rho_o + 0.1103\gamma P_o} \quad \text{km} \tag{4.13}$$

where γ is the zenith attenuation (dB) to be measured from radiometric data employing Eqn.(4.1). Further from Eqn.(4.12), integrated water vapour content, i.e. total mass of water vapour contained in a vertical column of cross section 1 square metre, W is given by,

$$W = \int_0^\infty \rho_v(h)dh$$

From Eqn.(4.12),

$$W = \int_0^\infty \rho_o e^{\left(-\frac{h}{H_\rho}\right)} dh \tag{4.14}$$

Here, ρ_o in gm/m^3, h and H are both in km, then Eqn.(4.14) reduces to

$$W = H_\rho . \rho_o . 10^3 \ \ g/m^2 \tag{4.15}$$

Eqn.(4.13) may be used for finding water vapour scale height H from antenna temperature obtained from radiometric observation. With these values of H and simultaneous values of surface water vapour density ρ_o (from radiosonde) the integrated water vapour content W may be calculated from Eqn.(4.15). A linear best fit equation is obtained for Calcutta.

$$T_a = 1.47\, W\,(\text{kg/m}^2) + 3.05 \tag{4.16}$$

or,

$$W = 68.027 \times 10^{-2}\, T_a - 2.075 \ \text{kg/m}^2 \tag{4.17}$$

Similar estimates for Antarctica was done and the regression equation so obtained may be given by,

$$T_a = 6.45\, W\,(\text{kg/m}^2) + 4.69 \tag{4.18}$$

or,

$$W = 0.155\, T_a - 0.727 \ \text{kg/m}^2 \tag{4.19}$$

The difference between Eqn.(4.17) and Eqn.(4.19) occurs due to wide difference in climatic conditions of Calcutta and Antarctica.

4. 3. Radiometric observations :

The 22.235 GHz radiometer was operated in emission mode with its antenna pointed towards zenith round the clock for a period of 3 years (1988-1991) at Calcutta. Also, the same radiometer was taken to Antarctica and operated for a period of 4 months during polar summer (Dec.1991-Mar.1992) at Indian base station 'Maitri'. The radiometer output is a representative of the emission noise temperature of the atmosphere which increases with increase of water vapour in the atmosphere. The radiometer was calibrated from time to time to ensure measurement accuracy. The following analysis is based on data for 'clear sky' conditions which means that measurements were made when clear view of the sun was available. Concurrent radiosonde data were used to analyse radiometric data.

A wide range of measurement values were identified to calculate emission noise temperature (K), zenith attenuation (dB), integrated water vapour content (gm/m^2) and regression analysis was also done. A strong correlation of absorption with surface absolute humidity has been found. In past, the correlation of total precipitable water with surface absolute humidity was studied by several investigators and unfortunately their conclusions are not in agreement. *Reber and Swope* [1972] report correlation coefficient of about 0.50 based on annual statistics. *Bolsenga* [1965] reported correlation coefficient 0.80 and *Reitan* [1963] has reported correlation coefficient as high as 0.99. Thus their is sufficient reason to conclude that surface absolute humidity is only a fair indicator of water vapour aloft. Unfortunately, it is very difficult to measure total precipitable water, surface absolute humidity is the best alternative parameter for comparison of zenith brightness vis-a-vis integrated water vapour [Altshular et al. 1988].

4.3.1. Observations at Calcutta :

In clear sky condition, the emission noise temperature of the atmosphere was found to vary between 35 to 140 K. In winter (Dec. to Feb.) it goes down to 30-35 K and in monsoon months it sometimes rise to 130 K as shown in Fig.4.1. Corresponding attenuation values were calculated and they were found to follow similar trend as with emission noise temperature. The attenuation values varied between 1.68 dB to 3.87 dB during the entire year. Mean attenuation values during winter, pre-monsoon, monsoon and post-monsoon periods are given in Table 4.1. Besides this, the integrated water vapour content was calculated from antenna temperature, using Eqn.(4.17) and is shown in Fig.4.1. The average values of integrated water vapour content for different seasons over Calcutta are given in Table 4.1.

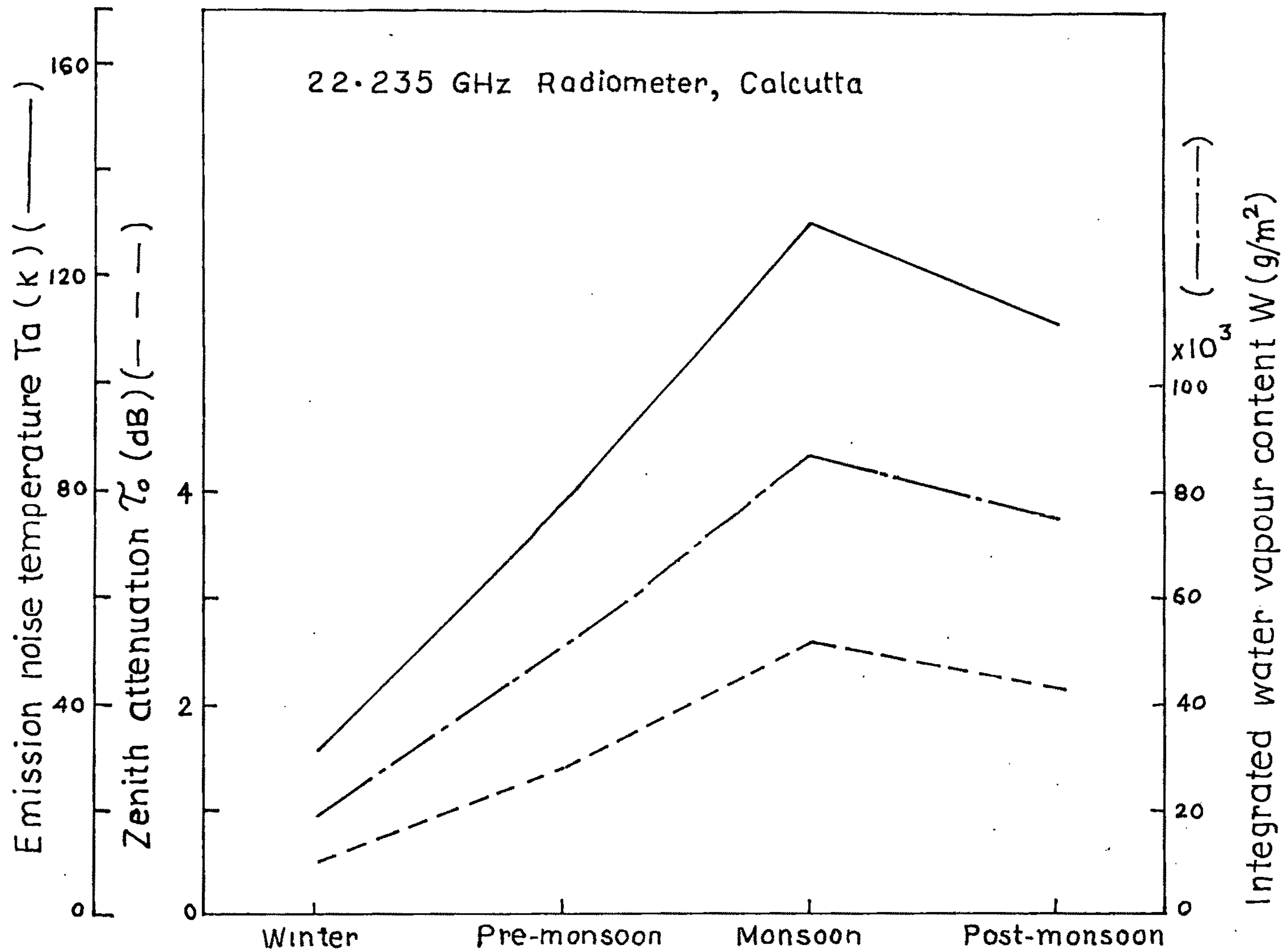


Fig.4.1 Average values of seasonal variation of antenna temperature (K) and water vapour content (g/m^2) observed by 22.235 GHz radiometer.

Table 4.1

Integrated water vapour content for different seasons at Calcutta

Season	Months	Mean attenuation (dB)	Mean integrated water vapour content W in kg/m^2
Winter	Dec. - Feb	1.68	19
Pre-monsoon	Mar. - May	2.54	50
Monsoon	June - August	3.87	87
Post-monsoon	Sept.- Nov.	1.76	74

Diurnal variation of communication parameters and integrated water vapour content of the atmosphere were available through continuous radiometric data. The diurnal variation of integrated atmospheric water vapour content for typical weather conditions are presented in Fig.4.2. On long term study, it is observed that integrated water vapour content attains a maximum value few hours after the mid day and a minimum value a few hours after mid night in different seasons. The delay of this maximum and minimum values of the communication parameters from mid day to mid night may be due to the thermal capacity of the surface layers.

The monthly variation of emission noise temperature, attenuation and water vapour content has been presented in Fig.4.3. The Figure shows that during the period Jan-Feb there is not much increase in the water vapour content. It starts rising from about the second week of March and maintains a rising trend upto the end of August. August being the highest in the water

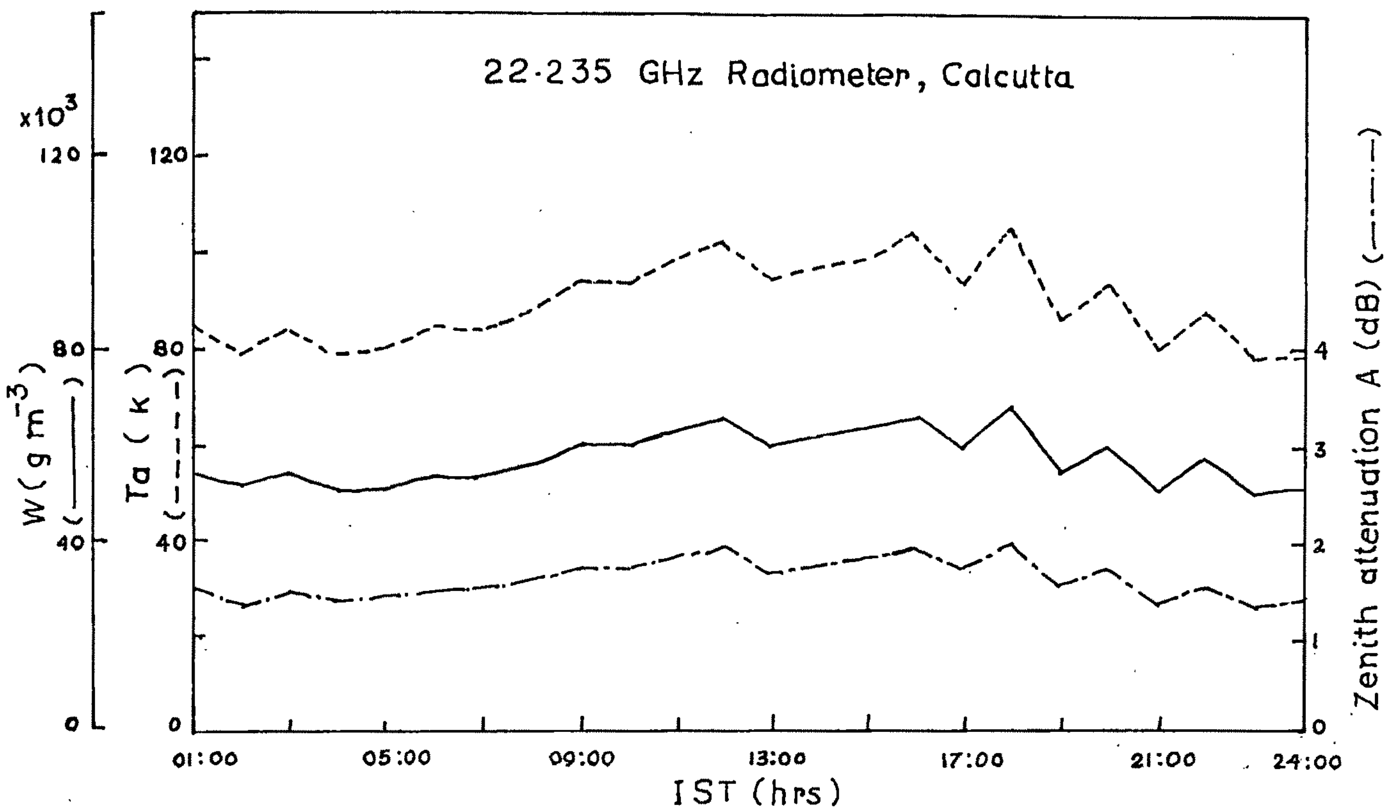


Fig.4.2 Diurnal variation of antenna temperature T_a(K), integrated water vapour content W (gm^{-2}) and zenith attenuation A(dB) over a year..

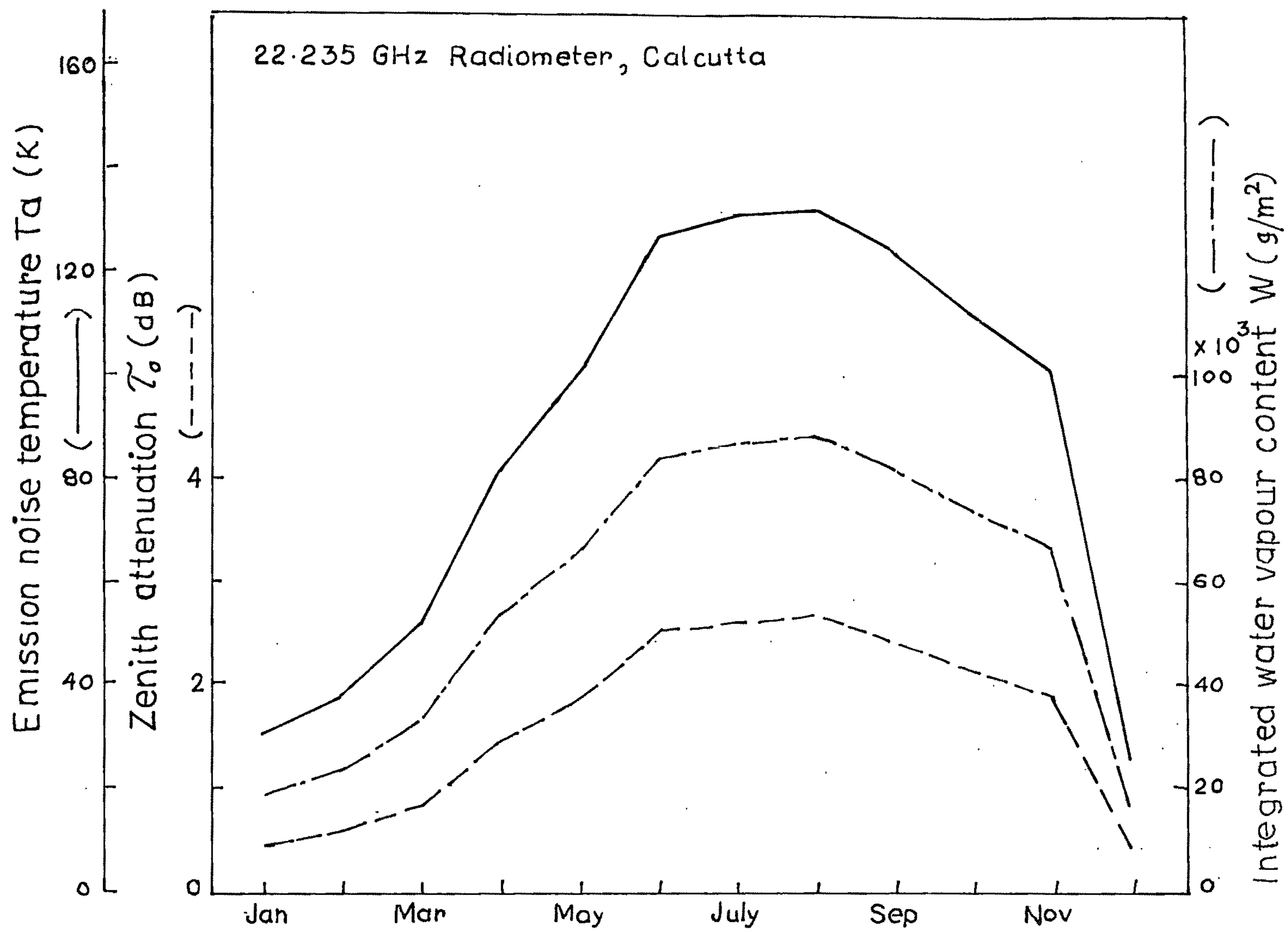


Fig.4.3 Average values of monthly variation of antenna temperature (K) attenuation (dB) and water vapour content observed by 22.235 GHz radiometer.

vapour content for the period June to August. It then falls off around the last week of November and continues to drop all through December and finally attains a steady low value during January. From Fig.4.3, it may be noted that variations of emission noise temperature and zenith attenuation are closely related with the variation pattern of integrated water vapour content. Thus we may conclude that 22.235 GHz emission noise temperature and zenith atmospheric attenuation originate mainly from the water vapour present in the atmosphere. Error estimate for integrated water vapour as measured by 22.235 GHz radiometer with respect to radiosonde was carried out. Fig.4.4 shows a correlation co-efficient of 0.73 and r.m.s. error of 0.36 g/m^2.

4.3.2. Observations at Antarctica :

The 22.235 GHz radiometric observation at Indian Antarctic base station 'Maitri' was carried out for 4 months during Dec.1991 to March 1992. During that period, the emission noise temperature of the atmosphere was found to vary between 20 to 70 K in clear sky condition. In December it goes down to 20 K and in February it sometimes rises to 70 K and in March it goes up to 40 K. This is shown in Fig.4.5. Corresponding attenuation values were found to vary between 0.32 dB to 1.24 dB. Mean attenuation values during pre-summer, summer and post-summer periods are given in Table 4.2. The Integrated water vapour content of the atmosphere were calculated from antenna temperature, using Eqn.(4.18) and is shown in Fig.4.5. The average values of integrated water vapour content for different seasons over Calcutta are given in the Table 4.2.

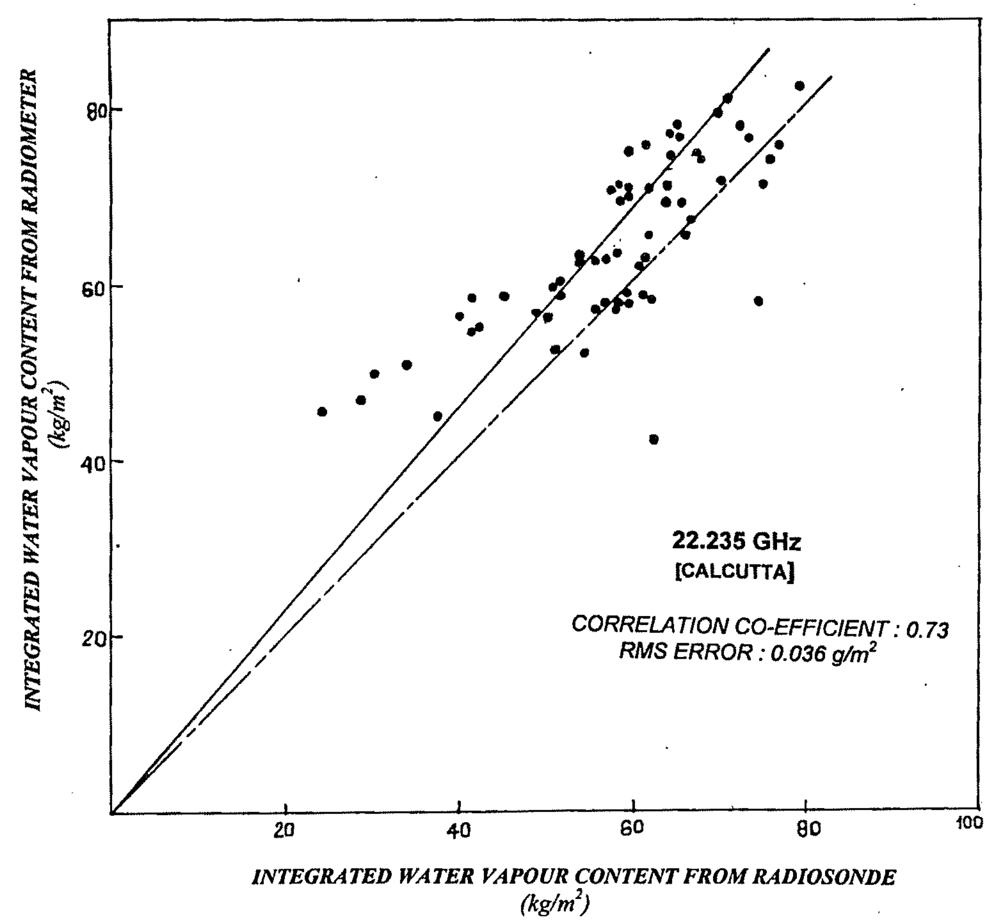


Fig.4.4 Error estimate for integrated water vapour as measured by 22.235 GHz radiometer with respect to radiosonde

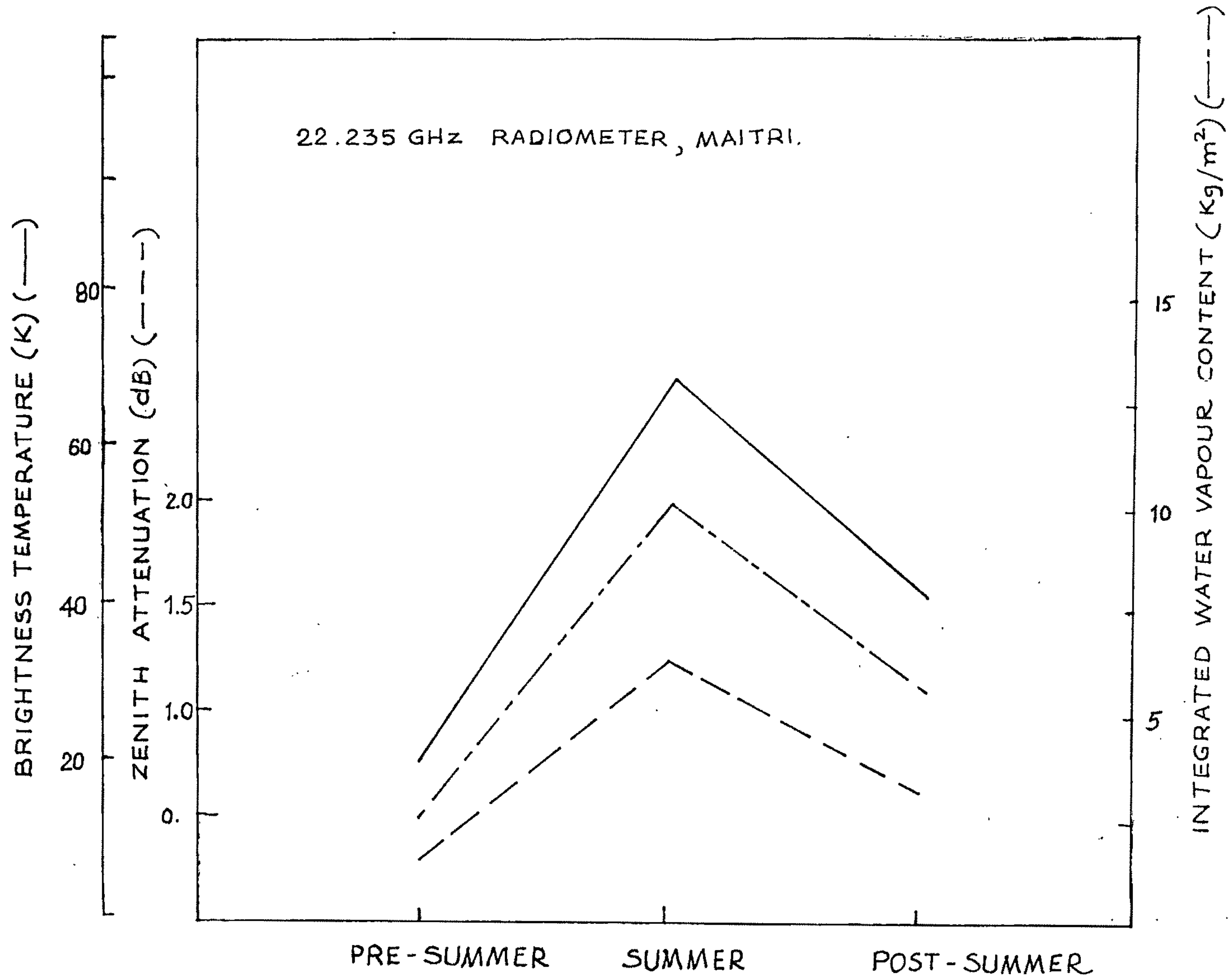


Fig.4.5 The variation of integrated water vapour zenith attenuation emission noise temperature

Table 4.2

Integrated water vapour content for different seasons at Maitri

Season	**Months**	**Mean attenuation (dB)**	**Mean integrated water vapour content W in kg/m^2**
Pre-summer	Nov-Dec.	0.32	2.373
Summer	Jan.- Feb.	1.24	10.12
Post-summer	Mar- April .	0.66	5.473

Diurnal variation of antenna temperature and integrated water vapour content of the atmosphere were also studied. The diurnal variation of integrated water vapour is presented in Fig.4.6. Diurnal variations observed were much lower as compared to those prevailing at Calcutta since solar radiation remains throughout day and night during polar summer. The monthly variations of emission noise temperature, attenuation and water vapour content have been studied which revealed that during the period of Jan-Feb there is no appreciable increase in the water vapour content. It starts rising from about the second week of January and maintains a rising trend upto the end of February. February being the highest in the water vapour content. It then goes down due to the onset of polar winter and continues to drop all through and finally attains a steady low value during July to August. Error estimate for integrated water vapour as measured by radiometer with respect to radiosonde was carried out. Fig.4.7 shows the correlation co-efficient of 0.94 and r.m.s. error of 0.086 g/m^2. A composite diagram of attenuation at Calcutta and Antarctica is given in Fig.4.8.

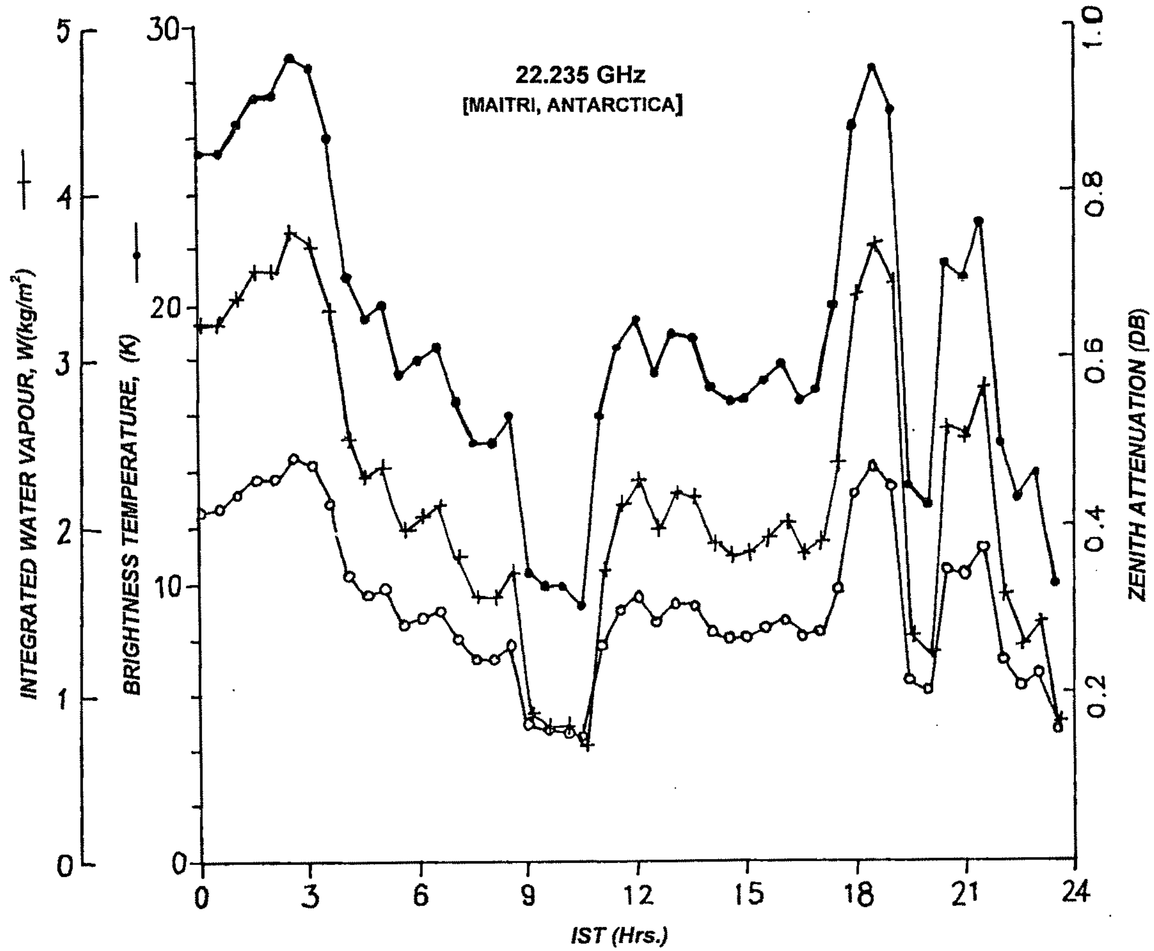


Fig.4.6 Diurnal variation of antenna temperature and integrated water vapour content of the atmosphere.

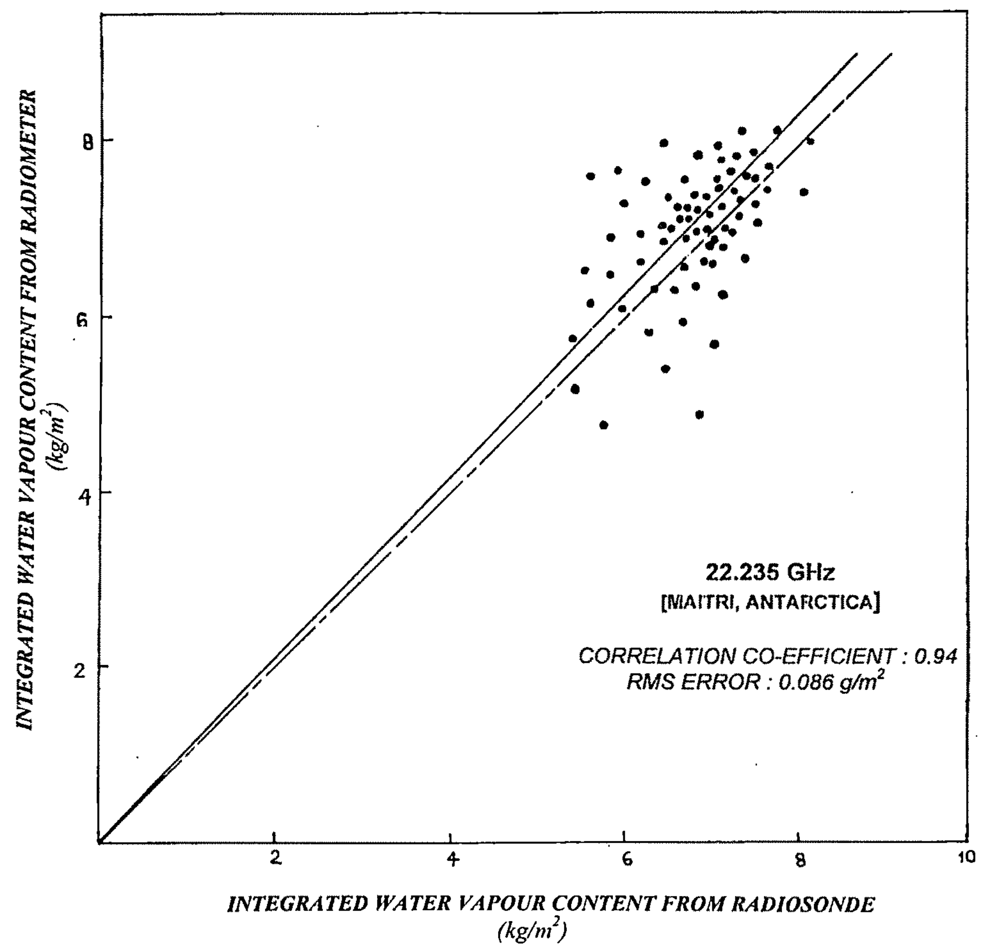
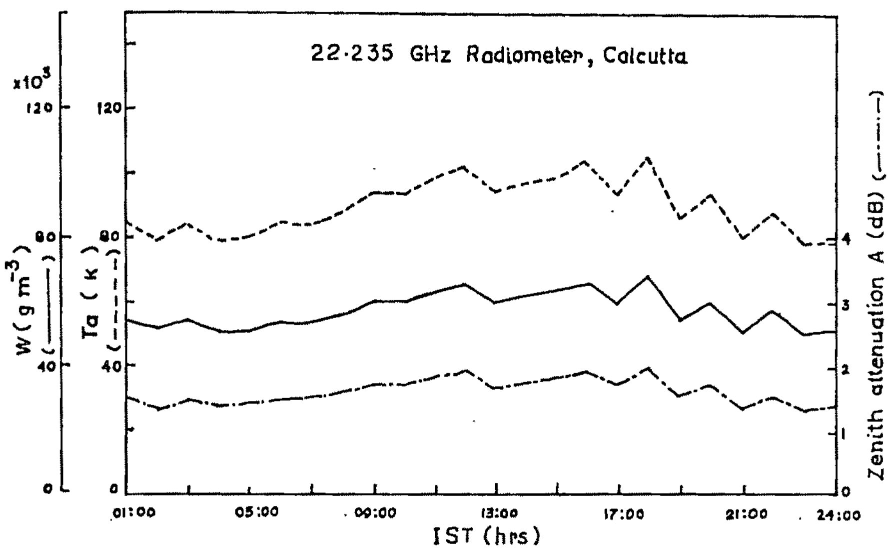


Fig.4.7 Error estimate for integrated water vapour as measured by 22.235 GHz radiometer with respect to radiosonde



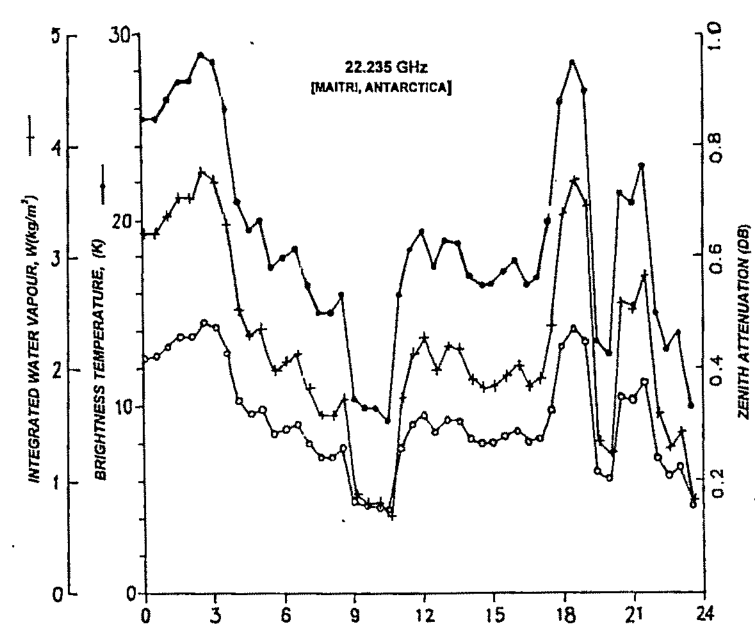


Fig.4.8 A composite diagram of attenuation at Calcutta and Antarctica

4.4. Discussion :

The radiometer used in the measurement was having sensitivity of around 1K. Radiometers are now available with sensitivity 0.01K. Cosmic background, reflections from surrounding objects including ground, flatness of the reflector may introduce an additional error to the extent of 8-10%.

In inversion technique, vertical distribution of water vapour has been assumed to be exponential. This may not be exactly true - multi-frequency radiometers, if used, may reduce errors in the inversion. At Calcutta, the radiosonde values are taken from India Meteorology Department and the site of balloon ascension is about 8 km apart from the radiometric observation site. Moreover continuous radiometric data is compared with radiosonde data measured two times in a day.

Zenith thermal emission depends on the vertical temperature distribution of the atmosphere. Accordingly, the value of T_m would vary. Therefore, the value of T_m should be different for Antarctica and Calcutta. For Calcutta T_m = 280 K and for Antarctica it is taken as 270 K. However, the error is not more than 4% as antenna temperature linearly varies with attenuation.

As discussed in Chapter 3, the 22.235 GHz is more suitable for measurement of water vapour at Antarctica rather than at Calcutta because of more pressure dependent line shape function which is significant in humid regions. Therefore, error estimate shows a value of 0.086 g/m^2 at Antarctica as compared to 0.36 g/m^2 prevailing at Calcutta. Thus, 22.235 GHz radiometer gives more accurate results at Antarctica.