3

A FRESH CONSIDERATION ON THE SELECTION OF RADIOMETER OPERATING FREQUENCY IN WATER VAPOUR REMOTE SENSING

3.1. Introduction :

In recent years, microwave and millimeter wave radiometers have emerged as powerful tool for remote sensing of atmospheric meteorological parameters, such as, temperature, water vapour, cloud liquid water. Knowledge of these parameters are not only useful to meteorologists but also to communication engineers for propagation studies in the mm-wave band. A well calibrated microwave radiometer, sensitive to a particular atmospheric parameter, may be used either in emission mode or absorption mode to monitor the dynamic variation of the parameter on a continuous basis except for some brief periods during heavy rains when radiometric sensing is obscured by the brightness temperature of raindrops approaching ambient temperature. The principal advantage of microwave and millimeterwave sensing is that it can penetrate aerosols, fog, cloud, dust etc. and permits very accurate remote sensing of the atmosphere.

The molecular resonance peaks are generally exploited for remote sensing of atmospheric gases, such as, water vapour and oxygen. For water vapour measurement, radiometers operating at either 22.235 GHz or 183.15

GHz would be ideal. But, *Westwater* [1967] pointed out that the operation of radiometer at resonant peak may induce serious errors in retrieval mechanisms, due to the height dependence of the pressure broadening of rotational lines. The pressure broadening effect is predominant at 22.235 GHz, as it is relatively weaker than 183.15 GHz line. Contribution of wings of the higher frequency lines are significant even at the peak of water vapour resonance line [*Croom*, 1965]. *Westwater* [1967] suggested that some offset frequency, such as, 21.0 or 24.4 GHz may be chosen as operating frequency where change in absorption caused by pressure broadening would be insignificant. At about 21.0 GHz, the pressure broadened line is approximately two third of its maximum emission intensity. Measurements at offset frequency are, in fact, less sensitive to the distribution of water vapour with altitude and are better correlated with the integrated values of water vapour. It is the purpose of this chapter to re-examine the need for an offset frequency of radiometer operation especially for regions with dry and cold climate like Antarctica.

3.2. Absorption Mechanism :

The water vapour molecule has a residual electrical dipole moment whereas oxygen has magnetic dipole moment. The moments result in forced rotation of these molecules by radio waves in microwave and millimeter wave bands. At low pressure, a small line width broadening takes place near the resonance line due to Doppler effect. At higher pressure, broadening of the lines occur due to collision of the molecules. The absorption of microwave and mm-wave emissions by atmosphere is governed by three factors; viz.,

- Line strength parameter (σ)
- Line width parameter (γ)
- Choice of frequency (f)

3.2.1. Line strength parameter (σ) :

The absorption line strength is proportional to the atmospheric gases like H_2O and O_2 mainly, while contributions from other trace gases are negligible. Contributions from these two gases, H_2O and O_2, could be estimated by the existing theories with reasonable accuracy. At the resonant frequency, the theoretical values match well with experimental data. The lines strength parameter can be given by;

$$\sigma = k_1 P T^{-3} + k_2 \rho_v T^{5/2} e^{-k_3/T} \qquad (3.1)$$

where P is the pressure in mb, T is the temperature in Kelvin and ρ_v is the water vapour density in gm/m^3. Here k_1, k_2 and k_3 are constants, each of them depending upon the operating frequency. The first term represents the contribution by oxygen while the second term being the contribution from water vapour.

3.2.2. Line width parameter (γ) :

Line width parameter is the most critical parameter on which the microwave and mm-wave attenuation depends. The absorption lines near resonance are broadened at low pressure only due to Doppler effect. At higher pressure, broadening of lines are further enhanced due to the collision of molecules.

The pressure broadening effect is caused by pressure induced molecular collisions between H_2O and N_2 molecules and further increased by temperature of the medium which increases the collision frequency. Estimation of line width broadening is given by *Van-Vleck-Weisskopf* line shape function. This was further modified by *Zhevakin-Naumov-Gross* using the parameters of *Waters* [1976] and the proposed line shape function correlates well with the experiment. Calculations of water vapour mass absorption coefficient for 10% change on linewidth constant are shown in Fig.3.1(a) [with *Van-Vleck-Weisskopf* line shape] and Fig.3.1(b) [with *Zhevakin-Naumov-Gross* line shape], both taken from *Hogg* [1982]. At 22.235 GHz, the absorption coefficient varies considerably with pressure because of its dependence on line shape function. In the figures it is important to note that at around 20.6 and 24.4 GHz, absorption coefficient remains unchanged with change in pressure. So, these two points are having pressure independent line width parameter. In both cases, a term γ, called the line width parameter is given by,

$$\gamma = 2.85\left(\frac{P}{1013}\right)\left(\frac{300}{T}\right)^{0.626}\left[1 + 0.018\frac{\rho_v T}{P}\right] \text{ GHz} \qquad (3.2)$$

the second term in the third bracket accounts for H_2O-H_2O collisions and may be neglected for low water vapour densities and Eqn.(3.2) takes the form,

$$\gamma = 2.85\left(\frac{P}{1013}\right)\left(\frac{300}{T}\right)^{0.626} \qquad (3.3)$$

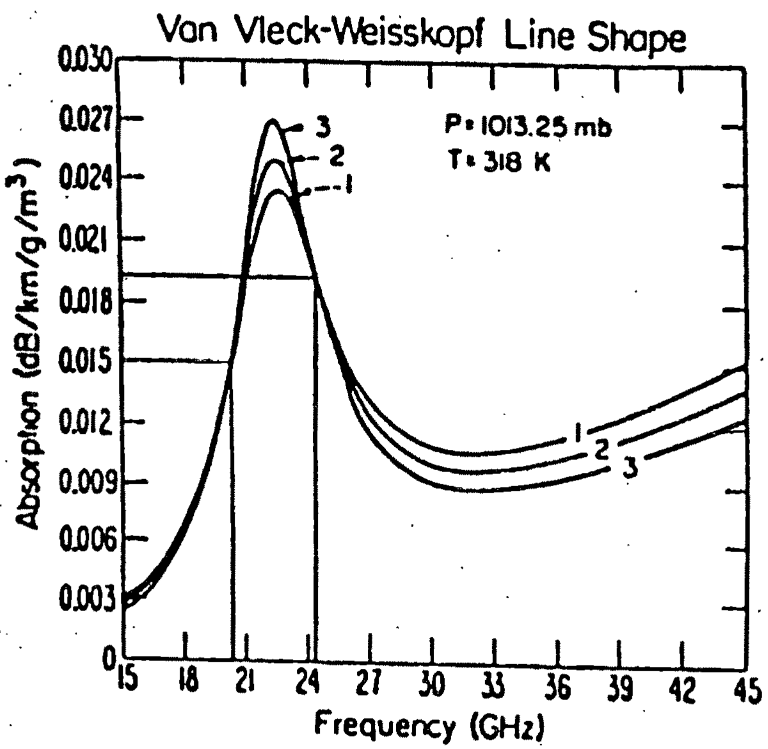

Fig.3.1(a)

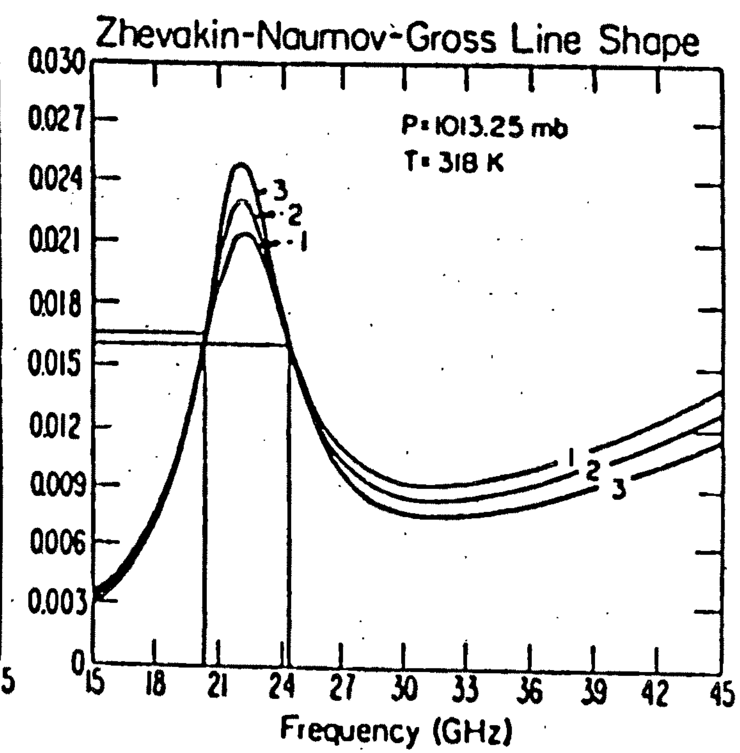

Fig.3.1(b)

Calculations of water vapour mass absorption coefficient for ±10% change on linewidth constant $\Delta\nu_0$;

1. Linewidth increased by 10% ,
2. Original linewidth,
3. Linewidth decreased by 10 %

[From Hogg, 1982]

Eqn.(3.3) forms the basis of considering line width constant as independent of water vapour density and explicitly dependent on pressure and temperature at low water vapour densities. From these, it is evident that at locations with low surface water vapour density like Antarctica, radiometric measurement of water vapour at 22.235 GHz will be influenced only by line strength factor where its line shape function will not change with the concentration of water vapour at different heights. Fig.3.2(a) and Fig.3.2(b) shows the line shape variation at different heights of atmosphere for two locations; one at tropical region Calcutta (lat.22°68′N, lon.88°32′E), and the other at Maitri, Antarctica (lat.70°45′S, lon.11°44′E), estimated from radiosonde value. It is clear from Fig.3.2(b) that, at Antarctica, the line shapes, even at 22.235 GHz remain almost unchanged at various levels of the atmosphere. But in Fig. 3.2(a), line shapes at 22.235 GHz change appreciably at different heights of the atmosphere at Calcutta.

3.2.3. Choice of frequency (f) :

In atmospheric remote sensing applications, the selected frequency should be very sensitive to the atmospheric parameter to be measured. *Meeks and Lilley* [1963] and *Hogg et al.* [1983] discussed in detail about the choice of frequency and prescribed some offset frequency away from 22.235 GHz as appropriate for all locations. Since line shape function remains almost unchanged with respect to height in regions with dry climate - use of 22.235 GHz resonance line for radiometric measurement of water vapour density would be fairly accurate for regions like Antarctica, where the higher sensitivity of the water vapour resonance line will, in fact, improve the accuracy.

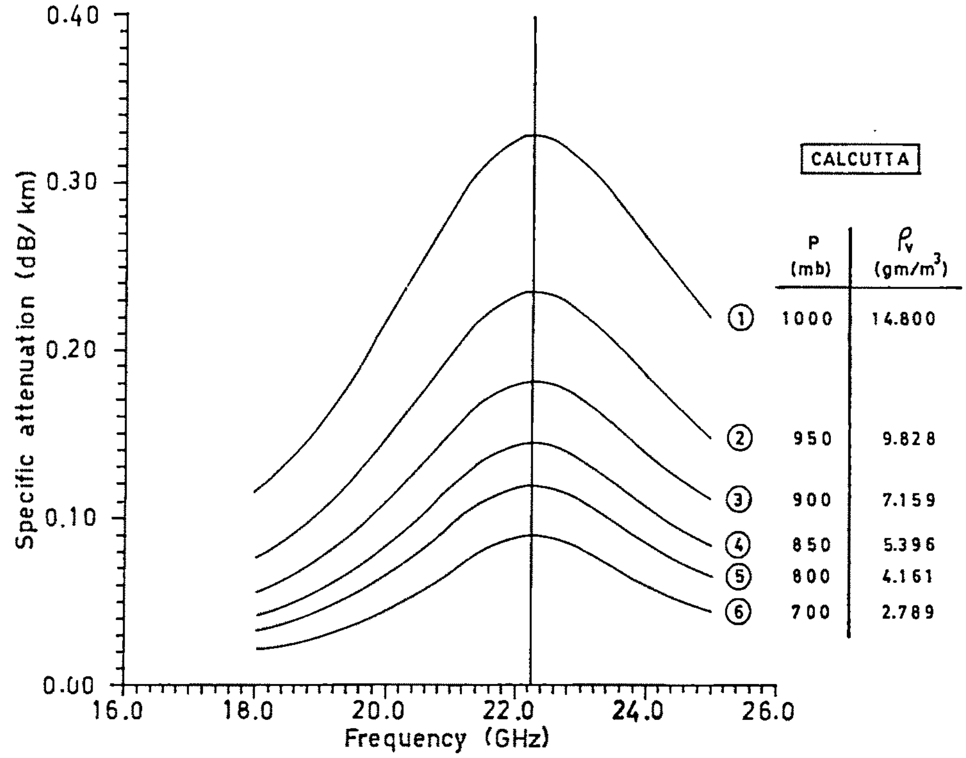

Fig.3.2(a) Line shapes at different altitudes of the atmosphere at Calcutta where variation in line shape profiles are clearly observed.

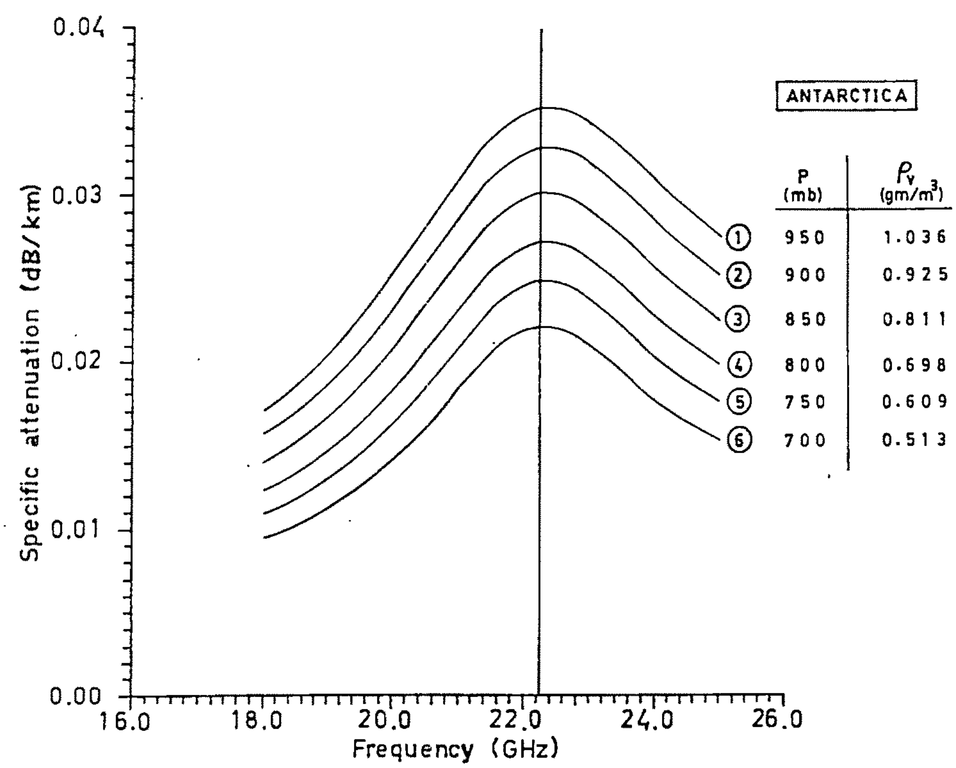

Fig.3.2(b) Line shapes at different heights of the Antarctic atmosphere which shows almost constant profile along the altitudes.

A frequency of around 20.6 or 24.4 GHz would, however, be an ideal choice for the humid tropical regions like Calcutta, where the line shape function would become height independent. Thus the choice of frequency should be site dependent, with the optimum frequency dependent on the water vapour content lying between 22.235 GHz and 20.6 GHz or between 22.235 GHz and 24.4 GHz, particularly if we consider the degradation of sensitivity at frequencies off resonance. For humid regions, the radiometer at the higher frequency of 24.4 GHz will be more expensive than that at 20.6 GHz and therefore, the frequency of 20.6 GHz is more popular off resonance frequency.

3.3. Retrieval of atmospheric water vapour by radiometric sensing :

Ground based radiometric observations can be successfully utilised to retrieve the height profile of the water vapour as well as integrated water vapour using statistical inversion techniques. In selecting the radiometer operating frequency, following criteria must be taken into consideration.

- The brightness temperature should be sufficiently sensitive to water vapour density and weakly sensitive to other atmospheric variables viz. temperature, pressure and height.
- For integrated water vapour measurement, the water vapour weighting function at the selected frequency should be height independent i.e. the weighting function should have a constant profile with height.
- For vertical profiling of water vapour, the water vapour density weighting function should be sufficiently different with respect to height.

3.3.1. Theoretical basis for inversion:

In absence of precipitation, scattering and polarisation effect, the downward emission by the atmosphere may be given by the radiative transfer equation [*Waters,* 1965] ;

$$T_b(\nu) = T_b^{ext} e^{-\tau_\nu(o,z)} \cos\theta + \int_0^z \alpha_\nu(z) T(z) e^{-\tau_\nu(o,z)} dz \cos\theta \qquad (3.4)$$

where θ is the viewing angle and z is the spatial co-ordinate of an emitting volume, T_b^{ext} is the radiation coming from external sources like stars, galaxies etc. At 22.235 GHz water vapour line and at higher frequencies, T_b^{ext} = 2.7 K as cosmic background radiation and $\tau_\nu(o,\infty)$ is called zenith opacity, i.e. total attenuation suffered by the atmosphere. For an upward looking radiometer, if only atmospheric thermal emission is considered, then Eqn.(3.4) reduces to

$$T_b(\nu) = \int_0^z \alpha_\nu(z) T(z) e^{-\tau_\nu(o,z)} dz \cos\theta \qquad (3.5)$$

where $\alpha_\nu(z)$ is the absorption coefficient and $T(z)$ is the thermometric temperature of the atmosphere. For simplicity, we shall restrict our discussion for zenith observation i.e., Eqn.(3.5) reduces to

$$T_b(\nu) = \int_0^z \alpha_\nu(z) T(z) e^{-\tau_\nu(o,z)} dz \qquad (3.6)$$

From Eqn.(3.6) one can derive brightness temperature from the knowledge of vertical distribution of temperature and absorption coefficient. The atmospheric absorption coefficient $\alpha_v(z)$ is the sum of the separate contributions of gaseous H_2O and O_2 in the absence of clouds and rain, neglecting absorption by other trace gases. Gaseous absorption is a function of temperature, pressure and water vapour density, whereas, cloud absorption depends mainly on temperature and liquid water density. Since the dependence of absorption on meteorological variables is non-linear, the dependence of brightness temperature on meteorological variables is also non-linear. In order to get an idea of how small changes in the meteorological variables give rise to small changes in brightness temperature, linearization is essential and is achieved by writing the Eqn.(3.6) as,

$$T_b(v) = \int_0^{\infty} W_\rho(v,z)\rho_v(z)dz \tag{3.7}$$

where $w_\rho(v, z)$ is the water vapour density weighting function and ρ_v is the water vapour density. By definition, weighting function is given by;

$$W_\rho(v) = \alpha_v(z)\frac{T(z)}{\rho_v(z)}e^{-\tau_v(o,z)} \tag{3.8}$$

where $\alpha_v(z)$ is the absorption by water vapour and oxygen, the term $\tau_v(o,z)$ is called the optical depth of the layer between o to z and

$$\tau_\nu(o,z) = \int_0^z \alpha(z')dz' \qquad (3.9)$$

where dz' is a small section between o to z layer. Now,

$$\alpha_\nu(z) = \alpha_{H_2O}(z) + \alpha_{O_2}(z) \qquad (3.10)$$

Estimated values of $\alpha_{H_2O}(z)$ and $\alpha_{O_2}(z)$ for Calcutta suggests that,

at resonance, $\alpha_{H_2O}(z) >> \alpha_{O_2}(z)$

then, $\alpha_\nu(z) \approx \alpha_{H_2O}(z)$

is a justified approximation because $\alpha_{H_2O}(z)$ becomes 30-50 times larger than $\alpha_{O_2}(z)$ at different times of the year. But such approximation is not valid for dry locations like Antarctica because the value of $\alpha_{H_2O}(z)$ is just 2-5 times higher than $\alpha_{O_2}(z)$. So Eqn.(3.8) is valid for Antarctica. For Calcutta, Eqn.(3.8) may be written as;

$$W_\rho(\nu) = \alpha_{H_2O}(z)\frac{T(z)}{\rho_\nu(z)}e^{-\tau_\nu(o,z)} \qquad (3.11)$$

and the expression for brightness temperature takes the form,

$$T_b(\nu) = \int_0^\infty \alpha_{H_2O}(z)T(z)e^{-\tau_\nu(o,z)}dz \qquad (3.12)$$

The Eqn.(3.8) & (3.9) represents the linearized form of atmospheric variables as weighting function for dry and wet locations. A wide range of weighting functions have been calculated for Calcutta (wet) and Antarctic (dry) climates. *Water's* model [1976] has been utilised for such calculations, since below 100 GHz, this model agrees better with measurements and above 100 GHz, *Liebe* [1989] model is superior [*Westwater et al* 1990].

Fig.3.3(a) shows the variation of water vapour weighting function drawn from the radiosonde values of Calcutta. Weighting function variation profile is shown for frequencies at 20.6 & 22.235 GHz. At Calcutta the 20.6 GHz profile indicates a constant trend with height. Therefore, 21.0 GHz should be selected for retrieval of integrated water vapour at tropical regions like Calcutta.

Fig.3.3(b) represents the estimated variation of water vapour density weighting function with height at Antarctica upto 4 kms, because radiosonde values, particularly relative humidity, were available only up to that level. Measurement with 22.235 GHz at Antarctica indicates a better choice for sensing of water vapour because of its independence with height and more sensitivity than that at 20.6 GHz. The maximum absorption is dependent on (i) line strength factor and (ii) line width parameter as given by *Ghosh & Edwards* [1956]. Their values are mainly decided by collisions between H_2O and N_2 molecules. The effects of H_2O-H_2O and H_2O-O_2 collisions are very small and for Antarctica they are even negligible. In Fig.3.2(b), the water vapour density weighting functions, as estimated for Antarctica, at 21.0 and 22.235 GHz are nearly constant through first 3 km of height. It has been found that 70-80% of the attenuation is caused by the lower 3 km of the atmosphere. Beyond 3 km, the weighting function tends to vary slightly for both 21.0 and 22.235 GHz lines.

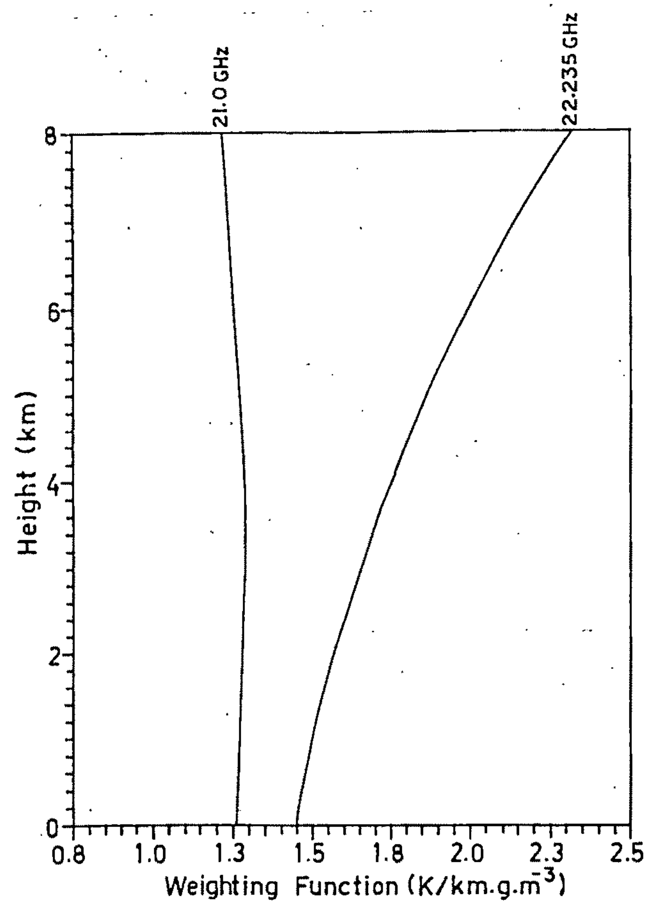

Fig.3.3(a) For Calcutta, water vapour density weighting function at 21.0 and 22.235 GHz. The trend shows that 21.0 GHz is clearly better for water vapour retrieval.

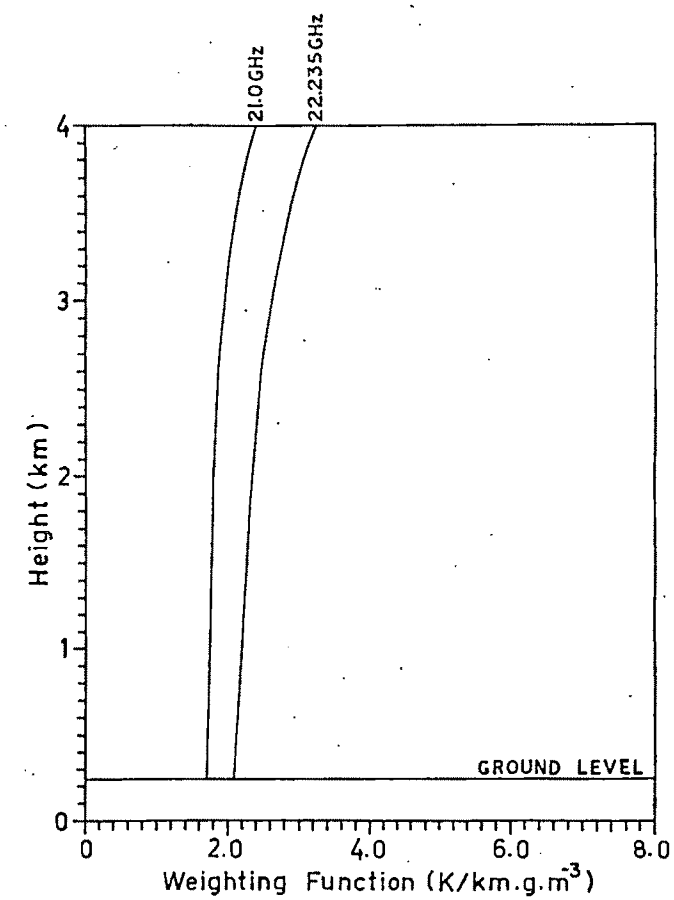

Fig.3.3(b) For Antarctica, water vapour density weighting function at 21.0 and 22.235 GHz. As trends are similar any frequency may be chosen for water vapour retrieval but 22.235 GHz should be preferred for its better sensitivity to water vapour.

The cause of bending may be due to the fact that radiosonde has poor accuracy in the relative humidity measurement, especially at high altitudes and low humidities. Apparently, both frequencies are suitable, as they exhibit similar trends, but 22.235 GHz may be preferred for its higher sensitivity to water vapour. Therefore, a 22.235 GHz radiometer can provide reasonably good information on integrated water vapour at Antarctica and also in regions with dry climate. Measurements at line-centre frequency of 22.235 has been reported by *Decker et al* [1978]. Apart from this, cloud liquid water has significant contribution to the brightness temperature of a upward looking radiometer. A two frequency radiometer combination, one close to water vapour resonant line and another selected at window frequency are specially useful in retrieval technique to segregate the cloud liquid water contribution from the total water vapour content. At Antarctica, cloud activity is usually very small. Very thin ice crystal clouds are often seen hovering there. Ideally, a pair of radiometers working at 22.235 and 31.4 GHz will be a suitable choice.

3.4. Discussion :

Measurement of height profile of water vapour with radiometers are studied by several authors at different frequency ranges, *Elegard et al.* [1982, 1985] The choice of radiometer frequency has strong influence on the measurement accuracy of the profile. A working frequency should be pressure insensitive one at around 22.235 GHz i.e. one which is independent of height. Selection of frequency at around 22 GHz lines are faced with complications as this region is affected by pressure broadening of resonance lines and temperature of the medium.

Locations with higher water vapour density are largely influenced by this effect. This problem should be avoided by selecting frequencies a few GHz away from line centre which are pressure independent. In such considerations, three fourth of the system sensitivity is sacrificed at the cost of having pressure insensitive measurements. For wet regions, selection of frequency would be very critical and will vary from place to place. Some offset frequency from the resonance peak may be ideal for measurement in wet regions.

Locations with dry climate can not influence retrieval process with considerable error. For places like Antarctica where both the surface water vapour concentration and the temperature are at lower values, the pressure broadening may not contribute significantly to affect the radiometric measurement even at the line-centre 22.235 GHz and retrieval of water vapour density would be fairly accurate.

However, introduction of strongly sensitive 183 GHz water vapour line can improve the retrieval accuracy to larger extent. The sensitivity can increase about 100 times for strong water vapour line at 183 GHz. The measurement accuracy at 183 GHz is specially high at lower altitude i.e. for surface to 900 millibar pressure level. The overall accuracy is far better, since 70-75% of attenuation is caused by this layer.

In ground based radiometric observation at 22.235 GHz in tropical regions, the output is often found to be saturated especially before, after, and during rain conditions. In such situations, the excess water vapour in the lower atmosphere results in higher zenith opacity. So, a zenith looking ground based water vapour radiometer can look through higher heights in dry climate and location than it can do in tropical climates.

Finally, it may be concluded from above discussion that 22.235 GHz radiometer is still a better option for water vapour retrieval of troposphere in regions with dry climate like Antarctica. Despite 22.235 GHz line being weaker than 183 GHz line, availability of mixers, oscillators and amplifiers in the low frequency range renders it a promising measurement frequency with reasonable accuracy at least for dry regions. Results clearly indicate that 22.235 GHz is a good choice for water vapour measurement at dry and cold regions, although in humid locations, suitable offset frequency still remains a better choice.