WATER VAPOUR PROFILING AT SOUTHERN LATITUDES BY DEPLOYING MICROWAVE RADIOMETER

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ABSTRACT

The radiometric data measured by multi frequency ground based scanning radiometer for the three location of Brazil namely Fortaleza, Belem and Alcantara, were used to retrieve the Water vapor profile. Amongst various methods of inversion techniques, the Backus Gilbert Synthetic Averaging Inversion Method is used. BIAS and RMS error are also derived over these three places. The brightness temperature measured by radiometer at frequency 22.234 GHz, 23.034 GHz, 23.834 GHz, 25 GHz and 30 GHz over these three places were used in this paper. Water vapour weighting function at this five frequencies are also determined over these three places to estimate the sensitivity of water vapour . The RMS error over Fortaleza, Brazil attains the maximum of 1.67gm/m3 at 1.0 km and becomes much smaller with increasing altitudes; while the BIAS keeps in the range of -1.36 to +1.65 gm/m3, the only exception seems to happen near the surface which is of about 4.73 gm/m3. While at Belem, Brazil, clearly the highest water vapour density profile retrieval accuracy comparable with the radiosonde observation is found to be on 15th June, 2011at 17:57 UTC with the resultant RMS error keeps in the range between 1.41 and 2.08 g/m3 except at sea level, while the BIAS measured lies in the range from -1.55 g/m3 to 0.29 g/m3. But the same reaches the maximum of about 2.47 g/m3around surface. A similar result of comparison between the vertical profiles of retrieved and radiosonde measured water vapour density is observed over Alcantara, Brazil on 15th March, 2010 at 17:56 UTC. The RMS error is less than equal to 3.16 g/m3 in between 1.0-6.0 km of the vertical atmospheric layers, while the BIAS lies in the range from -1.60 g/m3 to 0.9 g/m3. But the inaccuracy of retrieval with resultant BIAS error is found to be 6.48 g/m3 down to surface. The observed differences were discussed in the light of spatial variability and temperature inversion.

KEYWORDS: *Microwave Radiometer, Water Vapour profile, Inversion, Brightness Temperature, Weighting function*

I. INTRODUCTION

Remote sensing by using microwaves has become an important diagnostic tool for probing the atmosphere and surface of planetary objects. The term microwave remote sensing encompasses the physics of microwave propagation and its interaction with atmospheric ambient particles. An attempt has been made to establish a link between microwave – sensor response and atmospheric thermodynamic parameters. The most important is water vapour profiling amongst all others due to its spatial variation.

Radiosonde observations (RAOBs) are considered to the most fundamental and acceptable method for profiling purposes, despite their inaccuracies, cost, sparse temporal variation and logistic difficulties. A better technology has been sought for the past few decades, but until now no accurate continuous all-weather technology has been demonstrated for probing the atmosphere. The only reasonable and acceptable solution is the highly stable frequency-agile radiometric temperature and hence water vapour measurements.

This radiometric method gives us continuous unattended measurements. It has also the capability to profile liquid water, a capability absent in RAOBs and all other systems except for in-situ aircraft devices.

The principal advantage of using microwave radiometer is their all-weather capability. The principal disadvantage is their sensitivity to propagation path effects that are induced by water vapour. But on the other hand, this becomes a boon to remote sensing scientists as far as the measurement of water vapour is concerned. It is impossible to model water vapour with a high degree of accuracy. But still, the most promising technique available making this measurement is the use of passive microwave radiometer.

It is well accepted that the thermal emission around 20-30 GHz depends on both water vapour and liquid water. Thus unless one restricts the problem to the clear sky conditions, one has to face the mathematical complexity, and in that case, the water vapour measurement will be highly influenced by an unknown amount of liquid water (Sen et al.1991). So care has to be taken to separate the brightness temperature data for clear sky condition only by recognizing the presence of over-head clods with the help of in-built infrared sensor in the radiometer itself (Karmakar 2013) which computes the cloud base temperature (Karmakar 2011) for the single frequency measurement. This measurement technique and the necessary algorithm have been developed by Karmakar (2011). In this context, the ground based microwave radiometric sensing appears to be one of the suitable solutions for continuous monitoring of ambient atmospheric water vapor. Radiometric data have been extensively used by several investigators (Westwater, 1972; Gordy, 1976; Westwater & Guiraud, 1980; Pandey et al. 1984; Janssen, 1985; Cimini et al. 2007; Karmakar & Chattopadhyay, 2004) to determine water vapor budget.

In this present context, water vapour profiles are derived from the radiometric measured brightness temperature for the three locations of Southern latitudes namely Fortaleza, Belem and Alcantara of Brazil by exploiting five frequency channels of the radiometer. Table 1, for example, shows the summary of measured brightness temperature in water vapour band for the above three location.

Table 1. Summary of brightness temperature measured in water vapour band at Fortaleza, Belem, Alcantara.

DATE	TIME	PLACE	Frequency in GHz				
			22.234	23.034	23.834	25.000	30.000
4/4/2011	17:56 UTC	Fortaleza	96.122	94.207	80.041	63.941	37.914
15/6/2011	17:45 UTC	Belem	87.796	88.768	73.052	57.619	33.439
15/3/2010	17:57 UTC	Alcantara	88.817	87.016	73.765	58.96	34.864

II. RADIATIVE TRANSFER EQUATION

The basic idea of radiative transfer and thermal emission are given by Westwater (2004) and their application to microwave radiometric remote sensing is given by Goody & Yung (1995). In this regard radiometric inversion principle has been discussed in the subsequent sections of the present work.

In microwave remote sensing the retrieval of atmospheric variables e.g., water vapour can be done by the inversion of the measured brightness temperatures in the water vapour absorption band around 20-30 GHz, ignoring the extra terrestrial noise. While considering the non-scattering atmosphere in local thermodynamic equilibrium, these sets of brightness temperatures, more preciously the apparent temperatures is related to the actual profile of atmospheric variable by the forward radiative transfer equation, given by(ulaby et al. 1986).

$$T_{DN}(\gamma,\theta) = sec\theta \int_0^{\infty} K_{\gamma}(z)\, g(z) e^{-\tau_{\gamma}\, sec\theta}\ dz \quad (1)$$

Where g(z) is the actual water vapour profile at height z, and $\tau_\gamma\,(0, z)$ is the zenith optical thickness of the atmospheric layer between the surface and height z, is basically the integrated attenuation from the limit 0 through z as shown by the following relation

$$\tau_\gamma\,(0, z) = \int_0^z k_\gamma(z')\,dz' \qquad dB \qquad (2)$$

If the upper limits of the above integral approaches infinity, then $\tau_\gamma$represents the zenith opacity or the zenith looking radio visibility of the ground based upward looking radiometer for the entire atmosphere,

$$\tau_\gamma = \tau_\gamma\,(0, \infty) = \int_0^\infty K_\gamma(z')\ dz' \qquad (3)$$

Here, the quantity $K_\gamma(z)$ is the total absorption coefficient of the atmosphere at radiometric channel frequency γ and at a height of z in km in the vertical atmosphere. In general this can be expressed as,

$$K_\gamma(z) = K_{g\gamma}(z) + K_{c\gamma}(z) + K_{p\gamma}(z), \qquad (4)$$

Where the symbols $K_{g\gamma}(z), K_{c\gamma}(z) and\, K_{p\gamma}(z),$ in the above equation are referred to as the absorptions due to gases, clouds, and precipitations, respectively.

III. INVERSION OF WATER VAPOUR

For the retrieval of vertical profile of atmospheric water vapour using zenith radiometric observations of the sky, equation (1) can be written in the following form of convolution integral,

$$T_{DN}(\gamma) = \int_0^\infty W(\gamma, z)\, g(z)\ dz \qquad (5)$$

Where $W(\gamma, z)$ is the averaging kernel or weighting function for water vapour (sought function) for the atmosphere extending between 0 to z km, is given by (Ulaby et al. 1986),

$$W(\gamma, z) = K_\gamma(z)\frac{T(z)}{g(z)}\ e^{-\tau_v\,(0,z)} \qquad (6)$$

The weighting function gives an estimate of the sensitivity of a particular channel i.e., the change in the radiometric brightness temperature of a specified channel for unit changes of a given atmospheric variable (e.g. temperature, water vapor density, and liquid water content) at a particular altitude is therefore a function of channel frequency and elevation angle also and thus indicates the ability to retrieve that particular parameter from passive microwave observations. Here, T (z) is the thermometric temperature of the atmosphere at height z (km).

However, for the sake of clarity the vertical profiling of water vapour weighting function at Fortaleza, Belem and Alcantara, Brazil at the five selected radiometric frequencies viz. 22.235 GHz, 23.034 GHz, 23.834 GHz, 25.00 GHz and 30.00 GHz is shown in Figure 1 – 3.

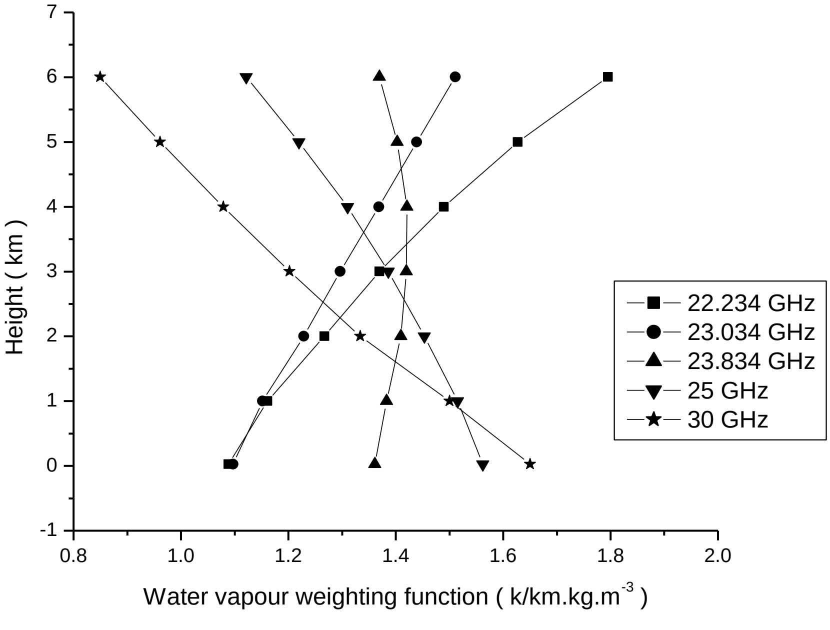

Figure 1.Comparison of height vs. weighting function corresponding to five frequencies for the location Fortaleza, Brazil, for the date 04.04.2011 at 17:56 UTC.

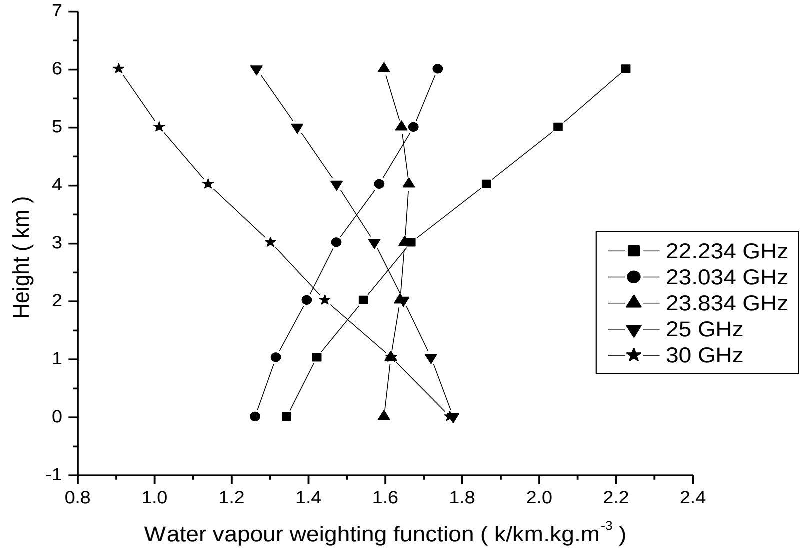

Figure 2. Comparison of height vs. weighting function corresponding to five frequencies for the location Belem, Brazil, for the date 15.06.2011 at 17:45 UTC.

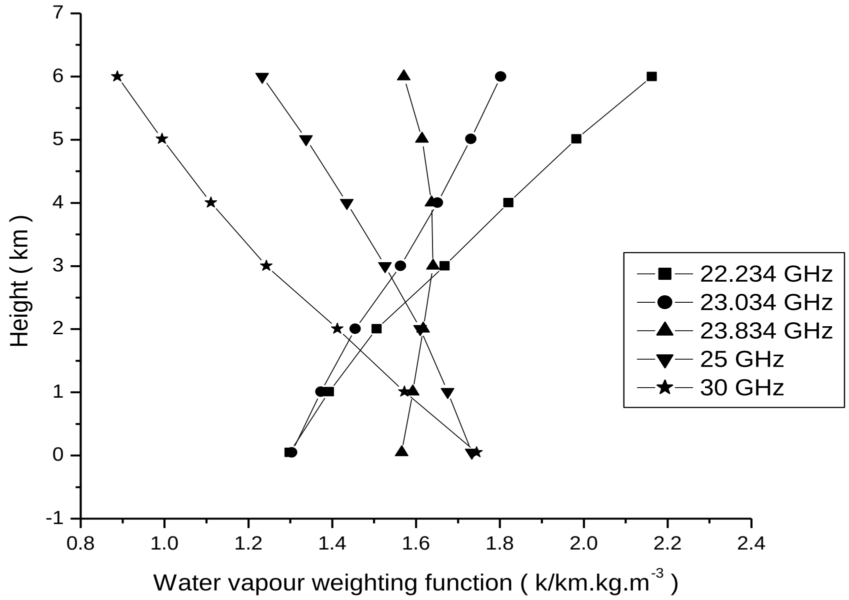

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Figure 3.Comparison of height vs. weighting function corresponding to five frequencies for the location Alcantara, Brazil, for the date 7.03.2010 at 17:57 UTC.

It is also clear from the Figure 1 through 3 that, at the respective places of choice in Brazil, the curves are steeper from the surface to a height of 2-3 km and tends to bend beyond the specified altitudes up to the top of the height at each location of Brazil during specified months. This indicates that, beyond the height of 2-3 km, the sensitivity of the selected radiometer channels to the variation of water vapour density is more significant as compared to lower altitudes. This inaccuracy might be due to the presence of temperature inversion around within 2-3 km which is very common occurance in the tropical locations. The same can be concluded for the vertical resolution of the retrieval of atmospheric parameter also. It is also clear from the above Figures that the weighting functions at the five frequencies of operation are somewhat similarly sensitive to changes in water vapor at lower altitudes, but have different sensitivities to changes in water vapor at higher altitudes. The weighting functions at 23.834 GHz, the curves are bending more above the height of 2-3 km in comparison to the weighting functions calculated at 22.234 GHz, 23.034 GHz, 25 GHz and 30 GHz irrespective of the places of choice.

Water vapour profiles can be obtained by measuring the radiometric brightness temperature, around the 20-30 GHz band using one of the popular inversion method namely Backus Gilbert Synthetic Averaging Inversion Method.

IV. THE BACKUS GILBERT SYNTHETIC AVERAGING INVERSION METHOD

According to this model the measured radiometric brightness temperatures $T_M(\gamma_i)$ are linearly related to the guess function of water vapour $g(z)$ being derived from radiosonde data by the relation

$$T_M(\gamma_i) = \int_0^{\infty} W_i \, g(z) \, dz \qquad i = 1, 2, \ldots, 5 \tag{7}$$

Here, i is the index of brightness temperatures at which observations being made and occupying maximum value of 5, $T_M(\gamma_i)$ denotes the mean radiating or brightness temperature at the i th channel frequency.

In practice we cannot measure the true $T_M(\gamma_i)$exactly because of experimental error which may include both measurement error and modeling error and errors due to approximation as well. So, equation (7) can be re-written as

$$T'_M(\gamma_i) = T_M(\gamma_i) + \epsilon_i \qquad i = 1, 2, \ldots, 5 \tag{8}$$

Here ϵ_i s the experimental error at each of the i^{th} radiometer frequency have zero i.e., $< \epsilon_i >=0$ and is statistically independent of sought function.

Now, by substituting the forward transfer model for the measurements of brightness temperature measurements into the equation for the retrieved profile, establishes a linear relation between estimated and the actual profile of water vapour by the averaging kernel. The averaging kernel being derived at each vertical layers of the retrieved profile using the relation

$$g'(z) = \sum_{i=1}^{5} a_i(z) T'_M(\gamma_i) \tag{9}$$

The vertical resolution of linear water vapour estimation approaches better with the decrease in the width of $a_i(z)$. The z dependent co-efficient $a_i(z)$ form an n × 1 column vector as given by

$$a_i(z) = \frac{R_i(z) U_i}{{U_i}^T {R_i}^{-1}(z) U_i} \tag{10}$$

Here, the function $R_i(z)$ is linearly related to the weighted sum of the error co-variance matrix S_ϵ and a factor determining the spreading of averaging kernel, a n × n vector *S(z)*, by the relation

$$R_i(z) = \alpha \, S(z) + (1-\alpha) r \, S_\epsilon \tag{11}$$

$$S_\epsilon = \langle \in \in^{T} \rangle \tag{12}$$

In practice the error co-variance matrix S_ϵ comprises of the error vector ϵ_i and it's transpose is also a n x n matrix.

The elemental n x 1 column vector U_i can be derived from the corresponding weighting function matrix at the particular altitudes z in km and the necessary relation for this purpose is as follows

$$U_i = \int_0^z W_i(z') \, dz' \tag{13}$$

The matrix $S(z)$ has the elements

$$S_{kl}(z) = 12 \int_0^z (z - z')^2 W_k(z') W_l(z') dz' \tag{14}$$

The maximum vertical resolution possible from a set of weighting functions can be determined from the coefficients of the averaging kernel which minimize $s(z)$ of averaging kernels subject to the condition that $W_k(z') W_l(z')$ is unimodular (Sahoo et al., 2011).

The multiplication factor r in the equation (11) is a positive constant (also referred to as the dimensionality factor) being generally set equal to 1. And the trade-off parameter α can takes up the values between 0 and 1. With the increase in the values of α from zero results in increasing vertical resolution with lower spread off at the expense of increasing sensitivity of the retrieved profile to random noise (Conrath, 1972).

V. RESULT AND ANALYSIS

Recalling that the experimental errors (∈)include both measurement errors as well as instrumental errors linked to radiometric observation which construct 1 x 5 matrix for five different radiometer channel frequencies associated with the water vapour absorption spectrum, assuming zero mean error. The range of these errors lies within -1 to +1. The Backus Gilbert Averaging Inversion method starts with the calculations of mean radiating temperatures T_M and $S_\in$ for five channels of radiometric observations separately as obtained from multichannel scanning radiometer (MP3000A, Radiometrics Corporation, USA) and the corresponding radiosonde observations being carried out at Fortaleza, Brazil on 4th April, 2011 at 17:56 UTC. A similar approach in deriving T_M and $S_\in$ for five channels of radiometric observations separately being carried out in the tropical locations of Brazil such as Belem, Brazil, on 15th June, 2011 at 17:45 UTC and Alcantara, Brazil, for the date 07.03.2010 at 17:57 UTC. Here $T_M(\gamma_i) = \int W_i(z)\, g(z)\, dz$ and error covariance matrix $\boldsymbol{S}_\in = \langle \in\in' \rangle$ forming one 1 x 5 and one 5 x 5 matrices respectively. The trade-off between the retrieval accuracy to noise and experimental errors and the vertical resolution of the averaging kernel is obtained by varying the trade off parameter α, which is basically a positive real quantity and depends upon the band of frequencies used and the time at which the observations were carried out. This can take up the values between 0 and 1, while keeping the dimensionality factor r as constant at 1. The approximated results of water vapour density retrieval being derived exactly at the vertical co-ordinates of 0.026 km, 1.0 km, 2.002 km, 3.003 km, 4.0 km, 5.001 km and 6.005 km respectively for a fixed value of tradeoff parameter and dimensionality factor. These values are compared with the corresponding radiosonde profile for the three places of choice results in finite variations in BIAS, RMS and STD indicate the effective inaccuracies. These are depicted in the Figures from 4 through 9 separately for the three places of choice.

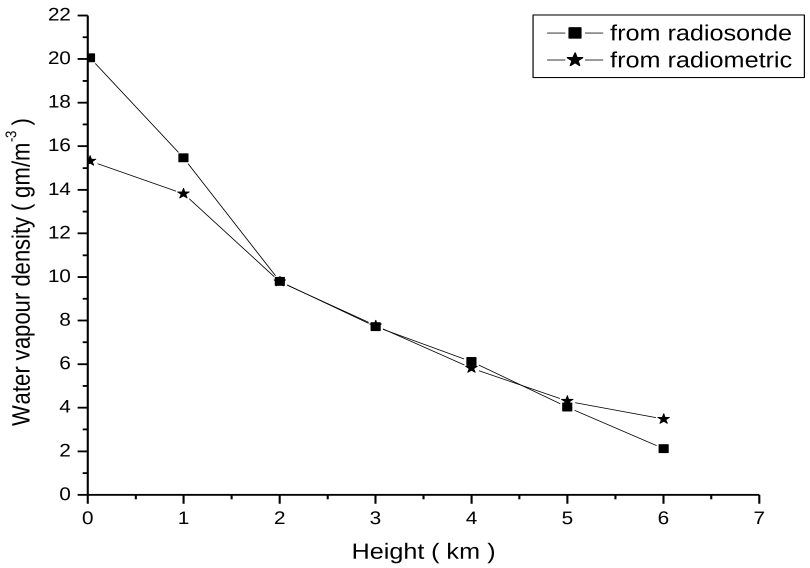

Figure 4. Comparison of variation of water vapour density with height for the location Fortaleza, Brazil.

The plots of the statistical difference between the vertical profiles of retrieved water vapour density using brightness temperatures measured by scanning radiometer and RAOBs measured water vapour density profile being derived at Fortaleza, Brazil on 4th April, 2011 at 17:56 UTC is shown.

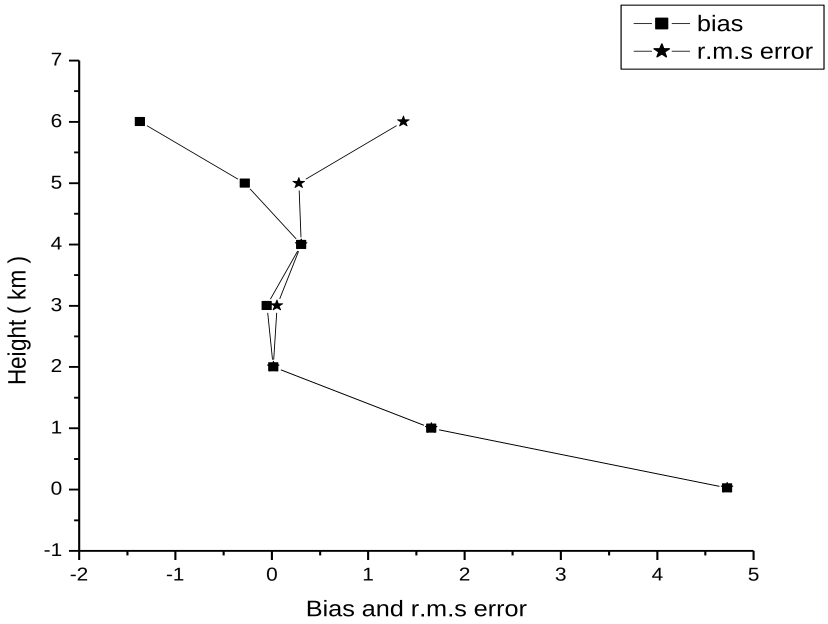

Figure 5. Variation of BIAS and RMS ERROR with height for the location Fortaleza, Brazil.

The result of the Backus Gilbert Synthetic Averaging Inversion Method being derived with $r = 1$ and fixed trade off parameter 0.7 is shown by solid line with star, while the corresponding radiosonde observations are given by solid line with squares.

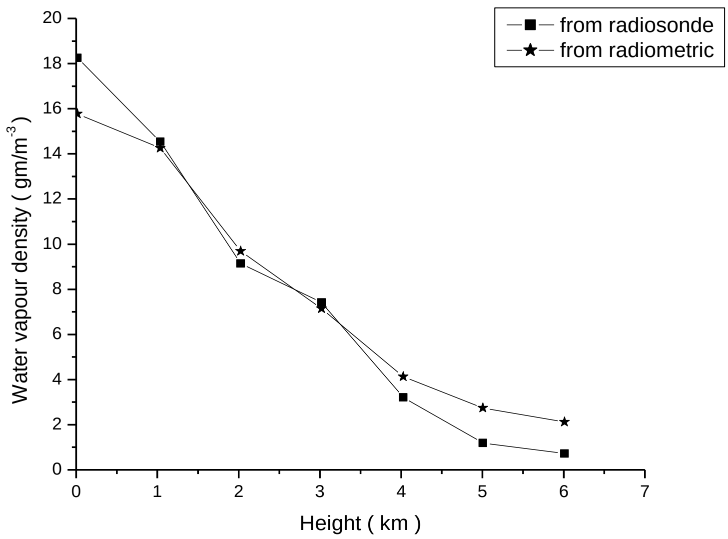

Figure 6. Comparasion of variation of water vapour density with height for the location Belem, Brazil.

The plots of the statistical difference between the vertical profiles of retrieved water vapour density using brightness temperatures measured by scanning radiometer and RAOBs measured water vapour density profile being derived at Belem, Brazil on 15th June, 2011 at 17:57 UTC is shown.

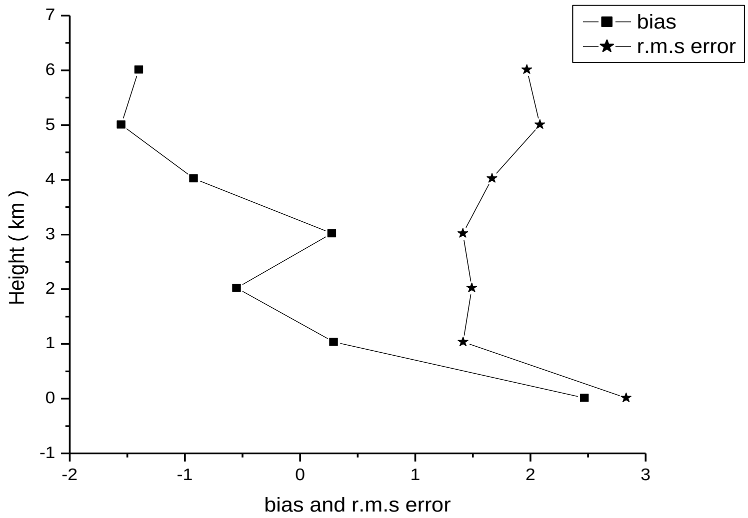

Figure 7. Variation of BIAS and RMS ERROR with height for the location Belem, Brazil.

This shows the comparison between retrieved estimation and RAOBs measurements as the mean value (BIAS), and the root mean square value (RMS) in the form of solid line with squares and stars.

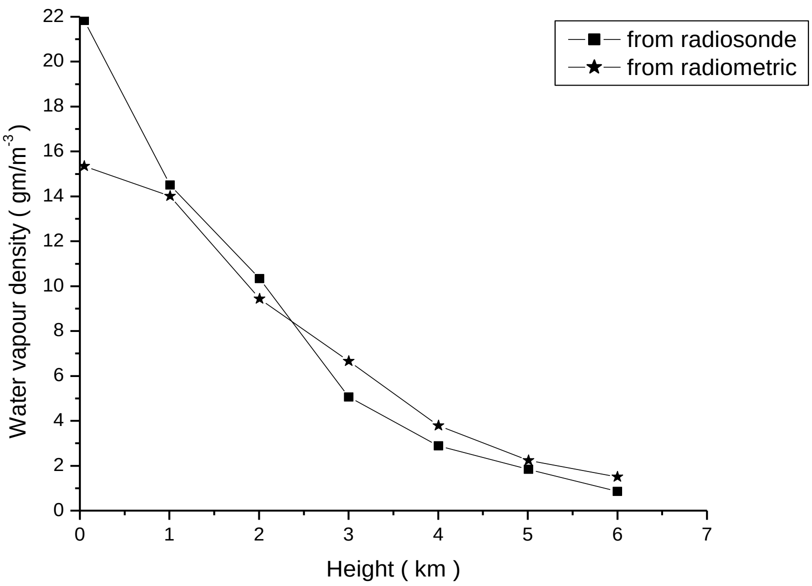

Figure 8. Comparasion of variation of water vapour density with height for the location Alcantara, Brazil.

The plots of the statistical difference between the vertical profiles of retrieved water vapour density using brightness temperatures measured by scanning radiometer and RAOBs measured water vapour density profile being derived at Belem, Brazil on 15th March, 2010 at 17:56 UTC is shown.

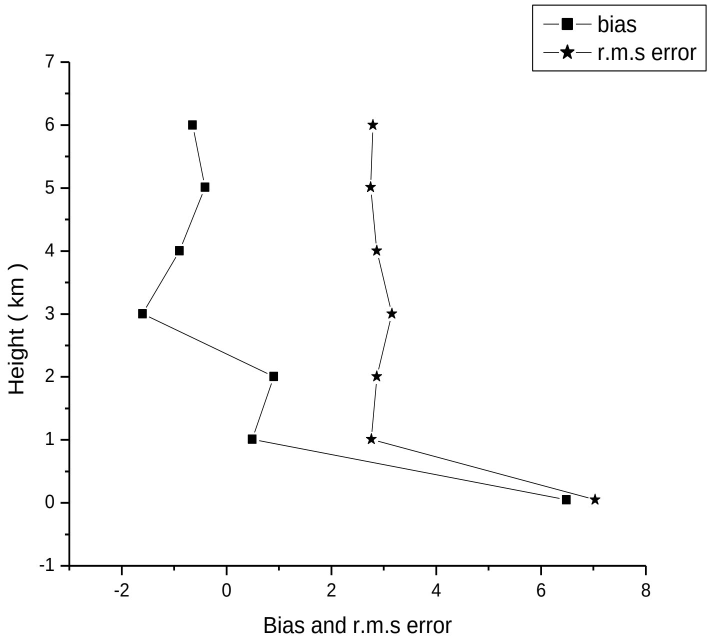

Figure 9. Variation of BIAS and RMS ERROR with height for the location Alcantara, Brazil.

VI. Discussions And Conclusions

Referring back to the Figure 4 ,it shows that the highest water vapour density profile retrieval accuracy comparable with the radiosonde observation being observed at the specified date and time beyond the height of 1.0 km for Fortaleza, Brazil. The RMS error attains the maximum of 1.67gm/m^3 at 1.0 km and becomes much smaller with increasing altitudes; while the BIAS keeps in the range of -1.36 to +1.65 gm/m^3, the only exception seems to happen near the surface which is of about 4.73 gm/m^3.

While at Belem, Brazil, Figures 6 and 7 clearly show that the highest water vapour density profile retrieval accuracy comparable with the radiosonde observation is found to be on 15th June, 2011 at 17:57 UTC for $r = 1$ and $\alpha = 0.7$ with the resultant RMS error keeps in the range between 1.41 and 2.08 g/m^3 except at sea level, while the BIAS measured lies in the range from -1.55 g/m^3 to 0.29 g/m^3. But the same reaches the maximum of about 2.47 g/m^{3}arround surface.

A similar result of comparison between the vertical profiles of retrieved and radiosonde measured water vapour density is being observed for Alcantara, Brazil on 15th March, 2010 at 17:56 UTC (Figure 8 and Figure 9). Here also the specified inversion algorithm is carried out using similar values of r and α as stated above. The RMS error is less than equal to 3.16 g/m^3 in between 1.0-6.0 km of the vertical atmospheric layers, while the BIAS lies in the range from -1.60 g/m^3 to 0.9 g/m^3. But the inaccuracy of retrieval with resultant BIAS error is found to be 6.48 g/m^3 down to surface.

The results are in good agreement especially over Fortaleza, Brazil while considering the RMS error, but this is partly supported by the results at Belem as well as Alcantara, Brazil. The derived RMS errors near the surface at the specified latitudes are 4.73, 2.83 and 7.03 g/m^3 respectively. At these three places of choice at the specified radiometric channel frequencies in the 20-30 GHz band statistically is inaccurate below 1.0 km, which might be due to the fact that the fairly high density of water vapour at the specified height is being affected by fairly high experimental error owing to the inversion of temperature which is considered to be the prominent occurrence in tropical latitudes.. It may also be noted that the reference radiosonde measured profiles are neither ideally vertical nor continuous in time and the short term variation of water vapour density is as much as 5-10% in the total precipitable water vapour (Spa¨nkuch et al. 2000).

VII. FUTURE SCOPE

In future we are very much interested to use others retrieval method such as optimal estimation method, neural network method etc. for retrieving of water vapour profile over the above said three places and to show that using of Backus Gilbert Synthetic Averaging Inversion Method for retrieving of water vapour profile is more better in terms of accuracy and resolution than using of the others methods. In future context, it will be very much useful to use the Backus Gilbert Synthetic Averaging Inversion Method for retrieval of temperature profile. Using the potential offered by ground-based multichannel microwave radiometry and the methods discussed in the present paper, system may be developed for continuous profiling.

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