



# Atmospheric Remote Sensing with a multi-frequency microwave radiometer in the 20-30 GHz band

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With the help of Ground Based seven channel K-Band humidity profiling radiometer, humidity at different height levels from 0 to 10 Km from ground has been obtained for two years from 2016 to 2017. Radiometer based zenith attenuation has been retrieved for the 20-30 GHz band which have been compared with ITU-R proposed attenuation estimation due to absorption by gases. ITU-R estimation has been found to underestimate zenith attenuation for tropical high rainfall region like Umiam. The Mean Atmospheric Temperature has been estimated from ground observations and Zenith Radiometer Attenuation through linear regression equations. Additionally, water vapour scale height has been estimated from zenith attenuation and surface meteorological parameters. Total water vapour has been also obtained from this and compared with Total water vapour estimated from IWV retrievals by radiometer. A regression relation has been found between IWV and 22.24 GHz brightness temperature obtained from Radiometer.

**Keywords:** Radiometer, Brightness temperature, Water vapour absorption, Humidity profile, Water vapour scale height

## 1 Introduction

Use of ground based radiometry for atmospheric remote sensing is mainly motivated by the fact that atmospheric profiles can be extracted for temperature and water vapour density due to presence of sharp absorption lines in absorption spectra of oxygen and water vapour, two primary components of standard atmosphere<sup>1-3</sup>. The energy they absorb can come from electromagnetic waves being used for various wireless communication purposes, which leads to attenuation of the signals. In rainy condition, additional scattering by rain drops also contribute to signal attenuation. By inverting the problem, researchers have shown that it is possible to use such data from ground based radiometer for short to medium term intense convection and rain prediction<sup>4,5</sup>. The absorption spectra of these gases have an otherwise continuum spectra and occasional line spectra at which absorption peaks (for water vapour at 22.235 GHz, 183.3 GHz and other higher frequencies and for oxygen at 50-60 GHz and at 118 GHz). But in the intermediate frequency range, several windows (35, 94, 140, 220 GHz) lie at which microwave communication link for earth-space satellite path is expected to perform better. Pressure broadening of absorption lines at different layers of

atmosphere causes a perception of broadened spectra at the receiver of radiometer. The Range of frequencies considered for this study, 20 GHz to 30 GHz is an interesting choice as due to presence of the weak and pressure broadened absorption spectra at 22.235 GHz, frequencies around 20 GHz can be considered optimal for water vapour profile extraction while frequencies around 30 GHz are more sensitive to liquid water<sup>6,7</sup>.

## 2 Methodology

### 2.1 Description of multi-frequency radiometer

The Microwave Radiometer RPG-GmBH Humpro-G3 is a humidity profiling radiometer with high temporal (1 sec) and spatial resolution (2° HPBW). It does humidity profiling of the planetary atmosphere from ground level to 10 Km height in 93 vertical levels of unequal level-width. It is a 7 channel radiometer with profiling at 7 different frequencies starting from around the water vapour absorption line at 22.234 GHz, 23.04 GHz, 23.84 GHz, 25.44 GHz, 26.24 GHz, 27.84 GHz, 31.4 GHz. The radiometer does a full sky scanning either in zenith or line of sight direction. It retrieves atmospheric parameters like microwave Brightness Temperature (K), Integrated Water Vapor (IWV) (Kg/m<sup>2</sup>), Liquid Water Path (LWP) (g/m<sup>2</sup>) with high degree of accuracy. The radiometer has variable vertical accuracy of 200 m in the range from 0 to

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2 Km, 400 m from 2-5 Km, 800 m from 5-10 Km and accuracy of 0.4g/m<sup>3</sup> for absolute humidity (RMS value) and 5% for relative humidity (RMS Value). The radiometer determines IWV with a remarkable accuracy of 0.20 Kg/m<sup>2</sup> RMS with a noise of 0.05 Kg/m<sup>2</sup> RMS value. It determines LWP with RMS accuracy of 20 g/m<sup>2</sup> and noise of 2g/m<sup>2</sup> RMS. All the seven channels have equal bandwidth of 230 MHz around the centre frequencies. With a radiometric resolution of 0.1 K at 1 sec integration time, the radiometer has excellent noise performance of less than 400 K system noise temperature. The absolute brightness temperature accuracy is 0.5K. The radiometer does brightness calculation with the application of Exact Planck's Radiation Law. Retrieval of atmospheric parameters is done through application of Neural Network or Linear/Non-Linear Regression. Integration time of the radiometer is greater than 0.4 seconds and sampling rate is greater than or equal to 1 Hz.

**2.2 Basic principle of radiometric retrieval of atmospheric parameters**

The radiometer receives radiation flux down welling from the atmosphere and the raw values are converted to equivalent brightness temperatures. Additionally, it gives a vertical profile of humidity at 93 height levels (ground level to 10 Km). A collocated automatic weather station provides ground level values of major atmospheric parameters like Temperature, Pressure, Humidity, Wind Velocity, Wind Direction etc. The surface values obtained from the Radiometer AWS has been compared with and validated from other meteorological sensors operational within 500 meter radius from the location of the Radiometer. These sensors are of higher accuracies and are used in other projects. Artificial Neural Networks are used for retrieving atmospheric variables from raw radiation intensities received due to their proven superior performance to iterative inversion analysis<sup>8,9,10</sup>. The Radiometric retrieval utilizes weighting functions to formulate the inversion problem to radiative transfer equation given as in<sup>11,12</sup>. The parameter cosmic background temperature (T<sub>bg</sub>) mentioned in the radiative transfer equation can be considered as 2.75 K as mentioned in<sup>13</sup>. The equation can be written in simplified form given in equation (1) by introducing the mean radiating temperature (T<sub>m</sub>) as shown in<sup>14</sup>.

$$\tau(\text{dB}) = 10 \log_{10} \frac{T_m - T_{bg}}{T_m - T_B} \quad \dots (1)$$

It was further shown that T<sub>m</sub> may be given by equation (2) to help linearize the exponential expression for Brightness Temperature.

$$T_m = \frac{\int T(h)a(h)e^{-\int a(h)dh}dh}{\int a(h)e^{-\int a(h)dh}dh} \quad \dots (2)$$

Now, Maitra et. al. have shown<sup>15</sup> that the mean atmospheric temperature T<sub>m</sub> depends on surface temperature T<sub>s</sub> and for a specific region, a linear relationship can be established between the two parameters given as in Equation (3).

$$T_m = A + BT_s \quad \dots (3)$$

A & B can be found through linear regression. Based on this theory, it can be claimed that with the knowledge of Zenith Attenuation (A<sub>z</sub>), T<sub>B</sub>, T<sub>m</sub> can be deduced.

**2.3 Determination of total gaseous absorption**

Total attenuation in zenith direction due to absorption by atmospheric gases is given as in equation (4).

$$A_z = Y_0 h_0 + Y_w h_w \quad \dots (4)$$

where, Y<sub>0</sub> and Y<sub>w</sub> are specific absorption coefficients and h<sub>0</sub> and h<sub>w</sub> are equivalent heights for oxygen and water vapour. Their formulas are taken from ITU-R recommendation<sup>16</sup>. These values are then compared with those retrieved from the Radiometer.

**2.4 Determination of water vapor scale height**

Water vapor scale height for a location can be determined using the method given by Karmakar<sup>17</sup>. He gives Equation (5) for specific attenuation coefficient α<sub>w</sub> (dB/Km) for water vapour absorption.

$$\alpha_w = 7.78 * 10^6 * F(T) * \rho(T) * (T^{0.52699} / P) \text{ (dB/Km)} \quad \dots (5)$$

where, F(T) is a slowly varying explicit function of temperature. ρ(T) is temperature dependent water vapour density value (gm<sup>-3</sup>) and P is total pressure (mmHg).

From statistical observation over 107 days at Umiam, it is assumed that for mean value of T at 293 K, F(T) = 1.32x10<sup>-7</sup> (K<sup>-1</sup>). Substituting this value in Equation (5), we get Equation (6)

$$\alpha_w = 1.027 * \rho(T) * (T^{0.52699} / P) \text{ (dB/Km)} \quad \dots (6)$$

Total attenuation due to water vapour ( $A$ , in dB) is obtained through an integration of Equation (6) over the observation path length, which yields,

$$A = 1.027 * (\rho_0 T_0^{0.52699} / P_0 H_1) \text{ (dB)} \quad \dots (7)$$

where,

$$H_1 = \frac{1}{H\rho} - \frac{1 - \left(\frac{0.52699R\beta}{g}\right)}{H\rho} \quad \dots (8)$$

$R$  is the universal gas constant,  $\beta$  is the adiabatic lapse rate of temperature at a location,  $T_0$ ,  $P_0$  and  $\rho_0$  are surface values for temperature (K), pressure (hPa) and water vapour density ( $\text{gm}^{-3}$ ).  $H_p$  and  $H_p$  are water vapour and pressure scale heights. Putting  $R = 2.9$  units,  $H_p = 8$  Km,  $g = 9.8 \text{ ms}^{-2}$ , we get,

$$H_1 = \frac{1}{H\rho} - \frac{1 - (0.155946\beta)}{8} \quad \dots (9)$$

Now, at Umiam, from radiosonde observations,  $\beta = 0.65 \text{ }^\circ\text{C}/100 \text{ m}$ . Therefore, putting this value and values of  $T_0 = 294 \text{ K}$  (average value),  $P_0 = 896 \text{ hPa}$  (average value) and average values for  $\rho_0 = 8.5 \text{ gm}^{-3}$ ,  $11 \text{ gm}^{-3}$ ,  $15 \text{ gm}^{-3}$ , for three seasons, we get,

$$\frac{1}{H\rho} = 0.1123 + \frac{0.1947}{A} \text{ November to February} \quad \dots (10)$$

$$\frac{1}{H\rho} = 0.1123 + \frac{0.252}{A} \text{ March to May} \quad \dots (11)$$

$$\frac{1}{H\rho} = 0.1123 + \frac{0.344}{A} \text{ June to October} \quad \dots (12)$$

Accordingly, the scale heights were calculated and plotted. Additionally, water vapour content is estimated as in Equation (13)

$$W = 10^3 * H_p * \rho_0 \quad \dots (13)$$

This is compared with Integrated Water Vapour ( $\text{Kg}/\text{m}^2$ ) Content retrieved by the Radiometer. A study was done to find a linear relationship between Integrated Water Vapour obtained by the Radiometer ( $\text{gm m}^{-2}$ ) and Brightness Temperature (K) obtained from the radiometer.

### 3 Results

#### 3.1 Observed humidity profile

A vertical profile of atmospheric humidity has been prepared for Umiam with the humidity values retrieved at 93 height levels of the atmosphere from 0

to 10 Km altitude above the radiometer. Data available for 107 days in the years 2016 and 2017 have been categorized into three different seasons: one Pre-Monsoon season extending from March to May, Monsoon season from June to October, Winter season from November to February. There are total 81 days in the first season, 17 days in the second and 09 days in the third season. The data is presented in Table 1.

From water vapour observations mentioned above, it can be safely claimed that the humidity in the atmosphere at Umiam, as observed by the Humidity Profiling Radiometer is of exponentially decreasing nature with increasing height. Also, as observed by the radiometer, scale heights for humidity can be determined from the data obtained. The variation between the three different seasons is also quite prominent.

Figure 1 shows a plot of variation of the mean surface temperature at Umiam, determined in the above mentioned way. Data for the plot consisted of total of 107 days in the years of 2016 and 2017. The days have been segregated in three groups, first group consisting of days in the month of March to May, which may be said as the pre monsoon period characterized by medium rainfall. The second group is consisting of days in the months from June to October, which is the monsoon season characterized by heavy rainfall. The third group consists of days in the months from November to February, which is the winter season characterized by scanty rainfall. The three groups have variable number of days, with the first group having 81 days, second group having 17 days and third group is having only 9 days.

Further, based on data provided by Maitra and Karmakar<sup>18</sup>, coefficients for the linear regression equation (17) can be computed through linear interpolation. Following this methodology, data in Table 2 was obtained.

The resulting  $T_m$  obtained using these coefficients with the regression Equation (3) shows impressive agreement with that obtained from the radiometer.

Table 1 — Mean values of various atmospheric parameters at surface level obtained from radiometer's AWS and validated from other meteorological sensors

Month range	Mean surface humidity ( $\text{gm}/\text{m}^3$ )	Mean surface temperature (K)	Mean surface pressure (hPa)
M03-M05	11	294	895
M06-M10	15	294	897
M11-M02	8.5	292	896

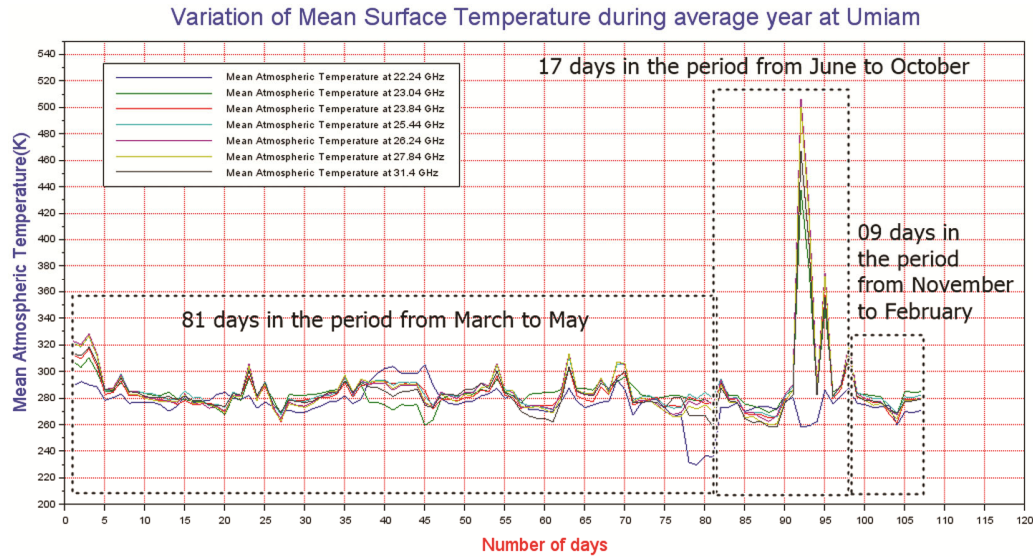


Fig. 1 — Variation of mean surface temperature (throughout a day) during an average year at Umiam (data for two years).

Table 2 — Regression parameters (A, B) of Equation (3) for 07 frequencies of radiometer obtained through linear interpolation of values provided by Karmakar.

Frequency (GHz)	A(K/°C)	B(K)
22.24	0.823	267.383
23.04	0.826	267.385
23.84	0.8289	267.3821
25.44	0.8349	267.3761
26.24	0.8378	267.3732
27.84	0.8438	267.3672
31.4	0.857	267.354

Table 3 — Calculation of scale height/equivalent height for dry air for seven frequencies of Radiometer

Frequency (GHz)	$h_0$ (Km)	$h_w$ (Km)
22.24	5.1963154	1.650866
23.04	5.1936924	1.6510522
23.84	5.1903608	1.6516027
25.44	5.1811395	1.653796
26.24	5.1750335	1.6554389
27.84	5.1592898	1.6598171
31.4	5.1035108	1.6747848

Similarly, the equivalent height for water vapour and oxygen may be given by the equations mentioned in<sup>19</sup> for frequencies below 350 GHz.

Using these equations,  $h_0$  and  $h_w$  at different radiometer frequencies calculated. Table 3 shows their values in non-rainy conditions. The specific attenuation coefficients (dB/Km) were also calculated for the seven frequencies of radiometer and shown in Table 4. Corresponding zenith path attenuations for the three seasons at radiometer frequencies are calculated and shown in Table 5.

Table 4 — Calculation of Specific Attenuation(dB/Km) for oxygen and water vapour at seven frequencies for the three seasons:

Frequency (GHz)	$\Upsilon_w$ (dB/Km)			$\Upsilon_0$ (dB/Km)		
	M03-M05	M06-M10	M11-M02	M03-M05	M06-M10	M11-M02
22.24	0.048	0.056	0.043	0.001	0.001	0.001
23.04	0.048	0.056	0.043	0.0009	0.001	0.001
23.84	0.048	0.056	0.043	0.0009	0.001	0.001
25.44	0.047	0.055	0.043	0.0008	0.001	0.001
26.24	0.047	0.055	0.043	0.0007	0.001	0.001
27.84	0.047	0.055	0.043	0.0006	0.001	0.001
31.4	0.048	0.056	0.043	0.0005	0.001	0.001

Table 5 — Total Zenith Attenuation (dB) for seven frequencies in the three seasons

Seasons	Mean $H_w$ (Km)	S.D. $H_w$ (Km)
M03-M05	1.941	0.62
M06-M10	2.853	1.74
M11-M02	1.22	0.3044

The seasonal variation of zenith total attenuation actually observed at Umiam for the two year period is plotted in Fig. 2.

### 3.2 Water vapour scale height

The Mean and Standard Deviation of the variation of water vapour scale height as observed at Umiam for the period of observation for the three seasons are given in Table 6.

The plot of Fig. 3 shows the best fit regression equation between IWV (gm m<sup>-2</sup>) and 22.24 GHz Brightness Temperature (K)(TB) during March-May at Umiam.

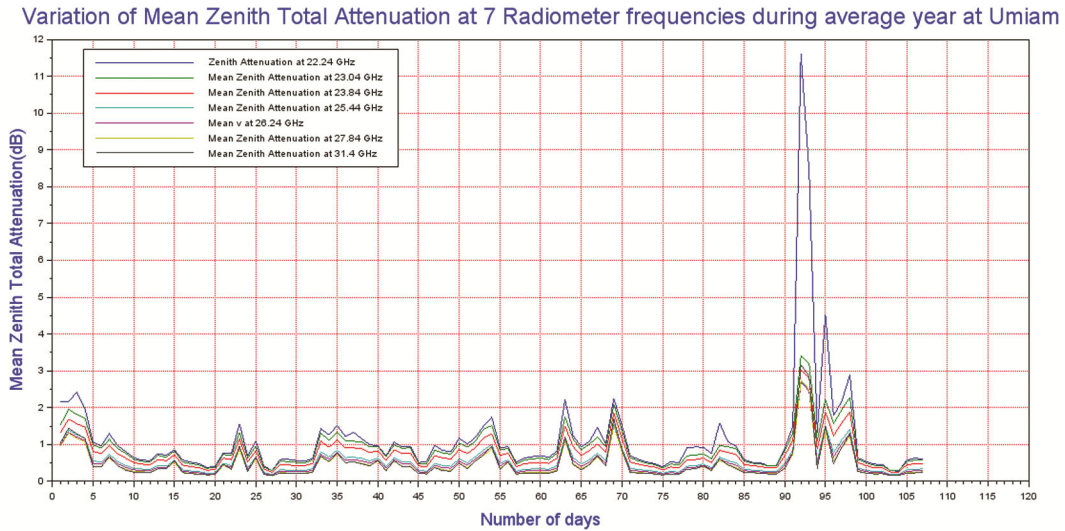


Fig. 2 — Variation of Mean Zenith Attenuation (throughout a day) for average year at the 7 frequencies (data for two years).

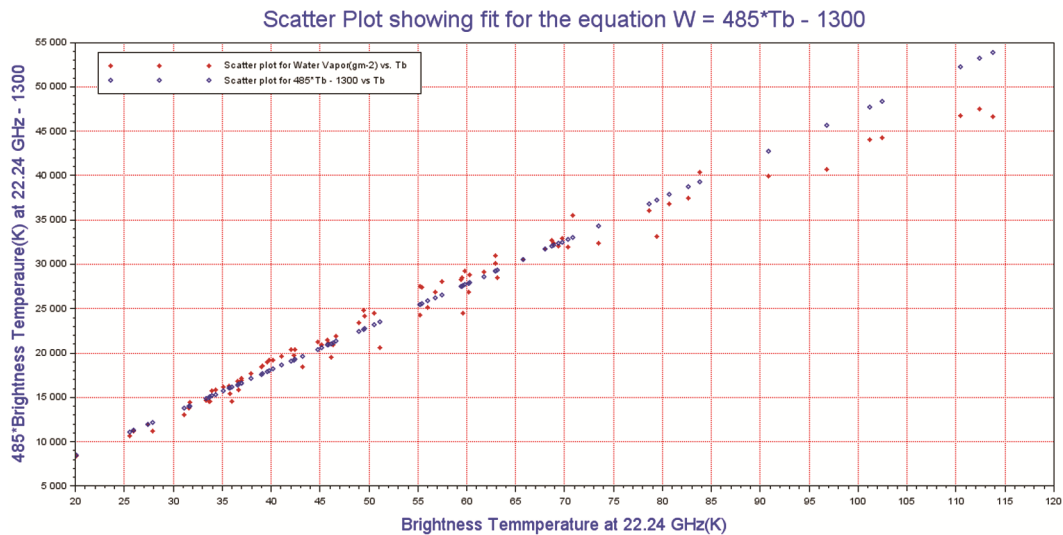


Fig. 3 — Scatter plot of IWV and brightness temperature at 22.24 GHz relation for M03-M0

Table 6 — Variation of water vapor scale height (Km)

Frequency (GHz)	Total Zenith Attenuation ( $A_z$ ) (dB)		
	M03-M05	M06-M10	M11-M02
22.235	0.0845	0.0972	0.0766
23.04	0.0843	0.0971	0.0763
23.84	0.0837	0.0964	0.0757
25.44	0.0824	0.0950	0.0746
26.24	0.0821	0.0946	0.0743
27.84	0.0818	0.0944	0.0740
31.4	0.0826	0.0956	0.0745

The relationship which best describes the equation for IWV and Brightness Temperature at 22.24 GHz is given in equation

$$W = 485T_B - 1300 \quad \dots (19)$$

#### 4 Discussion

Firstly, with the obtained vertical absolute humidity profiles, it can be said that for all seasons, the absolute vertical humidity decreases almost exponentially. The mean value of surface absolute humidity is lowest in the season from November to February and gradually increases through the seasons from March to May and June to October. This is expected as the first season was the driest at Umiam while the other two were increasingly wetter. For the dry air attenuation, it was generally found that ITU-R predicted value of total zenith attenuation was much lower than that actually recorded by radiometer. This can be due to additional attenuation by clouds. Water vapour scale heights obtained from prediction found

to be lower than the actual IWV obtained from radiometer. Recently it has been shown that Global Navigation Satellite System which works by Earth-Space fixed link satellite communication link in the lower microwave frequency range (primarily L band, 1-2 GHz), can be an indirect source of estimation of atmospheric water vapour, either through elimination of other error terms (use of differencing techniques or dual frequency receiver)<sup>20</sup> or by use of LEO satellites through Radio Occultation<sup>21</sup>. The future studies should compare the profiles derived from such techniques as well. The regression equation obtained between IWV and Brightness Temperature at 22.24 GHz needs to be tested over longer period of time to confirm. The radiometer data should be compared with other Radiometer data from different locations. Due to dearth of data from other locations under the project, the comparison could not be done in this study and will be done in future studies. For most of the humidity profiling measurement and attenuation and brightness temperature measurements, zenith mode data has been used due to the transparent nature of the atmosphere at the frequencies near 22 GHz. At that frequency, even for low elevation angles, saturation of brightness temperature is negligible.

## 5 Conclusion

Vertical Humidity profile for 93 altitude levels starting from 0 Km to 10 Km for 107 days spanning two years have been retrieved from the Humidity Profiler Radiometer. Zenith Attenuations retrieved at seven frequencies of operation have been used to estimate mean radiating temperature of atmosphere. This mean radiating temperature has been fitted to a linear regression equation with surface temperature. With the AWS of the radiometer, surface parameters like temperature, total pressure, humidity etc. have been retrieved and seasonal mean of these values have been determined. Water Vapour scale height for the three seasons have been determined and compared

with radiometer retrieved IWV. A linear regression based equation has been found between IWV and brightness temperature at 22.24 GHz.

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