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# Validation of ground-based microwave radiometer measurements over a tropical coastal station

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## Abstract

Ground-based, passive, multi-frequency microwave radiometer profilers (MRP) are very powerful tools to provide vertical profiles of atmospheric parameters under almost all-weather conditions. However, these retrievals are to be validated through other independent estimates, before these are used for scientific studies. Such a validation exercise has been carried out for the MRP, operational at the tropical coastal station, Thiruvananthapuram (TVM), which has been in regular operation since 2010. The validation is done through the inter-comparison of the MRP measured brightness temperature ($T_b$) with those simulated using microwave radiative transfer scheme that uses collocated and concurrent profiles of temperature and humidity from radiosonde. The analyses have shown a very good correlation (~0.9) with 0.5 K bias for V-band frequency channels while for the K-band frequency channels a 3-5 K bias is seen due to the variability in the water vapour content. The direct comparison of retrieved relative humidity with those derived from radiosonde measurements, yielded good agreement below 8 km altitude.

## 1. Introduction

The techniques of atmospheric temperature and humidity sounding using upward looking ground-based microwave radiometer from the terrestrial surface are well established [1]. It makes use of the microwave emissions from oxygen and water vapour in the rotational resonant bands. The sensitivity of oxygen and water vapour emissions, respectively, to temperature and humidity is not degraded by radiation from the terrestrial surface, in case of upward looking radiometer. This facilitates more accurate retrievals of temperature and humidity profiles over the land surface (continental region) with relatively high vertical resolution in the boundary layer and in the lower troposphere, than satellite based soundings. The major advantages of ground-based multi-frequency microwave radiometric observations are their ability to produce all weather, round the clock observations with high temporal resolution besides continuously observing the build-up of atmospheric humidity and their phase change to liquid during the evolution of convections, which is important for improving the now-casting, short-term precipitation forecasting and weather modification [2]. Such measurements also provide continuous database to study the development of boundary layer structure which have application in air pollution, aerosol dispersion and to study the severe weather conditions followed by strong convections [3].

The retrieval of temperature and humidity profiles from a multifrequency radiometer observation includes the conversion of the measured brightness temperature ($T_b$) at different frequencies into atmospheric parameter through inversion techniques, in which the simulated radiances using a forward radiative transfer (RT) model based on the prior information of atmospheric parameters are compared with the radiometer multichannel observations. The RT based forward model transforms the state space of the temperature, humidity and liquid water profiles into observation space of radiances measured by the radiometer. The key component of the forward model is the microwave Radiative Transfer Model (RTM).

The simulation of $T_b$ in the forward model mainly depends on the weighting functions for each frequency at each zenith angle, which in-turn depends on atmospheric absorption of that channel frequency. There are different microwave RTMs employed in the retrieval techniques and general discussions on these models are well discussed. These models while matching well among them at peak resonant frequency and nearby channels, however, show discrepancies at far wings and window channels. The performances of these different models are validated 5 and shown that the Rosenkranz 1998 (Ros 98) model provides better result at these resonant frequencies. In this analysis the Ros 98 model has been used.

The MRP has been extensively used to study atmospheric boundary layer features, to understand the lower atmospheric thermodynamics and convection processes over the mid-latitude region [4]. However, such studies are very much limited over the equatorial regions, despite the tropics being a seat of very complex atmospheric processes. Extensive application of MRP measurements for thermodynamical processes involved in convective systems, identification of convective systems, altitude structure of water vapour and its variability during the active and break period of Indian monsoon have been reported for the coastal location, Thiruvananthapuram (TVM, 8.5° N 76.9° E), where a multi-frequency MRP has been in regular operation since 2010 [5, 6]. The proximity of the MRP site to the Arabian Sea coast and the prolonged monsoon season experienced here, which causes higher atmospheric humidity condition for almost half of the year, makes this location of special importance. In view of these special regional features, it is essential to carry out detailed and thorough validation of the MRP derived parameters to ascertain the accuracy and consistency of the data over a longer time period and derived information over the tropics for scientific studies. The validation processes mainly include 1) the inter-comparison between MRP observed $T_b$ and simulated $T_b$ based on microwave radiative transfer (RT) computation applying to the radiosonde temperature, pressure and humidity profiles, and, 2) an inter-comparison of retrieved atmospheric profiles such as temperature and humidity parameters from MRP with the corresponding parameters measured by the collocated and concurrent radiosonde data.

## 2. Data and Instruments

The details of the study region, radiometer installation and its mode of operation over TVM are presented [7]. The technical details of the profiler can also be found and through online (www.radiometrics.com) also. The radiometer measures Tb through a sequential scan of 5 frequencies in the K-band (22.23 GHz-30.0 GHz) and 7 in the V-band (51.2 GHz-58.8 GHz). The bandwidth for each channel is 300 MHz. A zenith looking infrared (IR) radiometer and a rain detector are also attached to the radiometer for estimating cloud base height and precipitation time, respectively. The K-band channels are calibrated to 0.3 K RMS by automated tipping procedures and V-band channels are calibrated to 0.5 K RMS with liquid nitrogen target [8].

The attached meteorological sensors provide pressure, temperature and humidity at surface level. The collocated i-met radiosonde (intermet, USA) ascend data with temperature (T) accuracy of ±0.3°C and 0.1% for relative humidity (RH) have been used for comparison during the period 2011-2013.

## 3. Microwave Radiative Transfer (RT) computation for the tropical atmospheric condition

The RT model computations are carried out for the down-welling components of atmospheric thermal emissions at frequencies relevant to the MRP. In the case of ground based observations, the only down-welling component of atmospheric thermal emission at a specified viewing angle need to be considered. Under local thermodynamic equilibrium condition, the atmospheric layers, which absorb microwave radiation and emit thermal radiation based on their physical thermal state. In the RT computation, a layered model of the atmosphere is considered where the atmosphere is stratified into number of horizontal layers and each layer is characterized with uniform pressure, temperature and water vapour profiles. Then, the absorption coefficient of water vapour and oxygen for each layer is computed. The product of this attenuation coefficient and the physical temperature gives the thermal emission of each layer. The resultant radiation from each layer is summed up to find the total thermal emission or $T_b$. These emitted radiations while propagating towards the radiometer direction is expressed in equation 1.

The $T_b$ (θ) in microwave regime extending from 1-300 GHz is calculated using the RTM model at zenith angle (θ) for the tropical condition prevailing over the TVM with the atmospheric parameters obtained from radiosonde ascents from the MRP site. The resonant absorption band for water vapour channels peaks at 22.23 GHz (weak), and at around 183.1 GHz (stronger). The oxygen absorption bands peak at around 60 GHz and 118 GHz. As the MRP operates in the absorption or emission bands around 22-30 GHz channel and 51-60 GHz channel, which is shown in the Figure 1, the comparison between the modelled $T_b$ and measured $T_b$ for these two bands of frequencies are presented in the next section.

## 4. Results and Discussion

### 4.1. RT model based $T_b$ simulation and comparison with MRP observations

The radiometer measurements are compared against simulated $T_b$ based on the RT model, applied to the collocated radiosonde ascents carried out for three-year period 2011-2013. Data from only those ascents reaching an altitude of ~20 km and above have been used for the RT simulation. A linear correlation analyses between $T_b$ measured and those simulated separately for each channel in the K- and V-bands, respectively, are shown in Figure 2 and Figure 3. These figures demonstrate very good agreement between the two retrievals (with slopes ~0.9) for those channels of the MRP located near the resonant emission spectral lines, while the agreement becomes weaker for those channels falling in the far wings.

Figure 2 shows that for the K-band, the comparison yields slopes of ~0.9, with a correlation coefficient > 0.9 in water vapour channel. The bias of ~4 K is attributed to the large sensitivity of these channels to water vapour, which would show large spatial variation in the coastal regions and the spatial drifting of the balloons (radiosonde) with time, while those at far wings which are sensitive to both liquid water and humidity the bias increases to ~5 K, as the RT model under clear sky condition does not account for the contribution from cloud liquid water. Hence at those channels the observations are overestimating the modelled $T_b$ values. The $T_b$ values for K-band channels varies from 40-120 K for peak channels and range decreases to ~30 K as on moving to wings. The temperature channels from 54.4 to 60 GHz near to the peak of the emission spectrum show good comparison with mean absolute difference of ~0.5 K which is within the system bias (Figure 3). The temperature channels in the far wings show a positive bias of ~5-7 K in 51-52.8 GHz channels. These channels at intermediate frequencies show large uncertainty particularly in the edge of oxygen absorption band near 51-53 GHz due to their sensitivity to the line coupling parameters [9] and are also affected by the humidity. From 52.8 GHz there is a sharp increase in oxygen absorption coefficient and the corresponding decrease in bias proves the accuracy and consistency of the resonant channels in probing lower atmospheric temperature profiles as shown in Figure 3. The variability of $T_b$ values in the peak emission spectrum of V-band channel is only ranging from ~296-302 K which increases as moving to wings. In the case of thermal channels the observations are underestimating the modelled values.

## 4.2. Sensitivity analysis

It has been shown in Figures 2 and 3 that both observed and simulated values of $T_b$ for water vapour channels and far wing channels of temperature show larger $T_b$ variability ranging from 20-100 K whereas the resonant thermal channels show lesser variability of 4-6 K. At each frequency a sensitivity analysis has been carried out by modifying the atmospheric parameters to assess the sensitivity of channels to humidity and temperature on $T_b$ simulation. In order to examine the sensitivity of water vapour channels to water vapour variability, an exponentially varying water vapour profile of the form, given by the equation (2) has been adopted.

By using this relation, the $T_b$ values for all water vapour channels are first evaluated for the basic atmospheric profiles. In the next step the humidity at each altitude level is varied by $\sim 5\%$ (for $\rho_O = 10\ g/m^3$) which brings $1\ kg/m^2$ variability in integrated water vapour content (IWV). The corresponding changes in simulated $T_b$ are estimated keeping other parameters fixed. The difference in $T_b$ per $kg/m^2$ variability of IWV for all the channels are estimated and depicted in Figure 4 (left panel). Maximum sensitivity to humidity is observed in resonant channels of 22.23 and 23.03 GHz and the sensitivity decreases exponentially towards 30 GHz. Over this tropical station the IWV varies in the range of 20-60 $kg/m^2$ from dry winter season to highly humid monsoon season, which brings large seasonal and intra-seasonal variability in the $T_b$ values of water vapour channels during the intra- seasonal periods. The lower frequency spectral region of water vapour channels are the primary channels for water vapour retrieval, at these frequencies when radiometer receives emission from both liquid water and water vapour, in case of cloudy conditions. In order to account for the liquid water emission contribution to water vapour channels, 30 GHz channel $T_b$ has been used, since 30 GHz has large sensitivity to liquid water emission as it increases proportional to the square of frequency thereby used for correcting the liquid water contribution in the water vapour retrievals.

The sensitivity curve for temperature variability shows that 1K change in the atmospheric temperature has maximum effect at resonant channels. At 58.8-54.4 GHz the variability is $\sim 1$ K and at wings it is only $\sim 0.5$ K as shown in the Figure 4 (right panel). Since the air temperature over the tropics does not depict large variations (diurnally or seasonally), there is no much variability observed in the thermal channels.

## 4.3. Inter-comparison of MRP retrievals with in-situ radiosonde measurements

An inter-comparison of the atmospheric humidity and temperature profiles retrieved from MRP measurements using Neural Network (NN) are compared with those measured concurrently using radiosonde ascends. This section is devoted for validating the temperature and humidity profiles retrieved from radiometric $T_b$. The analysis is aimed at examining the accuracy of MRP retrievals for temperature and humidity apart from the consistency of radiometer data for a longer period. The analysis is carried out for clear sky and cloudy sky conditions but excluding the rainy days. The MRP retrieved atmospheric profiles are then compared against collocated radiosonde observations for four years from 2011-2014. The clear sky days are identified as days for which the IR temperature (measured by IR radiometer attached to the MRP) values <270 K and rainy periods are rejected when radiometers rain flag was present [10]. The MRP retrievals are averaged in the ±30 minutes period centered at radiosonde ascent time. Figure 5 shows the comparison of temperature, relative humidity and specific humidity profiles between MRP derived and radiosonde measured for clear sky condition which reveals the better agreement in the lower altitudes for all the parameters. The RH also shows good agreement up to an altitude of ~6 km and above which slight discrepancy is present.

The good agreements are attributed to: a) Radiosonde measurements in the lower atmospheric regions are closer (spatially) to MRP site, so that both the instruments sample the same atmospheric regions; and b) Weighting functions of the MRP for most of its channels reside in the lower altitude region of atmosphere, below 8 km and hence yields good comparison in the lower altitude atmosphere region. The discrepancies above 8 km are attributed to different factors: Spatial separation: As the balloons ascents gradually, they also drift spatially from the MRP location and depending on the wind speed and direction. Hence the balloon would have drifted by 10 to 100 km, by the time the balloon reaches an altitude of ~10 km; coarser vertical resolution of MRP: Radiosonde measurements show clear inversion of temperature at ~2 km altitude level. The MRP retrieved temperature profile does not capture the temperature inversion as conspicuously as of the radiosonde (Figure 5), even though the former indicates a very weak inversion above 2 km altitude. The profiles merge at ~4 km. This weak inversion in MRP retrieved temperature profiles are mainly attributed to the coarser vertical resolution, ~100 m for MRP, due to the higher smoothening effect of the inversion methods with height; and at higher altitudes > 8 km the a prior information is given to Neural Network (NN) which is based on the climatology of the respective parameters and biased towards winter dry condition and hence at the upper levels Jacobians are fixed and retrievals will not modify the a priori above this level[5]. The standard deviation (SD) for the parameters, shown in Figure 6, suggest that the radiosonde measurements show larger fluctuation than the MRP retrievals owing to the coarser vertical resolution of MRP.

Figure 7 shows the results of a similar comparison carried out for the cloudy con- ditions. The temperature profiles compare well and the inversions that are observed in clear sky conditions are absent during cloudy condition. The RH at the upper altitude levels above 5 km shows large discrepancies as the climatology used in the NN does not account for the cloudy condition. The standard deviation values for the parameters during cloudy condition are shown in the Figure 8. Since over this region most of the days are overcast, the numbers of cases are more during cloudy condition (120 profiles) and less during clear condition (50 profiles). Unlike in clear sky condition, the humidity profiles show large deviation at higher altitudes > 3 km in cloudy conditions.

The mean bias and RMS difference (RMSD) for the clear and cloudy conditions are shown in the Figure 9 and Figure 10, respectively. Compared to the radiosonde measured temperature, MRP retrieved temperature is negatively biased for clear sky condition, ranging from 0.5 K-3 K up to ~7 km and beyond that it is ~2.5 K up to 10 km. Under cloudy condition, they are positively biased; ranging from 0.5-1 K up to ~7 km and beyond that it is negatively biased by ~2.5 K. This shows that the climatology values of temperature are always underestimate of the radiosonde measurements. The climatology is more weighted towards the winter period and for clear condition as radiosonde upper air measurements are mostly absent during rainy and cloudy periods. Hence the upper level, above 8 km, temperature and humidity are slightly colder and drier and hence reflects in the bias. The RMS values are < 2 K up to 6 km and above which it increases to ~4 K. The comparison of water vapour shows that there is a wet bias of ~10% for RH and ~1.5g/m$^3$ for vapour density are observed both for clear and cloudy conditions up to 6 km. Since the RH is a derived parameter from the MRP measurements of temperature and water vapour density, the bias and RMS difference values are larger. Above 6 km bias during the clear sky condition is ~10% which increase to ~30% during the cloudy cases as the radiosondes are drifted away causing large water variability with location. The bias in vapour density also shows higher RMS value during cloudy condition.

## 5. Conclusion

The detailed validation has been done to ascertain the accuracy and consistency of the MRP over the tropical region close to equator for longer period during the prolonged cloudy and monsoon seasons. Forward Radiative Transfer Model for ground based MRP has been used for simulating the $T_b$ values based on the concurrent and collocated radiosonde measurements. These simulated and measured $T_b$ values are compared for all the operational channels of MRP and exhibited good correlation of ~0.9 with 0.5 K bias for peak resonant and near resonant thermal channels (V-band). The peak water vapour resonant channels show less bias, which increases with increasing frequency from 3-7 K. This variation is attributed to water vapour variability and liquid water contributions that are not considered in the models. Comparison between retrieved profiles from MRP measurements and that measured by collocated and concurrent radiosonde ascents for a four-year period reveals that the temper- ature profiles show good comparison during cloudy condition with < 1 K up to an altitude of 7 km and above that ~2.5 K bias whereas during clear sky condition the bias is larger, 0.5-3 K up to ~ 7 km and beyond that it is ~2.5 K up to 10 km. Water vapour density profiles show good comparison for both during clear and cloudy conditions (< 1.5 g/m$^3$) whereas RH profiles show large discrepancies (~10-15% at < 4 km) during cloudy condition. From these analyses, it has been concluded that MRP measurements under equatorial condition agree well with concurrent and collocated radiosonde measurements during a four year period which also confirm the consistency and stability of the MRP system for the utility of data over TVM under tropical condition with prolonged monsoon period.

## 6. Equations

$$T_b(\theta) = T_{extra} e^{-\tau_0 \sec\theta} + \sec\theta \int_0^\infty \kappa(z) T(z) e^{-\tau(0,z)} dz \quad \textbf{(1)}$$

where τ is the opacity of the atmosphere, κ is the absorption coefficient of the medium, z is the height level and θ is the angle of incidence.

$$\rho(z) = \rho_0 e^{-z/H} \quad \textbf{(2)}$$

where $\rho_0$ is the surface water vapour density, $z$ is the altitude level and $H$ is the scale height (considered to be 2 km).

## 5. Figures and Tables

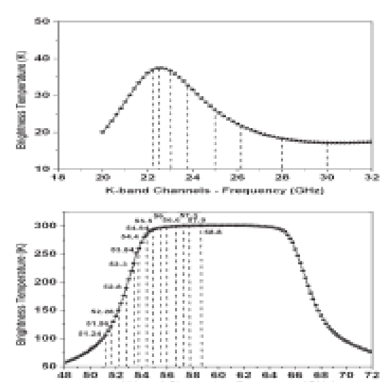

**Figure 1.** The down welling brightness temperature for K-band channels (upper panel) and V-band channels (lower panel) frequency range computed from RTM at zenith angle.

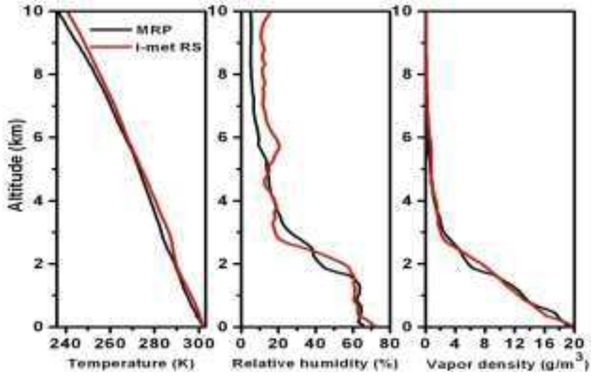


**Figure 2.** The down welling brightness temperature for K-band channels (upper panel) and V-band channels (lower panel) frequency range computed from RTM at zenith angle.

## 6. Acknowledgements

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