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# Ground Based Microwave Radiometric Technique in Remote Sensing

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**Abstract.** As an important tool of atmospheric remote sensing, microwave radiometers are used for temperature profiling and vapor and liquid column measurements. In addition, ice water path can be retrieved using radiometer observations. In this review, the potential of radiometers is demonstrated by comparison with radiosonde data and observations using Global Positioning Systems (GPS).

Performance of various mathematical retrieval methods for water vapor and cloud liquid water profiles using microwave radiometer measurements are compared. These include regression methods, Newton iteration and neural networking. A specific case of temperature inversion near the ground and its retrieval by Philips-Twomay method is discussed.

*Keywords* : microwave radiation, atmospheric remote sensing

## 1. Introduction

The instruments that can measure the atmospheric radiation can be classified into two broad categories – the active and the passive instruments. Radars and lidars come under the first category whereas microwave radiometers and infrared spectrometers fall into the second one. Radars have high spatial resolution, sensitive to microphysical quantities but expensive and difficult to operate. On the other hand, radiometers are relatively inexpensive, ideally suited for remote observations but they can measure only cumulative parameters and the spatial information of physical quantities like temperature and water vapor are difficult to retrieve.

Microwave Radiometers can be either ground based or satellite borne. At present Advanced Microwave Sounding Units (AMSUs) are used on NOAA's TIROS (Television Infrared observation Satellite) satellites to provide temperature and water vapor profiles. They have low spatial and temporal resolution but large spatial coverage. So at a specific location, if we require vertical temperature distribution, ground based radiometer will be useful. The large emission measured by satellite based instrument comes from the top of the atmosphere whereas for a ground based instrument, it comes from lower layers. So if temperature inversion occurs near the ground, a satellite based instrument will not be able to measure it. The number of channels in the ground based instrument can be increased making the retrieval more accurate. The noise level in the ground based instrument also can be reduced considerably making the performance better. Ground based radiometers are used as a validation for satellite sensors.

The applications of microwave radiometers are numerous – detection of aircraft icing, atmospheric radiation flux studies, weather forecasting are to name a few. In the recent years astronomers have been using it as a site survey equipment to quantify the water vapor content in the atmosphere. The data collected is used in the feasibility study for setting up an infrared or millimeter wave observatory (Ananthasubramanian et al. 2002).

Microwave radiometry is a vast topic and excellent text books (Ulaby et al, 1982), review articles (Westwater, 1993) and research papers (Liebe, 1989, Li et al, 1997, Solheim et al, 1998, Rosenkranz, 1998) have been written. In this paper we are confined to ground based microwave radiometry.

## 2. Microwave Spectrum in Earth Atmosphere

Microwave profiling methods described in this paper make use of atmospheric radiation. The zenith path atmospheric absorption is shown in figure 1. The feature at 22.2 GHz is a water vapor resonance that is pressure broadened according to the pressure altitude of the water vapor distribution, while the feature at 60 GHz is the Oxygen resonance. The feature at 118.75 GHz is again due to Oxygen rotation line and 183 GHz absorption is from water vapor. The liquid water absorption increases approximately as the square of the frequency in this region.

By scanning outward from 60 GHz line center where the opacity is so great that all signal originates just above the antenna, onto the wing of the line where the radiometer "sees" deeper into the atmosphere, one can obtain altitude information. Emission at any altitude is proportional to the local temperature; thus the temperature profile can be retrieved.

Water vapor profiles can be obtained by observing the intensity and shape of emission from pressure broadened water vapor lines. The line at 183 GHz is used by satellites. The high opacity of this line hides the emission from ground level, eliminating this error source but precluding profiling of low altitudes. The line at 22 GHz is too transparent for effective profiling from satellites but suitable for ground based observations. The intensity of emission is proportional to vapor density. Therefore one can get water vapor profiles from measurements.

At the ground surface level, by observing the sky at the zenith angle, one can obtain the brightness temperature $T_B$ which is related to the emission from atmosphere by

$$T_B(f) = T_C e^{-\tau_f(0,\infty)} + \int T(z)\alpha(f,z)e^{-\tau_f(0,z)}dz, \qquad (1)$$

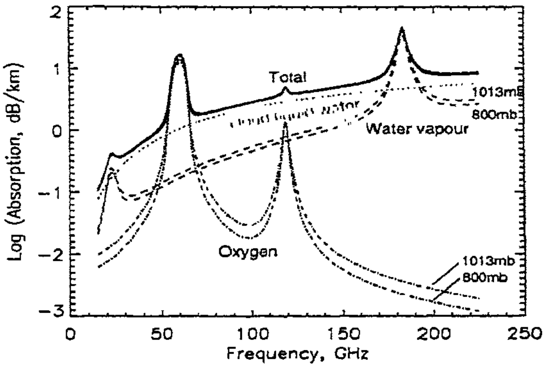

**Figure 1.** Contribution to atmospheric absorption by oxygen, water vapor and cloud liquid in the microwave range. Absorption at two pressures are shown. The cloud is 1 km thick with 0.5g/m$^3$ Liquid Water Concentration.

where $T_C$ is the cosmic background radiation; $\tau_f(0,\infty)$ is the total optical depth; $T(z)$ is the physical air temperature in Kelvin. $z$ is the zenithal position and $\alpha$ is the attenuation coefficient at frequency $f$. The optical depth is

$$\tau_f(0,z) = \int_0^z \alpha(f,z')dz'. \tag{2}$$

If the observation is at an angle $\theta$ from zenith, then $\cos(\theta)$ factor will enter the equation (1) in a trivial way. This fact is used for calibration purposes.

When absorption, emission and scattering are present, the equation of transfer is

$$\mu\frac{d\mathbf{I}(\tau,\mu,\phi)}{d\tau} = \mathbf{I}(\tau,\mu,\phi) - \frac{\omega}{4\pi}\int_0^{2\pi}\int_{-1}^{+1}\mathbf{P}(\mu,\phi;\mu',\phi')\mathbf{I}(\tau,\mu',\phi')d\mu' d\phi' - \\ -\frac{\omega}{4}\mathbf{P}(\mu,\phi;\mu_0,\phi_0)\mathbf{F}e^{-\tau/\mu_0} + (1-\omega)\mathbf{B} \tag{3}$$

Here **I** is the Stokes vector, $\omega$ is the albedo for single scattering, **P** is the phase matrix, **F** is the solar flux incident on the atmosphere in direction $\mu_0$, $\phi_0$, where $\mu_0$ is the cosine of the angle made by the ray to $z$ axis and $\phi$ is the azimuthal angle referred to a suitable x-axis. Total attenuation consist of absorption and scattering coefficients and the albedo is the ratio of scattering to total attenuation.

When liquid droplets or large aerosol and ice particles are present the simple emission model is inadequate (Vivekanandan et al, 1991). This is indicated in figure 2 (Zhang et al. 2000). They have done the calculations for a parametric atmosphere of $T_A = 283°K$, integrated vapor $\nu = 0.6$ cm surface pressure $P_0 = 84$ KPa, Liquid Water Concentration=0.5g/m$^3$, cloud base height 3km with thickness of 1km. The droplets have modified gamma distribution.

For low frequencies the results do not differ because Rayleigh scattering is valid. At higher

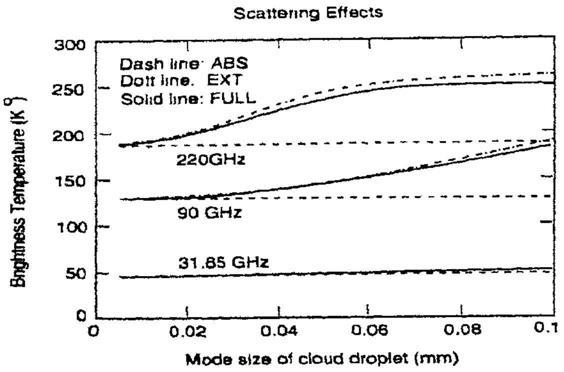

**Figure 2.** Comparison of radiation from liquid cloud using absorption (ABS), Rayleigh scattering (EXT) and Mie scattering (FULL) approaches.

frequencies even Rayleigh scattering is not valid but Mie scattering is necessary. Most of the retrieval techniques at present use only emission model and so they can not retrieve the physical parameters in the presence of thick clouds.

## 3. Comparison of Radiometer Measurements with other Instruments

Radiosondes are the instruments flown in balloons which make in-situ measurements. Radiosonde observations (RAOBs) are the fundamental method for atmospheric temperature, wind and water profiling in spite of their inaccuracies, cost, sparse temporal sampling and logistical difficulties. A better technology has been sought for many decades, but until now, no accurate all weather technology has been demonstrated. Laser radars (Lidars) and Fourier transform infrared spectrometers can profile temperature and water vapor, but not in the presence of cloud. On the other hand radiometric temperature and water profilers give continuous, unattended profile measurements. They also have capability to profile cloud liquid water, a capability absent in RAOBs and all other systems except for in-situ aircraft devices.

German Weather Service has been evaluating the use of radiometric and wind profilers for use in operational weather forecasting. Radiometric soundings before and after the radiosonde launch time were collected. The results of 18 months observations of the radiometer in operation in an unattended mode was presented by Guldner and Spankuch (2001). They conclude that the accuracy of the retrieved profiles of radiometric observations show 0.6 K near the surface and 1.6 K upto 7 kms in summer, and 4 kms in winter. For water vapor, corresponding values are 0.2-0.3 $g/m^3$ near the surface and 0.8-1.0 g $m^{-3}$ from 1-2 km altitude.

In the last decade, ground based GPS receivers have been developed as all-weather and low cost remote sensing systems of the atmosphere. It is based on the principle that the amount of water vapor contained in the neutral atmosphere is strongly related to the propagation delay of the

GPS observations. The Integrated Precipitable Water Vapor (IPWV) is the height of liquid water that would result from the condensation of all the water vapor in a column from the surface to the top of the atmosphere. IPWV derived from GPS, water vapor radiometer, and RAOBs have been compared (Pacione et al. 2002) for the Cagliari site (Italy) on a seasonal and annual basis. The data acquired was analysed using GIPSY-OASIS II software (Webb and Zumberge, 1997) which takes the ionospheric time delays into account. The GPS shows an accuracy of 0.136 cm with a bias of -0.049 cm throughout 1999.

## 4. Retrieval Methods

Simple physical methods which oversimplify the real problems are less accurate than statistical ones, but statistical methods offer no insights to the physical processes. Most of the existing algorithms break down if Mie scattering due to ice and water drops is present because the earlier models are based on absorption. A forward model in which microwave brightness temperature is calculated from given atmospheric parameters plays a key role in understanding microphysics and retrieval of the same. First we will describe some statistical methods.

The regression method uses the traditional linear statistical inversion technique summarized by Westwater (1993). The independent vector **y** contains the brightness temperatures, surface vapor density and surface temperature and pressure. The dependent vector **x** contains the water vapor profile, and integrated liquid. They are related as

$$\mathbf{x} = \mathbf{a} + b\mathbf{y} \tag{4}$$

where **a** and $b$ are obtained from a statistical ensemble of radiosonde profiles using multivariate regression methods. For example, in the case of dual channel radiometer mean radiating temperature at frequency $f$ can be defined as,

$$T_m(f) = \frac{\int_0^\infty T(z)\alpha(f,z)e^{-\tau_f(0,z)}dz}{\int_0^\infty \alpha(f,z)e^{-\tau_f(0,z)}dz}, \tag{5}$$

$$\tau(dB) = 4.343ln\left(\frac{T_m(f) - T_C}{T_m(f) - T_B(f)}\right) \tag{6}$$

$$IPWV = a_0 + a_1\tau_1 + a_2\tau_2, \tag{7}$$

where the retrieval coefficients $a_i$ convert atmospheric opacities $\tau_1$ and $\tau_2$ into IPWV. The monthly statistical coefficients $a_i$ have been estimated by applying algorithms based on transfer theory to the large historical base of RAOB profiles.

Neural network method can handle nonlinearity in the remote sensing problems. When ice is present, only neural network method has been successful at present to retrieve the Ice Water Path, IWP (Li et al. 1997). The network can be described as a parametrized mapping from an input vector $a(0)$ to an output vector $a(L)$

$$\mathbf{a}(L) = \phi(\mathbf{W}, \mathbf{a}(0)) \tag{8}$$

where **W** is the vector of weights and $L$ is the number of layers in the network. In the first phase, a set of data generated from the parametrized radiative transfer model is used to train a data driven neural network model that maps from parameter space ($\overline{P}$) to measurement space ($\overline{m}$). The forward model contains the gradient information of measurements with respect to parameters. In the second phase, an inverse model is constructed based on this gradient information which provides us a way of searching for solutions in parameter space for a given measurement. Unfortunately the radiative transfer model is characterized by many-to-one mapping. Explicit inverse method resolves the mapping problem by averaging across multiple targets. But an average of many possible inversions may not be even an inversion. Iterative inversion algorithm is an interesting approach. The idea is to repeatedly present outputs to the forward model and search for a solution in the input space of the model while freezing the weights. So instead of updating weights, the iterative approach updates the inputs of forward models. So the iterative inverse starts with an initial guess. Comparison of all these methods with observations can be found in Solheim et.al. (1998).

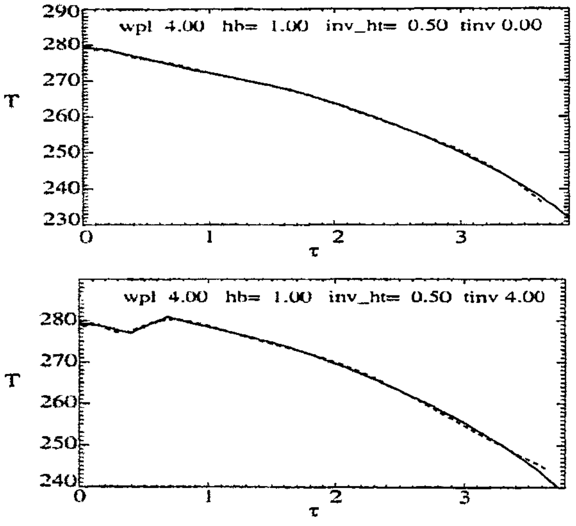

**Figure 3.** The exact (solid) and the retrieved (dashed) temperature profiles using Philips-Twomay algorithm are shown for two different type of atmospheres; One with inversion near ground (bottom panel) and the other with constant decrease of temperature (Rangarajan et al., 2003).

Philips-Twomay method (Twomay, 1977) is used to retrieve the temperature profile both in the presence of temperature inversion near the ground and in an atmosphere with an uniform temperature gradient.

$$\sum_{i=1}^{N}[I(\mu_i) - \sum_{j=1}^{M} C_{ij}S_j]^2 + \lambda_0 \sum_{k=1}^{M}\sum_{j=1}^{M} H_{kj}S_kS_j = \text{a minimum} \qquad (9)$$

where $\lambda_0$ is the strength of the smoothing. $C$ is the quadrature matrix and the smoothing matrix

$H$ is determined by

$$\sum_{j=1}^{M} H_{kj} S_k S_j = \frac{1}{2} \sum_{k=2}^{M-1} (S_{k-1} - 2S_k + S_{k+1})^2 \tag{10}$$

The equation is expressed in matrix form as

$$(\mathbf{I} - \mathbf{CS})^* \mathbf{C} = \lambda_0 \mathbf{S}^* \mathbf{H} \tag{11}$$

where * denotes the transpose. Finally the solution is

$$\mathbf{S} = (\mathbf{C}^* \mathbf{C} + \lambda_0 \mathbf{H})^{-1} \mathbf{C}^* \mathbf{I} \tag{12}$$

Once the temperature is accurately determined, it makes it easy to apply iterative neural network to infer other quantities.

## 5. Summary

We find that ground based radiometric technique allows us to calculate the physical parameters like liquid water path, integrated water vapor of the troposphere with reasonable accuracy. Among the retrieval methods, a combination of physical methods like Philips-Twomay with Neural network holds promise for the future. That is, an initial solution may be generated by Philips-Twomay method followed by neural network. Iterative Neural network can handle nonlinear microwave scattering problems and hence is better suited for the retrieval of ice water path.

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