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Measurements of atmospheric water vapor with microwave radiometry

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A dual-channel, ground-based microwave radiometer, working at the frequencies 21.0 and 31.4 GHz, an infrared spectral hygrometer, and radiosondes have been used for comparative measurements of the integrated amount of precipitable water vapor in the atmosphere over a period with zenith water vapor contents varying between 6 and 26 mm. The microwave radiometer was found to give comparable or better formal accuracy than the radiosondes, the absolute accuracy of which is believed to be about 1 mm. The rms difference of the integrated amount of water vapor in the zenith direction measured with the microwave radiometer and with radiosondes was 1.2 mm for all data, and 0.8 mm for a selected group of good weather data. These are lower formal errors than previously reported. It is shown that the simplified relation between the radiometer antenna termperatures and the integrated amount of water vapor in this case contributes with a formal error of about 0.3 mm. It is suggested that mean ground weather data can be used to adapt this relation to other sites and seasons.

1. INTRODUCTION

Several methods are used to measure the integrated amount of water vapor, often called integrated precipitable water vapor (IPWV), and the cloud liquid in the atmosphere. One of the new and very promising methods is microwave radiometry, which can be run in an unattended continuous mode and has the specific advantage of almost all-weather capability. Both ground-based [*Westwater*, 1978; *Guiraud et al.*, 1979; *Snider et al.*, 1980] and satellite-based [*Staelin et al.*, 1976] instruments have been used. A microwave radiometer designed for this purpose is often called a water vapor radiometer (WVR). There are, however, other methods to determine the IPWV, e.g., correlation with ground surface weather measurements, integration of radiosonde profiles, infrared spectral hygrometer (IRSH) measurements, and aircraft soundings. Ground surface weather measurements are easy to perform, but there are often rather low correlations between local humidity and IPWV. The radiosonde is in principle a simple instrument, but it has poor accuracy in the relative humidity measurements, especially at high altitudes and low humidities. It is also difficult to perform continuous measurements, and it is impossible to control the path of the radiosonde through the atmosphere. The most common infrared spectral hygrometer (IRSH) measures the ratio of the radiation from the sun at two frequencies on and off a water vapor line. The hygrometer is calibrated by means of an independent instrument, e.g., radiosondes, so that an empirical relation between the measured intensity ratio and the integrated amount of water vapor can be deduced. The hygrometer cannot be used at night (except a construction reported by *Büscher and Lemke* [1980]) or when clouds obscure the sun. Furthermore, an assumption of a horizontally stratified atmosphere is required to deduce the IPWV in any other direction than toward the sun. Finally, the method of aircraft soundings has high accuracy but is limited in altitude and too expensive for routine observations.

Accurate measurements of the integrated amount of cloud liquid are difficult to perform. The traditional method is aircraft soundings. The possibility of using a WVR is therefore of great interest, and its capability has been demonstrated by *Snider et al.* [1980].

The main purpose of the experiment described in this report was to investigate the accuracy of IPWV results obtained with microwave radiometry. Data from three of the four methods described above are therefore compared in section 5 with results from simultaneous WVR observations. In order to understand the WVR results, an improved theory relating the observed brightness temperatures and the IPWV is included, followed by a short description of the various instruments.

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2. THEORETICAL BACKGROUND

We define IPWV as

$$\text{IPWV} = 10^{-3} \int_{h_0}^{\infty} a(h)\, dh \qquad (1)$$

where $a(h)$ is the water vapor density in g/m^3, h is the height in m; h_0 is the ground altitude, and IPWV is expressed in millimeters. The measured sky brightness temperature T_A is

$$T_A = T_{bg} e^{-\tau_\infty} + \int_{h_0}^{\infty} T(h)\alpha(h) e^{-\tau(h)}\, dh \qquad (2)$$

where $\tau_\infty = \int_{h_0}^{\infty} \alpha(h)dh$ is the opacity of the atmosphere, $\tau(h) = \int_{h_0}^{h} \alpha(h)dh$ is the opacity up to the height h, T_{bg} is the cosmic background radiation of 2.8 K, $T(h)$ is the physical temperature, and $\alpha(h)$ is the total absorption coefficient caused by water vapor, liquid water, and oxygen, i.e., $\alpha = \alpha_v + \alpha_l + \alpha_0$. In order to get rid of the influence of α_l, which is highly variable compared with α_0, two observation frequencies will be used.

The theory, which will result in a simplified relation between (1) and (2), will from now parallel that given by *Wu* [1979] for the tropospheric path delay. Let us introduce the so-called 'linearized' brightness temperature

$$T'_A = T_{bg}\left(1 - \int_{h_0}^{\infty} \alpha\, dh\right) + \int_{h_0}^{\infty} T\alpha\, dh$$
$$T'_A = T_{bg} + \int_{h_0}^{\infty} (T - T_{bg})\alpha\, dh \qquad (3)$$

Notice that $T'_A \approx T_A$ if $\int_{h_0}^{\infty} \alpha\, dh \ll 1$.

T'_A can be expressed in the measured antenna temperature T_A, as

$$T'_A = T_{bg} - (T'_{\text{eff}} - T_{bg}) \ln\left(1 - \frac{T_A - T_{bg}}{T_{\text{eff}} - T_{bg}}\right) \qquad (4)$$

with

$$T_{\text{eff}} = \frac{\int_{h_0}^{\infty} T\alpha e^{-\tau}\, dh}{\int_{h_0}^{\infty} \alpha e^{-\tau}\, dh} \qquad (5)$$

and

$$T'_{\text{eff}} = \frac{\int_{h_0}^{\infty} T\alpha\, dh}{\int_{h_0}^{\infty} \alpha\, dh} \qquad (6)$$

T_{eff} is often called the effective temperature of the atmosphere. Thus we can obtain T'_A from T_A if T_{eff} and T'_{eff} are known. T_{eff} and T'_{eff} can be determined from radiosonde profiles. However, it is easily shown that an error as large as 10 K in T_{eff} and T'_{eff} will hardly affect T'_A for typical brightness temperatures below 100 K. This accuracy can be achieved from an empirical formula and the ground surface temperature [*Wu*, 1979].

If two linearized antenna temperatures, at the frequencies f_1 and f_2, (T'_{A,f_1} and T'_{A,f_2}) are combined, we obtain the following equation

$$\frac{T'_{A,f_1} - T_{bg}}{f_1^2} - \frac{T'_{A,f_2} - T_{bg}}{f_2^2} = \int_{h_0}^{\infty} W'(h) a(h)\, dh + T'_0 \qquad (7)$$

$W'(h)$ is a weighting function defined as

$$W'(h) = \frac{T - T_{bg}}{a}\left(\frac{\alpha_{v,f_1}}{f_1^2} - \frac{\alpha_{v,f_2}}{f_2^2}\right) \qquad (8)$$

and the parameter T'_0 is given by

$$T'_0 = \int_{h_0}^{\infty} (T - T_{bg})\left(\frac{\alpha_{0,f_1}}{f_1^2} - \frac{\alpha_{0,f_2}}{f_2^2}\right) dh \qquad (9)$$

if $\alpha_l \sim f^2$ [*Staelin*, 1966].

Equation (7) demonstrates that there is a linear relation between the IPWV and the linearized antenna temperatures if $W'(h)$ is independent of the height h. The shape of the weighting function depends mainly on the frequencies used, and an unsuitable choice of frequencies will make it more sensitive to variations in the meteorological profiles. We assume that the two frequencies are chosen so that $W'(h)$ is constant, and we obtain

$$\text{IPWV} = c_0 + c_1 T'_{A,f_1} + c_2 T'_{A,f_2} \qquad (10)$$

with

$$c_0 = (T_{bg}(f_2^{-2} - f_1^{-2}) - T'_0) \cdot 10^{-3}/W' \qquad (11)$$

$$c_1 = 10^{-3}/(W' \cdot f_1^2) \qquad (12)$$

$$c_2 = -10^{-3}/(W' \cdot f_2^2) \qquad (13)$$

The weighting function will be discussed further in section 5.

3. INSTRUMENTATION

Water vapor radiometer. The WVR is a dual-channel radiometer working at the frequencies 21.0 and 31.4 GHz, with equivalent design for the two channels. The horn antennas are conical, dielectrically loaded, with beamwidths of 6°. The design is of Dicke-type with two reference loads at 77 and 313 K. The system temperature is about 550 K for both channels with a bandwidth of 1 GHz. The sensitivity resolution is limited by the analog to digital conversion to about 0.3 K. The time constant used during the experiment was 1.0 s. The WVR is shown in Figure 1.

Infrared spectral hygrometer. The IRSH was borrowed from the Max-Planck Institut für Radioastronomie, Bonn, Federal Republic of Germany, and previous observations with this instrument have been reported by *Greve* [1978]. The IRSH measures the ratio of the solar radiation at two wavelengths in the infrared spectrum, in this case at the wavelengths

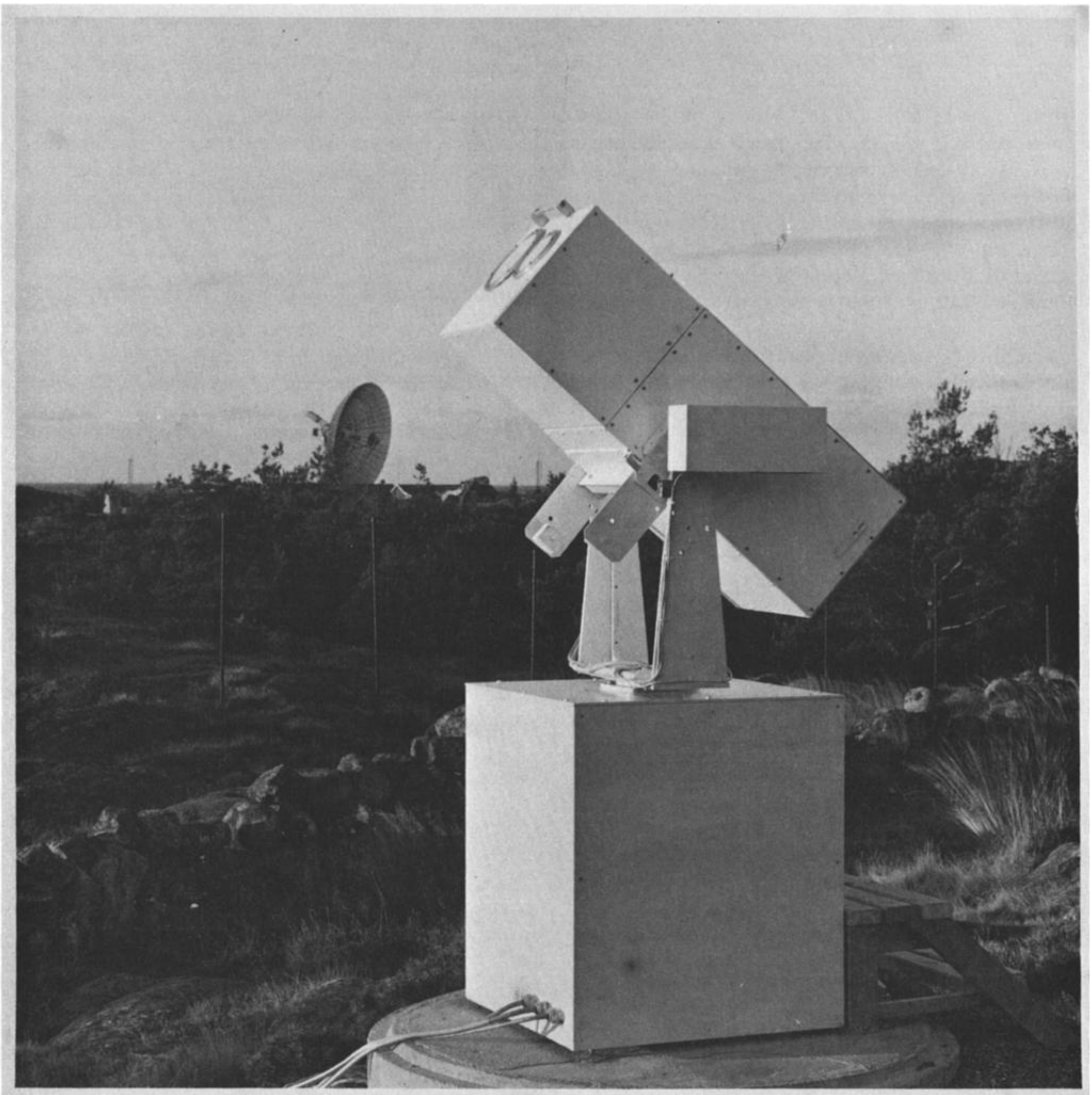

Fig. 1. The water vapor radiometer at the Onsala Space Observatory.

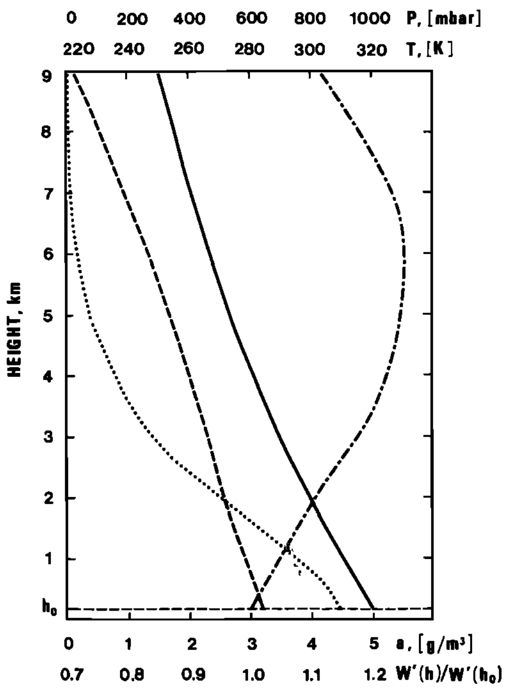

Fig. 2. The mean atmospheric profiles for Gothenburg-Landvetter Airport May 1980; the solid line is pressure, the dashed line is temperature, the dotted line is water vapor density, and the dashed-dotted line is the normalized weighting function, $W'(h)/W'(h_0)$. $W'(h)$ is defined in section 2 (h_0 is 155 m).

880 and 931 nm, with bandwidths of 50 nm. The attenuation of the atmosphere in this part of the spectrum is given by *Allen* [1973].

Radiosondes. The radiosondes were manufactured by Vaisala Oy, Helsinki, Finland.

4. MEASUREMENTS AND DATA REDUCTION

The measurements were made in May and June, 1980, at Gothenburg-Landvetter Airport, Sweden, where radiosondes were launched twice a day, at noon and midnight. The mean atmospheric profiles and the weighting function, described in section 2, during May 1980 are shown in Figure 2.

Water vapor radiometer. Simultaneous observations with the WVR and the radiosondes resulted in 40 separate measurements. In order to obtain the linearized antenna temperatures from the WVR raw data, a technique similar to the one described by *Claflin et al.* [1978] was used.

Infrared spectral hygrometer. The IRSH measurements were restricted to observations in the direction of the sun when there were no clouds in the line of sight, which resulted in only seven simultaneous observations with the WVR and the IRSH. In order to get enough data to calibrate the instrument, we therefore continued these measurements until the middle of August. In all, 31 simultaneous observations with the IRSH and radiosondes were made. For each of the 31 observations we measured the ratio V_1/V_2 of the two IR intensities with the IRSH, and fitted these ratios to the corresponding radiosonde observations by means of the least squares method. The relation

$$\text{IPWV} = c_1 e^{c_2 V_1/V_2} \tag{14}$$

earlier used for this instrument (A. Greve, personal communication, 1980), showed good agreement with the data and was therefore used.

Radiosondes. The radiosonde measures the pressure, the temperature, and the relative humidity as functions of the height. The water vapor density can be calculated from the relative humidity by means of the known relations for the water vapor pressure [*Crane*, 1976], and the ideal gas law. The water vapor density was then integrated with height from the ground up to the 300 mbar pressure level, at about 9000 m, according to equation (1). The integration was done numerically between characteristic points in the measured temperature and (or) relative humidity profiles. The liquid water content of the atmosphere was calculated from a cloud model, where we assumed that a relative humidity exceeded 96% indicated clouds and that all clouds had a liquid water density of 1 g/m^3 [*Handbook of Geophysics*, 1960].

5. RESULTS AND DISCUSSION

Integrated precipitable water vapor (IPWV): The data are arranged into two groups, one containing all data and the other what we call "good weather data." Good weather data are obtained from observations made when clouds covered less than half the sky. This condition indicates a more homogenous atmosphere, which is important for a comparison of observations made in different directions through the atmosphere. We also expect a higher accuracy in the WVR data because of the low probability of heavy rainfall and large amounts of cloud liquid, which prevents the sky brightness temperatures from being saturated.

The results are shown in Tables 1 and 2, where we present the rms differences and the regression coefficients obtained when the data from the various instruments and methods are fitted, by means of the

TABLE 1. Rms Differences for the Integrated Precipitable Water Vapor in the Zenith Direction Obtained With Various Instruments and Methods When Data Were Fitted to and Compared With Radiosonde Data

Predictor	Fit	rms Difference: All Data, mm	rms Difference: Good Weather Data, mm
1. Mean	...	5.2[b]	5.0[c]
2. Ground surface water vapor density	$IPWV = c_0 + c_1 a_0$	2.6[b]	2.3[c]
3. IRSH	$IPWV = c_0 \exp(c_1 V_1/V_2)$	1.9[d]	1.9[e]
4. WVR, 21 GHz channel only	$IPWV = c_0 + c_1 T'_{21}$	2.2[b]	1.1[c]
5. WVR, with $c_2 = -f_1^2/f_2^2 \cdot c_1$	$IPWV = c_0 + c_1 T'_{21} + c_2 T'_{31.4}$	1.2[b]	0.9[c]
and including the weighting function	$IPWV = (c_0 + c_1 T'_{21} + c_2 T'_{31.4})/W'(0)$	1.2[b]	0.9[c]
7. WVR, no constraint on c_1 and c_2	$IPWV = c_0 + c_1 T'_{21} + c_2 T'_{31.4}$	1.2[b]	0.8[c]
8. WVR, with theoretical antenna temperatures and $c_2 = -f_1^2/f_2^2 \cdot c_1$	$IPWV = c_0 + c_1 T'_{21} + c_2 T'_{31.4}$	0.3[b]	0.2[c]

[a] IPWV calculated from radiosonde data.
[b] 40 data points.
[c] 22 data points.
[d] 31 data points.
[e] 17 data points.

least squares method, to the radiosonde data. Figure 3 shows the IPWV derived from radiosonde data compared with the surface water vapor density, IRSH, and WVR data, respectively. These plots contain the complete set of observations.

The simplest way to predict the IPWV is to use the mean seasonal value, calculated from previous radiosonde observations. A mean of 14.9 mm during the experiment gives an rms difference as high as 5.5 mm. This value will increase if the means from previous years are used instead. To reduce this difference by a factor of 2, we can instead use the water vapor density at the ground. However, the correlation between IPWV and ground surface water vapor density varies from site to site. Observations of high as well as low correlations have been reported (*Robson and Rowan-Robinson* [1979], and their reference list). Factors such as the climate and the topography of the area around the site play an important role. The improvement we obtain by using the IRSH is surprisingly low, but this may be partly due to the fact that the measurements with the IRSH were done during a period with higher humidity than during the experiment with the WVR (see Figure 3).

TABLE 2. Regression Coefficients Obtained for all Data

Predictor[a]	c_0^b	c_1^b	c_2^b
2	0.95	2.021	...
3	672.0	−4.04	...
4	0.95	0.483	...
5	−0.60	0.800	−0.358
6	−2.36	1.872	−0.837
7	−0.70	0.764	−0.304
8	−1.30	0.865	−0.387

[a] See Table 1.
[b] IPWV in millimeters, a_0 in [g m^{-3}], T in [K], and W' in $10^{-3} \cdot$ [K km^{-1}/(g m^{-3} GHz^2)]

A compromise between the inexpensive IRSH and the dual-channel WVR is a one-channel radiometer at 21.0 GHz. The accuracy for good weather data is almost as high as the accuracy obtained with the dual-channel WVR. However, if we consider the entire group of data, we find that if the amount of cloud liquid in the atmosphere increases, the accuracy decreases and is almost as bad as when we used ground surface water vapor density measurements only. The accuracy achieved with the dual-channel WVR is remarkably high. The radiosonde specifications by the manufacturer give an rms error of the same order as the rms difference between the WVR and the radiosondes. The slight improvement in accuracy obtained if we omit the constraint on the constants c_1 and c_2 (see equations (12) and (13)) shows that the theory in section 2 is quite accurate.

No improvements of the rms difference were obtained when the actual values of the weighting function at the ground were included in the regression analysis. This is easily explained if the expressions for the absorption coefficients due to water vapor [*Waters*, 1976] are inserted in (8). The value of the weighting function is mainly dependent on the tem-

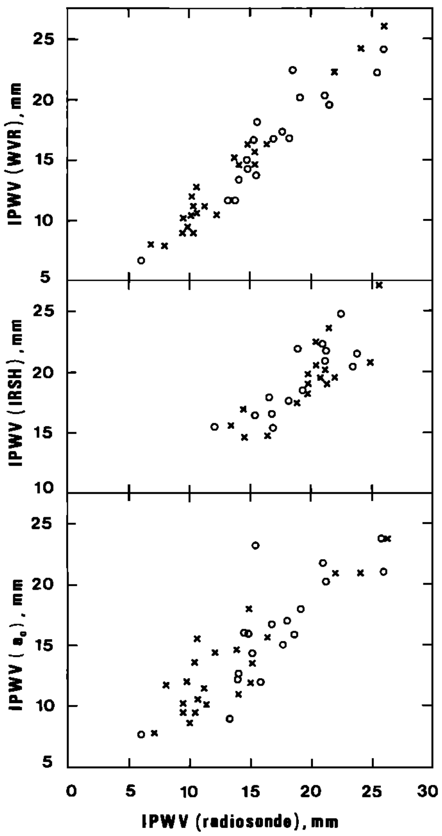

Fig. 3. The IPWV in the zenith direction obtained from the WVR (predictor 7, Table 1), the IRSH (predictor 3, Table 1), and the ground water vapor density (a_0) observations (predictor 2, Table 1) versus the IPWV calculated from radiosonde data. The symbols denote cross: good weather data (less than half the sky covered by clouds) and open circle: remaining data (more than half the sky covered by clouds).

perature and the pressure. Short time variations in the ground temperature uncorrelated with changes at higher altitudes will therefore decrease the accuracy of the regression analysis. On the other hand, we realize that a long-term mean of the weighting function at the ground level can be used as a correction factor for measurements at different climatological conditions (seasons and sites). The mean value of $W'(0)$ during these observations was $2.25 \cdot 10^{-3}$ $[K^{-1}/(\mathrm{g\ m^{-3}\ GHz^2})]$.

The error introduced by the WVR theory (see section 2), mainly due to a nonconstant weighting function, can be calculated by deriving the theoretical antenna temperatures from the radiosonde profiles and thereafter fit these temperatures to the IPWV:s calculated from the same profiles (predictor 8, Table 1 and 2). This rms error of 0.3 mm for all data, is the error obtained if the WVR and radiosonde measurements are free from errors and the expression for the absorption coefficient is correct.

The seven simultaneous measurements made with the WVR and the IRSH give a rms difference of 1.8 mm. If the errors of the instruments are not correlated, this implies that the WVR has the highest relative accuracy of the instruments used. However, it is important to remember that the low number of simultaneous measurements means that this result is just an indication.

It should be pointed out that the absolute accuracy of the IPWV calculated from radiosonde data is unknown. Therefore, a systematic error in radiosonde data will imply the same systematic error in the results from the WVR and the IRSH. However, during clear sky conditions a mean difference of 1 K was obtained between the antenna temperatures measured with the WVR and the theoretical antenna temperatures calculated from radiosonde data. This mean difference corresponds to an error in the IPWV of less than 1 mm in the zenith direction.

Finally, it should be mentioned that the radiometer has also been used to determine water vapor profiles in the atmosphere [*Skoog et al.*, 1982].

Cloud liquid. There were only 17 observations made when the radiosonde and/or the WVR detected liquid water in the atmosphere. This fact together with the poor method to measure liquid water with the radiosonde implies that it is not meaningful to derive an empirical formula from these data. Instead, we chose to calculate the integrated amount of liquid water from the antenna temperatures with the formula given by *Guiraud et al.* [1979] (corrected for a misprint to $L = -0.018 - 0.00114T(20.6) + 0.00284T(31.6)$). These results were then correlated with the amount of liquid water estimated from the radiosonde profiles. The obtained correlation coefficient was 0.7. We are convinced that the main error source is the method to calculate the liquid water from the radiosonde data, which implies that the observations described here are insufficient to determine the capability of the WVR to measure integrated amounts of liquid water (see, however, *Snider et al.* [1980] for an alternative method of comparison).

6. CONCLUSION

The results show that the microwave radiometer has an accuracy comparable with or slightly better than the radiosonde to measure the integrated amount of water vapor in the atmosphere. Although we have not discussed the calibration procedure in this report, it is important to calibrate the radiometer against an independent instrument or method with as low systematic error as possible. This can be done with the predictor 7 or 8 (Tables 1 and 2), i.e., by using radiosondes or the theory for water vapor absorption, respectively. The obtained regression coefficients can be adjusted, by using the mean ground value of the weighting function, to suit a site with different climatological conditions.

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