DETERMINATION OF ATMOSPHERIC PRECIPITABLE WATER AND HUMIDITY PROFILES BY A GROUND-BASED 1.35 cm RADIOMETER*

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ABSTRACT

In four seasons of 1982 measurements of atmospheric water vapor profiles and total precipitable water were made by a ground-based microwave radiometer operating at 1.35 cm wavelength. All data were processed by using Monte Carlo method. The statistical results of more than seventy cases show that the relative error compared to the radiosonde observations is 5.3% for the total precipitable water vapor and less than 20% for humidity profiles in the lower atmosphere below 750 mb. In addition, the relationship between the weather background and both the humidity profiles and the total precipitable water vapor were analyzed.

I. INTRODUCTION

In the past twenty years, a great number of works in remote sensing of atmospheric precipitable water were conducted and a series of results were obtained in both space-borne and ground-based experiments[1]. In the late sixties, the exploration for remote sensing of atmospheric humidity profile started. In seventies, the microwave radiometer operating at atmospheric water vapor channeles was flown on Nimbus-5. At the same time, a similar instrument was used on the ground to measure water vapor profiles in the troposphere[2]. Later, by use of statistical inversion method, Hogg et al[3]. obtained statistical results of atmospheric precipitable water vapor and some retrieved humidity profiles on the basis of measurements by a ground-based radiometer operating at both 1.35 cm and 0.8 cm wavelengths. In China, Zhao Bolin et al[4]. also obtained profiles of nine cases and their average using a 1.35 cm radiometer. However, in statistical representative sense, available data were not enough to show the feasibility of microwave remote sensing of humidity profiles and the retrieval accuracy.

Recently, we made some theoretical investigations and numerical experiments for the determination of the humidity profile by statistical simulation method (i.e., the Monte Carlo method), Xue Youngkang's work[5],[6] show that this method has an advantage in improving the retrieval accuracy and in revealing the fine structure of the humidity profile. Based on these researches, we developed a radiometer operating at 1.35 cm wavelength[7] and made field observations in Jan., Apr., Jul., Aug. and Oct. in 1982. The observations lasted for 7—10 days every month. Thus, systematic seasonal representive data were obtained. All data were processed by Monte Carlo method. In this paper the statistical error and some retrieved atmospheric precipitable water and humidity profiles are given. Some problems associated with the retrieval method and measurement accuracy are discussed. Besides, a preliminary analysis on the relationship between the humidity field and weather background is made.

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II. THE INSTRUMENT AND ITS CALIBRATION

The instrument we used is an impulse noise-input null-balanced Dicke type microwave radiometer. The block diagram and the fundamental specifications of the radiometer are shown in Fig. 1 and Table 1 respectively. (See reference [7] for technical details). The instrument was

Table 1. The Radiometer System Characteristics

Frequency	22.235 GHz ±200 MHz	
Antenna	Diameter	1.5 m
	Gain	> 35 db
	Main lobe	0.6 degree
	Sublobe level	< −20 db
Feed	Conical horn	
Total Noise Coefficient	9.4 db	
Intergral Time	3.3 second	
Resolution	$\Delta T_{min}=0.3$ K	

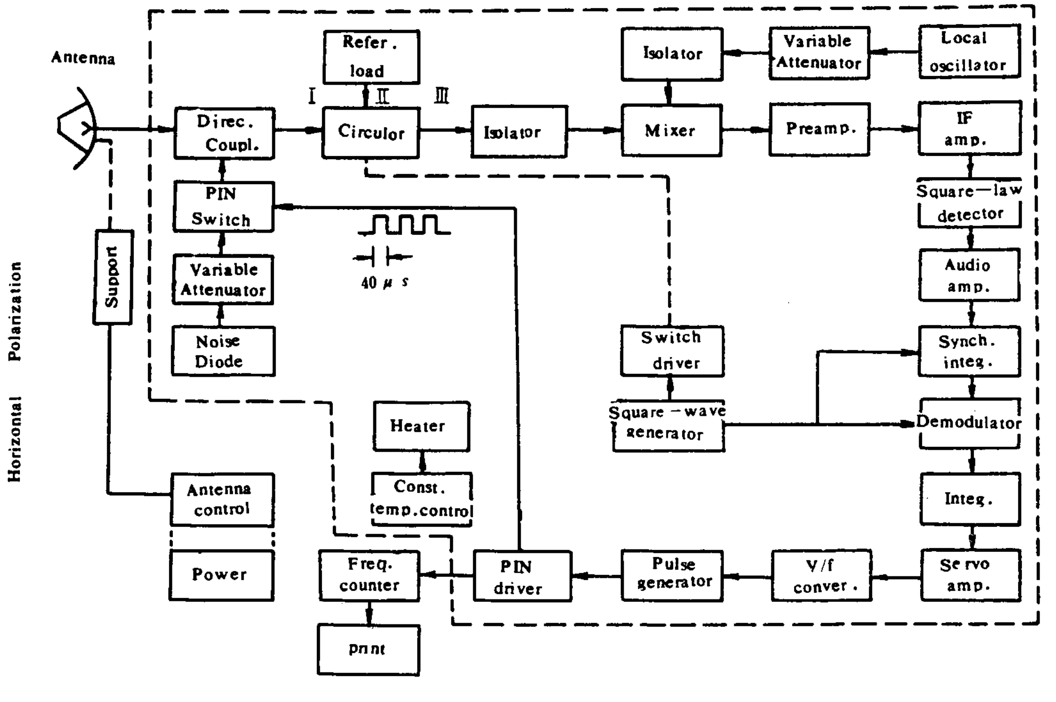

Fig. 1. The Block diagram of the radiometer.

calibrated either by a constant low temperature terminal load (liquid nitrogen of 77K) or by comparing the instrument reading with the brightness temperature calculated by the clear-air radiative transfer equation. The brightness temperature values used in our inversion were obtained by the latter method. The former was sometimes used to check and monitor the stability of the instrument when it was necessary.

Sixteen observation elevation angles were taken, ranging from 1 to 90 degrees. It is found that the accuracy of calibration is related to the region of elevations of calibration samples. The calibrated accuracy of the sample set at higher elevations is better than that at lower elevations. This is because the instrument error at higher elevations is less than that at lower elevations. However, in order to obtain a good inversion accuracy we must use the information at lower elevations. In consideration of the above mentioned factors, the elevations used in calibration are 10, 20, 15, 18, 20, 25, 30, 40, 60 and 90 degrees.

Multi-regression calibration formulae are used to convert the instrument reading to the brightness temperature

$$\hat{T}_b(\theta_i)=\sum_j C_{ij}f(\theta_j), \tag{1}$$

$$i=1,\ 2,\ \cdots\cdots,\ n \text{ and}$$
$$j=1,\ 2;\ \cdots\cdots,\ m,$$

where θ is the elevation, f instrument output, T_b the calibrated brightness temperature, $C_{i,j}$ the element of the coefficient matrix which is previously obtained by fitting calibration samples. More than 70 sets of data are calibrated this way, We compare the calibrated brightness temperature using the simultaneous radiosonde data on the basis of the radiation transfer equation. The average errors are given in Table 2.

Table 2. The Average Errors of Natural Calibration

Month	January	April	July	August	October	Average
Error K	1.28	1.62	1.90	3.65	3.66	2.89
No.of Examples	5	17	15	22	18	77

III. INVERSION METHOD

The detailed and systematic discussion about the inversion method has been given in References [5,6]. Here only a few problems are associated with the accuracy of the results, such as surface constraint condition, the first guess and the selection of observation angles, are briefly explained.

The ground-based microwave remote sensing equation for humidity of clear air is

$$T_b=\int_0^\infty e^{-\int_0^Z k_\lambda \sec\theta dz'} k_\lambda T \sec\theta\, dz, \tag{2}$$

where k_λ is the absorption coefficients of atmospheric gaseous constituents, T the atmospheric temperature profile. As the kernel function of the equation is closely related to the humidity profiles, this equation is a nonlinear Fredholm intergral equation. Rodgers[8] indicated that in order to obtain a useful solution, some constraints must be applied even if the equation was linear. We examined the correlation of channels and found that there were only a few pieces of indepentent information in the radiative measurements near the water vapor absorption line of 22.235 GHz. Obviously, in order to determine the humidity profiles we must provided some additional information on the radiative measurements. For the ground-based remote sensing the surface meteorological parameters can be used as the known conditions. Thus, in Monte-Carlo retrieving process the observed surface humidity is always regarded as the center of random sampling.

In addition, a first guess humidity profile is obtained from a given temperature profile by means of temperature-humidity regression matrix which is previously obtained from history radiosonde data classified monthly and in time sequence of sounding. Considering that there is a good relationship between the moistures in the lower and upper atmosphere, we construct a "factor" vector which combines the value of surface water vapor with the temperature vector, to predict the first guess humidity profile. In this way, the accuracy of first guess is largely improved. For instance, the r.m.s errors of the regression value of relative humidity obtained from the temperature radiosonde data of 19 LMT. of July, Beijing, are 0.115 and 0.131 for the cases with and without surface water vapor value, respectively.

It should be noted that in the numerical experiment, simulated observations of only two elevations were used, and the criterion was

$$\max_{i=1,2} |\tilde{T}_{bi} - T_{bi}| \leqslant \delta, \tag{3}$$

where $\tilde{T}_{bi}$ is the brightness temperature by random sampling, T_{bi} is that by measurement. However, taking into account the calibration and observation errors in the brightness temperature, we utilize the measurements of seven elevations, 15, 18, 20, 25, 30, 40 and 60 degrees, to retrieve the humidity profile. The corresponding criterion is

$$\sqrt{\frac{\sum_{i=1}^{7} (\tilde{T}_{bi} - T_{bi})^2}{7}} < \delta, \tag{4}$$

where δ is taken to be 3K

IV. MEASUREMENTS

In Jan., Apr., Jul., Aug. and Oct. in 1982, field observations were carried out for 7—10 days every month. The obtained data were divided into two kinds, one was known as comparison data which was obtained when radiosonde was releasing at the Beijing Meteorological Station (07, 13, 19 LMT), the other was taken in intervals of one or two hours during a day , which was called evolution data. The former had more than 70 cases while the latter was obtained only under some interesting weather conditions in July and August. The surface temperature and humidity were also measured by Assman psychrometer. All data were processed by Monte Carlo method. The results are analysed as follows:

1. *The Amount of Atmospheric Precipitable Water and its Temporal Evolution in Clear Day*

The amount of atmospheric precipitable water vapor is an important parameter not only to meteorology and weather forecast but also to radio astronomy and radio communication. Therefore, its measurement is of practical significance. Contrary to the method Hogg and others ultilized, we do not use the relationship between the radiative brightness temperature and total precipitable water but integrate the retrieved humidity profile over all altitudes. A comparison of total precipitable water between the radiometry measurements snd radiosonde is given in Fig. 2. The total precipitable water vapor ranges from 0.26 to 5.35 gram/cm, covering the range of humidity change during a year. The errors of retrieved total precipitable water are listed in Table 3. The correlation coefficient between the radiometry measurements and radiosonde is 0.99 Considering that the instrumental error of radiosonde in humidity measurement is about 3—10%[1)], we believe that the retrieved accuracy is satisfactory. For the data of April as it was quite dry in that month, the relative error is relatively large. However the rms error is quite small.

Table 3. Errors in Retrieved Precipitable Water

Month	January	April	July	August	October	Average
Total RMS Error (g/cm)	0.048	0.059	0.12	0.196	0.073	0.112
Relative Error (%)	6.0	9.3	3.5	5.5	2.4	5.3

For cases of temporal evolution of total precipitable water are given in Fig. 3, in which the curves show the measurements by radiometer and the triangles show those by radiosonde. Although these four cases are all in fine days, the surface weather charts show different weather situations: On 13 July a cold front was moving towards this station at 8 LMT a.m.; on 15 and 16 July the station was under the control of high pressure. In the morning of 18 Aug. this station was in the north—western air flow behind a cold front, then another cold front moved from the same direction to this station at 14 LMT, and at 17 LMT this cold front was close to the station. From Fig. 3 we can find that the temporal evolution of the total precipitable water under different weather conditions is different. Behind a cold front the total precipitable water tends to decrease, while before a cold front it tends to increase. When the high pressure controls this station, the total precipitable water is stable and slightly increases in the afternoon. The above preliminary analysis for a limited number of cases suggests that we will be able to develop some models about the relationship between total precipitable water and the weather background if the cases are much more. Furthermore, some characteristics of the evolution of precipitable water useful to weather forecast will be found. In Fig. 3(d) we can also see that the diurnal variation of the total precipitable water for a clear day can be quite large.

1)Liang Qixian, The comparison between Chinese and American operational sounding systems "59—701" and "VIZ 1292--GMD", Report at "Annual conference of Chinese Meteorology Society", 1982.

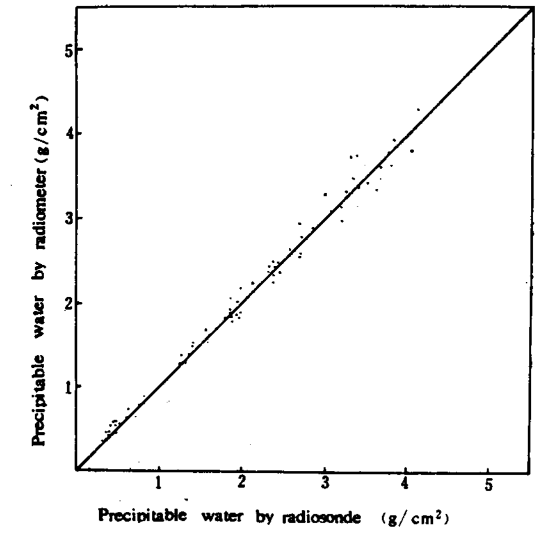

Fig. 2. Comparison of precipitable water between the radiometer measurements and radiosonde.

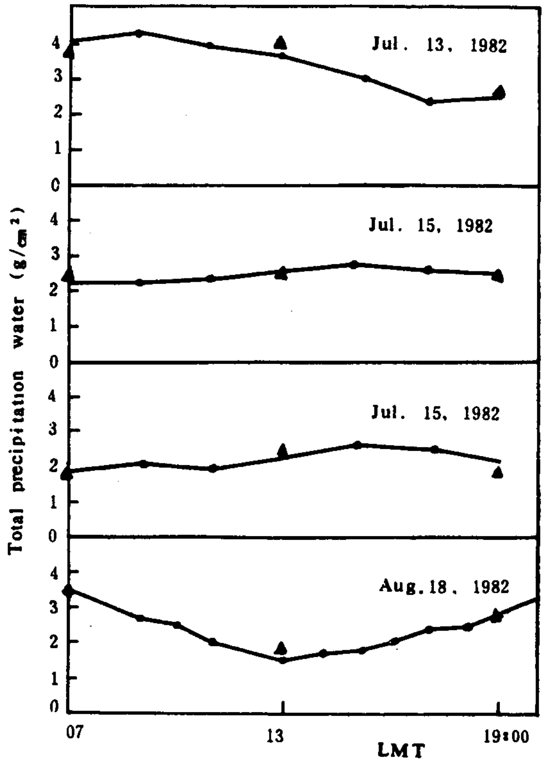

Fig. 3. Temporal evolution of total precipitable water.

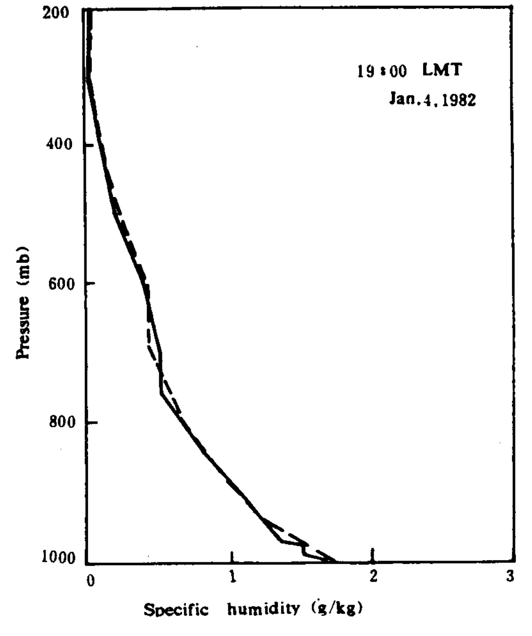

Fig. 4. An example of retrieval water vapor profiles.

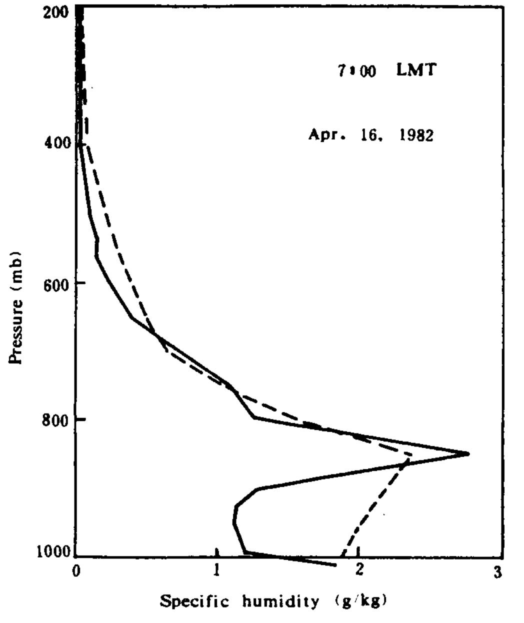

Fig. 5. An example of retrieval humidity profiles with an inversion.

2. *The Water Vapor Profiles and Its Temporal Evolution in Clear Day*

Shown in Table 4 are the statistical results of retrieved humidity profiles. It can be seen that the relative errors are less than 20% for the lower atmospheric layers (below 750 mb) and 30—50% for the upper layers (from 700 to 200 mb). Similar statistical results of the first guess are also shown in Table 5. A comparison between Table 4 and 5 indicates that the rms error of mixing ratio reduces by a factor of 1.5 at the altitude from 850 mb to 600 mb and by a factor of 1.25 from 500 mb to 400 mb. However, it reduces much less above 300 mb. These are consistent with the results of numerical experiment and show that retrieval accuracy of humidity profiles by Monte Carlo method is higher than that by regression method using radiosonde temperature profiles. In order to show the advantages of this method, two cases of retrieval profiles are given in Fig. 4, 5. Fig. 4 is a case in winter after a snow 19 LMT, Jan. 14, 1982. It is a typical case in which the retrieved profile duplicates radiosonde one. Shown in Fig. 5 is a case with humidity inversion. From Fig. 5 we can see that the Monte Carlo retrieval method is able to response the structure of humidity inversion. In our measurement there are twelve cases in which the structure of humidity inversion can be correctly reflected. They are about 31 percent of all cases in which humidity inversion structure is present. Although the humidity inversion structure can be reflected, the retrieval error for these cases is larger than that without himidity inversions. In the real atmosphere the cases with humidity inversion are about a half of total cases and this is one of the reasons why there are large errors at some altitudes.

Table 4. Errors of Retrieved Water Vapor Profiles

	Month	No. of Samp.	Pressure (mb)												
			1000	950	900	850	800	750	700	650	600	500	400	300	200
Relative Errors (%)	1	5	3.9	13.4	11.6	10.6	8.8	10.8	12.8	10.8	26.0	27.6	15.5	27.1	17.3
	4	17	10.8	25.8	26.1	31.4	15.7	16.1	18.3	23.7	46.6	54.6	25.1	46.7	75.6
	7	15	4.6	12.5	19.7	23.2	12.7	12.8	14.3	25.5	29.4	30.0	32.6	34.1	25.6
	8	22	3.1	14.4	16.4	14.4	12.5	16.8	28.9	39.6	59.8	57.2	43.6	39.0	35.5
	10	18	5.0	14.6	15.5	22.3	32.2	36.0	66.0	27.3	23.7	42.3	27.0	55.0	21.0
	Average (Total 77)		5.6	16.5	18.6	21.3	17.5	19.8	31.1	28.0	40.1	46.7	31.0	43.0	49.6
RMS Errors (g/kg)	1	5	0.10	0.343	0.225	0.179	0.123	0.151	0.119	0.126	0.220	0.087	0.020	0	0.014
	4	17	0.334	0.664	0.635	0.465	0.218	0.159	0.200	0.216	0.23	0.133	0.052	0.014	0.009
	7	15	0.571	1.13	1.98	1.55	0.81	0.66	0.71	1.00	0.74	0.40	0.177	0.070	0.09
	8	22	0.476	1.93	1.94	1.41	1.00	1.171	1.09	1.12	1.22	0.695	0.468	0.167	0.033
	10	18	0.60	1.32	1.06	1.13	0.87	0.74	0.93	0.48	0.599	0.236	0.087	0.043	0.005
	Average (total 77)		0.449	1.24	1.33	1.07	0.696	0.67	0.71	0.67	0.69	0.363	0.199	0.074	0.031

Table 5. RMS Errors of First Guess Profiles (g/kg)

Month	No.of Samp.	Pressure (mb)						
		850	700	600	500	400	300	200
1	5	0.504	0.424	0.093	0.062	0.023	0.007	0.033
4	17	0.95	0.42	0.31	0.16	0.074	0.014	0.01
7	15	1.43	1.34	1.10	0.64	0.24	0.076	0.04
8	22	2.07	1.76	1.64	0.84	0.58	0.18	0.08
10	18	1.43	1.11	1.18	0.24	0.109	0.039	0.004
Average (total 77)		1.45	1.14	1.03	0.46	0.26	0.079	0.036

Finaly, a temporal evolution of humidity profiles on 16 July 1982 is given in Fig. 6. On that day a high pressure controlled the ground surface, and there was a NW air flow on the isobaric surface of 500 mb. In Fig. 6 there is a 1.5 km thick humidity inversion in the afternoon which got stronger gradually and was strongest at 15 LMT and then was getting weaker and gradually dissipating. The tendency of the evolution of humidity profiles coincided with that shown by radiosonde data at 07, 13, 19, LMT, in which the humidity inversion formed at 13 LMT and dissipated at 19 LMT. All these indicate that the measurement by a radiometer can offer some information on the evolution of humidity profiles.

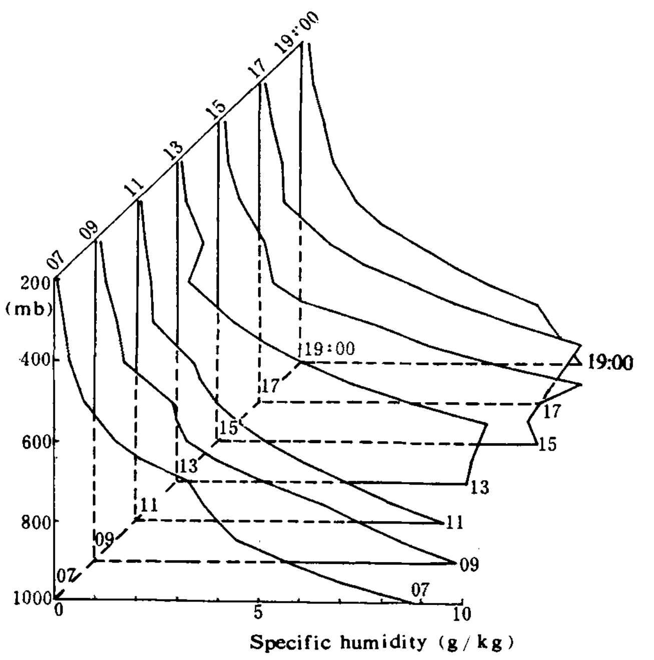

Fig. 6. An example of humidity profile evolution.

V. CONCLUSIONS

(1) The statistical results for more than seventy cases show that the RMS error of the retrieved total precipitable water compared with the radiosonde measurements is 0.11 g/cm and its relative error is 5.3%. For the determination of humidity profiles, the relative error is 20% in the lower atmospheric layers (below 750 mb) and 30—50% in the upper layers (above 700 mb). The Monte Carlo method does not require high measurement accuracy, and it is able to reflect the structure of humidity inversion, so that it is of value in practical application.

(2) The analyses of some cases indicate that temporal evolution of total precipitable water is related to weather background and the remote sensing of the temporal evolution of humidity profiles using a radiometer is possible. It is expected that when the interval of observation is reduced, the ground-based remote sensing can be applied to the study of the evolution of water vapor field in meso-and small-scale weather systems.

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