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A DUAL-FREQUENCY METHOD OF ELIMINATING LIQUID WATER RADIATION TO REMOTELY SENSE CLOUDY ATMOSPHERE BY GROUND-BASED MICROWAVE RADIOMETER

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Abstract—Ground-based microwave radiometer is the main device to remotely sense atmosphere passively which can detect the water vapor density, temperature, integral water vapor, etc. Because of the influence of cloud liquid water on the brightness temperature measured by microwave radiometer, the cloud needs to be modeled to retrieve the parameters of cloudy atmosphere. However, the difference between the cloud model and actual cloud may bring on some error in retrieval. Based on the relation between absorption coefficient of liquid water and frequency, a dual-frequency method of eliminating liquid water radiation which is not based on modeling cloud is put forward to retrieve the parameters of cloudy atmosphere. Historical radiosonde data are employed in the calculation of retrieval coefficients to profile the water vapor of cloudy atmosphere. The simulation and experiment results show that the dual-frequency method can eliminate the radiation of liquid water effectively and has a higher precision than conventional method. The integral water vapor in cloudy atmosphere is also retrieved by the dual-frequency method, and the precision is comparable with the method of modeling cloud.

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1. INTRODUCTION

Radiometer is investigated more and more for its wide application to meteorology, radar domination, navigation, etc. [1–15]. Ground-based microwave radiometer is the main device to remotely sense atmosphere passively which can detect the water vapor density, temperature, integral water vapor, etc.. For measurement in very dry conditions, typically in Arctic, several high frequency channels around water vapor line are added, and a 1-D variational retrieval technique has been developed [16–18]. Radiometer profiling during dynamic weather conditions is discussed and shows that the accuracy of radiometer retrievals is similar to radiosonde soundings when used for numerical weather prediction [19]. The method of artificial neural network is used in various fields [20–24]. Artificial neural network is increasingly used for its more accurate estimation of the atmospheric parameters in the case of strong nonlinearities [25–32]. A neural network is used to obtain vertical profiles of temperature from microwave radiometer data. In certain cases, such as one with a large temperature inversion, the neural network produces good reproductions of the profiles [26]. A 22-channel microwave radiometer for the profiling of tropospheric temperature, humidity, and cloud liquid water has been developed on the basis of artificial neural network which has 10 channels along the 22.235 GHz water vapor line, 10 channels along the 60 GHz oxygen complex, and 2 channels at 90 GHz [27]. A neural network algorithm for the radiometer data to retrieve atmospheric profiles has been developed for data feature extraction and dimensionality reduction [28]. The neural network combined with the natural orthogonal functions shows a good capability of exploiting information provided by other instruments, such as a laser ceilometer [31]. An algorithm that incorporates output from two retrieval techniques, namely, a physical-iterative approach and a computationally efficient statistical method, has been developed to retrieve atmospheric parameters [33]. An integrated profiling technique combined with cloud radar and ceilometer for the retrieval of the atmospheric parameters by radiometer is assessed [34]. Water vapor profiles that range from the earth's surface to the upper stratosphere at around 60 km have been measured by microwave radiometer and Raman lidar [35]. The combination of satellite and ground-based retrievals allows for a detailed assessment of complex cloudy atmosphere [36].

Generally, historical radiosonde data from certain locations are employed in the calculation of retrieval coefficients by various methods. Since there is no information of cloud in the radiosonde data, cloud models are inserted in radiosonde profiles [28, 30, 32, 37–40]. Due to the complexity of cloud, the cloud models may vary evidently from the actual cloud to bring on certain retrieval error.

Based on the relation between absorption coefficient of liquid water and frequency, a dual-frequency method of eliminating liquid water radiation which is not based on modeling cloud is put forward to retrieve the parameters of cloudy atmosphere. Historical radiosonde data of 10 years in Nanjing China station are employed in the calculation of retrieval coefficients to profile the water vapor of cloudy atmosphere. The simulation and experiment results show that the dual-frequency method can eliminate the radiation of liquid water effectively. So the error in modeling cloud can be avoided to improve the retrieval precision. The dual-frequency method is also applied to the retrieving of integral water vapor in cloudy atmosphere. Compared with the conventional method, the dual-frequency method omits the complicated process of modeling cloud yet without losing the retrieval precision.

2. THE DUAL-FREQUENCY METHOD OF PROFILING WATER VAPOR OF CLOUDY ATMOSPHERE

2.1. Theory Analysis

2.1.1. The Combination Form of Dual-frequency Attenuation

Ranging between 3 GHz and 34 GHz, the absorption coefficient of liquid water can be expressed as [41]:

$$\alpha_L = \exp\left[-6.866(1 + 0.0045t)\right] \cdot f^{1.95} \cdot M \tag{1}$$

where t denotes the temperature of the cloud liquid water, f the frequency, and M the liquid water content. By using (1), α_L can be written as a function of the height r and the frequency f:

$$\alpha_L(r, f) = coef(r) \cdot f^{1.95} \tag{2}$$

where $coef(r)$ represents the parameter related only with the liquid water at the height of r.

Without considering the scattering effect of atmosphere, the attenuation of zenith direction is expressed as:

$$\begin{aligned} \tau(f) &= \int_0^\infty \left[\alpha_L(r, f) + \alpha_a(r, f)\right] dr \\ &= \int_0^\infty \left[coef(r) \cdot f^{1.95} + \alpha_a(r, f)\right] dr \end{aligned} \tag{3}$$

where α_L denotes the absorption coefficient of liquid water and α_a denotes the absorption of atmosphere (including the absorption of oxygen and vapor). Establish the combination form of dual-frequency attenuation:

$$\begin{aligned}\tau(f_1,f_2) &= \tau(f_1)/f_1^{1.95}-\tau(f_2)/f_2^{1.95}\\ &= \int_0^{\infty}\left[coef(r)+\alpha_a(r,f_1)/f_1^{1.95}\right]dr-\int_0^{\infty}\left[coef(r)+\alpha_a(r,f_2)/f_2^{1.95}\right]dr\\ &= \int_0^{\infty}\left[\alpha_a(r,f_1)/f_1^{1.95}-\alpha_a(r,f_2)/f_2^{1.95}\right]dr \end{aligned} \tag{4}$$

Formula (4) has eliminated *coef* related with the liquid water. No matter what state the cloud is in the propagation path, the radiation of the cloud can be eliminated. So it can be set as an input when using statistical retrieval algorithm to profile the water vapor density. Establish the dual-frequency retrieval model of linear regression algorithm as an example:

$$H = a_0 + a_1P_0 + a_2T_0 + a_3H_0 + a_4\left[\tau(f_1)/f_1^{1.95}-\tau(f_2)/f_2^{1.95}\right] \tag{5}$$

where H denotes the water vapor density at different heights of the atmosphere. P_0, T_0, H_0 denote the pressure, temperature and water vapor density of ground, respectively, $\tau(f_1)$, $\tau(f_2)$ the attenuation at the given frequency of microwave radiometer, and a_0, a_1, a_2, a_3, a_4 the regression coefficients. To get the regression coefficients, we use the history radiosonde data (including sunny day and cloudy day) to calculate the attenuation, just considering the absorption coefficients of oxygen and vapor but the absorption coefficient of liquid water which can avoid modeling cloud.

Further more, we can establish the multi-frequency retrieval model which can also eliminate the radiation of the liquid water:

$$\begin{aligned}H &= a_0 + a_1P_0 + a_2T_0 + a_3H_0 + a_4\left[\tau(f_1)/f_1^{1.95}-\tau(f_2)/f_2^{1.95}\right]\\ &\quad +a_5\left[\tau(f_1)/f_1^{1.95}-\tau(f_3)/f_3^{1.95}\right]\dots \end{aligned} \tag{6}$$

Since the dual-frequency and multi-frequency retrieval model eliminate the radiation of the liquid water, the regression coefficients can be applied to the profiling of water vapor in cloudy atmosphere.

2.1.2. Mean Radiation Temperature of Cloudy Atmosphere

The attenuation of the cloudy atmosphere can be calculated by [38]:

$$\tau = \ln\left(\frac{T_m-2.73}{T_m-T_b}\right) \tag{7}$$

where T_b is the brightness temperature measured by microwave radiometer and T_m the mean radiation temperature of the cloudy atmosphere. T_m can be obtained by:

$$T_m = a_0 + a_1T_0 + a_2RH_0 \tag{8}$$

where T_0, RH_0 denote the temperature and relative humidity of ground respectively. For the sake of avoiding the complicated process of modeling cloud, the coefficients a_0, a_1, a_2 are regressed by history radiosonde data that only the absorption coefficients of oxygen and vapor are considered, but that of liquid water is not considered. The root mean square errors of calculating T_m at different frequencies using the radiosonde data of the years from 1986 to 1995 in Nanjing China station are obtained, as shown in Table 1.

Table 1. The rms errors of calculating T_m in cloudy atmosphere (K).

	23.8 GHz	26 GHz	28 GHz	30 GHz
error	2.5442	2.7805	3.1416	3.7520

The retrieval error source of dual-frequency method comes mainly from two aspects: the error of calculating T_m and the error of the retrieval algorithm.

2.2. Simulation

2.2.1. Linear Regression

The algorithm of linear regression (LR) is used to profile the water vapor density [31, 42]. 90% of the radiosonde data in June of the years from 1986 to 1995 in Nanjing China station are chosen to calculate the regression coefficients, and the remainder is used to evaluate the retrieval precision in cloudy atmosphere. 4 retrieval methods are compared.

Method 1: calculate the brightness temperature at 2 frequencies with the relative humidity 92% as a threshold of existing cloud liquid water. The regression formula is:

$$H = a_0 + a_1 P_0 + a_2 T_0 + a_3 H_0 + a_4 T_b(f_1) + a_5 T_b(f_2) \tag{9}$$

where H denotes the water vapor density at different heights of atmosphere. P_0, T_0, H_0 denote the pressure, temperature and water vapor density of ground respectively, and $T_b(f_1)$, $T_b(f_2)$ denote the brightness temperature at the frequencies of 23.8 GHz and 30 GHz of microwave radiometer. The atmosphere is divided into 47 layers of which the thick is 100 meters below 1 km, and 250 meters between 1 km and 10 km.

Method 2: calculate the attenuation at 2 frequencies with the relative humidity 92% as a threshold of existing cloud liquid water.

The regression formula is:

$$H = a_0 + a_1 P_0 + a_2 T_0 + a_3 H_0 + a_4 \tau(f_1) + a_5 \tau(f_2) \tag{10}$$

where $\tau(f_1)$, $\tau(f_2)$ denote the attenuation at the frequencies of 23.8 GHz and 30 GHz of microwave radiometer.

Method 3: dual-frequency method that calculates the attenuation at 2 frequencies without considering the absorption coefficient of liquid water. The regression formula is (5) where f_1 is 23.8 GHz and f_2 is 30 GHz.

Method 4: multi-frequency method that calculates the attenuation at 3 frequencies without considering the absorption coefficient of liquid water. The regression formula is (6) where f_1 is 23.8 GHz, f_2 is 30 GHz and f_3 is 26 GHz.

The next step is evaluating the retrieval precision in cloudy atmosphere. In view of the difference between the actual cloud and cloud model, calculate the brightness temperature and attenuation based on the remainder historical data with the relative humidity 85% as a threshold of existing cloud liquid water. The root mean square error of each sample is calculated as follows:

$$E_{\mathrm{RMS}} = \sqrt{\frac{1}{Q}\sum_{i=1}^{Q}\left(H^i_{\mathrm{Retr}} - H^i_{\mathrm{Radio}}\right)^2} \tag{11}$$

where Q is the total number of the layer, and H^i_{Retr}, H^i_{Radio} are water vapor density retrieved and measured respectively in the ith layer. The retrieval errors of different methods below 5 km are compared in Figure 1 where the ground-based microwave radiometer is sensitive to the atmosphere. The abscissa represents the difference between the actual liquid water amount and that of the cloud model, namely, the error of liquid water amount. It is seen that the retrieval errors of method 1 and 2 increase slowly along with the error of liquid water amount while the retrieval errors of dual-frequency and multi-frequency method are almost independent of the error of liquid water amount.

The retrieval errors of all methods below and above 5 km are shown in Tables 2 and 3. The precision of all methods are close to each other below 5 km when the error of liquid water amount is less than 3.5 mm, and the precision of dual-frequency and multi-frequency methods are higher than other methods below 5 km when the error of liquid water amount is more than 3.5 mm. All methods are relatively accurate above 5 km due to the large dependence on the ground meteorological data of retrieval precision above about 5 km.

To analyze the reason that the retrieval error of multi-frequency method is greater than dual-frequency method when the error of liquid

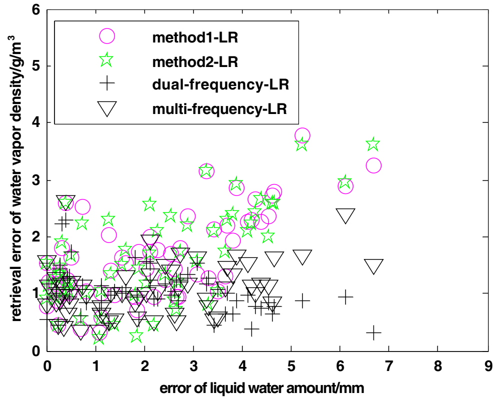

Figure 1. LR retrieval errors versus liquid water amount error below 5 km.

Table 2. Comparison of retrieval errors of water vapor density between all methods below 5 km (g/m^3).

	method 1	method 2	dual-frequency method	multi-frequency method
error of liquid water >= 3.5 mm	2.5301	2.5769	0.7447	1.3989
error of liquid water < 3.5 mm	1.3734	1.3525	1.1329	0.9782

Table 3. Comparison of retrieval errors of water vapor density between all methods above 5 km (g/m^3).

	method 1	method 2	dual-frequency method	multi-frequency method
error of liquid water >= 3.5mm	0.3517	0.6373	0.2551	0.5731
error of liquid water < 3.5 mm	0.4804	0.4674	0.4490	0.3184

water amount is more than 3.5 mm, the attenuation is calculated by using real T_m instead of the T_m calculated by ground meteorological data to profile the water vapor density. The retrieval errors are shown in Figure 2. The mean rms of the retrieval error of dual-frequency method is 1.0501 g/m^3 while that of multi-frequency method is 0.7700 g/m^3. So we conclude that the error of T_m and the more error items than dual-frequency method may cause greater retrieval error of multi-frequency method.

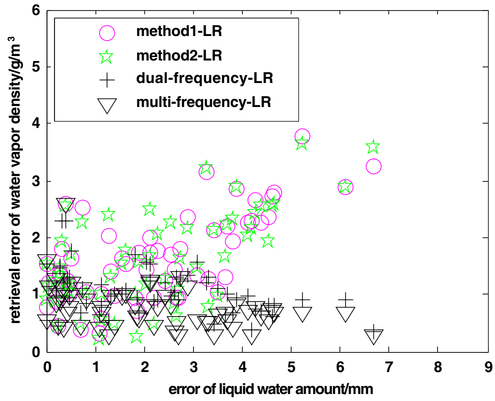

Figure 2. LR retrieval errors versus liquid water amount error below 5 km using real T_m.

The dual-frequency and multi-frequency methods have eliminated the liquid water radiation, so the error brought on by modeling cloud is avoided. In the actual atmosphere, the style of cloud can be much more complicated which will reflect the superiority of dual-frequency and multi-frequency methods even more.

2.2.2. Artificial Neural Network

Similarly, artificial neural network (ANN) is used to compare the dual-frequency method with the conventional method [26]. The training data are the same as those in Section 2.2.1. In the algorithm, the output is a weighted sum of its input. The weights are determined during the training process that adjusts the weights iteratively to reduce the difference between the actual output vectors and the estimated output vectors. For method 1, the input variables are:

$$input_1 = [P_0, T_0, H_0, \tau(f_1), \tau(f_2)] \tag{12}$$

where P_0, T_0, H_0 denote the pressure, temperature and water vapor density of ground, respectively, and $\tau(f_1)$, $\tau(f_2)$ denote the attenuation at the given frequency of microwave radiometer. For the dual-frequency method, the input variables are:

$$input_2 = \left[P_0, T_0, H_0, \tau(f_1)/f_1^{1.95} - \tau(f_2)/f_2^{1.95}\right] \tag{13}$$

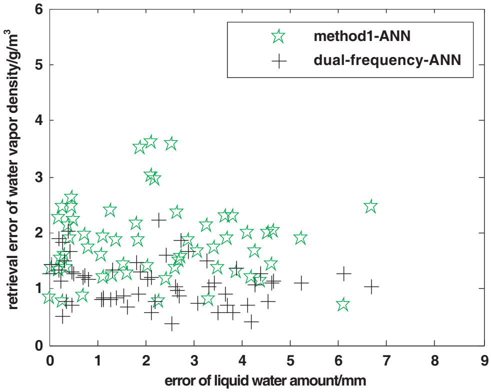

Figure 3. ANN retrieval errors versus liquid water amount error below 5 km.

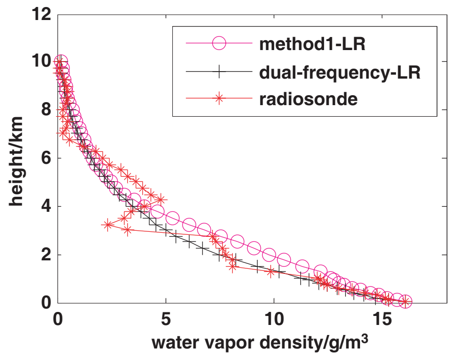

Figure 4. A typical sample of profiling the water vapor density.

The output vectors are the water vapor density at different heights of atmosphere. The retrieval errors of the two methods below 5 km are compared in Figure 3. It is seen that the retrieval errors of dual-frequency method are mainly less than that of method 1 due to eliminating the liquid water radiation.

2.3. Validation by Measured Data

An experiment was conducted in Nanjing in June 2007 by utilizing microwave radiometer combined with radiosonde. The central frequencies of the microwave radiometer are 23.8 GHz and 31.65 GHz. 11 samples of cloudy days were chosen to compare the retrieval errors of method 1 and dual-frequency method of linear regression below 5 km,

Table 4. Comparison of retrieval errors below 5 km between 2 methods of linear regression/g/m^3.

	retrieval errors of method 1	retrieval errors of dual-frequency method
2007.6.1pm	1.4402	1.3224
2007.6.3am	2.0949	1.8365
2007.6.3pm	2.1374	2.0593
2007.6.5am	1.9877	1.7468
2007.6.9pm	2.3388	2.4727
2007.6.18am	1.4909	1.3031
2007.6.26am	1.8703	1.6096
2007.6.14pm	1.6440	1.0126
2007.6.15am	1.6682	0.7051
2007.6.15pm	2.0739	1.1806
2007.6.26pm	1.3511	0.8479

as shown in Table 4.

From Table 4 we know that the advantage of dual-frequency method is not very evident for samples 1 to 7 because of the little liquid water in cloud. The last 4 samples are during heavy cloudy conditions, and the water vapor density profile retrieved by dual-frequency method has a better agreement with the radiosonde data. Figure 4 shows a typical sample at the night on June 14.

3. THE DUAL-FREQUENCY METHOD OF RETRIEVING INTEGRAL WATER VAPOR OF CLOUDY ATMOSPHERE

3.1. Theory Analysis

The path-averaged mass absorption coefficients of water vapor and liquid water are defined as follows [38]:

$$\bar{\alpha}_V = \frac{\int_0^\infty \alpha_{\text{vap}}(r)\rho_{\text{vap}}(r)dr}{\int_0^\infty \rho_{\text{vap}}(r)dr} = \frac{\tau_V}{V} \tag{14}$$

$$\bar{\alpha}_L = \frac{\int_0^\infty \alpha_{\text{liq}}(r)\rho_{\text{liq}}(r)dr}{\int_0^\infty \rho_{\text{liq}}(r)dr} = \frac{\tau_L}{L} \tag{15}$$

where ρ_{vap} and ρ_{liq} denote the water vapor mass density and the mass of liquid water per unit volume of cloud, respectively; α_{vap} and α_{liq} denote the unit density absorption coefficients of water vapor and liquid water, respectively; τ_V and τ_L denote the attenuation of water vapor and liquid water respectively; V and L denote the integral water vapor (IWV) and liquid water amount respectively. By using (14) and (15), total attenuation at the frequency f can be obtained:

$$\tau(f) = \tau_{dry}(f) + \tau_V(f) + \tau_L(f) = \tau_{dry}(f) + \bar{\alpha}_V(f)V + \bar{\alpha}_L(f)L \quad (16)$$

where τ_{dry} denotes the attenuation of oxygen. Two frequencies can be chosen to calculate V and L:

$$V = [\tau(f_1)\bar{\alpha}_L(f_2) - \tau(f_2)\bar{\alpha}_L(f_1) - \tau_{dry}(f_1)\bar{\alpha}_L(f_2) + \tau_{dry}(f_2)\bar{\alpha}_L(f_1)]D^{-1} \quad (17)$$

$$D = \bar{\alpha}_V(f_1)\bar{\alpha}_L(f_2) - \bar{\alpha}_V(f_2)\bar{\alpha}_L(f_1) \quad (18)$$

where τ_{dry} is regarded as a steady constant, and $\bar{\alpha}_V$, $\bar{\alpha}_L$ have no explicit dependence on the vertical distribution of water vapor and liquid water. So the integral water vapor can be written as follows:

$$V = a_0 + a_1\tau(f_1) + a_2\tau(f_2) \quad (19)$$

Calculate the ratio of a_1 to a_2 using (17) and (19):

$$\begin{aligned} a_1/a_2 &= -\bar{\alpha}_L(f_2)/\bar{\alpha}_L(f_1) = -\left[\tau_L(f_2)/L\right]/\left[\tau_L(f_1)/L\right] \\ &= -\int_0^{\infty} \alpha_L(r, f_2)dr \Big/ \int_0^{\infty} \alpha_L(r, f_1)dr \\ &= -\int_0^{\infty} coef(r) \cdot f_2^{1.95} dr \Big/ \int_0^{\infty} coef(r) \cdot f_1^{1.95} dr = -f_2^{1.95}/f_1^{1.95} \quad (20) \end{aligned}$$

The linear regress formula of dual-frequency method is as follows:

$$V = b_0 + b_1 \left[\tau(f_1)/f_1^{1.95} - \tau(f_2)/f_2^{1.95}\right] \quad (21)$$

Rewrite (21) as the format of (19):

$$\begin{aligned} V &= b_0 + b_1 \left[\tau(f_1)/f_1^{1.95} - \tau(f_2)/f_2^{1.95}\right] \\ &= b_0 + b_1/f_1^{1.95} * \tau(f_1) - b_1/f_2^{1.95} * \tau(f_2) = a_0 + a_1\tau(f_1) + a_2\tau(f_2) \quad (22) \end{aligned}$$

The ratio of a_1 to a_2 is:

$$a_1/a_2 = \left(b_1/f_1^{1.95}\right) / \left(-b_1/f_2^{1.95}\right) = -f_2^{1.95}/f_1^{1.95} \quad (23)$$

The result is the same as (20), from which we can see that (21) and (19) are equivalent essentially.

3.2. Simulation

To retrieve the integral water vapor of cloudy atmosphere, 90% of the radiosonde data in June of the years from 1986 to 1995 in Nanjing China station are chosen to calculate the attenuation, and the remainder is used to evaluate the retrieval precision in cloudy atmosphere. Three retrieval methods are compared.

Method 1: calculate the attenuation at 2 frequencies without considering the absorption coefficient of liquid water. The regression formula is (19).

Method 2: calculate the attenuation at 2 frequencies with the relative humidity 92% as a threshold of existing cloud liquid water. The regression formula is (19).

Method 3: dual-frequency method that calculates the attenuation at 2 frequencies without considering the absorption coefficient of liquid water. The regression formula is (21).

For comparison, the regression coefficients of above 3 methods are listed in Table 5. It is seen that the regression coefficients of method 2 are close to that of dual-frequency method.

Table 5. Comparison of regression coefficients between different methods.

	Method 1	Method 2	Dual-frequency
a_0	-2.9106	0.8323	0.6956
a_1	155.8181	231.6546	231.8999
a_2	55.3553	-148.0297	-147.0379
a_1/a_2	2.8149	-1.5649	-1.5771

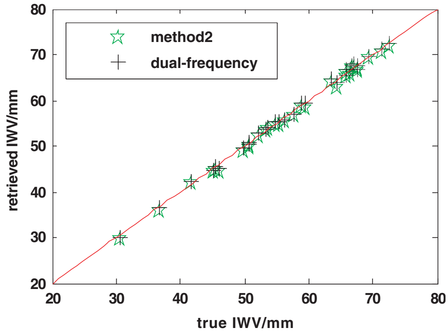

Figure 5. Scatterplot of retrieved integral water vapor versus actual IWV for the test dataset.

To evaluate the retrieval precision of cloudy atmosphere, calculate the attenuation based on the remainder historical data with the relative humidity 85% as a threshold of existing cloud liquid water. 30 samples are chosen as shown in Figure 5. The mean rms errors of method 2 and dual-frequency method are 0.9021 mm and 0.5402 mm, respectively, which are comparable.

4. CONCLUSION

The dual-frequency method which is not based on modeling cloud can eliminate the radiation of liquid water effectively. So it can avoid the error brought on by modeling cloud to improve the retrieval precision when profiling the water vapor of cloudy atmosphere. The integral water vapor of cloudy atmosphere can be also retrieved by dual-frequency method which is demonstrated in theory, and the retrieval precision is comparable with the method of modeling cloud. Similarly, certain frequencies can be chosen for the radiometer data to retrieve relative humidity, temperature, etc. based on the absorption characteristics of atmosphere at different frequencies. Furthermore, other retrieval techniques can be used to validate the dual-frequency method.

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