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Retrieving Cloudy Atmosphere Parameters from RPG-HATPRO Radiometer Data

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Abstract—An algorithm for simultaneously determining both tropospheric temperature and humidity profiles and cloud liquid water content from ground-based measurements of microwave radiation is presented. A special feature of this algorithm is that it combines different types of measurements and different a priori information on the sought parameters. The features of its use in processing RPG-HATPRO radiometer data obtained in the course of atmospheric remote sensing experiments carried out by specialists from the Faculty of Physics of St. Petersburg State University are discussed. The results of a comparison of both temperature and humidity profiles obtained using a ground-based microwave remote sensing method with those obtained from radiosonde data are analyzed. It is shown that this combined algorithm is comparable (in accuracy) to the classical method of statistical regularization in determining temperature profiles; however, this algorithm demonstrates better accuracy (when compared to the method of statistical regularization) in determining humidity profiles.

Keywords: atmosphere, microwave sounding, troposphere, temperature, humidity, atmospheric optics

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INTRODUCTION

Progress in technology has led to the commercial production of compact-size high-precision ground-based microwave instruments for remote sensing of the atmosphere in automatic mode. Foreign manufacturers Radiometer Physics GmbH [1] and Radiometrics [2] can be given as an example. In the Russian Federation, an automated temperature profiler (MTP-5) to sound the atmospheric boundary layer [3] has been developed and certified and a multichannel microwave radiometric complex (its patent name Mikroradkom) has been developed to continuously and automatically measure temperature profiles in the troposphere and both integral water-vapor and liquid-water contents in clouds [4]. An international network that unites researchers using ground-based microwave instruments for atmospheric remote sounding has been organized [5]. One of the actual problems is the development of an optimal standard procedure of processing ground-based microwave measurements in order to obtain homogeneous data series at the observation network of microwave radiometers, which is being set up now [6].

In 2012, at the Faculty of Physics, St. Petersburg State University (SPbSU), scientists started to use a RPG-HATPRO microwave radiometer (a humidity and temperature profiler manufactured by the German Radiometer Physics GmbH company) [1]. This radiometer has seven channels within the oxygen absorption band and seven channels within the water-vapor absorption line (1.35 cm); this instrument is designed to determine both temperature and humidity profiles in the troposphere and cloud liquid-water content in automatic continuous mode. Both temperature and humidity profiles and cloud liquid-water content have been determined at SPbSU since 2012 (when this radiometer was put into operation) with the aid of software (given by the HATPRO instrumentation manufacturer) based on the square-regression method. The results of a comparison between tropospheric temperature profiles determined on the bases of this software and radiosounding data obtained at the Voeikovo station (at a distance of 50 km from the point of the experiment) showed that the accuracy in determining temperature profiles on the basis of radiometer data is inadequate [7]. In connection with this, at present, two data-processing methods are being developed: the regression method and the so-called physical method based on the linearization of the microwave radiative transfer equation and on the construction of inverse operator. Let us emphasize that, unlike the regression method used by the designers of this instrumentation, in the regression method under development the solution operator is constructed directly on the basis of measurement results corresponding to radiosonde data instead of model calculation results.

In this work, (1) a physicomathematical formulation of the problem of simultaneously determining cloudy atmosphere parameters, which is based on the inversion of the linearized equation of radiative transfer, is given (its special feature is the use of additional measurements and a priori information of different types); (2) a procedure of adjusting an algorithm for integrated HATPRO data processing is described; (3) both accuracy and vertical-resolution estimates in determining both temperature and humidity profiles from HATPRO data are given; (4) both temperature and humidity profiles obtained from ground-based microwave measurements and from radiosounding are compared; and (5) the accuracies of the combined algorithm and the classical method of statistical regularization are analyzed.

Data obtained from measurements of downwelling microwave radiation only in the zenithal direction without angular scanning are considered in this work. Such an approach does not require using the approximation of horizontal atmospheric homogeneity, which cannot be valid under various real atmospheric conditions.

A PHYSICOMATHEMATICAL FORMULATION OF THE PROBLEM

The brightness temperature T_B recorded in the spectral channels of the HATPRO radiometer is determined from the equation of microwave radiative transfer, which can be written in the form of the following nonlinear functional F:

$$T_B(\nu) = F_\nu\left[T(z), p(z), q(z), w(z)\right], \tag{1}$$

where ν is the channel center frequency; z is height; and $T(z)$, $p(z)$, $q(z)$, and $w(z)$ are the vertical profiles of temperature, pressure, absolute humidity, and cloud liquid-water content, respectively (these parameters are to be retrieved).

In the finite-dimensional vector-matrix representation, the total vector of variations in the parameters to be retrieved with respect to their means is written in the following form:

$$\begin{aligned} &\delta\mathbf{x}^+ \\ &= (\delta T(z_1), \delta T(z_2), \ldots, \delta T(z_L), \delta p(z_1), \\ &\quad \delta p(z_2), \ldots, \delta p(z_L), \\ &\quad \delta q(z_1), \delta q(z_2), \ldots, \delta q(z_L), \delta w(z_1), \\ &\quad \delta w(z_2), \ldots, \delta w(z_L)), \end{aligned} \tag{2}$$

where z denotes altitudinal levels numbered from 1 to L, δ denotes variation, and "+" denotes transposition. If it is necessary that the algorithm for solving the inverse problem should include (in addition to microwave measurement data) different types of information on atmospheric parameters (a priori statistical data, independent measurement results, physical relations between these parameters, and physical limits on obtained values), it is convenient to represent this information as a set of independent "virtual" measurement data. In this case, the problem under consideration is formulated in the form of the following system of the vector-matrix equations:

$$\begin{cases} \delta\mathbf{r}_1 = \mathbf{C}_1\delta\mathbf{x} \\ \delta\mathbf{r}_2 = \mathbf{C}_2\delta\mathbf{x} \\ \ldots\ldots\ldots\ldots \\ \delta\mathbf{r}_N = \mathbf{C}_N\delta\mathbf{x}. \end{cases} \tag{3}$$

Here, the first equation is a vector-matrix analog of the linearized equation of microwave radiative transfer, and the following N-1 vector-matrix equations describe (in linearized form) additional measurements of the atmospheric parameters or additional conditions imposed on them in the form of virtual measurements. The vector $\delta\mathbf{r}_1$ is the vector of variations in brightness temperature with respect to its means calculated on the basis of mean profiles of atmospheric parameters and $\mathbf{C}_1$ is the linearized integral operator of the forward problem of microwave radiative transfer, which is formed from weighting function values with the corresponding quadrature coefficients. The vectors $\delta\mathbf{r}_2$, $\delta\mathbf{r}_3$, etc., are the vectors of variations in the results of virtual measurements with respect to their means and $\mathbf{C}_2$, $\mathbf{C}_3$, etc., are the linearized operators that describe virtual measurements. Such a comprehensive approach (with the use of different additional conditions in the form of virtual measurements) to the solution of the inverse problem has successfully been used in interpreting satellite data on outgoing radiation measured with CRISTA instruments [8] and ground-based data obtained with a microwave ozonometer in the region of an ozone-absorption line of 110 GHz [9, 10]. Formally, one can combine the results of all measurements (including virtual ones) into a single vector and, correspondingly, use a combined matrix of linearized measurement operators. However, we will not use such a combination to make analyzing contributions by the measurements and a priori information of different kinds easier.

The solution of system of equations (3) on the basis of the method of least squares in the iterative process is written in the form

$$\begin{aligned} \mathbf{x}_{k+1} &= \mathbf{x}_m + \left(\sum_{i=1}^{N}\mathbf{C}_{ik}^{+}\mathbf{E}_i^{-1}\mathbf{C}_{ik}\right)^{-1} \\ &\times\left[\sum_{i=1}^{N}\mathbf{C}_{ik}^{+}\mathbf{E}_i^{-1}\left(\mathbf{r}_i - \mathbf{r}_{ik} + \mathbf{C}_{ik}(\mathbf{x}_k - \mathbf{x}_m)\right)\right], \end{aligned} \tag{4}$$

where k is the iteration number, i is the identifier of the type of measurements (including virtual ones), m is the parameter mean, $\mathbf{E}_i$ denotes the matrices of errors of measurements (including virtual ones), $\mathbf{r}_{ik}$ denotes the results of applying nonlinearized measurement operators to solution values obtained at the kth step of the iteration process, and $\mathbf{C}_{ik}$ denotes the linearized operators calculated on the basis of solution values obtained at the kth step. The estimates of errors in determining the sought-for parameters at different heights yield the diagonal matrix elements:

$$\mathbf{F} = \left(\sum_{i=1}^{N} \mathbf{C}_i^{+} \mathbf{E}_i^{-1} \mathbf{C}_i \right)^{-1}. \tag{5}$$

The method of estimating the information content of measurements in solving inverse problems of remote sounding, which is based on an analysis of the so-called averaging kernels, is extensively used now [11]. In the problem statement under consideration, the expression for the matrix of averaging kernels (averaging operator) has the following form:

$$\mathbf{A}_{(a_1,a_2,\ldots)} = \left(\sum_{i=\mathbf{1}}^{N} \mathbf{C}_i^{+} \mathbf{E}_i^{-1} \mathbf{C}_i \right)^{-1} \left(\sum_{i=(a_1,a_2,\ldots)} \mathbf{C}_i^{+} \mathbf{E}_i^{-1} \mathbf{C}_i \right), \tag{6}$$

where the set of the indices (a_1, a_2,...), according to which summation is performed in the second brackets, corresponds to the types of measurements (including virtual ones), for the combination of which the matrix of averaging kernels is calculated. In determining height profiles, the physical meaning of the averaging operator is in the fact that each of its columns shows how a local parameter variation at the corresponding height level is smoothed due to the use of the inverse operator that includes the measurements of the (a_1, a_2,...) types.

Since the problem formulated is multiparametric and the vector of the parameters to be retrieved is compound, the averaging operator will have a block structure. Below we will consider the diagonal blocks of the averaging operator as individual matrices corresponding to each of the parameters to be retrieved: temperature, pressure, absolute humidity, and cloud liquid-water content. For these blocks, one can calculate the number of the degrees of freedom for signal (DOFS) as a trace of the matrix corresponding to the block and the value of vertical resolution in determining the value of a parameter at the given height z_i as a height range $z_i \pm \Delta z$ for which the sum of the corresponding diagonal elements of the matrix block is approximately equal to one.

Some detailed examples of such calculations in analyzing the informativeness of different problems of atmospheric remote sounding can be found in [12–14].

The classical statistical-regularization method (known in English literature as the optimal estimation method) widely used in solving improperly posed inverse problems can be represented as a special case of the above physicomathematical formulation; in this case, the total number of measurement types is two (microwave measurements and a priori statistical information as virtual measurements), the linearized operator of virtual measurements is unit ($\mathbf{C}_2 = \mathbf{I}$), and the corresponding error matrix is a covariance matrix of the parameters to be retrieved.

FEATURES OF ALGORITHM TUNING

The algorithm was tuned in several steps:

1. Models of the physical state of the atmosphere were constructed for numerical experiments. These models included both profiles of parameters with constant altitudinal gradients and with inversions. Both cloud and cloudless situations were simulated.

2. In the course of numerical experiments according to a closed-loop scheme (an initial atmospheric model—calculating brightness temperature in radiometer channels—solving the inverse problem—comparing the results with data of the initial model), the virtual-measurement parameters that provide minimum errors, solution stability, and a stable convergence of the iterative process were selected.

3. On the basis of the results of a comparison between brightness temperature data calculated from radiosonde measurements under the conditions of a stable cloudless atmosphere and obtained from synchronous microwave measurements, the center frequencies of the spectral channels of the HATPRO radiometer (installed at the SPbSU) were corrected.

The characteristics of the measurements (including the virtual ones), which were considered in solving the inverse problem of temperature–humidity sounding, are given in Table 1. In addition to the results of measurements in 14 channels of the HATPRO radiometer, we also considered (as actual) temperature, pressure, and relative humidity data obtained from measurements with meteorological sensors attached to the radiometer. The values of errors of actual measurements are declared by the manufacturer of the instrumentation. The rest of the data given in Table 1, which refer to the virtual measurements, require explanations. The specified variability of temperature and absolute humidity exceeds their statistical values a few times, and there is no correlation between their values obtained at different heights. Thus, the situation of the absence of a priori statistics was simulated. The problem of determining the profile of the liquid-water content of clouds was not stated; only their total water reserve, which is equal to the profile integral, was analyzed. The height range for the liquid-water content profile was taken equal to 0.5–7 km. The main a priori constraint was the condition of profile smoothness. The derivatives of the profiles of temperature and absolute humidity with respect to height were taken equal to the derivatives of their mean profiles. The values of errors in the corresponding virtual measurements were chosen according to the results of numerical experiments. The inclusion of relative humidity into a set of virtual measurements and variability constraints seems natural. The values of its mean and rms deviation were selected according to the results of numerical experiments, and the absence of negative values of relative humidity and its values exceeding 100% was a selection criterion. Taking into account the condition of hydrostatic equilibrium is also natural. The formula for the operator of the corresponding

Table 1. Characteristics of measurements (including virtual ones) considered in solving the inverse problem

Number	Type	Measured parameter	Errors (rms deviation values)
		Actual measurements	
1	Microwave measurements	Brightness temperature	0.1 K for humidity spectral channels, 0.2 K for temperature channels
2	Surface sensor data	Temperature, pressure, and relative humidity	1.0 K, 1 mb, and 5% for temperature, pressure, and relative humidity, respectively
		Virtual measurements	
3	Variability of parameters	Temperature, pressure, absolute humidity, and liquid-water content of clouds	25 K, 3%, 1000%, and 100% for T, p, q, and w, respectively
4	Profile smoothness	Temperature and absolute humidity derivatives with respect to height	6 K/km and 70%/km for dT/dz and dq/dz $(100/q)$
5	Variability of relative humidity	Relative humidity	50% (at a mean relative humidity of 50%)
6	Hydrostatic equilibrium	Pressure	0.01–0.2% (of the values corresponding to hydrostatic equilibrium)

virtual measurements can be found in [10]. The physical meaning of errors in these virtual measurements is an expected difference between pressure values obtained for the given height from the solution of the inverse problem and from calculations according to the hydrostatic equation on the basis of pressure and temperature at the rest of the heights.

ACCURACY, HEIGHT RANGE IN DETERMINING THE PARAMETERS, VERTICAL RESOLUTION

Figure 1 shows the errors in determining both temperature and humidity profiles, which were obtained from calculations of the error matrix **F** (Eq. (5)).

The values of the a priori uncertainty of the parameters, which are given for comparison in Fig. 1, require additional explanations. When using the traditional method of statistical regularization, as an a priori uncertainty, it is common practice to take the value of the rms deviation from a parameter's mean at different heights, which is determined as a square root of the corresponding diagonal elements of the covariance matrix. In the case under consideration, when several a priori constraints of different types are present in estimating the a priori uncertainty of the parameters, one should consider the whole set of these constraints, namely, the error matrix (instead of the statistical covariance matrix) calculated with consideration for only the results of virtual measurements, which was done in this work. It is easy to see that, if there is only one constraint and this constraint is determined by a priori statistics, the error matrix for the virtual measurements coincides with the a priori covariance matrix.

The values of errors in determining temperature amount to less than 2 K up to a height of 2 km, 2–3 K at heights of 2–6 km, and 3–4 K at heights of more than 6 km. The local minimum of errors in determining humidity at the land surface is explained by precise measurements with humidity sensors. It follows from Fig. 1c that the relative error in measuring absolute humidity does not exceed 20% and 30% up to heights of 2 and 5.5 km, respectively.

Figure 2 shows the vertical resolution in determining the profiles. On the basis of the given data, one can differentiate individual altitudinal layers in which the means of the atmospheric parameters are independently determined. Let us consider temperature as an example. At a height of 0.6 km, $\delta z = 0.8$ km. It follows from this that one can determine a layer within which the mean temperature is retrieved independently of other layers as $0.6 \pm \delta z/2$, i.e., 0.2–1.0 km. One can determine the next layer within a height range of 1.0–5.0 km $(3.0 \pm 4/2)$, because the resolution is 4 km at a height of 3 km. For the profile of humidity, the troposphere may similarly be divided into layers. As for the water-content profile, one can differentiate two layers: 0–4.0 km (the resolution is about 4 km at a height of 2 km) and 4.0–7.0 km (the resolution is about 3 km at a height of 5.5 km). This suggests that the results of microwave measurements contain not only data on the integral liquid-water content of clouds, but also some amount of data on the vertical water-content distribution.

Table 2 gives the DOFS values for microwave measurements (approximate estimates of the number of

Table 2. DOFS values for microwave measurements (approximate estimate of the number of independently determined profile parameters)

Calculation conditions (see the text)	Temperature	Absolute humidity	Liquid-water content of clouds
A1	2.4	2.3	1.9
A2	4.1	3.9	1.3

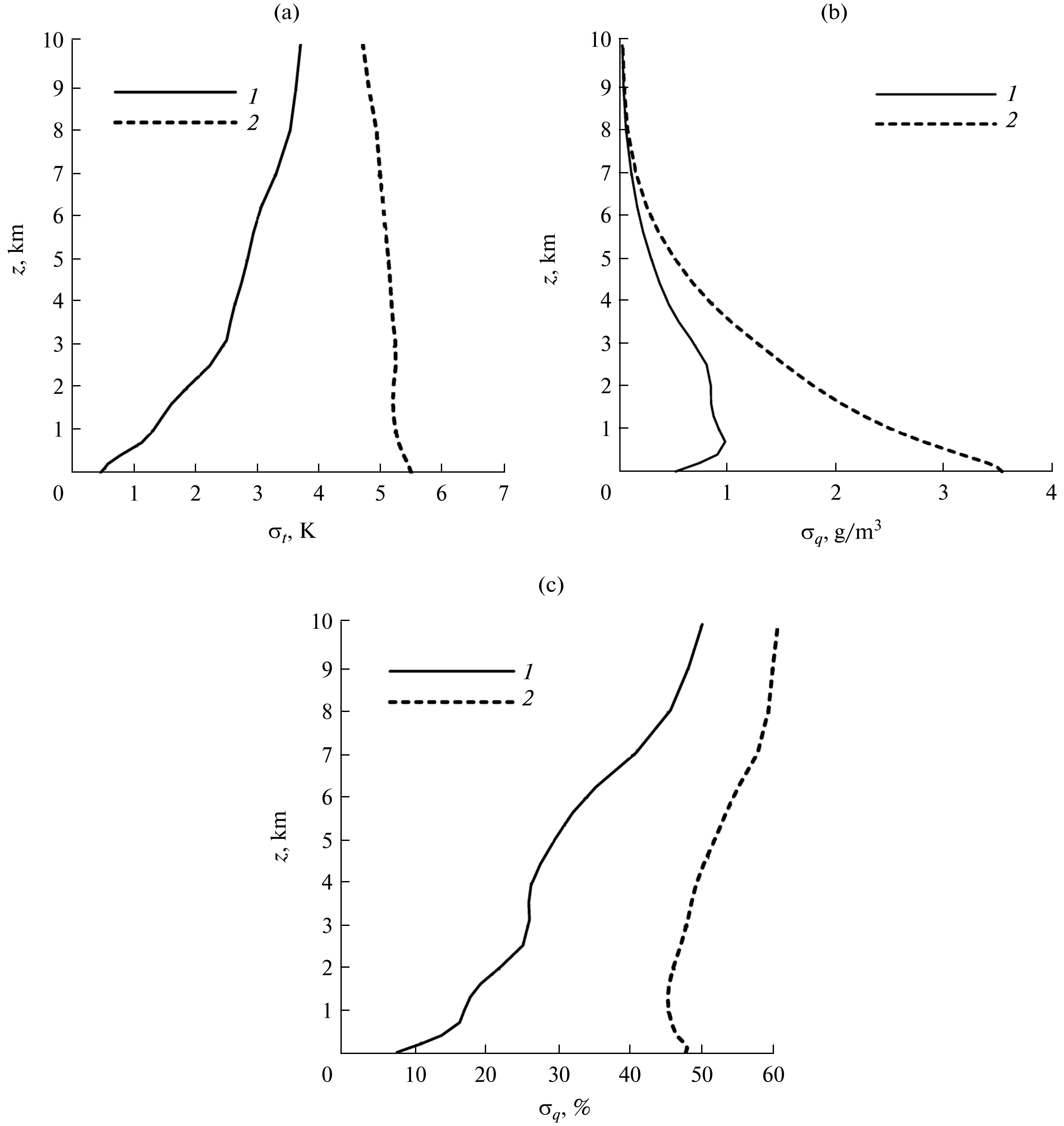

Fig. 1. Error estimates (curves *1*) in determining the profiles of (a) temperature, (b) absolute humidity, and (c) absolute humidity expressed in percent with respect to the used mean profile. Curves *2* correspond to the values of a priori uncertainty.

independently determined profile parameters). The A1 calculation conditions corresponded to the whole set of both actual and virtual measurements. For all physical quantities, the number of parameters independently determined from microwave measurements is 2. If the results of measurements with surface sensors, which are independent of microwave measurements, are taken into consideration, we will obtain three determined parameters individually for temperature and humidity, i.e., in the fourth upper layer, the result is determined mainly from virtual measurements. The A2 calculation conditions simulate the classical scheme “microwave measurements plus a priori statistical information” (only the measurements of types 1 and 3 from Table 1 are taken into account). These calculation conditions show the limiting informative capacity of microwave measurements, because in our case the constraints imposed by the virtual measurements of type 3 on the profiles (see Table 1) are very weak. We see that the potentialities of the microwave measurements under consideration (without using outside information) imply that the four parameters of both temperature and humidity profiles and one parameter for the water content, i.e., the integral liquid-water content of clouds, are independently determined. Let us emphasize that there is no disagreement between the DOFS values calculated under the two calculation conditions: using additional information in the form of virtual temperature and humidity measurements decreases the informative contribution of microwave measurements to the determination of temperature and humidity (DOFS values decrease for temperature and humidity); however, on the whole, it increases the accuracy of their determination. Both the vertical-resolution and DOFS estimates obtained are close to those given by other authors, in particular, the DOFS values amount to about 4 and 2 for temperature and humidity, respectively, in [15], and a significant decrease in vertical resolution with height and its low values even in the atmospheric boundary layer (at a height of 400 m, the resolution is 300 m) are shown in [16].

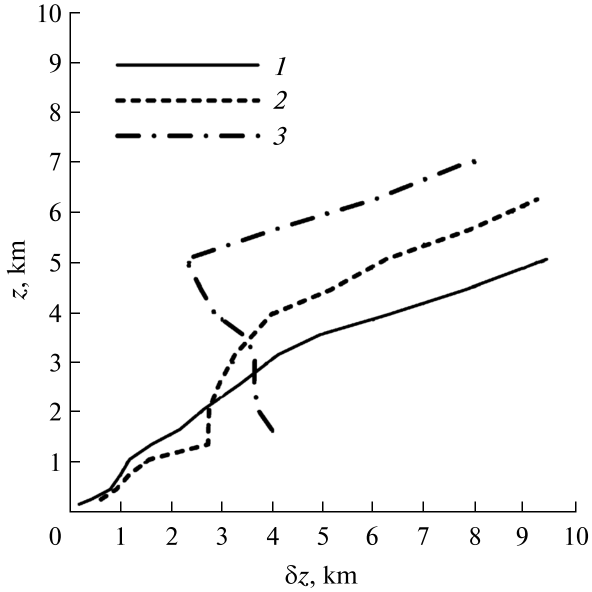

Fig. 2. Estimates of the vertical resolution δz in determining the profiles of (*1*) temperature, (*2*) absolute humidity, and (*3*) liquid-water content of clouds.

EXAMPLES OF PROCESSING EXPERIMENTAL DATA

In order to test the described algorithm under significantly different (cold and dry and warm and humid) atmospheric conditions, we selected the results of microwave measurements taken over 2 months (March and September 2013). To analyze the accuracy in determining the profiles of temperature and humidity, the results of microwave measurements were taken synchronously with the daytime launching of radiosondes from a radiosounding station in the village of Voeikovo (Leningrad oblast). Because of a significant spatiotemporal variability of cloudiness characteristics, the validation of the algorithm in determining the liquid-water content of clouds is a separate difficult task beyond the scope of this work. Nevertheless, a qualitative agreement was observed between liquid-water content data obtained with the aid of the described combined algorithm and with the aid of the regression algorithm of the instrumentation designer (the quantitative disagreement varied from a few percent to a few tens of percent). When comparing with radiosonde data on temperature and humidity at a given height, we use the following three characteristics: the mean disagreement M, the rms disagreement S, and the standard deviation from the mean disagreement σ, which characterize systematic, total, and random errors (by analogy with [7], in which one can find the corresponding formulas). Figure 3 shows the height dependence of these characteristics. The systematic error (in absolute value) of temperature profiles may reach 3 K for March and September 2013.The most probable cause of significant systematic errors is apparently a residual uncertainty in the frequencies of the temperature channels of the instrument after their correction. The total and random errors in determining the profiles of temperature are somewhat smaller for September than for March.

The errors in determining relative humidity for September are significantly smaller than those for March. In September, the mean disagreement in absolute value throughout the entire height range (except for a narrow region below 0.6 km) does not exceed 10%. In March, the values of M for relative humidity exceed (in absolute value) 10% starting from a height of 2.5 km. The total error in determining relative humidity for September amounts, on average, to about 15% throughout the entire height range, while that for March it amounts to about 20%. However, the random error for March amounts, on average, to 15%, which is close to that for September.

Let us compare between the results obtained using the combined algorithm and the classical method of statistical regularization. The mean profiles and covariance matrices of temperature, pressure, and absolute humidity (which are necessary for the statistical-regularization method) and their corresponding cross-covariance matrices were calculated on the basis of radiosonde data obtained at the Voeikovo station in March and September 2013 (all in all, 119 radiosonde launchings). The comparison results are given in Figs. 5 and 6 for September and March 2013, respectively, in terms of the disagreement characteristics M and S (systematic and total errors). In addition to the results obtained individually using the combined algorithm (CA) and the statistical-regularization method (SRM), the results obtained from their joint use (CA + SRM) are also shown. The distinctive features of these methods are given in Table 3.

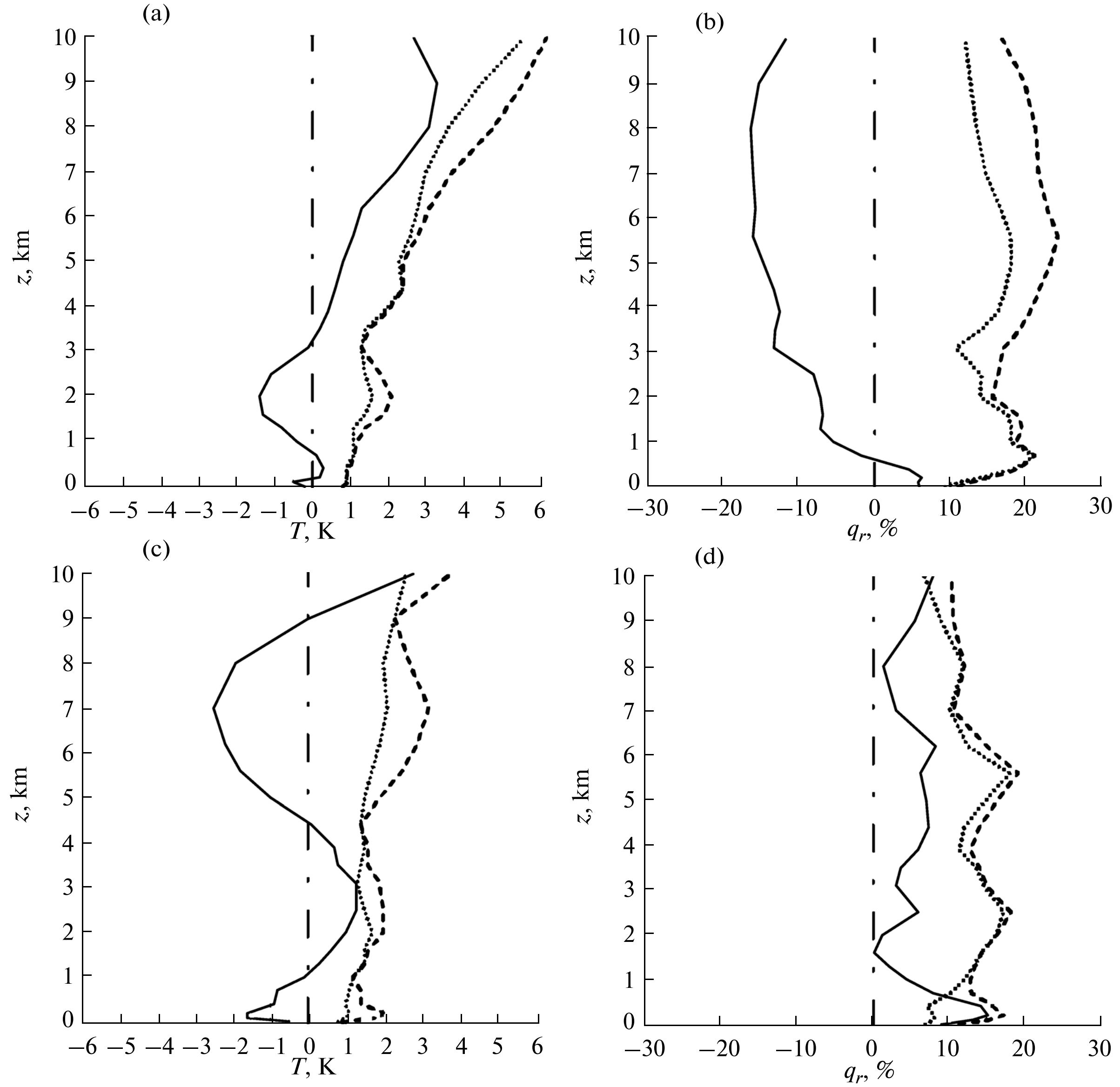

Fig. 3. Characteristics of disagreement between the results of microwave and radiosonde measurements of the profiles of temperature T and relative humidity q_r for March (top) and September (bottom) 2013: M (solid line), S (dashed line), and σ (dotted line).

In determining the profiles of temperature within a height range of 5–10 km for March, the SRM provides better accuracy. The opposite situation is observed for the profiles of absolute humidity in March 2013: the SRM yields the worst results (Fig. 4, on the right, at the top and at the bottom); namely, the mean disagreement in absolute value reaches 30% at a height of about 1 km and 60% at a height of 6–7 km. Through-

Table 3. Comparison of methods (algorithms) for solving the inverse problem

Notation/name	Actual measurements	Virtual measurements
CA/combined algorithm	Microwave measurements, surface sensors	Types 3–6 in accordance with Table 1
SRM/statistical-regularization method	Microwave measurements, surface sensors	Only type 3 (see Table 1), but mean profiles and covariance matrices were obtained from radiosounding data
CA + SRM/combined algorithm plus statistical regularization	Microwave measurements, surface sensors	Type 3 as in SRM and types 4–6 in accordance with Table 1

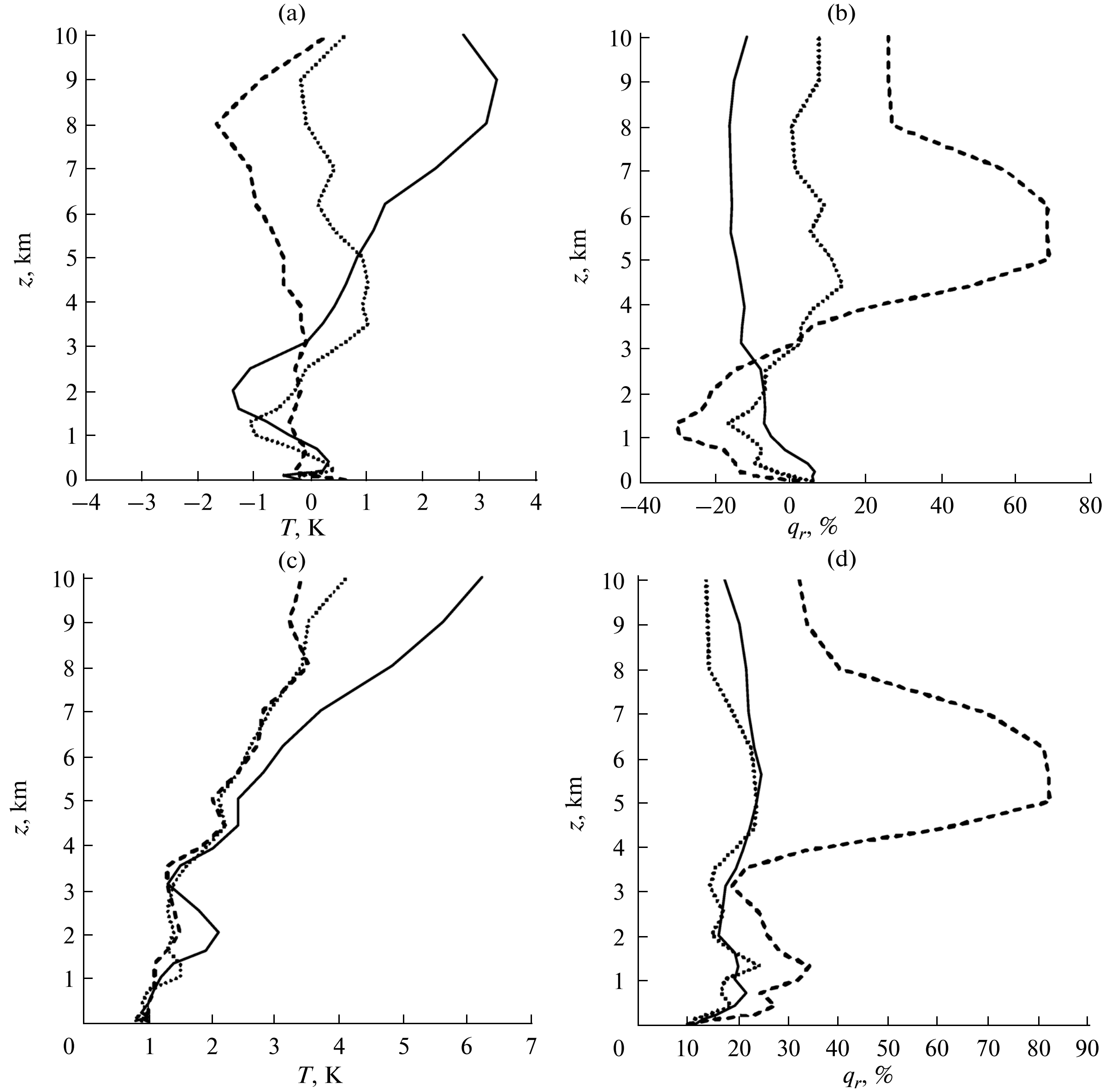

Fig. 4. Characteristics of disagreement between the results of microwave and radiosonde measurements of the profiles of temperature T (the values of (a) M and (c) S) and relative humidity q_r (the values of (b) M and (d) S) for March 2013: combined algorithm (solid line), statistical-regularization method (dashed line), and CA + SRM (dotted line).

out the entire height range, both CA and CA + SRM provide significantly smaller total errors in determining relative humidity. In this case, using CA + SRM does yield a noticeable advantage (in accuracy) over CA.

For September (Fig. 5) and March 2013, both SRM and CA + SRM have some advantages in determining the profiles of temperature. As for the profiles of relative humidity, unlike the results obtained for March, the SRM yields less accurate values only within a height range of 3–10 km. At heights of 0–3 km, both M and S values obtained using the SRM are smaller than those obtained using other methods. However, these differences are insignificant. At heights of 3–10 km, the CA yields the most accurate estimates in determining the profiles of relative humidity. It is important to note that CA + SRM yields significantly higher disagreement values when compared to the CA, which was not observed in March. The following explanation can be given to these nonobvious results: the water-vapor content in the troposphere is characterized by a very strong variability (by an order of magnitude and more); in this case, the distribution of its variations is different from the normal one, which may result in poor accuracy even in the presence of an adequate a priori covariance matrix.

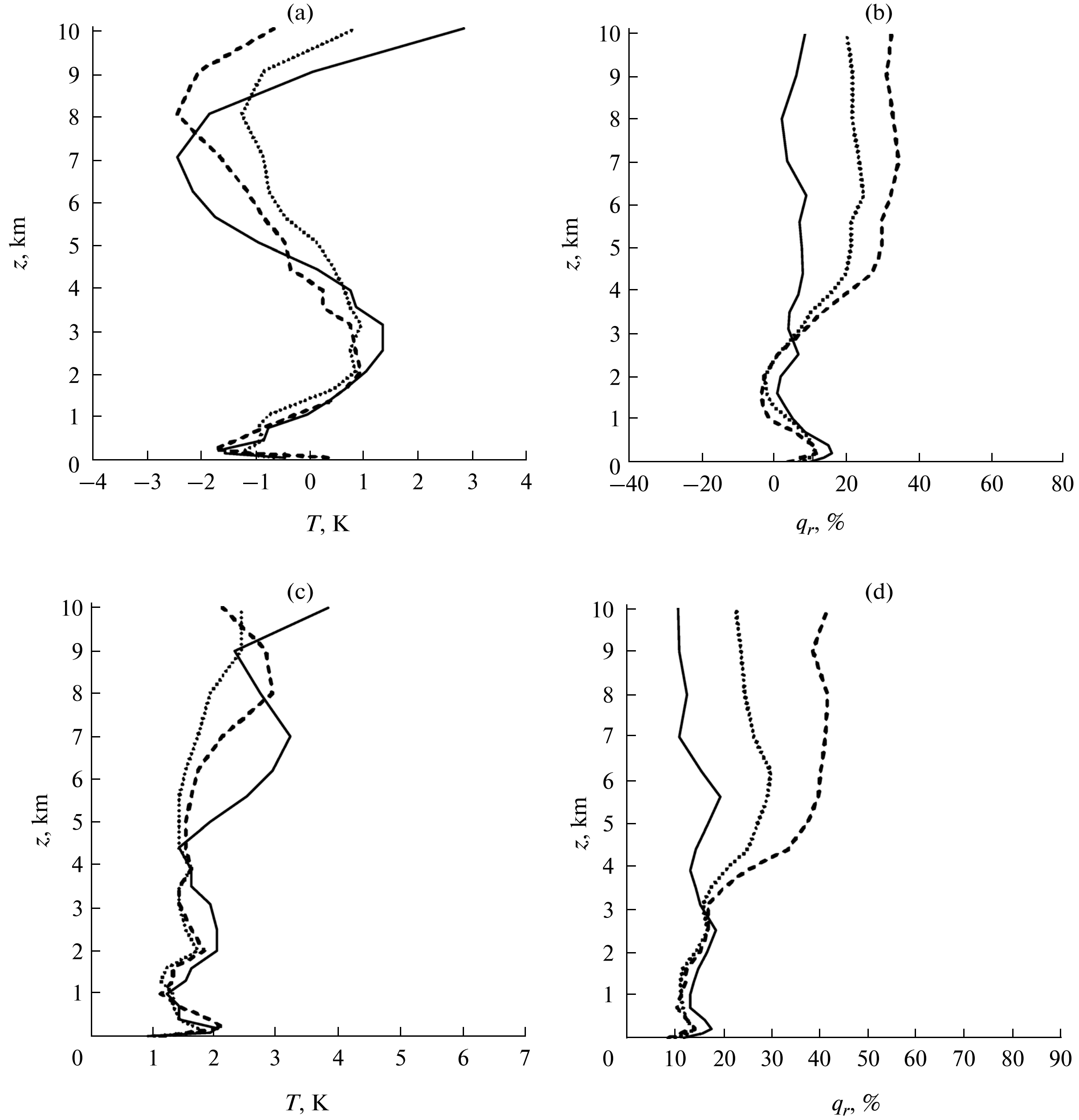

Fig. 5. Characteristics of disagreement between the results of microwave and radiosonde measurements of the profiles of temperature T (the values of (a) M and (c) S) and relative humidity q_r (the values of (b) M and (d) S) for September 2013: combined algorithm (solid line), statistical-regularization method (dashed line), and CA + SRM (dotted line).

Figure 6 gives both the temperature and absolute humidity profiles obtained on March 19, 2013, with different methods (CA, SRM, and CA + SRM). These results are interesting for analysis, because radiosonde data show the presence of strong temperature and humidity inversions. For the profile of temperature obtained with the SRM, the best agreement with radiosonde data is observed: its inversion is reproduced at a height of 1–2 km, and the disagreement is minimum up to a height of 10 km. The CA results within the inversion region yield the zero temperature gradient and the disagreement with radiosonde data significantly increases above 5 km. Using CA + SRM reproduces an inversion; however, it does not reach the SRM accuracy for either the middle or upper tropospheres. The situation is opposite with the profile of humidity. Inversion is best reproduced by the CA: the height of maximum humidity is in agreement within a few hundreds of meters, and the error of maximum values amounts to 30%. The other methods (SRM and CA + SRM) show the presence of inversion; however, the error in determining the height of maximum inver-

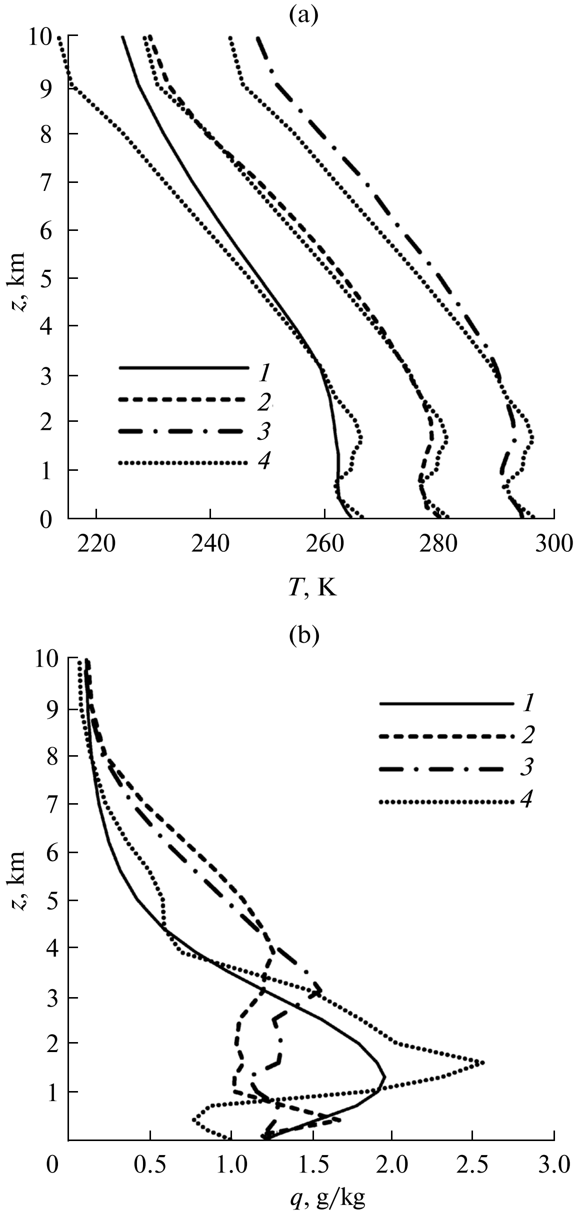

Fig. 6. Temperature (top) and mass water-vapor concentration (bottom) profiles obtained from microwave measurements on March 19, 2013, using different methods: (*1*) CA, (*2*) SRM, and (*3*) CA + SRM. Curves *4* correspond to radiosounding results. The temperature profiles corresponding to SRM and CA + SRM are shifted by 15 K and 30 K, respectively, in relation to the profile corresponding to CA for better visual perception of the graph.

sion amounts to 1–2 km and the error of maximum values amounts to 40–50%.

CONCLUSIONS

An algorithm for simultaneously determining both temperature and humidity profiles for the troposphere and the liquid-water content of clouds on the basis of ground-based microwave-radiation measurements has been developed. One special feature of this algorithm is the integrated use of different measurements and a priori information on the parameters to be retrieved. The RPG-HATPRO radiometer data obtained in the course of atmospheric remote sounding experiments carried out at the Faculty of Physics, St. Petersburg State University, are given (only the results of measurements taken in the zenith direction without angular scanning are considered). Both temperature and humidity profiles obtained from ground-based microwave measurements and from radiosonde measurements in March and September 2013 are compared. The rms disagreement between microwave and radiosonde data on temperature did not exceed 3 K up to a height of 6–7 km. The rms disagreement between microwave and radiosonde data on relative humidity amounted to about 15% for September and about 20% for March throughout the entire height range under consideration (0–10 km). It is shown that this combined algorithm is comparable in accuracy to the method of statistical regularization in determining temperature profiles; however, this algorithm demonstrates better accuracy in determining humidity profiles when compared to the method of statistical regularization.

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