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REMOTE SENSING OF ATMOSPHERE, HYDROSPHERE, AND UNDERLYING SURFACE

Comparison of Radio Sounding and Ground-Based Remote Measurements of Temperature Profiles in the Troposphere

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Abstract—A ground-based experiment on microwave temperature sounding in the troposphere with a RPG-HATPRO instrument, which has been performed at the Faculty of Physics, St. Petersburg State University since June, 2012, is described. On the basis of comparison of the results with radio sounding data, the temperature retrieval errors have been estimated using an algorithm provided by the manufacturer of the instrument. The errors have been compared with corresponding values for similar instruments functioning abroad. The conclusion has been drawn about a need to develop specialized algorithms and data processing procedures which include adaptation and correction of algorithms accounting for peculiarities of a specific instrument and experimental conditions.

Keywords: ground-based microwave remote sensing, tropospheric temperature.
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INTRODUCTION

Techniques for remote sounding of the atmosphere on the basis of microwave (MW) radiation measurements, including thermal sounding in the oxygen band 50–60 GHz have been developed since the middle of the 20th century. Significant successes have been achieved in theoretical studies, including improvement of algorithms for inverse problem solutions, and in experimental researches directed to refinement of spectroscopic data on MW radiation absorption by oxygen and design of up-to-date precision automated equipment. In particular, in past years,

– thermal sounding techniques for the middle atmosphere (stratosphere and mesosphere) on the basis of high-resolution MW radiation measurements have been developed [1–4];

– equipment for temperature profile monitoring in the boundary layer with a high vertical resolution has been designed, which allows the study of the dynamics of formation of temperature inversions and sharp jumps in air pollution concentrations due to the absence of mixing [5–7];

– commercial manufacturing of multichannel precision automated complexes for simultaneous temperature–humidity sounding of the atmosphere has been started [8, 9];

– unique research and universal standardized (unified) algorithms have been developed for processing MW measurements carried out with commercial MW instruments; international measuring networks have been created with the use of MW equipment [9–11].

Small series of instruments (MTP-5 and RPG-HATPRO profilers) for tropospheric researches are produced in Russia [7] and Germany [12]. A MW RPG-HATPRO profiler (Radiometer Physics GmbH) started to be used at the Faculty of Physics, St. Petersburg State University in 2012 [12]. The profiler has seven channels in the oxygen absorption band 0.5 cm and seven channels in the water vapor absorption band 1.35 cm; it is intended for continuous automated measurements of temperature and humidity profiles in the troposphere and integrated water vapor. We should note that experimental researches of the atmosphere with the use of ground-based MW instruments started at the Faculty of Physics, St. Petersburg State University in 2007: remote measurements of the stratospheric and lower mesospheric ozone have been carried out with the use of a radiometer designed at the Institute of Applied Physics, Russian Academy of Sciences (Nizhni Novgorod), which is capable of recording radiation in the ozone absorption line at 110 GHz [13].

The temperature, humidity, and integrated water vapor profiles are retrieved with the use of software provided by the HATPRO (Humidity And Temperature PROfiler) manufacturer. The aim of this work is to estimate and analyze errors of retrieval of tropospheric temperature profiles with this software in different seasons on the basis of comparison of the temperature values retrieved from radio sounding data (radio sounding station in Voeikovo vil., Leningradskaya region). The urgency of this work is caused by the following:

Table 1. Central frequencies f and halfwidth Δf of temperature channels of the RPG-HATPRO radiometer

f, GHz	51.26	52.28	53.86	54.94	56.66	57.30	58.00
Δf, MHz	230	230	230	230	600	1000	2000

– errors of the manufacturer's algorithm (MA) need to be estimated in different conditions of instrument operation to determine the limits of MA applicability;

– MA errors are to be compared with the accuracy of temperature profile retrieval required for solution of specific scientific problems (e.g., satellite data validation) to answer the question of a need for the development of a specialized improved algorithm.

Similar studies were carried out previously in Western Europe: errors of tropospheric temperature profile retrieval were estimated in [14] on the basis of MW radiation measurements with HATPRO instruments at the Payerne station in Switzerland. These estimates were based on the comparison with about 3.5 years of radio sounding data of temperature measurements. The authors used an algorithm similar to MA but refined and adapted to the specific radiometer used.

EXPERIMENT AND CALCULATION DETAILS

Technical specifications of MW RPG-HATPRO radiometers are described in detail on the manufacturer's site; the installation, maintenance, and measurement manuals can be also downloaded from there [12]. The central frequencies and halfwidth of the so-called "temperature' channels of the RPG-HATPRO radiometer are given in Table 1. The form of typical spectral instrument functions for these channels can be found in [14].

The profiler has been mounted on a mast on the roof of the building of the Institute for Physics, St. Petersburg State University (the coordinates are 59.88107° N, 29.82597° E). The angular vertical scanning is carried out northward in a north–south plane. The instrument operates continuously, in two modes. The intensity of downward MW radiation is measured in the main mode in the zenith direction; data are output once every 2 s. An additional mode is switched on periodically (once every 20 min), during which the angular scanning is carried out. The additional mode is intended for an increase in the temperature measurement accuracy in the boundary air layer. This combination of modes is suggested by the manufacturer; it allows a significant increase in the information content of MW measurements of the temperature profile.

The MA algorithm, which is implemented in the RPG-HATPRO radiometer, is based in the quadratic regression method (basically, the manufacturer also provided linear regression and neuron network algorithms, but they are absent in our case). The algorithm is adjusted by the manufacturer in the following sequence.

1. A radio sounding data bank is created, which includes measurements during several years at a radio sounding station, the nearest to a point where a customer plans to install the instrument.

2. The brightness temperatures are calculated in the instrument channels for different states of the atmosphere described by the radio sounding data and model values of the integrated water vapor.

3. The quadratic regression coefficients are calculated.

The MA for the radiometer purchased at St. Petersburg State University was adjusted by the manufacturer on the basis of radio sounding data received at Voeikov station (Leningradskaya oblast, 50 km from the point of MW measurements considered) during a period before 2012.

In this work, radio sounding data from Voeikov weather station for a period from June 2012 (the time when the radiometer started to operate) were taken for the comparison. The radio sounding data were loaded from the data bank of the University of Wyoming [15].

We use three parameters for the qualitative description of mismatch between the MW and radio sounding data on the temperature at an altitude specified:

the average divergence

$$M = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i),$$

the rms divergence

$$S = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2},$$

and the standard deviation from the average divergence

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - y_i - M)^2},$$

where N is the number of pairs of temperature values compared; x and y are the temperature values from MW and radio sounding at a specified altitude, respectively. If the radio sounding data are taken as a standard, then the parameter M characterizes the systematic error of MW measurements of the temperature profile, S characterizes the total error, and σ is the error without a systematic component.

Table 2. Measuring periods, for which the comparison with radio sounding data was carried out, dates of calibrations, and rms divergence S at different altitudes

Period	Time	Date of calibration with the use of liquid nitrogen	Rms divergence S (K) at altitudes of (km)		
			0.5	1.5	2.5
Summer 2012	June 1–August 31, 2012	May 31, 2012	1.2	1.5	1.8
Autumn 2012	September 1–November 30, 2012	–	1.1	1.6	2.4
Winter 2012	December 1, 2012–February 28, 2013	February 18, 2013	2.0	2.0	2.0
Spring 2013	March 1–May 31, 2013	–	1.2	1.2	2.0
Summer 2013	June 1–August 31, 2013	June 03, 2013	2.0	1.5	2.3
February 2013	January 15–February 13, 2013	February 18, 2013	1.2	1.9	3.0
March 2013	March 1–31, 2013	–	0.8	1.2	2.0

DISCUSSION OF RESULTS

Let us consider Table 2, which shows the measuring periods for which the comparison is carried out, dates of calibration with the use of liquid nitrogen as a cold load, and the rms divergence S at different altitudes. The calibration with the use of liquid nitrogen as a cold load was carried out three times: before the radiometer started operating, in eight and in 12 months. During the period under study, the rms divergences of the temperature measured from radio sounding data were within the 1.1–2.0 K limits at an altitude of 0.5 km, 1.2–2.0 K at 1.5 km, and 1.8–2.4 K at 2.5 km. Table 2 shows that the errors noticeable decreased after the calibration at the end of winter, 2012. This is seen from the two last rows, where the errors immediately before the calibrations and after it (February and March, 2013) are given. After the calibration, the errors decreased by 0.4 K at an altitude of 0.5 km, by 0.7 K at 1.5 km, and by 1.0 K at 2.5 km.

Figure 1a shows the altitude dependencies of different parameters of the divergence between MW and radio sounding data in spring, 2013. The altitude range 0–10 km is shown, since just this range for temperature profile retrieval has been suggested by the manufacturer. The dependencies are typical for all the periods of MW measurements at St. Petersburg State University after June, 2012. The average divergence M is close to zero and does not exceed 1 K up to an altitude of about 1.2 km, then the modulus of M increases quite rapidly and attains ~5 K at an altitude of 4 km and ~8 K at 8–9 km. The rms divergence S is about 1–2 K up to about 2 km, then it continuously grows up to 8.5 K at an altitude of 9 km. The error without a systematic component (σ) is close to the total error S up to an altitude of 2 km and slightly higher above, which witnesses a significant contribution of the systematic component of the error.

It is well known that ground-based measurements of downward MW radiation of the atmosphere in the

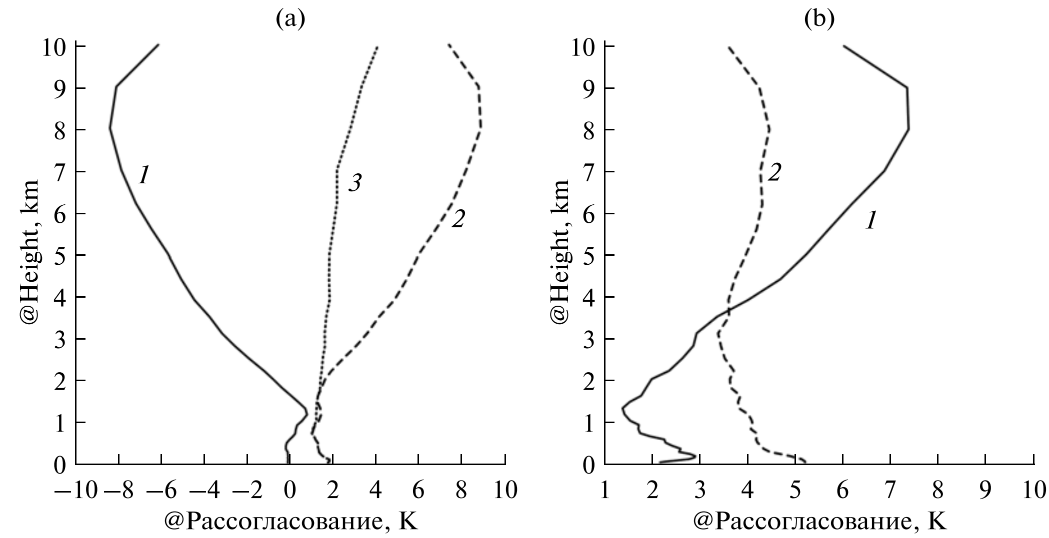

Fig. 1. Comparison between (a) MW and radio sounding data on temperature in spring 2013 (M (*1*), S (*2*), and σ (*3*)) and (b) divergence S (*1*) and natural temperature variability (*2*) in summer, 2013.

oxygen band in channels with low spectral resolution (see Table 1), which does not allow profiles of individual lines to be recorded, carry information about only lower tropospheric layers (see, e.g., [16]). Figure 1b shows real information content of MW measurements at different altitudes. The radio sounding measurements in the troposphere are highly accurate (<0.5 K); therefore, natural rms variations during the summer, 2013, calculated from radio sounding data at different altitudes, are compared with the rms divergence S of MW temperature measurements. They become equal at an altitude of about 3.5 km, and the errors of ME temperature measurements become higher than the natural variations in the temperature above. Let us note that the natural temperature variations were about 4 K during this season. The average divergence M is very large at altitudes above 2–3 km (see Fig. 1a) and the error is almost totally determined by the systematic component; therefore, the analysis of possible causes of this fact is of interest. The following main sources of the systematic component of the error can be mentioned:

– mismatch between a statistical ensemble used for the regression operator calculations and specific atmospheric situations during the measuring period;

– errors of methods for calculation of the absorption coefficients during calculations of the brightness temperature in the spectral channels of the radiometer;

– mismatch between instrument parameters simulated for the calculations of the brightness temperature (frequency, spectral width, spectral transfer function of channels, direction pattern, etc.) and the radiometer used;

– uncontrollable errors during absolute calibration of the instrument.

The first above-mentioned sources of significant systematic errors seems to be of low probability, since the sign and value of the average divergence are the same for all the measuring periods analyzed (all the seasons). We estimated the effect of mismatch between the statistical ensemble and the temperature measurement results to the first approximation by means of construction of a linear regression operator on the basis of radiometric and radio sounding measurements in spring, 2013, and using it for the radiometric measurements in summer, 2013. The average divergence from the radio sounding data was not higher than 1 K up to an altitude of 7 km and 2 K up to 8 km. Above 8 km, the average divergence grew up to 5.5 K at an altitude of 10 km. Thus, the first source cannot be the main cause of the systematic error.

The second source is also of low probability, since its effect should be noticeable for all altitudes. In addition, we should emphasize that modern techniques for absorption coefficient calculations are sufficiently accurate, which has been verified by practical radiometric measurements.

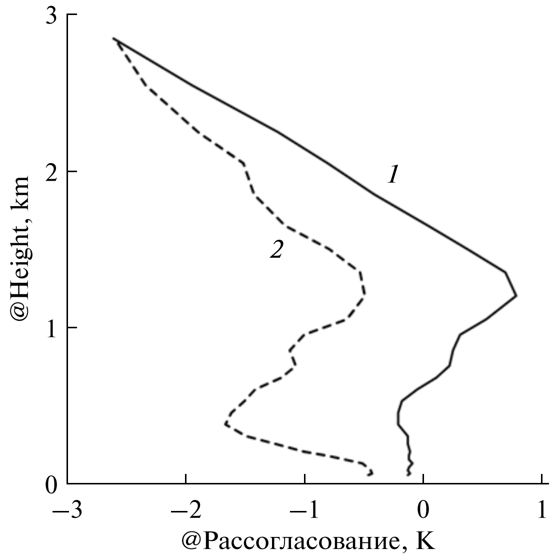

Fig. 2. Altitude dependencies of the average divergence M for spring, 2013 (*1*) and summer, 2013 (*2*).

To estimate the effect of the third source, we used a linear regression operator, constructed on the basis of data for spring, 2013, for processing the measurement results for the same period (spring, 2013), simulating a systematic error in different spectral channels of the HATPRO radiometer. The comparison with the radio sounding data has shown that systematic errors in the brightness temperature of 1 K in the 3rd "temperature" channels 53.86 GHz provides for average divergence values of 1.7, 2.2, 2.5, 2.7, and 2.6 K at altitudes of 3, 4, 5, 6, and 7 km, respectively. Systematic errors in other spectral channels weakly affect the temperature measurement results above 3 km.

To study the fourth source, we simulated systematic errors in all "temperature" channels simultaneously. The calculations have shown insignificant (within 1 K) average divergence between MW and radio sounding measurements, equal for all altitudes.

Finally, we can conclude that we have not succeeded in identifying exactly a source of the systematic error of the MA at altitudes above 3 km. However, mismatch between the instrument parameters simulated and the radiometer used is apparently the most probable source of this error. As an example, we can point out that frequency of channels of the radiometer used can differ from standard ones. In this case, the manufacturer provided a special correction procedure. Since significant systematic mismatch was observed for altitudes above 3 km, the 0–3 km air layer is considered below.

Figure 2 shows variations in the average divergence M versus the measuring period.

It should be noted that the altitude variations in the average divergence are similar for all the time periods under study (Table 2); the only difference is a horizon-

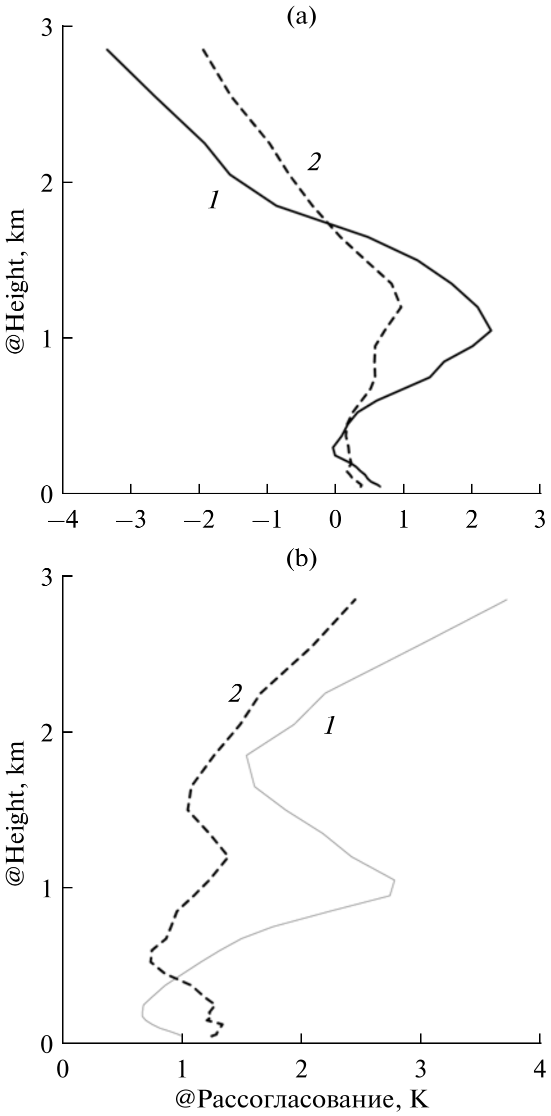

Fig. 3. Altitude dependencies of the (a) average divergence *M* and (b) rms divergence *S* for the periods before ("February, 2013" (*1*)) and after the calibration ("March, 2013" (*2*)).

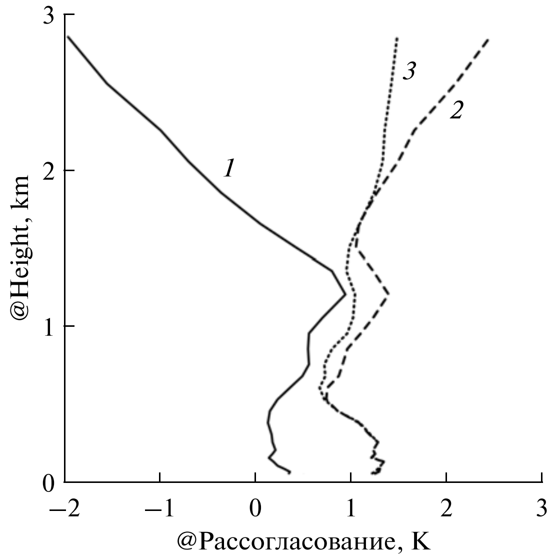

Fig. 4. Altitude dependencies of *M* (*1*), *S* (*2*), and σ (3) for March, 2013.

tal shift of the curves. Correspondingly, the value and sign of the average divergence change. It is seen from Fig. 2 that the average divergence does not exceed 1 K in modulus and is alternating in sign in spring, 2013, at an altitude 0–1 km; the temperatures retrieved with the MW method are systematically lower than the radio sounding data for summer, 2013, and the absolute average divergence attains 1.7 K in this period.

Figure 3 confirms the importance of periodic calibration of the instrument.

The average divergence in the 0–1.5 km altitude range decreased after a calibration by 0.6–1.0 K. The values of rms divergence in the 0–3 km layer were 1–3 K before the calibration (February, 2013); they did not exceed 2.5 K at an altitude of 0–2 km and attained 2.5 K only at an altitude of 2.5 K after the calibration (March, 2013). The differences between the MW temperature measurement errors before and after the calibration were the highest in the 0–2 km layer and equaled 0.5–2.5 K.

To show capabilities of the MA immediately after a scheduled calibration of the instruments, let us consider Fig. 4, where all parameters of divergence between MW and radio sounding measurements in March, 2013, are plotted. It is shown that MK measurements allow temperature profiles to be retrieved with systematic errors of 0–2 K and rms errors of 1–2.5 K at altitudes of 0–3 km. Elimination of the systematic components of divergence, as seen from the altitude dependence of σ, results in differences from radio sounding data by 0.5–1.5 K.

Let us compare our estimates of temperature profile retrieval errors with results from other authors. Using the comparison of 18 months of MW retrieved temperature values with radio sounding data, it is shown in [16] that two methods differ by 0.6 K near the surface and no more than by 1.6 K at an altitude of 7 km in summer and 4 km in winter. The temperature and humidity profiles were retrieved with the use of multiple linear regression, which turned out to be more accurate than the artificial neural networks, especially for humidity. The regressions were built on the basis of simultaneous radio sounding and MW measurements of downward radiation.

This approach has certain advantages: it does not require the use of radiation atmospheric model, and the inverse operator of the technique can be refined periodically. The parameters of MW sounding of vertical temperature profiles with the HATPRO spectrometer are analyzed in detail in [14]. The authors of this work first

Table 3. Estimates of the error of temperature profile retrieval from measurements of downward MW radiation found from the comparison with radio sounding data (the altitude of boundary layer is 2 km)

Source	Random error	Systematic error	Total error	Note
This work	1.0–1.5 K in the boundary layer	±1.0 K	1.0–1.5 K in the boundary layer, 2.5 K at an altitude of 3 km	RPG-HATPRO radiometer
[16]	–	–	0.6 K near the surface, <1.6 K up to an altitude of 7 km in summer and 4 km in winter	TP/WVP 3001 instrument (Radiometrics Corporation)
[14]	0.5 K in the boundary layer 1.7 K at an altitude of 4 km	±0.5 K	–	RPG-HATPRO radiometer
[17]	0.5–1.5 K at an altitude of 0–0.5 km 1.5 K at an altitude of 0.5–3.5 km	±1.0 K in the boundary layer	–	TP/WVP 3001 instrument (Radiometrics Corporation)
[5]	1.0–1.5 K up to an altitude of 3 km	±1.0 K	–	RPG-HATPRO radiometer

calculated and corrected the systematic divergence between the measured and calculated spectra of the brightness temperatures for clear sky conditions. Then, the same measurements were used for solution of the inverse problem and the comparison with radio sounding measurement results. The study has shown that the random divergence between the MW and radio sounding results was 0.5 K in the lower boundary layer and increased up to 1.7 K at an altitude of 4 km. Systematic differences between local and remote temperature measurements attained ±0.5 K.

Temperature profiles retrieved from MW and radio sounding measurements carried out within the TUC (Temperature, hUmidity, and Cloud) experiment from December, 2003, to February, 2004, at the Payerne weather station (Switzerland) were compared in [17]. The temperature profiles were retrieved from MW measurements by several different methods. The comparison results have shown that random errors of the MW technique are about 1.5 K up to an altitude of 3.5 km, while systematic errors are 1.0 K. The following errors of the MW technique were obtained in [5] on the basis of 80 comparisons with radio sounding data: the random component of the error is 1.0–1.5 K and the systematic component, ±1.0 K in the 0–3 km altitude range. These estimates corresponded to the combined observation mode (zenith + angular scanning).

Estimates of the errors calculated in this work and by other authors are given in Table 3 for convenience. As seen, two groups of error estimates can be distinguished. Works [14, 16] relate to the first group, where small errors are given for a high upper limit of temperature sounding by RPG-HATPRO and TP/WVP 3001 instruments. Thus, an error of lower than 1.6 K up to an altitude of 7 km in summer has been reported in [16]. The second group includes estimates which are characterized, first, by a low sounding upper limit (up to 3.5 km) and, second, by higher errors in the boundary layer [5, 17]. Our estimates are close to the second group; the errors are comparable in the boundary layer and are higher than values reported by other authors above 3 km. This fact witnesses advantages of specialized algorithms and processing procedures, including algorithm adjustment and correction accounting features of a specific instrument and experimental conditions.

CONCLUSIONS

The ground-based MW temperature sounding of the troposphere with the use of the RPG-HATPRO radiometer operating at St. Petersburg State University provides for rapid information up to altitudes of 3–4 km, if the MA is used for the data processing. In this case, the temperature measurement errors are 1.0–1.5 K in the boundary air layer and 2.0–3.5 K in the 2–4 km layer. Above 4 km, errors of the remote measurements become higher than natural temperature variations. The experience has shown that calibrations of the radiometer with the use of liquid nitrogen are required to be carried out more often than recommended by the manufacturer.

There are potential capabilities of increasing the upper limit of the temperature sounding and decreasing the errors by means of the development of specialized algorithms and processing procedures, including adjustment and correction of the algorithm accounting features of the specific instrument and experimental conditions. (This conclusion is also confirmed by foreign experience using analogous instruments).

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SPELL: 1. Feigin, 2. Rossa, 3. Lohnert
@Рассогласование, K
@Height, km