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OPTICAL INSTRUMENTATION

Ground-Based Microwave Temperature Profilers: Potential and Experimental Data

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Abstract—Calculated (potential) and experimental parameters (accuracy, vertical resolution, and calibration) of ground-based temperature profilers are analyzed. At the moment, single-channel scanning microwave profilers (MTP-5) are widely used for atmospheric boundary layer temperature profile measurements, and multifrequency microwave radiometers (MP-3000A, RPG-HATPRO, and MICRORADCOM) are used for tropospheric temperature profiling. Data of the MICRORADCOM profiler, which operated from January 1, 2014, to January 1, 2015, in Dolgoprudny, Moscow oblast, are considered in more detail.

Keywords: microwave remote sounding, temperature profiles, troposphere, atmospheric boundary layer

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INTRODUCTION

Temperature is a key parameter in the description of different atmospheric processes: thermal conditions, circulation, different waves, etc. The most common stratification of the atmosphere is with respect to the temperature: troposphere (0–15 km), stratosphere (15–55 km), mesosphere (55–85 km), thermosphere (85–400 km), and exosphere (>400 km). The lower troposphere, the altitude of which changes from 100 to 1600 m depending on latitude, has a special name—the atmospheric boundary layer (ABL) [1]. Data of contact temperature sensors of radiosondes, balloons, aircrafts, high-altitude meteorological masts, and remote instruments: optical (lidars) and radio acoustic sounding systems (RASS) were commonly used for temperature profiling [2]. In the late 1950–1960s, remote super-high frequency radiometric methods for studying the atmosphere began developing; now they are called microwave radiometric methods [3–7].

Radiometric sounding methods are based on the reception of atmospheric (thermal) radiation in the millimeter wave range and correlations between radio parameters of this radiation (attenuation, intensity, polarization, etc.) and physical parameters of the atmosphere. The use of several (most sensitive) spectral ranges of the microwave (MW) region allows measurements of several physicochemical parameters of the atmosphere, in particular, altitude temperature distribution, total water vapor, integral content and temperature of cloud liquid water, and concentrations of some impurity gases [3].

In this work, we consider radiometric methods for profiling the tropospheric temperature on the basis of measuring the intrinsic thermal radiation of molecular oxygen in the Earth's atmosphere, which has several spectral lines in the 5-mm wavelength range (frequency of 60 GHz) and quite high relative concentration (20.95%) stable up to altitudes of 80 km. The intrinsic radiation of molecular oxygen changes with altitude depending on temperature, which allows temperature profiling [3–8]. After the beginning of the artificial Earth satellite epoch (1960–1970s), different satellite radiometric devices were designed for profiling tropospheric temperatures; they are being actively developed at present [9–12]. In particular, nadir satellite MW radiometers NEMS, SCAMS, MSU, SSM/T, and AMSU have been designed, as well as MW limb radiometers MLS, MAS, and AMAS [9]. Ground-based MW temperature profilers were designed in different laboratories and universities around the world (e.g., in Switzerland, the profiler ASMUWARA), especially for measurements in the lower troposphere (lower 3 km), where satellite data on temperature profiles could not be received or data accuracy is low (mainly due to the effects of Earth's surface radiation and clouds) [6, 8]. However, only single prototypes of these instruments were designed, and commercially produced instruments appeared at the end of the 20th century. Thus, a MW radiometric MTP-5 profiler was designed in Russia in 1993 for profiling the ABL temperature (more than 80 such profilers are used now in different countries); a MP-3000A instrument, in the United States, for profiling the temperature in the troposphere up to altitudes of 10 km, and a similar RPG-HATPRO profiler, in Germany (www.attex.net, www.radiometrics.com, www.radiometers-physics.de).

In 2013, another multichannel MW profiler was designed in Russia for measurements of the tropospheric temperature and total water vapor, called MICRORADCOM [13]. Monitoring networks have been created of these devices in different countries. Rich experience of the use of MW temperature profilers has been accumulated, which has shown that actual and rating (advertised) parameters of these devices can differ. This was one of the reasons for this work. Another reason is a wish to attract the attention of specialists in fundamental and applied atmospheric physics (studies of aerosol, radiation transfer in the atmosphere, simulation of radiative processes in the atmosphere, development of prognostic models, etc.) to capabilities of this new class of devices which have been recommended for wide use by the World Meteorological Organization [2].

FEATURES OF MICROWAVE RADIOMETRIC AIR TEMPERATURE PROFILING

The use of passive radiolocation methods of the Earth's atmosphere by its (thermal) radiation is based on the solution of an integral radio radiation energy transfer equation in a medium with a specific geometry and on knowledge of conditions for MW radiation interaction with the atmosphere [3]. The MW radiation transfer in the Earth's atmosphere is accompanied by its absorption and scattering due to interaction with atmospheric gases and hydrometeors (snow, rain, clouds).

When sounding the atmospheric temperature profiles in MW absorption bands of molecular oxygen, the brightness temperatures measured can be represented by an integral Fredholm equation of the first kind and in the general case is written as [3, 14]:

$$\mathrm{T_b}(\theta, \nu) = \int_0^H K(h, \nu) T(h) dh + \Delta(\theta, \nu), \qquad (1)$$

where θ is the zenith observation angle; ν is the frequency of the radiation received; H is the altitude of an atmospheric layer under study; $K(h, \nu)$ is the integral equation kernel; $T(h)$ is the solution sought; $\Delta(\theta, \nu)$ is the measurement error. Incorrectness of the problem to be solved leads to instability of the solution. Construction of stable solution (1) is based on the use of additional a priori information about the solution sought, i.e., about the temperature profile $T(h)$ [7, 14, 15]. The most commonly used methods for solution of inverse problems of remote atmospheric sounding are the method of statistical regularization, iteration method, Tikhonov regularization method, regression method, and neuron network method [8, 12, 15, 16]. The molecular oxygen absorption coefficient is usually calculated by the technique described in [16].

The statistical regularization method is mainly used in MTP-5 (Russia) and RPG-HATPRO (Germany) profilers, with autocorrelation temperature matrices as a priori information built for certain regions from radio sounding data. The neuron network method is used in MP-3000A (United States). This method provides for quite high accuracy in the case of permanent adjustment of the profiler with the use of data from a close aerological station and regular radiosonde data. This method also allows controlling the quality of absolute calibrations. For this, atmospheric temperatures are measured at different altitudes with a radiosonde and brightness temperatures are calculated from them with the use of a Rayleigh–Jeans approximation and compared with actual radiometer-measured brightness temperatures. There are three main methods for retrieval of temperature profiles from ground-based MW radiometric measurements [7]:

(1) from measurements of thermal radiation at one frequency at different zenith angles (angular method, used in MTP-5);

(2) from measurements of thermal radio radiation at several wavelengths located on a slope of the absorption band in the 5-mm range at a fixed angle (frequency method);

(3) from measurements of thermal radiation at several wavelengths and angles (combined method used in RPG-HARPRO, MP-3000A, and MICRORADCOM).

All the above methods are identical in the sense of principal capabilities and provide close accuracy. The angular method is the slowest, since the scanning is carried out sequentially, but it provides for a higher vertical resolution in the ABL. The most rapid is the frequency method with simultaneous reception at all frequency channels. In view of the above, we consider the combined method as a compromise, which allows sounding in the troposphere [7].

As usual, any measurement method has advantages and disadvantages. The MW radiometry is a passive method, i.e., the device radiates nothing and can be used inside settlements. The equipment is compact and allows mobile measurements. Measurements can be carried out under clouds, and MW profilers for ABL (e.g., MTP-5) ensure measurements under any weather conditions. Their main disadvantage is low vertical resolution as compared to active methods (lidar, RASS) and contact sensors of radiosondes [2]. Another disadvantage of MW thermal profilers is a need for absolute calibrations, i.e., elimination of a dependence of brightness temperature in kelvin at different angles (or frequencies) on antenna temperatures measured in mV [3, 7, 17, 18]. Though this dependence is linear, it is difficult to derive it with a required accuracy, which is one of main problems in radiometric measurements. For this, different MW targets with liquid nitrogen and internal noise genera-

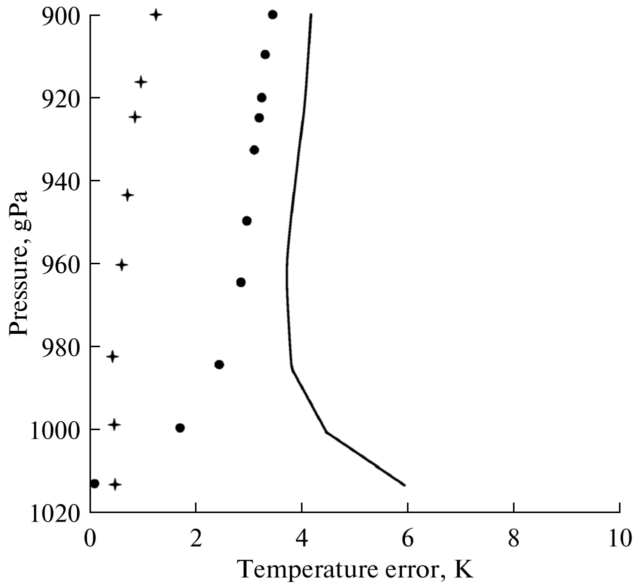

Fig. 1. Errors of temperature profiling calculated in a climate model (solid curve), with the use of data on current surface air temperature (dots), and MTP-5 data (crosses).

tors are used [7, 17]. The radiometer antenna is directed to a target or targets, with two different temperatures, which ensures "cold" (with the liquid nitrogen temperature $T_1 = 77$ K) and "warm" (e.g., $T_2 = 293$ K) points [7, 17]. Approximate assessments are the following: the accuracy of absolute calibration should be no worse that 1–2° at a sensitivity of hundredths of a degree for up-to-date radiometers. One of the main requirements for up-to-date radiometers is highly stable calibration [17, 18]. Let us consider the features of radiometers with application of the elevation and combined measuring methods.

MIRCOWAVE ELEVATION SCANNING PROFILER

This profiler type is mainly used for temperature profiling in ABL [8, 18, 19], where there are several specific difficulties. First, the temperature contrasts are low. The contrast of brightness temperatures from the horizon to zenith is usually no more than 2 K when measuring at a wavelength near 5 mm. This requires a temperature profiler sensitivity of no worse than 0.1 K at an integration time constant of 1 s. The antenna should have a narrow beam; the half-power antenna pattern should be no wider than 3°, with strongly suppressed minor lobes (no worse than –30 dB) [8, 19, 20]. The variety of temperature profile types in the ABL is much wider than in higher tropospheric layers. Along with adiabatic profiles, profiles with temperature inversions (surface, raised, and double) are often observed here [1]. This produces significant difficulties in solutions of inverse problems, i.e., retrieval of temperature profiles according to Eq. (1).

Table 1. Vertical resolution Δ of a scanning radiometer located at an altitude of 10 m above the Earth's surface versus altitude H of the atmospheric layer under study

H, m	10	50	100	200	300	400
Δ, m	7.5	25	65	130	225	300

Data on a local ABL temperature profile can be retrieved from a climate model, refining it with knowledge about current surface air temperature and local short-term forecast data. Therefore, remote sounding data can be interesting if they are much more accurate than data simulated. The climate model is mainly based on radio sounding data. In practice, radiosondes are launched every 12 h in Russia. This is insufficient for monitoring temperature inversions (while a MW temperature profiler can reliably measure the profiles every 2 min and provide for a complete pattern of development of temperature inversions). A matrix approach to assessment of measurement errors with the use of covariance matrices for optimal retrieval of temperature profiles was considered in [19] for data of ground-based radiometric measurements. Data from climatic models, forecasts, or any other data with known accuracy can be the first a priori approximation. The error covariance matrix S can be written as

$$S(x) = C - CK(x)^T \times \left\{K(x)CK(x)^T + E + F\right\}^{-1} K(x)C, \quad (2)$$

where x is the air temperature profile; C is the expected covariance of previously known errors; K is the model gradient (weight function); E is the expected covariance of errors measured; F is the expected covariance of model errors. Both S and K are considered independent of the current temperature profile.

Figure 1 shows the measurements errors calculated for pressure layers of up to 900 hPa (this corresponds to an altitude of about 1 km) [19].

The analysis carried out in [4, 6, 18, 19] has shown that the use of ground-based radiometers in atmospheric thermal condition monitoring provides for a significant gain in accuracy as compared to data of climate models and forecast data. Let us now analyze the weakest point of the method suggested, i.e., its vertical resolution. The delta function has been suggested in [18] for estimation of the vertical resolution. The calculation results for the vertical resolution are given in Table 1.

It is seen that a resolution of about 65 m and lower (down to 7.5 m) can be implemented below 100 m, and the resolution significantly decreases as the altitude

Table 2. MTP-5 data in comparison with radiosonde data

H, m	0	50	100	150	200	250	300	400	500	600	800	1000
dA_V	0.33	0.42	0.28	0.14	–0.02	–0.12	–0.18	–0.25	–0.23	–0.18	–0.04	–0.19
RMSD	1.10	1.10	0.91	0.76	0.74	0.71	0.70	0.69	0.72	0.78	0.90	0.91

dA_V is the mean difference ($T_{\text{sonde}} - T_{\text{radiometer}}$), deg.; RMSD is the root-mean-square deviation of the difference.

increases. At altitudes higher than 400 m, the vertical resolution drops drastically. However, this drop is not so sharp in practice when using different profile types in a priori data (e.g., an adiabatic profile; the vertical resolution is close when measuring at 100 and 1000 m). Data are usually approximated in layers during processing in MW temperature profilers, and the approximated data rate is certified for the profilers instead of the vertical resolution (e.g., 50 m).

Let us briefly consider real specifications of MW profilers for ABL using the commercially produced MTP-5 device as an example [18, 20]. The sounding is carried out at one wavelength (56.6 GHz) at 11 angles; scanning from the horizon to zenith takes 2 min. The reduced sensitivity (at an integration constant of 1 s) of the radiometric detector is 0.07 K in the 400-MHz transmission band. A switching direct-gain radiometer with output MW amplifier and digital low-frequency part is used. The altitude range is 0–1000 m; the data rate is 25 m up to 100 m and 50 m above 100 m. The measurement error is 0.2–1.2°C in the whole altitude range (versus profile type). The in-service power consumption is 60 W, the mass is 20 kg. The half-power antenna pattern width is 2.2°. A weather protection system ensures operation under outer temperatures from –80 to +50°C under any weather conditions except for showers. One of the main advantages of this profiler is completely automated operation, including automated adjustment to atmospheric radiation toward the horizon. Table 2 compares MTP-5 data with data from 113 launches of radiosondes at the Dolgoprudny aerological station, carried out from June 1 to September 3, 2013.

It should be noted that comparison with radiosonde data should be carried out very carefully, having in mind that a sonde measures the temperature with a contact sensor at a local point, while a radiometer measures the layer-integral temperature, and a sonde flights quite far from the MW radiometer site. Thus, a comparison with sensors mounted at special masts and balloons is more correct. Such comparisons were also performed in [18, 19]. At present, new tools appear—drones with contact sensors and vertical flight up to altitudes of 5 km, which are optimal for the comparison, in our opinion.

MTP-5 radiometers are widely used in ecological monitoring, regional forecasting of weather and pollution propagation, environmental safety of nuclear power plants, in airports, and in scientific researches on atmospheric physics and polar researches (in particular, they were used at the SP-39 and SP-40 drifting ice stations and at the continental Antarctic station KONKORDIA) [21–27].

GROUND-BASED MULTICHANNEL MICROWAVE PROFILERS

Ground-based multichannel MW temperature profilers are intended for measurements of tropospheric temperature profiles up to altitudes of 10 km. The measurements are usually carried out at 6–7 frequencies at a slope of the molecular oxygen absorption band (from the 51–58 GHz range) [3, 5, 7, 28–32]. Variations in radiation of water vapor and cloud liquid-drop moisture cannot be ignored in these measurements; therefore, these profilers obligatory contain channels near the resonance frequency of water vapor radiation (22.235 GHz) and a so-called transparency window (where the total radiation of molecular oxygen and water vapor is minimal, 35–38 GHz) [7, 14].

The total absorption coefficient of molecular oxygen, water vapor, and cloud liquid-drop moisture should be used in calculations by Eq. (1) [7, 14]. This makes the measuring complex significantly more difficult that a single-channel scanning profiler for ABL. In addition, automated calibration by atmospheric radiation toward the horizon is impossible here, and an external MW liquid nitrogen-cooled target should be used [29–31]. It is also desirable to have additional equipment for measurements of the cloud base (e.g., an IR radiometer) [31]. In this case, as shown in [28], the vertical resolution in multifrequency measurements in ABL is no higher than 400 m, even in lower layers. Therefore, scanning of at least one frequency channel maximally close to the resonance frequency of molecular oxygen radiation should be provided [29, 31].

The calculation for a multichannel (7 channels) MW radiometer with three-frequency scanning was carried out in [29] for profiling tropospheric temperatures. The results are given in Table 3.

Table 3. Vertical resolution values calculated for seven channels of a scanning radiometer

H, m	25	50	100	150	250	500	750	1000	1500	2000	2500
Δ, m	20	46	97	151	232	469	789	953	1651	1770	3544

The vertical resolution of ground-based MW profilers has been estimated in [28] with the use of wavelet analysis, and the results have been compared with Backus–Gilbert calculation results [33]. It has been shown that a single-channel scanning radiometer with the wavelength close to the molecular oxygen absorption maximum (5 mm) has a higher vertical resolution in the 0–1 km altitude range; multichannel radiometers with zenith sounding have higher resolution in the 1–2 km range, and the vertical resolution sharply decreases above 2 km for both radiometer types. The comparison results for vertical resolution of a multichannel profiler and satellite instruments are given in Table 4 [12].

As seen from the table, satellite instruments cannot compete with ground-based profilers in the lower troposphere, but the situation is reversed at altitudes higher than 4 km.

Let us briefly consider specifications of real devices with the simplest profiler MICRORADCOM as an example [13]. In contrast to MP-3000A and RPG-HATPRO, it is mounted on the base of a trailer. A temperature from 20 to 22°C is maintained inside the trailer year-around. An operator works inside the trailer, where controlling computer, 6-channel MW radiometer (frequencies of 53.3, 53.95, 54.48, 55.01, 55.74, and 56.72 GHz), single-channel radiometer (frequency of 22.235 GHz) for measuring the total water vapor column, single-channel radiometer (frequency of 37 GHz) for measuring the integral cloud liquid water (kg/m^2), GPS/GLONASS receiver, and power supply units for all devices are mounted. On the trailer roof, scanning single-channel MW radiometer with a frequency of 56.6 GHz (MTP-5), automated weather station (measurements of surface air temperature and pressure, wind, and liquid precipitation), and video camera for fixing clouds are mounted [13]. Routing measurements of the air temperature profiles and total water vapor have been carried out using MICRORADCOM since December 1, 2013, as well as comparisons with data from radiosondes which are located immediately near the Dolgoprudny aerological station. Figure 2 shows MICRORADCOM output signals, and Fig. 3, comparison results for temperature profiles measured with MICRORADCOM and from a radiosonde under clear sky conditions.

Table 4. Vertical resolution of a ground-based multichannel profiler in comparison with vertical resolution of a satellite radiometer

H, m	100	500	2100	4000	6000	8000	10000
Δ, m (ground-based profiler)	25	300	1500	2800	6000	6000	8000
Δ, m (satellite profiler)	–	–	1500	2000	2000	2000	2000

Estimation of MICRORADCOM data array for more than the year of observations allows the following conclusions. The mean difference with the ABL radio sounding data is 0.3–0.6 K at altitudes of 0–1.6 km and 1.6 K at an altitude of 4 km under clear sky and 2.3 K in clouds. Above 4 km, the temperature profiles were successfully retrieved only under clear sky, and results similar to those shown in Fig. 3 were obtained only in 10% of cases [34]. This is a little better than the RPG-HATPRO results obtained in [35], where the RMS error was 1.0–1.5 K in ABL, 2.0–3.5 K at altitudes of 2–4 km, and up to 8 K above 4 km. Figure 4 shows the results of a one-year comparison of ABL temperature profiles (up to 1 km) measured with a radiosonde and with MICRORADCOM.

CONCLUSIONS

The analysis of potential and experimentally tested capabilities of MW temperature profilers allows the following conclusions. Design of an up-to-date MW amplifier provides for an increase in the sensitivity and stability of existing MW millimeter wavelength range radiometers by about an order of magnitude. This allows their use in monitoring of the thermodynamic state of the troposphere. The greatest progress is achieved in measurements of temperature profiles in ABL, where the accuracy satisfies many fundamental and applied problems of controlling and forecasting the state of this layer, the most important for human life. Similar results can be expected for higher air layers (1–4 km) by means of improvement of calibration characteristics and algorithms for temperature profile retrieval. As for altitudes from 4 to 10 km, we believe that progress can be expected here due to the use of satellite devices, since ground-based measurements

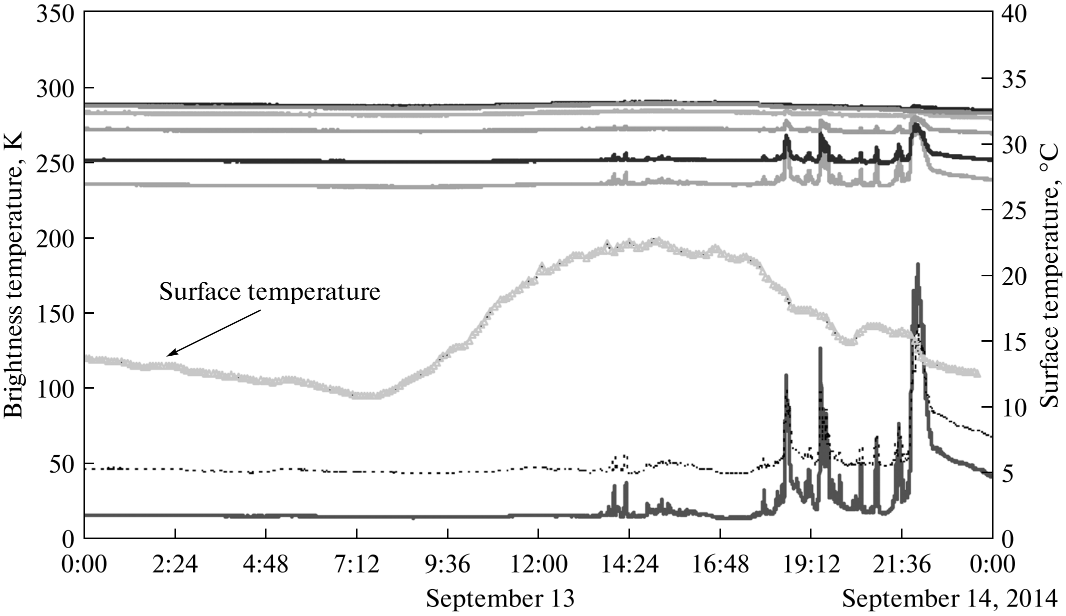

Fig. 2. MICRORADCOM output signals at frequencies of 22.235, 37, 53.3, 53.95, 54.48, 55.01, 55.74, and 56.72 GHz (from the bottom up). The surface air temperature is 10.5–23°C, relative humidity is 40–100%; haze and single cirrus clouds before 11:00, cumulus and cumulo-stratus clouds after 14:00, and light rain at 18:30–22:00.

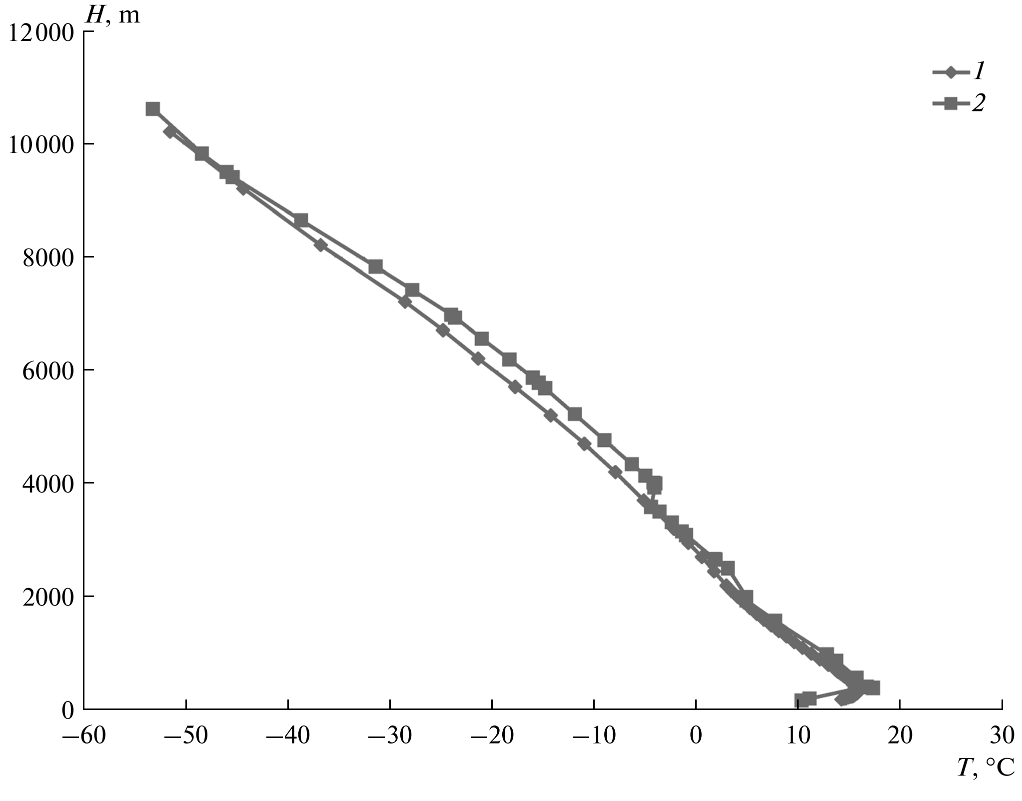

Fig. 3. Comparison of radio sounding (*1*) and MICRORADCOM (*2*) data (04:00:00, December 09, 2014).

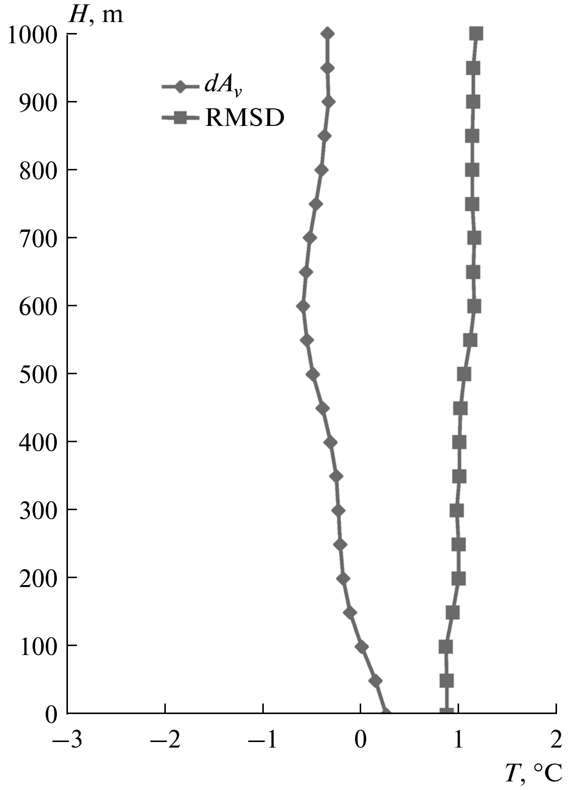

Fig. 4. Comparison of data on temperature profiles measured with a radiosonde and the MICRORADCOM complex (“boundary layer” mode, MTP-5, 496 pairs for 2014). General results from 496 comparisons: $dA_V = -0.30$, RMSD = 1.15.

have insufficient vertical resolution at these altitudes and strongly depend on low clouds. To carry out the comparisons, drones, with contact temperature sensors, vertical takeoff and landing, and flight altitudes of up to 5 km, are the most promising in our opinion.

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