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Atmospheric Temperature Sounding with the Fourier Spectrometer

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Abstract—Preliminary results of a space experiment using the IKFS-2 infrared sounder (Meteor-M2 satellite) showed high-quality of measurements of spectra of the outgoing thermal radiation of the atmosphere–surface system and the adequacy of developed IR radiation atmospheric models in the 15-μm carbon gas absorption band used to recover the vertical profiles of the atmospheric temperature. Outgoing radiation spectra measured by IKFS-2 instruments make it possible to restore vertical temperature profiles with errors close to 1K in most of the 0–30 km high-altitude region, except for the lower troposphere and altitudes above 30 km, where these errors are close to 2–3K.

Keywords: satellite remote sounding, atmospheric temperature, IKFS-2 FTIR spectrometer, fast radiative model

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1. The idea of using measurements of Earth's outgoing thermal IR radiation spectra for the remote atmospheric temperature vertical profiling was first proposed in the 1950s [1, 2]. The first experiments on the implementation of the spectral method of temperature sounding from space were successfully carried out on the meteorological spacecraft (SC) NIMBUS-3 in 1969 [3, 4]. In the Soviet Union, the first experiments on thermal atmospheric sounding were carried out in 1971 [5], and in 1983–1988 the remote atmospheric temperature sounding system was operating based on IR spectroradiometers mounted on operational polar-orbiting weather satellites of the Meteor-2 series (NN 9–17) [6]. The accuracy and vertical resolution of satellite remote sounding of foreign and domestic meteorological SC were inferior to those of upper air sounding. Later, both abroad and in our country, there were numerous theoretical and experimental studies, as well as equipment developments, aimed at the implementation of user requirements (see the User Requirements for Observation section of the World Meteorological Organization's website, https://www.wmo-sat.info/oscar/observingrequirements). In particular, for the global numerical weather prediction, temperature-sounding data should have an accuracy better than 1 K and a vertical resolution of ~1 km in the troposphere.

In July 2014, Meteor-M2 SC was launched, the second polar-orbiting weather satellite of the Meteor-M series [8]. Meteor-M series satellites were commissioned and the onboard mission equipment is operated by Roshydromet (SRC Planet). Onboard the SC, there are different instruments for the remote sounding of parameters of the atmosphere and surface of the Earth, including the IKFS-2 FTIR spectrometer developed at the Keldysh Research Center. The main technical characteristics of the IKFS-2 equipment obtained during the ground calibration and confirmed during flight tests of the Meteor-M2 SC are given in the Table 1 [9, 10]. Note a sufficiently broad spectral region of outgoing thermal radiation measurements (5–15 mm) and a high spectral resolution (0.4 cm^{-1}) at a low level of random measurement errors (0.15–0.4 mW/(m^2 sr cm^{-1}). The outgoing radiation IR spectrum detected by the IKFS-2 Fourier spectrometer contains 2000 channels.

According to the results of numerical simulations and satellite experiments conducted in recent years [7, 11], a high spectral resolution and a large number of spectral channels of IKFS-2 measurements are sufficient to achieve the accuracy and vertical resolution of the reconstructed temperature profiles mentioned

Table 1. Main technical characteristics of IKFS-2

Parameter	Value
Working spectral range	5–15 μm (660–2000 cm^{-1})
Spectral resolution	0.4 cm^{-1}
Noise equivalent spectral radiance, NESR(ν)	0.1–0.3 mW/(m^2 sr cm^{-1})
Swath	1000–2500 km
Spatial resolution at nadir	35 km

above. This is indirectly confirmed by investigations of the information value of IKFS-2 data given in [12].

2. Data from satellite measurements after radiometric and spectral calibration are used for the solution of inverse problems of atmospheric remote sounding. The onboard radiometric calibration is carried out by periodic instrumental measurements of space radiation (zero radiation in the IR spectral region) and simulated blackbody at a known temperature. The spectral calibration (association with the wavenumber scale) is carried out using a reference laser, which is also part of the device.

The quality of onboard radiometric and spectral calibration of IKFS-2 measurements is characterized by Fig. 1. In this figure, mean differences and standard deviations between measurements of spectra by IKFS-2 and the IASI hyperspectral infrared sounder that has functioned since 2006 are given. The IASI interferometer mounted on European MetOp series SC has a high-accuracy and stable radiometric calibration system, which makes it possible to use IASI as a reference device for the intercalibration of different satellite IR instruments [7]. Measurements with a time difference of about 20 min, with the distance between the centers of pixels of IKFS-2 and IASI of no more than 10 km, and the zenith angle difference of no more than 2° were used in comparison. All measurements were carried out over the water surface in the latitudinal belt 65S–65N. As can be seen from the figure, for the 15-μm spectral region of the CO_2 absorption band (660–750 cm^{-1}) used for atmospheric temperature sounding, mean (curve *2* in Fig. 1) and mean squared (curve *3* in Fig. 1) differences are close or even less than the NESR, the spectral radiance equivalent to the noise of IKFS-2 measurements mean squared for the period of comparisons on August 22–23 (curve *1* in Fig. 1), which indicates high accuracy of the radiometric calibration of the instrument.

3. For the analysis and interpretation (inversion) of IKFS-2 measurement data, i.e., in order to obtain atmospheric sounding products, it is necessary to develop fast and high-accuracy radiation calculation procedures, known in the literature as fast radiative models (FRM). Such a FRM, developed based on the known RTTOV FRM (http://nwpsaf.eu/site/softwave/rttov/), makes it possible it numerically simulate (with the desired accuracy and high performance) spectra of the outgoing radiation measured by IKFS-2 and their

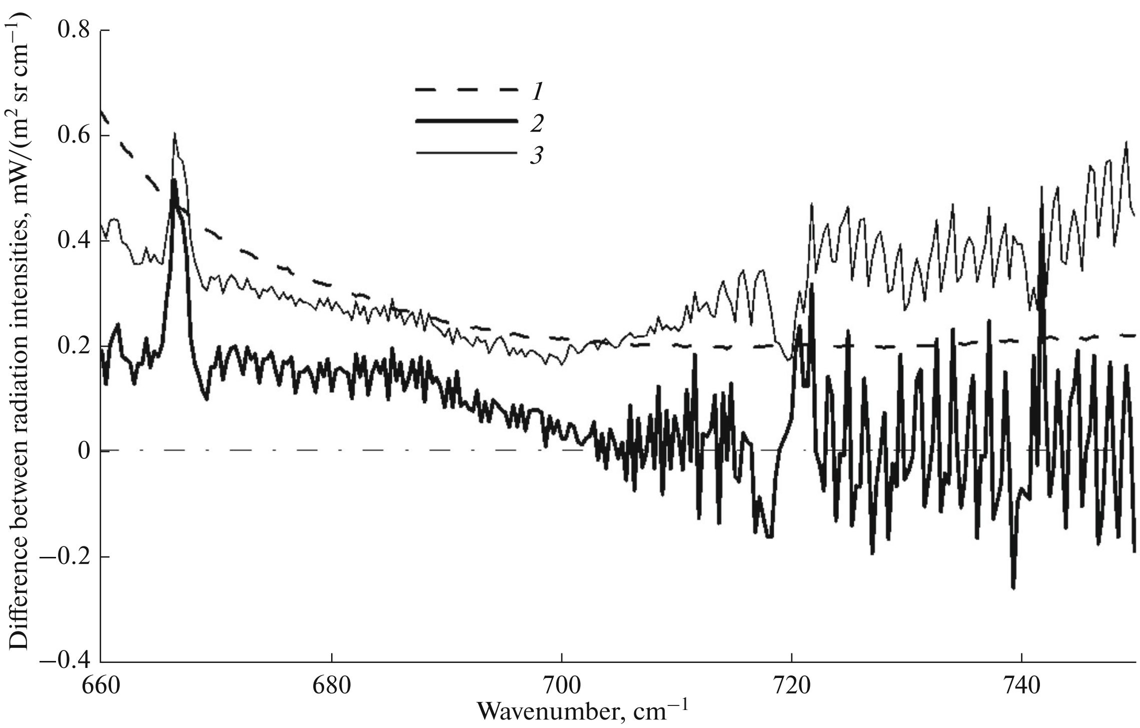

Fig. 1. Mean difference and standard deviation of measurement difference of IKFS-2 and IASI in matched pairs on July 22–23, 2015. Designations of the curves: (*1*) NESR IKFS-2, the root-mean-square value for all comparisons; (*2*) the mean difference between the measured radiation intensities, IKFS-2 minus IASI; and (*3*) the mean-square difference.

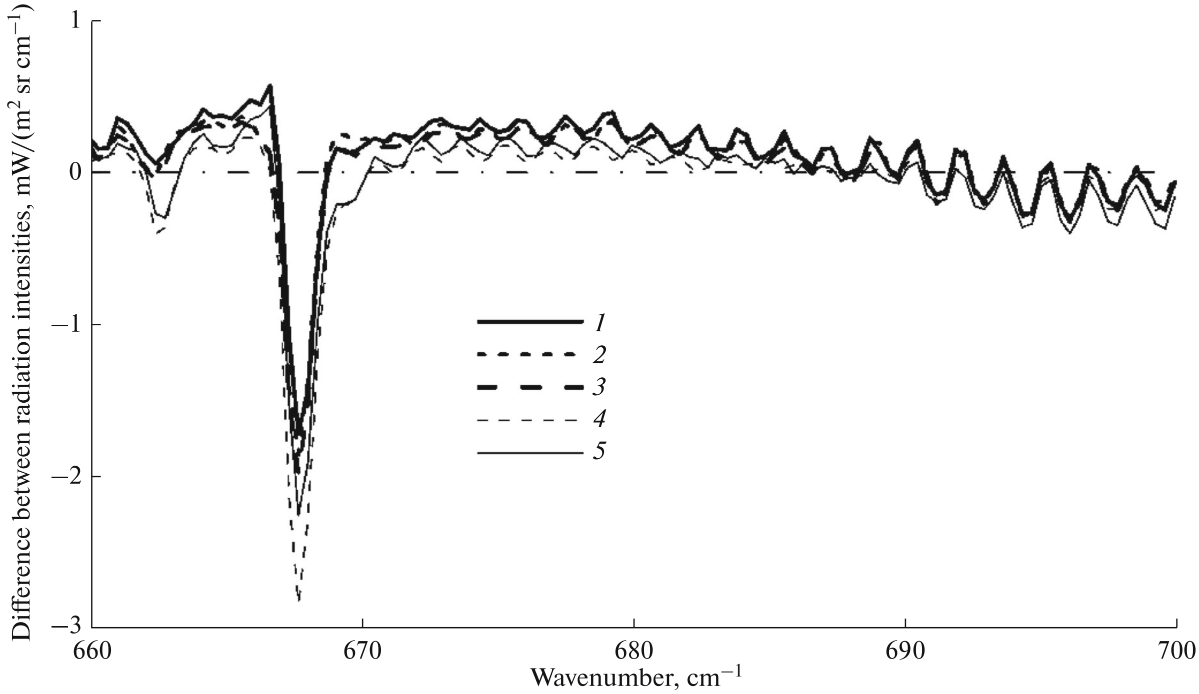

Fig. 2. Mean differences between measured and calculated spectra for three IR sounders and for different time periods (2015). The spectral region for the stratospheric temperature sounding. Designations of the curves: (*1*) IKFS-2, February 5–6; (*5*) August 20–22; (*2*) IASI-A, February 5–6; (*4*) August 20–22; and (*3*) IASI-B, February 5–6.

variations, depending on variations of the parameters of atmosphere and surface [13].

Figure 2 shows mean differences between spectra of the outgoing radiation measured and calculated by the FRM from [13] in the CO_2 absorption band for a large ensemble of atmospheric conditions. In the figure, it can be seen that systematic differences between model and actual IKFS-2 measurements are less than 0.5 mW/(m^2 sr cm^{-1}), as well as for IASI-A and IASI-B. Large differences in channels near the center of the CO_2 absorption band (667 cm^{-1}) are caused by the lack of high-accuracy information about the stratospheric temperature at altitudes of 30–50 km, i.e., in the region where the outgoing infrared radiation is formed for the specified spectral interval.

In Fig. 3, a comparison of calculated and measured spectra in the transparency window of 8–12 μm window is given. It shows a systematic overestimation of the calculated values compared with measurements, which is about 1.5 mW/(m^2 sr cm^{-1}). This overestimation is also characteristic for IASI-A and IASI-B.

One possible cause of the bias is that, in the atmospheric radiation model, the radiation aerosol extinction is not taken into account, e.g., [14, 15]. It is currently difficult to take it into account because there are no synchronous data about the IR optical characteristics of aerosols at satellite sounding stations.

4. As was indicated above, the main target application of the IKFS-2 IR sounder is the remote vertical temperature profiling. Different algorithms [15–18] and corresponding software were developed in order to solve this classic inverse problem of satellite meteorology: multiple linear regression algorithms, artificial neural network algorithms, and the physical and mathematical iterative algorithm based on the statistical regularization method. At the first stage, regression algorithms are usually used. At the second stage, it is expedient to use an iterative algorithm if the difference between the measured and calculated radiation spectra exceeds a predetermined threshold (residual criterion).

It is important to emphasize that the effective use of the listed algorithms is possible only when solving two auxiliary problems, i.e., cloudiness detection in the field of view of the instrument and correction of biases between the satellite data and the numerical simulation results.

Figure 4 shows an example of the vertical distribution of the temperature profile restoration error based on IKFS-2 measurements under cloudless conditions. Data for October 17, 2015, over the water surface identified as cloudless data was used for an analysis of remote-sounding error statistics. The mean-square difference between the accepted satellite estimations and spatially matched synchronous data of the 6-h numerical forecast of temperature fields made by the global forecast system of the National Centers for Environmental Prediction (NCEP GFS) was used as a quantitative error measure. These data are considered the reference. Two types of satellite estimations are

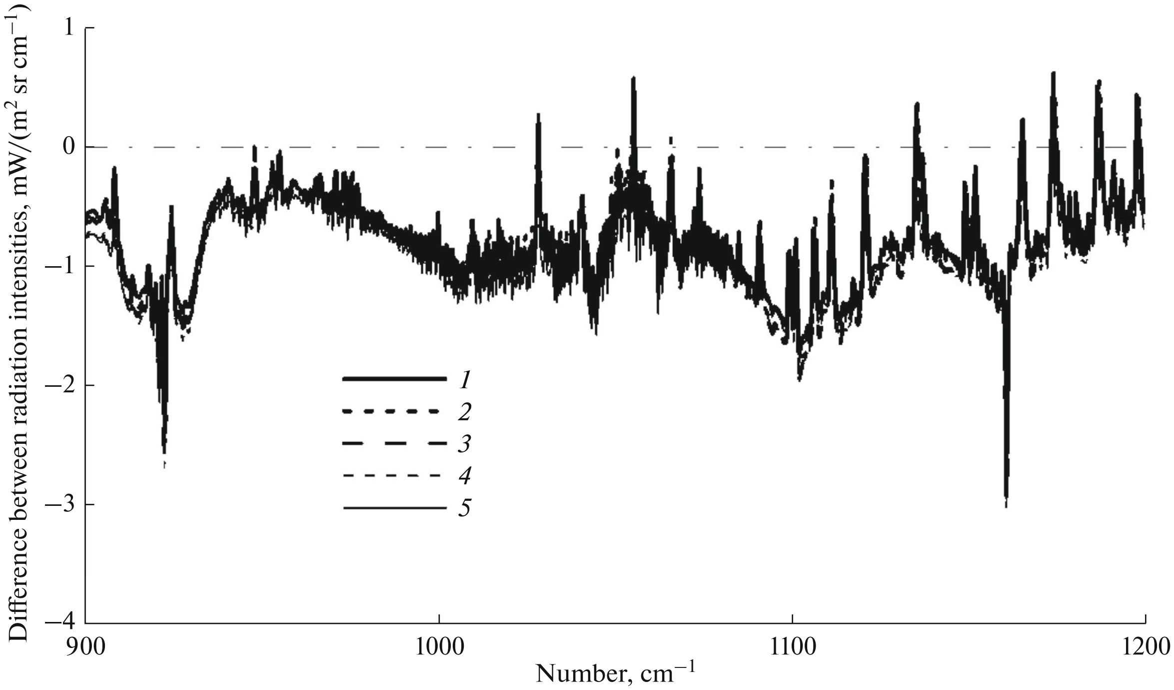

Fig. 3. Mean differences between measured and calculated spectra for three IR sounders and for different time periods (2015). The spectral region is the transparency window. (*1*) IKFS-2, February 5–6; (*5*) August 20–22; (*2*) IASI-A, February 5–6; (*4*) August 20–22; and (*3*) IASI-B, February 5–6.

used in comparisons, i.e., without vertical averaging and with averaging (for matching the vertical resolution of restored and reference profiles). It should be noted that, according to the estimations of the Hydrometeorological Centre of Russia, the root-mean-square error of the given forecast data (in comparison with radiosounding data) is in the range 0.6–1.4°C for the layer of 1000–40 hPa.

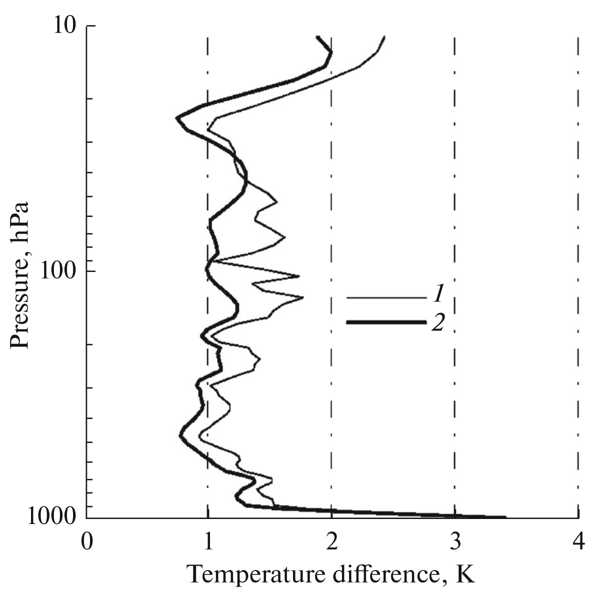

Fig. 4. Mean-square differences of restored temperature profiles and analysis of NCEP GFS data. October 17, 2015. (*1*) Direct comparison of the profiles of the two types of source data and (*2*) vertically averaged taking into account averaging kernels.

Figure 4 shows that, in most of the troposphere (the 1000–100 hPa layer), temperature determination errors are ~1 K when matching the vertical resolution of satellite estimations and the reference data (taking into account averaging kernels of remote satellite measurements). A marked increase in the error of remote measurements near the surface is presumably caused by the inaccurate setting of the surface radiating capacity when solving the inverse problem and above-noted systematic overestimation of the calculated radiation values compared with the measured values in the transparency window of 8–12 μm.

The error of satellite temperature-sounding results can be estimated by the comparison with the closest (in time and place) air-sounding data. Such comparisons made for the sample of pairs of satellite estimation–radiosonde limited by size provide results close to those given in Fig. 4.

5. The main results of the space experiments and conducted investigations can be summarized as follows:

(i) The developed IKFS-2 IR satellite sounder records the spectra of the outgoing infrared radiation of the atmosphere–surface system with high radiometric accuracy corresponding to the modern-world level.

(ii) The IR radiation models (including the FRM) adequately describe IKFS-2 spectral measurements in a 15-μm CO_2 absorption band used to restore the atmospheric temperature vertical profiles. In the transparency window of 8–12 μm, systematic overestimations of the calculated values are observed, which is probably caused by the effect of the aerosol component of the atmosphere, which is not taken into account in the radiation model of the atmosphere.

(iii) Interpretation of the spectra of outgoing radiation measured using IKFS-2 instruments under cloudless atmosphere conditions makes it possible to obtain vertical temperature profiles with errors close to 1 K in most of the 0–30 km high-altitude region, except for the lower troposphere and altitudes above 30 km, where these errors are close to 2–3 K.

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