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RUSSIAN FTIR SPECTROMETER (IKFS-2) FOR METEOROLOGICAL SATELLITES: FLIGHT EXPERIENCE AND FURTHER DEVELOPMENT

In the document, the first Russian IKFS-2 spectrometer operation is analyzed. It was launched in July 2014 on the "Meteor-M" No.2 meteorological satellite. IKFS-2 belongs to a class of hyper- spectral IR sounders, designed to measure the outgoing IR radiance spectra and to provide information on the thermodynamic parameters and the composition of the atmosphere such as vertical temperature and humidity profiles, estimates of the ozone, carbon dioxide, and other trace gases total column content. Since launch, the instrument performance has been remained stable, and the actual IKFS-2 characteristics (threshold value of NESR, uncertainty of onboard radiometric and spectral calibrations, spectral resolution) meet the planned requirements.

Besides, the document also presents the technical characteristics of prospective FTIR IKFS-3 & IKFS-GS spectrometers to be developed for future Russian LEO & GEO meteorological satellites, namely "Meteor-MP" and "Electro-M".

1. INTRODUCTION

The first Russian advanced infrared (IR) atmospheric sounder IKFS-2 was launched in July 2014 on the "Meteor-M" No.2 meteorological satellite. IKFS-2 is a Fourier transform spectrometer covering the spectral domain of 5–15 µm. It belongs to a class of hyperspectral IR sounders, designed to measure the outgoing IR radiance spectra and to provide information on the thermodynamic parameters and the composition of the atmosphere such as vertical temperature and humidity profiles, estimates of the ozone and other trace gases total column amounts. In the document, the IKFS-2 operation on board "Meteor-M" No.2 is analysed, including the assessment of the measurements' quality (the errors of radiometric and spectral calibration) and their information content. Since launch, the instrument performance has been remained stable, and the actual IKFS-2 characteristics (threshold value of NESR, uncertainty of onboard radiometric and spectral calibrations, spectral resolution) meet the planned requirements. There is a good agreement between IKFS-2 measurements and measurements of other satellite instruments (SEVIRI, IASI), which are treated as reference ones.

The operational IKFS-2 L2 processor has been developed and tested to carry out the retrieval of the set of target geophysical parameters including atmospheric temperature and humidity profiles, surface temperature as well as ozone, carbon dioxide, methane, and nitrous oxide total content. To monitor the quality of retrieved products and to validate the algorithms used, a special tool has been designed dedicated to the intercomparison of L2 products and reference meteorological observations.

The obtained results confirm the proper quality and stability of IKFS-2 radiometric and spectral characteristics as well as L2 products. Therefore, the IKFS-2 is used for intercalibration IR channels of Russian MSU-MR scanners installed on board LEO satellites of the Meteor-M series and MSU-GS scanners installed on board GEO satellites of the Electro-L series. The spectrometer is also a likely candidate for a GSICS reference instrument like European IASI FTIR spectrometer.

By the end of the decade, Russia (Roscosmos) is expected to launch a new meteorological Meteor-MP satellite. Its onboard payload will include an IKFS-3 FTIR spectrometer. The first launch is scheduled for 2029.

The development of an IKFS-GS Fourier spectrometer, which will be installed on the new Russian geostationary meteorological Electro-M satellites, is also underway. A feature of the device is the regional coverage mode with a doubled spectral resolution.

2. FLIGHT EXPERIENCE

2.1. IKFS-2 characteristics and performances

The Fourier transform spectrometer IKFS-2 consists of an opto-mechanical unit installed in the open space on the instrument platform of the spacecraft, and the electronics module, located in a pressurized compartment. The instrument is based on Michelson interferometer with a double pendulum optical path difference (OPD) scan mechanism, cross-track scanning device and two stage passive radiant cooler to provide cooling of the MCT (HgCdTe) photoconductive detector. The design of the device is shown in Figure 1.

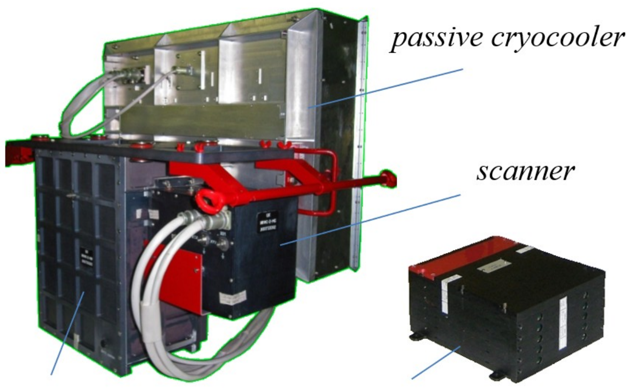

Figure 1:IKFS-2 design.

The opto-mechanical unit includes:
- scanner module that allows scanning the field of view (Earth views) and pointing at reference radiation sources (internal calibration blackbody and deep space) during calibration views
- interferometer module that generates an interference signal as a function of the OPD between the two arms of the interferometer
- passive radiant cooler to provide cryogenic temperatures of the photoconductive detector.

The electronic module is designed for device operation control, preliminary processing measurements, and generating packages of scientific and service data.

The main technical characteristics of IKFS-2 are presented in Table 1.

Table 1. IKFS-2 technical characteristics

Spectral range	660-2000 cm^{-1}
Spectral resolution (non-apodized)	0.4 cm^{-1}
Radiometric calibration error	< 0.5 K
Radiometric noise (NESR)	0.15-0.3 $mW \cdot cm/(m^2 \cdot sr)$
Instantaneous field of view IFOV diameter at SSP	40 mrad 30 km
Swath width Spatial sampling	1000-2500 km 60-110 km
IFG period (sweep + reverse time)	0.6 s
Data rate	600 kb/s
Mass	50 kg
Power	50 W

The IKFS-2 instrument status and data quality have been comprehensively investigated during the commissioning phase and exploitation. Intercomparisons of IKFS-2 data with collocated IASI and CrIS spectra shows that the discrepancies in the average spectra and their variability do not exceed measurement noise.

To continuously monitor the IKFS-2 radiometric and spectral calibration accuracy and stability, intercalibration with independent measurements of SEVIRI/Meteosat-10 -11 are made for six last years. The procedure of SEVIRI and IKFS-2 intercomparison is almost fully identical to well-known SEVIRI-IASI one (EUMETSAT,2016). SEVIRI channels 5-11 centered at 6.2, 7.3, 8.7, 9.7, 10.8, 12.0, 13.4 µm are used. For each IKFS-2 spectrum, satisfying proper co-registration criteria with SEVIRI (in time, geographical coordinates, and surface incidence angles), the recorded spectral radiances were convolved with the SRFs of each SEVIRI IR channel, and converted to brightness temperatures. As a result, so-called IKFS-2 synthetic SEVIRI IR measurements were obtained. Then, these values with space resolution in nadir approximately 3 km were compared to the brightness temperatures (BT) measured by SEVIRI and averaged within the IKFS-2 effective field of view (30 km).

Using intercalibration data of SEVIRI and IASI available on GSICS portal, there is a possibility to organize also the “double difference” method of IKFS-2 (monitored instrument) and IASI (reference instrument) intercomparison with SEVIRI used as intermediary (transfer) instrument. The results of such intercomparison (from Feb 2015 to May 2019) in SEVIRI channels are summarized for more than four years and presented in Figure 2. The bias of all channels, except from 13.4 µm, are consistent within ~ 0.3 K. BT differences in 13.4 µm channel are changing in time identical to SEVIRI-IASI divergence.

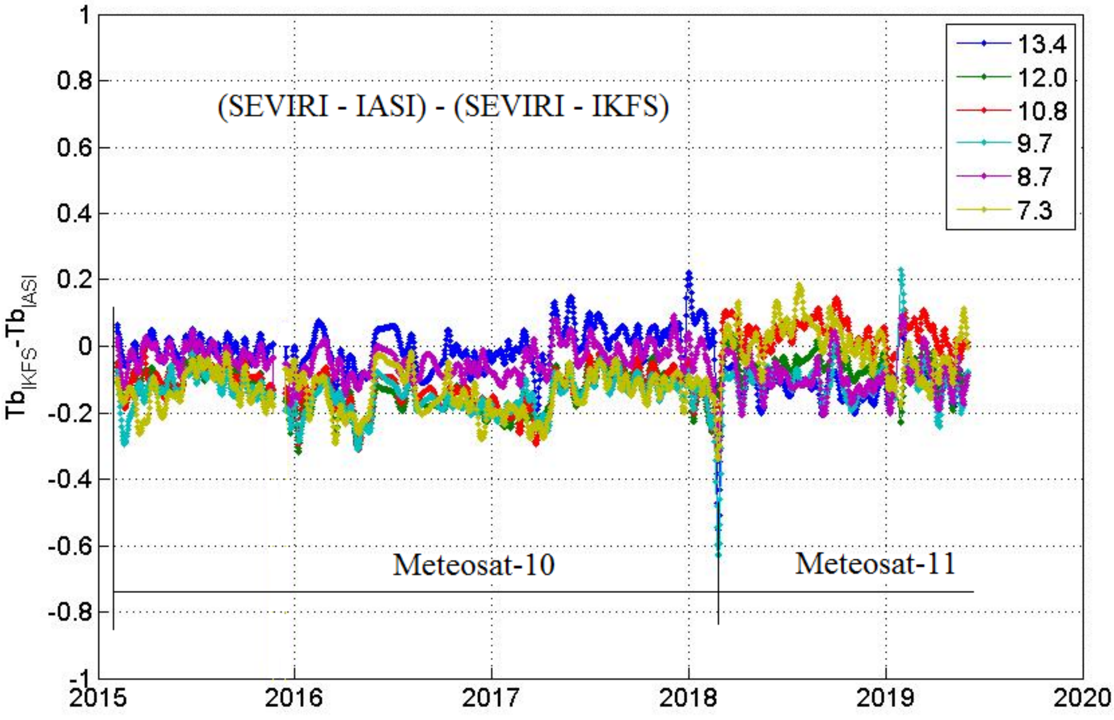

Figure 2: IKFS and IASI intercomparison results in different SEVIRI spectral channels by double differences method

2.2. Atmospheric sounding products, assimilation trials

The performance characteristics (spectral and radiometric calibration, instrumental noise) of IKFS-2 proved to be in full accordance with predetermined specifications. It means that the radiance products (calibrated apodized radiances spectra, level 1C, HDF5 format) can be used for remote atmospheric sounding applications.

The operational IKFS-2 L2 processor has been developed and tested to carry out (for each single FOV) the retrieval of the set of target geophysical parameters including atmospheric temperature and humidity profiles, surface temperature as well as ozone, carbon dioxide, methane, and nitrous oxide total content (in clear sky conditions). To monitor the quality of retrieved products and to validate the algorithms used, a special tool has been designed dedicated to the inter-comparison of L2 products and reference meteorological data. The radiosonde profiles and GFS NCEP analyses matched in space and time with retrievals are used as validation reference. Figure 3 shows example of global vertical accuracy statistics assessed through the comparison with closely collocated radiosonde profiles. As seen from Figure 3, the error statistics in 2018 for one and ten months are quite similar for both samples. The accuracy of IKFS-2 based temperature profile retrievals, estimated by comparison with radiosondes, is approximately 1.5K in the troposphere and reduces to about 2-3 K in the lower troposphere and stratosphere. Mean characteristics (bias and standard deviation) of difference are very close with ones of comparison with GFS NCEP analyses.

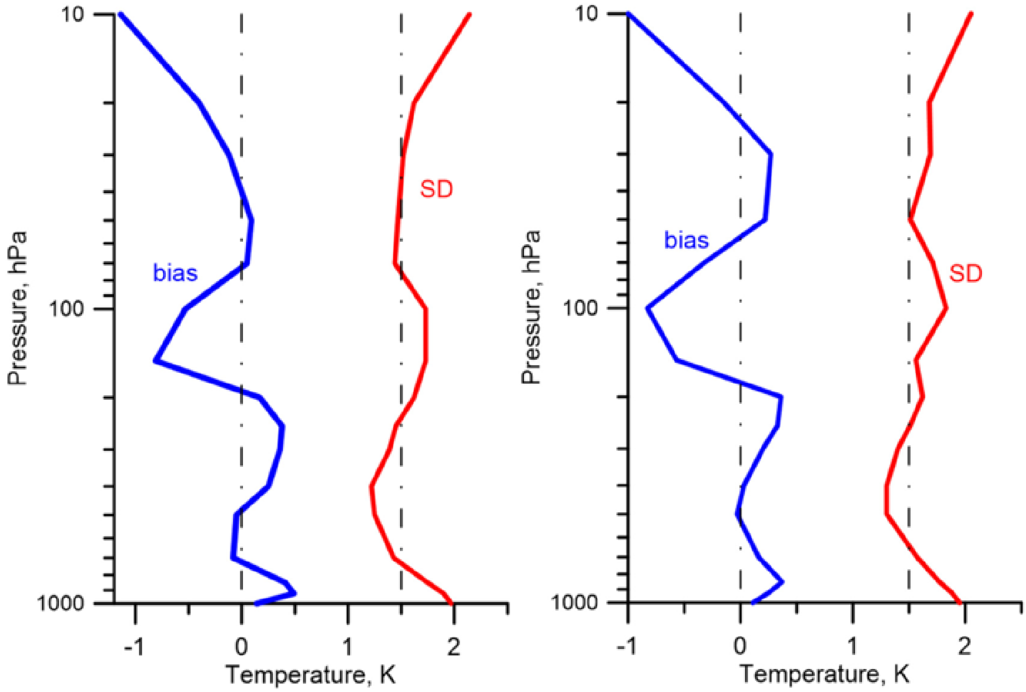

Figure 3. Error statistics (bias and SD) of radiosonde minus (IKFS-2)-based temperature profiles; the averaging period of July 2018 (left side) and of Jan–Oct 2018 (right side)

Results of comparison statistic for relative humidity profiles versus radiosonde profiles and GFS NCEP analyses data in Russian Far East for July 2020 are shown in Figure 4. The time shift between the satellite and radiosonde measurements or GFS NCEP data was less than two hours. Spatial distance is less 50 km for radiosonde measurements and less 10 km for prognostic data. On the whole, the difference between IKFS-2 estimates and reference data is less than 25%.

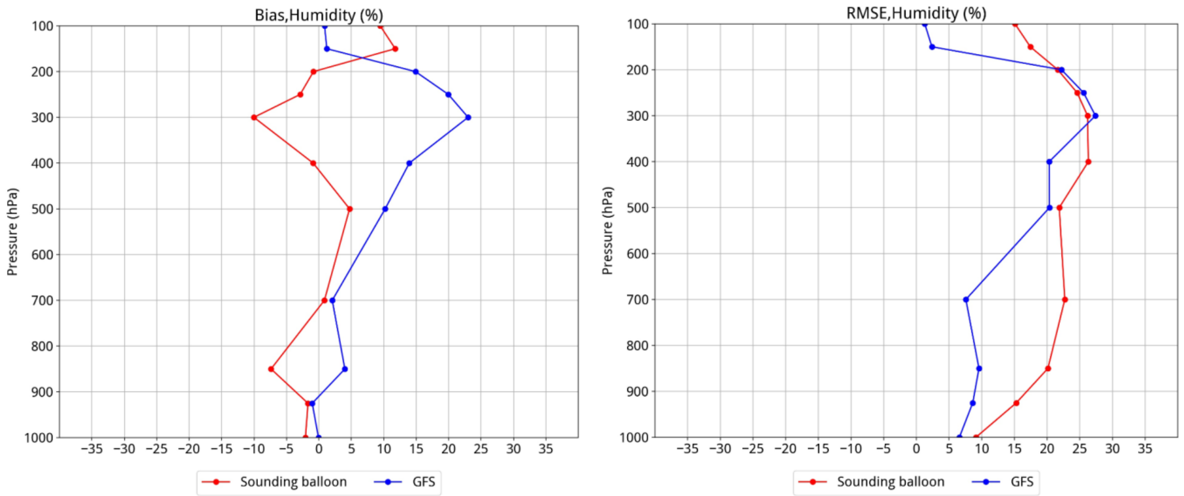

Figure 4. Error statistics (bias - left side and RMSE - right side) of radiosonde minus IKFS-based relative humidity profiles in Russian Far East; the averaging period of July 2020

The total ozone column (TOC) in the atmosphere by IKFS-2 data is determined using artificial neural network (ANN) algorithm. For the ANN training, the OMI L2 TOC products (taken for the period of 2015-2017) were used.

Table 2 presents the results of the comparison of TOC estimates derived from observations of the three satellite instruments: IKFS-2, OMI and GOME-2. This instrument is accommodated on the same Metop platforms as the IASI instrument. The datasets for comparison do not incorporate the IKFS-2 data used for the construction of the retrieval method.

Table 2. Comparison of TOCs estimates derived from IKFS-2, OMI and GOME-2 data at different seasons (R – correlation coefficient)

Sensors	March–May			June–August			September–November		
	R	Bias (%)	SD	R	Bias (%)	SD	R	Bias (%)	SD
IKFS-2-OMI	0,99	−0,1	2,7	0,98	−0,1	2,1	0,99	−0,1	3,1
IKFS-2-GOME-2	0,98	0,7	4,0	0,97	−1,9	2,3	0,99	−1,2	3,9

Figure 4 shows the TOC evolution estimated from different satellite data (IKFS-2, OMI, SBUV, and IASI) at several Russian ground- based stations for winter 2016. All satellite data generally provide a good description of the TOC temporal variations, including the short-term ozone loss in winter. The differences for some days increase up to 5–15%, which may be caused by the spatio-temporal mismatch of the various measurements.

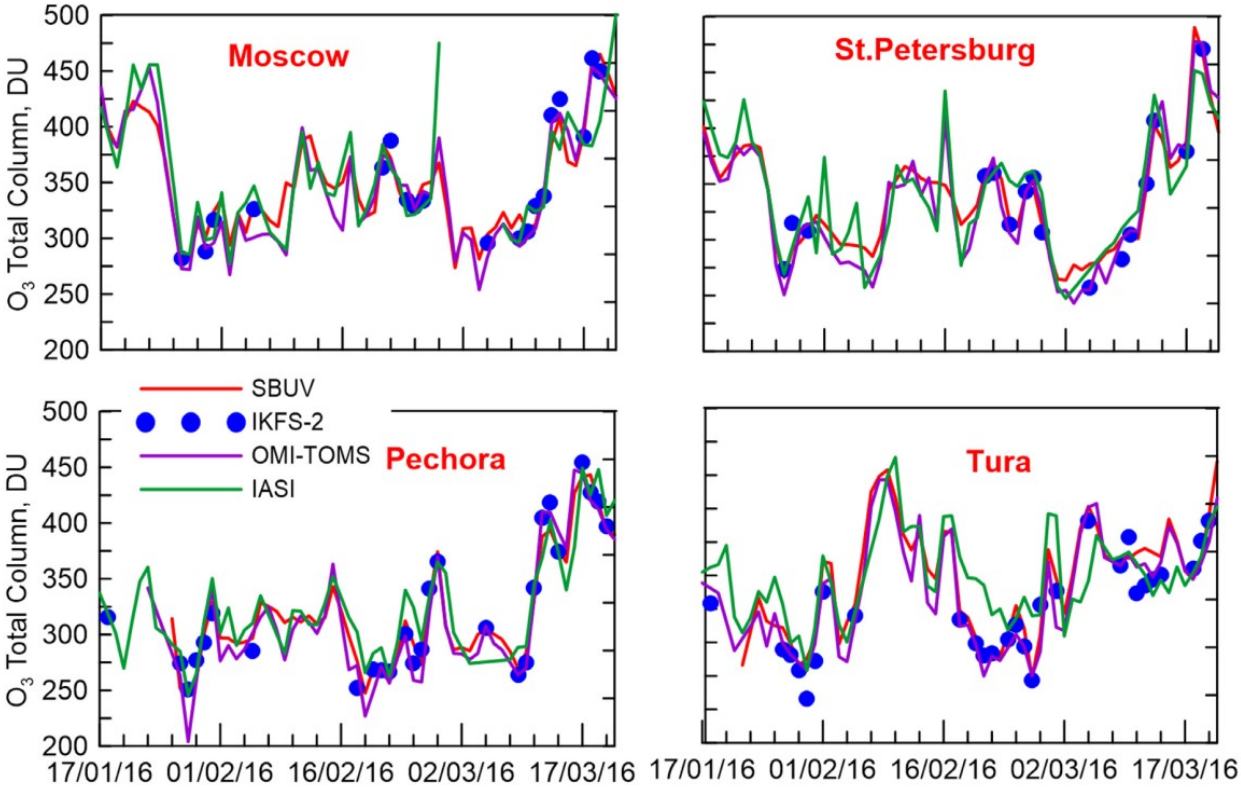

*Figure 4 Comparison of various satellite-based TOCs estimates (IKFS-2, OMI, SBUV, and IASI) over different ground-based stations (*Timofeyev et al. JQSRT, Vol. 238, November 2019, 106579, http://doi.org/10.1016/j.jqrst.2019.106579)

The high stability of IKFS-2 radiometric characteristics allows to develop algorithm to retrieve of CO_2 column-averaged dry-air mixing ratio (XCO2) from its data. To develop such algorithm we used contact measurements of CO_2 ratio in the dry air at the ZOTTO (ZOtino Tall Tower Observatory) in Central Siberia. The measurements at the tower on 6 levels (from 4 to 301 m) were carried out in 2016. The coincidence of the measured concentrations on different levels indicates convective mixing of the atmosphere which makes it possible to use them as a reference for satellite algorithm development. The RMS error of the XCO2 maps under clear sky conditions does not exceed 2 ppm. To estimate it, we used comparisons with independent measurements in ZOTTO observatory and Mauna Loa performed in 2017.

The first version of XCO2 maps with cloud mask are shown in Figure 5 for Central Siberia (a) and the Pacific Ocean in the region of Hawaii (b).The efficiency of the cloud mask form IKFS-2 data is validated by the images of scanners with high spatial resolution of MODIS/Aqua (for Central Siberia) and AHI/Himavary-8 (Pacific Ocean). The scanner images are shown in the upper right corner of the pictures.

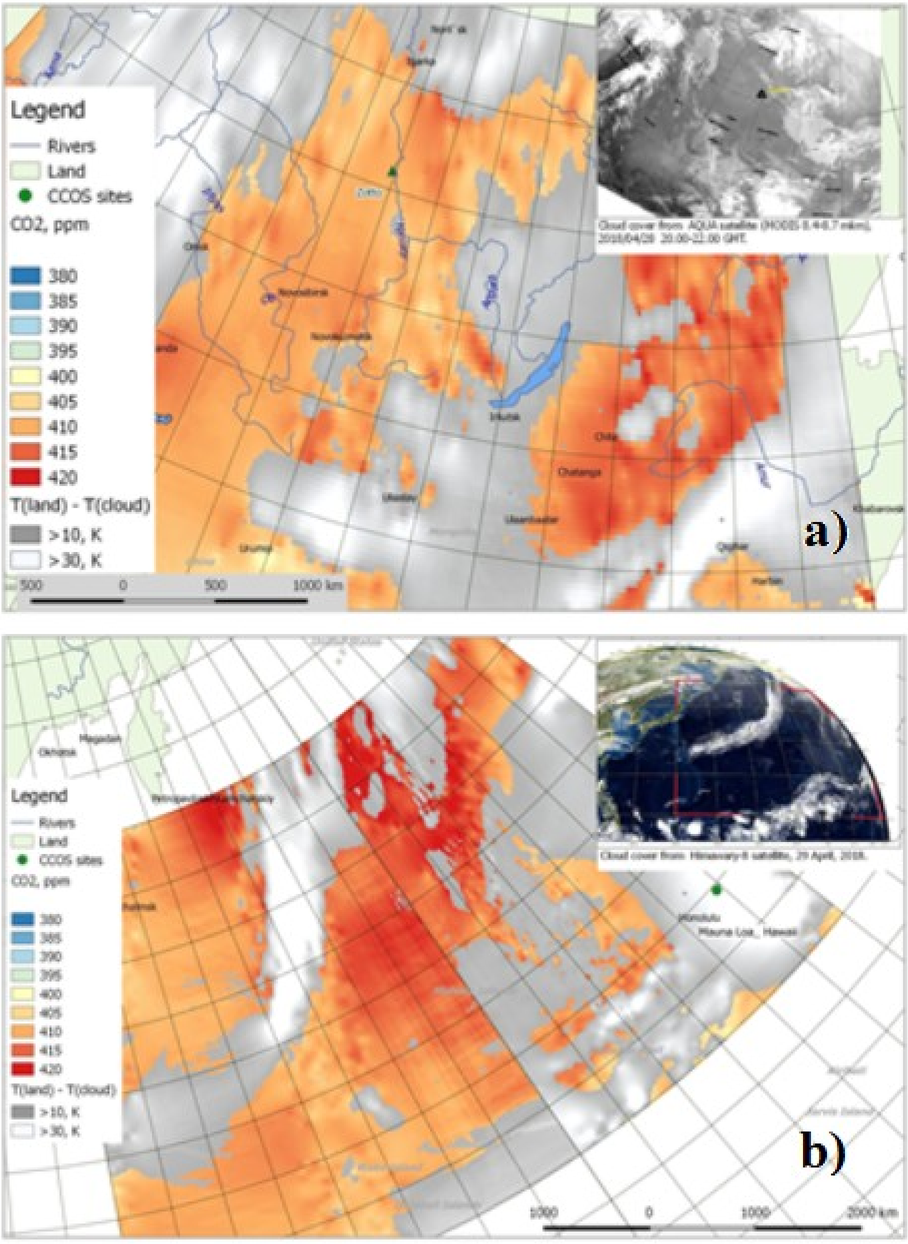

Figure 5. Maps of CO2 ratio with cloud mask, 29 April 2018;
a) Central Siberia; b) the Pacific Ocean in the region of Hawaii

The quality of XCO2 estimates based on IKFS-2 measurements was analyzed by comparison with OCO2 measurements over Central Siberia. An example of such comparison is shown in Figure 6. There are presented trajectories of the OCO2 satellite with its XCO2 estimates (https://co2web.jpl.nasa.gov/) as well as the values calculated according to IKFS-2 data in the form of a color map with a concentration scale. The XCO2 value measured at Zotto observatory is also indicated. The bias between IKFS- 2 and OCO2-based XCO2 estimates in average are less than one gradation of the map color scale (5 ppm). Similar results of comparison were obtained on 5 August 2020 (see Figure 7).

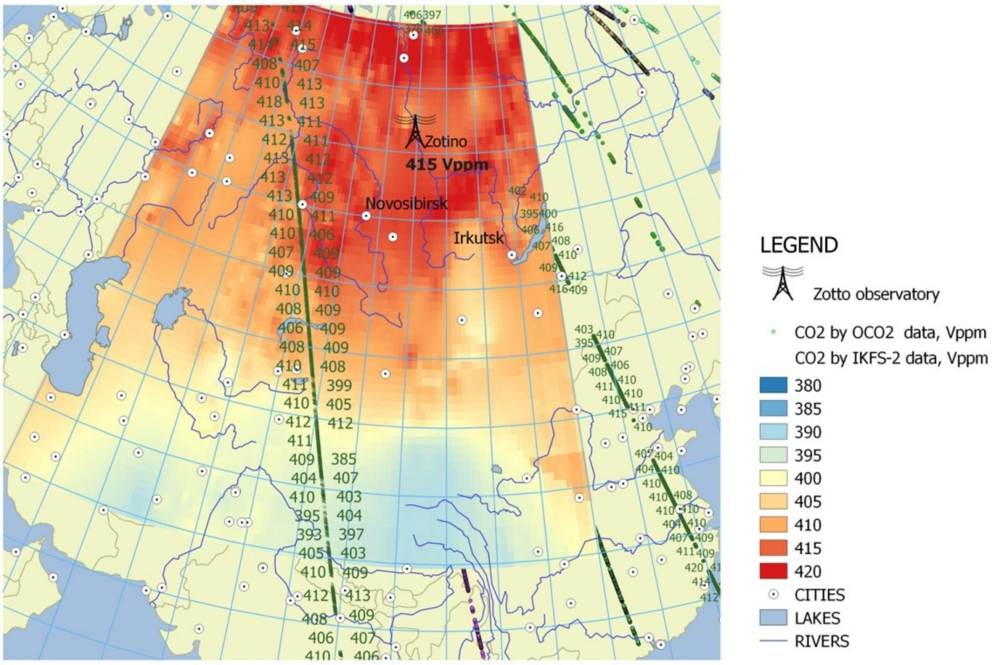

Figure 6. Map of IKFS- 2 and OCO2-based XCO2 estimates, 8 April 2019

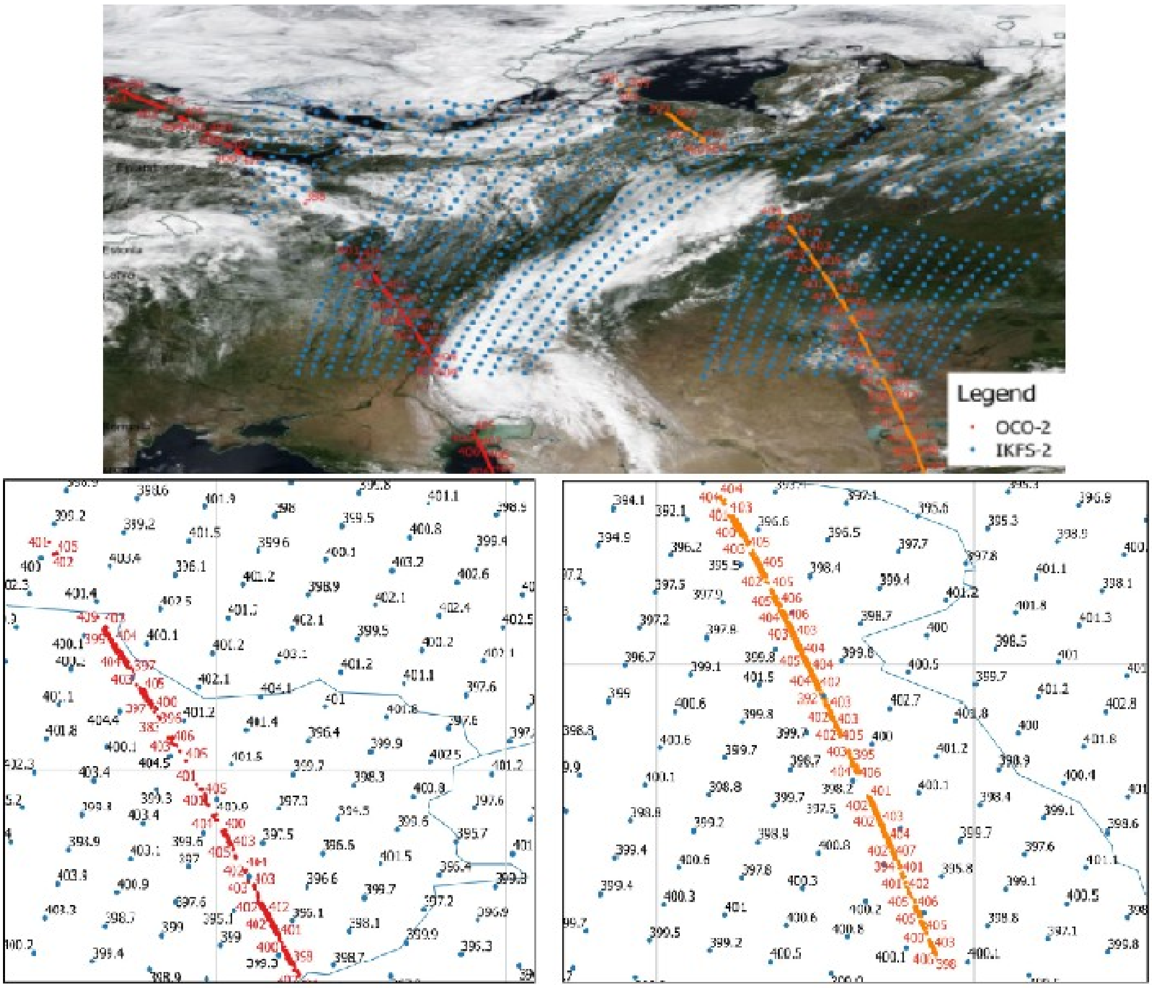

Figure 7. Comparison of IKFS- 2 and OCO2-based XCO2 estimates, 5 August 2020

When analyzing the data (Figure 6 & 7), cloudiness was identified using the visible and near-IR channels of the MSU-MR/Meteor-M No.2 sensor.

The obtained results confirm the proper quality and stability of IKFS-2 radiometric and spectral characteristics. It has been proved in several papers (see, for example, Timofeyev Y. M., A.B. Uspensky, F.S. Zavelevich et al. Hyperspectral infrared atmospheric sounder IKFS-2 on “Meteor-M” No. 2 – Four years in orbit // JQSRT, Vol. 238, November 2019, 106579, http://doi.org/10.1016/j.jqrst.2019.106579).

Therefore, we use IKFS-2 for intercalibration IR channels of Russian scanners MSU-MR installed on board LEO satellites of the Meteor-M series and MSU-GS installed on board GEO satellites of the Electro-L series. Currently, the IKFS-2 data records are freely available from the archive of the Russian Cal/Val system for Satellite Data and Products: http://planet.rssi.ru/calval/public-ikfs-en. So, the spectrometer is also a likely candidate for a GSICS reference instrument like IASI FTIR spectrometer.

Besides, the use of clear-sky infrared radiances in selected temperature sensitive IKFS-2 channels in the data assimilation system of the Hydrometcentre of Russia was investigated. The comparison with the NCEP 6h forecast showed that the accuracy of IKFS-2 data was comparable with that of IASI observations. A positive impact of both IKFS-2 and IASI data on three-day weather forecasts was found, see, for example, Tsyrulnikov M. D. et al (2019), Development of the data assimilation scheme of the Hydrometcentre of Russia // Hydrometeorological Research and Forecast. № 4 (374). C. 112-126. [in Russian].

3. FURTHER DEVELOPMENT

At present, only one IRFS-2 spectrometer is successfully operating in orbit. Two subsequent instruments were lost during the unsuccessful launch of the Meteor-M satellite No.2-1 in November 2018 and after an unexpected depressurization of the instrument compartment of the Meteor-M No.2-2 satellite in December 2019. In accordance with the existing Russian Federal Space Program, the next spectrometer will be launched in August 2021 on board the Meteor-M satellite No.2-3. The IKFS-2 series will be continued until the Meteor-M satellite No.2-6 scheduled to launch in 2025.

By the end of the decade, Russia is expected to launch a new meteorological Meteor-MP satellite. Its onboard payload will include an IKFS-3 FTIR spectrometer. Specifications for this instrument are shown in the left part of Table 3. The first launch is scheduled for 2029.

The development of an IKFS-GS Fourier spectrometer, which will be installed on the new Russian geostationary satellites of Electro-M series, is also underway. Specifications for this instrument are shown in the right part of Table 3. A feature of the device is the regional coverage mode with a doubled spectral resolution

Table 3. Technical characteristics of Russian promising FTIR spectrometers

FTIR spectrometer	**IKFS-3**	**IKFS-GS**
Platform	Meteor-MP (SSO, 820 km)	Electro-M (GSO)
Spectral range	3.6-15.5 μm (645-2760 cm^{-1}) LW: 645-1200 cm^{-1} MW: 1200-2000 cm^{-1} SW: 2000-2760 cm^{-1}	LWIR: 700-1210 cm^{-1} MWIR: 1600-2250 cm^{-1}
Spectral resolution	0.25 cm^{-1} (nominal) (MPD = 2 cm)	0,5 cm^{-1} (MPD = 1 cm)
Radiometric noise (NEdT@280K)	LW: 0.2…0.3 K MW: 0.2…0.5 K SW: 0.5…2.0 K	LWIR: 0.3…1.0 K MWIR: 0.3…1.8 K SW: 0.5…2.0 K
Radiometric calibration uncertainty	0.3 K	0.5 K
Spectral accuracy	3 ppm	3 ppm
Scanning mode	-	global coverage (60 min) regional coverage
Field of view (at nadir)	IFOV: 14 km (17 mrad) FOV: 50x50 km2 (5 pixels)	8 km
Swath width spatial sampling	2200 km 30 km	-
IFG scan period	-	(10-11) s
Mass	120 kg	250-300 kg
Power consumption	120 W	300-400 W

Data rate	3 Mbit/s	150 Mbit/s