ROCKET AND SPACE INSTRUMENTATION AND INFORMATION SYSTEMS
2015, vol. 2, issue 4, c. 30-39

**AEROSPACE METHODS OF SENSING THE EARTH, PLANETS AND OTHER SPACE OBJECTS.
GEOECOLOGY AND SPACE SEARCH AND RESCUE SYSTEMS**

UDC 629.785

Low resolution multispectral scanning device MSU-MR for the space information complex Meteor-M. Principle of operation, evolution, perspectives

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Annotation. The principle of operation, design features and directions of development of MSU-MR devices intended for operation as part of Meteor-M satellites No. 1 and No. 2 are considered. The equipment performs continuous survey of the Earth surface. Observation is carried out in six spectral channels. The spatial resolution in the nadir is 1 km, the swath of 2950 km.

Keywords: meteo-satellites, spectrozonal Earth observation, scanning device

Multiband scanner of low spatial resolution MSU-MR for space-based informational system "Meteor-M". The principle of operation and development prospects

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Abstract. This paper explains the principle of operation, construction details and development prospects of MSU-MR apparatus series. These apparatuses are intended for operation on board of meteo satellites "Meteor-M" No. 1 and No. 2. MSU-MR uninterruptedly observes the Earth in six spectral bands with spatial resolution of 1 km in the 2950 km field of view.

Key words: meteo satellites, multiband remote sensing of the Earth, scanning system

Introduction

At present, in accordance with the Concept for the Development of the Russian Space System of Earth Remote Sensing [1], it is planned to significantly increase the constellation of Meteor-M series specialised hydrometeorological satellites (developed by VNIIEM Corporation JSC) operating in sun-synchronous orbits with an altitude of 830 km. One of the most important instruments installed on these satellites is a low-resolution multiband scanning device - MSU-MR (Fig. 1), developed by JSC Russian Space Systems to solve hydrometeorological problems. The first MSU-MR device was manufactured for the spacecraft

"Meteor-M No. 1, the operation of which began in October 2009 and has been successfully continued until now (more than 5 years). The MSU-MR device provides global continuous observation of clouds and the Earth's surface in a 2950 km coverage area with a spatial resolution of 1 km in the spectral range from 0.5 to 12.5 μm. The main technical characteristics of the MSU-MR instruments (currently in operation) are given in Table 1. The information (image fragments) generated by the ISU-MR is presented in Fig. 2.

The analogue of the MSU-MR device is the American AVHRR (Advanced Very High Resolution Radiometer) radiometer, which is part of the NOAA satellite measuring complexes (orbital altitude 870 km) and provides image acquisition in 6 spectral channels (0.58-0.68),
0,725-1,1, 1,58-1,64, 3,55-3,93, 10,3-11,3 и 1 1,4-12.4 μm) with a resolution of 1.1 km.

With the help of information received from the Meteor-M satellite's MSU-MR instrumentation, various applied and scientific research tasks can be solved. First of all, it is an operational forecast of weather conditions based on measurements of environmental parameters: surface temperature, precipitation, cloud distribution, wind speed, etc. [4]. [4]. The data received from the satellite are used to study the climate and factors influencing its change, to study the movements of glaciers and icebergs, volcanic activity, early detection of forest fires is possible.

At present, two Meteor-M satellites are successfully operating in orbits: No. 1 (launched in 2009) and No. 2 (launched in 2011) with MSU-MR instruments No. 1 and No. 2, respectively. During the development of MSU-MR No. 1, many technological and design solutions were used for the first time in the practice of Russian space instrument engineering (small element assemblies of infrared receivers, a system of passive radiation cooling of these receivers, systems of onboard calibration of infrared channels, etc.). Some of the applied solutions are extremely difficult or even impossible to verify during ground testing of the instrument. Flight tests, while confirming in general the correctness of the implemented hardware design principles, revealed some shortcomings of the first device. Analyses of the received images and telemetry information allowed to determine the factors and their degree of influence that have the greatest impact on the quality of the received information, and the MSU-MR instrument was used for this purpose.

No. 2 was already created taking into account all the identified problems, wishes and comments of end-users of satellite data.

Principle of operation

The principle optical scheme of the multi-zone scanning device MSU-MR is presented in Fig. 3. 3. The device contains two identical independent optical-mechanical systems (main and backup). In the course of the device operation the operator can switch to another set at the command of the operator.

Each opto-mechanical device system includes:

– A flat scanning mirror with a double-sided reflective coating that rotates continuously in a circular motion by means of a drive;

– 6 information optical blocks, forming images in 6 spectral ranges: 0.5-0.7, 0.7-1.1, 1.6-1.8, 3.5-4.1, 10.5-11.5,
11.5-12.5 μm;

Fig. 1. External view of the MSU-MR device

Table 1: Tactical and technical characteristics of MSU-MR devices and their foreign analogue

Parameters	LSG-MR NO. 1	LSG-MR NO. 2	AVHRR
Orbital altitude	835	835	833
Number of channels	6	6	6
Spectral ranges, µm	0,5-0,7 0,7-1,1 1,6-1,8 3,5-4,1 10,5-11,5 11,5-12,5	0,5-0,7 0,7-1,1 1,6-1,8 3,5-4,1 10,5-11,5 11,5-12,5	0,58-0,68 0,72-1,00 1,58-1,64 3,55-3,93 10,30-11,30 11,50-12,50
Capture band, km	2800	2950	2900
Surface resolution, km	1,0	1,0	1,09
Signal-to-noise ratio in visible and near-infrared channels:			
• 0.5-0.7 µm;	700	1900	300-500
• 0.7-1.1 µm;	600	1000	300-500
• 1.6-1.8 µm	250	500	300-500
Noise-equivalent measured temperature difference at 300 K IR channel level, K:			
• 3.5-4.1 µm;	0,2	0,09	0,12
• 10.5-11.5 µm;	0,2	0,04	0,12
• 11.5-12.5 µm	0,3	0,07	0,12

Figure 2. Information generated by the MSU-MR device. From top to bottom: synthesised RGB image (0.5-0.7 μm; 0.7-1.1 μm; 1.6-1.8 μm); 3.5-4.1 μm; 10.5-11.5 μm; 11.5-12.5 μm

– 6 units of radiometric on-board calibration (one for each information unit), optically connected to the information channels through the scanning mirror and rotating mirrors.

To optimise the device layout, in- formation optical blocks with ranges from 0.5 to 1.8 μm and 3.5 to 12.5 μm, as well as their corresponding calibration blocks, are located on opposite sides of the scanning mirror.

Cooling of the mid- and far-infrared receivers (3.5 to 12.5 microns) is carried out by a common passive radiation cooling system oriented towards outer space.

The scanning mirrors are made of CO-115M sital and measure 165 × 175 × 36 mm. The mirrors are lightened by means of a system of mutually perpendicular holes, which is also used to locate in them the elements of the rotation axis and the struts of the frame in which the mirror is suspended. During operation, the mirrors make a uniform circular motion at a speed of 3.25 r/sec. The scanning mirrors are rotated by independent rotation drives. The rotation axes of the mirrors coincide with the spacecraft motion direction. The rotation of the sighting axis with the help of the scanning mirror and movement of the spacecraft itself allows for continuous trace imaging at a viewing angle of 110° . The mirrors have a double-sided reflective coating, which makes it possible to reduce the drive rotation speed by half and to place the optical blocks forming images in the most optimal way.

Optical blocks of the ranges from 0.5 to 1.1 μm include: a filter forming the spectral range, a rotating mirror, a three-lens lens having a focal length $f' = 150$ mm and an entrance pupil $D = 50$ mm, a single-element radiation receiver. The size of the sensitive element of the radiation receiver is (0.2 × 0.2) mm.

The optical unit of the range from 1.6 to 1.8 μm includes: a filter forming the spectral range, a rotating mirror, a three-lens volume with a focal length $f' = 150$ mm and an entrance pupil $D = 50$ mm, an aperture with a diameter of 0.2 mm, a system for transferring the image of the aperture to the radiation receiver and a single-element radiation receiver. Since the size of the sensitive element of the radiation receiver in the channel (0.3× × 0.3) mm, then the instantaneous channel field forms-The radiation is transferred from the aperture to the radiation receiver by an additional optical system.

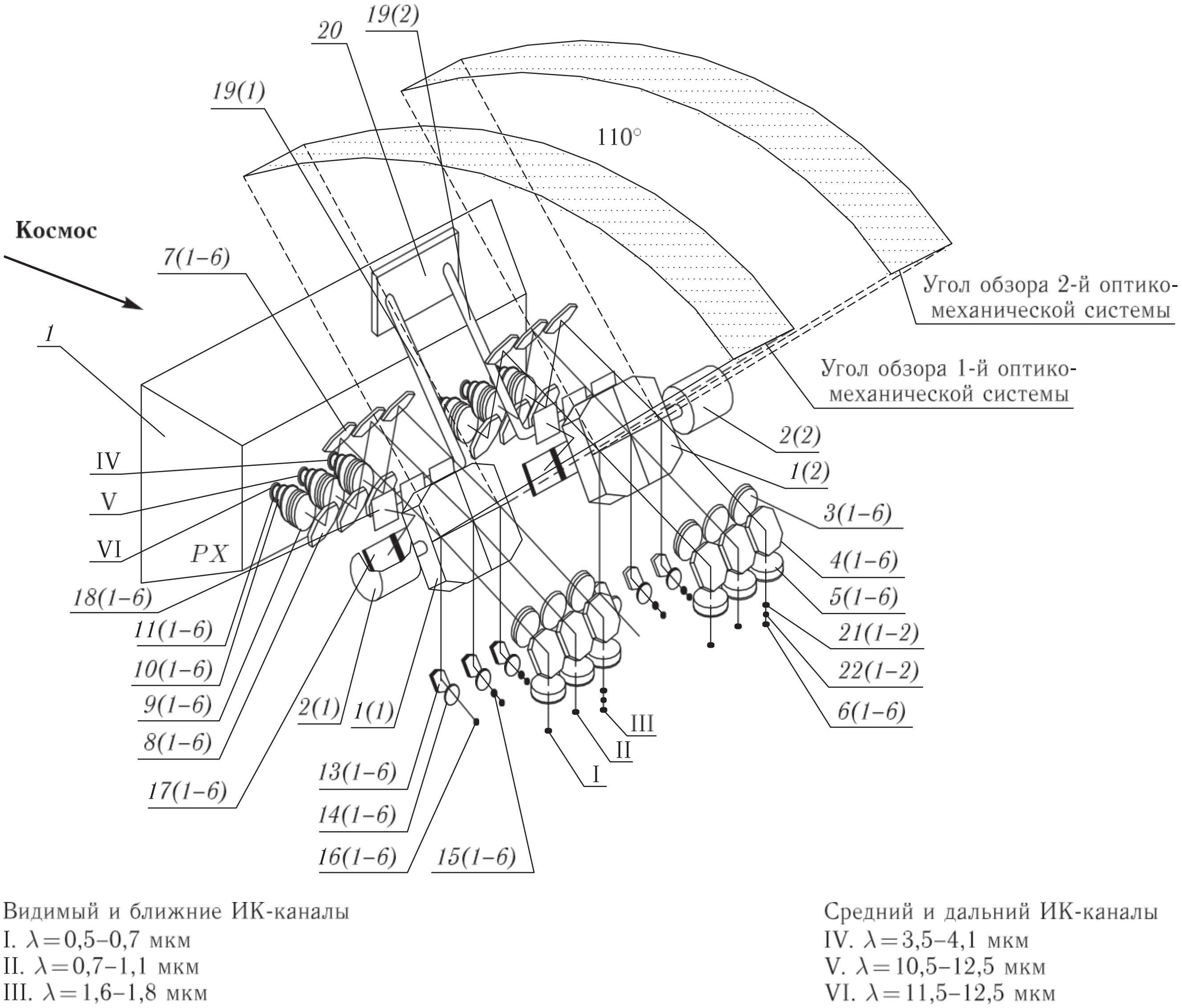

Figure 3. Principal optical scheme of the MSU-MR device:
1 - scanning mirror, *2* - drive, *3* - filter, *4* - rotating mirror, *5* - lens, *6* - receiver radiation, *7, 8* - rotating mirrors, *9* - lens, *10* - filter, *11* - radiation receiver, *12* - radiation cooling system for radiation receivers, *13* - rotating mirror, *14* - lens of the calibration channel in the range of 0.5-1.8 μm, *15* - filter of the calibration channel in the range of 0.5-1.8 μm, *16* - reference stabilised radiation source in the range of 0.5-1.8 μm, *17* - simulator of absolutely black body with temperature 313 K, *18* - simulator of absolutely black body with temperature 258 K, *19* - heat pipe, *20* - radiation cooling screen of simulator of absolutely black body *18*, *21* - aperture, *22* - image transfer system.

Optical blocks of the ranges from 3.5 to 12.5 μm include: rotating mirrors, a three-lens lens, a filter forming the spectral range, a four-element radiation receiver. The lenses are made of germanium, have a focal length $f' = 40$ mm and an entrance pupil. $D = 45$ mm. The size of the sensitive element of the receiver is (0.05×0.08) mm. IR receivers are oriented along the scanning axis, as a result, each surface point is projected sequentially onto each element of the photodetector, and then four received samples are averaged from each point, i.e. the time delay and signal accumulation (TDA) mode is implemented in the IR range. Structurally, the receivers are rigidly fixed on the radiation cooling system oriented towards space, which allows to obtain a temperature of 78-80 K in the area of sensitive elements of the receivers during the operation of the device.

The task of the information channel calibration blocks is to form reference radiation streams of a certain spectral composition and a given intensity (close to the upper level of the dynamic range), which are input into the main (measuring) path of the device and pass through all its elements. Input of the radiation formed by the calibration units is performed by means of a scanning mirror in each line outside its active part.

Calibration blocks of information channels, providing images in the range from 0.5 to 1.8 microns, include: a rotating mirror, a lens, a filter and a stabilised radiation source (incandescent lamp TRSH1600-2200).

The channel calibration units in the range from 3.5 to 12.5 μm include two simulators of absolutely black bodies, one of which has a temperature of 320 K and the other 255 K. The set temperature and its stabilisation during operation on the simulators of absolutely black bodies having a temperature of 320 K is achieved by means of a regulated heating element. On simulators of absolutely black bodies having a temperature of 255 K - by means of a radiation screen oriented to space, and the connection between the simulators of absolutely black bodies and the screen is carried out through heat tubes, and the value and stabilisation of the temperature is carried out by a regulated heating element.

The required operating temperature of infrared photoprocessors is 78-80 K. The passive radiation cooling (RC) system is used to ensure the temperature regime (Fig. 4). The advantage of such systems is that they have almost unlimited operating life and do not require constant power supply during operation.

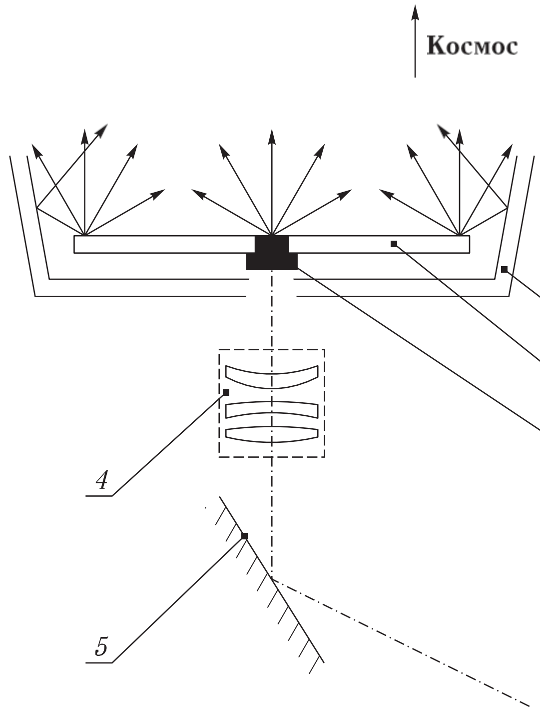

Fig. 4. Radiation cooling system of IR-photo receivers: *1* - photodetector, *2* - second stage of RC, *3* - insulating layers of the first stage of RC, *4* - lens, *5* - system of rotating mirrors.

Photodetectors *1 are* installed on a flat surface - the second stage of the rocket booster *2*, which has an equal (at normal spacecraft orientation) temperature of 78-80 K. Insulating layers of the first stage *3* are used to exclude radiation from warm body elements. The temperature of the first stage is 150 K. A prerequisite for the operation of the RC is the absence of radiation from the Earth and the Sun in the field of view of the cooling system. Hence, there is a limitation on the placement of the system onboard the spacecraft depending on the orbit parameters.

In the process of creating the MSU-MR device, Russian enterprises developed and manufactured modern element base: electromechanical drive of the scanning mirror (VNIIEM Corporation JSC), multi-element IR photodetectors (Sapphire NPO), radiation cooling system of IR photodetectors (NIIEM NPO), a large complex of works on modernisation of bench metrological equipment was carried out in Russian Space Systems JSC.

Figure 5. Effect of cryoprecipitation on the image quality of the 11.5-12.5 μm channel. On the left - before "cleaning", on the right - after "cleaning"

Design solutions realised in the creation of the ISA-MR No. 2 most affecting the quality of information received

One of the most difficult-to-remove factors that degrade image quality and radio metric accuracy is the formation of cryo-settings, consisting mainly of water molecules deposited on the coldest surfaces, in particular on the entrance windows of photographic receivers.

To counteract this effect, the "cleaning" mode of the PC is used, in which the second stage is heated up to 40° C. The effect of cryo-precipitation can be visually assessed in Fig. The influence of cryo-precipitation on the image quality can be visually assessed from Fig. 5.

However, during the "cleaning" session, water molecules remain inside the PC and over time they again deposit on the entrance windows of the photodetectors. To combat this phenomenon, the design of the PC was changed in ISU-MR No. 2, namely, the location of the heat-insulating walls was changed. They are positioned at an angle relative to each other. diverge towards the outer surface of the RH (in ISU-MR No. 1 walls are arranged in parallel), which allows water molecules after several collisions with the walls in the process of "cleaning" to fly into the open space. The difference between the design of the first and the second version of the radiation cooler is shown in Fig. 6. 6.

In addition, the photodetectors were redesigned to provide an increased temperature of the photodetector entrance window relative to its housing. As a result, the redistribution of cryo- precipitation during cooling occurs - most of the molecules are deposited on the surrounding walls and the colder housing.

Another difficulty of working with passive radiation cooling systems is the impossibility of full simulation of operating conditions during ground testing, and calculations have large errors due to insufficient information on the changes in the properties of materials, in particular heat capacity and elastic modulus, at cryogenic temperatures. In the MSU-MR installed on Meteor-M spacecraft No. 1, the temperature of the photodetectors was 100 K, which did not allow the required sensitivity of the photodetectors to be realised. To reduce

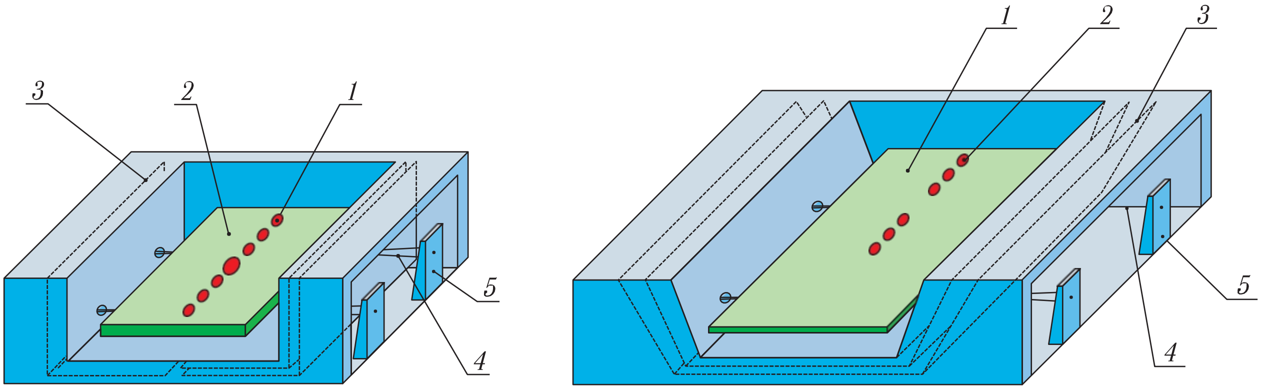

Figure 6. Design of the radiation cooler of the MSU-MR device No. 1 (left) and MSU-MR No. 2 (right):
1 - photodetectors, *2* - second stage of radiator (78 K), *3* - first stage of radiator (150 K),
4 - threads holding the second stage, *5* - threads fastening posts

Figure 7. Black Sea surface, comparison of information in the 10.5-11.5 μm channel.
Meteor-M satellite No. 1 (left): 26.05.10 yr, $_{\Delta \mathrm{Tequ}} = 0.15$ K;
Meteor-M satellite No. 2 (right): 29.09.14, $_{\Delta \mathrm{Tequ}} = 0.05$ K

temperature in the next instrument installed on Meteor-M spacecraft No. 2, the area of the radiating surface of the cooling system was increased and some design improvements were made, which made it possible to achieve an operating temperature of 78 K and to increase the radiometric sensitivity by a factor of three. The efficiency of this solution can be clearly seen on the images shown in Fig. 7. 7.

The measures taken made it possible to significantly increase the rate of cleaning of the inner volume of the RC from cryo-settings. A comparative quantitative assessment of the rate of change in the values of the dynamic range of video signals in the IR channels of MSU-MR No. 1 and No. 2 is presented in Fig. 8.

In compiling global meteorological maps of the Earth's surface using video information obtained by the MSU-MR No. 1 instrument, it was established that a field of view of 2,800 km at an orbital altitude of 835 km did not ensure overlapping of images of the Earth's surface at the equator. In the second instrument, the field of view was increased by an angle of 2.07°, with a field of view of 2,950 km, which made it possible to draw a complete map of the Earth's surface without omissions in the equatorial zone (Fig. 9).

The complex of constructive modifications allowed to increase significantly the radiometric accuracy of the device. According to this indicator, the MSU-MR instrument
No. 2 is at the state-of-the-art of apparatus of a similar class.

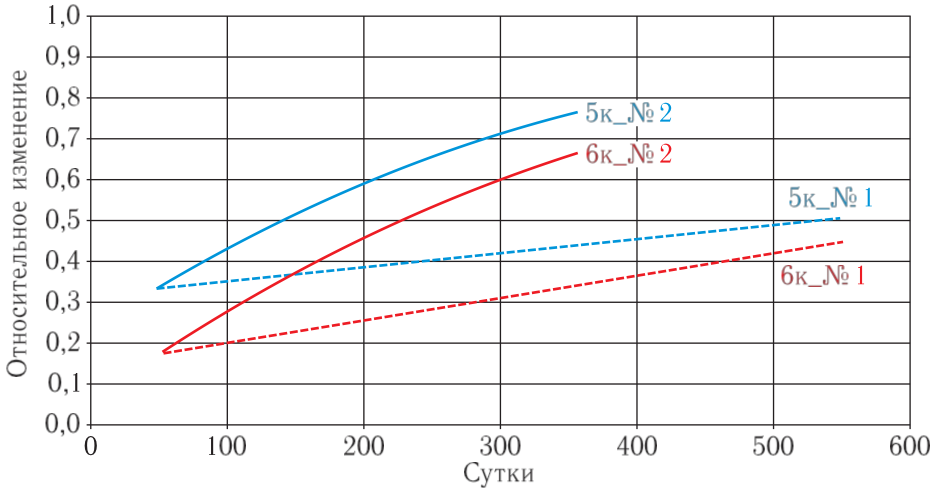

Fig. 8. Variation of values of dynamic range of IR channels of MSU-MR No. 1 and MSU-MR No. 2 equipment

Figure 9. Increase in the viewing angle of ISU-MR No. 2 (top) by an angle of 2.07° relative to ISU-MR No. 1 (bottom)

Future

At present, Russian Space Systems JSC is manufacturing MSU-MRs for Meteor-M satellites No. 2-1 and No. 2-2 and preparing for production for Meteor-M satellites.

№ 2-3 и № 2-4. The launch of these satellites will make it possible to create a full-fledged low-orbit hydrometeorological constellation.

In parallel with the production of the new apparatus, work on its improvement continues:

– the control system of on-board reference radiation sources of infrared channels is adjusted, which will make it possible to exclude the influence of abnormal situations (e.g., spacecraft turnaround) on the stability of radiometric accuracy and provide the possibility to correct the conversion characteristic (dependence of the output signal on the radiation temperature) for observation of extended radiation sources with increased temperature;

– A system for on-board focusing of infrared lenses is being developed, which will significantly reduce the duration and cost of ground testing of the equipment, as well as ensure focusing in real orbital conditions;

– The system of providing the temperature mode of photodetectors of visible spectrum dia- bands with increased stability to improve radiometric measurement accuracy is being developed;

– Design and electrical engineering changes aimed at speeding up and automating the creation of devices are carried out.

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