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Evolution of ERS Equipment of the MSU-MR Series as Related to Increasing the Accuracy of Radiometric Measurements and Expanding Performance Capabilities

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Abstract. This work is devoted to the description of the technical evolution of the MSU-MR equipment installed on Meteor-3M series spacecraft. After the launch of each successive spacecraft of the series, the development team generates new ideas concerning the modernization of the MSU-MR equipment in order to improve its metrological characteristics. This work describes in detail both the improvements of the MSU-MR equipment already tested during flight tests (expansion of the temperature measurement range, remote adjustment of the parameters of electronic signal generation paths and of the temperatures of black body simulators, refinement of the method of laboratory focusing) and of the equipment yet to be subject to flight tests (remote focusing, increasing the cooling capacity of the radiator of the black body simulator, as well as a number of others).

Keywords: Earth remote sensing, satellite equipment, equipment modernization, infrared spectrum, radiometric accuracy of measurements

Introduction

The Meteor-M No. 2-2 spacecraft (SC), manufactured by JSC "VNIIEM Corporation", was successfully launched into a circular sun-synchronous orbit on July 5, 2019 as part of a project for forming a Russian Earth remote sensing satellite constellation (ERS) [1]. Among the target equipment on board the SC is the low-resolution multispectral scanner MSU-MR manufactured by JSC "Russian Space Systems" (hereinafter referred to as MSU-MR 2-2).

The equipment of the MSU-MR series is designed to solve such hydrometeorological tasks as determining the temperature of land and water areas, mapping clouds, determining their altitude and water supply, and etc. To date, MSU-MR 2-2 equipment has successfully completed flight tests and has been accepted for operation. The principal characteristics of the MSU-MR 2-2 equipment confirmed in the course of flight tests are given in the Table. Currently, the MSU-MR equipment for the Meteor-M No. 2-3 SC is being prepared for launch.

This is the fourth launch for the MSU-MR series equipment. Previously, satellites were launched in 2009, 2014 and 2017 (the launch of the Meteor-M No. 2-1 spacecraft in 2017 ended in failure). The design and general principles of operation of the MSU-MR series of equipment are described in detail in [2], the attainable accuracy values in determining the temperatures of water areas are given in [3]. The present paper focuses on the improvements implemented in the MSU-MR 2-2 and 2-3 equipment, as well as the planned improvement of subsequent instruments of the series.

Modernization of MSU-MR instruments for the Meteor-M No. 2-2 SC. Optimization of the boundaries of the measured temperature range in channels 4–6

The most important feature first implemented in the MSU-MR 2-2 equipment was the expansion of the range of measured temperatures in channels 4–6. The range was 220–320 K in all three channels in earlier MSU-MR instruments.

Spectral ranges 10.5–11.5 μm and 11.5–12.5 μm are intended for determining the temperature of the underlying surface – land, water areas, ice, clouds, etc. However, there are a number of objects with temperatures below 220 K (mainly high clouds and polar caps). Accordingly, their temperature could not possibly be determined based on data from the MSU-MR instruments of the Meteor-M No. 1 and 2 SC [4]. When creating the MSU-MR 2-2 instruments, the lower limit of the measured temperatures in channels 5 and 6 was lowered to 190 K by changing the analog gain of signals without significant loss in radiometric resolution (Fig. 1). The signal values of registered temperatures are transmitted without limitations. The image is given in stereographic projection, a coordinate grid is superimposed.

Table. Main characteristics of the MSU-MR equipment of the Meteor-M No. 2-2 SC

Parameter	Parameter value
Average orbit altitude, km	832
Swath in the direction perpendicular to the direction of SC flight, km	2900
Linear resolution on the surface in the sub-satellite point, km	1.0
Number of channels	6
Boundaries of spectral ranges in channels 1–6, 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
Range of measured effective brightness in channels 1–3, W/(m²·sr): • 0.5–0.7 μm • 0.7–1.1 μm • 1.6–1.8 μm	 0–85 0–71 0–10
Signal-to-noise ratio in channels 1–3: • 0.5–0.7 μm • 0.7–1.1 μm • 1.6–1.8 μm	 1000 800 600
Range of brightness temperatures measured in channels 4–6, K: • 3.5–4.1 μm • 10.5–11.5 μm • 11.5–12.5 μm	 220–380 190–320 190–320
Noise equivalent differential temperature at 300 K in channels 4–6, K: • 3.5–4.1 μm • 10.5–11.5 μm • 11.5–12.5 μm	 0.06 0.06 0.07
Bit depth of output signal, bit	10

The 3.5–4.1 μm spectral range is optimal for detecting and registering seats of fire. For this reason, the upper limit of the range of measured temperatures in channel 4 was significantly increased (up to 380 K – in order to register signals from high-temperature objects). Since the bit depth of the output signal remained the same and is only 10 bits, the expansion of the temperature range still requires high radiometric resolution values in the 220–320 K range to be maintained, a nonlinear hardware-software algorithm for generating the output signal was implemented in this channel.

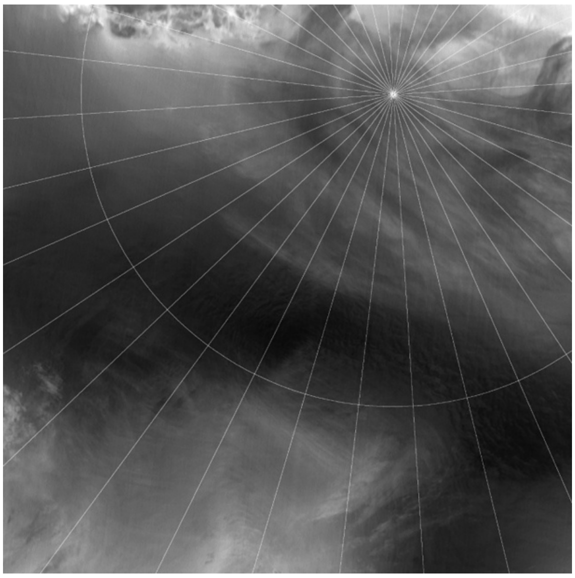

Fig. 1. Fragment of an image of the South Pole obtained in channel 5 by the MSU-MR instrument of the Meteor-M No. 2-2 satellite on July 23, 2020.

Linear photodetectors, with four photosensitive areas (PAs) in each, oriented along the scanning direction [5] are used in channels 4–6 of the MSU-MR equipment. Previously, identical electronic signal shapers were used in each of these channels, and the output digital signal was the signal from all four PAs that was summed with the necessary time delays and averaged (digital time delay and accumulation mode). The averaged signal from the first three PAs is generated in such a way in channel 4 of the MSU-MR 2-2 instrument. The analog gain for them corresponds to the temperature range of 220–230 K. The gain from the fourth PA is set significantly lower, so that the upper level of the temperature range for it reaches the value of 380 K [6]. The specific values of analog gain are selected during ground-based adjustments.

Now the operation of shaping the output signal in channel 4 is performed according to the following algorithm:

$$U_{output} = \\ = \begin{cases} \alpha \bar{U}_{PA\ No.\ 1\text{–}3} + \beta U_{PA\ No.\ 4}, \text{when } \bar{U}_{PA\ No.\ 1,2,3} < U_0 \\ \alpha U_0 + \beta U_{PA\ No.\ 4}, \text{when } \bar{U}_{PA\ No.\ 1,2,3} \geq U_0, \end{cases}$$

where U_{output} is the output signal in channel 4;

$\bar{U}_{PA\ No.\ 1,2,3}$ is the averaged signal from PA No. 1–3 of the photodetector of channel 4 (obtained with the typical gain);

$U_{PA\ No.\ 4}$ is the signal from PA No. 4 of the photodetector of channel 4 (obtained with a reduced gain value);

U_0 is the level of the digital limitation of the $\bar{U}_{PA\ No.\ 1,2,3}$ signal;

α and β are the constant scale factors used during digital processing.

Figure 2 demonstrates a fragment of an image in channel 4. Seats of fire are clearly visible in the image.

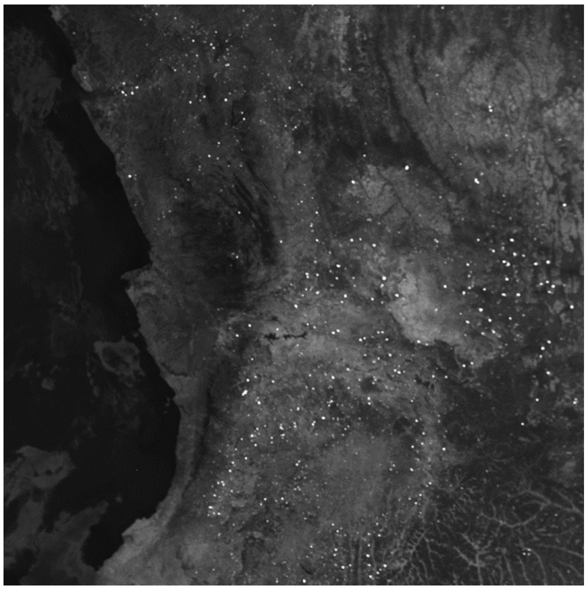

Fig. 2. Fragment of an image of the western coast of Africa obtained on July 23, 2020 in channel 4 of the MSU-MR instrument of the Meteor-M No. 2-2 satellite.

Remote adjustment of parameters of electronic signal shaping paths and of temperatures of black body simulators

Experience of MSU-MR equipment operation, starting from its first launch, has demonstrated the need to regulate the transmission factors of the amplification paths during flight operation in all channels together with the temperatures of the "cold" and "hot" black body simulators (hereinafter referred to as BBS-C and BBS-H, respectively). The possibility of such adjustments by commands from the Earth was implemented during the creation of the MSU-MR 2-2 equipment.

To maintain the dynamic range of the signal within the set limits in channels 1–3 of the MSU-MR series equipment, automatic adjustment of the zero brightness signal to the specified level of "black" by changing the value of the constant component of the signal in the analog path is introduced. In channels 4–6, the "cold" signal from the BBS-C is adjusted to the specified level in a similar way. The possibility to change the value of the preset signal adjustment levels in the entire range of the output signal, as well as the gain values in the range from $K \times 0$ to $K \times 3$ (K is the gain of the preamplifier) with 10-bit accuracy is provided. The functional diagram of the modified analog paths of the MSU-MR 2-2 instrument is given in Fig. 3.

The purpose of the units shown in Fig. 3:

– B_1 is the radiation receiver;

– PA-RC is the preamplifier consisting of a U_1 amplifier with a fixed gain K and an amplifier-adder U_2, where the "black" ("cold") level is corrected;

– SPU is the signal processing unit consisting of :

- an amplifier U_3 with variable gain, made of an analog multiplier, controlled by the voltage from the digital-to-analog converter (DAC) U_6 through a code transmitted from the ground;
- an integrator U_4, electronic switch S_1 and DAC U_5 that shape the error signal between the measured level of the "black" ("cold") in the video signal and the one specified by the code from the ground, which is fed into the amplifier-adder U_2 as a control signal.

In order to ensure the required radiometric accuracy during the operation of the ERS equipment of the optical and infrared ranges, calibration is required. This concerns, first of all, calibration against onboard radiation sources. In the infrared range of the spectrum, such sources are the black body simulators (BBSs). In the equipment of the MSU-MR, the calibration of channels 4–6 is conducted with the use of a BBS with temperatures close enough to the lowest (BBS-C) and highest (BBS-H) levels of the temperature range.

The BBS-C (BBS-H) unit is a single structure with three segments – one for each channel 4–6. They use heaters, which maintain the temperature of the radiating surface at a certain level by heating it from the initial value to the set one. The initial temperature of the BBS-H corresponds to the steady-state temperature of the device body, which is approximately 15°C. The initial temperature of the BBS-C ranges from −20 to −15°C and is ensured by the heat removal from the unit through a heat pipe to a passive external radiator, which radiates this energy into space.

The BBS unit includes R_T heating elements that are powered from the onboard circuit (OBC), temperature sensors implemented in the feedback of the thermal control system T_{FB}, telemetry temperature sensors T°_{TM}, and an analog thermal control system. All these elements are mounted on a base made of aluminum alloy. The base surface facing inside the instrument cavity is emitting and has a special coating with a high blackness coefficient. In earlier devices of the MSU-MR series, the setting of specified temperature values was performed during the ground adjustment procedure of the BBS unit without

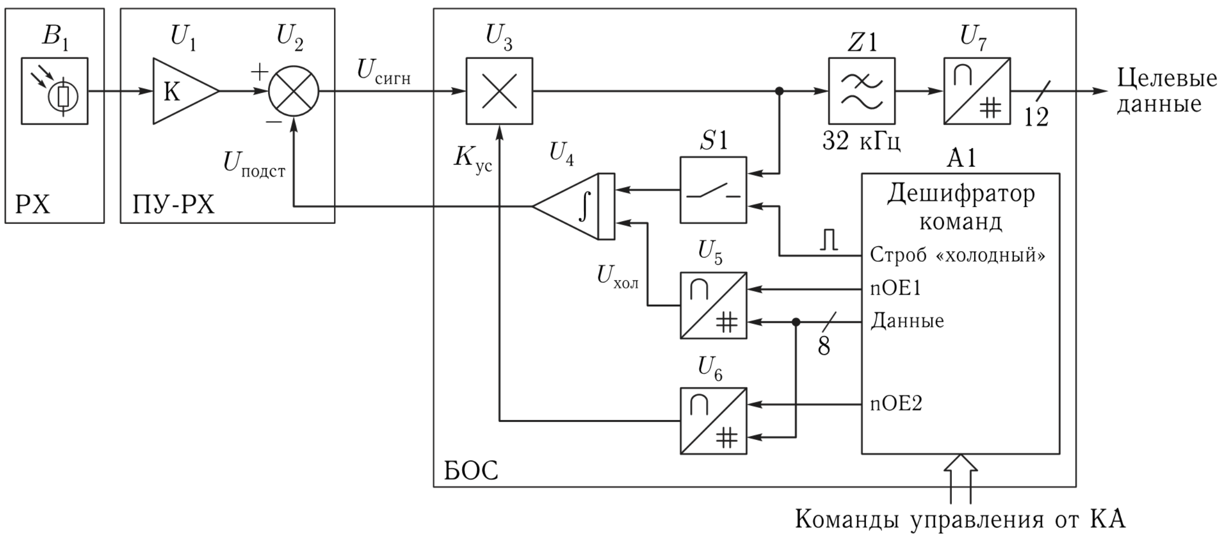

Fig. 3. Functional diagram of the analog paths of MSU-MR 2-2 equipment.

the possibility of changing it during flight operation. This temperature is 40°C for the BBS-H and −13°C for BBS-C. However, due to a combination of internal and external factors, the thermal environment of the MSU-MR may change after the SC is launched into orbit, thus leading to the need to adjust BBS temperatures. This is especially true of the BBS-C, since the possibility of adequate correction of its temperature directly depends on the cooling capacity of the radiator in conditions of variable ground clutter and on the thermal conductivity of the heat transfer tube.

In order to correct the BBS temperature during the flight of MSU-MR 2-2 equipment, an element for controlling the set temperature value of the radiating surface T_{set} (Fig. 4) was introduced into the thermal control system. A DAC of domestic production acts as the controlling element and sets the voltage of thermal control system installation, thus allowing the stabilization of the radiating surface temperature at a set level in the range from 30°C to 60°C for the BBS-H and from the minimum temperature of −20°C to 0°C for the BBS-C. The DAC is controlled by sending special commands through the command link of the SC [7].

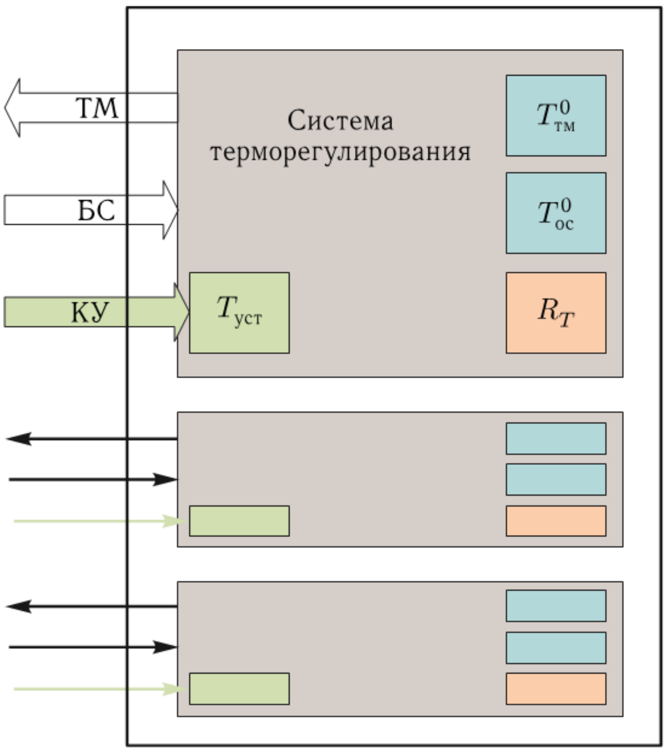

Fig. 4. Functional diagram of the BBS block of the MSU-MR 2-2 instrument.

During flight tests, the operability and reliability of the command control of the BBS-C temperature were successfully confirmed. However, the control unit and signal processing unit of the MSU-MR 2-2 allows the updated settings to be stored only in the volatile memory, i.e. all settings return to their original values after the device is restarted. This drawback is eliminated in the MSU-MR 2-3 equipment that is being prepared for launch.

Improved methodology for focusing channels 4–6 of the MSU-MR equipment in ground-based conditions

The operation of infrared photodetectors (IR photodetectors) implemented in channels 4–6 of the MSU-MR equipment require cooling to the level of nitrogen temperatures (70–80 K). Since the lifetime of the MSU-MR is no less than 5 years in continuous operation mode, a passive system of radiation cooling (RC) was used to cool the IR photodetectors. The system has an almost unlimited MTBF resource. RC is a complex structure with several layers of mirror screens and two radiating surfaces – radiators of the 1st and 2nd stages. At the second stage of the RC, where the IR photodetectors are installed, the minimum temperature is achieved with the help of radiant heat flux multilayer shielding and the minimization of conductive heat fluxes, for which the 2nd stage of the RC is mechanically suspended on thin filaments.

During ground adjustments and tests, the 2nd stage of the RC is cooled by contact by means of a heat exchanger through which liquid nitrogen is circulated. The cooling of the 2nd stage of the RC at normal atmospheric pressure would lead to immediate ice formation on the windows of the IR photodetector. In order to prevent the freezing of the IR photodetector input window, the inside is sealed and evacuated with the use of specialized support equipment (hereinafter referred to as EV RC). In this case, the external atmospheric pressure causes the deformation of the housing (the base) of the RC, as a result of which the spatial position of the 2nd stage and, accordingly, of the of the IR photodetector changes relative to the focal planes of the objective. Since the dimensions of the RC of the first MSU-MR were relatively small (due to which the temperature of the photodetector did not reach the specified value), the indicated deformations were insignificant and there were no serious problems with focusing channels 4–6. However, as a result of a significant increase in the area of the RC for the MSU-MR of the Meteor-M No. 2, this effect was noticeable. This became finally clear during flight tests of the device onboard the Meteor-M No. 2 SC when the images for some channels turned out to be strongly defocused.

Based on a theoretical analysis and experimental studies, a method for focusing channels 4–6 in a low-pressure chamber was designed and implemented.

The essence of the methodology is that the device with an installed EV RC is placed in a low-pressure chamber (at normal pressure). After reaching the operating temperature of the IR photodetector, the air is pumped out of the chamber to a pressure of about 20 mm Hg. At the same time, due to the intensive boiling of liquid nitrogen in the EV RC bath, the total volume of the bath is rapidly cooled to its freezing point and the boiling seizes. In this state, the modulation transfer coefficient (MTC) in channels 4–6 is measured with the implementation of equipment located inside the vacuum chamber, including a mirror collimator, a line target with a remotely controlled device for moving and controlling its position, and a BBS – the illuminator of the line target (Fig. 5). Based on the results of analyzing a series of images at various positions of the line target relative to the focal plane, the value of the correction to be made to the axial position of the objective of the channel is determined for each channel.

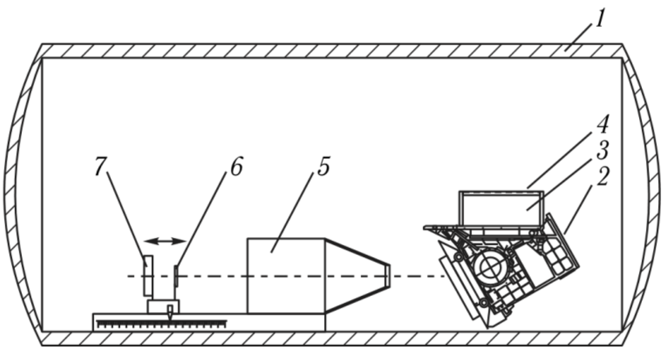

Fig. 5. Scheme of improved laboratory focusing of channels 4–6 of the MSU-MR equipment: *1* — low-pressure chamber; *2* — MSU-MR equipment; *3* — focal plane of objectives of channels No. 4–6; *4* — RC of the MSU-MR; *5* — collimator; *6* — line target; *7* — BBS.

MSU-MR 2-2 flight tests confirmed the feasibility of focusing using the developed method. Nevertheless, it was not possible to achieve the limit values of MTC that were demonstrated in terrestrial conditions. Therefore, it was decided to design and introduce precision focusing of channels 4–6 onboard the SC into the MSU-MR instrument, starting with MSU-MR 2-3.

Modernization of MSU-MR equipment for the METEOR-M No. 2-3 SC. Remote focusing of channels 4–6

The most important feature first implemented in the MSU-MR 2–3 equipment was the modification of the unit of objectives of channels 4–6. Specially designed stepper-motor mechanisms were introduced into the unit that made precision focusing of objectives independently for each of the channels in the course of normal operation possible with the use of commands from the ground (Fig. 6). The objectives move along an optical axis in increments of 0.01 mm in the range of ±2.8 mm, which is sufficient to compensate RC deformation.

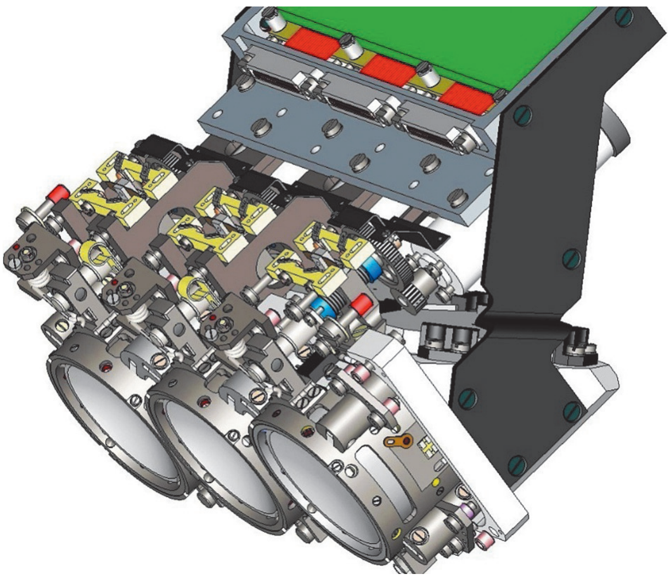

Fig. 6. 3D-model of the unit of objectives of channels 4–6 with a focusing system.

The functional diagram of the focusing unit is shown in Fig. 7. The focusing of each objective (O) is performed with the help of stepper motors (SM) by the rotation of the threaded rod (TR) forming a screw pair with a nut locked to the lens barrel. In order to obtain minimum spacing of objective movement, two reducers (R) are implemented: one integrated into the stepper motor and an additional one that is part of the structural design. When the limit position is reached, the mechanical contact of the end probe (C) closes and stops the movement. The stepper motors are controlled individually by control commands (CCs) by means of an interface unit powered from the onboard circuit (SC IU). In focusing mode, the following operations are performed sequentially: the motor is selected, power is supplied to it, the step counter is set and a command is issued to move a specific number of steps in the selected direction. At the same time, the position of the motor is telemetered and transmitted in the service part of the data line. The position of the objective that provides the best focus is determined by analyzing the quality of the underlying surface image.

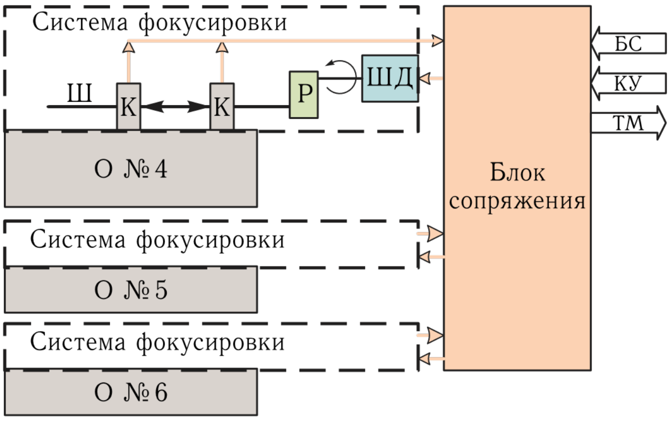

Fig. 7. Functional diagram of the focusing unit of channels 4–6.

Modification of the BBS-C radiator

Flight tests of the MSU-MR 2-2 equipment demonstrated the insufficient cooling capacity of the BBS-C radiator, which resulted in a diurnal and pass variation of the BBS temperature exceeding specified limits. Based on the results of flight tests, it was decided to upgrade the BBS-C radiator. In the MSU-MR 2-3 instrument, the area of the radiator (and hence the cooling capacity) is increased by 16.5%. In order to reduce the thermal load, the thermal decoupling of the radiator with the device case, with RC and mats of screen vacuum thermal insulation was strengthened. The contact area between the radiator and heat pipe was increased. In addition, three thermal sensors were installed on the radiator for telemetric control of its temperature.

Saving DAC settings

The electronics of the signal control and processing unit of the MSU-MR 2-3 instrument was refined – an electrically erasable reprogrammable read-only memory was added. This made it possible to implement the function of storing the control codes transmitted from the Earth in order to optimize BBS temperatures and the parameters of the electronic paths for signal shaping.

Transition from the adjustment of the “cold” level to the adjustment of the “hot” level

The automatic adjustment of the level of the analog signal to a given value allows counter-balancing the changes in the constant component of the signal. Theoretically, in view of the possibility of changing the channel conversion factor (in particular, due to an increase in photodetector sensitivity conditioned by a gradual decrease of water vapor concentration in the gas cloud surrounding the SC, which takes place in channels 4–6), such adjusting would be correct for the midrange point of the average analog-to-digital conversion range so that the increase in sensitivity leads to minimal risks of the signal going out of the ADC range. The signal from the BBS-C satisfies this condition quite well since its temperature is close to the middle of the main range of measured temperatures 220–320 K. However, since the stability of the BBS-C depends on the change in the temperature of its radiator, the use of the signal from the BBS-H as a reference signal gives a better automatic adjustment of the signal level.

In earlier instruments of the MSU-MR series, it was not possible to save the changes of the parameters of the electronic paths of signal formation and BBS temperatures introduced by commands from the Earth; therefore, automatic adjustment was performed according to the signal from the BBS-C. Automatic signal adjustment in the MSU-MR 2-3 instrument is conducted by the signal from the BBS-H. This will allow for greater stability of the constant component of the signal. If the change in the sensitivity coefficient of the photodetector is great, then the possibility of reprogramming the DAC and saving the settings will counter-balance this.

Change of the type of calibration lamps of the calibration system of channels 1–3 and their mode of operation

Starting with the MSU-MR 2-3 instrument, a new type of certified lamps will be used in the onboard calibration system and in channels 1–3. Their mode of operation has also been changed.

The experience of more than five years of MSU-MR equipment operation on the Meteor-M No. 1 and 2 SC showed that the degradation of calibration lamps brought about by their continuous burning significantly exceeds the change in the conversion factors of channels 1–3. The calibration lamps for the MSU-MR instrument will have to operate in the following mode: continuous burning time – 1 hour; power-on time – 1 week. This mode of operation will significantly save their resources and, therefore, will boost the calibration accuracy of channels 1–3 over a long time interval. The absence of calibration during the time when the lamps are off will not affect calibration accuracy because there is no high-frequency interference in these channels, and this will not affect the correction of the long-term trend of the channel conversion factor.

The experimental "all-around observation" mode

In accordance with its purpose, the MSU-MR series equipment creates images of the underlying surface at a viewing angle of 110° centered at the sub-satellite point in the direction perpendicular to the motion of the SC. This viewing angle is formed by the continuous rotation of a double-sided plane-parallel scanning mirror. An experimental mode referred to as "all-around observation" is implemented in the MSU-MR 2-3 instrument: the transmission of a signal registered in the 110° viewing angle with a sequential shift of the center of the viewing angle by 72° every 64 image lines (approximately every 10 seconds). This mode allows us to sequentially obtain an image of the inside of the instrument in each channel. The main goal of this mode is to search for flare light (including flare light from the underlying surface) in order to put forward recommendations for the further modernization of the MSU-MR instrument.

Prospects for the further development of the MSU-MR series equipment. Refinement of the BBS-C and its radiator

Specific steps aimed at improving the radiometric accuracy should be taken. Today it is obvious that the existing system of "cold" calibration has two drawbacks that introduce uncertainty into the measured characteristics. One of them is associated with an insufficiently high degree of blackness of the BBS radiating surface (the blackness coefficient is $\varepsilon \approx 0.97$). In the presence of variable ground clutter of the working surface by radiation from the Earth, which cannot be eliminated within the framework of the existing equipment design, this leads to the uncertainty of the actual radiation temperature of the BBS-C [8]. An increase of coefficient ε to a value of the order of 0.99 can be achieved by forming a special profile on the emitting surface and implementing currently known special coatings.

The second drawback of the cold calibration system is the presence of fluctuations of the thermodynamic temperature of the BBS-C. The reason is the same: the clutter of the radiator by radiation from the Earth, the intensity of which changes with diurnal and pass variation. The additional heat load on the radiator can be, according to estimates, from 6 to 12 W. A significant reduction of this load can be achieved by introducing reflector screens into the structure of the radiator.

The introduction of double-loop control regulation will help to achieve an increase in the accuracy of maintaining the set BBS-C temperature to a level of ±0.05 K. The first (coarse circuit) loop should be located in the heat exchange zone of the heat pipe and radiator. Its task is to maintain a constant temperature in this zone with relatively low accuracy, of the order of ±0.5 K. The second loop that is part of the BBS-C must monitor these fluctuations. Increased accuracy is achieved because this regulator has to operate in a narrow range of power variations.

Remote changing and saving of all settings of the control and signal processing unit

By analogy with the mechanism for remotely changing and saving DAC settings, the same capabilities should be implemented for other constants employed in device operation.

Conclusion

The evolution of instruments belonging to the MSU-MR series is an illustrative example of how the essential features and design errors of these devices, which are subsequently eliminated, become known in the process of device operation. This evolutionary process makes it possible to identify the most successful design solutions and use the experience gained to develop new, more advanced equipment.

References

1. Kontseptsiya razvitiya rossiyskoy kosmicheskoy sistemy distantsionnogo zondirovaniya Zemli na period do 2025 goda [Concept for the development of the Russian Earth remote sensing space system for the period up to 2025]. Moscow, Roscosmos, 2006, 77 p. (in Russian).
2. Akimov N.P., Badayev K.V., Gektin Yu.M. et al.. Mnogozonal'noye skaniruyushcheye ustroystvo malogo razresheniya MSU-MR dlya kosmicheskogo informatsionnogo kompleksa "Meteor-M". Printsip raboty, evolyutsiya, perspektivy [Multichannel scanner of low spatial resolution MSU-MR for space-based informational system "Meteor-M". The principle of operation and development prospects]. *Raketno-kosmicheskoye priborostroyeniye i informatsionnyye sistemy* [Rocket-Space Device Engineering and Information Systems], 2015, Vol. 2, No. 4, pp. 9–13. (in Russian)
3. Aleksanin A.I., Gektin Yu.M., D'yakov S.E., Zaytsev A.A., Kachur V.A. Uchet vliyaniya krioosadkov pri kalibrovke IK-kanalov radiometra MSU-MR [Cryoprecipitation influence accounting in IR-channels calibration of MSU-MR radiometer]. Issledovaniye Zemli iz kosmosa [Exploration of the Earth from space], 2018, No. 1, pp. 1–9. (in Russian)
4. Kiseleva Yu.V., Ryzhakov A.V., Kozlov D.A., Rublev A.N. Kontrol' kalibrovki IK kanalov skanera MSU-MR po dannym nazemnykh izmereniy polyarnykh poligonov [Control of the calibration of the IR channels of the MSU-MR scanner according to the data of ground measurements of polar test sites]. *Mezhdunarodnaya shkola-konferentsiya molodykh uchenykh "Klimat i ekologo-geograficheskiye problemy Rossiyskoy Arktiki". Sbornik tezisov dokladov* [International school-conference for young scientists "Climate, geography and environment of the Russian Arctic". Proceedings.] (Russia, Apatity, September 4–10, 2016). Elektrostal, OOO "Kaem", 2016, pp. 100. (in Russian)
5. Akimov N.P., Gektin Yu.M., Novikov M.V., Smelyanskiy M.B. *Mnogozonal'noye skaniruyushcheye ustroystvo dlya distantsionnogo polucheniya izobrazheniy v shirokom ugle* [Multi-zone scanning device for remote generation of images in wide angle of observation]. Patent No. 2306583 of the Russian Federation. G02B 23/12 (2006.01) (published 20 September 2007). Application No. 2005138576/28 of 12 December 2005. (in Russian)
6. Andreyev R.V., Gektin Yu.M., Zaytsev A.A., Ryadnov A.Yu., Formenov D.V., Frolov A.G. Sposob registratsii vysokotemperaturnykh ob"yektov apparaturoy DZZ s primeneniyem modifitsirovannoy peredatochnoy kharakteristiki priyemnogo trakta [A method for registering high-temperature objects with ERS equipment using a modified transfer characteristic of the receiving path]. *Aktual'nyye problemy sozdaniya kosmicheskikh sistem distantsionnogo zondirovaniya Zemli* [Current problems of creating space systems for Earth remote sensing]. Moscow, 2016. (in Russian).
7. Frolov A.G., Serebryakov D.S., Puzakov N.P. et al. Programmno-apparatnaya realizatsiya kompensatsii vozdeystviya destabiliziruyushchikh faktorov na opornyye istochniki izlucheniya i trakt formirovaniya videosignala v sostave apparatury DZZ [Hardware and software implementation of the compensation for the impact of destabilizing factors on the reference radiation sources and the video signal formation path as part of the remote sensing equipment]. VIII Vserossiyskaya nauchno-tekhnicheskuyu konferentsiya *"Aktual'nyye problemy raketno-kosmicheskogo priborostroyeniya i informatsionnykh tekhnologiy"* [All-Russian scientific and technical conference "Current problems of rocket and space device engineering and information technology"]. Moscow, 2016. (in Russian)
8. Gektin Yu.M., Gerasimov D.D., Zaytsev A.A., Kiseleva Yu.V., Rublev A.N., Smelyanskiy M.B. Analiz vneshnikh vozdeystviy na sistemu bortovoy kalibrovki nizkoorbital'noy apparatury distantsionnogo zondirovaniya v infrakrasnom diapazone [Analysis of external influences on the onboard calibration system of low-orbit remote sensing equipment in the infrared range]. *59-ya nauchnaya konferentsiya MFTI s mezhdunarodnym uchastiyem: tezisy dokladov* [59th MIPT scientific conference with international participation: abstracts], (Russia, Moscow, November 21–26, 2016). Moscow, 2016. Available at: http://conf59.mipt.ru/static/reports_pdf/2707.pdf. (in Russian)