

Earth sensing capabilities yesterday and today

P. Razzhivalov^{1,2} , N. Korobova^{2,*}  and S. Shatalova² 

¹ Joint Stock Company Space Rocket Centre «Progress» – Scientific and Production Enterprise «OPTEKS», Russia, Zelenograd, Moscow

²Institute of Nano – MicroSystem Technology National Research University of Electronic Technology (MIET), Russia, Zelenograd, Moscow

*e-mail address: korobova0210@gmail.com

At present, the expansion of the orbital constellation of Earth remote sensing satellites continues. The technical characteristics of the imaging equipment are being improved. The article discusses the main reasons for the inaccurate referencing of Earth remote sensing data, namely, the errors in measuring the parameters of the orbit and the error in the orientation of the spacecraft. It has been established that the Glonass / GPS systems are responsible for the first error, and the devices for determining the coordinates of stars (orientation sensors by stars) are responsible for the second. The analysis of the modern devices characteristics for determining the stars coordinates of spacecraft from well-known world companies has been carried out.

It has been established that the results of measurements of these systems and devices must be taken into account in the geometric correction of images. The problems associated with the stages of development, production and control tests of the performance of these devices have been identified. The solution of these problems will make it possible to equip spacecraft for remote sensing of the Earth with star sensors, which, working in conjunction with imaging equipment, will be able to provide the required characteristics of the images obtained with a spatial resolution of less than 40-50 cm and a spatial reference accuracy of 2-3 m. The accuracy of devices measurement for determining the coordinates of stars affects the accuracy of the images binding of Earth remote sensing. It was found that the accuracy sensor characteristics of the Space Research Institute of Russian Academy of Sciences are in the range from 1 arc.sec. up to 2 arc.sec. The main contribution to the error is made by the standard deviation of measurements carried out with the help of devices for determining the coordinates of the stars (random error).

Key words: remote sensing, star sensor, error, orientation.

PACS numbers: 07.87.+v, 07.60.-j.

Introduction

The concept of remote sensing appeared in the 19th century following the invention of photography [1], and astronomy was one of the first areas in which this method was applied. Subsequently, remote sensing began to be used in the military field to collect information about the enemy and make strategic decisions. During the American Civil War, photographs taken with unguided aerial vehicles were used to observe the movement of troops, the supplies, the progress of fortifications and to assess the effect of artillery shelling. As a result of research funded by various states, technologies were developed that made it possible to create sensors, first for military purposes, and then for civilian use of this method.

After the Second World War, the remote sensing method began to be used for monitoring the environment and assessing the development of territories, as well as in civil cartography. In the 60s of the XX century, with the advent of space rockets and satellites, remote sensing went into space.

The new era of remote sensing is associated with manned space flights, reconnaissance, meteorological and resource satellites. The first television system to systematically survey the Earth's surface for meteorological purposes was installed on the American Tiros-1 spacecraft launched on April 1, 1960.

The first Russian satellite of a similar purpose, Kosmos-122, was launched into orbit on June 25, 1966. Since that moment, television systems for observing the Earth from space have become

widespread. A whole area of scientific and technical activity was formed, which was named – Earth Remote Sensing (ERS) [2].

Systems and data of remote sensing of the Earth

Remote sensing data refers mainly to satellite images or images that are obtained during observation of the Earth's surface by aviation and space vehicles equipped with various types of imaging equipment – remote sensing systems [1-5]. The range of using images is very wide. Below are some of the main areas:

1. Land use and mapping of land resources.
2. Research on urban growth.

3. Agriculture.
4. Groundwater mapping.
5. Flood control.
6. Hydro-morphological research.
7. Mapping of vacant land.
8. Regional planning.
9. Fight against natural disasters.

Thus, remote sensing systems are used to survey large areas of the Earth's surface in order to obtain operational and up-to-date information about the area of interest. In this case, both the usual shooting mode – monochrome (black and white), and multispectral (color) are used. Examples of space images [6], obtained in the course of space imagery by remote sensing systems on board the spacecraft, are presented in Figures 1a and 1b.



a



b

Figure 1 – Satellite images: a – monochrome (Constanta, Romania), made by the “Geoton” imaging equipment, “Resurs-P” spacecraft, 2014; b- multispectral satellite image (Karlstad, Sweden), made by the “Geoton” imaging equipment, “Resurs-P” spacecraft, 2014.

As you can see, the obtained images have different “scales”. This is one of the most important characteristics of ERS systems – spatial resolution [7]. Spatial resolution is determined by the size of the smallest object that can be identified. The factors that affect the spatial resolution are: the spacecraft orbital altitude, the size of the photosensitive elements of the imaging equipment, and the focal length of the optical system.

Spatial resolution images are differentiated into the following categories and are determined by the size of the smallest element of the earth's surface displayed on it:

- Very low resolution – more than 10 km;
- Low – 1 – 10 km;

- Medium – 100 – 999 m;
- Relatively high – 50 – 99 m;
- High – 20 – 29 m;
- Very high 1 – 19 m;
- Ultra-high resolution – up to 1 m.

Low spatial resolution images show only large objects. Fine details of objects can be seen in high-resolution images. Here are some more examples (Fig. 2- 3) of remote sensing data [7].

Continuous improvement of the spatial resolution is the main trend in the development of remote sensing systems, as well as the improvement of other key characteristics of the remote sensing spacecraft: swath, survey performance and accuracy of spatial referencing [8].



Figure 2 – The city of Aragama (Japan) before (above) and after the tsunami on March 11, 2011 (below) in ultra-high resolution satellite panchromatic images.

Spatial referencing (some sources also use analogous terms: coordinate referencing, geodetic referencing) is the process of assigning to each image element its geographical or cartographic coordinates. Thus, the image is linked to the Earth's surface. This process is performed using special software [9], based on various methods of image processing. The result of spatial referencing and the subsequent processing stage are: creation of two-dimensional and three-dimensional maps, atlases for mapping purposes, etc.

At present, the expansion of the orbital constellation of Earth remote sensing satellites (ERS) continues [10-14]. Within the framework of

the Federal Space Program of the Russian Federation for 2016-2025, it is envisaged to create an ERS spacecraft of ultra-high spatial resolution. This spacecraft will be equipped with onboard target equipment providing a spatial resolution of less than 40-50 cm from an orbit height of 700 km with a spatial reference accuracy of 2-3 m [15]. Thus, it is planned to improve the main characteristics of the ERS spacecraft by 2-3 times in comparison with the best domestic spacecraft "Resurs -P" [16], which at the same time will allow achieving the characteristics of the world foreign leaders in the creation of ERS spacecraft – the USA, France, Korea [16-18]. The corresponding comparison table 1 is shown below.

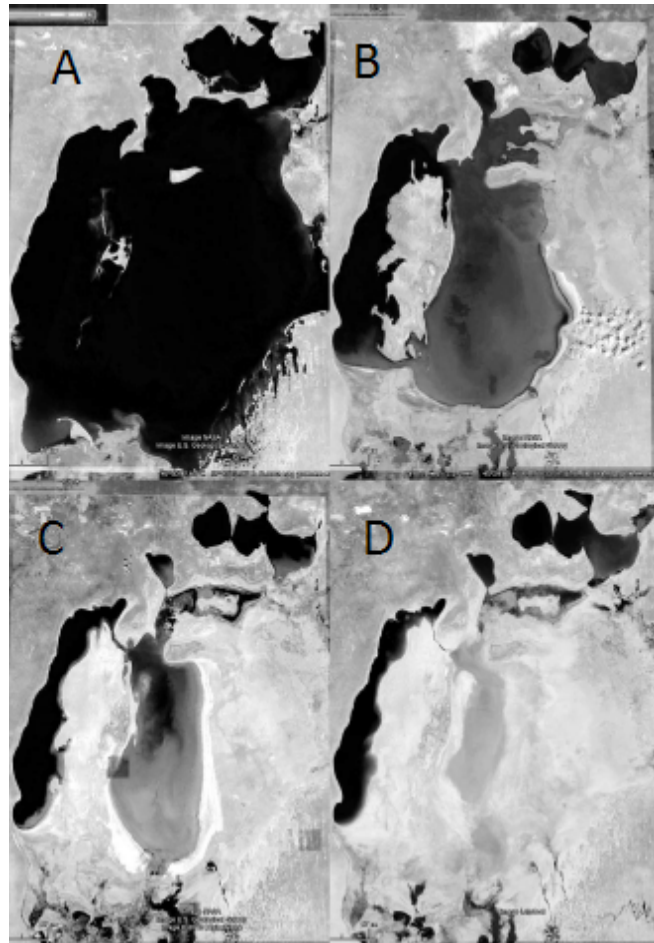


Figure 3 – Drying up of the Aral Sea: 1973 (A), 1999 (B), 2004 (C) and 2013. (D) (based on Google Earth, 2013).

Table 1 – Characteristics of modern Earth remote sensing spacecraft.

Characteristics of the space craft	Resource-P (Russia)	Kompsat-5 (Korea)	Pleiades (France)	World-View-4 (USA)	Advanced space craft (Russia)
Launch year	2013 2014 2016	1013	1A -2012 1B -2014	2016	2020-2025
Mass,kg	6275	1400	970	2087	-
Shooting strip width, km	38.5	5	20	13.1	-
Spatial resolution, m	<1	1	0.5	0.25-0.3	<0.4
Spatial reference accuracy, m	<15	<12	4.5	<3	<3

The main reasons for the inaccurate referencing of the remote sensing data are the errors in measuring the parameters of the orbit and the error in the orientation of the spacecraft [8]. Glonass / GPS systems [19] are responsible for the first error, and the devices for determining the coordinates of stars are responsible for the second. The results of measurements of these

systems and devices are taken into account in the geometric correction of images, thereby ensuring their initial reference with an accuracy determined by the accuracy of measuring the parameters of the orbit and orientation angles. Thus, the measurement accuracy of the device for determining the coordinates of the stars affects the accuracy of image referencing.

Devices for determining the coordinates of stars

It should be noted right away that the term device for determining the coordinates of stars also has the following names, which are used in various literary sources: star sensor, astro-device, star orientation sensor, astro-sensor, star tracker, and star device, and star coordinator, optoelectronic device of orientation and navigation spacecraft. In order not to get confused in the terminology and to simplify the perception of the work, we will take one single term as the main one – a device for determining the coordinates of stars (DDCS). DDCS is a device from the spacecraft, which is a sensitive element of the attitude control system.

The development of space technology is largely associated with the improvement of spacecraft control systems. In connection with the high and constantly increasing requirements for the accuracy of control systems, as well as due to the need to ensure the autonomy of their functioning, a device for determining the coordinates of stars is used as primary information devices, which determine the angular position of the apparatus relative to astronomical sources of radiation (astro-orientations) – stars, the Sun, planets [19]. Thus, the device for determining the coordinates of stars is a sensitive element of the spacecraft attitude control system.

The main tasks of the device for determining the coordinates of stars are [3-5, 9-10]:

- determination of one's own orientation in space and, therefore, the apparatus on which it is installed;
- guidance of a device installed on the spacecraft in a given direction;
- increasing the accuracy of the spatial referencing of the resulting images.

The tasks considered on any spacecraft are solved in the conditions of its operation – in a certain space orbit, according to the stars available for observation, in the presence of interfering radiations of various kinds, design constraints of a specific type of spacecraft, its energy, dynamic and other characteristics. Taking into account the above, a complex of technical requirements is imposed on modern spacecraft orientation and navigation devices, the main of which are [19]:

- high accuracy of angular measurements;
- the required sensitivity – the ability to work on the radiation of those stars that provide the required measurements;
- noise immunity – resistance to the effects of various interference emissions of both natural and artificial origin;

- functioning at various motions of the spacecraft with significant angular velocities and accelerations;
- performing a set of complex functions – search and detection of stars, their selection against the background of interference, tracking, accurate measurement of angular coordinates, recognition of groups of stars and determination of triaxial orientation;

- performance under the influence of space factors (deep vacuum, solar radiation, ionizing radiation, gas and dust environment) for a long time (up to 10-15 years);

- the impact of various factors on the part of the spacecraft – mechanical, thermal, electrical, etc.

All these requirements must be taken into account when designing modern DDCS spacecraft.

Modern devices for determining the coordinates of stars

At present, in the world there is a fairly large number of firms and companies that are engaged in the development of DDCS [20-23]. The characteristics of some devices are presented in Table 2.

In the United States, DDCS is manufactured by Ball Aerospace [20] (see Figure 4). The company has vast experience. Its instruments have functioned or are functioning on spacecraft XTE, MSX, Terra, WIRE, SWAS, IKONOS, QuikSat, GOES, Aqua, Space Shuttle, Deep Impact, ACE, SOAR, etc.

Analyzing the parameters of the devices, one can see that the company has come a long way in the development and improvement of its products. The arsenal of the manufacturer's products reflects the main directions of its development. A series of high-precision instruments ST-601 and ST-602 with an $8 \times 8^\circ$ field of view has been created. Modification of the ST-621 instruments is intended for reusable use on the Space Shuttle. Devices with a wide field of view ST-621 $20 \times 20^\circ$ have been developed. The disadvantage of building these devices is that they are not autonomous. The devices have a built-in processor that processes video information; however, the procedure for calculating the orientation is performed in the spacecraft onboard computer, where the star catalog is stored. Only the latest modification of the ST-633 device, which the company positions as completely autonomous, has the ability to calculate the orientation and issue it in the form of quaternions. The manufacturer indicates that the devices use a radiation-resistant element base capable of withstanding a dose of ionizing radiation of 10^5 krad.

Table 2 – Characteristics of the device for determining the coordinates of stars (DDCS)

Device	Manufacturer	Accuracy ($\sigma_{x,y} / \sigma_z$), angles	Max. angular velocity, deg / s	View Field, degrees	Information refresh rate, Hz	Power consumption, W	Weight, kg
HD-1003 (2001)	Goodrich (USA)	2/40	2	8x8	2	10	3.9
HE-5AS (2006)	Terma (Denmark)	3/16	2	22x22	4	8.5	2
AA-STR (2007)	Galileo Avionica (Italy)	6/50	2	20x20	10	7	1.5
ASTRO APS (2007)	Jena-Optronik (Germany)	2/15	5	20x20	10	9	1.8
HAST (2010-2012)	Ball Aerospace (USA)	0.2*	-	8x8	2	120	13.6
HYDRA (2010-2012)	SODERN (France)	6*	10	23x23	30	15	3.4
AURIGA (2017-2018)	SODERN (France)	6/40	0.5	-	5	1	0.2
348K (2013)	«NPP «Geophysics-Space»»	15*	0.2	15x15	5	7	3.7
BOKS-M 60 / 1000(2009)	SRI RAS	1/10	3	18x18	4	10	4.5

The values denoted by * are equal to three axes characteristic due to the use of multiple optical units [23].



Figure 4 – Appearance of DDCS ST-633 (left) and ST-602 (right), Ball Aerospace (USA).

One of the developments of Ball Aerospace, which is distinguished by high accuracy rates, is DDCS HAST [20]. A feature of this autonomous DDCS is that the latter consists of two optical blocks and one electronics unit, which allows obtaining uniform information along all three axes of the device. The main characteristics of HAST are presented in Table 2. It is worth noting that the accuracy for the DDCS HAST means the residual systematic error in accordance with [20].

Another company on the market is the international company TERMA [23], which includes specialists from Denmark, Germany, the Netherlands and the USA. Their instrument HE-5AS [23] (see Fig. 5) is used as a standard DDCS on the TacSat-2 spacecraft [22].

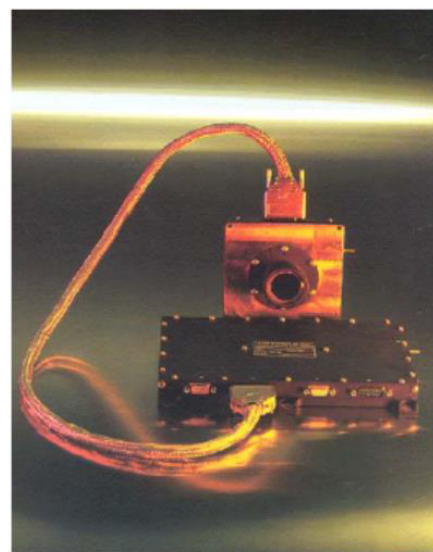
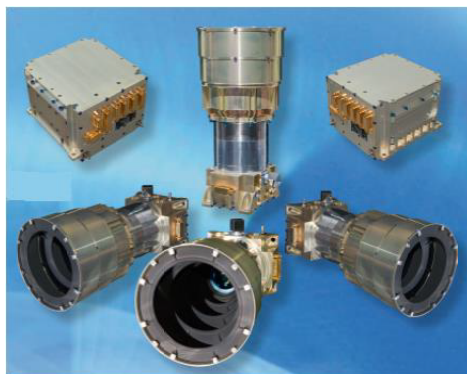


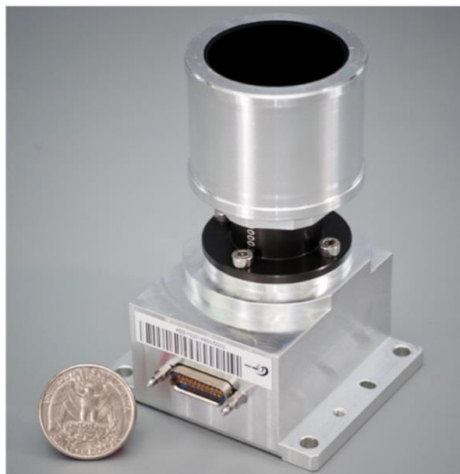
Figure 5 – Appearance of DDCS HE-5AS by TERMA

Before the launch on the TacSat-2 spacecraft, this device had experience of operating only on two spacecraft of the Navy and the US Air Force MiTeX (Micro-Satellite Technology Experiment) [24, 25]. The accuracy characteristics of this DDCS are presented in [26].

The French company SODERN [21] has significant experience in creating DDCS. Today it is one of the world leaders in the production of DDCS. During its existence, the company has produced more than 60 devices for space corporations in ten countries of the world. Today it produces DDCS SED20, SED26, SED36, HYDRA and AURIGA [21, 23] (see Figures 6a, 6b).



(a)



(b)

Figure 6 – Appearance of SODERN company (France) devices: a- HYDRA; b – AURIGA

In recent developments by SODERN (SED36 and HYDRA), there is a tendency to separate the optical block from the electronics block. When a certain number of optical units are used, as, for example, in the HYDRA instrument – four, the system ceases to be sensitive to illumination by the Sun or the Earth,

and, importantly, it becomes sufficient to control the spacecraft attitude without additional angular motion meters on board. A new achievement of the company is the production of DDCS AURIGA. It combines low manufacturing cost and high performance, and takes into account the latest trends in the development of the micro-nano satellite market. At the beginning of 2018, SODERN carried out flight tests of DDCS AURIGA. All of the listed SODERN DDCSs are autonomous, i.e. are able to determine the orientation parameters using their own computing facilities. And what we can say about the accuracy characteristics of the DDCS SODERN. It is interesting to note that for HYDRA DDCS, according to [21], the error does not exceed the range 1-3 arc.sec. But in [26], the specified value of accuracy for this DDCS has a value ~ 6 arc. sec. Consequently, the assessment of the accuracy of the DDCS can be performed with large deviations due to the lack of data on the final error or due to the presence of several data on the values of the angular error, the comparative analysis of which is difficult.

Jena-Optronics, Germany, is another leading global manufacturer of DDCS [22]. The first CCD-based stellar instrument was developed by Jena-Optronics jointly with the Space Research Institute of the USSR Academy of Sciences (now SRI RAS, Russia). Today the company produces three models of DDCS: ASTRO 10, ASTRO 15 and ASTRO APS [22]. All devices are self-contained. The main characteristics of ASTRO APS are presented in Table 2.

The ASTRO-APS device is one of the smallest in terms of weight and dimensions in its class. As for the accuracy characteristics, then the official website of the firm [22] presents: random error («Random Error») through the reference axis (less than 1 arc. sec), random error along other axes (less than 8 arc. sec), and systematic (Bias Error) in over the entire operating temperature range for all axes – less than 5 arc.sec. There are no designations, but it can be assumed that the random error across the reference axis is “ σ_z ”, and random errors along the other axes are “ $\sigma_{x,y}$ ”. Then the ASTRO APS accuracy can be written as: 1/8 arc.sec.

One of the leading organizations in Russia for the development of DDCS is SRI RAS [27]. The BOKS DDCS produced by the Institute successfully operate on the Yamal geostationary satellites and the International Space Station (ISS), the Kosmos-2410, Kosmos-2420, Meteor-M spacecraft [28, 29], etc. Today SRI RAS is releasing new lines of DDCS: BOKS-M [26, 30] (see Figure 7). The main technical characteristics of BOKS-M and the new DDCS with two exhaust gases are presented in Table 2.



Figure 7 – Appearance of DDSCS series BOKS, SRI RAS (Russia)

It should be noted that in order to improve such indicators as weight, dimensions, power consumption, noise immunity and accuracy, SRI RAS managed to implement the concept of an integrated spacecraft orientation device. Angular velocity sensors (AVS) were integrated into the BOKS-MF and BOKS-M60 instruments. Later, methods were developed for testing angular velocity sensors as part of the DDSCS using the created bench base [8]. By changing the focal length and the amount of exhaust gas, while maintaining the same electronic unit (which in fact will be universal), SRI RAS plans to create a small-sized device with low power consumption, equally suitable for use in solving various problems: observation of the lunar surface from a landing spacecraft; observation of the sun in order to determine the parameters of orientation; observation of stars in order to determine the parameters of orientation. If we consider the accuracy characteristics of the BOKS, then, as can be seen from the above references, SRI RAS by accuracy means the root-mean-square deviations of measurements of the instruments being carried out for each of the optical axes (random error).

Conclusions

1. The performed review of modern devices for determining the coordinates of stars showed that: developers of DDSCS use different characteristics to express accuracy, such as residual systematic error (Ball Aerospace, DDSCS HAST) or random error (SRI RAS, BOKS); comparison of the values of the DDSCS errors of different firms leads to ambiguous results; - when assessing the accuracy characteristics of the DDSCS, the effect of temperature deformation and other thermo-mechanical processes is not taken into account.

2. Analysis of the DDSCS accuracy characteristics of the company SRI RAS – BOKS showed that, in accordance with Table 2, the accuracy of the DDSCS lies in the range from 1 arc.sec. up to 2 arc.sec. The main contribution to this error is made by the standard deviation of the measurements carried out by the DDSCS (random error). It is necessary to compare the values of the measurement errors for an estimated calculation of the thermal deformation effect on the accuracy of the DDSCS (systematic error).

References

- 1 Braun A. C. More accurate less meaningful? A critical physical geographer's reflection on interpreting remote sensing land use analyses // *Progress in Physical Geography*. – 2021. DOI: 10.1177/0309133321991814.
- 2 Abdollahi A., Bakhtiari H.R.R., Nejad M.P. Investigation of SVM and level set interactive methods for road extraction from google earth images // *Journal of the Indian Society of Remote Sensing*. – 2018. – Vol. 46. – Pp. 423-430.
- 3 Razzhivalov P., Kalugin V., Korobova N. Complex modeling of thermal calculation for device determining the Star coordinates // *IEEE. Russia Young Researchers in Electrical and Electronic Engineering Conference*. – 2019. – Pp. 2003-2007. DOI: 10.1109/EICoNus.2019.865714.

- 4 Razzhivalov P., Korobova N., Mahonin N. Analysis of the stellar sensors characteristics to determine the criteria for assessing the accuracy // *Proceed. IEEE Conf. Russian Young Researchers in IEEE, EIConRus.* – 2020. – Pp. 2164-2169. DOI: 10.1109/EIConRus49466.2020.9039325
- 5 Razzhivalov P., Kalugin V., Korobova N. Estimation of the external factors influence on the sensor accuracy // *Proceed. IEEE Conf. Russian Young Researchers in IEEE, EIConRus.* –2018. DOI: 10.1109/EIConRus.2018.8317413.
- 6 Russian space systems: Scientific center for operational monitoring of the Earth [Electronic resource]. – Access mode <http://www.ntsomz.ru>.
- 7 Sutyryna E.N. Remote sensing of the earth. – Irkutsk: ISU. 2013, – 165 p.
- 8 Korobova N., Razzhivalov P., Kalugin V., Timoshenkov S., Artemov E. Error angle determination of the star sensor with liquid cooling // *Proc. SPIE 9200, Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications VIII.* –2014. 920015. DOI:10.1117/12.2059260.
- 9 Campbell J. B., Wynne R. H. Introduction to remote sensing. – New York: Guilford Press, 2011, – 670 p.
- 10 Emery W., Camps A. Introduction to satellite remote sensing: Atmosphere, ocean and land applications. Amsterdam. Elsevier, 2017, 845 p.
- 11 State Corporation for Space Activities «ROSCOSMOS» [Electronic resource]. – Access mode: <http://en.roscosmos.ru>
- 12 Russian space systems [Electronic resource]. – Access mode: <http://russianspacesystems.ru>
- 13 State Space Research and Production Center named after M.V. Khrunicheva [Electronic resource]. – Access mode: <http://www.khrunichev.ru>.
- 14 United Rocket and Space Corporation [Electronic resource]. – Access mode: <http://www.rosorkk.ru>.
- 15 Krutskikh N.V., Mironov V.L., Ryazantsev P.A. The use of GIS-technologies for mire studies. *Proceedings of the International conference InterCarto. InterGIS.* –2018. –Vol.24(1).- Pp. 405-418.
- 16 Earth Observation Portal. [Electronic resource] – Access mode: <https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/worldview-4>.
- 17 Earth Observation Portal [Electronic resource]. – Access mode: <https://directory.eoportal.org/web/eoportal/satellite-missions/p/pleiades> .
- 18 Earth Observation Portal [Electronic resource]. – Access mode: <https://directory.eoportal.org/web/eoportal/satellite-missions/pag-filter/-/article/kompsat5>
- 19 Eissfeller B., Ameres G., Kropp V., Sanroma D. Performance of GPS, GLONASS and Galileo. *Proc. Of. Photogrammetric Week '07.* –2007. –Pp. 185-199.
- 20 Ball Aerospace [Electronic resource]. – Access mode: <http://www.ball.com/aerospace/markets-capabilities/capabilities/technologies/components/star-trackers>.
- 21 Sodern Company [Electronic resource]. – Access mode: http://www.sodern.com/website/fr/ref/Optroniques_215.html .
- 22 Jena Optronik Company [Electronic resource]. – Access mode: <http://www.jena-optronik.de/en/aocs/astro-aps.html>.
- 23 Terma company [Electronic resource]. – Access mode: <https://www.terma.com/capabilities/space-systems>.
- 24 Gunter's Space Page [Electronic resource]. – Access mode: http://space.skyrocket.de/doc_sdat/mitex-a.htm.
- 25 Aerospace Research Central [Electronic resource]. – Access mode: <https://arc.aiaa.org/doi/abs/10.2514/6.2007-5434>.
- 26 Dyatlov S.A. Review of spacecraft attitude control star sensors // *Modern problems of orientation and navigation of spacecraft: collection of proceedings of the All-Russian scientific and technical conference.* M.: Rotaprint SRI RAS, –2009.
- 27 Space Research Institute [Electronic resource]. – Access mode: <http://www.iki.rssi.ru>.
- 28 Avanesov G.A., Bessonov R.V., Forsh A.A., Kudelin M.I. Analysis of the current state and prospects for the development of stellar orientation devices of the BOKS family // *Izv. Universities. Instrumentation.* – 2015. – Vol. 58. – P.1.
- 29 JSC «NPP» Geofizika-Cosmos «[Electronic resource]. – Access mode: <http://www.geofizika-cosmos.ru/napravleniya-deyatelnosti/optiko-elektronnye-pribory-orientacii-i-navigacii-kosmicheskikh-apparatov/napravlenie-1.html>.
- 30 Kondratyeva T.V., Nikitin A.V., Polyansky I. V. The accuracy of the coordinate referencing of the video data of the MSU-100/50 cameras of the Meteor-M1 // *Modern problems of remote sensing of the Earth from space.* – 2013. – Vol. 10. – P.1.