Synthetic Aperture Orbital Telescope for Earth Remote Sensing Equipment

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Abstract

The object of the research is the development of the method of aperture synthesis of a mirror system designed for remote sensing of the Earth.

The analysis of existing methods for the formation of the synthesized aperture was carried out, their accuracy, cost, and mass-dimensional characteristics were evaluated. A new version of the optical system of the synthetic aperture mirror lens is presented and its optimization is performed in the *Zemax* software package. An estimate of the accuracy of the designed system has been made; a design variant has been developed that includes a transformation mechanism when the telescope is put into near-earth orbit.

As a result of the study, the design parameters of the base lens were determined: a focal length of 13 m, a main mirror diameter of 800 mm, a field angle of 0.25° for modifying a telescope for a low orbit; and the entire telescope as a whole: the lag from the main axis of the telescope is 1.2 m, the angle of rotation of the flat mirror for combining images (45 + 1,5)°, the signal-to-noise ratio (189 in a low orbit with an angle of the Sun 0°, 15 in the geostationary orbit with a sun angle of 60°).

It has been established that the use of aperture synthesis technology allows the development of high-resolution optical-electronic systems with lower production and operation costs compared with classical methods for forming the surface of the main mirror. In the course of the simulation, the instability of the values of the frequency-contrast characteristic with increasing angle of view was determined, which is important for a low near-earth orbit, and the requirement for positioning elements of the optical system was established.

Keywords: orbital telescope, mirror, synthesized aperture.

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Орбитальный телескоп с синтезированной апертурой для аппаратуры дистанционного зондирования Земли

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Объектом исследования являлась разработка метода апертурного синтеза зеркальной системы, предназначенной для дистанционного зондирования Земли.

Проведен анализ существующих методов формирования синтезированной апертуры, оценена их точность, стоимостные, а также массогабаритные характеристики. Представлен новый вариант оптической системы зеркального объектива с синтезированной апертурой и выполнена его оптимизация в программном пакете *Zemax*. Произведена оценка точности спроектированной системы, разработан вариант конструкции, включающий механизм трансформации при выводе телескопа на околоземную орбиту.

В результате исследования определены конструктивные параметры базового объектива: фокусное расстояние 13 м, диаметр главного зеркала 800 мм, угол поля зрения 0,25° для модификации телескопа для низкой орбиты; и всего телескопа в целом: отставание от главной оси телескопа 1,2 м, угол поворота плоского зеркала для совмещения изображений (45 + 1,5)°, отношение сигнал/шум (189 на низкой орбите с углом Солнца 0°, 15 на геостационарной орбите с углом Солнца 60°).

Установлено, что использование технологии апертурного синтеза позволяет разрабатывать оптико-электронные системы высокого разрешения с меньшими затратами на производство и эксплуатацию по сравнения с классическими методами формирования поверхности главного зеркала. В ходе проведения моделирования была определена неустойчивость значений частотно-контрастной характеристики при увеличении угла поля зрения, что актуально для низкой околоземной орбиты, а также установлено требование по ошибкам позиционирования элементов оптической системы.

Ключевые слова: орбитальный телескоп, зеркало, синтезированная апертура.

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Introduction

One of the main requirements for modern orbiting telescopes is to ensure the maximum resolution of the optical system while maintaining a high level of image contrast. The formation and characterization of Earth remote sensing data (ERS) is determined by the orbit height of the spacecraft (SC), the type of sensors and imaging equipment used, which in turn determine: the scale of the maps, the bandwidth and the width of the territory, as well as the resolution of the images. A large number of spacecraft for remote sensing are designed based on the conditions of their work in low orbits 400–800 km.

The spectral resolution of the optical-electronic systems of a spacecraft is determined by the atmospheric transparency windows in the visible (380–720 nm) and near infrared (720–1300 nm) spectral regions. Some sensors of some satellites (for example, IRS-P6 or SPOT 5) use the middle infrared range (up to 1.75 μm) or the far infrared range 10.4–12.5 μm (Landsat 7 ETM +) (Table 1) [1, 2].

The spatial resolution determines the smallest size of objects that can be distinguished in the image and can be carried out both in panchromatic mode (more accurate) and in multispectral mode. Today, ultra-high-resolution images include images in which objects of 0.3–0.9 m in size are visible [3].

The actual task remains to increase the temporal resolution, which determines the frequency of obtaining images of a specific area on the earth's surface. For existing space remote sensing satellites, the best spatial resolution is 1–3 days. In this case, the duration of observation for one surface area is limited to a time interval of not more than 1 min [4]. However, there are a number of areas that require almost continuous surveys for a sufficiently long period of time (for example, meteorology – during the development of cyclones and hurricanes, agriculture – monitoring of areas covered by forest fires, as well as the military area and antiterrorist operations for tracking facilities that pose a potential threat, and other emergencies).

Table 1

Main technical characteristics of spacecraft with high and ultra-high resolution sensors for remote sensing

Space satellite (sensor)	Opto-electronic system (camera)	Spectral resolution (μm)	Swath (km)	Temporary Resolution (days)	Spatial resolution, (m)	Map scale
Landsat 7 ETM+	SMA+SLC	0.45–2.35; 10.4–12.5	185	16	15	1:100 000
Resourcesat-1 (IRS-P6)	LISS-III,IV; AwiFS	0.52–1.70	23.9; 70; 141; 740	5	56; 23.5; 5.8	1:50 000
SPOT 5	HRS	0.45–1.75	60; 1000–2000	26; 1	5−10; 1000	1:25 000
ALOS	PRISM, AVNIR-2	0.42–0.89	35; 70	46	10−2.5	1:25 000
EROS-B,C	ELOP	0.50–0.90	16–7.14	15	2.8−0.7	1:10 000
Resource DK	Geocon-1	0.50–0.80	4.7–28.3	6	2−3	1:5 000
OrbView 3, 4	OHRIS (TMA)	0.45–0.90	8 × 8	3	4−1	1:5 000
IKONOS-2	Eastman Kodak (RPC)	0.45–0.88	11,3 × 11,3; 11 × 100	14	3.28−0.82	1:5 000
GeoEye-1	Kodak и ITT Industries	0.45–0.92	15.2	1−3	1.65−0.41	1:2 000
WorldView-3	Eastman Kodak	0.40–2.25	17.6	1−3	1.24–0.31 (VNIR); 3.72 (SWIR); 30 (CAVIS)	1:2 000
QuickBird-2	BGIS-2000 (BHRC 60)	0.45–0.90	16.5	1−5	2.44–0.61	1:2 000

The increase in temporal resolution is possible in two directions. The first is the formation in orbit of a group of spacecraft synchronized in a photograph when working on a specific part of the surface. In connection with the occasional occurrence and solution of the above problems from an economic point of view, the implementation of such a satellite placement option is not always justified. The second is an increase in the height of the orbit of the spacecraft, which leads to an increase in the time of its stay over a specific part of the earth's surface. Launching the satellite into a geostationary orbit (GSO) (35.786 km above sea level) with rotation in the direction of the Earth's rotation, with an orbital speed of 3.07 km/s, ensures their mutual synchronization (sidereal day: 23 h 56 min 4,091 s). The disadvantages of telescopes located at the GSO include the total delay of the transmitted signal of about 2–4 s and the impossibility of observing parts of the Earth's surface at high latitude (81°–90°) or significant signal shielding by ground objects already at latitude (from 75°).

To form a high-resolution image with a telescope located in a GSO, the aperture of its main mirror should be about 30–40 m. Making such a mirror and then placing it into orbit is a difficult task. In classical spacecraft for remote sensing (Table 1) the aperture of the input window of the optical system is about 0.4–1.1 m.

An increase in the aperture of the main mirror leads to additional difficulties associated with an increase in its mass, as well as the need to install additional mechanisms for balancing and adjusting. In addition, technological costs associated with the formation of a high-quality reflective surface increase. Creating systems with a large aperture was made possible by splitting the main mirror into segments [5, 6].

According to the theory, in a synthesized aperture telescope, the final image is formed from separate fragments of several mirror modules and is equivalent in quality to a telescope with a solid mirror surface, provided that the images are geographically acceptable and phase synchronized. Today, the problems of simulating synthetic aperture systems from a practical point of view have been successfully solved only for ground-based observatories: the Very Large Telescope of the South European Observatory (VLT ESO); Hopkins multi-mirror telescope (MZT) and mainly for radar systems (Murchison Radio Astronomy Observatory, ASKAP). Orbital telescopes with segmented elements of the main mirror are implemented only in James Webb Space Telescope (JWST) [7]. Design options for orbital telescopes with synthetic aperture are currently lacking.

The purpose of the research was to develop a concept and determine possible options for building a high-resolution orbital telescope with a synthesized aperture of the main mirror for a remote sensing satellite located in a geostationary orbit.

Analysis of the effectiveness of systems with segmented and synthesized apertures

In the TCA based on the power modules, the optical axes of the lens are parallel to each other, and the rear focal segments are reduced to a single point by a system of mirrors (Figure 1).

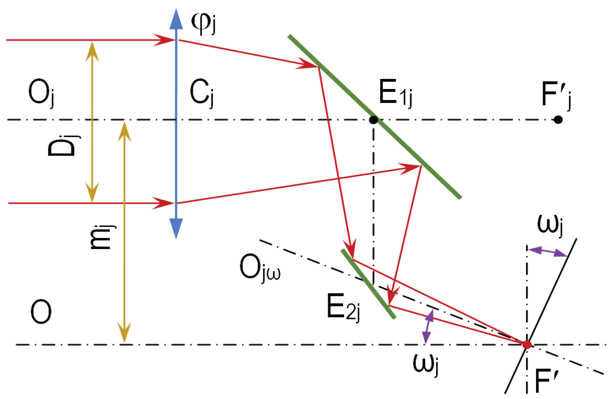


Figure 1 – Optical scheme of the power module of the telescope

It can be seen from the figure that the focal plane of the *j*-th objective forms an angle ω_j with the plane passing through the point F' perpendicular to the optical axis of the telescope. The inclination of the focal plane leads to a longitudinal defocusing of the image, and to a transverse shift of it in the common image plane. In addition, the tilt of the image causes a phase shift of the light oscillations, which leads to disruption of the phase conjugation of the folding wavefronts. The formation of a synthesized aperture by combining individual power modules provides a relatively low image quality (at $m_0 = 1$ m, and $W = 1''$, $W_{00ji} = 10$ μm) [8].

The main advantage of afocal systems is to maintain the parallelism of the beams after passing through the modules – there is no image tilt. In this regard, to project an image onto a photodetector, a collector telescopic system is needed, to which high demands are made. The telescopic system T_j, through a system of flat mirrors E_{1j} and E_{2j}, generates light for the focusing system φ. A generalized optical scheme can be represented as a combination of afocal modules and a central focusing system (Figure 2).

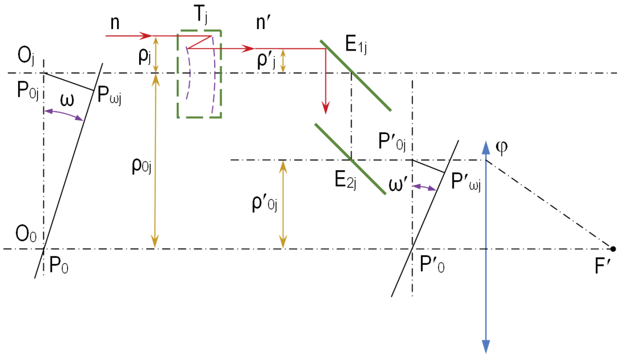


Figure 2 – Optical scheme of a synthetic aperture telescope from afocal modules

A serious obstacle to the composition of the optical system of the synthesized aperture from afocal modules is the curvature of the image, the elimination of which is possible in principle by the complexity of the module circuit or the introduction of adaptive systems. Then the main problem is the condition for the fulfillment of the invariance of the collector system, in which the Fresnel number for the system must correspond to the Fresnel number of the entire telescope, which significantly increases the complexity of this component.

The results of the analysis of the conceptual schemes of telescopes with segmented and synthesized apertures of the main elements for a number of key characteristics are presented in Table 2.

Table 2

Comparison of properties and characteristics of telescopes with a segmented main mirror, synthetic aperture telescope with power and afocal modules

The name of the characteristic	Segmented main mirror	Synthesized aperture	
		With power modules	With afocal modules
Shielding factor	0.07–0.15	0.7–0.9	0.8–0.9
Phase shift	0.110* μm m_0 = 3.3 m, 2ω = 2.2 × 4.4′	10 μm m_0 = 1 m, 2ω = 2″	0,033 μm m_0 = 1 m, 2ω = 1′
Optional equipment	Adaptive mirror curvature monitoring system	Module Position Control System	Collector Telescope Module Position Control System
Features of manufacturing technology	Difficulties in the development of aspherical surfaces	High requirements for equality of focal lengths and curvature of images	High requirements for the telescope-collector and the curvature of images
Assembly and adjustment	Precise mirror curvature setting automatically	High complexity of the adjustment of individual modules and their system relative to the receiver, requiring special equipment	The adjustment difficulty is high, but fewer parameters are being monitored than in the system with power modules
Cost coefficient	1**	0.76**	0.84*
Weight	m = 300–800 kg	m/γ***	m/0.8γ***

* JWST compliant [9]
** according to the source [10]
*** γ – the ratio of the diameter of the equivalent aperture to the diameter of the module

Optical system of a synthetic aperture telescope and image quality assessment

Based on the analysis of existing models of optoelectronic systems of the Earth remote sensing satellite, the main technical parameters have been formed, which the new version of the synthetic aperture orbital telescope (TSA) should satisfy (Table 3). Let us take the TSA system based on the power modules, which are the Nesmith system, for calculation.

The diameter of the synthesized aperture is determined taking into account the maximum allowable dimensions of the launch vehicle, equal to 4000 mm for the diameter. Accepting design technological gaps equal to 500 mm in diameter, the TSA optical system should be inscribed in a circle with a diameter of D_{eq} = 3500 mm. The diameter of the main mirror of the module is set to D_{mod} = 800 mm, taking into account the need to observe intermodular gaps ΔN_1.

Table 3

Initial technical parameters of the synthetic aperture telescope

Parameter name	Numerical value
Orbit height:	
low	750 km
GSO	36000 km
Working spectral range	0.4–0.85 nm
Number and type of spectral channels	1 (panchromatic)
MTF on the Nyquist frequency	0.3
Capture width (at an altitude of 750 km)	12 km
Spatial resolution	0.3 m
The minimum height of the sun to the surface normal	60°
Overall dimensions of the system, not more (L×D)	12000 × 4000 mm
Lens weight, not more	180 kg

The shielding factor is assumed to be q = 0.23 to meet the requirements for luminosity and system dimensions, and the beam convergence index is β = 0.46 to comply with the maximum relative aperture (1:7.5) of the main mirror.

In the *Zemax* software package, we introduce a system of flat mirrors for carrying out the image and optimize the system – assign OPDX as the operand of the standard automatic optimization, assign the radii of curvature of the mirrors, air gaps along the optical axis and the Conic operator of many orders (up to 4-th order) with variable optical system parameters responsible for the shape of the surface of the mirrors. As a result of the optimization, the design parameters of the base telescopic module were determined, from which the model of the entire TSA was made (Figure 3).

The pixel size in modern CCD-line-ups is 6–8 μm, while the number of lines in integral assemblies reaches 12–14 pcs., which ensures the geometric and energy parameters of the required linear resolution on the ground (0.3 m).

Figure 4 shows the graphs of the frequency-contrast characteristic (MTF) and point spreading functions (PSF) showing the quality of the designed optical system.

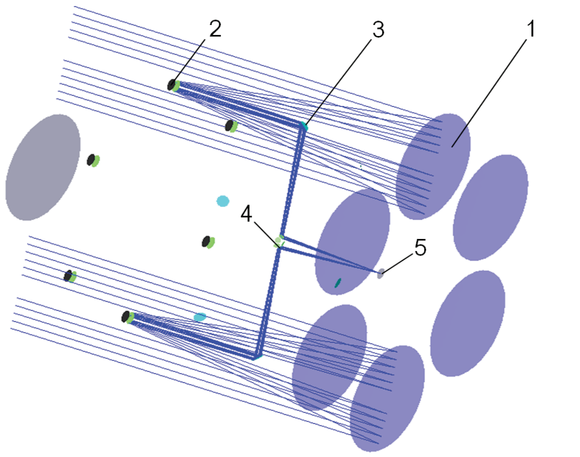
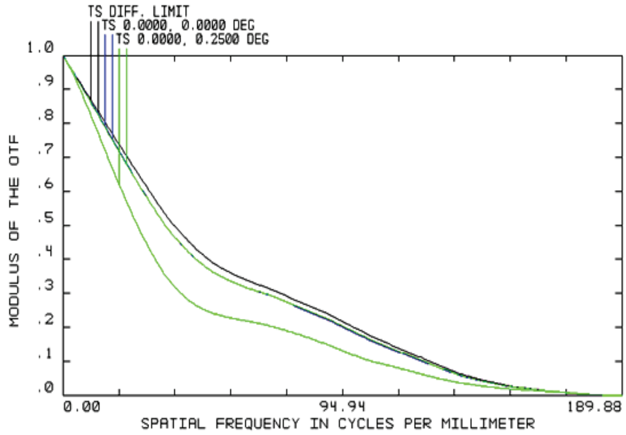
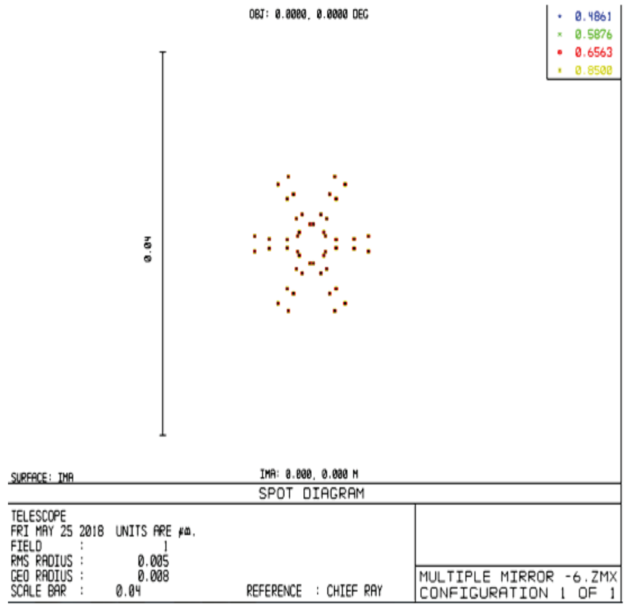


Figure 3 – Ray path in synthetic aperture telescope (model *Zemax*): 1 – main mirror; 2 – secondary adaptive mirror; 3 – flat mirror; 4 – swivel mirror; 5 – phase sensor plane



a

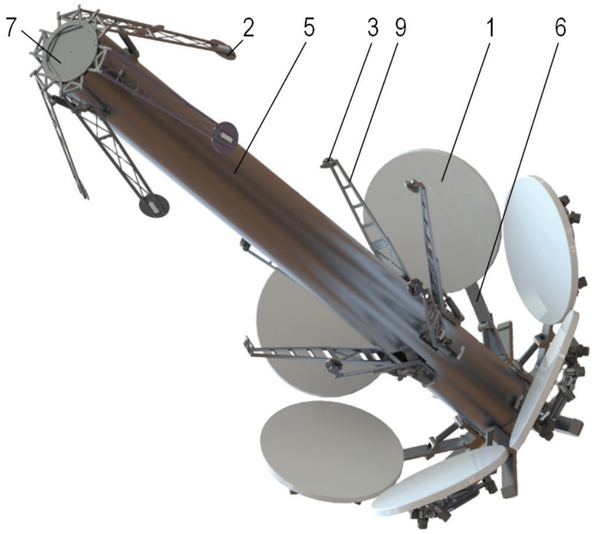


b

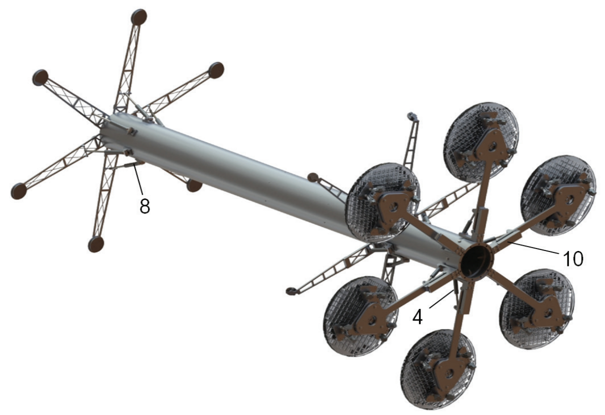
Figure 4 – System quality functions: *a* – frequency-contrast characteristic diagram for two angles (0° and 0.25°); *b* – graph of the point spreading functions for four wavelengths (indicated in the figure)

The concept of transformation options for the design of a synthetic aperture telescope

The layout of the in-orbit output should ensure the durability of the system with starting overloads; therefore, the optimal solution is to place the optical components on the moving arms reducing the distance of the mirrors from the main axis of the TSA. The result of the graphical simulation of the system is presented in Figure 5.



a



b

Figure 5 – Result of graphical simulation of a synthetic aperture telescope system: *a* – in the position of putting into orbit; *b* – in working position in geostationary orbit. 1 – the module of the main mirror; 2 – module of the secondary adaptive mirror; 3 – the module of a flat mirror; 4 – the piston; 5 – housing column; 6 – lever; 7 – base ground; 8 – the piston; 9 – bar; 10 – break block

The design of the TSA includes a number of moving elements of three types: transformational, adjusting, modal. The transformation includes the piston groups of the modules of the main mirrors 1, secondary mirrors 2 and flat mirrors 3. The piston 4 is installed in the axles, the axis connects the piston with the mount on the column-body 5, the axis is mounted on the lever 6 of the main mirror, in the unopened state the piston holds the lever under angle 45° to the axis of the TSA, in the open position, the lever rests against the abutment area of the base 7 of the secondary mirror unit (Figure 5*a*). The piston 8 is installed in the axles, the axis connects the piston with fastening on the column body 5, the axis is mounted on the bar 9 of the flat mirror 3, in an undisclosed state the piston holds the bar at an angle of 20° to the axis of the TSA, in the open position the bar abuts against the base of the block base kink 10 (Figure 5*b*).

The orientation of the main mirror 1 in space is carried out along five axes at the expense of six actuators 2, rigidly fixed in pairs on the bracket 3 at an angle of 20° to each other. When a control voltage is applied, the actuator stem 4 performs a linear movement along the axis and acts on the thrust bearing 5 with an elastic tip 6. The brackets 3 are interconnected by a common frame base 7 (Figure 6).

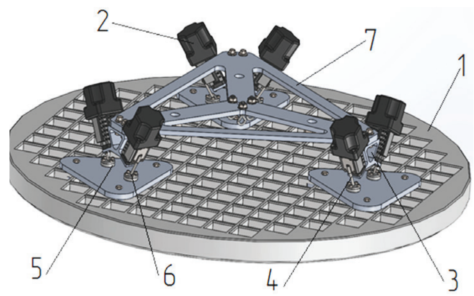


Figure 6 – The mechanism of orientation of the main mirror: 1 – the main mirror; 2 – actuator; 3 – bracket; 4 – stock; 5 – thrust bearing; 6 – tip; 7 – base

Based on all the specified parameters, the calculation was performed in *MathCAD* using the brightness data of the Earth's surface and the receiver data. Table 4 shows the resulting values of the signal-to-noise ratio.

Table 4

Signal-to-noise ratio for various modes of operation of a synthetic aperture telescope

Sun height / Orbit height	90° (zenith)	30°
750 km	189.3	79.7
36000 km	26.3	15.56

The obtained values are satisfactory for remote sensing equipment. Thus, the operability of the system of a synthetic aperture telescope was proven.

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Conclusion

Various synthetic aperture systems for Earth remote sensing equipment are considered. Mathematical modeling has shown that it is possible to meet the requirements for linear resolution on the ground that meet overall and energy criteria, while the positioning errors and the relative position of the individual components should not exceed the dimensions of the working wavelength.

The main design parameters of the synthesized aperture telescope were determined: the lag from the main axis of the telescope is 1.2 m, the angle of rotation of the flat mirror for image alignment (45 + 1.5)°, the signal-to-noise ratio (189 in low orbit with the angle of the Sun 0°, 15 in a geostationary orbit with a Sun angle of 60°), as well as the parameters of the base lens: a focal length of 13 mm, a main mirror diameter of 800 mm, a field of view angle of 0.25°.

The prospect for the development of research in this area can be called the development of the method of phasing images of individual modules with various levels of accuracy (coarse, medium, fine adjustments). Also of interest is the deepening of modeling the system of a synthetic aperture telescope to achieve higher quality indicators of the formed image. Work on the design may include a modification of the transformation mechanism in order to reduce the longitudinal size of the system.

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