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Relativistic Gravitational Experiment in the Earth Orbit. Concept, Technology, and Configuration of Satellite Constellation

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Abstract—An arrangement of the orbital experiment on the measurement of the light propagation delay in the gravitational field of the Earth (Shapiro effect) using laser interferometry based on a cluster of small spacecraft (SC) is proposed. SC layouts, launch technology, and high-precision measurements of their orbital parameters are considered.

Keywords: fundamental gravitational experiments, post-Newtonian parameters, laser interferometry, small spacecraft

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INTRODUCTION

On February 11, 2016, an event occurred, the importance of which for fundamental physics cannot be overestimated. On this day, it was announced that the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected a gravitational signal, supposedly from the merger of two ~30 solar mass black holes (Abbott et al., 2016), which brilliantly confirmed the prediction of the general theory of relativity (GTR). Thus, the era of gravitational-wave astronomy has begun.

The development of space technologies and cluster satellite systems in particular opens up new opportunities in measuring the subtle gravitational effects underlying the relativistic theories of gravity including the GTR.

The placement of instruments in space makes it possible to use conditions with a special dynamic "purity" that cannot be achieved in terrestrial laboratories but that is crucial for the success of precision experiments. In particular, for many fundamental gravitational experiments, the placement in space becomes inevitable.

Laser Interferometer Space Antenna (LISA), the ESA–NASA joint mission (launch is planned in 2034), is the most famous of the space projects aimed at detection and observation of gravity waves in the frequency domain of 10^{-4}–1 Hz. LISA consists of three identical spacecraft in a heliocentric orbit at a distance of five million kilometers from each other. Fluctuations in the distance between two spacecraft caused by the passage of the gravitational-wave radiation will be measured by laser interferometers with picometric accuracy (LISA: Probing the Universe with Gravitational Waves, 2007; Laser Interferometer Space Antenna@, 2009; LISA Spacecraft Description, 2009). The experimental satellite @LISA Pathfinder@ was launched on December 3, 2015. The purpose of this mission is to test the measuring equipment for the gravitational-wave experiment in space flight conditions. The spacecraft (SC) has two inertial sensors, a laser interferometer measuring the distance between them, a drag-free control system, and an ultraprecise micropropulsion system (http://sci.esa.int/lisa-pathfinder/).

From the standpoint of experimental verification of gravitation theories, our Solar System is a unique laboratory, in which there are conditions necessary for the most important fundamental research. The Sun has a much more powerful gravitational field than the Earth. Therefore, the relativistic gravitational effects are much more pronounced (the potentials near the Sun and in terrestrial conditions differ by 3000 times).

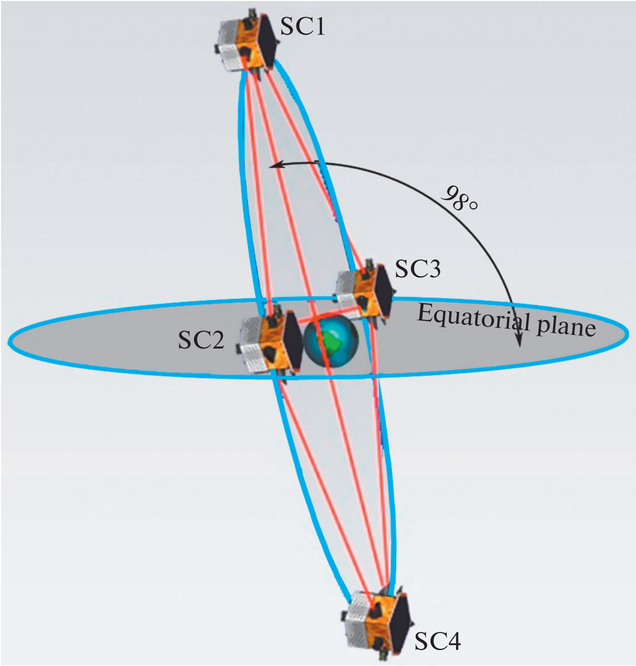

Fig. 1. Design of the space experiment on the measurement of the relativistic light delay.

However, estimates show that in Earth orbit it is possible to carry out precise gravitational experiments, and satellite launch into Earth orbit is much simpler than into solar orbit. In particular, the idea of a gravitational-wave experiment is proposed, which in general repeats the concept of the LISA project in the gravitational field of the Earth (Luo et al., 2016).

Cluster technologies and precision laser interferometry can also be used in gravitational experiments of another type, such as the measurement of parameters of the parametrized post-Newtonian formalism (PPN parameters). In this experiment, the light propagation delay in the gravitational field (Shapiro effect) is the measured value (Will, 1993).

Modern technologies for measuring time and distance make it possible to carry out experiments to measure post-Newtonian effects (PPN parameters) in near space, in Earth orbit, with an accuracy that will make it possible to draw conclusions on the existence of a new physics with scalar fields. Currently, the most accurate value of the most fundamental PPN parameter γ was obtained from the CASSINI mission $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$ (Bertotti et al., 2003).

In this paper, we consider the construction of a cluster system in the gravitational field of the Earth based on spacecraft developed at NPO Lavochkin for the experiment on measuring the parameter γ at the 10^{-9} accuracy level based on the methodological proposals of the Sternberg Astronomical Institute of Moscow State University.

1. CONFIGURATION OF A CLUSTER OF SMALL SPACECRAFT IN CIRCULAR EARTH ORBIT IN THE GRAVITATIONAL FIELD OF THE EARTH

Detailed development of the design of the orbital experiment for determining the PPN-parameter γ showed that the configuration of four satellites in circular orbits (Fig. 1) is optimal from the standpoint of the experiment feasibility and provision of measurements of the required accuracy.

This configuration forms a redundant architecture of optical links that eliminates the need for expensive drag-free space systems. All four spacecraft are placed in one plane and separated from each other by a distance of up to 200000 km. Spacecraft are arranged in the orbit in the form of a cross. The initial true anomalies of spacecraft: for SC 1 = 0°, for SC 2 = 315°, for SC 3 = 45°, and for SC 4 = 185–195°. In Euclidean space such geometry is redundant, and by measuring only five of six distances it is possible to calculate the sixth. Geometric redundancy is the key element that makes it possible to identify deviations from Euclidean geometry. The sixth distance SC 1–SC 4 is also measured. This trajectory of the light beam passes close to the Earth, and, therefore, the gravitational field of the Earth along it is the strongest. The difference between the measured and calculated values of the SC 1–SC 4 distance gives an estimate of the Shapiro delay effect. However, it is difficult to measure the constant delay. It will be renormalized into the usual Newtonian delay. In order to measure the relativistic delay, it is necessary to modulate it in time. Modulation can be achieved by a small change in the radius of the fourth satellite. Thus, during the experiment SC 4 periodically changes its orbit, once every 10–30 days.

Each spacecraft is equipped with three sets of laser interferometric transceivers used to measure mutual distances with high accuracy (~0.1 nm). In order to achieve the γ parameter measurement accuracy of 10^{-9}, the measuring error of mutual distances during the signal accumulation for 1 s should not be more than 0.1 nm (10 nm for the accumulation time of ~10 s, accordingly).

In order to ensure the specified accuracy in measuring intersatellite distances, all four spacecraft should be in the same plane and spacecraft positions relative to the center of mass of the Earth should be known, which leads to the requirement to control the spacecraft position in space with an accuracy of ~10 cm.

Table 1 presents the orbital parameters of the spacecraft in the experiment to measure the relativistic light delay in the gravitational field of the Earth (determination of the PPN parameter γ).

2. INSTRUMENTS FOR MEASURING INTERSATELLITE DISTANCES

The main instrument for measuring the distance between satellites is a relay heterodyne laser interferometric system. In the PPN experiment, the laser system operates in the rangefinder mode, which measures the cumulative phase shift in the case of multiple passes of a light beam between satellites. The drag (intersatellite distance) is determined by measuring the phase shift between the reference and the measured signal. Instruments that provides the required measurements include the following:

—Laser interferometer (accuracy up to 0.1 nm at a distance of up to 10^5 km per 1 s).

—High-precision frequency standard (reproduction accuracy of 10^{-13}).

—System of reduction (compensation) of nongravitational disturbances based on high-precision three-axis electrostatic accelerometers (no worse than 10^{-9} m/s^2).

The optical layout of such a platform is shown in Fig. 2.

3. LAYOUT OF A SMALL SPACECRAFT WITH A MEASURING APERTURE FOR LASER INTERFEROMETRY OF GRAVITATIONAL EFFECTS

Each of the four SC clusters for measuring the relativistic light delay in circular Earth orbit carries the same complex of scientific equipment, which consists of three 20-cm aperture telescopes connected optically with test masses of electrostatic accelerometers. Telescope mirrors are based on a lightweight construction with a small linear thermal expansion coefficient. The optical system of the telescope is the classical layout of the off-axis Cassegrain telescope. The distance between the mirrors is 300 mm. Specified test masses are the reference masses of the spacecraft, the carriers of geodesic motion.

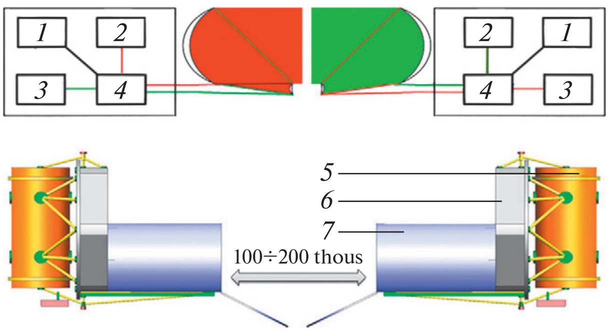

Fig. 2. Design of optical measurements. (1) Hydrogen frequency standard, (2) laser system, (3) accelerometer test mass, (4) optoelectronic system, (5) accelerometer, (6) optical platform, and (7) telescope.

Table 1. Basic parameters of the spacecraft of the orbital experiment for measuring the relativistic light delay in the gravitational field of the Earth

Circular Earth orbit with a radius of	~100 000 km
Distance between satellites (max)	~200 000 km
Orbit inclination	~98°
Angular position of SC 1, SC 2, SC 3, and SC 4	0°; 45°; 315°; 185°–195°

Test masses are carefully shielded from external and internal disturbances, so that in the end they can move only under the influence of gravitational forces (i.e., along a geodesic trajectory). Relative microdisplacements of test masses on different spacecraft will record the Shapiro delay.

In addition, the scientific equipment (SE) of each spacecraft includes a hydrogen frequency standard designed for the generation of highly stable, spectrally pure signals and for frequency and time measurements.

A circuit of three telescopes of one spacecraft is pointed at each of the three spacecraft of the space cluster in two stages. Coarse pointing is carried out by spacecraft orientation, and the precise pointing is conducted by precision motors for rapid control of the telescope rotation with an angular resolution of ~0.2 arcsec. The SC SE layout is shown in Fig. 3. The main composition is given in Fig. 4.

The spacecraft will be a hexagonal prism. The "roof" of the spacecraft is a thermal honeycomb panel

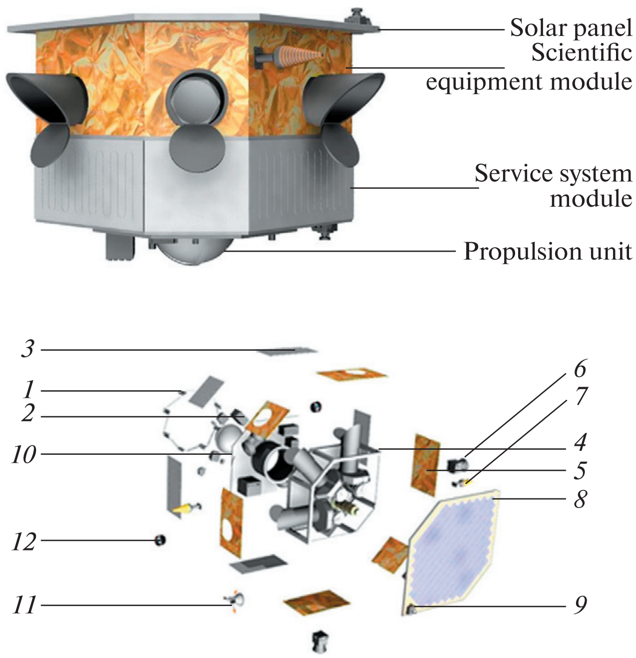

Fig. 3. General view of the spacecraft scientific equipment module.

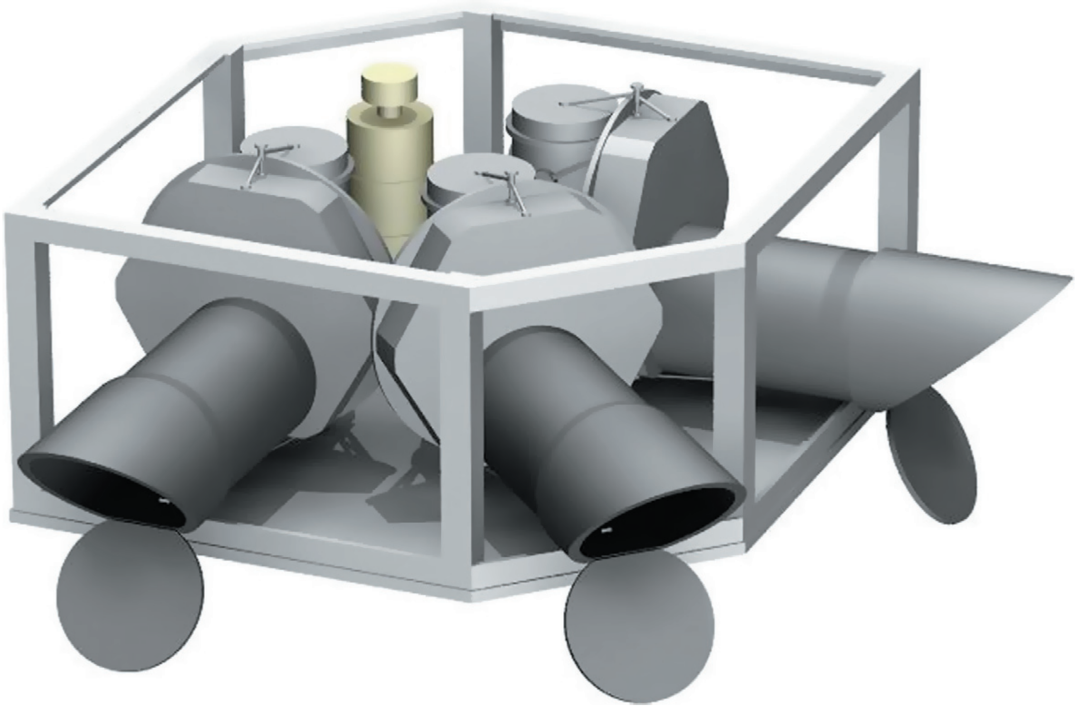

Fig. 4. Small spacecraft components. (1) Detachable frame, (2) propulsion unit, (3) thermal control system radiators, (4) scientific equipment module, (5) screen-vacuum heat insulation, (6) star sensor, (7) semidirectional antenna, (8) solar panel, (9) solar sensor, (10) service system module, (11) beacon, and (12) corner reflector.

(THP) that protrudes relative to the prism edges, creates a shadow, and, thus, protects the telescopes of the laser interferometer from direct sunlight. Solar panel photovoltaic cells and a solar sensor are on the top of the THP.

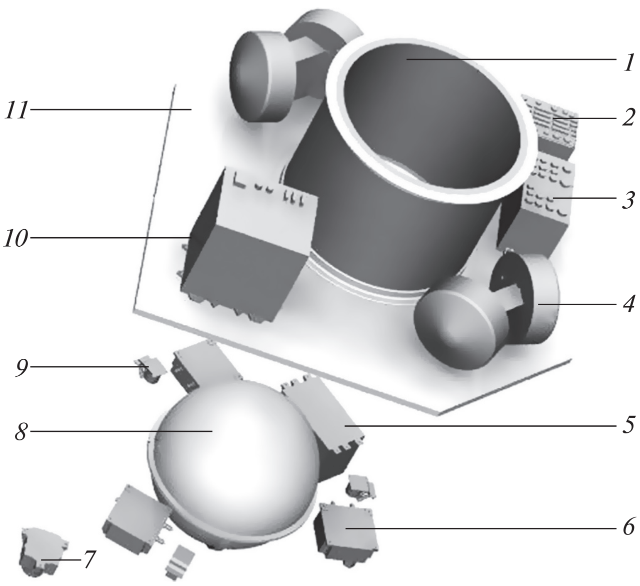

Fig. 5. Module of service systems and propulsion unit of small SC. (1) Power tube, (2) onboard radio complex, (3) automation and stabilization complex, (4) flywheel engine unit, (5) conversion and control system, (6) gas distribution module, (7) xenon supply unit, (8) xenon storage unit, (9) stationary plasma engine, (10) battery, and (11) THP.

The detachable frame is the power component of the structure and is necessary for attaching the spacecraft to the mounting plate located on the propulsion unit (PU). The detachable frame is a welded structure in the form of an octagonal prism and is made according to the "saw" layout.

The service system (SS) module consists of the THP, on which a circular carbon fiber power tube is installed by means of frames, and the main service systems located on it (Fig. 5).

A metal part in the form of an octahedron is attached to the bottom of the bottom plate of the THP of SS module for attaching a spacecraft with a detachable frame. The PU is also mounted on the bottom of this THP. Thermal control system radiators are attached to side faces of the SS module.

The SE module consists of the THP, which is installed on the power tube, the construction of the power frame and the sheets located on the edges of the power frame. On the THP plate is the scientific equipment, which consists of three telescopes and a hydrogen frequency standard. Semidirectional antennas and a radio beacon are attached to the vertical rack of the power frame. Star sensors are installed on the side faces of the SE module. There are also corner reflectors on the side faces that are turned to the Earth

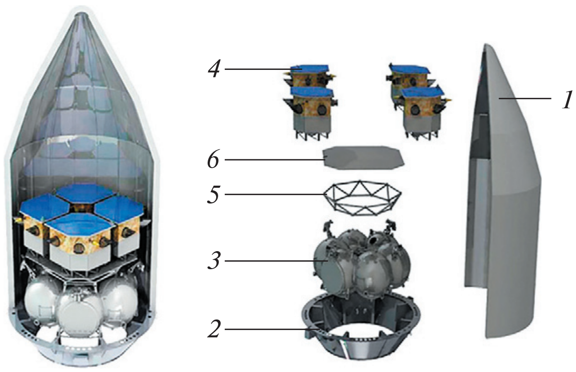

Fig. 6. Composition of the main elements for the horizontal placement of four spacecraft. (1) Payload fairing, (2) adapter, (3) propulsion unit, (4) spacecraft (4 units), (5) detachable frame, and (6) mounting plate.

during the flight. The SE module is covered with screen-vacuum heat insulation.

A solar panel is installed on top of the power frame of the SE module. The solar panel is a THP on which solar panel photovoltaic cells and a solar sensor are mounted. Another solar sensor is located on the back of the spacecraft, on the bottom of the THP of the SS module. The area of solar panel photovoltaic cells is 1.5 m^2.

The module of SS and PU (Fig. 5) consists of the power tube, the THP, the onboard radio complex, the automation and stabilization complex, two flywheel engine units, the conversion and control system, three gas distribution modules, the xenon supply unit, the xenon storage unit, three stationary plasma engines, the battery, and the digital computer located on the THP.

For the injection of four small SCs, it is planned to use the three-stage middle-class launcher Soyuz-2.1b of Soyuz-2 family as the main payload fairing.

It is proposed to use an adapter, a metal structure with places for mounting the spacecraft on the launch vehicle.

The composition of the main elements for the case of the horizontal placement of four spacecraft is shown in Fig. 6.

The mass summary of spacecraft components is presented in Table 2.

4. INJECTION TECHNOLOGY OF A SPACECRAFT CLUSTER FOR LASER MEASUREMENTS OF GRAVITATIONAL EFFECTS

A single injection scenario using the Soyuz launch vehicle and the Fregat upper stage is considered for the launch of two spacecraft (Asyushkin et al., 2014). Figure 7 shows the injection scenario of the first spacecraft.

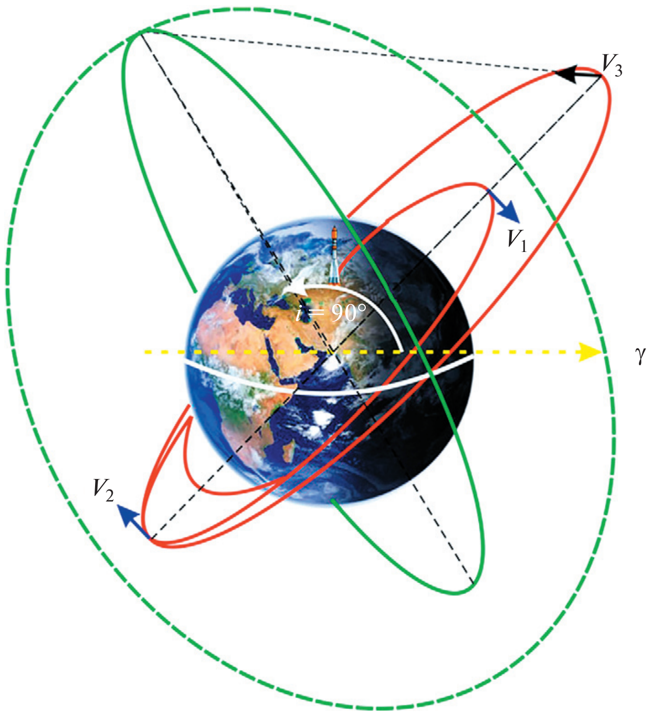

Fig. 7. The first spacecraft injection scenario into a working orbit.

The launch vehicle injects the reentry vehicle (spacecraft and upper stage) into a circular reference satellite orbit with an altitude of 200 km. On the first reference orbit pass, the upper stage is activated for the first time (V_1), as a result of which the reentry vehicle

Table 2. Mass summary of SC components

№	Name	Mass, kg	Number
1	Optical system	20	3
1.1	Laser + optical platform	10	3
1.2	Accelerometer	10	3
2	Scientific complex electronics	15	3
3	Hydrogen frequency standard	25	1
4	Primary structure	8	1
5	Propulsion unit	13	1
6	Onboard control system	17	1
7	Power supply system	20	1
8	Onboard cable network	2	1
9	Thermal conditioning means	4	1
10	Antenna-feeder system	1	1
11	Oboard radio complex	2	1
12	Telemetery system	1	1
13	Corner reflector	0.5	2
14	Radio beacon	1	1

Scientific equipment, 130 kg. Service systems, 70 kg. Total, 200 kg.

Table 3. Payload mass when injecting into specified orbits

Perigee height, km	Apogee height, km	Inclination, deg.	Payload mass, kg	Injection time, h
100000	100000	54.6	850	~17.04
100000	100000	90		

is injected in the first transfer orbit, the height of the apogee of which is 350 km, and the perigee argument differs from the perigee argument of the first-type working orbit by 180°. In this orbit, in the apogee area the launch vehicle (V_2) is activated for the second time, and the reentry vehicle is injected in the second transfer orbit. The height of the apogee of this orbit is equal to the height of the apogee of the working orbit of the first type. The upper stage with four spacecraft continues to form a working orbit with a different inclination. For this purpose, the upper stage PS is activated for the third time in the area of the descending node of the second transfer orbit, and the reentry vehicle is injected into the fourth transfer orbit, which is almost in the Earth's plane with an inclination of ~98 deg. Then, all the spacecraft that are put into the working orbit are separated from the upper stage. Further maneuvers of this spacecraft are carried out using its own propulsion system.

Payload mass when injected into the specified orbits is given in Table 3.

5. HIGH-ACCURACY SPACECRAFT POSITIONING FOR GRAVITATIONAL MEASUREMENTS

When the state of all spacecraft is established, and their coordinates are determined using radiotelemetry, laser beams are aimed at each other, and the measurement is carried out.

As an additional option to the laser system, highly stable radio beacons are mounted on the spacecraft (Kosov et al., 2011), which together with the terrestrial radiointerferometer will make it possible to determine the position of the spacecraft SC 1–SC 4 with an accuracy of 1–2 cm. Laser corner reflectors are also installed on spacecraft, similar ones are installed on GLONASS (Shargorodskii et al., 2013), which will make it possible to determine the distances to the spacecraft of the proposed arrangement with an accuracy of 1–10 mm.

The measurement plan is shown in Fig. 8.

CONCLUSIONS

In order to implement space projects aimed at measuring subtle gravitational effects underlying relativistic theories of gravity, it is necessary to develop a cluster satellite system. Such systems require a high-precision measurement of intersatellite characteristics.

Stringent requirements for the accuracy of determining the parameters of the trajectories of spacecraft and satellites make it necessary to have an accelerometer on board of any spacecraft capable of effective measurement of all the nongravitational accelerations acting on the spacecraft. Joint use of modern means of multifrequency radio tracking and onboard accelerometry makes it possible to make spacecraft almost insensitive to the effects of nongravitational disturbances, i.e., to consider the spacecraft almost drag-free.

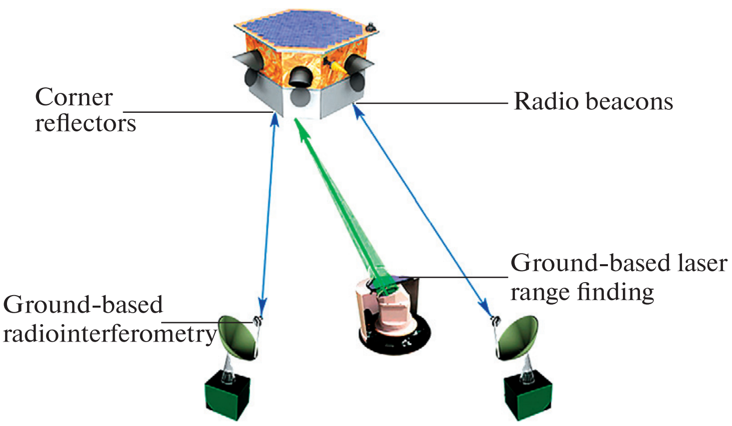

Fig. 8. Earth-spacecraft distance determination plan.

The development of a technology for measuring intersatellite distances at an accuracy level of 0.1–0.01 nm based on transponder laser interferometry (LISA system and technology study report, 2000; Yeh et al., 2011) and nongravitational acceleration compensation technologies (drag-free satellite technology) based on accelerometers with a sensitivity of 10^{-10} m/s^2/Hz$^{1/2}$–10^{-15} m/s^2/Hz$^{1/2}$ (LISA System and technology study report, 2000; Hu et al., 2014) make it possible to plan space projects in the field of fundamental gravity.

This paper shows the possibility of the development of a cluster satellite system for measuring the relativistic light delay in the gravitational field of the Earth based on available small SC.

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