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THE GAMMA–400 PROJECT

INVESTIGATION OF COSMIC GAMMA-RADIATION AND ELECTRON-POSITRON FLUXES IN THE ENERGY RANGE 1–3000 GeV

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ABSTRACT

Cosmic gamma-radiation in the energy range 1-3000 GeV belongs to the high-energy part of electromagnetic radiation spectrum and is connected with the processes of generation and acceleration in the Universe (pulsars, microquasars, active galactic nuclei, blazars, and so on) and also with the processes of very-high-energy cosmic-ray particle interaction with the matter of the Universe. Cosmic high-energy gamma-radiation can appear as a result of annihilation or decay of Weak Interacting Massive Particles (WIMPs) being dark matter components according to some theoretical models. From the other side, annihilation or decay of WIMPs can lead to the generation of high-energy electrons and positrons, which are supposed to be also detected by the gamma-telescope.

The GAMMA-400 project presents main scientific directions and problems of the project, the state of solving these problems at present, the requirements to the scientific equipment (gamma-ray telescopes), the description of the GAMMA-400 gamma-ray telescope, the requirements to the space complex (spacecraft and ground stations), to scientific data processing, to the analysis and application of scientific results in the science and practice; the schedule of the project realization; the scientific and industrial organizations, participating in the project and their responsibilities.

It is proposed to begin space measurements in 2017.

1. SCIENTIFIC DIRECTIONS AND PROBLEMS OF THE PROJECT.

The contemporary status of fundamental researches in the field of cosmology, astronomy, high-energy particle physics, and cosmic rays suggests some problems, which can not be solved without using the results of very-high-energy (10^9-10^{12} eV) extra-atmospheric gamma-ray astronomy and simultaneous investigations of high-energy electron-positron component of galactic cosmic rays. Because of this, main directions of investigations in the GAMMA-400 project are stated.

Main directions of investigations.

- The study of physical processes in the astrophysical objects, emitting very-high-energy gamma-radiation (from 1 GeV to 3 TeV);
- The study of the nature and properties of Weak Interacting Massive Particles (dark matter components) by the processes of their annihilation and decay on gamma-quanta and electron-positron pairs.

The problems of the project.

1. The search for new galactic and extragalactic discrete gamma-ray sources of very high energy, which can be, in particular, the supernova remnants, pulsars, accreting objects, microquasars, active galactic nuclei, blazars, quasars and study of known ones; measurements of their energy spectra and luminosity.

2. The identification of discrete gamma-ray sources with known radiation sources in the other energy ranges, including discrete sources detected by ground-based gamma-ray telescopes in the energy range above 10^{12} eV.

3. The monitoring of energy spectra and luminosity of very-high-energy gamma-ray sources for studying the nature of their variability.

4. The search for and study of very-high energy gamma-ray bursts (above 1 GeV).

5. The measurement of energy spectra of galactic and extragalactic diffuse and isotropic gamma-radiation. The search for spectral anomalies. The search for gamma-ray lines in the spectra of discrete gamma-ray sources, diffuse gamma-radiation generated in the processes of annihilation and decay of dark matter components.

6. The detection of electron and positron fluxes with the energy above 1 GeV, the measurement of the energy spectra of these particles, the detection of peculiarities of their spectra, which could be connected with the processes of annihilation or decay of dark matter components.

7. The detection of high-energy gamma-radiation and electron and positron fluxes from solar flares.

2. EXPECTED RESULTS.

2.1. Gamma-ray astronomy observations.

● In five years of observations, several complete sky surveys will be performed and point source sensitivity of $5 \cdot 10^{-9}$ photon/cm^2·s will be reached.

● It is supposed that with angular resolution ~ 0.05º in the energy range 1-3000 GeV some thousands of galactic and extragalactic discrete gamma-ray sources will be detected. About 25% of discovered sources will be identified.

● Expected statistics of gamma-radiation measurements from discrete sources of pulsars Crab, Geminga, and Vela is presented in the Table 1.

Table 1.

Energy, GeV	Crab J(>100 MeV)= $226.2 \cdot 10^{-8}$ photon·cm^{-2}·s^{-1} k=2.19*	Geminga J(>100 MeV)= $352.9 \cdot 10^{-8}$ photon cm^{-2}·s^{-1} k=1.66*	Vela J(>100 MeV)= $834.3 \cdot 10^{-8}$ photon cm^{-2}·s^{-1} k=1.69*
	The number of detected photons**		
> 1	1.9x10^7	0.9x10^7	2.2x10^7
> 30	1x10^4	3x10^4	7x10^4
> 100	0.8x10^3	4x10^3	9x10^3
> 1000	5	90	200
> 3000	0,5	15	30

*Flux J and spectral index k are taken from the data of the 3-rd EGRET catalogue [1].
**100-day duration of observations, the GAMMA-400 area is 6400 cm^2.

● Energy spectra and luminosity curves will be measured for all discrete sources.

● About 100 gamma-ray bursts will be detected with gamma-ray energy above 1 GeV.

● Expected statistics of diffuse gamma-radiation measurements in the direction to the galactic center is presented in the Table 2.

Table 2.

Energy, GeV	The number of detected photons*
> 1	$3x10^6$
> 30	$1.3x10^4$
> 100	2000
> 1000	50
> 3000	10

*1-year duration of observations, the GAMMA-400 geometric factor is 0.7 $m^2 \cdot sr$, the efficiency of gamma-ray conversion is 0.55, spectral index of differential energy spectrum when observing in the direction to the Galaxy center k=2.6 (the diffuse gamma-radiation differential energy flux in the direction to the Galaxy center J (E_γ = 1 GeV) = $4 \cdot 10^{-1}$ $m^{-2}s^{-1}sr^{-1}GeV^{-1}$ according to the EGRET data [2] was used for an estimation).

● The isotropic component of gamma-radiation will be separated from discrete sources, the energy spectrum will be measured, and the search for peculiarities of gamma-ray spectra will be performed.

The obtained observational data will allow one to construct consistent particle acceleration model for galactic relativistic objects, supernova remnants, microquasars, in particular, to clarify the mechanism of accretion energy transfer into the jet energy, to investigate the evolution processes of these objects, to study the mechanism of luminosity curve variation of pulsars and other astrophysical objects, to perform the search for relativistic constant and variable objects in the vicinity of solar system.

2.2. The nature of dark matter and the sources of high-energy electrons and positrons.

According to some existing theoretical models, the dark matter particle annihilation and decay processes lead to generation of different elementary particles, including gamma rays, electrons, and positrons [3, 4]. To detect them it is necessary to measure the energy spectra of annihilation and decay products, namely, the spectra of gamma rays and electron-positron component of cosmic radiation in the energy range 1-3000 GeV. The admixture of proton component in the electron-positron spectrum must be not less than 15%. It is supposed that total number of detected electrons and positrons will be not less than 10^5 particles. The search for peculiarities in the spectra will be obtained and possibly energy lines will be resolved.

The results of high energy electron-positron component measurements will allow one to determine their generation sources, which could be known astrophysical objects as supernova remnants, pulsars, possibly, micropulsars and so on. In this case, there is a possibility to measure the spatial distribution of pulsars, to measure physical conditions of electron-positron pair generation in great magnetic fields, particle escape from the source into interstellar space, and conditions of their propagation in the interstellar matter.

However, the most important result of studying high-energy electron-positron component would be the discovery of the correlation of these fluxes with the processes of annihilation or decay (or both processes simultaneously) of supersymmetrical weak interacting massive particles (WIMPs) as neutralino, Kaluza-Klein bozons and others. At the same time, the possibility appears to estimate WIMP’s mass in the inaccessible for the particle accelerators energy range.

2.3. Gamma-radiation of solar flares.

The suggested measurement period coincide with the end of 24^{th} and the beginning of 25^{th} solar cycle and one would expect detecting about ten unique solar flares with gamma-ray energy above 1 GeV. It will be enough for checking the existing models of particle acceleration in the Sun during the flares, including the theory of “collective acceleration” proposed by V. Veksler [5].

3. SCIENTIFIC APPARATUS.
THE GAMMA-RAY TELESCOPE GAMMA-400.

3.1. Main requirements to the gamma-ray telescope.

To realize scientific program taking into account technical level of existing gamma-ray telescopes [7], cosmic-ray particle spectrometers [8], and our preliminary developments [9, 10] when designing and developing scientific equipment in the GAMMA-400 project, the following important telescope performances will be reached:

1. Telescope geometric factor has to ~ 0.7 m^2sr.
2. Angular resolution $\Delta\theta \sim 0.05°$.
3. Point source sensitivity (100-day observations) $F_{min} \sim 5 \cdot 10^{-9}$ cm^{-2} s^{-1}.
4. The energy range for gamma rays, electrons, and positrons is 1–3000 GeV.
5. Energy resolution over indicated energy range is ~ 1-2%.
6. When detecting electron-positron component in the indicated energy range, the proton contamination has to be less than 15%.

3.2. Physical scheme of the GAMMA-400 gamma-ray telescope.

The scheme of detector arrangement in the GAMMA-400 gamma-ray telescope is presented in Fig. 1.

The gamma-ray telescope consists of three blocks.

1. In the top, the tungsten converter C is located, where gamma-quantum generates the electron-positron pair. Converter consists of four tungsten layers interleaved by silicon strip detectors. Above the converter two layers of scintillator anticoincidence counter AC and side anticoincidence counter SAC are placed, where charged particles are detected and gamma-quanta are not detected. Above anticoincidence counter the transition radiation detector TRD is placed. It allows one to discriminate electrons (positrons) from protons. Below the converter two scintillator detectors S1, S2 of the time-of-flight (TOF) system at the distance of 600 mm one from another and three layers of silicon strip detectors CD1, CD2, CD3 are installed. TOF determines the direction of particles motion. AC and S1 detectors also send signals to the backsplash rejection system (BR), which allows one using the time-of-flight method to reject events, when AC detects primary charged particle from event, when AC detects soft secondary particles generated in the calorimeter by high-energy shower. CD1-CD3 allow one to determine conversion point and motion trajectory of detected particles.

2. In the middle of the instrument, the coordinate-sensitive calorimeter is located. It serves for measurement of detected particle energy and shape of shower of secondary particles generated by primary particle. Calorimeter consists of three modules CC1, CC2, CC3. Two first modules consist of eight thin tungsten layers (0.25 and 0.5 rl, respectively) each, interleaved by silicon strip detectors and the third one consists of eight layers of $PbWO_4$ scintillator blocks interleaved by silicon strip detectors. After each calorimeter module fast plastic scintillator detectors S3, S4, and SLD are placed. Signals from these detectors are used to elaborate trigger signal and to determine additional characteristics of secondary particle shower.

3. In the bottom, neutron detector ND is placed, which is used for detecting neutrons, generating when particle interacting in the calorimeter. The information on the neutron number allows one to distinguish events of particles of the electromagnetic and hadronic nature.

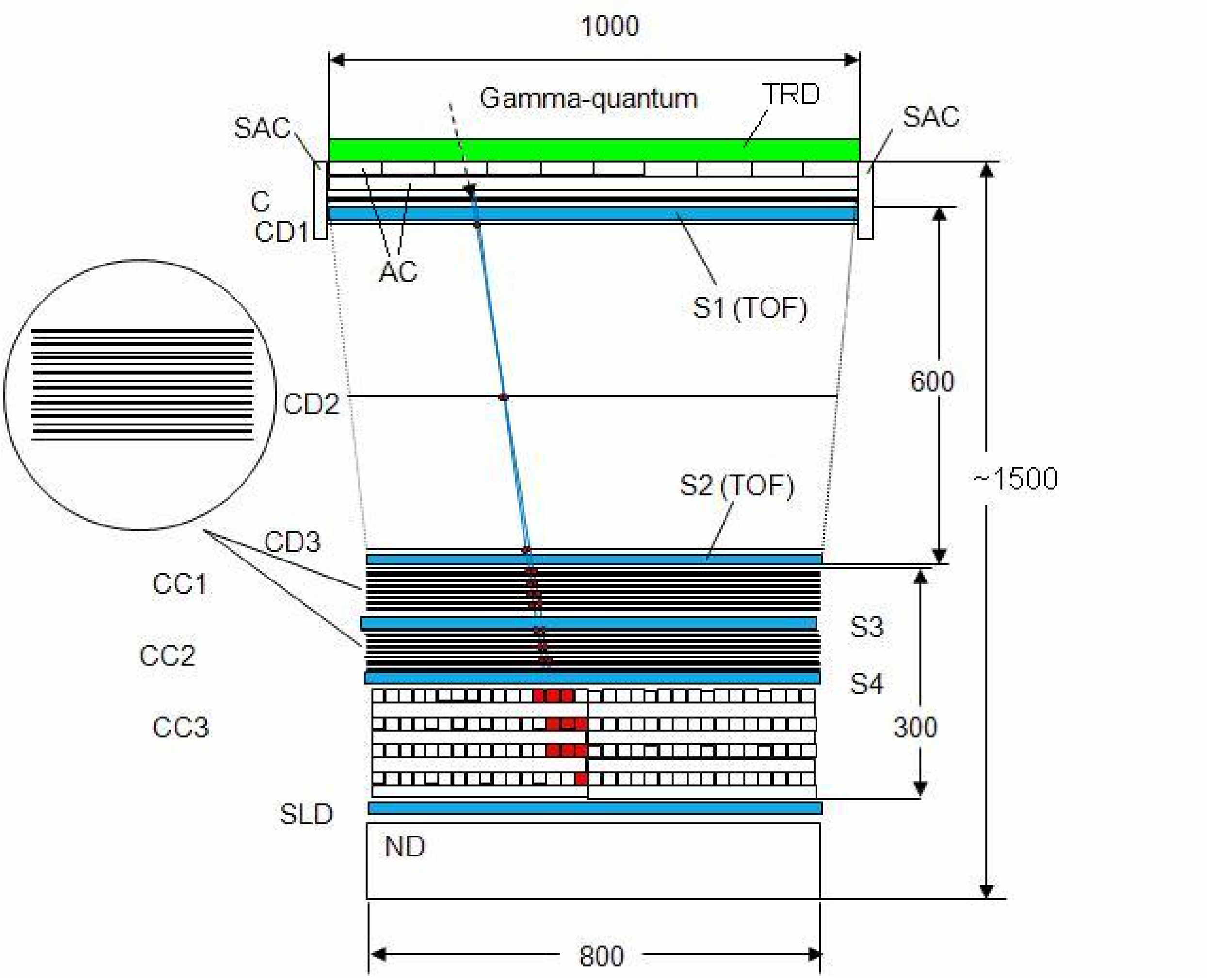

Fig. 1. Physical scheme of the GAMMA-400 gamma-ray telescope.

TRD – transition radiation detector; AC – anticoincidence detector; SAC – side anticoincidence detector; C – tungsten convertor; S1, S2 - time-of-flight (TOF) scintillator detectors; CD1, CD2, CD3 – coordinate silicon strip detectors; CC1, CC2 – coordinate sensitive calorimeters (W + silicon strip detectors); CC3 - coordinate sensitive calorimeter (W + $PbWO_4$ scintillator + silicon strip detectors); S3, S4 - scintillator detectors; SLD - scintillator shower leakage detector; ND – neutron detector.

3.3. Modes of the GAMMA-400 gamma-ray telescope functioning.

3.3.1. Detection of primary gamma-quanta.

Gamma-quantum passes the scintillation anticoincidence detector AC without interaction (that differs from the charged particles). In the tungsten converter C (0.8 rl), gamma-quantum converts into the electron-positron pair. This pair is detected by the silicon strip detectors CD1 - CD3, providing the information about the particle trajectory and by TOF detectors S1 and S2. TOF allows one to measure the particle motion direction (top-down or down-top) by the time correlation between signals in S1 and S2. Then electron-positron pair interacts in two modules of coordinate–sensitive calorimeter CC1 (2 rl) and CC2 (4 rl) generating electromagnetic shower. The calorimeter CC3 (22.5 rl) is composed of $PbWO_4$ scintillators interleaved by silicon strip detectors. The further shower development and its detection occur in this calorimeter. Gamma-ray energy is measured using summary signal value from the calorimeter. The coordinate sensitivity of calorimeter allows one to determine shape of the shower and to get additional information for selecting of hadron and electron components in detected cosmic radiation.

The measurement of secondary particle flux escaping from the calorimeter is performed in the shower leakage detector SLD.

Neutron detector ND is intended to detect the number of neutrons originating in hadron or electromagnetic showers, developing in the calorimeter when detecting primary protons or electrons (positrons) and gamma rays and, therefore, select two types of particles.

The trigger elaboration scheme of the GAMMA-400 gamma-ray telescope is shown in Fig. 2.

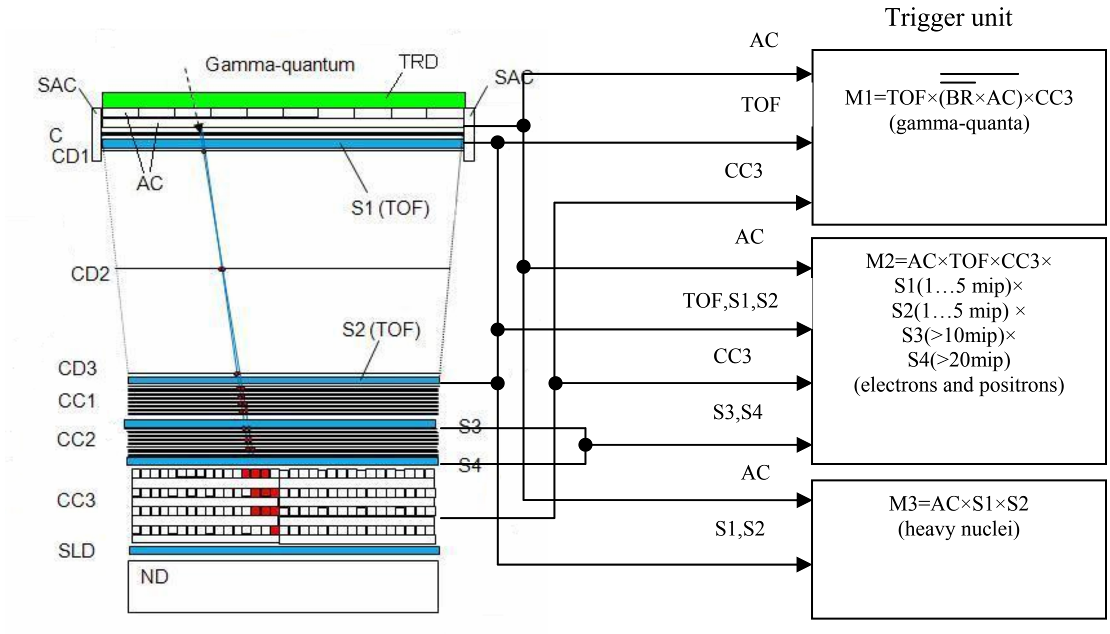

Fig. 2. The scheme of the GAMMA-400 gamma-ray telescope triggers.

3.3.2. Detection of galactic electrons and positrons.

The detection of primary (galactic) electrons and positrons is analogues to detection of primary gamma rays, but it is necessary to take into account that detection of charged particles will cause the scintillation pulse in anticoincidence counter.

3.3.3. The methods of electron(positron)-proton discrimination.

The following methods can be used for electron(positron)-proton separation:

1. According to the depth of shower starting point in the calorimeter. Nuclear interaction length, characterizing the development of hadron shower is more by a factor of 10 than radiation length, characterizing the development of electromagnetic shower. Because of this, more than 95% of electrons initialize the electromagnetic shower at the depth less than 3 rl. At the same time, protons and other hadrons initialize the hadron shower at much more depth in the matter and even can penetrate the whole calorimeter depth without generation of shower. This difference in the shower characteristics serves as the feature allowing one to distinguish protons and electrons (positrons or electron-positron pair generated by primary gamma rays).

2. According to the longitudinal and traversal shower profiles in the calorimeter. The electromagnetic shower has the form different from hadronic shower, being symmetrical relative to the particle trajectory axis, and gives the main part of energy release within one Moliere radius from the shower axis. At the same time protons loose their energy through the generation of π^+, π^-, and π^0 mesons, having wider angular distribution. Also hadronic shower has higher transverse dimensions, nonuniform energy release in the longitudinal and traversal directions and possible deviation of shower axis from the motion direction of primary particle.

3. According to the correlation of total energy release in the calorimeter and energy release in the shower leakage detector. The presence of these correlations allows one to discriminate electrons (positrons) and protons with higher efficiency (using the threshold dependent of both energy releases) than using thresholds for energy releases in the calorimeter and SLD separately.

4. According to the number of neutrons detected in the neutron detector. It is known that interaction of hadrons in the calorimeter in contrast to electrons and photons is accompanied by larger neutron release.

5. According to detection of transition radiation generated by high-energy electrons and positrons in the radiator of transition radiation detector.

3.4. Main physical and technical characteristics of the GAMMA-400 gamma-ray telescope.

Main physical and technical characteristics of the GAMMA-400 gamma-telescope are shown in Table 3.

Table 3. Main physical and technical characteristics of the GAMMA-400 gamma-ray telescope.

Energy range	1-3000 GeV
Converter thickness	0.8 rl
Converter area	1000 x 1000 mm^2
Calorimeter thickness	~28.5 rl
Calorimeter area	800 x 800 mm^2
Angular aperture	~ 1.5 sr
Geometrical factor	0.7 m^2sr
Conversion efficiency	0.55
Coordinate resolution	1 mm
Angular resolution	~ 0.05°
TOF time resolution	500 ps
Telemetry downlink	20 GB/day
Dead time	~ 1 ms
Energy resolution (at E=100 GeV – 3 TeV)	~ 1%
Total mass of scientific equipment	~ 1700 kg
Dimensions	1.5×1.5×2.0 m^3
Power consumption	800 W
Lifetime	not less than 5 years

4. REALIZATION OF THE GAMMA-400 EXPERIMENT.

4.1. Measurement conditions.

The GAMMA-400 spacecraft (Fig. 3) consists of:

the GAMMA-400 gamma-ray telescope;

the KONUS-FG apparatus (the detection of gamma-ray bursts);

the NAVIGATOR base service unit.

The spacecraft should be launched into high-apogee orbit of an artificial Earth's satellite (AES).

Parameters of AES operational orbit:

apogee altitude is 300 000 km;

perigee altitude is 500 km;

inclination to the equator plane is 51.8°;

orbital period is 7 days.

The ballistic lifetime in AES operational orbit is not less 10 years, the duration of active spacecraft operation in AES operational orbit is not less 5 years. The spacecraft have a propulsion. During the active spacecraft operation there is a possibility to perform corrections for forming and supporting orbit parameters.

The GAMMA-400 spacecraft launch should be performed from the Baikonur cosmodrome with the two-stage launch vehicle and Fregat-SB booster. The launch vehicle launches the spacecraft into primary elliptic orbit with the perigee of 170 km and the apogee of 400 km. The spacecraft transfer from primary orbit to operational one is performed with the help of two burns of booster propulsion.

When measuring the gamma-ray telescope axis is pointed out at the investigated parts of celestial sphere according to the measurement program and stabilized in this position with an accuracy of not worse than 1 arc minute. The precision of measurement of source position on the celestial sphere must be not worse than 30 arc seconds.

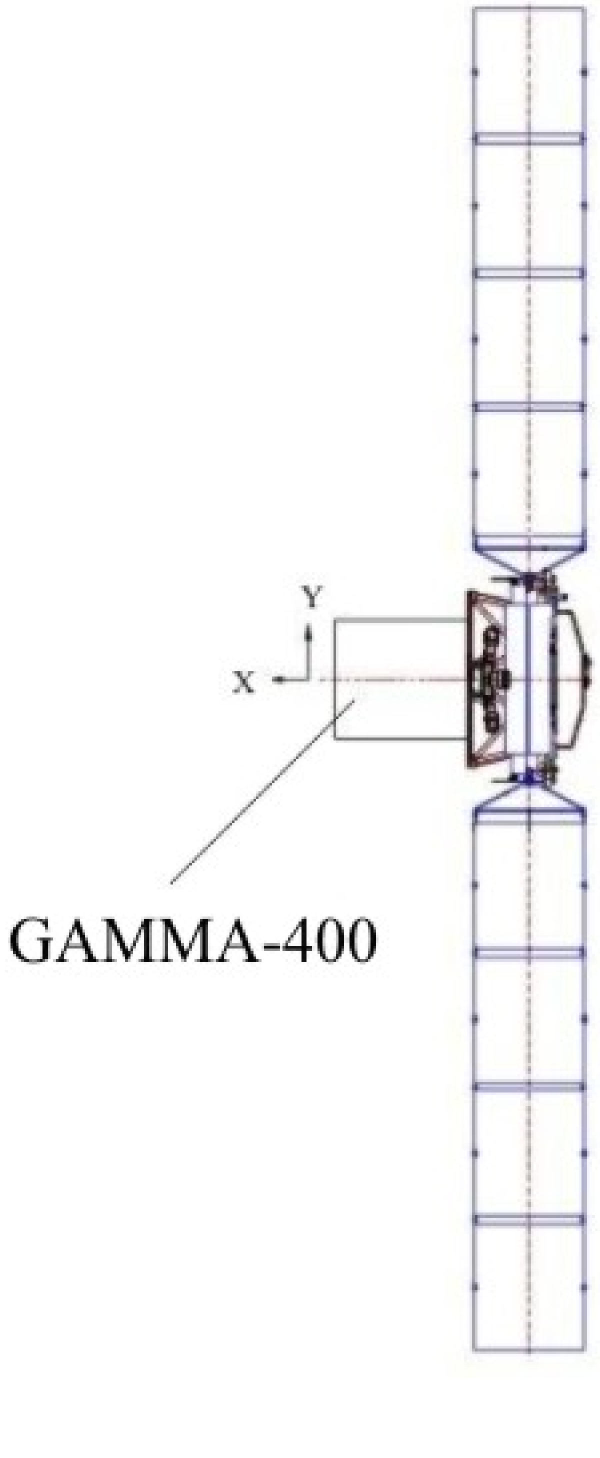

Fig. 3. The GAMMA-400 spacecraft in flight.

4.2. The Navigator base service unit.

The Navigator base service unit includes systems necessary to support the spacecraft operation including scientific equipment at all stages of its autonomous flight.

The following main systems compose the Navigator base service unit:

on-board control complex;
on-board apparatus of the command-measurement system;
antenna feeder system;
telemetry system;
on-board memory;
solar battery orientation system;
power supply;
propulsion;
supporting system of thermal conditions;
high informative radio complex with the antenna feeder system.

The base unit represents an octagon body, on which faces are installed propulsion elements, solar panels with rotation drives, radiators of the supporting system of thermal regime; the complete apparatus of the base unit. The experimental equipment (the GAMMA-400 gamma-ray telescope and the KONUS-FG system for gamma-ray burst detection) is installed on flat top body surface.

4.3. Transmission and reception of the data, telemetry data processing.

Telemetry downlink is ~ 20 Gbyte/day. Maximum rate of downlink is 300 Mbit/s. The transmission rate of telemetry data about scientific equipment state and measurement conditions is ~ 30 Mbit/s depending on the distance to the spacecraft in the mode of on-line transmission or reproduction from storage device.

After analyzing the quality of transmission and reception of scientific information in receiving station, the data are sent to LPI and MEPHI for joint processing and analysis.

5. SCHEDULE OF PROJECT REALIZATION.

Table 4.

1.	Optimization of the GAMMA-400 gamma-ray telescope physical scheme (LPI, MEPHI).	**2009**
2.	Development of draft design taking into account temperature conditions, radiation conditions, reliability control, and financial support (LPI, MEPHI, Lavochkin Research and Production Association, All-Russia Research Institute of Electromechanics and Iosifyan Plant).	**2010-2011**
3.	Preparation of documentation for the gamma-ray telescope, development, production, and testing some systems and laboratory models in All-Russia Research Institute of Electromechanics and Iosifyan Plant and other organizations (LPI, MEPHI, Ioffe Institute, IHEP).	**2012-2013**
4.	Gamma-ray telescope assembly in All-Russia Research Institute of Electromechanics and Iosifyan Plant, testing, calibration at an accelerator (LPI, MEPHI, IHEP).	**2014-2015**
5.	GAMMA-400 installation on the Navigator platform, complex testing in Lavochkin Research and Production Association, final operations on cosmodrome (LPI, MEPHI, Ioffe Institute, All-Russia Research Institute of Electromechanics and Iosifyan Plant).	**2016**
6.	Flight test (LPI, Mephi, Ioffe Institute).	**2017**
7.	The measurements in orbit, data acquisition, and processing.	**2017-2022**

6. GAMMA-400 COLLABORATION.

- Head institute – Lebedev Physical Institute (LPI)
- Lavochkin Research and Production Association (development of the Navigator platform, launch realization, realization and control of space flight)
- Cooperators:

- Moscow Engineering Physics Institute (MEPHI) (in part of development and production of scientific equipment, detector adjusting, participation in calibration, flight test, and scientific data analysis);
- All-Russia Research Institute of Electromechanics and Iosifyan Plant (development and production of the gamma-ray telescope construction, assembly and testing some systems and telescope as a whole);
- Ioffe Physical Technical Institute (development, production, calibration of the KONUS-FG system, flight control, data processing and analysis).

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