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CONCEPTUAL DESIGN OF GEOPHYSICAL MICROSATELLITE

The research covers issues related to the measurement of Earth gravitational field (EGF) parameters in the space. The radiophysical method for the measurement of gravitational frequency shift of electromagnetic radiation using existent GNSS and its two variants have been developed. A geophysical microsatellite has been designed to implement the radiophysical method of EGF measurement and to enable the researchers to monitor the Earth plasmasphere and magnetosphere.

Key words: earth gravitational field, radiophysical method, and GNSS.

INTRODUCTION. HISTORY OF EARTH'S GRAVITATIONAL FIELD STUDY

Currently, the satellite measurement of Earth's geophysical parameters is one of the fastest growing areas of remote sensing. Given the crucial importance of timely information on the characteristics of the gravitational field to solve many scientific, technical, and applied problems in geodesy, geophysics, environmental protection, life safety, and so on, it can be stated that the research of new methods and tools for measuring the parameters of the gravitational field of Earth (EGF) and other planets of the solar system is very relevant.

One of the first projects aimed at measuring the parameters of the EGF is LAGEOS (Laser Geodynamics Satellites). LAGEOS is a group of research satellites designed to calibrate the orbital ranging lasers for studying the geodynamics and refining the EGF parameters [1].

The LAGEOS spacecrafts (SC) were launched in 1976 and in 1992. They solved the following problems:

- Determination of the Earth's shape (geoid);
- Determination of tectonic plate movements associated with the continental drift.

LAGEOS are passive satellites located at a very stable medium earth orbit (MEO), which reflect the laser beam sent from the earth. Due to this, the position of satellites and the Earth surface points is calculated with very high accuracy. Each satellite is a sphere having a diameter of ~ 60 cm and a weight of 410 kg. In its thin aluminum shell, there are 426 corner reflectors distributed evenly. Four of them are made of germanium in order to obtain measurements in the infrared range for experimental study of reflectance and orientation of the satellite. The satellites have neither onboard sensors nor control system. The measurements are performed by transmitting the pulsed laser beams from the ground stations to the satellites. The transit time is calculated with high accuracy, which allows the ground stations to measure their scattering with an accuracy higher than 1 in a thousand miles.

The analysis of data for 11 years showed that the satellite orbit shifted by 2 meters annually in the direction of rotation of the Earth. This shift is 99% consistent with the general theory of relativity predicting the dragging of inertial frames of reference by rotating body.

The CHAMP (Challenging Minisatellite Payload) and GRACE (Gravity Recovery and Climate

Experiment) projects [13] deal with EGF tasks through precise positioning of satellites using GPS and laser ranging, with the help of *Black Jack* receiver specially developed for this purpose, which provides positioning with accuracy of 2—3 mm.

The EGF parameters are determined by the evolution of the satellite orbits, which is controlled by a network of ground stations. As a result, a model describing the Earth's geoid (the surface of smooth gravitational potential) with an accuracy of up to 1 m has been built. The tasks of CA CHAMP (launched in 2000) and GRACE (launched in 2003) were to improve accuracy of geoid radius measurement up to 1 cm at a spatial resolution 550-650 km, i.e. to improve the existing model by two orders of magnitude due to 16-channel board GPS receiver that can determine its current position independently. The TRSR-2 receiver (JPL, USA) receives signals from 12 satellite GPS; thereafter, in 10 seconds, the onboard navigation problem is solved as the components of location and velocity vectors, as well as time are defined. The data are collected and transmitted to the Earth for accurate reconstruction of the orbit with an accuracy of about meter, without distortion of GPS signals. The other four channels of the instrument are used for GPS altimetry experiments. The CHAMP project also includes careful consideration of all the non-gravitational perturbations of the satellite orbit: the aerodynamic drag, solar radiation pressure, light reflected from the Earth, and others. To do this, the satellite is equipped with a STAR accelerometer of National Center for Space Studies of France (produced by the ONERA), which is installed near the center of mass of the spacecraft.

The spacecraft flights require accurate determination of their position by ground facilities. For this purpose, on the bottom plane of the spacecraft (250 mm below the center of mass), there is a laser reflector of the four Laser Retro Reflector prisms with an aperture of 38 mm. Because of the reflector's small size, the distance to the spacecraft is measured with an accuracy of 1–2 mm. In addition to precise determination of the orbit and calibration of onboard GPS-receiver the reflector will be used for the «bicolor» laser ranging experiments. The purpose of the construction of new laser stations with the lasers operating at two frequencies is to eliminate errors due to the atmosphere heterogeneity.

The CHAMP model detects only medium-sized details of the gravitational field. However, it can be linked to the results of ground-based measurements and the above-ocean altimetry data by adding the necessary elements. It will be possible to convert the height measured by satellite navigation systems with respect to the earth ellipsoid with an accuracy of a few centimeters, into the «normal» height above sea level. Therefore, the expensive geodetic measurements will not be necessary anymore.

Within the framework of GRACE project, two identical spacecrafts, *Tom* and *Jerry,* were put into orbit with a radius of 500 km above the Earth to collect the most accurate data on EGF. The distance between the very spacecrafts is 220 km. Any changes between the spacecrafts are monitored by microwave rangefinder with an accuracy of up to microns. The spacecraft location above the Earth is determined by GPS system. The resolution is approximately twice better as compared with CHAMP [16].

The result of *Tom* and *Jerry* satellites operation was a new gravity map of our planet. The developed models allow the researchers to define acceleration of gravity with an accuracy better than 5 mGal at a spatial resolution of 400 km [14].

On July 19, 2007, in Turin (Italy), the European Space Agency presented GOCE (Global Ocean Circulation Experiment) spacecraft for observing the gravitational field and the ocean circulation regime with the framework of the first *Living Planet* ESA mission. The SC is designed to measure the EGF distribution using ultra-precise gravity gradiometer. The main contractor of this project is *Alenia Spazio,* an Italian company. *Astrium Gmb*, *Alcatel Space Industries*, and *ONERA* provided various equipment for the spacecraft (platform gradiometer, gradiometric, and accelerometer, respectively).

SC GOCE [13] has a length of 5 m and a diameter of 1 m. It is equipped with three pairs of triaxial gradiometers located at a distance of 0.5 m, a 12-channel GPS-receiver, and a laser reflector. The satellite makes it possible to measure the EGF anomalies with an accuracy of 1 mGal at the spatial resolution of 100 km; the geoid shape accuracy is 1—2 cm. The GOCE was launched in 2009 from the Plesetsk space-launch complex using a *Rocket* launch vehicle. The satellite is located at an altitude of about 250 km. Unlike the preceding spacecrafts in which all the research instruments are placed inside, in the GOCE satellite, a part of the equipment is located on structural elements.

It is planned to obtain with the help of GOCE spacecraft a unique information that can be used in a variety of fields: physics of the Earth, oceanography, in studies of the dynamics of moving ice and sea level changes.

All these projects have a common drawback: they use the measurements of ballistic parameters of test bodies in the space, for which it is necessary to create additional special space facilities and equipment. In connection with this problem, recently some projects based on measurements of radio relativistic gravitational frequency shift of electromagnetic waves of highly stable sources of electromagnetic radiation of both natural and artificial origin (for instance, ACES and SAGAS projects) have been launched on the existing space and ground infrastructure, in particular, on the existing global navigation satellite systems (GNSS).

ACES (Atomic Clock Ensemble in Space) is a project of the European Space Agency, in which highly stable atomic clock will be placed on the International Space Station, in 2015. The operation in a microgravity environment surrounding the International Space Station will provide stable and precise coordinates of time for different areas of research, including general theory of relativity, time and frequency metrology, and others.

The modern spacecraft equipment comprises a cesium clock for the long-term stability and a hydrogen maser for the short-term stability (or PHARAO and SHM), which will generate a reference frequency instability and an error of $1 \cdot 10^{-16}$.

Communication in the microwave region (MWL) and optical connection (ELT) will allow the ACES clock signals to be available for terrestrial laboratories equipped with atomic clock. The comparison of atomic frequency standards for the «*space-Earth*» and the «*Earth-Earth*» types will be used for studying Einstein's general relativity, including for making accurate measurements of the redshift of radiation from the International Space Station to Earth's surface under the influence of gravity acceleration (the accuracy of redshift measurement is expected to be $4 \cdot 10^{-11}$), for searching the temporal variations of fundamental constants, as well as for analyzing the Lorentz invariance. The measurement results can also apply to the field of geodesy, optical transmission of time signals, and distance measurement. According to the available data, the ACES clock will work 100 times more precisely than the clocks used on modern GPS satellites.

These experiments on measuring the change in frequency of radiation under the action of gravity at the ISS completely complies with the definition of radiophysical gravimeter [5, 9].

The SAGAS (Search for Anomalous Gravitation using Atomic Sensors) project was submitted to the European Space Agency in June 2007, in response to the request for proposals within the framework of the *Cosmic Vision 2015—2025* program. The proposed mission focuses on the study of the solar system in 2020—2030 (general theory of relativity, distribution of mass in the Kuiper Belt and in the Jovian system, as well as large-scale gravitational phenomena) over long distances (up to 53 a.u.l.) using highly sensitive atomic sensors (optical clock, absolute cold atom accelerometer, optical communication), which allow the researchers to perform measurements with an accuracy by several orders of magnitude better than the modern counterparts.

High-accuracy variables (relative frequency, Doppler frequency shift, non-gravitational acceleration) will be calculated combining the fundamental data and the measurements obtained. The local gravitational potential can be measured with an error of less than 10^{-17} based on the relative frequency (< 10 cm at the geocentric distance), which can be obtained for the time-varying parts of the potential.

In addition, the mission will contribute to the improvement of the PHARAO cold atom technique and the LISA (Lasers Ineterferometric Space Antenna) laser communication, as well as to the development of the ground segment (networked telescopes for measurements in the deep space and optical clock) for broadband data transmission in the solar system.

METHODS OF GRAVITATIONAL FIELD MEASUREMENTS

The author hereof has developed a method for measuring the EGF based on measuring the change in the frequency of electromagnetic radiation under the action of gravity followed by determining the gradient or the gravitational acceleration. This method can be conditionally divided into two varieties:

- Differential radiophysical and
- Integral radiophysical.

The technical difference between these two types is that in the differential method the gravitational frequency shift is measured between the two receivers of electromagnetic radiation, while in the integrated one it is measured between the radiation source and the receiver.

The Differential Method

The differential measurement equation is obtained as follows: it is assumed that the points with gravitational potentials u_0 and u_1 are separated in height above the Earth at a sufficiently small distance ΔH where variable u can be considered virtually linear. Then, expanding u_1 in series near u_0 and being limited with linear terms with respect to ΔH, to simplify the analysis, we obtain

$$u_1 = u_0 + \frac{\partial u}{\partial H}\Delta H + \ldots \,. \qquad (1)$$

Since the vertical gradient of potential is nothing else but the gravitational acceleration $g = \frac{\partial u}{\partial H}$, then in view of (1) we get the equation $f_{0\ldots}$, from which one can obtain an equation for determining the value of g by gravitational shift Δf of signal with frequency f while this signal passes through sufficiently small distance ΔH in nonuniform gravitational field:

$$g = \frac{\Delta f}{f}\frac{c^2}{\Delta H}. \qquad (2)$$

Taking into account (2), the error equation for the case when f_0 and f_1 are measured separately is as follows:

$$\frac{\sigma_g^{\ 2}}{g^2} = 2\cdot\left[\frac{c^2}{g\cdot\Delta H}\right]^2\cdot\frac{\sigma_f^{\ 2}}{f^2} + \frac{\sigma_{\Delta H}^{\ \ 2}}{(\Delta H)^2}. \qquad (3)$$

Proceeding from (3) one can conclude that even having a relative error of frequency synchronization for reference generators located at different heights at the level of $1\cdot10^{-17}$ the error of acceleration of gravity is 10 mGal on the basis of 10 km.

It should be noted that this method provides for the direct measurement of the difference between the frequencies instead of ascertaining separate frequencies, so one can get an equation for the differential method error as follows:

$$\frac{\sigma_g^2}{g^2} = \frac{\sigma_{\Delta H}^2}{(\Delta H)^2} + \frac{\sigma_{\Delta f}^2}{(\Delta f)^2}.$$

Let us assume that σ_g = 100 mGal, i.e.

If ΔH = 10 m, $\sigma_{\Delta H} = 10^{-4}\cdot 10\text{ m} = 10^{-4}\cdot 10^4\text{ m} = 1\text{ m}$ can be achieved using the same GNSS receiver and the reference base station.

If height difference is 10 m, then $\Delta f = 10^{-6}\cdot 10 \times 1.5\cdot 10^9 = 1.5\cdot 10^{-6}$ Hz.

Due to the fact that $\sigma_{\Delta f}/\Delta f = 10^{-4}$, $\sigma_{\Delta f} = \Delta f \times 10^{-4} = 1.5\cdot10^{-6}\cdot10^{-4} = 1.5\cdot10^{-10}$ Hz; this is requirement that is quite realizable.

The radiophysical method was studied experimentally within STCU project no. 3856.

For implementing an experiment to determine the earth gravitational acceleration near the surface the researchers have used the differential method for measuring the difference between two

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frequencies using a CNT-91 frequency counter as phase comparator which operates in the time interval measurement mode (Fig. 1). Incoming signal with a frequency of 5 MHz was fed to both inputs of the frequency counter.

This method allows the researchers to obtain measurements with high accuracy even with a relatively inaccurate instrumentation provided the known value is reproduced more accurately. The method accuracy increases as the difference between compared values decreases. For determining the acceleration of free fall near the earth's surface, the equation (2) is used in this case.

To reduce the impact of distance measurement and instrument errors (which are mostly random) on the result the data were cleaned from noise with the use of direct wavelet transform (wavelet db4, 12 levels of decomposition), thresholding of wavelet coefficients, and subsequent recovery of the signal [2]. Thereafter, a trend line was built. The coefficient before the linear term of trend line equation gives us the magnitude of gravitational frequency shift obtained experimentally. The time series obtained this way represents the absolute error of the measurement of relative frequency instability of CNT-91 counter with averaging time of 1 s.

For the CNT-91 frequency counter no. 1 the coefficient of linear approximation which corresponds to the frequency difference of $8.73 \cdot 10^{-16}$ and $g = 9.81$ m/s^2 gives an error of 1.2%. At the same time, for the CNT-91 frequency counter no. 2 the coefficient of linear approximation has the opposite sign and corresponds to the frequency difference of $9.04 \cdot 10^{-16}$; it gives an error of 4.7% for $g = 9.81$ m/s^2.

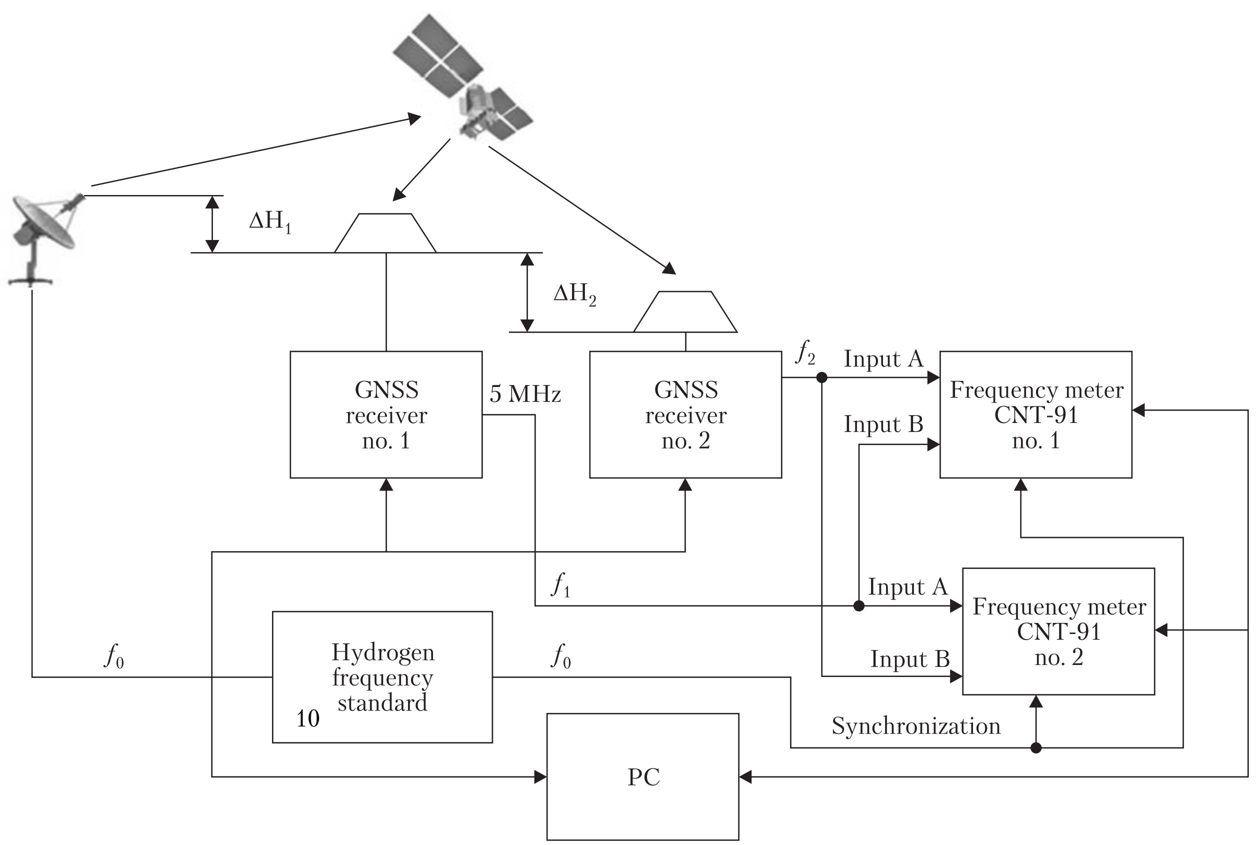

Fig. 1. Flowchart of experiment for determination of acceleration of gravity by two GNSS receivers with two cross-connected frequency counters

When removing the noise from the data with respect to the trend line systematic error was separated. Taking into consideration this systematic error, the total experimental error is as follows:
- For CNT-91 no. 1: 0.6%;
- For CNT-91 no. 2: 2.9%.

Thus, it can be stated that the gravity acceleration at the Earth's surface can be measured using two serially produced GNSS receivers having a special frequency output, on the basis of 10 m with an accuracy of up to 100 microGal, which is in good agreement with the theoretical calculations.

The Integral Method

Let us analyze the requirements for the algorithm of frequency shift calculation when the electromagnetic waves travel from the areas with weaker gravitational field and experience the gravitational blue shift. In this case [15]:

$$\frac{f_0 - f_1}{f_0} = \frac{1}{c^2}(u_1 - u_0), \qquad (4)$$

where u_0 and f_0 are gravitational potential which corresponds to the position of radiation source (e.g., a geostationary satellite transmitter) and the frequency of carrier signal transmitter at the same point; u_1 and f_1 are the gravitational potential and the frequency of carrier signal at the observation point; c is light speed.

The equation (4) which connects potential u_0 at the point where the signal has frequency f_0, with potential u_1 at the point where the signal frequency is f_1 does not take into account any relative movement of the signal transmitter and the receiver and can be expressed by the formula:

$$u_1 = u_0 + c^2(1 - \frac{f_0}{f_1}), \qquad (5)$$

where u_1, u_0 are unknown values; f_1, f_0 are the signal frequencies determined directly (or indirectly), which are the initial values for calculating u_1 by the formula (5).

Insofar as, in generally, both u_0, and u_1 are unknown, it is necessary to have relations which are complementary to (5) and link u_1 and u_0. For this, one can use a well-known model of the Earth gravitational field. For example, we present the gravitational potential as expanded in spherical harmonics [12]:

$$u(r,\theta,\lambda) = \frac{GM}{R}\sum_{l=0}^{l_{\max}}\sum_{m=0}^{l}\left(\frac{R}{r}\right)^{l+1} \cdot P_{lm}(\sin\theta) \times$$
$$\times [C_{lm} \cdot \cos(m\lambda) + S_{lm} \cdot \sin(m\lambda)], \qquad (6)$$

where r, θ, λ are spherical coordinates in a coordinate system with the reference point at the center of mass of the Earth; P_{lm} are Legendre polynomials; C_{lm}, S_{lm} are serial expansion coefficients determined by experimental data on the stage of the model development; G, M are the gravitational constant and the mass of the Earth, respectively; R is average radius of the Earth.

Equation (6) gives us the necessary relation between u_0 and u_1, because it describes the gravitational potential at an arbitrary set of points of the near-Earth space, and consequently, at the points with potentials u_0 and u_1.

The expansion coefficients C_{lm}, S_{lm} are determined from the system of equations:

$$\frac{GM}{R}\sum_{l=0}^{l_{\max}}\sum_{m=0}^{l}\left(\frac{R}{r_{x_i}}\right)^{l+1} \cdot P_{lm}\left(\sin\theta_{x_i}\right)\left[C_{lm} \cdot \cos\left(m\lambda_{x_i}\right) +\right.$$
$$\left. + S_{lm} \cdot \sin\left(m\lambda_{x_i}\right)\right] = \frac{GM}{R}\sum_{l=0}^{l_{\max}}\sum_{m=0}^{l}\left(\frac{R}{r_{y_j}}\right)^{l+1} \times$$
$$\times P_{lm}\left(\sin\theta_{y_j}\right)\left[C_{lm} \cdot \cos\left(m\lambda_{y_j}\right) + S_{lm} \cdot \sin\left(m\lambda_{y_j}\right)\right] +$$
$$+ c^2\left(1 - \frac{f_{y_i}}{f_{x_j}}\right),$$

where r_{xi}, θ_{xi}, λ_{xi} are spherical coordinates of a set of points indexed $i = 1, 2, ..., I$ (I is the number of points), which correspond to I locations of the signal receiver (f_{xi} is frequency of signal received at these points); r_{yj}, θ_{yj}, λ_{yj} are spherical coordinates of a set of points indexed $j = 1, 2, ..., J$ (J is the number of points), which correspond to J locations of the signal transmitter (f_{yj} is frequency of signal emitted at these points).

The coordinates of r_{xi}, θ_{xi}, λ_{xi} points are determined on the basis of GNSS measurements. The coordinates of r_{yj}, θ_{yj}, λ_{yj} points are determined on the basis of satellite ephemerides received

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from the GNSS measurements in the navigation message.

The f_{xi} frequencies are measured directly at the receiver output; the f_{yj} frequencies are determined using GNSS messages.

The model accuracy is determined by the number of terms in the expansion of l_{max}, as well as by the accuracy of determination of r_{xi}, θ_{xi}, λ_{xi}; r_{yj}, θ_{yj}, λ_{yj}; f_{xi}, f_{yj} for $i = 1, 2, ..., I$; $j = 1, 2, ..., J$ [11].

The block diagram of the integral method test using *Gravika* software and hardware complex with DL-V3 GNSS-receiver is showed in Fig. 2.

A project on the experimental study of the integral radiophysical method is planned to be implemented within the framework of cooperation with the *Kyiv Polytechnic Institute* National Technical University of Ukraine under the Master Agreement between *Pivdenne* Design Office and higher education institutions of MESU.

MONITORING OF EARTH'S PLASMOSPHERE AND MAGNETOSPHERE

The proposed method describes the Earth's magnetic field using a mathematical representation of World Magnetic Model (WMM). However, the WMM parameters are determined using the integral data (which reflect the contribution of the whole magnetic field spatial profile on the path of electromagnetic waves) obtained as a result of multi-GNSS measurements [4].

To restore the geomagnetic field using GNSS measurements the researchers use a simplified model that does not take into account the refractive effects of higher orders for GNSS signals in an inhomogeneous ionosphere and includes measurements at two frequencies by two receivers on the basis of known length:

$$N_e = \frac{2}{C_x \cdot L} \cdot \frac{L \cdot \left(f_1^3 - f_2^3\right) - \left[f_1^3 \cdot \Delta S(f_1) - f_2^3 \cdot \Delta S(f_2)\right]}{(f_1 - f_2)},$$

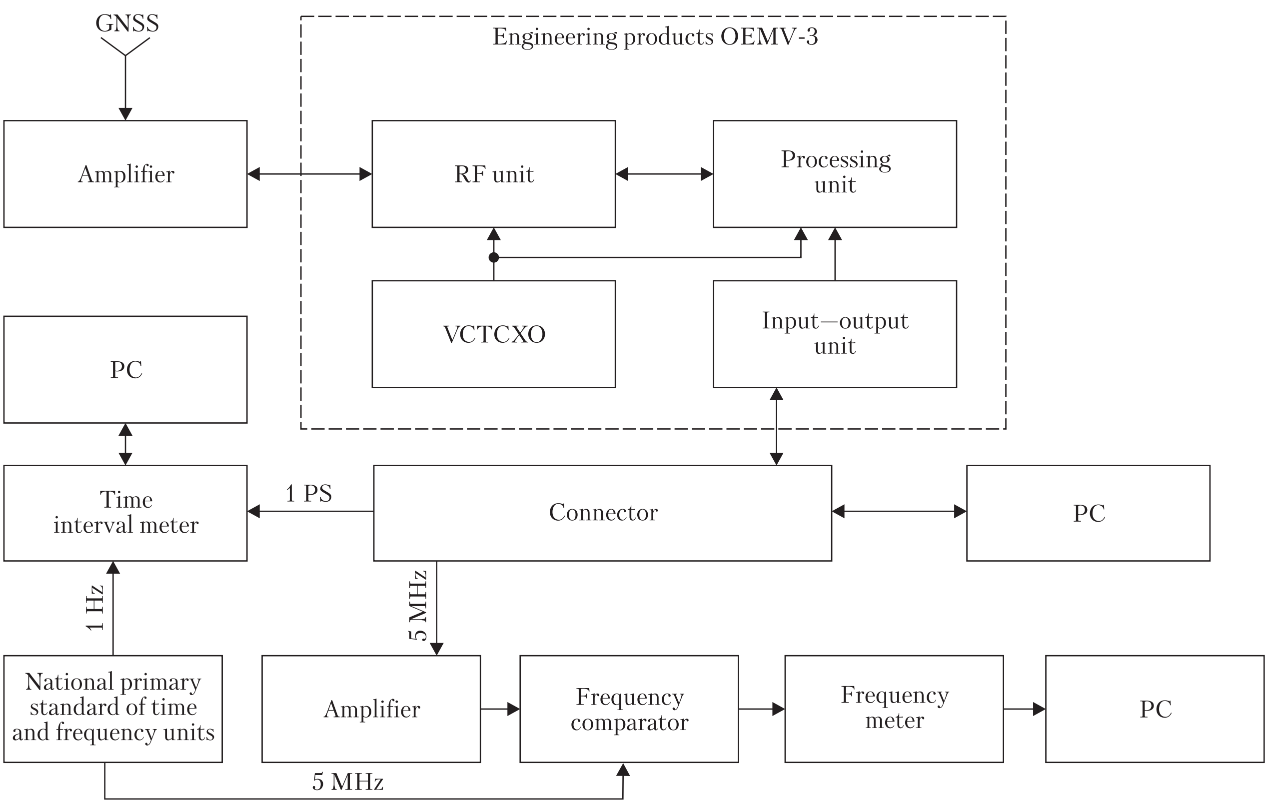


Fig. 2. Block diagram of the test of *Gravika* software and hardware complex with DL-V3 GNSS-receiver

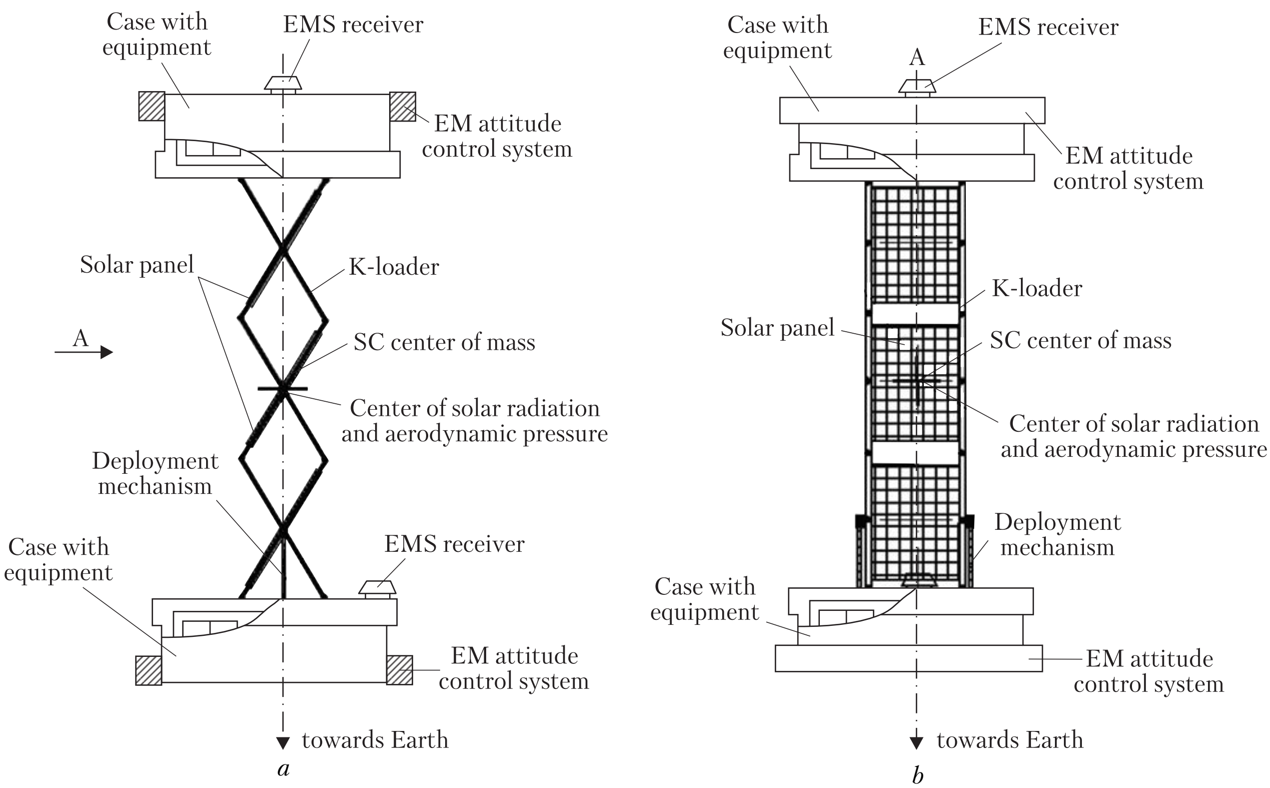
$$H_0 = -\frac{f_1 f_2}{C_y \cdot \cos\theta} \cdot \frac{L \cdot \left(f_1^2 - f_2^2\right) - \left[f_1^2 \cdot \Delta S\left(f_1\right) - f_2^2 \cdot \Delta S\left(f_2\right)\right]}{L \cdot \left(f_1^3 - f_2^3\right) - \left[f_1^3 \cdot \Delta S\left(f_1\right) - f_2^3 \cdot \Delta S\left(f_2\right)\right]}.$$

Here N_e is electron density; H_0 is magnitude of the geomagnetic field (field strength); θ is angle between H_0 and the direction of signal propagation; $\Delta S = S_A - S_B$; S_A, S_B are pseudo-ranges at points *A* and *B* on the frequency f_i measured by GNSS receivers; C_x, C_y are known constants; f_i is frequency of GNSS signals; *L* is pre-measured distance between two receivers.

DESIGN-LAYOUT SCHEME OF GEOPHYSICAL MICROSATELLITES

Taking into account the specific requirements for the implementation of radiophysical differential method a gravity-oriented geophysical microsatellite was designed. The spacecraft block diagram is showed in Fig. 3.

The microsatellite consists of a hardware carrying body made of two separate parts connected to each other with a yoke consisting of two parallel hinged pantographs with links and rectangu-



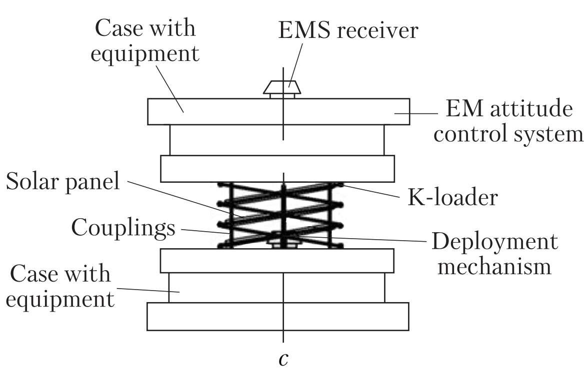


Fig. 3. Design of SC: *a* — in-space front view; *b* — left view; *c* — view in stowed position

lar solar panels attached. This spacecraft design makes it possible to align the center of mass and the center of solar and aerodynamic pressure on solar cell, which eliminates the effect of external torque on the spacecraft orientation.

The receivers mounted on the body make it possible to measure the gravitational field parameters using the radiophysical differential method (that does not exclude the implementation of the radiophysical integral method) and to monitor the Earth's plasmasphere and magnetosphere.

CONCLUSIONS

The geophysical microsatellite project is innovative in terms of both the method of measurement and SC design-layout scheme for the following reasons:

- The radiophysical method allows the researchers to measure the gravitational potential and the gravitational acceleration [5—10];
- The design-layout scheme of geophysical microsatellite [3] eliminates the need for an active stabilization system, ensures constant illumination of solar panels, removes external disturbance torque, and allows the researchers to measure the EGF parameters and to monitor plasmasphere and magnetosphere of the Earth;
- The radiophysical method is based on the measurement of relativistic effect (gravitational frequency shift of electromagnetic signal) which is substantially smaller than the Doppler frequency effect and the influence of propagation medium.

These issues are not discussed in this paper, but should be studied in subsequent research.

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Державне підприємство
«Конструкторське бюро
"Південне" ім. М.К. Янгеля»,
Дніпропетровськ

КОНЦЕПТУАЛЬНИЙ ПРОЕКТ ГЕОФІЗИЧНОГО МІКРОСУПУТНИКА

Стаття присвячена проблемі вимірювання параметрів гравітаційного поля Землі з космосу. Автором розроблено оригінальний радіофізичний метод і два його різновиди виміру параметрів гравітаційного поля Землі, що заснований на вимірюванні гравітаційного зрушення частоти електромагнітного випромінювання з використанням існуючих глобальних навігаційних супутникових систем. Запропоновано конструктивно-компонувальну схему геофізичного мікросупутника, що реалізує радіофізичний метод вимірювань гравітаційного поля Землі і забезпечує моніторинг плазмосфери і магнітосфери Землі.

Ключові слова: гравітаційне поле Землі, радіофізичний метод, глобальні навігаційні супутникові системи.

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КОНЦЕПТУАЛЬНЫЙ ПРОЕКТ ГЕОФИЗИЧЕСКОГО МИКРОСПУТНИКА

Статья посвящена проблеме измерения параметров гравитационного поля Земли из космоса. Автором разработан оригинальный радиофизический метод и его две разновидности измерения параметров гравитационного поля Земли, который основан на измерении гравитационного сдвига частоты электромагнитного излучения с использованием существующих глобальных навигационных спутниковых систем. Предложена конструктивно-компоновочная схема геофизического микроспутника, которая реализует радиофизический метод измерений гравитационного поля Земли и обеспечивает мониторинг плазмосферы и магнитосферы Земли.

Ключевые слова: гравитационное поле Земли, радиофизический метод, глобальные навигационные спутниковые системы.

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