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Relativistic gravimetry

S.A. Matviienko[1,2], 2022

[1]State Space Agency of Ukraine, JSC «RPC» «KURS», Kyiv, Ukraine
[2]National Antarctic Scientific Center of Ukraine, Kyiv, Ukraine
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Work on the creation of a device that will be able to measure the parameters of the Earth's gravitational field in space was started at the State Design Office «Yuzhnoye» in 2001 as part of the formation of a scientific research program on the «Sich-1M» spacecraft. But since there were no devices in the world to directly measure the parameters of the Earth's gravitational field in space, the idea arose to use the relativistic «red shift» effect to solve this problem. The possibility of practical implementation of this idea arose in 2008—2010 during the implementation of the STCU project No. 3856 «Measurement of the parameters of the Earth's gravitational field using navigation satellite systems». Within the framework of this project, for the first time, a differential radiophysical gravimeter was created and tested, in which the radiation of navigation satellites was used as a source of highly stable radiation. Radiophysical method for measuring the parameters of the Earth's gravitational field based on the results of dissertation research, 4 patents for an invention of Ukraine, 2 copyright certificates were obtained, and 16 articles were published in scientific journals. In 2012, the fundamental patent No. 98358 «Method for measuring geodetic parameters and a device for its implementation» was obtained, which was recognized in 2014 as the best patent of Ukraine in the absolute nomination in the competition «Best Patent of Ukraine». This patent formed the basis for the creation of the «Gravika» — navigation control and correction station. This work has been continued at JSC «RPC «KURS» since 2015. Since 2015, JSC «RPC «KURS» has been the head organization in the NSAU for the creation of a coordinate-clock and navigation support network for Ukraine. In 2016, it was created, certified and put into operation control and correction station (CCS) «Gravika», which can simultaneously operate both as a navigational base station and as a gravimeter, that is, to solve a complete geodetic problem. The principle of operation of the gravimeter is based on the relativistic effect of «red shift». One of the main technical and economic problems is the need to use a highly stable hydrogen frequency standard as part of the Gravika control and correction station, the cost of which is at least USD 80,000 (code «Geomonitoring») in order to develop a concept for creating, on the basis of the existing network of coordinate-clock and navigation support in Ukraine, a complex a clear geophysical monitoring system using the Gravika control and correction station and a satellite system for relaying signals of a highly stable TWSTFT frequency standard. Such a solution will make it possible to abandon the use of a frequency standard at each station and thereby reduce the cost of the CCS and the system as a whole. In addition, the work of the CCS «Gravika» showed the possibility of predicting seismic activity within a radius of 500 km from the station. A three-axis version of the gravimeter was also implemented, which allows you to simultaneously measure the absolute, relative values of the gravitational acceleration and the angle of inclination of the gravitational acceleration vector. Such functionality makes the radiophysical gravimeter indispensable when used on mobile vehicles, including space vehicles.

Key words: radiophysical method, navigation support network of Ukraine, complex geophysical monitoring system, relativistic «red shift» effect.

Introduction. For the most complete and deep understanding of the geophysical processes occurring in the near-Earth space and the lithosphere, it is necessary to reconstruct the global space-time distribution of the gravitational and magnetic fields with high accuracy and resolution from gravimetric measurements of ground stations. Possession of such information and the construction of a monitoring system on its basis is extremely important for solving many fundamental scientific and technical problems in such areas as geodynamics, geodesy, the study of the internal structure of the Earth, geological history, and many others. Astrometry and geodetic issues are equally important for determining the main directions and reference surfaces used for spatio-temporal referencing. The addition of existing and prospective global navigation satellite systems (GNSS) with global geophysical monitoring significantly expands their capabilities in various technical applications and opens up fundamentally new areas of use and research. In this context, knowledge of the gravitational field parameters becomes important for celestial mechanics since it provides ballistic and navigation requirements for controlling the motion of all space objects operating in the regions where these fields are determined. Thus, gravimetry in combination with GNSS finds application in various fields of science and technology and makes it possible to create fundamentally breakthrough technologies.

The current state and development of space technology and measuring technology and its new developments make it possible to assert the possibility of implementing such a project of a global monitoring system. Using a new method of the radiophysical method for measuring the parameters of the gravitational field, based on the use of the relativistic redshift effect, it is possible to create a complex geodetic system thatis a prerequisite for the effective implementation of such a project.

The article presents the results of experimental tests and certification of the world's first geodetic control and correction station. The station is currently in trial operation in Zolochiv, Ukraine, part of the national RTK network.

Modern state of research. Radiophysical methods (methods based on measuring the characteristics of electromagnetic signals) are now widely used to solve many problems of environmental monitoring [Fedynskiy, 1964; Parkinson, 1986; Brunelli, Namgaladze, 1988; Astanin, Kostylev, 1989; Johnson, Kileen, 1995]. With the development of space (satellite) technology, the scientific and technical direction associated with the use of radio measurement to solve problems of monitoring, received significant impetus for its further development: there are opportunities to improve accuracy, resolution, range of measuring equipment (RME), it is proposed to use new radio technical RMEs to measure additional physical characteristics of outer space [Belyaev et al., 1995; Vladimirskiy, Temuryants, 2000]. The problem of monitoring the Earth's gravitational field (EGF) and diagnostics based on monitoring the geological, seismic and weather conditions of the planet is a separate topical area of human activity [Grushinskiy, Sazhina, 1981; Tsuboi, 1982].

Geophysical studies of the Earth are currently one of the most dynamic areas in which remote methods are widely used. Given the exceptional importance of operational information on the characteristics of the Earth's gravitation field (EGF) for solving many scientific and technical, and applied problems in such fields as geodesy, geophysics, environmental protection, life safety, etc., it can be started the relevance of development and research of new methods and tools for measuring parameters of EGF and gravitation field of others planets.

Currently, absolute (ballistic) and relative gravimeters are widely used [Peshekhonov, 2017]. Since the principle of operation of these gravimeters is based on Newton's laws, we call modern gravimetry «Newtonian gravimetry». Newtonian gravimetry is characterized by a drawback due to the principle of equivalence of gravitational and inertial accelerations and does not allow conducting on moving objects.

Relativistic gravimetry does not have such shortcomings, being based on half-reports of A. Einstein's General Theory of Relativity.

Relativistic gravimetry is the science of measuring quantities that characterize the gravitational field using the redshift effect of the frequency of an electromagnetic signal.

Accordingly, in relativistic gravimetry, it is necessary to distinguish between radiophysical, optical, and radioisotope methods for measuring EGF parameters.

Theradiophysical method of measuring the EGF parameters is based on measuring the gravitational displacement of the frequency of the electromagnetic signal in long radio waves, radio-, and microwaves.

The optical method of measuring the parameters of the EGF is based on measuring the gravitational displacement of the frequency of the electromagnetic signal in the IR, optical, and UV frequency range.

The radioisotope method of measuring the EGF parameters is based on measuring the gravitational displacement of the frequency of the electromagnetic signal in the X-rays frequency range.

The author of the article has been developing the radiophysical method for measuring the EGF parameter since 2000. The result of this activity is the dissertation «Radiophysical method for measuring the Earth's gravitational field» [Matviienko, 2012], eight patents of Ukraine [Makarov et al., 2008; Matviienko, 2008, 2010, 2017a,b, 2018; Matviienko et al., 2010, 2012], more than 60 scientific publications, and a certified valid differential radiophysical gravimeter, which was created by order of the National Academy of Sciences of Ukraine as part of the experimental design work «Navigation-RNIS».

Radiophysical method of measuring earth gravitational field. In order to implement the monitoring system of the EGF, not only high-quality models are required that describe it with sufficient accuracy, but also precise local measurements of this field. Moreover, the measurement equipment should be inexpensive, such that it would allow its placement on geophysical micro-satellites, from which groups are formed similar to those used in GNSS. The composition of the grouping and their configuration should be made so that when assimilating these measurements into the mathematical model of the EGF, one can find a solution of inverse gravity problems that satisfies those requirements that are defined by all the previously mentioned areas and applications. Of course, measurements carried out by the group of geophysical micro-satellites should be supplemented by a complex of ground measurements.

All existing methods of the EGF measurements implemented in the previous projects have one common disadvantage: they use measurements of ballistic parameters of test bodies in space, which require the creation of additional specialized space vehicles and special equipment, which may cause some difficulties in their use in groups for geophysical monitoring.

A group of Ukrainian scientists and specialists based on ideas of and led by S.A. Matviienko developed, investigated, and tested the radiophysical method for measuring the parameters of the EGF, which is based on measuring the magnitude of the frequency change of electromagnetic radiation under the action of gravity with the subsequent determination of the EGF gradient or the free-fall acceleration. In the radiophysical method of measuring the gravitational potential, the relativistic redshift effect is used, which manifests itself precisely in the frequency shifting of the electromagnetic signal propagating in a non-uniform gravitational field.

This method has two varieties:

– differential radiophysical method;

– integral radiophysical method.

The differential radiophysical method is based on measuring the gravitational displacement of the frequency of an electromagnetic signal between several receivers of this signal.

The differential radiophysical method and gravimeter are protected by a patent of Ukraine [Matviienko et al., 2012].

The integrated radiophysical method is based on measuring the gravitational displacement of the frequency of the electromagnetic signal between the radiation source and the receiver of this signal.

The integrated radiophysical method and gravimeter are protected by a patent of Ukraine [Matviienko et al., 2010].

Differential radiophysical method of measurement. The differential equation of measurements is obtained as follows: we shall assume that the points with gravitational potentials are spaced apart in height above the Earth at a rather small distance, on which the variable can be considered almost linear on spatial variables. Then, expanding in a series nearby and limiting by linear on expansion members to simplify the analysis, we obtain

$$u_1 = u_0 + \frac{\partial u}{\partial H}\Delta H + \dots . \quad (1)$$

Since the vertical gradient of the potential is nothing more than the gravity acceleration $g = \frac{\partial u}{\partial H}$, then, taking into account (1), we obtain an equation $\frac{f_0 - f_1}{f_0} = g\frac{\Delta H}{c^2}$ from which we obtain an equation for determining the value of g by the gravitational shift Δf of the signal with the frequency f during the passage of this signal of some rather small distance ΔH in a non-uniform gravitational field

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

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

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

As it follows from (3) that even with the magnitude of the relative error of synchronization of the frequencies of the GNSS reference generators located at different heights, at the level of 1×10^{-17}, we obtain the error of determining the free-fall acceleration in the form of a value of 10 mGal based on 10 km.

In addition, it should be stressed, not individual frequencies are measured, but directly the difference between these frequencies. Therefore we obtain the error equation for the differential method in the form

$$\frac{\sigma_g^2}{g^2} = \frac{\sigma_{\Delta H}^2}{(\Delta H)^2} + \frac{\sigma_{\Delta f}^2}{(\Delta f)^2} . \quad (4)$$

Assume that σ_g=100 mGal, that is

$$\frac{\sigma_g}{g} = \frac{100\cdot10^{-3}}{10^3} = 10^{-4} .$$

If ΔH=10 m, then $\sigma_{\Delta H}=10^{-4}\times10$ m$=10^{-4}\times$ $\times10^4$ mm=1 mm can be provided with the use of the same GNSS receivers and reference base station.

With a height difference of 10 m we obtain $\Delta f=10^{-16}\times10\times1.5\times10^9=1.5\times10^{-6}$ Hz.

Due to $\frac{\sigma_{\Delta f}}{\Delta f} = 10^{-4}$, $\sigma_{\Delta f}=\Delta f\times10^{-4}=1.5\times10^{-6}\times$ $\times10^{-4}=1.5\times10^{-10}$ Hz, that is a requirement that can be satisfied.

For the practical realization of the experiment for determining the free-fall acceleration near the Earth's surface, a differential method for measuring the difference between two frequencies was implemented using a phase comparator. The CNT-91 frequency meter can be used, which operates in the mode of measuring time intervals (Fig. 1). A signal with a frequency of 5 MHz was supplied on both inputs of the frequency meter.

This method makes it possible to receive the measurement results with high accuracy even in the case of the use of inaccurate measurement units if the known value is reproduced with greater precision. The method's accuracy increases with a decrease in the difference between the comparable values. In this case, equation (2) is experimentally implemented to determine the free-fall acceleration near the Earth's surface.

To reduce the effect of long-range measurements' and instrumental errors, mostly random, the data were denoised using of direct wavelet transform (wavelet db4, 12 levels of decomposition), threshold processing wavelet coefficients, and subsequent signal recovery. After that, the trend line was built. The coefficient of the linear term of the trend line equation gives us the value of the gravitational frequency shift obtained from the experiment. The time series obtained is an absolute value of measurement error of relative frequency instability of the frequencymeter CNT-91 with a time averaging of 1 second.

The created differential radiophysical gravimeter (Fig. 2) was calibrated and certified at the National Scientific Center «Institute of

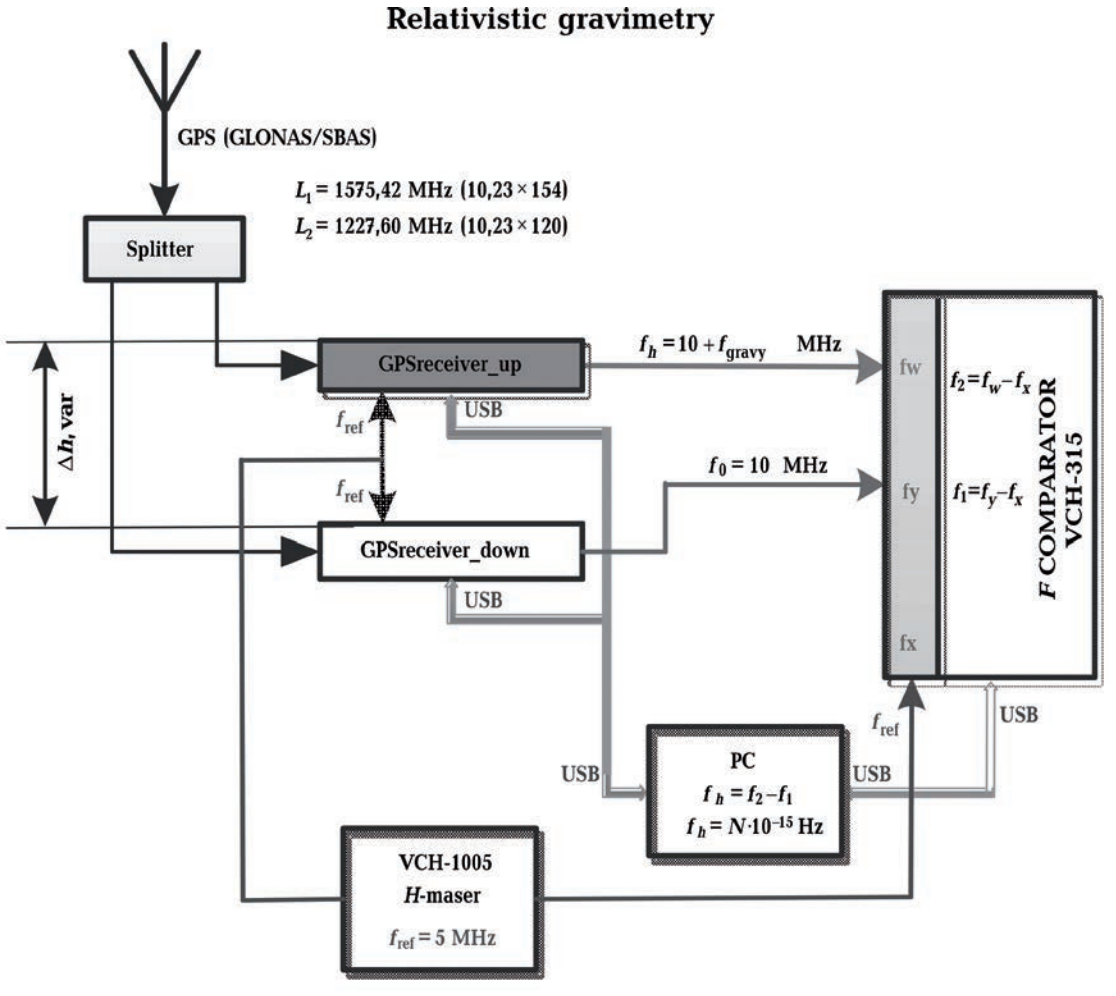

Fig. 1. Scheme CCS «Gravika».

Metrology» in Kharkiv according to the Sovereign primary standard of the unit of acceleration of gravity using the Sovereign primary standard of time and frequency.

As a result of calibration, the standard uncertainty of gravitational acceleration was determined at the level of 102 μGal. The graph of the calibration results is shown in Fig. 3.

It should be noted that after 23.00 when the subway trains stop running, the discrepancies in the measurement results of the standard and differential radiophysical gravimeter do not exceed 20 μGal. Moreover, the sensitivity of a differential radiophysical gravimeter at the level of 2—3 μGal was experimentally proved. However, in calibration certificate UA 01 No. 3782 dated July 30, 2019, a value of 102 μGal was recorded.

Integrated radiophysical method. Let us analyse the requirements for the algorithm for calculating the frequency shift when the electromagnetic waves come from zones with a weaker gravitational field and undergo gravitational violet displacement. According to [Matvienko, 2012], we have

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

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

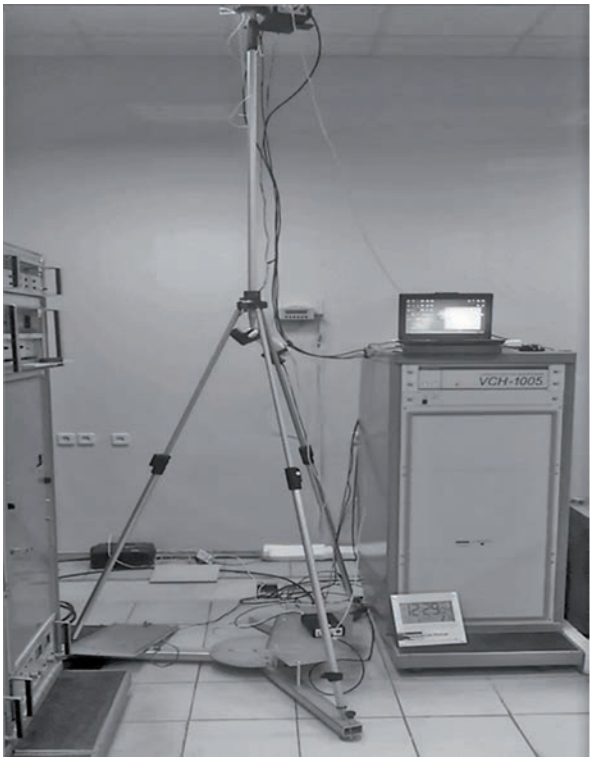
Fig. 2. CCS «Gravika» — differential radiophysical gravimeter.

The equation (4) that connects the potential u_0 at the point where the signal has a frequency f_0, with the potential u_1 at the point where the signal frequency is f_1, does not take into account the possible relative motion of the emitter and receiver of the signal and can be given in the following form

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

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

Since, in the general case, both u_0 and u_1 are unknown, it is necessary to have additional to (5) relationships that associate u_1 and u_0. One of the known models of the Earth's gravitational field can be used as such a relationship. For example, representation of the gravitational potential in the form of a decomposition on spherical harmonics [Matvienko, 2012]:

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

where φ, λ, r are spherical coordinates in the coordinate system with the beginning at the Earth center of the masses; $P_{\rm lm}$ are attached Legendre polynomials; $C_{\rm lm}$, $S_{\rm lm}$ are coefficients of the expansion, which are determined by any experimental data at the stage of model construction; f and M are the gravitational constant and the Earth's mass respectively; R is the Earth's average radius.

The formula (6) gives us the necessary relation which binds u_0 and u_1 since it describes the gravitational potential in an arbitrary set of points of the near-Earth space, and hence at points with potentials u_0 and u_1.

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

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

where r_{x_i}, φ_{x_i}, λ_{x_i}, are spherical coordinates of a certain set of points, marked by the index i=1, 2,...,I (I is a number of these points), which correspond to the I locations of the signals receiver (is the frequency of the signal received at these points); r_{y_i}, φ_{y_i}, λ_{y_i}, are the spherical coordinates of some set of points marked by the index j=1, 2,...,J (J is the number of these points), which correspond to J location of the emitter of signals (position of spacecraft(SC)) (f_{y_i} is the frequency of the signal emitted at these points).

The coordinates of the points r_{x_i}, φ_{x_i}, λ_{x_i} are determined according to the GNSS measurements.

The coordinates of the points r_{y_i}, φ_{y_i}, λ_{y_i}

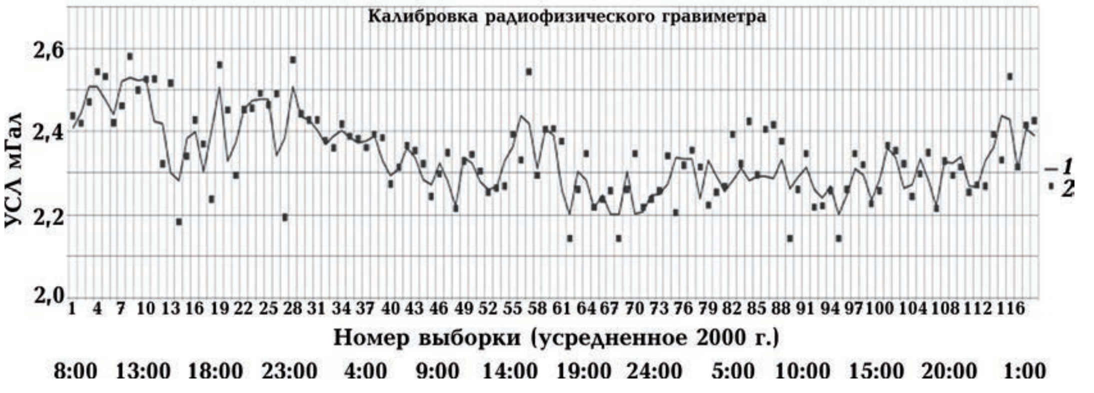

Fig. 3. Calibration results of CCS «Gravika».

Fig. 4. Variations in the acceleration of free fall.

are determined by the spacecraft's ephemeris, also obtained during the GNSS measurements, in the navigational message.

Frequencies f_{x_i} are measured directly from the receiver output.

Frequencies f_{y_j} are determined using the GNSS message.

The accuracy of the model is determined by the number of members of the $l_{\max}$ expansion, as well as by the accuracy of the determination of the values r_{x_i}, φ_{x_i}, λ_{x_i}, r_{y_j}, φ_{y_j} [Matviienko, 2021].

Estimation of influence of gravitational shift of frequency on a navigation signal. Due to the influence of gravity on the navigation signal, there is an error in determining the *z* coordinate. It is known that the acceleration of free fall varies with a height of 3 μGal/cm. Fig. 4 shows a graph of variations in the acceleration of free fall. From this graph we can conclude that the z coordinate error can reach 20 cm or more.

Geophysical micro-satellite «Gravisat». Considering the specific requirements for implementing the differential radiophysical measurement method of the EGF, a draft of the magnetic gravity-oriented geophysical micro-satellite was developed. The photo of the spacecraft is shown in Fig. 5.

The microsatellite consists of a body with equipment, made in the form of two separate parts, connected by a cross-arm, which is a pair of parallel articulated parallelogram pantographs with links and attached rectangular solar panel [Matviienko, 2017b, 2018].

The design of the spacecraft also allows fitting the center of mass with the center of solar and aerodynamic pressure on a solar battery, which sufficiently decreases the disturbing moment on the spacecraft's orientation.

Fig. 5. Geophysicalmicro-satellite «Gravisat».

The installation of the electromagnetic signal receiver on the parts of the body will enable to measure the parameters of the gravitational field using the differential method of the radio-physical method, that does not exclude the implementation of the integrated radio-physical method, and will provide monitoring of the Earth magnetic field (EMF), as well as other parameters of the Earth magnetosphere plasma.

Measurement of the EGF and the EMF for the monitoring system should be carried out in a sufficiently large number of points of the near-Earth space, using for this purpose both the grouping of geophysical micro-satellites and numerous ground stations. Only for the measurement system sufficiently distributed in space is it possible to provide a good solvability of the inverse problems of magnetogravimetry and to construct high-quality models of these fields.

Elaboration of the possibility of creating a combined navigation and gravity network. The modern coordinate basis of all geospatial data in Ukraine is the State Geodetic Reference Coordinate System USK-2000, implemented on the ground by points of the State Geodetic Network (SGN). Since 2013, the SGN geoportal has been operating https://dgm.gki.com.ua/.

State geodetic network — a network of geodetic points, evenly built on the ground (territory of the state), which ensures the spread of the state coordinate system, heights and gravimetric system and geodetic data bank — a system consisting of databases of geodetic points, measurements on them (satellite, geodetic, leveling, gravimetric), database management systems of geodetic points and application software for data processing, storage, and protection, organization of access to geodetic information.

Reference systems are used for the functioning of the SGN: coordinate system — USC-2000; altitude system — Baltic in 1977; Gravimetric Reference System — International Gravimetric System of 1971 (IGSN-71).

The components of the SGN are geodetic (planned), leveling (height), and gravimetric networks, the points of which must be combined or between which a reliable geodetic connection is established (paragraph 10 of the Procedure for building the State Geodetic

Network, approved by the Cabinet of Ministers of Ukraine on August 7, 2013). № 646 «Some issues of implementation of the first part of Article 12 of the Law of Ukraine «On Topographic, Geodetic and Cartographic Activities» (from now on referred to as the Procedure). In accordance with items 11, 12, and 13 of this Procedure:

– geodetic (planned) network includes the Ukrainian permanent (permanent) network of observations of global navigation satellite systems and geodetic (planned) networks of 1, 2, and 3 classes;

– leveling (height) network includes leveling (height) networks of I, II, III, and IV classes;

– the gravimetric network includes a fundamental gravimetric network and a class 1 gravimetric network.

Locations of geodetic points are determined based on the need to ensure their long-term elevation, preservation, and convenient use, considering the work area's physical and geographical conditions, depth of soil freezing, hydrogeological regime, and other features of the area. However, they are in economic and economic areas and require monitoring of the condition of geodetic points.

Periodic inspections and updates of geodetic, gravimetric points, and leveling benchmarks are carried out as needed, but at least once every ten years, and in cities and areas of active economic activity — at least once every five years.

To date, according to information from the bank of geodetic data, the total number of geodetic points DGM geodetic (planned) on the territory of Ukraine is 17,957 points, including1 class — 813 points (Fig. 6); 2nd class — 6,133 points; 3rd class — 11,011 points; in addition, 13,590 geodetic points of the 4th class condensation network.

It is necessary to modernize the SGN of Ukraine, taking into account the modern

Fig. 6. Map-scheme of the geodetic (planned) network of the 1st class of Ukraine.

requirements and experience of European countries.

The Gravimetric Network of Poland (POGK) was established in 1994—1997. It covered 12 absolute fundamental stations. In 1999—2010, a systematic modernization of the Polish gravimetric network was performed (Fig. 7).

In 2012, the project of a new gravimetric network in Poland was approved, later implemented. The new network consists of 28 fundamental points, on which absolute observations are made with the FG5 gravimeter and 169 basic points (observations with the absolute gravimeter A10). The error in determining free-fall acceleration does not exceed 4 μGal at the base stations and 10 μGal at the base stations.

The State Fundamental Gravimetric Network of Ukraine consists of 17 main gravimetric points and one main gravimetric point, «Poltava» (part of the State Gravimetric Network 1 class (SGN-1) and the State Fundamental Gravimetric Network (SFGN) of the Soviet Union.

At the beginning of 1988, Ukraine was provided with a gravimetric network of 126 points of the 2nd class with a mean square error of ±35 μGal. In 1993, the work on balancing the 3rd class gravimetric support network (GSN-

Fig. 7. Map-scheme of the gravimetric network of POGK Poland.

3) was completed. 3760 points were identified and processed. The root mean square error was ±30 μGal. The territory coverage by gravimetric surveys was about 30 % (depending on the region and scale).

In 2009, the GSN-1 and GSN-2 points were inspected (Fig. 8). It was established that 109 points of GSN-1 were completely or partially preserved, and 17 points were completely destroyed.

The State Gravimetric Network of Ukraine does not meet modern requirements for the accuracy of absolute and relative gravimetric measurements, the density of points on the survey area. Ukraine remains the only European country not yet fully covered by 1:50,000 gravimetric surveys, which greatly complicates its participation in creating consolidated gravimetric data for the whole of western and central Europe.

To solve these problems, the accuracy of measuring free-fall acceleration at any point on Earth should be in the range of 0.01—0.1 mGal relative to the initial world gravimetric level.

To ensure the maximum possible accuracy of observations and long-term safety of fundamental gravimetric network points, they are placed in capital buildings, if possible in astronomical, geophysical observatories and points of the Ukrainian permanent (permanent) network of observations of global navigation satellite systems or near them at an average distance of 200—300 km.

At the points of the fundamental gravimetric network, the absolute and relative determination of the acceleration of free fall, coordinates, and heights is done. The hydrogeological regime analysis according to the data of specialized organizations is carried out.

Such requirements can be easily fulfilled

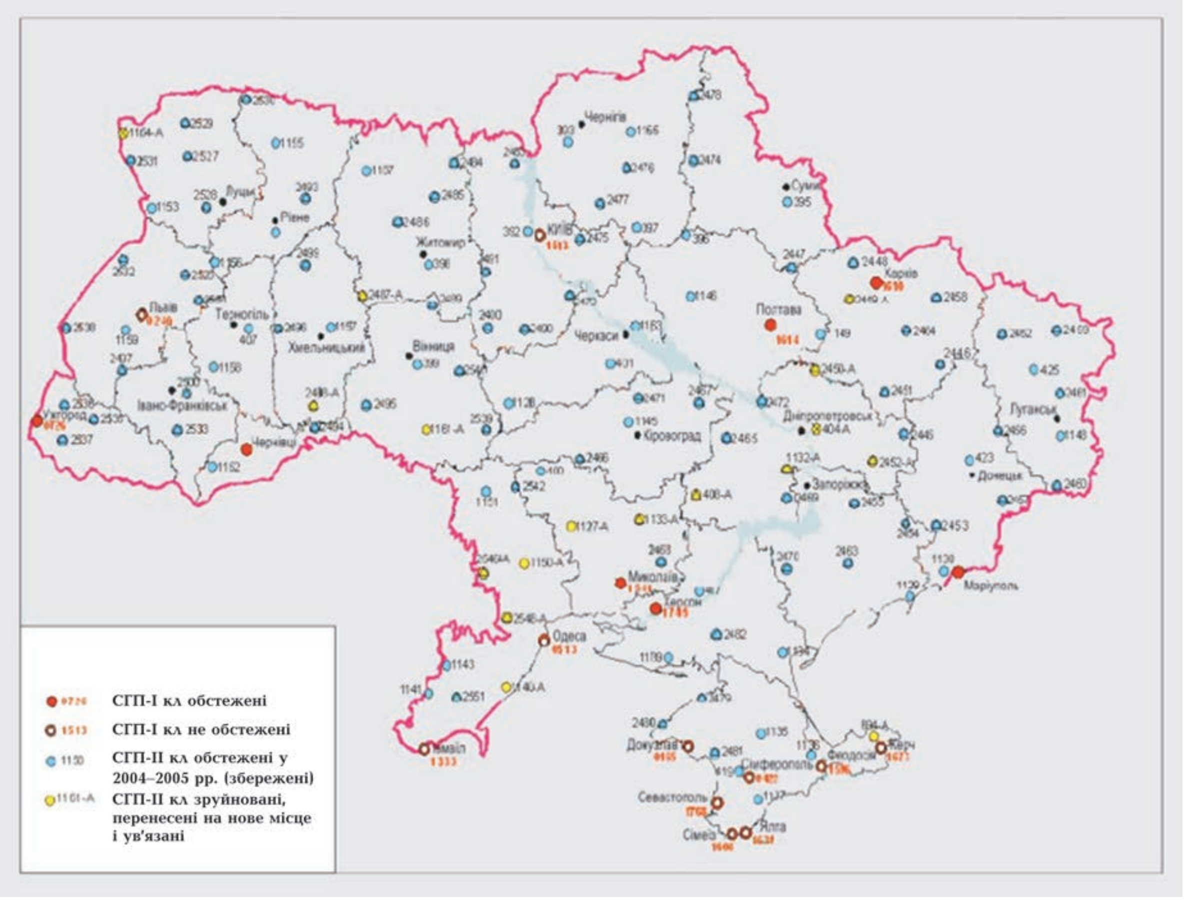

Fig. 8 Map-scheme of inspection of points of the gravimetric network of 1 class and 2 class (as of 01.09.2009).

when using CCS «Gravika». The development of such a network should be performed in conjunction with the development of the main gravimetric network of Ukraine. Using a radiophysical gravimeter as a basic circuit provides an extremely important advantage — obtaining data continuously and in real time.

Results. The innovative technology of the radiophysical method for measuring the gravitational field, using the CCS «Gravika», makes it possible to create a united geodetic (navigation-gravitational) network. At the same time, the differential radiophysical gravimeter allows measuring the absolute, relative acceleration of gravity and the angle of inclination of the gravitational acceleration vector. Taking into account the change in the gravitational acceleration value will also significantly reduce the errors in measuring the coordinate along the axis. It is also of great practical interest to develop a method for predicting seismic activity based on the measurement data of a differential radiophysical gravimeter.

The concept of building a combined navigation-gravity system using a geostationary communication satellite to ensure highly stable synchronization based on the coordinate-time and navigation support system of Ukraine. The State Gravimetric Network of Ukraine does not meet modern requirements for the accuracy of absolute and relative gravimetric measurements, the density of points on the survey area. Ukraine remains the only European country that is not yet fully covered by 1:50,000 gravimetric surveys, which greatly complicates its participation in creating consolidated gravimetric data for the whole of western and central Europe.

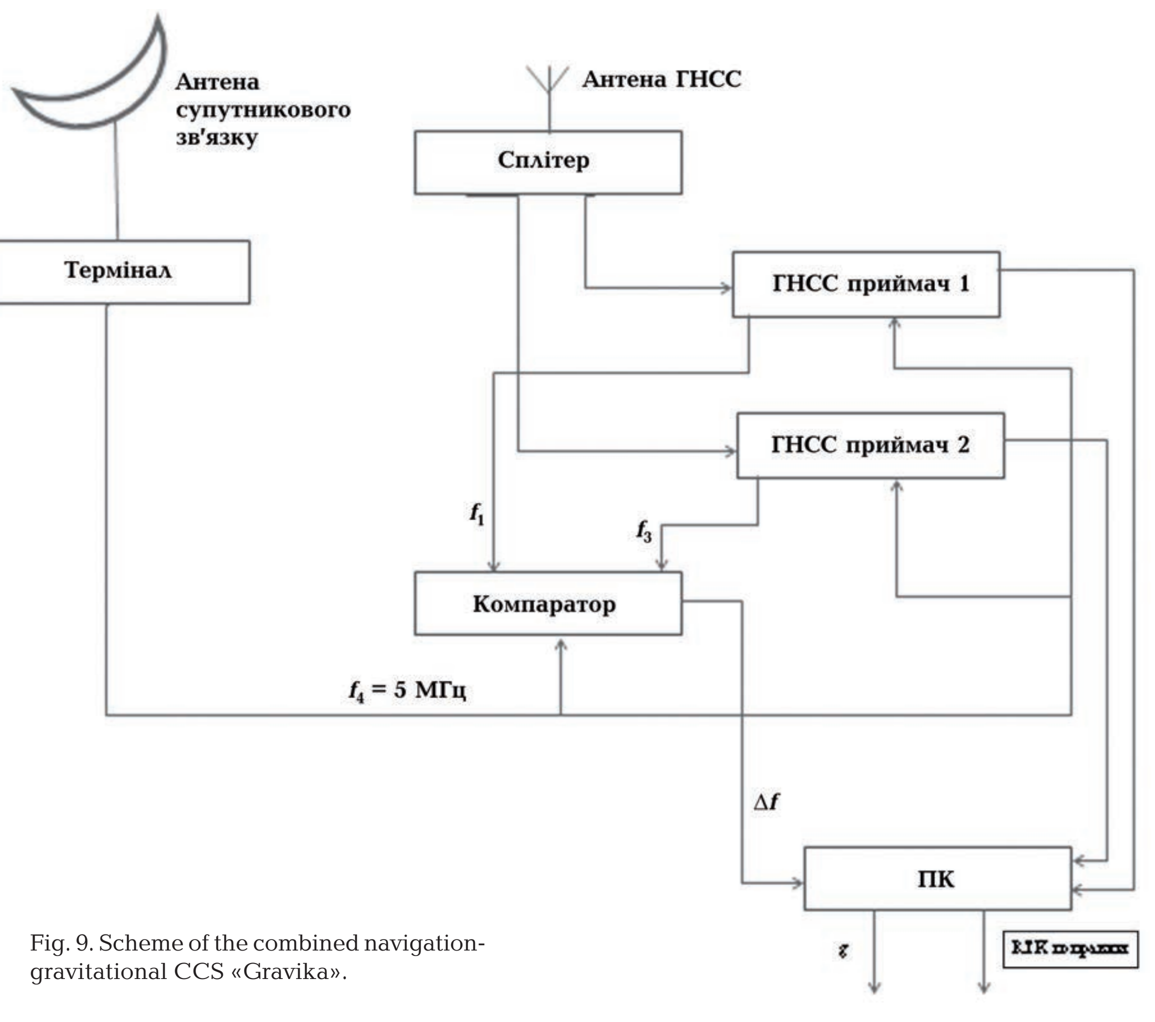

Fig. 9. Scheme of the combined navigation-gravitational CCS «Gravika».

To solve this problem, it is necessary to include in the RTK-network at least 50 CCS «Gravika» using a geostationary communication satellite to ensure highly stable synchronization (Fig. 9).

As part of CCS «Gravika», the most expensive element of the station, the hydrogen frequency standard, which costs UAH 8 million, has been replaced by a VSAT terminal, which costs UAH 60,000.

When analyzing economic indicators, one needs to decide on which model the system will be created. The following system creation options are possible:

– creating its own closed system that will meet the needs of users exclusively within Ukraine;

– entry of Ukrainian users into the existing European system as a Ukrainian segment of users.

When creating one's own independent TWSTFT system, one needs to consider the following.

Economic indicators of creation and operation of the system of two-way satellite transmission of frequency and frequency signals are divided into two groups of indicators:

– one-time costs for the creation and implementation of the system;

– regular costs associated with operating the system.

One-time costs include the costs associated with setting up a VSAT network and installing VSAT terminals directly at the service points, which are designed to provide two-way satellite time and frequency signals. The following costs include:

At the system level:

• development of a working design of the system and a typical working design of the VSAT-terminal installation;

• certification of the VSAT-terminal by national certification bodies, obtaining a permit for import and operation;

• concluding a contract for the lease of satellite capacity, conducting tests for the admission of the central terminal of the VSAT network to work with the selected satellite. The cost of the contract for the lease of satellite capacity depends on the following indicators:

– selected frequency range: band C, band Ku, band Ka. The vast majority of equipment and satellites use the Ku-band, but the provision of services for the TWSTFT system is possible in other frequency bands: C- and Ka;

– bandwidth: 1.5 MHz frequency band is enough for the system to work at the first stage;

– selected satellite and satellite operator: the cost of the satellite resource varies from the choice of operator and frequency range. The highest cost of a satellite resource is reported by SES (Luxembourg) for satellites in the orbital position of 19.2°N. The resource costs up to 8 thousand dollars for the frequency band 1 MHz per month. The European company Eutelsat sets the cost of the resource for satellites in the Ku-band up to 5 thousand dollars for 1 MHz per month. Of the top operators of satellite systems, the most democratic are the prices of Intelsat, which on average provides the resource of its own satellites in the Ku-band at 2.8—3.0 thousand dollars per 1 MHz per month. The given prices are applied in case of the conclusion of long-term contracts with a duration of 1—3 years. The resource cost in the frequency range C is slightly less and is 60—80 % of the cost of the resource in the range Ku.

However, it should be noted that not all operators have their own resources in this frequency range:

– the duration of the contract for the use of satellite resources. There are several options for providing a satellite resource: providing a resource on a long-term basis, i.e., around the clock for at least one year (preference is given to contracts with a duration of services from 3 to 5 years); providing a resource on a short-term basis, i.e., for several months; providing a resource by prior order. In terms of resource cost, the most profitable is the conclusion of long-term contracts. For short-term contracts, coefficients from 1.5 to 3 are used. The cost of a resource by pre-order (for the period of a short session) is calculated with a coefficient of 8 or more;

– obtaining permits for the use of frequency resources in Ukraine. The costs of obtaining permits are determined by the current legislation of Ukraine, which sets tariffs for the provision of services of relevant bodies and institutions (including SE «UCRF»);

– creation of a mobile certification laboratory for initial and scheduled certification of VSAT-terminal equipment to assess the shift of the relative time scales of the central time standard and local time and frequency standards. According to expert estimates, the creation and certification of a mobile certification laboratory will cost 30—50 thousand dollars. This price includes the equipment of the VSAT terminal, the measuring equipment intended for transportation as part of a mobile object, and the use of the trailer chassis. If the car is used as a vehicle, the car's value must be added to the specified value.

At the object level (separately for each object): supply of VSAT-terminal; development of a working project for the installation of equipment, obtaining appropriate approvals from regulatory authorities (supervisory authorities); installation of equipment, commissioning, the connection of VSAT-terminal to the system; station certification after installation and connection to the system using a mobile certification laboratory.

These costs can be calculated using a standard system for calculating the cost of work, which includes: materials and equipment; staff salaries; travel expenses; total expenditures; administrative expenses; costs of third-party organizations (subcontractors); costs of obtaining permits; in general, according to the expert estimate of the cost of installing one point of connection services to the TWSTFT system, one can estimate 4—5 thousand dollars, provided one uses one's own mobile laboratory.

The second group of costs is operating costs. Operating costs include: payment for the leased satellite capacity. In the case of using the 1.5 MHz frequency band, the cost of renting the resource can be estimated at 3.5—4.5 thousand dollars a month; staff costs; electricity costs, utilities; costs for periodic inspection (certification) of VSAT-terminals to maintain the accuracy of the time support system (frequency of inspection once a year).

The main item of operating costs is the payment of the leased capacity of the satellite.

It is possible to reduce costs if one joins the existing European TWSTFT system as a Ukrainian consumer segment. In addition to the benefits of connecting its own network of the exact time and frequency sources to the European metrology frequency and frequency support system, this solution will also have positive economic performance. First of all, it is possible to reduce the cost of renting a satellite resource, as the resource is leased for the entire system, and Ukrainian consumers will pay for the resource in proportion to the share of total time during which signals are transmitted between Ukrainian stations.

Other costs will be kept at the previous level. An increase in costs can be expected if a mobile station is used to certify VSAT terminal equipment owned by a foreign organization. In this case, such certification can be carried out in the form of a session, which involves the movement of a mobile laboratory on the route between facilities in Ukraine and the inspection and certification of these facilities lasting 1—2 working days at each location.

Thus, the combined navigation-gravity system's proposed scheme will solve the problem of high-precision positioning and monitoring of the gravitational field and the problem of creating a Ukrainian single time system and Ukraine's entry into the existing international TWSTFT system.

Conclusions. The combined navigation-gravity system with the use of geostationary communication satellite can in principle be created based on CCS «Gravika» using TWSTFT technology, which will exclude from CCS «Gravika» the most expensive element of the frequency standard and use instead TWSTFT subscriber equipment, which costs no more than 3 thousand euros. In addition, the use of TWSTFT technology will solve the problem of creating a single time system in Ukraine, which cannot be solved for more than two decades.

Given the global trend of creating national gravimetric networks using ballistic gravimeters, Ukraine also needs to solve this problem, which will cost at least 50 million euros. The combined navigation-gravity system will completely solve all the tasks facing the gravity network.

In addition, implementing a combined navigation and gravity system will solve the problem of forecasting for 24 hours of seismic events according to the monitoring of the Earth's gravitational field, which is one of the most acute problems of safe human activity.

It should also be noted that the results of work with the CCS «Gravika» make it possible to create on its basis a three-axis platform less radiophysical gravimeter, which will measure not only the absolute and relative values of gravitational acceleration with a resolution no worse than 10 μGal. Such a gravimeter will be installed onboard the Ukrainian icebreaker Noosphere, where it will be used to solve the problems of the scientific program of the National Antarctic Scientific Center of Ukraine.

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Релятивістська гравіметрія

С.А. Матвієнко*[1,2]*, 2022

[1]Державне космічне агентство України, АТ «НВЦ КУРС», Київ
[2]Національний антарктичний науковий центр України

Роботи зі створення приладу, який зможе вимірювати параметри гравітаційного поля Землі в космосі, було розпочато у ДКБ «Південне» у 2001 р. у рамках формування програми наукових досліджень на космічному апараті «Січ-1М». Оскільки у світі не було розроблено приладів для безпосереднього вимірювання параметрів гравітаційного поля Землі в космосі, виникла ідея використати для вирішення цього завдання релятивістський ефект «redshift». Можливість практичної реалізації цієї ідеї виникла у 2008—2010 рр. під час реалізації проєкту УНТЦ № 3856 «Вимірювання параметрів гравітаційного поля Землі за допомогою навігаційних супутникових систем». У рамках цього проєкту вперше було створено та випробувано диференціальний радіофізичний гравіметр, у якому як джерело високостабільного випромінювання використано випромінювання навігаційних супутників. За результатами проєкту було захищено дисертацію «Радіофізичний метод вимірювання параметрів гравітаційного поля Землі» та отримано 4 патенти України на винахід, 2 свідоцтва про авторське право, опубліковано 16 статей у наукових журналах. У 2012 р. було отримано фундаментальний патент № 98358 «Спосіб вимірювання геодезичних параметрів та пристрій для його здійснення», який визнаний у 2014 р. найкращим патентом України в абсолютній номінації у конкурсі «Кращий патент України». Патент ліг в основу створення навігаційної контрольно-коректувальної станції (ККС) «Гравіка». Ця робота була продовжена у АТ «НВК «КУРС» — з 2015 р. — головна організація в НКАУ щодо створення координатно-годинної та навігаційної мережі забезпечення України. У 2016 р. створено, сертифіковано та введено в експлуатацію ККС «Гравіка», яка може одночасно працювати і як навігаційна базова станція, і як гравіметр, тобто вирішувати повне геодезичне завдання. Принцип роботи гравіметра ґрунтується на релятивістському ефекті «redshift». Однією з основних техніко-економічних проблем є необхідність використання високостабільного водневого стандарту частоти у складі ККС «Гравіка», вартість якого становить не менш як 80 тис. дол.. США. У рамках Договору № 79/27/03 від 27.03.2020 р. між НКАУ та АТ «НВК «КУРС» (шифр «Геомоніторинг») було розроблено концепцію створення на базі існуючої в Україні мережі координатно-годинного та навігаційного забезпечення комплексної чіткої системи геофізичного моніторингу з використанням ККС «Гравіка» та супутникової системи ретрансляції сигналів високостабільного стандарту частоти TWSTFT. Таке рішення дасть змогу відмовитися від використання стандарту частоти кожної станції і цим знизити вартість ККС і системи загалом. Крім того, робота ККС «Гравіка» показала можливість прогнозування сейсмічної активності у радіусі 500 км від станції. Також, реалізований тривісний варіант гравіметра, що дає змогу одночасно вимірювати абсолютні відносні значення прискорення вільного падіння і кут нахилу вектора прискорення вільного падіння. Такі функціональні можливості роблять радіофізичний гравіметр незамінним при використанні на мобільних транспортних засобах, у тому числі космічних.

Ключові слова: радіофізичний метод, мережа навігаційного забезпечення України, комплексна система геофізичного моніторингу, релятивістський ефект «червоного зміщення».