UDC 550.34:550.83 DOI: https://doi.org/10.15407/geotm2026.176.137

Anatolii Bulat[1], orcid.org/0000-0002-6541-2140
Kateryna Babii[1], orcid.org/0000-0002-0733-2732
Serhii Matviienko[1,*], orcid.org/0000-0002-9727-810X
Serhii S. Matviienko[2], orcid.org/0009-0004-8936-1183
Arnolds Ubelis[3], orcid.org/0000-0002-6211-7701

[1]*M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, Ukraine*
[2]*National University "Kyiv Aviation Institute", Kyiv, Ukraine*
[3]*National Science Platform FOTONIKA-LV, the University of Latvia, Riga, Latvia*
**Corresponding author e-mail:* matvienko_2005@ukr.net

PATHWAYS FOR THE IMPROVEMENT OF THE GRAVIMETRIC METHOD FOR EARTHQUAKE PREDICTION

Abstract. Among statistical and empirical methods of earthquake prediction, geophysical measurements are the most informative, as they reflect the state of tectonic plates, which are the root cause of earthquakes. Among geophysical methods, the most accurate is the gravimetric method as it enables the recording of changes in the Earth's gravitational field associated with the stress accumulation in seismically active zones. The gravimetric method for earthquake prediction is based on monitoring changes in the Earth's gravitational field prior to seismic events due to mass redistribution in the Earth's crust and upper mantle.

Based on the radiophysical method of measuring parameters of the Earth's gravitational field, three relativistic gradiometers - RG-1, RG-2, and RG-3 - were developed, tested, and certified. As a result of the measurements, anomalous disturbances of the gravitational field along the vertical axis at the level of 200 μGal were detected, which are associated with earthquakes. Thus, the possibility of detecting and fixing earthquake precursors associated with gravitational waves was demonstrated. Gravitational waves originate at the epicenter of an earthquake due to the active movement of tectonic plates, at least a day prior to the earthquake itself, as a result of which an anomalous surge of the gravitational field occurs, accompanied by three-dimensional propagation of the gravitational wave at the speed of light. Relativistic gravimeters can be designed as three-axis, which makes it possible to apply the trilateration method to determine the location of the earthquake epicenter. However, this task can only be solved if at least three three-axis relativistic gravimeters are available, whose standards are synchronized using the satellite-based method TWSTFT, which ensures synchronization accuracy of no worse than 1 ns.

Thus, having behind many years of research with relativistic gravimeters, the authors demonstrate in this paper the feasibility of implementing the gravimetric method for earthquake prediction at a new technological level using the relativistic "redshift" effect. The most promising pathway to implement this method is to create the systems for gravitational field monitoring using three-axis relativistic gravimeters and the satellite-based TWSTFT method.

Keywords: seismic activity prediction, gravimetric method, radiophysical method, relativistic gravimeter.

1. Introduction

Monitoring seismic activity is integral to the strategy for reducing the risk of natural disasters, especially in earthquake-prone regions. Its relevance is explained by several scientific, social, and economic factors.

The most widespread approaches are statistical prediction methods, which were studied by K. Aki, B. Gutenberg, and C.F. Richter in the 1940s–1960s. Statistical methods for predicting seismic activity rely on the analysis of historical seismic events, identification of spatiotemporal patterns, and the assessment of the probability of future earthquake occurrence [1, 2]. For example, at the seismic station RA086 in the city of San Tome, earthquake observations are conducted in the Pacific Ocean, where 5224 earthquakes were recorded [3]; in the Azerbaijan-Alborz seismotectonic province, 26836 events were recorded [4]; and 9648 earthquakes were localized around the Tanlu fault zone in eastern China [5]. These studies are carried out to compare the maximum magnitude of past and expected earthquakes [6], to create

Received: 28.12.2025 Accepted: 11.02.2026 Available online: 31.03.2026

earthquake catalogs [4], and to cluster seismically active zones [7]. The main objective in these works is not only to observe the earthquake event but also to identify anomalies associated with earthquakes for their subsequent prediction.

Early precursors of earthquakes can be deformations of the Earth's crust, increased surface temperature [8], changes in electromagnetic and gravitational fields [9], shortened intervals between events, increased magnitude scale and pronounced foreshock swarms immediately preceding the main shock [10], fluctuations of the Earth's surface [11], monitoring of hydrogeodynamic parameters of groundwater [12], etc. These approaches form the background for the development of seismic hazard models at both local and global scales. Currently, several statistical methods exist for predicting seismic activity. In modern research, these methods are being improved through the development of machine learning models [13], ensemble learning techniques such as stacking [14], stochastic modeling [15], and unsupervised, semi-supervised, and supervised learning algorithms based on earthquake clustering models [7]. However, these methods do not provide an accurate prediction of earthquakes in either time or space.

In addition, geophysical, geochemical, biological, and space-based methods of earthquake prediction are also widely used. These methods rely on empirical data obtained with specialized measurement instruments. Among them, geophysical measurements are the most informative because they reflect the state of tectonic plates, which is the root cause of earthquakes. Geophysical prediction methods are based on the analysis of changes in the Earth's physical fields that precede seismic events. The most widely used geophysical method is gravimetry.

2. Methods

The gravimetric method enables the recording of changes in Earth's gravitational field associated with stress accumulation in seismically active zones. In particular, prior to strong earthquakes, local anomalies of the gravitational field are observed, caused by deformations of the Earth's crust. High-precision gravimetry can detect submillimeter displacements of rock masses, which can serve as potential precursors to seismic events [16].

The gravimetric method for earthquake prediction focuses on monitoring changes in the Earth's gravitational field that occur prior to seismic events due to mass redistribution in the Earth's crust and upper mantle. Any process of stress accumulation in tectonic faults is accompanied by microdeformations that can cause local variations in the force of gravity (Δg) [16].

These variations are measured using modern, highly sensitive gravimeters capable of detecting and recording alterations in the range of 10^{-8}–10^{-9} m/s². Having the data of these observations, gravimetric anomaly fields are constructed and analyzed in dynamics to identify potentially dangerous zones of seismic activity.

Depending on the scale of research, the following methods are distinguished:

- regional gravimetric observations – conducted for monitoring the tectonic structures of large fault systems;

- local gravimetric profiles – conducted in areas of active faults or in zones where increased seismicity is expected.

Pre-earthquake processes include:

- accumulation of tectonic stresses in the Earth's crust;
- deformation of rocks and change in density of rock mass;
- uplift or subsidence of crustal blocks (detected by geodetic measurements);
- redistribution of underground fluids, which changes local mass contrasts.

These processes lead to the appearance of gravitational anomalies, which can be recorded several days or even weeks before the main earthquake.

Gravimetric observations are actively used in Japan, China, Italy, Turkey, as well as within the Carpathian region of Ukraine (Transcarpathian seismically active belt).

Studies conducted in Italy and Japan have shown that anomalous variations in the gravitational field (up to 50–200 μGal) were observed 5–20 days prior to strong earthquakes (M > 5.5). Within the Carpathian region, similar studies were conducted at the S. I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine, where short-term anomalies were recorded before weak seismic events in the Uzhgorod–Mukachevo area [17].

The combination of gravimetric monitoring with GPS and interferometric data (InSAR) ensures more accurate identification of areas with increased seismic hazard [18].

The work of E.N. Khalilov, Doctor of Technical Sciences, is of great importance in determining the location of an earthquake. In 2013, he developed a new instrument for experimental study of spatiotemporal variations of measured values of *G* (the gravitational constant), which he named the ATROPATENA detector [19, 20].

The ATROPATENA station is a system of sensors, enclosed and isolated from the environment, which is based on the physical principle of the Cavendish balance. The device is equipped with small weights at the ends of two (instead of one) mutually perpendicular equalizing beams suspended on fibers. Between them, small and large weights are placed at an equal distance. The ATROPATENA station measures the index ΔG, which is between the gravitational constant *G* (the initially measured value of *G*) and the values measured by the Cavendish balance at the moment of measurement of *GF* [19]:

$$\Delta G = G - GF\ . \qquad (1)$$

The ATROPATENA-AZ station (Baku, Azerbaijan) was used to record gravity anomalies prior to strong earthquakes. From 2008 to 2013, the ATROPATENA earthquake prediction stations of the Global Network for Forecasting Earthquakes (GNFE) recorded gravity precursors of earthquakes before all strong earthquakes in Europe, Asia, and Southeast Asia. The scheme and general view of the ATROPATENA-AZ station are shown in Fig. 1.

Analysis of more than 100 gravimetric records obtained from the ATROPATENA stations before, during, and after strong earthquakes in various regions of the world from 2008 to 2011 confirmed the registration of gravitational precursors prior to strong earthquakes [19].

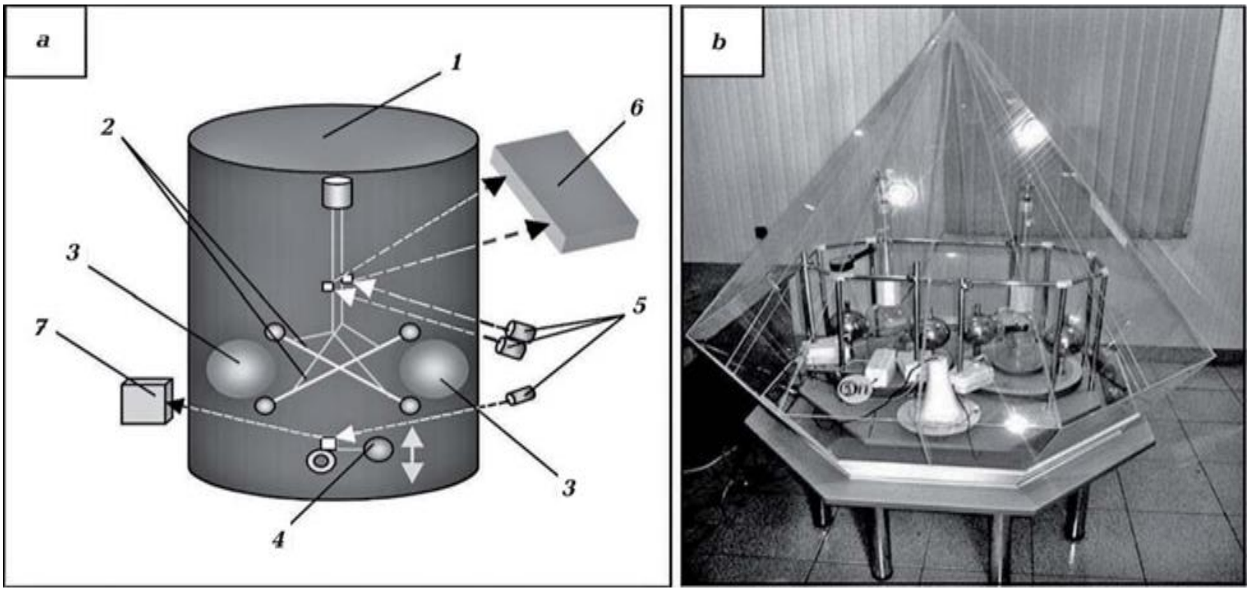
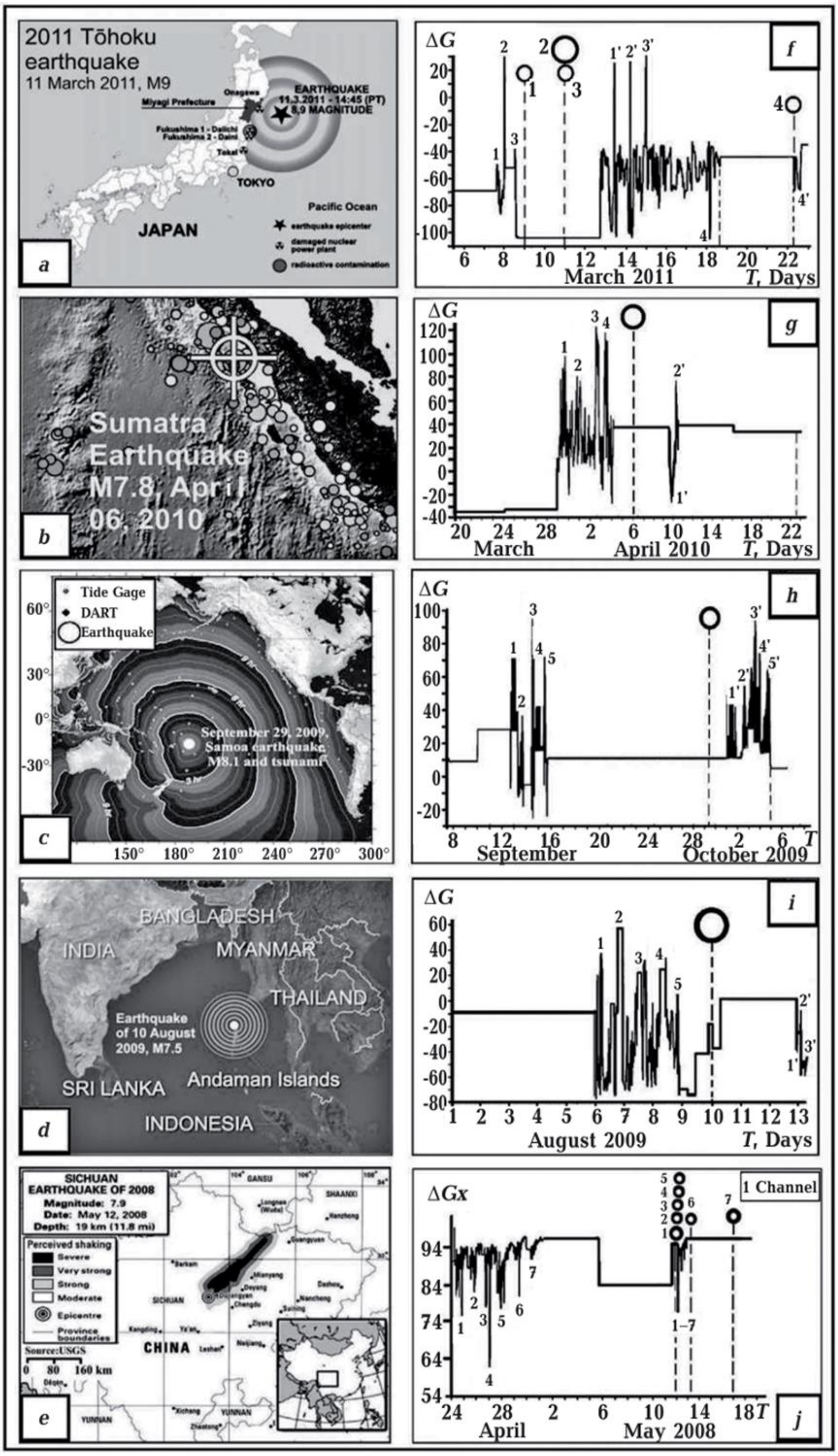


Figure 1 – Scheme (a) and general view (b) of the ATROPATENA station [19,20]

The first type of precursors includes anomalies observed before strong earthquakes - these are precursors of earthquakes, and the second type includes anomalies recorded after strong earthquakes (secondary anomalies), which are formed as a result of the emission of tectonic waves at the moment of the earthquake and the release of tectonic energy. Between these two types of anomalies, in the vast majority of cases, a long-term gravitational anomaly is recorded, characterized by increased or decreased values of the ΔG and Δg indices, which usually remain stable for 2–15 days. These characteristic features of gravitational anomalies are observed in more than 90% of cases. According to Dr. Khalilov, gravitational predictors of strong earthquakes are the result of the emission of tectonic (stress) waves from earthquake epicenters 2–10 days before the event [19, 20]. The time of detection of gravitational predictors of strong earthquakes also depends on the distance between the ATROPATENA station and the earthquake epicenter. The duration of three-dimensional gravitational anomalies varies from 10 minutes to 10–12 hours and depends on the geological structure of the epicentral zone. Dr. Khalilov reached a very important conclusion: the ΔG and Δg indices are universal predictors of earthquakes and are recorded in more than 90% of cases. Some earthquake prediction results from the ATROPATENA station are shown in Fig. 2.

In Figure 2, the ΔG axis represents an index defined as the difference between the gravitational constant G (the initial measured value of G) and the values measured by the Cavendish balance. Values of the ΔG index correspond to G starting from the third digit after the decimal point; 1, 2, 3... are the number of gravitational precursors; 1', 2', 3' denote secondary gravitational anomalies. The earthquake moments are marked with circles.



(a) – Tohoku, March 11, 2011, M9.0; (b) – Sumatra, April 6, 2010, M7.8; (c) – Samoa, September 29, 2009, M8.1; (d) – Andaman Islands, August 10, 2009, M7.5; (e) – Sichuan, May 12, 2008, M7.9; (f) – gravimetric record from the ATROPATENA-ID station (in Indonesia) before, during and after the earthquakes; (g) – the same in Sumatra; (h) – the same for Samoa; (i) – same for the Andaman Islands; (j) – gravimetric record from ATROPATENA-AZ station (in Azerbaijan) before, during and after the Sichuan earthquake

Figure 2 – Maps of the epicentral zone of earthquakes [19, 20]

The results of measurements with the ATROPATENA instrument at various locations around the Earth convincingly demonstrate the presence of gravitational precursors (gravitational waves) arising in the horizontal plane 2–10 days before strong earthquakes.

Thus, in the implementation of the concept of earthquake prediction through the measurements of gravitational waves using a relativistic gravimeter, three main problems remain:

- the absence of a three-axis relativistic gravimeter;
- the creation of a modern gravimetric network in Ukraine;
- synchronization of measurement data obtained from relativistic gravimeter.

Therefore, the purpose of this work is to analyze the results of experimental research and to improve the geophysical monitoring system using a differential radiophysical gravimeter and satellite-based retransmission of signals of a highly stable frequency standard to identify correlations between anomalous disturbances in the Earth's gravitational field (precursors) and actual earthquake events.

3. Theoretical part

The gravimetric method for earthquake prediction is based on observations of local variations in the force of gravity (*Δg*). Mathematically, variations in gravitational acceleration can be expressed as:

$$\Delta g = G\int_V \frac{\Delta\rho(r)}{r^2} dV, \tag{2}$$

where *Δg* is the change in gravitational acceleration (m/s²); *G* is the gravitational constant, $G = 6.67430(15)\times10^{-11}$ $m^3\cdot kg^{-1}\cdot s^{-2}$; *Δρ(r)* is the density variation within the volume element *dV* (kg/m³); and *r* is the distance from the observation point to the mass element (m).

The main obstacle to the development of the gravimetric method for earthquake prediction is the lack of modern gravimeters capable of providing continuous measurements of gravitational acceleration along three axes with an accuracy of at least 1–5 μGal.

This problem can be solved using a relativistic gravimeter (RG) [21, 22] and a radiophysical method for measuring parameters of the Earth's gravitational field (EGF). This method is based on measuring the change in frequency of electromagnetic radiation under the influence of gravity, followed by determining the EGF gradient or gravitational acceleration [23]. In the radiophysical method, the relativistic "redshift" effect is used to measure the gravitational potential, which manifests as a frequency shift of an electromagnetic signal propagating through an inhomogeneous gravitational field.

Currently, three types of relativistic gravimeters - RG-1 (a, Figure 3), RG-2 (b, Figure 3), and RG-3 (c, Figure 3) - have been developed, tested, and certified. They serve as the basis for the development of a three-axis relativistic gravimeter.

a) b) c)

a) – RG-1 gravimeter; (b) – RG-2 gravimeter; (c) – RG-3 gravimeter

Figure 3 – Types of relativistic gravimeters

One of the fundamental provisions of the general theory of relativity, formulated by A. Einstein in 1915, is the phenomenon of gravitational redshift. It consists in a change in the frequency of electromagnetic radiation when the signal moves from a region with one gravitational potential to a zone with another one. If the radiation propagates “upward” in the gravitational field (i.e. away from the center of a massive body), its frequency decreases, which is a shift towards the red region of the spectrum.

Mathematically, this effect is described by the relation:

$$\frac{\Delta f}{f} = \frac{gh}{c^2}, \tag{3}$$

where *Δf* is the change in signal frequency (Hz); *f* is the initial frequency (Hz); *g* is gravitational acceleration (m/s²); *h* is the distance between the frequency generator and receiver (m); and *c* is the speed of light, *c* = 299,792,458 m/s.

The first laboratory measurements of this phenomenon were carried out in 1959–1960 in the well-known Pound-Rebka experiment at Harvard University, which confirmed the predicted formula (3) with an accuracy of 1%.

However, the authors' experimental studies of relativistic gravimeters showed that the measured results do not coincide with the values calculated using formula (3). To explain this discrepancy, we considered the basic formula of the gravitational frequency shift (2) without local restrictions. This relation makes it possible to connect height variation with the measured frequency change:

$$\frac{\Delta f}{f} \approx -\frac{\Delta\Phi}{c^2} = \frac{g_1 h_1 - g_2 h_2}{c^2} \approx \frac{\Delta g \Delta h}{c^2} \tag{4}$$

The relation (4) is used in processing the measurement results of relativistic gravimeters, where frequencies are compared at two points that differ not only in height but also in local gravitational acceleration. This is not just an educational special case, but a working formula for real measurements. The most important thing is that the relative frequency shift of the useful signal measured by formula (4) is directly proportional to *Δg* - the difference in gravitational acceleration depending on height, which, according to formula (2), is a potential precursor of a seismic event. This makes the relativistic gradiometer an indispensable tool for predicting seismic events.

Under real conditions, when the gravitational acceleration varies at different low altitudes, the difference in geopotentials is determined by the formula:

$$\Delta\Phi \approx g_1 h_1 - g_2 h_2 \qquad (5)$$

To calculate tensor of gradients of the gravitational field, the following relation is used:

$$\Gamma_{ij} = \frac{\partial g_i}{\partial x_j} = \frac{\partial^2 \Phi}{\partial x_i \partial x_j}, i, j = x, y, z. \qquad (6)$$

The use of the relativistic “redshift” effect in gravimetry forms the background for the transition to absolute quantum-relativistic methods for determining the gravitational potential. Such methods combine advances in time metrology, quantum optics, and gravimetry, enabling the measurement of gravitational variations caused even by minor tectonic processes [24].

4. Experimental part

The first experimental studies aimed at identifying correlations between anomalous disturbances of the Earth's gravitational field and earthquake events were carried out by S.A. Matvienko during the development of a geophysical monitoring system using a differential radiophysical gravimeter and satellite-based retransmission of signals of a highly stable frequency standard.

At the State Enterprise "Ukrmetrteststandart", more than 130 daily measurements were performed using the relativistic gravimeter RG-1 during the period from June to October 2019. First, according to formula (2), the relative frequency shift $\Delta f/f = 10^{-12}$ was measured and recorded in the calibration certificate UA 01 No. 3782 dated 16.07.2019. Further, according to formula (4), changes in the absolute value of the gravitational acceleration *Δg* were recorded at the level of 400 μGal at a distance of $\Delta h = 200$ cm. According to formula (6), this corresponds to a gradient value $G_z = 200\mu Gal/m = 2{,}0\times10^3 E = 2kE$. This result allows us to conclude that the relativistic gravimeter not only performs the functions of a gradiometer but also records anomalous disturbances in the gravitational acceleration, which a classical gradiometer cannot.

Thus, a series of operation results for RG-1 were obtained:

- graphs of measurements of changes in the gravitational acceleration during the measurement period;
- graphs of measurement errors of coordinates *along the vertical axis*;
- table of earthquake events during the measurement period;
- combined graph of measurements of changes in gravitational acceleration and earthquake events.

Figures 4–6 show specific examples of graphs of measurements of changes in gravitational acceleration prior to earthquakes in Ukraine.

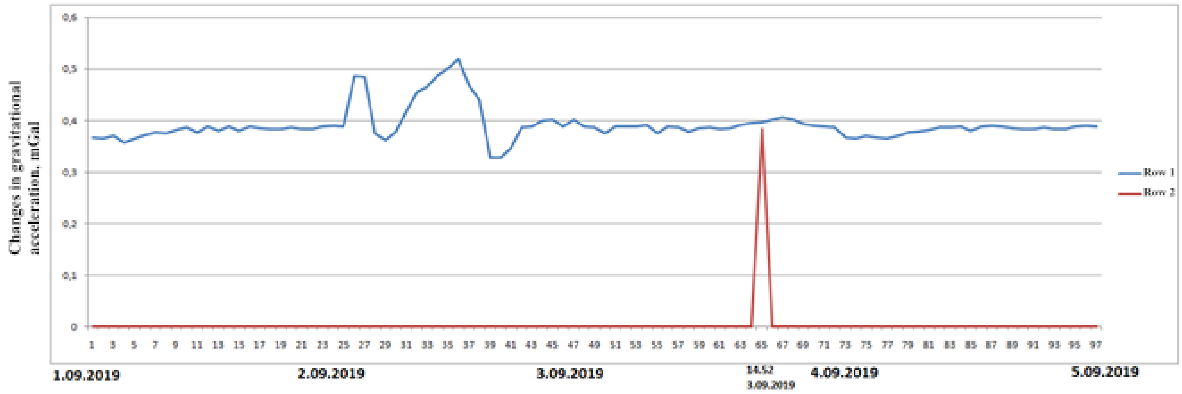


Figure 4 – Graph of changes in gravitational acceleration (averaging over an interval of 1 hour) and earthquake occurrence in Romania (magnitude 4.5)

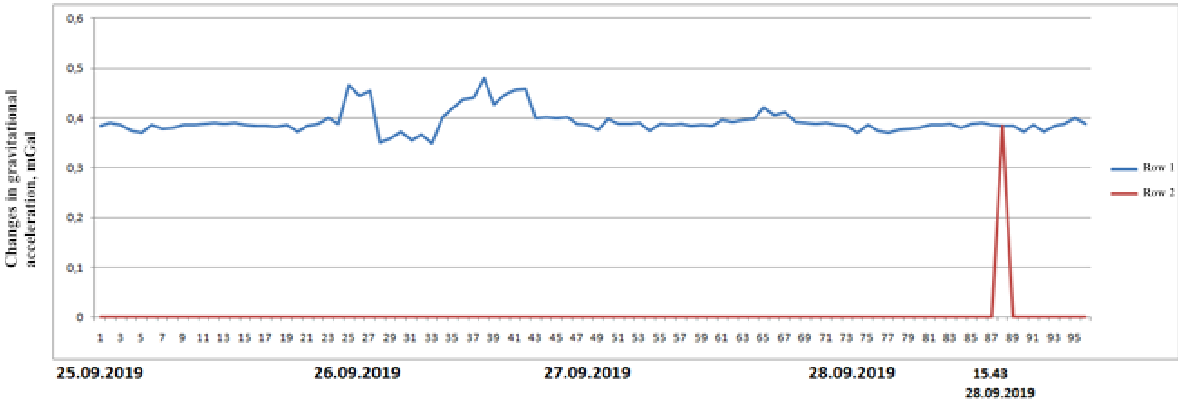


Figure 5 – Graph of changes in gravitational acceleration (averaging over an interval of 1 hour) and earthquake occurrence in Transcarpathia (magnitude 2.0)

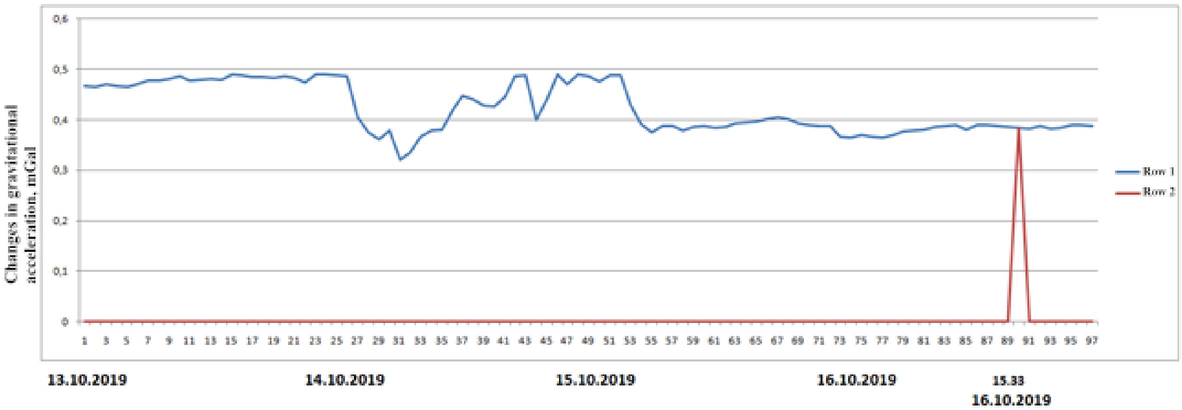


Figure 6 – Graph of changes in gravitational acceleration (averaging over an interval of 1 hour) and earthquake occurrence in the Ivano-Frankivsk region (magnitude 2.7)

Thus, the graphs of gravitational acceleration changes demonstrate that the RG-1 gravimeter recorded precursors in advance. For example, on September 3, 2019, at 14:52, an earthquake with a magnitude of 4.5 occurred in Romania, while the RG-1 gravimeter had already recorded a series of precursors in advance - on September 2 (see Fig. 4). The next case concerns an earthquake on September 28, 2019 in Transcarpathia with a magnitude of 2.0, for which the RG-1 gravimeter recorded a series of precursors in advance - during the whole day of September 26 (see Fig. 5). The same thing happened after the earthquake of October 16, 2019 in Ivano-Frankivsk region with a magnitude of 2.7 - the RG-1 gravimeter recorded a series of precursors in advance on October 14 and 15 (see Fig. 6).

Therefore, it was demonstrated that anomalous disturbances of the Earth's gravitational field in the vertical plane can be recorded 1–2 days prior to an earthquake at the level of Δg = 100–200 μGal using a single-axis relativistic gravimeter RG-1.

The results of measurements obtained with the ATROPATENA instrument at different locations on the Earth convincingly demonstrate the presence of gravitational precursors (gravitational waves) in the horizontal plane 2–10 days before strong earthquakes, and the results of measurements using the RG-1 confirm the presence of gravitational precursors in the vertical plane. The combination of these results allows us to conclude that the gravitational wave arising from tectonic motion is three-dimensional.

Based on these considerations*, the Bulat-Matvienko hypothesis* was formulated:

- *External and internal natural and anthropogenic disturbances of various types of tectonic plates constantly affect the stress-strain state of the Earth's geological structure, gradually changing it to an extremely stressed state, forming earthquake epicenters in certain locations, which generate three-dimensional propagation of gravitational waves at the speed of light and anomalous disturbances of the gravitational acceleration and the gravitational field, whose ratio makes possible to determine the power of expected earthquakes and their location in time and underground space.*

Based on this hypothesis, we can determine the location of a future earthquake using triangulation. Triangulation is one of the main methods for determining the spatial positions of seismic event sources and is widely used in applied and regional seismology. The method relies on the analysis of the temporal characteristics of seismic wave arrivals recorded by a network of seismic stations with known coordinates. We apply this method to determine the coordinates of future earthquakes.

In the seismological practice, classical angular triangulation is transformed into a trilateration problem, where the position of epicenter is determined by the distances to several seismic stations calculated from the differences in the arrival times of longitudinal (P) waves.

Let the coordinates of the *i*-th seismic station be $(x_i; y_i)$, and let the time of registration of the *P*-wave be t_i. The distance to the epicenter is determined by the ratio:

$$r_i = v_p(t_i - t_0), \tag{7}$$

where v_p is the average velocity of longitudinal waves in the Earth's crust, t_0 is the moment of earthquake origin.

The coordinates of the epicenter $(x; y)$ are obtained from the system of equations:

$$(x - x_i)^2 + (y - y_i)^2 = r_i^2, i = 1,2,3. \tag{8}$$

When using an excess number of seismic stations, the system is solved by the least-squares method, which reduces the influence of random errors and improves the reliability of the results. The accuracy of epicenter localization largely depends on the geometry of the station network, the accuracy of time synchronization, and the adequacy of the environment's velocity model. Despite these limitations, the triangulation method remains a basic tool for operational seismological data processing and is used in both automated monitoring systems and analyses of regional seismic activity.

Having analyzed the ground-based and satellite-based methods for transmitting time and frequency signals, it is possible to conclude unequivocally that the satellite-based method TWSTFT ensures accuracy of no worse than 1 ns, and, at the same time, provides global coverage at a significantly lower cost of the system implementation [23].

Therefore, experimental studies have demonstrated the following advantages of the gravimetric method for predicting seismic activity:

• high sensitivity to underground mass redistributions;
• suitability for long-term monitoring;
• independence from weather and geomagnetic conditions;
• compatibility with satellite gravity missions (GRACE, GOCE).

Further improvement of the gravimetric method for earthquake prediction is associated with:

• creation of more sensitive and stable gravimeters;
• integration of satellite-based and ground-based data;
• application of artificial neural networks for recognition of pre-seismic patterns;
• creation of a national gravimetric monitoring network within seismically active regions of Ukraine.

Further research. It should be noted that the ground-based implementation of the gravitational method for seismic activity prediction creates the prerequisites for the development of a global space-based system for monitoring seismic activity and the Earth's gravitational field, Gravisat.

5. Conclusions

The results of experimental studies on the creation of a geophysical monitoring system using a differential radiophysical gravimeter and satellite-based retransmission of signals of a highly stable frequency standard have allowed us to identify a correlation between anomalous disturbances in the Earth's gravitational field and earthquake events.

The theoretical foundations of the gravimetric method for earthquake prediction were further developed by refining formula (3) of the relativistic gravitational frequency shift to determine the value of the earthquake predictor Δg - the difference in the values of the gravitational acceleration depending on the height - and correlating it with the results of measurements using the relativistic gravimeter.

Gravitational precursors of earthquakes were experimentally recorded as anomalous disturbances of the Earth's gravitational field in the vertical plane 1–2 days before the earthquake event at the level of Δg =100–200 μGal using the single-axial relativistic gravimeter RG-1. This demonstrated a correlation between gravitational precursors and earthquake events, revealing a daily interval between precursor detection and earthquake occurrence.

A hypothesis was formulated regarding the generation and propagation of seismic gravitational waves as earthquake precursors.

Three modifications of the relativistic gravimeter were developed: RG-1, RG-2, and RG-3.

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Shcherbyna S.V., Feshchenko A.I. and Pigulevsky P.G. (2025), "A review of earthquake precursors", *Geofizychnyi Zhurnal*, no. 47(2), pp. 359–363, https://doi.org/10.24028/gj.v47i2.322579

2. Batur, M. and Babii, K. (2024), "Exploring global technogenic earthquakes from a scientometric prospective: research trends, semantic analysis, and research drivers", *Environmental Earth Sciences,* vol. 83, article number 530, https://doi.org/10.1007/s12665-024-11830-9

3. Ali, Garba & Barka, Jonathan & Mbiimbe, Edwin & Ezekiel, Kamureyina & Garba, Mustafa (2025), "Seismic Station RA086 Statistical Analysis of Earthquake Data Using Shake Net and Grapher on the Global Seismic Activity: Analyzing Earthquake Patterns, Clustering, and Implications for Hazard Assessment", *International Journal of Inventive Engineering and Sciences*, no. 12, pp. 23–31, https://www.doi.org/10.35940/ijies.K1128.12111125

4. Valerio, E., Manzo, M., Casu, F., Convertito, V., De Luca, C., Manunta, M., Monterroso, F., Lanari, R. and De Novellis, V. (2020), "Seismogenic Source Model of the 2019, M_w 5.9, East-Azerbaijan Earthquake (NW Iran) through the Inversion of Sentinel-1 DInSAR Measurements", *Remote sensing*, no. *12*(8), pp. 1346, https://doi.org/10.3390/rs12081346

5. Zou, K., Lei, J. and Zhao, D. (2025), "Machine-learning based earthquake detection and location around the Tanlu fault zone in eastern China", *Geophysical Journal International*, Vol. 245, Issue 1, ggag014, https://doi.org/10.1093/gji/ggag014

6. Farman Mustafa and Jaber Ali (2025), "Comparison of Seismic Hazard Studies in Iraq in Predicting Future Earthquakes". *International Journal of Environmental Sciences*. 2383–2391. https://doi.org/10.64252/znh1fs20

7. Bala, T. and Hamza, E. (2016), "Statistical Learning Systems For Clustering Of Seismic Activities", *International Conference On Information Complexity And Statistical Modeling İn High Dimensions With Aplications (Icsmhd-2016)*, Nevşehir Kapodokya, Turkey, May 2016.

8. Imran, A. and Nor, S. (2024), "Early Warning Technologies and Methods for Predicting Earthquakes from Precursors", *The 6th International Dicle Scientific Research and Innovation Congress*, Diyarbakir, Turkey, 25–26 May 2024, available at: https://www.researchgate.net/publication/383665226_Early_Warning_Technologies_and_Methods_for_Predicting_Earthquakes_from_Precursors (Accessed 20 December 2025)

9. Pihulevskyi P.H., Kendzera O.V., Babii K.V., Anisimova L.B. and Kyryliuk O.S. (2023), "Connection of Kryvbas tectonics with natural and technogenic seismicity", *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, no. 2, pp. 5–10, https://doi.org/10.33271/nvngu/2023-2/005

10. Tomokazu, K. (2025), "Exploratory Statistical Analysis of Precursors to Moderate Earthquakes in Japan", *GeoHazards*, no. 6, pp. 82–85, https://doi.org/10.3390/geohazards6040082

11. Bulat, A.F., Voropaiev, H.O., Rudnytskyi, O.H., Babii, K.V., Voziianov, V.S., Makeiev, S.Iu., Hovorukha, O.V., M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (2024), *Sposib kontroliu kolyvan zemnoi poverkhni ta prohnozu seismichnoi aktyvnosti* [Method for monitoring earth surface vibrations and predicting seismic activity], State Register of Patents of Ukraine, Kiev, UA, Pat. No. 159236.

12. Pihulevskyi, P.H. and Svystun, V.K. (2011), "Results of monitoring hydrogeodynamics groundwater parameters in aseismic regions of Ukraine (Dnepropetrovsk region)", *Geodynamics,* Vol. 11, no. 2, pp. 241–244, https://doi.org/10.23939/jgd2011.02.241

13. SoltaniMoghadam, S., Ansari, A., Etemadsaeed, L., Tatar, M. and Mahmoodabadi, M. (2025), "A Machine Learning Model for Earthquake Location in Permanent Seismic Network", *Science and Technology Conference 2025- SnT2025*, Vienna, Austria, 8–

12 September 2025, available at: https://conferences.ctbto.org/event/30/contributions/5927/attachments/3212/6947/P3.5-207-SoltaniMoghadam.pdf (Accessed 20 December 2025)

14. Xiaolin, C., Daicheng, P. and Li, L. (2025), "Forecasting Future Earthquakes with Machine Learning Models Based on Seismic Prediction Zoning", *Applied Sciences*, no. 15(24), article number 13116, https://doi.org/10.3390/app152413116

15. Şahin, Ş. (2024), "Statistical Seismology-Şakir Şahin-published", *Advances in Earthquake Research and Engineering*, pp. 1–22, https://doi.org/10.5772/intechopen.1007119

16. Eshagh, M. (2013), "An integral approach to regional gravity field refinement using earth gravity models", *Journal of Geodynamics,* Vol. 68, pp. 18–28, https://doi.org/10.1016/j.jog.2013.03.001

17. Snopek K., Meier T., Endrun B., Bohnhoff M. and Casten U. (2007), "Comparison of gravimetric and seismic constraints on the structure of the Aegean lithosphere in the forearc of the Hellenic subduction zone in the area of Crete", *Journal of Geodynamics*, Vol. 44, Issues 3–5, pp. 173–185, https://doi.org/10.1016/j.jog.2007.03.005

18. Bezada, M. J., Schmitz, M., Jácome, M. I., Rodríguez, J., Audemard, F. and Izarra, C. (2008), "Crustal structure in the Falcón Basin area, northwestern Venezuela, from seismic and gravimetric evidence", *Journal of Geodynamics*, Vol. 45, Issues 4–5, May 2008, Pages 191–200, https://doi.org/10.1016/j.jog.2007.11.002

19. Khalilov, E.N. (2004), "*Gravitational waves and geodynamics*", Elm–ICSD/IAS, Baku-Berlin, 321 p.

20. Khalilov, E., Starostenko, V., Kendzera, A., Mubarak, A., Qaisar, M., Sjamsinarsi, R., Sartohadi, J., Wahyudi, W. and Yatman, C. (2011). "Global gravitational effects before and after strong M8.9 Japan earthquake of march 11, 2011", *Proceedings of the International Congress "Natural Cataclysms and Global Problems of the Modern Civilization"*, Istanbul, 19–21 September 2011, available at: https://www.researchgate.net/publication/329505938_Global_Gravitational_Effects_before_and_after_Strong_M89_Japan_Earthquake_of_March_11_2011 (Accessed 20 December 2025)

21. Matviienko, S.A. (2021), *Reliatyvistskyi hravimetr ta sposib vymiriuvannia znachennia pryskorennia vilnoho padinnia* [Relativistic gravimeter and method of measuring the value of the acceleration of gravity], State Register of Patents of Ukraine, Kiev, UA, Pat. No.124381.

22. Matviienko, S.A., Matviienko, O.S., Matviienko, S.A. (2021), *Mobilnyi dyferentsialnyi radiofizychnyi hravimetr ta ta sposib vymiriuvannia znachennia pryskorennia vilnoho padinnia* [Mobile differential radiophysical gravimeter and method of measuring the value of the acceleration of gravity], State Register of Patents of Ukraine, Kiev, UA, Pat. No. 126226.

23. Matviienko, S.A. (2012), *Radiofizychnyi metod vymiriuvannia parametriv hravitatsiinoho polia Zemli*, [Radiophysical method of measuring the parameters of the Earth's gravitational field], State Register of Patents of Ukraine, Kiev, UA, copyright certificate No. 42468.

24. Kopeikin, S.M. and Mazurova, E.M. (2015), "Relativistic geodesy and gravimetry: new opportunities for Earth observation", *Physics-Uspekhi*, no. 58(5), pp. 458–472.

ШЛЯХИ УДОСКОНАЛЕННЯ ГРАВІМЕТРИЧНОГО МЕТОДУ ПРОГНОЗУ ЗЕМЛЕТРУСІВ

Булат А.Ф., Бабій К.В., Матвієнко С.А., Матвієнко С.С., Юбеліс А.

Анотація. Серед статистичних та фактичних методів прогнозування землетрусів, найбільш інформативними є геофізичні вимірювання, оскільки вони відображають стан тектонічних плит, що є першопричиною землетрусів. Серед геофізичних методів найбільш точним є гравіметричний метод, який дозволяє реєструвати зміни у гравітаційному полі Землі, пов'язані з накопиченням напруги в сейсмоактивних зонах. Гравіметричний метод прогнозування землетрусів ґрунтується на спостереженні за змінами гравітаційного поля Землі, що виникають унаслідок перерозподілу мас у земній корі та верхній мантії перед сейсмічними подіями.

На базі радіофізичного методу вимірювання параметрів гравітаційного поля Землі створені, випробувані та сертифіковані три релятивістські градієнтометри RG-1, RG-2 та RG-3. В результаті вимірювань були виявлені аномальні збурення гравітаційного поля по вертикальній осі на рівні 200 μGal, які пов'язані з землетрусами. Таким чином, була доказана можливість виявлення та фіксації провісників землетрусів, які пов'язані з гравітаційними хвилями. Гравітаційні хвилі виникають в епіцентрі землетрусу, в результаті активного руху тектонічних плит, принаймні за добу до самого землетрусу, внаслідок чого відбувається аномальний сплеск гравітаційного поля, який супроводжується тривимірним поширенням гравітаційної хвилі зі швидкістю світла. Релятивістські гравіметри можуть бути створені тривісними, що дає можливість застосувати метод трилатерації для визначення місцезнаходження епіцентру землетрусу. Але це завдання можливо вирішити при умові наявності не менш ніж трьох тривісних релятивістських гравіметрів, стандарти яких будуть синхронізовані між собою за допомогою супутникового методу TWSTFT, який забезпечує точність синхронізації не гірше 1 нс.

Таким чином, у статті на базі багаторічних робот з релятивістськими гравіметрами показана можливість реалізації гравіметричного методу прогнозу землетрусів на новому технологічному рівні з використанням релятивістського ефекту «red shift». Найбільш перспективним шляхом реалізації цього методу є створення систем моніторингу гравітаційного поля з використанням тривісних релятивістських гравіметрів та супутникового методу TWSTFT.

Ключові слова: прогноз сейсмоактивності, гравіметричний метод, радіофізичний метод, релятивістський гравіметр.