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Project to Implement an International Gravimetric Datum in Western Ukraine

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Abstract
Since 2015, one can observe the intensive work of surveying contractors and scientists implementing the International Gravimetric Reference System ITGRS/F. The paper presents the main application principles of this system. It is intended to replace the previous version of the IGSN-71 by highlighting the modern role of absolute gravimetric observations and the emergence of precise sensors enabling permanent observations of the Earth's gravitational field in superconducting gravimeters. As part of the presentation, the implementation of this system in Poland will be discussed. The experience of Polish research groups will be used to modernise a fragment of the western part of the fundamental gravimetric matrix for Ukraine. The authors presented the role of implementing the gravimetric system in this country and discussed the modernisation plans according to new technical standards. The paper addresses the modularity aspect of creating a modern gravimetric reference frame based on autonomous observations with an absolute gravimeter, which is so relevant to the current situation in Ukraine.

Keywords
gravimetry, ITGRS/F, reference frame, absolute gravimeter

Introduction

Since 2015, the work of the geodetic community on introducing and implementing the new definition of the International Gravimetric Reference System/Frame ITGRS/F has been progressing. The paper presents the main implementation principles of this system. Ultimately, it is intended to replace the previous version of the IGSN-71 datum, highlighting the potential use and even dominance of absolute gravity observations and the emergence of precise sensors for permanent observations of the Earth's gravity field in the form of superconducting gravimeters (Wziontek, 2021). The publication will discuss the definition of the international gravimetric system and the method of its implementation in the territory of Poland. The history of the implementation of the gravimetric system in Ukraine and plans for its modernisation following new technical standards for the implementation of the new gravimetric system are also presented. The authors also attempt to apply the geopotential model to capture the difference in gravimetric reference levels between the Polish system (compatible with the ITGRS) and the Ukrainian Poltava system. All units of gravity accelerations are set in Gals, mGals or μGals, which are typical units for gravity, with $10^{-2}ms^{-2}$ form Gal and typical SI unit for acceleration, mGal is $10^{-5}ms^{-2}$, and μGal is $10^{-8}ms^{-2}$.

Research Area

1. Definition of the International Gravimetric Reference System

The globalisation of reference systems in geodesy began in the penultimate decade of the 20th century, with the definition of the International Terrestrial Reference System (ITRS) and the International Celestial Reference System (ICRS). The problem of unifying geometric and gravimetric systems was postponed due to the least significant technical advances in these fields compared to what GPS/GNSS and VLBI techniques had brought about. At that time, the aspect of these systems was dominated by local realisations of systems of at most continental scale and, in the aspect of gravimetric reference, by the old IGSN-71 system based on only a few absolute observations and jointly aligned spans forming a network with almost global coverage (Morelli et al. 1974). However, this system had several drawbacks, such as the inhomogeneity of the measurement epoch, the basing of the definition of gravimetric level on a small number of absolute points, and the assumption of static of the system. These factors did not stand the test of time with observational reality at the time of the development of methods for measuring the gravity of gravity by ballistic methods or tracking changes using superconducting methods at the time of the development of methods for measuring the gravity of gravity by ballistic methods or tracking changes using superconducting methods, did not stand the test of time with observational reality. Therefore, at the end of the 20th century, the concept of separating the IGSN into a subnetwork of quasi-permanent absolute measurements IAGBN, i.e. a set of points measured every period by absolute methods, emerged. This was the forerunner of impending changes in the definition of the gravimetric system, changes resulting from technical advances in instrumentation and the need to note the kinematics of the Earth's physical field (Boedecker G., 1998).

In 2015, a resolution was adopted at the IUGG Assembly in Prague to introduce a new definition of the gravimetric reference system and system (ITGRS/F). This system is intended to replace the IGSN71 and IAGBN systems by implementing the ITGRF. According to the new definition, the ITGRF system is realised through points at which determinations of the absolute value of gravity are made by ballistic (free-fall) methods. Several requirements were given in the resolution and subsequent technical standards for metrological control of time and frequency standards and a technical standard for the elaboration of results, including the elimination of time-varying tides, reduction of observations to a zero-tide system, reduction to a standard atmosphere in the DIN5450 model, reduction due to pole movement. Models for eliminating the ocean tidal effect and non-tidal effects of the atmosphere and hydrology were also recommended. This means that the user was given a clear rationale for how gravity values should be measured by ballistic methods and how they should be developed. The metrological aspect concerning the measurement consistency of ballistic gravimeters became a significant issue in the system definition. Here, periodic participation in international calibration meetings was recommended as a standard for comparing standards, but also the need to maintain the points of the system on which quasi-permanent g observations are made (at least every 2 months). The set of points also mentions permanent calibration stations on which not only observations are made with an absolute gravimeter (AG) but also a superconducting gravimeter (SG) is used, which continuously measures the variation of the gravitational field at the station (Wziontek, 2021.

2. Polish path to establish base gravimetric points in ITGRF

Therefore, today, when creating gravimetric "networks", one should think mainly about using absolute ballistic gravimeters, such as the FG5x and A10 designs, and one should take care of proper metrological control of these instruments by participating in comparison meetings and conducting base points through quasi-permanent AG observations or a combination of AG + SG measurements. There are two such stations in Poland, at the geodetic observatories in Józefosław (WUT) and Borowa Góra (IGIK) (Barlik et al., 2009), (Sas-Uhrynowski, 1998), (Sas-Uhrynowski, 2000),

After 2011, the basic gravimetric set in Poland underwent a thorough modernisation and became the first ever gravimetric base established by absolute gravimetric survey methods. This was made possible by disseminating absolute gravimeters of the FG-5 and A10 types. A team of the Faculty of Geodesy and Cartography of the Warsaw University of Technology, together with the Institute of Geodesy and Cartography, designed 30 points of the foundation base (1^{st} class) and 168 points of the base subset (2^{nd} class) and then measurements were made with an accuracy of 0.004mGals on the 1st class points and 0.010mGals on the 2nd class points. The implementation of this base involved the use of absolute observations only, so there was no need to adjust the network. This method of realising the gravity base predominates nowadays and, with specific technical rigour, meets the conditions for the realisation of the ITGRF (Wziontek, 2021). These technical standards were fulfilled in the recent realisation of the fundamental and base stations. The points of the foundation base were located inside buildings, and their function is, besides referencing, also the definition of bases for the calibration of relative gravimeters and the integration with points of foundation geodetic matrices of other types (horizontal EPN GNSS network, vertical UELN network). The points of the fundamental base are located in the field, are easily accessible and serve strictly to establish relative measurements. It is also worth mentioning that the fundamental and base gravimetric points are in the group of basic networks updated every 10 years. This means that every 10 years, all base points are reviewed, any damaged points are stabilised, and all points of the bases are remeasured. Poland used the technical infrastructure acquired at the beginning of the 20th century as a set of FG5 and A10 ballistic gravimeters. Using both ballistic gravimeters to establish bases with technical standards was fulfilled in the recent realisation of the fundamental and base matrices. The technical standard for measuring the points of the fundamental base included a daily observation series with a measurement uncertainty of about 2μGals and reductions in the real gravity field resulting from measurements of the nonlinear relationship of gravity with height (nonlinear gradient) with a reduction error of no more than 4μGals. Two independent measurement sessions were used on the base 2^{nd} class stations after the instrument orientation was changed, and the maximum difference in the results of the two determinations did not exceed 10μGals. An essential element of the infrastructure related to the quality of the Polish gravimetric network was the technical standards of measurement and calculation and the existence of two sites in Poland related to the implementation of the system. This is because the observatories in Józefosław and Borowa Góra served for continuous control of the stability of the sensors between each other, using comparison meetings every six months and metrological control of individual sensors using quasi-permanent observations of the variation of the gravitational field and comparison with the gravity change function resulting from the registration with a superconducting gravimeter (Walo, 2010), (Kryński, 2013), (Olszak T. et al., 2024).

3. Main needs for upgrading the gravimetric base in Ukraine

The need to review and modernise the basic gravimetric network of Ukraine stems from the lack of a modern definition of the gravimetric reference level in the country. The gravimetric network should play the role of a reference of measurements of the nature of geophysical exploration and estimation of deposits, the basis for the implementation of a uniform elevation system and, finally, the metrological basis for calibration measurements of relative gravimeters and other devices using the parameters of the Earth's gravitational field (barometers, inertial platforms, etc.). It, therefore, plays an important role in the process of national reconstruction and will be one of the fundamental elements of the geodetic infrastructure in the form of the realisation of reference points. The lack of any modern definition of the international gravimetric datum on the territory of Ukraine is due not only to the era of implementation of the only post-war measurements (the 1970s) but also from the point of view of technical standards and observational techniques in which significant changes have occurred in the past decades.

The most important of these are:

- adapting the final definition of the ITGRS/F International Gravity System standard as part of the clarification of the call for the establishment of such a system passed at the IUGG General Assembly in Prague in 2015,
- establishing in neighbouring countries (Poland, Slovakia) a gravimetric base based on the use of autonomous observations made by ballistic gravimeters with an accuracy of $(2\text{-}10)\cdot 10^{-8}$ ms,$^{-2}$
- the availability of equipment and observatories in the above-mentioned neighbouring countries, together with measuring teams to guarantee the feasibility and correctness of observations,
- the existence in Poland of two gravimetric laboratories implementing the ITGRS/F system: the Borowa Góra site, having the status of a local calibration centre (integration of quasi-permanent absolute (AG) observations with tidal observations performed with a superconducting gravimeter (SG) and the Józefosław site as a point implementing the system based on quasi-permanent observations with a ballistic gravimeter,

- the need arising from implementing the EVRF uniform European height system requires precise gravimetric information on the repertoires implementing this system.
- another important fact is that the gravimetric system in Ukraine is very archival and does not guarantee compliance with modern geophysical, geodetic and metrological standards. Taking into account the fact that the fundamental gravimetric network is a component of the State Geodetic Network, which should be integral for the whole of Ukraine, we propose to start work on revision, design and modernisation of the gravimetric base stations by the international standard ITGRS/F in the territory of Western Ukraine.

3.1 Historical outline of the gravimetric network of Ukraine

The gravimetric network is a part of the structure of Ukrainian geodetic networks, consisting of the State Geodetic Network of Ukraine containing 16 permanent GNSS network points and 815 points measured periodically by GNSS, several thousand km of levelling lines containing 218 points of the EVRF2019 system and the first and second class gravimetric control network points, established in the 1970s. Those "layers" need fast modernisation, especially to agree with common standards.

The available 1st class gravimetric network on the territory of Ukraine consists of 17 principal points, one fundamental - the national gravimetric point Poltava and 37 relative measurement points. Poltava, the only absolute fundamental gravimetric point in the country, was recently rebuilt (Dvulit, 2009; Dvulit, Entin & Kucher, 2009; Dvulit, 2016), so the absolute value is unreliable. This makes it impossible to modernise the archival gravimetric network by adjustment with reference to the value determined contemporaneously at the Poltava point. Most of the points of the DFGM (Ukr. "National Fundamental Gravimetric Network") were determined in 1979-1983 with an absolute ballistic GABL gravimeter with an accuracy of about 10μGals, and the points of DGM_1 were determined by measurements with AGAT gravimeters relative to the main gravimetric point of Russia – Lyodovo (Dvulit, 2009). After the network adjustment, an average accuracy of 30μGals was obtained. Unfortunately, such assumptions for the construction of the state gravimetric network of Ukraine do not meet modern requirements for the classification of gravimetric points, the accuracy of absolute and relative gravimetric measurements, and the principles of densification of network points. The Russian system does not have a reference to the global system, so the data collected in it is impossible to integrate with European or global databases. In the paper (Sydorenko et al., 2006), a variant of the construction of the DFGM of Ukraine was proposed in the form of a latitude and longitude scheme with two almost orthogonal gravimetric relative bases - latitudinal (Kharkiv - Dnieper - Simferopol) and meridian (Kharkiv - Poltava - Kyiv - Rivne - Lutsk) with an initial gravimetric point in the village of Liptci in the Kharkiv Oblast. From today's perspective, it is outdated because there are faster and more economical methods of establishing gravimetric control points by absolute measurements. In addition to these premises, the most important is that absolute measurements allow for the highest accuracy and do not require alignment (Boedecker G. et al., 2005), (Walo, 2010), (Krynski et al., 2013).

The modernisation of Ukraine's gravimetric network (GMU) by modern global and European standards is a crucial task for increasing the economic potential and defence capabilities of the state. Gravimetric and astronomical-geodetic data are a significant component of modern military combat support for the destruction of enemy command and strategic points, reliable military direction, organisation of military interaction during warfare, effective combat use of missile and artillery forces, expansion of radiolocation stations and modern navigation. Gravimetric data are also used for topographical support of troops. The main task is to determine the relationship between the shape of the Earth's surface and the characteristics of the Earth's gravitational field, whose parameters are a component of the astronomical geodetic and gravimetric data used to calculate ballistic missile trajectories, determine the parameters of satellites' orbits and prepare their launch into orbital space.

Updating and modernising the basic gravimetric base under the international standards established by the Gravimetric Commission of the International Geodetic Association will also address the following tasks:

- increasing the accuracy of higher-class levelling for the establishment of the state geodetic network at height system,
- obtaining a precise geoid model for the territory of Ukraine to ensure a fully functioning network of GNSS stations,
- integration of surveying, levelling and gravimetric measurements into a single national geodetic reference system linked to global and European geodetic systems;
- increased accuracy in determining interference potential, height anomalies, plumb line deviations and other characteristics of the Earth's gravitational field.

In order to upgrade the GMU, the following steps are required:

- updating the points of Ukraine's gravimetric network, performing high-precision levelling to provide an elevation link between gravimetric and levelling points,
- carrying out precise GNSS observations and angular/linear measurements to obtain the coordinates of the gravimetric points in the current datum.

- establishing a gravity-geodetic link between the nearest gravimetric, geodetic, levelling points and GNSS stations will make it possible to implement a universal network of points, which will become a substantial information base for the enhancement of the country's defence capabilities, as well as for comprehensive engineering work and numerous scientific studies.

3.2 Current status of the basic gravimetric network in Ukraine

Poltava is home to one of the Primary Gravimetric Grid (PSG) points of the same name as the city. It has a long series of repeated determinations of the Earth's gravity and is currently the main gravimetric point of Ukraine. No measurements have been made at other PSG points in Ukraine from the mid-1980s to the present day. The accuracy of the PSG of Ukraine (at the time of measurements) does not meet modern requirements. Therefore, it is morally obsolete and needs to be modernised. To modernise the PSG of Ukraine according to international standards established by the International Gravimetric Commission of the International Geodetic Association, it is necessary to ensure the operation of 40 points of the primary network and 200 points of the Class I network.

An important practical aspect of modernising the Ukrainian PSG is that in recent years, there has been active cooperation between Ukraine and the European Union on integrating the Ukrainian height system into the European Vertical Reference System. Work has been carried out on Class I levelling between the height points of the Ukrainian and Polish height systems, and data from the Ukrainian site has been incorporated into the implementation of EVRF 2019. To improve the accuracy of the European altimetric system on Ukrainian territory, it is necessary to modernise Ukraine's PSG and make the corresponding changes to the levelling data. Therefore, in the first stage of the modernisation of the PSG of Ukraine, it is necessary to develop a gravimetric network on the territory of the western part of the country, which will make it possible to obtain gravimetric corrections to high-precision levelling data for the unification of the Ukrainian and European height networks. To solve this problem, it is necessary to establish at least 5 points of the fundamental gravimetric points with free-fall gravity determination by the absolute method and at least 20-25 points of the 1st class points with free-fall gravity determination by the relative method.

It should be noted that a reconnaissance of Ukrainian PSG points was carried out in 2008, during which 54 first-class PSG-1 points were found. Among them, 14 points are located in the Crimean Peninsula, 6 points in the Poltava region and 27 in Central and Eastern Ukraine. There are 7 points preserved in the western part of Ukraine, which can serve as a basis for starting the reconstruction of the PSG of Ukraine and implementing a new gravimetric system. These points are located in six regional centres of Ukraine: Lviv, Uzhgorod, Chernivtsi, Lutsk, Rivne, Khmelnytskyi, as well as in Kamenets-Podolskyi, Khmelnytskyi region (Fig. 1).

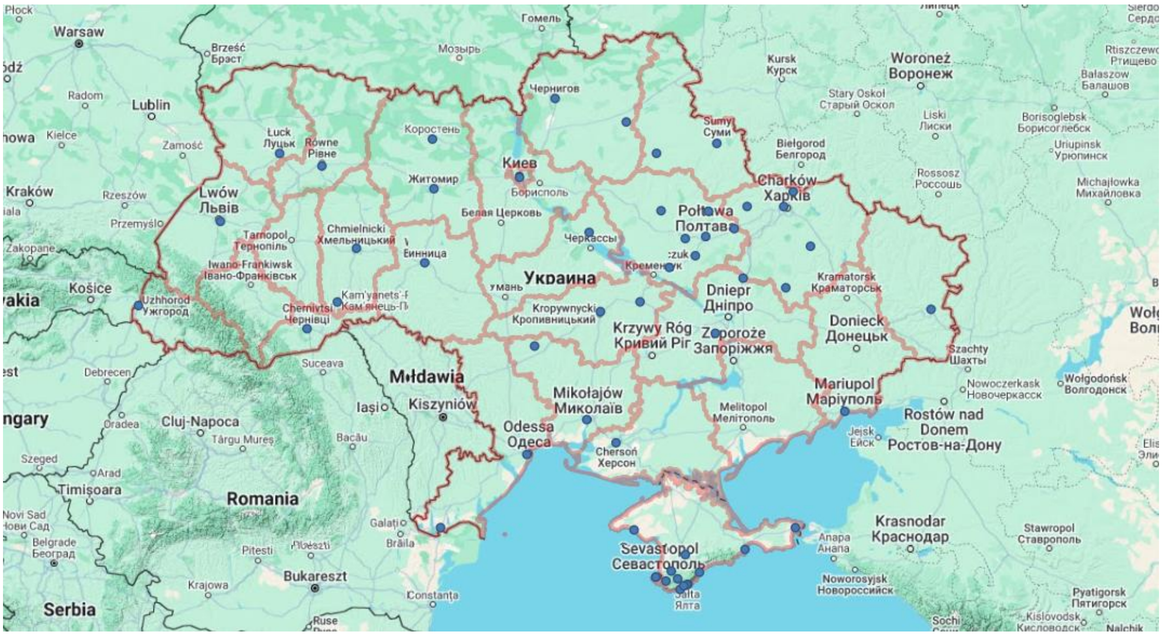


Fig.1. Current state of the basic gravimetric network of Ukraine

An important practical aspect of modernising the Ukrainian SG is that in recent years, there has been active cooperation between Ukraine and the European Union on integrating the Ukrainian height system into the European Vertical Reference System (EVRS). Work has been carried out on Class I levelling between the height points of the Ukrainian and Polish height systems, and data from within Ukraine has been incorporated into the implementation of EVRF 2019.

4. Plans to modernise the basic gravimetric base in Ukraine

To improve the accuracy of the European altimetric system on the territory of Ukraine, it is necessary to modernise the SGN of Ukraine and make appropriate changes to the levelling data (Dvulit & Kucher, 2009) (Dvulit & Smelyanets, 2013).

According to the international standards established by the International Gravimetric Commission of the International Association of Geodesy (IGC IAG), the primary network should consist of evenly spaced points with a recommended density of one point per 15000 km^2, on which gravity should be determined exclusively by the absolute method using modern ballistic gravimeters. The core network shall consist of absolute and relative gravimetric survey points, and the density of core network points (including core points) shall be at least one point per 2500 km^2. To modernise the SGN in Ukraine, it is necessary to ensure the operation of 40 core and 200 Class I network points.

In the first stage of the modernisation of the SGN of Ukraine, it is necessary to develop a gravimetric network in the western part of Ukraine, which will make it possible to obtain gravimetric corrections to precise levelling data to unify the Ukrainian and the remaining European heights networks. To solve this problem, it is necessary to establish 7 points of the basic gravimetric base with the determination of gravity by the absolute method and at least 20-25 points of the 1st class network with the determination of gravity by the relative method or field absolute measurements by using of A10 portable gravimeter.

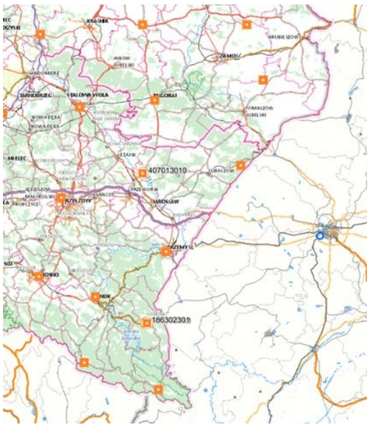
It is, therefore, necessary to limit the relative measurements to measurements of vertical gradients and to perform the alignment of the absolute points to the near excentres. It is envisaged that the alignment of the relative terrestrial gravity observations within each absolute gravimetric point will be performed.

The following work is envisaged as part of the collaboration:

- use of existing gravimetric measurements - especially absolute measurements made in Ukraine,
- perform measurements with an absolute gravimeter of the FG-5 class on points of the foundation network,
- perform measurements with a class A-10 gravimeter on points of the core network,
- periodic check of absolute instruments during the European calibration campaign,
- establishment of a calibration base for the control of relative gravimeters (meridional base in the western parts of Ukraine) - absolute measurements,
- calibration of relative gravimeters on selected sections of the calibration base,
- vertical gradient measurements at all points in the primary grid,
- boundary reference of absolute points on both sides of the national border.

4.1 Project establishing a modern gravimetric base in western Ukraine

The realisation of the International Gravimetric Frame on Ukraine's territory (Fig. 2a,b) should be revised to progress gravity measurement methods. At this point, the proposition of first-stage modernisation of base stations will be described for only the western part of Ukraine. The implementation of the system through absolute points allows for the staging of work related to measurements because the resulting control network, consisting of absolute observations, does not require joining in the adjustment process. Such concepts were implemented in Sweden, Germany and Poland. However, it should be remembered that precise measurements should determine the structure of the fundamental control network with an accuracy of g of 4μGals, and the number of points should correspond to the density of 1 point per 15000km^2.


a)

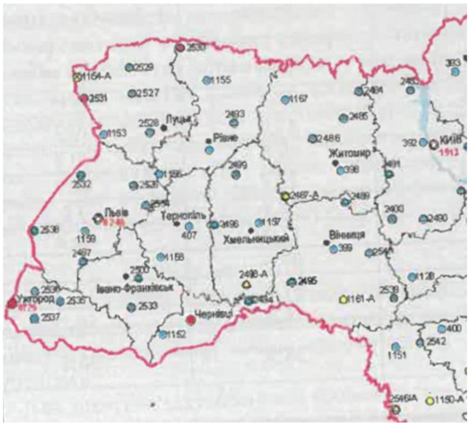

b)

Fig. 2a. - South-eastern part of the Polish gravimetric fundamental and base points. Orange squares mean localisation of gravimetric base on Poland (source Geoportal.gov.pl)

Fig. 2b. - Western part of the Ukrainian gravimetric network. Red dot – 1st class network, blue dot – 2nd class network (source (Dvulit, Kucher, 2009)

Considering the current situation in Ukraine, it is postulated to upgrade the western part of the existing gravimetric network of Ukraine, consisting of 7 points: Uzhgorod, Lviv, Chernivtsi, Lutsk, Rivne, Khmelnytskyi, Kamenets Podolskyi.

It is a fragment of an existing network which ensures that several objectives can be met:

- use of the existing site means no work on the design and construction of the poles
- Create a calibration base between the Chernivtsi - Lviv - Rivne points with gravity increments of +90mGals and +150mGals, respectively, a possible extension to the Pop-Ivan Observatory.

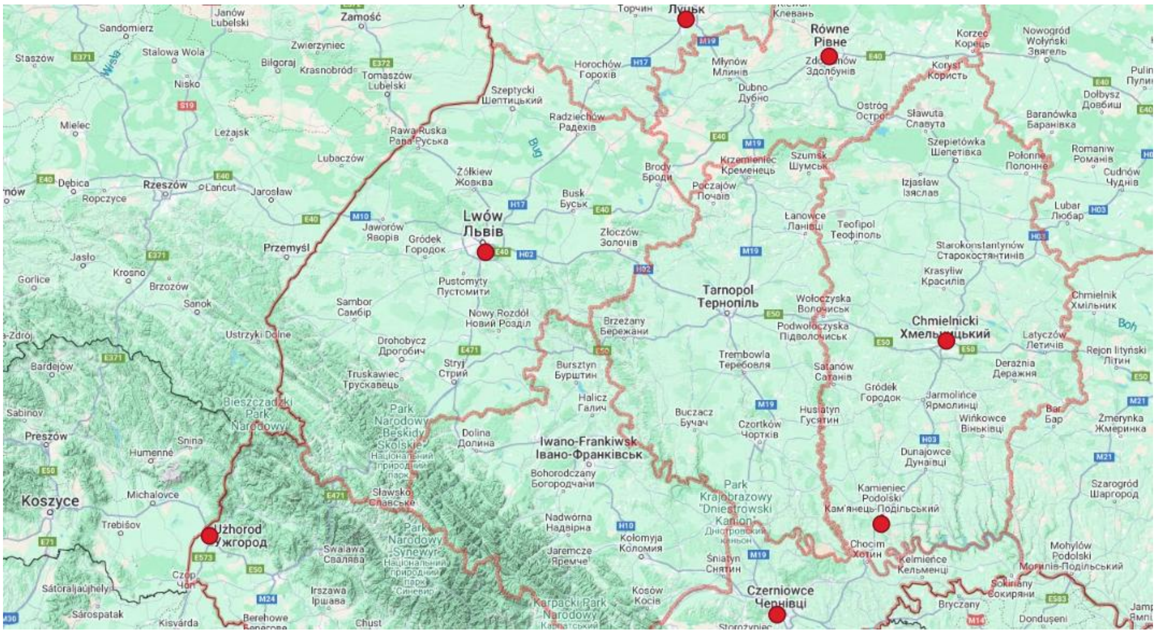


Fig. 3. Location of points to be upgraded in phase I for the western part of Ukraine

Timetable for Phase I works:

- determination of the existence of points, their condition, geodetic referencing and selection of a point in the Pop-Iwan Observatory (end of calibration base);
- possible construction and surveying works, the time required for point stabilisation before measurements - summer-autumn gravimetric surveys - spring to autumn on the proposed cycle as below:
- cyclic measurement every 1 month at the site in Józefosław (ITGRF/S realisation point) - 3 epochs (months)
- measurement (in the same period) at the Borowa Góra site (IGIK observatory, ITGRF/S calibration site due to the presence of the SG sensor) - 1 epoch of two,
- measuring the one epoch at the UA ITGRF/S main site in Lviv - 1 epoch,
- measurements performed at 3 of the 6 points of the western part of the gravimetric network (at choice) with measurement of the gravity variation function (actual gradient), geodetic coordinates and elevation of the point on the outer excentre,
- measurement of the 2nd epoch at the UA ITGRF/S main site in Lviv - 2nd epoch,
- measurements on another 3 of the 6 points of the western part of the gravimetric network (to be selected) together with the measurements described in point 4,
- epoch three measurements at the UA ITGRF/S main site in Lviv - epoch 3,
- measuring points 3-5 and 7 in the interval of 1 month, interspersed with the measurements in Józefosław.

Carrying out cyclic measurement every 1 month at the Jozefoslaw site (ITGRF/S realisation point) - 3 epochs (months) in a similar standard as point 1, measurement (in the same period) at the Borowa Góra site (IGIK observatory, ITGRF/S calibration site due to the presence of the SG sensor) - Jozefoslaw, together with Borowa Gora, would therefore be a measurement bracket, as there is infrastructure and observational material related to AG + SG measurements on these points, the Lviv point would be designated for this purpose on the territory of western Ukraine, the remaining points would be designated in one epoch, possibly 4 + 4 points could be measured, i.e. two different epochs could be realised on two points out of 6.

The technical standard for gravimetric surveys will include:

- determination of the vertical gradient of the gravity of gravity at heights of 0 - 20 - 60 - 100 – 140 cm above the measurement mark in two independent measurement cruises with the condition that the difference between the determinations is less than 0,004mGals at a height of 130 cm,
- measurement with an absolute gravimeter FG5 with a session length of min. 24h and a determination uncertainty of less than 0,002mGals at an effective height (approximately 125cm) above the survey mark.

This standard of gravity measurements and determination of reduction function gives us the total uncertainty of gravity, reduced on the pillar, not much than 0,004mGals, which is a satisfied value from geodetical and metrological points of view.

5. An attempt to determine the difference between the gravity levels of Poland and Ukraine - numerical analyses

The Poltava system was implemented in the existing Ukrainian gravimetric network. There are no direct gravimetric measurements between the Polish and Ukrainian bases, so a direct analysis of the level difference is impossible. In this section, an attempt is made to identify the potential offset and scale difference of the Poltava array relative to the international gravimetric array by comparing it with the results of the UNIGRACE project and existing geopotential models, one from the high-resolution domain using hybrid satellite and ground-based data and one from the satellite-only domain. The point of comparison with terrestrial data uses TBG absolute gravimeter survey data incorporated in the UNIGRACE project and the ICAG international calibration campaigns. Still, it is not a contemporary implementation of ITGRS/F, the differences of which, however, should be assessed at the level of 10-20mGal in relation to the way the points from the UNIGRACE project were implemented supported by data from the participation of gravimeters in the international calibration campaigns (Boedecker, G et al., 2005).

5.1. Determination of the difference between the gravity levels of the International Gravimetric System and the POLTAWA System using data from the UNIGRACE project

The first approach uses results from the UNIGRACE campaign, implemented as a project to integrate the gravimetric matrices of Eastern European countries into the international gravimetric system. This project played a very important role in this issue, as well as integrating elevation systems or linking geoid models. It was carried out within Ukraine with the TBG ballistic instrument belonging to the Kharkiv Metrology Institute. This instrument was used only within Ukraine, but it also participated in the international calibration campaign ICAG2005, during which it determined a difference to other ballistic gravimeters, defining a gravimetric reference level. According to the publication from ICAG2005, it was relatively small as +5mGal with an error estimated at ±20mGal (see fig. 4)

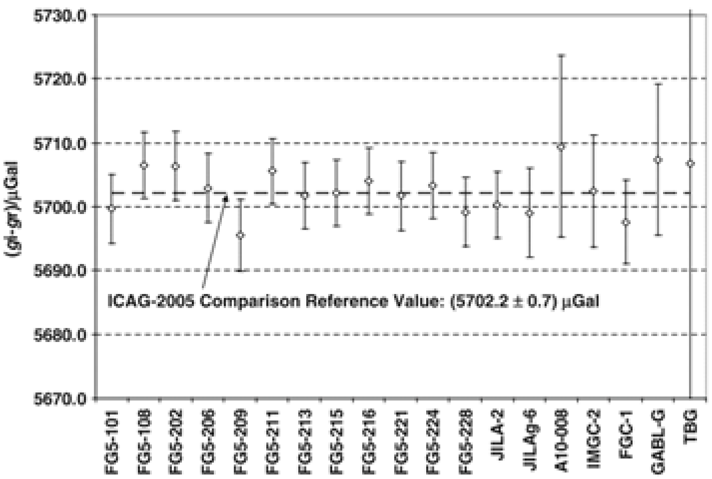


Fig.4. Graph of the results of determining the differences of the absolute gravimeters participating in the IGAG 2005 campaign (based on Vitushkin et al. (2010)

Comparing the results of determining the absolute values of gravity against the catalogue data in the Poltava system were obtained at five points located in the area of Ukraine g-value differences shown in Table 1.

Table 1 *Values of gravity in the Poltava System and the UNIGRACE Campaign from Ukraine*

Lp.	Name	φ[deg]	λ [deg]	$H_{BalticSea}$ [m]	gPOLTAVE [mGal]	Mg [mGal]	gUNIGRACE [mGal]	mg [mGal]	dg UNIGRACE-POLTAWA [mGal]
1	Poltava	49.604167	34.545000	146.044	980992.970	0.022	980992.696	0.020	-0.274
2	Uzhhorod	48.627500	22.290000	125.469	980929.038	0.020	980928.599	0.020	-0.439
3	Lviv	49.814167	24.060833	320.357	980926.596	0.023	980926.287	0.020	-0.309
4	Kyiv	50.423333	30.523333	141.364	981060.671	0.022	981060.412	0.020	-0.259
5	Kharkiv	50.020000	36.231667	152.945	980997.331	0.021	980997.016	0.020	-0.315

One should note certain systematic changes, not only in terms of sign. At the main point in Poltava, this difference is the smallest in absolute value, while it increases systematically in proportion to the distance between points, understood as the difference in gravity of gravity, reaching a value of 0.439mGals at the most distant point in Uzhhorod, a value almost 60% higher than at the central point in Poltava. This proves the existence of a constant offset factor in the Ukrainian gravimetric network realising the Poltava system, resulting from an error in the realisation of the g-value at the point in Poltava by using an instrument of lower precision than in the UNIGRACE campaign and a systematic error resulting from calibration errors of relative gravimeters realising relative spans in the Poltava system. A graphical representation of the differences between the layout realised through the ICAG2005 campaign and the Poltava layout is shown in Figures 5 and 6.

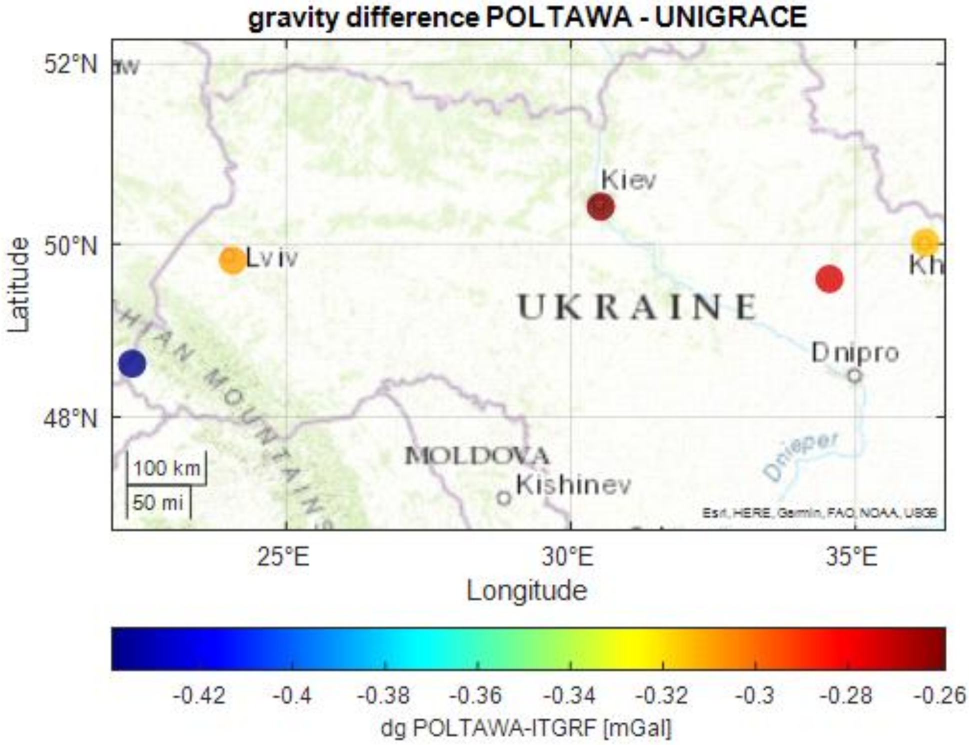


Fig. 5. Differences in gravity between the Poltava and UNIGRACE levels (ICAG2005)

Difference modelling usually uses an analytical or interpolation function formation approach, but this is not the optimal solution for such a small number of points with such heterogeneous densities. For more than 50% of the area of Ukraine, an extrapolation approach will be used.

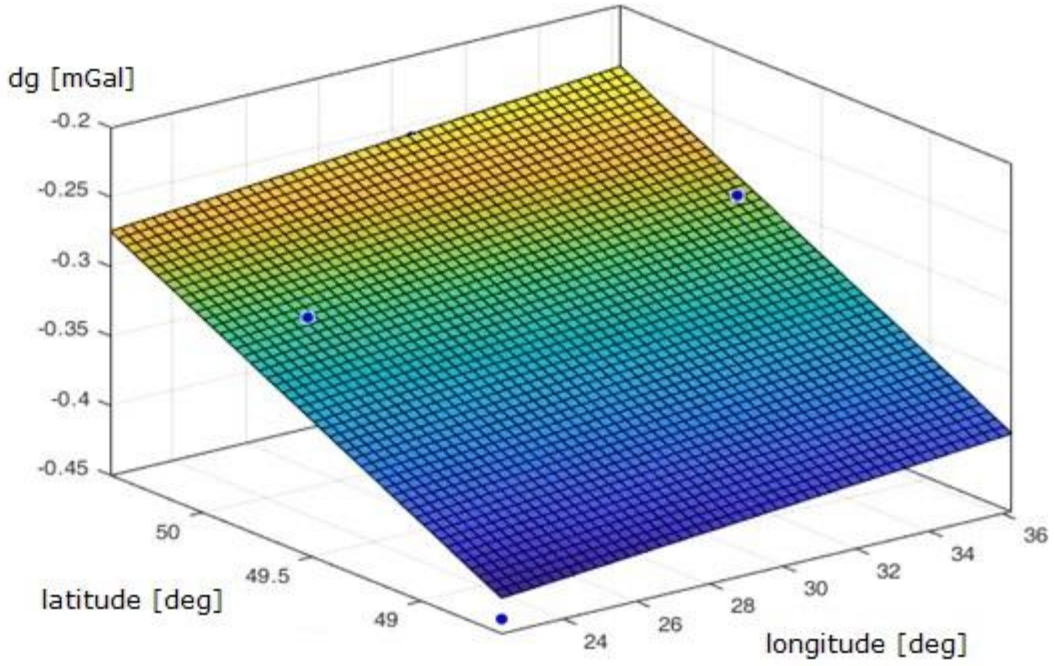


Fig. 6. Model of differences in gravity dg [mGals] between the Poltava system and the UNIGRACE level (ICAG2005) for the area of Ukraine

Estimation of a linear relationship, based on the simple linear function φ and λ (in degrees) gave the result dg in mGals as

$$dg(\varphi, \lambda) = -4.514 + 0.002183\,\lambda + 0.0831\,\varphi \quad (1)$$

with an error of 0.041mGals based on five combined points.

Another approach is to try to estimate the 'parallel shift' or offset of the layouts at the Poltava implementation point and the scale relationship. This is justified because the network was mainly based on absolute measurements relative to the Poltava point. By determining the offset and scales, the results were obtained:

Table 2 *Determination of scale factors for the spans of the gravimetric networks of Ukraine in relation to the results of the UNIGRACE campaign*

	DgUNIGRACE-POLTAWA [mGal]	dgP[mGal]	dgU [mGal]	k = dgP/dgU
Poltava – Uzhhorod	-0.439	-63.932	-64.097	0.997426
Poltava – Lviv	-0.309	-66.374	-66.409	0.999473
Poltava – Kyiv	-0.259	67.701	67.716	0.999778
Poltava – Kharkiv	-0.315	4.361	4.320	1.009491
			mean	**0.998892**
			SD	**0.001279**

Obtaining an offset of -0.274mGals and a scale factor of 0.998892, based on three spans. The elimination of the shortest one, relative to Kharkiv, was dictated by its low relative accuracy. The results are characterised by a scale error of 0.001279, giving a conversion error of 0.128mGals for a span with a hypothetical gravity difference of 100mGals. From today's perspective, this magnitude is unacceptably large, exceeding the accuracy of absolute measurements by almost two orders of magnitude. The first modelling approach, based on a polynomial based on geodetic coordinates, gives more stable results. However, it should be noted that this is an extrapolative approach in half of Ukraine (Boedecker G. et al., 2005).

5.2 Determination of the difference between the levels of the international gravity system and the POLTAWA system using data from global geopotential models

A set of gravimetric and integrated base points in Poland, shown in Figure 7, will be used to determine the accuracy and difference of the models with respect to the ground data. The idea of this analysis is to find the offset between the ground data in Poland and the accuracy of the models and repeat this analysis for the points in Ukraine. Any level difference will appear as the variation in the offset for data from both countries. It should be noted that the points of the gravimetric bases in Poland are implemented identically to the ITGRF definition (fundamental and base network) or close to this definition (Polref networks) for data from which no calculation of the influence of the standard atmosphere on the gravity value was performed. The error from this point of view should be estimated at max. 5μGals.

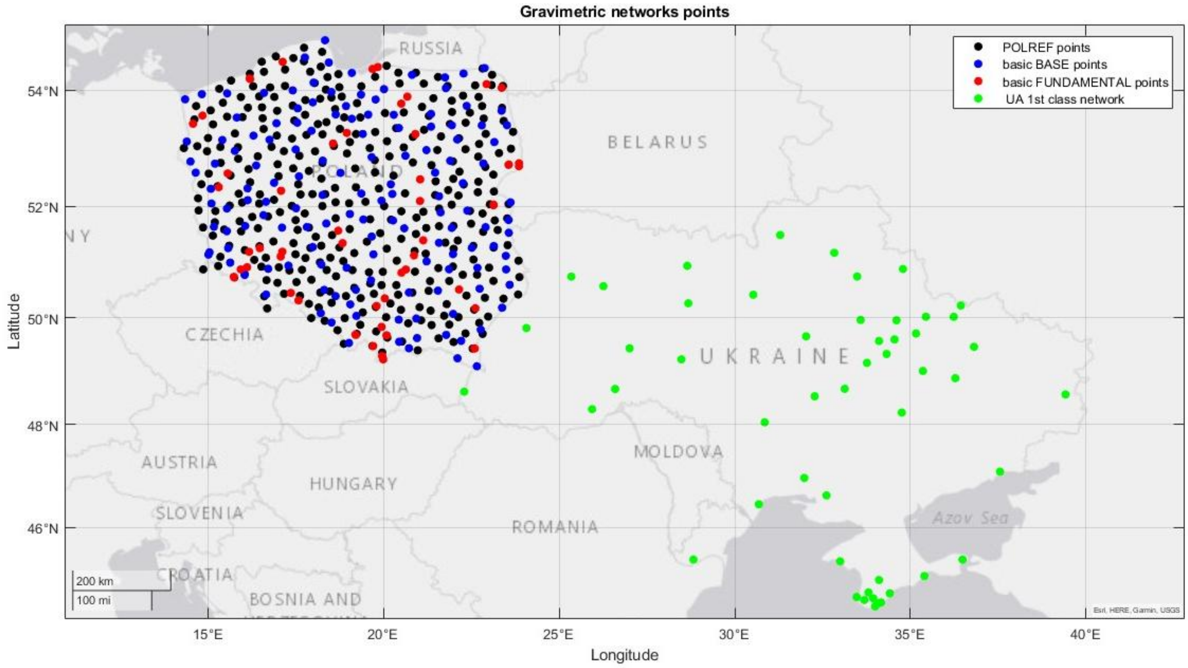


Fig. 7. Presentation of the distribution of test points for studying the relationship between the levels of the gravimetric nets of Poland and Ukraine using GGM models (black dots are relative points of Polref network, red are fundamental absolute network, blue are base absolute network, green are base 1st class points of Ukrainian network)

Model data from the three different GGMs for the Polish gravimetric stations were obtained using the ICGEM calculation service. As part of the calculations, gravity (model gravity) and topo over geoid (topography determined from the ETOPO model) functions were determined for the GRS80 ellipsoid and the zero-tide permanent tidal system. As part of the analyses, calculations were performed against three geopotential models:

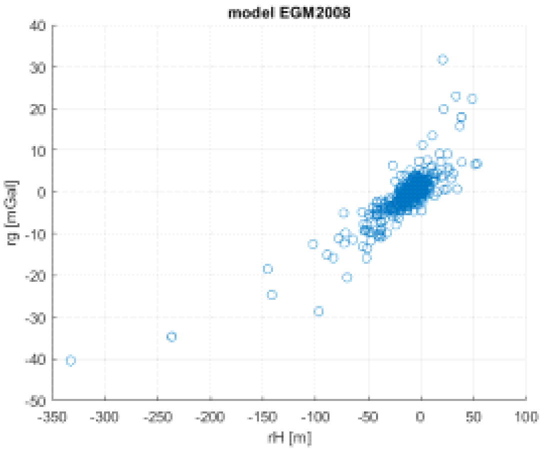
I. EGM2008: This is a combined model consisting of data from the GRACE mission and information extracted from global free-air anomaly sets determined from a 5' grid (Pavlis et al., 2012). Its maximum degree of expansion is 2159.

II. EIGEN-6C4: The model name is an acronym for the European Improved Gravity model of the Earth by New Techniques. Also, it is a combined model consisting of data from the satellite missions LAGEOS, GRACE, GOCE and ground-based missions of the Danish University of Technology (Förste et al., 2014) with a maximum degree expansion of 2190.

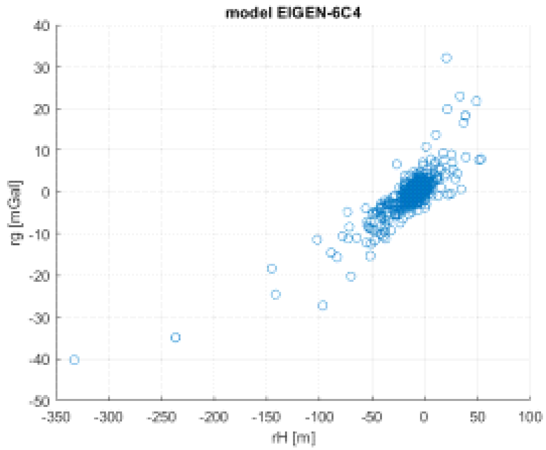
III. GOCO06s: A model developed by the GOCO (Gravity Observation Combination) project consisting only of satellite data collected over 15 years by 19 satellites (Kvas et al., 2021) from the GRACE and GOCE missions. The maximum model development is 300.

On this basis, the differences between the model values and the measured values (derived from the acquired gravity base data) of the gravity were determined (Fig.8):

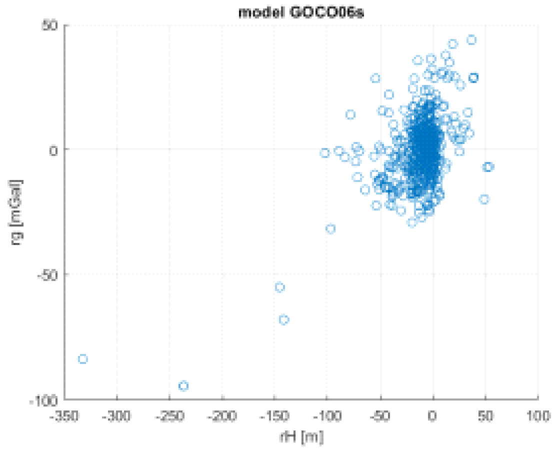
$$rg = g_{model} - g_{pom} \tag{2}$$



(a) Model EGM2008.



(b) Model EIGEN-6C4.



(c) Model GOCO06s.

Fig. 8. Differences in gravity values between field and model GGM data from the Polish area

The correlations obtained show that looking for a mathematical rule for a model built solely from satellite data is difficult. GGMs consisting of satellite and ground measurements are definitely better suited for this. The EIGEN-6C4 model was used for further analysis, which gave virtually identical relationships to EGM2008. The next step was to determine the same functions based on the EIGEN-6C4 model for data from the Ukrainian network. Thus, only the rg gravity differences were calculated in the same way. Table 3 presents the result of the statistical analysis of the differences between the Polish and Ukrainian sets that were obtained.

*Table 3. Statistical analysis of differences in model and measured **rg** gravity based on data from Poland and Ukraine.*

Difference rg = g_{model} **-** g_{pom}				
Country	**Min [mGal]**	**Max [mGal]**	**Mean [mGal]**	**Standard deviation [mGal]**
Poland	-40.28	32.13	-0.32	8.20
Ukraine	-18.63	51.61	10.16	11.48

For both the Polish and Ukrainian datasets, similar model errors were obtained, which were 8.20mGals and 11.48mGals, respectively. However, the average difference between the model gravity from the GGM and the measured gravity derived from the data differs significantly in both cases. For the Polish set, the difference is a mere -0.322mGals, while for the Ukrainian set, the difference is almost 10 mGals larger, amounting to exactly 10.157mGals. Comparing the results with the previous point, we note that modern GGM models cannot capture the difference between the systems in the case of Poland and Ukraine. This is probably due to the heterogeneous accuracy of the models in Poland and Ukraine, conditioned by the availability of gravimetric data. From this point of view, purely satellite models are not yet capable of doing so due to their low spatial resolution (Kozielewicz M., 2024).

Summary

The use of UNIGRACE campaign data provided an opportunity to determine the difference between a gravity system close to the modern definition and the archived Poltava system. It can be estimated by order of a few tenths of a mGals, but the number of points and their distribution does not give a chance to create a good conversion function of the Poltava system to the modern system. The only solution is to collect archival relative observations and re-align them, which will increase the number of points and their distribution, understood as cumulative points. However, the best outcome would be to select points and remeasure them according to the ITGRF standards in force today.

From the point of view of applying geopotential models, quite different results were obtained, suggesting that the difference in network levels between Poland and Ukraine is up to 10mGals. The difference corresponds to the accuracy of the models within Ukraine, so may be due to random errors. Nevertheless, when analysing the difference in Poland between the levels of the combined geopotential models, a much smaller "shift" value was obtained. The question, therefore, arises whether the data provided by the Ukrainian side for the databases feeding the creation of GGM models implement the IGSN71 system or do not yet refer to the Potsdam system with an offset of about 14mGals. We cannot determine this using data from the gravimetric network, as it is unknown how the defined gravimetric databases as references were transferred to the international databases.

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References

Barlik, M. et al. (2009). Investigations of the long-standing gravity changes on the main tectonic units on Polish territory in a period 2006-2009 (in Polish). Warszawa: Wydawnictwo Politechniki Warszawskiej.

Boedecker G. (1988). The International Absolute Gravity Basestation Network (IAGBN). Absolute gravity observations data processing standards and station documentation. BGI Bull d'Inf 63:51–57

Boedecker, G., Francis, O., Kenyeres, A. (2005). Unified European Gravity Reference Network 2002 (UEGN02) — Status 2004. In: Jekeli, C., Bastos, L., Fernandes, J. (eds) Gravity, Geoid and Space Missions. International Association of Geodesy Symposia, vol 129. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-26932-0_50

Dvulit P. D. (2009). The gravimetric network of Ukraine: current state and prospects for development // Geodynamics. – No. 1. – P. 44–46. https://doi.org/10.23939/jgd2009.01.044

Dvulit P. D., Kucher O. V. (2009). The main directions of development of the state gravimetric network of Ukraine, Bulletin of geodesy and cartography. – No. 6. – P. 11–13.

Dvulit P. D., Entin V. A., Kucher O. V. (2010). The development of the state gravimetric network of Ukraine as a priority component of programs on the problems of mineral and raw material provision of the country, Mineral resources of Ukraine // Scientific journal. - K. №2. -P. 5–6.

Dvulit P. D., Smelianets O. V. (2012). About the necessity of modernization of Ukraine gravimetric network. JGD.2012; Volume 13, Number 2: pp. 34-37 https://doi.org/10.23939/jgd2012.02.034

Foerste, Christoph; Bruinsma, Sean.L.; Abrikosov, Oleg; Lemoine, Jean-Michel; Marty, Jean Charles; Flechtner, Frank; Balmino, G.; Barthelmes, Franz; Biancale, Richard (2014): EIGEN-6C4 The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse. GFZ Data Services. https://doi.org/10.5880/icgem.2015.1

Kozielewicz M. (2024). Accuracy analysis of combining gravimetric data for transboundary observation datasets. MSc Thesis of Faculty of Geodesy and Cartography WUT. Warsaw (in Polish)

Kucher O.V., Renkevich O.V., Lepetyuk B.D., Zayets I.M. (2003). Scientific and technical

Scientific and technical support for the implementation of the reference coordinate system for the territory of Ukraine, Modern achievements of geodetic science and production, Lviv, 2003, pp. 23-31.

Krynski J., Olszak T., Dykowski P. (2013). New gravity control in Poland – needs, the concept and the design. GEODESY AND CARTOGRAPHY, 62(1), pp. 3-21.

Kvas, A., Brockmann, J. M., Krauss, S., Schubert, T., Gruber, T., Meyer, U., Mayer-Gürr, T., Schuh, W.-D., Jäggi, A., and Pail, R.: GOCO06s – a satellite-only global gravity field model, Earth Syst. Sci. Data, 13, 99–118, https://doi.org/10.5194/essd-13-99-2021, 2021.

Morelli C, Gantar C, Honkasalo T, McConnell R, Tanner J, Szabo B, U U, Whalen C (1974). The International Gravity Standardization Net 1971 (I.G.S.N.71). International Association of Geodesy, Special Publication 4 https://apps.dtic.mil/dtic/tr/fulltext/u2/a006203.pdf.

Olszak T, Rosowiecka O, Musiatewicz M. (2024) Modernization of the basic gravimetric control network Polish Geological Institute - implementing a modern international gravimetric system and relationship with the historical Potsdam system. Reports on Geodesy and Geoinformatics. 2024;117:1-10. doi:10.2478/rgg-2024-0001.

Pavlis, N. K., S. A. Holmes, S. C. Kenyon, and J. K. Factor (2012), The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), J. Geophys. Res., 117, B04406, doi:10.1029/2011JB008916.

Sas-Uhrynowski, A. C. (1998). A new national gravity control network - POGK97 (in Polish). Proc. of the Institute of Geodesy and Cartography(98), pp. 41-49.

Sas-Uhrynowski, A. C. (2000). A new gravimetric control network for Poland. Reports on Geodesy (8), pp. 55-60.

Vitushkin, Leonid & Jiang, Z. & Robertsson, Lennart & Becker, Matthias & Francis, Olivier & Germak, Alessandro & D'Agostino, G. & Palinkas, Vojtech & Amalvict, M. & Bayer, R. & Bilker-Koivula, Mirjam & Desogus, S. & Faller, J. & Falk, R. & Hinderer, Jacques & Gagnon, C. & Jacob, T. & Kalish, E. & Kostelecky, J. & Wilmes, H.. (2010). Results of the Seventh International Comparison of Absolute Gravimeters ICAG-2005 at the Bureau International des Poids et Mesures, Sèvres. 10.1007/978-3-642-10634-7_7

Walo J., Red. (2010) Jednolity system grawimetrycznego odniesienia polskich stacji permanentnych GNSS i poligonów geodynamicznych. Oficyna Wydawnicza Politechniki Warszawskiej, 2010.

Wziontek, H., Bonvalot, S., Falk, R. et al. (2021) Status of the International Gravity Reference System and Frame. J Geod **95**, 7 https://doi.org/10.1007/s00190-020-01438-9