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On-Ice Gravity Variations Estimation for Data Correction at Frozen Waterbodies

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Abstract: The paper presents the results of experimental studies carried out on the ice of the Gulf of Finland near St. Petersburg in February 2024. The primary objective was to assess the feasibility of using a static station on the ice to correct gravity variations caused by ice cover movements, thereby improving the quality of ground-based gravity survey data obtained from frozen water bodies. The relevance of this work stems from the need for high-precision gravity measurements in ice-covered areas, where standard techniques often yield noisy data. We hypothesized that low-frequency noise from ice oscillations affects both a static and a rover gravity meter simultaneously, or with a minor time shift depending on the distance between them. A field experiment was conducted using two gravity meters (Scintrex CG-5 and CG-6) to analyze the correlation of gravity time series at distances ranging from 0 to 2000 m. Preliminary results confirmed a significant correlation in the low-frequency signal component up to a distance of approximately 500 m (correlation coefficient of 0.73 at 500 m). This validates the proposed correction method in principle but significantly limits its application to detailed, small-scale surveys in shallow water bodies. Filtering and subtracting the low-frequency noise recorded by the static station led to a reduction in the standard deviation of the measurements. Beyond the methodological testing, the study addressed a geological objective: mapping buried valleys that pose a hazard to construction in the city's coastal reclaimed areas. Observations along one profile revealed a negative gravity anomaly, which is interpreted as a possible continuation of a buried river valley previously identified on the nearby coast. The research is currently limited by the specific conditions of one water body and warrants further investigation under different environmental settings to assess the broader applicability of the method.

Keywords: on-ice gravity survey, static station, gravity exploration, gravity meter, buried valley

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Review

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1. Introduction

Gravity survey is one of the most important methods of exploration geophysics. Tasks for this method at different stages of geological exploration are associated with regional structures mapping, faults tracing, deposits ore-controlling structures localization etc. [*Kalinin et al.*, 2024; *Martyshko et al.*, 2024; *Talovina et al.*, 2024]. A large part of these problems can be solved successfully only using quality gravity results [*Kalinin et al.*, 2023; *Yakovleva et al.*, 2022]. So, the growing demand for high-precision gravity led to the need for measurements with μGal precision in challenging conditions, such as over water bodies [*Bolshakova and Fedorova*, 2021; *Mingaleva et al.*, 2022].

The relevance of this work is related to the presence of areas covered by lakes or other closed and shallow water bodies which are required for accurate gravity investigations. The quality of data obtained by airborne meters or shipborne is incomparable to modern ground gravity surveys [*Vyazmin et al.*, 2024]. Another approach is a survey carried out in winter on the ice using a land relative gravity meter.

Studies on gravity survey on the ice are known and were performed on seas and lakes in northern regions. As has been demonstrated by practice and published materials, gravity data, obtained on the ice, are complicated by a number of additional effects compared to surveys on land. Ice-based gravity measurements are currently performed with reduced accuracy to 0.15–0.6 mGal [*Märdla et al.*, 2015; *Oja et al.*, 2013; *Ugalde et al.*, 2006], although there is potential for improving survey quality.

The increased noise in the ice gravity data can be confirmed with Figure 1 [*Medvedev et al.*, 2024]. Data were collected both on the ice and coast. Despite similar conditions for ice and ground surveys, as seen in Figure 1, the quality of ice surveying is an order worse than stations located off the ice. The wind impact on the equipment is practically the same, and some points on the coast are in open areas, just like the surface of the lake. The increased dispersion of ice gravity data can be associated with the response of the ice to wind effects.

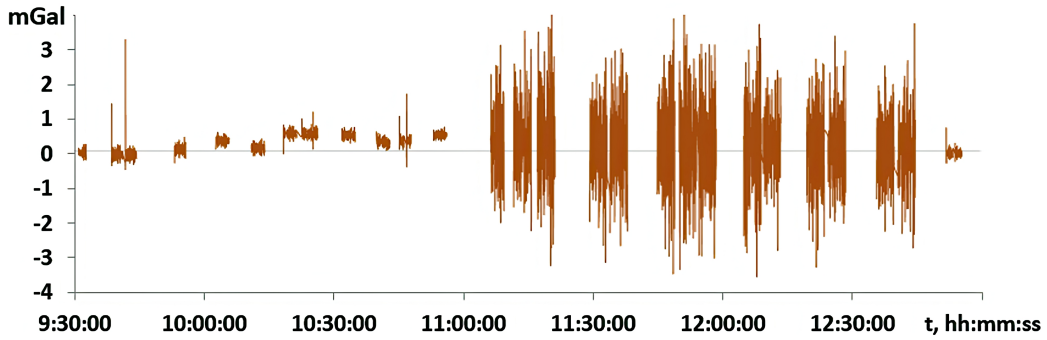


Figure 1. Typical example of the gravity time series collected on land (till 11:00:00 and the last station) and ice [*Medvedev et al.*, 2024].

The standard deviations (SD) for coastal and ice points have different levels. As can be seen for points on ice the standard deviations exceed the variability of values between points caused by geological reasons, and anomalies with amplitudes up to 1 mGal cannot be reliably estimated and interpreted in this form. So, the main purpose of this work is to show the possibility of improving gravity surveys quality on ice. The second goal is to evaluate the characteristics of gravity measurements in ice conditions, describe the noises and ice oscillations. We propose to use a static station to correct temporal variations embedded in gravity data collected on the ice.

2. Materials and Methods

Experimental field research was carried out near the north of St. Petersburg, Russia, in winter 2024. Observation stations were set on the ice of the Gulf of Finland. This region has a cold winter climate, with transitional climate from continental to marine. The average February temperature is about −5 °C. In winter, westerly and southwesterly winds prevail. This territory is swampy, and there are many lakes, so survey on ice is highly relevant for this region.

Geologically, St. Petersburg is at the junction of the Baltic Shield and the Russian Plate. The Baltic Shield is composed of Archean–Early Proterozoic metamorphic and intrusive complexes. The Russian Plate is made up of Early Proterozoic and Phanerozoic sedimentary terrigenous and carbonate sedimentary rocks of the Vendian, Cambrian, Ordovician, and Devonian (Figure 2a). The sedimentary cover is overlain by Quaternary sediments of various genesis and lithology. On the gulf floor adjoining the city, there is a layer of recent sediments of different composition. Changes in the thickness of Quaternary sediments are determined mainly by the paleorelief of the surface of pre-Quaternary rocks. On average, it is 20–30 m, locally reaching 100–130 m in buried valleys [*Medvedev et al.*, 2024]. Study line is in the area of Vendian rocks occurrence and is complicated by buried channels according to data collected on the coast (Figure 2b). The boundaries of paleovalleys are drawn along the section corresponding to the maximum gradient of immersion of the surface of the pre-Quaternary relief using geophysical and borehole data (Figure 2c).

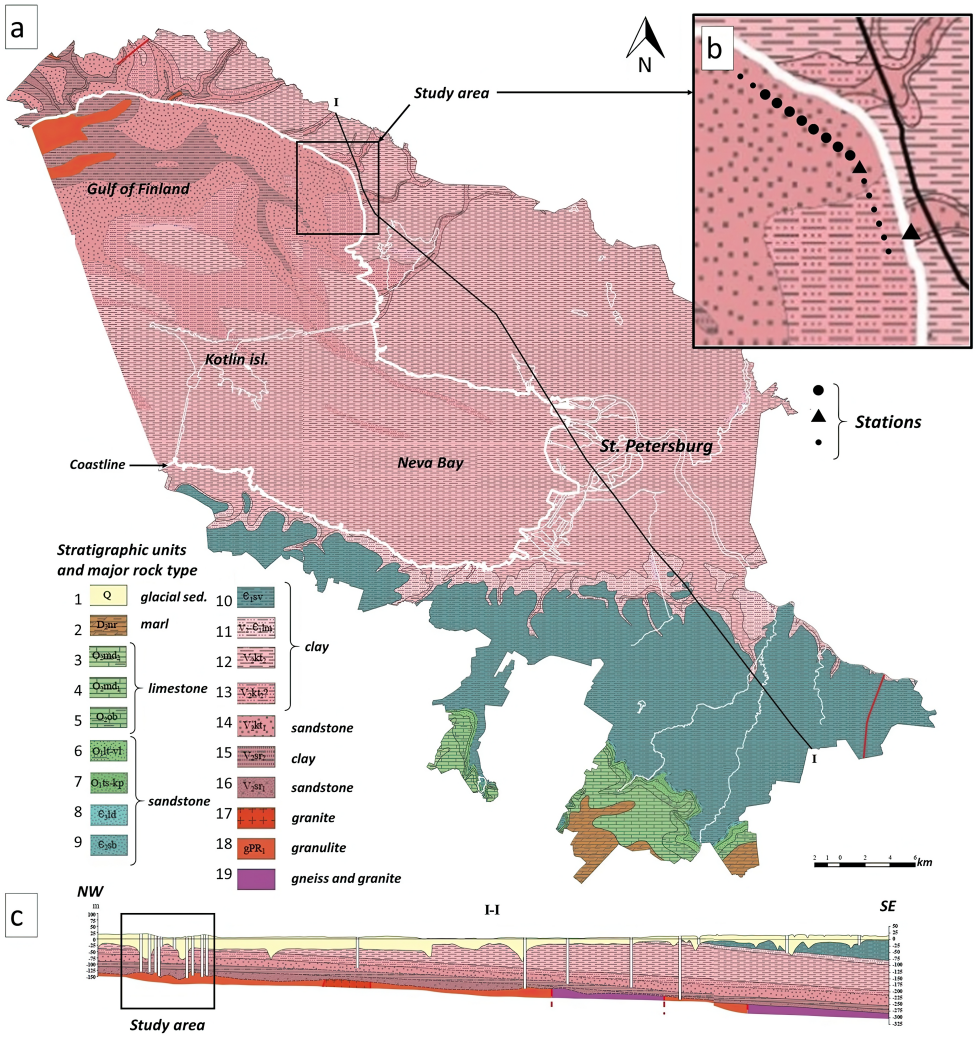


Figure 2. Map of pre-Quaternary sediments near St. Petersburg (*a*), study area (*b*) and the geological section along line I–I (*c*) [*Geological...*, 2009]. In Figure 2, the numbers indicate: 1 – Quaternary system. Undifferentiated deposits. 2 – Devonian system. Middle section. Marls, dolomites, carbonate clays, interlayers of sandstones and siltstones, at the base in places brecciated dolomites. 3 – Ordovician system. Limestones are unevenly clayey with layers of marl, in the upper part – with rare lenses of oil shale. 4 – Limestones are unevenly dolomitized, with ferruginous oolites at the bottom. 5 – Limestones and dolomites with thin layers of marls and clays, with brown iron-phosphate oolites at the base. 6 – Glauconite sandstones and glauconite limestones and dolomites. 7 – Sands and sandstones with phosphate shell detritus, mudstones – dictyonema shales. 8 – Cambrian system. Quartz sands and sandstones with admixture of phosphate detritus. 9 – Quartz sands and sandstones with rare thin layers of siltstones and clays. 10 – Siltstone clays, with rare quartz sandstone layers at the top and bottom, in the roof in places with kaolinite weathering crust. 11 – Sandstones and siltstones are clayey, alternating with clays at the top, with inclusions of glauconite. 12 – Vendian system. Clays are compacted greenish-gray, thin-layered with organic films, with siderite lenses. 13 – Alternating clays, siltstones and sandstones with the former predominating at the top, with siderite lenses. 14 – Fine-grained sandstones, inequigranular to coarse-grained at the base, siltstones and clays with siderite lenses at the top. 15 – Clays compacted with argillites, gray and variegated, in places clayey siltstones, at the base sandstones of various grains. 16 – Sandstones of various grain sizes, coarse-grained and gravelly at the base, compacted clays and gray argillites at the top. 17 – Kuznetsk granite complex: biotite porphyro-blastic granites. 18 – Lower Proterozoic. Lakhdenpohsky undifferentiated metamorphic complex with folded tonalite intrusions: granulites, amphibolites, crystalline schists, gneisses. 19 – Archean undifferentiated. Migmatized gneisses and granites (only in section).

Paleochannels are usually filled with lower density sediments, and, thus, are a good target for gravity surveying. The study of such geological structure is interesting for clarifying the Quaternary history of the region and infrastructure spatial planning. Intensive economic growth led to a construction boom in St. Petersburg. The features of construction changed significantly: the height of buildings increased, underground space is actively developed, and reclaimed coastal waters territories are being built up. Buried valleys are areas of sharp depressions of the pre-Quaternary relief, reflecting, in most cases, an ancient buried river network. The presence of paleovalleys in the construction area is an extremely unfavorable factor. There was an accident in the St. Petersburg subway due to buried valley (1974), since then they are considered as a dangerous object for construction in the region [*Dashko and Kolosova*, 2025; *Lebedeva et al.*, 2020].

The model of the buried valleys location on land in the city is accurate, but in the water area it is of poor quality because of data deficiency. The geological objective of the work is to study gravity field anomalies over a buried channel. We need to understand if we can prospect them with good quality in the Gulf of Finland using gravity data.

We are going to improve collected on ice data quality using a static station to correct noise. The method of geophysical measurements using a static (base) station is widely applied in the study of magnetic anomalies. The measured variations of different periods are related to changes in the magnetic field over time, which are unpredictable, despite some cyclicity, but most importantly, they exhibit little spatial variability. But in the classical techniques of land gravity surveys, there are no tasks for measuring simultaneous variations with static station. We have an idea about benefits of simultaneous gravity time series measurements for ice-based surveys.

A significant source of noise in gravity surveys on ice comes from vertical ice movements, which are influenced by wind, currents, tides, and other factors. The gravity field itself remains unchanged, but due to the rise and fall of the ice, the height of the gravity meter's position changes, which affects the measurement results (a height change of 3 cm can cause a change in the gravity field of approximately 8 μGal). An even greater disturbance is caused by the acceleration of the movement of ice on which the gravity meter is placed up to tens of mGals [*Abramov et al.*, 2013; *Andreev et al.*, 2023]. If it is assumed that these movements exhibit little lateral variability (if the ice sheet is considered as a membrane experiencing its own oscillations), the method of measuring the gravity field using a variational station can be applied.

The idea of our experiment consists of using of simultaneous measurements of two gravity meters for correction of one gravity meter data by means of the second one. It can be useful in case of presence of low-frequency movements at the large area of the ice, covering water body (Figure 3). It was hypothesized that noise affects both the static station and roving gravity meters simultaneously, or with a slight time shift depending on the distance.

The noise involves both high frequency (wind shaking) and low frequency ("slower" ice rebounds) components. The data from the gravity meter – on-ice static station g_s can be approximately represented as

$$g_s = g_{s,const} + g_{s,ice} + g_{s,wind},$$

where $g_{s,const}$ – the constant value at the static point; $g_{s,ice}$ – the influence of ice variations; $g_{s,wind}$ – high-frequency influence of wind, cracks in the ice, traveling waves and other asynchronous interference.

The data from the roving gravity meter g_i is, by the same logic,

$$g_i = g_{i,const} + g_{i,ice} + g_{i,wind},$$

where $g_{i,const}$ – the constant value (searched); $g_{i,ice}$ – the influence of ice variations, correlating with the data of the basic ice gravity meter; $g_{i,wind}$ – high frequency wind influence, etc.

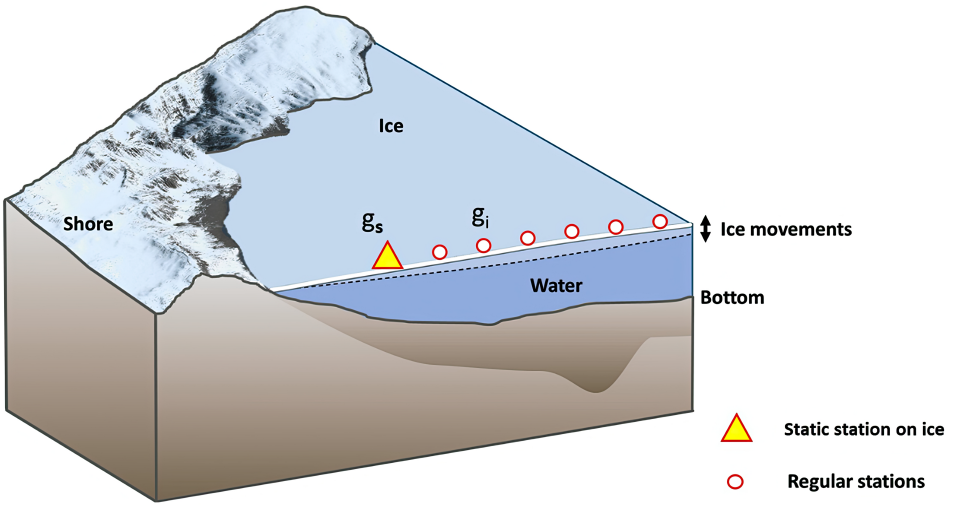


Figure 3. Water body scheme with ice oscillations and stations.

The formulas do not account for the effects of pressure, temperature, tidal forces, the instrument's intrinsic noise (including drift of the sensing element), and random interference. The first three factors are identical for instruments at the order and at the static stations and are compensated for by signal subtraction. The instrument's intrinsic noise and random interference are cumulative; in this problem, we neglect their estimation and correction.

If we assume the approximate equality of the influence of ice variations within the survey points,

$$g_{s,ice} = g_{i,ice},$$

then subtracting the low-frequency data from the static station gravity meter from the mobile gravity meter data will allow us to take into account the influence of ice oscillations, which have the significant negative effect on the quality of the data.

$$g_{i,corr} = g_i - g_{s,ice} = g_{i,const} + g_{i,wind}.$$

As a result, the adjusted value contains the required constant value and the influence of high-frequency interference, which would be excluded by averaging. It is not correct to do the same with ice oscillations. We want to use a short measurement duration (no more than some minutes), to get a high productivity, so the average value of low-frequency interference will strongly depend on waves periods in the survey window, and whether these are complete periods. Thus, excluding one half of the low-frequency wave from the survey cycle at a 250 m (15 seconds) survey point changes the average value by 30 μGal.

It is important to evaluate the possibility of on-ice static station use to improve the quality of gravity survey data collected from ice.

Studies were conducted in February 2024 in the Gulf of Finland during the testing of various measurement methods under ice conditions.

The line of stations was located at distance near 500 m from the coast. The line crossed the proposed channels of the buried valleys.

Weather conditions are an important factor in performing high-precision work due to the influence of wind, pressure drop or temperature on measurements [*Andreev and Muhamadiev*, 2018; *Andreev et al.*, 2023]. During the measurements, the temperature ranged from −3 to −5 degrees, with a south-east wind of 20–40 km/h, gusting up to 60 km/h.

Bathymetry variation between stations along this line is between 5 and 6 m. This bathymetry data is based on 2013 echolocation and was measured with a plumb line on some stations in holes drilled with a hand auger. The ice thickness was measured at research points and ranged from 30–50 cm.

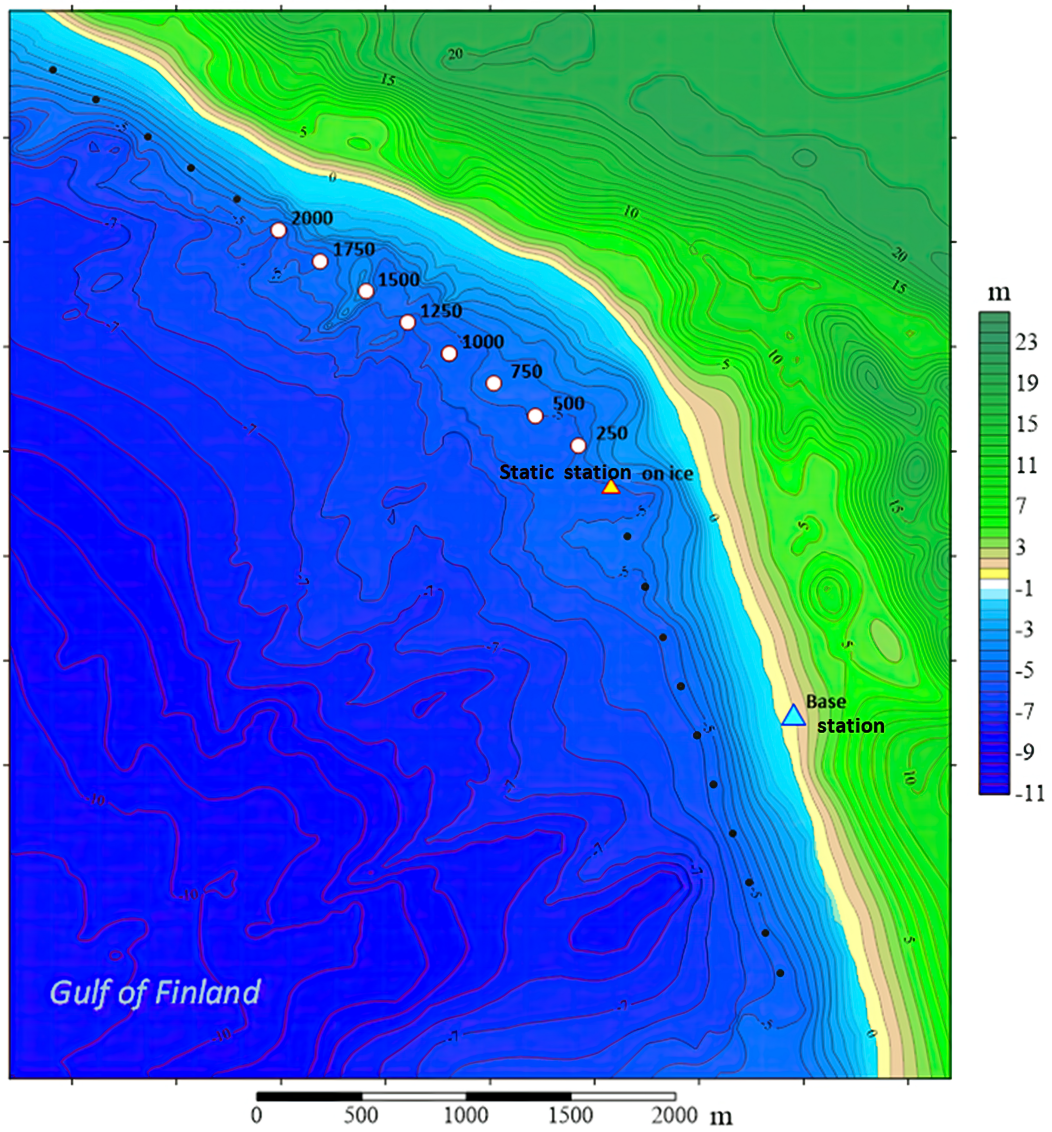


Figure 4. Bathymetry and relief map near the site of gravity measurements on ice. Regular stations with classical processing are shown as black dots. Stations with variation measurements are shown as large white dots. Triangles are static and base stations (static station for on-ice variation measurements and ground base station on the coast for gravimeter drift control).

Two gravimeters were used: Scintrex Autograv CG-5 and Scintrex Autograv CG-6 (Figure 5). The start and end of the measurement loop were at the coastal base station for both meters. But one of them (CG-5) recorded continuous time series for several hours at the one place (st. 0, static station on the ice on Figure 4). CG-5 recorded raw data at a frequency of 6 Hz. The second one was used as ordinary gravimeter with raw data recording. CG-6 raw data had a frequency 10 Hz for gravity data. Measurements with the moving gravity meter were done over 4 cycles of 120 seconds each. Then the gravity meter was moved to the next station at distances of 250 m, 500 m, 750 m, and up to 2 km.

The coordinates and absolute elevations of the stations were obtained using dual-frequency GNSS receivers Javad Triumph 2 using Real Time Kinetic (RTK) differential mode with a remote static station "GEOSPYDER". The nearest static station was 3.5 km away from the site of the work. The processing of the baseline was performed automatically in the Javad Mobile Tools mobile software. The vertical and horizontal standard deviation does not exceed 5 cm. The plumb was used for measurements of ice thickness and bottom depth.



Figure 5. Overview of the study: photo of the work process: Scintrex Autograv CG-5 (*a*) and CG-6 (*a*, *b*) gravity meters, Javad Triumph 2 GNSS receiver (*a*, *b*).

3. Results

We compared "gravity time series" to evaluate correlations. First, a visual comparison of the curves, obtained from the two gravity meters, was carried out (Figure 6). The starting points of the measurements at each station are marked by peaks on the graphs to more accurately synchronize the data from different devices. These peaks are associated with the operator's actions on the instrument, which were done simultaneously, synchronized by radio communication. For further analysis and calculations, such peaks were removed to prevent artificial influence on the calculated correlation characteristics.

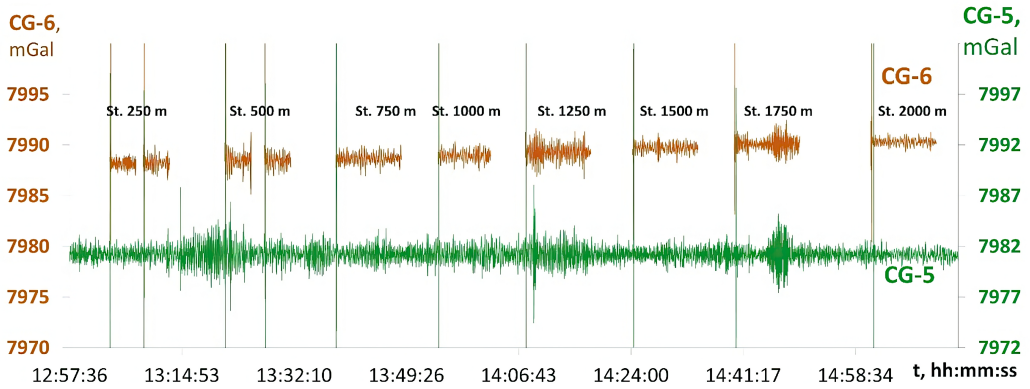


Figure 6. Graphs of gravity time series for measurement points of 250–2000 m (CG-6), gravity meter CG-5 is on the static station (0 m).

Let us analyze the graphs obtained for the station where the CG-5 and CG-6 devices were positioned together and simultaneously recorded gravity field sensor data. When the gravity meters were at the same station the curves appeared visually identical (Figure 7a). The gravity meters were set there with a distance between the devices of about 1 m.

The paired linear correlation coefficient (k) allows us to numerically assess the convergence of the data. But the CG-5 gravity meter records data at a frequency of 6 Hz, while the CG-6 records at 10 Hz. To calculate the paired correlation coefficient between the data, it was necessary to interpolate the data from one of the devices to ensure that gravity field measurements from both gravity meters were available at the same time. It was decided to interpolate the less frequent data from the CG-5 gravity meter to 10 measurements per second, matching the CG-6 device. At this station, the gravimetric data coincide with a correlation of 0.99 with an amplitude of about 2 mGal (Figure 7a). This indicates a low level of the instrument's intrinsic noise and random interference. Such a large amplitude of interference is typical specifically for ice measurements and is not associated only with a change in the heights of the gravity meters – to explain the amplitude of oscillations of

1 mGal, changes in height with an amplitude of meters would be necessary, which are not observed. The most likely cause is the acceleration with which the ice moves.

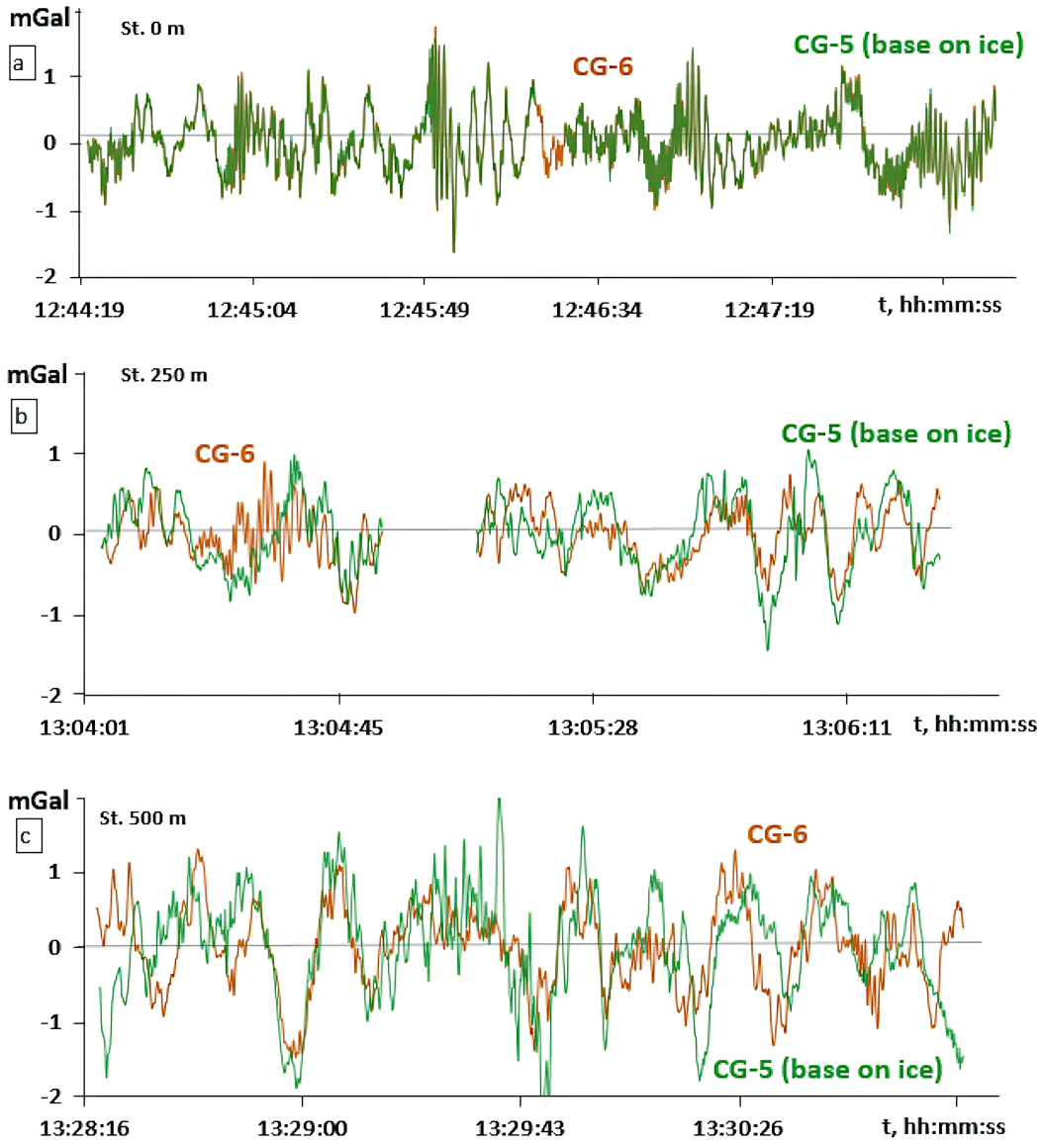


Figure 7. Time series of gravity data obtained with CG-6 during on-ice measurements at stations 0 m (*a*), 250 m (*b*), 500 m (*c*) compared with CG-5 data collected on the static station.

Next, a comparison of the graphs of the data from the CG-5 and CG-6 gravity meters was performed at different positions of the mobile gravity meter.

At the station 250 m (= distance between the gravity meters), the visual similarity was partially lost (Figure 7b), and the paired linear correlation coefficient was 0.55 with approximately 1400 correlated pairs (after excluding the initial recording interval with peaks and the noisy fragment). For the 500-meter distance, a coefficient of 0.49 was obtained (Figure 7c), with the number of correlated pairs equal to 1734. At such a distance, the synchronization of the ice sheet movements, reflected in the gravity meter signals, was significantly lost. Nevertheless, a similar analysis was performed for the further stations, and the correlation coefficients are presented in Table 1. For comparison, values around 0.06 or lower (in absolute value) with approximately 1000 correlated pairs at a standard significance level ($\alpha = 0.05$) indicate random data scatter and a complete lack of connection between the data.

It can be seen here that the correlation coefficient still shows a relationship between the data up to a distance of 1500 m, but the main change occurred at a distance of less than 250 m.

Table 1. Correlation coefficient of the gravity time series for different stations

Station (distance between gravity meters), m	Correlation coefficient of the gravity time series
0	0.99
250	0.55
500	0.49
750	0.24
1000	0.25
1250	0.19
1500	0.07
1750	0.00
2000	−0.03

Next, multitaper spectra were calculated using R. The spectra of the curves at the St. 0 m coincide in the low-frequency (LF) range and differ slightly in the high-frequency (HF) range (Figure 8). For other cases spectra of different gravity meters looks similar with a little difference at all the analyzed frequencies. They have higher values at frequencies 0–0.8 Hz with a decrease in amplitudes by 3–4 orders at frequencies greater than 1.5 Hz.

To identify the main frequencies and amplitudes associated with ice oscillations, we analyzed time series at the land station (Figure 9). They have great differences compared with on-ice stations. We do not observe synchronicity, the amplitude of variations is much smaller and their frequency is higher.

Spectra have important differences with on-ice stations. The lower values can be seen on LF part of spectra with decrease from 1 Hz (Figure 10).

The amplitude of ice-generated noise is two orders of magnitude larger than that on land and it consists of LF data mainly with frequency up to 1 Hz.

If we compare the values of the low-frequency component of the registered signals, the correlation coefficient increases and reaches 0.65 and 0.73 for 250 and 500 m, respectively (Table 2). In this regard, the idea of the proposed method for introducing the correction is as follows. So, next we corrected CG-6 time series with only low-frequency component of CG-5 data. Filtering in the frequency domain, with the separation of a signal into low-frequency and high-frequency components, helped to divide data (Figure 11).

Table 2. Correlation coefficient of the LF and HF components for stations 0–500

Station (distance between gravity meters), m	Correlation coefficient of the gravity time series	Correlation coefficient of the LF component	Correlation coefficient of the HF component
0	0.99	0.98	0.99
250	0.55	0.65	0.23
500	0.49	0.73	−0.03

The goal is to achieve the significant improvement of the data quality. So, out first step is reducing the SD of the time series. LF-correction for stations at 250 m and 500 m between gravity meters shows visually similar variability of data before and after correction (Figure 12).

The noise reduction is not so good as expected based on the ice "oscillation" hypothesis, but it is better than the current one. The numerical comparison of data before and after variations correction (Table 3) shows that our calculations allowed to reduce the SD.

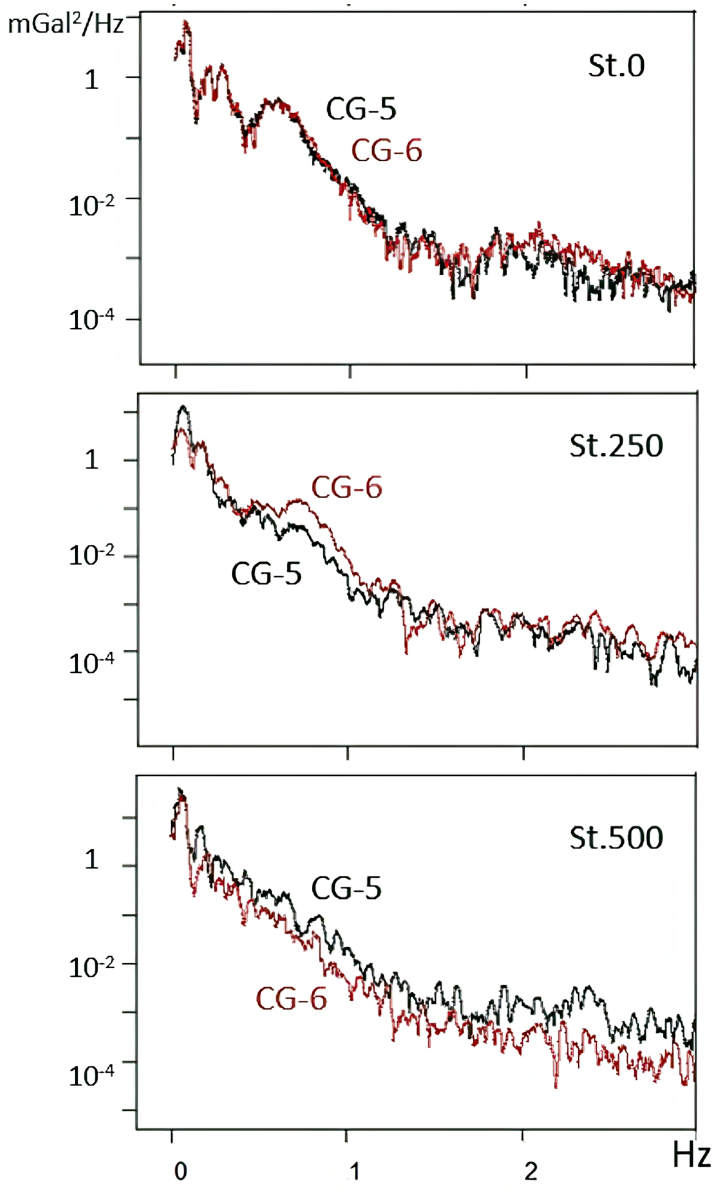


Figure 8. Multitaper spectra of gravity time series at different stations on ice (CG-5 data collected on the static station St. 0, CG-6 data – on St. 0, 250, 500).

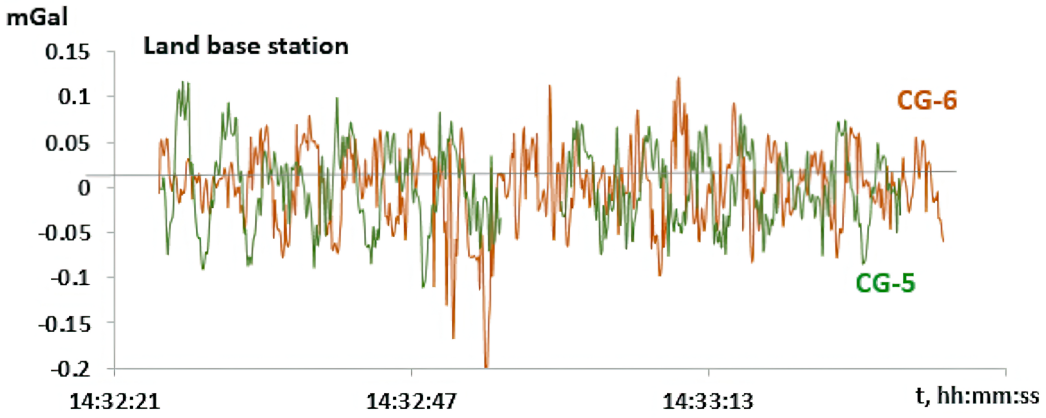


Figure 9. Time series of gravity data obtained on ground, at the land base station.

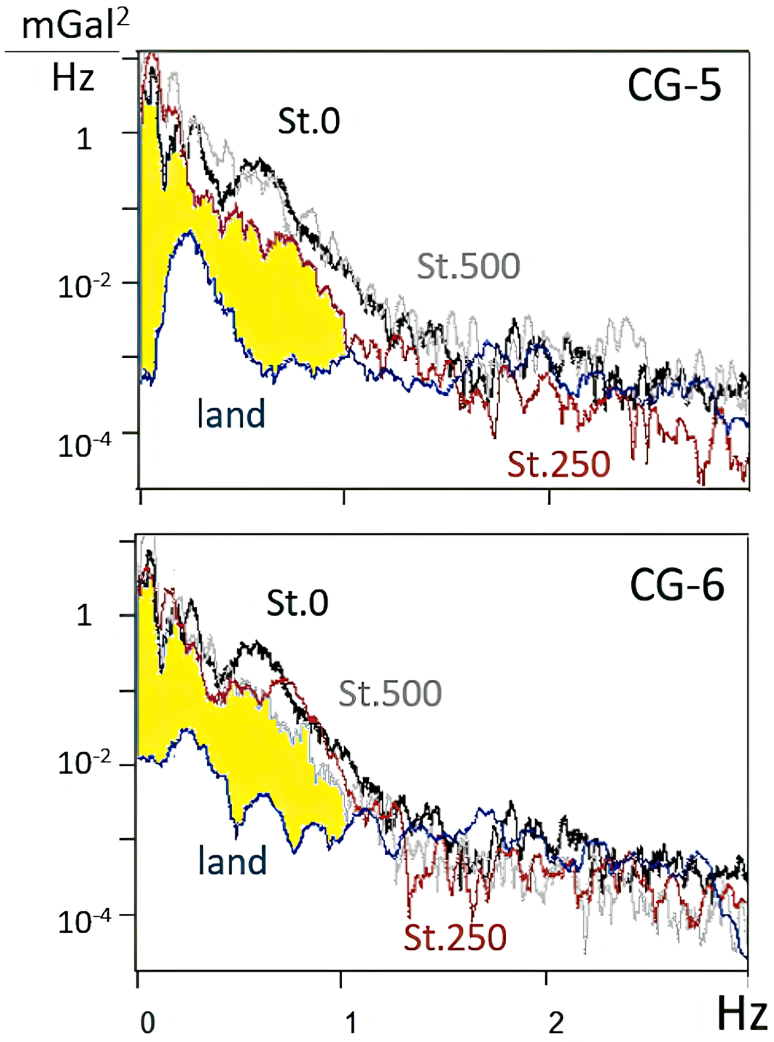


Figure 10. Multitaper spectra of gravity time series for different gravity meters at the ice and land. The difference between ice and land spectrums is yellow.

Table 3 shows the data standard deviations SD before and after correction.

Table 3. SD of the gravity time series before and after correction

Station	SD CG-6, mGal	SD CG-5 (static station on the ice), mGal	SD CG-6 with variations correction, mGal
0	0.43	0.42	0.06
250	0.36	0.45	0.35
500	0.57	0.70	0.51

As a geological result, we have the data along the line, where some points were measured with the technology with static ice station. Besides, all our stations were processed with usual method, and every station was controlled. We calculated the Bouguer anomaly and its local component. An intensive negative anomaly is observed opposite one of the paleochannels mapped on the coast. The anomaly amplitude reaches −1 mGal and it correlates with the results we obtained earlier on the coast [*Budanov et al.*, 2020] (Figure 13). The anomaly of the second buried valley, apparently with less amplitude, adjoins it from the north, forming a "step". It can be assumed that the paleovalleys are filled with rocks of different densities.

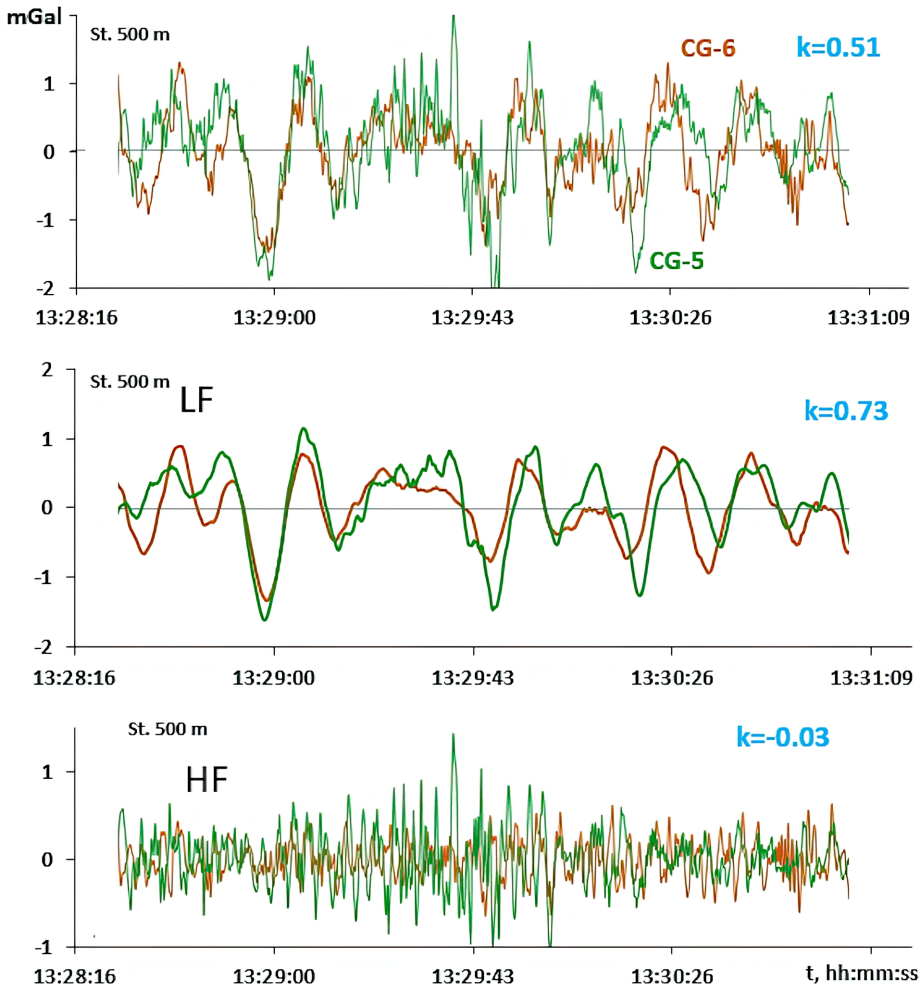


Figure 11. Example of dividing of time series for LF and HF components with a border 1 Hz.

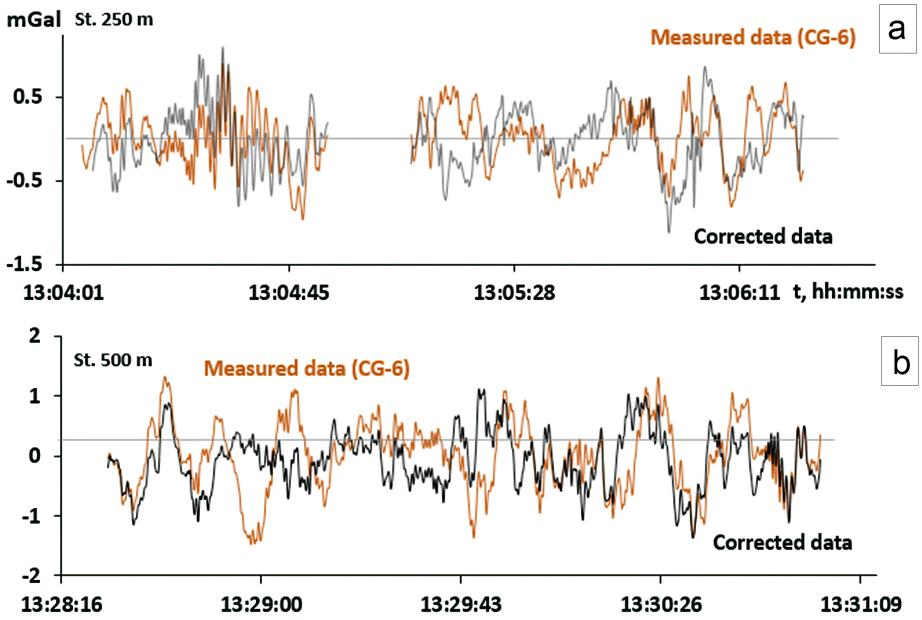


Figure 12. Data before and after variations correction for stations 250 m (*a*) and 500 m (*b*).

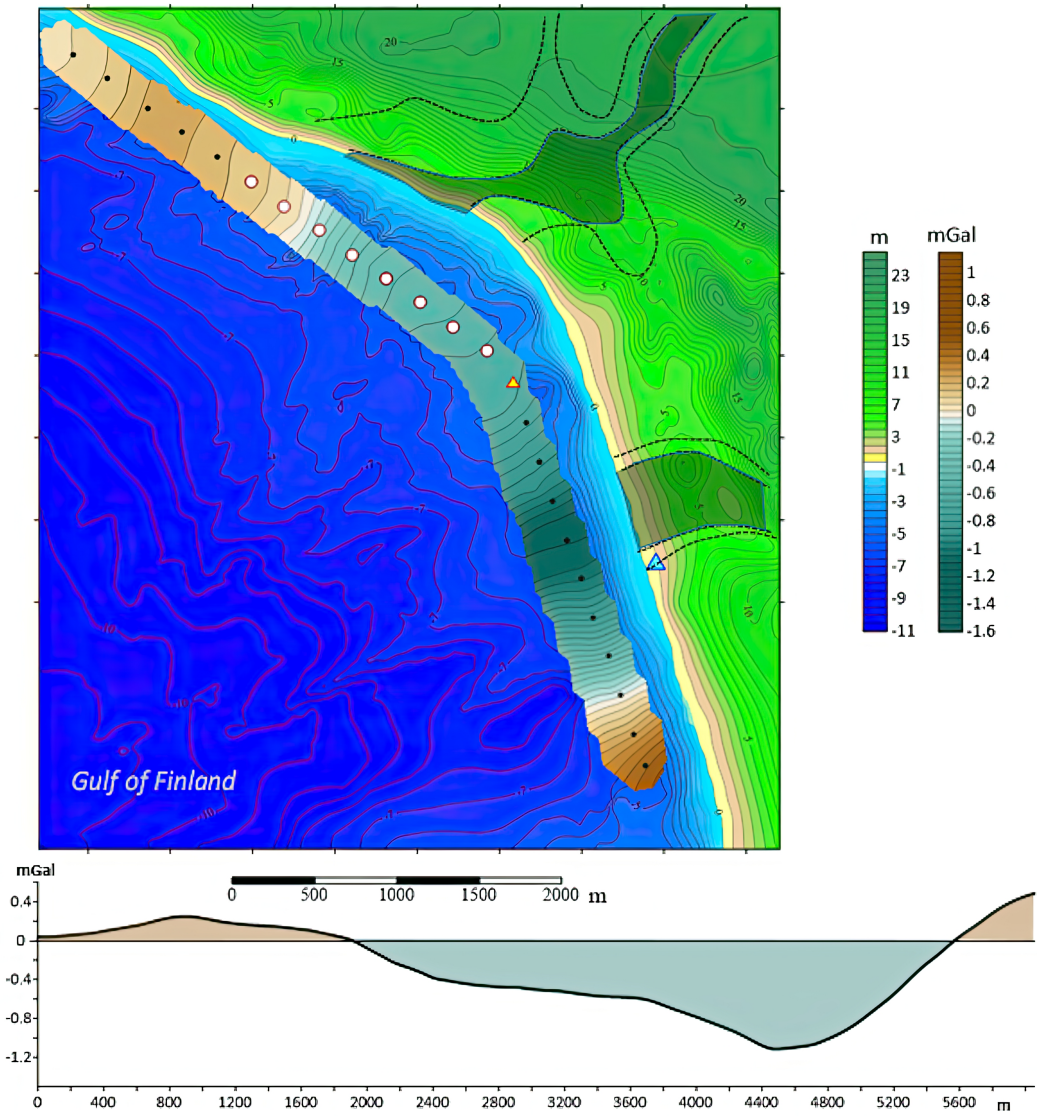


Figure 13. Gravity surveys results collected along the line on ice. Local component of Bouguer gravity field on the map of relief and bathymetry (*a*), and in graph (*b*). Black lines present lithological boundaries and estimated buried valleys from the map on Figure 2. Regular stations with classical processing are shown as black dots. Stations with variation measurements are shown as large white dots. Triangles are base and static stations.

4. Discussion

It is already clear that using a gravity meter as a variation station, based on our results, can only slightly improve the quality of measurements by eliminating noise related to ice oscillations, as the recorded variations likely extend no more than 500 m. The correlation coefficient of the gravity field measurements when the gravity meters were positioned at the same station (1 m apart) was 0.99. When one device was moved 500 m across the ice, the correlation coefficient dropped to 0.49, raising questions about the applicability of this data for noise reduction. However, the allocation of the low-frequency component allows achieving a correlation coefficient of 0.73. The result of one experiment cannot be generalized to significantly different water bodies, where ice movements may be synchronized over larger areas. These results can also vary significantly depending on weather conditions, especially wind. For example, the Gulf of Finland does not freeze completely in typical winters, and there is open water in the deepwater areas, which can significantly influence wave propagation under the ice. We see the need to continue research

to find ways to improve the quality of on-ice gravity surveys. In addition, the method may be useful for solving problems related to filtering out seismic noise in mines [*Bychkov et al.*, 2024]. The variations in gravity data, collected on the ice-covered waterbodies, have spatial differences, probably related to the characteristics of the wave process beneath the ice in the specific water area. Next, the authors plan to examine the variations in the gravity data along a profile perpendicular to the shoreline. In future implementations of this correction method, it would be useful to test measurements at both static and regular stations using the more modern Scintrex Autograv CG-6 gravity meter due to the more convenient raw data recording format. It would also be desirable to incorporate continuous high-precision GPS receiver positioning, which is currently unavailable to the authors for technical reasons. The improvement of data processing could be achieved through calculating the cross-correlation function between gravity meter records for more accurate synchronization of the values over time and tracking wave-like accelerating ice movements.

5. Conclusion

The main practical result of this study is the experimental confirmation that using a static gravity meter on ice can partially suppress noise caused by ice oscillations. However, this method is effective only at short distances. The correlation between the time series of two gravity meters (one static, one mobile) drops sharply from 0.99 (at 1 m) to 0.49 (at 500 m). For the low-frequency component of the signal, which corresponds to ice bending, the correlation remains moderate (up to 0.73 within 500 m), but this is insufficient for full noise correction. Our results answer the main research question: can we improve the quality of on-ice gravity surveys using a static station? Yes, but only for very limited areas – within the first hundreds of meters. At distances of 250 m and 500 m, the standard deviation of the corrected data decreased only slightly (from 0.36 to 0.35 mGal and from 0.57 to 0.51 mGal, respectively). This improvement is not yet sufficient for interpreting anomalies with amplitudes up to 1 mGal. Thus, the hypothesis that an ice sheet behaves as a laterally uniform elastic membrane proved to be only partially true. Travelling waves, wind-induced vibrations, and cracks break the spatial coherence of ice movements beyond 250–500 m. The practical implication is clear: the proposed correction method is suitable only for detailed surveys over small targets (e.g., shallow paleochannels) with dense station spacing.

In future work, we will analyze long-term time series from static stations to better characterize the low-frequency (LF) component. This component could be crucial for planning gravity surveys on ice, as the minimum duration of gravity measurements must exceed the full period of ice oscillations. The LF signal is expected to vary between different water bodies and therefore requires site-specific measurement using static observations. We also plan to test this approach on smaller, fully frozen lakes without open water, and to include continuous high-precision GNSS measurements to separate vertical displacement from acceleration noise. The ultimate goal remains achieving a resolution of tens of μGal for on-ice gravity surveys.

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