Russian Journal of Earth Sciences

Express Method of Field Measurements to Create a Three-Dimensional Model of an Ice Formations

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Abstract: This article describes a new, efficient, and quick method for conducting field measurements to create a three-dimensional model of ice formations. The method involves the use of a total station geodetic instrument, a powerful LOZA georadar, and an unmanned aerial vehicle with a camera. The technique is especially useful for measuring unstable ice formations with horizontal dimensions ranging from 50 to 300 meters. Examples of applying this method during winter fieldwork on the Sakhalin Island's eastern shelf in 2019 are provided.

Keywords: field measurements of ice characteristics. ice formations, 3-dimensional model, georadar LOZA, unmanned aerial vehicle.

Citation: Pisarev, S. V., A. P. Vergun, A. I. Berkut, F. P. Morozov, P. A. Morozov, and P. L. Vorovsky (2024), Express Method of Field Measurements to Create a Three-Dimensional Model of an Ice Formations, *Russian Journal of Earth Sciences*, 24, ES3008, EDN: ALPCXQ, https://doi.org/10.2205/2024es000911

Research Article

Received: 27 March 2024
Accepted: 13 May 2024
Published: 16 August 2024

Introduction

When designing structures in the sea covered by ice, it is necessary to take into account the ice loads that may be applied to the structures. In order to calculate these ice loads, a significant amount of information is required, including information about the morphometric characteristics of ice formations (IFs) – their geometric dimensions, the relief of their upper and lower surfaces, their thickness, and so on. An IF is understood to be an element of the ice cover that is characterized by a specific set of features – for example, ice fields, ice ridges, floebergs, rubble fields, and icebergs [*GOST R 58283-2018*, 2018; *World Meteorological Organization (WMO)*, 2014].

The most frequently used modern method for measuring the relief and the dimensions of the upper (above the water level) and lower (beneath the water level) parts of the IF is the determination of the horizontal coordinates and heights of points on the IF with a distance between the points of 5 m (in some cases 2.5 m) and subsequent mechanical drilling of ice at these points to measure ice thickness. Coordinates are determined in the local coordinate system associated with a concrete IF. The relief of the IF surfaces is determined relative to the water level in the ice hole drilled at the zero point of the local system of coordinates [*Mironov, Ye. U. et al.*, 2015].

If thermal drilling is used during the period of time that was spent on mechanical drilling, then, since thermal drilling is faster, more ice holes can be drilled and thus potentially obtain more detailed information about the thickness of the IF. It should be noted that the equipment for performing thermal drilling weighs 100–200 kg, which is about an order of magnitude more than the weight of the equipment for mechanical drilling. The personal experience of the authors of this article indicates that moving thermal drilling equipment among ice ridges requires considerable time.

The surface topography of the ice sheet can be determined more accurately using a geodetic laser scanning system, while the underwater topography can be measured using systems that use side-scan sonars. [*Mironov, Ye. U. et al.*, 2015]. Laser scanner and side-scan sonar measurements require several hours of continuous operation because of the methods of measurement used by these devices themselves, the need to change the position of the scanner and sonar in order to measure the entire ice field, as well as the need to drill new ice holes at each new position of the sonar. If it is necessary to stop the measurements because, for example, the ice field has been destroyed, the evacuation of the scanner and the sonar to a more stable platform (a ship or shore) must be done carefully and cannot be completed within less than 15 to 20 minutes. In addition, both devices are quite heavy (several dozen kilograms) and expensive (10 million Russian rubles or more). During the work, both devices usually require an electrical generator, which further adds to the weight of the devices if they need to be quickly evacuated.

When using a laser scanner, there is an additional difficulty due to the scanning of the surface occurring in a horizontal direction and within the line of sight of the scanner. Therefore, in order to scan a hammock with a ridge that is taller than the scanner on a tripod, it is necessary to scan it from at least two different sides. If the ice cake (or small ice cake, thin young ice or open water), is close to one side of the hummock, it is not possible to install the scanner there. This means that it is also not possible to measure the complete topography of the ridge in such cases.

When the authors of this article carried out field winter ice surveys on the eastern shelf of Sakhalin Island in 2016, it turned out that 80% of the largest, in terms of volume, IFs in this area were hummocky or layered first-year ice with horizontal sizes of 50–300 m only. The landing to the such IFs from icebreaker, for performing a set of measurements, has always been accompanied by the risk of a quick split of the IF due to the difference in the drift vectors of the ship and ice [*Pisarev*, 2016]. In order, on the one hand, to ensure that three-dimensional (3D) IF models are created with maximum accuracy, and, on the other, to be able to, if necessary, quickly evacuate the measuring equipment from an ice floe in case of emergency, in 2019, when studying the IFs of the eastern Sakhalin shelf again, a new, extremely effective express method of measurements was implemented.

In this article, we will briefly describe how field measurements were conducted on drifting IFs, how the results were processed, and provide several examples of three-dimensional models of the IFs studied on the eastern shelf of Sakhalin in the winter of 2019.

Field Measurements

During field work in 2019 on the eastern shelf of Sakhalin Island among the drifting ice, the IFs of the largest volumes were selected. High-resolution satellite images analyses, visual observations from a helicopter, from an unmanned aerial vehicle (UAV) and from the icebreaker's navigation bridge were used for the selection. Unfortunately, even the largest local IFs were potentially unstable. The first cause of instability is a collision, sometimes leading to a split, of the selected IF with the icebreaker and (or) other surrounding ice floes. The second reason is the swell, which on some days spread from the ice-free Pacific Ocean and destroyed the IF on which the measurements were carried out (Figure 1, right).

After a group of specialists with equipment was landed on the selected IFs, a wide range of measurements of various characteristics of the ice and the water column under the ice was carried out. In relation to the topic of this article, five main devices were used to measure the 3D characteristics of a selected IF – a set of geodetic milestones (see Figure 1 (right), Figure 2), a 50 m long topographic tape measure, a Kovacs ice drilling equipment, a total station Sokkia SET230 RK3, a ground penetration radar (GPR) LOZA B and a UAV DJI Phantom 4 PRO.

The surface of each selected IF was marked by geodetic milestones with a step of 5 m. (The markup was carried out in full accordance with [*Mironov, Ye. U. et al.*, 2015]). As a rule, the area covered by milestones was smaller than the entire IF because of two main reasons. Firstly, frequent cracks in the ice at the edge of the IF made it impractical to stay in that area for any significant period of time. Secondly, it was unsafe to stay for an extended

Figure 1. The most voluminous IF among the 22 investigated during the 2019 winter expedition was numbered 18 and was moored to an icebreaker on its starboard side. Length of the icebreaker is 73 meters and its beam athwartships is 15.5 meters. A photo was taken using a UAV (left). A crack on the IF numbered 14 formed due to swell arriving through drifting ice from the ice-free Pacific Ocean (right).

period near the ice anchors that the icebreaker used to moor to the IF. At each IF, two to four thick wooden logs, installed almost vertically into holes drilled into the ice, served as ice anchors (Figure 1). When we worked on three of the twenty-two IFs we surveyed, the load on the mooring ropes became so great that the logs snapped and flew apart in unpredictable directions. However, we determined the boundaries of each IF by measuring the coordinates of a station rod with an ejector at several points along the boundary.

In the case that an ice ridge existed on the selected IF, rows of geodetic milestones were laid perpendicular to the ridge at its intersection point. One of the lines was laid in the place of the maximum heights of the ice ridge. Each milestone received its own unique number. The letters in the number designate a number of milestones located approximately parallel to the moored icebreaker or ice ridge under study, although the number designates milestones in a direction perpendicular to the icebreaker or ridge. Part of the IF, covered with milestones, formed a geodetic polygon (Figure 2).

After marking the geodetic polygon, a total station survey was conducted. The purpose of the survey was to determine the height of the IF at the points where milestones were installed and build a map for the placement of milestones in a local coordinate system. A total station was placed on flat ice, which was labeled as the zero of horizontal coordinates within the local 3D coordinate system related to the specific IF. At the site where the total station was mounted, an ice hole was created with an auger bit to the water line, and a vertical zero mark was attached to the water level within the hole in the local 3D coordinate system. Subsequently, the local positions of each point where geodetic milestones were installed, as well as additional points along the perimeter of the IF and the locations where 3–5 identification markers were placed for UAV photography, were identified. Sheets of bright, non-white building insulation measuring 20×20 cm were fixed to the IF surface as identification marks. At each installation point, mechanical drilling was used to determine the ice thickness.

The work listed in this section, with the exception of determining the coordinates of identification marks, is not directly related to the express method we propose, but it is the most frequently used [*Mironov, Ye. U. et al.*, 2015] for creating a 3D model of the IF. During the 2019 expedition, we used the most frequently used method only because we were not yet completely confident in the effectiveness of our new express method.

The implementation of our new method involves performing only part of the work above – installing a total station and installing two extreme milestones along each line, with determining their coordinates and the thickness of ice in those coordinates using mechanical drilling. Then, determining the coordinates for identification marks and other points along the boundary of the IF is done.

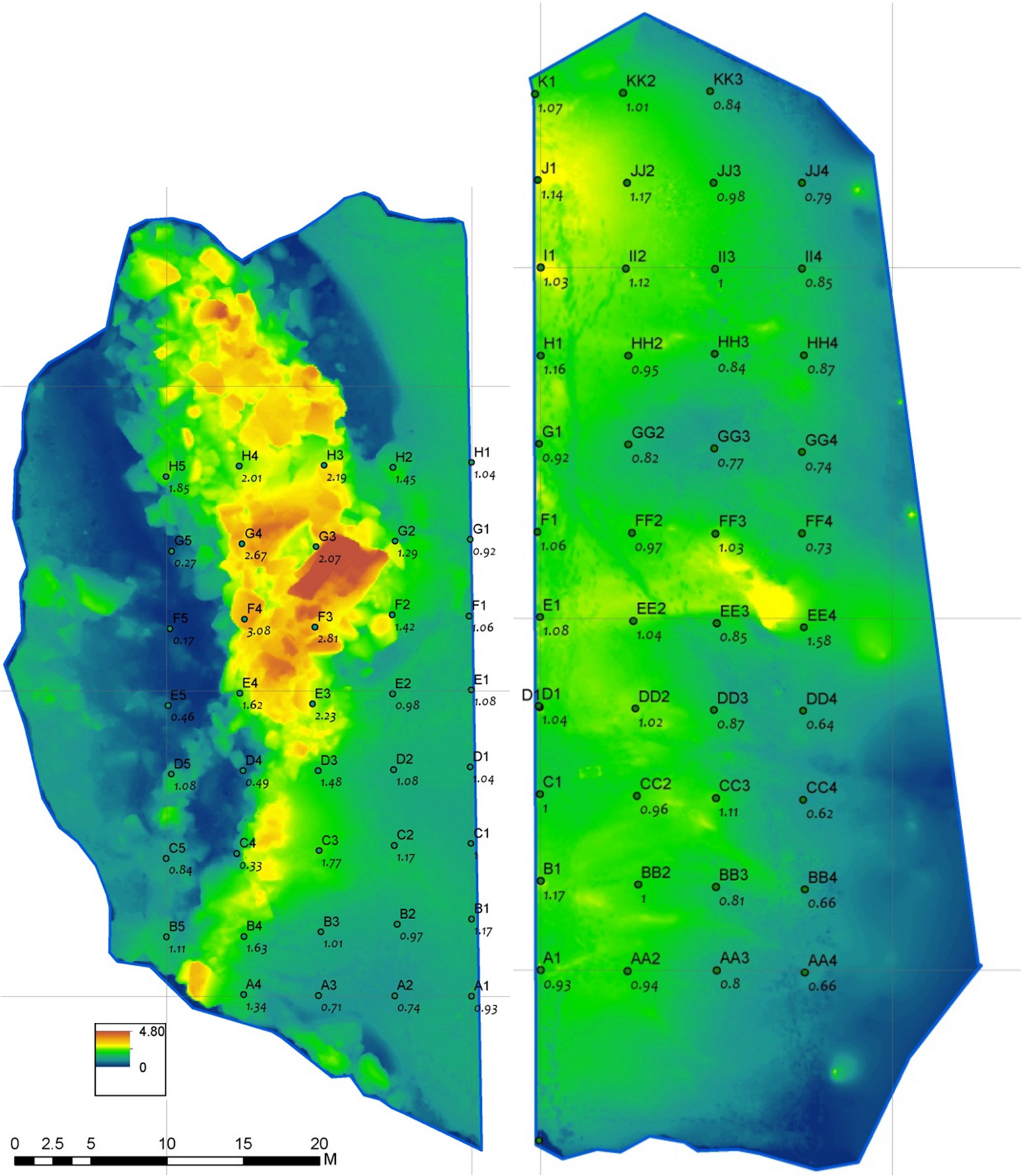

Figure 2. Surface topography of IF number 18: A set of measurements was carried out on this thick IF over two days, and the results are shown separately for the hummocky part (left) and flat part (right). Dots indicate the positions of milestones. Letters and numbers above the dots are the identification numbers of the milestones of the polygons, while the numbers below the dots indicate the heights in the local coordinates determined using a total station. Color indicates the height determined by the UAV.

Our new method suggests using an UAV instead of a total station or laser scanner to measure the topography of the IF. UAVs have been used for almost 10 years in industrial and scientific activities when performing topographic, geodetic, cadastral works, as well as engineering and geodetic surveys. When processing data from UAVs, a well-tested complex of photogrammetric works is being performed to obtain a digital terrain model. An example of the application of a well-known method using UAVs and photogrammetry to determine the relief of the upper surface of sea ice is well presented in [*Borodkin et al.*, 2018]. We used UAV for our purposes following the algorithms developed in geodesy and cartography. To obtain a series of photographs of the surface of each of the measured IFs, we performed UAV flights in manual mode, at an altitude of 80–100 m with a photographing frequency of 30 frames per minute and with an overlap of images by 60–80%. The UAV camera has always been aimed strictly at the nadir. UAV takeoffs and landings were carried out both from the ice surface and from the deck of the icebreaker. The duration of flights in all cases did not exceed 15 minutes.

A continuation of the application of our new method was the measurement of ice thickness using the GPR LOZA B along each row of geodetic milestones and in the middle lines between them. The spatial resolution of the GPR measurements was 0.2 m along the rows of milestones, and 2.5 m between the rows. The characteristics of the sea salt ice thickness meter, GPR LOZA, which is new for ice researcher, and the experience of successful use are detailed in [*Morozov et al.*, 2021]. In areas with great variation in ice topography, we found it helpful to take additional mechanical thickness measurements to verify our GPR readings.

Data Processing

Based on the results of the UAV survey, a digital elevation model (DEM) was created for every IF using Agisoft PHOTOSCAN. DEM is a collection of heights taken at the nodes of a certain network of points with coordinates and encoded in numerical form. The method for processing UAV survey data is described in detail in literature [*Eltner et al.*, 2016; *Koci et al.*, 2017]. Based on our measurements in 2019, we created DEMs for the IFs first with a step size of 0.1 meters vertically and horizontally.

The technique for processing GPR measurements using the program package supplied with it is described in [*Morozov et al.*, 2021]. The GPR measurement area was smaller than that covered by the DEM, as the radar survey was only carried out within the established geodesic milestones.

It is necessary to note that, since the dielectric constant of sea ice is 5–6 and that of air is 1, the direction of the probing beam from the GPR towards the lower hemisphere is determined. The cone angle of this diagram can be calculated by taking the arcsine of 1 divided either by the refractive index or by the square root of the dielectric constant in the medium. For the diagram of GPR LOZA, the angle is 26 degrees [*Morozov et al.*, 2021], and the diameter of the integral reflection area, with an average ice thickness of 9.2 meters, such as for IF 18, exceeds 2.5 meters.

Taking into account the size of the reflection zone, it was decided to increase the distance between GPR measurements along the rows of geodetic milestones from 0.2 m to 1 m. The horizontal spacing of the DEM was also increased from 0.1 m to 0.5 m. Then, using standard two-dimensional linear interpolation from the MATLAB data processing software, the ice thickness measured by-GPR were transferred to the coordinate grid of DEM points. After that, the heights of the initial DEM at grid nodes were subtracted from the measured ice thickness at these same nodes. As a result, the DEM was taken as the surface portion of the 3D IF model, and the measured thickness minus the DEM height was taken as underwater part of IF.

Examples of the 3D Models of the IFs

As can be seen in Figure 1 (left part) and Figure 2, IF 18 consists of a flat and hummocky area. Due to the large average ice thickness of IF 18 (9.2 m), the application of the most frequently used method for determining ice thickness through mechanical drilling had to be done over two work days. It was decided to present the surface features and 3D models of each area separately in Figure 2, 3, 4, 5.

The reader familiar with the characteristics of the ice on the eastern shelf of Sakhalin Island knows that the oldest and thickest ice there is first-year one. Even in severe winters, the thickness of such smooth ice does not exceed 1.2 meter [*Astafyev et al.*, 1997]. Therefore, it's strange that the flat portion of IF 18 has a thickness of about nine meters (Figure 3, 4, 5). This large thickness of IF 18 can be explained by the fact that it consists of layered, first-year ice.

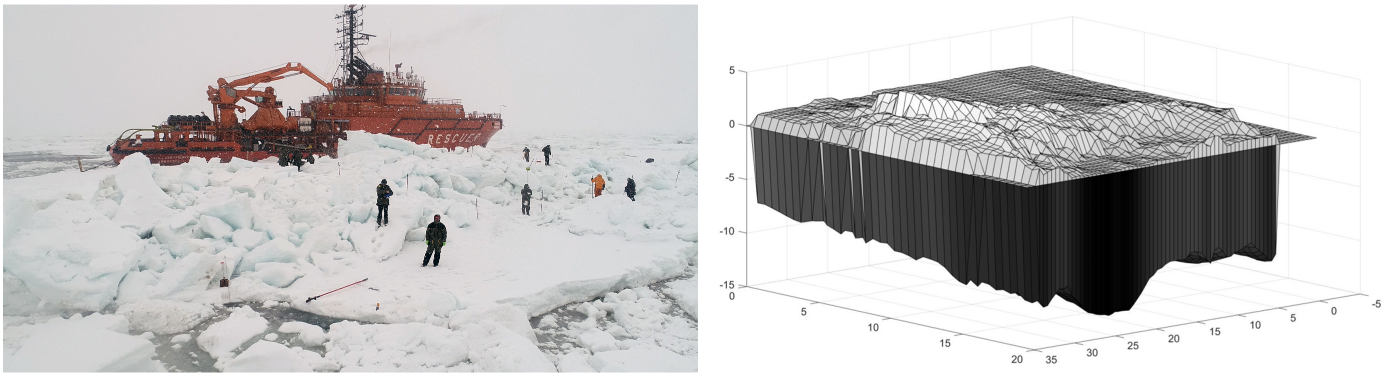

Figure 3. View from a UAV of the hummocky part of IF18 (left). 3D model of IF18 from one of the possible viewing angles (right). In a 3D image, 1 m vertically is equal to 10 m horizontally. The horizontal surface corresponds to sea level. View of the IF18 3D model from approximately the same angle as in the photo on the left.

Depicted as a monolith in the 3D model, the flat part of IF 18 actually consists of more than ten compressed layers of first-year ice blocks. The horizontal dimensions of the blocks are tens of times larger than their vertical dimensions. These layers can be seen in GPR measurements, photographs taken by remotely operated underwater vehicles, and in ice core structures. [*Morozov et al.*, 2021; *Pisarev and Tsvetsinskiy*, 2021].

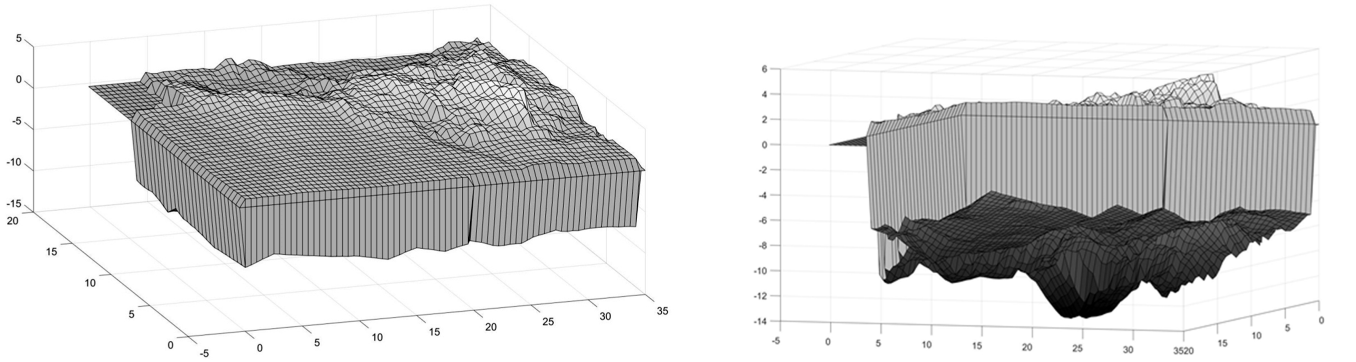

Figure 4. 3D model of IF 18. In the figure, 1 meter vertically is equal to 10 meters horizontally. The horizontal surface corresponds to sea level. Views of IF18 from the sides of the beginning of GPR profile measurements (Figure 2, left) and from the side of an icebreaker (Figure 1, 3, 5, left). The images in the current figure differ only due to the choice of different sea level slope angles.

An experienced ice observer can identify IF of layered first-year ice among the floes of regular, one-layer first-year ice due to its abnormally high surface position above sea level. The finding that many of the largest IF on the eastern shelf of Sakhalin Island are made up of layered first-year ice is an important discovery from our expeditions in 2016 and 2019. [*Pisarev and Tsvetsinskiy*, 2021]. However, a more detailed description of the properties of layered first year ice and the possible reasons for its formation are beyond the scope of this article.

The 3D model of the part, consisting of hummocks, of IF 18 also looks unusual in the case that such a shape was created as a result of only the ridging process. (Figure 3, 4, 5). Although the keel of the ridge is noticeable (the maximum thickness, according to both mechanical drilling and GPR, is slightly more than 14 meters), in general, it seems that the layering process played an essential role in creating the volume of IF.

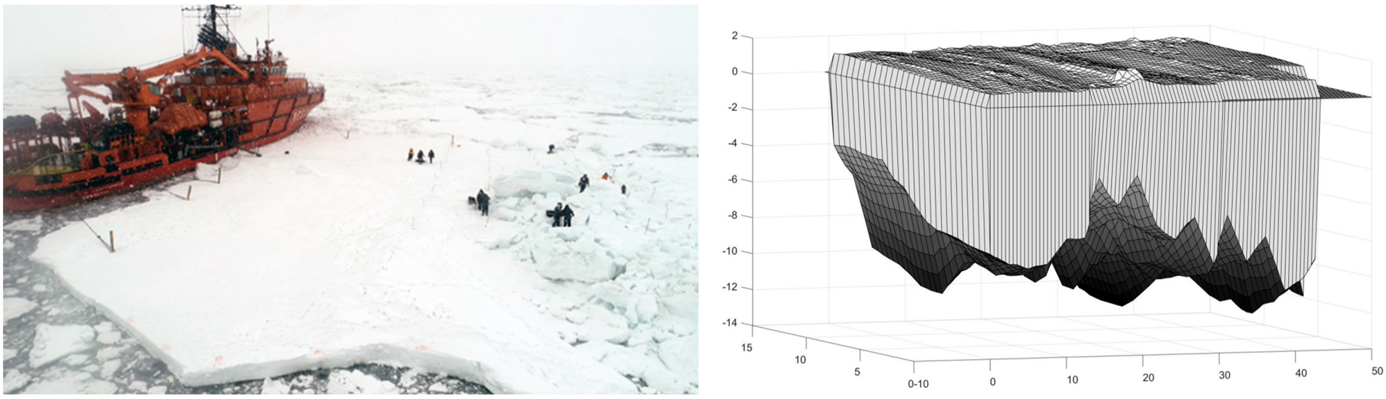

Figure 5. The view from a UAV of the flat part of IF 18 (left). A 3D model of IF18 from one of the possible viewing angles (right). In a 3D image, 1 meter vertically is equal to 10 meters horizontally. The horizontal surface corresponds to sea level. The horizontal axis from −10 to −50 meter is located parallel to the icebreaker in Figure 1 (left) and the left part of Figure 5.

Conclusions

The first advantage of our express method compared to the more widely used one is its ability to quickly remove our light instruments from a collapsed ice field. When implementing our method to build a 3D model of IF, each specialist performing measurements on an unstable IF had no more than 5–10 kg of measuring equipment with him. Each specialist could dismantle their equipment in 1–3 minutes and quickly evacuate aboard the icebreaker.

Another method, which was mentioned earlier in this article [*Borodkin et al.*, 2018] and which, like our method, can be defined as new, also involves the use of an UAV to build the relief of the upper part of the IF as part of creating a 3D model. However, to measure the lower part of the LO, this new method involves the use of a round-scan sonar. The sonar was lowered using a tripod and a hand winch on a steel cable to a depth of up to 95 m through pre-drilled holes with a diameter of 0.5 m located evenly along the perimeter of the studied ice object at a distance of up to 60 m. The survey through the one hole covers a circle with a radius of 100 m, in the center of which there is a sonar. Survey from a single point without taking into account preparatory work, such as drilling an ice hole, deploying and configuring equipment, takes, according to the authors, 1.5 hours. According to our estimates, before the sonar begins its measurements at a depth in the water column, the entire complex of equipment preparation will take at least 2 hours. The evacuation of the sonar itself and heavy auxiliary equipment from the measuring point will take about one hour in the most favorable case. In general, the method of creating a 3D model using UAVs and round-scan sonar is definitely not suitable for rapid evacuation, and, it seems, that this method is not as fast as the one we propose in this article.

Thanks to the smaller volumes of mechanical drilling and the measurements of coordinates for geodetic markers, our express method, along with providing the possibility of rapid evacuation, also saves time when measuring a specific IF. The amount of time that can be saved varies depending on various factors in expeditionary work, and it may not be possible to calculate in advance for all possible situations. As an example, let's estimate the time savings for working on IF 18, which has already been discussed here.

During measurements at IF18, in order to implement the most frequently used measurement method, 82 geodetic milestones were installed and their three-dimensional coordinates determined. In addition, the coordinates of 17 more points along the boundary of the IF and 5 identification marks for referencing UAV images were also determined.

The use of our express method in this part of fieldwork allows us to reduce the number of milestones on the geodetic polygon from 82 to 27. Although this involves the measurement of local coordinates for the remaining 5 identification marks, it does save time by avoiding the need to install and determine the coordinates for 39 additional points on the IF18 geodetic polygon. Assuming the qualifications of two surveyors, this saves 2.8 hours of measurement time (or approximately 50% of the total time spent measuring local coordinates on the geodetic polygon).

To measure the thickness of the ice using mechanical drilling, 390 running meters were drilled in the hummocky area of IF 18 and 357 running meters in the flat area. The total time spent on drilling simultaneously by two qualified teams of three people was approximately 12 hours of continuous work. At the same time, two specialists used a GPR to measure 15 profiles in the hummocky area and 21 in the flat area. About 3 hours were spent taking measurements along these profiles. Most of the time was spent on measuring the ice thickness with the GPR from the top of the ice blocks that form the hummocks. Measurements with the LOZA B GPR, with control drillings at the start and end of each second profile, can reduce drilling time by about 50%. Drilling at a single control point for each second profile, as experience with GPR measurements has shown, is also sufficient, allowing for a time savings of about 75%.

As a result, using our express method for performing measurements in order to create a 3D model of ice formation for IF18 allow us to spend approximately 4 hours instead of 12 hours when using the most frequently used method.

Acknowledgments. This research was supported by the State Task of the Shirshov Institute of Oceanology FMWE-2024-0016 and RSF grant of Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation No. 22-12-00083 “Deep GPR: theory, methods, experiment”.

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