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INFORMATIVENESS OF GROUND PENETRATING RADAR METHOD FOR INVESTIGATIONS OF THE GLACIERS ON GALINDEZ, WINTER AND SKUA ISLANDS (THE ARGENTINE ISLANDS, RESULTS FOR THE PERIOD APRIL TO NOVEMBER 2017)

A. P. Chernov

Institute of Geology, Taras Shevchenko National University of Kyiv, 90 Vasylkivska Str., Kyiv, 03022, Ukraine,; State Institution National Antarctic Scientific Center, Ministry of Education and Science of Ukraine, 16 Taras Shevchenko Blvd., Kyiv, 01601, Ukraine, achernovp@gmail.com

Abstract. In this paper results of ground penetrating radar (GPR) surveying of island's glaciers are shown. The main **objectives** were testing of VIY-3 300 GPR in weather conditions of Antarctica and check which information about glaciers can be obtained with this equipment. **Methods:** results of GPR surveying on Galindez Island were compared with results of video-impulse radiolocation method (1998 year), vertical electric-resonance sounding (2004 year) and meteorological data (2014-2017). Common offset modification of the GPR method was applied; central frequency of ground coupled antenna: 300 MHz. **Results:** GPR profiles were recorded along 2 glaciers on Winter island, 2 glaciers on Skua island and along 1 glacier on Galindez island. Several anomalies were indicated, which interpreted as layering of the ice, glacier's bed, fissures, voids, areas of higher moisture content and potential glacier conduits. Further GPR monitoring of the glaciers' interior should be done to obtain clear information about mentioned heterogeneities and about their future development. **Conclusions:** VIY-3 300 GPR works properly in conditions of Antarctica and is suitable for identification of heterogeneities in glaciers up to 27.5 meters. Mentioned equipment can be easily transported, recording of the profiles on mentioned glaciers could be done by one person. Speed of work is 300 meters in 20 minutes for new area (first time surveying on glacier) and 600 meters in 30 minutes for monitoring site (while monitoring on Galindez island).

Key words: Ground penetrating radar (GPR), glacier, islands' glaciers, ice, Antarctica, VIY-3 300, 300 MHz, common offset.

ІНФОРМАТИВНІСТЬ ГЕОРАДАРНОГО МЕТОДУ ПРИ ДОСЛІДЖЕННІ ЛЬОДОВИКІВ НА ОСТРОВАХ ГАЛІНДЕЗ, ВІНТЕР ТА СКУА (АРГЕНТИНСЬКІ ОСТРОВИ, РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ ЗА ПЕРІОД КВІТЕНЬ-ЛИСТОПАД 2017)

А. П. Чернов

ННІ «Інститут геології» Київського національного університету імені Тараса Шевченка, м. Київ; Державна установа Національний антарктичний науковий центр МОН України, м. Київ, achernovp@gmail.com

Реферат. В роботі представлені результати георадарних досліджень острівних льодовиків. **Мета досліджень:** випробувати придатність георадара VIY-3 300 для роботи в умовах Антарктики та перевірити інформативність застосування даної апаратури для дослідження льодовиків. **Методи:** результати георадарних досліджень льодовика на острові Галіндез порівнювались з результатами відеоімпульсного радіолокаційного методу (результати 1998 року), вертикального електрорезонансного зондування (2004 р.) та з даними метеорологічних досліджень (2014-2017). Застосовувався метод сталого розносу між антенами георадара; центральна частота антени: 300 МГц. **Результати:** Записано профіля вздовж 2 льодовиків на острові Вінтер, 2 льодовиків на острові Скуа та одного льодовика на острові Галіндез. Зареєстровані аномалії проінтерпретовані як шаруватість льоду, підошва льодовика, тріщинуватість, пустоти, місця підвищеної вологості та потенційні водні канали. Для точної характеристики неоднорідностей та для прогнозу їх подальшого розвитку, треба робити подальший георадарний моніторинг льодовиків. **Висновки:** Георадар VIY-3 300 цілком придатний для роботи в умовах Антарктики та на записаних профілях є інформація про неоднорідності в льодовиках до глибини 27.5 метрів. Апаратура легко транспортабельна та польові дослідження на згаданих острівних льодовиках можуть проводитись однією людиною. Швидкість роботи складає 300 метрів за 20 хвилин при дослідженні нової ділянки та 600 метрів за 30 хвилин при моніторингових дослідженнях за наміченою траєкторією.

Ключові слова: Георадар, льодовик, острівні льодовики, Антарктика, VIY-3 300, 300 МГц, сталий рознос, лід.

ИНФОРМАТИВНОСТЬ ГЕОРАДАРНЫХ ИССЛЕДОВАНИЙ ЛЕДНИКОВ НА ОСТРОВАХ ГАЛИНДЕЗ, ВИНТЕР, СКУА (АРГЕНТИНСКИЕ ОСТРОВА, РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЙ ЗА ПЕРИОД АПРЕЛЬ-НОЯБРЬ 2017)

А. П. Чернов

УНИ «Институт геологии» Киевского национального университета имени Тараса Шевченко, г. Киев; Государственное учреждение Национальный антарктический научный центр МОН Украины, г. Киев, achernovp@gmail.com

Реферат. В данной работе представлены результаты георадарных исследований островных ледников. **Цели работ.** Тестирование георадара VIY-3 300 на работоспособность в условиях Антарктики, определение информативности оборудования для исследования ледников. **Методы**: результаты георадарных исследований на острове Галиндез сравнивались с результатами метода видео-импульсной радиолокации (1998 год), вертикального электрорезонансного зондирования (2004 год) и метеорологическими данными (2014-2017). Применялась модификация георадарных исследований с постоянным разносом между антеннами, центральная частота антенны: 300 МГц. **Результаты исследований.** Георадарные профиля были записаны вдоль 2 ледников на острове Винтер, 2 ледников на острове Скуа и вдоль одного ледника на острові Галиндез. Идентифицированные аномалии проинтерпретированы как слоистость льда, ложе ледника, трещины, пустоты, места повышенной влажности и предполагаемые водные каналы. Для точной характеристики неоднородностей и прогноза их дальнейшего развития необходимо проводить дальнейшие георадарные мониторинговые работы на ледниках. **Выводы.** Георадар VIY-3 300 можно успешно применять для работы в Антарктических условиях. Этой аппаратурой идентифицируются неоднородности в толщи ледников до 27.5 метров. Георадар легко транспортируется, запись профилей на упомянутых ледниках может делать один человек. Скорость работы составляет 300 метров за 20 минут на новой местности и 600 метров за 30 минут при мониторинговых исследованиях по намеченной траектории.

Ключевые слова: Георадар, ледник, островные ледники, Антарктика, VIY-3 300, 300 МГц, постоянный разнос, лед.

1. Introduction

The earliest information about glaciological observations in the area of the Antarctic Peninsula is dated by the beginning of 20-th century (Gourdon, 1908). The investigations of the glacier of Galindez Island were started in 1960 by British scientists. It was established that most parts of the glacier are moving with minor velocity, reduction of main ice results in plastic deformation and causes slipping of lower glacier surface with changing velocity on the fractured bedrock surface. This process causes deformation and fractures of the glacier, cracks are at right direction to the glacier movement (Tretyak et al., 2016).

For the last 50 years, 244 glaciers of the western coastline of the Antarctic Peninsula decreased in dimensions (Tretyak et al., 2016). Information about changes in island's glaciers movement, deformation and geometrical parameters is considered as an indicator of worldwide climate changes (Tretyak et al., 2016; Levashov et al., 2004). British scientists (Thomas, Sadler, British Antarctic Survey) noted that the ice cap of Galindez Island like the other Argentine Archipelago islands is a relict of the ordinary shelf glacier, which subsequent evolution needs further studies. The discrete monitoring of Galindez Island ice cap state shows that unstable balance of the levels of accumulation and ablation during the last decades tends to the predominant ablation (thawing and evaporation) which yields in negative mass balance of this glacier, diminishing of the ice cap′s volume (Levashov et al., 2004).

Therefore, during several short-term expeditions, the geodetic and electromagnetic research of island's glaciers were organized. Most research were devoted primarily to the investigations of the glacier on Woozle hill (Galindez Island). The first observations of glacier's thickness on Woozle hill were performed during the 2-nd Ukrainian Antarctic Expedition in 1998 by Y. Macheret and M. Moskalevskiy. They a applied video-impulse radiolocation method and determined that maximum thickness of the ice was 59 m; velocity of electromagnetic waves was 167.8±2 m/μs. In addition, scientists are concluded that this glacier related to the type of warm glaciers (Bakhmutov et al., 2006**).** In 2004, the thickness of the ice cap on Galindez Island was measured with vertical electric-resonance sounding. Results of the research showed that there was small ice thickness on its north-, east- and west-margins, thicker ice (up to 30–40 m) was in central part. The thickest ice (up to 45–48 m) was observed in the southern part of this glacier (Levashov et al., 2004). As a result of terrestrial laser scanning and stereo photogrammetric survey, the digital terrain model of the glaciers on Winter and Galindez islands was created. Model shows that velocity of Winter and Galindez glaciers melting increased almost 8 times according to the analyzed data for the period 1956-2014 (Tretyak et al., 2016).

Authors of previous research pointed out that monitoring of glaciers on the Argentine Islands is important and should be done regularly (Glotov et al., 2003; Bakhmutov et al., 2006**).** During the 22-nd Ukrainian Antarctic Expedition (2017-2018), the ground penetrating radar (GPR) method has been applied for investigations of glaciers near the Ukrainian Antarctic Akademik Vernadsky station. GPR observation is an effective tool for investigations of glaciers' structure, identification of fissures, conduits and voids in glacier (Lamsters et al., 2016; Bernarda et al., 2014; Pourrier et al., 2014; Karuss et al., 2015); identification and monitoring of ice caves (Colucci et al., 2014), characteristic of ice and snow physical properties (Godio et al., 2015; Forte et al., 2013; Previati et al., 2011). The aim of the investigations during April-November 2017 was to determine the VIY3-300 GPR informativeness for investigation of glaciers around ‑ Vernadsky station. According to the above mentioned results of glaciers' investigationsz,, it was anticipated that with GPR VIY3-300 fissures, voids and water channels in the glaciers could be indicated to a depth of 25-28 meters. In this paper a review of the GPR on Galindez, Winter and Skua Islands is presented.

2. Methods and equipment

The term 'ground penetrating radar' (GPR), 'ground-probing radar', 'sub-surface radar' or 'surface-penetrating radar' (SPR) refers to a range of electromagnetic techniques designed primarily to locate objects buried beneath earth's surface or located within a visually opaque structure. Since 1930, stepped electromagnetic research method was used as a method for the ice thickness evaluation. GPR sounding is applied in the practice of engineering and geotechnical studies intensively since the 1970s (Daniels, 2006). Over the past 15-20 years, GPR method has become quite widespread and today the scope of application is growing steadily.

The essence of GPR sounding is registering of electromagnetic waves, which are generated by transmitter and reflected from boundaries between parts of investigated environment with different electrical and magnetic properties (Chernov, 2016). There are 3 main parameters of electromagnetic waves which are recorded during sounding:

1) wave arrival time *t* (in nanoseconds (ns)) – the time period which lasts between moment of electromagnetic wave radiation from transmitter and electromagnetic wave coming to the receiver from the investigated environment;

2) signal's amplitude – the intensity of fluctuations of electromagnetic waves (measured in dB);

3) frequency of signal or central frequency of antenna – the number of periods of waves oscillation per unit of time (as usual for GPRs in megahertz (MHz)).

On the common resulting radargram (Fig. 3a), amplitude for exact time (left axis) and depth (right axis) is shown along the distance (vertical axis). Depth of investigation in meters depends on velocity of electromagnetic wave in investigated medium. Velocity in the medium calculated according to the formula:

$$v = c / \sqrt{\mu\varepsilon} \tag{1}$$

where c = $3 \cdot 10^8$ m/s – the speed of electromagnetic wave propagation in vacuum (speed of light), μ and ε – relative magnetic permeability and relative permittivity of investigated environment respectively; for purpose of represented investigations while counting it was considered that μ=1.

An amplitude of the reflected signal increases on the border between parts of the medium with different electro-magnetic properties. An amplitude directly depends on contrast of the medium in relative permittivity (ε). Investigated medium primarily consisted of ice, snow, rocks, water and voids. These substances differ in relative permittivity: ε (ice) =3-4; ε (snow) =1.4-3; ε (rocks) =5-7; ε (water) = 80, ε (voids) = ε (air) = 1 (one). Therefore, it is possible to distinguish these parts of the medium on radargrams. The distance between transmitting and receiving antennas was constant during the investigations – common offset modification was applied.

The sounding was done with VIY-3 300 GPR. Parameters of the survey: frequency of antenna: 300 MHz, step of surveying: 94-158 mm, time-window (depth of the survey): 330 ns, vertical sampling: 500 points, average stacking: 2. Depth of the sounding according to the obtained velocity in glaciers (170 m/μs) was 28 m. Sites of investigation were located on 3 islands: glacier on Galindez Island (on Woozle Hill), 2 glaciers on Winter Island and 2 glaciers on Skua Island. Surveying on Woozle Hill have been done once per month along the same direction since April 2017. Surveys on Skua and Winter Islands were done in May and Septemberz.The main profiles were recorded along the glaciers (Fig.1) and above identified anomalies perpendicular profiles were recorded.

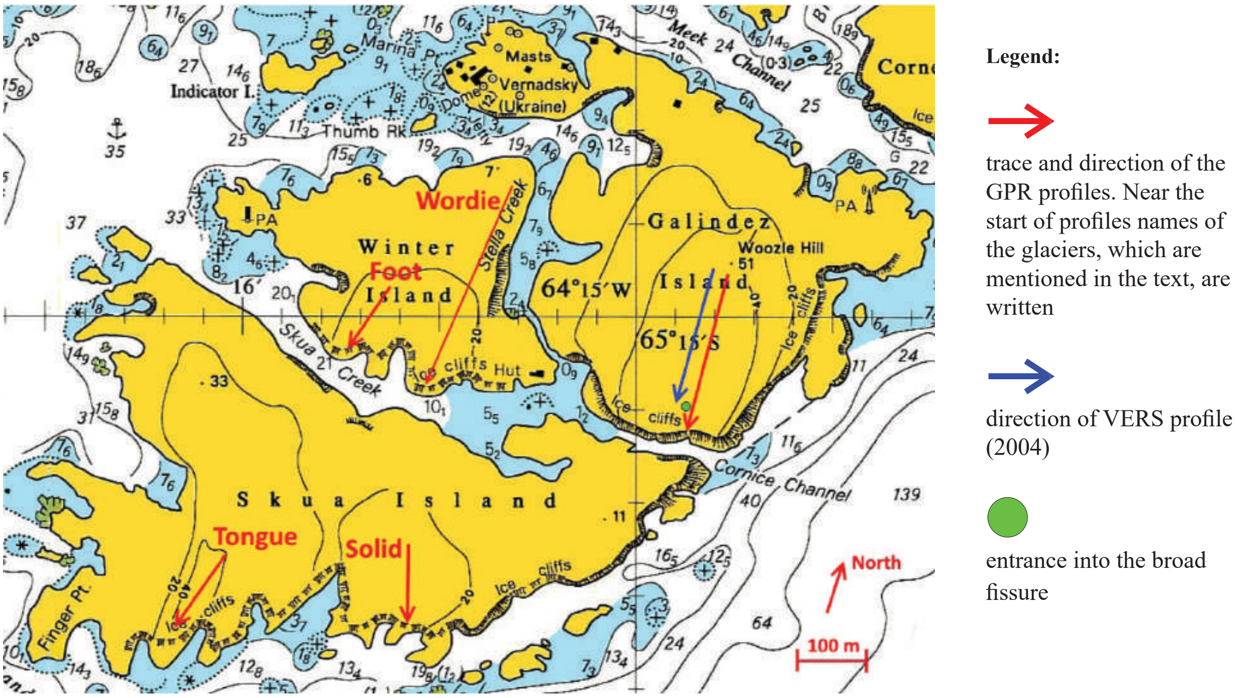
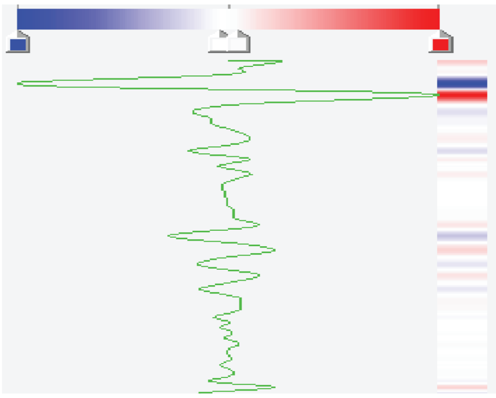


Fig.1. Map of surveyed glaciers location.

The results of the GPR sounding on Woozle Hill were compared with data of snow level on the glacier and the glacier's temperature (meteorological reports from Ukrainian Antarctic Akademik Vernadsky station 2014-2017).



GPR profiles were processed in programs Synchro3 and Planner produced by LLC Transient Technologies (producers of VIY GPRs). In these programs, several tools were used for processing of GPR profiles: 1) «Wavelet filter» that performs convolution of the track with the function of a given period; 2) «Background removal» was used to minimize noises from the device and surroundings around the objects; 3) «Gain» was intended for setting the level of signal amplification to obtain more informative data; 4) "Band Bass Filter" was applied to decrease noise on radargrams; 5) "Nonlinear Amplifier" was used for clear identification of the anomalies on GPR profiles with increasing of their amplitude over background signal.

Fig. 2. Color palette dependence from amplitude of the signal.

Fig. 2 represents correspondance of colour to the amplitude of the signal that was applied to represented radargrams.

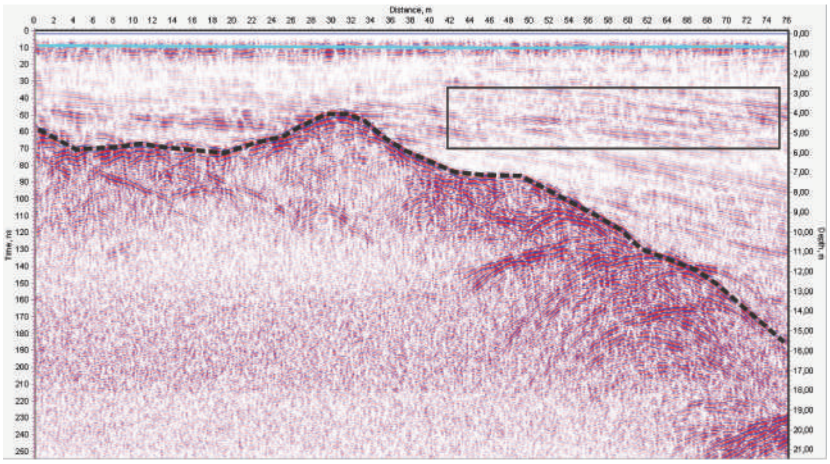


Fig.3a – recorded in August 2017.

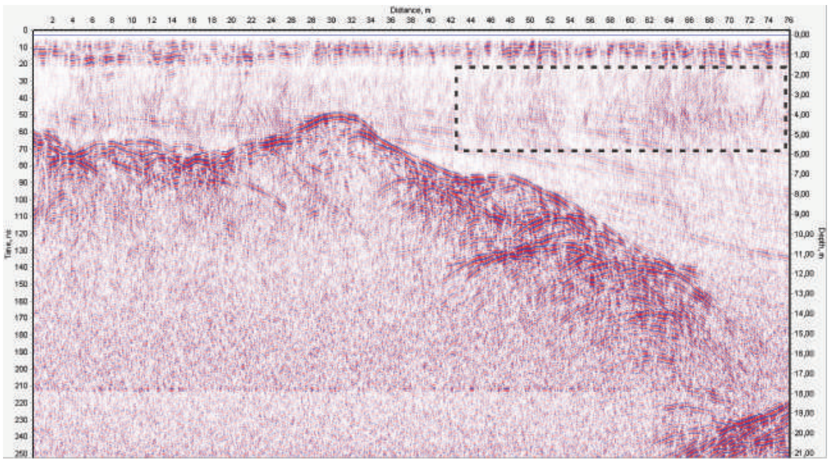


Fig. 3b – recorded in November 2017.

Fig.3. Radargrams from Woozle Hill.

Legend for pictures:

example with anomaly from border between snow and ice

example of anomaly from zones of increased moisture content

example of anomaly from ice layering

example of anomaly from border between ice and rock (glacier's bed)

3. Results and Discussion

There are several types of informative anomalies were distinguished on the radargrams. Reflections were interpreted as: 1) border between snow and ice; 2) layering of the ice; 3) zones of increased moisture content; 4) fissures, voids, glacial conduits; 5) border between ice and rock (glacier's bed).

Border between snow and ice is located on the depth up to 1.5 meters on the investigated sites. This border was indicated on radargrams thanks to reflections at a depth of about 1 m (Fig. 3 a; Fig. 5).

There are linear anomalies represented by tilted lines of higher amplitude on GPR profiles (Fig. 4 a, Fig. 6-8). Reflections of such kind can be provoked by presence of heterogeneities in glacier connected with changes of ice accumulation conditions and by areas of permanent liquid water presence.

An increasing of outside temperature and the temperature of the glacier (Meteorological reports 2014-2017) leads to saturation of moisture from the upper layers of melted snow into the ice through micro-fissures. Therefore, in December probable location of parts with higher moisture content were indicated in the upper layers of Woozle Hill's glacier (Fig. 3 b), which were invisible on the radargrams while surveys during the colder season (Fig. 3 a). The main source of fresh water for glacier feeding on Galindez island is infiltrated water from the upper layer of the glacier, so higher moisture content in summer is its common feature.

In the glaciers, hyperbolic anomalies are indicated (Fig. 4a; Fig. 4-8), which could be provoked by presence of glacial conduits (Karuss et al., 2015). These anomalies break the layering of ice and also less intensive fissures are indicated in the layers of ice. On Woozle Hill broad fissure was indicated with GPR (Fig. 9) and location of the void was approved by insitu observations in the fissure. Its height was 4 m, 3-4 m in width and about 10 m in length.

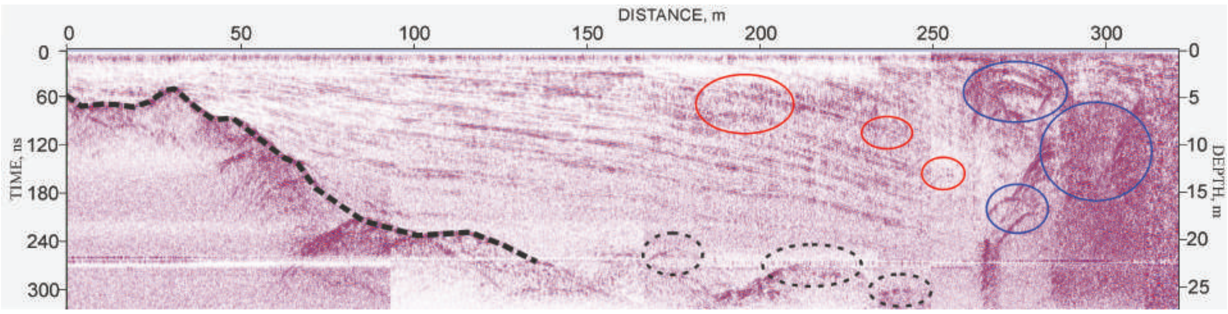


Fig. 4a – GPR profile (August-September 2017).

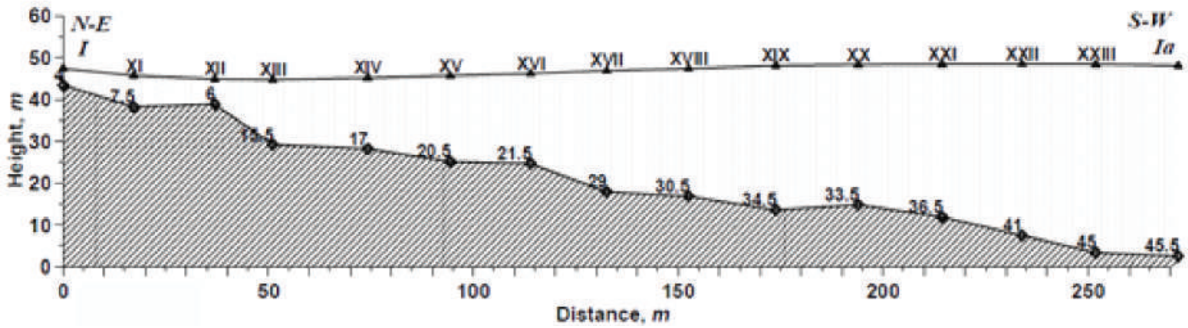


Fig. 4b – picture of the results of VERS (Levashov et al., 2004).

Fig. 4. Results of the surveying on Woozle Hill.

Legend for pictures:

Parts of rocks or voids in the ice and rocks near the border between rock and ice

fissures

Voids and/or glacial conduits

The border between ice and rock (glacier's bed) is clearly observed along whole glaciers on Winter Island (Fig. 6-7), on Solid glacier on Skua Island (Fig.8) and on the first 120-130 m along profile on Woozle Hill (Fig. 4a). On the rest part of Woozle Hill and on Tongue glacier on Skua Island this border was not clearly indicated, because probably the thickness of the ice was more than maximum depth of acquisition (28 m).

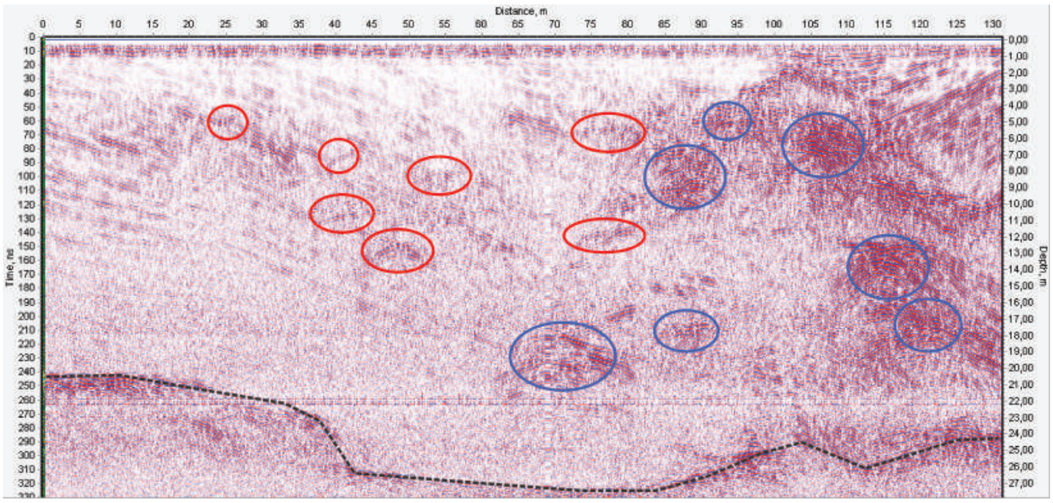


Fig. 5. Radargram recorded along the glacier Tongue (for explanation of signs see *Fig*. 3-4).

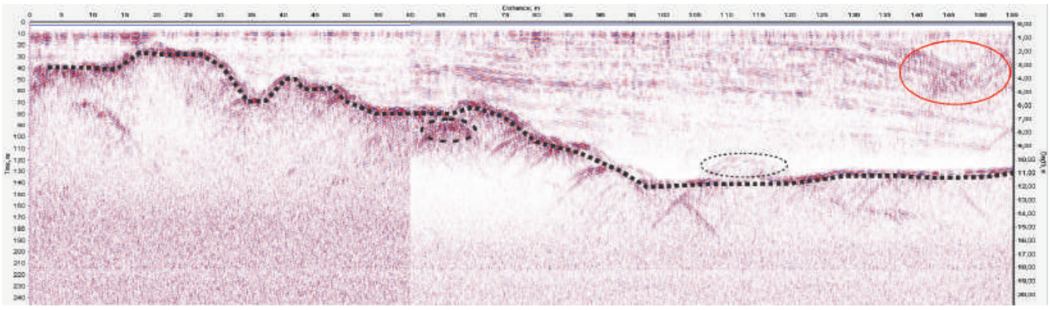


Fig. 6. Radargram recorded along glacier Foot (for explanation of signs see *Fig*. 3-4).

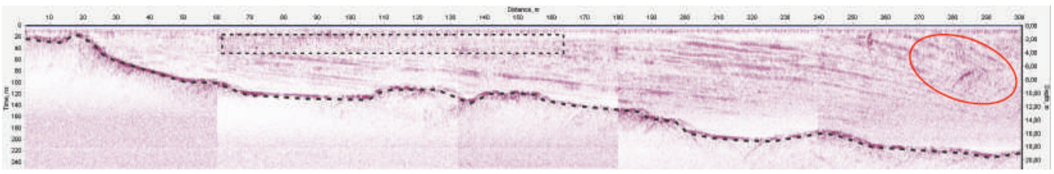


Fig. 7. Radargram recorded along glacier Wordie (for explanation of signs see *Fig*. 3-4).

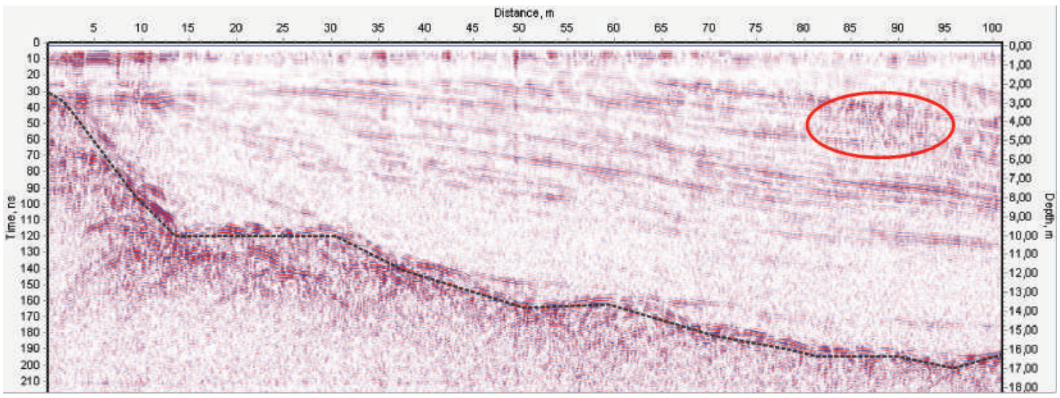


Fig. 8. Radargram recorded along glacier Solid (for explanation of signs see *Fig*. 3-4).

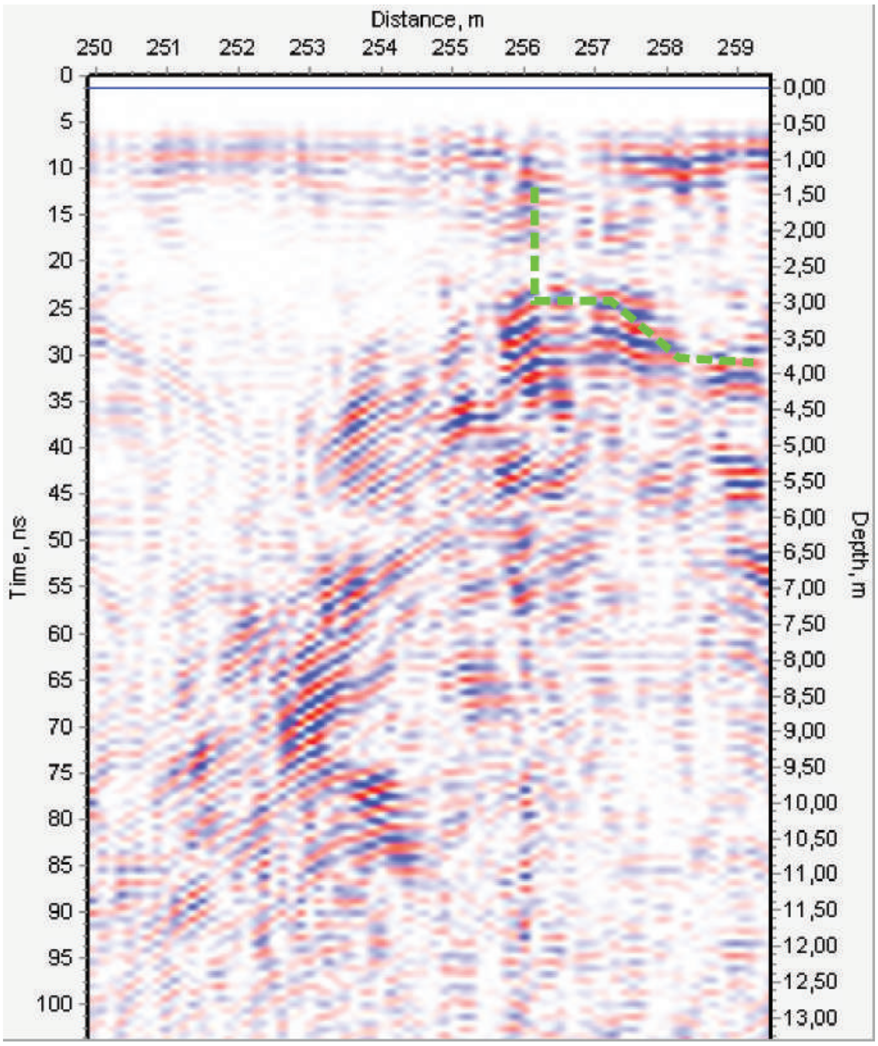


Fig.9. Anomaly across the broad fissure. Green dashed line marks approved borders of the void.

Radargrams recorded on Woozle Hill were compared with the results of vertical electric-resonance sounding. Fig. 4 a, b show that information about glacier's bed is well correlated between results from both methods. The velocity of electromagnetic waves is well correlated with the results of previous investigations: 170 m/µs (GPR, 2018) and 167.8±2 m/µs (video-impulse radiolocation method, 1998). In addition, on the radargram information about layering of the ice, location of fissures and potential water conduits is represented. Zone of fissures spreading is located on the distance 145-330 (to the very edge of the glacier) meters along the monitoring profile. Three levels of fissuring could be depicted: weak (145-185) – crevices are seldom identified and located in the layers of ice on the depth more than 4 m; medium (185-250) – fissures are more often identified, but anomalies from layering of the ice are still distinguished, fissures spread to the depth of 2 m; strong (250-330) – broad fissures, which break anomalies from layering, fissures reach upper surface of the ice.

In the area of extreme fissuring, insitu analysis was done (Fig. 9). The area of weak and medium fissuring spreading slightly changes during different seasons.

In the glaciers Foot and Solid the least amount of fissures were indicated. However, on the last 15-25 m of these glaciers fissures also have been indicated (Fig. 6, 8). In the structure of Wordie glacier anomaly from layering is worse identified along first 170 m to the depth of 3 m. This peculiarity could be as a result of ice saturation with moisture or because of intensive cracking of ice or because it is not ice, but firn. On the rest 130 m layering is visible from the depth 1 m, but final 47 m on radargram are covered with fissures and linear anomalies are more tilted down.

The structure of Tongue glacier on Skua Island differs from the other glaciers. Ice is full of fissures, layering is worse indicated and linear anomalies are more tilted down (Fig. 5). On the first 70 m fissures are located deeper than 4 m. Farther along profile, there are strong anomalies, which break layering and spread to the upper surface of the ice (95-115). Near the edge of the glacier (115-130), reverse (in relation to the layering up to 95 m) inclination of layering anomalies is observed.

Further GPR monitoring of the glacier interior should be done to obtain clear information about mentioned heterogeneities and about their future development. According to the meteorological observations on Woozle Hill (meteorological reports Vernadsky station 2014-2017), temperature of the upper layer of ice changes from -5°C (in July-September) to 0°C (in December-February). Possibly, during the period of higher temperatures, glacier conduits can be recognized and other "dry" heterogeneities should be better visible during lower temperatures of the glacier.

4. Conclusions

Information about interior heterogeneities (fissures, voids, layering, glacier's bed, areas with higher moisture) in islands' glaciers in Antarctica to a depth of 27.5 m can be successfully obtained with VIY-3 300 GPR. Mentioned equipment can be easily transported to the site of investigation, recording of the profiles could be done by one person. Speed of work with mentioned in the text parameters of the survey is 300 m in 20 min for new area and 600 m in 30 min for monitoring site on Woozle Hill.

Changes of islands' glaciers' are considered to be indicators of climate changes. Therefore, further GPR monitoring of glaciers on Galindez, Winter and Skua islands is recommended for better understanding of the interior processes and prediction of further changes in glaciers.

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