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A BRIEF REVIEW OF GROUND PENETRATING RADAR INVESTIGATION RESULTS OF ICE CAPS ON GALINDEZ, WINTER AND SKUA ISLANDS (WILHELM ARCHIPELAGO, ANTARCTICA) FOR THE PERIOD APRIL 2017 — JANUARY 2019

ABSTRACT. This paper represents results of GPR surveying of the ice caps on Galindez (–64.24716W; –65.24992S), Winter (–64.25954W; –65.24944S) and Skua (–64.26530W; –65.25309S) islands (Wilhelm Archipelago, Antarctica) for the period April 2017 — January 2019. The main **objectives** were identification of the ice layering, monitoring of interglacial heterogeneities (crevasses, interglacial channels and voids) and measurements of the ice thickness. **Methods:** Surveying on the glaciers has been done with ground coupled shielded bowtie antenna VIY3-300 (300 MHz) GPR and with air coupled dipole Zond 12-e (75 MHz) antenna system. Monitoring investigation of glacier's interior has been done with VIY3-300. Zond 12-e was applied mostly for indication of the ice-rock border. Monitoring investigation has been done on one (1) ice cap on Galindez Island, on two (2) ice caps on Winter Island and on two (2) ice caps on Skua Island. Monitoring with VIY3-300 GPR of the ice cap on Galindez Island has been done once per month since April 2017. Four surveys were done on Winter Island: May 2017, January, May and October 2018. Four periods were surveyed on Skua Island: May and September 2017, January—February and October 2018. Monitoring with VIY3-300 has been done on the same position (according to the GPS data) each time. For precise investigation during February—March 2018, islands were covered with a grid of profiles with 25 meters spacing between them. **Results:** Three (3) to eight (8) strong internal linear reflections are detected in the ice caps, heterogeneities are visible closer to edges of the glaciers, seasonal anomalies in glacier`s interior are observed and a maximum ice thickness of 35 meters on Galindez Island is obtained. Seasonal anomalies were traced better in November—January 2017—2018 than during November—January 2018—2019. Reflection from the ice-rock border is better visible on the data from Zond 12-e, but layering and interior structure are better identified with VIY3-300. This spatial resolution difference evidently happened because central frequency of antenna was 4 times higher in VIY3-300 than in Zond 12-e. Further monitoring of the ice caps on Galindez, Winter and Skua islands is recommended to trace their evolution. It is crucial to continue these scientific observations in the future because changes of small ice caps in West Antarctica are indicators of global warming.

***Keywords*:** ground-penetrating radar (GPR), ice cap, glacier, Wilhelm Archipelago, Antarctica, monitoring, Zond 12-e, VIY3-300, ice structure.

INTRODUCTION

First glaciological observations in the area of the Argentine Islands (–64.24716W; –65.24992S) were started at the beginning of 20th century during the first French expedition in 1903—1905, when the islands were mapped and named for the first time (Balch, 1911; Charcot, 1905, 1930). During the British Graham Land Expedition (1934—1937) varied surveys were performed and more detailed topographic maps were published (Fleming et al., 1938). Thomas and Sadler from British Antarctic Survey (Thomas, 1963; Sadler,

1968) started the first detailed investigations of the glacier on Galindez Island in 1960th. It was established that most parts of the glacier are moving with minor velocity, melting of 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).

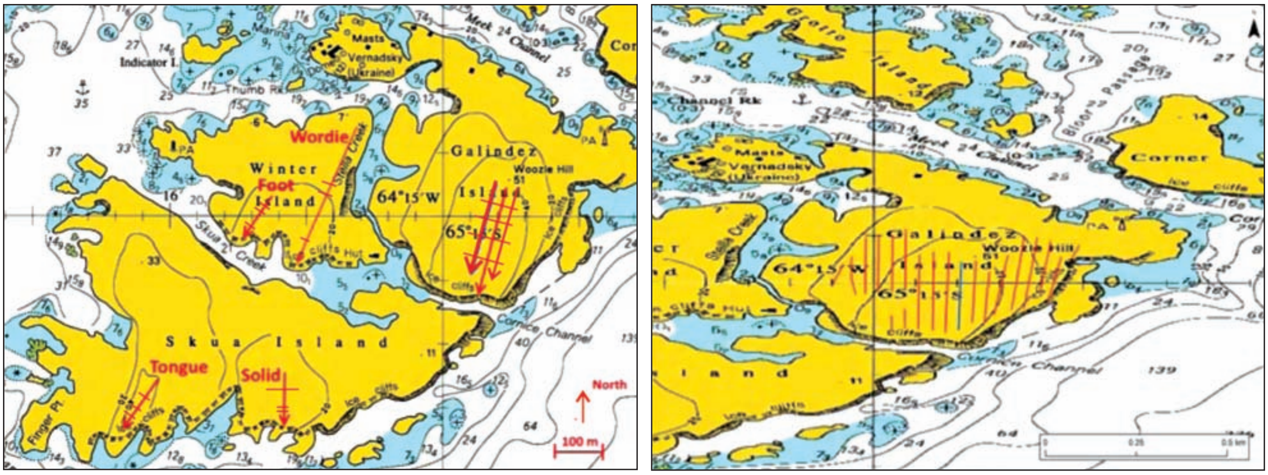
For the last 50 years, 244 glaciers of the western coastline of the Antarctic Peninsula decreased in dimensions (Tretyak et al., 2016). Information about changes of island's glacier movement, deformation and geometrical parameters is considered as an indicator of worldwide climate change (Tretyak et al., 2016; Levashov et al., 2004). British scientists from the British Antarctic Survey (Fleming et al., 1938; Thomas, 1963; Sadler, 1968) have noted that the ice cap of Galindez Island like the other ice caps on the Argentine Islands is a relic of the ice shelf, 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 and diminishing volume of the ice cap (Levashov et al., 2004).

Therefore, during several short-term expeditions, the geodetic and electromagnetic research of island's glaciers was organized. Most of the research was devoted primarily to the investigations of the glacier on Woozle hill (Galindez Island). Y. Macheret and M. Moskalevskiy performed the first observations of glacier's thickness on Woozle hill during the 2-nd Ukrainian Antarctic Expedition in 1998. They applied a 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 is 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, more thick ice (up to 30—40 m) was in central part and the maximum thickness (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 models of the frontal parts of the glaciers on Winter and Galindez islands were created. Models show that the melting velocity of the glaciers on Winter and Galindez islands 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). 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). Therefore, in April 2017 the ground penetrating radar (GPR) investigations of glaciers on the Argentine Islands (Wilhelm Archipelago, Antarctica) were started. First results of GPR surveying showed that interior heterogeneities (fissures, voids, layering, glacier's bed, areas with higher moisture) can be successfully indicated with VIY-3 300 GPR till the depth of 27.5 m (328 ns) (Chernov, 2017, Chernov et al., 2018). In this paper, authors review results, which were obtained with VIY3-300 and Zond 12-e for the period April 2017 – January 2019.

MATERIALS AND METHODS

Two GPR systems were applied for the surveying. VIY3-300 (300 MHz, ground coupled, shielded bow-tie antenna) has been used for monitoring of the ice caps since April 2017 and Zond 12-e (75 MHz) was applied primarily for the investigations of the ice thickness in February—April 2018. The GPR data from VIY3-300 was processed with Planner and Synchro software (free of charge), radargrams from Zond 12-e were processed with Prism 2.6 software (supplied with Zond 12-e). The main steps of processing were the



a b

Fig. 1. Sites of the GPR monitoring with VIY3-300 (*a*) and example of the surveyed profiles on Galindez island with Zond 12-e (*b*). The main places of the survey are marked with red arrows and lines, represented names of the ice caps mentioned in the body of article

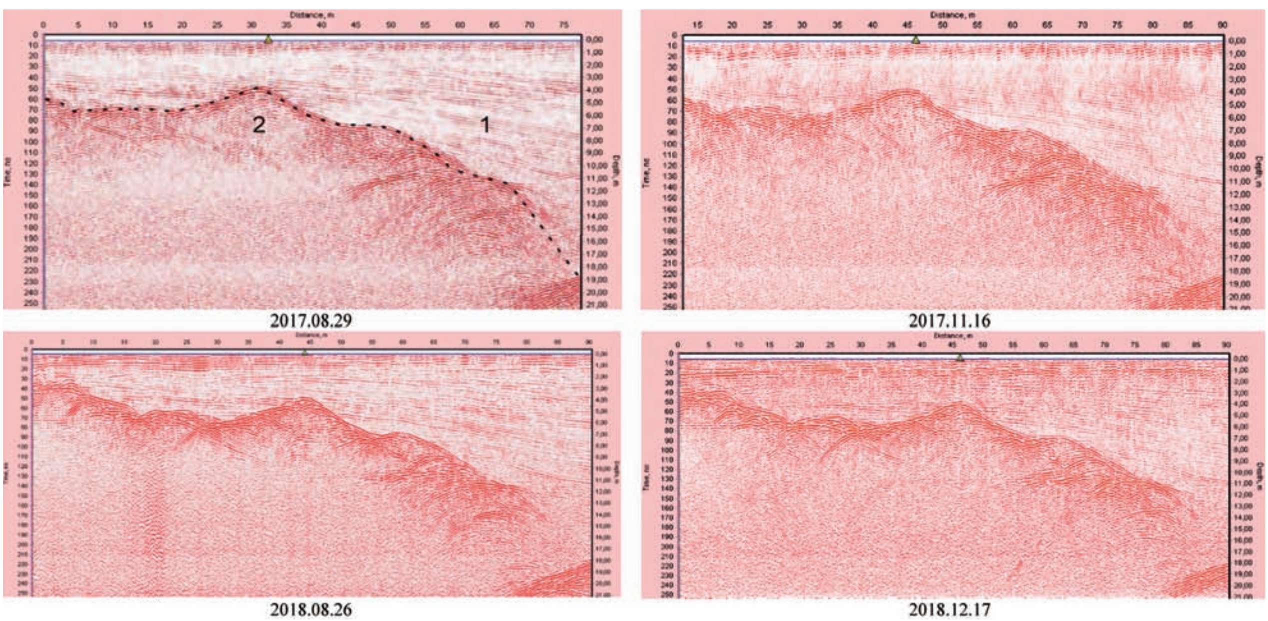


Fig. 2. Comparison of the first part of profile on Woozle Hill in Summer, Winter 2017 and 2018. Central direction on Fig. 1 a. Numbers on radargram 2017.08.29 mark different medium: 1 — ice with reflections from borders between some layers; 2 — bedrock; Dashed line marks example of reflection from ice-rock border

application of wavelet filter, background removal filter, time-dependent signal gain function and Ormsby band-pass filter. Dielectric permittivity 3.11—3.55 was applied during processing of the data from both GPR systems. For the data from VIY3-300, non-linear amplifier, rectifier and Hilbert filter were applied to highlight reflections from the medium. Recording of the profiles with VIY3-300 was done with 330 ns for time window, 500 samples per trace, average stacking was 2 and 94 mm for the step of measurement. Accor-

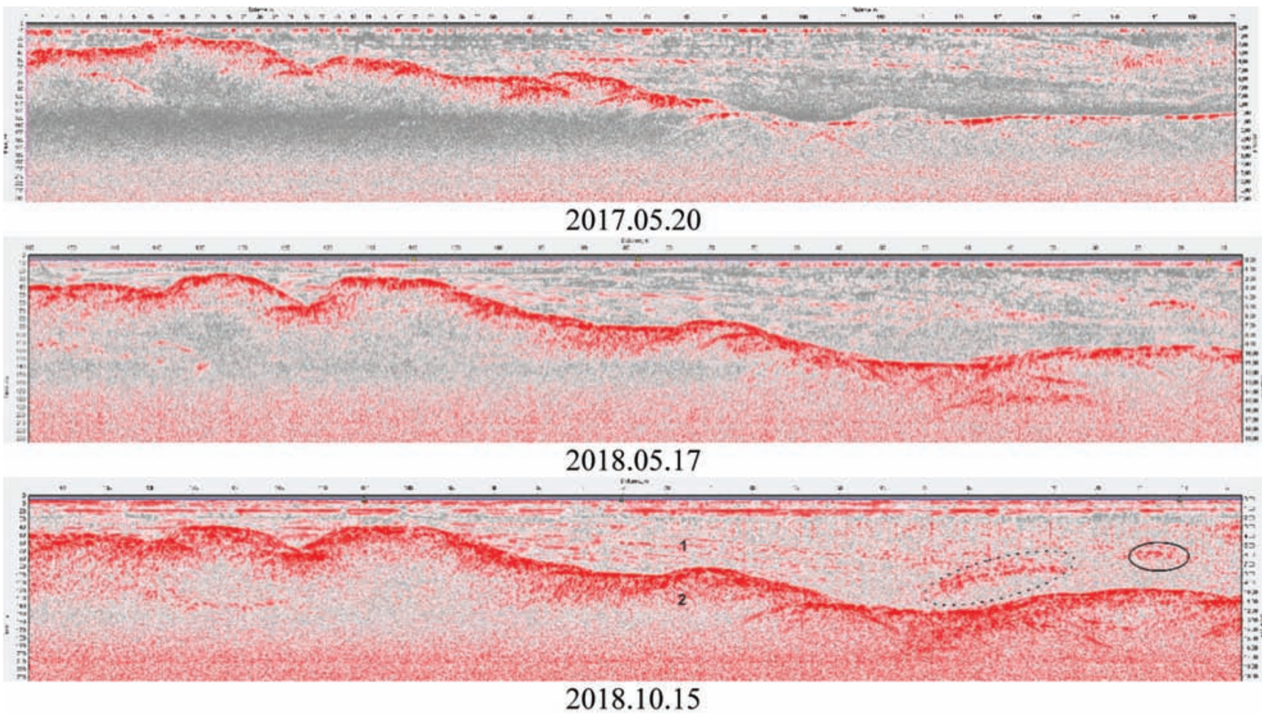


Fig. 3. Radargrams from the ice cap Foot (Fig. 1 a) in different periods of 2017 and 2018. Processed with Hilbert filter. Dashed line oval marks an example of the heterogeneity (fissure or area with higher moisture content), which is also visible on the radargrams from previous periods; solid line oval marks a new heterogeneity that was not previously observed

ding to the information from Transient Technologies LLC (VIY manufacturer), for VIY3-300 horizontal resolution is 0.13—0.14 m (¼ of the wavelength) and horizontal accuracy 94—188 mm (1—2 of aquisition step). For Zond 12-e, vertical resolution 1.31 meter and lateral accuracy up to 6.32 m. Average difference between depth measurements for two GPRs was less than 0.5 meters and maximum 2.0 meters.

Profiles were recorded across and along the ice-caps. Figure 1 represents directions of the survey from both GPRs. Monitoring with VIY3-300 GPR of the ice cap on Galindez Island (Woozle Hill) has been done once per month since April 2017. Four surveys were done on Winter Island (ice caps Wordie and Foot): May 2017, January, May and October 2018. Four periods were surveyed on Skua Island (ice caps Tongue and Solid): May and Seprtember 2017, January-February and October 2018. Ice cap on Galindez is located on the same island with Vernadsky station, so it is possible to do the survey each month. It is harder to get to Winter and Skua islands, so survey was done not so regularly on their ice caps. Monitoring survey has been done on the same place each time (coordinates were obtained with portable GPS Garmin) and major directions are shown on the Fig. 1.

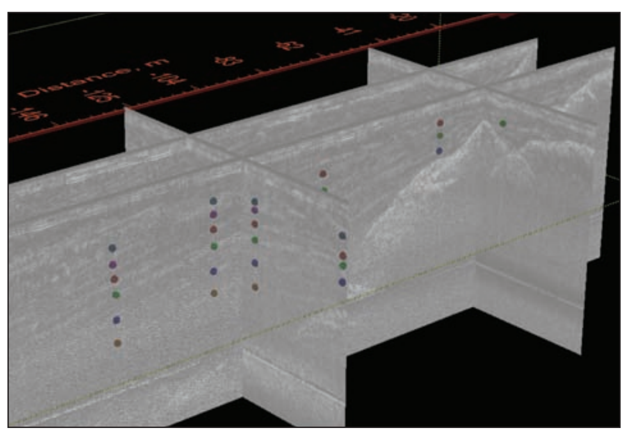


Fig. 4. 3D View of profiles with layering from the ice cap on Woozle Hill. Spheres of the same color mark the same reflective borders

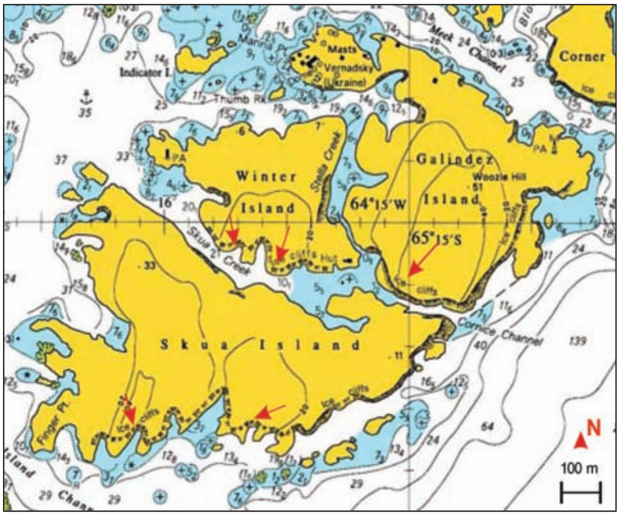
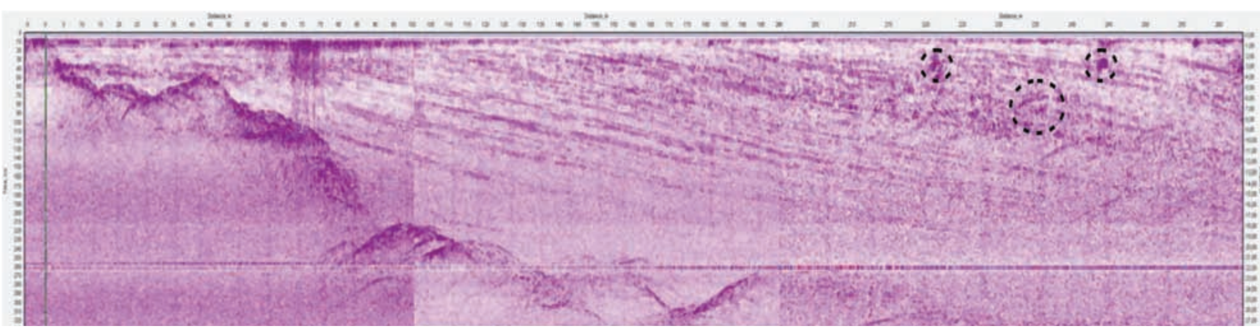


Fig. 5. A map with the ice caps slope direction, according to the identified reflections from borders between layers along and across the glaciers

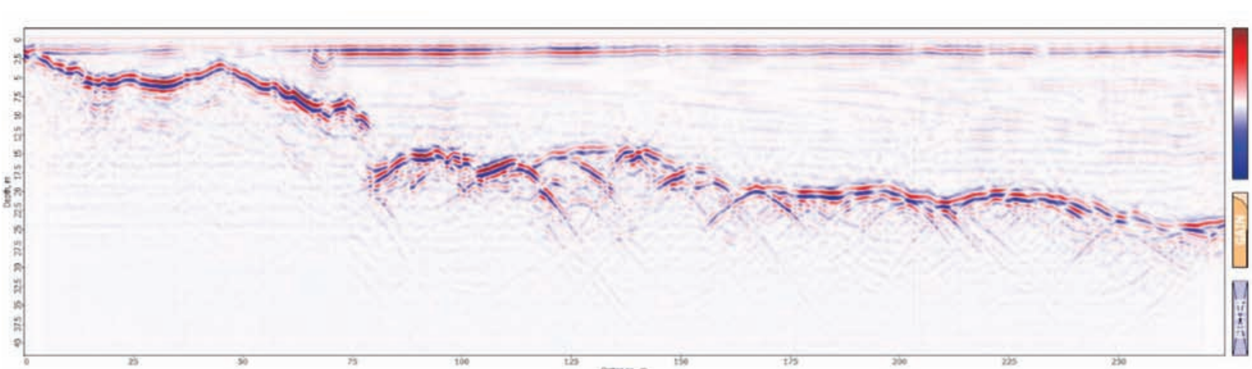
Survey of the whole islands was done with Zond 12-e and VIY3-300 in February-April 2018. These profiles were recorded along the grid of profiles with 25 meters spacing between them. An example of the surveyed directions along Galindez Island is on Fig.1 b. Coordinates of the profiles were recorded with GNSS receiver Magellan ProMark 3.

RESULTS AND DISCUSSION

Monitoring of the ice caps helped to trace seasonal and long-term changes inside the ice. Strong linear reflections along ice caps were indicated, which are interrupted by anomalies from heterogeneities (moisture content, crevasses, voids) and reflections from ice-rock border are visible (Fig. 2, Fig. 3). Figure 2 shows representative results from Galindez Island. Layering of the ice is the best visible in August. It was



a



b

Fig. 6. Comparison of GPR profiles from VIY 3-300 (*a*) and Zond 12-e along Woozle Hill in March 2018 (central direction on the Fig. 1 *a* and a blue line on Fig. 1 *b*). Dashed line oval marks an example of the heterogeneity (fissure or area with higher moisture content); numbers mark different medium: 1 – ice with reflections from borders between some layers; 2 – bed-rock

noticed that the visibility of the upper layering (to 70 ns — 5.8 meters) was the worst in November 2017, but in 2018 this phenomena occurred in December. In 2017 these upper layers of the ice were also not clearly visible in December and January—February 2018. However, there is less visibility only in December 2018 but in January 2019 layering is clearly visible.

This phenomenon occurs possibly because the upper layers of ice were saturated with meltwater. Accordingly, in summer 2017—2018, there was better saturation with water and less water came into these layers in summer 2018—2019.

On the other islands one of the most representative data after monitoring was observed on the ice cap Foot on Winter Island (Fig. 3). Along the last 40 meters reflections from heterogeneities are visible and on the October 2018 radargram on distance 40—25 meters from the edge of the glacier bright reflection on the depth 10—7 meters is clearly visible. These reflections can occur as a result of a new crevasse formation or seasonal changes of interior moisture content.

Surveying of the ice caps in different seasons helped to identify linear reflections and trace them around the whole glacier (Fig. 4). There are layers, which are visible at least on the half of ice caps and a few more are visible closer to the edges. These anomalies occur possibly because of the border between layers with different structure of the ice.

There is a contrast of dielectric properties between parts of ice with different physical properties and so we get a reflection of electromagnetic signal on these borders. There are major directions of the linear reflections slope for all glaciers, which are steeper closer to edges of the glaciers. As a result of interpretation, a map with slopes was generated for surveyed locations (Fig. 5).

Figure 6 shows comparison of GPR profiles informativeness from different GPRs. Reflection from the ice-rock border is better visible on the data from Zond 12-e, but layering and interior structure are better identified with VIY3-300. This spatial resolution difference evidently happened because central frequency of antenna was 4 times higher in VIY3-300 than in Zond 12-e.

CONCLUSIONS

As a result of the surveying, information about the internal structure of the ice caps was obtained. On Galindez Island in the central part of Woozle Hill, 7 reflective borders were indicated and two more are visible on radargrams closer to the Cornice Channel. On Winter Island, 5 layers are stretching along the whole glacier Wordie and three more layers are identified on the edge closer to the Skua creek. Four layers are stretching along the whole glacier and a one more layer was distinguished on the edge closer to the Skua creek on the ice cap Foot on Winter Island. On Skua Island inside the ice cap Solid, 3 layers are stretching along the whole glacier and 5 layers were matched closer to the edge. In the other ice cap Tongue from Skua Island, 7 layers are stretching along the glacier and 8th layer was distinguished on the edge closer to the Finger point. Probably, more thinner layers could be distinguished, and this detail should be specified during further investigations.

Interior heterogeneities were identified in the final third part (closer to the cliffs) of the ice caps on Galindez, Winter and Skua islands. Their origin should be specified during further observations. The maximum ice thickness at the surveyed sites was 35 meters that was reached on the ice cap on Galindez Island. This thickness differ from the maximum thickness of 59 m (results of video-impulse radiolocation investigations in 1998) (Bakhmutov et al., 2006) and 45—48 meters (results of vertical electric-resonance sounding in 2004) (Levashov et al., 2004). This variation in numbers occur because of the difference in technical resolution of the equipment and possibly because of the ice melting.

Further monitoring of ice caps should be done more regularly on the Skua and Winter islands to trace interior changes more precisely. Further research should be done to understand the nature of electromagnetic wave reflectors.

Results from these islands will be compared with surveys on other ice caps of Wilhelm Archipelago islands for understanding of general trends and history of their evolution. Moreover, ice caps on the territory of the Western Antarctic Peninsula are vulnerable to global warming, therefore monitoring of their changes can help to understand global temperature variations.

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СТИСЛИЙ ОГЛЯД РЕЗУЛЬТАТІВ ГЕОРАДАРНИХ ДОСЛІДЖЕНЬ ЛЬОДОВИКІВ НА ОСТРОВАХ ГАЛІНДЕЗ, ВІНТЕР ТА СКУА (АРХІПЕЛАГ ВІЛЬГЕЛЬМА, АНТАРКТИКА) ЗА ПЕРІОД КВІТЕНЬ 2017 – СІЧЕНЬ 2019

РЕФЕРАТ. В роботі представлені результати георадарних досліджень льодовиків на островах Галіндез (–64.24716W; –65.24992S), Вінтер (–64.25954W; –65.24944S) та Скуа (–64.26530W; –65.25309S) (архіпелаг Вільгельма, Антарктика). Головною **метою досліджень** було виявлення шаруватої будови льодовиків, моніторинг внутрішніх неоднорідностей (тріщини, внутрішні канали та пустоти) та вимірювання товщини льоду. **Методи:** дослідження льодовиків проводилось за допомогою георадарів VIY3-300 (300 МГц) та Zond 12-е (75 МГц). Георадар VIY3-300 представляє собою екрановану антену, яка призначена для роботи в контакті з поверхнею. Дипольна антена Zond 12-е призначена для роботи без контакту з поверхнею. Моніторингові дослідження внутрішньої будови здійснювались за допомогою георадара VIY3-300, а Zond 12-е переважно використовувався для виявлення границі між льодом та гірською породою. Моніторинг проводиться на одному льодовику на о. Галіндез, двох льодовиках на о. Вінтер та на двох льодовиках на о. Скуа. Моніторинг за допомогою георадара VIY3-300 проводиться кожного місяця на о. Галіндез з квітня 2017. Чотири рази проводилась зйомка на о. Вінтер: травень 2017, січень, травень та жовтень 2018. Чотири рази записано профіля на о. Скуа: травень та вересень 2017, січень-лютий та жовтень 2018. Моніторингові профіля записуються за однаковою траєкторією (згідно координат GPS приймача) кожного разу. Для більш докладних досліджень протягом лютого-березня 2018 ділянки островів з льодовим покривом було пройдено сіткою профілів з відстанню 25 метрів між ними. **Результати:** в льодовиках виявлено від 3 до 8 лінійних відбиттів, спостерігаються сезонні аномалії в структурі, неоднорідності спостерігаються ближче до краю льодовиків та максимально виявлена потужність льоду складає 35 метрів на о.Галіндез. Сезонні аномалії краще спостерігались у листопаді-січні 2017—2018 аніж протягом листопада-січня 2018—2019. Відбиття від границі лід-гірська порода краще видно на результатах з Zond 12-е, але шаруватість та внутрішня структура краще відображаються на даних з VIY3-300. Рекомендовано робити подальший моніторинг льодовиків на островах Галіндез, Вінтер та Скуа, щоб відслідкувати та передбачити їх подальші зміни. Продовження цих наукових спостережень є важливим, тому що зміни малих покривних льодовиків Західної Антарктики є індикаторами глобального потепління.

Ключові слова: георадар, покривні льодовики, острівні льодовики, архіпелаг Вільгельма, Антарктика, моніторинг, Zond 12-е, VIY3-300, структура льоду.