Earth`s Cryosphere, 2016, vol. XX, No. 1, pp. 82–90 **http://earthcryosphere.ru/**

GROUND-PENETRATING RADAR SOUNDING OF ICE CREVASSES IN THE AREA OF THE RUSSIAN PROGRESS AND MIRNY STATIONS (EAST ANTARCTICA) DURING THE FIELD SEASON OF 2014/15

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The results of the experimental ground-penetrating radar profiling in the area of Russian Progress and Mirny wintering stations are discussed. The tests were carried out during the austral summer field season of the 60th Russian Antarctic expedition of 2014/15. The scientific investigations were aimed at identifying and localizing crevasses in the near-surface glacier. The GRP soundings were carried out at the frequencies of 270 MHz, 400 MHz and 900 MHz, and sounding at the frequencies in the range from 400 MHz to 900 MHz was found to be most promising for solving applied tasks. The works also demonstrated that the cracks located inside the snow-firn layer can form very weak diffracted waves. In addition, the diffracted waves formed by crevasse walls could serve as a reliable basis for developing a velocity model to recalculate the travel time into the depth. It becomes especially important when ice core data are unavailable or when multi-offset sounding is not possible.

East Antarctica, Progress Station, Mirny Station, ground-penetrating radar profiling, ice crevasses

INTRODUCTION

Indicating and locating crevasses in the near-surface part of a glacier play an important role in ensuring safety of Antarctic stations, work sites and field camps, as well as in forming a general concept of our planet's cryosphere [*Melnikov, 2014*]. According to the strategic plan of the Russian Antarctic expedition (RAE), the base of the Russian logistic traverses to the Vostok Station and inland in general was moved from the Mirny Station to the Progress Station. The first traverse took place as part of implementation of scientific and logistical programs of the 53rd Russian Antarctic expedition (RAE) in the field season of 2007/08. However, the route passes a zone of crevasses, which makes it dangerous for the people and the vehicles they use. Therefore, search for the routes involving crossing the crevasses with minimal risk and identifying and locating crevasses in this region are the priority tasks of the RAE. In addition, the airfields of the coastal Antarctic stations are located on glaciers, so timely identification of even small crevasses is required to ensure safety of Antarctic aviation's operation. Thus, investigation of glacier crevasses as such, their identification and localization have important applied relevance.

During the austral summer field season of the 60th RAE (2014/15), a number of geophysical studies were undertaken in the area of the Russian coastal Progress and Mirny Stations. GSSI SIR-3000 GPR radars were used, with antennas ensuring the frequency of the sounding pulses of 270, 400, and 900 MHz manufactured by GSSI (Geophysical Survey Systems Inc., USA). The radar characteristics are provided in [*GSSI Antennas Manual, 2014*]. The studies were aimed at identifying and investigating crevasses of relevant sizes. Tests were conducted to reveal the possibilities of the equipment available with the RAE regarding the tasks set and refinement of the methodology used. This paper presents the results of these studies.

INVESTIGATIONS ON A MODEL OBJECT

The complex investigations of the near-surface crevasses were started on December 27, 2014 by forming a GPR time section for sounding a model object. For this purpose, in the dense snow in the area of the runway of the Mirny Station, a trench was dug 60 cm deep and 42 cm wide, crossed by a bridge from pressed snow about 10 cm thick. Tracks 375 cm long were located orthogonally to the trench and crossed it on the snow bridge (Fig. 1). In these works, a manual 900 MHz GPR was used.

At the initial stage of the works, a metal plate was placed on the crevasse bottom, after which GPR sounding was performed. The plate reflected the signal generated with minimal losses, and the return signal was very intensive. It allowed precise identification of the bottom of the "crevasse". A GPR time-section is shown in Fig. 2, *a*. The position of the antenna on the snow surface corresponds to intense reflection *1*. Reflection *2* is related to a bridge across the "crevasse" formed from tamped snow. Intense subhorizontal reflection *3* is caused by the metal plate. Diffracted waves *4*, looking like hyperbolic reflections with one developed branch and one suppressed branch are generated from the plate edges. The plate

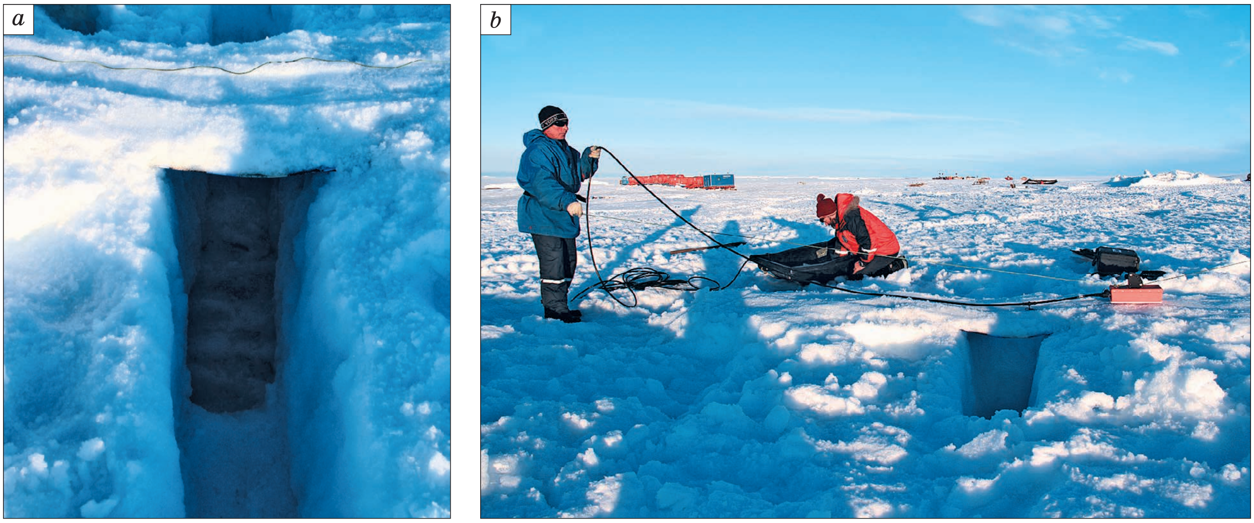

Fig. 1. A model crevasse (*a*) and experimental and methodological works (*b*) in the area of the runway of the Progress Station.

A photo by S.S. Pryakhin (December, 2014).

margins are marked with the apexes of the diffracted waves. Below *3* there is a series of intense reflections *5*, resulting from reverberations induced by the metal plate.

Using the hodographs of the two diffracted waves in the framework of a uniform medium model, the wave velocity in the snow cover was calculated. Both values are equal to 17.62 cm/ns, which corresponds to dielectric permittivity of 2.9. In general, the values obtained look quite realistic and correspond to values for snow-firn or dense snow at a temperature close to melting [*Macheret, 2006*]. Theoretical hodographs of the diffracted waves are shown in Fig. 2, *a* with dashed lines. They are made in the framework of a single-layer medium model [*Popov, 2002; Vladov and Starovoitov, 2004; Macheret, 2006*].

At the end of this stage, GPR profiling was conducted without using a metal plate. A time-section is shown in Fig. 2, *b* it contains reflections *1* and *2* reflected from the snow cover surface (a direct wave) and the bridge across the "crevasse", accordingly. Then we observed intense reflection *6*, characterized by the same delays as reflection *3* from the plate (Fig. 2, *a*). Surprisingly high intensity *6* can be attributed to melting of the near-bottom part of the "crevasse" and to formation of the ice crust. It has greater dielectric permittivity than snow and hence generates more contrast reflection. Diffracted waves *7* generated by the elements of the "crevasse" are observed on the right and left sides of *6*.

Thus, a conclusion can be made regarding the practical possibility of using hodographs of diffracted waves generated by the elements of crevasses, in order to develop a velocity model of a medium. This circumstance is important for interpreting data in the absence of *a priori* notions (in particular, when ice core data are unavailable or when multi-offset sounding is not possible).

SOUNDING CREVASSES AT DIFFERENT FREQUENCES

The Russian Antarctic expedition used three varieties of frequencies: 270, 400 and 900 MHz for the second stage of the investigations. Each of the frequencies provides its own approach to investigating the glacier section, i.e., they are complementary. Ground-penetrating radars with the frequency of 270 MHz have the highest operating depth. They allow reliable reflections to be obtained not only from the layers occurring in a glacier at the depths reaching 70 m but also successful sounding of moist snow and firn (the specific absorption of electromagnetic waves in which is higher [*Macheret, 2006*]). At the same time, this device has insufficient resolution for small objects to be sounded and their details to be discerned. Sounding at the frequency of 400 MHz is a certain compromise. On the one hand, it ensures the operating depth of several dozens of meters, and on the other hand, it allows rather reliable investigation of structures up to 1 m. Ground-penetrating radars with the frequency of 900 MHz have the lowest operating depth of about 10 meters. However, they ensure the highest resolution for the depth and are able to sound structures of the size of less than 20 cm.

One of the numerous crevasses located not far from the main buildings near Mirny Station was used as the object of studies (Fig. 3, *a*). It is 85 cm wide

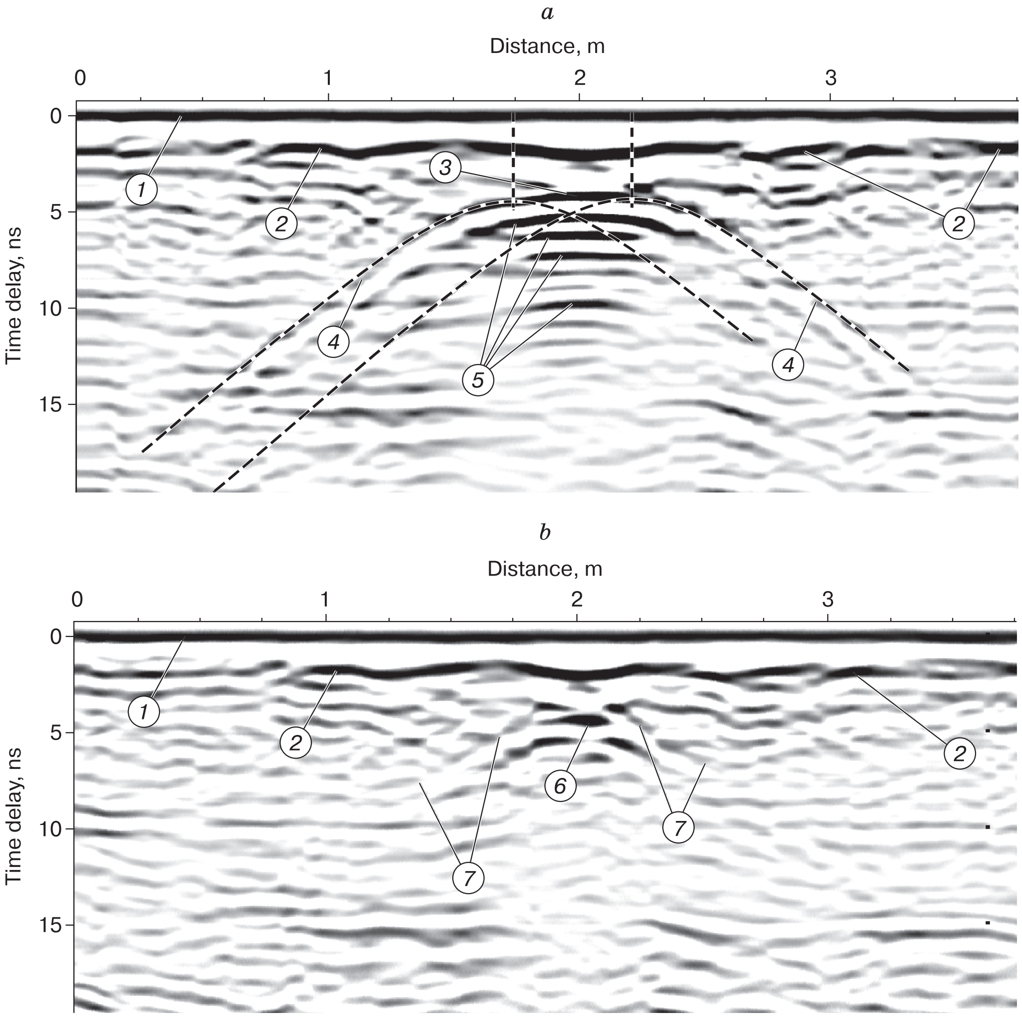

Fig. 2. A GPR time-section over the model crevasse with a metal plate on the bottom (*a*) and without it (*b*) in the area of the planned runway of the Progress Station.

1 – zero mark; *2* – reflection from the lower boundary of pressed snow (snow bridge); *3* – reflection from the surface of the metal plate; *4* – diffracted waves generated by the metal plate; *5* – diffracted waves caused by reverberation of the metal plate; *6* – reflection from the near-bottom part of the crevasse; *7* – diffracted waves generated by the crevasse elements. Theoretical time path curves of the diffracted waves are shown by dashed lines.

and several hundred meters long both sides. The crevasse walls are vertical. The measured depth of the snow bridge in the area of investigation was 35 cm. The crevasse depth was 430 cm, with a layer of melted water 210 cm thick located at the distance of 220 cm from the snow surface. The indicated parameters made the object ideal for making different tests.

Intense reflection *1* formed by a sounding pulse is observed in the time sections of the GPRs (Fig. 3, *b*–*d*). The position of the crevasse is marked by *2*. Intense reflections *3* and *4* are formed from the surface of melted water located at approximately the same depth from the snow surface. However, the travel time of these reflections *3* and *4* is 15.42 and 21.84 ns, accordingly. This may be explained as follows. Reflection *4* is formed by an electromagnetic wave, which, spreading in the snow-firn thickness, reflects from the water surface and returns, thus having a different propagation velocity. Supposing the depth of the water layer to be almost constant, the indicated delay corresponds to effective dielectric permittivity $\overline{\varepsilon}_1 = 2.2$ (with the average propagation velocity of the electromagnetic waves in the medium being $\overline{v}_1 = 20.2$ cm/ns). The time travel delay *3* corresponds to $\overline{\varepsilon}_2 = 1.11$ ($\overline{v}_2 = 28.5$ cm/ns). Such a small value is related to the fact that the wave propagated within an open crevasse for the longer part of its travel. Indeed, the total time of the wave propagation of in *N*-layer medium τ_Σ is composed of the time of its propagation in each *i*-th layer τ_i. In its turn, the latter

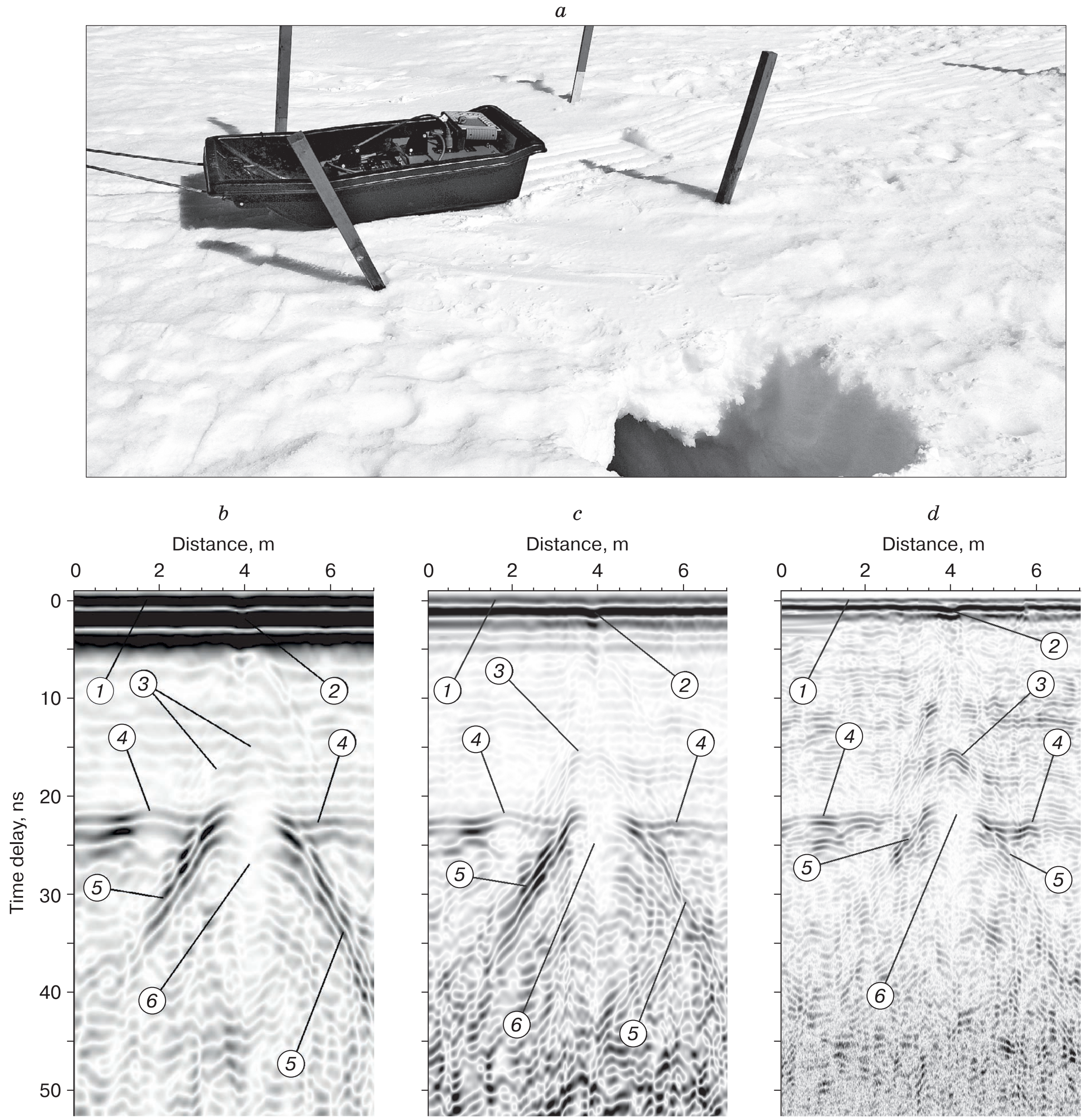

Fig. 3. A view of the test site with a crevasse (*a*) and GPR time-sections obtained at frequencies 270 MHz (*b*), 400 MHz (*c*) and 900 MHz (*d*) in the area of the planned runway of the Mirny Station.

1 – zero mark; *2* – reflection corresponding to the position of the crevasse; *3* – reflection from the water surface within the limits of the crevasse; *4* – reflection from the water surface outside the crevasse; *5* – a diffracted wave generated by the crevasse walls; *6* – attenuation of the reflected signal caused by the presence of a thick layer of melted water. (A photo by V.S. Popov, January, 2015).

depends of the depth of layer T_i and its dielectric permittivity ε_i:

$$\tau_\Sigma = \frac{2}{c}\sum_{i=1}^{N} T_i \sqrt{\varepsilon_i}\,, \quad (1)$$

where c is the velocity of propagation of electromagnetic waves in vacuum.

In the given case, the depths of the first and second layers are equal to 35 cm and 185 cm, with dielectric permittivity values being 2.2 и 1.0, respectively. Considering (1), we obtain the theoretical value for delay of reflection *3* as equal to 15.79 ns, which differs from the measured value only by 2 %, i.e. is within the limits of the measurement error.

It follows from analysis of Fig. 3, *b–d* that contrast *3* decreases as the frequency decreases, while contrast *4* remains practically the same. This is related to the fact that the main part of the spherical wave reflected from the flat surface is generated in the so-called first Fresnel zone, which is a circle with the radius r_f:

$$r_f = \frac{1}{2}\sqrt{\lambda T}, \qquad (2)$$

where λ is the wave length in the medium; T is the difference from the source of signal to the reflector [*Boganik and Gurvich, 2006*]. In accordance with (2), for sounding with frequencies 270 MHz, 400 MHz and 900 MHz, the value of r_f is 78, 64, and 43 cm, accordingly. Thus, with relatively low-frequency sounding, the generation area of the reflected signal was greater than the area of the water surface in the crevasse, while its vertical walls restricted the energy flux.

Diffracted waves *5* are formed from the vertical angles of the crevasse, and the near-top part *5* marks its borders.

In all the time sections below *3*, we observe attenuation of the reflected signal *6*, indicating the presence of a rather large layer of melted water, the specific absorption in which, depending on temperature, exceeds the respective parameter for snow and ice by approximately two orders [*Finkelshtein et al., 1977; Macheret, 2006*]. The absence of signal attenuation outside the crevasse suggests that the magnitude of the water-bearing horizon *4* is much less than the depth of water in the crevasse and is likely to equal a value of about ten centimeters or less.

Analysis of the available ground-penetrating time sections (Fig. 3, *b–d*) corroborates that, as the sounding frequency increases (and hence the wavelength decreases), refinement and contrast improve. The fragments of the crevasses formed in atmospheric ice, the size of which is of practical importance, are rather strong reflectors. The available equipment makes their identification and sounding at the frequencies of 400 MHz and 900 MHz.

Crevasses forming distinct diffracted waves

Theoretically, to form contrast diffracted waves as applied to the objects of studies, it is necessary to observe at least one of the conditions: 1) significant difference of the real part of the values of dielectric permittivity of media forming the boundary; 2) the least, compared to the wavelength, roughness of the media separating boundary. Crevasses formed in ice, irrespective of their origin, meet these conditions, as much as it is generally possible. Similar near-surface objects can be observed in the regions with insignificant positive or negative specific accumulation, in

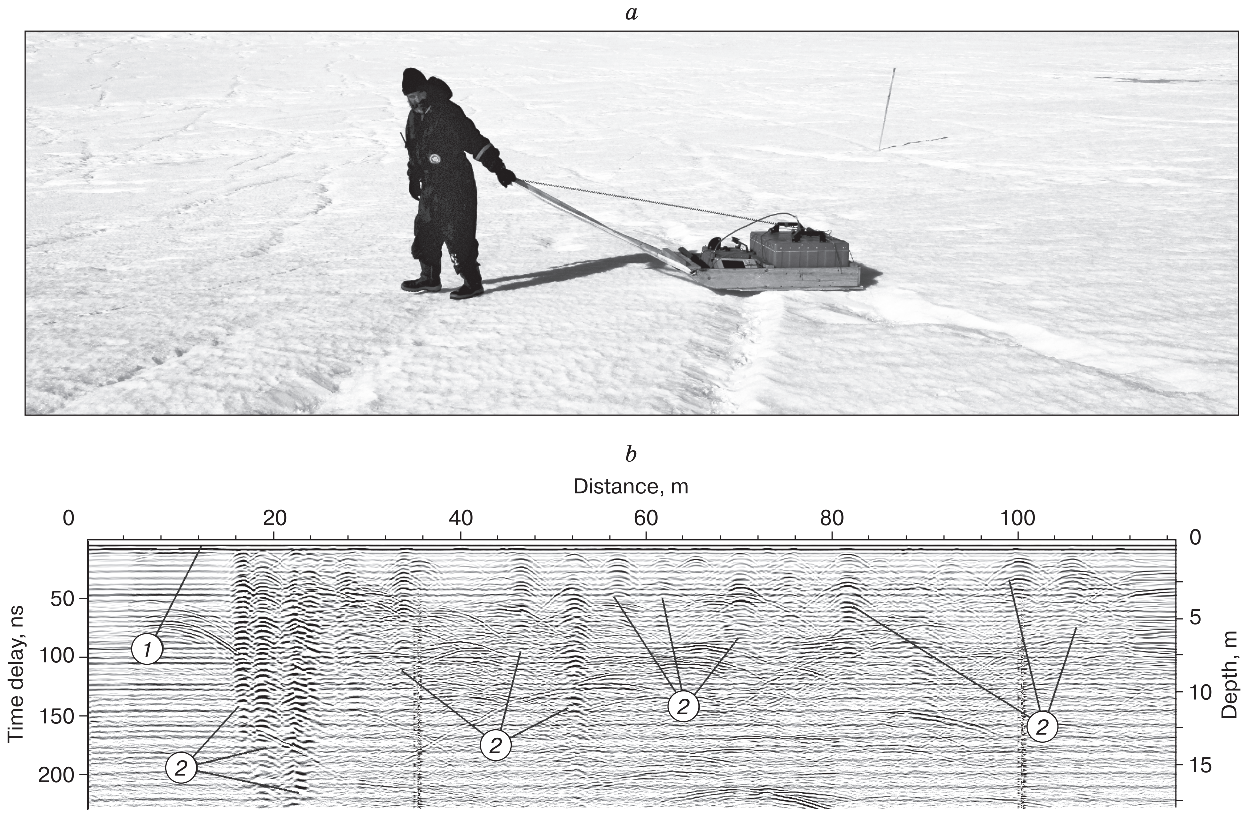

Fig. 4. Healed crevasses in the area between the field Progress-1 and Progress-3 (*a*) bases and the ground-penetrating radar time section obtained by identifying healed crevasses (*b*).

1 – zero mark; *2* – diffracted waves generated by crevasse elements. (A photo by A.O. Sandalov, February, 2012).

particular, between the field Progress-1 and Progress-3 Stations, as well as in the immediate proximity of the Mirny Station. Sounding of open crevasses located in the atmospheric ice mass has been discussed above.

During the summer field season of the 58th RAE (2012/13) in the area between the Progress-1 and Progress-3 stations, experimental and methodological studies were conducted to study healed crevasses [*Popov and Eberlein, 2014*]. They were presumably formed due to compression of the crevasses of the Dålk Glacier as it flew onto the rock outcrops of the Larsemann Hills. In this region, snow cover is practically missing, and these objects stand out as distinct extended linear structures (Fig. 4, *a*).

Fig. 4, *b* shows ground-penetrating time section for the route located orthogonally to the extension of the crevasses. In the upper part, there is intense reflection *1*, formed by a sounding pulse. The contrasting diffracted waves *2* are generated by healed crevasses. As the snow-firn thickness is practically absent, recalculation of the time section into a depth section (the right-side vertical axis in Fig. 4, *a*) was made based on the assumption that dielectric permittibility of ice was equal to 3.17 [*Macheret, 2006*].

Crevasses forming poorly expressed diffracted waves

It was shown in the previous sections that the contrast range of a diffracted wave depends on configuration of the crevasse walls and the Fresnel factor. In this sense, the cavities in the snow and firn thickness are not contrast objects. The cause of this is quite evident. Firstly, the dielectric permittivity of snow and firn is only 2–2.5 times higher than that of air. This means that the maximum possible Fresnel factor (i.e., for the case of mirror reflection, which is not used in practice) is about 20 %. Secondly, as snow is rather soft material, the boundary between the media becomes more distinct, and its roughness increases. Thus, crevasses formed in the areas having different conditions of snow accumulation will differ for their conditions of distribution of electromagnetic waves. Hence, ground-penetrating sounding radar-induced time sections will differ, too. Visual comparison demonstrates that the crevasses developed in the area of the Mirny Station drastically differ from those formed on the Progress–Vostok logistic traverse route.

To ensure more detailed study of the crevasses formed in the large snow and firn thickness, on February 5, 2015, ground-penetrating radar profiling was conducted at the frequencies 270 MHz and 900 MHz for a large crevasse, into which a fuel tank partly fell in 2012 (Fig. 5, *a*). The works were conducted at a point with coordinates 69°34.025′ S; 76°15.782′ E at a distance of about 200 m from the main route.

Fig. 5, *b* shows one of the ground-penetrating radar time sections obtained for the route located in perpendicular to the direction of the crevasse under study. Sounding took place at the frequency of 900 MHz. Intense reflection *1* is formed by the sounding pulse and marks the start of the radio sounding record. In the central part of the section, significant attenuation of the reflected pulses *2* is observed, related to the presence of the crevasse. Its width is about 5 m.

It is to be noted that the diffracted waves formed by the walls of crevasse *3* are expressed extremely poorly. This makes this object essentially different from the similar objects which are adjacent (reflections *4*) or located in other areas. This is primarily related to the rough shape of the walls and to the fact that they are formed by the snow-and firn thickness, which has less contrast. While on the right-side boundary diffracted waves *3* can be discerned, they are absent on the left-side boundary. Hence, we can assume the first wave to be more even than the second one.

The crevasse is crossed by a thick snow bridge, the thickness of which, in accordance with direct measurements, is 80 cm. Reflection *5*, rather clearly seen with the time travel delay 8.06 ns, is related to its lower part. In this case, dielectric permittivity of the snow is 2.3, and the wave propagation velocity in the medium is 19.9 cm/ns. Similar values were obtained for the snow-and-firn thickness in the area of Mirny Station.

The absence of reflections inside area *2* (except for the branches of hyperbolic reflections related to diffracted waves) allows us to assume that the crevasse is mostly hollow inside. Otherwise, ice lumps or snow would inevitably form at least a diffracted wave. Yet, individual reflections *6* are observed in the near-top area, which are related to such objects. Judging by the intensity of the reflected signal, these are likely to be ice, not snow, fragments.

The crevasse investigated is of the most dangerous type, as it is most difficult to identify such crevasses.

THE USE OF A GROUND-PENETRATING RADAR FOR THE PURPOSE OF OPERATIVE IDENTIFICATION OF CREVASSES

Safety of driving motor vehicles in the areas with underlying crevasses is of peculiar importance. There is an opinion that operative analysis of data obtained from a ground-penetrating radar, the antenna of which is fixed on a long boom in front of a tractor, is capable of preventing a fall into a crevasse (Fig. 6). The author believes this is a dangerous illusion. Indeed, a ground-penetrating radar is a powerful geophysical instrument allowing solution of a wide range of scientific and applied problems in the area of glaciology, quaternary and engineering geology, as well *a*

b

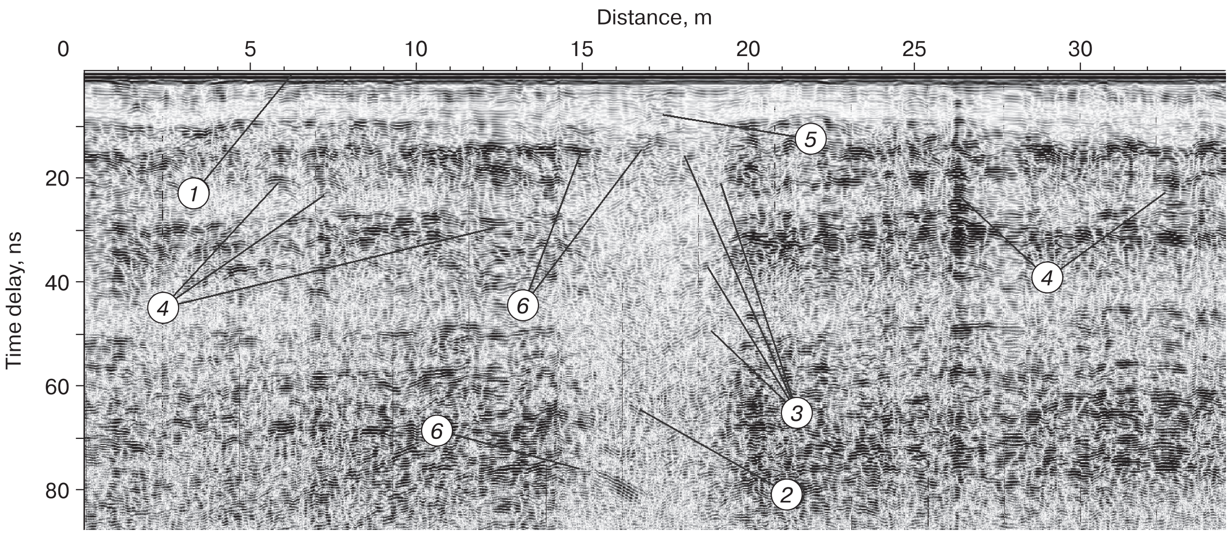

Fig. 5. A crevasse in the area of the crawler-tracked sledge march Progress Station – Vostok Station (*a*) and a ground-penetrating radar time section obtained by identifying it (*b*).

1 – zero mark; *2* – significant attenuation of reflected pulses related to the presence of a crevasse; *3* – diffracted waves generated by fragments of crevasse walls; *4* – reflections caused by crevasses with relatively even walls; *5* – reflection from the lower boundary of the snow bridge; *6* – reflections formed from presumably ice canopies or destroyed fragmentary snow and ice bridges. (A photo by I.K. Vdovenko).

as of nondestructive inspection. It is this radar that is most suitable for resolving the issues of identifying the presence of a crevasse and its coordinates in the body of a glacier. This is mentioned in numerous publications and is corroborated by the results of the works conducted. However, no matter how numerous the operating advantages of ground-penetrating radars are, they are not capable of doing wonders.

Firstly, it is not a computer, an instrument, but a human who processes the geophysical data obtained. It is on this person's education and experience that the results of interpreting the data obtained depend. At that, it is to be realized that for a number of reasons, radio sounding data, and especially sounding data provided by a ground-penetrating radar, are most difficult to interpret.

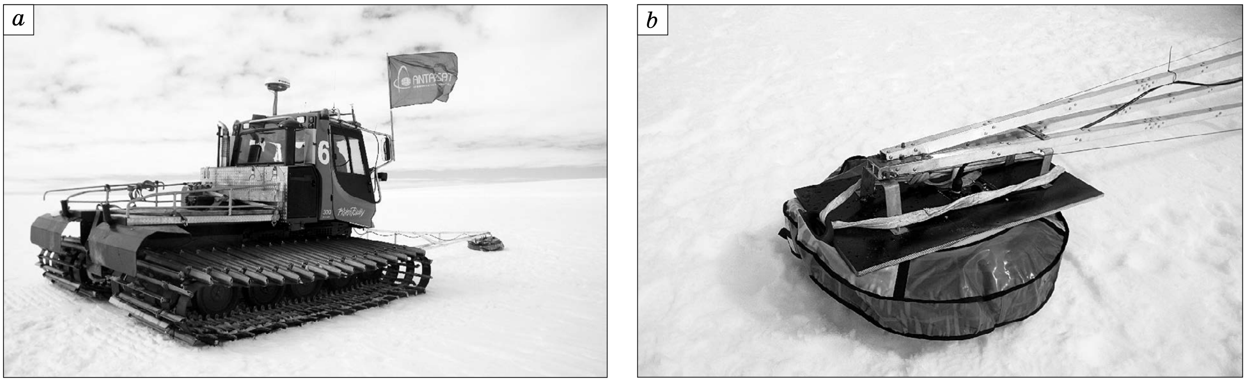

Fig. 6. Devices designed for remote identification of near-surface crevasses in the glacier body with ground-penetrating radars at the Progress Station.

a – general view; *b* – the offset antenna. (A photo by S.P. Polyakov, December, 2012).

Secondly, considering the high velocity of the putative transport vehicle (5–10 km/h), an operator has just a few seconds to take a decision. This is practically an unfeasible task even for a professional: the indicated moment is so brief that the decision taken may turn out to be correct only due to random chance.

Thirdly, analysis of the time section shown in Fig. 5, *b* demonstrates that signs of approaching a crevasse (diffracted waves) are either absent or expressed only slightly in the configuration of the crevasses, which cuts down the decision-making time even further. It stands to reason, of course, that another situation is also possible: the presence of intense diffracted waves. However, an operator should be able to understand within a very short time lapse that the diffraction observed is really a diffracted wave coming from a crevasse but not from a surface reflector (for example, a fuel tank or barrel) or from the layers of the snow and firn thickness.

Fourthly, objectively speaking, it is possible to understand that the observed reflection is a diffracted wave only after the antenna crosses the reflector forming the wave and the top of the diffracted wave appears on the monitor. Yet, this will occur only when the caterpillar or the wheels of the transport vehicle start crossing the dangerous zone and then falling into the crevasse.

In the authors' opinion, the conclusion is the following: in order to find out whether there are crevasses in a certain area or not, ground-penetrating radar sounding should be conducted in accordance with all the rules of performing geophysical works of this kind. To be true, such an approach does not imply fast actions, yet, this is the most reliable and relevant method of solving the task set.

CONCLUSION

The experimental and methodological studies conducted by the 60th RAE have shown the following:

1. Ground-penetrating radar sounding at the frequencies ranging from 400 MHz to 900 MHz is a perspective method for solving applied tasks of identifying crevasses in the near-surface part of a glacier.
2. Crevasses in atmospheric ice are rather reliably identified by intense diffracted waves.
3. The configuration of crevasses in the snow-and-firn layer may be such that the diffracted waves characteristic of such objects may be expressed rather poorly. This makes identification of such objects difficult, especially during production works. Attention should be paid to the areas of a GPR time-section in which attenuation of the reflected signal takes place, which is not related to equipment failures.
4. Diffracted waves formed by the walls of a crevasse may become a rather reliable basis for developing a velocity model of a medium, especially when ice core data are unavailable or when multi-offset sounding is not possible.

Guided by the general geophysical ideas, the authors believe that this kind of works should be supported by acoustic methods of investigating glaciers in the snow and firn cover [*Epifanov, 2014*], in order to understand the glacier structure better.

The authors express their gratitude to the administration of the Russian Antarctic expedition and to Antraverse Service Ltd. for the possibility of conducting ground-penetrating radar works. They also thank the pilots of the 60th RAE E.G. Gruzinov, S.V. Kashin, A.I. Kutsuruba, Yu.I. Nezderov, S.S. Pryakhin, and N.V. Sandalyuk for their help in the works.

The study was conducted with the financial support of the Russian Foundation for Basic Research (project 16-05-00579-A).

References

Boganik, G.N., Gurvich, I.I., 2006. Seismic Survey, AIS, Tver, 744 pp. (in Russian)

Epifanov, V.P., 2014. Acoustics application for snow cover study. Kriosfera Zemli XVIII (3), 101–113.

Finkelshtein, M.I., Mendelson, V.A., Kutev, M., 1977. Radio Sounding of Earth Covers. Sov. Radio, Moscow, 176 pp. (in Russian)

GSSI Antennas Manual. Geophysical Survey Systems, Inc. Salem, 2014, 99 pp. (NH,USA, MN30-903 Rev. E).

Macheret, Yu.Ya., 2006. Radio-echo sounding of glaciers, Nauchnyi Mir, Moscow, 392 pp. (in Russian)

Melnikov, V.P., 2014. The Cryosphere: A holistic approach. Kriosfera Zemli XVIII (4), 3–12.

Popov, S.V., 2002. Identifying the average propagation velocities of electromagnetic waves in a glacier by hyperbolic reflections from inhomogeneous entities. Materialy Glyatsiol. Issled., No. 92, 223–225.

Popov, S.V., Eberlein, L., 2014. Investigation of snow-firn thickness and ground in East Antarctica by means of geophysical radar. Led i Sneg, No. 4 (128), 95–106.

Vladov, M.L., Starovoitov, A.V., 2004. Introduction to Ground-penetrating Radio-Echo Sounding. Moscow University Press, Moscow, 153 pp. (in Russian)

Received March 5, 2015