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Velocity of radio-wave propagation in ice at Vostok station, Antarctica

Sergey V. POPOV,[1] Alexander N. SHEREMET'YEV,[1] Valery N. MASOLOV,[1] Valery V. LUKIN,[2]
Anatoliy V. MIRONOV,[1] Vadim S. LUCHININOV[3]

[1]*Polar Marine Geological Research Expedition (PMGRE), 24 Pobeda Street, Lomonosov, 189510 St Petersburg, Russia*
E-mail: spopov@polarex.spb.ru
[2]*Russian Antarctic Expedition (RAE), 38 Bering Street, 199397 St Petersburg, Russia*
[3]*GNPP "Sevmorgeo", 36 Rozenshteyna Street, 198095 St Petersburg, Russia*

ABSTRACT. During the austral summer field season of the Russian Antarctic Expedition in 1999/2000, wide-angle reflections experiments were performed in the vicinity of the Russian station Vostok. A 60 MHz ice radar system with 12-bit digital recording was used. The measurements were taken along two perpendicular lines directed south–north and east–west with a distance of 200 m between marks. We used a one-layer model (without snow–firn zone influence) for the calculations. We calculate that the average velocity of radio-wave propagation in the ice sheet is 168.4 ± 0.5 m μs^{-1}. The same velocity was derived from hyperbolic diffractions from internal discontinuities. The results allow more accurate depth interpretation of radio-echo soundings.

1. INTRODUCTION

Throughout the last several years the Polar Marine Geological Research Expedition (PMGRE) has carried out radio-echo sounding (RES) investigations of lake Vostok beneath the Antarctic ice sheet (Masolov and others, 1999; Lukin and others, 2000; Popov and others, 2000). To increase the accuracy of the RES data, PMGRE measured the radio-wave propagation velocity in ice in the vicinity of the Russian station Vostok during austral summer field season 1999/2000. The measurements were carried out using the wide-angle reflection method (Popov and others, 2001). Similar measurements previously performed in Antarctica (Robin and others, 1969; Clough and Bentley, 1970; Trepov, 1970; Jiracek and Bentley, 1971; Van Autenboer, 1972; Drewry, 1975; Bogorodsky and others, 1985; Sheremetiev, 1989) have given velocities of 166–171 m μs^{-1} for glacier ice and 171–175 m μs^{-1} for ice shelves. The distribution of the velocities in Antarctica is shown in Figure 1. The chart was calculated based on the sources mentioned above. Comparable values have been calculated from the electromagnetic properties of ice (Khokhlov, 1970; Luchininov and Macheret, 1971; Luchininov, 1977; Bogorodsky and others, 1983). These sources give $\varepsilon \approx 3.17$ ($v = 168.5$ m μs^{-1}). According to Figure 1 we expected the velocity of electromagnetic waves in ice near Vostok station to be about 168 m μs^{-1} ($\varepsilon = 3.174$).

2. EQUIPMENT

The wide-angle reflection measurements were made with a system consisting of the 60 MHz ice radar RLS-60-98, a digital processing interface (DPI) and a satellite navigation system (Masolov and others, 1999; Lukin and others, 2000; Popov and others, 2000, 2001). The DPI is based on the industrial computer "Favorite-IPC" with a SBC-8259 processor (Axiom Technology Co). The analog–digital transformation used a 12-bit analog–digital converter AD9042AST (Analog Devices Inc.). The digitizing of the radar output data and its stacking were carried out in real time. The ice radar system specifications are given below:

mean frequency	60 MHz
pulse repetition frequency	600 Hz
pulse length	0.5 μs
peak pulse power	60 kW
bandwidth of the reception channel	3 MHz
time-step of digitization of the RES signal	0.05 μs
amplitude step of digitization of the RES signal	0.24 mV
stacking (integration) rate	256 sum
registration interval	1 s

The very widely spaced receiver and transmitter required a special system to trigger the receiver. We used a sound system whereby the leading edge of a sound pulse provided the trigger.

3. RES TECHNIQUE

The wide-angle reflection soundings were made along two lines (northern with an azimuth 335° and western with an azimuth 245°), each of them divided into 18 segments of 200 m (Fig. 2). The lines were laid out with a theodolite, with a maximal deviation of ±0.05° from a straight line. Marking was done with a 100 m metal tape with a margin of error of ±0.1 m. The transmitting antenna was fixed near a snow-bound metal beam (point 0, Fig. 2). The receiving antenna was fixed on the roof of a mobile beam and, during the moving, was positioned strictly above marks at 3 m height from the ice surface. The velocity was calculated with a one-layer model which assumed a horizontal subsurface interface. The correctness of the applied model was confirmed by the natural measurements. It was provided with a RES survey

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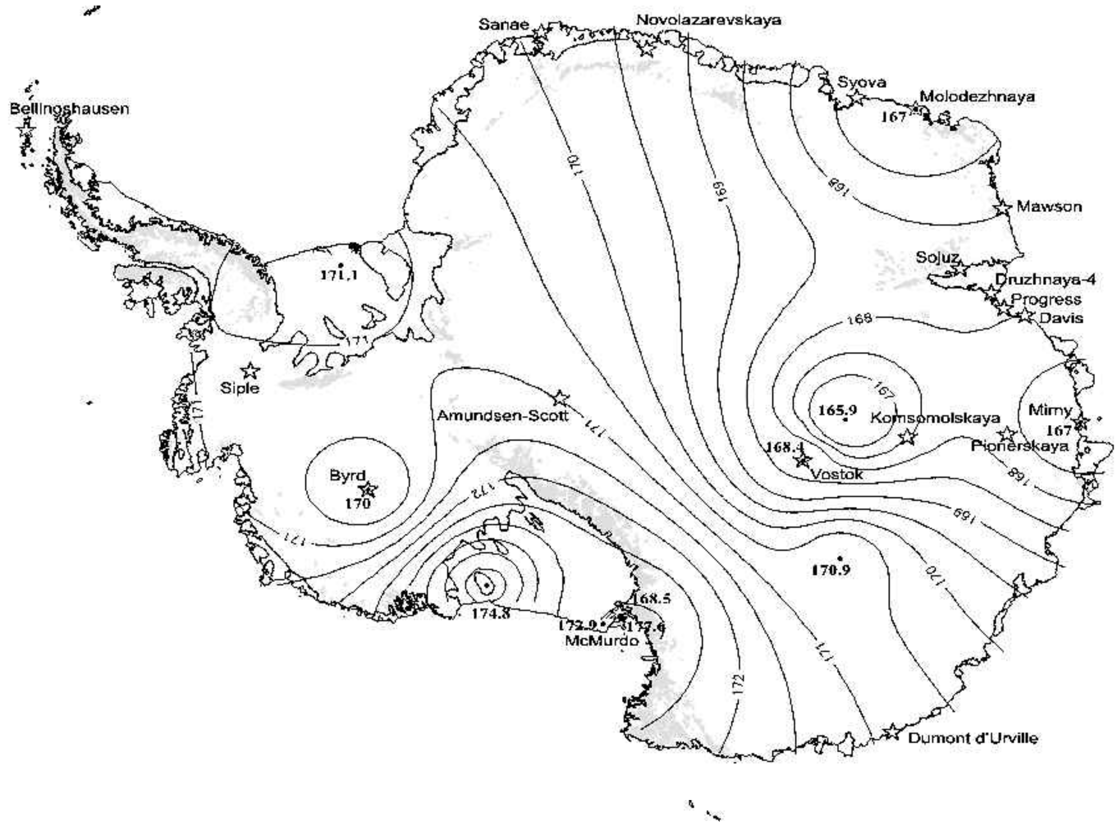

Fig. 1. Velocity of electromagnetic wave propagation in Antarctic ice sheet. Black points show measured data.

around Vostok station and mapping of the ice base of the area (Popov and others, 2001). One of the RES records is shown in Figure 3.

It is necessary to note that it would have been more correct to use the common depth point (CDP) technique, i.e. both antennas move equally from a center point (Bogorodsky and others, 1983). Unfortunately, this was technically impossible. The CDP technique is necessary when dealing with an inclined ice base, because then the point of reflection is fixed. In our case we dealt with horizontal layers, for which the points of reflections are fixed because of the extremely simple geometry of radio-wave propagation.

4. PROCESSING OF THE DATA AND RESULTS

The average velocity of radio-wave propagation in ice was calculated following Bogorodsky and others (1985). The mathematics of the geometry of radio-wave propagation are given as $b^2 + (2T)^2 = L^2$, where b is the distance between the antennas, T is the ice thickness and L is the radio ray distance in ice, for horizontal layers. $L = v\tau$, where v is the average velocity of the radio-wave propagation in ice and τ is the delay of the reflected signal. By simple substitution

$$\tau^2 = \frac{b^2}{v^2} + 4\frac{T^2}{v^2}, \tag{1}$$

and we fit a straight line by the least-squares regression method (LSM). The regression coefficients are given as:

$$v = \frac{1}{\sqrt{a_1}}, \qquad \text{and} \qquad T = \frac{1}{2}\sqrt{\frac{a_0}{a_1}}, \tag{2}$$

where a_1 and a_0 are the coefficients at the first and free members accordingly. Equation (1) and the coefficients (2) were calculated for each line (Fig. 4).

The average velocity of the radio-wave propagation in ice is found to be 168.36 m μs^{-1} for the northern line and 168.43 m μs^{-1} for the western line. Therefore, the average englacial velocity in the lake Vostok area is 168.4 ± 0.5 m μs^{-1}. An account for the air layer only changes the second decimal and is not important.

5. HYPERBOLIC DIFFRACTION PROCESSING

It is also possible to determine the average velocity of electro-

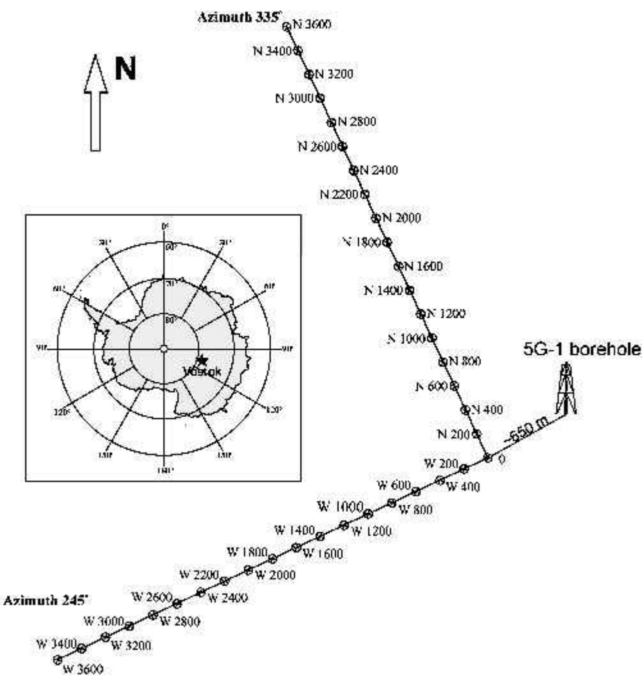

Fig. 2. Wide-angle reflection technique location chart.

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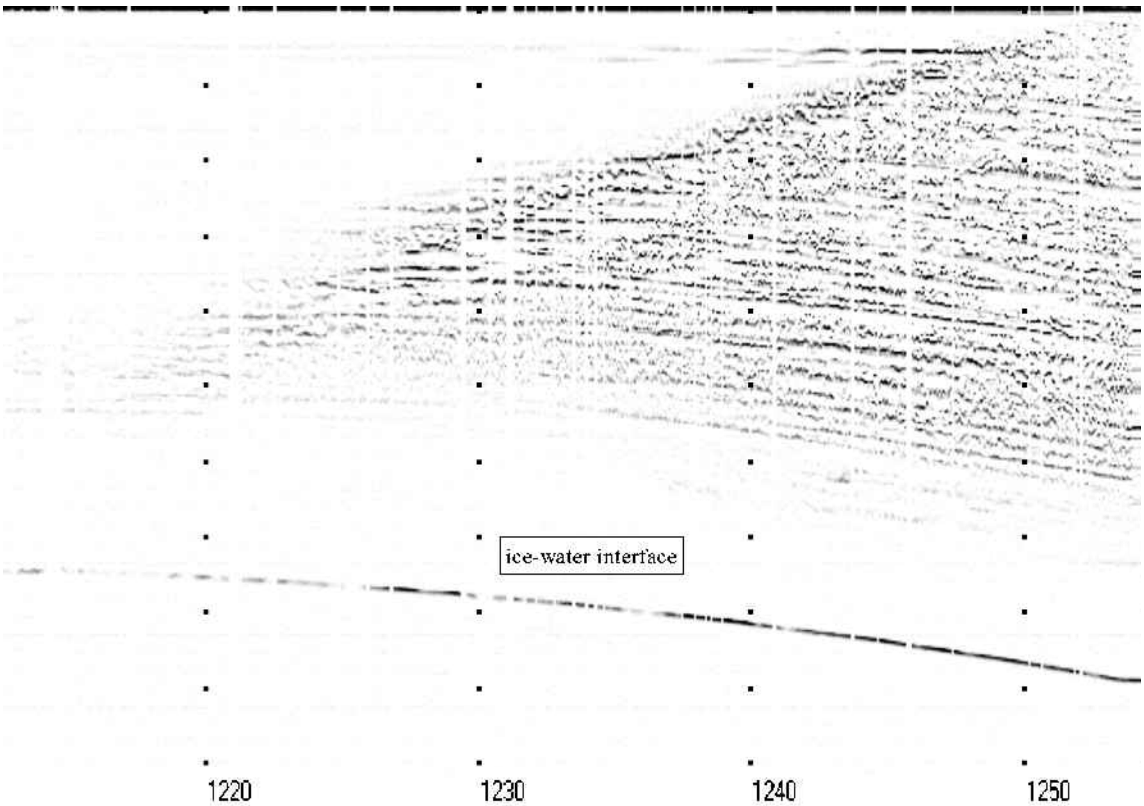

Fig. 3. RES record (western leg).

magnetic wave propagation using the hyperbolic diffractions (Macheret, 2000; Vasilenko and others, 2001). Radio-wave rays from a point diffractor are shown in Figure 5. If x_0 is the value of the abscissa at the apex of the hyperbola, ξ_i is the distance between x_0 and x_i, T is the ice thickness, d is the lateral distance between the reflector and the RES route, and τ_0 and τ_i are delays of the reflected signal (they correspond to distances L_0 and L_i), then, for the ray at x_0

$$L_0^2 = T^2 + d^2 = \frac{1}{4} v^2 \tau_0^2 \,,$$

and at x_i we have

$$L_i^2 = T^2 + \zeta_i^2 = T^2 + d^2 + \xi_i^2 = L_0^2 + \xi_i^2 \,,$$

where

$$\tau_i^2(\xi_i^2) = \tau_0^2 + 4\frac{\xi_i^2}{v^2} \,. \qquad (3)$$

We can calculate a linear fit using regression coefficients calculated by LSM (Equation (3)). The velocity v can be found through Equation (2), as described in Macheret (2000) and Vasilenko and others (2001).

We estimate our error, δv, is

$$\delta v = v\sqrt{\left(\frac{\delta\tau_0}{\tau_0}\right)^2 + \left(\frac{\delta\xi_i}{\xi_i}\right)^2 + \left(\frac{\delta\tau_i}{\tau_i}\right)^2} \,. \qquad (4)$$

Z-record modeling (Fig. 6a) gives the relative height value δv. The errors $\delta\tau_0$ and $\delta\tau_i$ can be estimated as approximately 0.25 μs ($\tau_0 \approx 45\,\mu$s). We estimate the error $\delta\xi_i$ ($\xi_i \approx 2000$ m) as approximately 30 m. Then, according to Equation (4), $\delta v \approx 2.8\,\mathrm{m}\,\mu\mathrm{s}^{-1}$, at $v = 168\,\mathrm{m}\,\mu\mathrm{s}^{-1}$, but the level of accuracy is unacceptable.

We can reduce the error (Popov, 2002) by considering the RES record amplitude $A = A(\tau)$. The digitizing was done on the leading edges (LES), i.e. on the maximum of the first derivative $\tau' = \mathrm{d}A/\mathrm{d}\tau$. With the understanding that the LES of the reflections must be positive, we redefine τ' as τ'_+ such that

$$\tau'_+ = \begin{cases} \tau', & \text{if} \quad \tau' > 0 \\ 0', & \text{if} \quad \tau' \le 0 \end{cases} \,. \qquad (5)$$

We then created a synthetic binary Z record that consists of two different values: black points (corresponding to peaks τ'_+) and white points (Fig. 6b). For obvious reasons, there will be a significant number of such peaks. We establish a limit ς, which allows us to plot only peaks with $\tau'_+ > \varsigma$. Therefore, we can reduce the number of the peaks by varying ς, which allows us to process the data more precisely (Fig. 6c).

We now estimate δv again (Equation (4)). The $\delta\xi_i$ can be estimated as 1 point (≈1.5 m). Practically the same value is obtained for the carrier position determination. Hence, it is possible to accept $\delta\xi_i \approx 3$ m. The error in determining the position of the hyperbola apex can be estimated as 1 point (≈0.05 μs). According to Figure 6c, the $\delta\tau_i$ could be estimated as 0.1 μs. Finally, δv could be as little as $0.75\,\mathrm{m}\,\mu\mathrm{s}^{-1}$ (≤0.5%).

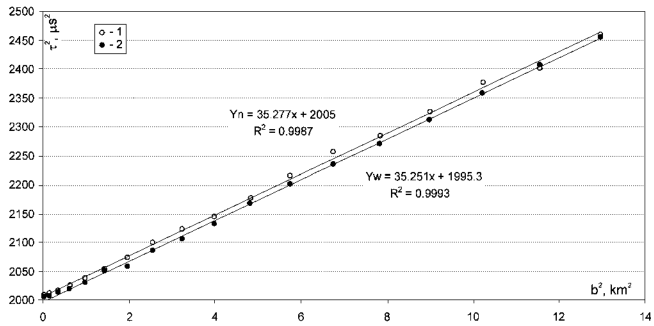

Fig. 4. Plots of the squares of the reflected signal delays vs squares of the distance between antennas, trend lines and best-fit equations. 1. The northern leg; 2. the western leg.

There were three hyperbolic reflections in the RES data. The velocities were 168.46, 168.52 and 168.46 m μs^{-1}. The average value is 168.5 m μs^{-1}. This is close to the value defined by the wide-angle reflection technique, so velocity determination by hyperbolic diffractions could be used in future RES investigations.

6. COMPARISON OF RESULTS WITH OTHER GEOPHYSICAL MEASUREMENTS

In addition to our work, vertical seismic profiling (VSP), thermometry, ice density determination and other geophysical investigations were carried out in borehole 5G-1 and its vicinity. We estimate ice thickness from the convergence of all available data on the ice thickness. Based on RES data, the ice thickness in the vicinity of 5G-1 borehole is 3775 ± 15 m. Based on VSP data, the ice thickness is 3760 ± 30 m (Popkov and others, 1999). The thermometry data give a value of 3776 ± 3 m (Salamatin and others, 1998). The divergence between all the data is <1%, which is quite good for so many methods.

7. DISCUSSION: FIRN CORRECTION

The precision of the velocity of electromagnetic wave propagation in ice by the wide-angle reflection method was

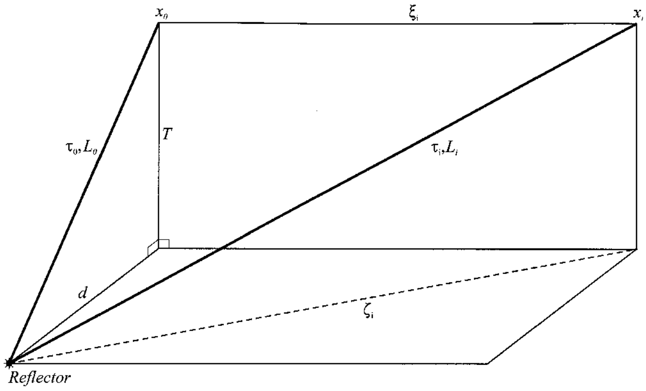

Fig. 5. Ray geometry of electromagnetic waves propagating from a point reflector.

discussed by Babenko and Macheret (1997). They used Rasmussen's approach by elliptic functions (Rasmussen, 1986) for the firn layer. Ice density, ρ, down the ice sheet was converted to refractive index n with the following dependence: $n = 1 + K\rho$, where $K = (8.51 \pm 0.1) \times 10^{-4}\ m^3\ kg^{-1}$ (Babenko and Macheret, 1997). We believe that the approach of Rees and Donovan (1992) was more correct because they used $K = (8.4 \pm 0.1) \times 10^{-4}\ m^3\ kg^{-1}$ (Rees and Donovan, 1992), but for our estimation this difference is not important.

We estimated the firn correction for the vicinity of Vostok

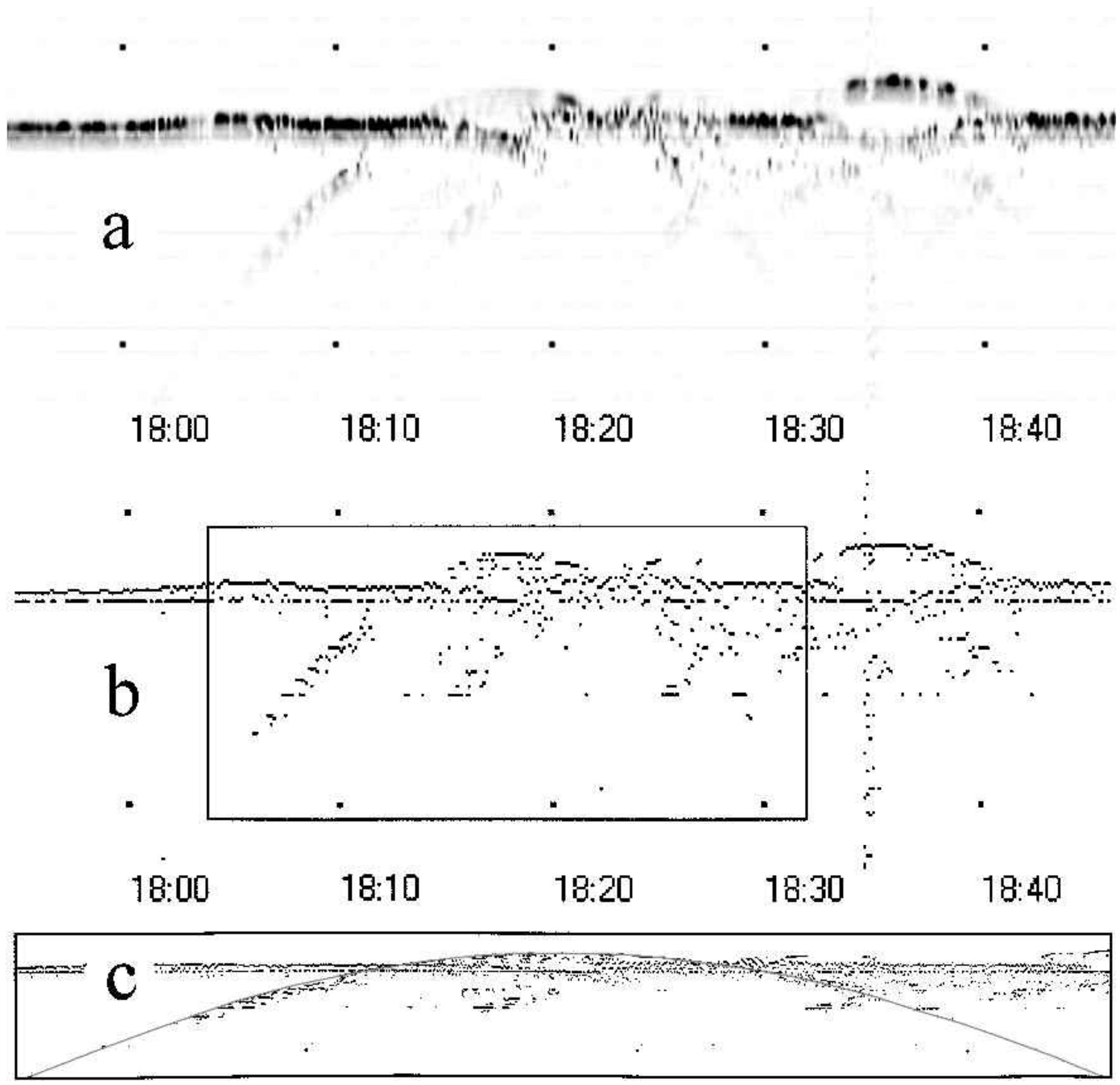

Fig. 6. Hyperbolic diffractions and their modeling; (a) Z record; (b) RES record formed using the described method; (c) modeling.

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station following Babenko and Macheret (1997). For an ice thickness of $T \approx 4000$ m, firn thickness of $T_{\text{firn}} = 105$ m (Salamatin and others, 1985) and surface snow density of $\rho_0 = 320\ \text{kg m}^{-3}$ (Ekaykin and others, 1998), the error of the velocity definition is $v \approx 0.04\ \text{m}\ \mu\text{s}^{-1}$ (~0.02%). Therefore, accounting for the firn layer impact on the velocity of electromagnetic wave propagation in ice is not important for RES investigations.

8. CONCLUSIONS

We have measured the electromagnetic wave propagation velocity in the vicinity of Vostok station by the wide-angle reflection method. It is a relatively complex method that requires some special observations that are not easy to perform. Our knowledge of the velocity in Antarctica forces us to lower the accuracy of ice-thickness measurements to 3% mainly because of velocity scattering. We also tried to analyze the diffractions from discontinuities in the ice. As shown above, this method could be used for a ground-based RES survey and would allow measurements of electromagnetic wave propagation velocity in remote areas with an accuracy due to velocity scattering of <0.5%.

On the other hand, it is important to define the velocity in remote parts of Antarctica (or the Arctic) for airborne RES. Perhaps this could be done based on an analysis of the diffraction from discontinuities, but for a more complex model. Solving this problem would lead to an increase in the accuracy of RES investigations.

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