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Radar measurements of thickness of "warm" glaciers*)

ABSTRACT: The radar device for measurement of thickness and structure of "warm" glaciers was used in this work. The measurement of thickness of dielectric is based here on the examination of transit time of hight frequency electromagnetic pulse throught the measured stratum.

A total ice volume of "warm" glaciers is in the melting temperature here. Such glaciers are characterized by a large number of internal structure defects. The electromagnetic wave reflections are caused not only b the glacier base but, additionally by ice crevasses, more imbided water layers and by all other defects of the internal glacier structure, too.

The simple statistical method was elaborated for differentiation of essential layers reflections from random reglections caused by less extented objects.

This method was used to obtain the two transversal profiles of the Hans Glacier (South Spitsbergen).

Key words: Arctic, Spitsbergen, radar sounding of glaciers

1. Introduction

The need to fix the geometry of investigated glaciers for estimation their masses and for solution their dynamical problems has been lasted in the program of glacial exploration of Polish polar expeditions for many years.

The thickness of Hans Glacier (the nearest glacier to the Polish Scientific Polar Station in Hornsund Fiord) has been tried to estimate on the base of the spectrum analysis of natural glacier clicks (Czajkowski 1977) and by the method so called "the small seismics" (Czajkowski, unpublished data). The average result, proportional to a big area of glacier was obtained in the first case and it was charged by a big error. In the second case the energy of stricking hammer was too small for the seismic examination of

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*) The work was made during the Summer Spitsbergen Expedition in 1979 organized by Institute of Geophysics, Polish Academy of Sciences.

glacier. There is no permission for making explosions in this area because of enviromental protection — so the seismic method can not be used. Therefore, it was necessary to take advantage of radar device to obtain accurate and easy for interpretation results.

The theory of radar measurements applicated to glaciers was elaborated by Ginzburg (1960), Bogorodskij and Rudakov (1962), Robin, Evans and Bailey (1969) and others.

Such measurements have been used for glaciers of Antarctic, Greenland and Alaska. They were performed by big aircrafts, helicopters and by vehicles crossing glaciers surface, too. To date elaborated methods are adequate for "cold" glaciers, where the total ice volume lasts in minus temperature. These glaciers have rather simple structure and are characterized by not quite extended net of crevasses. However, our attention lays on "warm" glaciers, small and full of crevasses with a very complicated internal structure. The temperature across the whole depth of glacier is close to 0°C in the area of our work, except the surface layer of few meters thickness (Grześ 1980).

A performation of air measurements on small glaciers gives a mean result because the sounding beam is too wide. It is difficult to determine the beam location precisely. In this case returns from mountain slopes surrounding the glacier and from the surface and the internal, moraine layers are registered, too.

The dissipation of energy is greater in the case of air measurements than in measurements made directly on the glacier surface.

It was necessary to elaborate the method of distinction of essential reflections caused by rocky ground of glacier and by his internal layers from random and local reflections. Than we decided to perform our measurements on the glacier surface to obtain the precise map of rocky glacier-ground.

2. Theory of measurements

Radar methods of thickness study of layered structures are based on the measurements of transit time of the pulse of electromagnetic wave through the measured layer. The radar-transmitter via an antenna emits the high-frequency short pulse of electromagnetic wave. The pulse runs through the measured layer, reflects from the boundary of layer and returns to the surface, where it runs through the antenna and the receiver to the indicator (Fig. 1). The direct pulse from the transmitter (so called sounding pulse) comes to the receiver regardless the pulse reflected by the ground (so called return). The delay time between these pulses is equal the double run-time of electromagnetic wave through the measured layer, under the condition that the distance between the transmitting and receiving antenna is sharp less than the thickness of layer.

We can determinate the thickness of layer when we know the mean velocity of wave propagation in the layer obtained from the simple formula:

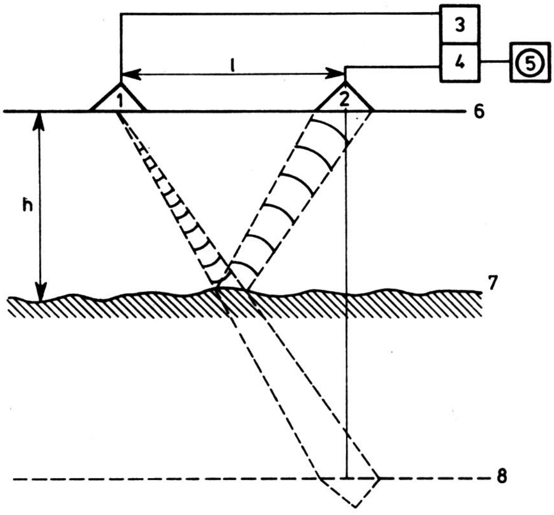

Fig. 1. The schematic diagram of the sounding method
1 — transmitting antenna, 2 — receiving antenna, 3 — transmitter, 4 — receiver, 5 — indicator, 6 — surface of glacier, 7 — rocky glacier ground, 8 — mirror reflection of glacier surface, l — distance between the transmitting and the receiving antenna, h — thickness of glacier

$$h = \frac{V_{av} \cdot t}{2},$$

where:

h — thickness of layer,
V_{av} — mean velocity of wave propagation,
t — double run-time of wave pulse through the layer.

When the velocity of wave propagation is different for the different depth of glacier we should joint the above mentioned quantities with the velocity distribution as follows:

$$t(h) = \int_0^{h_{\max}} V(h)\, dh$$

Radar methods give the possibility to investigate media composed of few layers. In this case we obtain a number of returns and we can calculate the corresponding thicknesses, when we know the wave velocities for the particular layers. Some returny from the defects of internal structure of glacier are registered, however, on the indicator, and they make troubles with interpretation.

The Maxwell equations determine the electromagnetic wave propagation in glaciers, which are dielectrics taking into account their electric conductivity.

Let us write these equations for medium without sources where the current $\vec{j}$ occure, and the time depending has the form $e^{-i\omega t}$ (where: ω — angular frequency):

$$\vec{\nabla} \times \vec{H} = -i\omega\varepsilon_0 \vec{E} + \vec{j}$$

$$\begin{aligned} \vec{\nabla} \times \vec{E} &= i\omega\mu_0 \vec{H} \\ \vec{\nabla} \times \vec{E} &= 0 \\ \vec{\nabla} \times \vec{H} &= 0 \end{aligned} \tag{1}$$

The first Maxwell equation we could write in the mentioned below form, when the current $\vec{j} = \sigma \cdot \vec{E}$ is present:

$$\vec{\nabla} \times \vec{H} = -i\omega\varepsilon \vec{\nabla} \tag{2}$$

Here: σ — the conductivity of the medium,

$\varepsilon = \varepsilon_0 + i\dfrac{\sigma}{\omega} = \varepsilon_0 + i\varepsilon_1$ — dielectric constant of the medium

From (1) and (2) we obtain the equations for the field components, for example for $\vec{E}$:

$$\vec{\nabla}^2 E_x + k^2 E_x = 0 \tag{3}$$

where: $k^2 = \omega^2 \varepsilon\mu_0$.
The solution of (3) has the form:

$$E_x = E_{0x} e^{ikr} \tag{4}$$

where:

$$|k|^2 = k^2 = \omega^2 \varepsilon\mu_0 = \omega^2 \varepsilon_0 \mu_0 + i\omega\mu_0\sigma$$

E_{0x} — wave amplitude depending on the excitation.

We have no dependence on x and y for the plane wave propagated in the z direction (i.e. to the bottom of layer), so the wave vector $k = [0, 0, k]$ and all components of $\vec{E}$ and $\vec{H}$ depend on z only, like e^{ikz}. Than we are interested in the length of wave vector (the number k). We assume: $k = \alpha + i\beta$, $k^2 = \alpha^2 - \beta^2 + 2i\alpha\beta$ and from the above mentioned form and equation (4) we obtain:

$$\left.\begin{aligned} \alpha^2 - \beta^2 &= \omega^2 \varepsilon_0 \mu_0 \\ \alpha \cdot \beta &= \frac{1}{2} \omega \sigma\mu_0 \end{aligned}\right\} \tag{5}$$

From the system of equations (5) we receive:

$$\left.\begin{aligned} \alpha &= \omega N(\omega) \\ \beta &= \omega K(\omega) \end{aligned}\right\} \tag{6}$$

where:

$$N(\omega) = \left\{\frac{\varepsilon_0 \mu_0}{2} \left[\left(1 + \frac{\sigma^2}{\omega^2 \varepsilon^2}\right)^{\frac{1}{2}} + 1\right]\right\}^{\frac{1}{2}}$$

and

$$K(\omega) = \left\{\frac{\varepsilon_0 \mu_0}{2} \left[\left(1 + \frac{\sigma^2}{\omega^2 \varepsilon^2}\right)^{\frac{1}{2}} - 1\right]\right\}^{\frac{1}{2}}$$

$N(\omega)$ — coefficient of refraction,
$K(\omega)$ — coefficient of attenuation.

The following denotations are used below for the convenience and the possibility of comparison with the other works:

$$\varepsilon = \varepsilon_0 \,(1 + i \operatorname{tg} \delta) \text{ where: } \operatorname{tg} \delta = \frac{\varepsilon_1}{\varepsilon_0} = \frac{\sigma}{\omega\, \varepsilon_0}.$$

Now the equations (6) have the following form:

$$\begin{aligned} \alpha &= \omega\, N(\omega) = \omega \left\{ \frac{\varepsilon_0\, \mu_0}{2} \left[(1 + \operatorname{tg}^2 \delta)^{\frac{1}{2}} + 1 \right] \right\}^{\frac{1}{2}} \\ \beta &= \omega\, K(\omega) = \omega \left\{ \frac{\varepsilon_0\, \mu_0}{2} \left[(1 + \operatorname{tg}^2 \delta)^{\frac{1}{2}} - 1 \right] \right\}^{\frac{1}{2}} \end{aligned} \tag{7}$$

The factor $e^{i\alpha}$ bears the responsibility for the propagation, and the factor $e^{-\beta z}$ — for the attenuation

Follows that we can obtain for the velocity of wave propagation in the medium:

$$V = \frac{\omega}{\alpha} = \frac{1}{N(\omega)} = \left\{ \frac{\varepsilon_0\, \mu_0}{2} \left[(1 + \operatorname{tg}^2 \delta)^{\frac{1}{2}} + 1 \right] \right\}^{-\frac{1}{2}} \tag{8}$$

Because the glacier is a dielectric, its relative permeability equals one, i.e. $\mu_0' = 1$. We receive:

$$V = \frac{1}{c} \left\{ \frac{\varepsilon_0}{2} \left[(1 + \operatorname{tg}^2 \delta)^{\frac{1}{2}} + 1 \right] \right\}^{-\frac{1}{2}} \tag{9}$$

where ε_0' is relative permitivity of the glacier, and c is light velocity in vacum. The dependence of dielectric constants of frequency for homogeneous dielectries is described by the Debay's equations:

$$\begin{aligned} \varepsilon_0 &= \frac{\varepsilon_p + (\omega\tau)^2\, \varepsilon_\infty}{1 + (\omega\tau)^2} \\ \varepsilon_1 &= \frac{(\varepsilon_p - \varepsilon_\infty)\, \omega\tau}{1 + (\omega\tau)^2} \end{aligned} \tag{10}$$

where: τ — the time of thermal relaxation of molecular polarization around the direction of the applied field

$$\text{and } \varepsilon_p = \lim_{\omega \to 0} \varepsilon_0, \quad \varepsilon_\infty = \lim_{\omega \to \infty} \varepsilon_1.$$

The expression (10) can be applied exclusively in the case when the medium is characterized by the single value of the relaxation time.

The factor ε_0 descends monotonically when the frequency grows up to the value ε_p, but the factor ε_1 runs to the maximum at the value $\omega = \frac{1}{\tau}$. The parameter τ is exponentially connected with the temperature:

$$\tau = a \exp(-bT),$$

where T — absolute temperature.

The validity of (10) applicated for fresh — water ices as well as glacial ices has been verified in many experimental works. Evans (1965) and Saxon (1950) state that $\varepsilon_\infty = 3.2$ and $\log \tau = \frac{2900}{T} - 15.3$ as well as ε_p is the function of temperature.

For example: $\varepsilon_p = 93$, when $t = 0°C$ and
$\varepsilon_p = 133$, when $t = -64°C$.

The dependence of the dielectric permittivity ε_0' on frequency for the different temperatures is shown on Fig. 2. The diagram shows ε_0' takes the value 3.2 for the frequency $f > 10^6$ Hz regardless temperature.

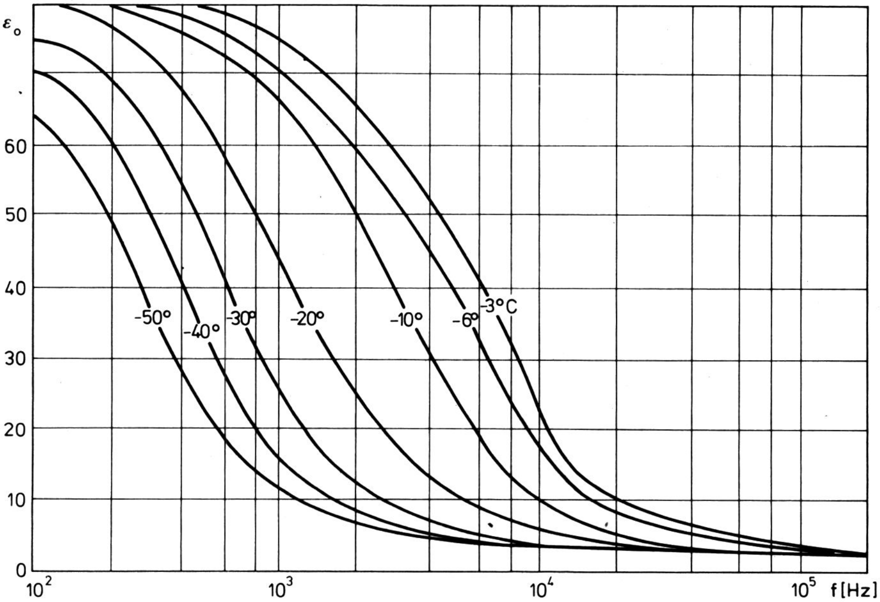

Fig. 2. Dielectric permittivity ε_0' in the function of frequency for different temperatures according with Eder (1947)

The dependence of tg δ on frequency for the different values of temperature is shown on Fig. 3, tg δ is almost independent on temperature and on frequency beeing sharp less than 1, when the frequency $f > 10^7$ Hz. Consequently the expression for the velocity of wave propagation in the ice for $f > 10^7$ Hz has the following form:

$$V = \frac{c}{\sqrt{\varepsilon_0'}}.$$

Therefore it is necessary to choose the frequencies $f > 10^7$ Hz because the velocity of propagation of electromagnetic wave in the ice is then independent of temperature. The lower frequency wave would be more convenient, because it would not be dissipated by small defects of glacier structure.

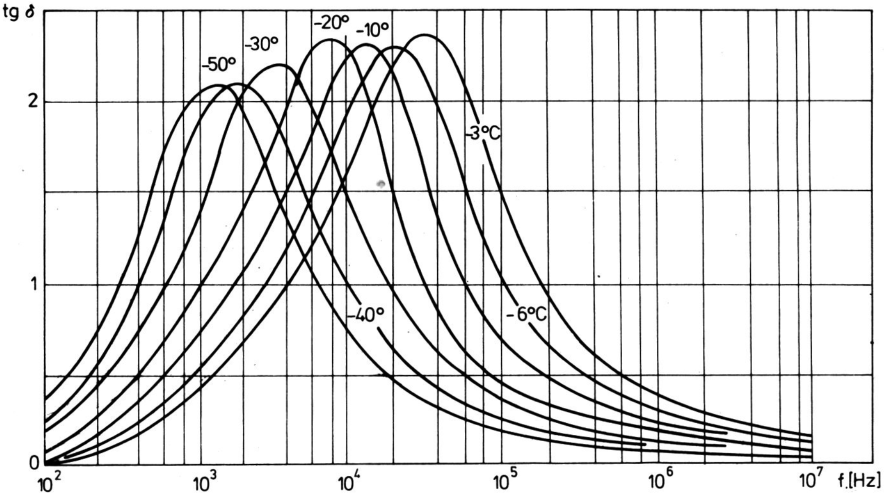

Fig. 3. Tg δ in the function of frequency for different temperatures, according with Eder (1947)

The loss of wave energy between the transmitting antenna and the receiving antenna is one of the basic factor in the radar sounding. We can specify here:

a) losses inside the medium as result of selfabsorption, related to the two-times transition of the wave trough the medium,
b) losses at the lower boundary of the layer,
c) dissipation losses at the lower boundary of the medium and at (on) the heterogeneous defects of the medium,
d) losses at the interface between an ice — an air,
e) losses caused by the focusing properties of medium,
f) polarization losses caused by the difference of polarization between the transmitting signal and the signal reflected by the ground.

The attenuation of signal in the medium strongly depends on temperature. The losses of energy can rise very much making the measurements impossible, when a water occurs inside the glacier or on its surface, so even when more imbibed water layers are present.

It is difficult to estimate theoretically a total attenuation in all circumstances, so it was more effective to check this relation experimentally on different glaciers with a variable structure and varied thermal conditions.

3. The device specification

The pulse, air radio altimeter for the high-altitude measurements (the type RW-10) was used. It has the following technical specification:

1. frequency of the carrier wave	440 MHz ± 1 MHz
2. peak power of transmitter	7 W
3. time of pulse duration	about 0.5 sec
4. frequency of pulse repetition	99921 Hz ± 25 Hz

5. receiving bandwith	6 MHz
6. sensivity of receiver	60 V
7. supply	A.C. 110±5%, 400 Hz±10%
8. input power	115 W
9. weight (without antennas and cables)	14 kg

The system obtains the required electrical parameters from the converter supplied with the voltage 26 V of rectified current.

This current is obtained before-hand from the rectifier supplied by the normal voltage (220 V, 50 Hz) generated by the alternator of 1 kW output power, driven by I.C. engine.

The system was installed in plastic containers on the Nansen sleigh. Two persons were enough to pull the sleigh from the one measuring point to the next one in the easy area, but four persons were necessary for a longer transport.

Antennas make one of the leading problems in the radar sounding. They should have the sharp characteristics because the emitted energy should be beam transmitted as much as possible.

It is important to avoid reflections caused by the mountains surrounding the glacier and by the outskirt crevasses of glacier, also.

Antennas should be light, easy for a transport and effortless in the time of instalation on glacier, too.

The antennas used during our measurements were pulled out one from another to a considerable distance.

The following factors were considered in the choise of antennas:
1. simple mechanical construction,
2. small dimentions and convenient operation, if possible,
3. beam transmission of the antennas,
4. possibility of obtaining the significant attenuation between the antennas.

The following types of antennas were taken into account:
1. the multi-element antenna of the type "Yagi",
2. the dihedral reflector antenna,
3. the parabolic antenna.

The dihedral reflector antenna "illuminated" by the typical for the radio — altimeter RW-10 half, wave dipole was selected. It is possible to set up the above antenna on ice directly, without the necessity to build an additional supporting construction as in the case of the "Yagi" type antenna. Our antenna is simpler mechanically than the parabolic, reflector antenna and les exposed to the change of electric parameters under the influence of mechanical deformations.

The side — stay radiation of the dipol was reduced thanks the addition of the two complementary, perpendicular walls to the dihedral reflector (an antenna — an antenna coupling). These walls reinforced the construction of antenna additionally (Fig. 4).

The dimentions of the whole construction are on Fig. 5.

The directional characteristics of used antennas were determined experimentally. Fig. 6 shows the E-plane characteristic and Fig. 7 the H-plane characteristic of them.

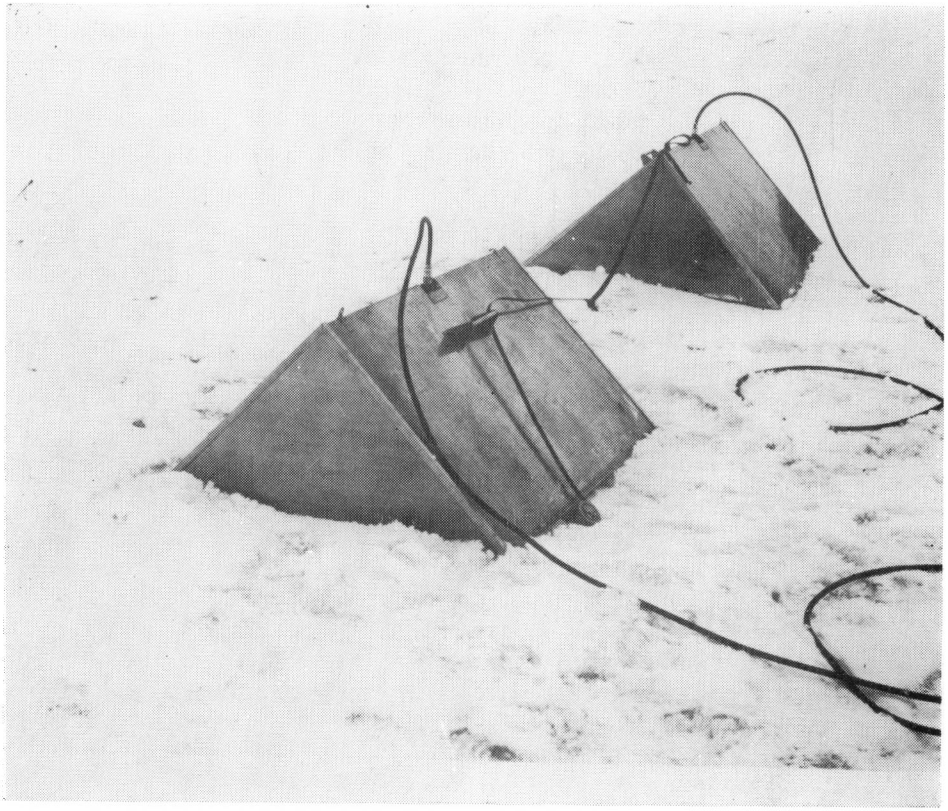

Fig. 4. Antennas on the glacier surface in the position of work

Photo R. Czajkowski

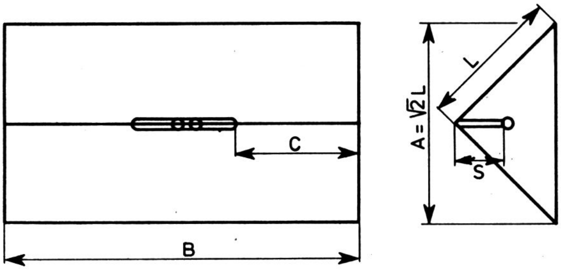

Fig. 5. The dimentions of antenna: S = 175 mm, L = 550 mm, C = 340 mm, B = 970 mm, A = = 680 mm

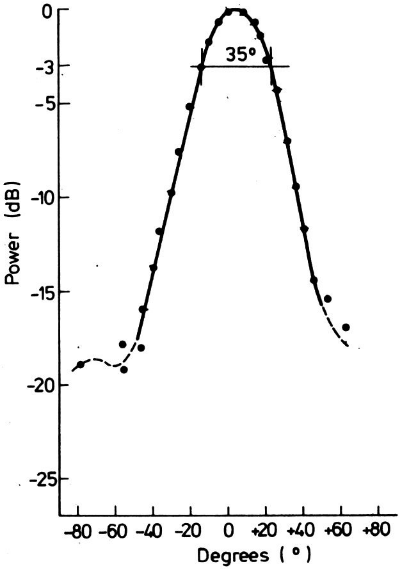

Fig. 6. The E — plane characteristic of antenna

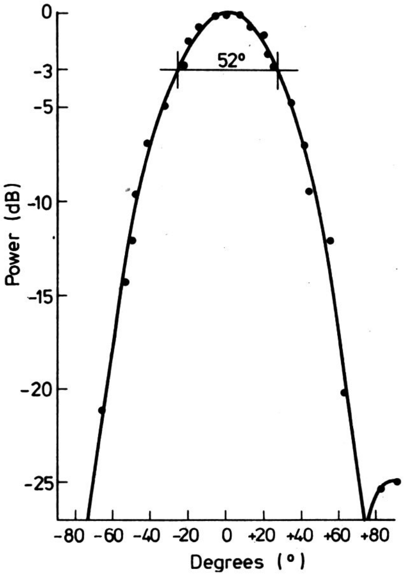

Fig. 7. The H — plane characteristic of antenna

The obtained results are satisfactory. A number of experiments were performed to determine the best dimentions of antenna and the position of the dipole in relation to reflectors.

4. Methodology

The first experimental soundings were realized on the relatively less fissured part of the Hans Glacier in the place where its thickness is not too great (60 ÷ 180 m).

The clear, single echo from the depth about 90 m (it corresponds to the transit time on the distance about 160 m in an air) was observed on the oscilloscope tube with the round — time base (Fig. 8a). Such picture was an exception on the examined glacier. The much more complicated picture shown on Fig. 8b and 8c was more frequently observed.

The experiments were performed for the variable positions of antennas. According to the theoretical expectation the best cooperation between the transmitting and receiving antenna exists at E-plane arrangement i.e. on the plane parallel to the directions of dipoles. It was no possible to put the antennas one to another nearer that to 2 m for the reason of the coupling, which appears in this moment.

Fig. 9 shows the set of equipment during the work on glacier.

The antennas were pull off one from the another starting at the distance 2.0 m with the step 10 cm. It became evident that the amplitudes of the signal reflected by the ground have a strong fluctuation. The diagram of amplitude variations of the signal reflected by the ground of the glacier for the various positions of antennas was constructed (Fig. 10).

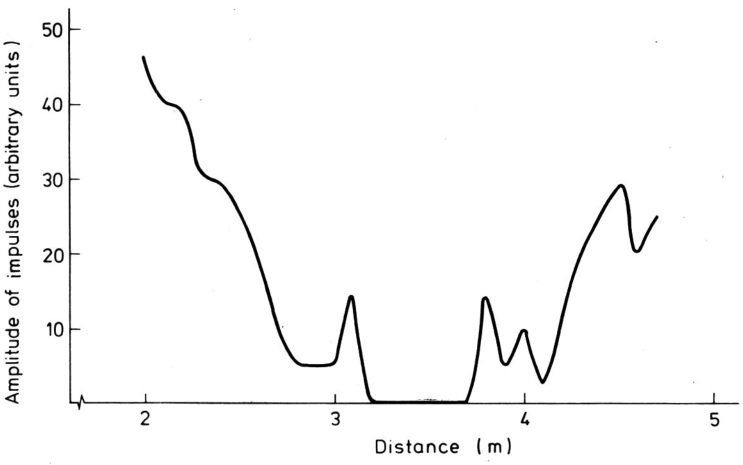

Fig. 10. The fluctuations of the reflected signal amplitude in the function of distance between the antennas

The measurements of the signal amplitude were realized only for the one amplification, with the constant parameters of transmitter and receiver. This diagram was obtained by pull off the receiving antenna from the transmitting one on distances from 2.0 m to 4.6 m. It was interesting that the reflected signal was not registered at all between 3.2 m and 3.7 m. If we had placed the antennas in this section only, we would have register the echoes from the glacier ground. Strong fluctuations of amplitude were observed on the other sections.

The above measurements were realized in a few places with come back to the first positions. The fluctuactions were the same when we came back to the same position of antennas. It is connected with the configuration of the glacier ground under the points of measurements, consequently.

Studies of the movement of glaciers by the radar soundings are planned in the future. Through the succesive measurements of the fluctuations in the

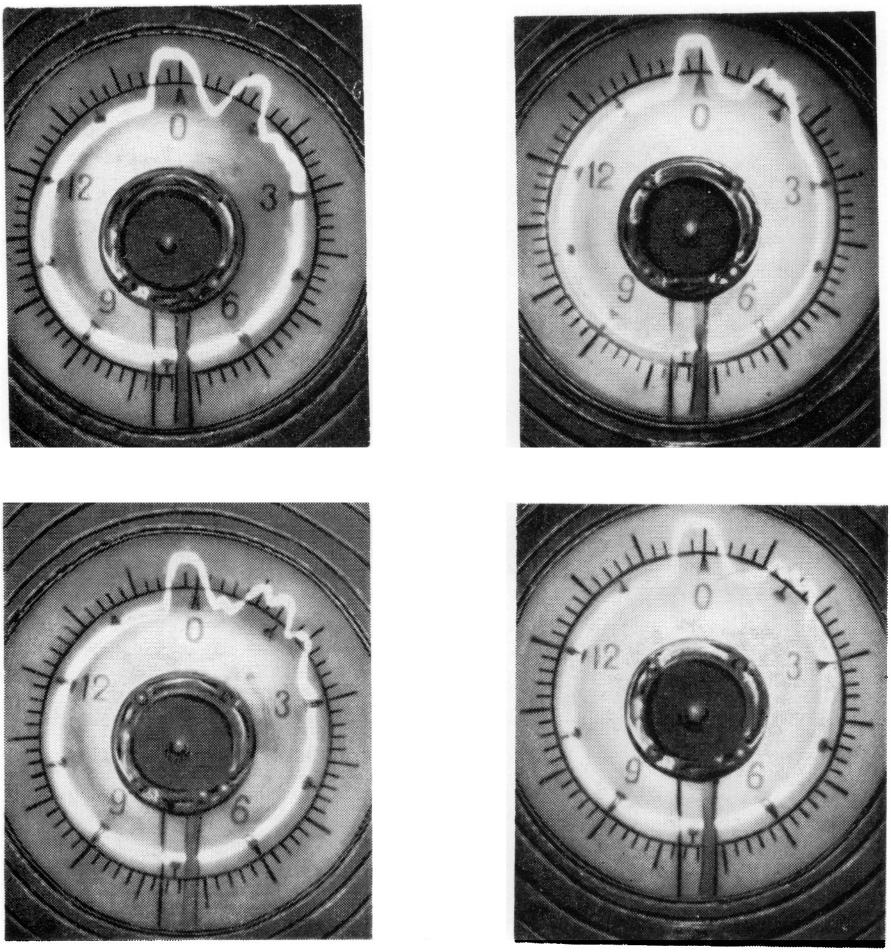

Fig. 8. The examples of echo picture on the oscilloscope tube with the round time base

Fig. 9. The equipment for measurements on the glacier

Photo R. Czajkowski

fixed point, and by the analysis of an autocorelation radius of fluctuations — the determination of the glacier displacements will be possible. The displacement should be however smaller, than the lengh of the base of measurement (a distance between antennas).

There was the necessity to elaborate the method to prevent the omissions of the important echoes and to eliminate the random reflections. The criteria of distinction the essential echoes registered on the oscilloscope were elaborated, using the simple statistical methods. Forty measurements in the each point were realized with the variable instalation of antennas. The antennas were pull off on the distance from 2.0 m to 6.0 m with the step 10 cm.

The further increase of the distance between the antennas was useless, because the strong attenuation of the reflected signal, connected with the characteristic of the configuration of antennas.

The positions of maximum were read off directly on the oscilloscope tube, and they were written down on the diagram especially prepared. The direct reading of results has the big advantage in comparison with the photograms.

The dynamics of the picture read on the oscilloscope was not big, it was estimated on about 9 dB. The sensivity of the system, however, is much more greater and amounts to about 140 dB. Using the big amplification in the receiver — the sounding signal picture was suffered from the strong distortion and the defousing. Finally, many reflections enter into such defocused, sounding pulse. It makes some troubles with the differentiation of reflections.

Than, to read the nearest echoes one should work with the small amplification and to increase it for the further echoes only.

In the case of making the photographs one should fix the average amplification or take a few photograms at various amplifications, but it extends the time of measurements considerably.

The maxima with the sharp characteristic i.e. with a form similar to the nondistorted sounding pulse were marked on the above mentioned diagram to make the interpretation of results fast and easy. The less distinct maxima were marked in the another way. On the base of this diagram, constructed for the all points of measurements, we have obtained the dependence between the occurance of probability of the maximum impulse amplitude and the various depth, from which the signal was reflected.

The information about the form of pulse was marked on the diagram of results, too.

The probability curves for the successive 11 points are shown on Fig. 11. A few harp maxima are visible on these curves — so they are still complicated. The interpretation of such diagram alone is impossible.

These date should be joint with the topographical levelling on the glacier — what gives the proper solution. The attitudes of the points of measurements, which were situated on the glacier surface were determined by the triangulation or by means of altimeter, transposing the values of altitude from the one point to the next.

The measurements along the profile were made with the step of 100 m.

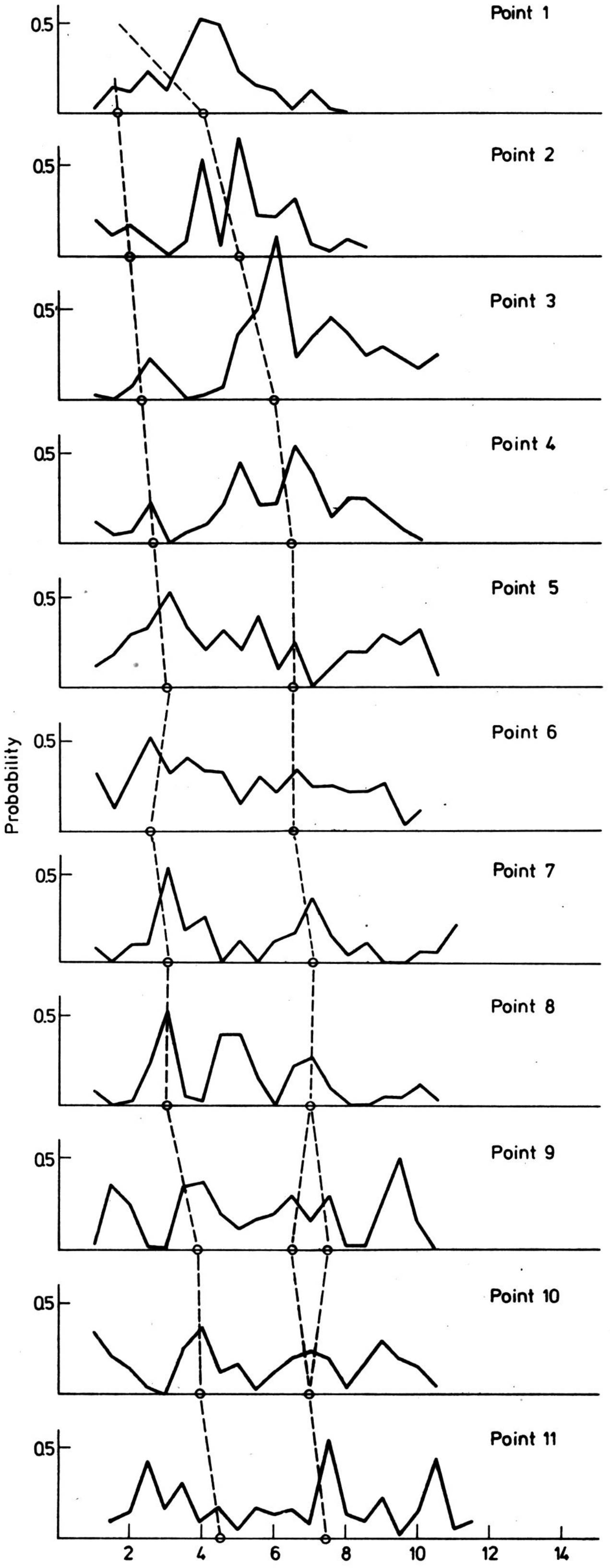

Fig. 11. Verte on next page

Our method let us to measure the thickness in 10 points per day (when the weather is good) — this means to obtain about 1 km of profile.

The neighbor points were jointed when they arranged in the local sequences after the description the most probable depths of immersion of reflecting layers to every adjacent point.

The ground of glacier is almost parallel to its surface except the area of breaks (i.e. exceptionally crevassed places or barriers of seracs) on the glacier surface. This is the reason that the choise of depth in any point is strongly connected with the immersion depth of layer or the depth of glacier ground in the previous point.

It is easy to choise the next points starting the measurements from small depths (the criterion of continuation). The criterion of continuation can be used also when the echoes from the layers inside the glacier are analysed. The objects noticed at least in the four adjacent points are enough to treat them as a layer. The general knowledge about the structure of glaciers helps in the choise of depths, too.

Tracing the circles from all points of measurements along the profile and making the envelopes of them the best picture of rocky basement of glacier can be obtained. However, the valley glaciers are usually flat, so the error of used above approximation is small.

It was necessary to determine the precise principles of measurements to avoid the coarse measuring errors.

The distance between the maximum of sounding pulse and the maximum of echo was treated as the delay time between these pulses. To determine the precise positions of the sounding pulse maximum, the two antennas were elevated to zenith, in order to obtain no echoes on the oscilloscope and this maximum was set as 0 on the oscilloscope, with the small amplification used. The shape of pulse was changeable in the time of experiments when the amplification was big — causing the apparent displacement of the pulse maximum to the left. However this effect is connected with the overcoupling of the receiver only.

It is important the sounding pulse lasts as long as 0.5 sec in our device, so all pulses coming at this time to the receiver are invisible. That is the reason, the layers which lie (inside the glacier) on the distance less than 20 m are observed. The error of determination of the maximum position on the osciloscope scale amounts 10 m. The error connected with the dielectrical constant unprecisely choosen was estimated on about 3 m (such estimation was made on the base of measurements described in previously mentioned papers). The error of the topography of glacier surface measured by altimeter is not greater than 2 m. The whole error of measurement taken as the summa of above mentioned errors should be not greater than 15 m. The additional source of errors is connected with the choose of unproper maxima of amplitude on the probability curve. But, it is more easy to interpretate the results from every second, third or so point of measurement — so this

Fig. 11. The probability of occurance of the maximal amplitudes for the succesive 11 points and the method of layer construction

mistake can occur in the case of the dense maxima only. It was observed that such error appears only when the maxima were situated more often than on every 10 m, so this error does not exceed 10 m also.

The construction of profile is shown on Fig. 11 and the glacier surface is taken as flat one. The probability curves of maximum apperance are presented for the all points of measurement. The lines representing the ground surface and the particular strata were lead across the points connected with the maxima. It has been noticed that the possibility of making mistake in the choose of the suitable maximum by this method, is small.

The profiles trough the glacier were obtained (Fig. 12 and Fig. 13) after the connection the altitude above sea level to the particular point. The obtained profiles are described more precisely below.

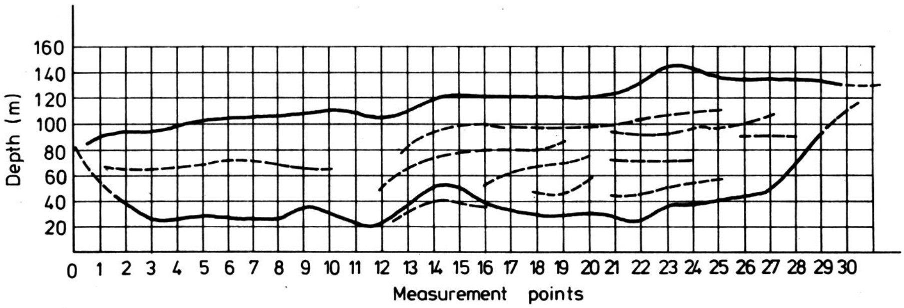

Fig. 12. Cross — section of the Hans Glacier along the first profile

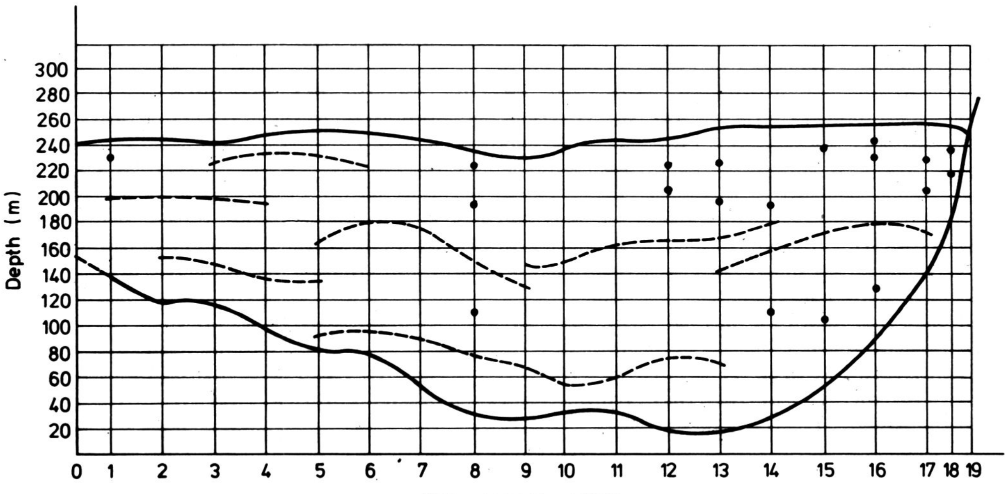

Fig. 13. Cross — section of the Hans Glacier along the second profile

Fig. 14. The head of the Hans Glacier in the begin of summer season of 1979

Photo R. Czajkowski

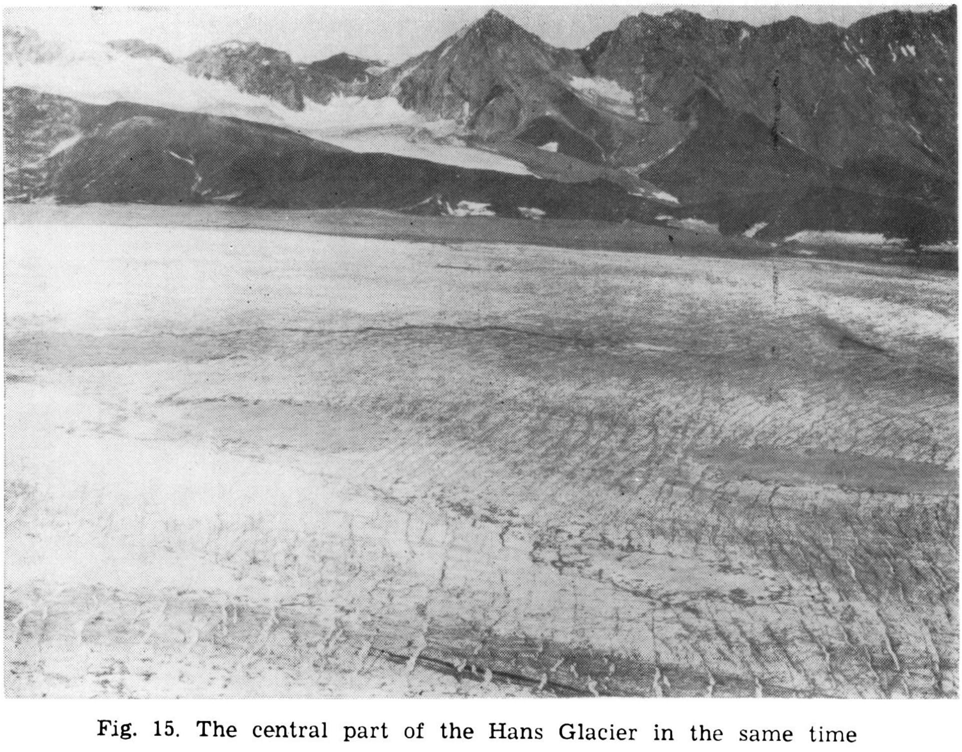

Fig. 15. The central part of the Hans Glacier in the same time

Photo R. Czajkowski

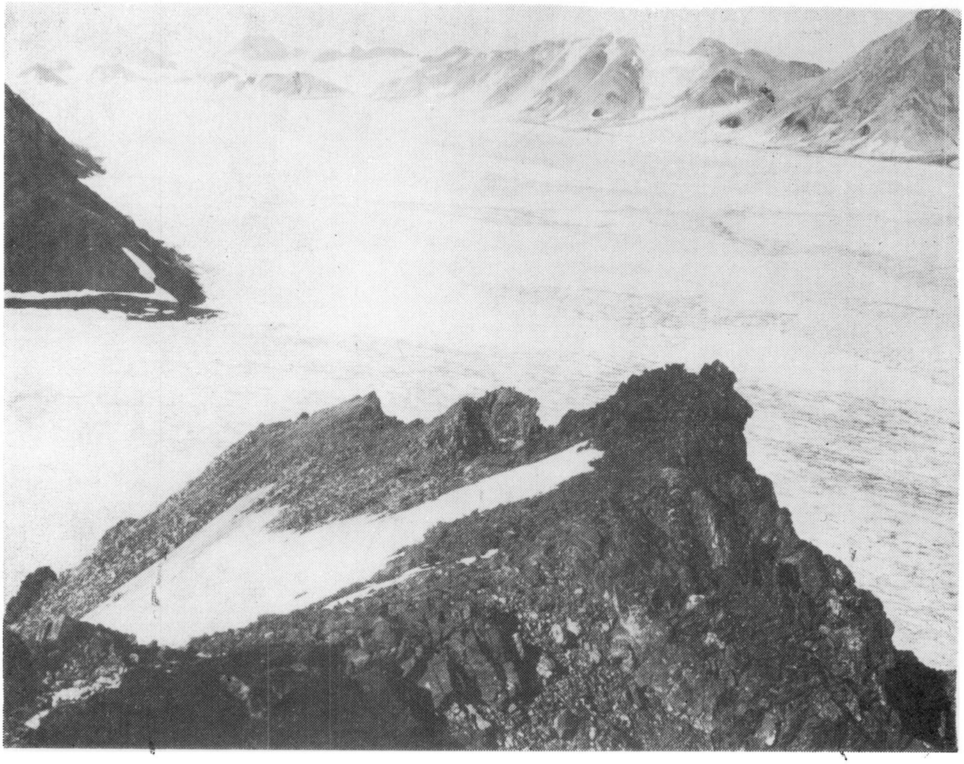

Fig. 16. The upper part of the Hans Glacier in the same time

Photo R. Czajkowski

5. Results

The measurements were performed on the Hans Glacier in the area of Hornsund Fiord. This glacier lies most closely to the Base of the Polish Scientific Station. The choose of this glacier was connected with its accessibility — what was especially important in the preliminary measurements. The Hans Glacier is 12 km long and over 3 km wide along with whole its longiness. It belongs, after the classification by Baranowski (1977) to the subpolar, sea, highlatitude type of glacier. It is swelled by a row of smaller glaciers as Tuv and Deilegg, and by cirque glaciers under Winertinden and Vardepiggen.

The limit of the firm field goes up contineously in the last years. The succesive parts of the Hans Glacier are presented on Fig. 14, 15 and 16. These photographs were made on 1979, July 10, on the very beggin of the Arctic summer season. The zone of ablation enlarged considerably in the later period. The small firn lasted in the higher parts of glacier in the end of summer. The big number of crevasses unshown earlier, has opened on the glacier. It looked as if the glacier has activated itself. But, because the process of snow melting away in crevasses and the surface state of crevasses — it is clear that the crevasses are the old ones.

The strong ablation caused the intense flow of water. All characteristic types of water flows (surface, inglacial and interglacial) were observed on the glacier.

This complicated picture was not stimulating for the radar sounding, because the water is the great obstacle for them. All depressions of glacier were filled up by firn saturated by water, and even by water itself. The radar soundings from the air are very difficult in such conditions. But the method described above let us to lead the measurements and to obtain the proper results.

The soundings has been made on two profiles (Fig. 16). The first profile runs from the slopes of Fugleberget to the depression between Fannypynten and Flatryggen. Almost the whole profile runs among the crevasses, being about 50 metres away themselves. As the photograph shows (Fig. 14), the first profile is situated on the right area of photo, quite parallely to its right margin. The profile reaches the field of ablation cones (seen on the photo) and its line is a little broken going between very near crevasses. The eastern part of this profile lies on the more cracked area, crossing even the field of seracs. The strongly folded surface of glacier suggested inequalities of its ground. The western part of the profile runs trough the less crevassed glacier, where the glacier surface is much more flat, so the thickness was smaller in this area.

The measurements were made with the step 100 m along the profile, but at the border of glacier, where we have expected to find the greater inclination of its ground, we took smaller steps.

Grześ (1980) has measured the temperatures on different depths of the glacier in the eastern part of profile in the same points. The whole mass of ice is in the temperature close to 0°C, apart from a few meters thick layer situated near the glacier surface.

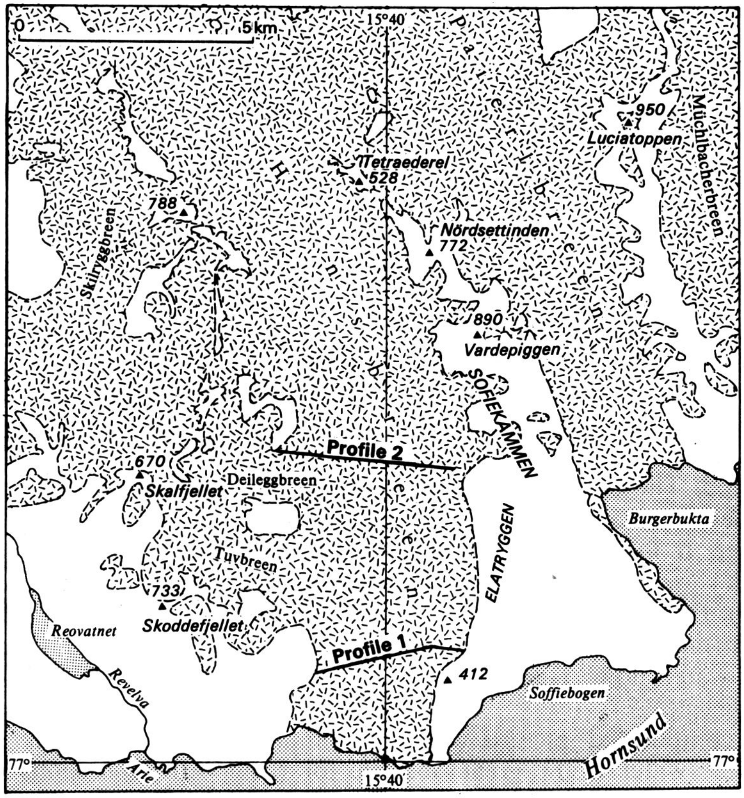

Fig. 17. Localities of two profiles on the glacier

According to the classification the minus temperatures should be present inside the glacier in the examined part. It seemed, that strong ablation caused the filtration of considerable quantities of water, making the temperature of the whole mass of ice higher.

The hot point drill was used to the temperature measurements. The maximum depth reached in these measurements was 27 m.

The complete result of the radar coundings on the first profile is shown on Fig. 12. One can see that the western part of glacier is flat and reaches the thickness about 80 m, according to our prediction. The more folded western part has the thickness about 110 m.

Echoes from the internal part of glacier were obtained among the reflections of wave caused by the glacier ground. The reflecting layer on the depth of 35 m was found in the western part, but it was devided on a few particular layers, on the different depths in the eastern part of profile.

It was hypothetically stated, that these ice layers were more imbibed water, draining the water from the whole water volume. This hypothesis was confirmed because it was observed that over the point number 12, above the profile an large lake was found in the depression, from which the water fell down into the glacier by wells. The above mentioned layers dit not exist in this point inside the glacier. But the layers we could observed diped down according to the direction of the well.

The observations and measurements gave us the previous conclusion, that the water is not drained t the Hansglacier border, but flows off by its central part and by inter — ice channels directly to the sea. Now we have confirmed this conclusion. It should be necessary make the radar measurements simultanously with hot point drills to verify the above hypothesis about the layer structure.

Two lines were drawn on the first profile between the point number 12 and number 16. They show the rocky ground of glacier. The continous one is more probable. The dividing of lines is caused by the width of directional characteristic of antennas. Our device gives us the mean depth from the measured area, but it was possible to obtain the picture of ground thanks to the statistical treatment of large amount of measurements.

It was interesting that the topography of glacier ground is mapped on its surface on the first profile. This effect is less visible on the second profile, because the depths are more greater there. The five — times diminishing of the depth scale versus the distance scale emphasised this effect (on Fig. 12).

The second profile was traced between Bergnova and Vinertinden. The profile runs in the central part of photo (Fig. 15), almost paralelly to its base. This profile lies about 3 km farther from the glacier head than the first profile. The whole second profile was situated in the ablation part of glacier, and its eastern part was more cracked similarly as on the first profile. The eastern edge of glacier was not reached in the time of measurements as the moraine layer separates its from the mountain slopes around the valley. The area covered by moraine is very craked, with the wide opened, former crevasses. It is the reason the profile ends with the big depths. But the much greater depths were noted on the second profile. The maximum depth is situated near to the center of valley and it reaches 230 m. It was possible to differenciate some layers inside the glacier on this profile (Fig. 13).

The accurate levelling was made along the first profile, but only the altimeter levelling on the second one. Let us pay attention, that the ground of two profiles lies over the sea level, but on the second one it is situated below the first one. The underglacial valley of the Hans glacier has a strong analogy to the neighbor Rew Valley, from which the glacier is retreated now.

Močeret and Žuravlev (1980) made the radar soundings on the Hans glacier simultanously using the helicopter. The good coincidence of the thickness of glacier in the points of intersection of profiles was obtained. Generally, the air measurements gave the results difficult to the proper interpretation because of the surface layer of ice filtered by water and the large flat-bottomed "lakes" which caused the strong attenuation of radar pulses energy. Making the measurements on the glacier surface we could choose the appropriate position of antennas. Additionally, the antennas set directly on the glacier surface are less responsive to a layer of water. The precise map of rocky glacier ground and the calculation of its mass, connected with it will be possible thanks the elaborated method and the used equipments, as we hope. The analogical measurements will be realized on the Warennskield glacier during the summer season 1980.

The further works on improvement of measurement methods as well as, on the new technical solutions will be conducted, too.

We had possibility to compare our results with other measurements made on the glacier. Geophysicists, leaded by professor S. Małoszewski made the gravimetric and magnetic measurements, during the same, summer Spitsbergen expedition, also along our first profile on the Hans glacier. It was possible to estimate he thickness of glacier in the western part of this profile basing on the magnetic measurements. Koblański (unpublished data) state that the mean thickness of this part of glacier is about 83 m, what confirm our results.

6. Conclusions

1. We dispose of the device now, which may be used for measurements of the "warm" glacier thickness up to 250 m. The measurement range may be smaller when the considerable quantity of water exists inside the glacier and on its surface, and when the glacier structure is very complicated.
2. The elaborated method may be used to analyze the internal structure of glacier, but it is necessary to make the measurements simultanously with the hot point drills for the adequate interpretation of results.
3. The fluctuation of the radar pulses amplitude reflected from the glacier ground would be used to the measurements of glacier movement, moreover.
4. The first results obtained on the Hans glacier seem to be enough precise for using themy by glaciologists. The obtained results describe well the contemporary state of this glacier.

I wish to acknowledge Professor J. Jankowski (Director of Institute of Geophysics P.A.S.) and Professor R. Teisseyre for the facilities, which enabled me the fast preparation and realization of the radar soundings programm. I would like thank Dr. A. Lizoń, who participated in the preparation of device, had projected the antennas and made the measurements together with me. A part of measurements was carried also by Dr. A. Koblański.

7. Summary

The device for the radar soundings of glaciers was used for the first time in Polish polar expeditions in Spitsbergen, in the summer season of 1979.

The pulse, air radio-altimeter working on high-frequency (440 MHz) and with the time of pulse about 0.5 μ sec was used in the measurements.

The device was supplied by petrol generator with the power of 1 kW. The equipment was installed on the Nanseń sleighs (Fig. 9) and the measurements were realized on the glacier surface, directly.

The frequency of work was choosen to make the dielectric constant of ice (i.e. the electromagnetic wave velocity in the ice also) independent of the temperature (Fig. 2).

The Hans Glacier (Fig. 14, 15 and 16) in its part, where the measurements were made, is the quasi-thaw and very cracked glacier — so the obtained reflections from the ground

gave the very complicated picture. The radar soundings were conducted to this time generally on "cold" glaciers, not very cracked and broad.

The electromagnetic waves in the quasi-thaw glacier are reflected not only by the glacier ground but also by the layers of ice filtered very much by water. The reflections caused by crevasses in the internal structure of glacier are also noted. Such crevasses are present more often in quasi-thaw glaciers than in cold glaciers.

To distinguish the casual reflections from the essential — ones the great number of measurements has been taken and the statistical methods of signals interpretation were used. Forty measurements in every point on the profile were made, with the pull — off of the transmmiting and receiving antennas with the step of 10 cm. The probability of occurance of the reflected wave maxima were checked (Fig. 11).

The most probable maxima were treated as the essential — ones and were compared with the results obtained in the neighbor points, which lied 100 m apart one from another. After such comparison the profile of glacier was drawn, on which there was the rocky glacier ground as well as another layers-reflected the electromagnetic wave (Fig. 12 and 13).

The geodetic measurements were taken on the glacier surface parallely.

The two profiles across the Hans Glacier were obtained thanks this method (Fig. 17). The elaborated method is so precise, that the fully geometry of glaciers would be described, what is especially needed for the estimation of glacier mass. The study of fluctuations of pulses reflected from the glacier ground give possibility to trace the glacier movement by the radar measurements.

8. Резюме

Летом 1979 г. на Шпицбергене впервые в истории польских экспедиций употреблено радарное устройство для зондирования ледников. Для измерений использовано воздушный импульсный радиоальтиметр работающий на частоте 440 Mhz и времени импульса около 0,5 сек.

Устройство питалось бензиновым генераторным составом с мощью 1 KW. Всё оборудование установлено на нансенских нартах (рис. 9). Измерения проводились непосредственно с поверхности ледника.

Частоту работы устройства подобрано так, чтобы диэлектрическая постоянная льда и скорость пропагации волны во льду была независимой от температуры (рис. 2).

Ледник Ханса (рис. 14, 15 и 16) в части, в которой проведено измерения является тающим ледником и очень потрескавшим, картина полученных отражений является очень сложной.

До сих пор методы радарных зондирований применялись в случае „зимных" ледников не потрескавших и распространённых. В тающем леднике электромагнитные волны отражаются не только от почвы, но и от слоев льда более пропитанных водой. Можем также наблюдать отражения от трещин (неоднородности) прерывистости во внутреннем строе ледника, которые чаще выступают в тающем, чем в зимнем леднике.

Чтобы различить случайные отражения от существенных проведено большое число измерений и применено статистические методы обделки сигналов. В каждом измерительном пункте проведено до 40 измерений раздвигая антены приёмную от передающей с ходом 10 см. Затем исследовано вероятность выступления максимов отраженной волны (рис. 11).

Призная более вероятные максима существенными и сравнивая их с результатами полученными в соседних измерительных пунктах расположенных в 100 м друг от друга, можно было наметить разрез ледника, на котором кроме намеченной скальной почвы возможно проследить другие горизонты отражающие электромагнитные волны (рис. 12 и 13). Этой методой сделано два разреза ледника Ханса, (рис. 17).

На поверхности ледника проведено геодезыйные измерения. Таким образом получено два профиля ледника Ханса. Выработанная методика является настолько подробной, что с её помощью можно будет определять полную геометрию ледников полезную для проведения биланса из массы.

Исследования флюктуяции отраженных сигналов от почвы привели к возможности радарных измерений движений ледника.

9. Streszczenie

Latem 1979 r. na Spitsbergenie zastosowano po raz pierwszy w polskich wyprawach urządzenie radarowe do sondowania lodowców. Do pomiarów wykorzystano impulsowy radiowysokościomierz lotniczy pracujący na częstotliwości 440 MHz i o czasie trwania impulsu ok. 0,5 sek.

Urządzenie zasilane benzynowym zespołem prądotwórczym o mocy 1 kW. Całość zainstalowano na saniach nansenowskich (rys. 9) i pomiary wykonywano bezpośrednio z powierzchni lodowca.

Częstotliwość pracy urządzenia dobrano w ten sposób by stała dielektryczna lodu, a zatem i prędkość propagacji fali w lodzie była niezależna od temperatury (rys. 2).

Lodowiec Hansa (rys. 14, 15 i 16), w części w której prowadzono pomiary, jest lodowcem „ciepłym" i bardzo spękanym, obraz uzyskiwanych odbić jest bardzo złożony. Dotychczas metody radarowych sondowań stosowano na ogół do lodowców „zimnych", mało spękanych i rozległych. W lodowcu ciepłym fale elektromagnetyczne są odbijane nie tylko od podłoża lodowca, ale i od warstw bardziej przesączonego wodą lodu. Możemy również obserwować odbicia od spękań w budowie wewnętrznej lodowca, które częściej występują w lodowcu ciepłym niż zimnym.

Aby rozróżnić odbicia przypadkowe od istotnych przeprowadzono dużą liczbę pomiarów i stosowano statystyczne metody obróbki sygnałów. W każdym punkcie pomiarowym wykonywano po 40 pomiarów rozsuwając anteny, odbiorczą od nadawczej ze skokiem 10 cm. Następnie badano prawdopodobieństwo występowania maximów fali odbitej (rys. 11).

Uznając bardziej prawdopodobne maxima za istotne i porównując je z wynikami uzyskanymi w sąsiednich pounktach pomiarowych położonych w odległości 100 m. od siebie można było wykreślić przekrój przez lodowiec, na którym poza zaznaczonym skalnym podłożem, można śledzić inne horyzonty odbijające fale elektromagnetyczne (rys. 12 i 13).

Na powierzchni lodowca prowadzono pomiary geodezyjne. W ten sposób uzyskano dwa profile przez lodowiec Hansa (rys. 12). Opracowana metodyka jest na tyle dokładna, że przy jej pomocy będzie można określać pełną geometrię lodowców potrzebną dla przeprowadzenia oszacowania masy lodowców.

Badania fluktuacji sygnałów odbitych od podłoża lodowca doprowadziły do możliwości radarowych pomiarów ruchu lodowca.

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