RADAR METHODS
FOR THE EXPLORATION OF GLACIERS

Thesis by

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ABSTRACT

The problem of finding the depths of glaciers and the current methods are discussed briefly. Radar methods are suggested as a possible improvement for, or adjunct to, seismic and gravity survey methods. The feasibility of propagating electromagnetic waves in ice and the maximum range to be expected are then investigated theoretically with the aid of experimental data on the dielectric properties of ice. It is found that the maximum expected range is great enough to measure the depth of many glaciers at the lower radar frequencies if there is not too much liquid water present. Greater ranges can be attained by going to lower frequencies.

The results are given of two expeditions in two different years to the Seward Glacier in the Yukon Territory. Experiments were conducted on a small valley glacier whose depth was determined by seismic sounding. Many echoes were received but their identification was uncertain. Using the best echoes, a profile was obtained each year, but they were not in exact agreement with each other. It could not be definitely established that echoes had been received from bedrock. Agreement with seismic methods for a considerable number of glaciers would have to be obtained before radar methods could be relied upon. The presence of liquid water in the ice is believed to be one of the greatest obstacles. Besides increasing the attenuation and possibly reflecting energy, it makes it impossible to predict the velocity of propagation. The equipment used was far from adequate for such purposes, so many of the difficulties could be attributed to this. Partly because of this, and the fact that there are glaciers with very little liquid water present, radar methods are believed to be worthy of further research for the exploration of glaciers.

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I. INTRODUCTION

The problem of finding the depths of glaciers comes under the subject of geophysics. The answers are of interest chiefly to geologists, but their determination involves the methods of the physicist. Sounding by seismic methods has been used successfully on glaciers where the dynamite charges could be placed in the solid ice.(1) More difficulty is experienced when the surface of the glacier consists of a thick layer of névé or firn. This acts as a sort of cushion which absorbs the energy of the blast. Seismic equipment is usually heavy enough so that considerable work is involved in transporting it; moreover, it takes an appreciable amount of time to make a sounding, especially if the surface layer of névé must be penetrated to place the charge in solid ice.

Gravity surveys can be used to give the configuration of the rock floor, but not the depth. The depth at one or more control points can then be ascertained by other methods. Since the neighboring topography introduces corrections to the raw data, gravity surveys are best suited to regions where the surfaces of the glaciers and surrounding land are gentle. This method is still in the development stage for application to glaciers, but undoubtedly will undergo more tests in the future, and probably will become an adjunct to other methods, principally seismic.

It was with the prospect of finding a rapid, convenient method to determine the depth, plus the hope that additional glacial information might be obtained, that radar techniques were tried.

II. THEORY

The solution of Maxwell's equations gives the formulas governing the propagation of a plane wave in an imperfect dielectric.[2] The steady-state solution is

$$\check{E} = \check{E}_0 \epsilon^{j\omega t - \check{\gamma} z} \tag{2.01}$$

where propagation is taken in the z direction and

$$\check{\gamma} = \alpha + j\beta$$

is the propagation constant. It is given by*

$$\check{\gamma}^2 = -\omega^2 \mu \varepsilon + j\omega\mu\sigma \equiv -\omega^2 \mu \check{\varepsilon} \tag{2.02}$$

where μ is the permeability and

$$\check{\varepsilon} \equiv \varepsilon\left(1 + \frac{\sigma}{j\omega\varepsilon}\right) = \varepsilon_0(\varepsilon' - j\varepsilon'') \tag{2.03}$$

is the complex permittivity. The conductivity is denoted by σ and the permittivity of free space by ε_0. The ratio of loss current to charging current is given by $\varepsilon''/\varepsilon'$. The loss angle δ is defined by

$$\tan\delta \equiv \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon} \tag{2.04}$$

Solving for the real and imaginary parts of the propagation constant gives

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\tan^2\delta} - 1\right)} \quad \text{nepers / meter} \tag{2.05}$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\tan^2\delta} + 1\right)} \quad \text{radians / meter} \tag{2.06}$$

The wave length is given by

$$\lambda = \frac{2\pi}{\beta} \quad \text{meters} \tag{2.07}$$

The wave impedance is given by

$$\check{\eta} = \sqrt{\frac{\mu}{\check{\varepsilon}}} \quad \text{ohms} \tag{2.08}$$

For low loss materials where $\tan\delta \ll 1$, these expressions become

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* The rationalized MKS system of units will be used.

$$\alpha \cong \frac{\omega}{2}\sqrt{\mu\varepsilon}\tan\delta \qquad \text{nepers / meter}$$

$$= 0.091\, f_{mc}\sqrt{\mu'\varepsilon'}\tan\delta \qquad \text{db / meter} \qquad (2.09)$$

$$\beta \cong \omega\sqrt{\mu\varepsilon} \qquad \text{radians / meter} \qquad (2.10)$$

$$\lambda \cong \frac{\lambda_0}{\sqrt{\mu'\varepsilon'}} \qquad \text{meters} \qquad (2.11)$$

where f_{mc} is the frequency in megacycles per second, λ_0 is the free space wavelength and

$$\mu_0 = \frac{\mu}{\mu'}$$

is the free space permeability. Also

$$\check{\eta} \cong \sqrt{\frac{\mu}{\varepsilon}} \qquad \text{ohms} \qquad (2.12)$$

Since the impedance of free space is 377 ohms, this last formula can be written for the case of non-magnetic materials

$$\check{\eta} \cong \frac{377}{\sqrt{\varepsilon'}} \qquad \text{ohms} \qquad (2.13)$$

When a plane wave of amplitude E_0 traveling in region 1 impinges with normal incidence upon a plane surface bounding region 2,(3) the amplitude of the reflected wave is

$$E' = \frac{\mu_2\check{\gamma}_1 - \mu_1\check{\gamma}_2}{\mu_2\check{\gamma}_1 + \mu_1\check{\gamma}_2} E_0 \qquad (2.14)$$

If region 1 is a perfect dielectric, the reflection coefficient, defined as the ratio of energy flow in the reflected wave to that in the incident wave, is given by

$$R = \frac{\mu_1^2\alpha_2^2 + (\mu_1\beta_2 - \mu_2\beta_1)^2}{\mu_1^2\alpha_2^2 + (\mu_1\beta_2 + \mu_2\beta_1)^2} \qquad (2.15)$$

If both regions are perfect dielectrics, the reflection coefficient is

$$R = \left(\frac{\eta_1 - \eta_2}{\eta_1 + \eta_2}\right)^2 \qquad (2.16)$$

Water consists of polar molecules and has high permittivity.(4)

In ice, however, the dipoles are frozen and the permittivity is much lower, except for very low frequencies.[5] Considerable theory has been developed for the permittivity, dispersion, and absorption in polar substances.[6,7] The specific inductive capacity and loss angle of ice and conductivity water, as measured by the MIT Laboratory for Insulation Research, are plotted in Figs. 2.1 and 2.2.[8,9] These graphs, plus information from other sources,[4,5] indicate that the specific inductive capacities of ice and water at 0° C in the range 100-200 megacycles per second can be taken as 3.4 and 88 respectively.

A mixture of air, ice, and water has a permittivity that is not obtained in a simple manner. A number of formulas have been given for the permittivity of mixed bodies. One formula is[10]

$$\frac{1}{\varepsilon_m + u} = \frac{V_1}{\varepsilon_1 + u} + \frac{V_2}{\varepsilon_2 + u} \tag{2.17}$$

while another one is

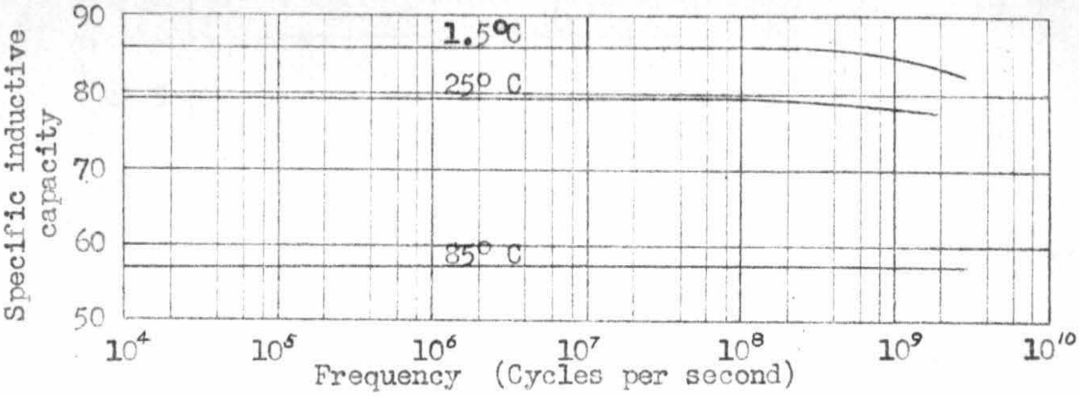
$$\varepsilon_m^k = V_1 \varepsilon_1^k + V_2 \varepsilon_2^k \tag{2.18}$$

where u and k are constants which usually have to be determined experimentally. In Eq. (2.18), V_1 and V_2 are the fractional part of the volume occupied by substances 1 and 2 respectively, and k ranges from -1 for dielectrics in series to +1 for dielectrics in parallel. The constant k is dependent upon the shape of the particles. The definition of permittivity is given by

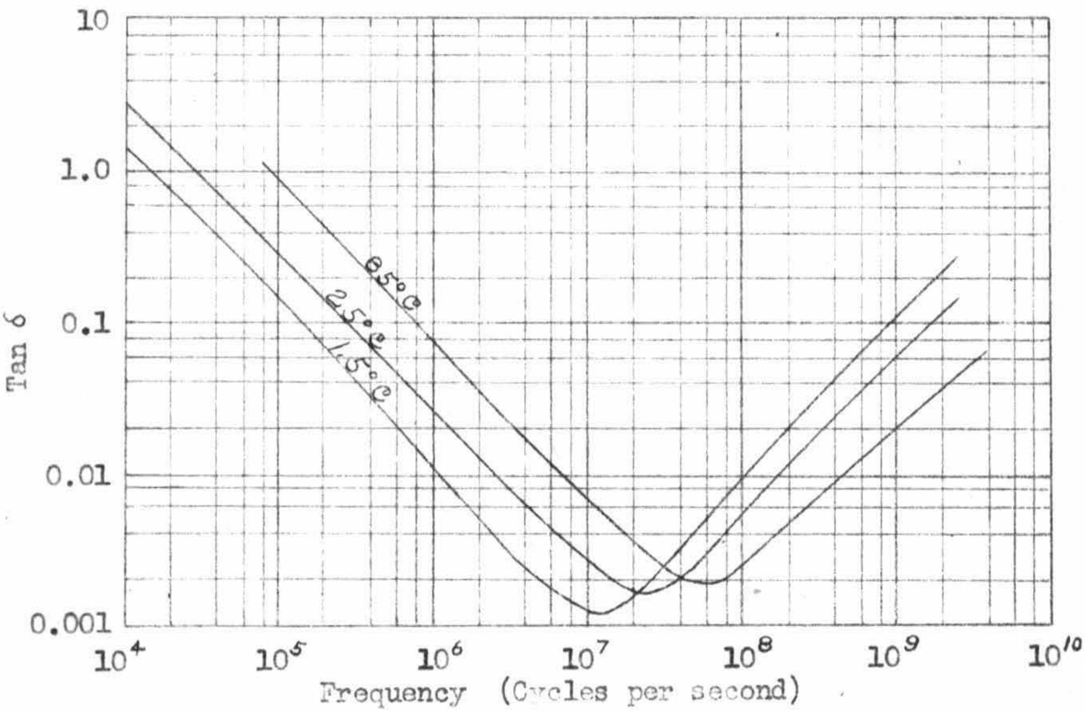
$$\varepsilon_m = 1 + 4\pi \int \frac{P}{E}\, dV \tag{2.19}$$

integrated over unit volume, where P is the polarization per unit volume and E is the field. Here it is more apparent that the permittivity is dependent upon the shape of the particles.

Wet snow is not just a simple mixture of air, ice, and water. It is composed of crystals which may vary in size and structure. Ice

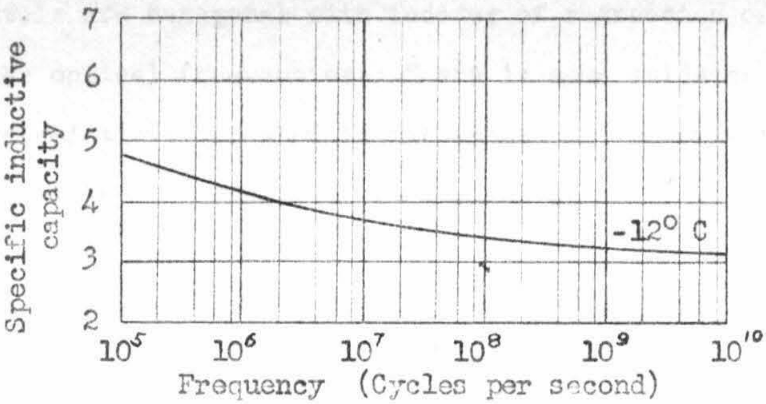


(a) Specific inductive capacity.

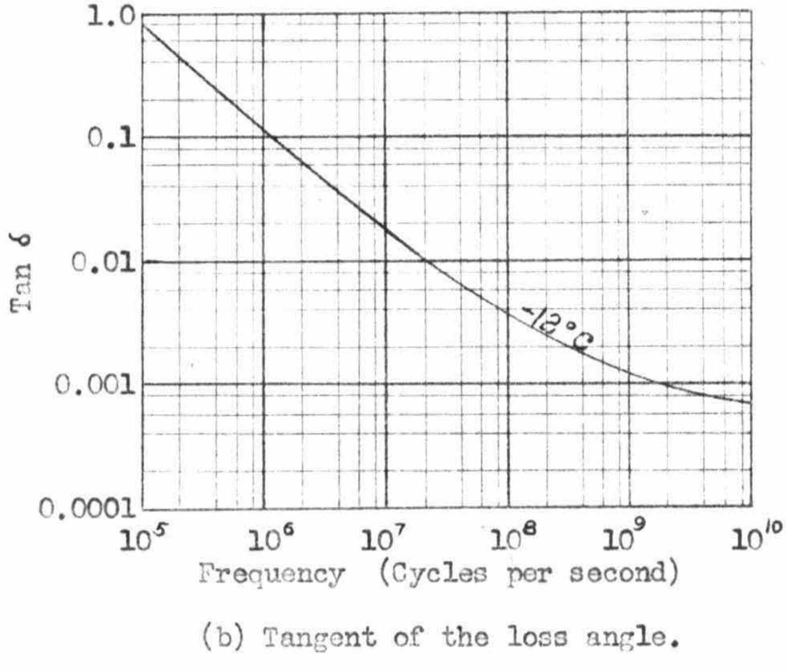


(b) Tangent of the loss angle.

Fig. 2.1 Dielectric properties of conductivity water.



(a) Specific inductive capacity.



(b) Tangent of the loss angle.

Fig. 2.2 Dielectric properties of ice (frozen conductivity water).

crystals are hexagonal with indexes of refraction of 1.309 and 1.313 at the optical frequencies. There is some evidence to indicate that the permittivity of snow is influenced by the orientation of the crystal axis.[11] Gerdel, at the Central Sierra Snow Laboratory, has obtained agreement within 25% between observed and calculated values of the permittivity for wet snow using values of 3.0 and 80.0 for the specific inductive capacities, and $k = 1$ in Eq. (2.18). Fig. 2.3 is a graph of the specific inductive capacity of wet snow as a function of density and liquid water content for $k = 1$, and specific inductive capacities of 3.4 and 88 for ice and water respectively.

The calculation of the permittivity of a wet glacier is not possible because the amount of each constituent is not known. Since air will be present in important quantities in only a relatively thin surface layer, it is not important. The important quantity is the amount of liquid water present. The only feasible way to find this is to compare the delay time for the reflection of electromagnetic waves to the known depth as determined by some other method. If the velocity of propagation is found to be constant or is predictable, then radar might be used successfully for "sounding".

The attenuation of electromagnetic waves in solid ice, calculated by Eq. (2.09) and the data of Fig. 2.2, is plotted in Fig. 2.4.

Before attempting the propagation of electromagnetic waves in glaciers, order of magnitude calculations should be made to determine the maximum range that can be expected. The problem will be set up with several simplifying assumptions. It will be assumed that the beam angle is small enough so that all the transmitted power impinges on the target, and that the target scatters the reflected energy over a half sphere. The power received back at the antenna is given by

$$P_r = P_t \frac{R}{2\pi r^2} A_r \, 10^{-0.2\alpha r} \tag{2.20}$$

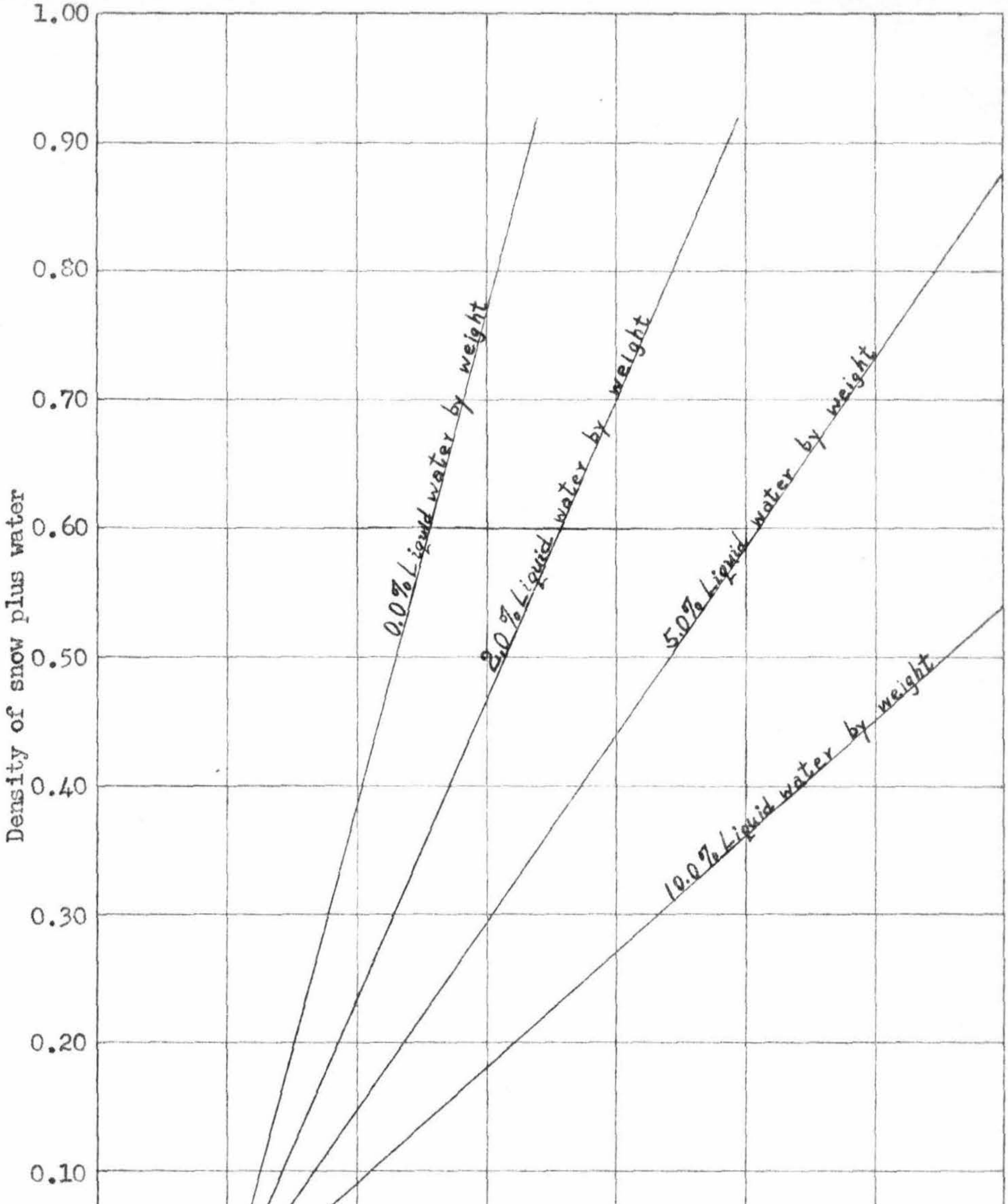


Fig. 2.3 Specific inductive capacity of wet snow.

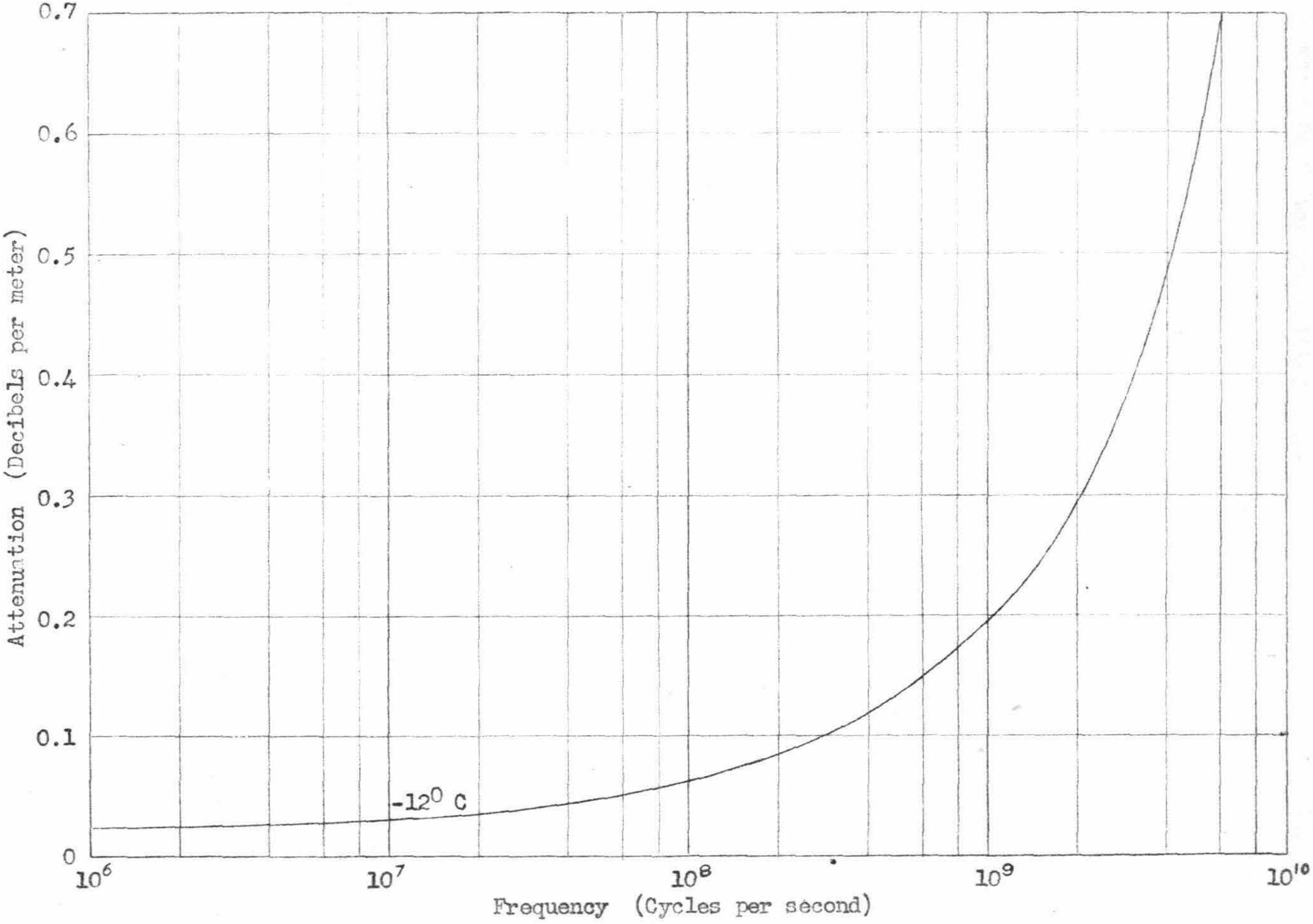


Fig. 2.4 Attenuation of electromagnetic waves in ice.

where P_t is the transmitted power,

R is the reflection coefficient of the target,

r is the range,

A_r is the receiving antenna effective cross section,

α is the attenuation constant in decibels per unit distance.

If a frequency of 180 megacycles per second is selected, minimum detectable power is assumed to be 10^{-13} watt, and other values applicable to the equipment to be used are substituted into Eq. (2.20), this gives

$$10^{-13} = 1000 \times \frac{0.2}{2\pi r_{max}^2} \times 6 \times 10^{-0.2 \times 0.08 r_{max}} \tag{2.21}$$

Solving this gives a value of a little over 600 meters, or approximately 2000 feet, for the maximum range. This looks promising since many glaciers have lesser depths. The most important thing that was taken for granted was the reflection coefficient of the bedrock floor. At these frequencies, rock acts as a dielectric in so far as its reflecting properties are concerned.(12) It is entirely possible that the permittivity of the rock might be the same as the ice just above it.

In Eq. (2.20) the damping factor, not the inverse square of the distance, plays the dominant role in determining the received power. If the value of r in the inverse square factor is assumed constant, the solution of the equation for the maximum range gives

$$r_{max} \cong \frac{5}{\alpha} \log_{10}\left[\frac{R A_r P_t}{2\pi r^2 P_{min}}\right] \tag{2.22}$$

where P_{min} is the minimum detectable signal. The values just used are now substituted into Eq. (2.22) plus the value of 600 for r. This gives

$$r_{max} = 62.5 \log_{10} (5.3 \times 10^9) = 607 \text{ meters} \tag{2.23}$$

From this, one can obtain an idea of the importance of the factors in the bracket of Eq. (2.22). For instance, if the transmitted power is changed by a factor of 100, the maximum range is only changed by a factor of 21%.

If the liquid water content at some place increased very slowly with distance to a large value, there would be little reflection of energy. The waves would just continue to propagate at a lower velocity. One might think that the range of the most distant echoes would tell whether the energy had been propagating through ice or water. However, calculation of the attenuation in conductivity water shows that it is approximately ten times that of ice at these frequencies. Since the ratio of the velocities of propagation is also nearly ten, the maximum delay times to be expected would be the same for propagation in either medium.

The method of introducing the energy into the ice must be considered. If the antenna is submerged in the névé, or a parabolic dish antenna is placed face down on the surface, then all the energy must go into the ice. If the antenna is some distance above the surface, some of the energy will be reflected. If the antenna is a great distance above the surface, the reflection coefficient is given by Eq. (2.16) and for an ice-air boundary would be less than 10%. Since the antenna will always be close to the ice, the rigorous solution must be worked out to get the answer. However, as shown by Eq. (2.23), a small amount of power lost is not of much importance; the more important consideration is the antenna field pattern.

An antenna in region 1 has a beam angle in degrees between half power points of approximately(13)

$$2\theta_1 \cong \frac{70\lambda_1}{d} \tag{2.24}$$

where λ_1 is the wavelength in region 1 and d is the dimension of the antenna in the plane where the field pattern is taken. This is only a good approximation for $d > 2\lambda_1$. Again, considering the case where the antenna is a great distance from the interface separating regions

1 and 2, Snell's law of refraction is

$$\sqrt{\varepsilon_1}\,\sin\theta_1 = \sqrt{\varepsilon_2}\,\sin\theta_2 \tag{2.25}$$

For small angles this can be approximated by

$$\theta_2 \cong \theta_1\sqrt{\frac{\varepsilon_1}{\varepsilon_2}} \tag{2.26}$$

giving as the beam angle in region 2 as

$$2\theta_2 \cong 2\theta_1\sqrt{\frac{\varepsilon_1}{\varepsilon_2}} \cong \frac{70\lambda_1}{d}\sqrt{\frac{\varepsilon_1}{\varepsilon_2}} \tag{2.27}$$

When an antenna of the same dimension is operated in region 2, the change in wavelength is given by the formula

$$\lambda_2 = \lambda_1\sqrt{\frac{\varepsilon_1}{\varepsilon_2}} \tag{2.28}$$

Therefore the beam angle in region 2 is

$$2\theta_2 \cong \frac{70\lambda_2}{d} = \frac{70\lambda_1}{d}\sqrt{\frac{\varepsilon_1}{\varepsilon_2}} \tag{2.29}$$

which is the same as Eq. (2.27). This may indicate that the physical size of the antenna determines the beam angle in region 2 regardless of which region the antenna is located in. To get the exact field pattern when the antenna is close to the ice requires the rigorous solution of this boundary value problem, but this would be extremely tedious. Even the case of a single oscillating dipole above the surface of a complex dielectric (earth) has received a great deal of attention from Sommerfeld and many others since 1909.[14]

It is obvious that the presence of ice in the local fields of the antenna will affect its input impedance. This can be taken care of by suitable matching methods. It is not necessary to know the input impedance, but if desired, it could be measured with a slotted line.

III. PRELIMINARY CONSIDERATIONS IN THE SELECTION OF EQUIPMENT

The first consideration should be given to the choice of frequency. The upper frequency limit is set by the increased attenuation of the waves in ice (Fig. 2.4). There are several factors which govern the lower frequency limit. For a given beam angle of the radiation pattern, the physical dimensions of an antenna vary inversely with the frequency. Considerable directivity is desirable so as to minimize echoes from the side, such as those from crevasses. If the beam angle is large, a horizontal discontinuity will give back a broad echo unless there is specular reflection. The increased antenna gain resulting from a small beam angle also increases the maximum range somewhat.

The choice of frequency is also correlated with the choice of pulse length. The length of pulse selected will depend upon whether the main interest is short minimum range or long maximum range. Even if it is the latter, too long a pulse cannot be allowed, because fairly good range resolution is necessary to separate the multitude of echoes that reflect back from a glacier. This also sets a lower frequency limit because it is difficult to generate a pulse of only a few cycles duration. However, the limit set by antenna size will usually be more important.

The choice of power output is not particularly difficult to make. As shown in Part II, a large increase in power output will not increase the range by a very great factor. The maximum size of the transmitter is governed by the amount of weight that can be tolerated. This is important because the equipment will usually be transported manually. With the exception of the power supply, the only part of the equipment whose weight will depend upon the power output is the transmitter. Therefore, there is very little point in conserving weight by making the transmitter extremely small. On the other hand, if the advantages of radar are to be realized, the transmitter must not be made so large that it contains a major portion of the total weight. Between either extreme there is plenty of latitude for a reasonable choice, and a transmitter which weighs one-fourth of the total weight seems like a good compromise.

IV. 1948 EXPEDITION

(a) Location and Equipment

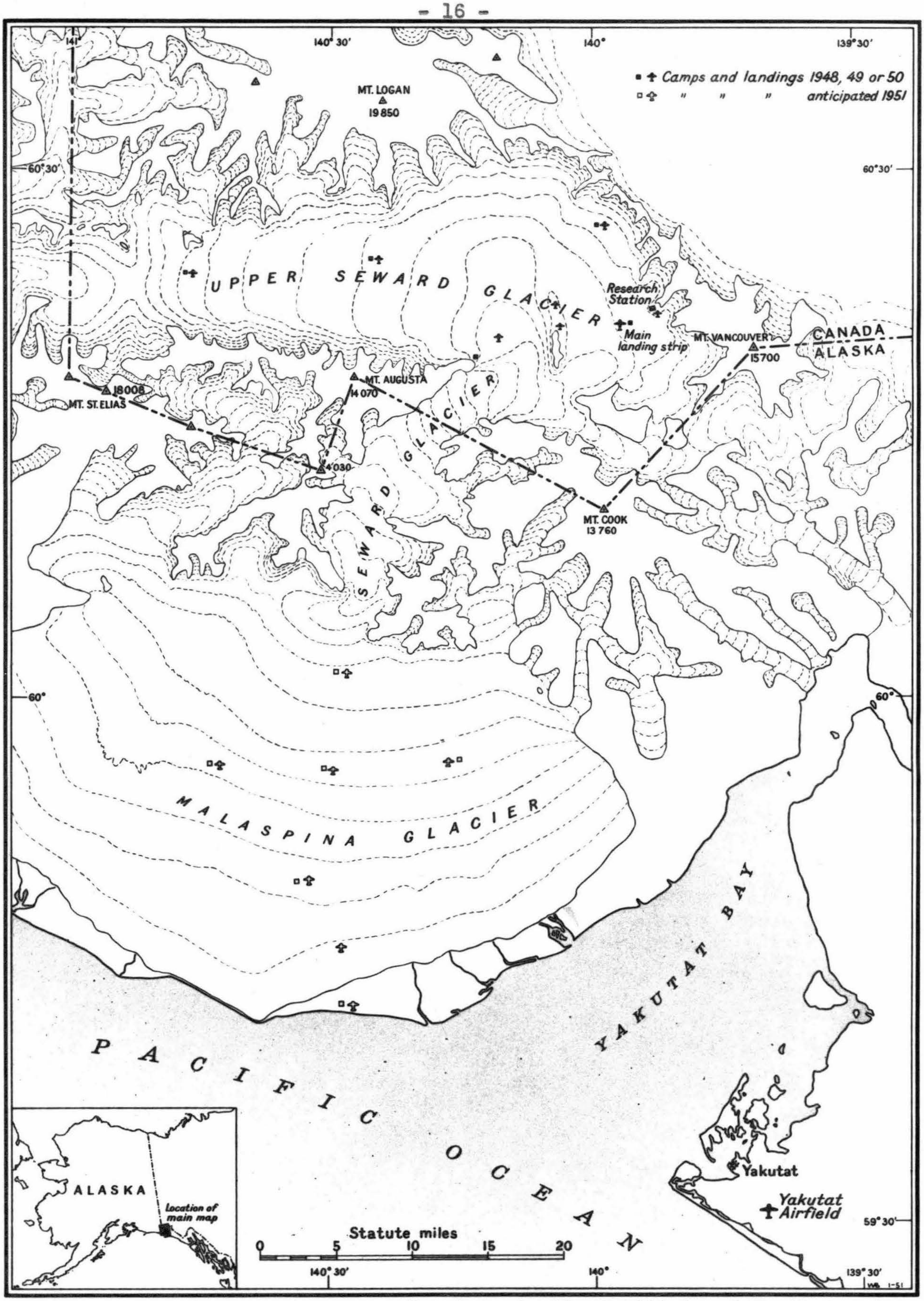
During the summer of 1948, experiments were conducted on the upper Seward Glacier to determine the applicability of radar methods to the problem of finding the depth of a temperate glacier. The base of operations was located about sixty miles north of Yakutat, Alaska in the St. Elias Mountains, Yukon Territory. Fig. 4.1 is a map of this region.

The equipment used was a modified SCR-718-A pulse type radio altimeter. Since the attenuation at the original frequency of 440 megacycles per second was thought to be too great, the original transmitter and mixer assemblies were removed and replaced by similar ones designed for 100 megacycles. This equipment had been designed to use separate transmitting and receiving antennas and it was decided to use the same arrangement.

The pulse repetition frequency, 98.356 kilocycles per second, was unusually high for pulsed radars. The information was presented on a cathode ray tube with a circular sweep of the same frequency. The air range corresponding to this frequency is 5000 feet. The output pulse originally was of 0.25 microsecond duration. This was lengthened to 0.4 microsecond. The peak power was approximately five watts.

The original equipment, being airborne, was designed to operate from 115 volt, 400 cycle current. In the aircraft, this was supplied by an inverter which, in turn, was supplied by a gasoline driven generator. The same method was used in the field.

The transmitting and receiving antennas were made identical. Each was a two-by-two broadside array of half-wave folded dipoles as shown in Fig. 4.2. The dipoles were submerged a quarter wavelength in the neve and the surface covered with a mesh screen to serve as a reflector. The wavelength depends upon the permittivity, which varies



Courtesy Arctic Institute of North America

Fig. 4.1

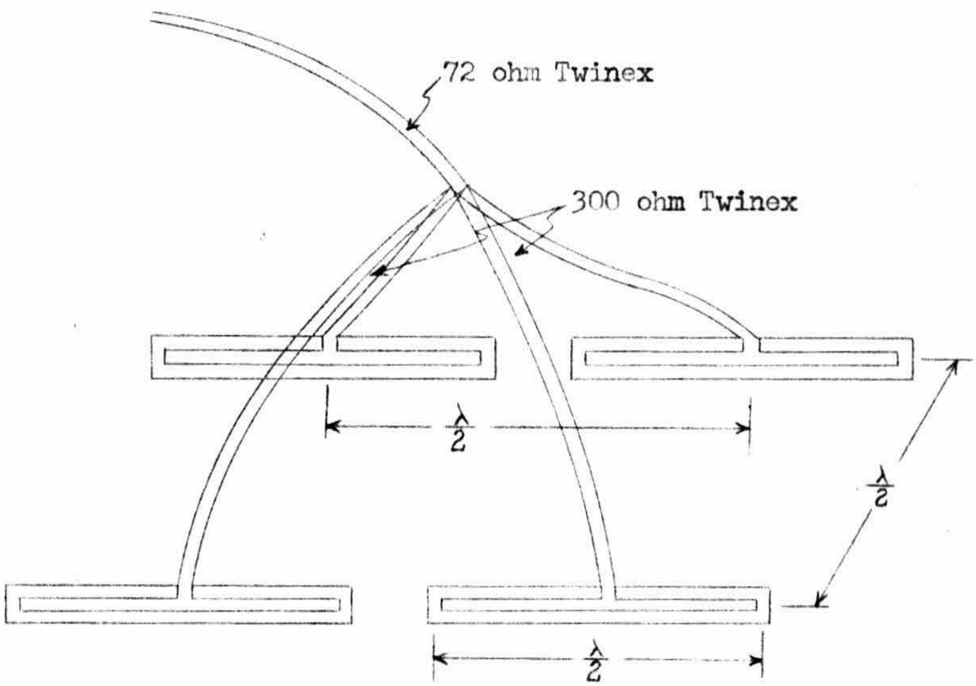


Fig. 4.2 Schematic of antenna used in 1948. A mesh screen placed one-quarter wavelength above the dipoles was used as a reflector.

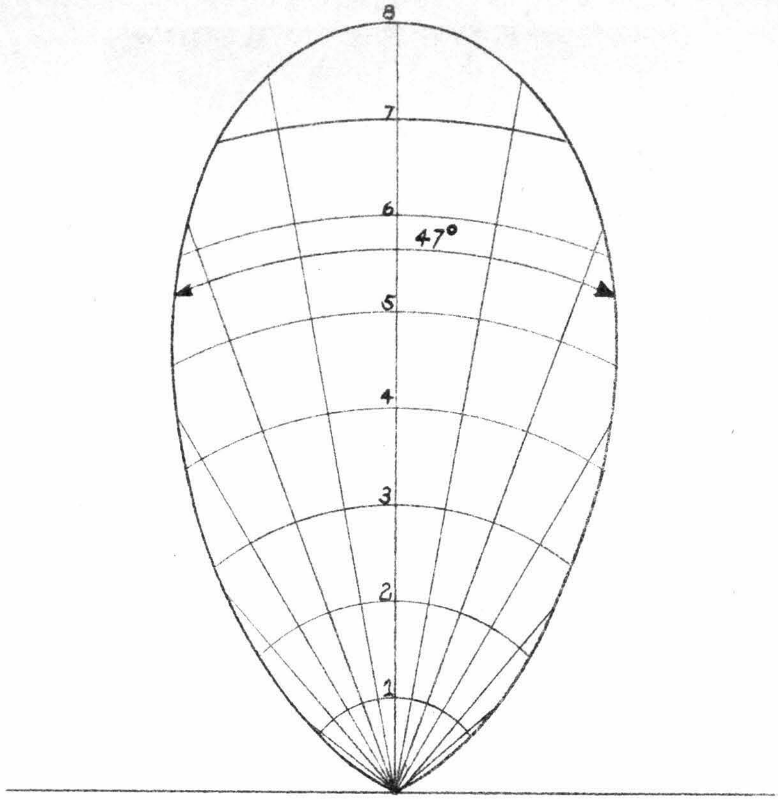
with the liquid water content. However, the antenna was designed for a specific inductive capacity of 2.5. Twinex was used so as to eliminate the balanced to unbalanced transformers which would have been necessary with coaxial line. The characteristic impedance of the Twinex was chosen to match the radiation resistance of the dipoles, which was estimated from the data available in the literature.[15,16,17] Balanced feeding of antennas is most satisfactory for broad-banding. Sufficient broad-banding was assured by using heavy elements and folded dipoles. The antenna patterns are shown plotted in Fig. 4.3.

The entire equipment was transported on an Army four-man arctic sled (Fig. 4.4a). The setup is pictured in Fig. 4.4b.

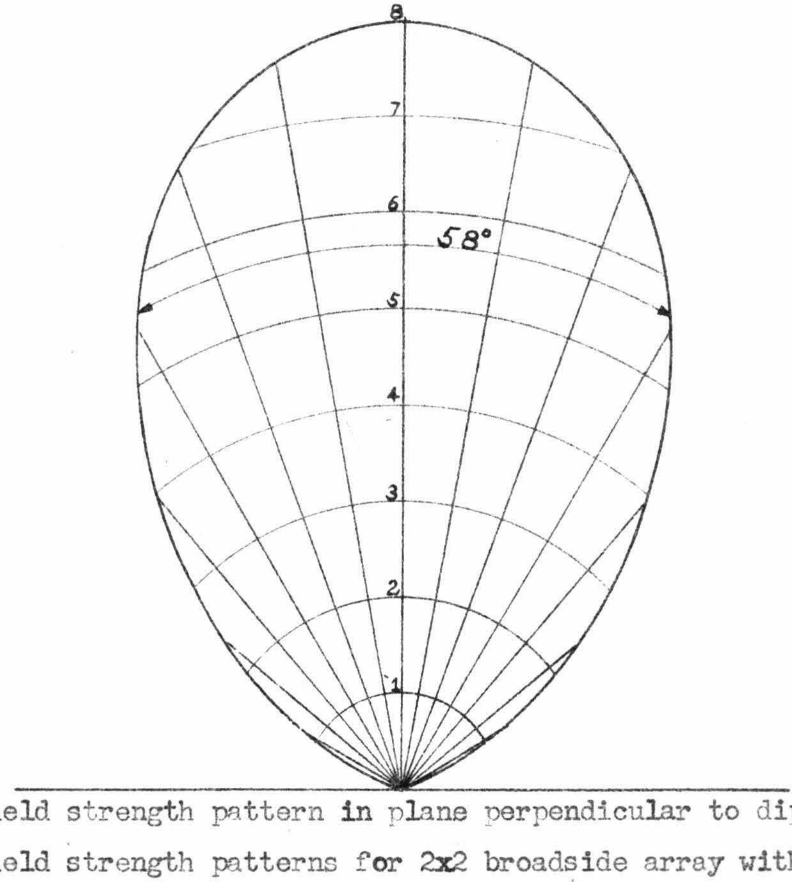
(b) Operation and Results

"Soundings" were first attempted on the main part of the upper Seward Glacier. Nothing consistent that looked like bedrock was found, so it was decided to work on something shallower. Later soundings by seismic methods showed that this first location was about 2200 feet deep.

The next set of locations was made on a small valley glacier at the eastern edge of the upper Seward Glacier proper, which was christened "Institute Glacier" by the members of the expedition. The route of the transverse profile is shown marked in Fig. 4.5. It ran from the research station on a nunatak in a southeastern direction to a mountain ridge (Fig. 4.1). Stations were spaced at approximately 500 foot intervals. So many echoes were received that their identification was quite uncertain. At some of the shallower stations two or three echoes were received equally spaced in time, and these were believed to be caused by multiple reflections. If it is assumed that reflection from a horizontal layer of dielectric discontinuity in the ice is more specular than that from the bedrock, then the echoes from bedrock should be broader than the others. This was one of the criteria used to get a



(a) Field strength pattern in plane parallel to dipoles.



(b) Field strength pattern in plane perpendicular to dipoles.

Fig. 4.3 Field strength patterns for 2x2 broadside array with reflector.

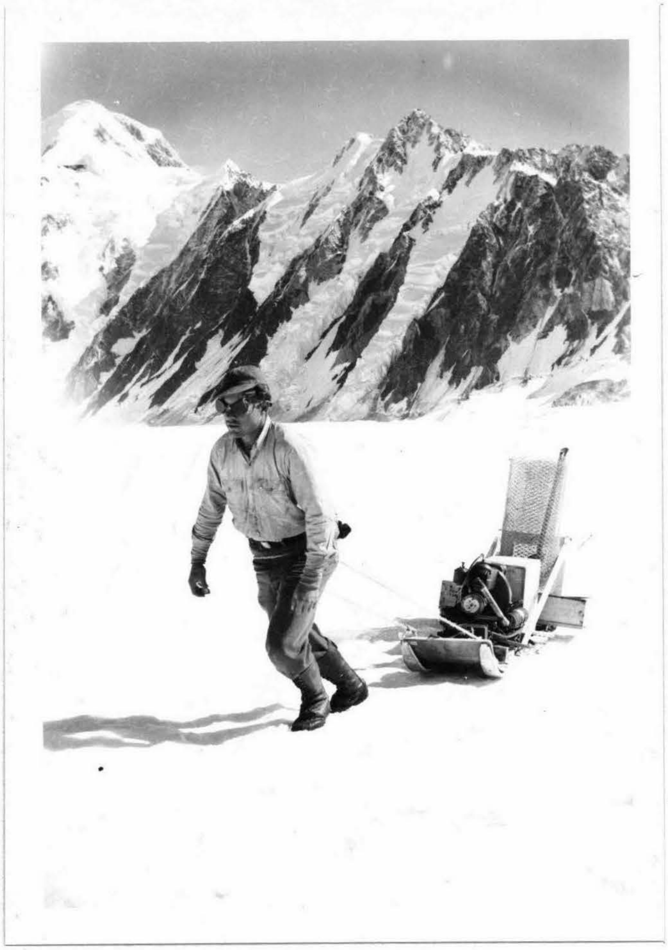


Fig. 4.4a Transportation of the equipment.

Fig. 4.4b Equipment set up for operation.

Courtesy Arctic Institute of North America

Fig. 4.5 Route of the profile across Institute Glacier. Distances were measured from the nunatak at the left.

curve of the apparent profile. Other considerations were that it must be continuous and the depth at each end be zero.

From the data taken, the curve of Fig. 4.6 was obtained. The depths shown are the equivalent air ranges and must be corrected for the velocity of propagation. It is of interest to note that the maximum range echoes were usually received at equivalent air ranges near 2000 feet, since this was predicted in Part II.

After the equipment had been operated for several days it became evident that there was room for improvement. One of the main disadvantages was the time necessary to take a reading. Under average conditions, only one station could be covered each day. This was because of the condition of the snow surface. A crust would usually freeze each night which was firm enough to support men and sleds. This would remain until about ten o'clock each morning. Until then the sled could be pulled by one man, and the best time to move the equipment was just before this crust melted. By that time the trenches for the dipoles could be dug quite easily. The complete operation of moving 500 to 1000 feet, taking a reading, and repacking took one man three to four hours. After that there was nothing to do but wait until the next morning for another frozen crust.

A considerable amount of time was necessary to install the antennas in the névé. If an antenna that could have been placed above the surface had been used, much time would have been saved. Regardless of the type of antenna, one for both transmitting and receiving would have saved both weight and time.

(c) <u>Other Methods</u>

Two other parties of the same expedition also attempted to measure the glacier depth. One group was from the National Research Council of Canada. Their method consisted of measuring the delay time for

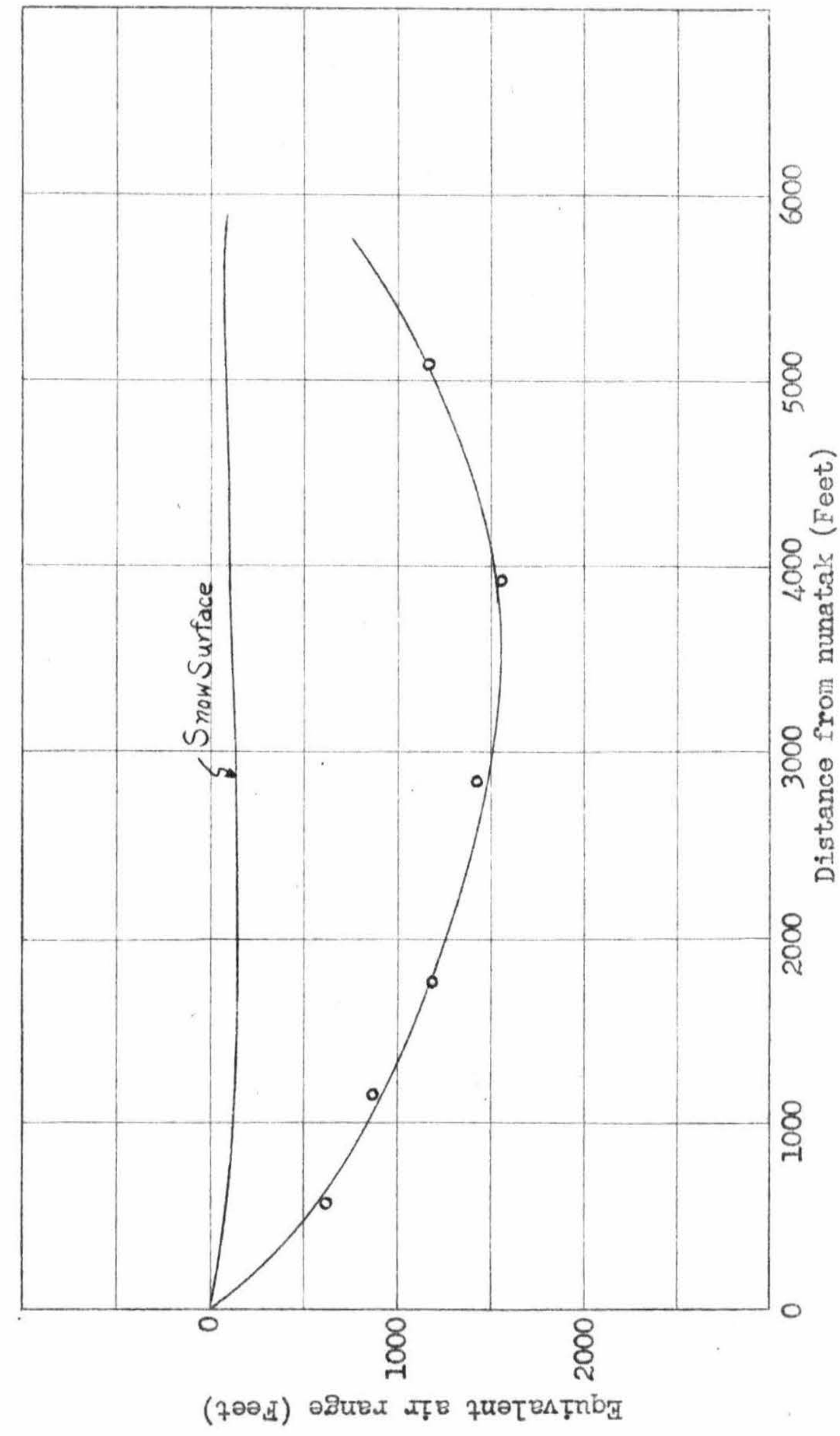


Fig. 4.6 Profile obtained by radar in 1948.

sound waves to reflect from the bedrock. The frequencies used were in the sonic range, extending from 100 cycles to 16 kilocycles per second. Bandpass filters enabled them to select the frequencies desired. A pulse of sound waves was obtained by detonation of an electric blasting cap designed for seismic use. Much difficulty was experienced in securing satisfactory geophone coupling and in transmitting a sound wave to the solid ice below the neve. Probably most of the explosion energy was dissipated in the immediate neighborhood of the charge. Consequently, no profiles were obtained and the technique, in its present form, was deemed unsatisfactory for the upper Seward Glacier.(18)

The other party, from the University of Toronto, experimented with conventional seismic equipment. Although this method had been proven on bare ice glaciers, the same difficulties were encountered that were mentioned above for the sonic method. Echoes from bedrock were finally obtained at one location by placing the dynamite in a crevasse at a depth of about sixty feet.(19)

V. GLACIOLOGY

The upper Seward Glacier is a relatively flat intermontane glacier of over 500 square miles area. There is an excess of accumulation over ablation of snow each year and the surplus flows out through a gap three miles wide. There is very little precipitation in the summer. The excess accumulation averages about 30 inches of water per year, but the precipitation for the winter of 1948-49 was estimated at 80 inches with a net accumulation of 69 inches.* Melting was sub-normal during the summer of 1949.

The density of the névé ranged from close to 0.50 at the surface to 0.85 at a depth of 50 feet. Horizontal blue ice bands were spaced at irregular intervals, but averaged every few feet. These had densities around 0.90 as compared to solid ice with a density of 0.917. Vertical columns of large ice crystals, loosely bound together and usually less than eight inches in diameter, extended between the ice layers. Most of these ended at ice layers. These are known as ice glands (Fig. 5.1).

The daily meltwater wave percolated downward at initial rates between 6 and 8 inches per hour. This rate became less as it progressed, the meltwater maximum descending the first 10 feet in 24 hours. The greater the depth, the more continuous is the meltwater flow. The largest amount of meltwater collected was 0.17 cc/cm^2-hr.

In 1948, standing water was found in several crevasses in the central part of the upper Seward Glacier at depths of 60 to 70 feet. One hole was bored by an electrically heated hotpoint to a depth of over 200 feet. The drilling rate for the upper part was 1.6 minutes

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* The study of the physical characteristics of the glacier was carried out by a group of geologists under the supervision of Dr. R. P. Sharp of this Institute.

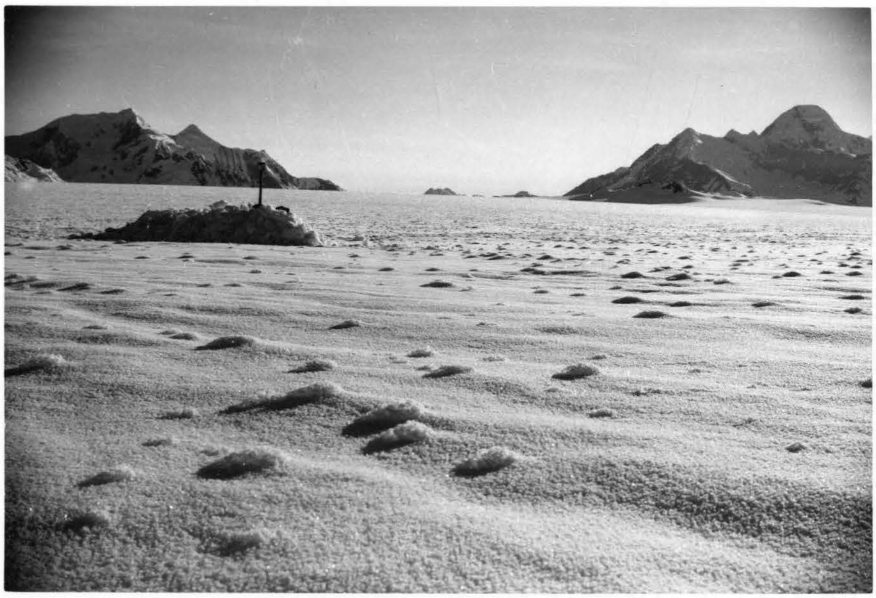


Fig. 5.1 Surface of the upper Seward Glacier. Elevations are ice glands.

per foot. At the water level in the neighboring crevasses, this rate decreased to 8 minutes per foot. Since the heat conductivity of water is approximately one-third that of ice,[20] this change might be explained by loss of heat due to convection. This would indicate that there is a water table, and that the liquid water content is greater below this level. However, in 1949, standing water was not found in crevasses that were penetrated to nearly 100 feet in depth. This disappearance or depression of the water table was probably due to the fact that the summer of 1949 was much cooler, so ablation was less.

Crevasses probably do not extend much more than a hundred feet in depth in any glacier.[21] Below this depth the pressure would keep any from forming, or plasticity is so great that those which do form close up quickly.

After the winter cold wave had dissipated, the temperature down to a 200 foot depth was found to be at the melting point, and presumably is at the pressure-melting point to the bottom of the glacier. This depression of melting point is only about one degree Centigrade per five thousand feet of depth.

VI. 1949 EXPEDITION

(a) Equipment

Experiments were continued in 1949 on the same profile of the Institute Glacier. The receiver and indicator were retained from the 1948 equipment but the rest of the equipment was different. A frequency of 180 megacycles per second was used because of the availability of transmitter, antenna, and receiver RF section.

The transmitter was a BC-1072-A, a component of the Signal Corps IFF equipment RC-148-A. The pulse length was shortened from 10 to 0.5 microsecond and the output was changed from balanced to coaxial output. Peak power was approximately one kilowatt. An AN-154-A antenna was used. This is the antenna for RC-145-A or RC-184-A IFF equipment, which, in turn, is associated with Signal Corps radar equipment SCR-545-A and SCR-584-A respectively. The only changes made were removal of the lobe switching device and a slight modification of the RF feed (Fig. 6.1). The antenna pattern is plotted in Fig. 6.2. This would be the pattern if it were operating in air and must be modified due to the effect of the ice. The RF section of the receiver was obtained from a BC-701 receiver. Block diagrams of the equipment are shown in Figs. 6.3 to 6.6.

Transmitter and receiver were connected to the same antenna by an antenna matching section taken from the BC-1267-A (the transmitter-receiver of the RC-145-A or RC-184-A). The purpose of this matching section was to guide all the transmitted energy from the transmitter to the antenna, and all the received energy from the antenna to the receiver. The principle is as follows: The transmitter, when not oscillating, looks like a pure reactance. If the distance from the transmitter to the junction is the proper length, the returning energy will see infinite impedance in the direction of the transmitter and, hence, will all go to the receiver, which is matched to the line. When the

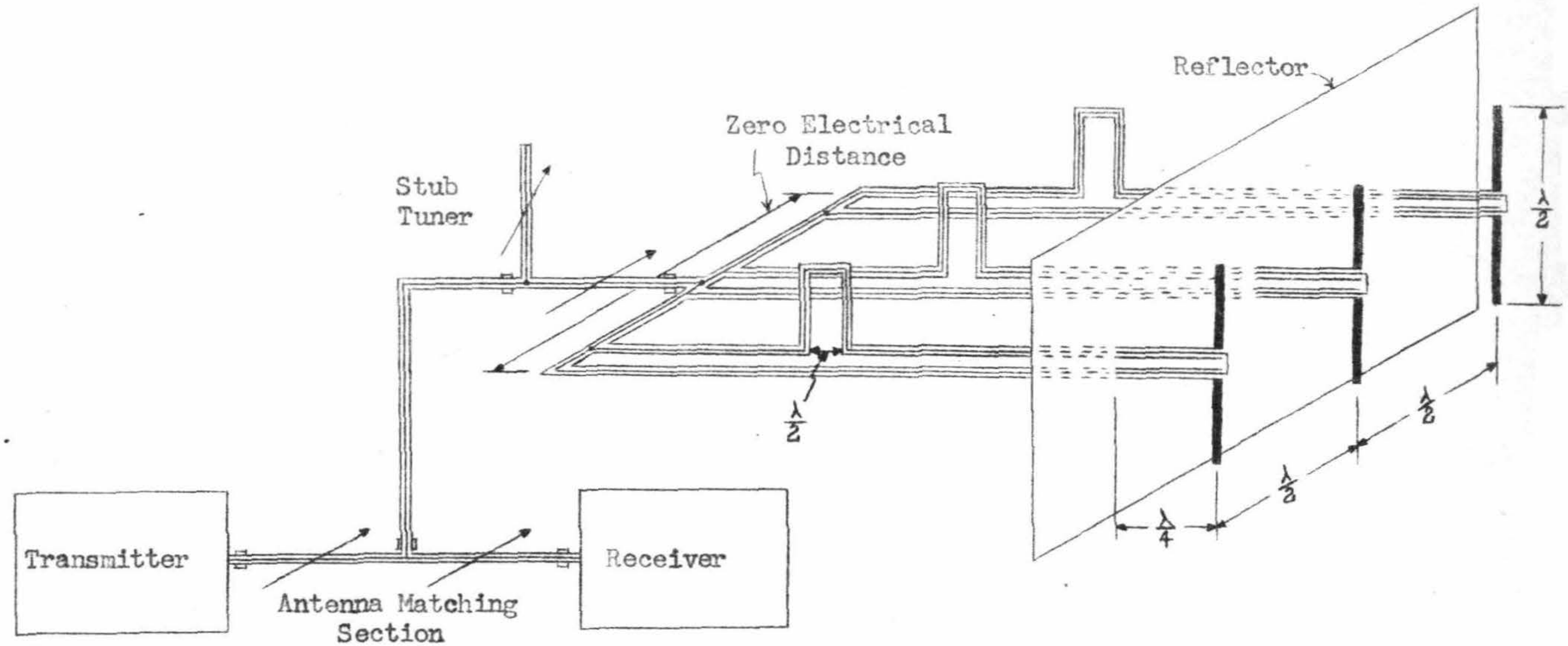
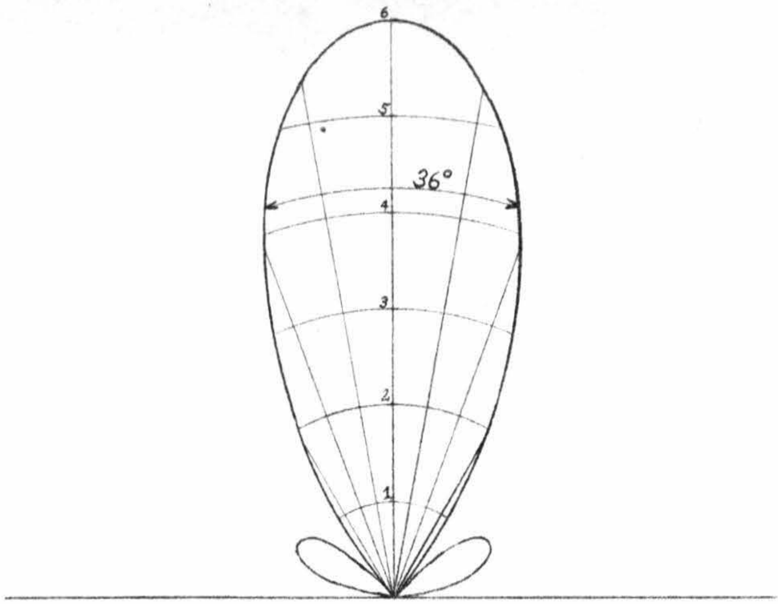
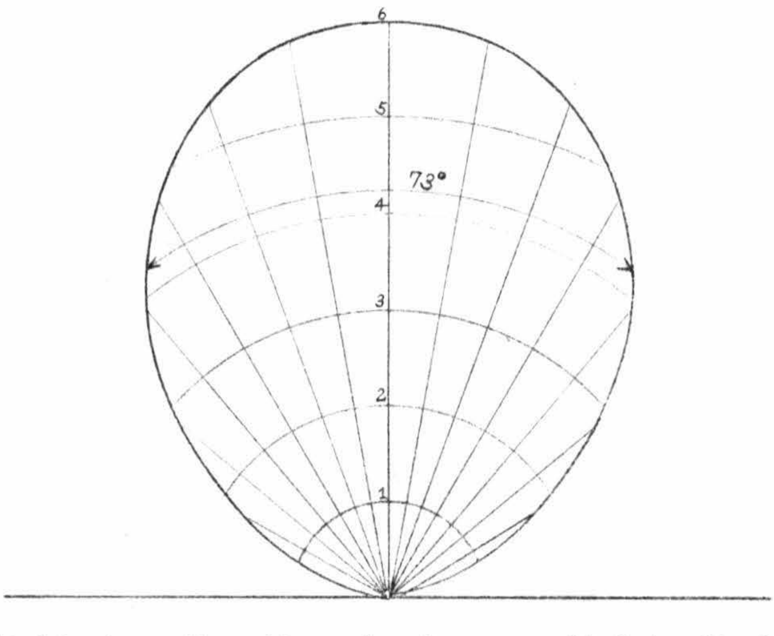


Fig. 6.1 Schematic of antenna used in 1949.



(a) Field strength pattern in plane perpendicular to dipoles.



(b) Field strength pattern in plane parallel to dipoles.

Fig. 6.2 Field strength patterns for 3x1 broadside array with reflector.

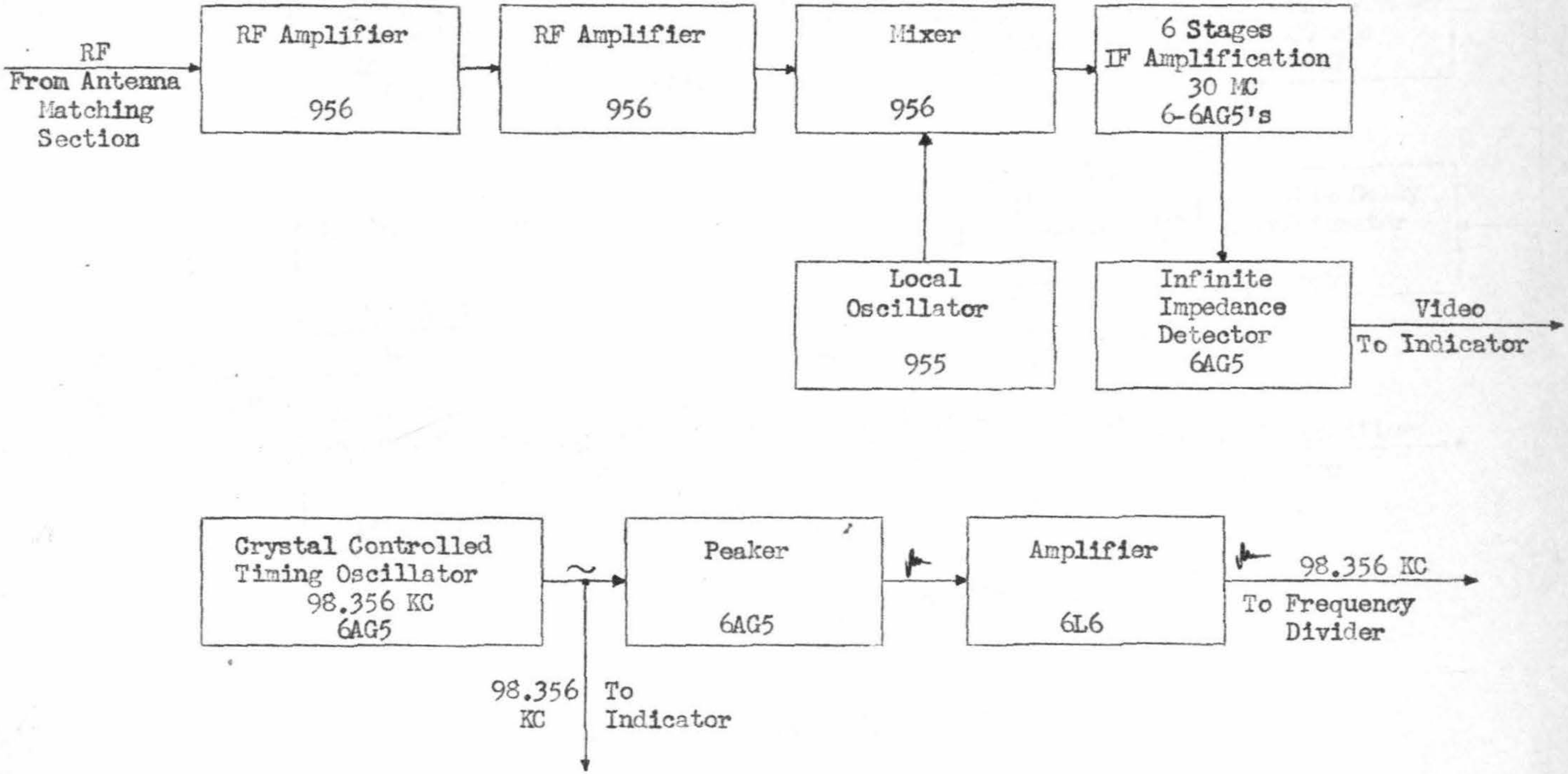


Fig. 6.3 Receiver block diagram.

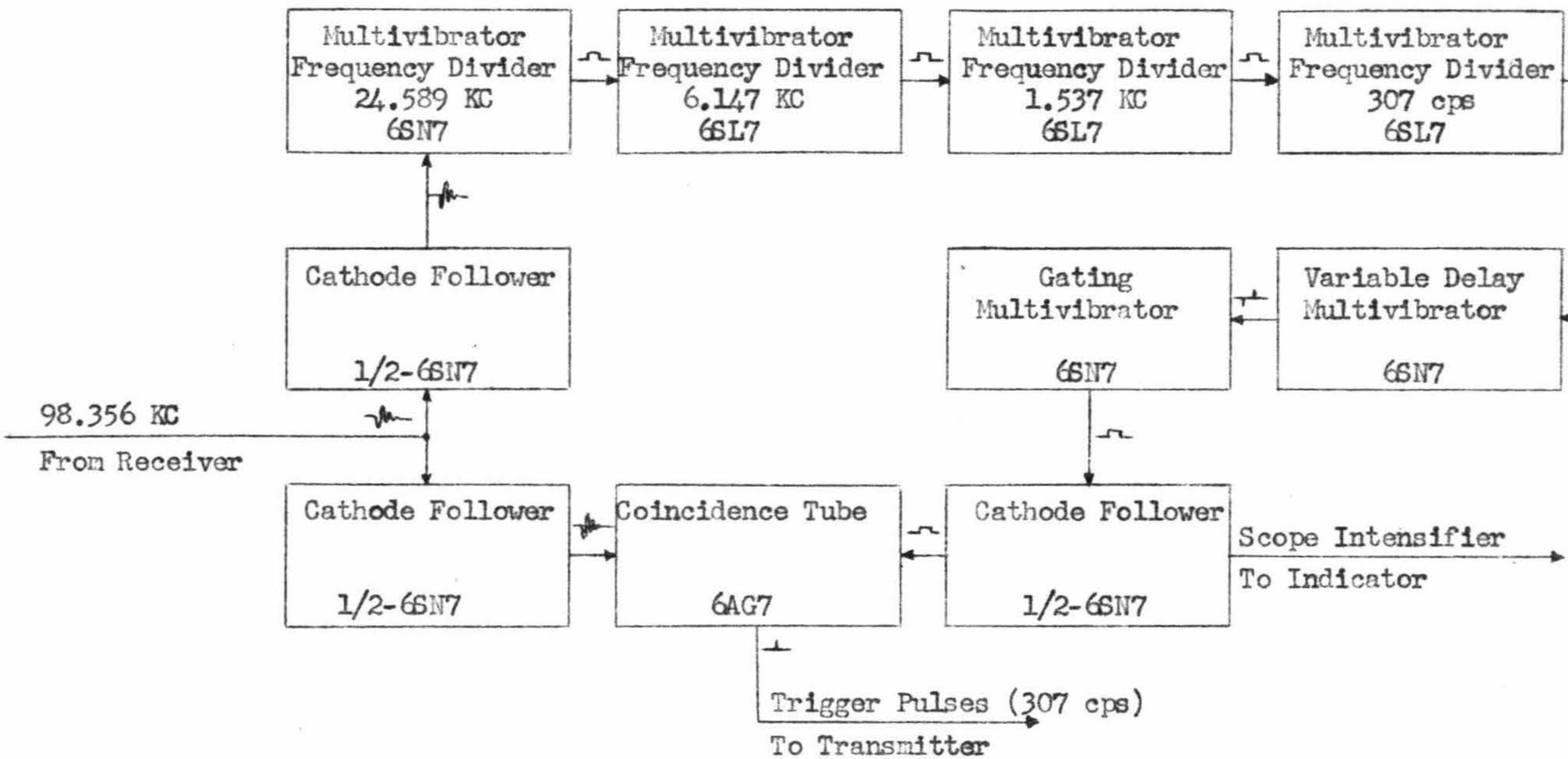


Fig. 6.4 Frequency divider block diagram.

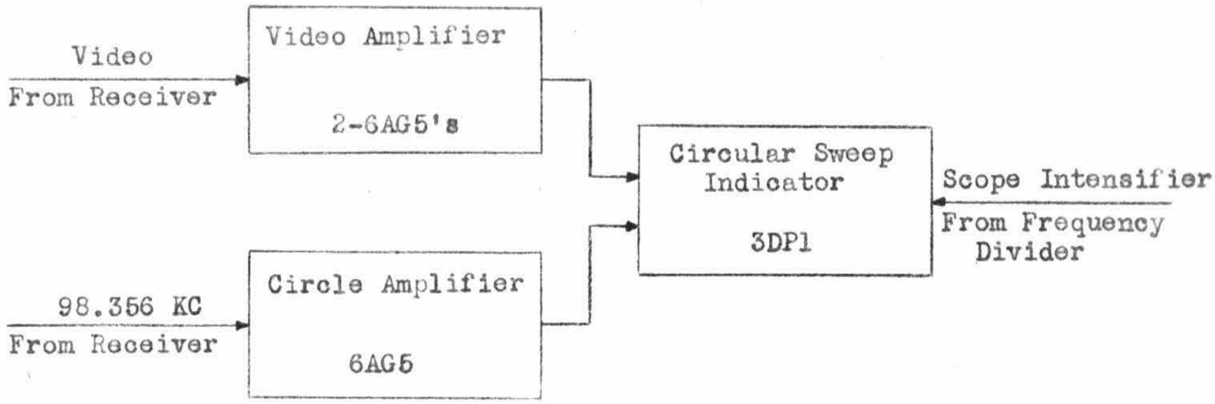


Fig. 6.5 Indicator Block Diagram

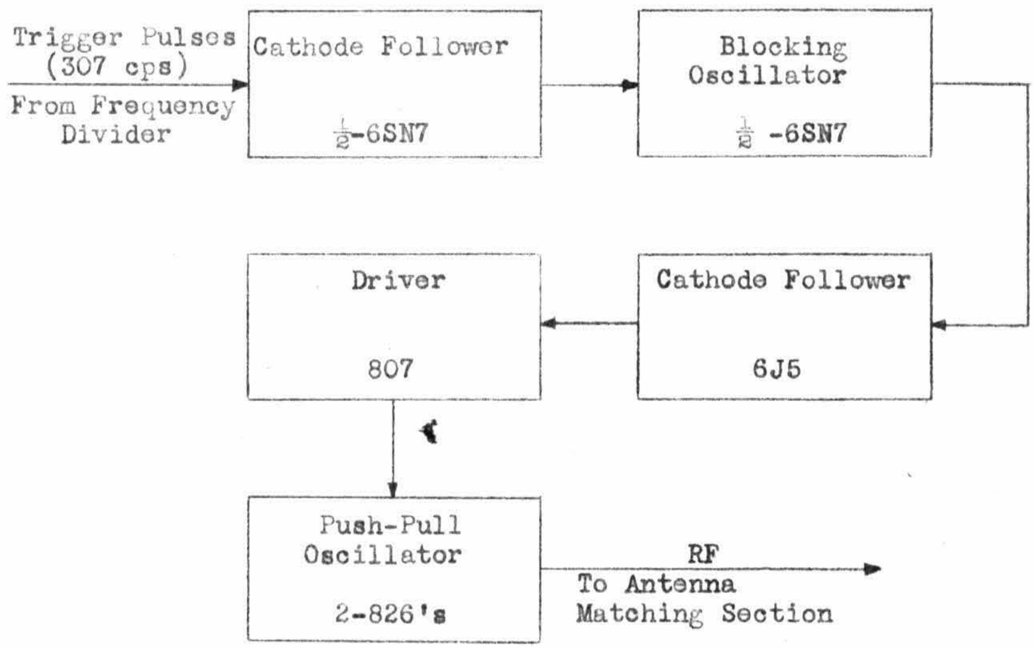


Fig. 6.6 Transmitter Block Diagram

transmitter is oscillating, it is matched to the line. At the start of oscillation, the coupling capacitor to the input of the receiver will charge up, and henceforward the receiver will look like a pure reactance. With the proper length of line this will be transformed to an infinite impedance at the junction, and all the transmitted energy will go to the antenna. A second matching section was used at the antenna as a stub tuner.

(b) Operation and Results

It had been hoped that with the improved techniques, radar sounding would be rapid and accurate so that much beneficial information on the topography of the bedrock floor could be obtained. As readings were taken at the stations on the Institute Glacier profile, it became apparent that the data were as confusing as in 1948. After most of the stations had been covered--the two remaining ones involving much labor because of the hillside they were located on--it was decided that the remaining time could be used to better advantage by experimenting with various techniques rather than collecting a host of data on other parts of the Seward Glacier.

The technique that had been used was suspension of the antenna above the surface as shown in Fig. 6.7. Various heights were tried. Because the beam angle was different in the planes parallel to, and perpendicular to, the direction of polarization, rotation of the antenna should have produced a change in the magnitude of any echo received from a target not on the axis of rotation. On the other hand, a target on the axis should have remained constant in magnitude. This assumes that the effective cross section of the target did not change with polarization. While this may not be entirely true, it was believed that rotation of the antenna would give some clue as to which echoes were returning from below and which ones came from the side, e.g., from

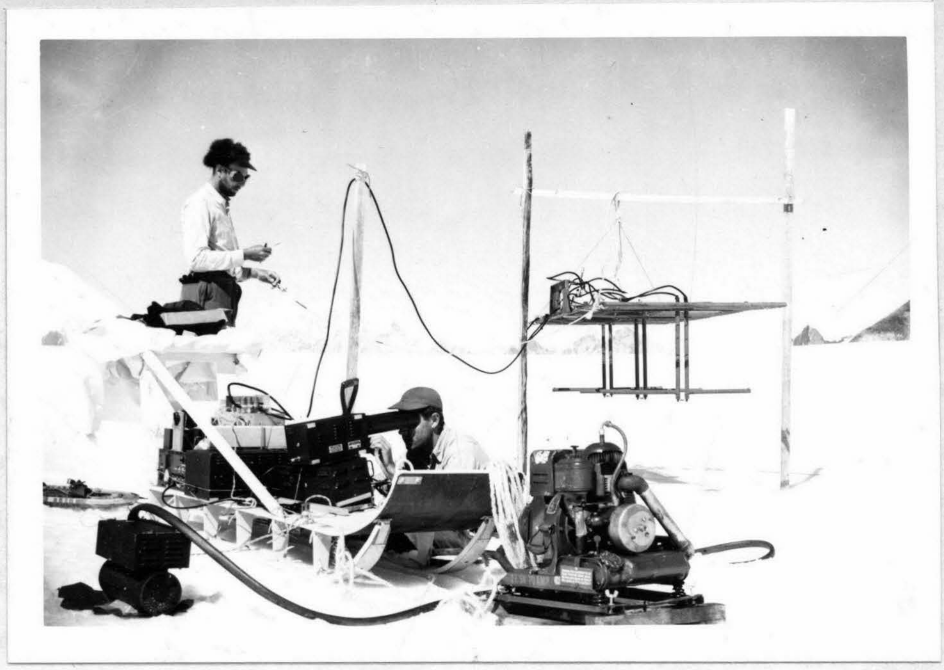


Fig. 6.7 Operation of the equipment.

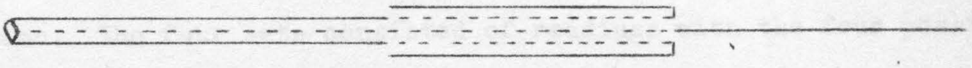


Fig. 6.8 Auxiliary receiving antenna.

crevasses. Almost all the echoes changed some when the antenna was rotated, so that any amount of data desired could have been obtained by taking a reading every few degrees. However, only two sets of readings per station were taken, the two antenna positions being at right angles to each other. The two directions were arbitrarily chosen as polarization parallel to, and normal to, the direction of glacier flow.

In order to investigate the polarization of the echoes, an auxiliary antenna, Fig. 6.8, was constructed in the field. This antenna was used for receiving. The transmitting antenna was directed horizontally in the direction of a nunatak. By rotating the receiving antenna, it was established that the echo was polarized in the same direction as the transmitted wave. The transmitting antenna was then directed downward. Trouble was experienced in getting a unique display, as the presentation even changed with motion of the receiving antenna parallel to itself. However, the echoes seemed to have no preferred direction of polarization. Due to the dissymmetry of the receiving antenna, quantitative information could not be obtained and the qualitative data just mentioned are questionable.

The profile was again retraced, taking four sets of data at each station. The four sets consisted of readings with the four possible combinations of the two antennas polarized parallel to, and perpendicular to, the direction of glacier flow. The various sets of data were not very consistent; nevertheless, the six sets of data at each station were superposed, and after giving each echo due weight according to its size, appearance, and consistency, the curve of Fig. 6.9 was selected as the most probable. The points plotted are the locations where good echoes were most consistent. Again, these depths are equivalent air ranges and must be corrected for the velocity of propagation. This

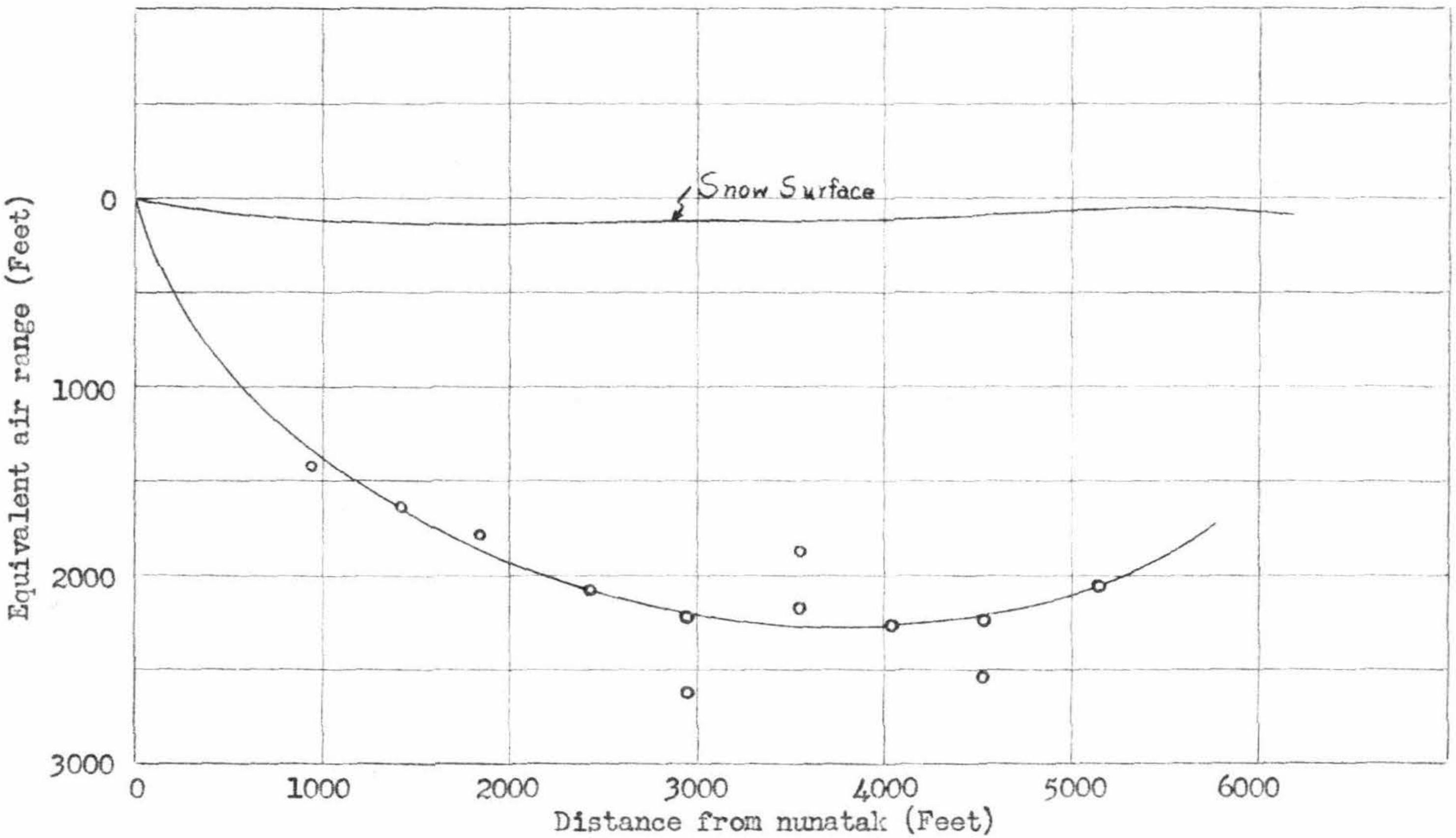


Fig. 6.9 Profile obtained by radar in 1949.

year, maximum range echoes were usually received at equivalent air ranges near 2500 feet.

One of the most distressing phenomena was the change with time of the echo display, even when the equipment had not been touched. It was first suspected that the temperature of the equipment was responsible. Therefore a series of experiments was conducted to determine the cause of this anomaly. The conclusion was that it was caused by something external to the equipment, presumably by percolating meltwater in the glacier as discussed in Part V.

Velocity of propagation measurements were made in the surface layer of the glacier. This was done by placing the antenna and a target in trenches 545 feet apart. The antenna in its pit is shown in Fig. 6.10, and the rest of the equipment in Fig. 6.11. The echo received was very large, showing that attenuation was no problem for distances of this magnitude, at least for propagation in the surface layer. The equivalent air range of the target, as determined by radar, was 910 feet. This gives a specific inductive capacity of

$$\varepsilon' = \left(\frac{910}{545}\right)^2 = 2.8 \tag{6.01}$$

Referring to Fig. 2.3, and assuming a density of 0.50, the liquid water content is seen to be 1.2%. This is within the limits as determined by other methods.

The biggest improvement in technique over that of the previous year was operation of the antenna from above the surface. The time to run a profile took about one hour per station, most of which was spent in taking down and setting up equipment. Stations were approximately 500 feet apart. Surface conditions were usually satisfactory from two o'clock until ten o'clock in the morning.

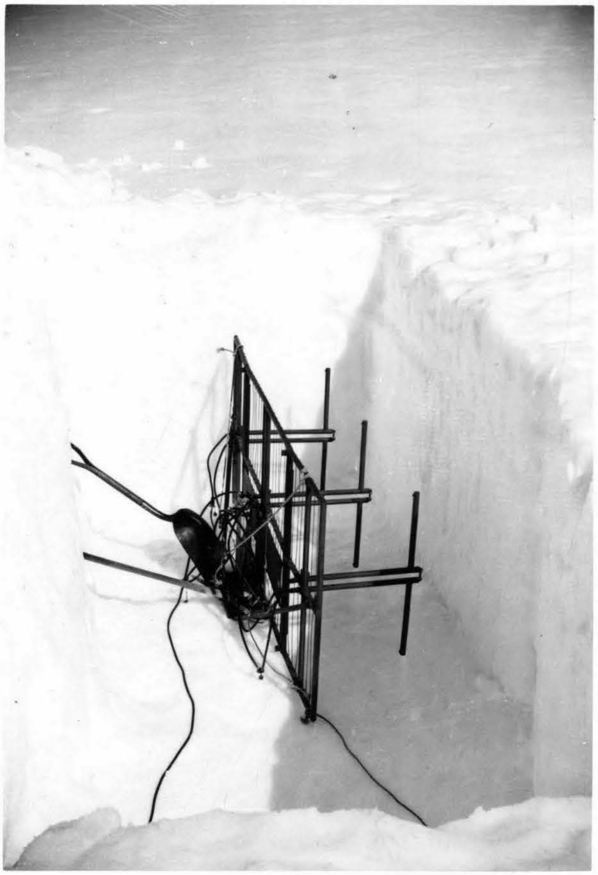


Fig. 6.10 AN-154-A antenna.

Fig. 6.11 Equipment set up for operation.

(c) Other Methods

In 1949, gravimetric and seismic investigations were carried out on the upper Seward Glacier.(22) Seismic soundings were successful, but the charge had to be placed in solid ice some sixty feet below the surface. It was not definitely established whether the necessary depth depended only upon the ice density, or whether a water table played an important part. Inasmuch as the drilling rate was about 1.6 minutes per foot, this part of the operation took from one to two hours. The receiver geophones were placed on the surface. The average rate of running a profile was two stations per day. Glacier depth was determined at five stations on the Institute Glacier. This seismic equipment was limited to thicknesses of ice greater than about a thousand feet.

The upper Seward Glacier is very favorable for gravity-meter observations because of the subdued relief of the snow surface, and the contrast in density between ice (0.9) and rock (2.7-3.0). Two surveys were made, one nearly seven miles long on the upper Seward proper, and the other across Institute Glacier. Under good sledding conditions, stations spaced 500 feet could be covered at the rate of one every ten minutes. From the data of gravity surveys, only the general shape of the bedrock floor can be obtained, not the absolute ice thickness. However, the ice thickness can be determined at several control points along the profile by seismic methods.

The ease of taking a gravity survey is offset by the labor and difficulty of interpreting results, expecially in a region such as this where no good maps of the topography exist. The topography must be known so that corrections can be applied to the raw data. Not only is a knowledge of the topography of the exposed land masses necessary, but also of the topography of the bedrock floor under the glacier. These latter data are not as important, however, because the relief is usually much more subdued. Two-dimensional analysis was used on the gravity-meter data of the Seward Basin. By trial and error, a profile was finally arrived at which was in accord with the gravity data.

Analysis of the Institute Glacier data was not made because of lack of information on the surrounding topography which consisted of large rock masses in the immediate vicinity. The data were used to estimate the remainder of the profile obtained by seismic methods. This curve is shown in Fig. 6.12.

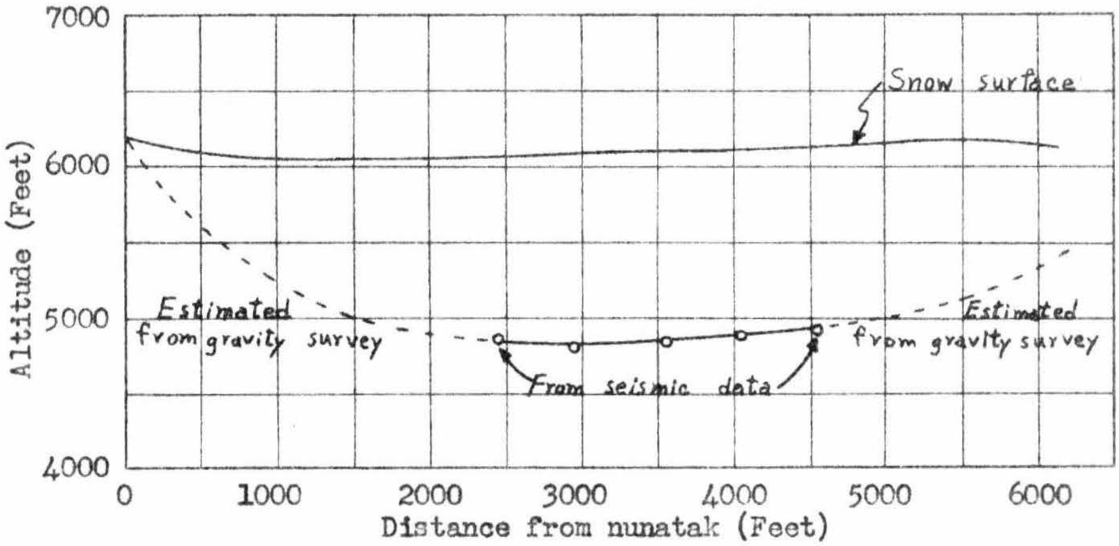


Fig. 6.12 Profile obtained by seismic and gravity methods.

VII. ANALYSIS OF EQUIPMENT

After a small amount of field work had been done in 1948, it became obvious that the equipment was not performing satisfactorily. Echoes changed in shape, magnitude, and range when the transmitter output coupling, receiver input coupling, or local oscillator coupling was varied, or when the Twinex cables were moved. To test the performance of the set when operating in the air, two half-wave dipoles were constructed and set up above the surface. A nunatak was about 1000 feet distant. Besides an echo which apparently came from the nunatak, other echoes appeared at ranges where there were no objects, at least not above the surface. The possibility existed that these other echoes came back from discontinuities in the glacier.

The components of this equipment that were retained for the succeeding year were the IF strip of the receiver and the indicator. After the equipment was put in a functional condition, it was tried out on the roof of Mudd Laboratory. Many echoes were received, some of which could be identified. All echoes changed when the antenna was rotated in direction, so operation was believed to be satisfactory. It would have been desirable to test it on the desert and to conduct more laboratory test, but time did not permit.

When field operations were begun in 1949, many anomalies appeared which were strikingly similar to those of the preceding year. Adjustments which caused the echo display to change were tuning of the receiver, transmitter output tank, antenna matching section or stub tuner, and movement of the antenna. When the antenna was directed horizontally toward a nunatak or the mountains, other echoes appeared besides those from visible objects, but again, the possibility could not be excluded that some energy was penetrating the surface and reflecting from a discontinuity in the ice. However, this was thought unlikely, since the identified echoes were quite stable to the various adjustments, while the others were not. Several times when the set had been tuned up on identified echoes, the coaxial cable between antenna matching section and the antenna was replaced by one of different length. This entailed retuning of the stub tuner, indicating that the line was not flat. The fact that the coaxial connectors were not the constant impedance type may have caused some trouble. A slotted line would have been very beneficial in obtaining optimum performance.

After field operations had been concluded, laboratory tests were conducted on the receiver to determine its qualifications for the work just completed.

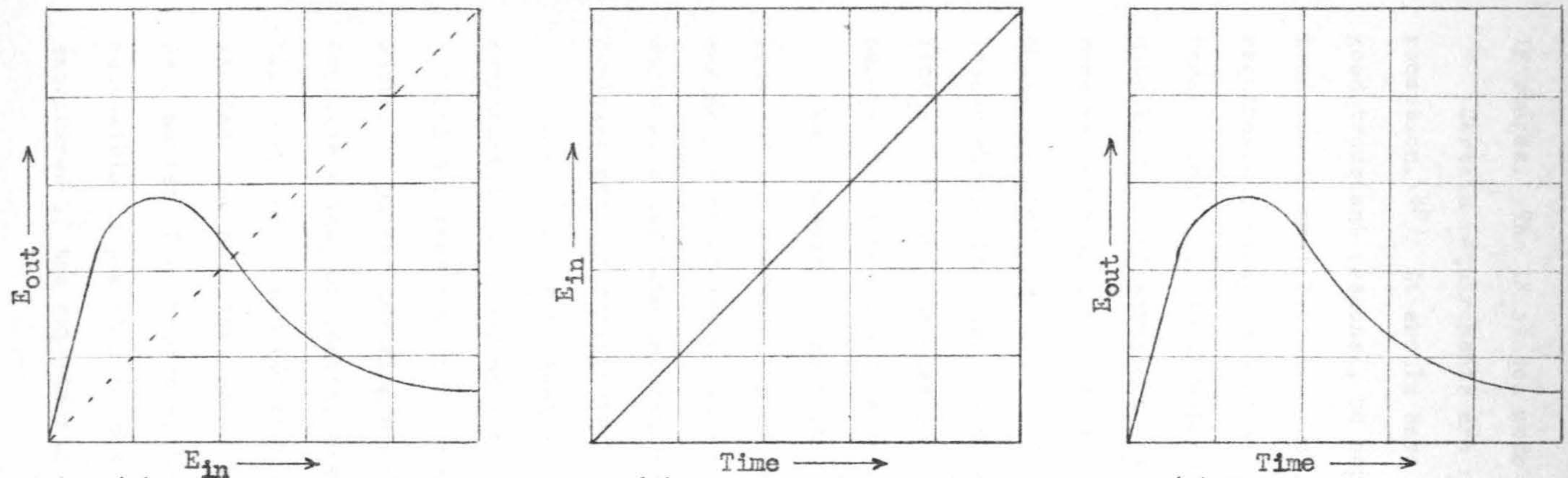
The requirements for a pulse amplifier capable of handling a large dynamic range of signals are very stringent.[23] Amplifiers often show a loss of sensitivity after a very strong pulse of short duration. The most common cause is collection of charge upon a grid coupling condenser. Another cause is the Whippany or blackout effect[24] and is thought to be closely analagous to the anode effect.[25] It is thought that a thin film of insulating material forms on the grid so that when grid current is drawn, electrons deposit on this layer and take an appreciable time, of the order of microseconds, to leak off. There is considerable variation of the blackout effect, even among supposedly identical tubes. This effect is most serious in the case of video amplifiers and plate detectors where this apparent change of grid potential shows up as a spurious signal instead of a change in gain, but the decrease in sensitivity is also an important consideration in high-level bandpass amplifier stages.

Probably the greatest cause of trouble in the receiver was the fact that the incremental gain of each IF stage was negative at the point where it was so overloaded that the input signal was equal to the output signal. The incremental gain is defined as the slope of the curve obtained by plotting input against output.[26] Such a curve is shown plotted in Fig. 7.1a. If the input of a stage is a signal which increases with time as in Fig. 7.1b, then the output will be the curve of Fig. 7.1c. Now if a second stage is connected to the output of the first stage, its output will be the curve of Fig. 7.1d. This can be continued for each additional stage added; the result is a hump for each stage. Of course, a decreasing signal will give a similar effect, so a large echo with a slow rise or decay time will appear as a number of echoes.

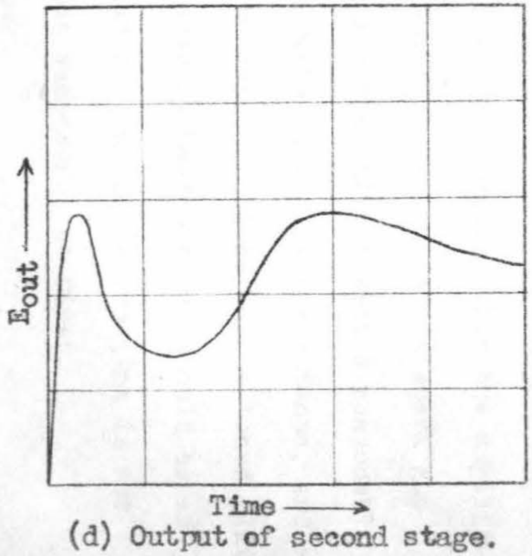
This performance was verified by observing the response of the receiver to RF pulses of various magnitudes and durations. When the IF stages were overloaded with a RF signal modulated by a sine wave, the hills and valleys interchanged as the gain was increased. The response of the video amplifier fell off too much for the lower frequency components of the pulses, and overshoot was excessive. A five-microsecond, two-millivolt pulse fed into the IF strip decreased the sensitivity considerably for a period of thirty microseconds.

The method of gain control is also important.[27,28] Reduction of plate or screen potential lowers the saturation level and should never be used when overload capability is of importance. The best way is to return the grid circuits to a variable negative voltage supply of low impedance for quick recovery from overload. The slight amount of detuning caused by change of bias will usually not be of importance, expecially in wide-band amplifiers. If the gain variation must be large, several tubes should be controlled so that none will be biased to cutoff.

The method of gain control for the receiver under discussion was variation of screen potential of the second RF stage and the first two



(a) Output vs. input. (b) Input of first stage. (c) Output of first stage.



(d) Output of second stage.

Fig. 7.1 Behavior of two stage amplifier if incremental gain is negative when input signal is equal in magnitude to output signal. All voltage scales and all time scales are the same.

IF stages. The IF stages were double tuned.

Certain requirements are necessary for a second detector for pulse reception.(29) It should have high gain, be reasonably linear, have good transient response, be capable of handling large signals, and not load the IF amplifier too much. The diode detector fulfills all these requirements except the first and last, and so is used most widely for radar receivers. In wide-band amplifiers, IF amplifier loading is usually not a disadvantage, as the stage must be loaded anyway. This receiver used an infinite impedance detector. It has low gain, but its chief disadvantage is that it is subject to overloading, though to a lesser extent than the plate detector. These faults probably made little difference because so much damage had been done to the signal before it reached the detector stage.

Measurement of the input impedance of the receiver using a slotted line and the output pulse of the transmitter showed that that there was no length of the antenna matching section (receiver branch) which would give infinite impedance at the junction. Clearly, this type of duplexer was not satisfactory.

In brief, the following suggestions are offered as a guide in the construction of radar equipment for future work in exploring glaciers: (1) build a receiver to the most rigid specifications for the amplification of pulses covering a wide dynamic range; (2) use a spark gap duplexer which, of course, also means a transmitter with a reasonably high peak power; and (3) provide adequate tuning at the antenna, and a slotted line detector, so that the transmission line can be tuned flat. As a matter of convenience, the laboratory headquarters should be as accessible as possible to the glacier so that excessive time is not sacrificed if the experiments are not successful at first.

VIII. DISCUSSION

If the equivalent air ranges found in 1948 are multiplied by 0.89 and those of 1949 by 0.58, the curves of Figs. 8.1 and 8.2 result. Comparing these curves with the depths obtained by seismic sounding, it is seen that both are in good agreement. However, these velocity of propagation factors were chosen so as to make the maximum depths check with the seismic data. It has been assumed that the average velocity of propagation was the same across the profile, which may not be exactly true.

If we had radar data for only one profile, there would be nothing wrong with this method. As discussed in Part II, the only sure way of finding the velocity of propagation is to work on a glacier of known depth. But whatever the velocity of propagation was, it should have been approximately the same for both years. The difference in frequency is a negligible factor. The liquid water content may have changed, but there was less melting in 1949 than in 1948, so the equivalent air ranges should have been smaller.

Again we encounter an unexplainable situation if we calculate what the specific inductive capacity must have been. Using the reciprocals of the above factors for the indexes of refraction gives 1.26 and 2.98 for 1948 and 1949 respectively. These are both less than that of solid ice without any liquid water. If the data of 1948 are discounted, and the velocity of propagation used for the seismic waves is assumed to be six or seven per cent too high, the 1949 radar and seismic curves agree, provided the glacier was dry. However, this is clearly an ad hoc hypothesis--the radar data are not substantial enough to justify questioning the seismic data.

If the conclusion as to the practicability of radar methods depended upon agreement with the seismic data for this one profile, it

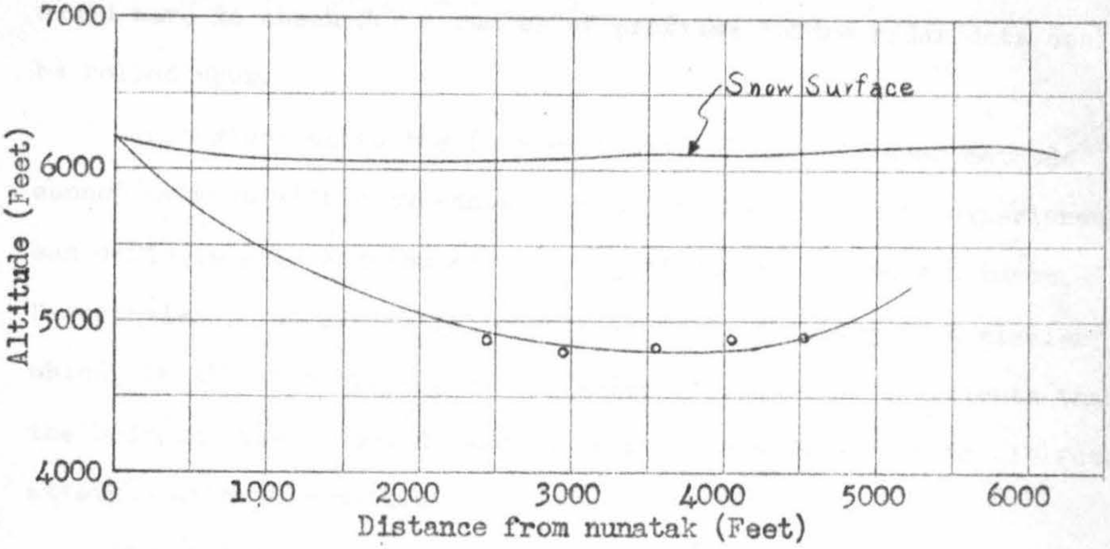


Fig. 8.1 Radar profile of 1948 for specific inductive capacity of 1.26.

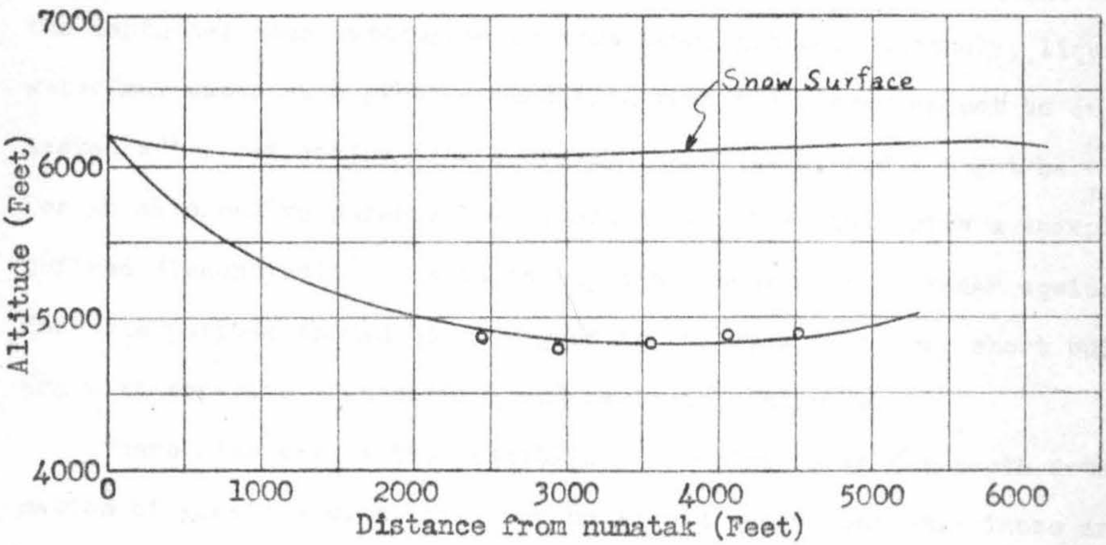


Fig. 8.2 Radar profile of 1949 for specific inductive capacity of 2.98.

would be worth while spending effort to obtain correlation. There are two reasons why this is not worth while. First, if agreement were obtained, it would be questionable. Second, radar and seismic data would have to check for a number of profiles before radar data could be relied upon.

Conclusions as to the future practicability of radar methods cannot be made with assuredness. Much of the difficulty experienced can definitely be attributed to the performance of the equipment. Nevertheless, the dielectric discontinuities existing in a glacier which, in all probability, have greater reflection coefficients than the bedrock itself, would seem to be a serious deterrent to all future attempts with this method.

As mentioned earlier, the presence of liquid water is considered to be the greatest obstacle. In the first place, the velocity of propagation cannot be predicted. This alone, however, would give radar an alternative use--that of finding the average liquid water content when the depth has been determined by some other method. Secondly, liquid water may cause such great attenuation that the energy cannot be detected after reflecting from bedrock. Here again, radar might be used for an alternative purpose. If there is a water table with a sharply defined discontinuity, its depth might be ascertained. Radar equipment for this purpose should be of higher frequency with a very short pulse, and with separate transmitting and receiving antennas.

There also exists the possibility of using radar for depth determination of glaciers with little or no liquid water content. There are high altitude glaciers in the polar regions where negligible melting takes place. Any free water formed at the lower depths by ice being brought to the pressure melting point should be small, and would probably exist only on the bottom.

Radar methods for glacier sounding must still be considered in the experimental stage. If profiles of some glacier are desired, results obtained by seismic methods would be the most reliable. These data could be augmented by gravity surveys if time, instead of equipment outlay, were more important. Both seismic equipment and gravity meters are fairly expensive. On the other hand, if suitable radar equipment could be obtained on the surplus market, the expenditure would be much less. Thus, radar methods offer one more advantage to the geophysicists who are interested in a long time program, and not just immediate results on some particular glacier.

REFERENCES

(1) Goldthwait, R. P., The Geographical Journal (1936), vol. 87, pp. 496-517.

(2) Ramo, S. and Whinnery, J. R., Fields and Waves in Modern Radio, Wiley (1944), pp. 270-279.

(3) Stratton, J. A., Electromagnetic Theory, McGraw-Hill (1941), pp. 494, 506.

(4) Lattey, R. T., Gatty, O., and Davies, W. G., Philosophical Magazine and Journal of Science (1931), vol. 12, pp. 1019-1025.

(5) Murphy, E. J., Electrochemical Society Transactions (1934), vol. 65, pp. 133-142.

(6) Debye, P., Polar Molecules, Chemical Catalogue Co. (1929).

(7) Fröhlich, H., The Theory of Dielectrics, Oxford (1949).

(8) MIT Laboratory for Insulation Research, Tables of Dielectric Materials (1944), vol. I, p. 62.

(9) MIT Laboratory for Insulation Research, Tables of Dielectric Materials (1945), vol. II, p. 220.

(10) Vieweg, V. R., and Gast, T., Zeitschrift für technische Physik (1943), vol. 24, pp. 56-62.

(11) Gerdel, R. W., Personal communication.

(12) Stratton, J. A., op. cit., p. 510.

(13) Ridenour, L. N., Radar System Engineering, McGraw-Hill (1947), p. 271.

(14) Stratton, J. A., op. cit., pp. 573-587.

(15) Papas, C. H. and King, R., Proceedings of the IRE (1948), vol. 36, pp. 736-741.

(16) Wheeler, H. A., Proceedings of the IRE (1948), vol. 36, pp. 478-487.

(17) Harrison, C. W., Jr., Proceedings of the IRE (1946), vol. 34, pp. 204P-209P.

(18) Northwood, T. D. and Simpson, F. W., Depth Measurements in the Seward Ice Field by Sonic Echo-Ranging, National Research Council of Canada (Division of Physics) Report No. PS-300 (1948).

(19) Salt, D. J., Seismic Operations on the Seward Glacier, a report to the University of Toronto (1948).

(20) Handbook of Chemistry and Physics, Chemical Rubber Publishing Co. (1949), pp. 1893, 1894.

(21) Seligman, G., The Geographical Journal (1941), vol. 97, pp. 295-317.

(22) Reese, J. R., Report of Gravimetric and Seismic Investigations of Upper Seward Glacier, St. Elias Mountains, Yukon Territory, July-August 1949, a report for California Institute course GE 297X (1949-50).

(23) Valley, G. E. and Wallman, H., Vacuum Tube Amplifiers, McGraw-Hill (1948), pp. 113-165, 274-300.

(24) Van Voorhis, S. N., Microwave Receivers, McGraw-Hill (1948), p.187.

(25) Copeland, P. L., Physical Review (1940), vol. 57, pp. 625-634.

(26) Van Voorhis, S. N., op. cit., p. 186.

(27) Valley, G. E. and Wallman, H., op. cit., p. 290.

(28) Van Voorhis, S. N., op. cit., p. 239.

(29) Van Voorhis, S. N., op. cit., p. 208.