

# INSTRUMENTS AND METHODS

## RADIO-FREQUENCY INTERFEROMETRY—A NEW TECHNIQUE FOR STUDYING GLACIERS

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**ABSTRACT.** A new method of electromagnetic sounding in resistive electrical environments has been developed for use in lunar exploration. It is applicable to the study of terrestrial glaciers and ice sheets. A horizontal electric dipole antenna on the ground is used to transmit power at frequencies of 1, 2, 4, 8, 16 and 32 MHz. A set of orthogonal receiving coils is mounted on a vehicle which traverses away from the transmitter. Field strength is recorded as a function of distance. Waves which travel above the surface interfere with waves from the subsurface, generating interference patterns which can be used to determine the dielectric constant, the loss tangent, and depth to reflecting horizons.

The technique was tested on the Athabasca Glacier in western Canada. At 1, 2 and 4 MHz the ice was found to have a dielectric constant of about 3.3, a loss tangent ( $\tan \delta$ ) which is roughly inversely proportional to frequency giving values of  $f \tan \delta$  in the range of 0.25 to 0.35 (where  $f$  is in MHz). These values correspond well with the known properties of ice near 0° C, which is a temperature typical of temperate glaciers. It has been possible to determine the depth of the ice but results are not always consistent with previous seismic and gravity surveys and with drilling. At frequencies of 16 and 32 MHz, scattering is the dominant feature of the results. At 8 MHz there is a transition from clear-cut interference patterns to the scattering patterns. From these findings, we suggest that the Athabasca Glacier has a large number of dielectric scatterers with dimensions less than about 35 m, probably due in large part to crevasses.

**RÉSUMÉ.** *Interferometrie de fréquences radio — une nouvelle technique pour l'étude des glaciers.* Une nouvelle méthode de sondages électromagnétique à travers des milieux électriques résistants, a été imaginé à l'usage des explorations lunaires. Elle présente des possibilités d'application dans l'étude des glaciers terrestres et des calottes glaciaires. Une antenne électrique dipolaire horizontale sur le sol est utilisée pour transmettre de l'énergie sur des fréquences de 1, 2, 4, 8, 16 et 32 MHz. Un ensemble de bobines réceptrices disposées orthogonalement est monté sur un véhicule qui circule à distance de l'émetteur. L'intensité du champ est mesurée en fonction de la distance. Les ondes qui se propagent au-dessus de la surface se combinent avec celles venues de dessous la surface, engendrant des interférences dont on peut se servir pour calculer la constante diélectrique, la perte en tangente et la profondeur des horizons réflecteurs.

On a essayé cette technique dans le glacier de l'Athabasca dans l'Ouest Canadien. A 1, 2 et 4 MHz, on a trouvé pour la glace une constante diélectrique de 3,3, une perte de tangente ( $\tan \delta$ ) qui est grossièrement inversement proportionnelle à la fréquence, donnant des valeurs de  $f \tan \delta$  de l'ordre de 0,25 à 0,35 (où  $f$  est en MHz). Ces valeurs correspondent bien avec les propriétés connues de la glace au voisinage de 0° C, température typique des glaciers tempérés. On a pu déterminer l'épaisseur de la glace mais les résultats ne concordent pas toujours avec les anciennes mesures sismiques et gravitaires, ni avec les forages. Pour les fréquences de 16 et 32 MHz, la dispersion est le trait dominant des résultats. A 8 MHz, il y a une transition entre un net phénomène d'interférence et la dispersion. A partir de ces constatations, nous suggérons que le glacier l'Athabasca possède un grand nombre de dispersants diélectriques mesurant moins d'environ 35 m, probablement en raison, pour une large part, de la présence de crevasses.

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**ZUSAMMENFASSUNG.** *Hochfrequenz-Interferenzmessung — eine neue Methode für Gletscheruntersuchungen.* Für den Gebrauch bei der Erforschung des Mondes wurde eine neue Methode der elektromagnetischen Lotung durch widerstandsfähige Oberflächenschichten entwickelt. Es besteht die Möglichkeit, damit terrestrische Gletscher und Eisschilde zu untersuchen. Eine horizontale elektrische Dipolantenne am Boden wird dazu benutzt, um Energie in den Frequenzen von 1, 2, 4, 8, 16 und 32 MHz auszusenden. Ein Satz von orthogonalen Empfangsspulen ist auf einem sich vom Sender weg bewegenden Fahrzeug befestigt. Die Feldstärke wird als Funktion der Entfernung aufgezeichnet. Die Wellen, die sich auf der Oberfläche und in den darunter liegenden Schichten ausbreiten, erzeugt Interferenzmuster, die zur Bestimmung der Dielektrizitätskonstante, der Verlusttangente und der Tiefe beliebiger Reflexionshorizonte verwendet werden können.

Die Methode wurde am Athabasca Glacier in Westkanada erprobt. Bei 1, 2 und 4 MHz wurde für das Eis eine Dielektrizitätskonstante von  $\epsilon$  3,3 und eine Verlusttangente gefunden, die angenähert umgekehrt proportional zur Frequenz ist und Werte von  $f \tan \delta$  im Bereich von 0,25 bis 0,35 (wobei  $f$  in MHz angegeben ist) ergibt. Diese Werte stimmen gut mit den bekannten Eigenschaften von Eis nahe  $0^{\circ}\text{C}$ , der charakteristischen Temperatur temperierter Gletscher, überein. Es ist möglich, die Eisdicke zu bestimmen, aber die Ergebnisse stehen nicht immer in Einklang mit früheren Bohrungen sowie seismischen und gravimetrischen Messungen. Bei Frequenzen von 16 und 32 MHz sind Streuungen das Hauptcharakteristikum der Ergebnisse; bei 8 MHz liegt ein Übergang von wohldefinierten Interferenzmustern zu Streumustern. Auf Grund dieser Ergebnisse schliessen wir darauf, dass im Athabasca Glacier eine grosse Anzahl von Streuobjekten vorhanden ist, deren Dimensionen unter  $\epsilon$  35 m liegen und die vermutlich zum grossen Teil Gletscherspalten zuzuschreiben sind.

## INTRODUCTION

The physical basis of the radio interferometry technique was described in detail by Annan (1973). The practical application was discussed by Rossiter and others (1973). The planned use of the technique in the exploration of the moon was described by Simmons and others (1972). Only a brief introduction to the experiment is given here; the reader interested in further description should consult the references above.

A horizontal electric dipole is laid on the surface and used to transmit electromagnetic energy at frequencies of 1, 2, 4, 6, 18 and 32 MHz in sequence. A coil mounted on a vehicle is used with the receiver. The vehicle is moved away from the transmitting antenna and the field strength at each frequency is detected and recorded on magnetic tape and on a strip chart recorder. One axis on the chart recorder is driven by an odometer, producing plots of field strength as a function of distance from the transmitter.

Energy is propagated from the transmitter to the receiver in three important waves (Fig. 1a). The first is the wave above the surface of the ice. Its velocity is the speed of light in vacuum. The second wave travels just below the surface of the ice. Its velocity is controlled by the dielectric constant of the ice. The interference between these two waves is used to determine the dielectric constant. The third wave travels through the body of the ice and is reflected from the glacier bottom. Its interference with the other waves causes modifications to the interference pattern which are indicative of the glacier depth. It should be noted that this wave is reflected from the bottom at different places depending on the separation between source and receiver. Since interpretation depends on characteristics of the whole curve, and since glacier depth may not be constant over the whole traverse, the measurement represents some sort of mean depth along the traverse line.

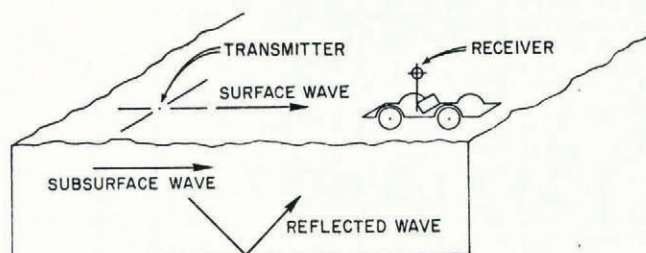


Fig. 1. (a) The three waves used in radio-frequency interferometry. The surface wave travels above the surface of the dielectric, the subsurface wave travels immediately below the surface in the dielectric. These two waves travel at different velocities and their beat frequency is a function of the dielectric constant. The third wave, designated reflected wave here, travels downward and into the dielectric and is reflected from some horizon at depth.

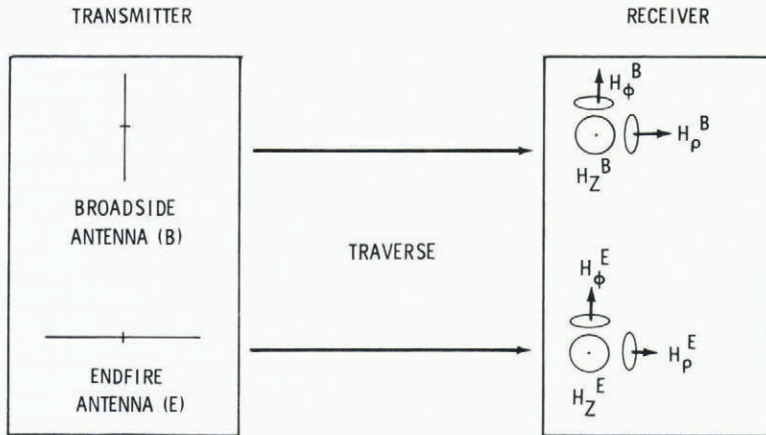


Fig. 1. (b) Relation of receiver components to transmitting antenna. The superscript *B* on the field components designates that measurements are taken broadside to the dipole. The superscript *E* indicates that the field components are measured with respect to the endfire antenna. The subscripts  $\rho$ ,  $\phi$  and  $z$  are those used in a right-handed cylindrical coordinate system. The transmitting antennas are actually coincident and there is only one set of receiving antennas. Each antenna is activated by the transmitter/receiver in the sequence shown in Figure 2.

In the present instrumentation, two orthogonal transmitting antennas are employed. Three orthogonal receiving coils are mounted on the traverse vehicle. By transmitting and receiving each of the possible combinations in sequence, six separate pieces of information are recorded at each frequency (Fig. 2). With six frequencies, 36 separate records are obtained as a function of distance from the transmitter. If the traverse is run orthogonal to one of the transmitting antennas, then three of the six components are maximum coupled and carry the interference patterns. The other three components are minimum-coupled. Ideally these components show near-zero amplitudes; in practice their amplitudes prove to be useful indicators of scattering from the subsurface or of reflections from lateral inhomogeneities such as valley walls.

One way of interpreting a set of field data is by matching theoretical curves with the observations (Annan, 1973). Families of theoretical curves for various dielectric constants, loss tangents and depths to reflector have been computed. To date our theory is adequate only for a single horizontal reflector in the subsurface. It may be a dielectric interface or a perfect (conducting) reflector.

We chose glaciers as the test area for our lunar experiment because the high electrical resistivity of ice is nearly unparalleled in other geological materials on earth. Because lunar rocks are exposed to a vacuum and are exceedingly dry, their resistivity should be similar to that of glacier ice, and quite unlike that of terrestrial rocks.

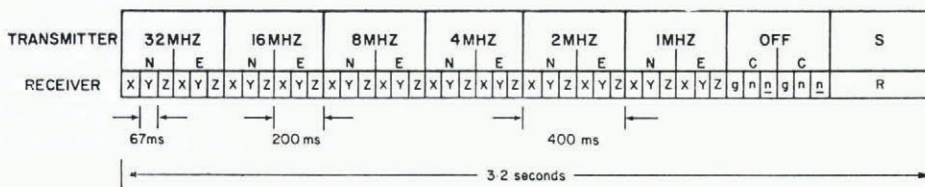


Fig. 2. Timing diagram showing sequence of transmitted signals and calibration data. *N* and *E* refer to alternate transmitting antennas; *x*, *y*, *z* refer to alternate receiving antennas; *C* refers to calibration with *g* referring to noise background with no transmitter on, and *n* and  $\bar{n}$  referring to noise from two known diode sources at the receiver input; *S* refers to transmitted synchronization signal and *R* to received synchronization signal.

## THE GLACIER

There have been several previous studies of the Athabasca Glacier. Most important from our viewpoint are the results reported by Paterson and Savage (1963), Keller and Frischknecht (1961), and Kanasewich (1963). These studies include the results of drilling, seismic and electrical soundings, and gravity surveys. Their results are illustrated in Figure 3, which specifically shows the depths determined by drilling. There are uncertainties in the precise values of the thickness, except in the immediate vicinity of drill holes and seismic sounding points. In particular, note that Keller and Frischknecht (1961), on the basis of an electrical sounding in the south-eastern part of the glacier, suggested a fairly shallow depth. This sounding is in the general vicinity of our sites 2, 3, 4 and 5. Paterson and Savage (1963) point out "that there is some evidence that a bedrock shelf may exist on the right (southeast) edge of the glacier . . . ; the seismic evidence, however, is not sufficient to establish its existence. Such a shelf has been indicated by the resistivity surveys of Keller and Frischknecht (1961) but not by the gravity surveys of Kanasewich (1963)". We will assume therefore that the drilling, seismic and gravity results are the most definitive.

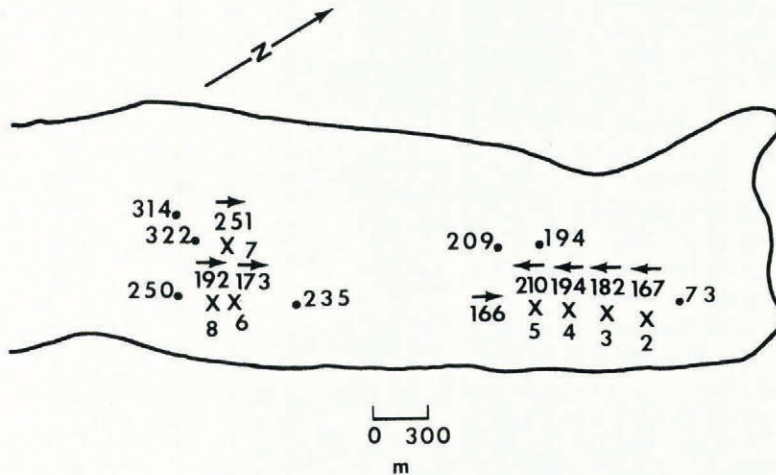


Fig. 3. Map of Athabasca Glacier showing locations of drill holes and radio-interferometry transmitter sites.

- 252 Station 9, depth 252 m, traversing down-glacier (north).
- x 9 Drill-hole, depth 112 m.
- 112

Watt and Maxwell (1960) measured the electrical properties of the glacier ice *in situ* on the Athabasca Glacier using frequencies from 20 Hz to 100 kHz. At the high-frequency limit they showed that the ice had a dielectric constant of about 3.2. This value is typical for pure ice, and in general the value is frequency and temperature independent from 100 kHz to 1 000 MHz (Evans, 1965; Gudmandsen, 1971). Also the depths of glacier ice as measured by radar-sounding field studies agree well with drilling results, if a dielectric constant of 3.2 is assumed (Gudmandsen, 1971).

The loss tangent of ice is controlled in this frequency range by the tail of the well-known relaxation which occurs in the audio-frequency range. In the range of our experiment (1–32 MHz) the loss tangent is inversely proportional to frequency  $f$ , so that  $(f \tan \delta)$  is nearly a

constant (Evans, 1965; Gudmandsen, 1971). However, this constant is strongly dependent on temperature; its value is about 0.30 at 0° C, a typical temperature for a temperate glacier, and about 0.10 at -20° C, a typical temperature for polar ice sheets (where  $f$  is in MHz). These values correspond to attenuation rates of 0.048 dB/m at 0° C and 0.016 dB/m at -20° C. This latter value is similar to the values estimated by Gudmandsen for the Greenland ice sheet.

The attenuation distance of electromagnetic energy in a dielectric is:

$$\frac{c}{\pi f \epsilon^{\frac{1}{2}} \tan \delta}$$

where  $\epsilon$  is the dielectric constant and  $c$  the velocity of light in vacuum.

The interferometry technique requires waves which are of similar amplitude. If a wave reflected from the glacier bottom is minute in comparison to the other waves, then it is unobservable. Increasing the power of the transmitter is of no benefit, for the relative power of the waves remains unaltered. The attenuation of waves in the ice consequently limits the detection of the bottom reflector to depths of a few hundred meters in temperate glaciers and a kilometer or two in polar ice sheets. Because  $f \tan \delta$  is nearly constant, the depth penetration is not frequency-dependent; rather it is temperature dependent.

#### GLACIER DATA

Data were collected at seven major sites on the glacier (stations 2-8 on Fig. 3). Interpretation was based on data from the transmitting antenna normal to the traverse line. Both radial ( $H_{\rho}^B$ ) and vertical ( $H_z^B$ ) components were examined (Fig. 1b). The tangential component ( $H_{\phi}^B$ ) would be zero if no lateral reflections were received. The true amplitude of this component is indicative of departures from these ideal conditions. The components from the antenna parallel to the traverse line ( $H_{\rho}^E$ ,  $H_{\phi}^E$ ,  $H_z^E$ , Fig. 1b) were also recorded but were not specifically used in the interpretation. More sophisticated future interpretations will probably use all the data.

Figure 4 shows the  $H_{\rho}^B$  and  $H_z^B$  components from one traverse (Run 26). Figure 5 illustrates the process of interpreting a profile for one component. A set of theoretical master curves is compared with the data. Our best fit in this case is for the dielectric constant of 3.3, loss tangent of 0.09, and depth of 2.425 wavelengths (182 m); a perfectly reflecting bottom is assumed.

Such an interpretation is not always unambiguous. There may be several different combinations of parameters which appear to fit the data equally well. In such cases the redundancy of several components and several frequencies comes into play. The criterion of consistency is applied to select the correct determination from the various possibilities.

The most consistent set of interpretations for Run 26 is tabulated in Table I. There is somewhat greater error in the interpreted depths for the low frequencies (1 and 2 MHz) because the curves have fewer features and generally less definitive character. It should be noted that the depth estimate discrepancy between curves exceeds the error of the individual depth estimates (Table II). This is probably because of the non-ideal glacier geometry; the non-planar and non-parallel bottom affects the various profiles in different ways.

If there is a single great difficulty in the interpretation of interferometry data, it is the sensitivity of curve shape to small changes in geometrical and electrical parameters. It is this sensitivity which causes the error estimate for the interpretation of a single profile to be small, while the inconsistency between curves may indicate considerably higher error. Present studies are aimed at finding ways to pre-process the data to reduce their sensitivity to small parameter changes.

At 8 MHz the field curves contain many more fluctuations than the theoretical curves. This is an indication of the influence of inhomogeneities within the glacier or of the surface roughness. Scatterers considerably smaller than a wavelength will influence wave propagation very little, while those exceeding a wavelength in size will modify the fields considerably. The appearance of wavelength-size disturbances at 8 MHz ( $\lambda = 37.5$  m) indicates that internal inhomogeneities in the Athabasca Glacier are seldom larger than several tens of meters. The strong disturbance in all Athabasca data at 16 and 32 MHz ( $\lambda = 18.7$  m and 9.4 m) indicates that scatterers of this size or less are common throughout the glacier.

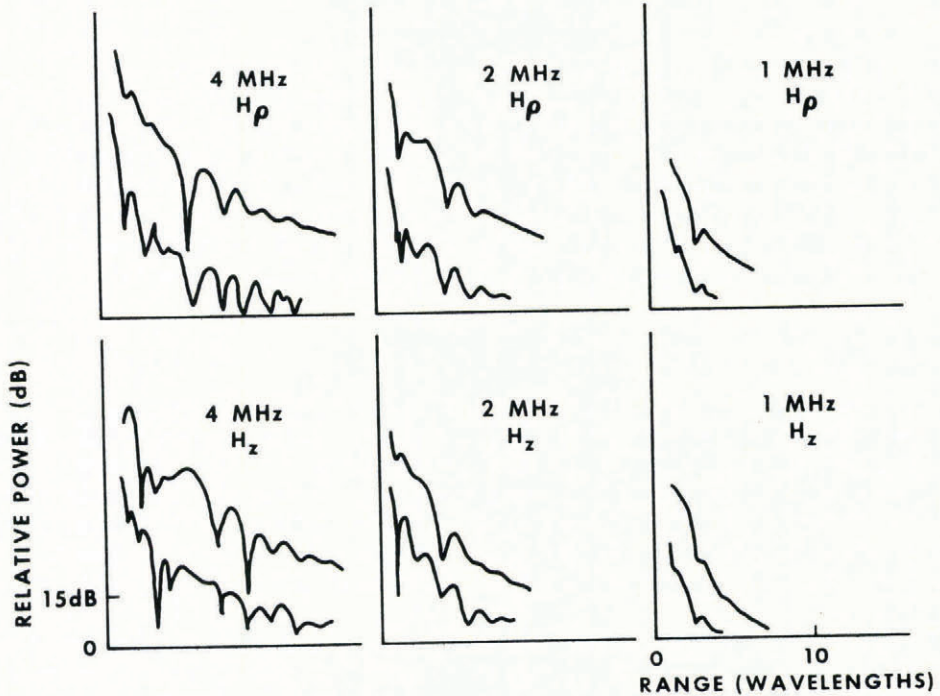


Fig. 4. Typical set of data for maximum-amplitude components  $H_\rho^B$  and  $H_z^B$  from the broadside antenna. Frequencies 1, 2 and 4 MHz are shown. Upper curves are theoretical curves for the parameters given in Table I [Run 26].

TABLE I. INTERPRETATION OF  $H_\rho^B$  AND  $H_z^B$  DATA. SITE 3S: RUN 26  
Dielectric constant for all fits = 3.3

Frequency MHz	Component	Loss tangent	Depth $\lambda$	Depth m
1	$H_\rho$	0.26	0.65	195
1	$H_z$	0.26	0.55	165
2	$H_\rho$	0.14	1.3	195
2	$H_z$	0.15	1.175	176
4	$H_\rho$	0.09	2.425	182
4	$H_z$	0.09	2.425	182
			Average	182 m

TABLE II. PRECISION OF INDIVIDUAL FIT

	1 MHz	2 MHz	4 MHz
Dielectric constant	$\pm 0.02$	$\pm 0.1$	$\pm 0.1$
Loss tangent	$\pm 0.01$	$\pm 0.01$	$\pm 0.005$
Depth m	$\pm 8$	$\pm 8$	$\pm 4$

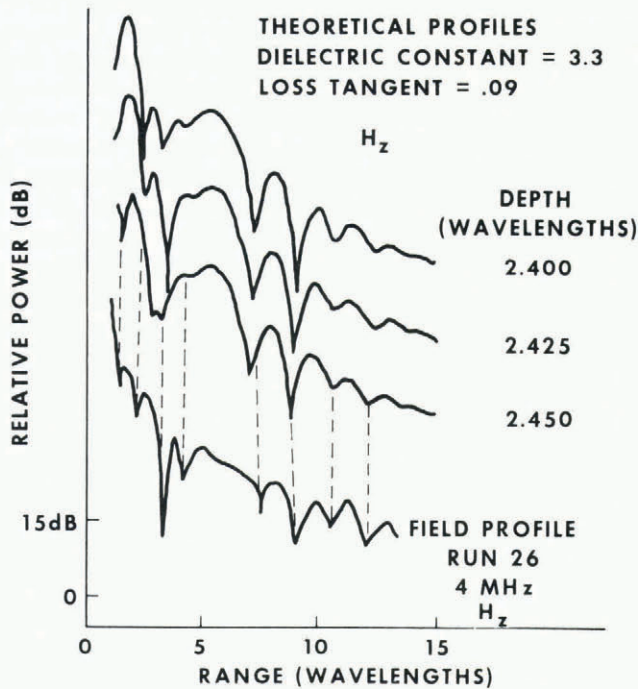


Fig. 5. Typical set of data at 4 MHz for the  $H_z^B$  component, with theoretical curves for three different depths. The theoretical curves are offset for clarity of presentation. The best fit is at 2.425 wavelengths (182 m) [Run 26].

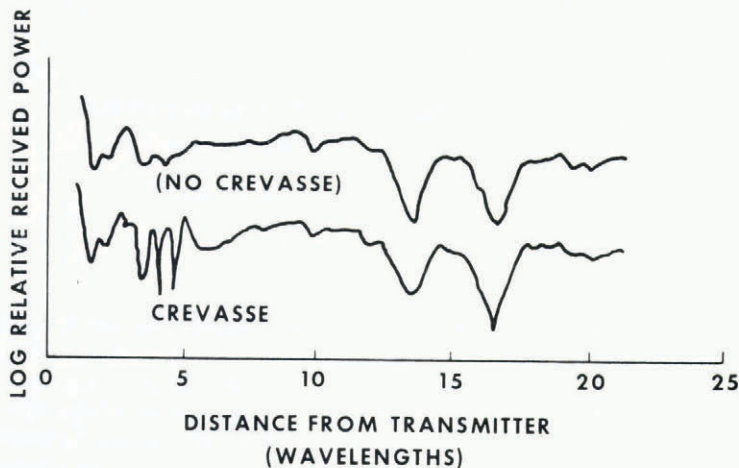


Fig. 6. Interference curve from crevasse in scale model. When scaled to 8 MHz, crevasse is  $30\text{ m} \times 30\text{ m} \times 3\text{ m}$  in size, 5 wavelengths from the transmitter. High interference frequency is apparent on the transmitter side of the crevasse and slight field-strength diminution on the opposite side.

## MODEL RESULTS

One particular type of scatterer has been investigated using a high-frequency analog scale model. The modeling medium was dielectric oil with a dielectric constant of 2.2 and loss tangent of 0.002. Because these properties differ somewhat from those of ice, the results must be taken as qualitative indications only. The modeling wavelength was  $\approx 5$  cm.

A crevasse was simulated with a styrofoam wedge (Fig. 6) (the dielectric constant of low-density styrofoam is approximately 1). The field-strength profile shows a high-frequency interference on the side of the crevasse nearer to the transmitter, and a minor diminution of field strength on the far side. Similar features are present on the curve from field data shown in Figure 7, although positive identification of the particular crevasse responsible for this pattern was not made in the field.

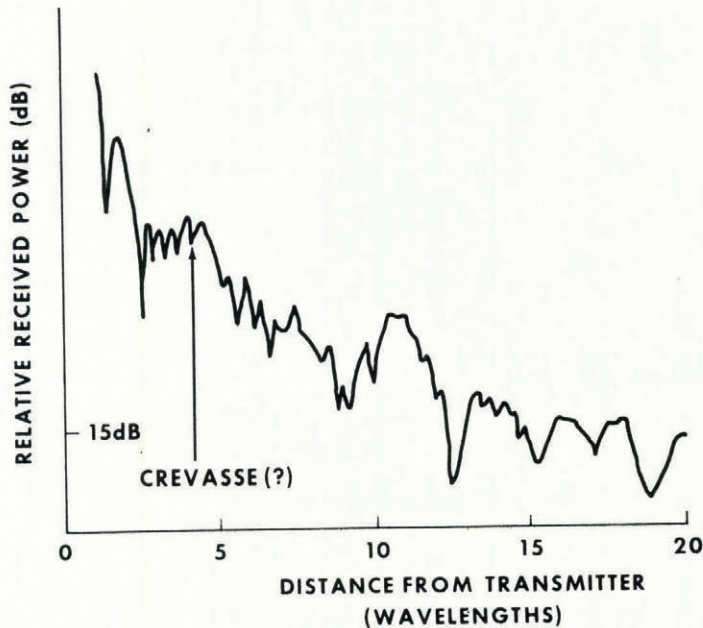


Fig. 7. Possible location of crevasse in field data.

## DISCUSSION

The best fits to all data were obtained for dielectric constant values of  $3.3 \pm 0.1$ . The loss tangents for the best-fit curves were from 0.18 to 0.26 at 1 MHz, 0.11 to 0.18 at 2 MHz, and 0.06 to 0.12 at 4 MHz. The mean value for  $f \tan \delta$  is approximately 0.3.

Depth determinations have been made using the average values of the most consistent set of fits at the various stations. These are tabulated in Table III and are located on the map of Figure 3. Except for stations 6 and 8, deeper depth determinations are obtained at stations higher on the glacier. Stations 3, 4 and 5 show particularly consistent results in comparison to drilling information. The apparently high depth gradient between station 2 and a nearby drill hole (depth 73 m) may be real, a result of extensions of the bedrock topography currently being exposed at the retreating terminus.



TABLE III. DEPTH DETERMINATIONS  
(AVERAGE 1, 2, 4 MHz.  $H_p$  AND  $H_z$ )

Site	Direction of traverse	Depth m
2	S	167
3	S	182
4	S	194
5	S	210
5	N	166
6	N	173
7	N	251
8	N	192

The interferometric depth determination at station 7 is not entirely inconsistent with drilling results, although the indicated depth is probably too shallow. This determination was fairly ambiguous because reflections from the bottom are weak in such deep ice. A further complication was the short traverse length imposed by rough surface conditions.

The most inconsistent results occurred at stations 6 and 8. These stations were near the side of the glacier, so observed reflections might not have come from directly below the traverse line. A hanging tributary glacier enters Athabasca Glacier a short distance above these stations; morainal material within the glacier may therefore have adversely affected the observations.

#### CONCLUSIONS

Radio interferometry appears to give reasonable estimates of glacier depth under favorable conditions. Erroneous estimates can be obtained when internal structure affects the observations and possibly when the bottom slopes too much relative to the surface. The limit of detectability of the bottom is about 300 m in temperate glaciers.

At the same time, the radio interferometry method gives an *in situ* measurement of both the dielectric constant and the loss tangent of the glacier ice. Hence there is no need to assume a dielectric constant in order to obtain a depth estimate, as is required by radar reflection techniques.

Scattering signatures in the curves may indicate the position (and possibly the orientation, if profiles are made in several directions) of crevasses or other near-surface scatterers. This detection is probably possible through many meters of snow cover, although it was only tested on bare ice in the ablation zone of the Athabasca Glacier.

As a field technique, radio interferometry is fast and simple. It requires an instrumented vehicle, but data collection is rapid if the glacier surface allows for easy driving. Operation on snow-covered portions of a glacier is probably easier than on the rough ice surface of the ablation zone.

Interpretation is fairly rapid. Collections of theoretical curves with appropriate parameters can be made up before the field trip. Daily comparison of the field data with these curves allows constant monitoring of results. Sophisticated analysis and processing must, of course, wait until a computer is available.

Methods are being investigated for making the data less sensitive to small variations of parameters. This will require computer processing of the data. Current theory is being extended to investigate the effects of sloping bottoms and other more complex geometries. The ultimate aim of the data analysis program is to use the full complement of redundant data to minimize the ambiguity of interpretation.

## ACKNOWLEDGEMENTS

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## REFERENCES

- Annan, A. P. 1973. Radio interferometry depth sounding: part I—theoretical discussion. *Geophysics*, Vol. 38, No. 3, p. 557–80.
- Evans, S. 1965. Dielectric properties of ice and snow—a review. *Journal of Glaciology*, Vol. 5, No. 42, p. 773–92.
- Gudmandsen, P. 1971. Electromagnetic probing of ice. (In Bahar, E., and others. *Electromagnetic probing in geophysics*. Boulder, Golem Press, p. 321–48.)
- Kanascwiche, E. R. 1963. Gravity measurements on the Athabasca Glacier, Alberta, Canada. *Journal of Glaciology*, Vol. 4, No. 35, p. 617–31.
- Keller, G. V., and Frischknecht, F. C. 1961. Induction and galvanic resistivity studies on the Athabasca Glacier, Alberta, Canada. (In Raasch, G. O., ed. *Geology of the Arctic. Proceedings of the first international symposium on Arctic geology, held in Calgary, Alberta, January 11–13, 1960*. Toronto, University of Toronto Press, Vol. 2, p. 809–32.)
- Paterson, W. S. B., and Savage, J. C. 1963. Geometry and movement of the Athabasca Glacier. *Journal of Geophysical Research*, Vol. 68, No. 15, p. 4513–20.
- Rossiter, J. R., and others. 1973. Radio interferometry depth sounding: part II—experimental results, by J. R. Rossiter, G. A. LaTorraca, A. P. Annan, D. W. Strangway and G. Simmons. *Geophysics*, Vol. 38, No. 3, p. 581–99.
- Simmons, G., and others. 1972. The Surface Electrical Properties Experiment, by G. Simmons, D. W. Strangway, L. Bannister, R. Baker, D. Cubley, G. LaTorraca and R. Watts. (In Kopal, Z., and Strangway, D. W., ed. *Lunar geophysics. Proceedings of a conference at the Lunar Science Institute, Houston, Texas, 18–21 October 1971*. Dordrecht, D. Reidel, p. 258–71.)
- Watt, A. D., and Maxwell, E. L. 1960. Measured electrical properties of snow and glacial ice. *Journal of Research of the National Bureau of Standards* (Washington, D.C.), Sect. D, Vol. 64, No. 4, p. 357–63.