RADIO-ECHO SOUNDING OF TEMPERATE GLACIERS: ICE PROPERTIES AND SOUNDER DESIGN CRITERIA*

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Abstract. This is the first paper in a two-part series which describes the design, operation, and testing of a successful 5 MHz radio-echo sounder for temperate glaciers. This part deals with the electromagnetic characteristics of temperate glaciers at radio frequencies. Earlier workers' problems in sounding through temperate ice are explained in terms of electromagnetic scattering by water-filled voids. The frequency dependence of the scattering indicates that returns from scatterers diminish rapidly at frequencies below about 10 MHz. A system with the following characteristics is recommended: a transmitted pulse with a center frequency of about 5 MHz, duration of about 1 cycle, and a receiver which is untuned and which measures field intensity rather than power. Spectral methods for studying the size distribution of scatterers are presented. An actual instrument and field trials will be described in a forthcoming publication by R. S. Vickers and R. Bollen.

Résumé. *Sondages par écho-radio dans les glaciers tempérés: propriétés de la glace et critères pour la construction des appareils de sondage.* Ceci est la première partie d'une série en deux articles qui décrit l'appareillage, la mise en oeuvre et le contrôle d'un appareil efficace à 5 MHz de sondage par radio-écho pour des glaciers tempérés. Cette partie traite des caractéristiques électromagnétiques des glaciers tempérés aux fréquences radio. Les problèmes rencontrés par les précédents chercheurs pour les sondages dans la glace tempérée s'expliquent par la dispersion électromagnétique dans les cavités remplies d'eau. L'influence de la fréquence sur la dispersion indique que le rayonnement renvoyé par les disperseurs diminue rapidement aux fréquences inférieures à environ 10 MHz. On recommande un appareillage ayant les caractéristiques suivantes: une impulsion transmise avec une fréquence centrale d'environ 5 MHz pendant environ un cycle, avec un récepteur qui est désaccordé et mesure l'intensité du champ, plutôt que la puissance. On présente des méthodes spectrométriques pour étudier la distribution en dimension des disperseurs. Un instrument réellement construit et des essais sur le terrain seront décrits en deuxième partie par R. S. Vickers et R. Bollen.

Zusammenfassung. *Radar-Echolotung temperierter Gletscher: Eiseigenschaften und Kriterien für den Bau des Lotgerätes.* Es handelt sich hier um den ersten Teil einer zweiteiligen Veröffentlichungsfolge, die den Bau, den Einsatz und die Erprobung eines brauchbaren 5 MHz-Radar-Echolotes für temperierte Gletscher beschreibt. Dieser Teil behandelt die elektromagnetischen Charakteristiken temperierten Eises im Radio-wellenbereich. Die Schwierigkeiten, mit denen frühere Forscher bei der Auslotung temperierten Eises zu kämpfen hatten, werden durch die elektromagnetische Streuung an wassergefüllten Hohlräumen erklärt. Die Frequenzabhängigkeit der Streuung lässt erwarten, dass Echos von Streuern rasch bei Frequenzen unter etwa 10 MHz abnehmen. Es wird ein System mit folgenden Kenngrössen empfohlen: Sendepulse mit einer Zentralfrequenz von etwa 5 MHz, Dauer etwa 1 Umlauf, Empfänger nicht abgestimmt, eher die Intensität als die Stärke des Feldes messend. Spektrale Methoden zum Studium der Grössenverteilung von Streuern werden angegeben. Ein ausgeführtes Gerät und Feldarbeiten werden in Teil II von R. S. Vickers und R. Bollen beschrieben werden.

Introduction

Of all the Earth's geological materials, the most favorable to probing by electromagnetic methods is glacier ice. Electrically, it is extremely resistive and comparatively homogeneous. Electromagnetic fields propagate through ice as waves, rather than by diffusion as in rocks. The utility of these properties has been spectacularly demonstrated by the soundings of the polar ice sheets through several kilometres of ice.

However, departures from the nearly homogeneous ice encountered in the polar regions have, until now, thwarted efforts to radio-sound temperate glaciers. Not only is the ice warmer in temperate glaciers, and therefore electromagnetically less transparent, but it is significantly less homogeneous. It is this latter factor which has kept temperate glacier soundings from being successful.

The importance of inhomogeneities (scatterers) within the ice was recognized by Smith and Evans (1972), who wrote that "the most important requirement [is]: to obtain first of all an unambiguous bottom echo, however poor in resolution, and to gain an understanding of

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those properties of the medium of propagation which are important in temperate glaciers". In discussing their model of ice-lens scatterers in firn, they recognized that returns from scatterers could obscure bottom returns: "[there are] two crucial factors in signal to scatter ratio: radio wavelength and effective [scatterer] radius. This is a new situation in which increased system performance will do nothing to improve the [signal-to-noise] ratio". However, their calculations were not altogether appropriate to scatterers within the bulk of glacier ice, and their suggestion was to use higher frequencies. We will demonstrate that the way to obtain an unambiguous bottom echo is to reduce the frequency. The attendant loss of resolution can be largely circumvented by using very short pulses (one or two cycles of the center or carrier frequency) and an untuned receiver which records the received electric field as a function of time rather than the received power or rectified and smoothed electric field at a single frequency as a function of time.

Before we discuss the effects of scatterers in detail, let us mention the experimental evidence of their importance. Smith and Evans (1972, fig. 9) showed two instances where bottom returns were obscured by scatter returns at depths of 100 to 150 m. More examples are shown by Davis (unpublished, p. 53–55). These serve as demonstrations that the problem exists— even in polar ice. An indication of the solution to the problem was provided by Strangway and others (1974). Their experiments on the Athabasca Glacier in Alberta, Canada, were done using continuous waves transmitted from horizontal electric dipoles on the ice surface. When their receiver was traversing away from the end of one of their transmitting antennas, the radial and vertical magnetic fields should have been weak, and the tangential field strong, if the ice was homogeneous and if the structure was horizontally layered. This expectation is derived from the symmetry of electromagnetic fields radiated from dipoles lying on layered structures. They found that the theoretical predictions worked well at 1, 2, and 4 MHz. At 8 MHz, however, the theoretically weak components were nearly as large as the theoretically strong ones. At 16 and 32 MHz all components were equally strong.

The depolarization of the waves—transferral of energy from predicted strong polarizations to predicted weak ones—can be attributed to (1) departures from layered geometry, and (2) departures from homogeneity. Departures from layered geometry can occur at the top or the bottom of the glacier. The effect of the bottom can be ruled out because (a) the effects of its irregularities should not be strongly frequency dependent, and (b) the depolarization effect was observed very close to the transmitter, where echo strength from the glacier bottom is negligible in comparison to the energy of waves traveling through the air and through the ice just beneath the surface. The effect of the rough glacier surface is not so easy to dismiss. However, the absence of such strong depolarization in a similar experiment carried out on the moon (Simmons and others, 1973), where the surface is nearly as rough as that of the Athabasca Glacier, indicates that surface roughness probably is not responsible for much of the depolarization. The only explanation left is inhomogeneities (scatterers) in the ice.

SCATTERING THEORY

In order to test hypotheses concerning the nature of scatterers within the ice, we need a theory which will predict the effect of scatterers on the radio signals. Smith and Evans (1972) presented a theory based on formulae for Rayleigh scatterers. Davis (unpublished) gave a modified theory which handles more general types of scatterers. The derivation given here follows Davis's derivation closely.

Smith and Evans's theory shows that the most serious effect of scatterers is not the attenuation of the signal, but rather the masking of the bottom return by the diffuse return from a multitude of scatterers. The attenuation problem can be attacked by increasing transmitter power and receiver sensitivity (system performance); the scatter-return problem can be solved only by varying frequency, pulse duration, or antenna gain.
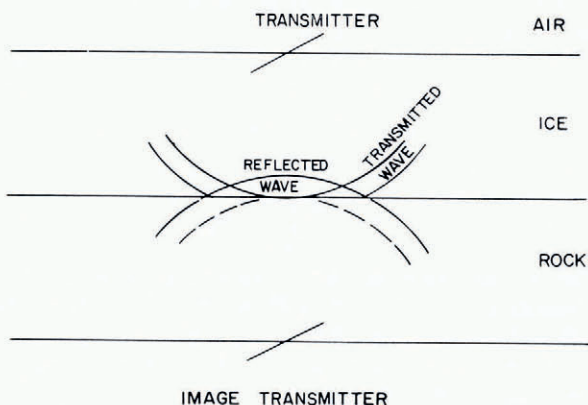
Fig. 1. *Diagram showing relative positions of transmitter, imaginary image transmitter, and ice–air and ice–bedrock interfaces. The image transmitter is a concept used in calculating the power reflected from the rock surface.*

We assume that the bottom of the ice sheet is a plane reflector with normal-incidence power reflection coefficient R. The reflection from this plane is the same as the transmission from an upward-directed transmitter at twice the depth of the planar reflector, in ice (Fig. 1). The power of this image transmitter is a factor of R less than the power of the actual transmitter. Otherwise the two are identical. At the receiver, the wave intensity of the signal I_p reflected from the bottom (or coming from the image transmitter) is

$$I_p = \frac{P_t R g_0}{4\pi(2r)^2} \tag{1}$$

where P_t is the transmitter-radiated power, g_0 the antenna gain looking down, and r the ice-sheet thickness.

The receiving antenna is steered toward this reflection, so the power it senses is

$$P_p A g_0 I_p = \frac{A P_t R g_0^2}{16\pi r^2} \tag{2}$$

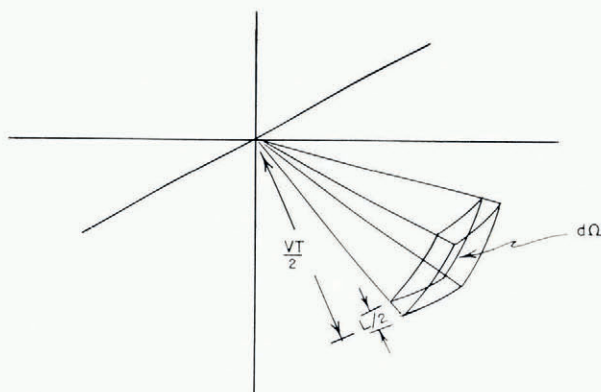where A is the monopole capture area, $\lambda^2/4\pi$.

Fig. 2. *Diagram showing an angular element of the spherical shell which generates the scatter returns at time t. v = radio-wave velocity in ice; l = physical pulse length in ice; $d\Omega$ = element of solid angle.*

As explained by Smith and Evans, the received power at time t after transmission is derived from a shell of thickness $l/2$ and radius $vt/2$, where l is the pulse length in ice, v is the wave velocity, and t is the time after transmission. At any particular direction Ω (which is a composite of azimuth and depression angles), the intensity of illumination I_i of the scatterers is

$$I_i = P_t g(\Omega)/4\pi(vt/2)^2. \tag{3}$$

The number of scatterers in the volume element (Fig. 2) is

$$N = \frac{ml}{2}\left(\frac{vt}{2}\right)^2 d\Omega \tag{4}$$

where m is the number of scatterers per unit volume. Each scatterer has scattering cross-section σ. The total energy scattered by the inhomogeneities in the volume element is $I_i N\sigma$. This energy is not scattered isotropically. When the backscatter gain g_{bs} and the geometrical spreading from each scattering center are accounted for, the wave-intensity I_s at the receiver, due to scatterers in one volume element, is

$$I_s(\Omega) = I_i N\sigma g_{bs}/4\pi(vt/2)^2. \tag{5}$$

$Ag(\Omega)$ is the antenna's capture area for waves from the direction of the volume element we are considering. The power P_s sensed in the receiver due to scatterers in that volume element is

$$P_s(\Omega) = Ag(\Omega)I_s(\Omega) = \frac{AP_t ml\sigma g_{bs}}{8\pi^2 v^2 t^2} g^2(\Omega) d\Omega. \tag{6}$$

We now compute the entire return by summing over Ω, the totality of solid angles:

$$P_s = \frac{AP_t ml\sigma g_{bs}}{8\pi^2 v^2 t^2} \int g^2(\Omega) d\Omega. \tag{7}$$

For any antenna, the integral of g over Ω must equal 4π for radiated energy to be conserved. The integral of g^2 over Ω, however, is a measure of antenna directionality. We will denote the integral on the right side of Equation (7) by $4\pi G$. For a monopole, $G = 1$.

As an example, the gain of an infinitesimal dipole is $g(\theta) = (\frac{3}{2})\sin^2\theta$, where θ is the angle from the axis of the dipole.

Integration of this over all solid angles gives

$$\int_0^\pi \int_0^{2\pi} \tfrac{3}{2} \sin^2\theta \, d\phi \sin\theta \, d\theta = 4\pi. \tag{8}$$

The directionality factor G is

$$G = \frac{1}{4\pi}\int_0^\pi \int_0^{2\pi} \frac{9}{4}\sin^4\theta \, d\phi \sin\theta \, d\theta = \frac{6}{5} = 1.2. \tag{9}$$

In order to compare the plane reflection to the scattered reflection, we will let $vt/2 = r$ in Equation (7).

$$P_s = \frac{AP_t ml\sigma g_{bs}}{8\pi r^2} G. \tag{10}$$

The signal-to-noise ratio (assuming we want to see the bottom, not the scatterers), is

$$\frac{P_p}{P_s} = \frac{Rg_0^2}{2ml\sigma g_{bs}G}. \tag{11}$$

For our previous example of a dipole antenna, the factor g_0^2/G is 1.9. More directional antennas will increase this factor somewhat.

Smith and Evans (1972, equation (20)) found that the signal-to-noise ratio was proportional to g_0 rather than our g_0^2/G. This result was based on the following assumptions: (1) the effective scattering volume is proportional to $1/g_0$, (2) the illumination of this effective volume is proportional to g_0, and (3) the receiver sensitivity to reflections from this volume is g_0. The total result is a scattering effect proportional to g_0, while the planar reflection is proportional to g_0^2, as we have shown. Smith and Evans's analysis is correct only in cases where the reduction in antenna beam width is proportional to maximum gain, so that G is proportional to g_0. For best performance, the antenna should be designed so that $g_{max}^2/\int g^2(\Omega)\,d\Omega$ is a maximum. This criterion is similar to a maximum directionality criterion for an antenna which only receives, but g is replaced by g^2 because the same (or a similar and approximately coincident) antenna is used for both transmitting and receiving.

Equation (11) was derived giving no consideration to either dielectric or scattering attenuation. We point out here, as Smith and Evans did, that the path length is the same for the bottom return and the scatter returns which arrive at the same time. The attenuation factor enters equally into the numerator and denominator of Equation (11), which is therefore equally valid for absorbing and non-absorbing media.

It may also be useful to take special note of the time-dependent form of the scatter returns, as given in Equation (7). Scatter-return power should be proportional to t^{-2}, or scatter-return amplitude to t^{-1}. This time dependence is one criterion for testing the theory. Davis (unpublished) shows how an additional factor of $\exp(-\alpha t)$ may be present owing to attenuation and scattering in the ice.

THE SCATTERERS

We herein hypothesize that the scatter returns in temperate glaciers are due to water-filled voids in the ice, and that this type of scatterer reasonably explains the available observations.

In a hot-point drilling program on the South Cascade Glacier, in north-west Washington State, S. M. Hodge (personal communication in 1974) has observed sudden drops of the hot-point drill of distances from a few tens of centimetres to a metre. These sudden drops seem to indicate a lack of mechanical and thermal resistance which can be explained only by the presence of voids. Because these voids are approximately uniformly distributed with depth (maximum depth = 200 m), they must be water-filled to endure the pressure. One void is encountered approximately every 400 m of drilling (i.e. in roughly half of the holes). These values are preliminary; there are not yet enough holes to have developed reliable statistical characterizations of the void encounters. There is no information available on the shape of the voids other than their vertical extent.

In order to estimate the number of scatterers per unit volume, we need to guess the shape of the voids. Our shape model will be a sphere—a choice dictated by the theoretical tractability of spherical or ellipsoidal scattering, and there being no basis for selecting any particular shape or orientation of ellipsoids.

A simple probability calculation allows us to determine the scatterer density and the volume fraction occupied by the scatterers. We assume that the voids are spherical with radius a and that there are m of them per unit volume. The horizontal cross-section of a scatterer is πa^2. We consider a surface area A on the glacier, and glacier depth D. The volume is AD and the number of scatterers is mAD. The projections of these scatterers onto the surface of the glacier cover an area $mAD\pi a^2$. Overlapping projections are all counted, for the drill would penetrate the corresponding voids and they would all thereby be counted during the drilling. The expected number of voids to be encountered in drilling a hole of depth D is the ratio of void projection area to surface area, which is $mD\pi a^2$. We therefore have

$$m = \frac{N(D)}{D\pi a^2} \tag{12}$$

where $N(D)$ is the average number of voids encountered in holes of depth D. Hodge has observed $N(200) \approx \frac{1}{2}$, so

$$m \approx \frac{1}{400\pi a^2}.$$ (13)

If the radius of the sphere is 1.0 m, then $m = 0.000\,8$ scattering centers/m³. The volume fraction occupied by the scatterers is

$$v = \frac{4}{3}\pi a^3 m = \frac{4}{3}a\frac{N(D)}{D}.$$ (14)

In our case this is

$$v \approx 0.003.$$ (15)

These numbers are all quite approximate.

In studying the effects of these water-filled voids as scatterers, we have assumed that they are spherical. Thus we have been able to apply Mie scattering theory, as described by Stratton (1941, p. 563). This is an exact theory based on the expansion of the incident plane wave (a good approximation to the spherical wave except very near the transmitter) and the scattered waves in spherical harmonic series. Rayleigh scattering is a special case of Mie scattering, applicable at frequencies where the scatterer is much smaller than a wavelength.

In Figures 3 and 4 we have plotted the Mie scattering cross-section and the cross-section multiplied by back-scatter gain, respectively, for water-filled spheres in ice. These are given in dimensionless terms, but the abscissa is proportional to frequency. Note the generally greater variability in Figure 4. This is due to the directionality of the scattering outside the Rayleigh-scattering (low-frequency) region.

Let us first locate ourselves on these plots for 1 m diameter spheres. The appropriate λ is that for ice, which is $(168\text{ m MHz})/f$, where f is the frequency. It is clear that scattering is "efficient" for radii exceeding $0.1\,\lambda$, or $(16.8\text{ m MHz})/f$. For this to equal the 1.0 m radius of our spheres, the frequency is about 17 MHz. All that we have learned so far is that below 17 MHz we should start to see rapidly diminishing effects from scattering. The important question is how badly obscured the bottom return is at 17 MHz; the answer to that question will determine how much the frequency needs to be reduced to bring out the desired reflection.
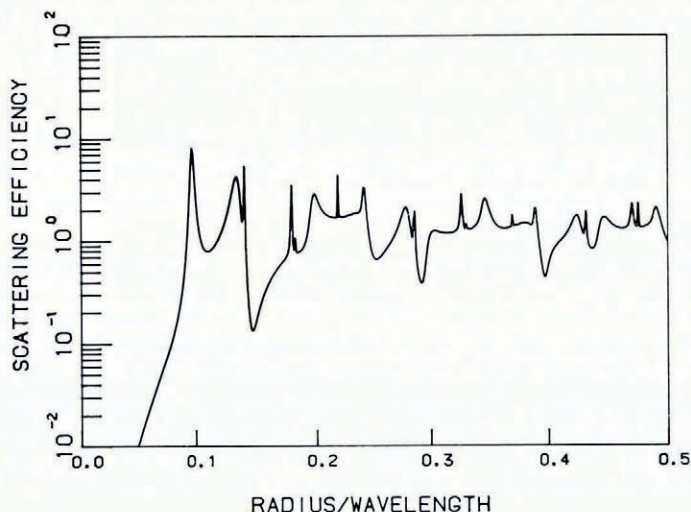

Fig. 3. *Total scattering efficiency (ratio of scattering cross-section to physical cross-section) for spherical Mie scatterers (Stratton, 1941), as function of size or frequency.*
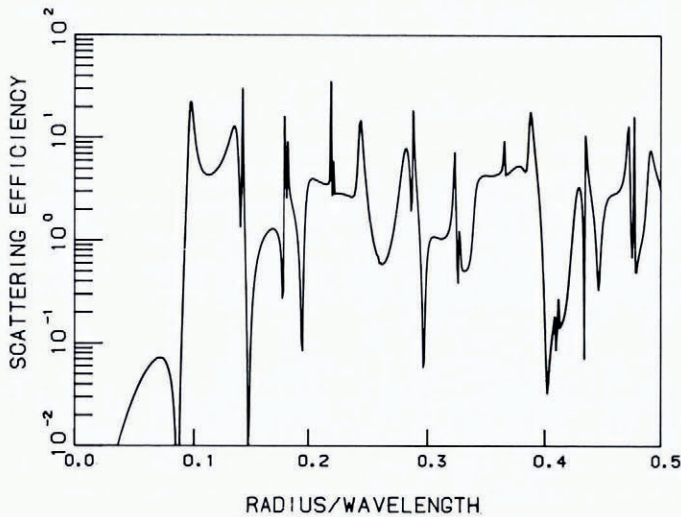
Fig. 4. Back-scatter efficiency as function of size or frequency. This takes the directionality of the scattering into account.

Using the same parameters as Smith and Evans, which are appropriate for the SPRI Mark II system, we can calculate the signal-to-noise ratio using Equation (11). These are: $R = 0.01$, $g = 2$, $l = 40$ m. We will assume $G \approx 2$. We use m from drilling results, $m = 0.000\ 8$. The center frequency is 35 MHz. This is roughly twice the 17 MHz critical scattering frequency, so $\sigma g_{bs} \approx \pi a^2 \approx \pi$. We now have

$$\frac{P_p}{P_s} = 0.1 = -10 \text{ dB}. \tag{16}$$

Equation (16) indicates that the bottom reflection is hopelessly lost in the scatter returns. If all other parameters could be kept the same, and only the carrier frequency changed, Figure 4 shows that f would have to be reduced to 15 MHz to achieve a signal-to-noise ratio of 1, and to 10 MHz to achieve a ratio of 10. In actuality, of course, the pulse length increases as frequency decreases unless a radically different engineering approach is taken. Pulse lengthening would make the 10 MHz signal-to-noise ratio about $+7$ dB instead of $+10$ dB.

These results seem to be at odds with the experimental results of Strangway and others (1974). Their continuous-wave experiment indicated that scattering was strong at frequencies as low as 8 MHz. We will demonstrate that these observations can be explained by assuming a distribution of scattering sizes rather than a single size. It might be noted that the discrepancy could be explained in terms of differences between the glaciers (South Cascade and Athabasca), but that a distribution hypothesis explains the observations without resorting to inter-glacier differences.

Let us initially assume that we have only two sizes of spherical scatterers, with radii 100 cm and 200 cm. In the Rayleigh region for those scatterers ($f < 8$ MHz), the scattering efficiency is proportional to the fourth power of radius. When this is multiplied by the physical cross-section πa^2, the absolute scattering cross-section for each scatterer is found to be proportional to a^6. Thus each 200 cm sphere scatters 64 times as much energy as each 100 cm sphere: if there are $\frac{1}{64}$ as many 200 cm spheres as 100 cm spheres, the two populations will have equal scattering effect.

In glacier drilling, however, the probability of encountering the 200 cm voids is quite small. The probability is proportional to the product of number of scatterers times cross-sectional area, so for our postulated population,

$$\frac{Pr(100)}{Pr(200)} = \frac{64(100)^2}{1(200)^2} = 16. \tag{17}$$

The drill would encounter 16 times as many 100 cm voids as 200 cm voids, but the radio-echo sounder is equally affected by both sizes. We conclude, therefore, that the most common sizes encountered in drilling might not be the most important to the radio-echo sounder.

We will now develop an expression for total scattering cross-section in the presence of a distribution of scatterer sizes. If the density of scatterers having sizes (radii) between a and $a+da$ is $m(a)\,da$, then the total scattering cross-section is

$$\sigma_T(f) = \int_0^\infty m(a)\sigma(a,f)\,da. \tag{18}$$

This integral has been computed numerically for back-scatter cross-section (from Fig. 4) for normal distributions of scatterers. Figure 5a shows back-scatter power as a function of frequency for scatterer distributions with maxima at 1.0 m and various widths (standard deviations). Figure 5b shows the same function for distributions centered at 0.5 m.

It is quite clear from Figure 5 that a Gaussian distribution of scatterer radii with a mean radius of about 1.0 m and a standard deviation of 0.2 to 0.4 m explains the scattering observations of Strangway and others (1974). Scattering is uniformly strong at frequencies of 16 MHz and higher, intermediate at 8 MHz, and weak at 4 MHz and below. Our explanation has been based on a theory which predicts only the relative dependence on frequency. This is necessary because the continuous-wave nature of Strangway's experiment would require an integration of scattering effects over the entire glacier volume—an integration which is of a complexity beyond the scope of this paper.

In our formulation using Mie theory, we computed the scattered energy at large distances from the scatterers. In a continuous-wave experiment like that of Strangway and others (1974), energy is received continuously from throughout the glacier. The receiver may be quite close to one or more scatterers. The scattered waves are expandable in spherical harmonics which correspond to radiation from dipoles, quadrupoles, etc. There are dipole terms which are proportional to f and f^3 in addition to the far-field f^4 terms we have considered (Stratton, 1941, p. 436). The wave amplitude from these terms diminishes rapidly with distance, but the receiver in a continuous-wave experiment could be sufficiently close for them to be important. The roll-off of scattering effects would then be much less sharp than for the far-field f^4 case. Because the curves of Figure 5 qualitatively fit the observations of Strangway's group so well, it is tempting to speculate that f and f^3 terms were unimportant and therefore that nearby scatterers were not frequently influencing the observations.

DESIGN CRITERIA FOR A SOUNDER

The foregoing discussion of the frequency dependence of the scatter returns has indicated that the desirable operating frequency for a temperate-glacier sounder is definitely below 10 MHz, probably about 5 MHz. If a tuned detector is used to look at the bottom reflection, it will require several cycles of this carrier frequency to generate a response. Each 5 MHz cycle represents a wave distance traveled of 34 m. Therefore, the resolution of a system using a tuned detector is likely to be unacceptable, particularly on shallow glaciers.

To obtain efficiency in the transmit and receive antennas at 5 MHz, fairly large antennas (tens of metres in size) must be used. This requirement does not preclude vehicular or airborne operation, but our initial design was based on surface operation. Without vehicular
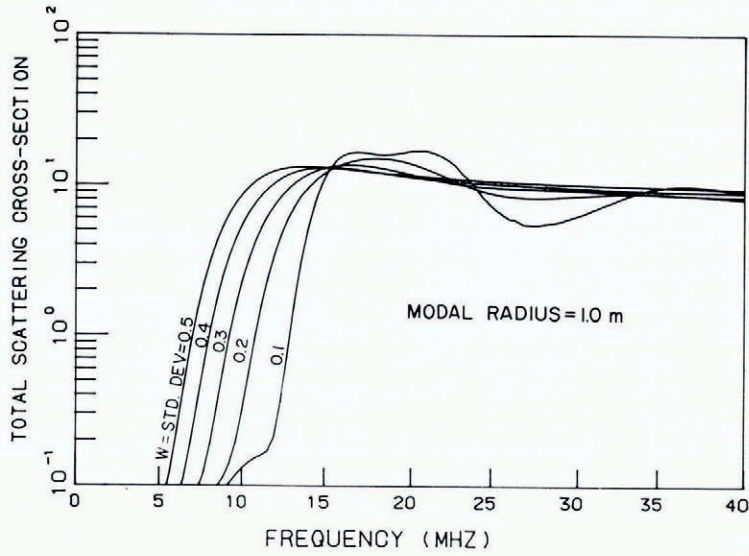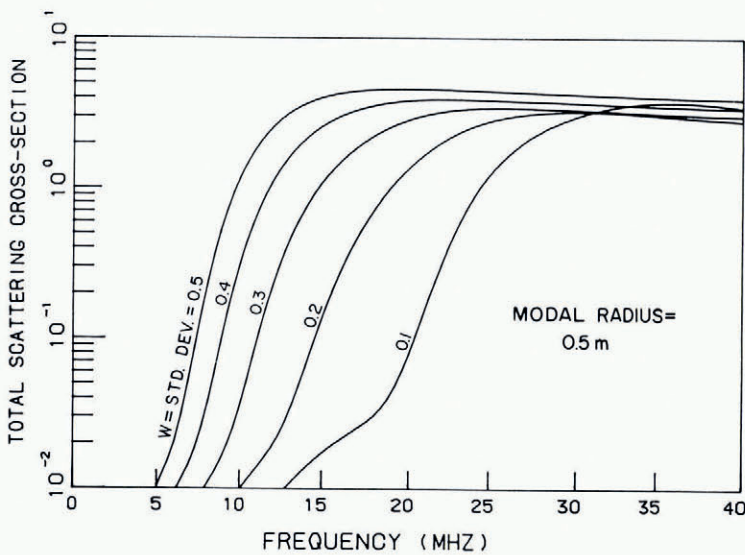
Fig. 5. *Dependence of scattered power on frequency for various Gaussian distributions of scatterer sizes:* (a) *Modal size* a = 100 cm; (b) *Modal size* a = 50 cm. W *is the standard deviation of the size distribution.*

noise sources, it was found that the radio-frequency noise environment was exceptionally clean both at South Cascade Glacier, Washington, and at Columbia Glacier, Alaska. In both places a small motor–generator was in operation in the immediate vicinity of the receiver, but it did not seem to introduce any significant noise. The only radio-frequency noise problem occurred at certain times of day when Citizens' Band (35 MHz) transmitters were operating in direct line-of-sight to the receiver. This noise source could probably be eliminated with band-pass

filters. Davis's (unpublished, p. 91) evaluation of the radio noise problem seems unduly pessimistic in the light of our experience.

In this low-noise environment, which probably occurs on most glaciers because of their cultural remoteness, the use of a tuned receiver becomes unnecessary. By looking directly at the unrectified signal as a function of time, instead of at received power at a certain frequency, it becomes possible to pick arrival times with an accuracy of a small fraction of a cycle. In this case, operation at 5 MHz, or even 1 MHz, can result in 10 m resolution.

There are now three requirements: (1) the center frequency should be low enough to avoid scattering, (2) the signal should be strong enough to be detectable, and (3) the signal should be strong in comparison to r.f. noise. For a specific mean power level, the best signal-to-noise ratio for radio-frequencies is obtained by containing the transmitted power in as short a pulse as possible. In opposition to this short-pulse requirement is the spectral broadening which occurs as the pulse is made short. Energy is spread into higher frequencies, where it is significantly more strongly scattered. This increased scattering decreases the ratio of bottom return to scatter return.

The spectral curves of Figure 5 suggest a means for studying scattering size distributions. If the waveform of the transmitted pulse is known, its power spectrum is known. The spectrum of scatter returns is the pulse specrum multiplied by a spectrum such as one in Figure 5. Thus the scatter return spectrum can be divided by the pulse spectrum to get curves similar to Figure 5. Various distributions (not necessarily normal distributions) can be tried until the model fits the observations. Repetition of the procedure with pulses of several different center frequencies should give reasonable definition of the scattering distribution. (In this procedure, calculation of the scattering spectrum would have to take into account the $\exp(-\alpha t)/t$ general time dependence).

CONCLUSIONS

The problems that have previously been encountered in sounding temperate glaciers can be attributed to water-filled voids in the ice. These are about 1 m in size. A sounder that transmits a pulse with center frequency 5 MHz and duration 1 cycle should give a good bottom-return/scatter-return ratio. By looking at the unrectified signal as a function of time, adequate depth resolution can be obtained. Void size distributions can be studied by examining the scatter return spectrum in comparison to the transmitted pulse spectrum. This information should be useful for studies in glacial hydrology.

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REFERENCES

Davis, J. L. Unpublished. The problem of depth sounding temperate glaciers. [M.Sc. thesis, University of Cambridge, 1973.]
Simmons, G., *and others*. 1973. Surface electrical properties experiment, [by] G. Simmons [and 19 others]. (*In Apollo 17. Preliminary science report. Prepared by Lyndon B. Johnson Space Center*. Washington, D.C., Scientific and Technical Information Office, National Aeronautics and Space Administration, 15-1–15-14. (NASA SP-330.))
Smith, B. M. E., *and* Evans, S. 1972. Radio echo sounding: absorption and scattering by water inclusion and ice lenses. *Journal of Glaciology*, Vol. 11, No. 61, p. 133–46.
Strangway, D. W., *and others*. 1974. Radio-frequency interferometry—new technique for studying glaciers, by D. W. Strangway [and 7 others]. *Journal of Glaciology*, Vol. 13, No. 67, p. 123–32.
Stratton, J. H. 1941. *Electromagnetic theory*. New York and London, McGraw-Hill Book Co.