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APPLICATION OF RADAR TECHNIQUES TO ICE AND SNOW STUDIES

By D. F. PAGE

(Communications Research Centre, Department of Communications, P.O. Box 490,
Station "A", Ottawa K1A 8T5, Canada)

and R. O. RAMSEIER

(Department of the Environment, 562 Booth Street, Ottawa K1A 0E7, Canada)

ABSTRACT. This paper presents an overview of the active microwave tools becoming available to the glaciologist with emphasis on recent radar developments as applied to floating ice. Sufficient theory is presented for the user to understand the techniques. Side-looking radar imagery is discussed using a number of examples resulting from the use of real and synthetic aperture, single and dual polarization. Recent studies of the microwave properties of ice and snow are reviewed, and are shown to be leading to significant advances in high-resolution radar techniques for accurate sounding of these materials. Remote sensing of fresh-water ice thickness is shown to be well established and operational, with similar techniques feasible in the near future for sea ice. It is pointed out that both imaging and probing radars applied to studies of sea ice and snow usually must be used in association with data from other sensors.

RÉSUMÉ. *Application des techniques radar actives a l'étude de la glace et de la neige.* L'article présente une revue générale des outils actifs à microradiations qui deviennent utilisables par le glaciologue en insistant sur les récents développements de l'application du radar aux glaces flottantes. On présente assez de théorie pour que l'utilisateur comprenne la technique. Les images d'un radar latéral sont discutées à partir de nombreux exemples résultant de l'utilisation d'une ouverture réelle et synthétique, d'une polarisation simple et double. Des études récentes sur les propriétés aux courtes longueurs d'ondes de la glace et de la neige sont passées en revue, et on montre qu'elles conduisent à des progrès sensibles par les techniques radar à haute résolution pour un sondage précis de ces matériels. La télédétection de l'épaisseur de la glace d'eau douce est montre-t-on solidement fondée sur le plan technique et opérationnel, des techniques analogues seront possibles dans un proche avenir pour la glace de mer. On conclue que les radars aussi bien superficiels que pénétrants appliqués aux études de glace de mer et de neige doivent être couramment employés en association avec les données provenant d'autres capteurs.

ZUSAMMENFASSUNG. *Die Anwendung aktiver Radarverfahren bei Eis- und Schneeuntersuchungen.* In diesem Beitrag wird ein Überblick über die mit aktiven Mikrowellen arbeitenden Verfahren gegeben, die dem Glaziologen zur Verfügung stehen, wobei der Schwerpunkt auf dem Einsatz neuerer Radarentwicklungen beim Treibeis liegt. Zum Verständnis der Verfahren wird die Theorie ausreichend dargelegt. Bildmaterial des Seitwärts-Radar wird an Hand mehrerer Beispiele diskutiert, die unter Verwendung von reellen und synthetischen Aperturen, einfacher und dualer Polarisierung erhalten wurden. Anhand einer Durchsicht neuerer Untersuchungen der Mikrowellen-Eigenschaften von Eis und Schnee wird gezeigt, dass diese zu bedeutenden Fortschritten bei Radarverfahren hoher Auf lösung zur genauen Lotung dieser Stoffe führen. Die Fernerkundung der Schichtdicke von Süsswassereis erweist sich als gut fundiert und Funktionstüchtig; ähnliche Verfahren werden in der nahen Zukunft auch für Seeeis zur Verfügung stehen. Es wird betont, dass bei der Untersuchung von Meereis und Schnee sowohl die abbildenden Radarverfahren als auch die Radar-Echolotung gewöhnlich auf Daten anderer Sensoren angewiesen sind.

I. INTRODUCTION

Radar is used in two different ways to study the properties and characteristics of ice and snow. In the first of these, the radar system develops an image, or radar photograph, of a wide geographic area, and information about the internal structure of the ice and snow is inferred from observations of its apparent surface structure in much the same way as is done with visual observations. The other way in which radar is used makes use of the fact that radio energy of sufficiently long wavelength is only partially reflected from an ice or snow surface or interface, while a substantial proportion of the energy can penetrate the material to be reflected from structural interfaces below the surface.

The ability to penetrate ice and snow is a major advantage of radio-wave remote sensors. Other advantages are that observations can be made in either daylight or darkness, and in all weather conditions provided that wavelengths longer than about 2 cm are used.

Radio-echo sounding is a well-known technique to glaciologists who have been using it for many years at low and medium radio frequencies. Of course, such radio-echo sounders are basically low-frequency radars. Because other authors in this Symposium will deal extensively with such sounders, this paper concentrates on radar techniques applied to studies of floating ice and snow. The active radar techniques described in this paper are restricted largely to frequencies above 1 000 MHz, and to a lesser extent to the intermediate range of frequencies down to 100 MHz. At these higher frequencies or shorter wavelengths, sophisticated radar technology has been highly developed for military purposes since World War II, and is recently being applied for non-military uses.

It is the intention in this paper to present an overview of the radar techniques that are becoming available to the glaciologist, with some examples of their use, some discussion of their advantages and disadvantages, and some indication of future possibilities. It is not possible here to deal in depth with the theory of the various radar systems or with the physical mechanisms involved in the interaction of radio waves with ice and snow. However, since the user must have a working knowledge of the principles involved in order to use the radar techniques to their maximum advantage and to be in a position to interpret the resulting data, some discussion of these principles will be given. The examples to be given here are taken largely from recent work in Canada concerned primarily with floating ice.

II. LARGE AREA IMAGING SENSORS

Rotating scan radar

The concentional radar developed for aircraft detection produces an image of a wide geographic area on a plan position indicator (PPI) oscilloscope. Radio energy is transmitted from an antenna rotating in a circular or sector scan; this energy is partially reflected from targets and terrain features, received by the same rotating antenna, and displayed on the PPI. The PPI is a polar display with the transmitter position at the centre; range or distance from the transmitter for each reflection is measured by the time taken between transmission and reception, and is displayed radially on the PPI. An example is presented in Figure 1 which

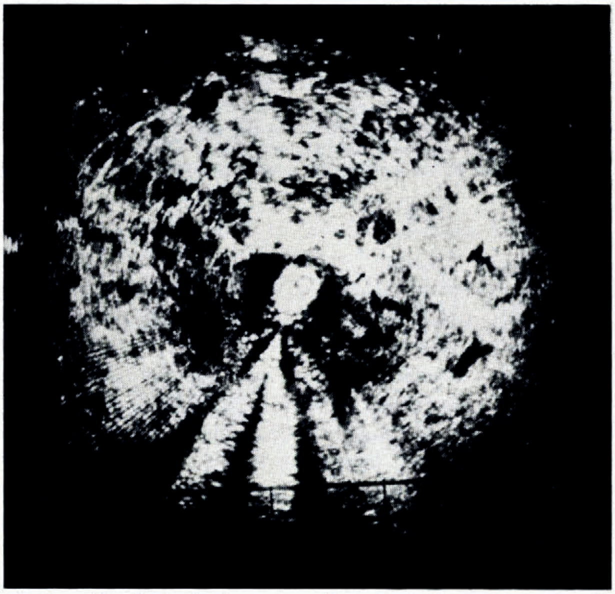

Fig. 1. Sector-scan navigation radar display in Argus aircraft over ice in Davis Strait off Baffin Island in April 1971.

shows the image produced on the PPI of a forward-looking, sector-scan, navigation radar in an aircraft flying in April 1971 over ice fields in Davis Strait off Baffin Island. It is interesting to note that the first discovery of an ice island is attributed to this type of radar carried on a U.S.A.F. aircraft, on 14 August 1946, approximately 500 km north of Alaska.

The ability to distinguish adjacent objects depends on the resolution of the radar. A limitation of this conventional rotating-scan radar is its very coarse azimuthal resolution. Although good range resolution can be obtained readily by suitably modulating the transmitted energy (wide bandwidth), the azimuthal resolution is determined by the angular width of the radio beam which in turn is determined by the size of the antenna. In practice, where the antenna must be rotated mechanically, it cannot usually be large enough to produce the high degree of azimuthal resolution desired for most remote-sensing purposes. Furthermore, because of the angular spread of the antenna beam, this azimuthal resolution of the image becomes coarser with increasing range from the transmitter.

SLR and its applications to ice studies

Side-looking radar, or SLR, is an airborne system using a different type of antenna scan system. The antenna is carried under the aircraft with its beam looking in a fixed sideways direction, at right angles to the aircraft track. Scanning is achieved by the forward motion of the aircraft so that the radar image obtained is in a Cartesian format rather than the polar format obtained with the conventional rotating scan. The SLR image is produced in a continuous strip as the aircraft moves along, and this image is usually recorded on film. Several studies of the application of such radars to ice studies have been reported, (Anderson, 1966; Guinard, [1970]; Johnson and Farmer, 1971; Larrowe and others, 1971; Biache and others, 1971; Loshchilov and Voevodin, 1972; Ketchum and Tooma, 1973; Jirberg and others, 1974; Gorbunov and Losev, 1974; Dunbar, 1975; Parashar and others, in press).

There are two basic SLR systems which differ markedly in the image resolution obtained, and incidentally, in the complexity and cost of the radar. The simplest type is the non-coherent or real-aperture SLR system, in which the azimuthal, or along-track, resolution is determined by the along-track beam-width of the antenna. The longest possible antenna is carried under the aircraft to obtain the narrowest possible along-track beam-width. As in conventional radars, the range resolution, or cross-track resolution, is determined by the modulation (bandwidth) applied to the transmitted energy (usually narrow pulses). Although it is relatively easy to achieve high cross-track resolution, the transmitter modulation is usually chosen so that this resolution approximates the more limited along-track resolution determined by the angular beam of the antenna. As in conventional radars, because of the angular spread of the antenna beam in the along-track direction, the along-track resolution of the resulting imagery is degraded linearly with increasing range from the transmitter.

Several examples of imagery obtained with an X-band real-aperture system are shown in Figures 2 through 5, each of which illustrates points of possible interest to the glaciologist. The SLR used was a Motorola AN/APS94D system flown by the Canadian Forces on an Argus aircraft. This system can image on both sides of the aircraft with possible range swaths 25, 50 or 100 km per side. All the imagery contains a non-imaged blind strip down the center of the track, which is outside the field of view of the antenna and is about twice as wide as the altitude of the aircraft. Range resolution is constant at about 30 m and along-track resolution is approximately 8 m per kilometer of range.

Figure 2, taken during Operation SKYLAB, shows part of the ice-covered Gulf of St. Lawrence and illustrates a number of interesting points. At the time this image was generated the north-western part of the Gulf was undergoing extensive ice formation, with the ice being advected to the south-east (Campbell and others, in press). The Quebec north shore west of Sept Îles is visible in the upper left-hand corner of the image. The dark area between

Fig. 2. AN/APS-94D SLR image, Gulf of St. Lawrence near north shore, west of Sept Îles, taken on 13 January 1974. Coverage is 25 km across track and 42 km along track.

the shore and the first radar returns from ice contains both open water in the form of a shore lead and newly formed sea ice. The lack of ability to distinguish between open water and new ice is characteristic of SLR imagery, there being little reflected energy because both have flat, specularly reflecting surfaces. Some shore-fast ice is visible at the lower edge of the shore.

The demarcation between this smooth ice and the floes in the central portion of the image is clearly visible. The smooth floes consisting of grey ice show a radar return from the edges only. Most of the ice on the right-hand side of the track is of this type. The bottom half of the left-hand image shows a very strong radar return, where the ice is older and has a rough surface. Some surface structure within the floes is clearly visible. A distinct characteristic of wide-area SLR imagery is the tendency for the amplitude of radar returns to decrease at longer cross-track ranges, as for example in the central area of the right-hand image, where the ice is uniform from the central blind strip to the tanker. This is due to the fact that the back-scatter radar energy decreases substantially as the slant angle of the radar beam increases from the nadir.

Two ships can be seen on the right-hand image, a tanker and the Department of the Environment oceanographic research vessel CSS *Dawson* whose track through the ice shows a strong return.

Figure 3 shows a map of the north-eastern tip of Ellesmere Island and a portion of Greenland. Two areas have been outlined, one showing parts of the Kennedy and Robeson Channels and the other, the Grant Ice Cap in the United States Range. These areas correspond to the SLR images shown in Figures 4 and 5 respectively. The Kennedy Channel portion of Figure 4 shows a large variety of multi-year ice structures mixed with first-year ice.

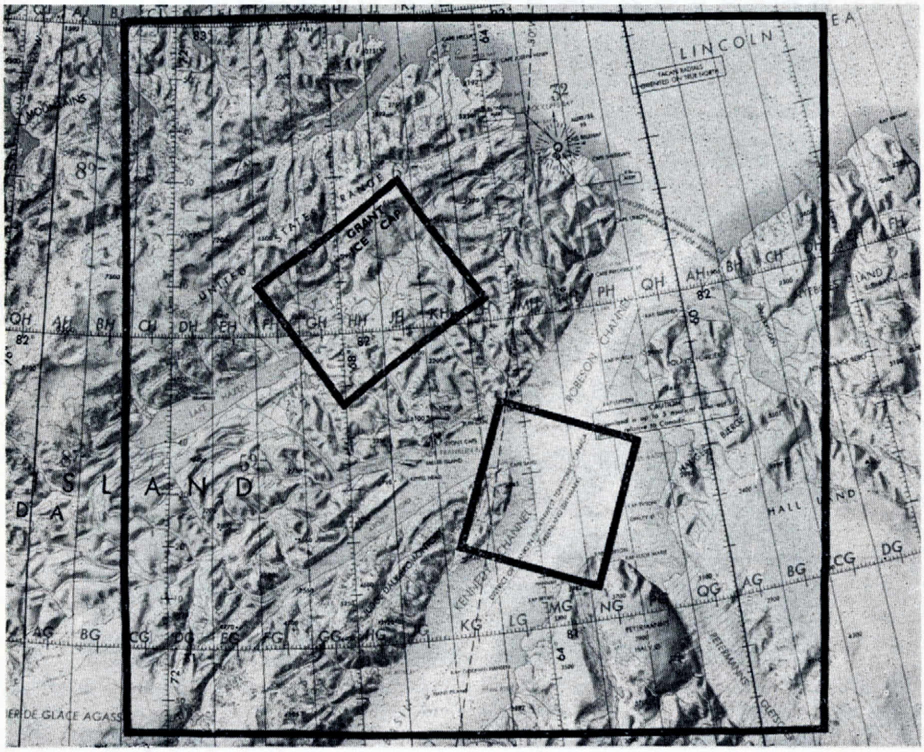

Fig. 3. Map of the north-eastern tip of Ellesmere Island and portion of adjacent Greenland, showing areas imaged in Figures 4 and 5.

In particular, note the relatively weak (dark) return from the newer ice which has formed in the large lead running horizontally on the bottom of the image. Two other characteristic effects in SLR imagery are evident in Figure 4. Because of the slanting angle of view, very high returns are obtained from the steep, rugged shore lines. Also as a result of this slanting view, there is a severe shadowing effect behind these high geographical features. In particular, note that the ice which extends into Lady Franklin Bay on the left-hand side of the image is not imaged because it is in the radar shadow of Cape Baird. Another striking example of this shadowing effect appears behind the small island off Kap Morton in the lower right-hand corner.

The Grant Ice Cap area indicated on the map of Figure 3 is shown imaged in Figure 5. The glacial tongues extending downwards from the ice cap can be seen clearly. They have a milky appearance which is characteristic of thick glacier ice in radar images. There is also some evidence that the radar can detect subsurface structure in this type of ice, although it would not be possible to establish this without extensive ground-truth information. Loshchilov (personal communication) did obtain radar imagery from glaciers showing subsurface structure which could be associated with foliation planes. The regular band structure across the image is due to uncompensated aircraft roll motion, and is to be ignored.

An operational application of this type of radar to fresh-water ice reconnaissance is shown in Figure 6. This imagery was obtained by the NASA Lewis Research Center during February 1974 over the western end of Lake Superior as part of a demonstration program for the extension of the navigable season in the St. Lawrence River and the Great Lakes. Above the

Fig. 4. AN/APS-94D SLR image of first-year and multi-year ice located in Kennedy and Robeson Channels taken on 13 January 1973. Coverage across track is 50 km and 54 km along track.

Fig. 5. AN/APS-94D SLR image of glacier ice off the Grant Ice Cap, United States Range, Ellesmere Island, taken on 13 January 1973. Coverage across track is 50 km and 63 km along track.

SLR image is an ice chart indicating the various ice types as interpreted from the radar image. In this system, after processing of the SLR images and preparation of the interpretive ice chart, the composite was sent by facsimile to a number of radio stations for transmission by radio link to vessels on the lakes. It is interesting to note the large number of ship tracks extending from Two Harbors in the most direct line to the THIN–MED ice. As in Figure 2, open water, which is indicated by the dashed lines in the water of the ice chart, cannot be distinguished from uniform thin ice in the Point Detour region in the SLR image.

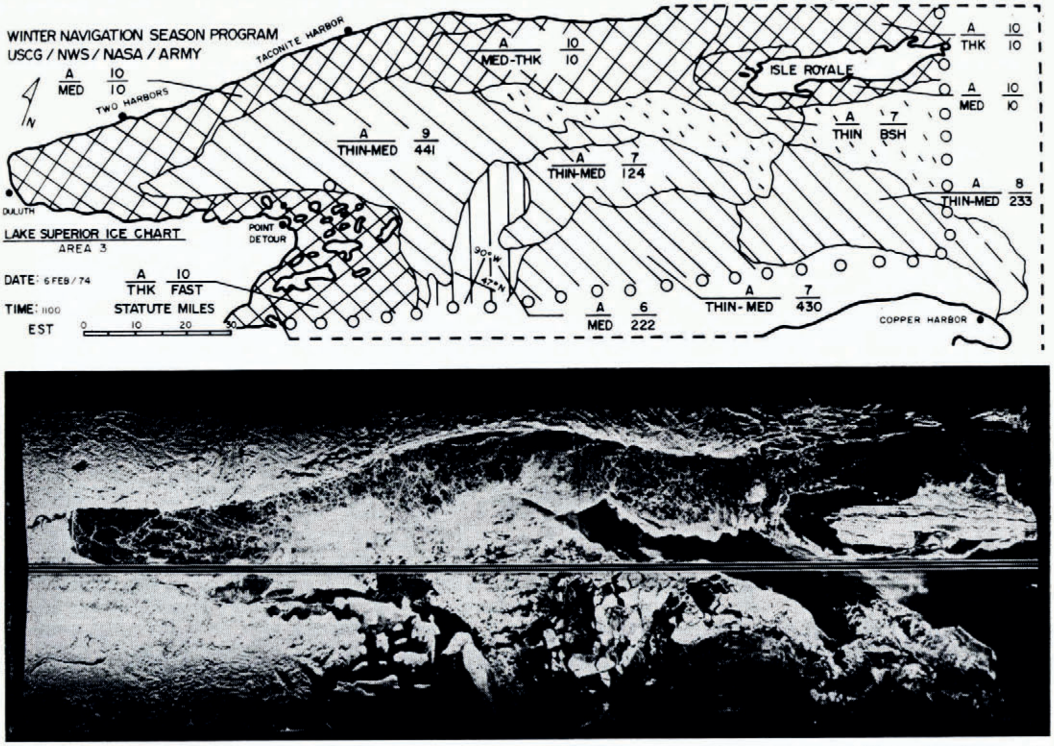

Fig. 6. AN/APS-94C SLR image of fresh-water ice taken on 6 February 1974 over the western part of Lake Superior, together with an interpretation of the ice types, (photograph provided by Dr H. Mark, NASA Lewis Research Center).

A number of further technical points must be borne in mind when interpreting SLR imagery. The brightness of the radar return from a given area is determined by its radar backscatter coefficient σ, which represents the energy scattered back to the radar by that area, expressed as a ratio of the radar energy illuminating it. The coefficient σ is dependent on the degree of surface roughness on the scale of a wavelength (3 cm at X-band); thus σ can be low for smooth water or smooth ice, and it can be high for ridged and broken ice surfaces. It is for this reason that young, smooth ice appears dark and indistinguishable from open water on many SLR images, while the brightest returns are produced by older ice which tends to be ridged, weathered and covered with mottled layers of crystallized snow. It is also the reason why the tonal and textural quality of the imagery obtained is very dependent upon the radar wavelength used. As reported by Ketchum and Tooma (1973), SLR imagery at wavelengths longer than 3 cm tends to lose the grey tones on the ice returns; they showed L-band (30 cm) imagery, for example, which was mostly black with only the major ice fractures and ridges showing as bright lines.

A point which has been noted by Jirberg and others (1973) is the fact that with fresh-water ice, significant radar returns can be obtained from the ice–water interface as well as from the air-ice interface, due to penetration of the ice by the microwave radiation. Thus it is that fresh-water ice types with a rough (not mushy) bottom profile such as consolidated brash, can produce bright returns on the imagery.

The backscatter coefficient σ, and thus the nature of the imagery, is sensitive to the polarization of the illuminating wave, as was demonstrated by Ketchum and Tooma (1973). The AN/APS94 system which produced the images shown in Figures 2 through 6 is horizontally polarized for both the transmitted and received wave (H–H). An example is shown in Figure 7 of dual-polarized imagery, taken in the Baie des Chaleurs of the Gulf of St. Lawrence with a Westinghouse 35 GHz system for the Canadian Ministry of Transport. This illustrates

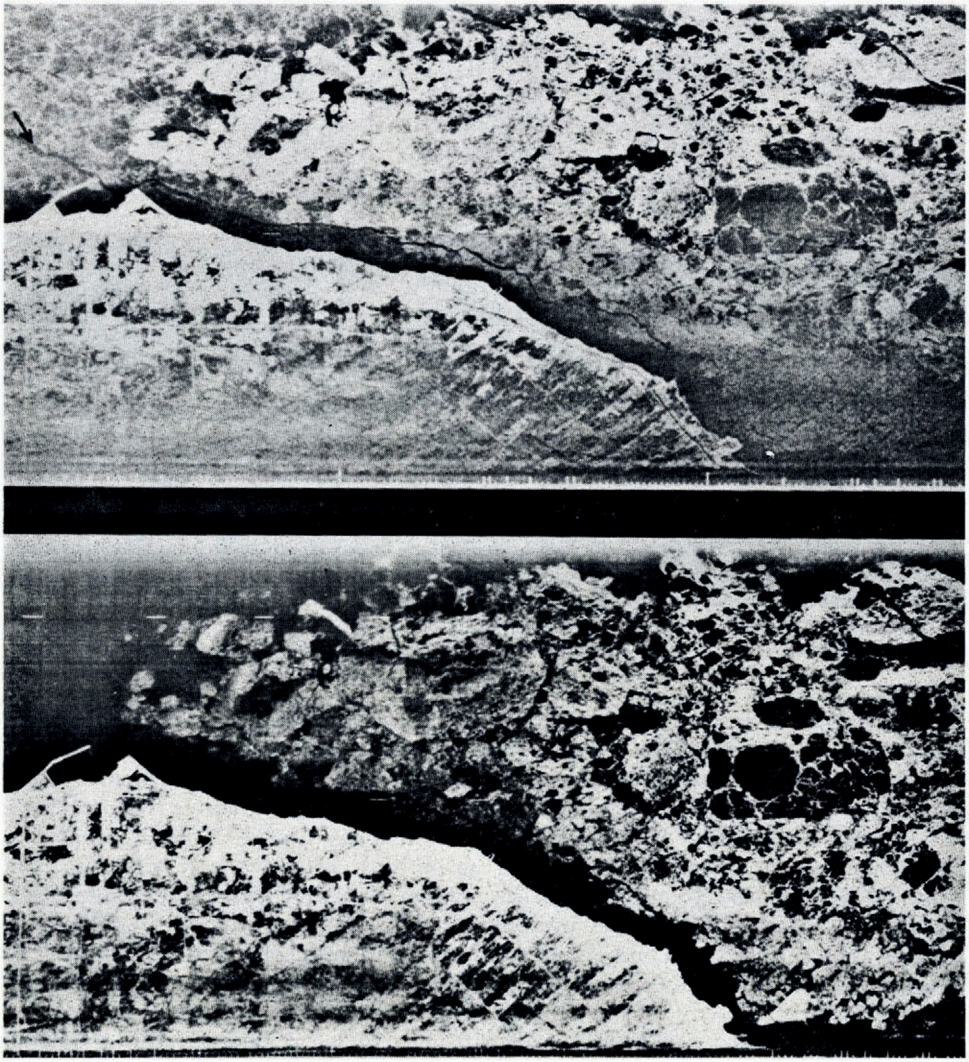

Fig. 7. AN/APQ-97 Westinghouse dual polarized 35 GHz SLR image taken over Baie des Chaleurs, Gulf of St. Lawrence on 1 March 1969. The top image is horizontally polarized (H–H) and the bottom image is cross polarized (H–V).

the substantial differences in image tone which can be obtained between H–H and H–V system modes. Note the greater visibility of an ice fracture running near the shore line (see arrow) on the H–H image; also more visible on this image is the structure of the newer grey ice in the upper left. On the cross-polarized image, however, note the improved visibility of the structure of the older grey-white ice in the lower right.

A further point regarding the imagery of Figure 7 is that it is taken with a system having a much shorter wavelength (1 cm) than that used for Figures 2 to 6. The structure of younger ice, often not visible with X-band or longer wavelength systems, is clearly visible with this shorter wavelength system.

The second, more complex and costly type of SLR is the coherent synthetic-aperture system. Here, the along-track beam-width of the antenna does not have to be very narrow to achieve high image resolution; in fact, the opposite is true. Consider a point on the ground being illuminated by many successive radar pulses as the antenna beam passes over it. If the phases of the radar reflections from that point are recorded as the antenna beam traverses the point, from one edge of the beam to the other, and if that phase history is subsequently processed in a suitable manner, the point can be imaged with very high resolution. Theory shows that the longer a point remains in the beam, the better it can be resolved in the resulting image; thus, theoretically, the wider the along-track antenna beam-width, the higher the image resolution. Furthermore, theory predicts that this high resolution is independent of target distance, so that equally high resolution is obtainable across the swath width of the image. Despite the theory, however, although very high resolution is indeed achieved with synthetic aperture SLR systems, this resolution is limited in practice by unavoidable perturbations in the flight path of the aircraft which restrict the time over which the signal phase history can be processed to produce the image.

In Figure 8 is shown a synthetic aperture SLR image produced by the Goodyear GEM-system employing the AN/APD-102 radar, when it was flown on 10 March 1974 over the Northumberland Strait between Pictou, Nova Scotia and Murray Harbour, Prince Edward Island. The resolution of this image is about 15 m and is constant across-track. All ice in this

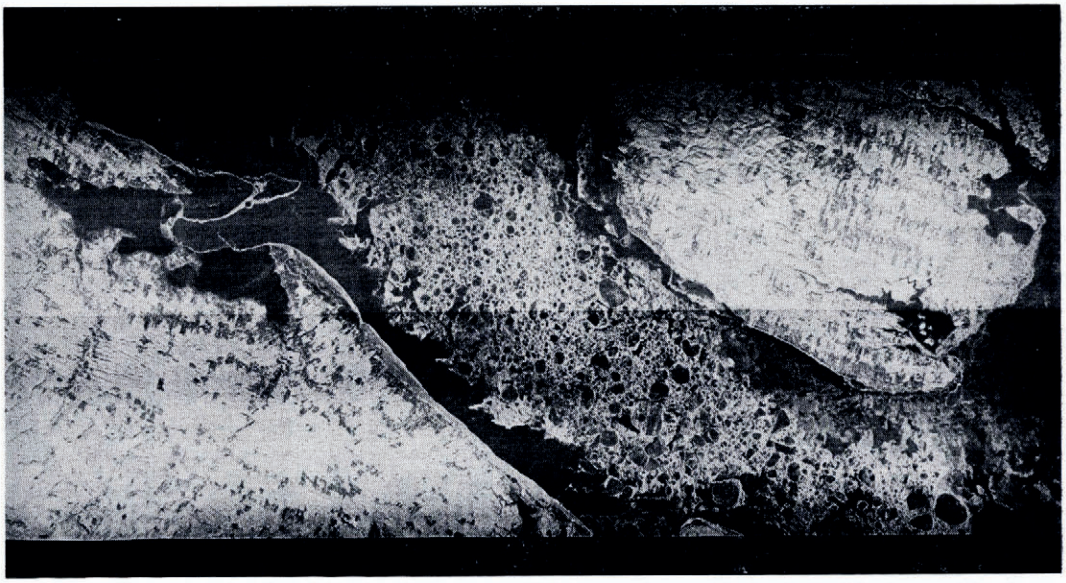

Fig. 8. AN/APD-102B Goodyear X-band synthetic aperture SLR image taken over Northumberland Strait on 10 March 1974 at an altitude of 11 300 m. Coverage is 36 km across-track and 45 km along-track, (photograph courtesy of Aero Service Corp.).

image is first-year sea ice having a concentration of 9/10 as determined from visual observations. The ice floes and the brash, including refrozen floes contained within the larger floes, are clearly visible. In this case, the dark edges along the shores represent shore leads. In the upper left-hand corner some shore fast ice is visible with an open-water lead intruding into the bay. Obvious advantages of this imagery over real-aperture imagery are the higher resolution and the uniformity of resolution and contrast across-track.

As an example of the application of SLR imaging systems to ice dynamics studies, we should note that the Arkticheskiy i Antarkticheskiy Nauchno-Issledovatel'skiy Institut in Leningrad has used a synthetic-aperture SLR, the RLS BO "Toros" system, to distinguish between different ice types and to determine ice drift (Gorbunov and Losev, 1974). The resolution of this radar is approximately 15 m. The ice types they can identify comprise newly-formed ice, grey ice, first year, and multi-year ice. The concentration of ice on the sea surface can be determined from the imagery, including a qualitative description of the ice surface (degree of hummocking). The amount, dimensions, distributions and orientation of channels and cracks can also be obtained. For the ice drift study which was carried out in the northern sea routes, the side-looking radar was mounted in an Antanov (AN-24) aircraft. Ice drifts for a two-day period were found to be between 25 to 50 km away from the shore and between 2.5 and 7 km near the shore. Results for the larger drift velocities were in error by only 1 to 2%, as compared to 10 to 20% for the lower velocities.

Snow detection with SLR

From the various examples of imagery presented above, it is clear that SLR images tend not to show reflections from snow surfaces, showing instead the stronger reflections from the surface underneath the snow. However, it has been observed by Waite and MacDonald that old, perennial snow is sometimes visible in SLR imagery. This is presumed to be due to volume scattering from the inhomogeneities which exist in old snow.

Future SLR applications

High-resolution SLR imagery is now becoming increasingly available from aircraft-borne coherent systems, and there is no doubt that these systems will contribute a great deal more to the glaciologist's knowledge through such experiments as AIDJEX, POLEX, etc. It is also probable that the most significant glaciological applications of coherent SLR imaging systems are yet to come—with satellite-borne systems providing continuous, high-resolution, synoptic coverage of large geographic areas. The imagery from these satellite systems will be comparable in resolution quality to that from existing airborne SLR systems; it will also compare favourably with the photographic imagery available from existing satellite systems, with the added advantages of independence of cloud cover and light conditions.

Calibration of SLR imagery—associated sensors

Although it has been shown that imaging systems are useful to the glaciologist, at least for qualitative purposes, it is also clear that definitive interpretation of this imagery will not be possible until more work has been done to relate the imagery to the physical properties of the ice. In this regard it must be noted that only a very small proportion of the ice imagery being collected is associated with extensive ground-truth information about the ice being imaged—a situation which is likely to continue, considering the vast geographical areas involved.

In the absence of ground truth, SLR imagery may be "calibrated" for more quantitative interpretation by the use of one or more associated sensors gathering information about specific ice properties. A property which could be used in this way is thickness, and radar sensors for remotely measuring ice thickness will be discussed in a separate section of this paper. Other associated sensors which can be used are optical and infra-red cameras and line-scan devices, laser profilometers, microwave radiometers and microwave scatterometers. Of these, the microwave radiometer and the microwave scatterometer offer some of the same operational advantages as radar (all-weather capability and independence of light level), and at the same time measure properties which complement the SLR information (Gloersen and others, 1973; Campbell and others, 1974; Meeks and others, in press). We will not deal here with the microwave radiometer, although it should be noted that extensive co-operative experiments have been carried out by the U.S.A. and the U.S.S.R. to relate and compare ice data from both radiometers and radars (Ramseier and others, 1974; Gloersen and others, 1974[a], [b]).

III. THE MICROWAVE SCATTEROMETER

The microwave scatterometer is an important radar instrument which has been used in association with SLR imagery, but which can also be useful as an independent sensor. The scatterometer is a calibrated down-looking airborne radar which is used to measure the backscatter coefficient, as a function of aspect angle, along a strip of terrain under the aircraft.

The work of Rouse (1969) and of Parashar and others (in press) should be noted with regard to the use of scatterometry in the identification of sea-ice types. They have explored the use of dual-polarized systems, and the use of two scatterometers operating at different frequencies, to assist in discriminating between ice types. The latter authors have reported the ability, in 85% of cases tried, to classify ice correctly into one of four gross thickness categories.

IV. PROBING ICE AND SNOW WITH RADAR

Introduction

That microwave radar can penetrate ice and snow is a fact that has long been suspected by aircraft pilots who have found their radar altimeters registering erroneously large altitude readings when flying over large glaciers. The radar altimeter is, in fact, a prototype of the probing type of radar sensor used to study the internal structure of ice and snow. Here, unlike the SLR imaging system, it is not the coverage area which is important, but the ability to measure range, i.e. depth, accurately.

A basic requirement for this type of radar sensor is that it be designed for good penetration of the ice and/or snow. Some knowledge of the electrical properties of these materials is essential for the users of these sensors, and of particular interest are the velocity and attenuation of radio waves propagating through them.

Electrical properties of ice and snow

The most important electrical property influencing the propagation characteristics of a medium is the relative permittivity:

$$\epsilon_r = \epsilon_r' - j\epsilon_r''$$

where ϵ_r' is commonly known as the dielectric constant of the medium.

The velocity of propagation is given by

$$v = \frac{c}{(|\epsilon_r|)^{\frac{1}{2}}}$$

where $c = 3 \times 10^8$ m/s is the velocity of electromagnetic waves in vacuum.

Thus, the time taken for propagation through depth h is given by

$$t = \frac{h(|\epsilon_r|)^{\frac{1}{2}}}{c}.$$

For our purposes, ϵ_r' and ϵ_r'' are variables which are dependent on the type of ice or snow, on temperature, and on the radio-frequency used. Attenuation of radio waves, usually expressed in dB loss per meter, is related directly to the loss tangent which is given by

$$\tan \delta = \frac{\epsilon_r''}{\epsilon_r'}.$$

Radar reflections occur whenever there is an abrupt change in the value of ϵ_r, i.e. where significant changes in ϵ_r take place within the distance of a wavelength of the radio wave. It is when such changes in ϵ_r take place at interfaces between air, snow, ice, and water that radar reflections can be expected from such interfaces.

Measurements of the permittivity of fresh-water and glacier ice have been made over wide ranges of temperature at frequencies extending upwards from very low frequencies to as high as 96.5 GHz, (Lamb and Turney, 1949; Cumming, 1952; Von Hippel, 1954; Yoshino, 1961; Perry and Straiton, 1973; Vant and others, 1974; private communication from W. B. Westphal). The loss tangent is very small at microwave frequencies, with values less than 2×10^{-3} at all temperatures lower than 0° C and all frequencies greater than 1 GHz, but rising substantially at frequencies less than 200 MHz. The real component of permittivity, ϵ_r', is found to be virtually independent of temperature and of frequency at frequencies above 100 MHz, with measured values ranging between 2.9 and 3.2, depending on the author.

Using a value for real relative permittivity of 3.14 (a good statistical average), we arrive at a velocity of propagation in fresh-water and glacier ice of 1.69×10^8 m/s, a value which can be considered to be independent of frequency and temperature. From the loss-tangent data, it is possible to predict that over the frequency and temperature ranges of interest here, attenuation in fresh-water and glacier ice will be less than 0.05 dB/m at 1 GHz and $-10°$ C, increasing approximately proportional to the square of the frequency, and increasing by about a factor of 2 with increasing temperature over the range $-40°$ C to 0° C.

The situation with snow and sea ice is more complex, reflecting the fact that these are complex materials occurring naturally in a number of types and in an endless variety of composites of these types. Permittivity measurements on snow have been reported by Cumming (1952) and Evans (1965), and have been reviewed by Vickers and Rose (1972) who have reduced the data to obtain approximations for attenuation and propagation velocity. For dry snow, these properties are found to be relatively independent of temperature for temperatures below 0° C. But they are very dependent on snow density, with freshly fallen snow giving an attenuation per unit length which is an order of magnitude less than that for fresh-water and glacier ice, and with a similar frequency dependence. This attenuation increases with increasing snow density, until in very hard-packed snow it approximates that for fresh-water or glacier ice. Similarly, velocity of propagation in dry snow decreases from very close to the free-space value for freshly-fallen, light snow to approximately the value for fresh-water or glacier ice when the snow is very hard-packed. Clearly, therefore, any radar sensor system for snow depth studies will require some associated means of establishing the snow density if the radar data are to be correctly interpreted.

The presence of water on or in the snow or ice, even in small quantities, seriously complicates the situation. An estimate by Royer (1973) gives an attenuation rate in water of 70 dB per meter for a frequency of 1 GHz and temperature of 0° C. It varies rapidly with frequency, and is greater by two orders of magnitude at 10 GHz. Clearly, the attenuation through wet snow or ice at microwave frequencies can be expected to be much higher than when water is not present.

Sea ice is the most difficult of all to characterize electrically. The presence of brine and salts in the ice causes relatively high attenuation at radio-frequencies, and problems arise from the fact that there are many different kinds of sea ice with an endless variety of concentrations and distributions of brine and salts. Nevertheless, a number of authors have attempted to measure losses in sea ice at various frequencies, and a summary of their findings is given in Figure 9. It should be noted that the points in Figure 9 represent measurements with both naturally occurring ice and laboratory ice; however, all the measurements were made using samples within the narrow ranges of temperatures and salinity shown.

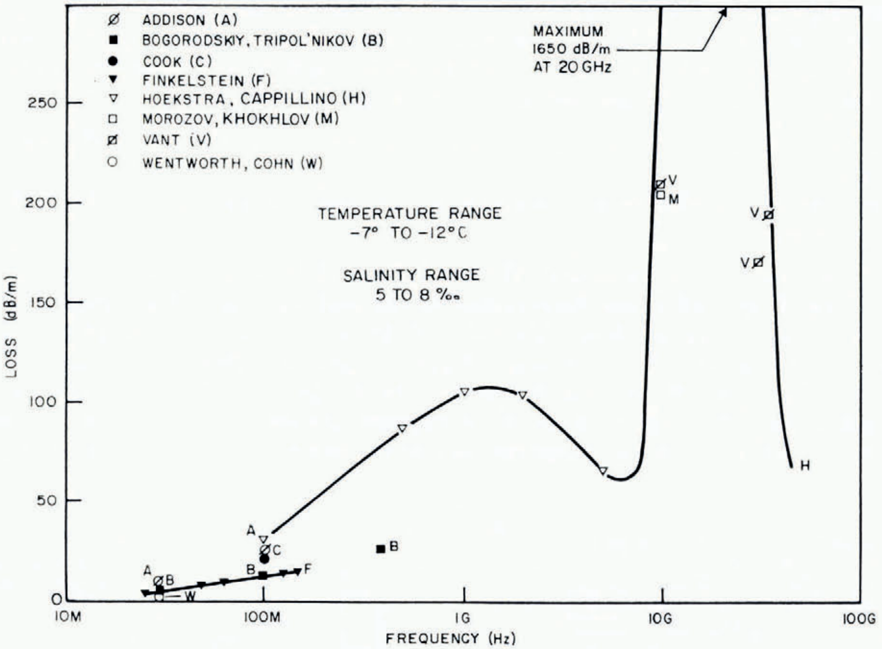

Fig. 9. Summary of loss data for ice of a standard salinity and at a standard temperature (provided by M. Vant).

A recent study by Vant and others (1974) has dealt in more detail with the electrical properties of different categories and types of sea ice. In their measurements, they have separated sea ice into the two categories: first-year ice and multi-year ice. They have further separated first-year ice into two types: frazil and columnar. Multi-year ice in their study consisted of recrystallized columnar ice. At a fixed frequency of 10 GHz the permittivity of these ice types was explored as a function of temperature. The dielectric constant ϵ_r' of both first-year types was found to approximate that for fresh-water ice at temperatures below −30° C, but to rise dramatically as the temperature increases towards 0° C. For multi-year ice, a similar temperature dependence was observed for ϵ_r', but the value at low temperatures was found to be substantially less than that for other ice types. Dielectric loss ϵ_r'' was found to vary considerably between sea-ice types, being very high for first-year types and substantially less for multi-year types.

The above observations of electrical properties for first-year sea ice are generally consistent with the fact that first-year ice contains brine pockets which freeze only at very low temperatures. The observations for multi-year ice are consistent with the known fact that these brine pockets drain out gradually and are replaced by air, with the result that multi-year ice is a complex and time-varying combination of ice, air, and brine.

Radar probes for floating ice

There is a need for ice depth sounders which will quickly and effectively provide ground truth for SLR imagery used for large-area ice reconnaissance. Such sounders are also expected to be invaluable for ice growth studies. In addition, there are major operational requirements for such sounders to make possible the safe and effective movement of vehicles on ice and of ships through ice. These requirements exist for both fresh-water ice and sea ice.

The first challenge in designing radars for depth sounding of thin floating ice is to obtain the very high resolution required—typically a few centimeters. In fact, there have been significant advances in radar electronics over the past decade which make possible the attainment of very high resolution for accurate depth-sensing systems. These advances have been in the development of wide-band techniques for modulating radar transmissions, and we will discuss the two basic approaches which are being used:

(a) wide-band frequency modulation of the carrier wave amplitude (FM/CW systems), and

(b) very short time-duration modulation of the radio energy (short-pulse and impulse systems).

Early experiments with a simple FM/CW radar at 10 GHz were reported by Christoffersen (1970), in which the radar was both surface-borne and airborne. These experiments confirmed that X-band is a poor choice of wavelength for sea ice. Another much lower frequency FM/CW system adapted directly from an aircraft altimeter system in the 420–470 MHz band is being used commercially for sea-ice sounding by Geophysical Service Incorporated; it is understood (personal communication) to be capable of measuring thicknesses greater than about 1 m and is intended for mounting on surface vehicles. Using information obtained

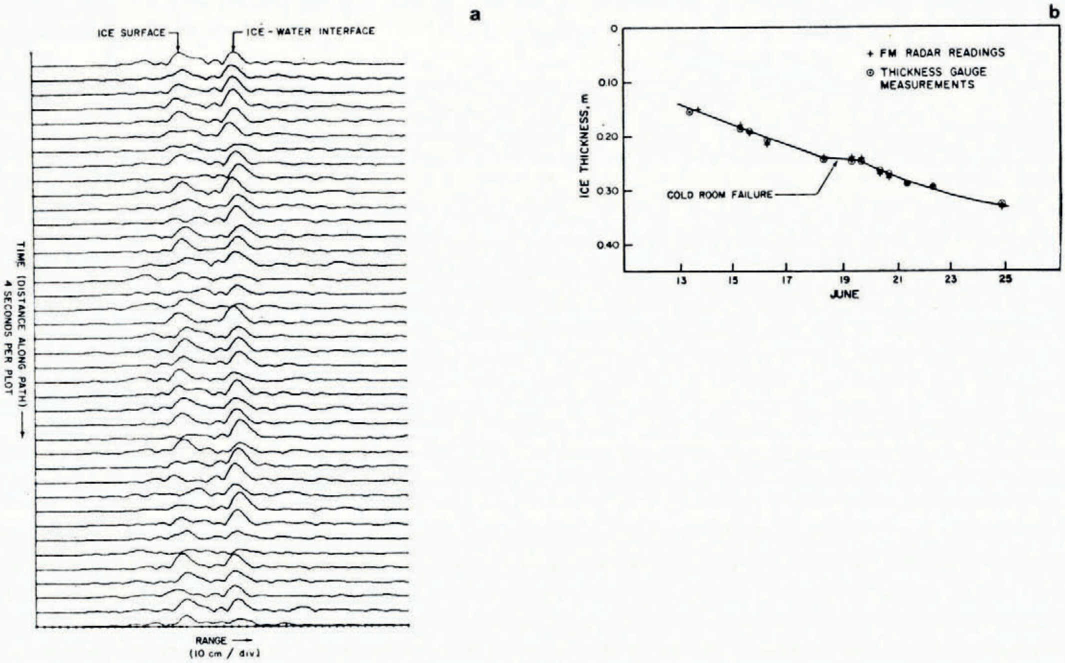

Fig. 10. (a) Profile of ice thickness obtained with FM/CW radar mounted on a moving sled. (b) Results of FM/CW radar ice thickness growth study.

from bore-hole samples, the system is calibrated for the wide range of propagation velocities to be expected in sea ice. An FM/CW radar at X-band, designed specifically for thin fresh-water ice and snow has been described by Page and others (1973) and in an improved version suitable for airborne use by Chudobiak and others (1974). Typical results obtained with this system mounted on a sled moving across the Ottawa River are shown in Figure 10a. These plots were produced by the digital computer processing of a magnetic tape record (Venier and others, in press). The same radar was used to monitor ice growth in a laboratory cold room as a function of time, and the results were compared with thickness-gauge measurements. As shown in Figure 10b, these results indicate that the radar measured ice sheets as thin as 15 cm to an accuracy of the order of ±1 cm.

A pulsed radar system using very short pulse (1.3 ns) modulation of a carrier wave at 2.7 GHz has been reported by Vickers and others (1974) for fresh-water floating-ice studies from a low-flying airborne platform. In trials over Lake St. Clair and Lake Superior, supported by auger teams on the ice, thicknesses of single, unbroken ice layers greater than 10 cm were measured to an accuracy of 2 cm.

Experiments with a much lower-frequency pulsed radar have been reported by Bogorodskiy and Tripol'nikov (1974) for airborne sounding of sea-ice thickness from an altitude of 100 m. A pulse length of 50 ns was used with a carrier frequency of 100 MHz. Good upper- and bottom-side returns were obtained with young-ice thicknesses up to about 1.5 m and old-ice thicknesses up to several meters. Despite the relatively long pulse length which undoubtedly limited the resolution of the thickness measurements, the feasibility of using an airborne radar to obtain both upper- and lower-surface returns from sea ice was demonstrated. The authors also carefully point out the problem of interpreting such sea-ice thickness measurements without accurate knowledge of the temperature and classification of the ice being sounded.

In the impulse system, a relatively new type of time-domain radar, a narrow burst of energy at baseband (d.c.) is used to produce very wide-band transmissions. Such a system is being used commercially by Geophysical Survey Systems, Incorporated, and its use for ice sounding from surface vehicles has been described by Bertram and others (1972) and Goodman (1974). With a 5 ns pulse, a wide range of sea-ice depths have been sounded using bore holes to calibrate the system for temperature and ice type.

A very narrow sub-nanosecond base-band pulse is the basis of an impulse radar system developed at the Communications Research Centre in Ottawa and tested in a co-operative ice studies program with the Canadian Department of the Environment. Designed for fresh-water ice studies, it selects and uses a frequency band of approximately 1 GHz of the impulse energy at X-band. A block diagram of this very simple system is shown in Figure 11a.

This radar was tested in the field during February and March 1974. The output display for this system mounted on a sled on the Ottawa River is shown in Figure 11b and 11c. The smaller reflection in Figure 11b was obtained from a snow-free, ice–air interface while the larger reflection comes from the ice–water interface; this is the normal situation with bare, dry ice. The reflections shown in Figure 11c were obtained in an area covered by snow containing a thin ice crust sandwiched between two layers of snow, as illustrated by the schematic vertical snow and ice profile.

In Figure 11d is shown a comparison of ice thickness as determined by bore-hole drilling and by the impulse radar mounted on a surface vehicle during trials on the St. Lawrence River near Wolfe Island. The continuous strip recording shown in Figure 11e was obtained during these trials on the St. Lawrence River. Below this record is plotted the ice thickness as read from this strip recording; also plotted are the measured ice thickness at five bore holes. The above results have shown the system to be capable of measuring fresh-water ice thicknesses as small as 15 cm with an accuracy of better than ±0.5 cm, when mounted on surface vehicles.

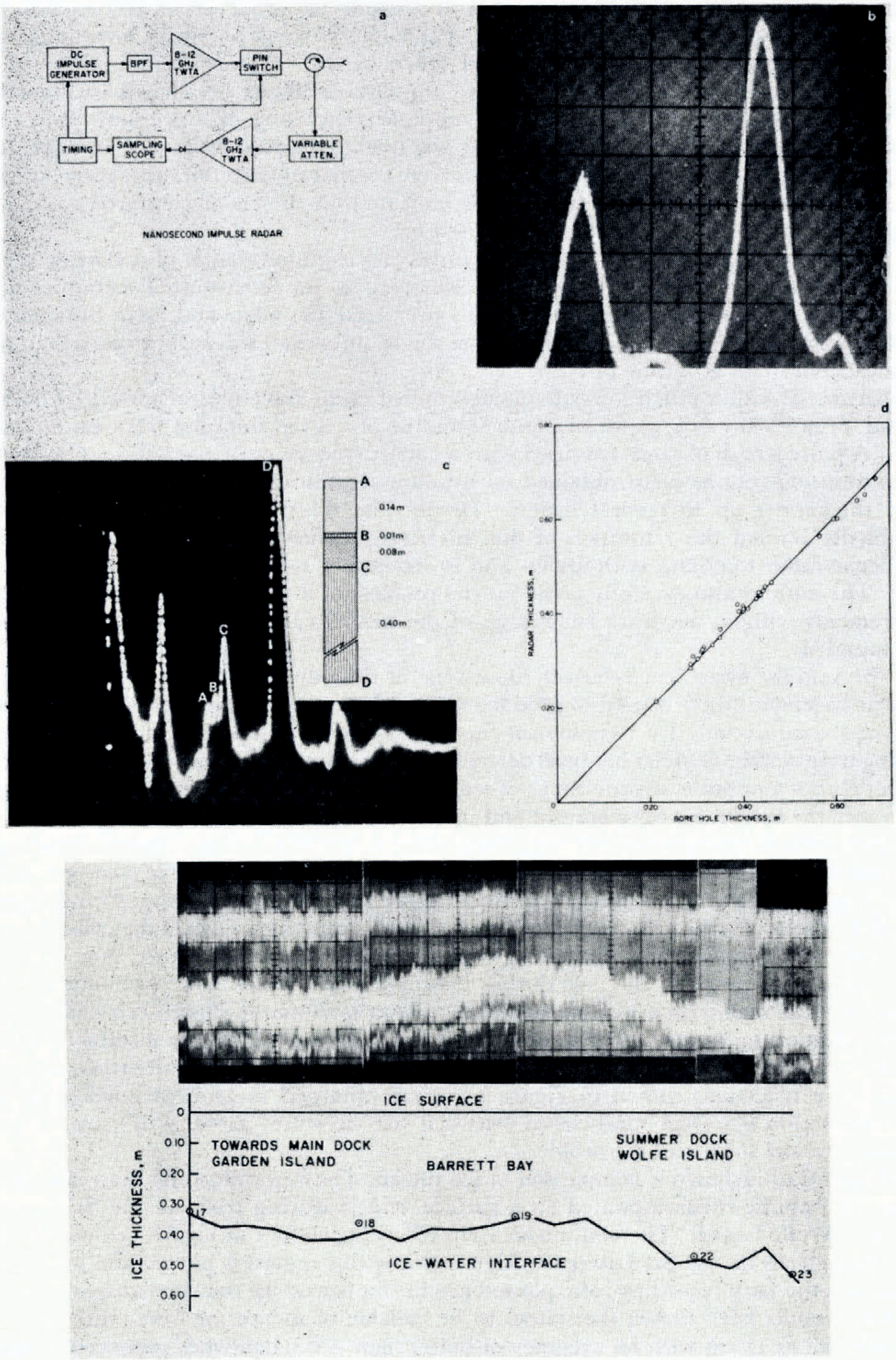
a
DC IMPULSE GENERATOR
BPF
8–12 GHz TWTA
PIN SWITCH
TIMING
SAMPLING SCOPE
8–12 GHz TWTA
VARIABLE ATTEN.
NANOSECOND IMPULSE RADAR
b
c
D
A
B
C
A
0.14m
B
0.01m
0.08m
C
0.40m
D
d
0.80
0.60
0.40
0.20
0
0.20
0.40
0.60
RADAR THICKNESS, m
BORE HOLE THICKNESS, m
ICE SURFACE
0
0.10
0.20
0.30
0.40
0.50
0.60
ICE THICKNESS, m
TOWARDS MAIN DOCK
GARDEN ISLAND
BARRETT BAY
SUMMER DOCK
WOLFE ISLAND
17
18
19
22
23
ICE-WATER INTERFACE

Fig. 11.

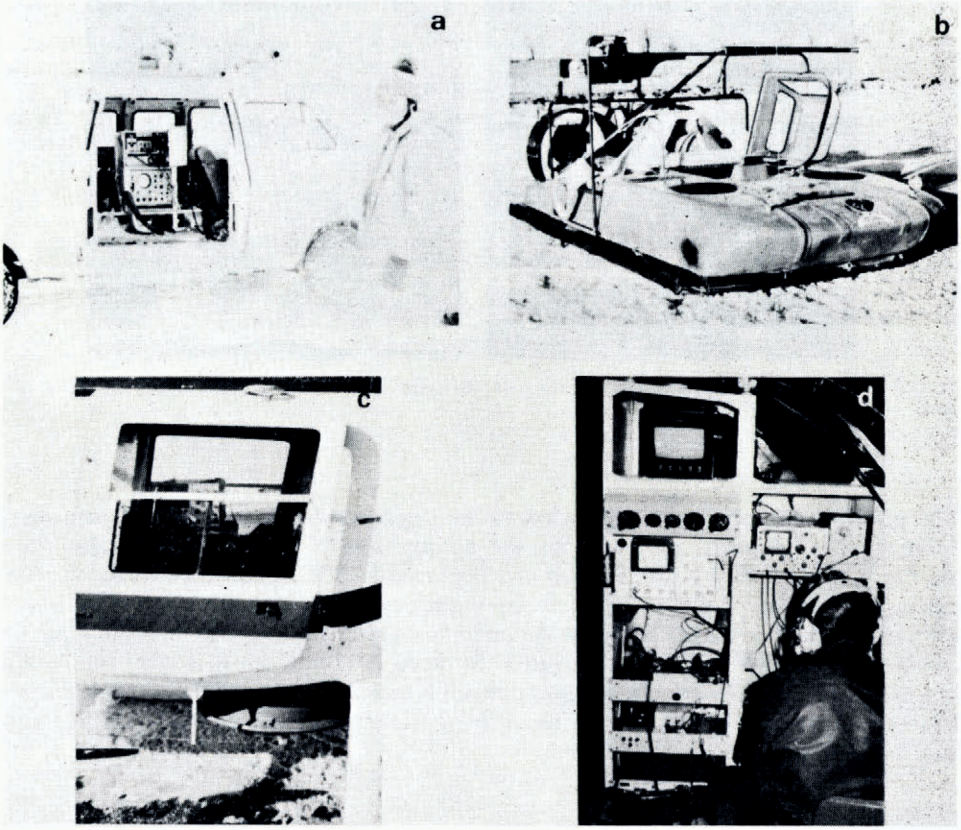

Fig. 12. Impulse radar mounted on (a) truck, (b) hovercraft, (c) helicopter, (d) DC-3 aircraft.

During these trials, prototypes of this radar were mounted on various vehicles, as shown in Figure 12. The radar returns shown in Figure 13a were obtained with the system mounted in a helicopter flying at an altitude of 30 m and at a velocity of 80 knots (40 m s^{-1}) over the St. Lawrence test area near Wolfe Island. Ice thickness of approximately 20 cm was measured to within ±10% of the value obtained by ground-truth measurements. Due to the fact that in this case the temperature was near the melting point and the surface of the ice was moist, the top-side ice return is much greater than the bottom-side return. The return shown in Figure 13b was obtained from a DC-3 aircraft at an altitude of 60 m and velocity of 120 knots (60 m s^{-1}) over Lake Nipissing. Again, the upper surface return is high because of surface moisture; in fact, this flight was carried out after a prolonged warm period during which daytime temperatures were above freezing.

Fig. 11. (a) Diagram of X-band nanosecond impulse radar. (b) Impulse radar return for 30 cm of bare river ice (1 ns/division horizontally). (c) Impulse radar return for river ice with snow cover as follows: A–B soft snow, B thin ice crust, B–C coarse granular snow, C–D ice (5 ns/division horizontally). (d) Comparison of ice thickness as measured using impulse radar and bore-hole drilling. (e) (i) Continuous strip profile of St. Lawrence River ice over a distance of 2 000 m. Vertical scale: ice thickness (0.16 m/division); horizontal scale: distance (100 m/division). (ii) Thickness interpreted from (i) and plotted, with five bore-hole measurements plotted for comparison.

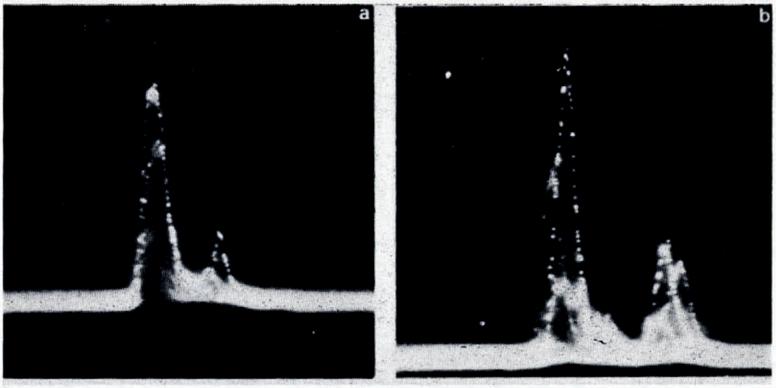

Fig. 13. Returns obtained with impulse radar mounted in (a) helicopter at altitude of 30 m, (b) DC-3 aircraft at altitude of 60 m.

Radar sounding of snow

The possibility of applying microwave radar designed with high range resolution to the sounding of snow depth is indicated by the results from X-band impulse radar shown in Figure 11c. This possibility was studied and reported by Vickers and Rose (1972) who used a short-pulse radar at 2.7 GHz to explore snow-pack stratigraphy with high resolution. They found that good radar returns could be obtained from internal structure in a snow pack when it contained no free water. They indicated the need to obtain snow density information to calibrate the radar. Their conclusion was that such a radar, with sufficiently high transmitter power, could be used operationally for monitoring snow-pack hydrology from either a surface or an airborne platform.

V. Discussion

The active microwave tools available to the glaciologist have been presented in this paper with an emphasis on recent radar developments as applied to floating ice. Of these, the usefulness of side-looking radar (SLR) systems for producing images of large ice areas under all weather and light conditions is becoming well established. In these radar images, snow cover tends to be transparent and ice structure is very apparent. The only major exception to this appears to be in the case of smooth and unbroken young ice which is often indistinguishable from open water in SLR imagery. Methods for the unambiguous interpretation of SLR imagery are being developed as more is learned of the electromagnetic properties of various ice types. In this regard, the use of other microwave sensors auxiliary to SLR is expected to be of continued interest, for example, microwave radiometers, scatterometers, reflectometers, and ice-thickness radars. The future development of satellite-borne SLR systems producing continuous, high-resolution images of large geographic areas will provide a great wealth of new data on ice structure and ice dynamics.

Recent studies of the electromagnetic properties of all types of ice and snow are leading to a much better understanding of these materials. This, together with recent advances in high-resolution radar techniques, is leading to the development of accurate, high-resolution sounding systems for all types of ice and snow. The accurate remote sensing of fresh-water ice thickness can be said to be well established. Airborne systems are being developed. The same can be said for snow pack, although techniques auxiliary to the radar are necessary to obtain information about the snow density. The radar sounding of sea ice has also been shown to be feasible if low enough frequencies are chosen. The ability to measure sea-ice thickness accurately is expected to follow from the application, at much lower frequencies, of the impulse and narrow-pulse techniques presently in use for fresh-water ice. As with the SLR, such thickness radars for sea ice are expected to require additional information about the ice type (e.g. dielectric properties) for proper interpretation of the measurements. Operational ice-thickness radars are therefore likely to be used in close association with such other sensors as microwave reflectometers, radiometers and scatterometers.

Finally, it should be noted that these high-resolution imaging and probing radars will undoubtedly have application in the future to studies of the internal structure of glaciers, ice caps and icebergs. In combination with other advances in radar technology, these techniques will provide the glaciologist with the most valuable tool yet available for the study of large ice and snow masses.

VI. Acknowledgements

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REFERENCES

Addison, J. R. 1969. Electrical properties of saline ice. *Journal of Applied Physics*, Vol. 40, No. 8, p. 3105–14.

Anderson, V. H. 1966. High altitude side-looking radar images of sea ice in the Arctic. *Proceedings of the fourth Symposium on Remote Sensing of Environment ... 1966. ...* Ann Arbor, Willow Run Laboratories, Institute of Science and Technology, University of Michigan, p. 845–47.

Bertram, C. L., *and others*. 1972. Locating large masses of ground ice with an impulse radar system, [by] C. L. Bertram, K. J. Campbell and S. S. Sandler. *Proceedings of the eighth International Symposium on Remote Sensing of Environment ... 1972. ...* Ann Arbor, Willow Run Laboratories, Environmental Research Institute of Michigan, [University of Michigan,] Vol. 1, p. 241–60.

Biache, A., *jr., and others*. 1971. Remote sensing of the Arctic ice environment, [by] A. Biache, Jr., C. A. Bay, R. Bradie. *Proceedings of the seventh International Symposium on Remote Sensing of Environment ... 1971. ...* Ann Arbor, Willow Run Laboratories, Institute of Science and Technology, University of Michigan, Vol. 1, p. 523–61.

Bogorodskiy, V. V., *and* Tripol'nikov, V. P. 1973. Elektromagnitnyye kharakteristiki morskogo l'da v diapazone 30–400 Mgts [Electromagnetic characteristics of sea ice in the range of 30–400 MHz]. *Doklady Akademii Nauk SSSR*, Tom 213, No. 3, p. 577–79.

Bogorodskiy, V. V., *and* Tripol'nikov, V. P. 1974. Radiolokatsionnoye zondirovaniye morskogo l'da [Radar sounding of sea ice]. *Zhurnal Tekhnicheskoy Fiziki*, Tom 44, Vyp. 3, p. 660–62.

Campbell, W. J., *and others*. 1974. Dynamics and morphology of Beaufort Sea ice determined from satellites, aircraft, and drifting stations, by W. J. Campbell, P. Gloersen, W. Nordberg and T. T. Wilheit. (*In* Bock, P., *and others, ed. COSPAR. Approaches to Earth survey problems through use of space techniques. Proceedings of the symposium held in Constance, F.R.G., 23–25 May 1973. Edited by P. Bock, with the assistance of F. W. G. Baker and S. Ruttenberg*. Berlin, Akademie-Verlag, p. 311–27.)

Campbell, W. J., *and others*. In press. Visual observations of floating ice from Skylab, by W. J. Campbell, R. O. Ramseier, W. F. Weeks and J. A. Wayenberg. [*In* Skylab 4 visual observations project report no. 2. Houston, Texas, Lyndon B. Johnson Space Center.]

Christoffersen, P. D. 1970. Recent radar soundings at fresh water ice and sea ice. (*In* Gudmandsen, P., *ed. Proceedings of the international meeting on radioglaciology, Lyngby, May 1970*. Lyngby, Technical University of Denmark, Laboratory of Electromagnetic Theory, p. 149–52.)

Chudobiak, W. J., *and others*. 1974. Radar remote sensors for ice thickness and soil moisture measurements, by W. J. Chudobiak, R. B. Gray, R. O. Ramseier, V. Makios, M. Vant, J. L. Davis and J. Katsube. *Proceedings. Second Canadian symposium on remote sensing, University of Guelph, Guelph, Ontario, Canada, April 29–May 1, 1974*. Ottawa, Canadian Remote Sensing Society, Vol. 2, p. 417–24.

Cook, J. C. 1960. RF electrical properties of salty ice and frozen earth. *Journal of Geophysical Research*, Vol. 65, No. 6, p. 1767–71.

Cumming, W. A. 1952. The dielectric properties of ice and snow at 3.2 cms. *Journal of Applied Physics*, Vol. 23, No. 7, p. 768–73.

Dunbar, M. 1975. Interpretation of SLAR imagery of sea ice in Nares Strait and the Arctic Ocean. *Journal of Glaciology*, Vol. 15, No. 73, p. 193–213.

Evans, S. 1965. Dielectric properties of ice and snow—a review. *Journal of Glaciology*, Vol. 5, No. 42, p. 773–92.

Finkel'shteyn, M. I., *and others*. 1970. Ob anizotropii zatukhaniya radiovoln v morskom l'du [On the anisotropy of radio-wave attenuation in sea ice]. *Izvestiya Akademii Nauk SSSR. Fizika Atmosfery i Okeana*, Tom 6, No. 3, p. 311–13.

Gloersen, P., *and others*. 1973. Microwave signatures of first-year and multiyear sea ice, [by] P. Gloersen, W. Nordberg, T. J. Schmugge and T. T. Wilheit [and] W. J. Campbell. *Journal of Geophysical Research*, Vol. 78, No. 18, p. 3564–72.

Gloersen, P., *and others*. 1974[a]. Ice thickness distribution as inferred from infrared and microwave remote sensing during the Bering Sea experiment, [by] P. Gloersen, R. [O.] Ramseier, W. J. Campbell, P. M. Kuhn and W. J. Webster, Jr. (*In Results of the U.S. contribution to the joint U.S.*/*U.S.S.R. Bering Sea experiment*. Greenbelt, Maryland, Goddard Space Flight Center, p. 103–21. (NASA X-910-74-141.))

Gloersen, P., *and others*. 1974[b]. Variation of ice morphology of selected mesoscale test areas during the Bering Sea experiment, [by] P. Gloersen, R. [O.] Ramseier, W. J. Campbell, T. C. Chang and T. T. Wilheit. (*In Results of the U.S. contribution to the joint U.S.*/*U.S.S.R. Bering Sea experiment*. Greenbelt, Maryland, Goddard Space Flight Center, p. 75–102. (NASA X-910-74-141.))

Goodman, R. H. 1974. Offshore exploration in the Arctic enhanced by ice measuring techniques. *Oilweek*, Vol. 25, No. 6, p. 10–12.

Gorbunov, Yu. A., *and* Losev, S. M. 1974. Ispol'zovaniye radiolokatsionnoy stantsii bokovogo obzora "Toros" dlya issledovaniya dreyfa l'da [Use of side-looking radar "Toros" to investigate ice drifts]. *Trudy Arkticheskogo i Antarkticheskogo Nauchno-Issledovatel'skogo Instituta*, Tom 316, p. 153–62.

Guinard, N. W. [1970.] The remote sensing of the sea and sea ice. *Proceedings of the sixth International Symposium on Remote Sensing of Environment . . . 1969*. . . . Ann Arbor, Willow Run Laboratories, Institute of Science and Technology, University of Michigan, Vol. 2, p. 737–54.

Hoekstra, P., *and* Cappillino, P. 1971. Dielectric properties of sea and sodium chloride ice at UHF and microwave frequencies. *Journal of Geophysical Research*, Vol. 76, No. 20, p. 4922–31.

Jirberg, R. J., *and others*. 1974. Application of SLAR for monitoring Great Lakes total ice cover, by R. J. Jirberg, R. J. Schertler, R. T. Gedney and H. Mark. (*In* Santeford, H. S., *and* Smith, J. L., *comp. Advanced concepts and techniques in the study of snow and ice resources*. Washington, D.C., National Academy of Sciences, p. 402–11.)

Johnson, J. D., *and* Farmer, L. D. 1971. Use of side-looking air-borne radar for sea ice identification. *Journal of Geophysical Research*, Vol. 76, No. 9, p. 2138–55.

Ketchum, R. D., *jr.*, *and* Tooma, S. G., *jr.* 1973. Analysis and interpretation of air-borne multifrequency side-looking radar sea ice imagery. *Journal of Geophysical Research*, Vol. 78, No. 3, p. 520–38.

Lamb, J., *and* Turney, A. 1949. The dielectric properties of ice at 1.25 cm. wavelength. *Proceedings of the Physical Society*, Sect. B, Vol. 62, Pt. 4, p. 272–73.

Larrowe, B. T., *and others*. 1971. Lake ice surveillance via airborne radar: some experimental results, [by] B. T. Larrowe, R. B. Innes, R. A. Rendleman, L. J. Porcello. *Proceedings of the seventh International Symposium on Remote Sensing of Environment . . . 1971*. . . . Ann Arbor, Willow Run Laboratories, Institute of Science and Technology, University of Michigan, Vol. 1, p. 511–21.

Loshchilov, V. S., *and* Voyevodin, V. A. 1972. Opredeleniye elementov dreyfa ledyanogo pokrova i peremeshcheniya kromki l'dov s pomoshchyu samoletnoy radiolokatsionnoy stantsii bokovogo obzora "Toros" [Determination of the drift elements of ice cover and ice edge movements by means of the airborne side-looking radar "Toros"]. *Problemy Arktiki i Antarktiki*, Vyp. 40, p. 23–30.

Meeks, D. C., *and others*. In press. A study of microwave emission properties of sea ice—AIDJEX 1972, by D. C. Meeks, R. O. Ramseier and W. J. Campbell. *Proceedings of the ninth International Symposium on Remote Sensing of Environment . . . 1973*. . . . Ann Arbor, Willow Run Laboratories, Environmental Research Institute of Michigan, [University of Michigan].

Morozov, P. T., *and* Khokhlov, G. P. In press. [Physico-chemical and electrical properties of near edge ice in the Bering Sea. Proceedings U.S.–U.S.S.R. Bering Sea experiment symposium, Leningrad, May 1974.]

Page, D. F., *and others*. 1973. Snow and ice depth measurements by high range resolution radar, by D. F. Page, G. O. Venier and F. R. Cross. *Canadian Aeronautics and Space Journal*, Vol. 19, No. 11, p. 531–33.

Parashar, S. K., *and others*. In press. Investigation of radar discrimination of sea ice, by S. K. Parashar, A. W. Biggs, A. K. Fung and R. K. Moore. *Proceedings of the ninth International Symposium on Remote Sensing of Environment . . . 1973*. . . . Ann Arbor, Willow Run Laboratories, Environmental Research Institute of Michigan, [University of Michigan].

Perry, J. W., *and* Straiton, A. W. 1972. Dielectric constant of ice at 35.3 and 94.5 GHz. *Journal of Applied Physics*, Vol. 43, No. 2, p. 731–33.

Ramseier, R. O., *and others*. 1974. Mesoscale description for the principal Bering Sea ice experiment, [by] R. O. Ramseier, P. Gloersen, W. J. Campbell, T. C. Chang. (*In Results of the U.S. contribution to the joint U.S.*/*U.S.S.R. Bering Sea experiment*. Greenbelt, Maryland, Goddard Space Flight Center, p. 31–74. (NASA X-910-74-141.))

Rouse, J. W., *jr*. 1969. Arctic ice type identification by radar. *Proceedings of the Institute of Electrical and Electronics Engineers*, Vol. 57, No. 4, p. 605–11.

Royer, G. M. 1973. The dielectric properties of ice, snow and water at microwave frequencies and the measurement of the thickness of ice and snow layers with radar. *CRC Report* No. 1242. [Dept. of Communications, Ottawa.]

Vant, M. R., *and others*. 1974. Dielectric properties of fresh and sea ice at 10 and 35 GHz, [by] M. R. Vant, R. B. Gray, R. O. Ramseier and V. Makios. *Journal of Applied Physics*, Vol. 45, No. 11, p. 4712–17.

Venier, G. O., *and others*. In press. Experiments with mobile X-band FM radar in measuring the thickness of fresh-water ice, by G. O. Venier, F. R. Cross and R. O. Ramseier. *CRC Technical Note*. [Dept. of Communications, Ottawa.]

Vickers, R. S., *and* Rose, G. C. 1972. High resolution measurements of snowpack stratigraphy using a short pulse radar. *Proceedings of the eighth International Symposium on Remote Sensing of Environment . . . 1972*. . . . Ann Arbor, Willow Run Laboratories, Environmental Research Institute of Michigan, [University of Michigan,] Vol. 1 p. 261–77.

Vickers, R. S., *and others*. 1974. Airborne profiling of ice thickness using a short pulse radar, by R. S. Vickers, J. Heighway and R. Gedney. (*In* Santeford, H. S., *and* Smith, J. L., *comp*. *Advanced concepts and techniques in the study of snow and ice resources*. Washington, D.C., National Academy of Sciences, p. 422–31.)

Von Hippel, A. R., *ed*. 1954. *Dielectric materials and applications*. Cambridge, Mass., Technology Press of Massachusetts Institute of Technology; New York, John Wiley and Sons Inc.; London, Chapman and Hall, Ltd.

Waite, W. P., *and* MacDonald, H. C. 1971. Snowfield mapping with K-band radar. (*In Short course. Radar remote sensing for geoscientists*. Lawrence, Kansas, University of Kansas, p. 5.4-1–5.4-26.)

Wentworth, F. L., *and* Cohn, M. 1964. Electrical properties of sea ice at 1–30 MC/S. *Radio Science Journal of Research NBS/USNC–URSI*, Vol. 68o, No. 6, p. 681–91.

Yoshino, T. 1961. Hyōkansetsu-jō no denpa denpa tokusei [Radio wave propagation on the ice cap]. *Nankyoku Shiryō: Antarctic Record*, No. 11, p. 228-33.

Zagorodnikov, A. A., *and others*. 1972. Two-dimensional statistical analysis of radar imagery of sea ice, by A. A. Zagorodnikov, V. S. Loshchilov and K. B. Chelysher. *Proceedings of the eighth International Symposium on Remote Sensing of Environment . . . 1972*. . . . Ann Arbor, Willow Run Laboratories, Environmental Research Institute of Michigan, [University of Michigan,] Vol. 1, p. 279–90.

DISCUSSION

R. VICKERS: With different polarizations you produce different images; have you considered using ratio techniques to distinguish ice types?

D. F. PAGE: This has not yet been done so far as I know, but is certainly worth exploring.