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A RADIOMETER METHOD FOR DETERMINING THE THICKNESS OF SEA ICE

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T.R. Hartz

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ABSTRACT

The disappointing performance of UHF and microwave radars for thickness measurements of sea ice can be attributed in large measure to the high absorption coefficients for such radiations. From a thermodynamic point of view this also means that the ice has a high emission coefficient and therefore should lend itself well to radiometer studies. This paper considers the use of airborne radiometers to monitor emissions from sea ice at ultra-high frequencies and, in particular, examines the possibility of obtaining ice thickness information by this means under certain limiting conditions. Although the situation is complicated because of the heterogeneous nature of sea ice and by the present lack of accurate information on the electrical properties of the ice, it is known that radiation in the indicated frequency range can penetrate a significant distance in the ice. Consequently, for a positive thermal gradient with increasing depth, and for dielectric absorption properties that are either constant or also increasing with depth, it will be shown that the observable radiation should be a characteristic function of ice thickness and of observing frequency. Observations on several frequencies can then be expected to yield an estimate of ice thickness.

The paper will discuss the expected results, the range of conditions under which the method might be applicable, and the kind of auxiliary information that might facilitate the data analysis.

INTRODUCTION

Experience has shown that conventional radar techniques are rather unsatisfactory for determining the thickness of sea ice. This situation is owing, in large part, to the severe attenuation suffered by UHF radiation in the ice. However, from a thermodynamic point of view, a high attenuation coefficient also means that the ice has a high emission coefficient for such frequencies. Accordingly, sea ice should lend itself well to VHF and UHF radiometer studies, especially under circumstances where the background interference levels are low, as they are likely to be in the Arctic.

Because of their ability to penetrate a significant thickness of sea ice, radio wavelengths appear to be better suited than infra-red wavelengths for sub-surface studies. In particular, the radiometer technique appears capable of providing a determination of ice thickness under certain circumstances. This paper will outline the kind of measurements that might be made and will discuss the results expected from such measurements. It will also consider the equipment requirements, along with some of the more obvious problems that may be encountered when applying the technique to an Arctic situation[2].

THEORY

A radiometer system is envisaged that can monitor the natural thermal emissions originating in the ice and water. This involves a sensitive radio receiver with a downward-directed antenna system that is carried on an aircraft flying over the sea surface as represented in Figure 1. For discussion purposes the ice is taken to be a horizontally-uniform sheet, beneath which there is a substantial depth of sea water. Winter conditions are assumed so that there is a positive gradient of temperature with increasing depth in the ice; however, the snow cover is taken to be insignificant at this stage. Neglecting for the moment any extraneous radiation, it is possible to describe the radiation reaching the radiometer in terms of the Rayleigh-Jeans formula,

$$E_f = \frac{2kT}{\lambda^2} \, . \qquad \ldots\ldots \text{(1)}$$

This represents the radiation from a black body in free space in a frequency range from f to f + Δf, where k is Boltzmann's constant, T is the absolute temperature, and λ is the wavelength. Because we are not dealing with a black body, the more appropriate relation is

$$B = \frac{2kT_B}{\lambda^2} \, , \qquad \ldots\ldots \text{(2)}$$

where B is the *brightness* in units of watts$\cdot m^{-2} \cdot Hz^{-1} \cdot sr^{-1}$, and T_B is the brightness temperature, which is the temperature that a *black body* should

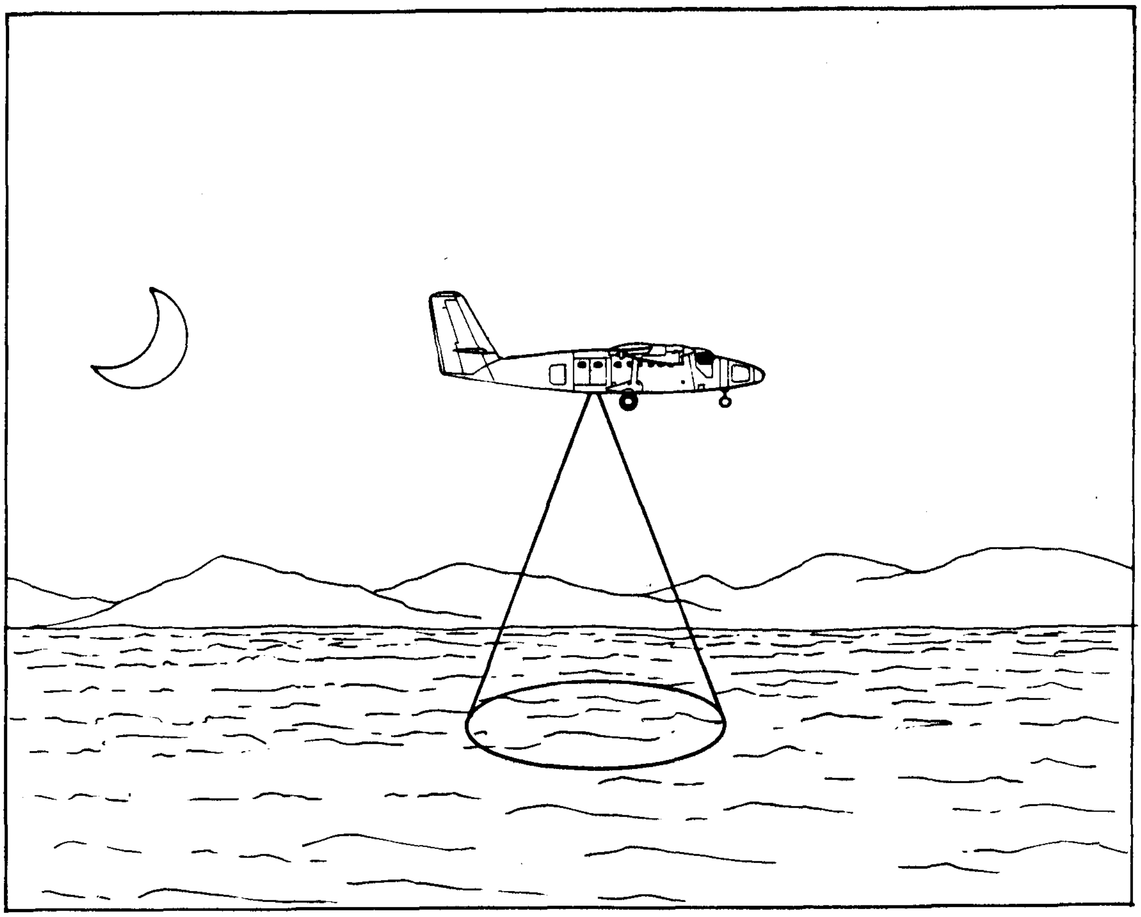

Fig. 1. Schematic representation of airborne radiometer system.

have to give the same brightness in the Δf interval. T_B is related to the temperature by the relation

$$T_B = \eta T \,, \qquad \text{..... (3)}$$

where η is the emissivity, a factor less than unity.

In the present application the radiometer is to measure the radiated power reaching it from the surface within the acceptance beam of the antenna. The power (in watts) measured is given by

$$P = kT_a \, \Delta f \,, \qquad \text{..... (4)}$$

where T_a is an apparent temperature that is usually called the antenna temperature.

For an ice surface that is more extensive than the antenna pattern, and for a lossless system, it can be shown that the observed temperature is independent of antenna gain, and that

$$T_a = T_B \quad . \qquad \ldots\ldots (5)$$

Accordingly, it will be convenient to use a temperature concept throughout the analysis, rather than one of energy or power.

Because the ice sheet is assumed to be homogeneous in the horizontal plane, but not in the vertical dimension, both T and η will vary only with depth. In addition, some portion of the emitted radiation will be reflected at the ice-air interface and only a fraction, represented by the transmission coefficient, τ_1 is observable. Furthermore, emissions from deep in the ice will be attenuated by the overlying layers. Consequently, the radiation contribution expected from the ice sheet can be expressed in terms of the depth parameter, x, as follows,

$$T_1 = \tau_1 \sum_0^t T_x \eta_x \exp \left(- \sum_0^x \alpha_x \Delta x\right) \quad . \qquad \ldots\ldots (6)$$

Here t is the ice thickness, and T_x, η_x and α_x are respectively the absolute temperature, the emissivity and the absorption coefficient at a depth x where the coordinates are as indicated in Figure 2. It is, of course, the unknown parameter, while the other three have depth variations that, while not known, can be approximated to some degree. For winter conditions T_x will lie between the surface temperature, T_0, (which is probably not too different from the mean air temperature in the absence of a snow cover) and that of the underlying water, T_w. As a not-too-critical approximation the profile can be taken as linear, so that

$$T_x = T_0 \left[1 + \frac{(T_w - T_0)x}{T_0 \, t}\right] , \qquad \ldots\ldots (7)$$

The energy absorbed in a Δx thickness of ice can be expressed in terms of the absorption coefficient, α, and the incident and emerging energy, P_0 and P_1, as

$$P_1 = P_0 \exp (-\alpha \Delta x) \quad . \qquad \ldots\ldots (8)$$

Here α can be defined in terms of the dielectric constant (i.e., the permittivity of the medium relative to that of free space), ε, the loss tangent, $\tan \delta$, and the free space wavelength λ_0, as follows,

$$\alpha = \frac{4\pi}{\lambda_0} \left[\frac{\varepsilon}{2} \left(\sqrt{1 + \tan^2 \delta} - 1\right)\right]^{\frac{1}{2}} \quad . \qquad \ldots\ldots (9)$$

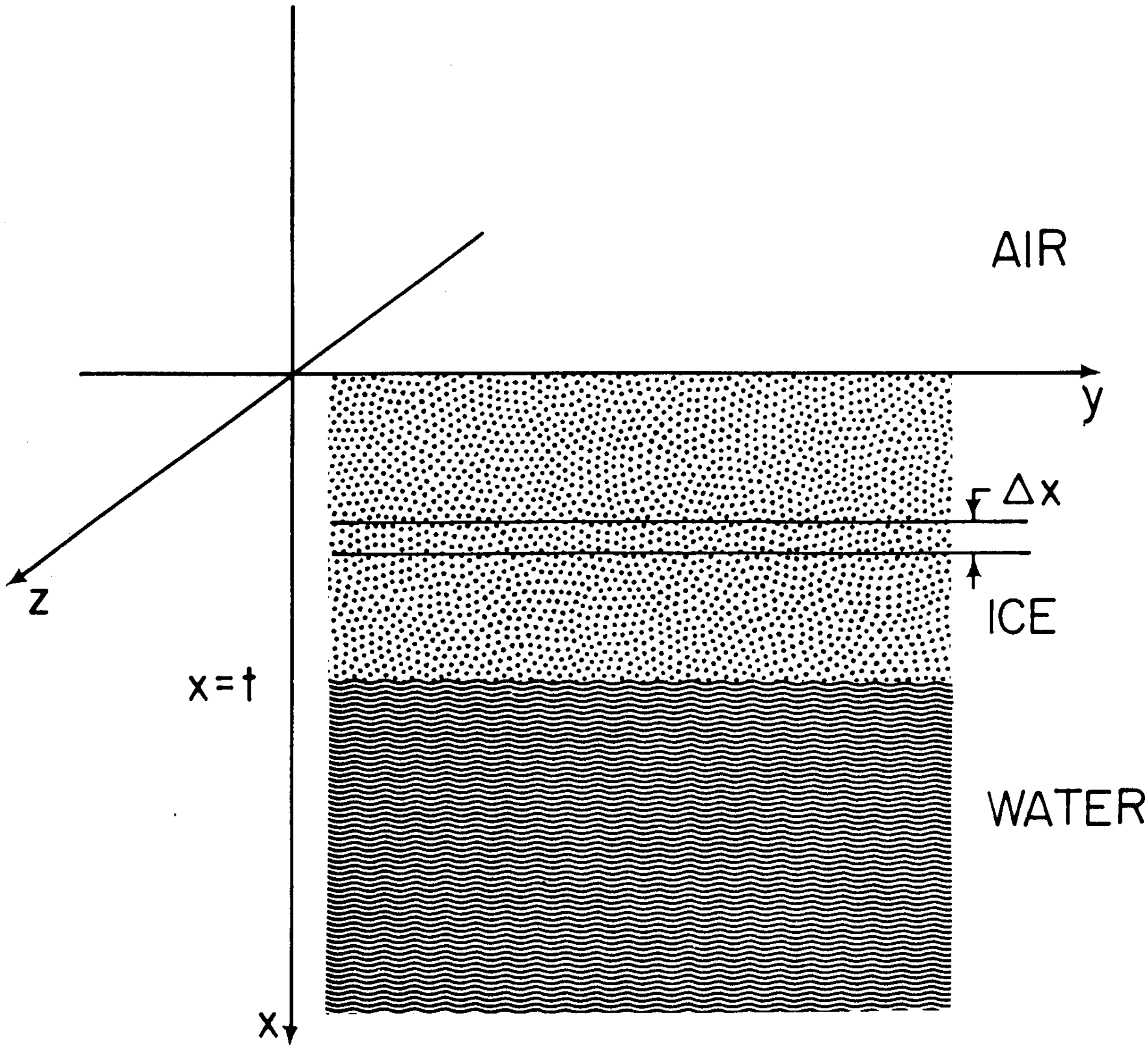

Fig. 2. Diagram depicting the system of coordinates used in the analysis.

For the wavelengths of interest the values of tan δ and ε are not known in sea ice. Estimates have been made on the basis of an extrapolation from lower frequencies, and these suggest than an ε value of about 4, independent of depth, and a tan δ value in the range 0.1 to 1.0 and increasing linearly with depth, may be reasonable first approximations.

In a local thermal equilibrium situation, the emissivity is related to the absorptivity, so that

$$\eta_x = 1 - \exp\,(-\,\alpha_x\,\Delta x)\;. \qquad \text{..... (10)}$$

In the event that t is sufficiently small, the radiometer will observe emission contributions from the water under the ice in addition to those from the ice. Because the water can be taken as isothermal and homogeneous, the emissions will be independent of depth in the water. However, they will depend on the transmission coefficient, τ_3, across the water-ice interface, on attenuation within the ice, on the ice thickness and on the transmission coefficient across the ice-air surface, τ_1. Accordingly, the radiation contributions coming from the water may be represented as

$$T_2 = T_w \phi , \qquad \ldots\ldots (11)$$

where ϕ is an involved function representing the indicated variation. A detailed evaluation of ϕ is possible using the formulation described by Stratton[1] but, because ϕ includes properties of the ice that are not well known, it will be sufficient for present purposes to use a simpler function. The approximation that is appropriate for the case of appreciable absorption in the ice sheet is

$$\phi = \tau_1 \ \tau_3 \ \exp \ (- \sum_{0}^{t} \alpha_x \Delta x) \qquad \ldots\ldots (12)$$

This approximation does not include the effects of interference between radiation reflected at the upper and lower boundaries of the ice sheet, but these effects are unlikely to be large if the absorption is significant.

The transmission coefficients, τ, can be described in terms of the refractive indices n_i and n_w, the refractive indices of ice and water, respectively, with that of air being taken as unity. Thus

$$\tau_1 = \frac{4 \ n_i}{(n_i + 1)^2} , \qquad \ldots\ldots (13)$$

and

$$\tau_3 = \frac{4 \ n_w n_i}{(n_w + n_i)^2} . \qquad \ldots\ldots (14)$$

It should be noted that this value for τ_3 applies to the plane-interface case. For sea ice the water interface is known to be rather diffuse and striated in the vertical direction. As a consequence the transmission coefficient is likely to be somewhat higher than the value given here. Since ice and water are poorly conducting dielectrics at the frequencies of interest, the expression for refractive index,

$$n = [\frac{\varepsilon}{2} \ (1 + \sqrt{1 + \tan^2 \ \delta}) \ ]^{\frac{1}{2}} , \qquad \ldots\ldots (15)$$

can be approximated adequately as

$$n = \sqrt{\varepsilon}. \qquad \ldots\ldots (16)$$

In the limiting case of t = 0, ϕ becomes simply the transmission coefficient across the water-air interface, τ_2, which is given by

$$\tau_2 = \frac{4\, n_w}{(n_w + 1)^2}\ . \qquad \ldots\ldots (17)$$

The airborne radiometer will measure T_a, the sum of the ice component, T_1, and the water component, T_2. Figure 3 shows the expected variations of these three temperatures with ice thickness, t (in this diagram t is given in arbitrary units because of the lack of precise values for the absorption coefficients). The measured T_a value must then be interpreted in terms of ice thickness, and for the method to be useful the thickness must be determined in absolute units. Considering the uncertainties in the foregoing development this may seem a formidable task, but on closer inspection the situation has a number of promising aspects. These will be discussed in the following section.

INTERPRETATION

It is obvious that the theoretical expressions derived above have to be related to the real world before this technique can be applied to the measurement of ice. The main problems at this stage are that sea ice is not a homogeneous substance, and that the transmission properties of VHF and UHF radiation in sea ice are not known other than in a qualitative sense. Nevertheless, it is still possible to draw some conclusions in certain limiting cases, particularly if one considers taking observations simultaneously on a number of widely-spaced frequencies. It is, of course, essential that as a prelude to any operational measurements, a fairly extensive series of 'calibration' observations be made under circumstances where the ice parameters can be verified. Hopefully, curves of brightness temperature versus ice thickness can be produced at a number of frequencies that would be representative of a small number of ice types (e.g., first-year ice, multi-year ice), against which operational measurements might be compared without having to know all the ice properties in great detail.

In the case of ice that is so thick that the contributions from the underlying water are negligible at the observing frequency, the brightness temperature is described by equation (6). Since the temperature gradient in the ice is likely to be low in such circumstances, the observed temperature will be only slightly higher than $\tau_1 T_0$. T_0 can probably be estimated fairly well on the basis of the mean air temperature and τ_1 can probably be specified within fairly narrow limits on the basis of experience and preliminary observations. It then remains to compare observations on different frequencies to find where a significant departure from $\tau_1 T_0$ occurs, as illustrated in

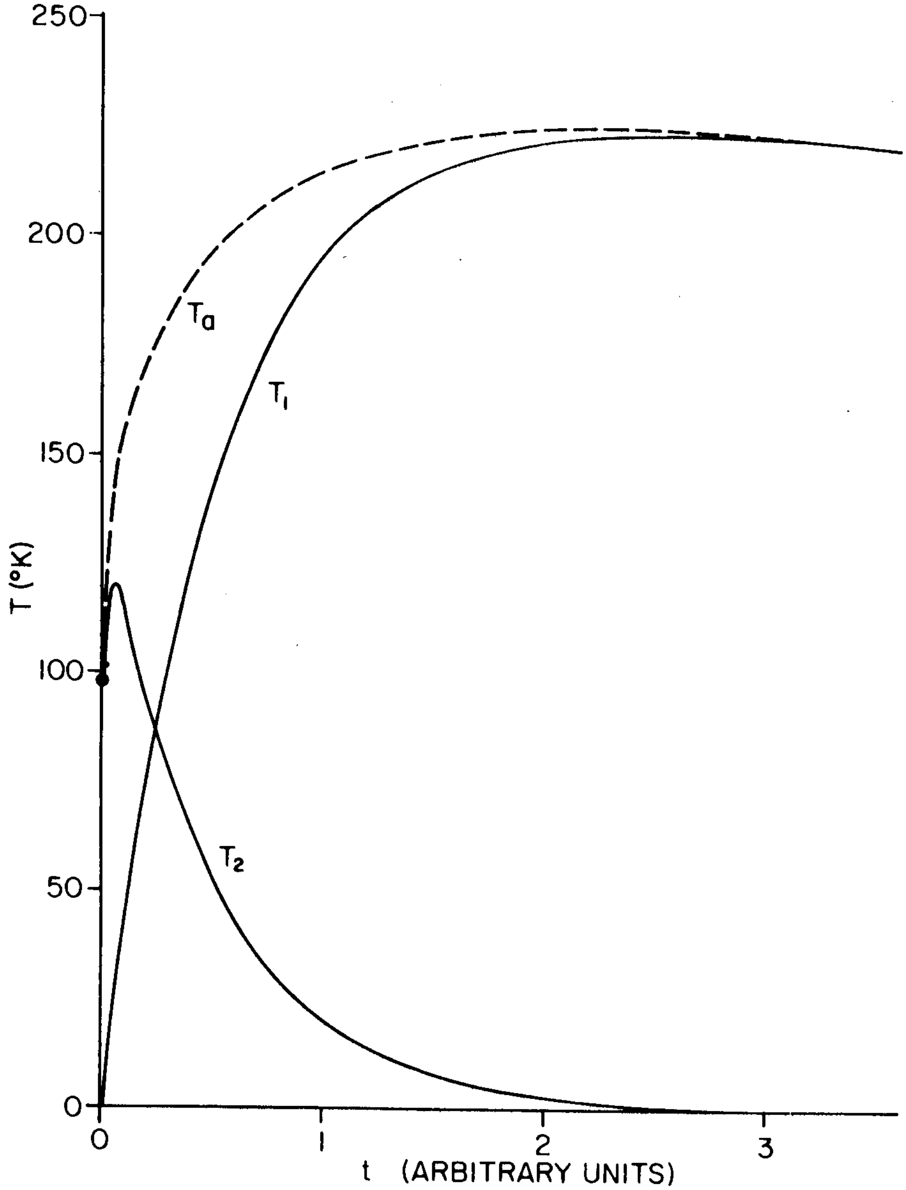

Fig. 3. Variation of T_1, T_2, and T_a with ice thickness.

Figure 4, which would then yield an estimate of t within certain limits that presumably will have been set empirically.

The situation for very thin ice is one in which the contributions from the ice are smaller than those from the water, though the latter are modified to a certain extent by the presence of the thin ice sheet. The detailed nature of this modification will depend on the particular ice properties, and experience will undoubtedly indicate how to evaluate this. In any event, the

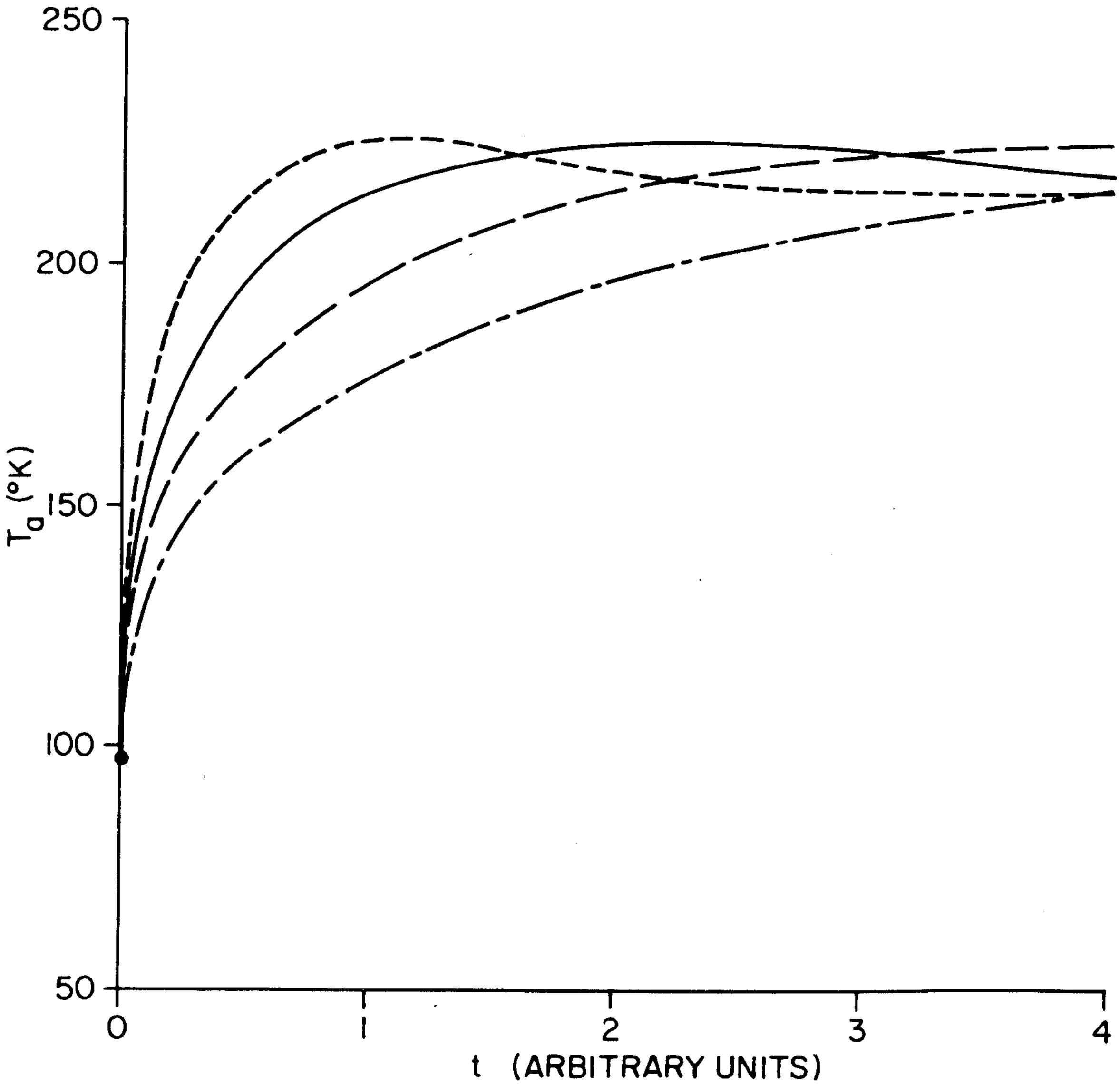

Fig. 4. Variation of the brightness temperature at four different frequencies with ice thickness.

observed brightness temperature is expected to fall substantially below $\tau_1 T_0$, as indicated in Figure 5. In the limiting case when t = 0, i.e., open water, the observed brightness temperature should be $\tau_2 T_W$, and both τ_2 and T_W are likely to be known fairly accurately. Thus for the thin-ice situation the brightness temperature should fall between $\tau_2 T_W$ and $\tau_1 T_0$, and again different frequencies can be expected to show different values so that a determination of t can probably be made without too much difficulty.

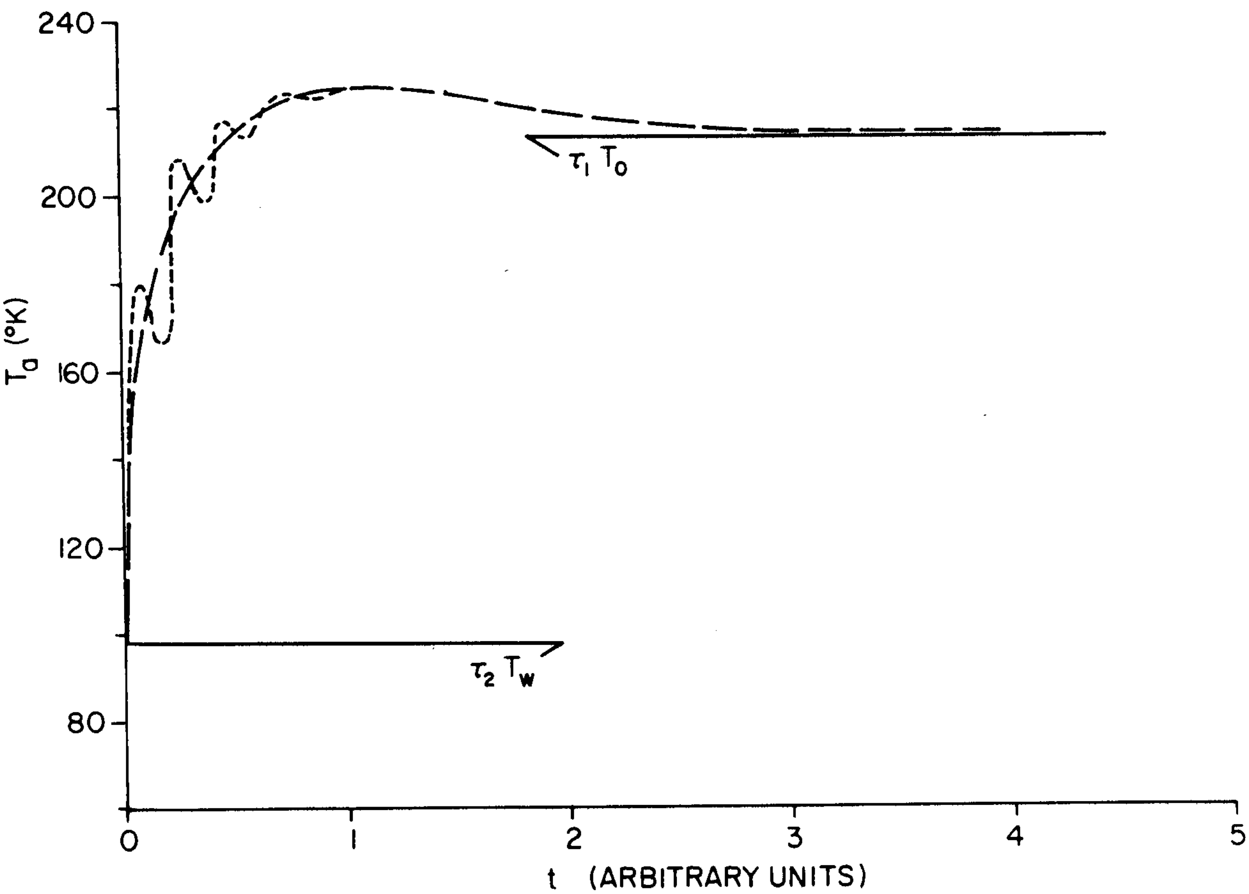

Fig. 5. Brightness temperature versus ice thickness in relation to the surface radiation, $\tau_1 T_0$, and to the radiation from open water, $\tau_2 T_w$.

For intermediate ice thicknesses the situation appears somewhat less predictable at this stage. The transmission coefficients are oscillating functions of the thickness t, although the amplitude of the oscillations is not expected to be very large in most cases. A comparison of observed temperatures at several frequencies will unquestionably be of considerable value (cf Figure 4), but it is not clear at present that an unambiguous estimate of t can always be expected. Clarification on this point will probably not come until some representative data can be analyzed.

SUPPLEMENTARY CONSIDERATIONS

The foregoing discussion has considered just the radiation expected from the ice and the underlying water. However, in an operational situation a number of additional factors and noise contributions would have to be considered. These cannot be discussed in detail here, but a general idea of the relative importance of some of the principal ones is required.

At frequencies above a few hundred MHz man-made interference is usually confined to line-of-sight propagation, so that only local interference sources are likely to be of concern. In the Arctic regions the VHF and UHF portions of the spectrum are not very crowded and it should not be too difficult to avoid man-made interference. The only source that may present serious problems is the aircraft carrying the radiometer, and here it will probably be necessary to take special measures to prevent interference from aircraft systems.

Some contamination from galactic radio noise that is reflected from the ice surface is expected. In the Arctic regions the galactic noise temperature varies from approximately 30°K at 400 MHz to about 2°K at 1500 MHz, with a small diurnal variation in each case. The reflected contribution amounts to $(1 - \tau_1)$ of the galactic temperature, and this is not expected to exceed 5°K for this range of frequencies, and will probably be less than 10°K for observing frequencies above about 200 MHz. This temperature is an additive component and should not present a major problem since it can be allowed for in the measurements.

Polarization considerations have not been included here since it is assumed that observations will be taken in the nadir direction. Atmospheric attenuation should not be a problem at the long wavelengths suggested as appropriate for these measurements, and noise contributions from the antenna and transmission lines to the radiometer can be kept to a minimum with proper instrumentation techniques. Of greater concern is the effect on the measurements of snow cover on top of the ice. The very small attenuation introduced at these wavelengths would probably be more than counteracted by somewhat increased ice emissions resulting from a higher ice temperature because of the insulating properties of the snow. On the other hand, the effect of the snow on τ_1 is not known at this time, though preliminary observations will undoubtedly be able to establish this.

The most serious problem probably involves the assumption of horizontal uniformity for the ice sheet. Arctic experience suggests that the more normal situation is one in which there are numerous pressure ridges and the other thickness variations where the ice is both thicker and thinner than the average. The radiometer, of course, can only produce a single value which essentially is an average over the surface included in the antenna pattern. If a significant portion of this consists of much thinner ice, some lowering of the observed temperature may occur, while the inverse may result from large areas of very thick ice. Furthermore, in the case of leads of open water or regions of very thin ice a substantial reduction in temperature should be observable. This suggests that special purpose radiometers might be devised with highly directional antennas to search out leads or ridges.

EQUIPMENT REQUIREMENTS

The radiometer technique appears capable of providing an estimate of the thickness of sea ice if observations are made on a number of frequencies. For adequate penetration in the ice these frequencies should all be less than about 1.5 GHz. The low-frequency limit will be set by the interference levels experienced and by galactic noise dilution, but at this stage it seems likely that observations can be made down to at least 200 MHz.

Each radiometer should be capable of measuring an apparent temperature in the range from about 70°K to about 300°K, with an accuracy of a few degrees. The antennas should be reasonably directional without being so large as to prohibit their use on an aircraft. The aircraft should be as free from interference as possible, and be flown at a modest height so that the antenna beam can sweep out a lane of the order of 100 ft. wide.

Auxiliary measurements that would be most useful include measurements of the surface temperature with an infra-red or microwave system, and possibly radar measurements on the nature of the surface itself. As well, several "calibration" sites would be useful along the route, where *in situ* measurements of the ice thickness and thermal profile could be obtained through telemetry.

Finally, it is admitted that the data interpretation may not always be easy; nevertheless, such radiometer measurements would contain information on the subsurface from which ice thickness may be obtainable in many cases. Whether this potential can be developed remains to be seen.

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2. Hartz, T.R. *A Radiometer Method for Determining the Thickness of Sea Ice.* Proceedings of the Seminar on Thickness Measurements of Floating Ice by Remote Sensing, held at Defence Research Establishment Ottawa, October 27-28, 1970.

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