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ICE(U) NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
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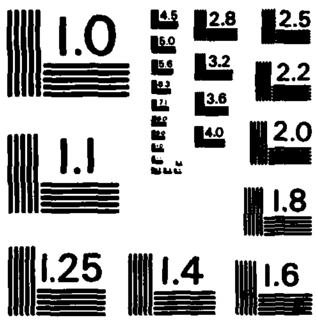

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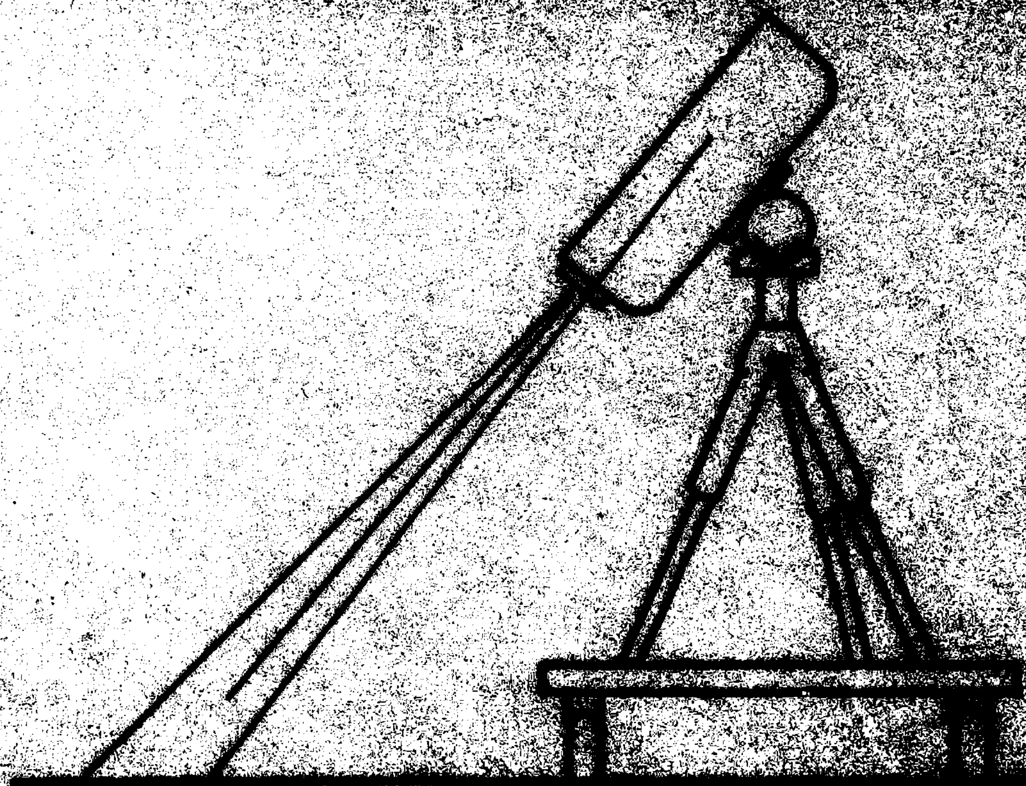

Abstract

The 33 GHz brightness temperature (T_b) of a 40-meter strip of multi-year ice was obtained using a sled-mounted radiometer. Snow accumulations along the strip varied from 0 to 40 cm. After the snow was removed, T_b was re-measured. Detailed comparisons of snow depth vs. change in T_b show that snow thickness or snow water equivalent alone are not sufficient to describe the emissivity of the snow pack.

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Acknowledgments

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In April 1976, NORDA obtained [illegible] passive [illegible] y [illegible] near Barrow, Alaska. This data was analyzed (Ketchum and Lohanick, 1980) to determine the usefulness of this remote sensor to interpretation of sea ice features and ice type. It was found that first-year ice and younger forms could be easily distinguished from multi-year ice, and younger forms could be easily distinguished from open water by using patterns and overall radiometric temperature (T_b). Multi-year ice has an average radiometric temperature several degrees below that of first year ice. It also has a broad range of radiometric temperatures over horizontal distances of the order of tens of meters. Figure 1 shows one portion of the 1976 imagery. Dark shades on the microwave image are high radiometric temperatures. The area is mostly multi-year ice.

There is no simple explanation for the great variation in T_b on a multi-year ice floe, but the floe is certainly composed of a less homogeneous medium than first-year ice, having undergone melt seasons and stresses due to pack ice motion and having been reconsolidated with other floes in the freezing seasons. But, is the variation in T_b due to the horizontal (and vertical) variation in the ice itself, or to the masking effect of a snow cover which is non-uniform because of the undulating surface of the floe, or is it due to both? Campbell et al. (1978) concluded that the effect of snow cover is very pronounced on first year ice and could be significant on multi-year ice. We look more closely at one of their deductions below. In this note, we consider data regarding the effects of the snow cover, and compare the data to a simple emission model for snow.

THE PRESENT EXPERIMENT:

In May 1980, Polar Oceanography Branch of NORDA carried the NORDA portable 33 GHz radiometer to sea ice near Barrow, Alaska. Virtually every type of sea ice was encountered, including a small multi-year floe with various types of snow cover.

The radiometer was mounted on a small sled, with the horn antenna looking to the side toward the surface (Figure 2) approximately 40° from nadir, and with the surface about 1.2 meters from the horn. The far field of this horn begins at approximately 1.2 meters from the horn, so we were not encountering changes in T_b due to the proximity of the surface. We chose an area of surface approximately 60 meters long and 1 meter wide, which crossed some relatively bare ice (snow cover less than, say 2 cm) and some with a snow depth up to 40 cm thick. The line was marked with a cord knotted at 10-meter intervals. Radiometric temperature was recorded continuously along the track on a strip chart recorder.

A transit consisted of one pass over the surface from both directions (See Figure 3). After three transits, we measured the thickness of the snow at 2-meter intervals and removed it with shovels, down to relatively bare ice. The surface was not swept clean, but all loose snow was removed. Some of its characteristics were noted, such as structure and density. Then, two more radiometer transits were completed.

THE PRESENT EXPERIMENT: (cont'd.)

One day later, the same area was once more measured with the radiometer. The surface was still relatively snow free, but two very thin ($\sim$2cm) and narrow ($\sim$15cm) drifts had developed across the track due to overnight winds. The radiometric temperature had not changed measurably from the previous day.

DESCRIPTION OF THE EXPERIMENT SITE:

Figure 4 is a vertical cross-section diagram of the study area. The relatively snow-free portions of the chosen area were multi-year ice with entrapped air bubbles and a thin (<2cm) crust of ice-snow. The two deep-snow-covered portions were found, after snow removal, to be frozen fresh water which was probably a part of the runoff which occurs in the summer melt season. These portions consisted of bubble-free and relatively brittle ice. We will call these portions melt ponds, although the overall shape of them was not investigated. The surface of these melt ponds was about 30 cm below the surface of the surrounding multi-year ice, so that, with the snow cover in place, the undisturbed surface of the study area was relatively flat.

The snow cover on the melt ponds proved to be of two distinct types. One snow type, we will call granular. It consisted of loose individual ice crystals approximately 2 mm in diameter. The second snow type can be best described as "igloo snow." When a shovel was pushed under the snow and lifted, it would come up in one large chunk. Its density was not very high, and when crushed in the hand, it fell into a very fine powder. Its undisturbed structure could best be described as a frozen "froth," with entrapped bubble size less than 1 mm.

RESULTS

Figure 5 shows T_b (Kelvins below ambient) along the track, both before (dotted) and after (solid) snow removal. The values plotted are averages over all the runs taken, although the differences between runs in any particular case were not more than a few Kelvins.

The T_b difference (Kelvins) along the track, and the measured snow depth (mm) are shown in Figure 6. Notice that the difference plotted is T_b (with snow) - T_b (without snow) to demonstrate the drop in T_b caused by a snow cover.

OTHER RESULTS

Quite recently, Ulaby and Stiles (1980) presented a semi-empirical model of the T_b of snow cover on an underlying medium, and tested it with field experiments. The model begins with a thin snow layer which emits its own thermal radiation, and absorbs and scatters the radiation from underlying layers. Several such layers are piled up on an underlying layer of soil. Transfer of radiation through this structure is solved using several simplifying assumptions. One of the main assumptions made in the model is that the absorption of radiation in the snow does not depend on angle (i.e., the scattering is isotropic).

OTHER RESULTS (cont'd.)

The resulting expression for the emissivity ϵ of the snow layer (the ratio of the T_b to the physical temperature T_o of the snow) is

$$\epsilon = A + Be^{-\alpha \sec\theta \cdot W} \qquad (1)$$

in which θ is the radiometer look angle with respect to nadir
α is the extinction coefficient (rate at which incident energy is lost by scattering and absorption)
A ,B are constants which depend on absorption coefficients in the snow and the Fresnel reflection coefficients between snow and soil, and soil and air.
W is the water equivalent of dry snow (the density of the snow (gm/cm^3) times its thickness).

Ulaby and Stiles performed field experiments to fit the three parameters in (1). Their results for 37 GHz were

$$\epsilon(27°) = 0.517 + 0.481e^{-0.0235W}$$
$$\epsilon(57°) = 0.586 + 0.273e^{-0.0617W} \qquad (2)$$

CONCLUSIONS

The two curves given in (2) above are plotted in Figure 7. Water equivalent W is changed to ρh, where h is the snow depth and ρ is the density. Our measured density for both snow areas was 0.34 gm/cm^3

We plot change in brightness temperature

$$\Delta T = T\text{ (with snow)} - T\text{ (without snow)}$$

for the entire length of the track, vs measured snow depth. Using (1) we have: (with $\epsilon = \frac{T_b}{T_o}$)

$$\Delta T = T(W) - T(W=0)$$
$$= T_o (A + Be^{-ah}) - T_o (A + B)$$
$$= BT_o (e^{-ah} - 1) \qquad (3)$$

where a is the appropriate constant in (2) multiplied by ρ = 0.34 gm/cm^3

The two curves for ΔT using (3) are plotted in Figure 7 using T_o=260K. A 500 mm deep snow layer would be expected to have a T_b about 40K lower than bare ice under these conditions.

CONCLUSIONS (cont'd.)

Since the snow depth measurements along the traverse were taken with some markers disturbed, it is not possible to compare the snow depth and T_b curves (Figure 6) point-for-point.

In Figure 8, we consider the distribution of snow depth and T_b separately for the two snow areas. The sampling intervals were 1 cm and 1K respectively.

Figure 8 shows that the undisturbed igloo snow was generally deeper than the granular snow, and that the resultant changes in T_b were markedly different. The magnitude of the change in T_b is not inconsistent with the Ulaby and Stiles model.

Comparing Figures 8a, 8b, and 6, we may also infer that once the igloo snow reaches depths of more than say 200 mm, ΔT_b reaches a limit, in this case -35K. Granular snow seems to display an effect on T_b for depths of at least 250 mm, but no deeper snow of this type was measured. This comparison seems to indicate that the extinction of 33 GHz radiation occurs within 20 cm in the igloo snow, and perhaps slower in the granular snow.

The important conclusion to be drawn from these results is the dependence of apparent T_b on snow type. Volume scattering effects are fully expected under these conditions, and scattering models (such as that of Grenfell (1981)) depend strongly on snow structure and properties. We believe that volume scattering is an important effect here, and it will, therefore, be the subject of our upcoming research.

We return to Campbell, et al. (1978) to note that one of their deductions regarding snow cover was made from studying the 37 GHz T_b of ice near a campsite (Juno) with an airborne radiometer. The effect of snow was to raise the T_b by 21K at a viewing angle of 45°. Ulaby and Stiles (1980) did not cite the Campbell et al. results. It is clear that this sort of discrepancy should be investigated in more detail.

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Grenfell, T. (1981). Proceedings of the Second Workshop on the Microwave Remote Sensing of Sea Ice & Icebergs, Langley Research Center, Hampton, VA, April 6-9, 1981, p. 388-391.

Ketchum, R. D. and A. W. Lohanick (1980). Passive Microwave Imagery of Sea Ice at 33GHz, Remote Sensing of Environment 9, p. 211-223.

Ulaby, F. T., and W. H. Stiles (1980). The Active and Passive Microwave Response to Snow Parameters 2. Water Equivalent of Dry Snow, Journal of Geophysical Research 85, v. C2, p. 1045-1049.

AERIAL PHOTO   1 km

MICROWAVE IMAGE

Figure 1. Microwave image of multi-year ice, and simultaneous photo of same area. Is motley nature of microwave image due to snow cover, ice structure, or both?

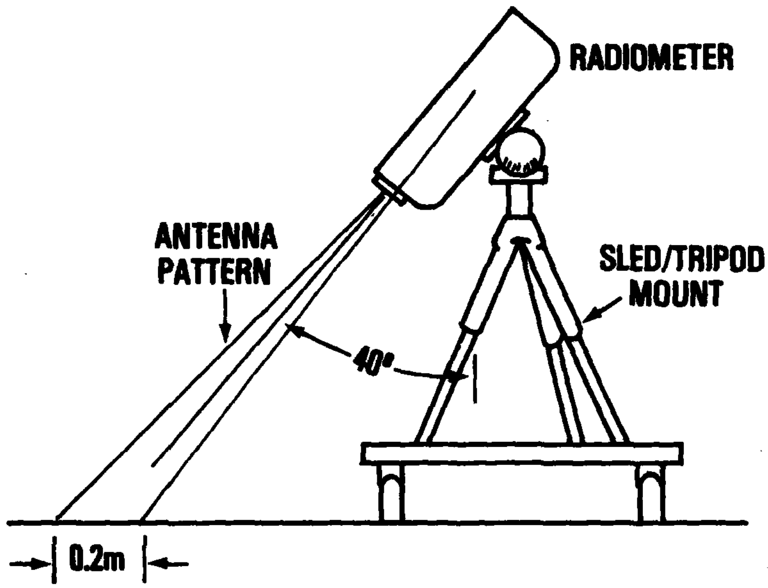

Figure 2. Radiometer configuration

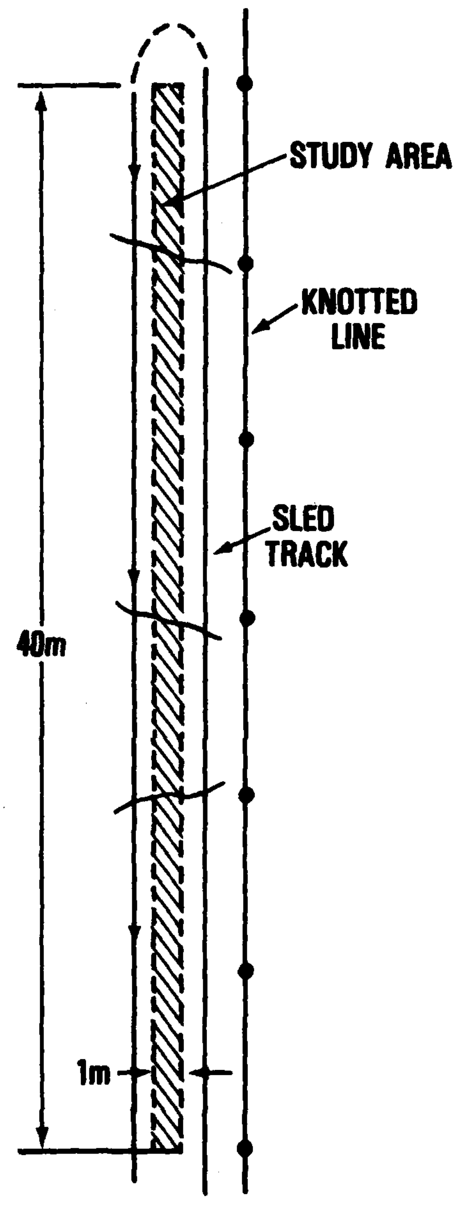

Figure 3. Top view of study area

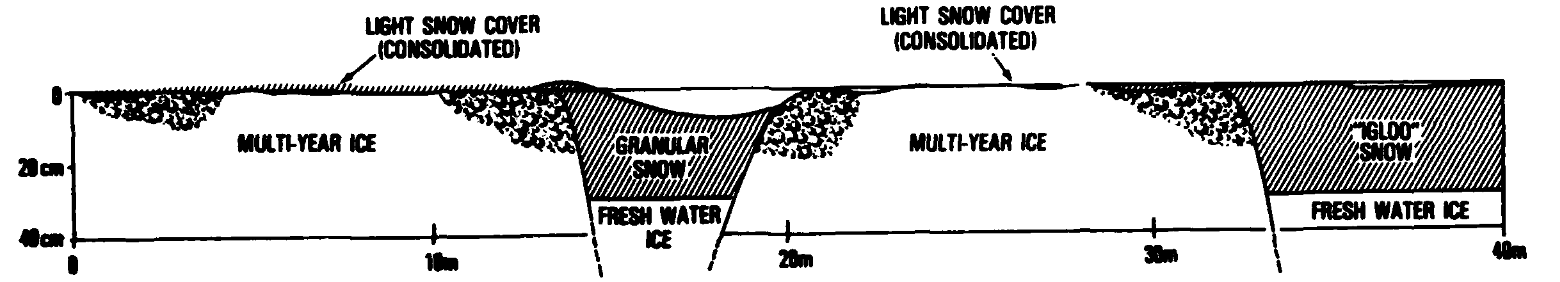

Figure 4. Vertical cross-section sketch of study area

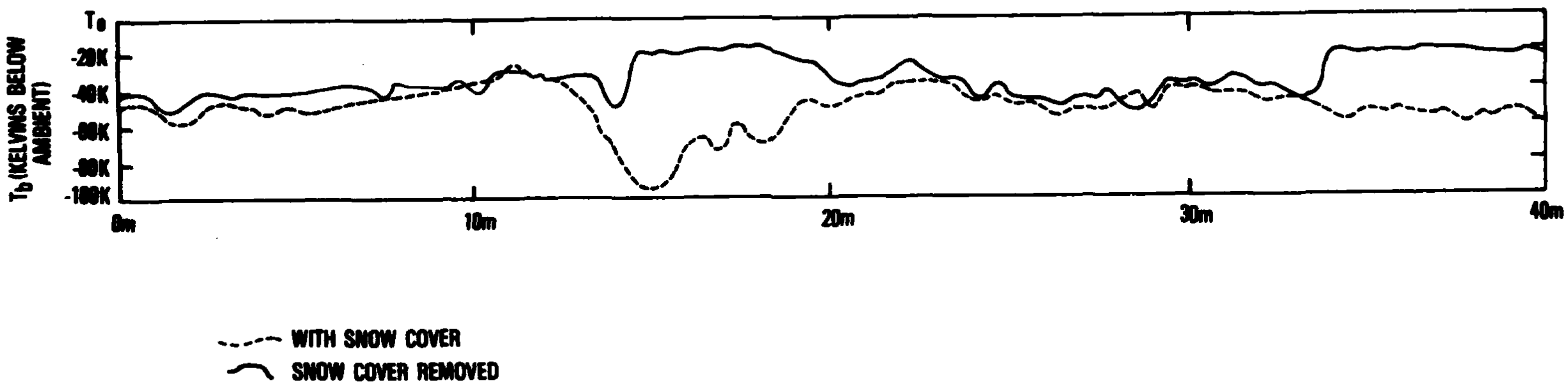

Figure 5. Brightness temperatures along track before and after snow removal

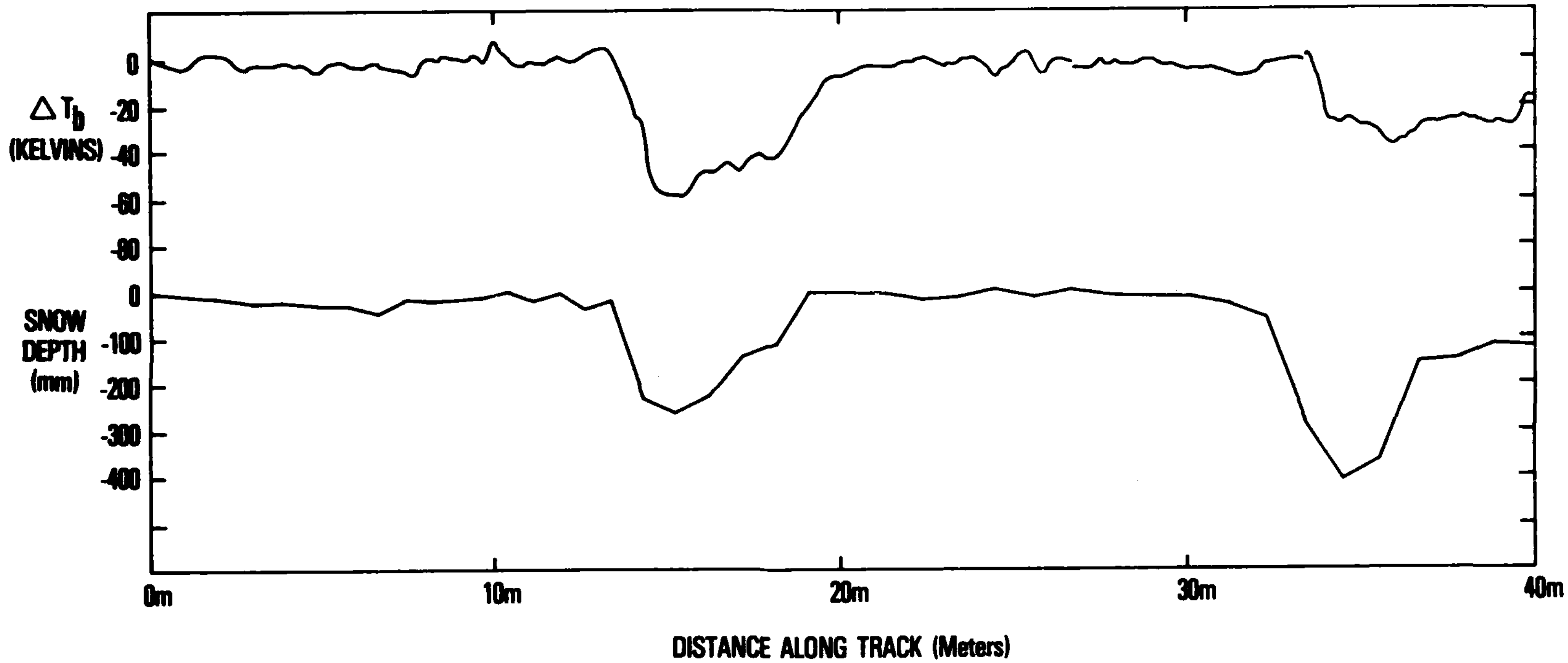

Figure 6. Brightness temperature difference due to snow cover (T_b (with snow) $-T_b$ (without snow)) and corresponding measured snow depth along test track

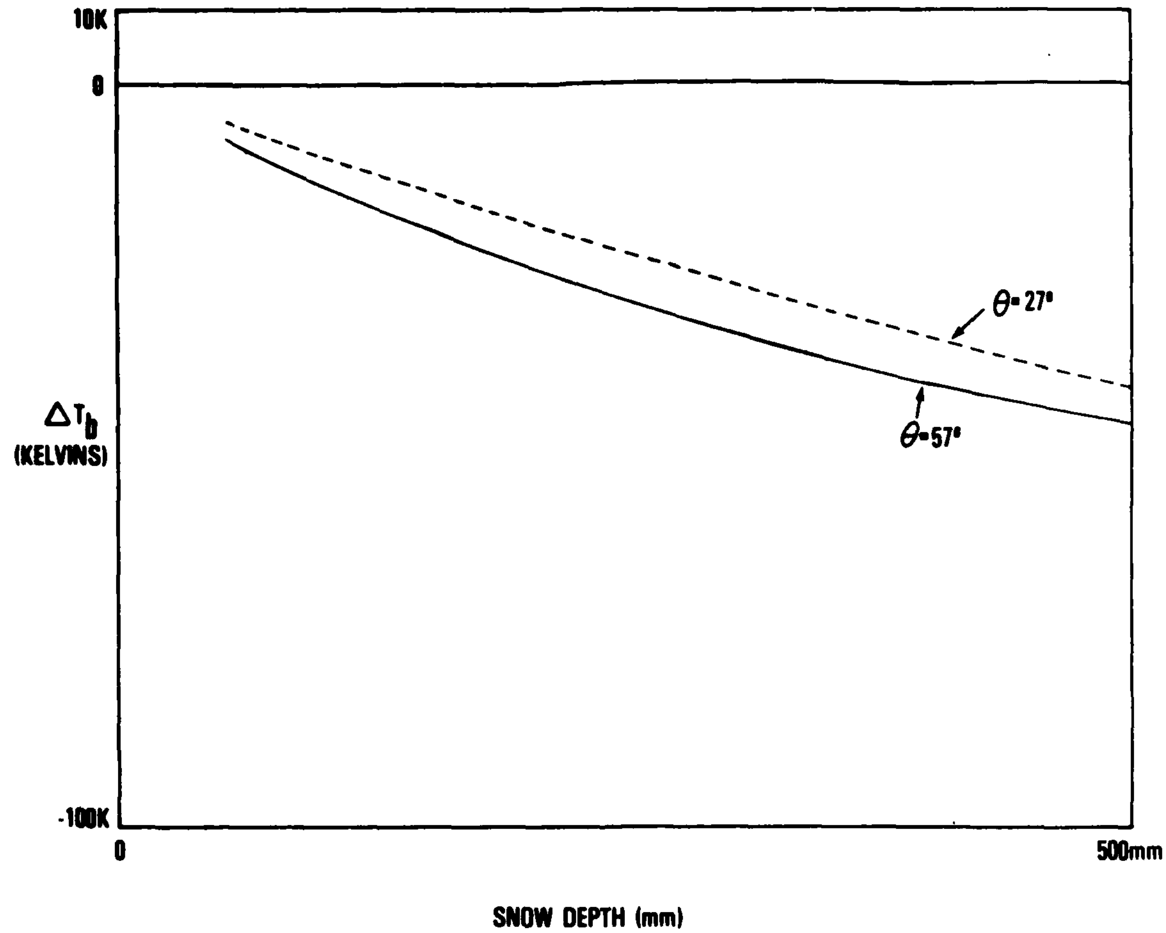

Figure 7. ΔT_b *vs. snow depth from model of Ulaby and Stiles (1980).*

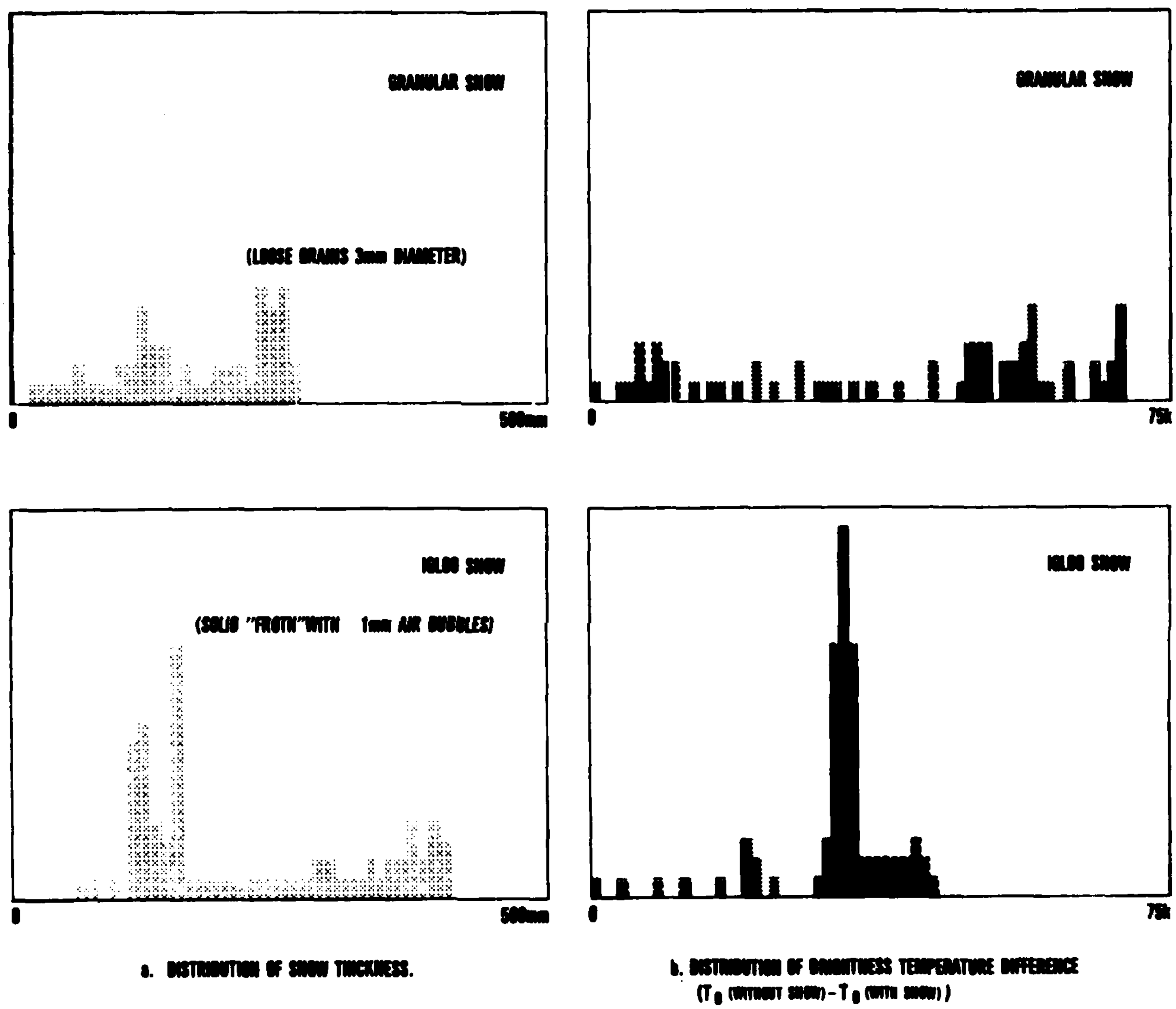

Figure 8. Comparison of effects of granular snow cover and igloo snow cover on multiyear ice brightness temperature. Note that the generally deeper igloo snow had a smaller effect on T_B than shallower granular sand.

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