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REMOTE SENSING OF SEA ICE IN NARES STRAIT AND THE ARCTIC OCEAN, MARCH 1973

By

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The material discussed in this paper was collected on a flight by an Argus aircraft of the Canadian Armed Forces Maritime Proving and Evaluation Unit on 8 March 1973. The flight originated in Thule, Greenland and ended at Bødø, Norway, and the operational part of the track, which is shown in Figure 1, was up Nares Strait, then from Alert to the North Pole and finally down the 4°E meridian to the ice edge at about 80° N.

A variety of sensors was carried, including an APS/94D sideways-looking airborne radar (SLAR), a Reconofax 13A infrared line scanner (IRLS) and a Spectra Physics laser profiler. There was also a Vinten 70-mm vertical camera, which, though of limited use because of light conditions, provided useful back-up on the first leg of the flight up to about 81°N.

Ground truth was unavailable, but an observer in the nose of the aircraft made visual notes throughout the flight for comparison with the imagery. Visibility was good over most of the track, with daylight up to about 81°N, then varying degrees of twilight to the pole, graduating to total darkness on the last leg. There was also a fair amount of cloud on the last leg, which interrupted laser and IRLS operation.

A flight of this length, and carrying such a variety of sensors, naturally generates a lot of data and this paper will deal with only part of it, including extraction of lead orientation from the SLAR, potential application of the IRLS for estimating percentage of open water and thin ice, and a very preliminary calculation of ridge height and frequency distribution from the laser trace. More detailed analysis of the laser data and of ways to simplify both collection and analysis techniques is in hand, as is also a study of the interpretation of SLAR and IRLS ice imagery.

LEAD ORIENTATION

One of the most striking features of the SLAR imagery of the Arctic Ocean is the information it contains about lead orientation. Figure 2 is a tracing showing the leads, open and refrozen, as they appear on the imagery. The leads were traced independently by both authors to minimize subjectivity of interpretation, and the results combined. The individual plots, in spite of certain differences, both showed the same strongly marked patterns, so the results may be accepted as reasonably accurate.

The SLAR was operating at a range of 50 kilometres a side, or a total image width of just over 100 km, except on the southbound leg between the pole and 87°16N, where the range was 25 km a side. This change was necessary because the flight altitude had been reduced from 4,000 ft to 1,000 ft for better laser results, and at this altitude it was found that almost no ice detail was obtainable at the 50-km range. At 87°16N cloud and strong headwinds necessitated a return to a higher altitude and the 50-km range was resumed. Between 84°58N and 84°30N there was a break in the imagery owing to the necessity to change the film.

The question arises of how we know that the features traced are leads. The SLAR does not recognize ice thickness as such; what it sees is basically ice roughness and smoothness. Smooth ice, or water, having no projecting surfaces to catch and return the radar signal, appears as a nil return, or black area, whereas rough ice appears bright. Thus there is no way of visually discriminating between open water and ice 2 metres thick, provided both are really smooth. Luckily in practice they seldom are completely smooth, or at least the ice is not. Small ridges or unevennesses in the ice surface very often betray its presence, while if there are ripples on water they show as a characteristic type of clutter. Nevertheless, the ice does sometimes appear completely flat, and the water area, if it is small, is often completely calm. Thus there is no guarantee that nil radar returns designate open water or even very thin ice.

However, in the Arctic Ocean most of the smooth areas do in fact represent the young ice that forms in leads, and when the smoothness is combined with a strong linearity of form it is fairly safe to label the features as leads. What cannot be determined is just how many are active or open leads and how many are refrozen, and if so how thick the ice is. In this case, since we had a visual observer in the nose of the aircraft, we do in fact know that on the first leg of the flight after leaving Alert the leads were nearly all frozen, whereas on the second quite a lot were open. Cloud and darkness prevented visual observation from about 88°00N to 85°00N on, but it is probable that the amount of water present increased all the way to the ice edge.

Another problem that arises is connected with wind-drift and aircraft attitude. The SLAR presents the track as a straight line, regardless of heading changes of crab, and as the angle of radar view in relation to the aircraft remains constant the result can be considerable distortion of the image. Between Alert and the North Pole our wind-drift changed from 4° starboard to 8° port, a total difference of 12° in the angle of crab. This must be allowed for in calculating the true lead orientation, a simple operation as long as the amount of drift is known. Figure 3 shows the corrected predominant lead orientation at various points. The dashed lines represent the uncorrected orientation, as it appears in Figure 2.

The kind of information in Figures 2 and 3 is of great value in studying the dynamics of sea ice, its deformation processes and the forces that control its movement. The capability of SLAR to show these patterns is therefore important, and has in fact been recognized before. Ketchum and Tooma (1973) mention it, though they do not explore the question, and D.A. Grant of DRB made a plot like ours from some high altitude imagery flown by the USAF in 1962. His report was, however, not published in the open literature and received little circulation. At the present time SLAR is the only airborne sensor which has this capability, as it is the only one that combines a sufficient width of coverage with the ability to distinguish the necessary differences in the ice. Satellites of course can cover even larger areas, and some of them have higher resolution, but they all have limitations either of orbital coverage or resolution or both, and none at present has the radar's all-weather capability. Most of the imagery being discussed here was obtained in twilight or darkness and some of it through cloud.

SLAR, of course, is not without its own limitations. An obvious one of the real aperture SLAR is rather low resolution, but this can be improved by using a synthetic aperture, and doubtless the best features of both types will eventually be combined. More basic is the problem already discussed, of distinguishing between different types of smooth surface.

An attempt was made to resolve this by using a densitometer, running a trace across a number of leads which by visual observations we were pretty sure was partly frozen and partly open. The results were inconclusive; there did appear to be a slight change of density between the thin ice and the water surfaces, but it was not always repeatable and may have been due to instrument vagaries. In any case the difference was so slight, and the density variations due to radar characteristics were so large, that there were wide discrepancies in the absolute density values involved, making interpretation very difficult. However, the technique might be worth further exploration.

IRLS AS A TOOL IN THE STUDY OF HEAT TRANSFER

IRLS, unlike SLAR, can distinguish between open water and ice during the arctic winter, and can even give information about the thickness of the ice. An attempt was made to estimate the percentage of open water from the IR imagery, and to assess heat transfer from the ocean to the atmosphere. This was largely unsuccessful, but it is hoped that with some refinements the technique may prove useful.

A strip of imagery was chosen, covering the area from 84°30N to 81°00N on the southbound leg. The atmospheric conditions were clear, and the aircraft was flying at an altitude of 6,000 feet, giving a coverage strip approximately 6.3 km wide. The imagery was placed on a calibrated densitometer at the Canada Centre for Remote Sensing, consisting of a uniformly illuminated light table, over which is located a high quality TV camera, a high resolution TV monitor, and associated electronics. The system allows for the presentation of up to 32 density slices over a variable range, each slice being presented as a different colour. The percentage of the total area represented by any grouping of density slices can be read off directly. This allows a relatively rapid method of determining how much of a given piece of imagery has densities within any specified range. The sample chosen for study had densities ranging from 0.45 to 1.5. This was sliced into 31 density ranges of 0.0339. The percentage of

TABLE 1

D. range	.45 .518	.518 .653	.653 .789	.789 .890	.890 1.026	1.026 1.5
%	0.07	1.3	2.13	7.8	36.3	52.4

each of several density ranges is shown in Table I.

It is safe to assume that the air temperature at this time of year would be much lower than the freezing point of water, and that the surface of very thick ice would approximate, in the absence of solar heating, the mean air temperature of the last few days. It is also safe to assume that open water would be at the freezing point of sea water, that is between -1 and -2°C.

In the thermal infrared frequencies, ice, snow and water all have an emissivity of near unity. It is therefore possible to relate thermal radiation at the surface to temperature. This means that if the atmospheric conditions are stable, and if the air temperature is known, it may be possible to calibrate the optical density on the IRLS imagery with surface temperature, by knowing the temperatures for the coldest (blackest) and hottest (whitest) portions of the imagery. Unfortunately in this case the necessary air temperature data was not available. Furthermore, the IRLS used, the Reconofax 13A, has an automatic gain control (AGC), a device designed to make the dynamic range of the image fit the dynamic range of the film. This makes it impossible to relate image densities to absolute values of temperature, since the AGC shifts both the position of any given radiation temperature on the grey scale and the relative rate of change of grey scale with radiation temperature. By examining the film, however, it is possible to estimate how much the AGC varied, and it would appear that for over 80% of the imagery studied it did not, in fact, vary greatly. The variations that did occur were in the direction of a decrease in optical density range with respect to thermal dynamic range.

If we make this assumption it means that we will tend to underestimate the percentage at the extremes by about 20%. Then, discarding the lowest density slice (0.07%) as representing the end-point vagaries of the device, and taking the two next lowest (1.3 2.13) as the amount of open water, we get a value of 3.43% which is lower than the 5% estimated by Swithinbank (1972) from the HMS Dreadnought trace of the underside of the ice between $80^{\circ}00$ and $90^{\circ}00$N at the same time of year, but higher than the 0.6% obtained by Koerner (1973) between $89^{\circ}00$ and $81^{\circ}00$N. In other words, it is within the range of what is clearly a quite variable figure.

Similarly, if we take the two highest density slices (52.4 36.3 = 88.7%) we get a figure which is not out of line with the findings of the same two studies for the proportion of multi-year ice.

Obviously this is only speculation, but the technique is not trivial. If a bore-sighted radiation thermometer was used in conjunction with a high dynamic range magnetic tape recorder it should be possible to estimate the exact heat transfer from the surface of the ice and water at the moment of the overflight. If the chance presents itself, we hope to further investigate these techniques.

LASER PROFILING

The laser profilometer carried on this flight measures the distance between the aircraft and the surface of the ice at a basic sampling rate of 5KHz (20 mm flying distance between samples at Argus speeds). The output is usually presented as a filtered analog signal. The machine measures only the last few digits of the altitude; that is, if the machine is working on the 10-foot scale, it is impossible to know how many tens of feet high the aircraft is, but the final remainder of 10 feet will be known to good accuracy. There is thus an end-of-scale ambiguity which, when combined with the effects of aircraft altitude variations, greatly complicates analysis of the results. These problems, however, are beyond the scope of this paper.

The value of ice profiling lies in the importance of ice ridges, on the one hand as a barrier to surface travel, and on the other as a factor in calculating the total volume of ice for studies of mass balance and heat budget. They also form a sort of integrating memory of storm activity, since most ridges are formed as a result of storms. Thus the main information to be extracted from the trace is the number, distribution and height of the ridges crossed.

In spite of some cloud over and other problems, a considerable amount of laser data was obtained. A computer-based analysis, including ridge height distribution and a study of the power spectrum to give information on possible periodicity, is underway. However, a preliminary manual count of ridges was also undertaken as a 'spot check'. Segments of the record were selected at intervals of approximately one degree, and, using a standardized procedure, the number of ridges over 2 feet high in each segment was counted, using a height increment of 2 feet. A magnetic tape record was used as the source and a high-speed ultra-violet sensitive paper chart record was made for each segment. A single operator did all the analysis, thus eliminating one source of error. In order to define the difference between two separate ridges and two peaks on the same ridge, it was arbitrarily decided that if the valley between two peaks went below half the height of the lower peak, the feature should be regarded as two separate ridges. A standard segment of 120 seconds was analyzed for each section. This corresponds to 10 km at an aircraft ground speed of 160 knots. A correction factor was then applied to the results to make them correspond to a 10-km section, regardless of the ground speed. The resultant ridge counts are shown in Figure 4.

The ridge statistics can be grouped into three sectors; Nares Strait, Alert to the North Pole, and from the North Pole south. It was possible to correlate the ridge counts in Nares Strait with visual observations, the Vinten camera imagery and the IRLS imagery. In this area there was sufficient solar heating to make the ridges quite visible on the IRLS. The ice in Nares Strait, which was shore-fast, had a considerable range of ice types, from quite rough to very smooth. There was one stretch of 10 km where only two ridges of greater than 2 feet were found.

The distribution of ridge counts in the Arctic Ocean shows a high variance, as is to be expected, but there is nevertheless an overall pattern, and this pattern is in general accord with the work of Wittman and Schule (1966) and Hibler et al (1974). The highest counts, with one exception, are in the area to the north of Ellesmere Island and Greenland, fairly close to land. This area is well known to have the roughest ice in the Arctic Ocean, owing to pressure against the coasts of the islands. Toward the pole the number and height of ridges tends to decrease, and toward the outer edge of the pack in the Greenland Sea it gets even less, as the ice moves out into open water. Both these trends are reflected in the laser counts. The one apparent anomaly is near the pole on the northbound leg, where the highest count recorded appears in an area that in general was fairly smooth. The count was rechecked and appears to be accurate, and it may reflect a real condition. On the other hand it is possible that the track flown may have coincided with the direction of a single ridge for quite some distance, crossing and re-crossing it to give a misleading result.

CONCLUSION

The results discussed here are presented as a preliminary interpretation of a multi-sensor exercise. More detailed analysis of all aspects is in hand.

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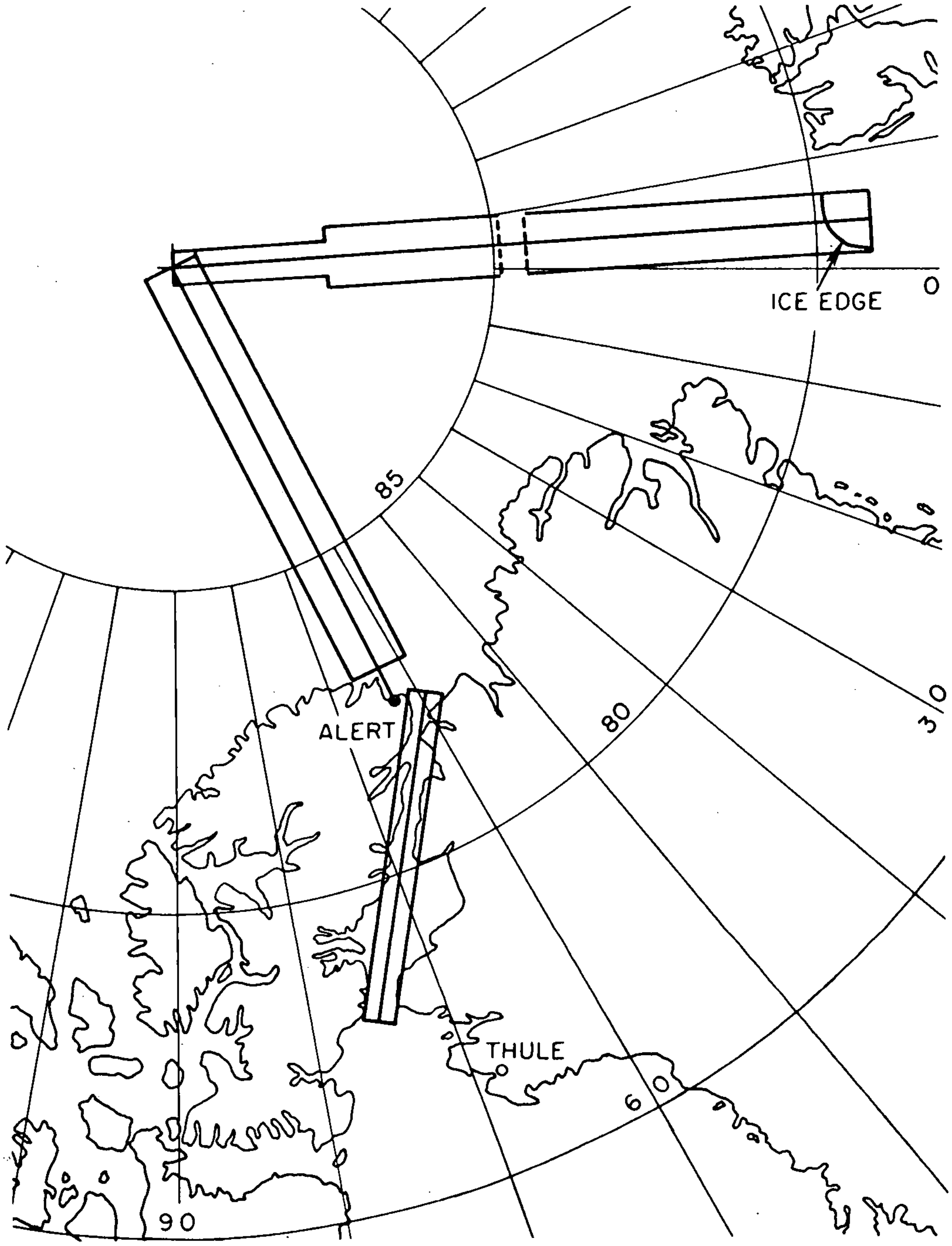

Fig. 1. Map showing the flight tracks over which imagery was obtained. The outer lines represent the limits of SLAR range in the various sectors.

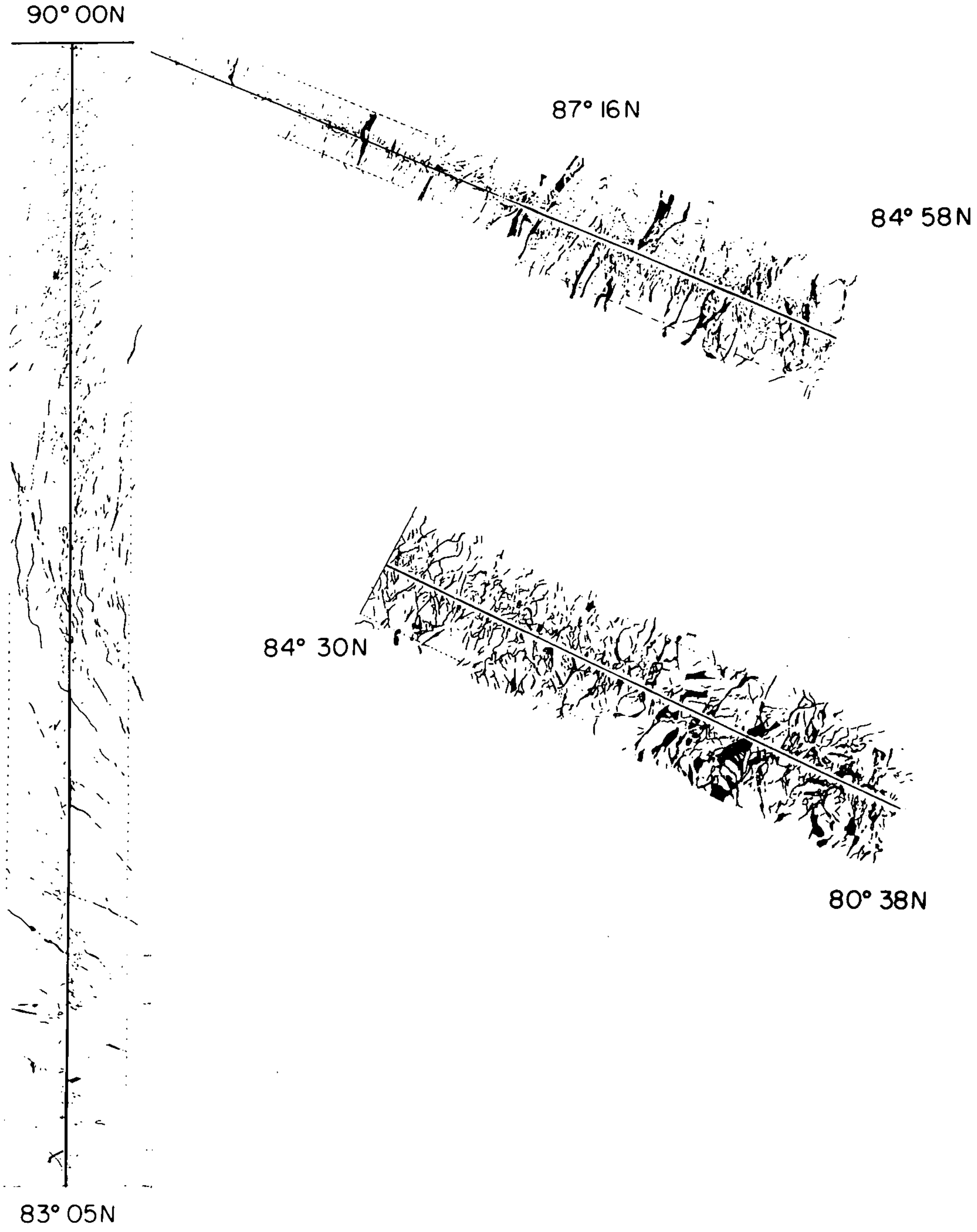

Fig. 2. Leads in the Arctic Ocean as traced from the SLAR imagery.

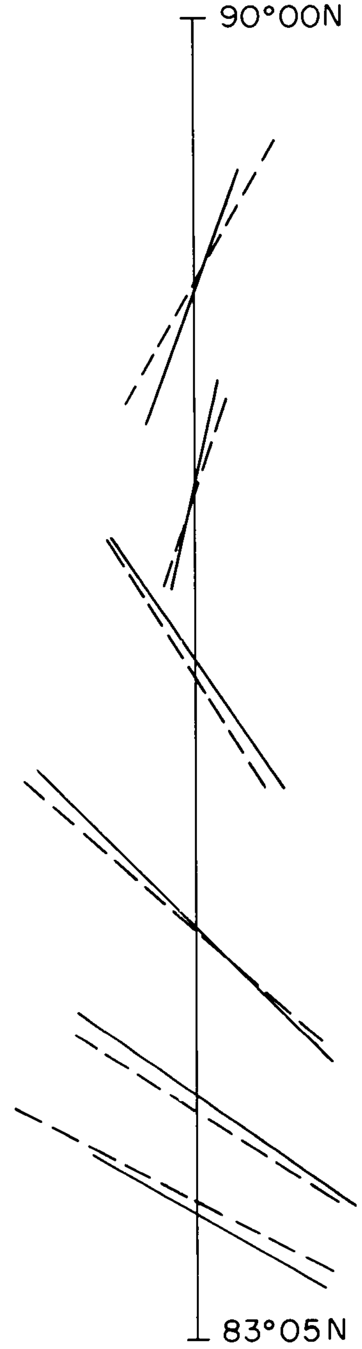

Fig. 3. Predominant lead directions between Alert and the North Pole, corrected for wind-drift (solid lines). The dashed lines represent the same directions as plotted directly from the imagery.

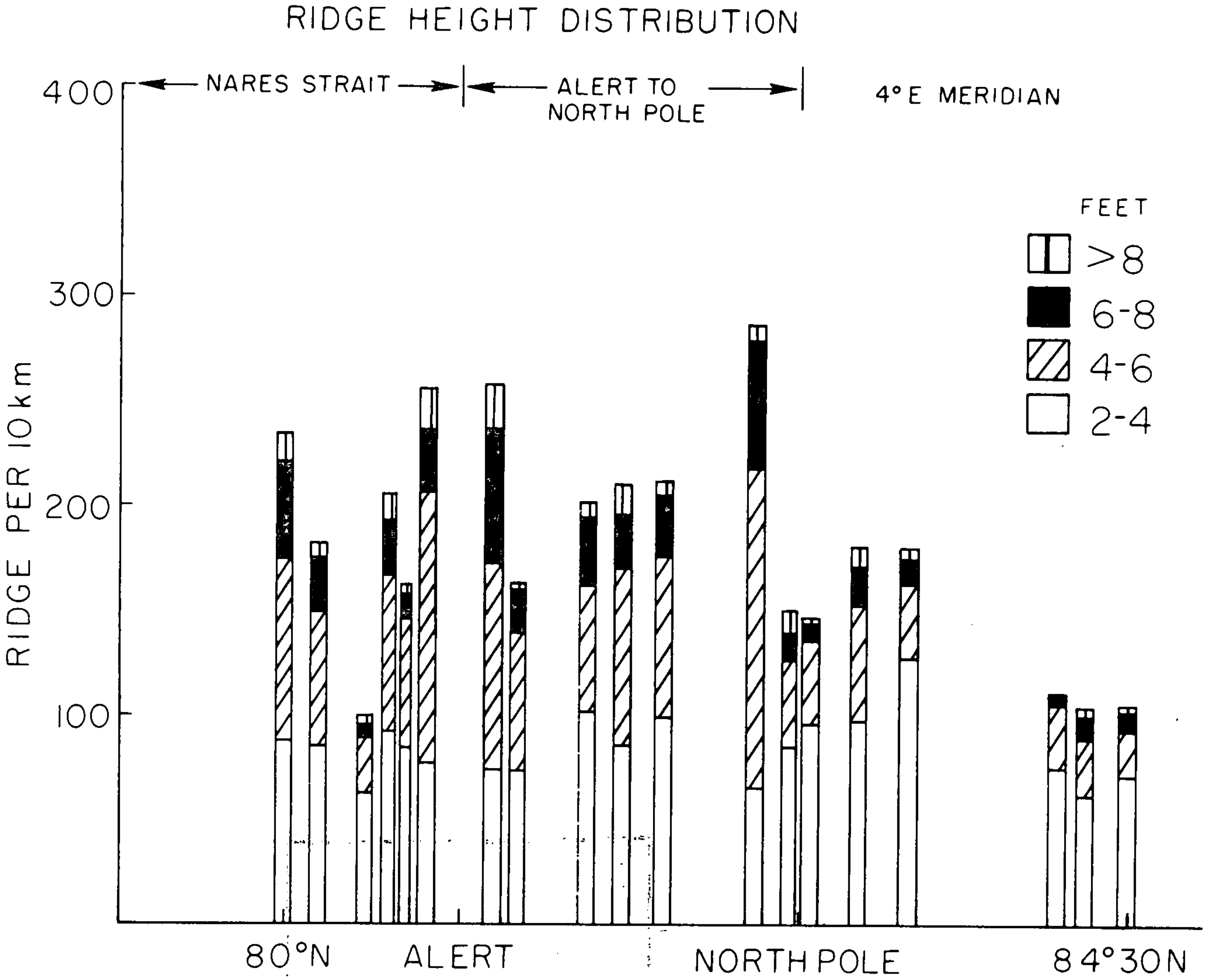

Fig. 4. Ridge height and frequency in sample sectors as extracted by manual count from the laser trace.

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