Morphology of a Multi-Year Ice Ridge in the High Arctic

D. N. Connors, E. R. Levine, and *R. R. Shell*
Naval Underwater Systems Center, Newport, RI 02841

ABSTRACT: The under-ice keel and topside sail structure of a multi-year ice ridge were surveyed with Mesotech and Digital Ice Profiling System (DIPS) acoustic profilers and a digital theodolite with an electronic distance meter, respectively. The keel, asymmetric in lateral slope, had a maximum ice draft of approximately 13 m. A comparison with the topside survey indicated that the mean keel to sail ratio was 4.8, with values ranging from 3 to 9. The mean displacement of the sail axis from the keel axis was 9.6 m. A comparison between tracks sampled 12 days apart by the two acoustic systems, coincident to within 2 m, showed excellent agreement in feature identification. A single realization of the two-dimensional spectrum of keel topography suggests anisotropy, enhanced variance in longer scales in the cross-ridge direction. The digital underside topography was input to the Rastor image processor, producing a colorized image of under-ice topography useful in further studies.

INTRODUCTION

A combination of acoustic imaging and conventional surveying techniques has been utilized to study the morphology of a multi-year ridge on a large ice floe in the high Arctic, for ice drafts on scales of order 10^{-1} to 10^{1} m, for horizontal scales on the order of 10^{0} to 10^{1} m. These data were used to characterize the ridge geometry, to expand the small available data base on the relationship between ridge sail to ridge keel characteristics, and to develop techniques for looking at the two-dimensional spectra of the ridge bottom roughness. Also, we have compared results from the two acoustic systems, because the Mesotech survey is usually not done, while the DIPS (Digital Ice Profiling System) upward looking acoustic measurements are routinely obtained by submarines. Our approach was to use conventional surveying techniques in the study of individual ridge sails (portion projecting above the water line) and acoustic techniques for the keel (portion projecting below the bottom of "flat" ice).

In previous work, Palosuo (1975) used an aerial stereoscopic camera and reference markers on flat ice to generate topographic maps of the topside surface with a vertical resolution of 0.25 m, while divers with marked lines and depth gauges obtained under-ice profiles and photographs. Kovacs *et al.* (1973) made three transects of a multi-year ridge using conventional surveying techniques for the topside measurements and a combination of sonar and drill holes to determine the under-ice profiles. These attempts at studying ridge morphology provided only snapshots of the features, and were generally quite labor intensive.

Remote sensing techniques have also been used to study the topside and bottomside of pack ice. In order to study the feasibility of determining the keel draft distribution from sail height distribution, Wadhams (1980) employed a submarine-mounted upward-looking sonar and an aircraft-mounted laser profilometer to characterize the bottom and topside statistics along 1000-km tracks. On average, the two data sets were displaced 2 km and were obtained up to 43 hours apart. Although pack ice drift was not reported in that study, our data set, taken in April in the same area, showed that drift ranged from 0.04 to 1.2 km/hr. A fairly comprehensive study of pack ice morphology was carried out by Garrison *et al.* (1978) using airborne photographic, infrared, microwave, and laser sensors. Under-ice data were obtained with a narrow beam (2°) submarine sonar tracked by means of a three-hydrophone array tracking range, accurate to approximately 5 m in the vicinity of the range. These data provided a qualitative description of generic ice types, but a quantitative description of ridge morphology was not possible due to a lack of navigational control. Power spectral density estimates (Hibbler and LeSchack, 1972) from ice draft data taken in a ridged area along two orthogonal tracks near an open lead were used to infer anisotropy in the under-ice canopy. Two-dimensional spectral analysis of the topside of the ice surface (Hibler, 1972) was performed from laser profiles obtained in a star pattern, and an anisotropy tensor was estimated for the region.

FIELD EXPERIMENT

During April 1986, an ice camp was established on an ice floe in the Lincoln Sea, north of 85° N, with dimensions of approximately 4 by 6 km. The multi-year floe was generally surrounded with heavily ridged first year ice. Two surveys were made of the under-ice canopy. The first survey, the primary data set of this paper (Figure 1), was directed to a region with multi-year ridges and hummocks-isolated mounds of ice and snow ranging in height from 1 to 2 m. Contours of under-ice topography (3 to 12 m) were obtained from an Offshore Survey and Positioning Services (OSPS) Acoustic Profiling System based on the Mesotech model 971 profiling sonar system. The sensor on this system employs a mechanically rotated stationary scanning transducer that emits a 330-kHz signal in a 2.1° beam. The stepping angles are 4.5° in the horizontal plane and 0.225° in the vertical plane. The Mesotech profiler was deployed through the ice at either a 40-m or 80-m depth at four sites which are depicted in Figure 1, which also shows segments of the DIPS tracks discussed below. At a particular site, alignment of the sensor is achieved by zeroing on a target deployed through a second hole at a known depth and distance from the sensor. For the deployment depths used in this study, the insonified footprint ranged from 1.5 to 2.4 m at site 3s and 2s (shallow) and 3.0 to 4.6 m at site 2d (deep).

Topside positions and elevations of the ridge sail were surveyed with a theodolite (Lietz/Sokkisa TMG, Model No. TM 20H) and range finder (Sokkisha EDM Model No. RED 2A) from a centrally located 7-m high tower and several of the Mesotech sites. Twenty-four measurements of range, bearing, height, snow depth, and width were taken of surface features and along the axis of the sail. Sail height was corrected for snow cover and freeboard to sea level, and sail width was determined to the break in slope at "flat" ice.

The second data set was obtained with a submarine-mounted

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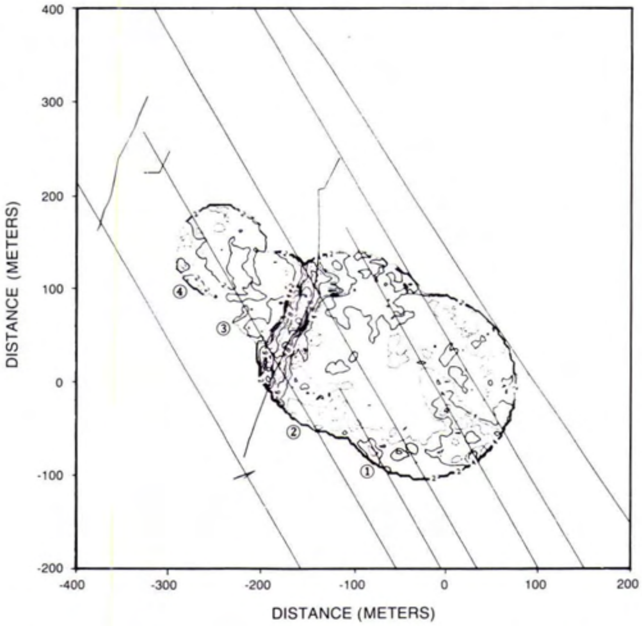

FIG. 1. Contours of ice draft (1m) in the (370.1-m by 370.1-m) region of the multi-year ridge from a composite of Mesotech data from sites 1 (lower right) through 4 (upper left). Also shown is the sail axis (thick line) and the DIPS tracks. The x and y directions are arbitrary.

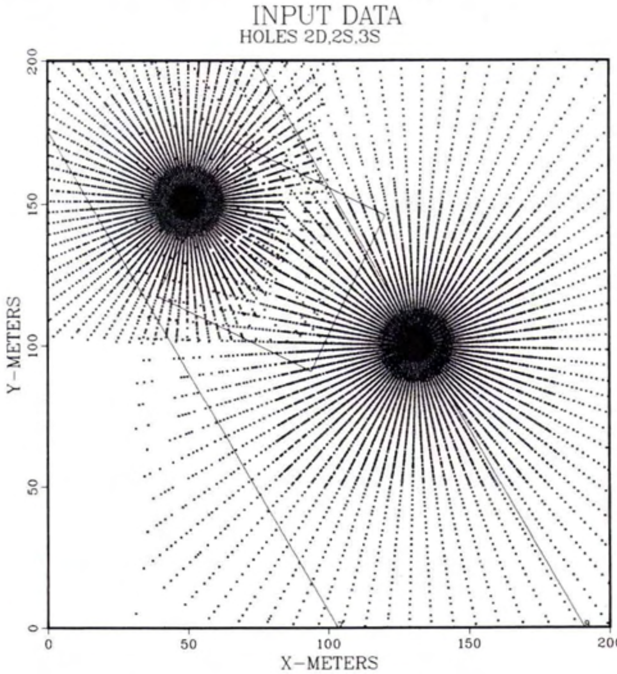

FIG. 2. Mesotech data point locations in the region between sites 2 and 3. Also shown are sections of DIPS tracks 7 and 9, and the box indicating the data used in the two-dimensional power spectral analysis. The x and y directions are arbitrary.

upward-looking sonar, DIPS, with a narrow beamwidth and a sampling rate of six per second. Considering the depth and speed of the platform, this results in a sample approximately every 0.5 m and a 2.1-m footprint. The system was tracked acoustically using six hydrophones arranged in a hexagonal array with a radius of 2.1 km around a central phone. The hydrophone positions were surveyed from the tower, and were periodically checked with a surveyed sound source with typical range closing errors on the order of 0.25 m. Sound velocity measurements were made daily with a Seabird temperature, conductivity, depth profiling system, to enable the determination of the acoustic paths and travel times. Relative system position, determined from travel times of a time synchronized source on the underwater platform, was known to 2 to 3 m. Seventeen parallel tracks (10 to 100-m spacing) were run under multi-year and first year ice over a 1.2- by 3.0-km box, the main axis of which was extensively surveyed on the topside.

ICE MORPHOLOGY

Data obtained with the acoustic source at 40 and 80-m at sites 2s, 2d, and 3s were used to create 200 by 200-m subset of the Mesotech data points for further study (Figure 2). Also shown are two DIP tracks (7 and 9) and the 61- by 61-m data set which was used for the two-dimensional spectral analysis, to be discussed later. Data spacing varied considerably for both geometric reasons and the horizontal and vertical incremental scanning step angles, with better coverage on the site 3 side (upper left) then the site 2 side (lower right).

These data have been mapped to a 169 by 169 grid using inverse square weighting, and were contoured in 1-m increments (Figure 3). The 140 m of keel shown is asymmetric, being steeper on the site 3 side (average slope ~ 27°) then on the site 2 side (average slope ~ 19°). The mean axial draft of the keel is 9.2 m and ranges from 12.9 m to 5.5 m, while the width is 43 m to the 3 m contour line (the e-folding ice draft is 3.4 m), with a range from 16 to 55 m. The steeper, left side, has a simpler topography while the right side of the keel displays a more rugged topography that includes three spurs projecting into the "flat" ice. The uppermost of these spurs, a major feature of the keel, has a draft of 7 m.

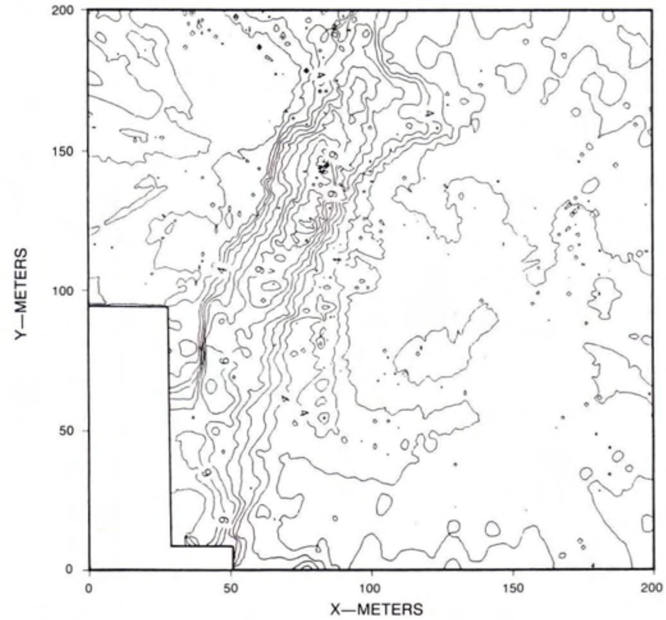

FIG. 3. Contours of ice draft (1m) from sites 2d, 2s, and 3s based on the data coverage shown in Figure 2. Data coverage was too sparse for contouring the lower left corner.

In order to compare under-ice and topside topography, 1-m

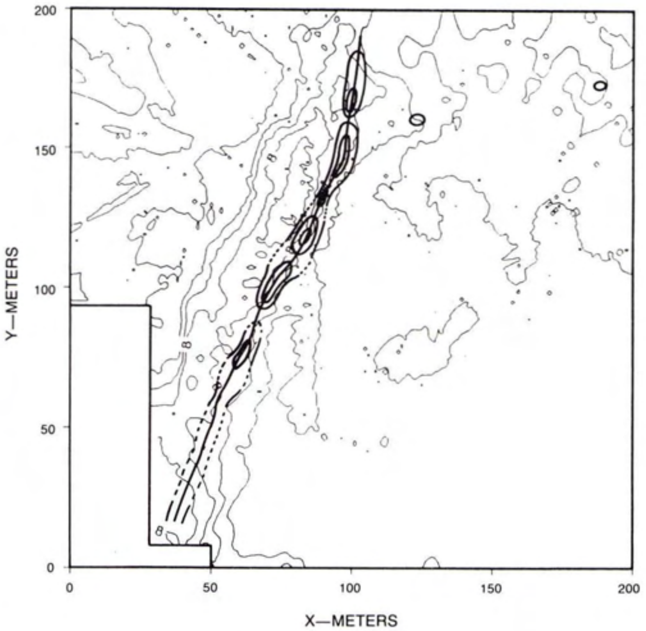

FIG. 4. Sail centerline and height contours (1-m interval) superimposed upon contours of ice draft (2m) from sites 2d, 2s, and 3s based on the data coverage shown in Figure 2.

contours of the ridge sail in the range from 1 to 3 m (darker contour lines) and the sail axis are superimposed on 2-m contours of the ridge topography, as shown in Figure 4. In general, the sail had a blocky (indicative of compressional rather then shear formation mechanisms) weathered appearance, exhibited a granular ice texture, and was mostly overlaid with densely packed snow. In addition to the overall sail/keel structures, two hummocks were observed in the Mesotech subarea which corresponded to under-ice features as shown in Figure 4. For the 140-m section of the ridge, the mean sail width to the 1-m surface contour was 11.9 m, and the ratio of mean sail to mean keel width was 3.6. The mean axial sail height was 1.9 m, with a range of values from 0.8 m to 3.2 m. The ratio of the mean keel draft to the mean sail height was 4.8, with a range from 3 to 9 obtained at the topside survey points relative to the closest axial keel draft along the ridge axis. There was a mean offset of 9.6 m between the sail axis and the keel axis.

The ratio of keel draft to sail height is often used to infer keel draft because of the greater accessibility of the topside topography. The above mean axial ratio is within the range of reported, generally, single point values. Garrison *et al.* (1978) obtain a ratio of 4.1 in a comparison of average sail height and sail density/km from nine laser transects to average keel draft and density/km from sonar data in the same area. When the mean laser-derived ice elevation is used for all the data and compared to mean ice draft, they obtain a ratio of 7.5. Results from Parmerter and Coon's (1972) one-dimensional kinematic pressure ridge formation model show that a considerable variation in the keel to sail ratio can occur. The most important factor is the termination point in the ridge building cycle, and a secondary factor is the thickness of the parent ice sheets. Early termination of the ridge-building cycle would favor low ratios, while proceeding full cycle would tend to produce higher ratios. Also, in the Parmerter and Coon model, asymmetric ridge profiles are generated when bending moments in the parent ice sheets are exceeded. Profiles can take on a variety of shapes, depending on when and where failure occurs in the cycle. A plausible explanation of the ridge profile under discussion, within the context of their model, would be early termination in the ridge-building cycle that had been preceded by bending failure in the thinner ice on the site 3 side of the ridge.

Two of the DIPS transects (taken 12 days later) cross the ridge within the boundary of the Mesotech survey and the section of ridge under discussion. Track 9 (right side in Figure 2) is the best example for comparison because it is most nearly coincident with several of the Mesotech scans (Figure 2) and passes within a metre of the site 2 hole. The offset between the track and the scans ranges from zero in the heavily sampled central portion of the section, to 1 m across the ridge, to 2 m in the "flat" ice. There are 419 equally spaced data points in the 218-m DIPS section. The Mesotech scans provide 126 unequally spaced data points along the track, using a 1-m search radius along most of the track, and a 2-m search for the ends of the track. Results, presented in Figure 5, show excellent agreement in feature identification between the one-dimensional realizations of the gross morphology between these two quite different techniques for observing under-ice characteristics. This is due to the near coincidence of the two tracks, and the accuracy and stability of the range during the 12 days. Ice draft at the closest approach to the site 2 hole, at 115 m along the track in Figure 5, is 2.8 m for the DIPS track, 2.7 m for Mesotech, and 2.65 m for a direct measurement of ice thickness in hole 2 (excluding 0.35-m freeboard). The mean ice draft for track 9 is 3.9 ± 2.1 m, greater than for the Mesotech 3.1 ± 1.7 m due, in part, to fewer Mesotech samples over the keel than along the flat ice.

TWO-DIMENSIONAL ANALYSIS

The Mesotech data enable the estimation of several examples of individual realizations of two-dimensional power spectra in the region of the multi-year ridge. Although enough realizations of this random topography were not obtained to place statistical confidence in the results, we do present one example in this paper in order to show the utility of the technique and begin the acquisition of an adequate data bank. Because the ice topography is essentially a two-dimensional process, and most previous spectral estimates are one dimensional, this approach can provide fundamental information necessary for interpreting one-dimensional power spectra such as questions of horizontal isotropy/anisotropy. As noted by Czarnecki and Bergin (1986), these questions become most important in regions where there are "special directions" in the surface under study, such as along- and down-ridge in the case of the ice ridge. These results are also tests of fundamental assumptions used in models of acoustic scattering by the under-ice surface (Kuo, 1988).

As previously discussed, raw data from sites 2s, 2d, and 3s were combined, and the box shown (Figure 2) was selected for further analysis. These data were mapped to a 1-m grid, shown in Figure 6, in the vicinity of the ridge keel. This example was chosen because the data coverage was superior, and it symmetrically straddles the ridge structure from the crest (~9 to 12 m) down to the 2 to 3 m contour. For the data subset chosen, the y axis is along the ridge and the x axis is across ridge. The mean and variance of these data are 5.34 m and 8.97 m^2, respectively.

The two-dimensional analysis routine computes power spectral estimates using a correlation method (Dudgeon and Mersereau, 1984) analogous to one-dimensional approaches (Blackman and Tukey, 1958). First, by least-squares methods, the mean and trends are removed from the data matrix, followed by computation of auto-covariance and application of a Parzen window to taper edge effects. The two-dimensional power spectral density estimates were computed by Fourier transforming these auto-covariance estimates. For this study, the spectra represent the distribution of variance over wavelengths from 2

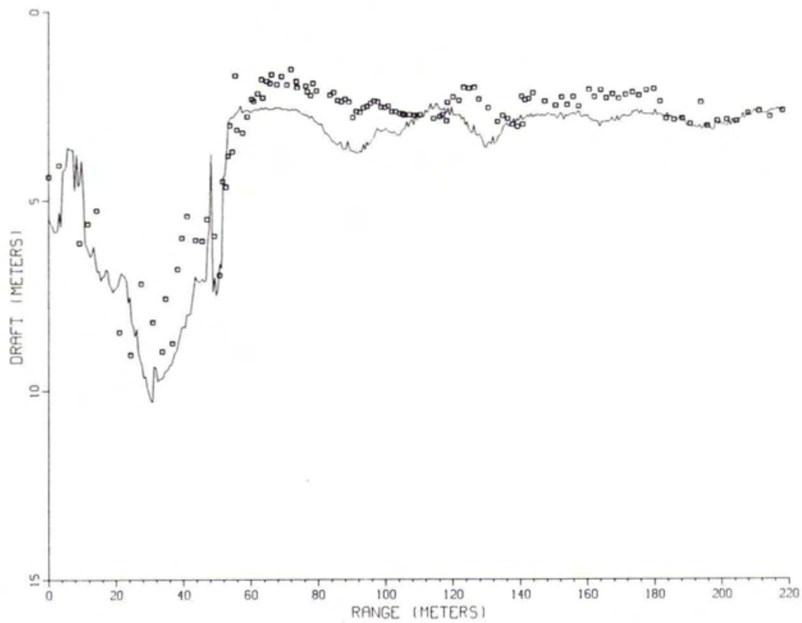

FIG. 5. Intercomparison of ice draft sections from Mesotech raw data and DIPS track 9.

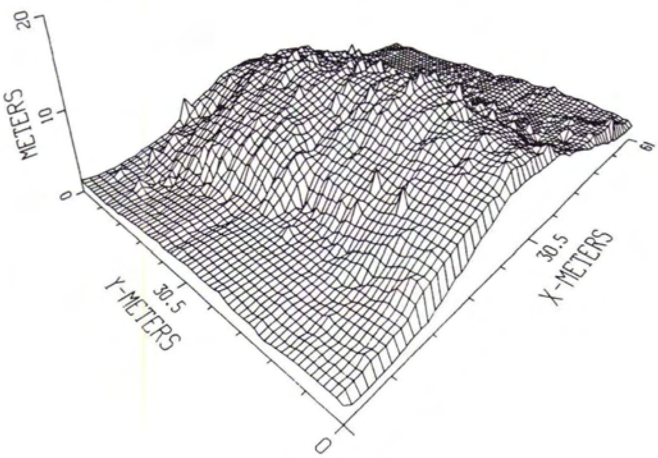

FIG. 6. Two-dimensional gridded topography (61 m by 61 m) with x,y directions across and along ridge, respectively.

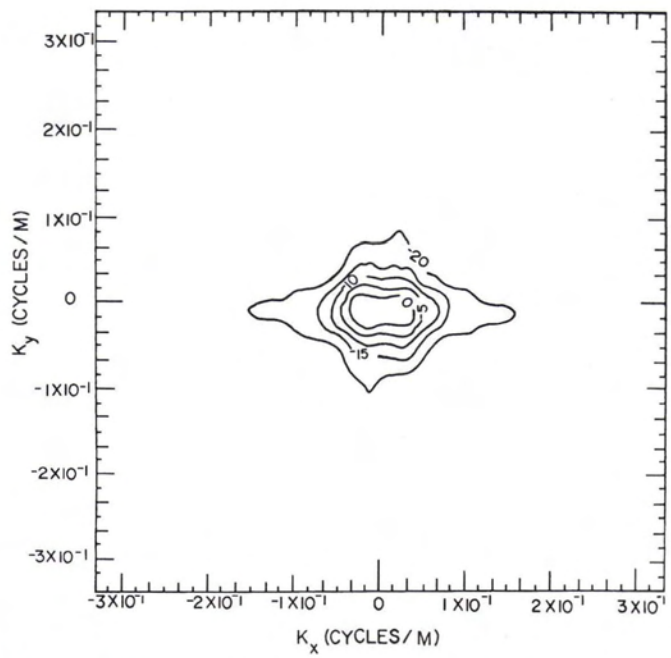

FIG. 7. Example of two-dimensional autospectral estimate from ice-ridge topography shown in Figure 6. Contours are in non-dimensional units of 10 log $\{(m^2/cpm)/(1m^2/cpm)\}$.

to 30 m. In future refinement of our analysis scheme we need to find optimum methods to filter out the overall ridge structure by the best available technique and examine the residual topography for its small scale variability.

In Figure 7, the two-dimensional (2D-PSD) estimated is shown in wavenumber space for κ_x, κ_y, the cross-ridge and along-ridge wavenumbers, respectively. Using the convention of Czarnecki and Bergin (1986), the parameter plotted in Figure 7 is 5dB contours of the log magnitude of the 2D-PSD (S) or power spectrum level (SL) given by

$$SL\ (\kappa_k,\ \kappa_y) = 10 \log\ [S\ (\kappa_x,\ \kappa_y)/\mathrm{PSD_{ref}}]\ \mathrm{dB}$$

where $\mathrm{PSD_{ref}} = 1\mathrm{m}^2/\mathrm{cpm}$ is a normalizing factor, making SL dimensionless.

Results, presented in Figure 7, show contours of SL in the range from 0 to -20 dB plotted as a function of wavelength in the x, y directions. Because noise level of the Mesotech data due to quantization in the vertical stepping of the transducer (0.16 m corresponds to a spectral noise level of approximately -10dB), interpretation of contours beyond this value are not warranted. For the contours in the 0 to -10 range, the results show anisotropy in the x direction, corresponding to increased spectral variance in the cross-ridge direction for the larger wavelengths for which contours are drawn. In order to show statistical confidence in this result, many such examples would have to be averaged to reduce the error of the spectral estimate.

For comparison, an individual realization of 2D-PSD estimates of seamount topography in a region with a wave-like structure showed enhanced spectral variance in the direction perpendicular to the wave crest (Czarnecki and Bergin, 1986), and also their ensemble averaged spectra does indicate some isotropy within selected wavenumber regions. The 2D-PSD estimated by Hibler (1972) for ice topside topography show indications of low frequency ridge structures peaked broadly near the 61-m wavelength, as well as high frequency snow dune lineation.

IMAGE PROCESSING

Two-dimensional Mesotech data were composited from all data collection sites, i.e., 1, 2, 3, and 4 (approximately 2×10^4 points), and subsequently mapped to a 169 by 169 grid with a 2.2-m spacing. The mapped data, position, and ice draft were input to the Rastor Image Processor at the NECOR/URI Sea Beam Development Center, a system designed for use in processing underwater topography, in order to produce an image that would simulate the view of an ice keel approximating that seen by a transiting submarine. The image was vertically enhanced by a factor of approximately 7.2 and rotated along each of its axes, and pseudocolor was applied to ranges of ice draft in 0.6-m intervals with a palate of colors (Plate 1) from magenta to orange to corresponding to ice drafts from 0 to 12.9 m.

The resulting colorized image (Plate 1) clearly shows the principal ice ridge of our study in relation in surrounding ridge and rubble structures. This view is looking downridge from the upper left-hand quadrant of Figure 1 looking towards the lower right hand quadrant. Indications of smaller ridge-like structures, which corresponded to topside hummocks, are clearly indicated towards the right-hand side of the image. Also evident is the rough nature of the surface in the flatter regions adjacent to the keels.

CONCLUSIONS

- Under-ice topography remotely sensed by acoustic methods and topside topography obtained with a theodolite and electronic distance meter can yield quantitative studies of two-dimensional ice morphology with sufficient resolution to sample major ice draft relief features on scales of order 10^{-1} to 10^{1}m over horizontal grids of order 10^{0}m.
- This ridge study provided a highly detailed view of a 140-m section of an asymmetric multi-year ridge with navigation sufficiently accurate to relate top and bottom topography. The mean keel-to-sail ratio, 4.8, was found to be well within the range previously obtained for single point measurements, and the axial variability of the ratio was quantified to be in the range from 3 to 9. Our observations of the ridge structure, i.e., low ratio of keel draft to sail height ratio, keel asymmetry, and non-alignment of sail axis and keel axis suggest early termination of the ridge building cycle, with more extensive parent ice sheet failure and steeper ridge building on the site 3 side, based on the model of Parmerter and Coon (1972).
- A comparison of data obtained within a metre along a 219-m swath from the two acoustic systems, the Mesotech and the DIPS, showed remarkable likeness in feature identification, and also provided a test of the navigational accuracy of the overall survey. For a one-dimensional view of the ice canopy, the DIPS system provides superior data resolution and distribution than the Mesotech system. However, for an ice camp application without additional support, a tight packing of shallow Mesotech sites would provide a detailed two-dimensional look at the under-ice canopy with sufficient data quality for most applications.
- A 61- by 61-m gridded data subset was used to estimate one realization of two-dimensional power spectral density in the vicinity of the ridge. This result suggests anisotropy, i.e., enhanced variance in the cross-ridge direction for the larger scales, as has been observed for other topographies including ice topside and seamount studies. Because bottomside data are routinely taken in one dimension only, more extensive studies of the two-dimensional topography may allow extrapolation of standard one-dimensional data to two dimensions for acoustic and other applications.
- Improved topside/bottomside morphology studies of individual ice features such as first and multi-year shear and pressure ridges, rubble fields, etc. would include more highly resolved sampling of both surfaces. The topside survey would include intensive sur-

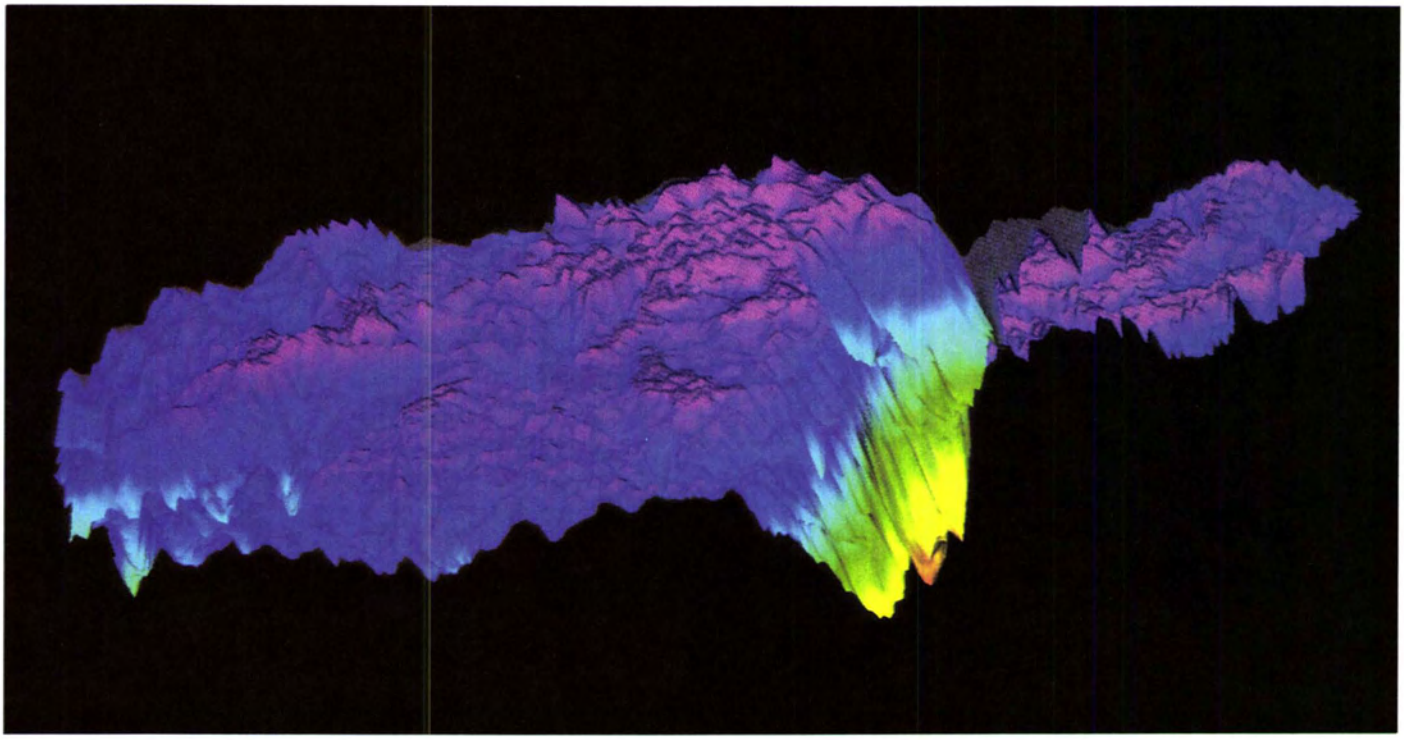

PLATE 1. Colorized image of under-ice topography based on all composited Mesotech acoustic data, produced on Rastor Image Processor.

veying over the entire study area with a digital theodolite with an electronic distance meter, stereo photogrammetric mapping, and snow depth determination. The bottomside Mesotech survey would be performed in a tight grid of overlapping sites, using a shallow source, with sufficient sampling for statistical confidence in power spectral density estimation. The potential of the Rastor image processor for data visualization and evaluation has not yet been fully exploited.

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