Proceedings of the International Conference "Underwater Acoustic Measurements: Technologies &Results"
Heraklion, Crete, Greece, 28th June – 1st July 2005

VOLUMETRIC MULTIBEAM SONAR MEASUREMENTS OF FISH, ZOOPLANKTON, AND TURBULENCE

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Abstract: *In late 2002 an evaluation of the mid-water survey capability of a high-resolution multibeam sonar (RESON SeaBat 8125) was performed. This was conducted as part of a larger investigation of zooplankton aggregations in Knight Inlet, B.C., and included simultaneous measurements with a conventional, three-frequency (38, 120, and 200 kHz), calibrated echo-sounder system. This multibeam sonar, adapted from a standard bathymetric system, operated at 455 kHz and provided 240 one-half-degree beams in the across-track plane with a one-degree along-track beam angle. The multibeam sonar was able to provide well-resolved mid-water images of fish schools (likely juvenile herring), crustacean zooplankton (dominantly euphausiids), and near-surface turbulent micro-structure features. Close comparisons with the echo-sounders confirmed the multibeam calibrations, allowing assessment of the multibeam volumetric sampling capabilities.*

Keywords: *sonar, multibeam, fish, zooplankton*

1. INTRODUCTION

Multibeam sonars offer considerable promise for high-resolution surveys of mid-water fish and zooplankton and investigation of oceanographic phenomena such as turbulence and internal waves. Compared to conventional echo-sounders, multibeam sonars provide improved spatial resolution, the ability to form 2-dimensional images of biologic and/or oceanographic phenomena, and a much larger overall sampling volume. This comes at a cost of greater sophistication in processing and display, dramatically larger data rates, a greater level of complexity in acoustic calibration, and complications due to non-vertical incidence angle sampling of the scatterers. Until recently, commercial multibeam sonar systems were generally designed for bathymetric survey applications, discarding the water column signals entirely. With the increasing capabilities of modern computers and data storage systems, water volumetric surveys have become feasible, and a number of investigators have begun to explore the potential applications [1,2].

This work focuses on evaluation of a commercial, high-resolution multibeam sonar (RESON Inc. Seabat 8125) during a vessel-based survey in a coastal fjord. The overall field trials were focused on zooplankton and fish aggregations in the presence of internal lee-wave phenomena formed by stratified tidal flows over underwater sills. In particular, data from a 3-frequency vessel-based echo-sounder and net trawls [3,4] can be used to identify the scatterers and quantify the acoustic backscattering strength at vertical incidence. The overall performance characteristics of the multibeam sonar can then be assessed through quantitative comparisons with the echo-sounders. This work will also delve into some of the issues and results from acoustic calibrations of this multibeam sonar.

2. INSTRUMENTATION AND EXPERIMENTAL

This work describes a field assessment of the RESON Seabat 8125 multibeam sonar which has been modified for volumetric sampling. This sonar system was originally designed for high-resolution swath bathymetric mapping, and thus was originally optimised to deliver only range to the seabed. During these sea-trials this multibeam sonar system was used for a conventional bathymetric survey. A small hardware and software modification allowed acquisition of full water-column *snapshots* (beam-former output amplitude vs. angle and range), however at a greatly reduced ping rate. During these trials the sonar head was mounted in a conventional bathymetric geometry: i.e. with the principal axis vertically downward with the 120° fan of beams athwartships. This sonar used a separate fan-beam transmitter which provided a 1.0° along-track beam-width to ±70° athwartship. The sonar operating frequency was 455 kHz, beam-forming echoes into 240 one-half-degree beams up to 120 m maximum range, with a sampling resolution near 3 cm. The receiver along-track beam-width was roughly 20°. For volumetric sampling purposes, the transmit power and pulse length (292μs) were set to system maxima. This pulse length corresponds to a 21-cm acoustic resolution, and created a sampling volume increasing from 3.2 litres at 10 m range to 460 litres at 120 m range. At the maximum range setting of 120 m the snapshot rate was 1 every 10 s. The receiver was set to maximum fixed gain (45 dB), with a time-varying gain of the form $30*\log_{10}[\text{range}] + 0.2*\text{range}$ within the first 42 m. The sonar was mounted on a retractable strut on the port side of the survey vessel (34 m LOA), at a depth of 3.4 m. A differential GPS system was used to record the ship position.

Acoustic calibration measurements on the RESON sonar were conducted using facilities at DRDC Atlantic, loosely following methods described in Cochrane et al. [5]. The required measurements were (i) to quantify the sonar time-varying gain (TVG) and noise limits, (ii) to verify the transmitter beam-pattern, and (iii) to measure the range- and beam-angle-dependent backscatter calibration coefficient. One of the interesting features of this sonar was a range-dependence in the beam-forming processor (called *dynamic focussing* by the manufacturer). This complication is necessary because of the fact that sonar *near-field* effects extend to ranges of roughly 40 m due to the relatively large transmitter and receiver apertures and the high acoustic frequency. Thus, it was found necessary to allow the systemic calibration coefficient to have both a range- and beam-wise dependence. This range-dependence was handled by defining a modified TVG which included both amplifier TVG and beam-former effects. The transmitter beam-pattern measurements were performed using a high-frequency, calibrated hydrophone recording system, and the backscatter measurements used solid steel target spheres carefully positioned in the transmit beam. Detailed results are contained in a technical report (presently in preparation), and will only be summarized here. The transmitter was found to have a 140° x 1° (to -3 dB) fan-beam, with <1 dB variation across the 120° swath. The transmitter narrow-axis beam-pattern was consistent with a standard line-array relation. The beam-wise variation in backscatter showed less than 2 dB variation across the entire swath, and so as a first approximation may be assumed uniform.

In addition, a three-frequency (38, 120, and 200 kHz), calibrated hull-mounted single-beam echo-sounder system was used. The beam-widths of the transducers were approximately matched, being 9.5°, 9.0°, and 7.0° (total width to –3dB) for the 38, 120, and 200 kHz transducers respectively. During all survey runs the echo-sounder was operated at a 1.0 Hz ping-rate, using a 0.5 ms gated-CW pulse. The raw echo-sounder data was converted to volumetric backscatter strength using the standard sonar equation, including corrections for transducer sensitivity, time-varying gain, geometric spreading and absorption loss, and insonified volume. For these echo-sounders the insonified volume increased from roughly 0.5 m^3 at 10 m range to roughly 40 - 80 m^3 by 100 m range. Note that these sample volumes were approximately 100 times larger than the individual beams in the multibeam sonar. However the total sampling volume of the multibeam sonar was roughly 15 times larger. Furthermore, at 120 m operating range the outer edges of the multibeam swath extended up to ±104 m across-track.

These multibeam sonar evaluations were performed during a 15-day sea-trial in Knight Inlet, British Columbia, forming part of an investigation on mechanisms for zooplankton aggregation at coastal sills. Knight Inlet is a fjord located on the south-central coast of British Columbia, fed by a glacier at its head some 90 km inland. The inlet features several underwater sills, with non-linear internal lee-waves occurring over these sill, creating strong turbulent dissipation in the resulting shear flows [6,7]. Acoustic backscatter from turbulent microstructure in these internal lee-waves was observed in both the multibeam sonar and echo-sounders [4]. The inlet also featured strong daytime scattering layers at 60-90 m depth, exhibiting clear nocturnal migration to the near surface, and interesting aggregation patterns near the sill. These layers were generally composed of larger crustacean zooplankton such as euphausiids (dominated by *E. pacifica*) and amphipods (both hyperiid and gammarid) [3]. In western parts of the inlet, numerous small fish schools, likely juvenile herring (*Clupea harengus pallasi*), were observed.

3. MULTIBEAM VS. ECHO-SOUNDER COMPARISONS

3.1. Fish Schools in Western Knight Inlet

Fish schools, likely 10 to 20 cm length juvenile herring, were commonly observed near an underwater sill at the western mouth of Knight Inlet. Figure 1 presents a typical 200 kHz echogram, revealing a fish school roughly 15 m high lying in 60 to 70 m depth on the upstream side of the sill. The maximum observed volume scatter strength at 200 kHz was approximately -40 dB (re m^{-1}), near the upper clipping threshold of this sounder, and thus is possibly a slight underestimate. Assuming a typical herring dorsal target strength of -45 dB (re m^2), this corresponds to a density of approximately 3.2 fish per m^3.

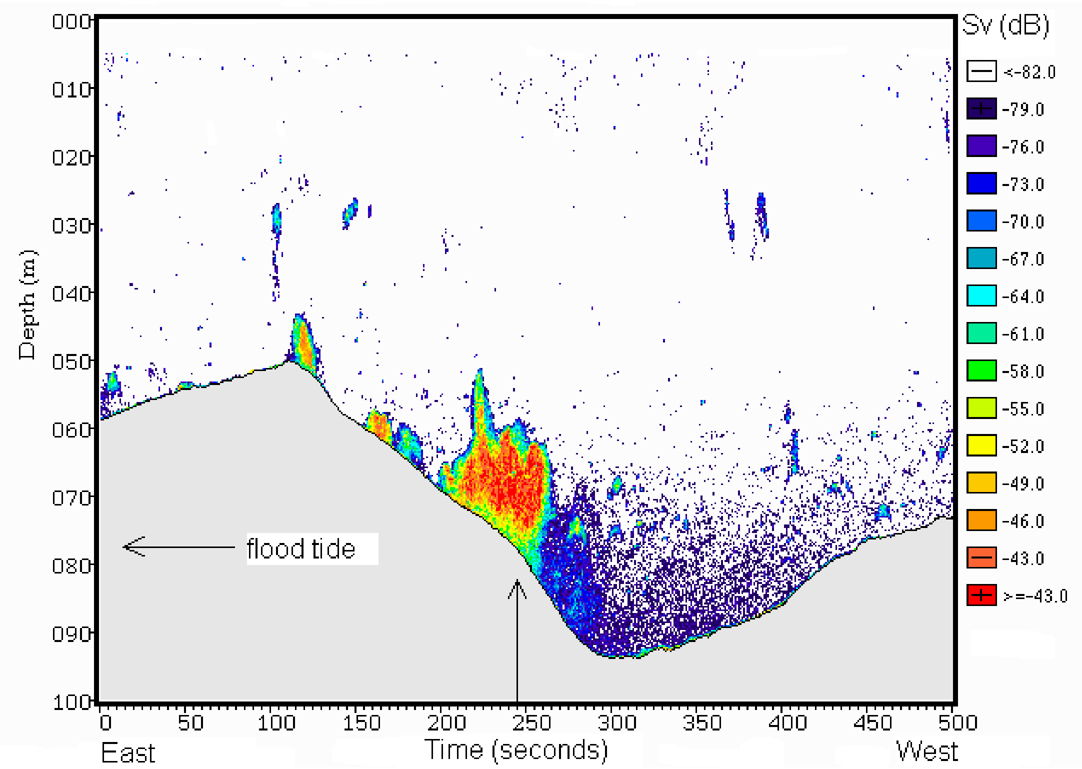

Figure 1 200 kHz volume back-scatter vs. depth and time echogram showing near-seabed fish schools in western Knight Inlet. Echogram starts 0908 PST, 19 Nov., 2002, with ship westbound during flood (eastbound) tide. Vertical arrow denotes time of multibeam sonar snapshot shown in Fig. 2.

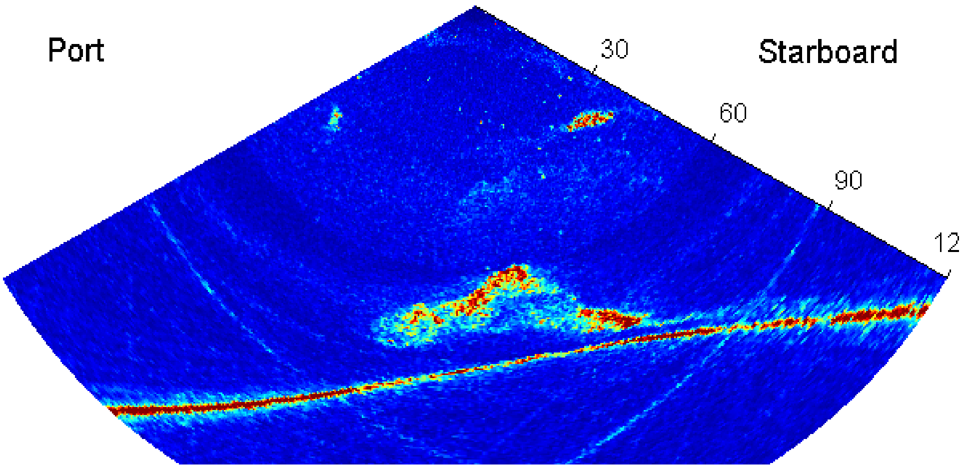

Figure 2 Multibeam sonar intensity (raw) image, taken at 0912 PST 19 Nov., 2002. Corresponds to time = 245 s in figure 1. Red linear feature sloping upwards from left to right is the seabed. Range in metres.

Figure 2 presents a corresponding multibeam snapshot through this same fish school. The image reveals a 2-dimensional, across-track structure of the school that is not visible in the echo-sounder data. It is apparent that the school is approximately 50 m in total across-track dimension (much wider than the echo-sounder beam), and apparently concentrated in 3 clusters of roughly 15 m dimension. Furthermore, the greater across-track swath area of the multibeam sonar has captured a smaller school near 40 m range on the starboard side, which was completely missed by the sounder. Estimates of volume scattering strength from this school cannot be extracted because the echoes were saturated in the A/D-beam-former (clearly, the receiver gain was set too high for fish). The two arcs crossing below the seabed are beam-former artefacts due to side-lobe contamination from the strong seabed echo. These arcs, with the occasional appearance of a ring at range corresponding to the nadir seabed echo, are generally present whenever seabed echoes are present in the data. Fortunately these cross-talk rings and arcs caused only minor interference to the survey data.

3.2. Zooplankton Aggregations near the Sill

During daylight hours, crustacean zooplankton were observed in mid-water scattering layers at roughly 70 – 100 m depth. These layers were often observed to be concentrated by tidal flows against the upstream side of a 65-m deep underwater sill, as shown in Figure 3. Net trawls through these layers found they were dominated by 15-mm length euphausiids (*E. pacifica*), with an average dorsal target strength of -83.1 dB (re m^2) at 120 kHz [3,8]. Using a published euphausiid scattering model [8], the predicted target strength for these euphausiids at the multibeam sonar frequency (455 kHz) was -86.4 dB. The euphausiid patch shown in the figure near 90 m depth had an average volumetric scatter strength of -65.1 dB (re m^{-1}), corresponding to an average euphausiid density of 63 per m^3.

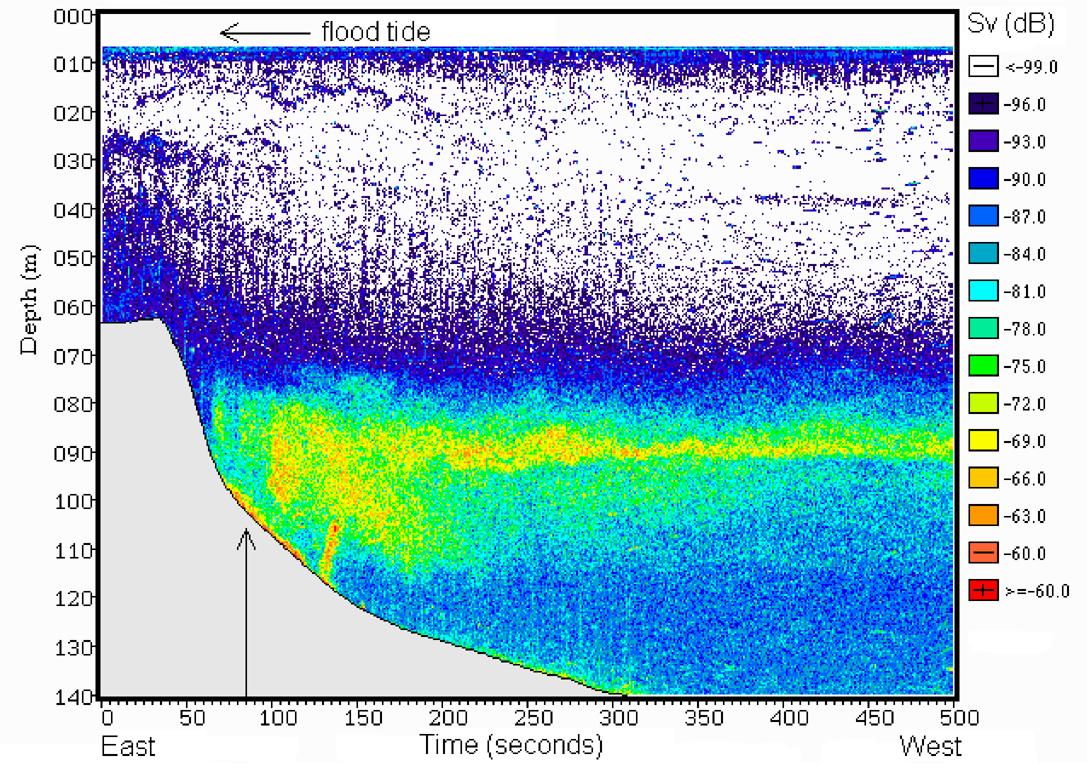

Figure 3 120 kHz volume backscatter vs. depth and time echogram showing near-seabed krill aggregations lying on the western slope of the sill. Echogram starts 1111 PST, 23 Nov., 2002, with ship westbound during flood (eastbound) tide. Vertical arrow denotes time of multibeam sonar snapshot shown in Fig. 4.

Figure 4 presents a corresponding multibeam snapshot through this same euphausiid scattering layer. Once again this snapshot revealed a 2-dimensional patchiness in the euphausiid scattering layer that was not apparent in the echo-sounder data, and in particular a stronger concentration on the starboard side where significant portions of it were missed by the sounder. The main scattering patch is approximately 50 m in the across-track dimension (much wider than the echo-sounder beam), and roughly 20 m high. In terms of volume scattering strength, the maxima in the center of the scattering patch (roughly 10° starboard from nadir) estimated with the multibeam sonar was -67 dB (re m^{-1}). This is approximately

2 dB less than observed with the 120 kHz echo-sounder, and entirely in agreement with the sounder given the slightly lower euphausiid target strength at the multibeam frequency.

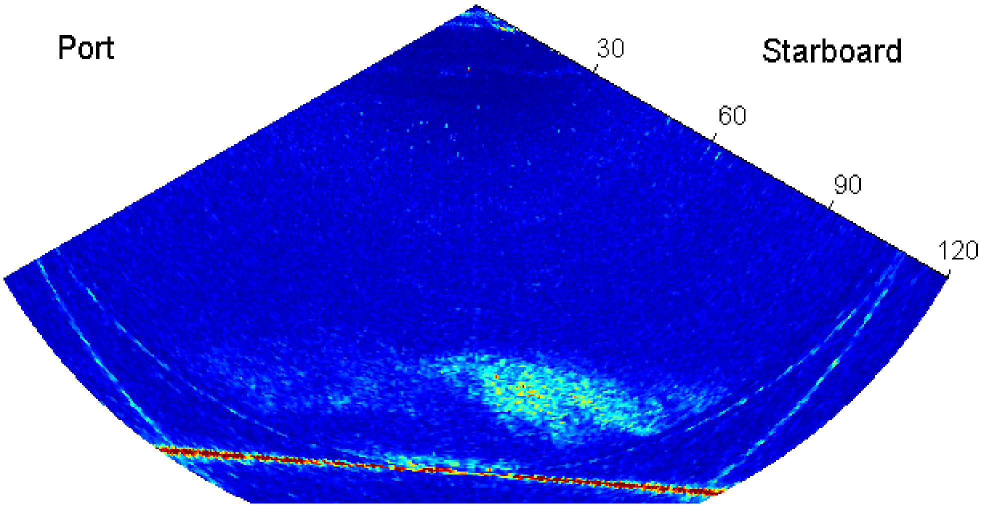

Figure 4 Multibeam sonar intensity (raw) image, taken at 1114 PST 23 Nov., 2002. Corresponds to time = 85 s in figure 3. Red linear feature sloping downwards from left to right is the seabed. Range in metres.

3.3. Turbulent Microstructure Scattering over the Sill

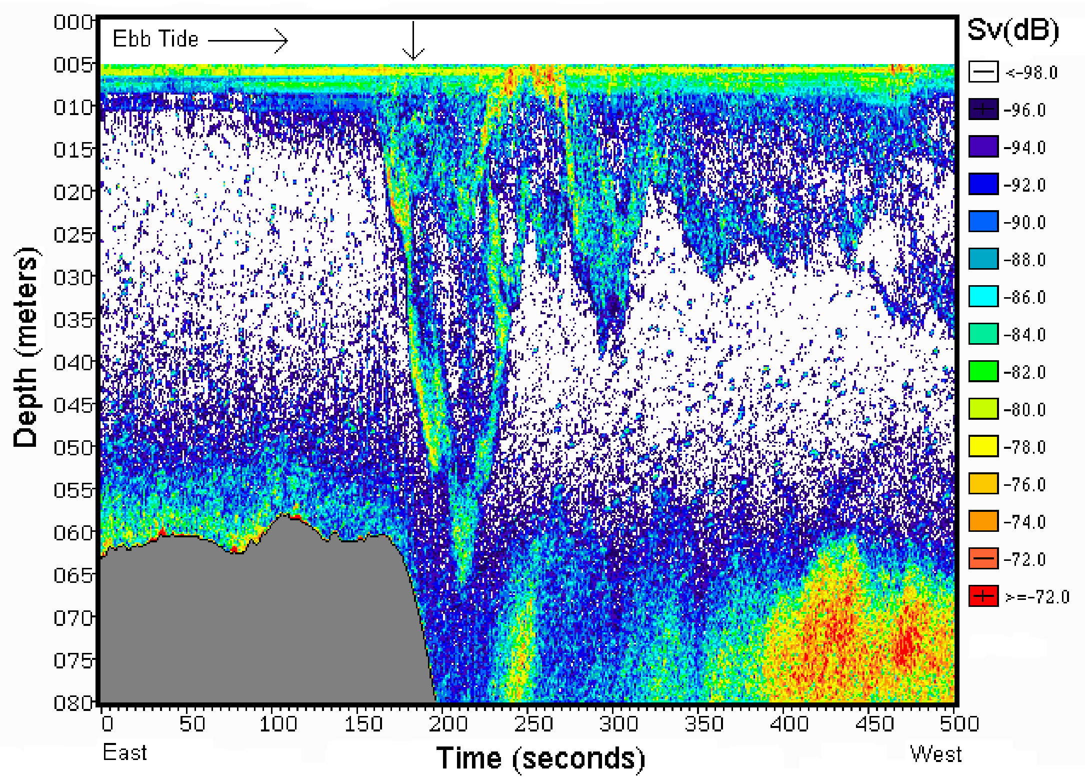

Figure 5 120 kHz volume back-scatter vs. depth and time echogram showing microstructure scattering in an internal lee-wave on the western side of the sill. Echogram starts 1421 PST, 17 Nov., 2002, with ship westbound during ebb (westbound) tide. Vertical arrow denotes time of multibeam snapshot shown in Fig. 6.

Non-linear internal lee-waves were commonly observed with the echo-sounders during transects over the sill, with a typical example presented in Figure 5. This echogram was taken during a westbound (downstream) transect at mid-ebb-tide. Upstream of the sill the pycnocline lay near 5 m depth. At the sill crest the pycnocline plunged to depths of 65 m before rebounding through several oscillations. This lee-wave structure was acoustically illuminated by backscatter from turbulent microstructure, induced by strong shear within the flow boundaries in the presence of thermo-haline stratification [4,9]. The echogram shows that these turbulent scattering layers were typically only 2 to 10 m thick, with volume scattering strength in the range -80 to -75 dB (re m^{-1}) at 120 and 200 kHz. Microstructure scattering models [9] predict similar volume backscatter strengths at the 455 kHz multibeam sonar frequency. During daylight hours negligible euphausiid abundances were found in the upper 60 m of the water column. A euphausiid scattering region downstream of the sill is evident in the lower right corner of Fig. 5.

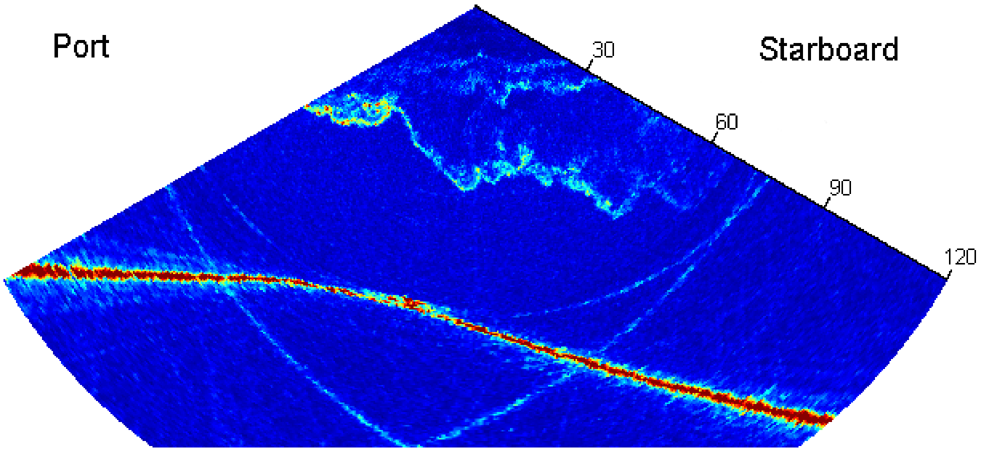

Figure 6 Multibeam sonar intensity (raw) image, taken at 1424 PST 17 Nov., 2002. Corresponds to time = 185 s in figure 5. Red linear feature sloping downwards from left to right is the seabed. Range in metres.

The multibeam sonar images through these lee-waves showed the turbulent scattering layers formed into across-track turbulent billows, as demonstrated by Figure 6. In this image there are three sinuous flow boundaries (near 12, 16, and 36 m depth in the nadir beam), with the lower flow boundary sloping downwards roughly parallel to the seabed. The most intense feature lies near 25 m depth on the port side, showing a tight swirl approximately 5 m high by 10 m in across-track dimension. The maximum predicted volume backscatter strength along the edges of this swirl was approximately -75 dB (re m^{-1}). In contrast, the maximum backscatter strength in the nadir beams along the lower flow boundary near 36 m depth was -79 dB. Overall, the higher spatial resolution provided by the multibeam shows these sinuous scattering layers were only 1 to 2 m thick.

4. DISCUSSION AND CONCLUSIONS

This volumetric multibeam sonar provided interesting, high-resolution views of relevant biologic and oceanographic phenomena. A particularly useful feature was the ability to provide 2-dimensional pictures of the spatial structure of the fish schools, euphausiid patches, and turbulent billows. In many instances the greater across-track sampling area of the multibeam sonar was able to sample mid-water objects missed by the echo-sounder. This 2-dimensional imaging capability should find application in studies of schooling behaviour and zooplankton patchiness. The images of cross-flow turbulent billows and flow boundaries were particularly dramatic (and to the author's knowledge the first ever reported), and should prove highly useful in determining spatial scales of the turbulent flows. With an increase in ping rate, it is conceivable that sequences of such multibeam sonar images could yield quasi-three-dimensional sampling of the mid-water scattering structures.

The signal to noise performance of the multibeam sonar was surprisingly good, readily sampling features with volume backscatter strengths as low as -80 dB (re m^{-1}). One major limitation was the relatively low ping rate, acquiring only 1 snapshot every 10 s at the 120 m range setting. This created spatial aliasing of the scattering features, which was particularly problematic for the highly dynamic turbulent billows. The acoustic calibration of the multibeam sonar was an elaborate process, due to the significant range variations in beam-former sensitivity. A related issue was that the transmitter and receive-array *near-field* distances were roughly 8 and 40 m, respectively, requiring use of a relatively large outdoor calibration facility. A further complication (not mentioned above) that arises with the new, quantitative multibeam measurements at off-vertical directions is the potential for anisotropic backscattering from objects such as fish, zooplankton, and turbulence.

5. ACKNOWLEDGEMENTS

This work was partially supported by a grant from the US Office of Naval Research, Biological and Chemical Oceanography program (Dr. Jim Eckman), with the RESON sonar contributed by Canadian Dept. of National Defence. The author is also grateful for the contributions of Dr. Dave Mackas of the Institute of Ocean Sciences, Sidney, B.C. and Prof. Mark Benfield of Louisiana State University during the overall Knight Inlet study.

REFERENCES

[1] Soria, M., Freon, P., and Gerlotto, F., Analysis of vessel influence on spatial behaviour of fish schools using a multibeam sonar and consequences for biomass estimates by echo-sounder, *ICES J. Mar. Sci.* **53**, 453-458, 1996.

[2] Gerlotto, F., Soria, M., and Freon, P., From two dimensions to three: the use of multibeam sonar for a new approach in fisheries acoustics, *Can. J. Fish. Aquat. Sci.* **56**(1), 6-12, 1999.

[3] Trevorrow, M., Mackas, D., and Benfield, M., Comparison of multi-frequency acoustic and in situ measurements of zooplankton abundances in Knight Inlet, B.C., *J. Acoust. Soc. Am.* (in press 2005).

[4] Trevorrow, M., Observations of acoustic scattering from turbulent microstructure in Knight Inlet, *Acoust. Res. Lett. Online* **6**(1), 1-6, 2005.

[5] Cochrane, N., Li, Y., and Melvin, G., Quantification of a multibeam sonar for fisheries assessment applications, *J. Acoust. Soc. Am.* **114**(2), 745-758, 2003.

[6] Farmer, D., and Armi, L., The generation and trapping of solitary waves over topography, *Science* **283**, 188-190, 1999.

[7] Klymak, J., and Gregg, M., Tidally generated turbulence over the Knight Inlet sill, *J. Phys. Oceanogr.* **34**(5), 1135-1151, 2004.

[8] Stanton, T., and Chu, D., Review and recommendations for the modeling of acoustic scattering by fluid-like elongated zooplankton: euphausiids and copepods, *ICES J. Mar. Sci.* **57**, 793-807, 2000.

[9] Seim, H., Acoustic backscatter from salinity microstructure, *J. Atmos. Oceanic Technol.* **16**, 1491-1498, 1999.