MULTIPLE-FREQUENCY MOORED SONAR FOR CONTINUOUS OBSERVATIONS OF ZOOPLANKTON AND FISH

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Abstract—**Moored, internally-recording acoustic instruments can acquire continuous profiles of echoes throughout the water column, thus providing a low-cost method to study the behavior and abundance of fish and zooplankton in oceans and lakes. Calibrated sonars with several frequencies allow some information about species composition and abundance to be deduced from acoustic backscatter data. The same instrument can be configured to look up from the bottom, down from the surface or horizontally from a CTD cage. In this presentation we describe an improved low power, battery-operated multi-frequency sonar capable of autonomously collecting data at high temporal and spatial resolution for periods of up to a year. The AZFP instrument (Acoustic Zooplankton and Fish Profiler) supports up to four frequencies in a single housing. The available operating frequencies are 38, 125, 200, 455 and 770 kHz. The transducers are co-located, with the same nominal beam widths of 7° or 8°, except at 38 kHz, where the beam width is 12°. The standard AZFP can be moored at depths up to 300m, and with modified transducers as deep as 600m.**

The recent improvements to the instrument include replacement of the signal detector with a wide dynamic range logarithmic receiver. The linearity of the receiver response has been improved, its instantaneous dynamic range has been increased to over 80 dB, and the requirement to pre-select one of four time-varying gain settings is no longer necessary, as the expanded dynamic range eliminated the need for a time-varying gain function. Additional noise reduction methods have also been implemented. The procedures used to calibrate acoustic performance of these instruments will be discussed. Typical minimum detectable volume backscatter strengths are -100dB at 20m range to -80dB at 100m range for the 125 and 200 kHz channels, and -80dB at 20m range for the 770 kHz channel. Sixteen GigaBytes (GB) of data storage is provided using a compact flash disk, which allows high temporal sampling rates (maximum 1 Hz) to be performed for shorter deployments. For longer periods, true arithmetic averaging can be done internally in both range and time to reduce the data storage space required. Low power consumption allows the instrument to collect data on four channels out to 100m range, pinging at 0.5 Hz for 150 days on a standard 200 Ampère-hours (A-Hr) battery pack.

To illustrate the potential of such observations, preliminary results from several deployments in Saanich Inlet, BC are discussed. The effects of seasonal and year-to-year variations in this area are shown in a segment of a six-year time series collected by a 200 kHz sonar mounted on the VENUS cabled observatory, with the data organized as depth-time 'cubes' to facilitate handling of such long time series. Data from recent nearby deployments of multiple-frequency instruments (125, 200, 455 and 770 kHz) shows examples of the additional information that can be obtained from simultaneous measurements at several frequencies.

Index Terms—**Battery-operated, multiple-frequency, internally recording, sonar, zooplankton, fish, long time series, acoustic volume backscatter.**

I. INTRODUCTION

Long time series of continuous data from moored acoustic instruments offer a low-cost method to study ecosystem changes by monitoring the behavior and abundance of fish and zooplankton in the ocean and in lakes. Calibrated sonars with several frequencies allow some information about species composition and abundance to be deduced from acoustic backscatter data. In this paper we describe an improved low power, battery-operated sonar with up to four frequencies capable of autonomously collecting data at high temporal and spatial resolution for periods of several months.

II. INSTRUMENT CHARACTERISTICS

The AZFP contains up to four acoustic channels; the frequencies available are 38, 125, 200, 455 and 770 kHz. The transducers for the 4 higher frequencies are located within a single housing; the larger 38 kHz transducer requires a separate housing. Figure 1 shows the configuration of the instrument with and without the 38 kHz channel, as well as an exploded view. Table 1 summarizes the AZFP's basic acoustic parameters for each of the available frequencies. Figure 2 shows an example of a 200 kHz transducer beam pattern; sidelobes are at -17 dB or less.

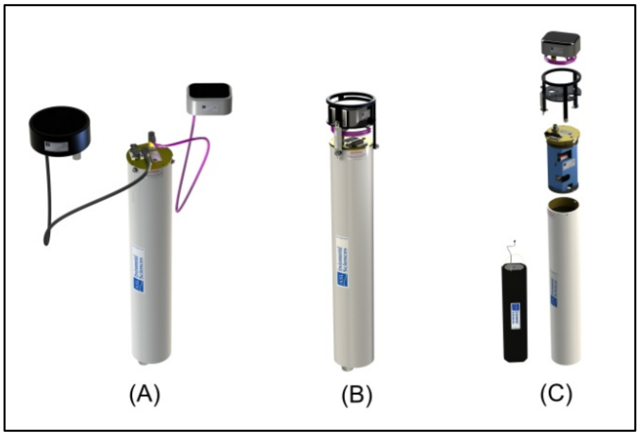

Fig. 1: Configuration of the AZFP: (A) with the 38 kHz channel, (B) as a 4-frequency 125/200/455/769 combination and (C) as an exploded view.

Table 1: Acoustic parameters of the AZFP channels

Frequency (kHz)	Nominal -3 dB Beam Angle (°)	Nominal Source Level (dB)
38	12	209
125	8	206
200	8	209
455	7	212
770	7	213

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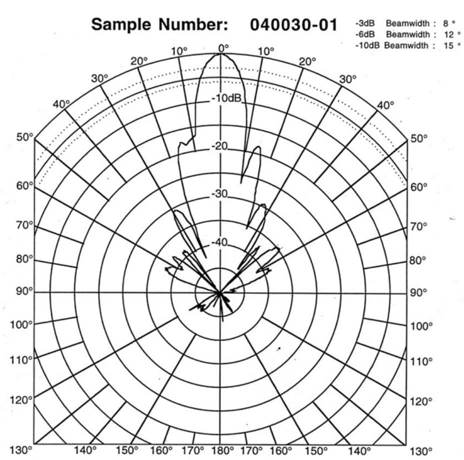

Fig. 2: Sample beam pattern for a 200 kHz AZFP transducer.

There are 16 GB of data storage available, and the standard battery pack of 200 A-Hr allows the instrument to sample on four channels to 100 m range, pinging every 2 seconds for 150 days. The pulse width is selectable between 100 and 900 µs, and averaging over range or time is available. The instrument can be installed looking upward, either from a bottom frame or in a taut-line mooring or it can be deployed looking downward from a surface buoy. The standard AZFP can be moored at depths of up to 300m, and with modified transducers as deep as 600m.

The AZFP incorporates significant improvements over its predecessor; the most important being the replacement of the signal detector with a wide dynamic range logarithmic receiver. Its instantaneous dynamic range of over 80 dB allows it to be operated without a time-varying gain, which, along with better linearity compared to the previous detector, simplifies data processing. Configuration changes in the electronics, mainly additional shielding and improved ground planes, have reduced self-noise as well.

Figure 3 illustrates the sampling schematically for an instrument with four channels. Sampling may be regularly spaced or in bursts; in either case, averaging in range or in time is optional. When a ping is to be emitted, transmission occurs from the highest frequency transducer first. After the listening period for that channel (determined by the maximum sampling range selected) has elapsed, the next channel down in frequency transmits, and so on until listening is complete for the last channel. The sequence is repeated at the selected ping rate; if burst sampling has been selected, transmissions cease after the number of pings per burst is reached, and the sequence starts again after the burst period has elapsed. The maximum sampling range, pulse length and range bin size may be set independently for each channel.

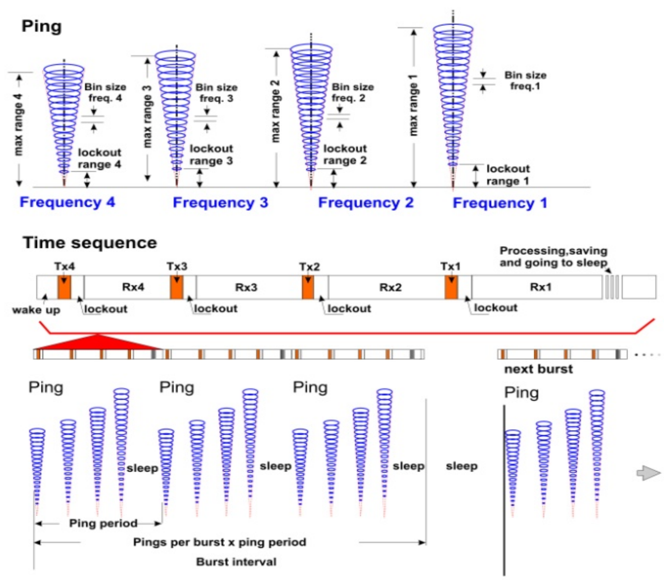

Fig. 3: Schematic of the instrument sampling scheme showing the ping and the burst.

Figure 4 shows a simplified block diagram of the instrument signal path for a single channel. Echoes arriving at the transducer pass through an amplification and band-pass filtering stage to the detector (Analog Devices 8310 demodulating logarithmic amplifier), whose output is a DC voltage linearly related to the input signal power (to within ±0.4 dB) with a dynamic range of up to 95 dB, although self-

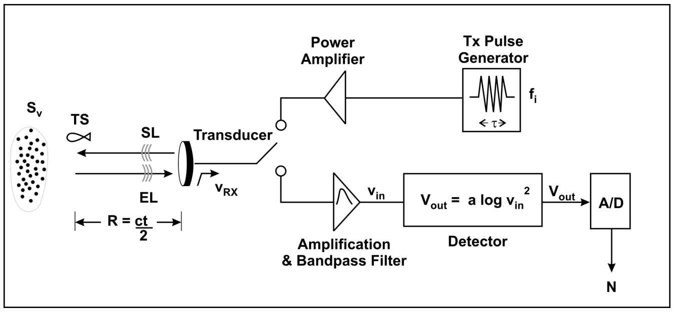

Fig. 4. A simplified block diagram of the instrument signal path for a single channel.

noise in the instrument limits the effective dynamic range to between 80 and 90 dB in most cases.

The output of the detector is digitized by a 16 bit A/D whose full-scale output is produced at an input voltage of 2.5V. Measuring the echo level at the transducer that produces the full scale count, EL_{max}, and the detector response, a, in V/dB allows the echo level at the receiver to be computed from the recorded counts, N, as below:

$$EL = EL_{max} - 2.5/a + N/(26214 \cdot a) \qquad (1)$$

Signals greater than EL_{max} are truncated at 65,535; the minimum detectable signal is determined by the instrument's internal noise. Volume backscatter (S_v) or target strength (TS) may then be calculated from N via the standard forms of the sonar equation:

$$S_v = EL_{max} - 2.5/a + N/(26214 \cdot a) - SL + 20 \cdot \log R + 2 \cdot \alpha \cdot R - 10\log(\tfrac{1}{2} c \cdot \tau \cdot \psi) \qquad (2)$$

$$TS = EL_{max} - 2.5/a + N/(26214 \cdot a) - SL + 40 \cdot \log R + 2 \cdot \alpha \cdot R \qquad (3)$$

where R is the range from the instrument (m), SL is the transmission source level (dB re 1μPa at 1 m), α is the absorption coefficient (dB/m), τ is the transmit pulse length (s), c is the sound speed (m/s) and ψ is the equivalent solid angle of the transducer beam pattern (sr).

If averaging has been selected, the AZFP performs a true arithmetic average of the data and stores the result as the data are being collected. The individual raw samples are not saved. Because of the limitations of the on-board processor and integer arithmetic, the conversion between logarithmic and linear values is done using a look-up table, which has a resolution of 0.013 dB. The resulting averages are converted back to logarithmic form before storage.

III. CALIBRATION

Calibrating the instrument requires measurement of five quantities: SL, EL_{max}, a, Ψ, and the internal noise. The transducer manufacturer's measurements for the beam pattern are used for Ψ. A calibrated hydrophone (Reson TC4035) with a stated accuracy of ±1 dB and a secondary source (calibrated with the reference hydrophone) are used to measure the on-axis values of the transmitted signal strength and the receiver response as a function of signal strength, respectively; the measurements are done at approximately 1 m range, at room temperature (19°C) and at approximately 0.5 meter water depth (Figure 5).

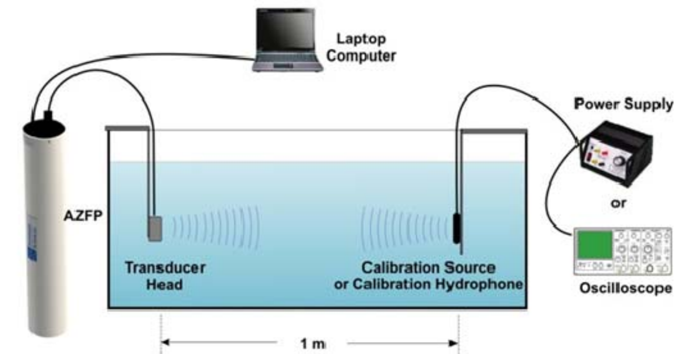

Fig. 5. AZFP acoustic calibration procedure.

Temperature stability is checked by placing the instrument in a freezer, while leaving the transducers and a target in the test tank. The instrument is cycled from +20C to -20C and back overnight, while recording the returns from the target. The returns are typically stable to within ±1 dB.

A secondary calibration check in a larger, enclosed outdoor tank is performed using a target sphere on the beam axis at approximately 4 m range (Figure 6). The target is a precision ½ inch diameter tungsten carbide sphere, whose target strength is free of resonances at the frequencies used (Figure 7). Figure 8 is an example of the returns from the target recorded by a 4-channel AZFP in the large tank.

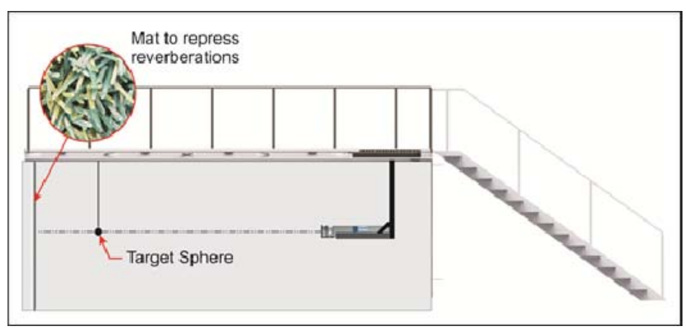

Fig. 6. Secondary calibration check performed in the outdoor tank at 4m range.

The mean self-noise level is typically between 10,000 and 15,000 counts; it is measured by operating the instrument in internal recording mode, on batteries and in air, with the sampling range set to > 300m. The self-noise is then taken as the mean of the counts at long range.

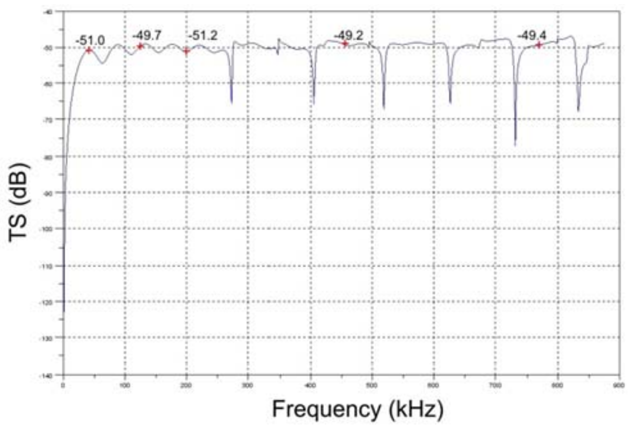

Fig. 7: Target strength (TS) characteristics of a ½ inch diameter tungsten carbide sphere at 12°C and 0 salinity.

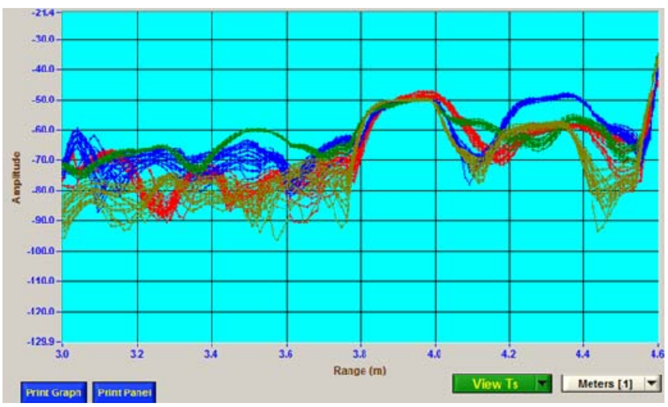

Fig. 8: Example of the returns from the target recorded by a 4-channel AZFP in the large tank (red: 125 kHz; blue: 200 kHz; green: 455 kHz; gold: 770 kHz). The vertical axis shows TS (dB).

Figure 9 shows representative limits of detectable S_v as a function of range for each of the AZFP frequencies, for average temperate zone coastal ocean conditions.

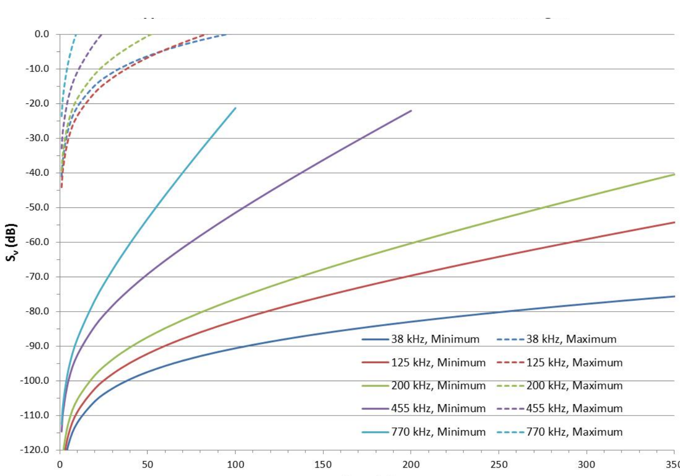

Fig. 9: Typical limits of detectable S_v as a function of range and AZFP frequency.

IV. Multi-frequency and Extended Time Series

Figure 10 shows an example of multiple-frequency data collected by an AZFP in Saanich Inlet, on Vancouver Island, British Columbia, Canada. The instrument was deployed looking downward from a drifting surface float, and backscatter data at four frequencies were collected from late afternoon until darkness.

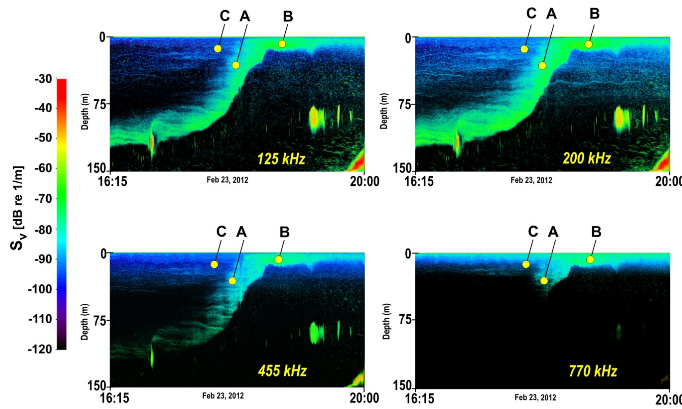

Fig. 10: Four-channel AZFP Data from Saanich Inlet on Vancouver Island, British Columbia. Points A, B and C are explained in the text.

The ascent of the scattering layer from approximately 100m depth to the surface may be seen clearly in the three lower frequency channels, but is detectable only after it passes through 40m in the 770 kHz channel, because of the limited detection range at the higher acoustic frequency. It is also apparent that S_v in the migrating layer is higher at 200 kHz than it is at 125 kHz, which in turn is higher than at 455 and 770 kHz. There is also another weaker, more diffuse layer continually present near the surface, in which S_v appears highest at 770 kHz. The differences in scattering strength with frequency can be used in this case to make inferences about the composition of the scattering layer.

As an example, we consider three locations marked in the echograms in Figure 10: A, in the ascending layer as it approaches the surface and is detectable at all four frequencies; B in the layer after it has reached the surface, and C, in the non-migrating surface layer. The dominant zooplankton species in the diurnally migrating layer in Saanich Inlet is known to be *Euphausia pacifica* [1] and is therefore taken to be the source of the backscatter signal at A and B. The zooplankton at C exhibit the strongest scattering at 770 kHz, indicating that a smaller organism, likely *Calanus plumchrus*, commonly found in the adjacent waters of the Strait of Georgia [2], is responsible.

Figure 11 compares the spectral signature of backscatter from these two organisms, using the model developed by Stanton et al. [3]. In the figure, the dotted lines indicate S_v as computed

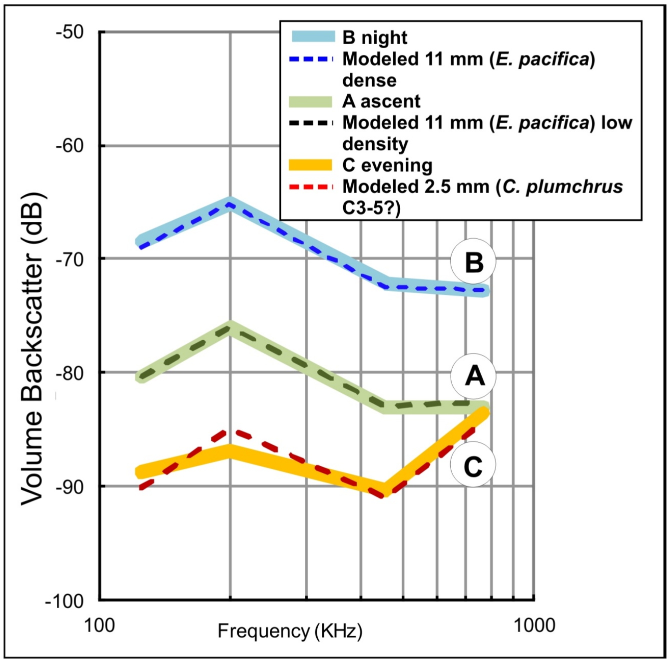

Fig. 11: Model and measured frequency dependence of S_v at the locations marked in Figure 10.

from the model and the coloured shading denotes the measured values for the three locations chosen in Figure 10. At A and B, the modeled values are for 11 mm euphausids, and the agreement with the measured spectral pattern is very good; the offset between the two lines of 11 dB indicates a 12 times denser population at B. At C, the modeled values are for 2.5mm *C. plumchrus*, and the agreement, while reasonable, is not quite as good as for the other two cases.

The low power consumption of the AZFP makes it possible to collect long time-series at high temporal and spatial resolution, thus allowing investigation of seasonal and inter-annual variability. Handling the large volume of data in such long time-series is challenging; Figure 12 shows an example of one technique for visualizing such data. In this example, a data cube concept is employed to represent the measured backscatter strength depth/hour/day time-series.

The data cube in Figure 12 shows a 14 month segment of S_v at 200 kHz, collectged by an older, more limited single-frequency version of the AZFP at the University of Victoria's VENUS cabled observatory site in Saanich Inlet, BC, on the Pacific coast of Canada. The front of the cube illustrates the variation of S_v as a function of depth throughout the day, averaged at 10 minute intervals. Subsequent days are conceptually arranged in sequence.

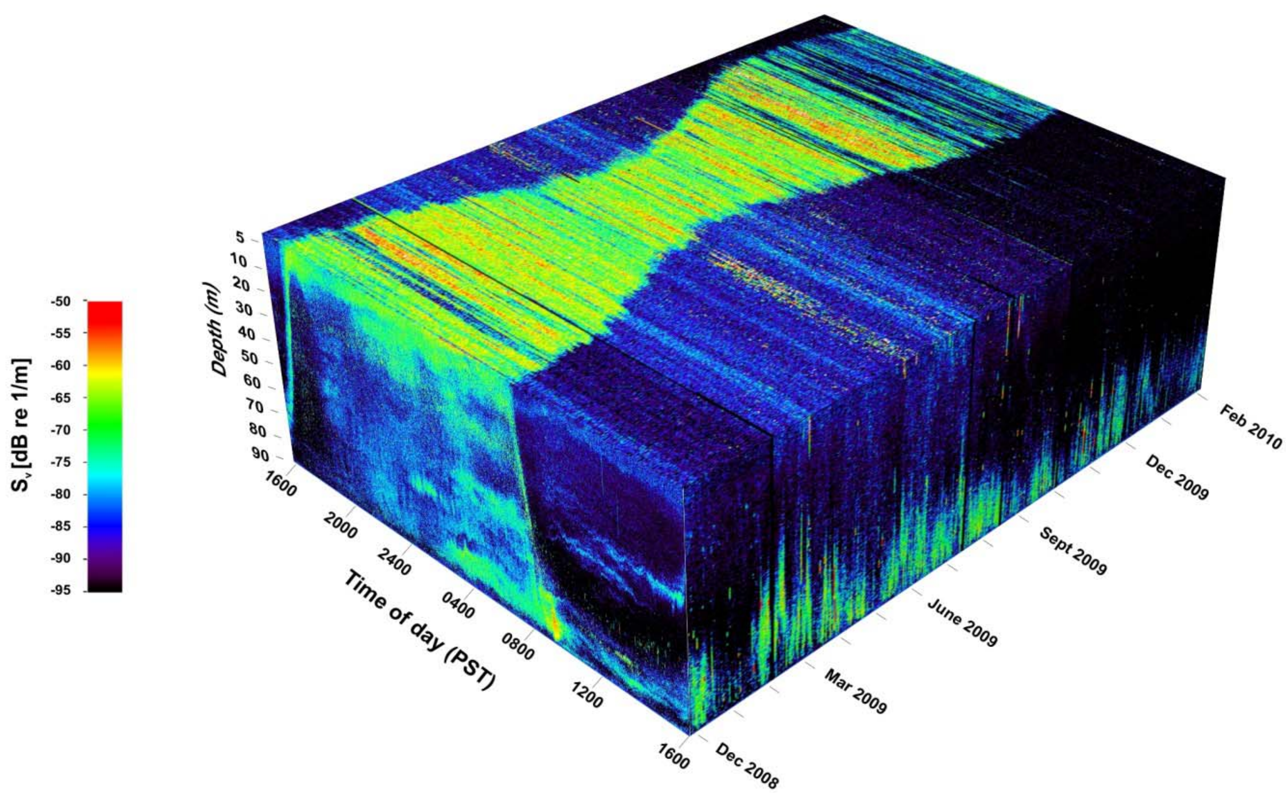

Fig. 12: Data cube showing a 14 month segment of a 6-year time-series of 200 kHz backscatter for the VENUS site in Saanich Inlet, British Columbia, Canada.

The top surface of the cube represents the daily variation of S_v at 5 m depth for the entire 14-month series. The seasonal changes in vertical migration timing associated with day length can be seen, as can variations in the strength of backscattering at that depth. The right side of the cube represents depth profiles for 1600 PST (2400 UTC) on each day of the profile. At that time of day, most scatterers are at depths below 70 m; a summer increase in scattering above 30 m is also visible.

V. Conclusions

Low power, multi-frequency scientific echo sounders, with their ability to collect long, high-resolution times series of acoustic backscatter strength, can be a valuable tool in furthering understanding of zooplankton populations and behavior. When used in conjunction with other resources, such as satellite remote sensing and vessel-based acoustic surveys and net tows, they can contribute significantly to understanding oceanic ecosystem dynamics.

Acknowledgments

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