HIGH RESOLUTION AND BROADBAND PROCESSING OF ACOUSTIC IMAGES OF THE MARINE BENTHOS

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ABSTRACT

High resolution acoustic imaging can be used to study benthic fauna and biogenic structures in near surface marine sediments. Currently used physical sampling methods disrupt structure and displace organisms, preventing the study of fauna in their natural sub-seabed setting. In addition to being important food for demersal fishes, the benthos living on and in the seabed sediments is strategic to the regeneration of nutrients which are vital to planktonic primary production. The benthos is thus an integral part of the fisheries production system. Through careful design, broad bandwidth acoustic signals can be generated to produce precision acoustical snapshots, with millimetre scale resolution, of the benthic fauna and of their undisturbed habitat. Advances in digital signal processing techniques fully exploit the information captured in this wide frequency domain. Unique classification and sorting of indices are made possible based on discrete frequency dependent signatures of the benthos. This paper presents the physics for precision characterization of the near surface seabed. Actual data are used to illustrate how broad bandwidth signals are necessary for the development of acoustic classifiers which recognize benthic fauna and their associated structures in sediments.

1. INTRODUCTION

The physical structure of the marine sub-bottom benthic habitat is determined to a large extent by benthic infaunal activities which, in aggregate, are referred to as bioturbation. Information on the biogenic structure of marine sediments thus provides information about the activities of benthic organisms, and about how these activities may be affected by anthropogenic disturbances. The impact of human disturbance on the marine benthos by a host of activities is drawing increasing attention as some economically important fish stocks decline. Reasons for stock decline are beyond the realm of current fisheries population prediction models.

PROCESSING OF MARINE BENTHOS ACOUSTIC IMAGES

Study of the ecology of the marine soft-bottom benthos has been hampered by some limitations of conventional grab and core sampling techniques (Mills, 1975). An important limitation is that the structural integrity of the sediment habitat is disturbed and ecological information is lost in the process of retrieving and processing sediments to obtain quantitative biological samples. Non-destructive sampling techniques such as side-scan sonar, camera, and video can only provide structural information on surface megafauna and sediment features but cannot produce images of subsurface sediment texture, fauna, and biogenic structures associated with bioturbation. Rhoads and Germano's Remots sediment profiling system (Rhoads and Germano, 1982) is capable of obtaining high resolution data from a vertical sediment face and has been useful in studies of infaunal succession. It is, however, restricted to the imaging of a vertical face cut into the sediment, with resulting displacement of features and restriction to a two-dimensional image. While x-radiography may be used to obtain images of sub-surface sediment structures, it requires a lengthy and destructive sampling process which substantially alters the *in situ* character of the sample in the process of data collection. In addition, the information provided has proven to be of limited use as it is visual and non-quantitative in character.

In an attempt to introduce non-destructive imaging techniques to overcome some of the above-mentioned problems, Orr and Rhoads (1982) used a 1.6 MHz acoustic backscattering system to image lamination and simulated benthic organisms within the upper 7 cm of a marine test sediment. The system could produce an image of sediment lamination within 3 cm of the surface and of worm tubes that are built above the sediment surface. It could not detect simulated organism structures in the sediment. Until now, further work on very high resolution acoustic imaging of surficial sediment features has not been reported in the literature. A need exists therefore for high resolution imaging of subsurface features of the soft-bottom benthos over relatively large spatial and depth scales, and with near-real-time data return. Studies on the effects of physical disturbance of the benthos and their recovery rates would greatly benefit from the ability to rapidly collect information on subsurface structures and fauna in a non-destructive manner.

Acoustic methods for benthic ecological studies are dictated by the resolution required to distinguish organisms and biogenic structures within the sediment with minimum interference and masking. It is desirable that the temporal resolution of a sound source be such as to prevent interference between thin sediment layers and "point" sources associated with benthic fauna. A short, broadband signal and narrow beam will reduce this interference. This would provide better signal-to-reverberation ratios when scattering is present in the medium. However, such pulse characteristics are rarely achievable using conventional seismic profilers. A tradeoff occurs between temporal resolution and depth of penetration, with the former requiring broadband, high acoustic frequencies and the latter requiring low frequencies (Guigné, 1986). Common acoustic sources such as those used for fisheries and plankton studies, and for geological studies of marine sediments, operate within the constraints of these tradeoffs. One approach which shows promise is to employ non-linear acoustical technology. The development of the parametric array allows for a broadband source to be realized in practice (Berktay *et al.* 1979). Its broad bandwidth and narrow beamwidth characteristics appear well suited for biological seabed applications.

The use of very broadband acoustics for benthic studies offers several advantages over physical sampling techniques. The response from temporally and spatially precise and coherent acoustics can indicate unique sediment characteristics. Images of biogenic structures and physical features of taxonomic groups of fauna can also be produced. These characteristics would be useful for non-destructive imaging of these features, especially where precise taxonomic information is less critical than non-taxonomic features of community structure. There are many instances in benthic ecological studies where these conditions would apply. For instance it would be considered strategic for rapid, non-destructive estimates of benthic biomass in areas of known faunal composition, and for studies of long duration effects of anthropogenic stress on benthic communities. The acoustic responses could be combined with periodic physical sampling to obtain correlative information on taxonomic shifts associated with acoustically-imaged structural changes.

Our objective has been to obtain high resolution acoustic images of trawled and untrawled areas of seabed to provide data on the impact of trawling on benthic productivity over the continental shelf of eastern Canada. Our custom-designed high resolution broadband array is to be mounted on a large area (0.5 m^2) pneumatically operated grab sampler equipped with a high resolution video camera. Further development is underway to deploy and operate the acoustic array on a bottom-referencing towed instrument vehicle. This acoustic-trawling study is part of the Northern Cod Science Program, instituted by Canada's Department of Fisheries and Oceans to investigate the decline of the valuable northern cod fish stock.

2. METHODS

Laboratory experiments were carried out in the research laboratory of Guigné International Limited (GIL), Newfoundland, Canada, and in mesocosms at Institut Maurice Lamontagne (IML), Québec, Canada. The latter were kindly made available for our use by Dr. Norman Silverberg and Dr. Jean-Marc Gagnon, Department of Fisheries and Oceans, Québec, Canada.

2.1 Experimental Setup and Calibration at GIL

Initial calibrations were performed in GIL's test tank (see Figure 1), using preserved animals. The tank was constructed of plexiglas with dimensions 120 cm length x 50 cm width x 100 cm height. A sheet of styrofoam was firmly fixed to the tank bottom as a highly reflective base. A moveable aluminum rack located across the top of the tank held the acoustic sensors in accurate alignment. The transducer and hydrophone were mounted in vertical stainless steel tubes held in the rack and driven by a worm gear device.

A parametric array transducer designed by Guigné International Limited was placed in fresh water 760 mm above the highly reflective bottom. A Brüel and Kjær 8103 cylindrical hydrophone was placed below the transducer and 360 mm above the bottom. This geometry was fixed throughout the tests. The broad secondary spectra produced from the source exhibited a range from 10 kHz to over 200 kHz. The signals showed a high level of coherency over the base reflector.

Experiments were conducted on well sorted No. 0 Alwhite Silica Sand with a mean diameter of 0.45 mm and mean porosity of 46.1%. The sand was soaked and washed three times in hot water (65 °C) to release air bubbles. The sand was then allowed to cool to room temperature and was transferred to the water-filled tank and levelled at a height of 110 mm over the styrofoam base. Stable measurements were made after water temperature equilibrium in the tank was reached.

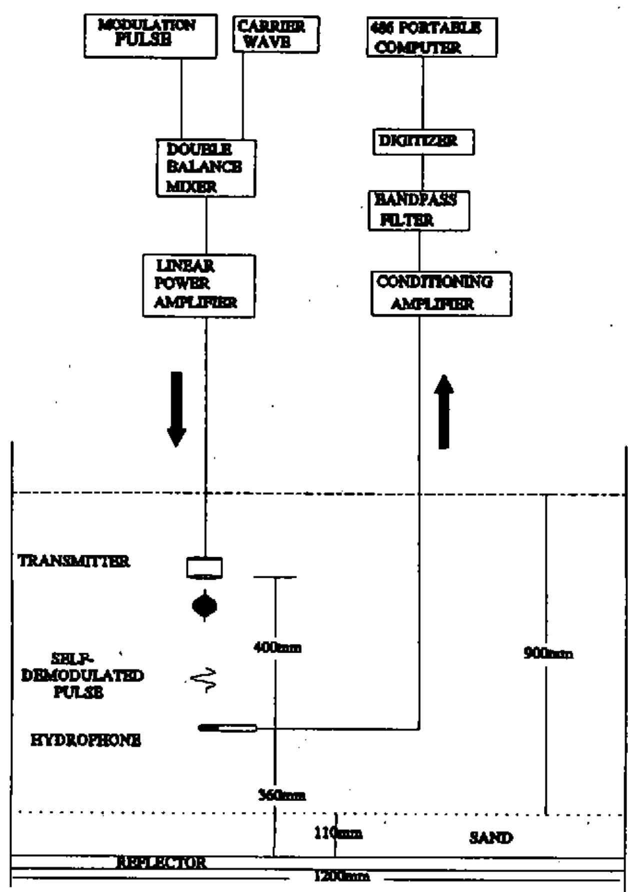

Figure 1. Schematic of Tank Setting in the Acoustic Laboratory of Guigné International Ltd.

2.2 Acoustical Profiling

Preliminary profiles were obtained from the undisturbed, level sandbed and three benthic species common to the Grand Banks of Newfoundland: a sea-urchin (*Strongylocentrotus droebachiensis*), a juvenile yellowtail flounder (*Limanda ferruginea*) and a clam (*Macoma calcarea*). The alcohol-(70%) preserved specimens were placed on the sandbed and imaged acoustically. For the bivalve *Macoma calcarea* additional experiments were performed with the clam buried in the sand. The procedure for burying the clam involved first adding sand into the tank raising the sand thickness to a height of 8 cm. The clam was placed on the 8 cm high surface and more sand was added to a total height of 17 cm. The first acoustic measurement was performed two days after to allow the sand to stabilize.

2.3 Acoustic Testing in the Benthic Mesocosms at IML

The configuration of the acoustic device used in the GIL test tank was retained for the IML mesocosm experiments. The transmitting and receiving sensors were calibrated in GIL's Research Laboratory before they were used at IML.

Three mesocosm tanks, specifically designed for benthic process studies, were used for the experiments. The tanks were 71 cm deep, 109 cm x 109 cm top area, and 103 cm x 103 cm bottom area. Temperature-controlled seawater circulation systems maintained the tanks at 4°C. The tanks were covered with polyurethane foam lids. Temperatures remained stable for at least two hours without the covering lids while the acoustic measurements were performed.

Sediment was collected from a 350 m depth in the Gulf of St. Lawrence with a 0.25 m^2 box corer. The sediment cores were kept in temperature-controlled chambers and transferred into the three mesocosm tanks shortly after sampling. Each tank held four 0.25 m^2 cores. The thickness of the sediment blocks is about 35 cm.

2.4 Signal Processing

The acoustical data were processed with GIL's *SONIQUE*^{CM} software to establish the key spectral signatures which could distinguish different species of macrobenthos. The effect of the reflective base or sediment matrix on the image of the test animal was investigated using impulse-response analysis such as that of echo reduction. The echo reduction (*ER*) of an organism may be defined in terms of the complex incident sound pressure and the complex reflected sound pressure. The following relationship expresses this:

$$\begin{aligned} ER &= 20 \log_{10} \left| \frac{incident \;\; sound \;\; pressure \; p_i}{reflected \;\; sound \;\; pressure \; p_r} \right| \\ &= 20 \log_{10} \left| \frac{1}{\hat{R}} \right| \end{aligned} \qquad (1)$$

where $\hat{R}$ is the complex reflection coefficient and the function $|\cdot|$ represents the modulus.

In order to accentuate the target echoes, the received signals were transformed into an envelope function which allow the data to be displayed in a similar manner to functions in the frequency domain. The Hilbert transform was used to create the complex analytic function. It is the resulting peak amplitudes of the magnitude envelope which make the curve maxima attractive as time markers. For more details on the application of the Hilbert transform to soundings refer to Guigné and Chin (1989) and Guigné *et al.* (1991).

Figure 2 shows the time history and Hilbert transform envelope series of a reflective pulse from the "azoic" sandbed. The instantaneous amplitudes of the envelope series represent pseudo-energy time curves. The peaks in the reflected energy histories are sharp and are easier to discern than the signals in Figure 2a. The echo reduction spectra in Figure 3 indicates the sandbed was fairly uniform and even.

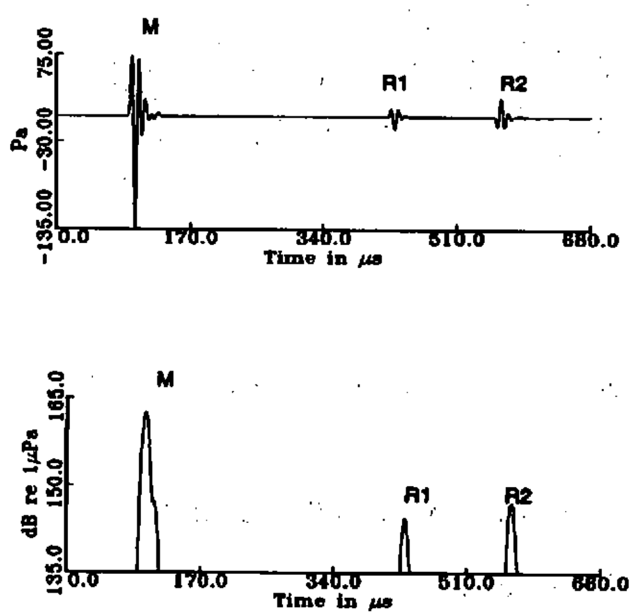

Figure 2. Time History and its Hilbert Transform Envelope Series

M is the first pulse received by hydrophone.
R1 is the reflective pulse from sand surface.
R2 is the reflective pulse off a styrofoam reflector.

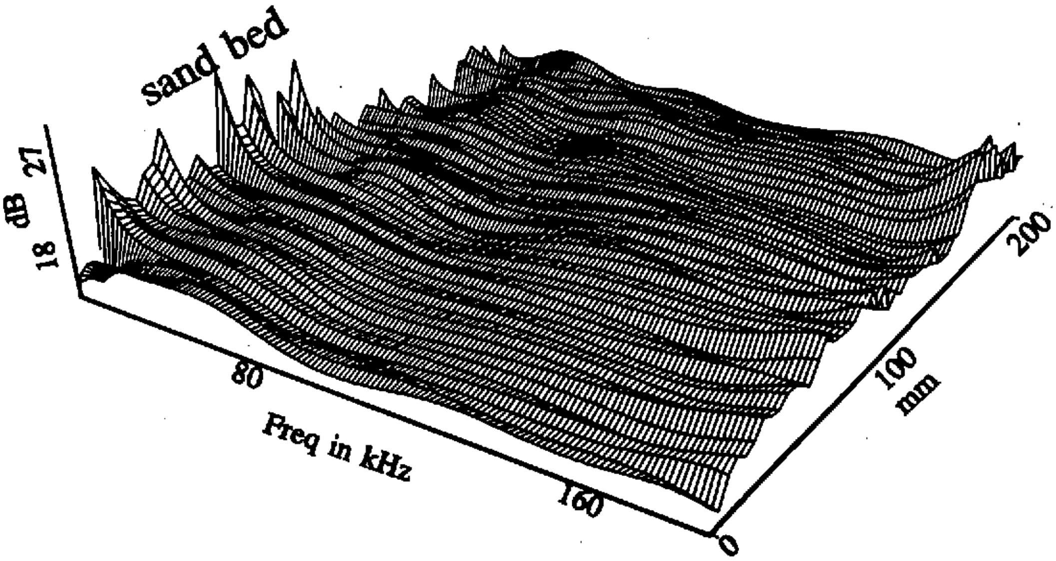

Figure 3. Echo Reduction of a Uniform Sand Bed

3. RESULTS AND DISCUSSION

3.1 GIL TEST TANK CALIBRATIONS

High resolution acoustic images of benthic macrofauna on and in the level sand base were obtained. The time histories of single cross-profile transects over the test animals demonstrate that GIL's transmitter had the resolving capability to obtain coherent images of the specimens without excessive scattering or noise (Figure 4). The shapes of the animals, in profile, and bottom contact with the sand are clearly definable. The Macoma clam buried in the sand was imaged with clarity equal to that of the clam on the sand surface. The coherent, high vertical resolution and lack of scatter cannot be attained using existing commercially available acoustic equipment.

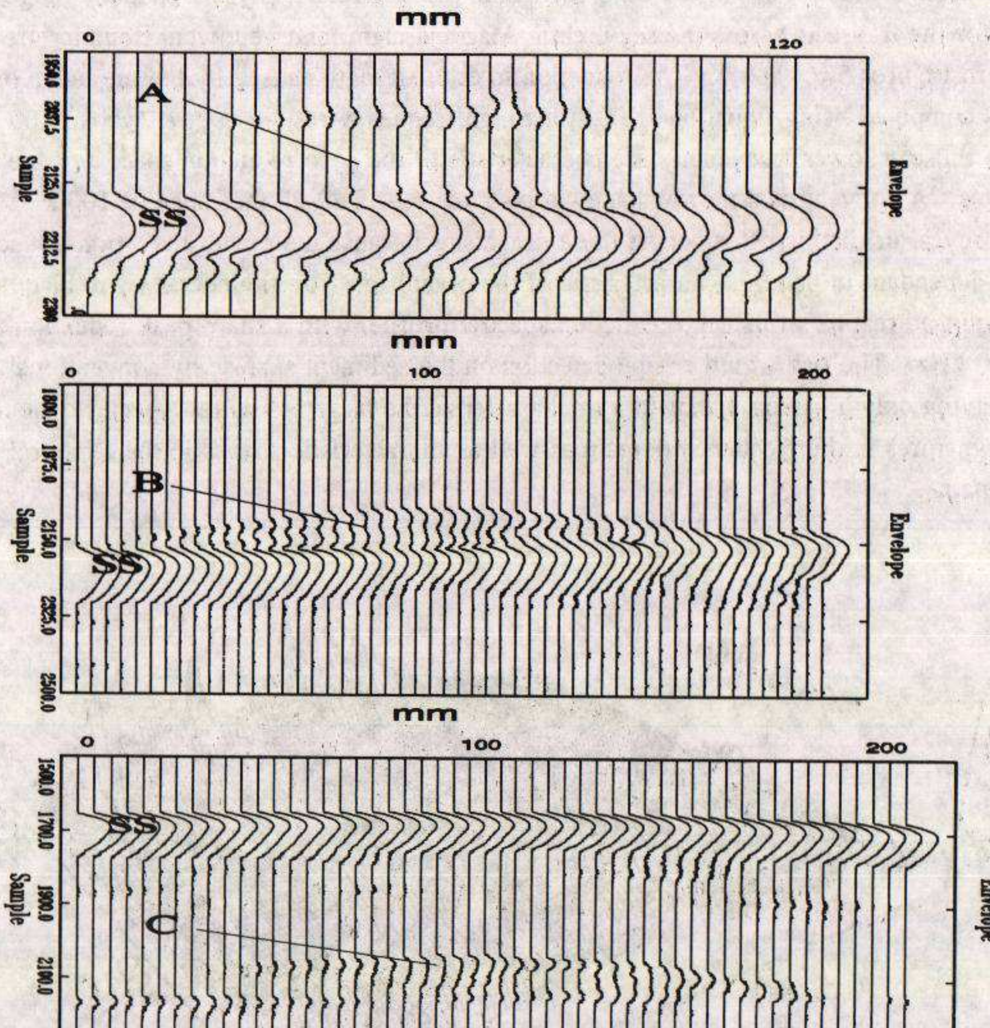

Figure 4. Hilbert Transform Envelop Series of Cross Profiles of Benthic Organisms Resting on Sandbed: Sea Urchin (A), Macoma Clam (B) and Yellowtail Flounder (D). (C) is the Macoma Clam buried in the Sand. SS indicates the Sediment Surfaces.

Three-dimensional illustrations of the echo reduction over the return signal frequency range (10 to 200 kHz) for the transects across the sea urchin, Macoma clam, and yellowtail flounder are illustrated in Figures 5, 6, and 7. The reduction in echo strength caused by the organism on or in the sand is computed using Equation 1. Distinct high frequency responses (*i.e.*, above 100 kHz) in addition to those at lower frequencies are characteristic of the echo reduction spectra of the two invertebrates. A conventional narrow bandwidth source especially in the range of 100 kHz or less would not reveal or distinguish amongst these organisms because their echo reduction effects are frequency-dependent in patterns characteristic of the organism. The flounder's swim bladder is the most pronounced feature of its echo reduction spectral profile, with a sharp peak reduction at around 130 kHz. The fish would escape detection on the sediment surface by conventional acoustic methods having only a narrow bandwidth to characterize the target. The test species demonstrate acoustic signatures in the frequency domain as well as characteristic shapes in the temporal and spatial domains.

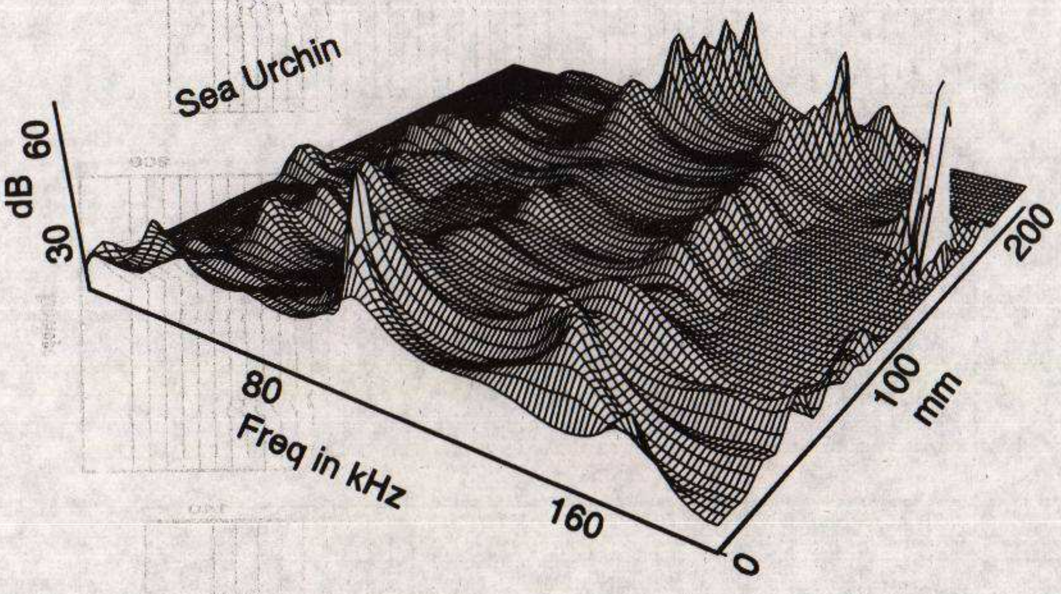

Figure 5. Echo Reduction Frequency Spectra from a Line Profile across a Sea Urchin *Strongylocentrotus droebachiensis* Resting on Sand Surface.

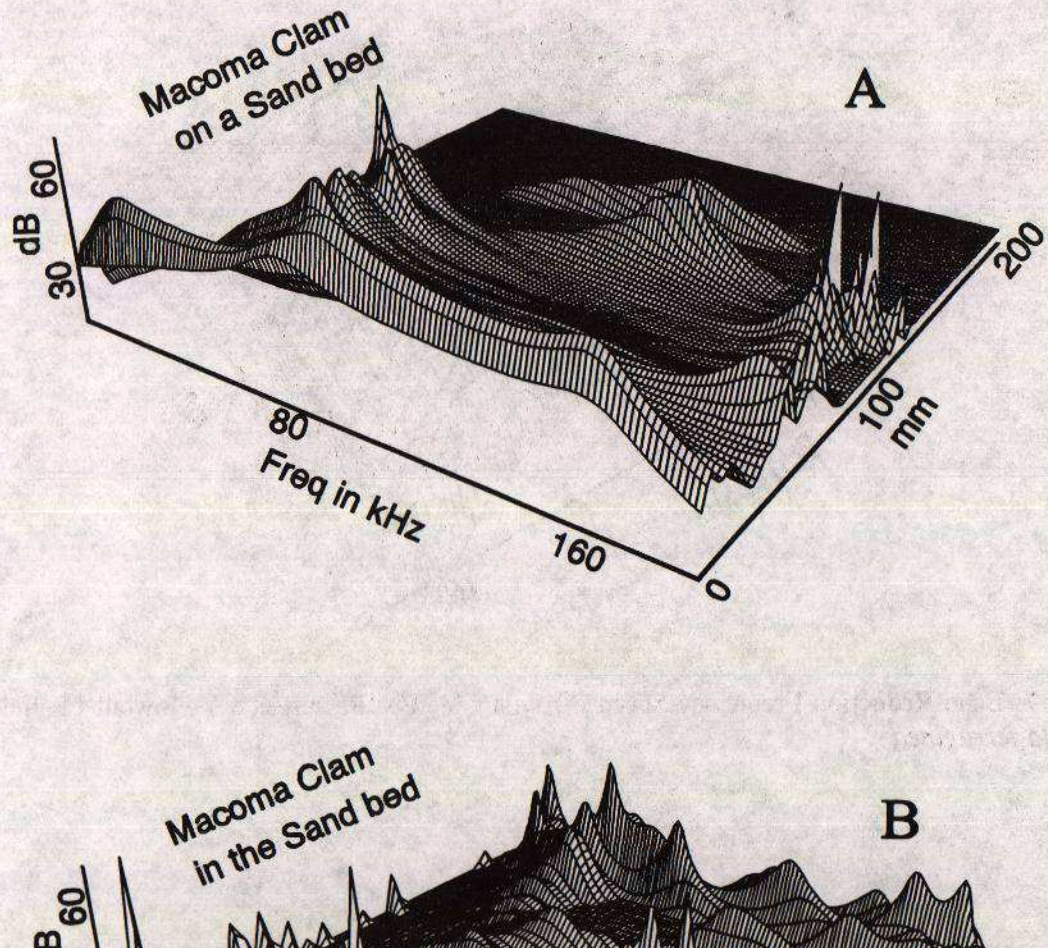

Figure 6. Echo Reduction Frequency Spectra from Line Profiles a Clam *Macoma calcarea* on a Sand Bed (A) and in a Sand Bed (B)

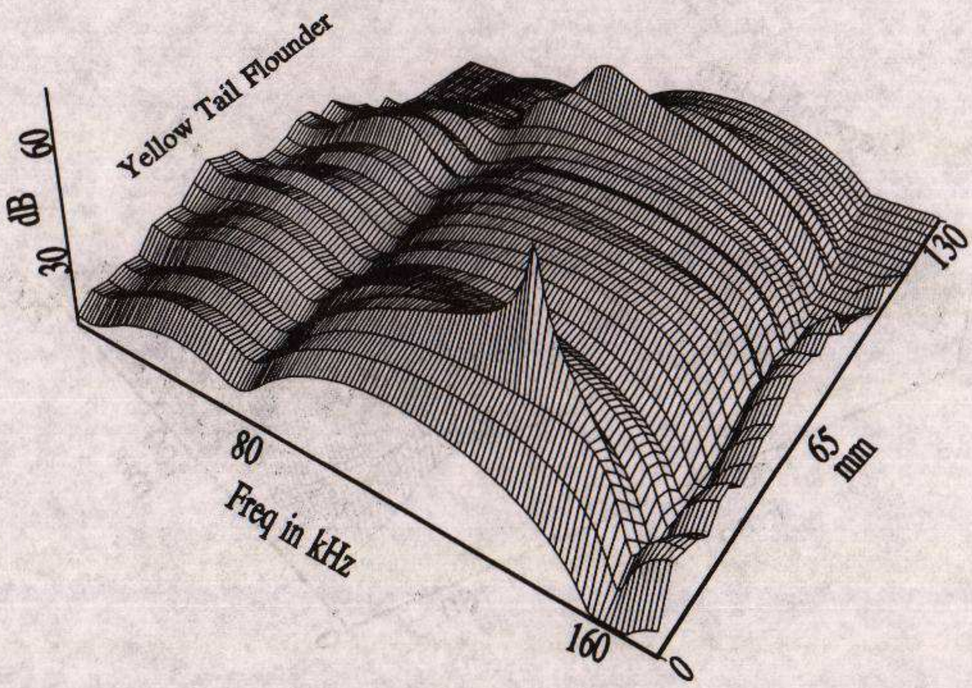

Figure 7. Echo Reduction Frequency Spectra from a Line Profile across a Yellowtail Flounder *Limanda ferruginea*

3.2 IML MESOCOSMS

Time history cross-profile transects through a mud urchin (*Brisaster fragilis*) buried under the sediment surface, and through an area of burrows made by mud shrimp (*Calocaris templemanii*) are illustrated in Figures 8a and 8b. The echo reduction profiles along the same transects are illustrated in Figures 9 and 10, respectively. The mud urchin appears as a coherent structure within a well-bioturbated sediment as indicated by the complex acoustic structure around it in Figure 8a. In the time domain, the nature of the coherent structure can be more clearly defined by its three-dimensional shape as reconstructed from adjacent transects. In the frequency domain, however, the echo reduction signature of the structure is distinguishable from the signature of the bioturbated sediment. In fact, the similarity between the mud urchin's acoustic signature and the sea urchin's signature in Figures 5 and 8a is obvious, giving some hints as to the origins of the signature in the structural composition and skeletal architecture of urchins. The mud shrimp burrows appear as a distinct zone in the transect illustrated in Figure 8b. The sediment has obviously more structure which is at a different scale than the adjacent area where little bioturbation was observed. Again, the echo reduction spectra in Figure 10 indicate strongly the two distinct zones of bioturbation along the transect. Unlike the mud urchin, however, the burrows appear in Figure 10 to be an intensification of a spectral pattern similar to the adjacent zone of light bioturbation; there is no dominant differentiable spectral quality.

4. CONCLUSIONS

The strength in the imagery centres on the broad frequency range inherent in the transmissions and on the narrow beam (devoid of significant side lobes) which maintains a high signal-to-reverberation ratio. Further calibration is underway to define the nature of structures revealed by the acoustic images with a view to understanding the determinants of the characteristic frequency domain signatures exhibited by different taxa of benthic fauna.

Using the echo reduction spectra then, it appears to be possible to determine the nature of sub-surface structures with some precision. Faunal taxa may be identifiable based on their composition and shape. They can be differentiated from sediment structures based on their echo reduction spectra. The rich information content of the echo reduction spectra is evident from Figures 9 and 10, keeping in mind that these illustrate only single line transects, and that the normal mode of data collection is to be over an area of sediment.

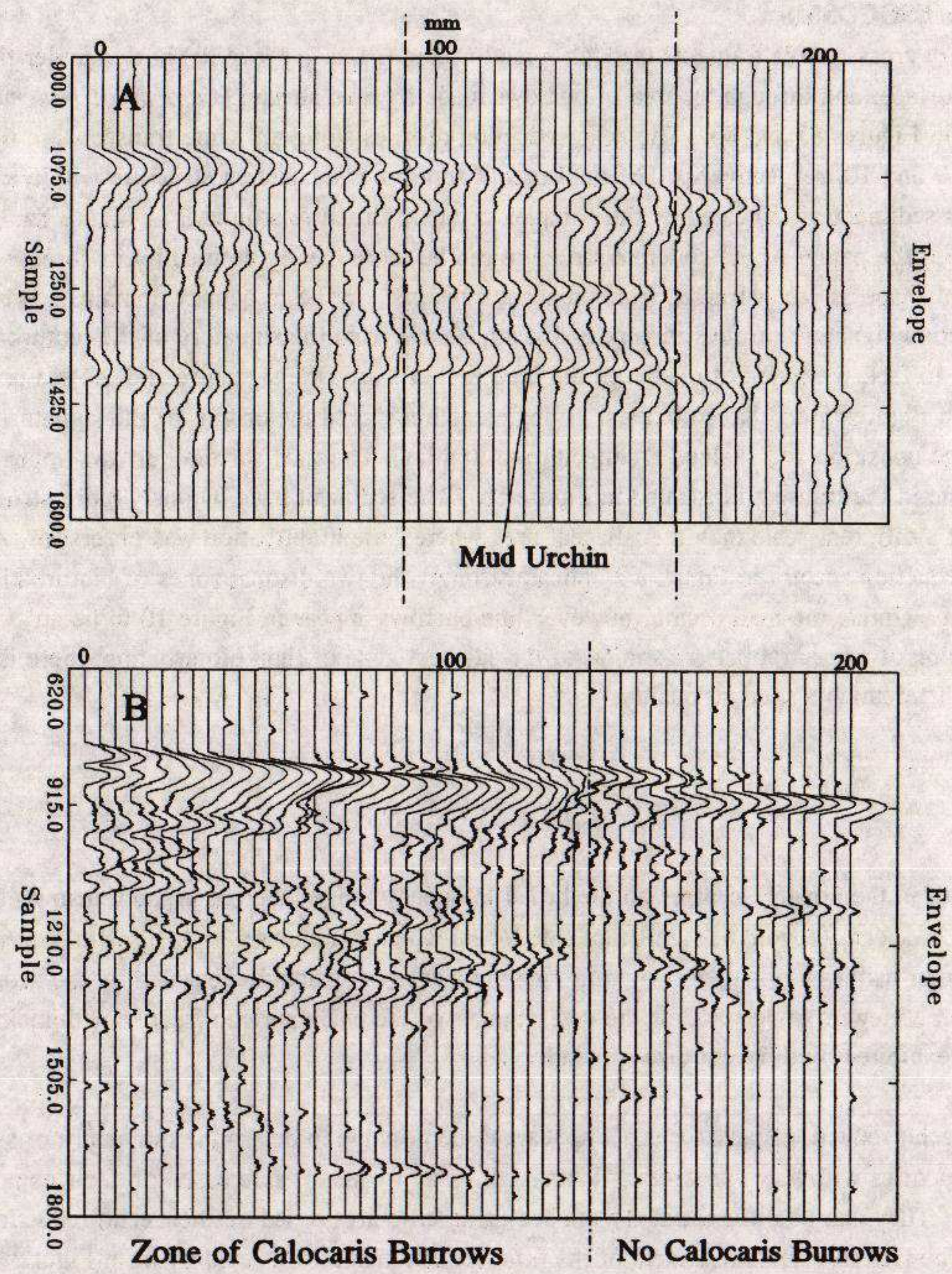

Figure 8. Hilbert Transform Envelop from Line Profiles across a Sediment Block with an Alive Mud Urchin *Brisaster fragilis* (A) and Burrows Made by Mud Shrimp *Calocaris templemanii* (B)

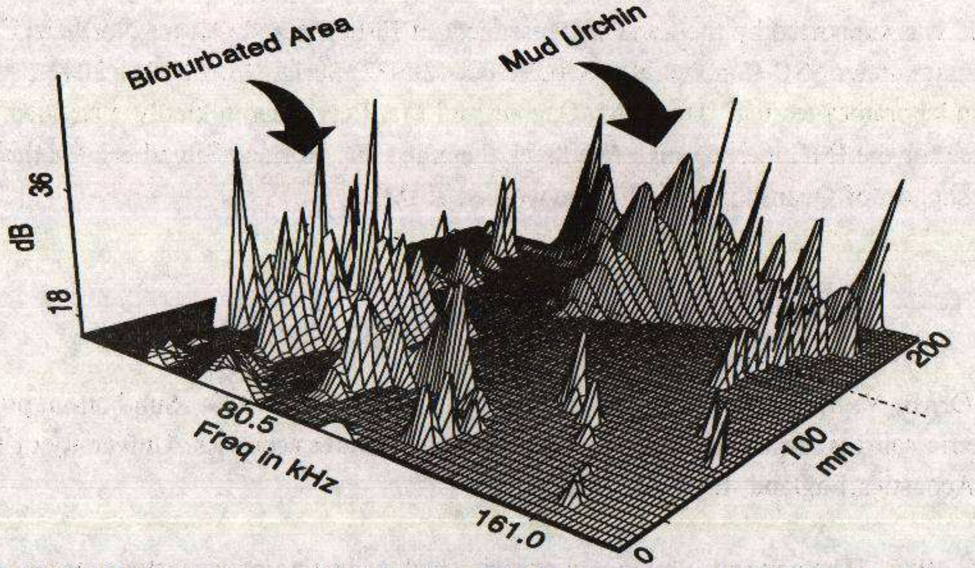

Figure 9. Echo Reduction Spectra from a Line Profile across an Undisturbed Sediment Block Containing a Buried Live Mud Urchin (Brisaster fragilis)

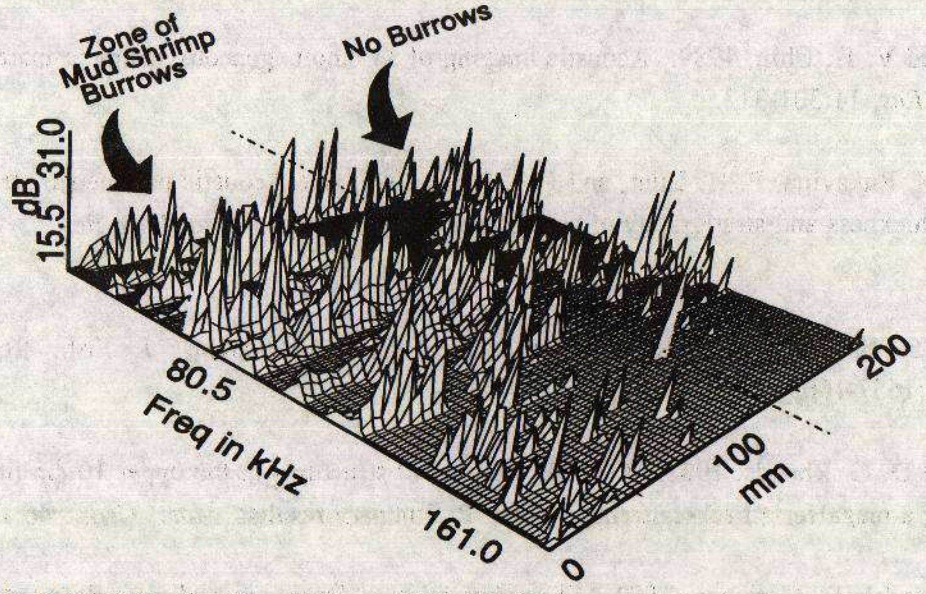

Figure 10. Echo Reduction Spectra from a Line Profile across an Area with and without Burrows Made by Mud Shrimp *Calocaris templemanii*

5. ACKNOWLEDGEMENTS

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