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OCEAN ACOUSTIC OBSERVATORY FOR PASSIVE MONITORING OF THE OCEAN

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1. INTRODUCTION

The Monterey Bay Aquarium Research Institute (MBARI) is located in Moss Landing, California at the heart of the nation's largest marine sanctuary. MBARI conducts innovative oceanographic research and development and operates as a non-profit oceanographic center funded by the David and Lucile Packard Foundation. MBARI's mission is to achieve and maintain a position as a world center for advanced research and education in ocean science and technology by developing better instruments, systems and methods for scientific research in the deep waters of the ocean. In support of this mission, MBARI embarked on a project for real-time and continuous passive acoustic monitoring of the ocean. The goal of the Ocean Acoustic Observatory project is to acoustically monitor marine biological [1-2], geological [2] and physical [3-4] activity off the California coast and to compare the results thus obtained with those from concurrent ocean bottom seismometers (OBS), land-based stations, visual surveys and other methods. The rationale behind using sound to monitor the underwater world is simple: sound is the only form of energy that can effectively propagate over long distances in water. Oceans are opaque to electromagnetic forms of energy such as radio, microwave, laser and visible light. Sound in the ocean plays the role of light in air. Long-range ocean acoustic observatories have great potential to help monitor, understand and predict the physical, geophysical and biological ocean environment. Passive acoustic monitoring provides a synoptic view of the ocean. Long-term research goals are to determine whether and in what ways these signals facilitate understanding and prediction of the geophysical and biological marine environment, particularly with regard to changes in the activity and health of the ocean ecosystems. Long-term development goals are to design and implement systems and algorithms to passively monitor acoustic environmental signals in the oceans over large spatial and temporal scales. Continuous real-time monitoring makes it possible to observe episodic and non-predictable events such as turbidity flows, underwater landslides and volcanic eruptions which may otherwise remain undetected and provides the opportunity to study them in real time.

2. RESEARCH OBJECTIVES

The major scientific objectives of this project are:

1) monitoring geological processes
2) marine mammal research
3) research in physical oceanography

2.1 MONITORING GEOLOGICAL PROCESSES

Monterey bay and canyon are natural laboratories for studying marine geological processes. The Monterey Bay region is located on an active global tectonic plate margin, situated within the San Andreas fault system, the transform plate boundary that marks the contact between the Pacific and North American plates. Here active tectonics associated with the oblique convergence of the plates stimulate marine geological processes through seismic events such as witnessed during the 1989 Loma Prieta earthquake. It is known that T-phase of marine geological events can travel long distances under water and have distinct acoustic signatures [1]. Some questions to be addressed in this regard are:

1) Do turbidity currents and landslides generate measurable sound?
2) If so, can acoustics be used to identify turbidity and mass wasting events?
3) What size earthquakes generate landslides/turbidity currents?
4) Can microseismicity be used to predict larger seismic events?
5) What is the earthquake recurrence interval?

2.2 MARINE MAMMAL RESEARCH

Monterey Bay is rich in marine life. Many species of whales, dolphins and seals have their habitat here or migrate along the coast (figure 1). Marine animals have distinctive acoustic signatures (figure 2) that make them prone to acoustic detection and classification [5-8]

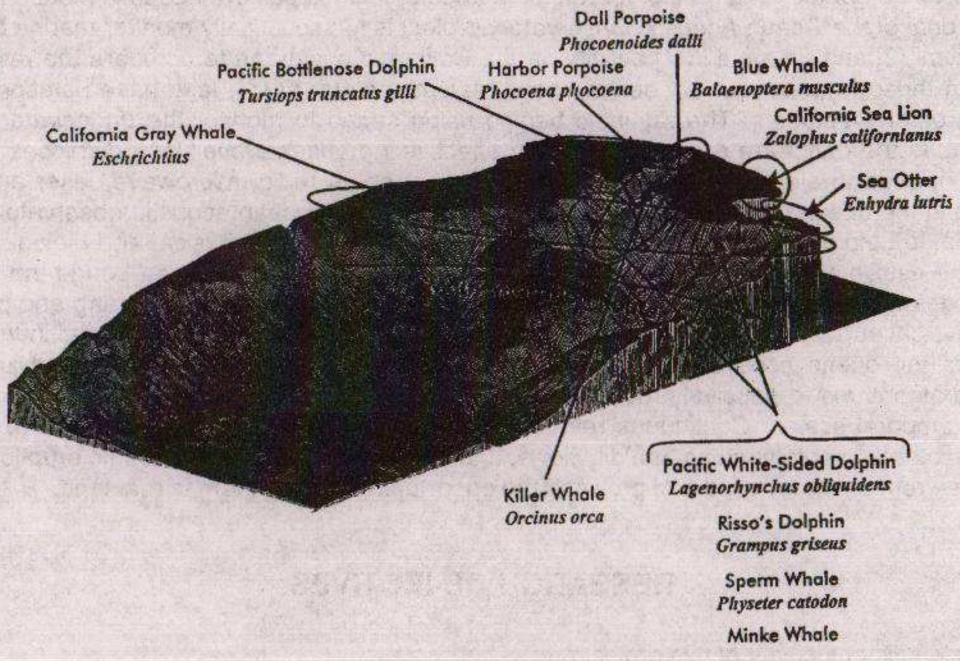

Figure 1. Marine mammal habitats in Monterey Bay

Some topics of general research interest are:

1) Temporal and spatial distribution of individuals and species
2) Identifying the critical feeding habitats of marine mammals
3) Measurement of communication and movements of schools of cetaceans,
4) Studying the effects of low frequency sounds on marine mammals.

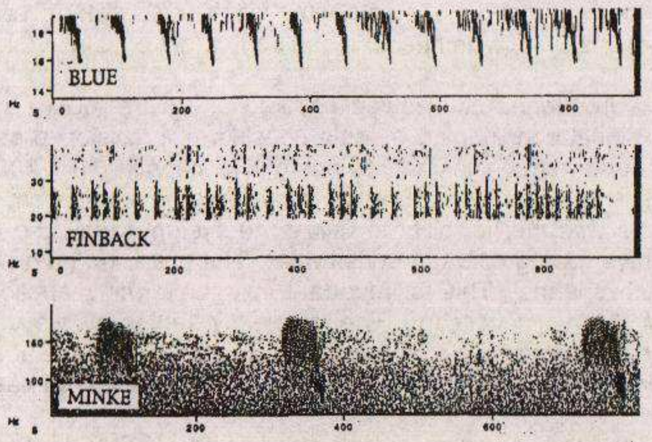

Figure 2. Acoustic signatures of three whales

3. SYSTEM DESCRIPTION

As part of the Ocean Acoustic Observatory project MBARI has developed a system for continuous and real-time processing of multi-channel acoustic data. Utilizing data from fixed or towed hydrophone arrays, intensive signal processing is used to form and display beams in real time. Post-processing includes computation and display of lofargrams, detection and classification of acoustic signatures and selective recording of raw and/or beamformed data.
The observatory system consists of two major components: the wet end and the dry end (figure 3). The wet end consists of fixed or towed hydrophone arrays and the telemetry cable.

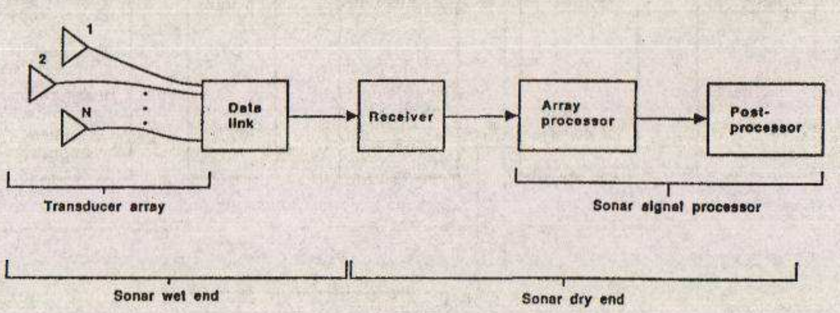

Figure 3. The wet-end and the dry-end

The dry end (figure 4) consists of the signal conditioning, beamforming, post-processing and storage subsystems. Using the ear-brain analogy, the wet end serves as the ear and the dry end as the brain of the system. The dry end can accept acoustic data from up to 32 analog channels and form up to 68 simultaneous beams in real time. This is expandable to 512 hydrophones and more than 68 simultaneous beams. With geological signals in the 0-100 Hz range and marine animals making sounds in the 10 Hz - 50 KHz range, MBARI's Ocean Acoustic Observatory uses a maximum sampling rate of 200 KHz per channel to capture these signals. The MBARI system uses high-speed, VME-based custom off-the-shelf hardware to provide the real-time, instantaneous response required in real-time monitoring operations. The entire system resides in a single VME box running under Vxworks as shown in figure 5. The system is a stand-alone computer with its own disk drive, tape drive, keyboard, mouse and display monitor. The system architecture can be thought of as a five-step pipeline.

1. Analog signals from hydrophones of a towed or fixed array are fed to a filter-amplifier signal conditioning unit. The signal conditioning module consists of precision programmable filters and amplifiers. The filter cut-off frequencies can be set in 1Hz steps in the 1-1023Hz range and 50Hz steps in the 1024Hz-63KHz range. Amplifier gains are programmable from -10 to 60dB in 0.1dB steps. This provides us with the flexibility to utilize the system in diverse operational scenarios with fixed or towed arrays having different sensitivities. The precision gain allows for independent fine adjustment of each channel. This is important in beamforming applications where precise control of the beam pattern is necessary. Fine frequency setting allows us to only process the frequency band of interest selected for the particular application. For example, most blue whale vocalizations are below 200Hz, so to study them only this frequency band has to be processed.

2. The output of the signal conditioning module is fed into the ICS-110A (Interactive Circuits and Systems Ltd., Ontario Canada) analog to digital converter (ADC) board. This is a 16-bit sigma-delta ADC with full simultaneous sample-and-hold and can easily handle the maximum data rate of 200kHz per channel. The word-serial-bit-parallel time multiplexed digital data stream from the ADC is outputted via a ribbon cable from the front panel data port (FPDP) of the ICS-110A to the FPDP port on the ICS-2200S beamformer card. The ADC board is software configurable. Number of channels (2 to 32), sampling frequency (400Hz to 200KHz) and sampling resolution (12 or 16 bits) can be set in ASCII configuration files that are read by the Vxworks operating system and passed along to the ADC card. The maximum sampling frequency is 100KHz in the 16-bit mode, and 200KHz in the 12-bit mode.

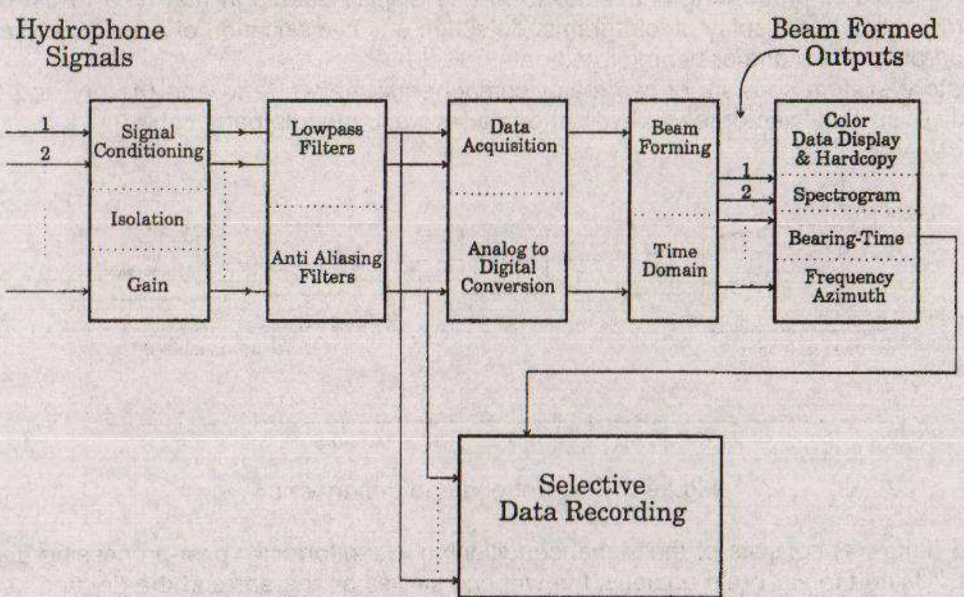

Figure 4. System block diagram of the dry end

3. The digital data stream is received by the FPDP interface on the ICS-2200S beamformer card that is physically located in the same VME box. ICS-2200S can keep up with the maximum sampling rate of 200KHz per channel and can compute up to 68 user-defined beams in real time. All the operational aspects of the beamformer card are configurable through software. The array geometry (number of hydrophones and their spacings), array shading options (uniform, Hanning,

Hamming, Blackman, etc.), number of beams, beam angles, interpolation options (sinusoidal, low-pass and broadband) and the number of interpolation coefficients can be set using ASCII configuration files. The beamformed data can feed into the ICS-115 analog to digital converter and/or the SKY Computers SKYbolt application accelerator through the "SKYburst" interface.

4. A four-processor application accelerator (SKYbolt) from the SKY Computers Inc. is used as the post-processing engine. SKYbolt is a 6U VME board and can handle data throughput rates of up to 40 megabytes per second and a peak computational speed of 320 Mflops (million floating- point operations per second). Callable libraries of mathematical and signal processing routines are also provided. All the post-processing functions such as spectrogram computation, detection, classification and localization algorithms are implemented on this card.

5. The time multiplexed digital data stream from the beamformer output can be converted to analog signals using the ICS-115 digital to analog converter (DAC) board. ICS-115 is a 32 channel 16-bit DAC. One can listen to any beam on a conventional audio system using the analog beam outputs. Similarly, beams can be recorded on an analog recorder or fed to another processing system that accepts analog inputs. Having the beams in analog form provides us with the capability to interface the beamformer output to other recording and processing systems that are not digitally compatible with the beamformer output data format.

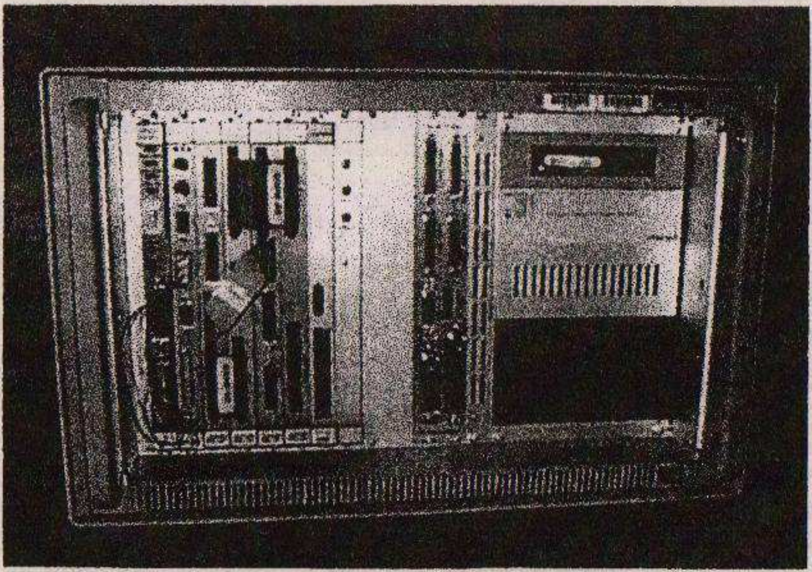

Figure 5. Picture of the Ocean Acoustic Observatory system

An overarching design criterion has been interface compatibility across all interfaces. This is dictated by the fact that data rates could be very high and there simply is not enough time for format conversions at the interface level. This strategy saved us a great deal of development time.

4. POST-PROCESSING OPERATIONS

All the post-processing operations on the beamformed data are performed on the SKYbolt card. One processor is dedicated to computing lofargrams on the computed beams, another performs automatic event detection on the beamformed data and the other two processors perform automatic classification on the detected events. Computed lofargrams are sent directly or across network to a display device. The raw hydrophone and/or beamformed data can be saved to disk, or tape. Furthermore, the system can perform event-based recording, storing only specific sounds of interest. For low frequency signals such as geological events or blue whale sounds, the system can run many times (as much as 30 times) faster than real time. A week's worth of recorded data can be processed in less than 5 hours. Thus, the system can serve as a test bed for rapid prototyping and evaluation of new signal processing techniques and algorithms using large quantities of data.

The system can be configured, operated and data displayed over a network or on a console monitor in real time. Our goal is to compile a catalog of underwater sounds corresponding to various biological, geological or physical phenomena. The system can operate continuously 24 hours a day, listening to the sounds of the ocean, detecting and comparing them to a database of known sounds and compiling a log of these detections. Sounds of unknown origin can also be identified and classified using ancillary information from other sources and added to the database. In short, the Ocean Acoustic Observatory serves as our eyes and ears underwater providing a continuous and real-time monitoring of the oceanic processes.

5. APPLICATIONS

To date, the observatory system has been employed in the following sea experiments:

1) Passive localization and tracking of harbor porpoise *Phocoena phocoena* in the gulf of Maine
2) Survey of sperm whales in the gulf of Mexico, USA
3) Blue whale surveys in Monterey Bay, California, USA

5.1 HARBOR PORPOISE TRACKING

Harbor porpoise Phocoena phocoena generate ultrasonic echolocation signals in the 110-150KHz frequency range and social calls below 20KHz. The high frequency "clicks" can be used to acoustically localize and track these animals in three dimensions at ranges within 500 meters. In addition, the lower frequency social calls may be used for long range localization. Harbor porpoise vocalizations were recorded on a 20 channel TEAC XR-7000 recorder during a one-week experiment in the Gulf of Maine. Localization was based on time-difference-of-arrival (TDOA) direction finding and line-of-position (LOP) fixing from two arrays spaced 60m apart. Each bottom-mounted array consisted of four hydrophones in a one-meter tetrahedral configuration cabled 300m to shore. Since the frequency range of the echolocation signals exceeds the maximum frequency that the system can handle, the recorded vocalizations were played back 4 to 8 times slower and processed by the system in real time. A real-time detector was also implemented on the SKY processor to detect and identify the echolocation signals. Localization was performed whenever the detector spotted a valid echolocation. A radar-type screen was used to display the animal positions. Using the observatory system, the large quantities of data from this experiment could be processed much faster than the conventional off-line methods.

5.2 SPERM WHALE SURVEYS

A three-week experiment to perform population surveys was conducted in the Gulf of Mexico, USA. An 8-element hydrophone array was towed behind an oceanographic vessel. The active section of the array was 80 meters long and the lead cable was 270m. This was a sparse array where the hydrophone spacings were optimized for narrow beam patterns over the frequency range of the sperm whale vocalizations [9]. Eight beams were formed in real time and beam lofargrams were displayed for visual detection and identification of the animals from their acoustic signatures. A 10-person visual observer team was conducting concurrent visual observations during the periods of good visibility.

5.3 BLUE WHALE SURVEYS

Blue whales generate sounds in the 10Hz to 100Hz frequency range. The pacific blue whales generate distinct sounds around17Hz, 51Hz and 93Hz. The observatory system was used to study the feasibility of acoustic detection, localization and population surveys. A weeklong experiment was conducted in the Monterey Bay national marine sanctuary in California. An 8-element hydrophone array was towed behind an oceanographic vessel. The array had a 60m aperture and a 100m lead cable. Real-time beamforming was performed while the ship was underway. Eight beams were formed (figure 6) that uniformly spanned the space (22.5 degrees apart). Real-time lofargrams were generated and displayed for the eight beams. Vocalizations were detected and identified by visually inspecting the lofargrams. The beam having the strongest signal was selected to correspond to the direction of sound arrival and the bearing to the animal.

Due to the array characteristics, the 51Hz and the 93Hz components of the vocalizations had better directivity. Weather permitting, concurrent visual surveys were also conducted to ground truth the acoustic data. The left-right ambiguity in the direction of sound arrival was resolved by moving along the direction orthogonal to the original transect. Most often, acoustic detections preceded visual sightings.

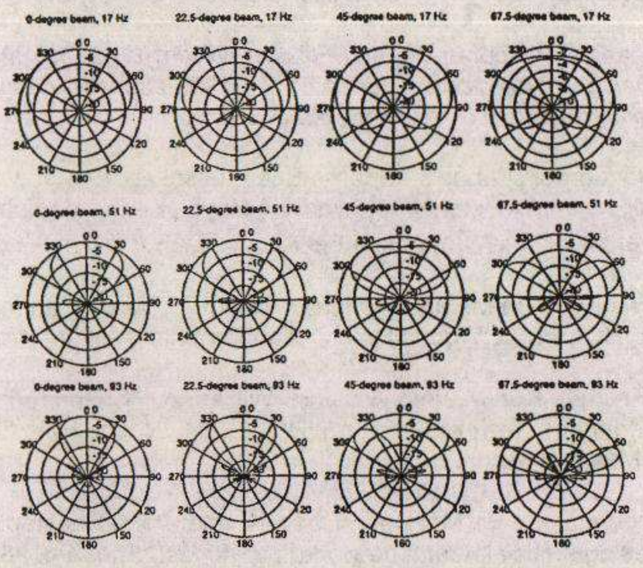

Figure 6. Array beam pattern at three dominant frequencies

5.4 GEOLOGICAL MONITORING

Through the Naval Postgraduate School, MBARI has been given access to the Point Sur Naval facility, a passive listening station located off Point Sur, California. The observatory system will be deployed at this facility to monitor the T-phase of marine seismic and other geological events that are demonstrated to travel over long distances under water [1].

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] Nishimura, Clyde E., and Conlon, Dennis M. 1994, "IUSS Dual Use: Monitoring Whales and Earthquakes Using SOSUS", Marine Technology Society Journal 27(4): 13-21.

[2] Munk, Walter H., Spindel, Robert C., Baggeroer, Arthur, Birdsall, Theodore G. "The Heard Island Feasibility Test", Journal of the Acoustical Society of America, **96**(4) pp. 2327-2342,

[3] Clark, Christopher W., and Ellison, William T. 1988, "Number and distribution of bowhead whales, *Balaena mysticetus*, based on the 1965 acoustic study off Pt. Barrow, Alaska," Scientific Report, *intl.* Whaling Commission, pp. 365-370.

[4] Baggeroer, Arthur B., Sperry, Brian, Lashkari, Khosrow, Chiu, Ching-Sang, Miller, James H., Mikhalevsky Peter N. and von der Heydt, Keith, "Vertical array receptions of the Heard Island transmissions", Journal of the Acoustical Society of America, **96**(4), pp. 2395-2413.

[5] Fristrup, Kurt M., and Watkins, William A., "Marine animal sound classification", Technical report WHOI-94-13, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts, USA.

[6] Fristrup, Kurt M., and Watkins, William A., "Characterizing acoustic features of marine animal sounds", Technical report WHOI-92-04, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts, USA.

[7] Potter, John R., Mellinger, David K. and Clark, Christopher W., "Marine mammal call discrimination using artificial neural networks", *J. Acoust. Soc. Am.* **96**(3), pp. 1255-1262

[8] Stafford, Kathleen M., "Characterization of Blue Whale Calls from the Northeast Pacific and Development of a Matched Filter to Locate Blue Whales on U.S. Navy SOSUS Arrays", Master's thesis, Oregon State University, Corvallis, Oregon, USA.

[9] Whitehead, Hal, and Linda Weilgart, "Click rates from sperm whales." *J. Acoust. Soc. Am.* **87**(4): pp. 1798-1806