AN ADVANCED CONCEPT DEMONSTRATION FOR MONITORING THE INDIAN OCEAN

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ABSTRACT

The Center for Monitoring Research (CMR) has embarked on an advanced concept demonstration (ACD) focused on improving nuclear explosion monitoring in the vicinity of the Indian Ocean. Central to the demonstration are the new hydrophone assets. These are the International Monitoring System's (IMS) hydrophone stations at Diego Garcia (part of the British Indian Ocean Territories) and Cape Leeuwin, Australia. The third Indian Ocean hydrophone station at Crozet Island will be simulated for purposes of this work because it is not currently operational.

The primary goal of the ACD is to demonstrate new approaches that improve the capability to detect, locate and characterize in-water sources in the context of an operational monitoring system. The advances that are being implemented include optimizing signal processing for the new tri-partite hydrophone array stations, improving acoustic propagation and attenuation models, making use of basin reflections, and creating visualization tools for more effective analysis.

A supporting effort for the ACD is to create realistic synthetic data for events of interest. Demonstrating the system improvement requires data representative of realistic scenarios that test the monitoring objectives. Large explosions are the primary events of interest. However there are no examples of large explosions since the new stations became operational. The few examples that are recorded in other ocean basins are of limited use because of the difference in instrumentation and basin characteristics, and therefore we require synthetic data. However, synthetics often contain many of the same assumptions that were used to create the operational system. The results from synthetics must be validated against real data to the extent possible. Thus, compilation of real data sets that can validate the synthetics and characterize the day-to-day system operation is also a major portion of the ACD.

OBJECTIVE

The CMR in Arlington, Virginia, has begun developing a series of Advanced Concept Demonstrations (ACD) that are designed to improve current operational nuclear-explosion monitoring systems by incorporating state-of-the-art research in a prototype operational system. The demonstrations concentrate on different regions that include test sites and geographic regions of interest. The demonstration described here focuses on the Indian Ocean, which is of particular interest because it is the first ocean basin covered by the new International Monitoring System's (IMS) hydrophone stations. The demonstration is currently under development with completion anticipated by the end of 2002.

The overall objective for the Indian Ocean ACD is to demonstrate new approaches that improve capability for monitoring in-water and sub-ocean sources in the Indian Ocean Basin with an emphasis on exploiting data from the new hydroacoustic stations. Our specific goal is to show improvement in detection, location, and characterization of events in the IOB compared to the current Nuclear Test Detection System (NTDS) at the CMR. The ACD will be assessed relative to the current baseline system. Some of the ACD components will provide new capability that does not exist in the current system while other parts will improve various aspects of the system's ability in detecting, locating, or characterizing an event.

RESEARCH ACCOMPLISHED

Hydrophone Array Processing

There are currently two new hydrophone stations operating in the Indian Ocean with a third scheduled to come on-line in spring of 2003. The operational systems are located off Cape Leeuwin, Australia, (HA01) and the island of Diego Garcia, British Indian Ocean Territories (HA08). The third station is located at Crozet Island in the southwest of the basin. These stations provide significantly higher quality data than the initial IMS hydrophone stations (e.g., Wake and Ascension Island).

The new stations consist of multiple hydrophones arranged as triads with inter-element spacing on the order of 2 km. The Cape Leeuwin station (HA01) is a single triad off the west coast of Australia. The Diego Garcia station (HA08) has two triads located northwest and southeast of the island to avoid blockage from the Chagos Archipelago. The station at Crozet (HA04) will also have two triads to the north and south of the island.

Figure 1. IMS Hydroacoustic Station Locations. Each triangle represents a triad of hydrophones. The current operational instruments are the two triads at Diego Garcia and the single triad at Cape Leeuwin. The two triads at Crozet are scheduled to come online in spring, 2003.

One of the efforts in this ACD is the implementation of coherent array processing of the triads in order to increase detection sensitivity. Current hydroacoustic station processing runs a detector on each individual hydrophone. Detections within a triad are then grouped, and azimuths are estimated by cross-correlating the waveforms. Although this method does produce accurate azimuths, it is not taking advantage of the possible signal gain using the triads as arrays. A 5-dB gain in the signal-to-noise ratio (SNR) is theoretically possible.

On initial examination, the triads appear inadequate to use as typical hydroacoustic arrays. The element spacing (~2000 m) is large relative to the typical signal wavelength (~200 m at 8 Hz), which results in severe spatial aliasing for narrow band signals (Figure 2). However, a signal with sufficient bandwidth removes much of degeneracy and allows the triads to be processed as coherent arrays (Figure 3).

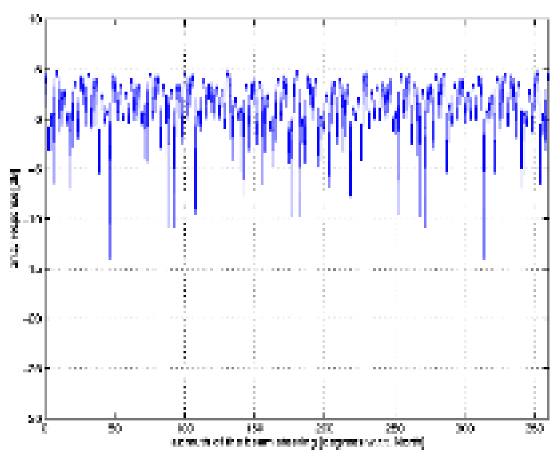

Figure 2 Array Beam Response for an Idealized Hydrophone Triad. The response is calculated for a monochromatic plane wave arriving from the south (8 Hz). The triad element spacing is much larger than the wavelength, which leads to the severe spatial aliasing.

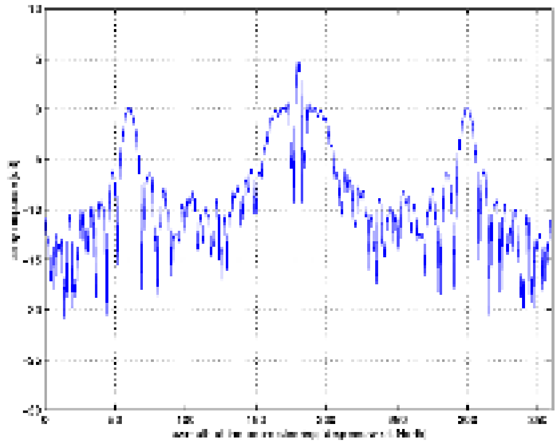

Figure 3 Array Beam Response for an Idealized Hydrophone Triad Using a Broadband signal. The response is calculated for a plane wave arriving from the south with energy between 6 to 10 Hz. The bandwidth of the signal reduces the side-lobes and produces a unique peak corresponding to the actual arrival azimuth.

The standard NTDS detection processing for coherent arrays uses what are known as beam recipes. The beam recipes specify a set of filter bands and steering angles that are used to compute beams. Each beam is fed into a signal detector that triggers on a preset SNR threshold. A suite of frequency bands is used because the band with highest SNR is not known a priori. The azimuthal spacing of the beam recipes depends on the width of the main lobe in the array's response function, which in turn depends on the center frequency of the signal. Table 1 specifies the number of beam recipes necessary for each frequency band necessary for coherent array detection processing. The total number of beams is 2690. This is significantly more than used for a typical seismic array that have on the order of a few hundred beams. This increase results in a considerably greater computational burden than current NTDS processing. However, initial results indicate that the system is capable of processing the typical hydroacoustic triad data.

Table 1. Predicted Main Lobe Width with Required Number of Beam Recipes

Frequency Band	Center Frequency (Hz)	Azimuth Main-Lobe Width (deg)	Number of Beam Recipes
1 - 2	1.5	19.02	20
1.5 - 3	2.25	12.66	30
2 - 4	3	9.49	40
3 - 6	4.5	6.32	60
4 -8	6	4.74	80
6 - 12	9	3.16	120
8 - 16	12	2.37	180
12 - 24	18	1.58	240
16 - 32	24	1.18	360
24 - 48	36	0.79	480
32 - 64	48	0.59	720
1 - 48	24.5	1.16	360
Total			2690

Capability Assessment

One technique for measuring the improvement of detecting and locating in-water events is to regionalize the basin into areas where some given criteria can or cannot be achieved. The variation in size of these areas between the current and ACD systems provides an intuitive quantification of the system's improvement. This analysis is in large part a predictive one because observational data do not exist to characterize the entire basin. These predictions will be validated using the available data.

We are dividing the basin into four main regions based on the ability to satisfy a set of criteria for an in-water explosion (an example of criteria set would be a detection threshold of mb=3.5 and 90% error ellipse area < 5000 km^2). The categories are:

1. Criteria achieved using the seismic network alone.
2. Criteria achieved using the hydrophone network alone.
3. Criteria achieved using some combination of the seismic and hydrophone networks together.
4. Criteria not achieved with the specified networks.

Because this particular ACD does not focus on enhancing seismic-only processing, the region covered by (1) should not change between the current and ACD systems and thus can be ignored for our purposes. It is useful to delineate area (2) because it should be relatively invariant to changes in a magnitude threshold criterion. This is due to the much lower detection threshold of the hydroacoustic network than the seismic network. The category (2) area established using an mb=3.5 threshold is nearly equivalent to the area found using mb=2.5 or even mb=1.5. It is the areas covered in (3) and (4) that we anticipate exhibiting the largest improvements (Figure 4). These areas also cover most of the ocean margins and are more relevant to security issues.

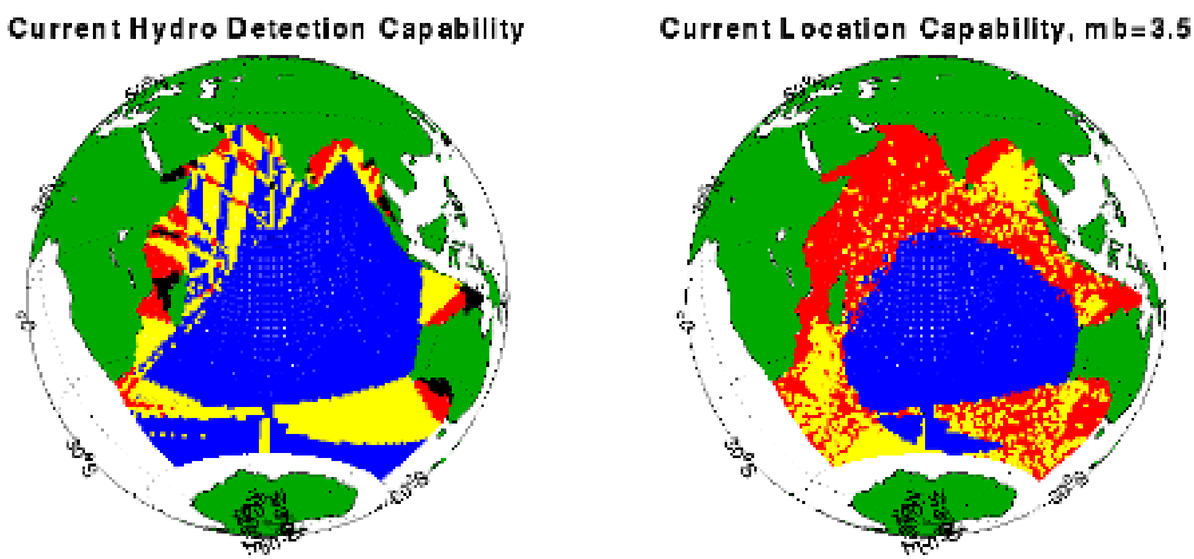

Figure 4. Example of Predicted Detection and Location Capability of the Current System. The left figure depicts hydroacoustic detection capability. The colors correspond to the number of detecting stations: 0-black, 1-red, 2-yellow, and 3-blue. The right figure depicts location capability using the criteria described in the text. The categorized regions are represented as different colors. Blue depicts the area that achieves the criteria using only the hydroacoustic network (category 2). Yellow depicts the area that achieves the criteria using both the hydroacoustic and the seismic network (category 3). Red depicts the area that does not meet the criteria (area 4). In this example the seismic-only processing (category 1) covers a minute region because of the low magnitude threshold. The ACD system is expected to reduce the area in red by improving measurements and models and by including new signal types such as reflected hydroacoustic signals.

Data Sets

Four sets of data will be used during this effort:

- The Calibration Data Set (CDS),
- The Fixed Data Set (FDS),
- Synthetic Data
- Live Data

The CDS will be a compilation of waveform data recorded during the calibration experiment conducted by Lawrence Livermore National Laboratory and Scripps Institution of Oceanography (Blackman *et al*., 2002) and data recorded during a seismic refraction experiment on the Southeast Indian Ridge (Cochran *et al*., 2002). These data contain the only real ground truth that we have for the new hydrophone stations. The sources that were used for both the calibration experiment and the refraction experiment were relatively small. The signals from these experiments will be primarily useful in validating travel-time modeling errors and possibly azimuthal measurement errors.

The FDS will provide a fixed set of hydroacoustic and seismic waveform data that can be used to assess and compare results of the different systems. The FDS contains a variety of signals from events throughout the IOB including mid-ocean ridge, trench, and inter-plate earthquakes. The variety of source locations will test the system's robustness and help validate our predicted assessments for monitoring signals of interest. In addition, the hydroacoustic waveform data cover a variety of noise conditions.

Because no large explosions have been recorded at the new hydrophone stations, synthetic waveforms are needed to characterize the system performance for a signal of interest. The synthetic waveforms will be generated by propagating an appropriate source function through range-dependent media extracted from oceanographic databases. The synthetics will be imbedded in typical background noise for the station.

The live data set consists of the waveform data from hydroacoustic and seismic stations that continuously arrive at the CMR. The ACD systems are intended to demonstrate prototype operational systems and as such are designed to process data in near real-time. The data include the hydrophone stations and primary IMS seismic stations.

Reflection Processing

The detection threshold of the hydroacoustic network for an in-water explosion is generally very low due to the efficient coupling of the source and the low attenuation within the ocean's sound channel. However, the geometry of the hydroacoustic network is not always sufficient to adequately constrain the event location. In these cases the current system relies on the seismic network. The ACD system will use hydroacoustic reflections in addition to the direct hydroacoustic and seismic signals to help constrain the location.

Reflections from earthquake-generated signals have been observed and identified at the hydrophone stations (e.g. Harben and Boro, 2001, Hanson, 2001). The azimuth estimates at the triads are generally accurate enough to identify the physical reflectors. Because the travel time between the reflector and the station can be computed, the reflector can be used as a synthetic omni-directional hydroacoustic station. These synthetic stations only provide an arrival time because it is not generally possible to determine the angle at which energy arrived at the reflector.

Hydroacoustic reflections can greatly improve the ability of the network to locate events. The reflections not only improve the geometrical coverage of an event, but they can also observe events where the direct path is completely blocked. Figures 5 and 6 show analysis of an event in the Mozambique Channel, which is one of the few areas in the Indian Ocean that have no direct path to any of the IMS hydrophone stations. This event would need additional information to constrain the location in the way that a regional seismic arrival would, but the reflections provide critical constraints for an event whose magnitude was near the seismic threshold.

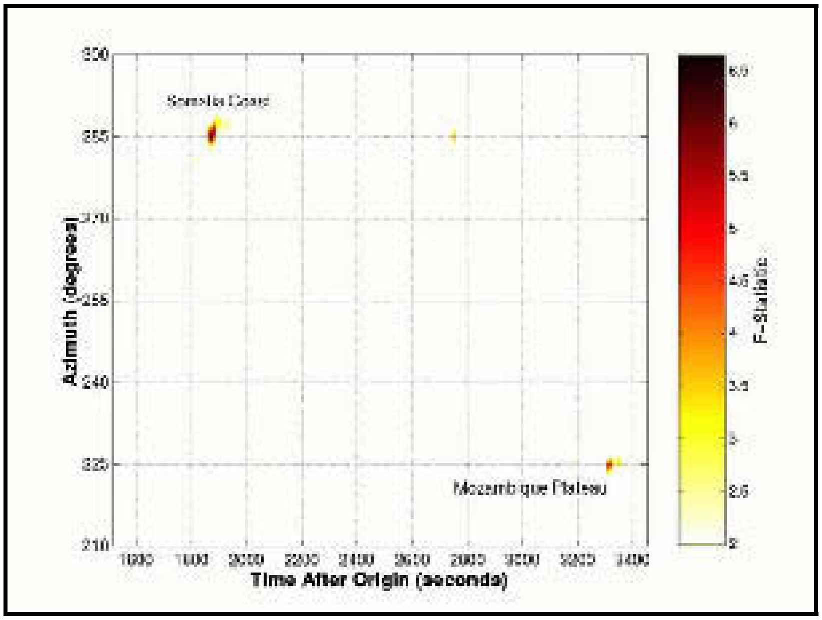

Figure 5. Time-bearing plot showing two reflections at the northern Diego Garcia triad for the event shown in Figure 6. The reflections are discrete arrivals that can be used to help constrain the event location. The azimuth estimates allow the physical reflector to be identified.

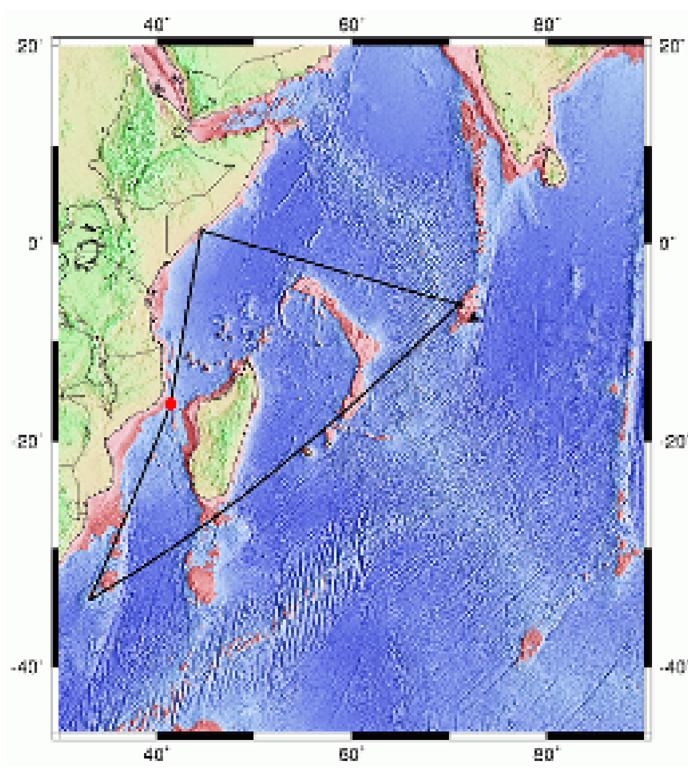

Figure 6. Example of reflections from a blocked event. The event occurred on April 2, 2002. The earthquake's epicenter is shown as the red dot in the Mozambique Channel. The black lines show the inferred path for the two reflectors seen in Figure 5. Bathymetry shallower than 2000 m is shaded pink to help identify potential reflectors. It is signals like these that will help improve the system's capabilities.

Visualization Tools

A large portion of the effort will be to provide an analyst with a set of tools that will enhance an analyst's ability to detect, locate and characterize an event. Some of these tools are standard applications that have been used by researchers for years, but have not been integrated into the NTDS operational environment for day-to-day operations. Other tools are implementations of novel methods that are relevant to the hydroacoustic monitoring problem. These components include a spectrogram tool, a cepstrum review tool, a blockage review tool, and an azimuth display tool. Figures 7 and 8 show examples of a spectrogram tool and a cepstrum review tool. Figure 5 shows an example of what the azimuth display tool will provide.

The spectrogram allows analysts to quickly identify signals and choose the frequency band that maximizes SNR. Small signals are observable that could be overlooked in a time series representation. The cepstrum tool allows the analyst to review results from automatic processing that are of critical importance in characterizing and identifying events. It can also be useful in associating arrivals to a single event because the cepstrum is relatively invariant to path effects. The blockage review tool will aid the analyst in associating arrivals and to look for evidence that contradicts a given location (such as no signal at an unblocked receiver). The azimuth display tool provides a detailed image of the coherent energy arriving at a hydrophone station. This is important for obtaining the best azimuth estimate for direct arrivals and for identifying potential reflections. All of these tools are intended for use in an operational system. They will be integrated into the analyst's environment to support routine analysis of events that are of potentially interest.

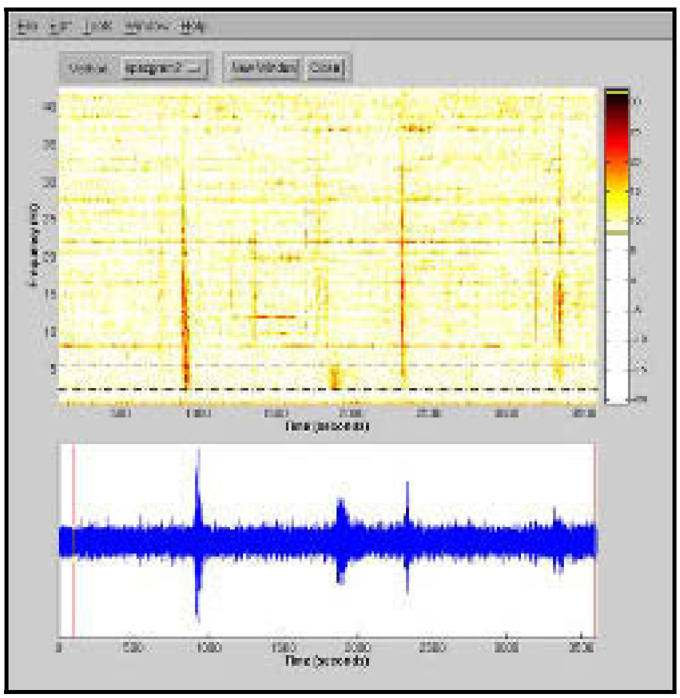

Figure 7. Example of a Spectrogram Tool. The spectrogram is the favored tool for analyzing hydroacoustic signals. The ACD is implementing an integrated spectrogram tool for analyst review. This particular spectrogram allows the analyst to simultaneously view the waveform and spectrogram, interactively choose filter bands, and adjust the color scale. The tool uses a sophisticated algorithm to enhance transient signals, which are the signals of greatest interest for test monitoring.

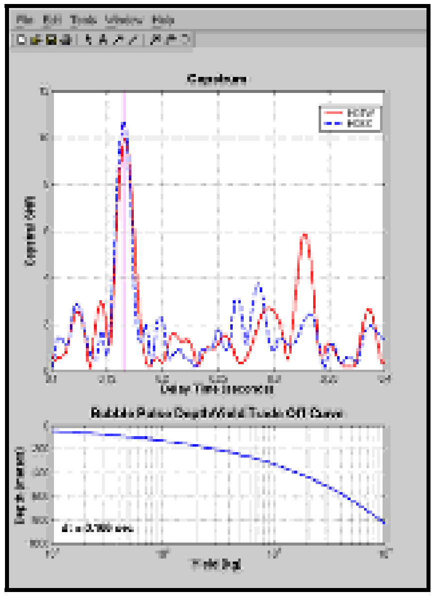

Figure 8. Example of a Cepstral Analysis Tool. The ability to review and modify cepstral results will be a new feature of this ACD. This tool allows the analyst to confirm the very important event characterization measurement. The estimated delay time (the first peak in the cepstrum) determines a depth/yield trade-off curve that will be used in determining a hydroacoustic magnitude. The automatic system picks the maximum peak that sometimes corresponds to the second bubble pulse and needs to be corrected by the analyst. The cepstra can also provide strong evidence for phase association as shown in this example with two signals measured at widely separated hydrophones that have nearly identical cepstral peaks.

Hydroacoustic Magnitudes

We are implementing a method for estimating a hydroacoustic station magnitude for in-water explosions. The energy measures extracted during processing (peak energy and total energy) provide some constraint on the magnitude of a particular event. However, it is difficult to directly determine quantities such as yield from these measures. The energy loss (transmission loss) due to propagation through the oceanic waveguide must be included in a yield determination.

Once a location for an event has been estimated, the transmission loss (TL) between the event location and a given hydroacoustic station can be calculated. TL is calculated for a number of potential source depths and across a wide frequency band. A standard model is used to calculate a set of candidate energy spectra as a function of charge weight and detonation depth consistent with the measured bubble pulse period. TL estimates and the source spectra are combined to predict a set of candidate energy spectra at the hydrophone station. The yield corresponding to the candidate spectra that best-matches the measured spectrum is used as the hydroacoustic magnitude estimate. This also provides an estimate of the source depth. An important feature of this approach is that it exploits the shape of the energy spectrum across the available frequency band. This shape provides critical information about the charge weight and detonation depth. Both the transmission loss and source spectra vary with frequency depending upon (among other factors) the source depth assumed.

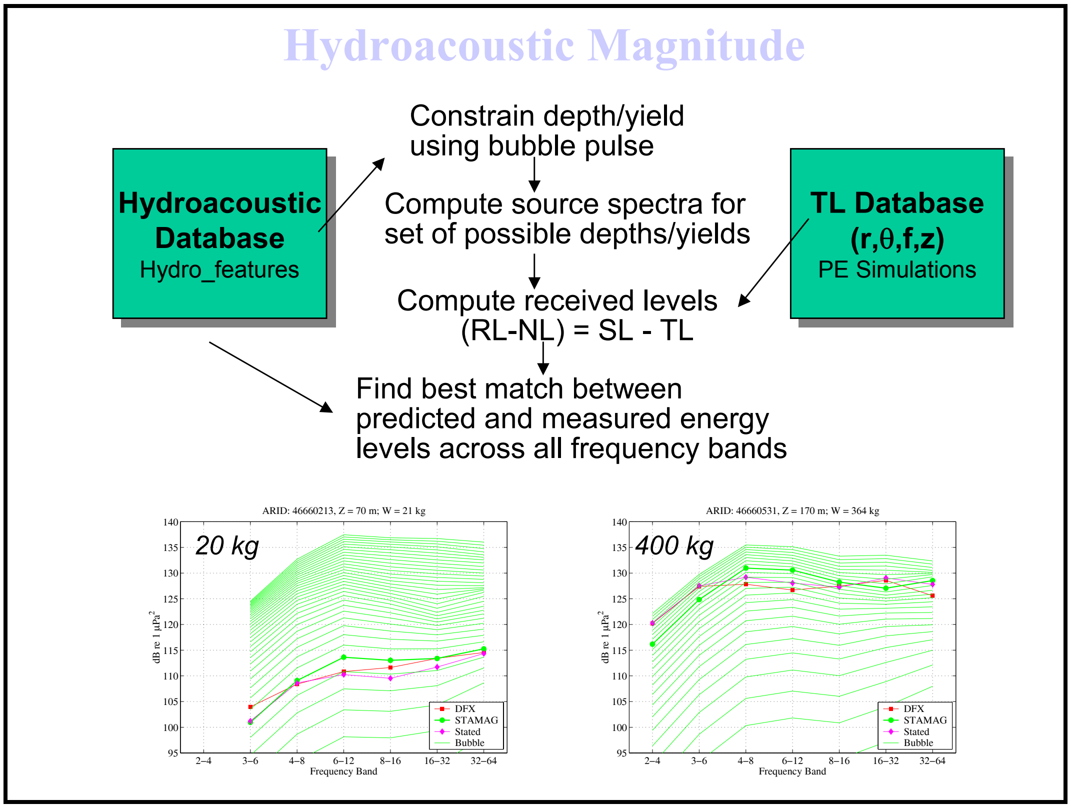

Figure 9. Estimation of hydroacoustic magnitudes. The received signal levels are matched to simulations based on source path and constrained using the bubble pulse depth/yield trade-off. The two examples use the actual measurements from explosions with nominal yields of 20-kg and 400-kg TNT equivalent.

Results using data from a well-documented seismic refraction survey show that accurate estimates of source yield and detonation depth are possible. This suggests that the measured spectral shapes and levels are sufficiently resolved in frequency, and that they can be predicted with sufficient fidelity using standard acoustic propagation codes and environmental databases.

CONCLUSIONS AND RECOMMENDATIONS

The new IMS hydrophone stations in the Indian Ocean provide a great opportunity to improve our hydroacoustic processing for detecting nuclear explosions in the region. This project will demonstrate enhancements in detection, localization and characterization of events occurring in the Indian Ocean Basin.

The Indian Ocean Advanced Concept Demonstration will improve detection by using coherent array processing and by providing analysts with visualization tools. The system's location capabilities increase by improving azimuth estimates, improving travel-time models, and incorporating hydroacoustic reflections into the location algorithm. The analyst will have significantly better resources to associate signals together including the spectrogram tool, the cepstral review tool, and the blockage review tool. New characterization abilities include the cepstral review tool and hydroacoustic magnitude estimation.

The data sets being compiled for the demonstration provide a unique resource that will be useful not only for evaluation of this project, but also for evaluating future enhancements to the system. There continues to be a need for definitive calibration data. This is especially true in regards to evaluating locations using reflected phases.

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REFERENCES

Blackman, D., C. de Groot-Hedlin, P. Harben, A. Sauter, and J. Orcutt (2002, submitted), Scattering and Propagation of Controlled Acoustic Signals Throughout the Indian Ocean Basin, *J. Acoust. Soc. Amer*.

Hanson, J.A. (2001), Initial Observations from the BIOT Hydroacoustic Station, *Proceedings from the CTBTO Hydroacoustic Workshop, October 8-11, 2001*.

Hanson, J.A., R. Le Bras, P. Dysart, D. Brumbaugh, A. Gault, and J. Guern (2001), Operational Processing of Hydroacoustics at the Prototype International Data Center, *Pure Appl. Geophys*., **158**, 425-456.

Harben, P.E. and C.O. Boro (2001), Implosion Source Development and Diego Garcia Reflections, *Proceedings 23rd Seismic Research Review,* 23-31.

Pulli, J.J. and Z.M. Upton (2001), Hydroacoustic Blockage at Diego Garcia: Models and Observations, *Proceedings 23rd Seismic Research Review,* 45-54.

Cochran, J.R. (2002), Cruise Report R/V Maurice Ewing, December 7, 2001 – January 25, 2002, Fremantle, Australia to Hobart, Australia, EW0114.