AN ACTIVE-SOURCE HYDROACOUSTIC EXPERIMENT IN THE INDIAN OCEAN

J. Roger Bowman[1], Jeffrey A. Hanson[1] and David Jepsen[2]

Science Applications International Corporation[1] and Geoscience Australia[2]

Sponsored by Army Space and Missile Defense Command

Contract No. W9113M-05-C-0138

ABSTRACT

The purpose of this project is to improve hydroacoustic discrimination of underwater events. The central element will be an explosive-source experiment conducted in the Indian Ocean offshore of Western Australia. We expect to conduct the experiment sometime in the middle of 2006. We will analyze high-frequency signals using data from hydrophone stations of the International Monitoring System (IMS). This is a joint project between the Science Applications International Corporation (SAIC) and Geoscience Australia. A feasibility study has been conducted that indicates the proposed experiment can be conducted economically and within existing environmental regulations.

The project will consist of three phases. The first phase will be experiment design, planning, and modeling. We will refine our preliminary designs (including finalizing the experiment site and defining the pattern, sizes, and deployment depths for shots) by analyzing high-frequency propagation and reflection losses using previously recorded data from natural and man-made sources. We will plan the logistics for execution of the experiment and will prepare and support applications for all required government permits.

We examined recordings of two explosions in the Bay of Bengal on May 5, 2004, to help guide the experiment design. These events are identified as explosions based on their high-frequency content and spectral scalloping. Bubble pulses are seen for direct arrivals at the four hydrophone triads examined and for reflected signals at three of the triads. The direct arrivals have consistent delay times with an average of 37.3 and 14.5 msec for the first and second events, respectively. Assuming the yield is the same for the two explosions, which have similar amplitudes, we infer that the second explosion is three times as deep as the first.

The second project phase will execute the field experiment itself. We will assemble personnel, equipment, explosives, and a marine vessel at the port of debarkation and transit to the experiment site. We will then deploy and detonate explosive charges and measure shot parameters.

In the third project phase, we will analyze and interpret data from the IMS hydrophone stations. We will improve knowledge of underwater event discrimination by determining the loss of high-frequency energy during reflection from coastlines and during propagation across partially blocked portions of the ocean's sound channel. We will also establish the ability to characterize events using reflected arrivals.

The principal products of this project will be the following:

- Unique ground-truth data set from in-water explosions comprising accurate source parameters and waveforms from IMS hydrophone stations
- Quantitative estimates of high-frequency reflection and propagation efficiency of hydroacoustic energy under different conditions
- Comparison between observed reflection and propagation loss and theoretical models

OBJECTIVES

This project is designed to improve discrimination of underwater seismic events and improve location of hydroacoustic sources in or just above the water column. Improvement in discrimination will be achieved by empirically quantifying and theoretically modeling high-frequency (greater than 30–50 Hz) loss of hydroacoustic energy propagating in the Sound Fixing and Ranging (SOFAR) channel from reflections off coastlines and interaction with bathymetric obstacles along path. We will also use variations in the observed residual amplitudes to identify important environmental factors that most impact high-frequency transmission loss. We will localize coastal reflector locations that will allow for better prediction of the reflected wave field. We will examine the robustness and accuracy of measuring bubble pulses from reflected or highly attenuated signals.

RESEARCH ACCOMPLISHED

We selected the Indian Ocean for this experiment because three hydrophone stations of the International Monitoring System have been installed in that ocean basin (Figure 1) and because abundant earthquakes along the mid-ocean ridges and the Java trench provide natural, surrogate sources to complement the planned explosions (Hanson and Bowman, 2005b). Our experiment will complement the earlier experiments conducted by the Scripps Institution of Oceanography and Lawrence Livermore National Laboratory (LLNL).

In 2001 Scripps and LLNL conducted the first calibration experiment in the Indian Ocean since the new IMS hydrophone stations began operating (Blackman et al., 2004). The experiment was a preliminary test to use various nonexplosive sources, such as airgun arrays and imploding glass spheres, as calibration events. The experiment ran an ocean transect from the Seychelles Islands to Perth, Australia, with 11 locations at which various sources were tested. They conducted a similar calibration experiment in 2003, crossing the Indian Ocean basin from Cape Town, South Africa to the Cocos-Keiling Islands using 2-kg SUS charges in addition to imploding spheres (Blackman et al., 2003; Harben et al., 2004). Both experiments provided data useful for many calibration needs. However, the sources used have limited ability to evaluate station effectiveness or processing approaches as a whole, because the signals generated do not allow for robust coherent processing and evaluation of large explosion discriminates. The chief reason for this is the low signal-to-noise (SNR) received levels at lower frequencies (less than20 Hz). The proposed experiment, with larger sources, will provide higher SNR across the spectrum, including at lower frequencies suitable for coherent signal processing. Our experiment will complement the earlier experiments, because it will produce signals better suited for processing with the large-aperture triad arrays and should also produce observable high-frequency reflected energy.

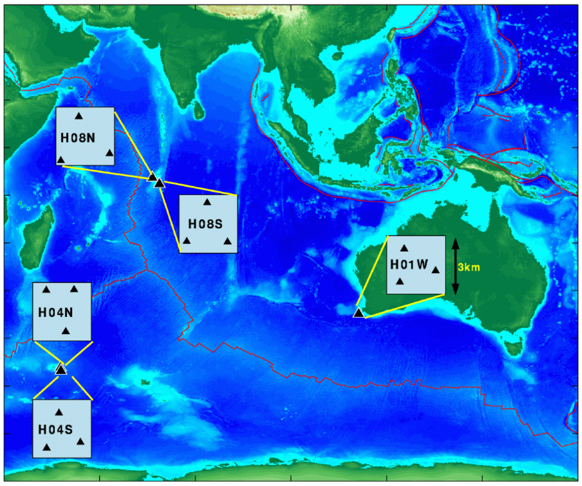

Figure 1. Seafloor bathymetry map with Indian Ocean hydrophone triad stations. There are five triads: Cape Leeuwin, Australia (H01W), Diego Garcia Island North and South (H08N, H08S), and Crozet Island North and South (H04N, H04S). Two elements at Crozet are not currently operational.

Experiment design and plans. We conceived the Indian Ocean experiment with limited geographical scale so that it could be executed with modest, commercially available resources and so that environmental regulations could be addressed in a single jurisdiction. Our preliminary design considers important logistical and practical constraints. These include

- Choice of port,
- Time of year,
- Maximum range from port,
- Maximum total amount of explosives, and
- Maximum source depth.

These logistical considerations are discussed below. Our preliminary designs considered two ports in Western Australia, Fremantle and Dampier (Figure 2). Fremantle is the principal port of Western Australia, near Perth. A ship out of Fremantle would likely be a fishing vessel. This port would have the advantages of accessibility and shorter transit to the experiment site than Dampier. Dampier is the principal town servicing the oil and gas industry in the offshore Northwest Shelf oil fields. A ship out of Dampier would more likely be a vessel designed for exploration or oil field servicing. Such a ship could probably better handle and carry more explosives, but ship time would be more expensive, and the experiment would require a longer transit. We selected Dampier as the base for the experiment because we were able to identify suitable ships to conduct the experiment there, but not in Fremantle.

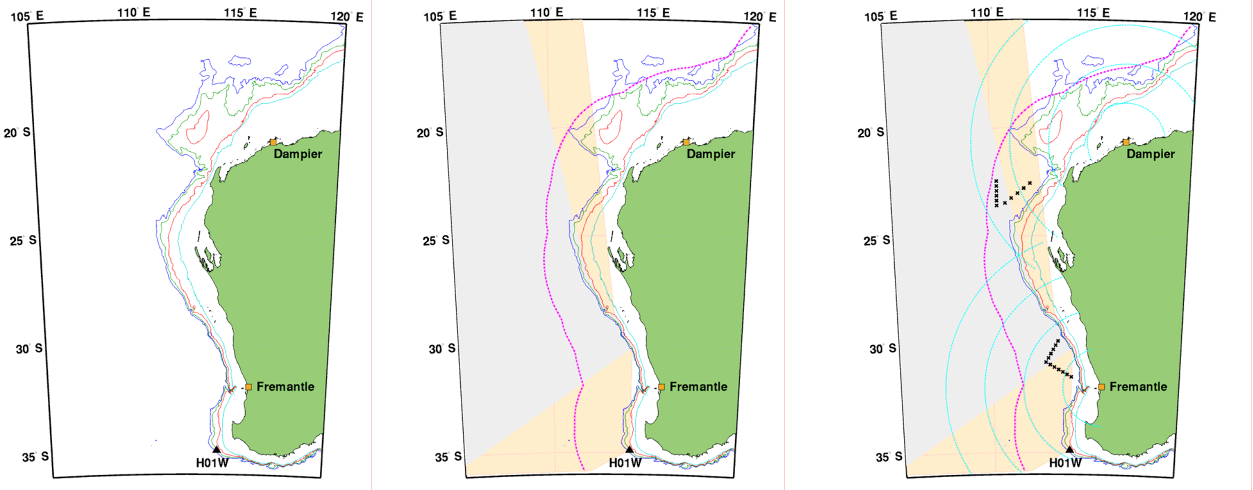

Figure 2. Bathymetry on the western continental slope of Australia. a) Contours are placed at 500-m intervals covering depths of 500 to 2000 m; the red contour represents a depth of 1000 m. b) Grey depicts areas with relatively clear paths to the three hydrophone stations. Beige represents the area with paths that intersect significant shallow waters to one or more stations. The blockage is based on approximate bathymetric boundaries and does not include small seamounts. The map also includes an approximation of the Australia's Exclusive Economic Zone (dashed line). c) Two potential experiment layouts. The black crosses represent shot locations. Semi-circles indicate distances from each port in steps of 200 km.

Related to the choice of home port is the maximum range from port. Our preliminary design constrains this range to 800 km. This is based on a 6-day cruise, allowing 3 days of round-trip transit time and 3 days of conducting the actual experiment. The range will also be affected by the state of the sea, and we anticipate conducting the experiment during the summer months to minimize chances of large swells.

Most vessels expected to be available for charter operate principally within Australia's Exclusive Economic Zone (EEZ). The boundary of the EEZ is shown in purple in the right panel of Figure 2. For these vessels, travel into international waters would require a ship to carry more insurance and a larger crew, thus increasing the experiment's cost. Our preliminary designs have thus been constrained to lie within Australia's EEZ. However, we retain the option during the design and planning phase to enter international waters if our scientific objectives cannot be met otherwise.

Portable explosives magazines available in Western Australia have maximum capacity of 500 kg. Some vessels could only accommodate a single magazine, whereas a larger vessel from Dampier might be able to carry two or more. Our preliminary designs assume a maximum of 1000 kg of explosives available for the experiment. The experiment layout will likely consist of approximately a dozen shot locations. The shots will be arranged to provide variations in direct path blockage and to provide a variety of event/reflector/station geometries. Various depths and shot sizes will be used to achieve desired SNR levels across different frequency bands while maximizing the total number of shots. The individual shot sizes will range from 20 to 80 kg.

We anticipate lowering explosives with a cable, and therefore, there is a practical limit on the maximum depth at which the sources may be deployed. Our preliminary design assumes a maximum source depth of 400 m. Important scientific considerations to be determined during the detailed experiment design include the following:

- Signal transmission loss to IMS stations
- Water depth
- Source yield and depth

Each of these scientific considerations is discussed here. The left panel in Figure 2 shows the bathymetry surrounding Western Australia that is less than 2000 m deep. In the center panel of Figure 2, an approximate boundary of the EEZ is shown, and a two-tone shading is used to indicate areas that have relatively clear paths to all three hydrophone stations (gray) and areas that are partially blocked to one or more stations (beige). Here, a clear path is defined as not crossing shallow waters (less than 1000 m) over a significant portion of the path length. Partially blocked paths are defined as paths with a significant portion that crosses shallow water to one or more stations. The shading does not take into account small features such as mid-ocean seamounts that will cause localized blockage.

Our preliminary designs constrain the experiment to deep-water locations (greater than 4000 m) to avoid complicating the direct arrival from near-source reverberations and/or reflections. Because the explosions are planned to occur at depth (i.e., in the sound channel), we do not have to rely on near-source bathymetry to horizontally scatter acoustic energy. This will simplify our analysis and make reflected energy easier to distinguish.

Source characteristics for an explosion are dependent on yield and depth. A small explosion (e.g., a 2-kg. SUS charge) might be enough to produce observable signal levels at high frequencies for the direct arrival. However, a larger explosive yield is needed to produce sufficient energy in the low-frequency bands and to produce observable high-frequency reflections. The left panel in Figure 3 shows source level (SL) as a function of depth for different size explosions. Near the surface, the SL is nearly constant with depth, but below a "corner," SL decreases rapidly with depth. Keeping sources shallow produces the largest source levels, but because of the sound channel (Figure 4), deeper sources will suffer less transmission loss. Thus, there is an optimal depth that maximizes the received levels for a given frequency band for a given yield. The right panel in Figure 3 shows preliminary predicted SNR at the Diego Garcia South triad for two frequency bands.

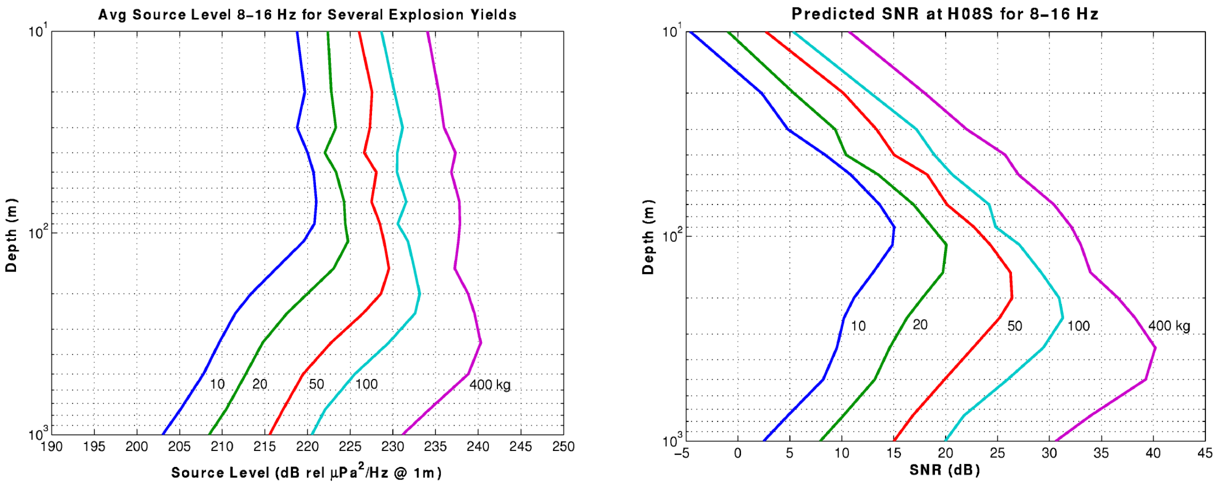

Figure 3. The predicted average SL and SNR for a suite of different yield explosions in the 8–16 Hz band. Near the surface, the source level is approximately constant with depth. Below some critical depth, which is a function of frequency and yield, the SL rapidly decreases. The SNR is predicted for Diego Garcia using the source level, an average noise level at Diego Garcia South, and a predicted transmission loss. The source level and transmission loss are functions of depth and display maxima that vary with yield and frequency. This estimation does not include any processor gain, which will effectively increase the SNR level in all the curves. Higher frequencies will have larger SNR because the explosives produce more high-frequency energy, and the ambient noise at the hydrophone stations is lower at the higher frequencies.

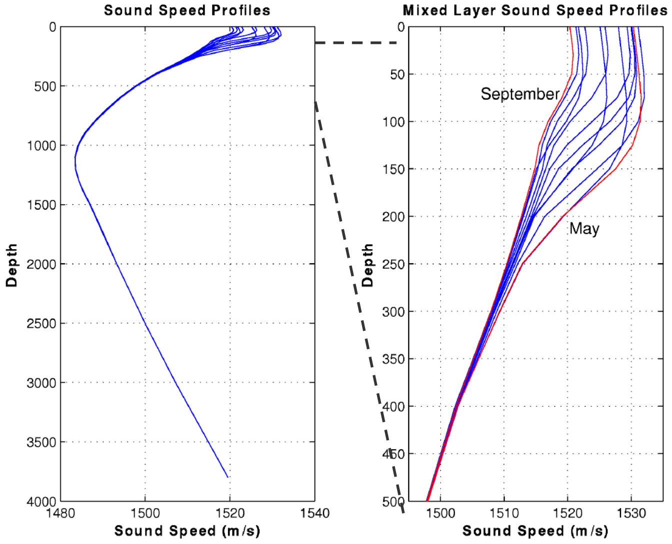

Figure 4. Sound speed profiles at the experiment location that were considered near Fremantle for each month of the year. The right panel is an enlargement of the left panel and shows the upper 500 m. For efficient long-range propagation the shots need to be below the mixed layer, which is the layer at the ocean's surface where the sound speed is nearly constant with depth. This is deepest in May (over 100 m) and shallowest in September (about 50 m). This thickness can vary from year to year.

Experiment phases. The project consists of three phases. We are currently in the first phase, which involves experiment design, planning, and modeling. We will refine our preliminary designs (including finalizing the experiment site, and defining the pattern, sizes, and deployment depths for shots) by analyzing high-frequency propagation and reflection losses using previously recorded data from natural and man-made sources. We will plan the logistics for execution of the experiment and will prepare and support applications for all required government permits.

The second project phase will execute the field experiment itself. We will assemble personnel, equipment, explosives, and a marine vessel at the port of debarkation and transit to the experiment site. We will then deploy and detonate explosive charges and measure shot parameters.

In the third project phase, we will analyze and interpret data from the IMS hydrophone stations. We will improve knowledge of underwater event discrimination by determining the loss of high-frequency energy during reflection from coastlines and during propagation across partially blocked portions of the ocean's sound channel. We will also establish the ability to characterize events using reflected arrivals.

Anticipated products. These are the principal products of this project:

- Unique ground-truth data set from in-water explosions comprising accurate source parameters and waveforms from IMS hydrophone stations
- Quantitative estimates of high-frequency reflection and propagation efficiency of hydroacoustic energy under different conditions
- Comparison between observed reflection and propagation loss and theoretical models

Explosion observations. Historical and recent recordings of underwater explosions have guided the design of our experiment in the Indian Ocean. Large underwater explosions are uncommon, so it is important to fully exploit those that have been well recorded. Here we present examples of explosions in the Indian Ocean in 2003 and 2004 recorded on IMS hydrophone stations and in the Pacific Ocean in 1996 recorded on the legacy Wake Island hydrophone station.

Figure 5 shows a spectrogram for two 2-kg SUS charges from the Scripps/LLNL 2003 Indian Ocean experiment (Blackman et al., 2003; Harben et al., 2004). The SUS charges produced impulsive signals with fairly large SNR at high frequency. Time delays across the hydrophones of the H08S triad are consistent with back azimuths to the sources, but because of the limited frequency range of the signal and the 2-km spacing of the hydrophones, coherent processing is not effective. This makes it difficult to identify reflections (if present at all) or to precisely estimate signal-back azimuth. Bubbles pulses are not evident in these signals (Figure 5), which is due to the small source and deep detonation. Our experiment will complement the earlier experiments, because it will produce signals better suited for processing with the large-aperture triad arrays. Our experiment should also produce signals that include observable high-frequency reflected energy.

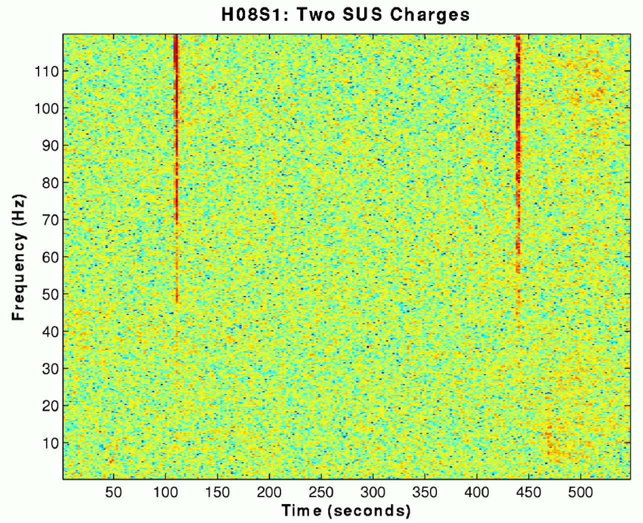

Figure 5. Spectrogram from H08S1 for two sources from the 2003 Indian Ocean experiment (Blackman et al., 2003). Sources were 1300 km south of H08S at depths of 915 m and 610 m, respectively. The signals have high SNR above 60 Hz and negligible energy below 30 Hz.

Figure 6 illustrates the high-frequency energy for an explosion of 20 kg at 3000 km distance in the Pacific Ocean. For large amplitude signals, this high-frequency content can be used to discriminate underwater explosions from other sources. (For smaller amplitude signals, the high-frequency content may also result from other causes, such as ice cracking at the Antarctic margin [Hanson and Bowman, 2005a] or air guns used for seismic reflection surveys [Blackman et al., 2004]).

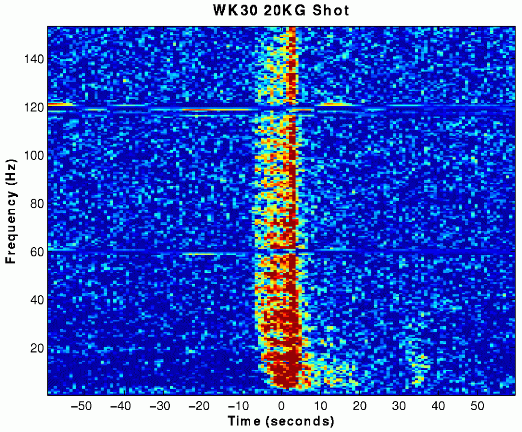

Figure 6. Spectrogram of a 20-kg explosion recorded at the WK30 hydrophone near Wake Island (Brumbaugh and Le Bras, 1998). Note the abundant energy content at frequencies up to 150 Hz. A faint signal 30 seconds after the main arrival at frequencies of 10-20 Hz is interpreted as a reflection, possibly off the Japanese coastline, based on cepstral analysis.

An important question for nuclear test monitoring is whether reflected signals, or the lack thereof, can be used for discrimination of underwater events. This question reduces to how much signal bandwidth and how much coherent signal is preserved upon reflection that can be used for discrimination. Figure 7 shows the spectra for direct and reflected signals from a submarine earthquake and a 400-kg explosion. The direct signal from the earthquake does not have sufficient high-frequency energy to determine whether such energy is preserved upon reflection. To answer this question will require high-frequency sources, such as the explosive sources proposed for our experiment.

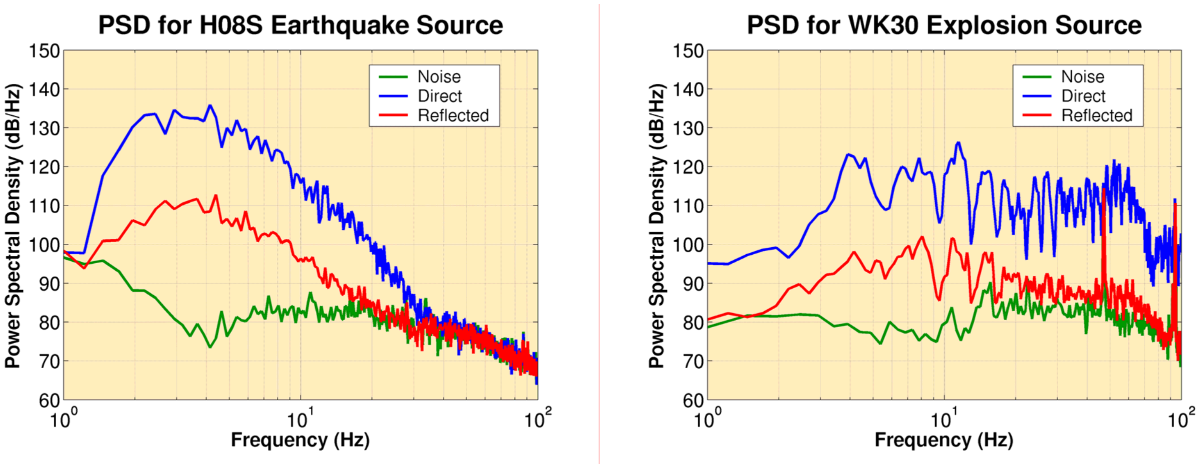

Figure 7. Spectra of direct and reflected signals from an earthquake (left) and a 400-kg explosion (right). The m_b 5.9 earthquake occurred along the Java trench and was recorded at Diego Garcia (H08S). The explosion was part of a Japanese refraction experiment in 1996 that was recorded at the Wake Island hydrophone station (WK30). Note that the refraction experiment was designed to propagate the hydroacoustic energy vertically and not horizontally over ocean basin distances. Our experiment will more efficiently transmit the energy into the SOFAR channel.

Two explosions in the Bay of Bengal were well recorded by IMS hydrophone stations on May 5, 2004 (Graeber and Firbas, 2005; Spiliopoulos and Jepsen, 2005; see Table 1). These were interpreted as explosions based on their high-frequency content and spectral scalloping. The two explosions were separated by about 45 minutes. Spectrograms at H01W for the two explosions in Figure 8 show that the direct signal, at 1800 seconds in these plots, is broadband, with energy from 5 Hz to more than 120 Hz. For the first event (left panel), a second signal is seen clearly 50 seconds after the direct arrival in the frequency band 10 to 80 Hz. For the second event (right panel), a weaker signal is seen at the same time in the frequency band 30 to 80 Hz. These are interpreted as reflected signals. A weaker signal around 1820 seconds is also likely to be a reflected signal.

Table 1. Attributes of Bay of Bengal explosions (Graeber pers. comm., 2005).

Time	Latitude	Longitude
2004 May 5 1528:04 UT	10.14	89.07
2004 May 5 1616:46 UT	10.01	89.50

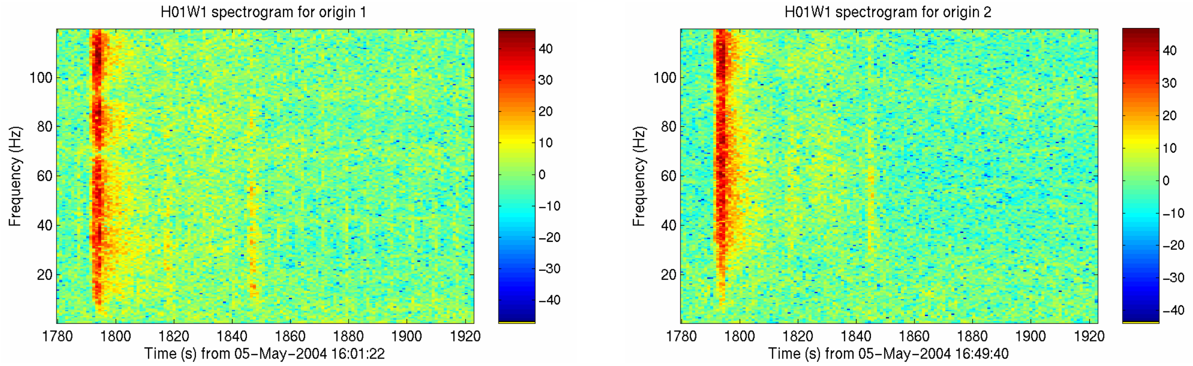

Figure 8. Spectrograms from H01W1 of Bay of Bengal events on May 5, 2004, at 1528 (left) and 1616 (right) UT. The direct signal near 1800 seconds has high signal-to-noise from 10 to 120 Hz for both events. The reflected signal near 1850 seconds is stronger for the first event, particularly between 10 and 60 Hz, but also seen for the second event between 30 and 60 Hz. A weaker signal near 1820 seconds may also be a reflection.

Analysis using all three triad elements provides an estimate of the arrival of coherent energy from any azimuth. For the first event, coherent energy is seen arriving at 1800 seconds from 327.9° and at 1850 seconds from 352.0°. We interpret these to be direct and reflected signals, respectively. The weaker signal at 1820 seconds did not have sufficient signal strength for estimation of its azimuth. Using the arrival time of the signals and the azimuth of arrival, the reflection point can be estimated (Hanson, et al., 2002; Hanson and Bowman 2005a). This is shown in Figure 9 for the larger reflection observed at Cape Leeuwin. The yellow circle indicates the explosion location estimated from the direct arrivals. The white square is the estimated reflector location using the measured back azimuth, the arrival time, and the event location. The reflection point coincides with the 1000 m bathymetric contour surrounding the Australian continental shelf. Reflections are also observed at H04N and H08S.

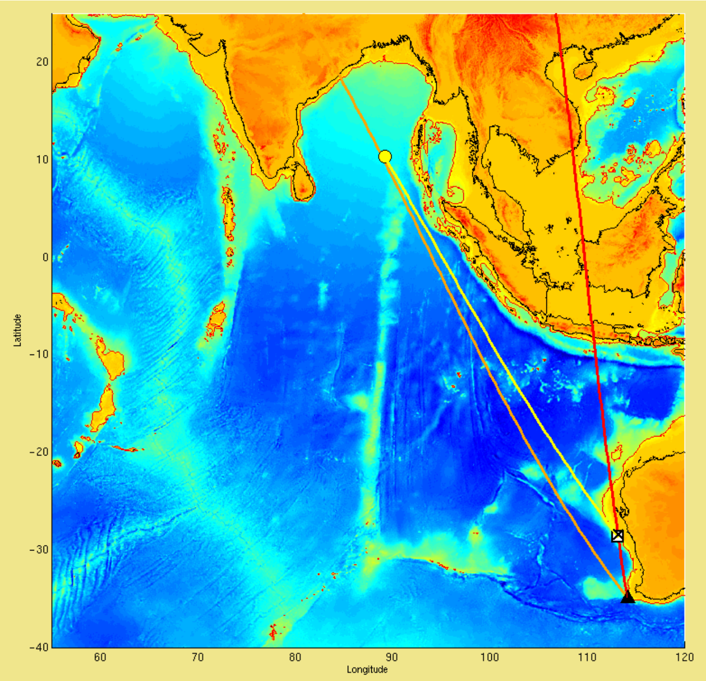

Figure 9. Reflector location from the first Bay of Bengal event on May 5, 2004, at 1528 UT observed at H01W (black triangle) in Australia. The orange line extending northwest from H01W shows the back-azimuth of the direct signal based on coherent triad processing. The red line extending north from the station shows the back-azimuth of the reflected signal. The yellow circle shows the location estimate derived from the direct arrivals. The square with a cross shows the estimated reflection point using the back-azimuth and arrival time of the reflected signal. It coincides with the 1000-m bathymetry contour (thin red surrounding landmasses) providing confidence that it is a true reflection.

The results of spectral and bubble-pulse analysis for the first Bay of Bengal event for four hydrophone stations are shown in Figure 10. For H01W (upper left panel), results are shown for both the direct and reflected arrivals. Similar spectral scalloping is seen for each of the stations. The direct signal is above the noise level from 5 to 120 Hz for H01W, H04N, and H08S. The low-freqency noise increases dramatically at H04S and obscures the signal below 10 Hz. The reflected signal at H01W is 5 to 10 dB above the noise level from 5 to 50 Hz but converges with the noise near 90 Hz. The bubble-pulse analysis uses an estimate of the autocorrelation. The first peak with a lag greater than zero corresponds to the first bubble pulse. The direct arrivals have consistent delay times with an average of 37.3 msec. This corresponds to about nine samples for these hydrophones. The reflected signals have autocorrelations that agree with the direct arrivals but are not as distinct. This is due to their lower SNR and limited bandwidth. The second explosion has an average delay of 14.5 msec, which corresponds to only four samples.

The bubble-pulse period can be used to determine a depth/yield trade-off curve. This is shown for the two explosions in Figure 11. The amplitudes of the two explosions are very similar. Assuming the yield is the same for the two explosions, the second explosion would have to be thee times as deep as the first. This is consistent with the observed frequency content of the signals. The first explosion has more low-frequency energy and less high-frequency energy than the second explosion as predicted from Figure 3. Depths between 50 and 1000 m correspond to yields from less than 1 kg to 100 kg. A transmission loss analysis could be conducted to constrain the yield, and consequently the depth, of the sources.

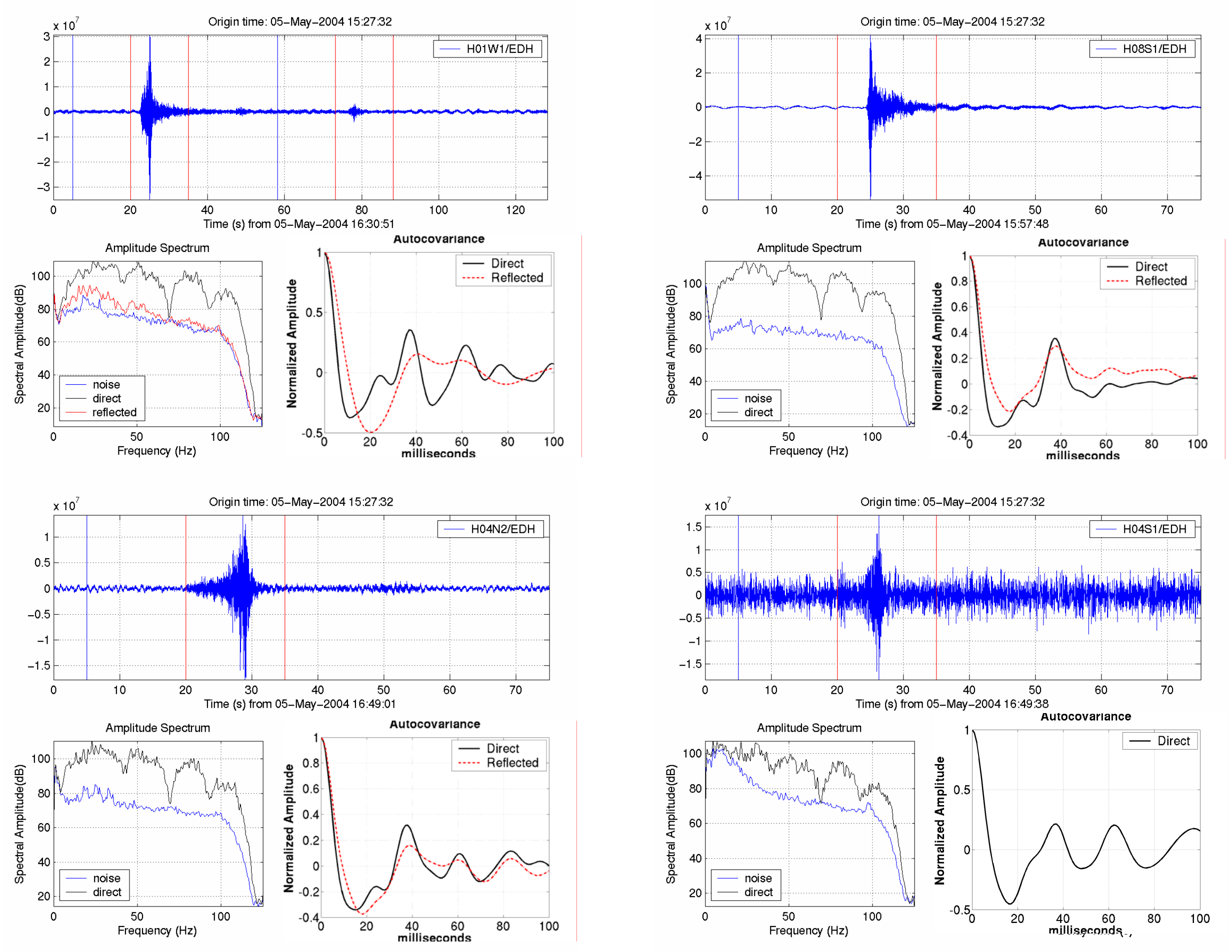

Figure 10. Spectral and bubble-pulse analysis of the first Bay of Bengal event on May 5, 2004 at 1528 UT. Clockwise from upper left, the stations are H01W, H08S, H04S, and H04N. For each station, the figure shows the unfiltered hydrophone waveforms, the amplitude spectrum, and autocovariance. Vertical red lines in the waveform plots represent the windows used for the signal spectra, while the blue vertical lines show the start of the noise windows, which end at the first vertical red line in each trace plot.

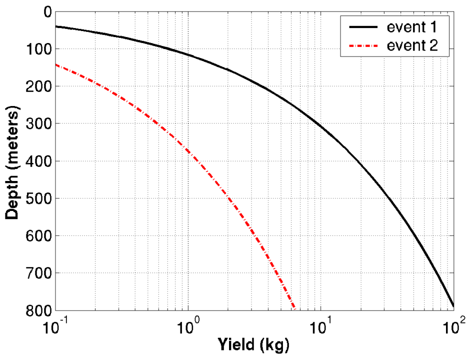

Figure 11. Depth/yield trade-off for the bubble-pulse delay times observed for the two explosions. The delay times are 37.3 and 14.5 msec for the first and second explosions, respectively. If the yields of the two explosions are equivalent, then the depth of the second explosion is approximately three times deeper than the first.

CONCLUSION AND RECOMMENDATION

A modest, but strategically important, experiment is being planned for next year off the western coast of Australia. The experiment is designed to quantify frequency dependent attenuation of partially blocked and reflected signals. A candidate port has been selected, Dampier. Preliminary shot locations have been selected that provide a variety of unblocked and partially blocked paths to the various hydrophone stations in the Indian Ocean. Numerous logistical and scientific issues with concern to the experiment have been or are being addressed.

Observations from previous experiments and sources of opportunity indicate that modest size explosives are effective in producing broadband signals with sufficient energy to have observable reflections. The frequency content of the signals is a function of depth and yield. Bubble-pulse periods can be used to identify reflected signals. Reflections with sufficient low-frequency energy can be located via coherent array processing. We conclude that moderate size explosions offshore of Western Australia will be effective in determining the loss of high-frequency energy during reflection from coastlines and propagation across partially blocked portions of the ocean's sound channel.

ACKNOWLEDGEMENTS

We thank Colin Reasoner for analysis of the 2004 Bay of Bengal explosions.

REFERENCES

Blackman, D.K., J.A. Mercer, R. Andrew, C.D. de Groot-Hedlin, and P. Harben (2003), Indian Ocean calibration tests: Cape Town-Cocos Keeling, in *Proceedings of the 25th Seismic Research Review–Nuclear Explosion Monitoring: Building the Knowledge Base*, Vol. 2, 517-523.

Blackman, D.K., C. de Groot-Hedlin, P. Harben, A. Sauter, and J.A. Orcutt (2004), Testing low/very low frequency acoustic sources for basin-wide propagation in the Indian Ocean , *J. Acoust. Soc. Am.*: 116, 2057.

Brumbaugh, D. and R. Le Bras (1998), Hydroacoustic signals from a ground-truth data set of marine explosions, SAIC Report, SAIC-98/3008.

Graeber, F. and P. Firbas (2005), Recent developments in hydroacoustic data processing at the IDC, Hydroacoustic Workshop, Victoria, BC, May 1-5, 2005.

Hanson, J., J.R. Bowman, J.R., and G. Beall (2002), An advanced concept demonstration for monitoring the Indian Ocean, in *Proceedings of the 24th Seismic Research Review–Nuclear Explosion Monitoring: Innovation and Integration*, Vol. 2, pp. 632-642.

Hanson, J.A. and J.R. Bowman (2005a), Methods for monitoring hydroacoustic events using direct and reflected T waves in the Indian Ocean, *J. Geophys. Res*., in press.

Hanson, J.A. and J.R. Bowman (2005b), Indian Ocean Ridge seismicity observed with a permanent hydroacoustic network, *Geophys. Res. Lett*., *L06301*, 10.1029/2004GL021931.

Harben, P.E., E. Matzel, D.K. Blackman, and D. Clarke (2004), Hydroacoustic blockage calibration for discrimination: Results from 2003 Indian Ocean cruise, and imploding sphere calibration source development, in *Proceedings of the 26th Seismic Research Review: Trends in Nuclear Explosion Monitoring,* Vol. 2, pp. 553-559.

Spiliopoulos, S. and D. Jepsen (2005), Studies in the Indian Ocean: Preliminary phase identification and synergies with the seismic network, Hydroacoustic Workshop, Victoria, BC, May 1–5, 2005.