ACOUSTIC SOURCES FOR BLOCKAGE CALIBRATION OF OCEAN BASINS: RESULTS FROM THE OCTOBER 2001 INDIAN OCEAN CRUISE

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ABSTRACT

Blockage and transmission loss calibration of hydroacoustic stations for explosion monitoring is important for assessing monitoring capability from new and existing stations. Unlike acoustic travel time, generally predicted with good accuracy by models, blockage and transmission loss predictions along many ray paths are poor. In large part, this is due to the relative coarseness of the global bathymetry databases for the acoustic frequency range of monitoring interest (1-100 Hz). When higher resolution bathymetry databases are integrated into models, blockage prediction accuracy improves; however, such high-resolution bathymetry databases are not available in large regions, such as the Indian Ocean, due to sparse coverage. A data-driven approach to the blockage and transmission loss prediction problem is an approach that sidesteps the bathymetry database problem as well as other difficulties such as modeling diffraction, higher modes, and providing predictions as a function of frequency. The data-driven approach requires a large number of ground truth events recorded at a specific station to calibrate it and allow prediction of blockage and transmission loss from a hypothetical source. Earthquakes can provide most of the calibration events but, with the exception of submarine volcanoes, there is no significant energy in the T-phase above about 15 Hz. To calibrate stations at higher frequencies, an artificial source is necessary. The purpose of the 2001 Indian Ocean cruise was to test three such sources at ocean basin scale.

Three sources were tested: an airgun array, a spherical implosion system, and a cylindrical implosion system. These sources were fired at numerous locations along a great circle ship-track between the Seychelles and Perth, Australia, and recorded at the Diego Garcia and Cape Leeuwin hydroacoustic stations. The airgun system was fired over shallow and/or sloping bathymetry along the track as much as possible to maximize coupling into the sound channel via bottom scattering. Although airgun signals were detected at Diego Garcia and at Cape Leeuwin, detections were not seen in several cases because the coupling was dependent on the complex process of bottom scattering into the SOFAR channel. The spherical implosion system was fired in two different configurations: 1-sphere and 5-sphere. The 22-liter single-sphere implosions were reliably detected at Diego Garcia for ranges from 800 km to 1200 km when fired at sound channel depths of 680 m. The 5-sphere shots were a cluster of 22-l spheres fired at 680 m. Both 5-sphere tests were reliably recorded at both Diego Garcia (4000- to 4500-km ranges) and Cape Leeuwin (1500- to 2000-km range). The sphere implosions produced useful signal from 40 Hz through 100 Hz. The sphere implosion systems also proved to be highly repeatable, especially the 1-sphere system. Tests with the cylindrical implosion system produced signal level too low to be detected at the International Monitoring System (IMS) hydroacoustic stations. A future cruise will test two additional sources: small explosives and a large continuous wave source previously employed in ATOC (Acoustic Thermometry of the Oceans Climate) experiments.

OBJECTIVE

The overall objective of this research is to assemble a database that provides accurate blockage prediction from any hypothetical oceanic source location to all hydroacoustic monitoring stations of interest. We know from experience that a model-based approach to this problem is not always accurate. The BBN Inc. code — HydroCAM — continues to be used at the National Data Center for model-based prediction of acoustic signal blockage. Model-based blockage predictions suffer, to first order, from the generally coarse bathymetry data available for the world's oceans. Less important, but significant, sources of model error are: ignoring scattering and diffraction, using only mode-1 propagation, and an inability to conveniently determine blockage as a function of source frequency.

The approach to improving blockage prediction in the world's oceans is to improve model capabilities by improving the resolution of the bathymetry databases and to assemble a database of ground truth events that define the blockage at any particular station. Emulating the regional seismic travel-time correction methodology, hydroacoustic ground truth data will trump any model prediction for locations close to where ground truth is available. The best prediction will transition to model-based when the location is far from any ground truth data. A critical issue in building the ground truth databases is understanding the suite of sources that will be needed and the limitations of each in providing the desired broadband blockage information. The nature of the source, accuracy of the source location, bandwidth of the source, and strength of the source will define the applicability of the source and the limitations for use in the database. For example, oceanic and near-coast earthquakes that generate large T-phases will certainly be a class of sources that make up a large part of a ground truth blockage prediction database. That they will not be the only class of sources is also clear since the bandwith is generally limited to 1-15 Hz (much lower than in-water explosions) and their location is difficult to accurately assess (DeGroot-Hedlin, 2001) because the T-phase is not necessarily generated at the earthquake epicenter. We seek to understand the sources we will need in a complete ground truth database. To this end we have completed a cruise that tests three sources: two implosion source systems and an airgun array. The man-made sources sought are those that complement the natural sources: energy in the higher frequencies of the monitoring band (15-100 Hz), accurate locations, and sufficient signal for ocean-basin propagation ranges. The research conducted and presented here has a focus on a sphere implosion system that appears to meet some of the criteria for a man-made source with blockage calibration utility, though other sources remain to be tested.

RESEARCH ACCOMPLISHED

The research accomplished falls under three headings: 1) Blockage Issues, 2) Implosion Source Studies, and 3) Cruise Results. Our discussion of blockage issues will map out some of the difficulties and concerns that must be at the forefront of any attempt to improve blockage prediction capabilities. The Implosion Source Studies section will document the progress made over the past year in understanding the glass sphere implosion source, its utility, and its limitation in controlled-source calibration. Finally, a summary of the Indian Ocean cruise results will be presented. This cruise took place in October 2001 and tested three different controlled sources for hydroacoustic monitoring station calibration at long ranges.

Blockage Issues

Acoustic blockage prediction in hydroacoustic monitoring has yet to be clearly defined by a concise set of measurements. Model predictions with HydroCAM, for example, can estimate if a particular source-receiver path is blocked or unblocked in accordance with a minimum-ocean-depth criterion along the path. When done for all source paths to a given receiver, a map of blockage for that ocean basin results. The maps generated are very different if the blockage criteria are 800 meters vs. 50 meters, and no single depth criterion produces a best or most accurate map. The reason the models are inadequate is that scattering, diffraction, and reflections - and their frequency dependence - is not accounted for. In addition, the bathymetry databases are inadequate for the acoustic frequencies of interest. Examples of model-predicted blockage at a 50-meter-depth criterion along a particular source-receiver path have been shown to have large amplitude signals from earthquake events that get through, although the coherency of the signals among the tri-partite sensors is significantly degraded (Harben, 2001). Completely blocked source-receiver paths have been shown to have consistent reflected phase arrivals from the same topographic feature.

Blockage prediction is needed to assess which hydroacoustic stations, for a particular source region, can be used in detection, location, and discrimination analysis. That assessment can be made, but it will not always be a simple *yes* or *no* answer for any particular station. A full assessment - which will be backed by a ground truth database - will need to have a set of measurements on direct path attenuation and scattering energy loss, loss in coherency due to scattering, and reflected phases that may be used in subsequent analyses, all with frequency dependence. The question of blockage along a particular path may have an answer like: full blockage at high frequency along the direct path, adequate signal-to-noise ratio (S/N) at low frequencies but with a complete loss of coherency between tripartite sensors (i.e. back azimuth estimation not possible), two consistent reflected phases for large source energy with unblocked paths. Deciding on the most appropriate measures and automating them in a ground truth database used for blockage prediction is an essential next step.

Implosion Source Studies

The development of an imploding glass sphere source has been documented in past reports (see Harben, 2000; Pulli, 2000; and Harben, 2001). Here we present new results from tests and models that improve our understanding of source phenomenology, repeatability, and utility in calibration.

The single-sphere implosion source signal has now been recorded four times under similar conditions, though in widely varying locations. The implosions were conducted at nominally 680-m depth and recorded with a hydrophone hung off the side of the ship, nominally 30-m deep. The recordings are all overplotted in Figure 1. The repeatability of the source is apparent. This is an important result for calibration purposes because it allows for accurate transmission loss and other amplitude-dependent measurements with this source.

We modeled the source (Tipton, 1991) using a C-language Arbitrary Lagrangian-Eulerian code (CALE). Although our results showed qualitative agreement, the modeled peak pressure was half that observed. In consultations with the glass manufacturer, we found that the glass spheres were sealed in a partial vacuum due to the high air temperatures in the vicinity of the molten glass. When we modeled partial vacuums within the glass sphere, we were able to resolve the inconsistency in peak pressure. The modeling predicts the glass sphere internal pressure as 1/6 to 1/8 atmosphere, consistent with air pressures at temperatures of molten glass.

The 5-sphere system had been tested once off the Pacific coast in 2001 at 137-m depth (see Figure 2, left panel). During this test, one of the spheres failed, and the resulting shock wave caused the other spheres to fail. This is evident in the recorded waveform. The beginning of the record has the characteristic signature of a single-sphere implosion -- the sphere that self-failed. The time between the first sphere shock wave and the larger grouping of impulses that follow is controlled not by the acoustic propagation time between spheres but by the collapse time. The implosions at 680 m (Figure 2, right panel) show a markedly different signature that can only be interpreted as a nearly simultaneous implosion of all five spheres due to the smashing cylinder. Apparently, the cracking propagates from sphere to sphere (which are touching) and hence the implosion timing of individual spheres is controlled by the acoustic propagation time. It is also evident that the 5-sphere system is not as repeatable as the 1-sphere source, though the waveforms are similar. This is consistent with expectations if the spheres are failing nearly simultaneously. Such a failure does not have spherical symmetry and will consequently have a complex radiation pattern.

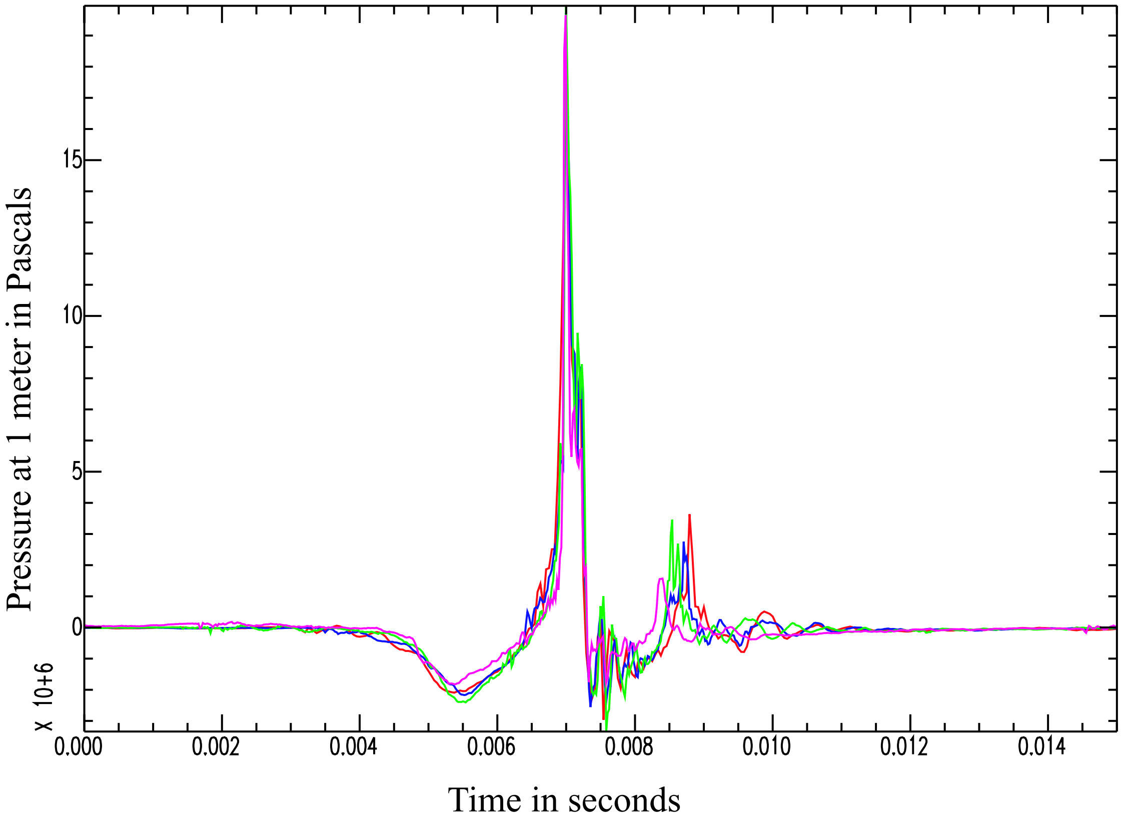


Figure 1. Repeated single-sphere implosions under similar conditions (680-m depth and projected to 1 m from the source). Note the good repeatability, especially for the implosion and main shock.

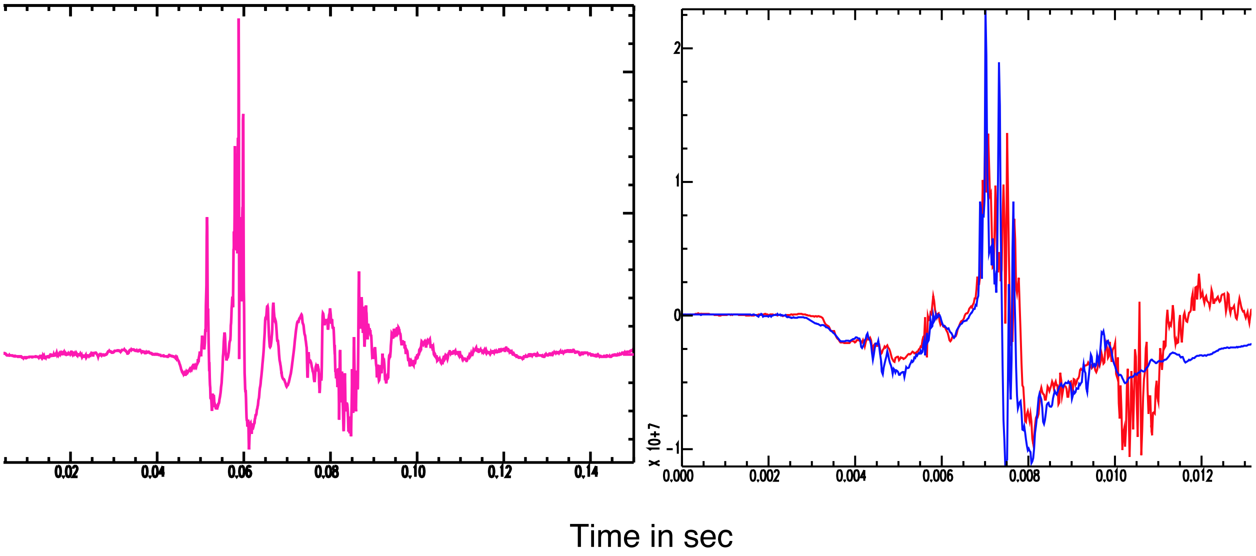


Figure 2. The 5-sphere implosion source waveforms are shown at 137 m (left) and for two tests at 680 m. Both plots are source strength at 1 m in Pascals. The horizontal axis is time in seconds. Note that the 137-m test was initiated by self-failure of a glass sphere. The 680-m tests were initiated properly by the cracking system.

Cruise Results

The purpose of the October 2001 Indian Ocean cruise aboard the Maurice Ewing was to produce acoustic signals at various locations in the Indian Ocean basin so that the nature of sound propagation, and losses, can be documented. One goal was to determine what types of topography are conducive to using large, shallow sources that require that energy be scattered off the seafloor into the SOFAR channel, for basin scale propagation. Another goal was to determine the range at which small, deep imploding sources can be detected at distant receivers. The acoustic sources consist of a large array of airguns, imploding glass spheres, and a triggered imploding cylinder. The receivers are permanently installed hydrophones that are part of the IMS that is overseen by the Comprehensive Nuclear-Test-Ban Treaty Organization. Each hydrophone station consists of three instruments. Two stations are deployed in the vicinity of Diego Garcia, on the east and west slopes of Chagos platform. One station is installed off Cape Leeuwin, southwestern Australia.

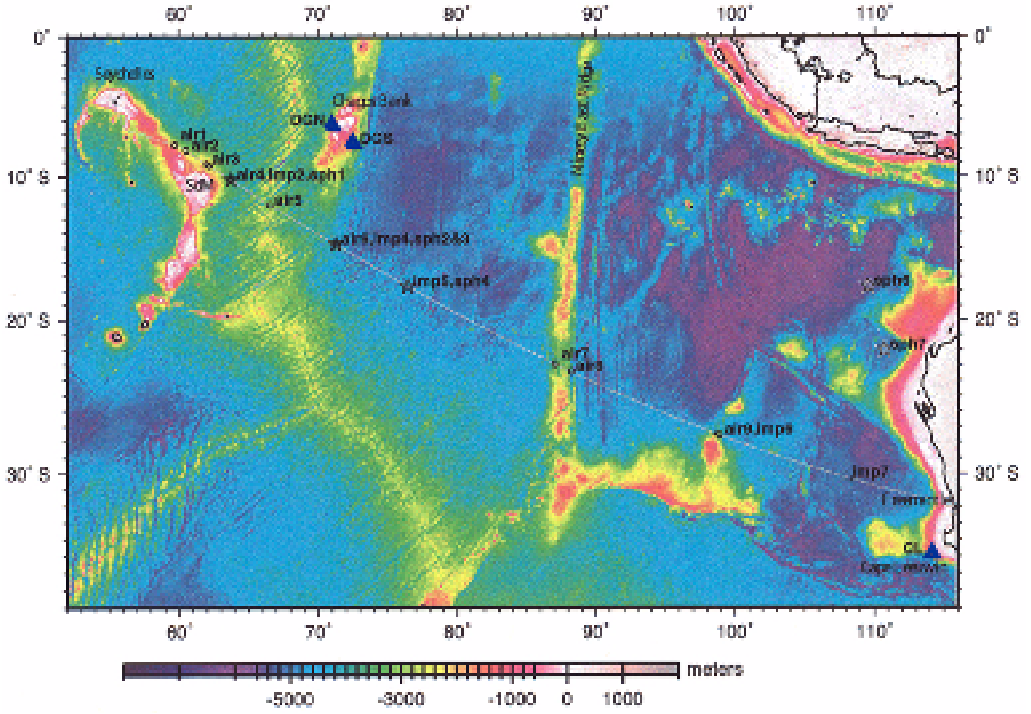


Figure 3. Topographic model of Smith and Sandwell (1997) in the Indian Ocean region is overlain by the 2001 R/V Ewing shiptrack (gray line) and the acoustic source locations for our experiment. IMS hydrophone stations are shown by blue triangles. Circles show where the airgun array shooting (air) was conducted. Stars show glass sphere (sph) implosion stations and 5-sphere implosions are highlighted in white. Crosses are where the MPL/SIO imploding cylinder (imp) was fired. SdM indicates Saya de Mahla bank.

The 'standard' Ewing array of 20 airguns was used. Total volume of the array was 8465 cubic inches. The shot interval was varied from 57 - 173 s. Each shooting period lasted about 30 min. The imploding glass spheres were those described above. Both 1-sphere and 5-sphere systems were tested. The triggered imploding cylinder was a 900-lb. reusable system which operates by using the available hydrostatic pressure at depth to mechanically open an empty 20-l cylinder upon electrical command. Displaced water fills the cylinder, generating an acoustical signal. We recorded all the implosion source waveform on a TEAC RD-145T 16-track using a calibrated (-194dB re 1V/uPa) Ball hydrophone. The hydrophone was deployed from the ship's deck. Shackles were attached to the cable to add weight, but at some stations the cable was not particularly vertical in the water. The sample rate was set to either 24000 or 48000 SPS for the stations.

The cruise track is shown in Figure 3 with the location of the IMS recording stations and the location of each source deployment. The cruise originated in the Seychelles and ended in Freeport, Australia, on the great circle path route between the two. Attempts were made to test airguns in areas of shallow and/or variable seafloor topography. The two 5-sphere shots, shown off the northwest coast of Australia, were conducted for us by researchers on a subsequent cruise.

Airguns: Near source recordings of the airgun array shots indicate very consistent source signatures. Shot durations are on the order of 40 ms, and most of the output energy is in the 6- to 110-Hz band, with peaks at 8 Hz and 14 Hz.

S/N for waveforms recorded at the IMS receivers in the Indian Ocean are shown as a function of frequency in Figure 4. Overall, S/Ns at Diego Garcia south (DGS) and Cape Leeuwin (CL) are much poorer than those at Diego Garcia north (DGN). In part, this is due to higher noise levels at these stations; noise levels at DGS and CL exceed those at DGN by about 6 dB and 12 dB, respectively. As expected, the S/N vary as a function of both source and receiver location mainly due to acoustic blockage. Propagation to DGS was blocked by the Chagos Bank for the first four airgun sites (the first 78 shots). Cape Leeuwin was expected to be blocked from the first site by the Saya de Malha bank and from some of the subsequent five sites by the Ninety East Ridge. Propagation to DGN was blocked by the Chagos Bank for all but the first four sites.

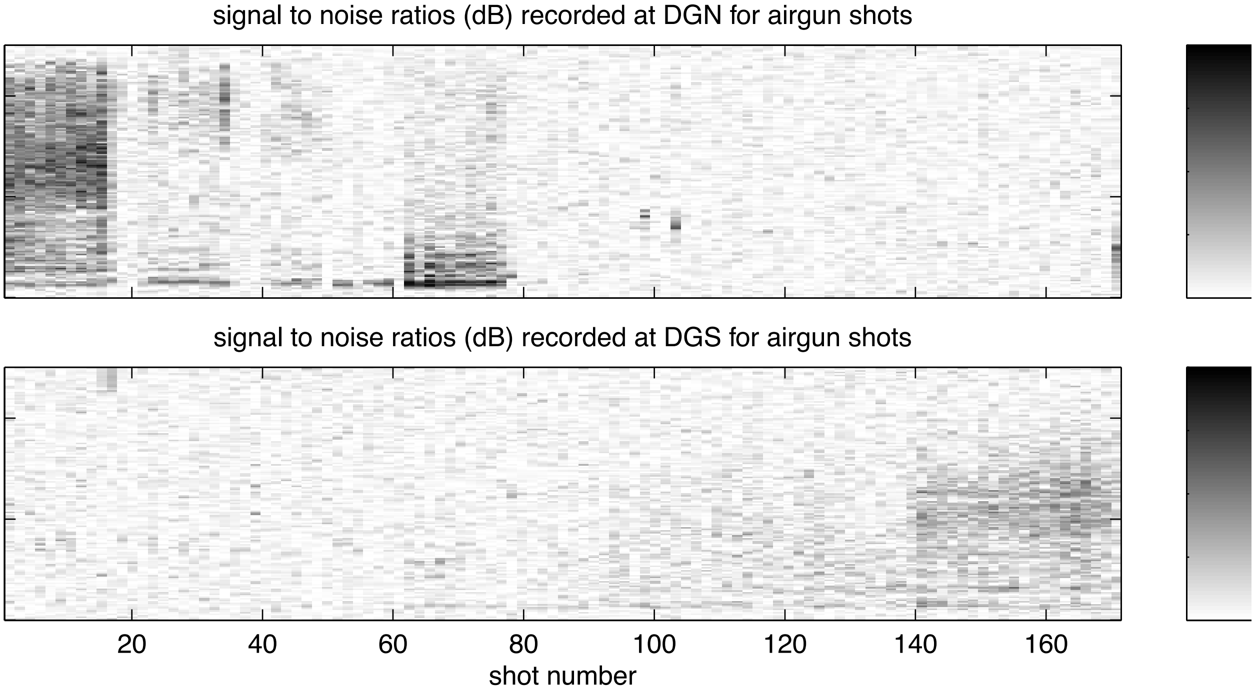


Figure 4. The S/N of the recorded waveforms are displayed in a shaded grey scale as a function of shot number and frequency. Note the recordings were at Diego Garcia north (top) and Diego Garcia south (bottom).

Bathymetry in the source region also affects the observed S/N. Waveforms were detected only when the airgun was shot over ridges, consistent with expectations. Shots 1-16 were located over shallow, sloping seafloor near the Mascarene Plateau just south of the Seychelles. Shots 62-78 were located over the Mid-Indian Ridge. Finally shots 141-178, detected at both DGS and Cape Leeuwin, were near the Ninety East Ridge. Modeling results indicate that energy from these shots couples to the SOFAR channel by downward propagation. However, several other sites were also located in shallow water, but coupled poorly to the SOFAR channel. Modeling is continuing to determine why.

Imploding Spheres: The imploding glass sphere tests showed that a single-glass-sphere system could be detected at unblocked ranges of at least 1200 km. The single-sphere spectra are shown in Figure 5 for three implosions conducted south of Diego Garcia and recorded at the north Diego Garcia station (left panel) and at the south station (center and right panel). The signals were not observable in the time records unless high pass filtered. We determined a good corner for the high pass to be about 40 Hz. The S/N difference as a function of frequency clearly demonstrates that the imploding sphere will be limited as a calibration source to frequencies above about 40 Hz.

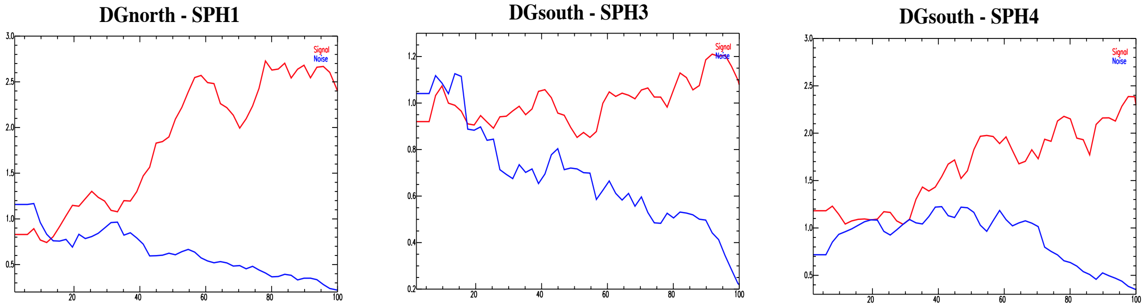
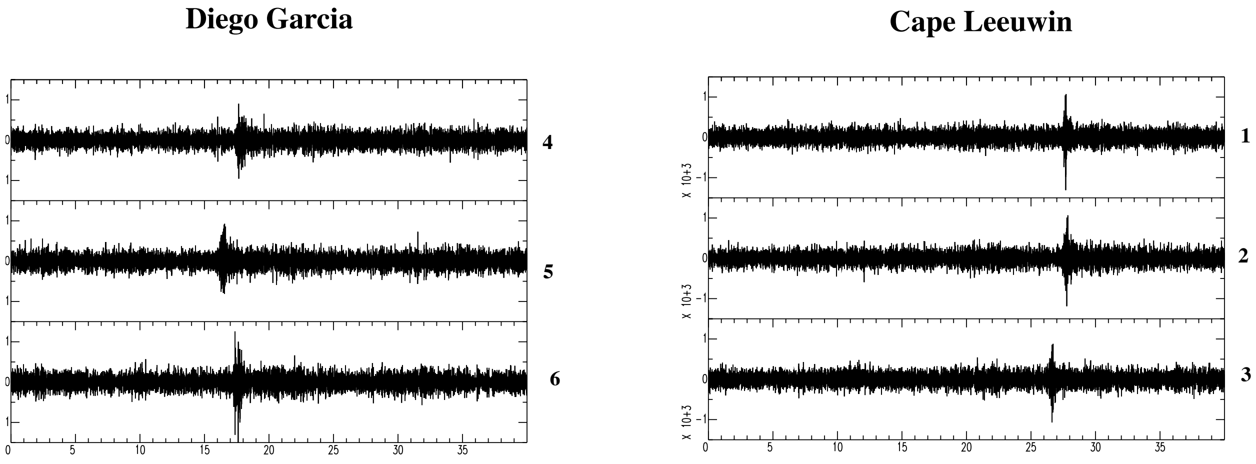


Figure 5. Spectra of the signal and pre-event noise levels for three single-sphere implosions as recorded at the Diego Garcia hydroacoustic monitoring stations. The horizontal scale is frequency in Hz. The vertical scale is normalized to 20-Hz noise levels in each case. The red curves are signal spectra, the blue are pre-event noise. A smoothed average of the three hydrophones at each station is shown.

The 5-sphere implosions were both conducted along the western Australia continental margin with ranges to Diego Garcia of 4168 km and 4397 km and ranges to Cape Leeuwin of 1960 km and 1465 km. The time waveform records are shown in Figure 6. The horizontal scale is in seconds with different time window lengths for the top panels compared to the bottom ones. The waveforms were 4-pole high passed at 40 Hz. Clearly, we are able to record a signal at both stations and hence have demonstrated the possibility of ocean basin scale calibration using the 5-sphere system. As with the single-sphere system, frequency content of the propagating signal is limited to 40 Hz and above. It is clear from the S/N of the recordings that the source strength is woefully inadequate for producing reflections off continental margins and islands that would be detectable. The relatively small amount of dispersion in the signal, after propagation over 4000-km ranges, indicated the implosion sources may be a good source for acoustic travel-time studies.

Imploding Cylinders: The cylindrical imploder (Sauter, 1996) was tested at six locations in the Indian Ocean. Although the imploding volume and test depth were similar, the imploding spheres had a peak pressure 20 times larger than the cylindrical imploder. This is due to the optimum convergent geometry of a sphere that gives rise to a larger shock wave. Because of the significantly lower peak pressures, the cylindrical imploder signals were not observed at the Diego Garcia and Cape Leeuwin stations.

5-Sphere Shot SPH5



5-Sphere Shot SPH6

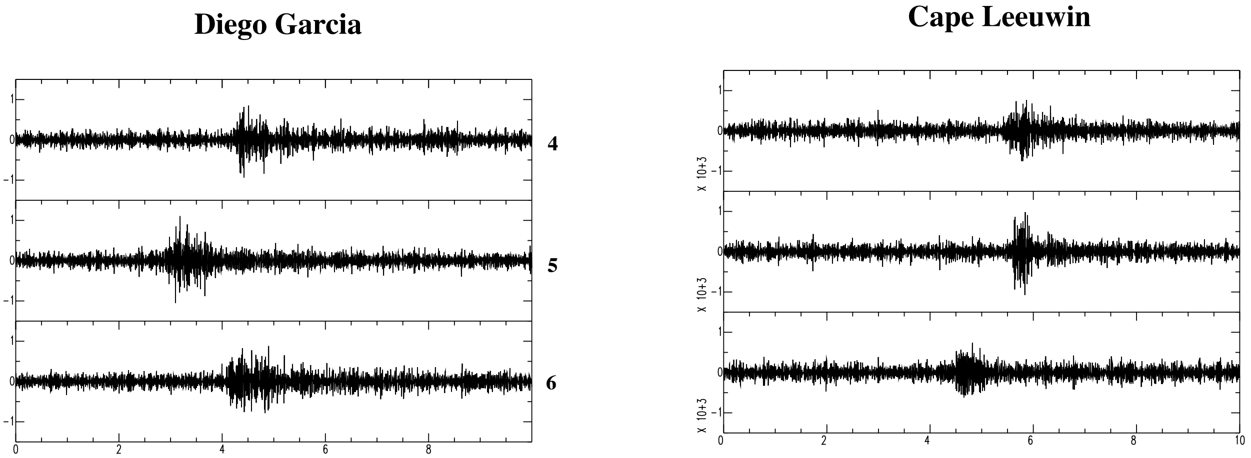


Figure 6. Recordings of the 5-sphere glass sphere implosions are shown with high-pass filtering at 40 Hz. The top two panels show the recording from shot SPH5 at both the Diego Garcia and Cape Leeuwin stations. The bottom panels shows the recordings for shot SPH6.

CONCLUSIONS AND RECOMMENDATIONS

The challenge of providing accurate assessments of acoustic signal blockage in the world's oceans is a large one. Purely model-based approaches fail because of inadequate bathymetric resolution in current databases and simplifying assumptions that make the calculations tractable. Establishing a database of ground-truth events is a strategy that is proving effective in regional travel-time calibration for seismic monitoring. Such an approach holds promise for acoustic signal blockage as well but has distinctly different technical issues that must be resolved. Unlike the solid earth, the acoustic medium is changing on a seasonal basis and hence a particular source-receiver path that is blocked in the summer could be open in the winter. Another issue is low-frequency (1- to 15-Hz) blockage vs. high-frequency blockage (15 to 100 Hz). Most earthquake sources are low frequency and hence can not be used to predict high-frequency blockage. Man-made sources can provide the high-frequency ground truth, and we are beginning to understand the utility of some types of man-made sources in providing ground truth for acoustic blockage prediction.

An Indian Ocean cruise conducted in October 2001 tested implosion and airgun sources at source-receiver distances up to 4400 km. The results show that the glass sphere implosion source has utility at long ranges but only in the frequency band of 40-100 Hz. The airgun sources, unfortunately, are not consistently useful because coupling into the SOFAR channel -- hence long-range propagation -- is controlled by bottom scattering, which is highly variable. A follow-on cruise scheduled for May 2003 in the Indian Ocean will test explosives, an ATOC-type fixed-frequency source, and glass sphere implosions. The results of this cruise should complete the ground work needed before planning a systematic man-made source calibration study of an ocean basin.

We have alluded to the importance of reflected acoustic phases for increasing monitoring capability of hydroacoustic networks without any hardware changes (see Pulli, 2000). The practical application of this will require ground-truth calibration of all the major reflectors in an ocean basin. To first order, we believe that earthquake sources will be the best way to accomplish this because the acoustic energy is great enough to generate reflected phases with adequate S/N at the receiver. It will be necessary to understand how the reflected phases are altered at higher frequency. For this, a man-made source will probably be used though we cannot say at this stage if anything other than a large explosion will be capable of generating the acoustic energy needed to provide adequate S/N on the reflected phases.

ACKNOWLEDGEMENTS

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