

**CALIBRATION OF HYDROPHONE STATIONS:
LESSONS LEARNED FROM THE ASCENSION ISLAND EXPERIMENT**

Philip E. Harben and Arthur J. Rodgers
Lawrence Livermore National Laboratory

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ABSTRACT

Calibration of hydroacoustic stations for nuclear explosion monitoring is important for increasing monitoring capability and confidence from newly installed stations and from existing stations. Calibration of hydroacoustic stations is herein defined as the near-field precision location of the hydrophones and determination of the amplitude response; and the regional-scale calibration of acoustic travel times, bathymetric shadowing, diffraction, and reflection as recorded at a particular station. An important type of calibration not considered here is ocean-basin-scale calibration of a hydroacoustic monitoring system.

To understand how to best conduct hydroacoustic station calibrations, an experiment was conducted in May 1999 at Ascension Island in the South Atlantic Ocean. The experiment made use of a British oceanographic research vessel towing an airgun array and collected data over three Missile Impact Location System (MILS) hydrophones that were in use by the National Data Center (NDC) and the prototype International Data Centre (pIDC). From the towed airgun data, we were able to determine the location for each of the three hydrophones to accuracy better than 100 meters in latitude, longitude, and depth. The agreement with the nominal locations was excellent in depth and to within 1 kilometer in latitude and longitude. The depths determined for the hydrophones and the ocean bottom depths determined from the ship's sonar system force the conclusion that all three hydrophones are located at or near the ocean bottom. Amplitude frequency response of the hydrophones was also calibrated using a calibrated, temporarily deployed hydrophone to determine the airgun source function. With the source function known, the amplitude and phase response of the hydrophones could be deconvolved from the recorded waveforms provided a "pure" source waveform arrival is identified on the recording. Unfortunately, since the hydrophones are located near the ocean bottom, the recording is contaminated by reflections and scattered energy, making a reliable deconvolution impossible. Instead, peak-to-peak amplitudes were used at the dominant source energy to determine clip levels and calibration factors (in pascals at 10 Hz) for each of the three hydrophones. Consistency was confirmed using background hydroacoustic noise.

Imploding sphere sources were tested as a potential method to couple hydroacoustic energy directly into the Sound Fixing and Ranging (SOFAR) channel (at a nominal depth of 700 meters) without the use of explosives. Tests near Ascension Island and off the Pacific coast of California have demonstrated that imploding spheres can be made to fail at prescribed depths and that the signals are similar in amplitude and frequency content to about 1 lb. of high explosive. Although the source has promise as an alternative to small explosions, like explosives, most of the acoustic energy is at frequencies above that of the hydroacoustic monitoring band for nuclear explosions (1–50 Hz).

The use of towed airguns for the near-field precision location and amplitude calibration of hydrophones is ideal. The precision of the source location and timing, the ease of obtaining a planned source shot geometry and numerous shots, and the relatively low-frequency content of the source (i.e., in the CTBT monitoring band) cannot be equaled with air-dropped explosives or most other methods. If the hydrophones are located on the ocean bottom, in situ calibration is very difficult, ideally requiring a co-located, calibrated hydrophone at each hydrophone needing calibration. This will not be necessary with the new floated hydrophone stations since a "pure" recording of the source will be possible. Imploding spheres and small explosive sources in the Sound Fixing and Ranging (SOFAR) channel need further evaluation as regional calibration sources due to the relatively high-frequency content of the source.

Key Words: T-phase, hydroacoustic

OBJECTIVE

Hydroacoustic monitoring for the Comprehensive Nuclear-Test-Ban Treaty (CTBT) has made use of some existing hydroacoustic stations not necessarily intended to be used for the purpose of CTBT monitoring. Some of these systems are very old with poor knowledge of the sensor calibrations and location in the ocean. New hydroacoustic stations, such as Diego Garcia, would benefit from an in-field experimental calibration. The calibrations of T-phase stations -- seismic stations on an island that conduct hydroacoustic monitoring for the CTBT through T-phase signals -- are also poorly understood, making it difficult to utilize such stations effectively in a network of monitoring stations. Finally, although many recognize the possible benefits of joint analysis of different monitoring technologies such as seismic, hydroacoustic, and infrasound, little effort has been expended on this topic, in part because there is not much data of this type to analyze and in part because it is not clear exactly how to analyze it.

The Ascension Island Experiment, conducted in May 1999, was an attempt to gather data that could be used to understand all of these technical issues. The experiment would specifically locate and calibrate the CTBT hydroacoustic monitoring station at Ascension Island, help determine how to calibrate T-phase stations, and would leave behind a continuous monitoring system consisting of nearly co-located seismic, hydroacoustic, and infrasound stations. It represented an experiment of opportunity through collaboration and cost sharing. Participant institutions included Lawrence Livermore National Laboratory, Cambridge University, Naval Research Laboratory, Scripps Institute of Oceanography, Los Alamos National Laboratory, the Provisional Secretariat, and the Center for Monitoring Research. This paper focuses on the most important objective of the Ascension Island Experiment; hydroacoustic station calibration. We present the analysis of the Ascension Island data to determine precision in-situ hydrophone locations, to calibrate a hydrophone monitoring system response using an airgun source, and the use of a safe deep water hydroacoustic source based on the implosion of a glass sphere for future long-range calibrations.

RESEARCH ACCOMPLISHED

The J.C. Ross, an icebreaker class oceanographic research ship belonging to the British Antarctic Survey, was hired for 4 days of airgun shooting around the waters of Ascension Island (Minshull, 1999). The ship was equipped with an 11-airgun array with a total shooting volume of over 6000 cubic inches. The track of the ship during airgun shooting is shown in Figure 1 with blowups in the immediate vicinity of the nominal locations of the Ascension hydrophones. During most of the shooting near the hydrophones, a single 1000 cubic inch airgun was used. The same airgun was fired over a temporary, calibrated hydrophone, providing the source characterization required for determining the calibration factors for the Ascension hydrophones. In addition, imploding spheres were tested during this cruise but the results presented here are for a subsequent test off the coast of California.

The ship track was determined by an on-board differential Global Positioning System (GPS) that archives time and position to 1 millisecond and 1 meter accuracy, respectively. For the analysis that follows, the ship track file was corrected to account for the difference in the position of the GPS ship antenna with respect to the towed airgun. The airgun position accuracy is estimated at 10 meters. Airgun depth was also corrected. The airgun depth is nominally 5 meters when the single gun was fired around ASC26 and 20 meters depth at the other hydrophones, when the full airgun array was deployed. The depth position accuracy is estimated to be 5 meters.

Experimental Determination of Hydrophone Locations:

In all, 35 airgun shots were used to determine a new location for ASC26. The direct arrival times were picked for each of the 35 shots and subtracted from the known shot zero-time to get a direct path traveltime from the airgun to the hydrophone for each shot. The corresponding travel times were compared with that determined by a ray tracing code that uses the nominal sound speed profile in the region and season (Levitus et al, 1994) at 1m-depth increments. The ray tracing code determines means and root-mean-square (RMS) residuals from all the shot locations for a specific trial hydrophone location in a 3-D grid. The procedure is applied to every trial location in the grid with increments of 55 meters in latitude and longitude and 3 meters in depth. A grid search routine then looks for the trial location in the 3-D grid with a minimum RMS value. The latitude and longitude with the minimum RMS value is taken as the location of the hydrophone. The depth of the hydrophone is determined by examining the means at each depth with the same latitude and longitude corresponding to the minimum RMS value. The depth closest to having a zero-mean

is taken as the best depth.

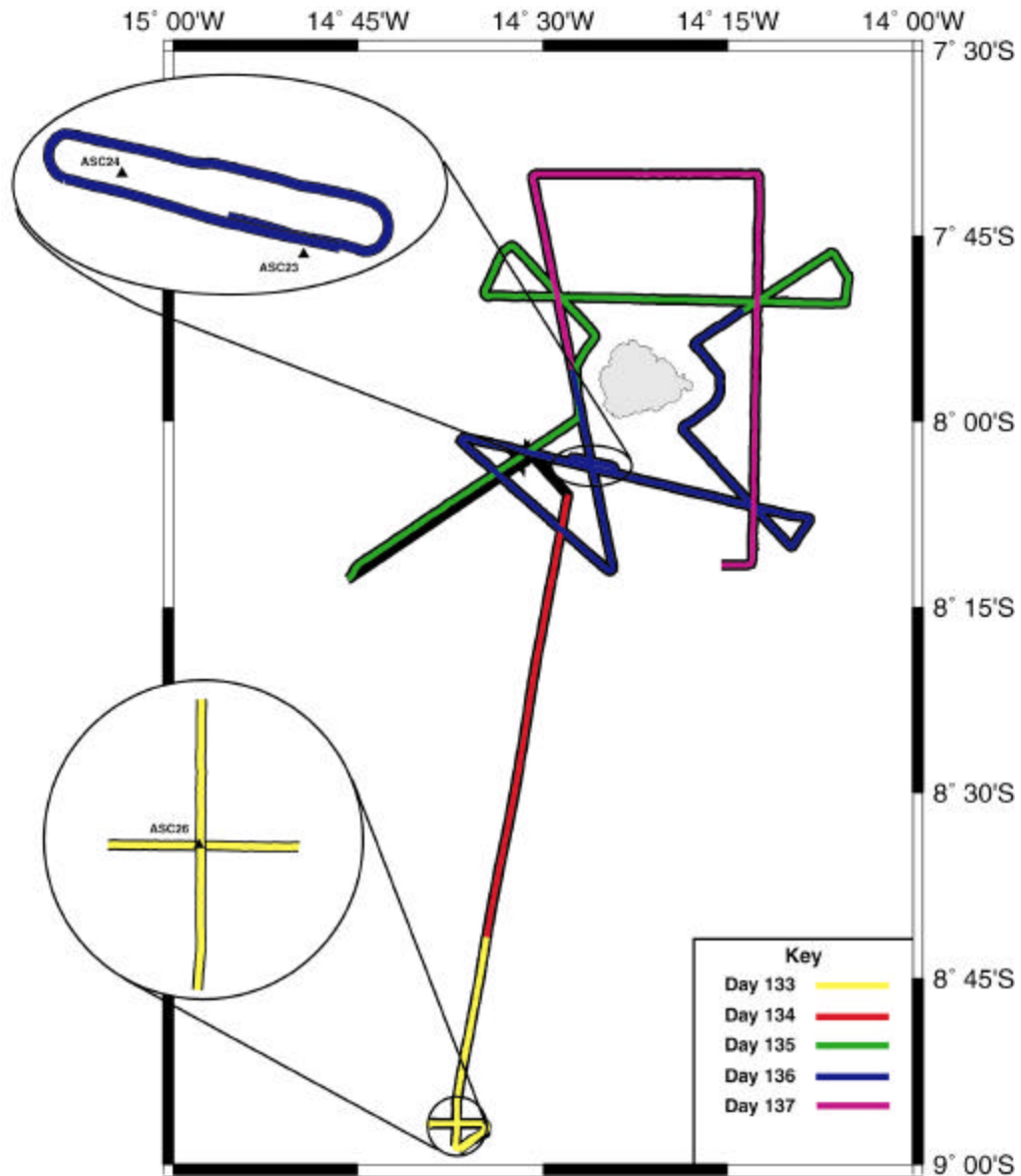


Figure 1. The J.C. Ross ship track during airgun shooting in the waters around Ascension Island. The blow-ups show the track in the immediate vicinity of the three hydrophones and plots their nominal location.

The results for ASC26 are summarized in Figure 2 by showing the individual airgun shots, old and new locations for the hydrophone, bathymetry data determined by the J.C. Ross along the ship track, and the raw airgun waveforms recorded by ASC26 and aligned with the ship position for that airgun shot. The raw waveform data clearly indicates a hydrophone location consistent with that determined by the location analysis procedure. Furthermore, the bathymetry values determined by the J.C. Ross are consistent with the 1.66-km depth determined for the hydrophone from the airgun data provided the hydrophone is located on or near the ocean bottom. The original 1957 installation report (Western Electric, 1961) gives the depth of ASC26 as 1.66 km with no mention of a floated hydrophone system, consistent with the airgun data and J.C. Ross bathymetry.

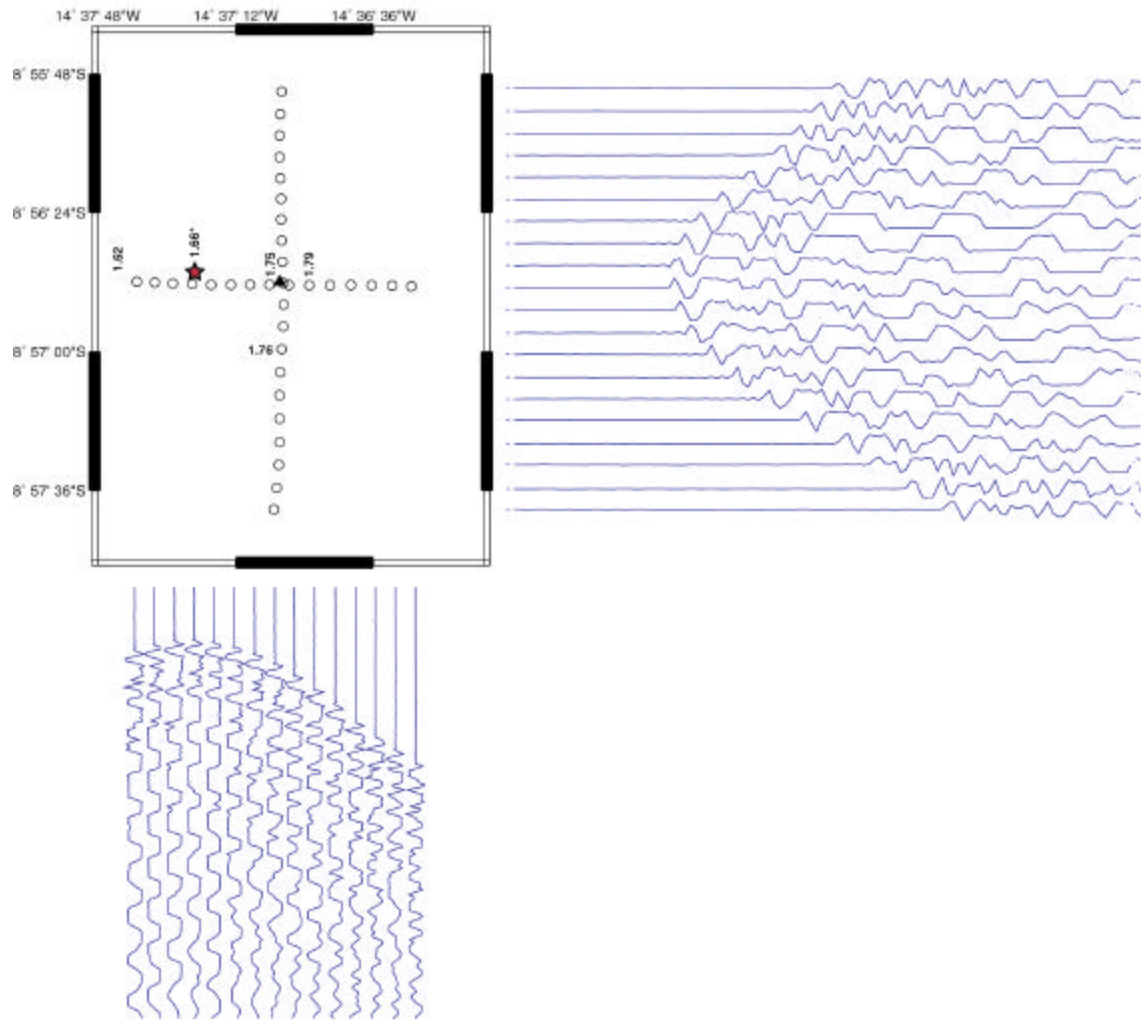


Figure 2. The old (black triangle) and new (red star) location for ASC26. The open circles are the locations of each airgun shot. The numbers associated with some circles are the ocean bottom depths in kilometers as determined by ship sonar. The 1.66-km depth is associated with the new location. The waveforms aligned with each shotpoint are the raw airgun signals recorded by ASC26 for that shot, beginning at shot time. The raw data clearly suggests the new location.

The racetrack pattern around ASC23 and ASC24 resulted in a large number of airgun shots in the vicinity of both hydrophones. Although all the data was initially used in the location analyses, an improvement in the mean and RMS fits was observed when direct traveltime paths greater than 1 second were omitted from the analyses. Consequently, the locations for ASC23 and ASC24 were conducted with all airgun shots that had less than a 1 second traveltime (e.g. were less than 1.5 kilometers from the hydrophone). The reasons for the higher RMS values using all the airgun data could be due to errors introduced by complications in the direct arrival by shadowing from bathymetric features and errors in the ray tracing routine and the sound speed profile, all of which are compounded by lower angle ray paths. Using the same procedure as outlined for ASC26, the ASC23 and ASC24 locations were determined using 46 airgun shots and 35 airgun shots respectively (Figure omitted due to paper length limitations). The bathymetry in the region shows considerable variability but is consistent with hydrophones that are near to the ocean floor. Traveltimes of reflected phases from ship locations nearest the hydrophones also point to a hydrophone depth that is very near the ocean bottom.

The three Ascension Island hydrophones presently in use by the NDC and pIDC have been located to an accuracy of at least 100 meters in latitude, longitude, and depth (Harben et al, 1999). It is clear from the hydrophone depths determined by the airgun shootings, the bathymetry determined by the J.C. Ross, and the original 1957 installation document that the hydrophones are located on or near the ocean bottom. The new locations are all less than a kilometer from the old locations, indicating that the old locations were more accurate than expected. Furthermore, the new depths are within 10 meters of the nominal locations.

A towed marine airgun with precision timing and differential GPS logging capability is a good method for determining the position of in-place hydrophones. Other methods to determine hydrophone locations such as air-dropped Signal Underwater Source (SUS) charges would have difficulty matching the precision of an airgun because the inherent SUS location and zero time errors are larger, the pattern of SUS charges is more difficult to control, and the number of charges used has practical and cost-driven limitations. Small implosive sources such as lightbulbs have been used from ships as hydrophone calibration sources and may be useful in location, though precision position determination and ease in deploying a large number of sources needs to be studied. It is not necessary to have as large or as capable a ship as the J.C. Ross to accomplish a location survey using airguns since it only requires a relatively small single airgun with precision timing and location. Such a system could be temporarily mounted on a relatively small ship near the survey location to minimize cost.

Determining Hydrophone Calibrations:

A temporary calibrated hydrophone moored at 925 meters depth was used to record the waveforms from a 1000 cubic inch airgun to determine the airgun source function. By repeated firings, the source function reproducibility was tested and shown to be highly repeatable. The source function for the airgun was determined using the direct phase recordings corrected by the known instrument response. The source was found to have a peak amplitude of 751 kPa at 1 meter, consistent with manufacturer specifications. Because all three Ascension hydrophones are located near the ocean floor, it was not possible to simply deconvolve the projected measured source function from the signals measured at the Ascension hydrophones to determine the hydrophone monitoring system amplitude and phase response. The direct arrival phase at the hydrophones was contaminated by nearly time-coincident bottom reflections and scattering (and to a lesser extent by Stoneley waves). Consequently, a procedure was developed to determine a calibration factor for each hydrophone, which is shown below for ASC26 Harben et al, Feb. 2000).

The recordings of the 1000 cubic inch airgun shots near ASC26 are best viewed in record section as shown in Figure 3. The record section proceeds from the recorded waveform of the airgun shot closest to ASC26 (top at 1.81 km) to the airgun shot farthest away (bottom at 8.63 km). The distances shown are direct acoustic path ranges and record sections plot each shot at an even spacing below the previous shot though the range between shots is not linear (particularly when the airgun is nearest the hydrophone). The record section clearly shows a number of phase arrivals. The Stoneley wave, traveling along the ocean-sediment interface, is ahead of the direct path acoustic wave but is small enough in amplitude that the coda does not significantly contaminate amplitude measurements and arrival picks of the direct hydroacoustic phase. The coda of the direct phase exhibits ringing for the closest airgun shots. The ringing corresponds to a clipped signal. We do not know if the signal clipping and ringing is due to the sensor or to system electronics. The ringing could also be the result of mechanical motion of the hydrophone cable system at high acoustic signal levels. The reflected phases are single (1st) and double (2nd) reflections off the free surface. As the source-receiver range increases, the direct arrival amplitude falls below clipping level and exhibits the peak-to-peak amplitude fall-off with distance expected by predictions based on directivity effects due to reflection off the free surface and geometrical spreading. By projecting the known source signal level to the range that clipping ceased, a clip level in Pascals for each of the hydrophone systems as well as a maximum signal level for linear system response could be determined.

The procedure for determining a calibration factor starts by determining an analysis window of source-receiver ranges. The ranges are chosen so that the minimum range is beyond the ranges that exhibit clipping (4.4 km for ASC26) and the maximum range is before the signal-to-noise ratio becomes too low for accurate peak amplitude measurements (7.5 km for ASC26). For each airgun shot record in the range analysis window, the peak to peak direct arrival amplitude is measured in raw counts. By projecting the source function to the range and conditions (i.e. accounting for directivity and spreading due to geometry but not attenuation which is negligible at these frequencies and ranges) of each airgun shot, the expected source level in Pascals is determined for that shot geometry. The

calibration factor (in counts / Pascal) is then determined by dividing the measured peak-to-peak amplitude by the projected source level for each shot and averaging over all shots in the range analysis window. It should be noted that the bulk of the airgun acoustic energy is centered at 10 Hz. All calibration factors and corrections were therefore conducted at 10 Hz and do not necessarily apply to acoustic frequencies more than an octave above or below 10 Hz.

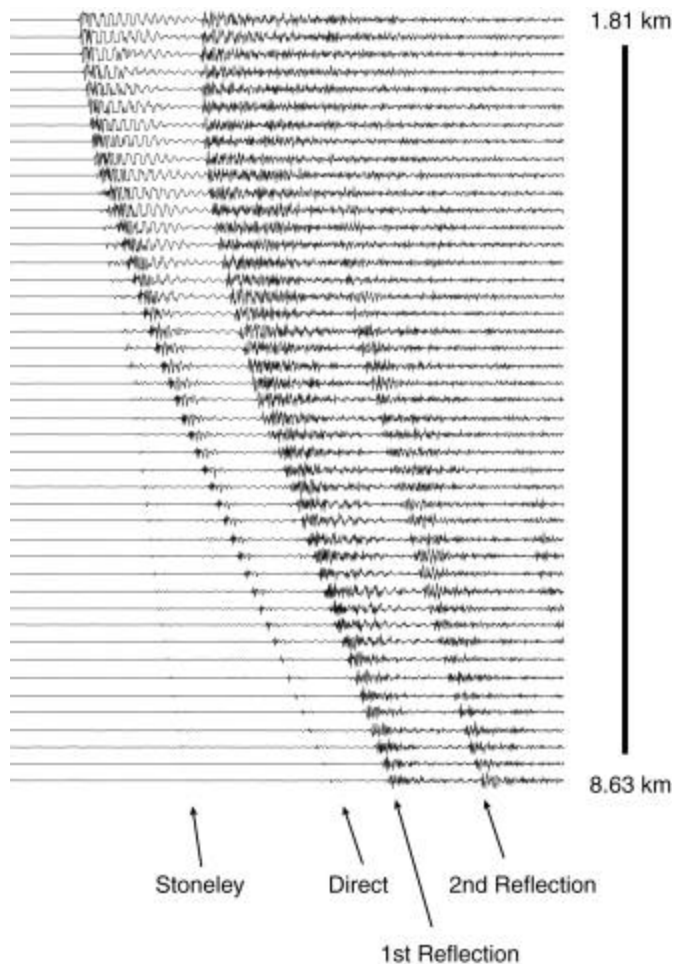


Figure 3. Record section for ASC26 with airgun shots nominally 150 meters apart. As the ship sails away from the hydrophone we see normal move-out and the development of distinct phases as labeled.

The results for the clip levels, the maximum levels with linear response, and the 10-Hz calibration factors for the three Ascension hydrophones are shown in the table below. The calibration factors were applied to a 5-minute noise period measured at each station and found to be self-consistent.

Hydrophone Name	Counts per Pascal (Ct/Pa)	Clip Level (Pa)	Max. Linear Level (Pa)
ASC26	3.5×10^5	29	20
ASC24	1.7×10^4	120	88
ASC23	8.8×10^4	102	68

A highly repeatable source like an airgun should be able to provide for effective amplitude and phase response calibration provided the hydrophone used to measure the source function and the hydrophone to be calibrated are able to measure a portion of the direct phase before scattered and reflected wave phases arrive. Another calibration strategy is to locate a calibrated hydrophone as near as possible to the hydrophone with unknown instrument

response. In this case, ambient background noise measurements may be sufficient to deconvolve an instrument response using the calibrated hydrophone as the “source function”. In the case of ocean bottom hydrophones, this is probably the only means to obtain a full amplitude and phase response curve. Newly installed floated hydrophone stations, on the other hand, will probably be easy to calibrate using a direct deconvolution of the projected source function.

Imploding Sphere Sources for Long-Range Calibration:

One way to accomplish long-range calibrations is to detonate a large number of small (1-2 lbs of high explosive) charges within the SOFAR axis on various tracks in an ocean basin, recording the signals at all operational hydroacoustic stations. Although pressure-detonated explosives are a simple, reliable, and flexible method to generate an impulsive hydroacoustic source at a desired depth, safety procedures, specialized training, and local regulations preclude their use on most ships. This leaves few alternatives as SOFAR axis sources, since airgun and most other seismic marine sources are designed for use only at shallow depths. Imploding spheres have a relatively long history of specialized use and are a potential acoustic source at mid-ocean depths and below; but they have not been deemed reliable because they fail well below or above the desired depth or do not fail catastrophically at all. If imploding spheres can be made reliable and can deliver an adequate signal for long range calibration, the method has the distinct advantage of having no stored energy at the surface and therefore no shipboard safety concerns and no special shipboard equipment requirements for deployment. This advantage allows for the possibility of deploying the spheres from a wide variety of ships on cruises for other purposes, thereby minimizing the costs associated with ground truth data collection. The need for an inexpensive source at the SOFAR axis that does not have the hazard and safety procedure problems of explosives was recognized in the recent International Workshop on Hydroacoustic Monitoring for the CTBT that met in Tahiti late September, 1999 (CTBTO/PTS/DASE, 1999). The workshop findings identify acoustic source development as a technical issue and advocate an approach to the problem that addresses the safety issue and the need for low-cost expendable sources.

An imploding source exploits the pressure difference between an enclosed volume of gas at nominal atmospheric pressure and the external water pressure at the implosion depth. A sudden catastrophic failure of the containing vessel leaves the relatively low-pressure gas bubble exposed to relatively high-pressure water and a rapid implosion ensues. The implosion momentum collapses the bubble radius to less than that required for an equilibrium pressure balance. At the instant of minimum bubble radius, the bubble begins expanding and radiates a positive acoustic pressure spike. This oscillation can continue for a few cycles, each with successively reduced pressure spikes as energy is dissipated and the bubble approaches a static equilibrium pressure. The process is similar to the bubble pulses seen from subsurface explosions, the gas globe from the explosion oscillating about the equilibrium pressure. One distinct difference is that in the case of underwater explosions there is an initial shock wave caused by ignition of the explosive and creation of the expanding gas globe consisting of explosion gas products. There is no such analog in an implosion. Another important difference is the relatively cold low-pressure gas inside the sphere compared to the high temperature dense explosive gas products in the gas globe. The bubble collapse details of the two cases cannot be directly compared.

If a glass sphere is of sufficient volume to produce the desired source signal level and has sufficient wall thickness to survive the water pressures in the operational depth range, the sphere failure must be initiated by some controlled method at a predetermined depth. Such a mechanical implosion initiation device was designed to crack the sphere at a preset depth, herein referred to as the “sphereracker” (Boro and Harben, 1999). The sphereracker was designed to be rugged enough to be reusable, heavy enough to sink the whole assembly loaded with the sphere, and without stored energy at the surface. In addition, use of inexpensive materials from standard stock was also a goal so that the sphereracker cost is low enough to allow for a use-once option in deployment. The device is shown in Figure 4 and consists of two orthogonal cut-out plates that hold the sphere and a cylinder-piston-ram assembly that punches a hole in the sphere. A rupture disk attached to one end of the cylinder assembly is calibrated to fail within 5% of the failure pressure, 1000 psi in our tests. Failure of the rupture disk results in an inrush of high-pressure water into the air-filled piston chamber, driving the piston -- and attached ram -- towards the glass sphere. The Custom Glass Shop, a Division of Kontes Glass Company (CGS) made the spheres. The spheres are a special order modification of a standard 22-liter laboratory boiling flask. The wall thickness is nominally 0.64 cm (0.25 inches) but, since each sphere is hand blown, the wall thickness can vary considerably. Our concern with these spheres was their survival at nominal SOFAR axis depths. Initial tests were conducted without the sphereracker to assure that the spheres would survive to SOFAR depths.



Figure 4. The spherecracker is shown on the right in the lowering orientation. The glass sphere is shown on the left atop a laboratory beaker.

An opportunity to conduct a field test with a CGS sphere and spherecracker came in February 2000. The spherecracker was loaded aboard the Research Vessel (R.V.) Sproul and tested west of San Diego CA at water depths around 1200 meters. The spherecracker was loaded with a 22-liter CGS glass sphere and was lowered until a 1000 psi rupture disk failed. After initiating a successful implosion, the spherecracker was recovered undamaged. By reloading the device with a new pressure disk and glass sphere, it could be used repeatedly. The impulsive hydroacoustic signal recorded from the implosion allowed accurate determinations of hydrophone depth, implosion depth and water depth from the surface reflected, bottom reflected, and 2nd bottom reflected phases, respectively (Harben et al, May 2000). The implosion occurred at 685 meters depth. The implosion signal was felt on the ship and recorded by a calibrated hydrophone suspended 13 meters deep. The recorded signal shown in Figure 5 was of short duration (less than 5 msec) and with a small bubble pulse about 2 msec after the main collapse. The event starts with a rarefaction as the sphere shatters and collapses. The large compressional pressure spike following the rarefaction occurs when the collapse reaches a minimum volume and reverses (begins expanding). The waveform was projected back to 1 meter by multiplying the hydrophone output by the distance of the hydrophone from the implosion, 672 meters. The peak pressure from the implosion is slightly larger than that from 1 lb of TNT at the depth of the test (Urlick, 1983). The source does not show any appreciable acoustic energy above background levels for frequencies below about 50 Hz. Above 50 Hz the source amplitude rises to a broad maximum at frequencies between 200 and 800 Hz. There is a relatively shallow high frequency roll-off of the source energy between 1 kHz and 10 kHz whereas the noise rolls off more steeply in this band. The consequence is that the signal-to-noise ratio is highest at about 10 kHz.

Long-range propagation of signals from small (1-2 lb) explosions within the SOFAR has been amply demonstrated (Harben et al, May 2000). Since the imploding sphere source within the SOFAR has a peak pressure amplitude similar to that of a small (1 lb) explosion and similar frequency content, it is reasonable to assume that the imploding sphere source signal will propagate for long distances within the SOFAR. The pressure amplitude spectra of the imploding sphere source shows that the bulk of the acoustic energy is well above the frequency band that is used for nuclear explosion monitoring (nominally 1-80 Hz). This means that travel times, shadowing, diffraction, reflections, etc. would be calibrated at frequencies starting at the high end of the nuclear explosion monitoring band and extending beyond it. For some parameters (e.g. travel time) this may be acceptable but for others (e.g.

shadowing) it may lead to inaccuracies. Potential methods do exist to excite lower frequencies from the imploding sphere. By increasing the volume of the sphere, imploding the sphere at a shallower depth, or through the use of multiple spheres simultaneously imploded, lower frequency energy can be excited.

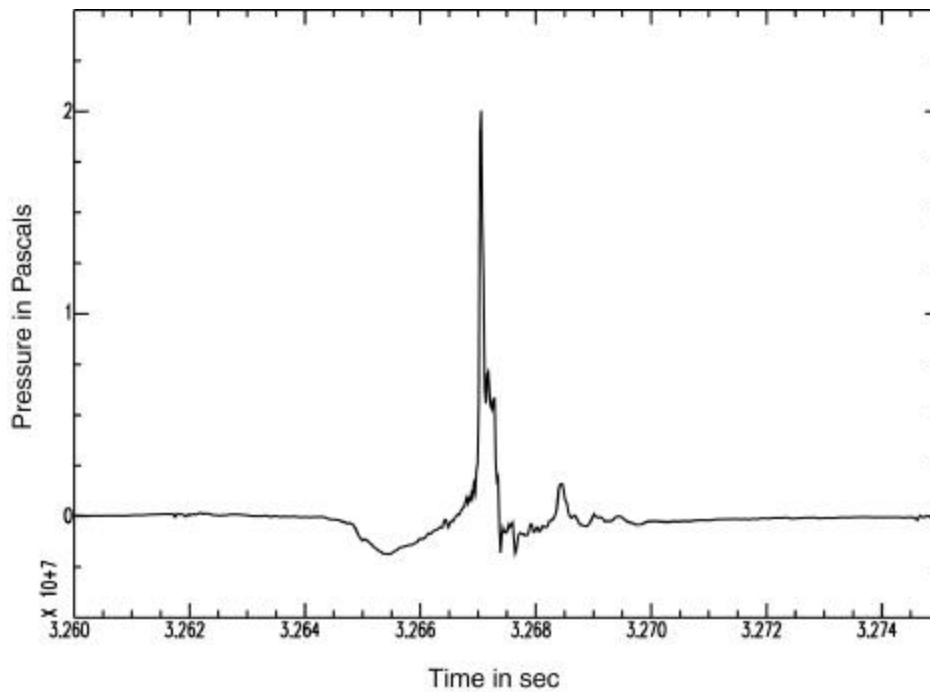


Figure 5. The calibrated pressure-time history of the implosion as recorded by a shallow ship-suspended hydrophone and projected back to 1 meter.

CONCLUSIONS AND RECOMMENDATIONS

It is clear that a towed airgun system with good timing and location control can accurately determine hydrophone location and calibration, provided the hydrophone is floated a sufficient distance from the ocean bottom so that a “pure” recording of the direct phase can be recorded before reflected phases arrive. Such calibrations are crucial in verifying location (and current drift limits) and in establishing the full in-field system response in physical units of pressure. Such calibrations should be conducted at every hydroacoustic station in the monitoring network.

Long-range calibrations that attempt to determine hydroacoustic features such as travel times, shadowing, reflections, etc. in the region of a station, or even for a whole ocean basin, have not yet been attempted. The Ascension experiment began that effort by developing an imploding sphere source and by evaluating airguns as longer-range SOFAR guided sources (Hanson and Harben, 2000). The next step is to actually conduct a regional scale calibration experiment using imploding spheres and an airgun source, comparing the two and determining how to conduct such calibrations on a routine basis.

The Diego Garcia hydroacoustic station has recently been installed and is an ideal candidate for the next in-field calibration site. From the experience gained at Ascension Island, the local calibration of Diego Garcia would best be accomplished using a towed airgun system. This would provide the most accurate measurements of hydrophone locations and of the system amplitude and phase response. Diego Garcia would also be a prime site for further experimentation with imploding spheres and airguns to calibrate longer range travel times and determine bathymetric and island shadowing at a station where little is known at present. Future calibrations are in order for Crozet Island and other upgraded and new hydroacoustic stations as they come on-line.

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