Broadband calibration of R/V Ewing seismic sources

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[1] The effects of anthropogenic sound sources on marine mammals are of increasing interest and controversy [e.g., Malakoff, 2001]. To understand and mitigate better the possible impacts of specific sound sources, well-calibrated broadband measurements of acoustic received levels must be made in a variety of environments. In late spring 2003 an acoustic calibration study was conducted in the northern Gulf of Mexico to obtain broad frequency band measurements of seismic sources used by the R/V Maurice Ewing. Received levels in deep water were lower than anticipated based on modeling, and in shallow water they were higher. For the marine mammals of greatest concern (beaked whales) the 1–20 kHz frequency range is considered particularly significant [National Oceanic Atmospheric Administration and U. S. Navy, 2001; Frantzis et al., 2002]. 1/3-octave measurements show received levels at 1 kHz are ∼20–33 dB (re: 1 μPa) lower than peak levels at 5–100 Hz, and decrease an additional ∼20–33 dB in the 10–20 kHz range. INDEX TERMS: 3025 Marine Geology and Geophysics: Marine seismics (0935); 3094 Marine Geology and Geophysics: Instruments and techniques; 6615 Public Issues: Legislation and regulation; 6620 Public Issues: Science policy; 4259 Oceanography: General: Ocean acoustics. Citation: Tolstoy, M., J. B. Diebold, S. C. Webb, D. R. Bohnenstiehl, E. Chapp, R. C. Holmes, and M. Rawson (2004), Broadband calibration of R/V Ewing seismic sources, Geophys. Res. Lett., 31, L14310, doi:10.1029/2004GL020234.

1. Introduction

[2] As anthropogenic activity in the oceans increases, the impact of these activities, including shipping, naval operations and seismic exploration, on the background noise levels of the oceans is a source of growing concern [National Research Council of the National Academies, 2003]. In addition, concerns have been raised about specific sound sources, in particular navy mid-range active sonar systems, having potentially physically damaging consequences on marine mammals [e.g., Balcomb and Claridge, 2001; Cudahy and Ellison, 2002], and navy low-frequency sonar impacting behavior [e.g., Miller et al., 2000]. The response of different species to different acoustic sources also is poorly understood, though a number of studies have been done [e.g., Richardson et al., 1995; McCauley et al., 2000]. For sperm whales exposed to seismic surveys, some studies suggest indifference to low levels [e.g., Madsen et al., 2002] or relatively short-distance aversion [Stone, 2003], whereas others suggest changes in calling patterns or behavior at long distances [e.g., Gordon et al., 2004].

[3] Seismic research, including oil exploration and geophysical studies, has been ongoing for decades. Over 90 large seismic vessels are currently in operational condition [Schmidt, 2004], with perhaps 15–20 active on any given day. Only one stranding event with a plausible spatial and temporal correlation has been recorded [Malakoff, 2002], and there is no proof that this correlation indicates a causal link. However, unequivocal behavioral and distributional effects have been demonstrated, occasionally at distances of 20 km or more [Richardson et al., 1995, 1999]. Therefore, it is prudent to better quantify the acoustic output of such seismic systems. It is important also that the characteristics of these sources be described at a broad range of frequencies, since different marine mammals are sensitive to different frequencies.

[4] During seismic operations subject to US jurisdiction, increasingly strict guidelines are adhered to for minimizing impacts on marine mammals in accordance with the Marine Mammal Protection Act (MMPA) of 1972. These include careful monitoring for marine mammal activity prior to and during seismic operations, and a gradual ‘ramp-up’ of the size of the operating seismic array over the course of 30–60 minutes. The ramp-up is designed to provide a warning to marine mammals that may not have been detected acoustically or visually, and allow them time to leave the immediate area. When mammals are seen within or near designated safety radii, it is now a common requirement that the airguns be powered down.

[5] Prior to operation an authorization to “harass” marine mammals must be obtained from the National Marine Fisheries Services. This requires a detailed environmental assessment as well as extensive review and a public comment period. Once an authorization has been granted, and the cruise takes place, marine mammal activity in the vicinity of seismic operations is monitored closely. At present, National Marine Fisheries Service defines the radii with received levels of 190 dB and 180 dB re 1 μPa (rms) as safety radii for pinnipeds and cetaceans, respectively. The radii with received levels 170 dB and 160 dB re 1 μPa (rms) are considered to be distances within which some marine mammals are likely to be subject to behavioral disturbance. For seismic experiments conducted by the R/V Maurice Ewing the sizes of these radii previously have been based on modeling but here we present results from the first well-calibrated broadband measurements of the R/V Maurice Ewing’s airgun array.

[6] In this paper, received sound pressure is expressed as the root-mean-square (rms) pressure level measured in μPa (re 1 μPa), which is a measure of the average pressure over the (variable) duration of the pulse. The calculation is done within a window length sufficient to capture the entire pulse (for this study, 0.5 and 1.0 s window lengths were used for
The deep and shallow sites respectively). The rms pressure is the preferred measurement reported in virtually all marine mammal studies. Note dB values reported in water differ significantly from those reported in air due to different reference systems and differing densities and sound speeds between the two mediums.

2. Experiment

[7] The calibration work was conducted aboard the R/V Maurice Ewing in late May and early June of 2003 in the Gulf of Mexico (Figure 1). Calibration measurements were conducted at shallow (~30 m) and deep (~3200 m) water sites. Plans to calibrate the array in slope water sites could not be carried out due to moderate winds, which prevented confident monitoring for marine mammals (specifically beaked-whales) at the necessary ranges. The seismic sources calibrated were a 20-airgun array, which contained subsets closely resembling the 6-, 10-, 12-, and 20-gun arrays to be used during future seismic programs, as well as a 2 GI gun array.

[8] A spar buoy was adapted to include two broadband hydrophones hung beneath the buoy, with a near-real-time telemetry link to the ship. The depths of the hydrophones were adapted by altering the length of cable. At the deep water site, the two hydrophones were deployed with 18 and 500 m of cable. At the shallow water site, both hydrophones were deployed at 18 m depth. The hydrophones were sampled at rates up to 50 kHz, to allow sound levels to be characterized as high as 25 kHz.

[9] The two hydrophones used with the LDEO spar buoy were based on Benthos Company Model AQ-1 hydrophones. The hydrophones were calibrated after the cruise in the U.S. Navy TRANSDEC facility in San Diego. They have a specified acoustic sensitivity of $-202.5 \pm 1$ dB relative to 1 V/µPa with a flat frequency response ($\pm 1.5$ dB) in a frequency band from 1 Hz to 10 kHz. The buoy hydrophones are essentially omni-directional ($\pm 1$ dB) below 5 kHz; however they become more directional, introducing up to a 10 dB uncertainty in the spectra at the highest frequencies. The post-recording processing corrected for all filter and instrument responses to give accurate records of the airgun pressure signal at all relevant frequencies up to 25 kHz.

[10] Airgun arrays are designed to focus energy downward rather than to the sides, and the design of the R/V Maurice Ewing arrays (athwart ship) leads to the highest received levels astern and forward of the ship relative to the port and starboard received levels at equivalent distances. Therefore, while shots were measured from a range of azimuths, only results from in-line shots were used to estimate radii (Table 1 and Figures 2 and 3), as these

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**Figure 1.** The study area for the May–June 2003 acoustic calibration study in the northern Gulf of Mexico, showing ship tracks at the three planned calibration sites. Calibrations were only conducted at the deep and shallow sites due to weather constraints at the slope site.

**Figure 2.** Received levels at deep calibration site for 6, 10, 12 and 20-gun arrays. Received levels are shown for the shallow (18 m) hydrophone (gray squares) and the deep (500 m) hydrophone (black circles). Note there is a paucity of data for the deep hydrophone due to clipping at the close ranges, and instrument related problems at the far ranges. However radii estimates must be based on the deep hydrophone measurements since the shallow hydrophone is subject to Lloyds Mirror effects. Clipped measurements are indicated by open symbols, and provide a lower limit on the possible dB level at that range.

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**Table 1.** Measured Values for 160–190 dB re 1 µPa (RMS) Radii\(^{a,b}\)

<table>
<thead>
<tr>
<th>Site/Array</th>
<th>Measured 190 dB</th>
<th>Measured 180 dB</th>
<th>Measured 170 dB</th>
<th>Measured 160 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep 20</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>~2.5 km</td>
</tr>
<tr>
<td>Deep 12</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>2.5 km</td>
</tr>
<tr>
<td>Deep 10</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>&gt;2 km</td>
</tr>
<tr>
<td>Deep 6</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>~1.5 km</td>
</tr>
<tr>
<td>Shallow 20</td>
<td>NC</td>
<td>~3.5 km</td>
<td>7 km</td>
<td>12 km(^e)</td>
</tr>
<tr>
<td>Shallow 12</td>
<td>NC</td>
<td>~2 km</td>
<td>5.5 km</td>
<td>9 km</td>
</tr>
<tr>
<td>Shallow 10</td>
<td>NC</td>
<td>~2 km</td>
<td>4 km</td>
<td>9 km</td>
</tr>
<tr>
<td>Shallow 6</td>
<td>NC</td>
<td>1.5 km</td>
<td>4 km</td>
<td>7 km</td>
</tr>
<tr>
<td>Shallow 2 GI</td>
<td>NC</td>
<td>NC</td>
<td>&gt;0.5 km</td>
<td>1.5 km</td>
</tr>
</tbody>
</table>

\(^{a}\)Deep site hydrophone may have been as shallow as 330 m, and so larger values may exist at greater depths.

\(^{b}\)NC indicates that results for the dB level were not constrained by the available data, mainly because measurements made close to the array were clipped. The proximity of the closest measurement to the airguns can be determined by looking at Figures 2 and 3.

\(^{c}\)This value may extend beyond 12 km, but no measurements were made beyond 11.7 km where a value of 160 dB was received – see text.
show the highest received levels at any given distance, and therefore represent the most conservative (i.e., precautionary) radii. Using these estimates provides the maximum protection for marine mammals in the area and simplifies the observation procedures by eliminating the need to consider azimuth in the observations.

[11] During operations with the 20-gun array, the number of airguns active varied from 6 to 20. The 20-gun array was discharged every 2 min in the following sequence: 6 guns (two shots), 10 guns ($\times$2), 12 guns ($\times$2) and 20 guns ($\times$2). The 2 GI guns were discharged every 30 s. While towing the arrays, the R/V Maurice Ewing approached the spar buoy from $\sim$10 km away, passed $\sim$100 m to the side of the buoy, and continued until it was $\sim$10 km beyond the buoy.

[12] The deep site calibration, conducted on 30 May 2003, recorded approximately 145 shots from the 20-gun array, equally divided among the four subset arrays with 6, 10, 12 and 20 airguns. The shallow site calibration, conducted on 2 June 2003, recorded a total of 290 shots, using the 20-gun array and its smaller subsets as well as a 2 GI gun array.

3. Results

[13] The records of the airgun pulses when the ship was closest to the buoy are clipped and underestimate the received levels. We examined all records before correcting for the instrument response and have labeled the data points from those records when some clipping occurred. Open symbols on Figures 2 and 3 represent clipped data. Clipping occurs when the signal exceeds the dynamic range of the digitizer, which leads to a “squaring off” of the peaks and troughs in the signal. On a large subset of the clipped records, the data are clipped only on one side (either just the positive or just the negative values) because of a nonzero mean due to pressure variations from buoy heave.

[14] For the deep site, only the 160 dB radii were clearly documented, given the clipping of records at the closest ranges. The 160 dB distances observed via the deep hydrophone suggest that the previously-predicted 160 dB radii tend to overestimate actual 160 dB distances in deep water (see Figure 2 and Table 1 versus Table 2). We can infer from the unclipped data, based on either spherical or cylindrical transmission loss, that the 180 dB radii for all arrays should occur at less than 1 km, and likely significantly less than 1 km. These results will need to be confirmed in future experiments with a larger number of observations at the closer distances.

[15] The shallow hydrophone recordings show significantly lower dB levels than recordings from the deep phone, due to a Lloyds Mirror effect (destructive interference between the direct arrivals and the reflections from the sea surface). This serves as a reminder that marine mammals at shallow depths in deep water areas can be exposed to levels considerably lower than the maximums received at deeper depths. However, this also reminds us that to make accurate estimates of maximum received levels at a given range measurements must be made at several depths. Ideally, future deep water measurements should utilize a vertical hydrophone array to ensure that peak levels at a given range are recorded regardless of depth.

[16] A related caveat for the deep site is that the deep hydrophone was at a maximum depth of 500 m set by the cable length, but may have been shallower due to drift of the buoy in a strong current. Analysis of reflected arrivals indicates it may have been as shallow as 330 m. Modeling of the effect of the free surface reflection suggests the peak signal strength at close ranges may be lower at 330 m than at deeper depths.

[17] For the shallow site, a larger number of measurements were obtained, providing empirical data on the 180, 170 and 160 dB radii for most of the airgun configurations (Figure 3 and Table 1). Due to clipping of close range arrivals, no measurements of the 190 dB radii were made. The 20- and 12-gun 180 dB radii were estimated based on measured levels that were close to 180 dB, but no measurements were made above 180 dB that were not clipped. The 170 dB radii were well documented for all but the 2 GI gun array, and 160 dB radii were documented for all arrays. These measurements

### Table 2. Predicted Values From Ray-Based Modeling for 160–190 dB re 1 $\mu$Pa (RMS) Radii

<table>
<thead>
<tr>
<th>Array</th>
<th>Predicted 190 dB</th>
<th>Predicted 180 dB</th>
<th>Predicted 170 dB</th>
<th>Predicted 160 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 gun</td>
<td>0.400 km</td>
<td>0.95 km</td>
<td>3.42 km</td>
<td>9 km</td>
</tr>
<tr>
<td>12 gun</td>
<td>0.3 km</td>
<td>0.88 km</td>
<td>2.68 km</td>
<td>7.25 km</td>
</tr>
<tr>
<td>10 gun</td>
<td>0.25 km</td>
<td>0.83 km</td>
<td>2.33 km</td>
<td>6.5 km</td>
</tr>
<tr>
<td>6 gun</td>
<td>0.05 km</td>
<td>0.22 km</td>
<td>0.7 km</td>
<td>2.7 km</td>
</tr>
<tr>
<td>2 GI gun</td>
<td>0.015 km</td>
<td>0.08 km</td>
<td>0.155 km</td>
<td>0.52 km</td>
</tr>
</tbody>
</table>

*Note that the same predicted values were used regardless of depth of site. These were the numbers used for the 2003 Gulf of Mexico Incidental Harassment Authorization (IHA) application, Environmental Assessment (EA) and fieldwork, as safety radii and potential harassment criteria. Some of these values are different from values quoted in more recent IHA Applications and EAs, which are based on re-interpretation of model outputs. Future IHA applications and EAs from LDEO will incorporate the results detailed in this paper.
suggest that, for shallow water, previously-estimated 180, 170 and 160 dB radii were underestimates of the actual distances where such levels occur (see Figure 3 and Table 1), and should be extended, particularly for the 180 dB radii. This result may vary with seafloor properties as signals over less acoustically reflective seafloors will decay more rapidly.

Figure 4 shows energy spectral density, appropriate for pulsed or transient signals, of a 20-gun array shot at the deep and shallow sites. 1/3-octave levels also are shown, since these are the most relevant values for marine mammal hearing. At the deep water site (for the deep phone), the energy peaks between 5 and 20 Hz and falls off rapidly above 100 Hz. At the shallow water site, the spectrum peaks between 30 and 80 Hz, with apparent attenuation of the lowest frequencies, but also falls off rapidly at frequencies above 100 Hz. For both sites, levels at ~1 kHz are approximately 40 dB less than the peak values for the energy spectral density, and 20 and 33 dB less for the deep and shallow sites respectively using 1/3-octave levels. Energy levels continue to drop at progressively higher frequencies, with 10–20 kHz levels being ~30–40 dB lower than at 1 kHz for the energy spectral density, and again 20 and 33 dB less for the deep and shallow sites respectively using 1/3-octave levels.

4. Summary

Results from the 2003 field program show that, for deep water, the previously utilized 180 dB and 160 dB radii may be conservative (overestimated), based primarily on the measured 160 dB levels for the 20- and 12-gun arrays. For the shallow water, 180–160 dB radii previously used should be expanded as detailed in Table 1. Note, for all these estimates, we have endeavored to use the maximum received levels at any given range rather than the average received level, to ensure the values used are conservative.

These results indicate that in shallow water, reverberations play a significant role in received levels. Previous modeling to estimate radii for permit applications had not accounted for bottom reverberations. Future modeling of seismic energy propagation should account for this effect, especially in shallow waters. The definition of what constitutes shallow water, and what constitutes deep water is a problem that should be tackled through both modeling incorporating reverberations, and through continued calibration measurements. In the meantime, caution should be taken to maintain appropriately large safety radii in shallow water operations, and consideration of these concerns should be incorporated into future seismic cruise planning.

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References

Cudahy, E., and W. T. Ellison (2002), A review of the potential for in vivo tissue damage by exposure to underwater sound, report for Department of the Navy, 6 pp., Dept. of the Navy, Washington, D. C.
Schmidt, V. (2004), Seismic contractors realign equipment for industry’s needs, Offshore, 64, 36–44.