3. ACOUSTIC CALIBRATION MEASUREMENTS[1]

Introduction

Lamont-Doherty Earth Observatory conducted an acoustic calibration study in the northern Gulf of Mexico in the late spring of 2003. This study was conducted in order to calibrate the various seismic sources to be used by the R/V *Maurice Ewing* during studies in 2003/2004. In particular, it was important to determine the distances at which received sound levels diminished below various values considered relevant in determining effects on marine mammals. The study relied on the generation of underwater acoustic pulses by various airgun arrays towed behind the *Ewing*, along with use of sound receiving and recording equipment to document the received sound levels and characteristics.

The airgun arrays used during the calibration study included 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.

As used in this report, "SPL" means Sound Pressure Level, and is equivalent to the rms (root mean square) pressure level averaged over the duration of the sound pulse. One of the main purposes of the acoustic calibration study was to measure the received sound levels and characteristics as a function of distance from the various airgun arrays commonly used by L-DEO. These data were to be used to verify, and if necessary adjust, the existing "safety radii and harassment criteria" used for mitigation during L-DEO's future seismic studies. 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.

Methods

A special spar buoy, developed by Spahr Webb's (L-DEO) group with assistance from Alan Nance, was used to collect the calibration data. Specifications of the buoy are described below, as well as calibration operations.

Instrumentation: Spar Buoy and Hydrophones

The spar buoy consisted of a plastic tube, 5.5 m (18 ft) long and 40.6 cm (16 in) in diameter, containing ballast and a variety of electronic equipment (Fig. 3.1). From the bottom upwards, the tube contained ballast weights, the data acquisition module, flotation, and a radio modem telemetry unit, including a GPS set. The buoy had battery power to operate for three days. The telemetry link enabled the shipboard party to acquire data in real time and to control the buoy's digitizer, choosing among two hydrophone channels, four fixed gains, and four digitizing rates (50, 25, 12.5, 6.25 kHz). At the deep water site, the two hydrophones were

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deployed with 18 and 500 m (59 and 1641 ft) of cable. At the shallow water site, both hydrophones were deployed at 18 m (59 ft) depth.

The two hydrophones used with the LDEO spar buoy were based on Benthos Company Model AQ-1 hydrophones. These hydrophones have a specified acoustic sensitivity of -202.5 ±□ dB relative to 1 V/□Pa with a flat frequency response (±□.5 dB) in a frequency band from 1 Hz to 10 kHz. The hydrophones are essentially omnidirectional (±□ dB) below 5 kHz. The amplifier response is not flat in frequency (see below) but is used to shape the response to maximize use of the dynamic range and to avoid clipping at low frequencies due to buoy heave. Each hydrophone was mounted within a silicone-oil-filled jacket fastened onto a small aluminum pressure case containing the amplifier and batteries for the amplifier. Cables with appropriate underwater connectors connected the output of the amplifiers (and ground return) to the buoy. The response of the hydrophones was measured through the underwater cables. Cable loss was determined to be insignificant at frequencies below 10 kHz.

FIGURE 3.1. The spar buoy used to measure sound levels of the various airgun arrays (photograph by J. Diebold).

A single resistor across each hydrophone and before the amplifier provided for a single high pass pole with a corner near 800 Hz (hydrophone A) and 400 Hz (hydrophone B). The presence of this pole prewhitens the response of the system to the airgun signal and prevents the hydrophone from clipping in response to the large pressure changes associated with buoy heave. This prewhitening filter reduces the gain at low frequencies where the pressure signals from the airgun are large. Both hydrophones also had a single low pass corner set to 3 kHz. The gain of the amplifiers (midband) was roughly 41 dB.

The post-recording processing corrected for the filter response to give accurate records of the airgun pressure signal at all relevant frequencies. The hydrophones were calibrated after the cruise in the US Navy TRANSDEC facility in San Diego. This facility consists of a very large fresh water tank and a system for providing calibrated signals at fixed ranges over a very broad range of frequencies (10 Hz to 20 kHz). The results from this facility suggest that the hydrophone responses were somewhat lower gain (V/Pa) than could be predicted from the manufacturer's specifications for the AQ-1 hydrophone. The received level data shown here use the measured responses determined in the TRANSDEC facility to convert the raw data to true pressure amplitude. Using the original gain values would predict smaller values for received level than shown here. We rechecked the calibration in a narrow frequency band (10-13 kHz) using another calibrated hydrophone in a tank at L-DEO and confirmed the TRANSDEC data were correct to within a few dB in this band.

The filter response was calculated in the Fourier domain. The recorded data were corrected for the instrument response by dividing the Fourier transform of the data record by the filter response and inverse Fourier transforming. A multipole high pass filter was applied to the corrected response before inverse transforming to avoid numerical problems at zero frequency. We experimented with different corner frequencies for this filter to confirm that the filter did not affect the estimate of received sound levels.

Measurements of Airgun Sounds

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 (□2), 12 guns (□2), and 20 guns (□2). The 2 GI guns were discharged every 30 s. While towing the arrays, the *Maurice Ewing* approached the spar buoy from ~10 km (5.4 n.mi.) away, passed ~100 m (328 ft) to the side of the buoy, and continued until it was ~10 km (5.4 n.mi.) beyond the buoy. Sound was recorded at the spar buoy, and data were recovered in near real time via radio telemetry to the *Ewing* from the buoy.

A radio signal from the ship selected the parameters of the sampling, including the gains, sampling rate and data channel to be digitized from the multiplexer in the buoy. A block of data (including the seismic pulses) was collected at the buoy and then transmitted back to the ship. Data transmission from the buoy to the ship took up to six times longer than data acquisition by the buoy. Thus data from the spar buoy were not continuous.

Calibration Sites

The initial plan was to conduct calibrations in three representative areas: deep water, where the signal would be dominated only by the direct arrivals from the arrays; shallow water, where reverberations would play an important role; and at intermediate depths on the shelf slope. The full plan was not carried out because of rough sea conditions on two days. The ship time available then limited the operations of the *Ewing* to the deep and shallow calibration sites (Table 3.1; Fig.□3.2).

TABLE 3.1. Sites visited during L-DEO's acoustic calibration study in the northern Gulf of Mexico, May–June 2003. For each calibration site, the table shows the dates spent at that site, whether the airguns were discharged at the site, and which array(s) were used.

Site	Water depth	Dates at site	Airguns	Array used
Deep	~3200 m (10,500 ft)	30 May*	Yes	6-20 Airguns
Slope	~500 m (1641 ft)	31 May – 1 June	No	No
Shallow	30 m (98 ft)	2 June	Yes	6-20 Airguns and 2 GI guns

*Testing of airguns and other equipment was conducted at the deep calibration site on 29 May 2003.

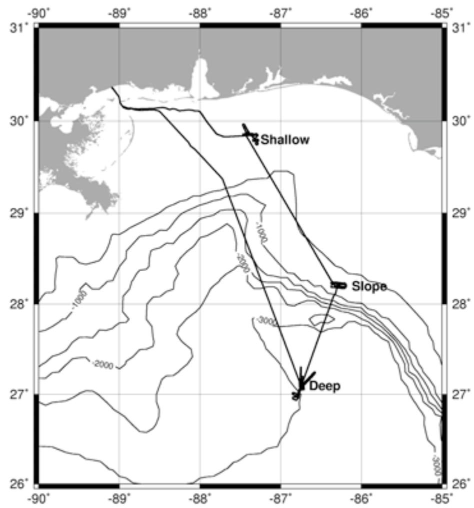


FIGURE 3.2. The study area for the May–June 2003 acoustic calibration study in the northern Gulf of Mexico, showing ship tracks at the three planned calibration sites. Calibrations were only conducted at the deep and shallow sites due to weather constraints at the slope site.

The deep site calibration was conducted on 30 May 2003. Approximately 145 shots were recorded from the 20-gun array, equally divided among the four subset arrays with 6, 10, 12 and 20 airguns. No GI guns were shot at the deep water site. A pair of new, factory-calibrated hydrophones were found to be too noisy to make reliable recordings, and the older set of hydrophones with less response at low frequencies (described above) was used instead. The calibration buoy's built-in GPS was also faulty, and a GPS module that is normally used on the *Ewing*'s hydrophone streamer (not deployed during this project) was substituted. The speed with which the spar buoy drifted was unexpected; subsequent runs were planned with the predicted buoy drift taken into account.

Two days (31 May and 1 June) were spent at the selected slope calibration site. However, no airgun operations were carried out. Sea conditions were too rough (10 kt wind) for effective visual monitoring of the safety zone for *Ziphius* (beaked whales), which were likely to occur at that site. Therefore, it was decided not to operate the airguns at that site.

On 2 June 2003, the source calibration was carried out at the shallow water site. A total of 290 shots were recorded, using the 20-gun array and its smaller subsets as well as the 2 GI guns.

Results

Results of the calibration indicate the following: (a) The model results currently used for establishing 190-160 dB radii appear to be slightly conservative (i.e. overestimate actual radii) for deep water sites, but under predict radii for shallow water (Tables 3.2 and 3.3 below). (b) The broadband acoustic spectra of the sounds from the airgun arrays fall off as predicted with increasing frequency. By far, the majority of the energy produced lies between 10 and 100 Hz.

Only results from in-line shots are shown (Fig. 3.3-3.10), as these show the highest received levels at any given distance, and therefore represent the most conservative radii. Modeling and measurements have shown that the highest received levels occur directly astern and in front of the bow, with levels being reduced at corresponding distances to the port and starboard sides of the ship. When the data from the side shots were included there was more scatter in the results, which could make results less clear. We have opted to display only the data from in-line shots rather than try to tightly define the lesser side-lobes. This 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.

The records of the airgun pulses when the ship was closest to the buoy are slightly clipped and may underestimate the received levels. We carefully 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 the figures 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.

The extensive prewhitening of the signal by the hydrophone responses before digitization in the buoy greatly diminishes the effect of the clipping on the measurements of the source waveforms. The effects of clipping would have been more severe with no-prewhitening. The prewhitening of the data by the hydrophone response shifts the peak energy in the recorded source data to frequencies above 1 kHz. Thus the clipping primarily affects the spectrum near 1 kHz. It has less effect at the low frequencies that dominate the true source waveform and has only a minor effect on measurements of either the rms level or the peak-to-peak levels (which depend primarily on the high source levels at low frequency). We confirmed this hypothesis by:

- artificially clipping records of originally unclipped data (before correcting for the hydrophone response) to values of one third of the peak-to-peak values seen in the raw records,
- then correcting for the instrument response, and
- comparing the resulting waveforms (and estimates of both rms and peak-to-peak values) to those obtained from the original data.

The resulting waveforms are similar when overlaid onto the waveforms without the artificial clipping, demonstrating that the clipping has had little effect on the low frequency parts of the waveform that dominate the airgun signal. We did not use clipped records in the analysis of the spectra of the source signals. In future experiments, we will use hydrophones with lower total gain to ensure the data do not clip at the closest source to buoy ranges.

For all plots, modeling results are shown as a predicted curve based on:

- calculating a near-field signal for each airgun array;
- calculating the travel time and distance for the direct and surface-reflected paths between each airgun and each point in a specified mesh;
- scaling the near-field signals by 1/R and shifting in time according to the travel time and distance; and

- summing the resulting signals to calculate peak, peak-to-peak and rms levels for the summed signal (e.g. Fig. 3.11).

For Figures 3.7 and 3.10 the modeling is the same as previously used to estimate the received levels and 190-160 dB radii quoted in the IHA Application for the Gulf of Mexico. Other Figures use the same modeling, but adjusted for depths of hydrophones. For details of the modeling, please see Appendix.

Deep Site

For the deep site, only the 160 dB radii were clearly documented, given the clipping of records at the closest ranges before correcting for the instrument response. 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 Fig. 3.4 and Tables 3.2 vs. 3.3). In general, however, the pattern of unclipped results tends to follow the shape of the predicted received level vs. range curve quite closely, but with most values being a few decibels lower than predicted for that range (Fig. 3.4).

We can infer the 180 dB radii from the data after making an appropriate correction for the clipping. Our analysis of clipped data shows that the clipped data under-predict the true levels by a few dB at the relevant ranges. The estimates of 180 dB radii for all the gun arrays operated at the deep site suffer from a paucity of observations at the relevant ranges (Fig. 3.4, 3.5), but the data suggest that the 180 dB radii for all arrays occur at less than 1 km, and are likely significantly less than 1 km. These results will need to be confirmed in future experiments with unclipped data and a larger number of observations at the closer distances.

We note that the recordings made at the shallow hydrophone show significantly lower dB levels than recordings from the deep phone, due to the surface ghosting effect (Fig. 3.11). This serves as a reminder that marine mammals at shallow depths in deep water areas are exposed to levels considerably lower that those at the deep hydrophone.

Shallow Site

Due to clipping of close range arrivals no measurements of the 190 dB radii were made, and only the 20-, 12- and 6-gun arrays had the 180 dB radii that were unambiguously constrained by the data. The 20- and 12-gun 180 dB radii were estimated based on nearby arrivals close to 180 dB, but no measurements were made above 180 dB that were not clipped. 170 dB estimates were made for all but the 2 GI gun array, and 160 dB estimates could be made for all arrays. These measurements suggest that currently used radii for shallow water are underestimated (see Table 3.3), and should be extended, particularly for the 180 dB radii.

For the shallow site, a larger number of measurements were obtained, and the data provide empirical data on the 180, 170 and 160 dB radii for most of the airgun configurations (Fig. 3.7, 3.8, 3.10). 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 suggest that, for shallow water, previously-estimated 180, 170 and 160 dB radii were underestimates of the actual distances where such levels occur (see Table 3.2 vs. 3.3), and should be extended, particularly for the 180 dB radii.

TABLE 3.2. Measured values for 190, 180, 170 and 160 dB re 1 µPa (rms) radii at the deep and shallow sites, for 20, 12, 10, 6 & 2 gun arrays. NC indicates that results for the dB level were not constrained, likely because measurements were not well defined by the available data, mainly because unclipped measurements were not made close enough to the array. The proximity of the closest measurement to the airguns can be determined by looking at Figures 3.3-3.11.

SITE/ARRAY	MEASURED 190 dB	MEASURED 180 dB	MEASURED 170 dB	MEASURED 160 dB
Deep 20	*NC*	*NC*	*NC*	~2.5 km
Deep 12	*NC*	*NC*	*NC*	2.5 km
Deep 10	*NC*	*NC*	*NC*	> 2 km
Deep 6	*NC*	*NC*	*NC*	~1.5 km
Shallow 20	*NC*	~3.5 km	7 km	*12 km**
Shallow 12	*NC*	~2 km	5.5 km	9 km
Shallow 10	*NC*	~2 km	4 km	9 km
Shallow 6	*NC*	1.5 km	4 km	7 km
Shallow 2 GI	*NC*	*NC*	> 0.5 km	1.5 km

*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.

TABLE 3.3. Predicted values for 190, 180, 170 and 160 dB re 1 µPa (rms) radii for 20, 12, 10, 6 & 2 gun arrays. Note that the same predicted values were used regardless of depth of site. These are the numbers previously used as safety radii and potential harassment criteria[2].

ARRAY	PREDICTED 190 dB	PREDICTED 180 dB	PREDICTED 170 dB	PREDICTED 160 dB
20 gun	0.400 km	0.95 km	3.42 km	9 km
12 gun	0.3 km	0.88 km	2.68 km	7.25 km
10 gun	0.25 km	0.83 km	2.33 km	6.5 km
6 gun	0.05 km	0.22 km	0.7 km	2.7 km
2 GI gun	0.015 km	0.05 km	0.155 km	0.52 km

Spectra

Figures 3.12 and 3.13 show energy spectral density for 20-gun array shots at the deep and shallow sites respectively. The energy spectral density is the appropriate calculation to make for a pulsed (transient) signal and differs from the power spectrum appropriate for continuous noise

[2] Note these were the numbers used for the 2003 Gulf of Mexico IHA Application, Environmental assessment and fieldwork. Some of these values are different from values quoted in more recent IHA Applications and EAs, which are based on L-DEO's re-interpretation of the model outputs.

sources. 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 tends to be flatter between 5 and 100 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. Energy levels continue to drop at progressively higher frequencies, with 20 kHz levels being ~40 dB lower than at 1 kHz.

Summary

Results from the 2003 field program show that, for deep water, the predicted 180 dB and 160 dB radii currently in use 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 currently used should be expanded as detailed in Table 3.2. Note that, for all these estimates, we have endeavored to use the maximum received levels at any given range rather than the average received range, to ensure that numbers used are conservative.

Spectra show that the majority of the energy is in the 5–100 Hz range. Levels at 1 kHz are ~40 dB lower than those at the frequencies with peak energy, and levels continue to diminish as frequency increases above 1 kHz.

One caveat for the deep site is that the deep hydrophone was at a maximum depth of 500 m, but may have been shallower depending on local currents. Analysis of reflected arrivals indicates it may have been as shallow as 330 m. For some measurements this depth may still have been subject to some surface ghosting effects. During the planned 2004 field program we expect to obtain deeper measurements for the deeper sites, and will attach a pressure gauge to the hydrophone so that depth can be well constrained. We also plan to make adjustments to the instrument response to ensure that nearby shots are not clipped.

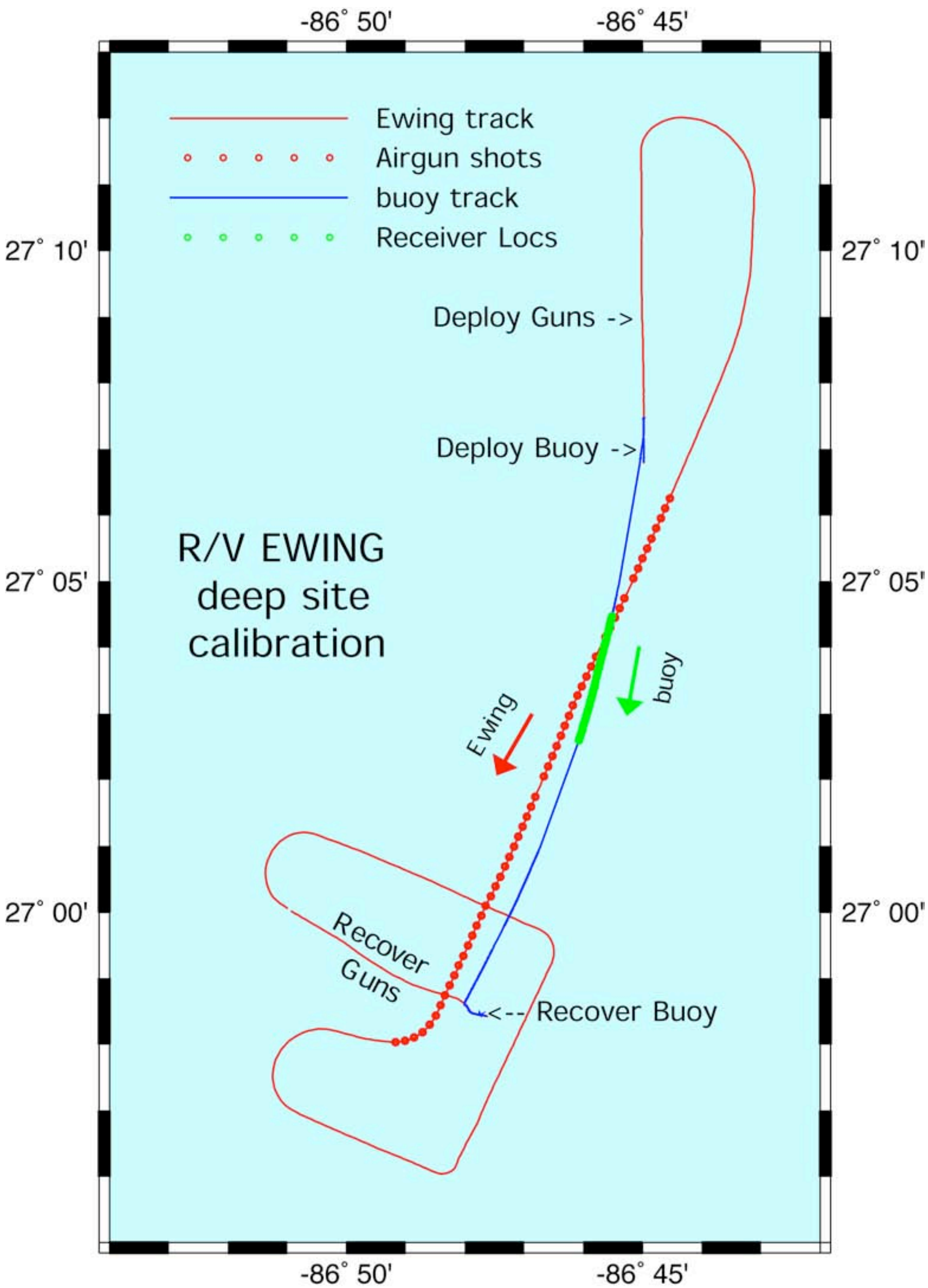


FIGURE 3.3. Map showing Ewing and buoy track during shooting at the deep calibration site. Green circles show buoy location during received shots (red circles).

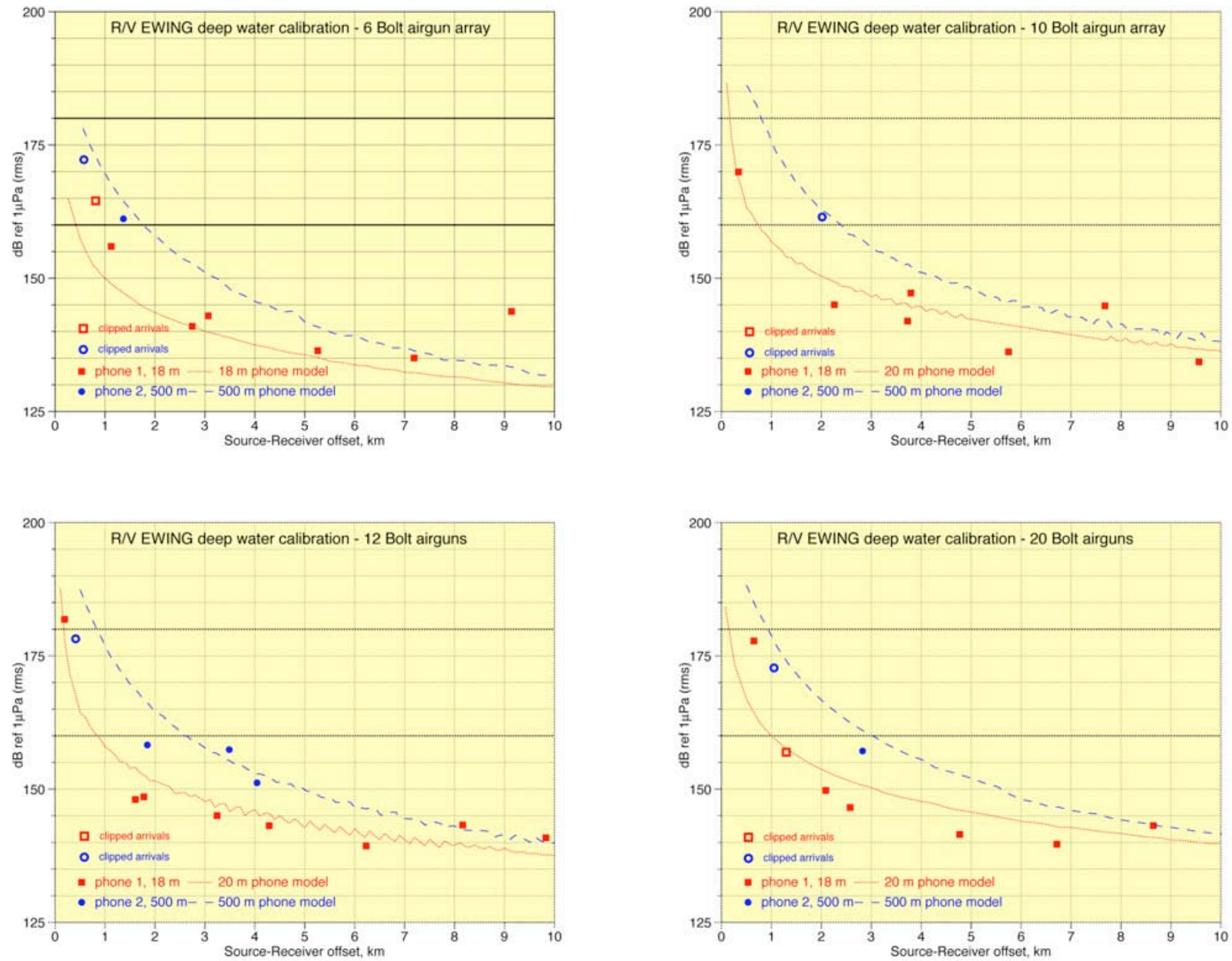


FIGURE 3.4. Received levels at deep calibration site for 6, 10, 12 and 20-gun arrays. Received levels are shown for the shallow (18 m) hydrophone (red squares) and the deep (500 m) hydrophone (blue circles). Dashed and dotted lines represent predicted received levels based on modeling for deep and shallow phone respectively.

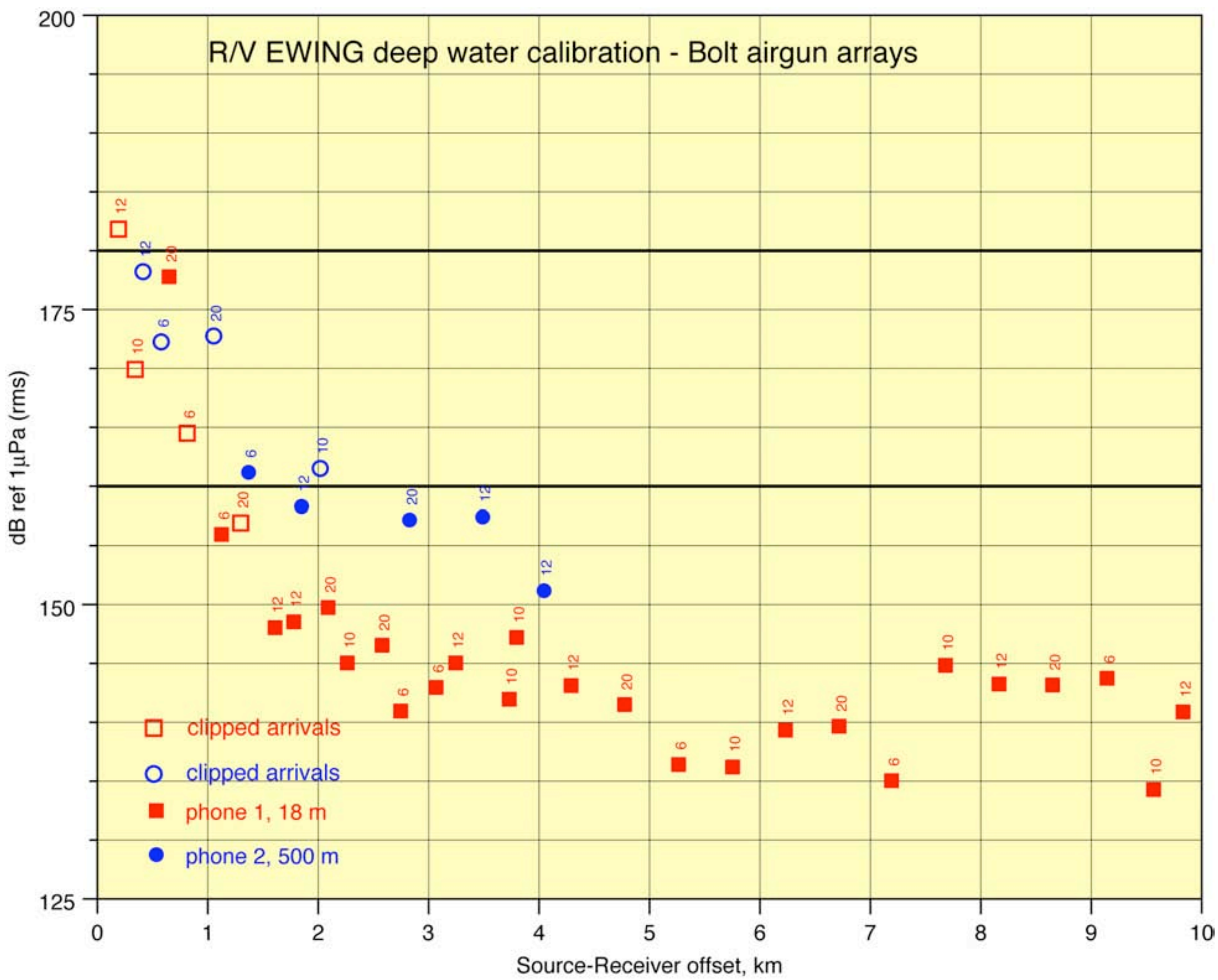


FIGURE 3.5. Received levels at deep calibration site for 6, 10, 12 and 20-gun arrays. Received levels are shown for the shallow (18 m) hydrophone (red squares) and the deep (500 m) hydrophone (blue circles). Each shot is labeled individually to indicate the array size (number of guns) from which it originated.

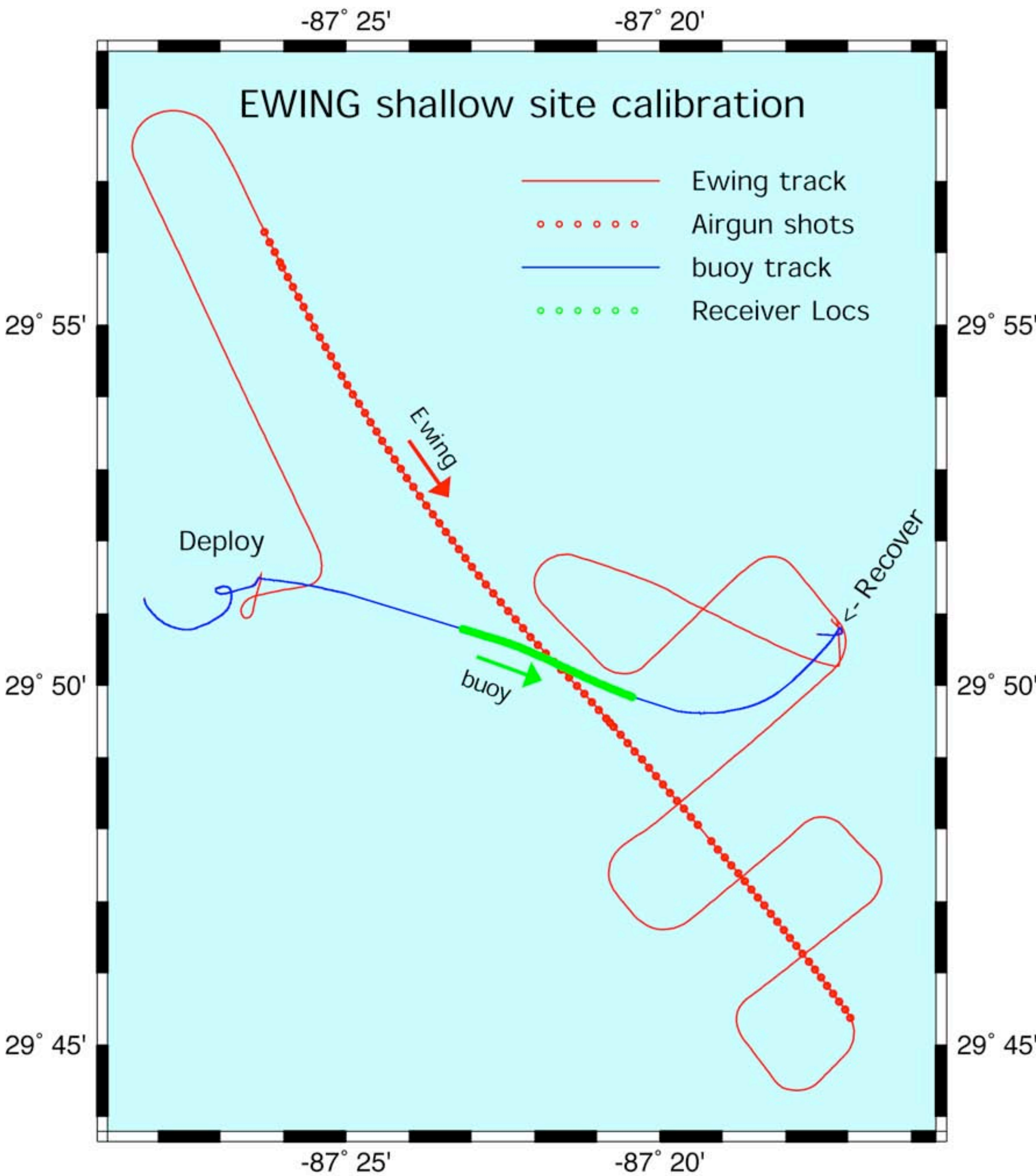


FIGURE 3.6. Map showing Ewing and buoy track during shooting at the shallow calibration site. Green circles show buoy location during received shots (red circles).

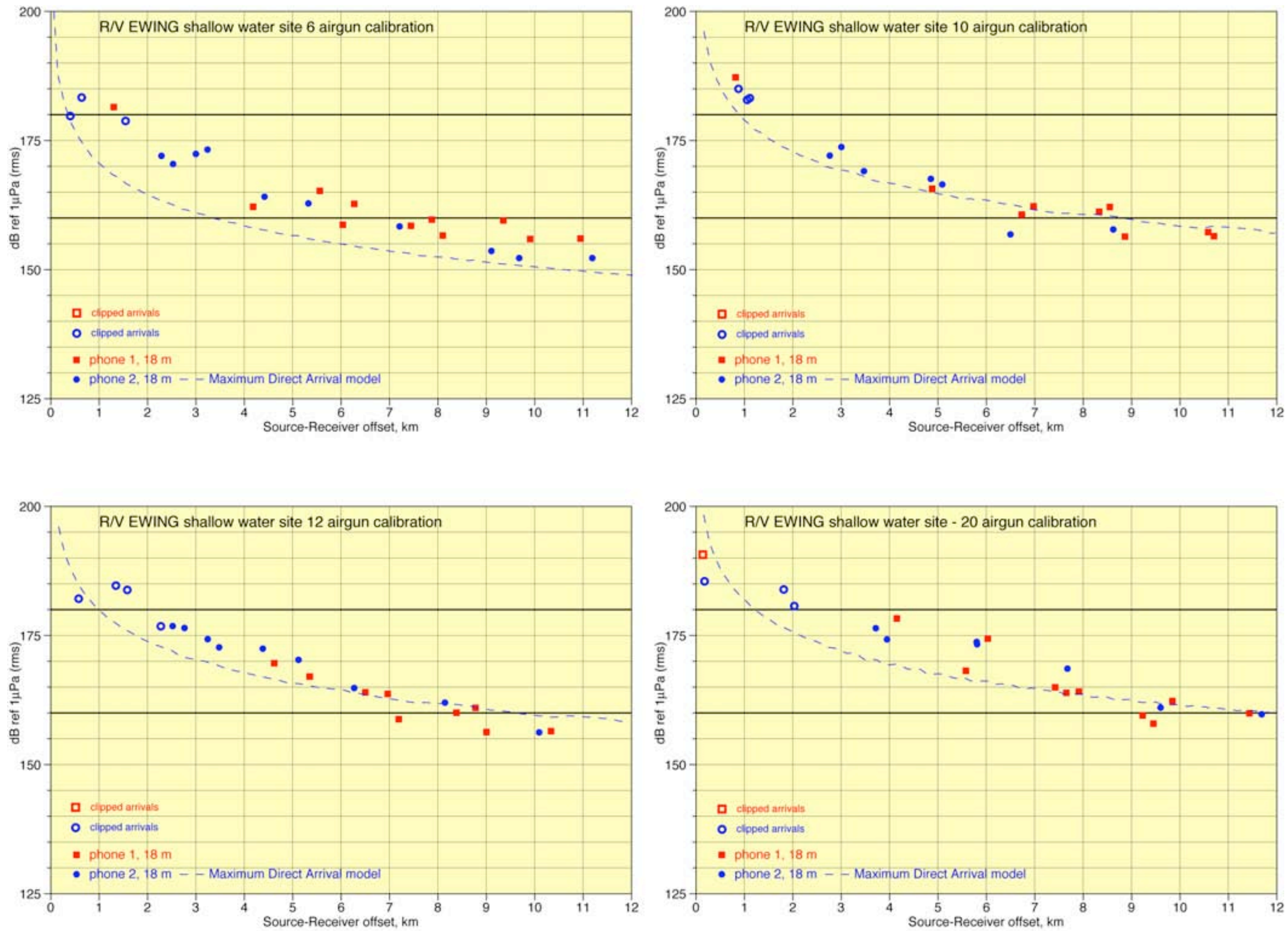


FIGURE 3.7. Received levels at shallow calibration site for 6, 10, 12, and 20-gun arrays. Received levels are shown for the two phones, both at 18 m. Dashed line represents predicted received levels based on modeling (see text).

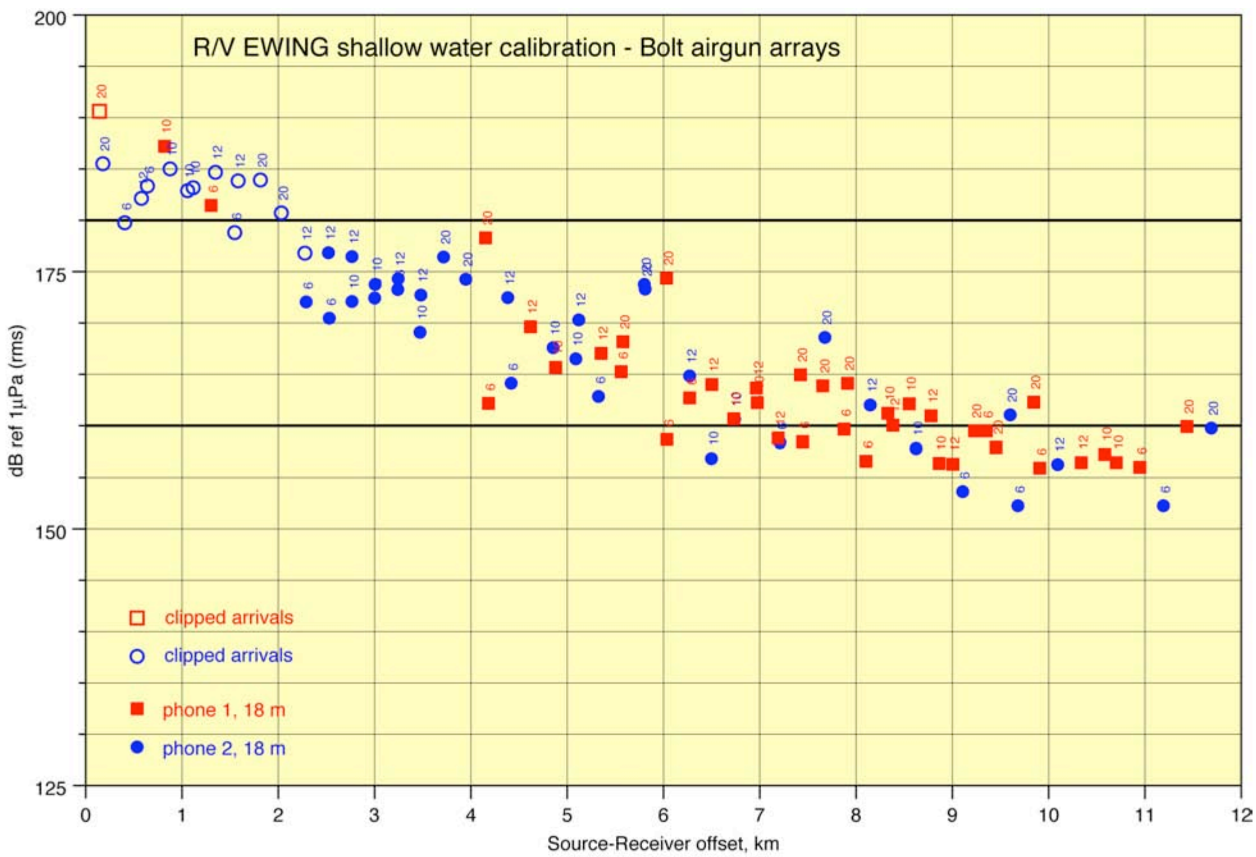
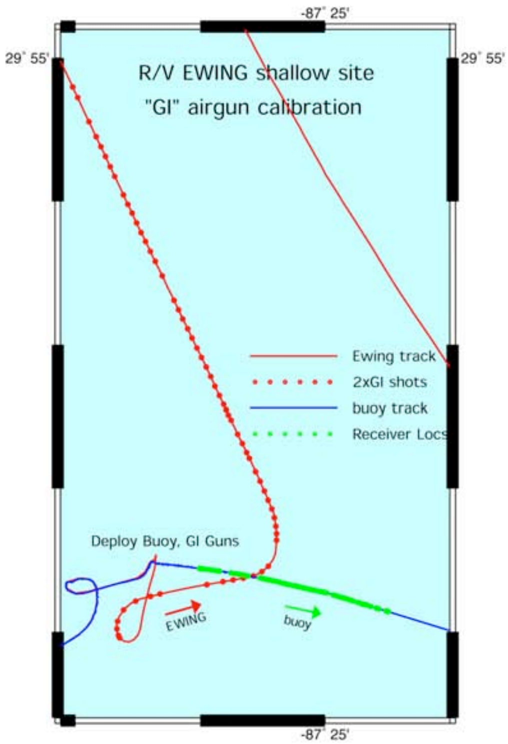


FIGURE 3.8. Received levels at shallow calibration site for 6, 10, 12 and 20-gun arrays. Received levels are shown for the two hydrophones, both at 18 m depth. Each shot is labeled individually to indicate array size (number of guns) from which it originated.



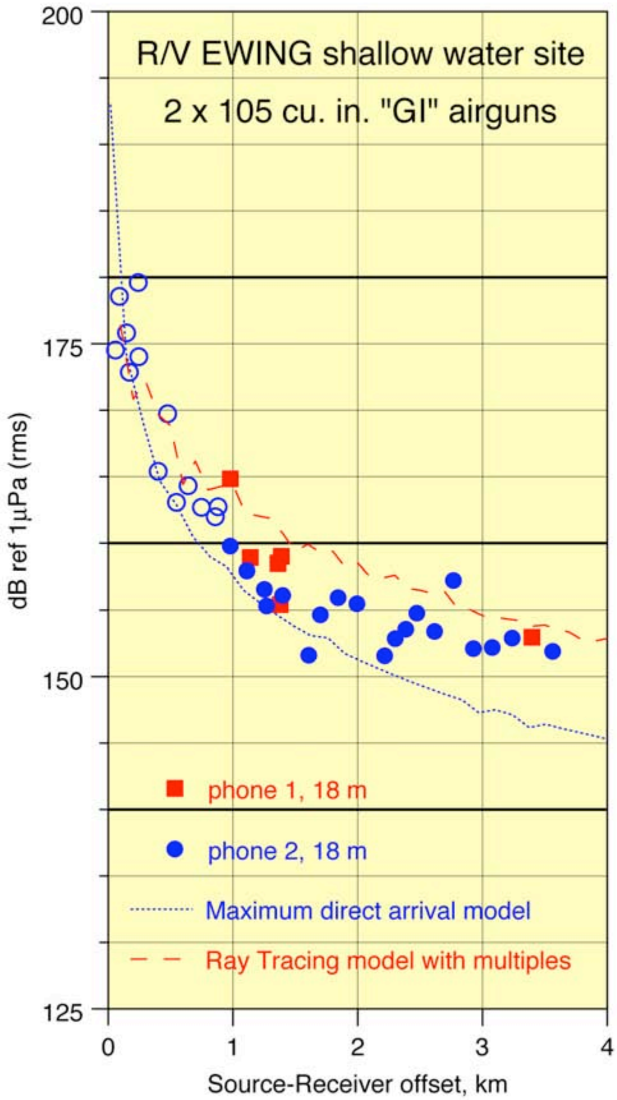


FIGURE 3.9. (LEFT) Map showing Ewing and buoy track during shooting of the 2 GI-guns at the shallow calibration sire. Green circles show buoy location during received shots (red circles).

FIGURE 3.10. (RIGHT) Received levels at shallow calibration site for 2 GI-guns. Received levels are shown for the two phones, both at 18 m. Dashed line represents predicted received levels based on ray-tracing modeling including multiples, and dotted line indicates predicted received levels based on maximum direct arrival modeling.

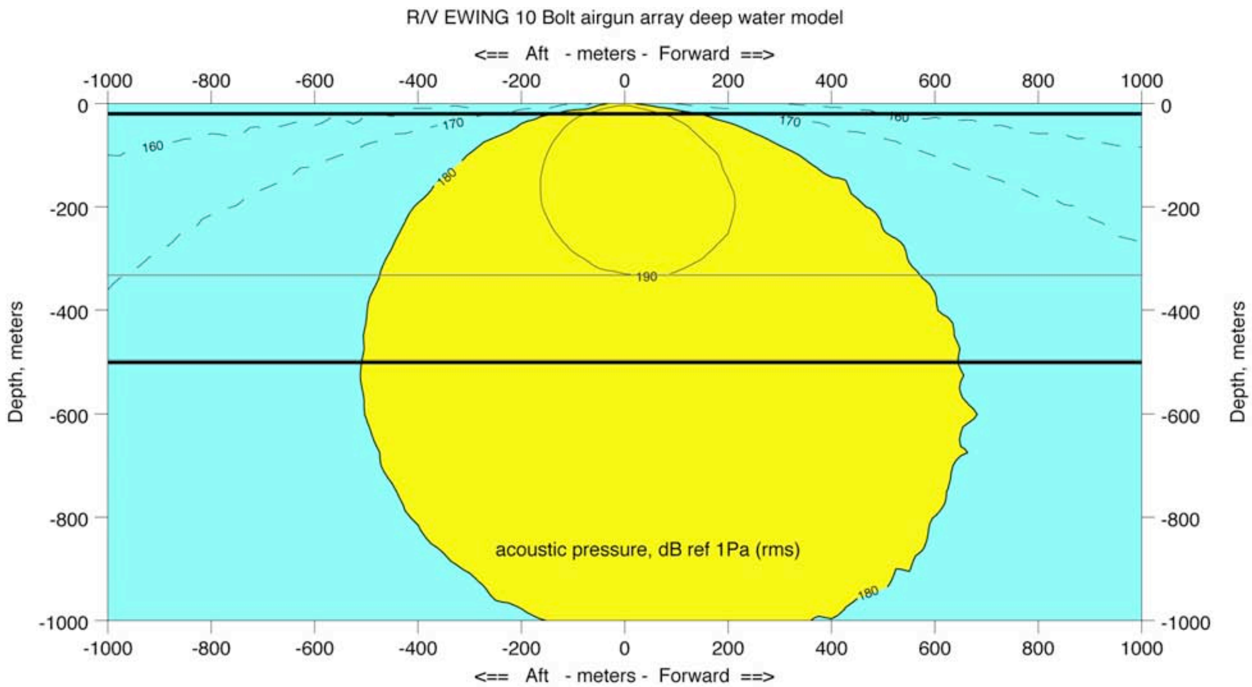


FIGURE 3.11. Model of the 10-gun array output in deep water. Note that near the surface there is a 'ghosting effect' where the surface reflection cancels out the direct arrival. For this reason results from the shallow phone at the deep site cannot reliably be used to constrain 190-160 dB radii. The maximum depths of the shallow and deep phone (18 m and 500 m respectively) are marked by black horizontal lines. The possible shallower depth of the deep phone (330 m) due to currents is marked with a gray line.

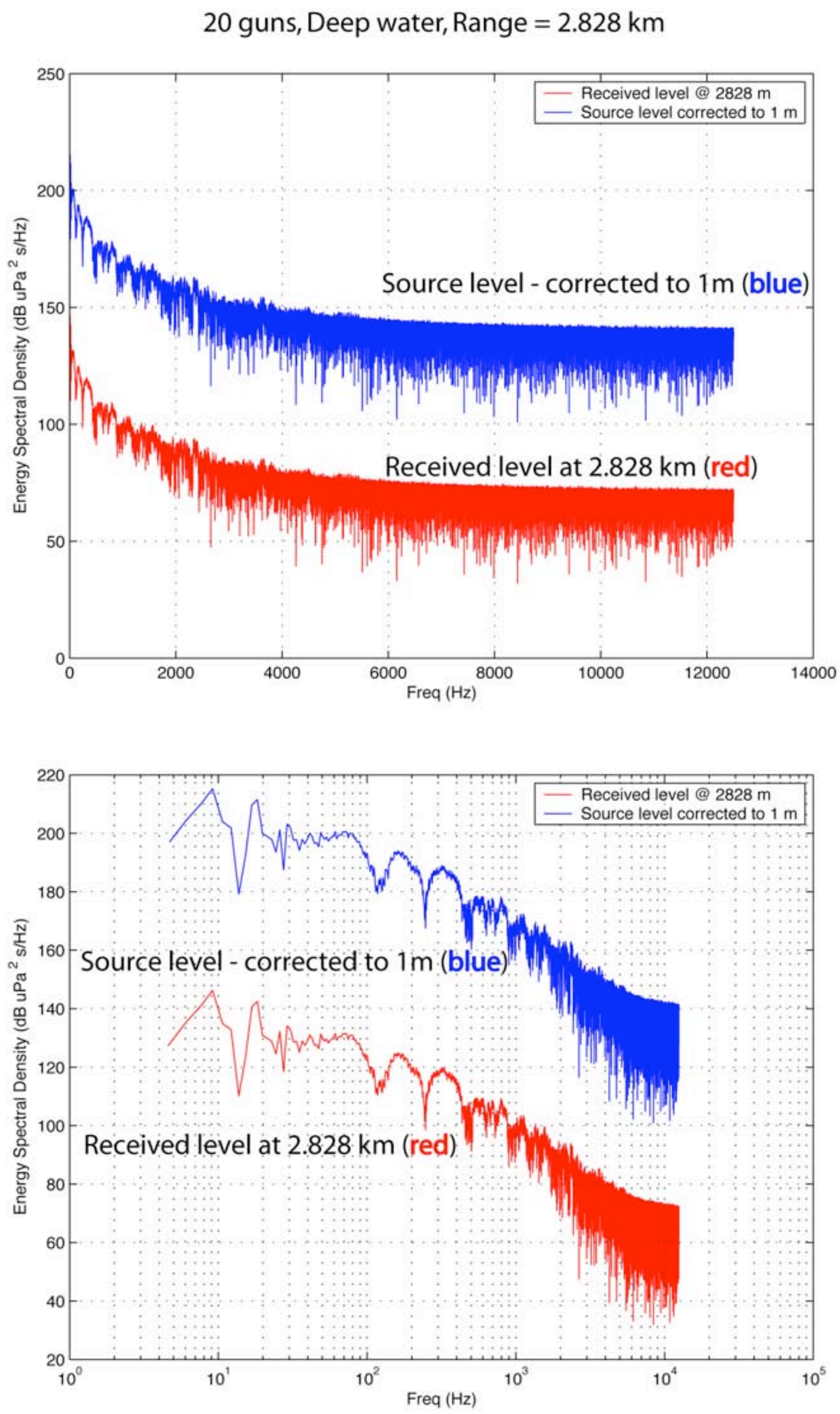


FIGURE 3.12. Spectra of 20-gun shot at the deep site shown with a linear (top) and log (bottom) scale to allow different features to be seen at the different scales. Red lines indicate the measured received levels at 2.828 km, and the blue lines represent the calculated source level at a nominal 1 m distance using a spherical spreading assumption to calculate transmission loss. (Because the source was not a point source, there would be no one location where levels this high would be measurable.) Note that peak energy occurs in the 5–100 Hz frequency range, with levels dropping off by about 40 dB from peak at ~1 kHz and continuing to drop rapidly thereafter.

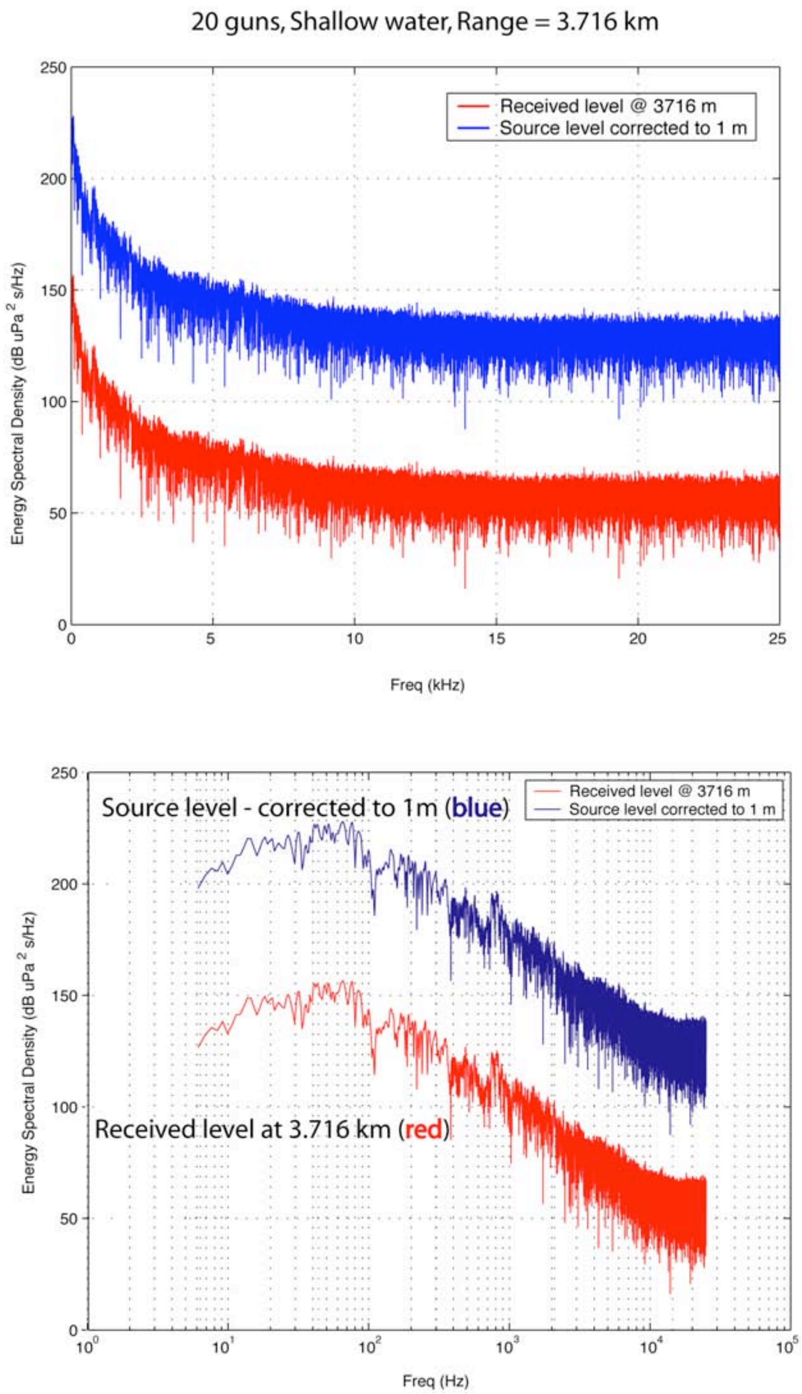


FIGURE 3.13. Spectra of 20-gun shot at the shallow site shown with a linear (top) and log (bottom) scale to allow different features to be seen at the different scales. Red lines indicate the measured received levels at 3.716 km, and the blue lines represent the calculated source level at a nominal 1 m distance using a spherical spreading assumption to calculate transmission loss. (Because the source was not a point source, there would be no one location where levels this high would be measurable.) Note that peak energy occurs in the 5–100 Hz frequency range, with levels dropping off by about 40 dB from peak at ~1 kHz and continuing to drop rapidly thereafter.