A brief overview of seismic air-gun arrays

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This article summarizes salient points one must know about seismic air-gun arrays to discuss seriously how they might affect marine life. It is by no means exhaustive but tries to be thorough enough without being too involved to deter the general reader.

Physical geometry of arrays. Figure 1 shows a portion of an air-gun array. Note the man kneeling for scale. The orange tubes that look like large hot dogs are the floats that support the air guns; the air guns themselves are hanging beneath the floats. Typical volumes of air expelled by air guns vary from 30 in³ to about 800 in³. When one speaks of the volume of an air gun, or about the size of an air-gun array, it is in terms of this volume (for a single gun), or the sum of the volumes of each gun (for the whole array). Array sizes cover a wide spectrum, but most will be 3000-8000 in³. An array generally consists of 3-6 subarrays, each subarray being a linear alignment of 4-8 individual guns. This means that each array will typically involve 12-48 guns. The seismic industry mostly uses arrays whose operating pressure is 2000 psi. Figure 4 (courtesy of Schlumberger) in the companion article by Dragoset in this issue shows an array that is 3397 in³ in total volume. This array has three subarrays (each line of circles), uses 24 air guns (each individual circle represents an air gun, except for circles at the head of each array, which represent three-gun clusters, and the nearest number represents the volume of that gun in in³), and measures 15 × 16 m. The location of the array is indicated in the inset photo of a seismic vessel.

A key concept is that an array is not a point source, but one that spans a small area. Array design is based on the desire to have a source that emits a very symmetric packet of energy in a very brief time, and with a frequency content that penetrates well into the earth. Those desires dictate how many guns of what size form the total array and the exact location of individual guns. Selecting gun volumes to minimize sound levels (after the initial pulse) is known as tuning the array. Adjusting the firing times of different guns so that all discharge simultaneously (i.e., all expel air at exactly the
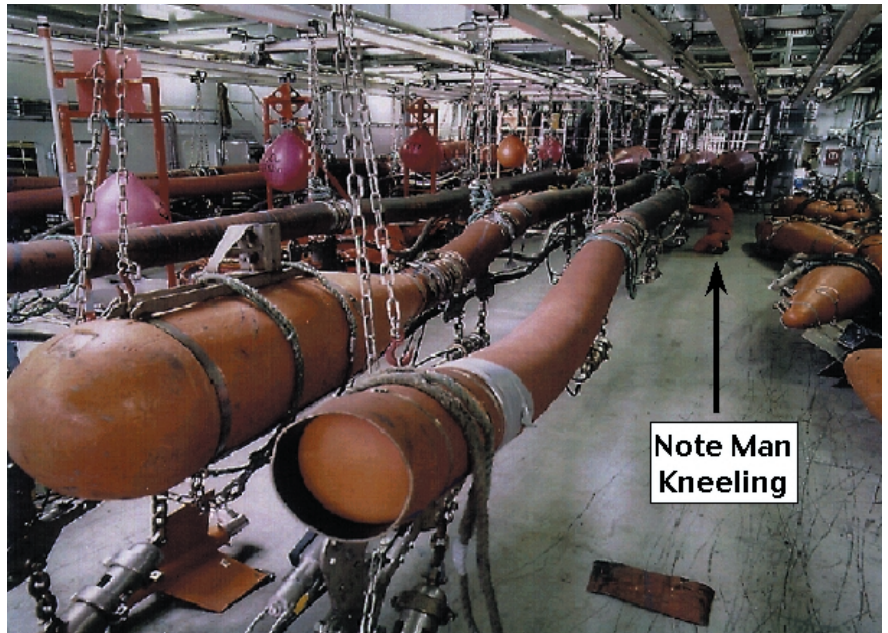

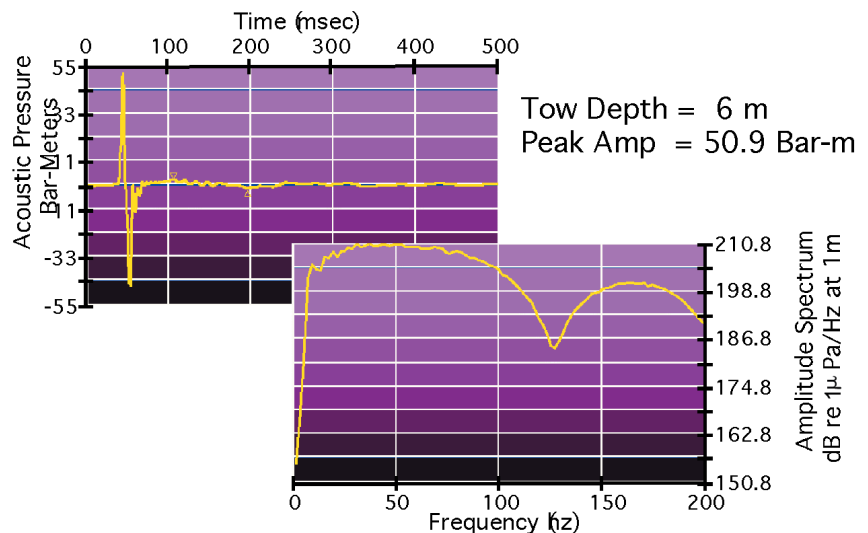
Figure 1. Portion of an air-gun array.

Figure 2. Back-calculated source signature and amplitude spectrum for 3397-in³ array.

same time) is known as synchronizing the guns. Figure 2 illustrates the symmetric packet of energy and the amplitudes of the different frequencies generated by the 3397-in³ source.

Calculating an array's energy output. The sound pressure (amplitude) generated by an array is:

1) linearly proportional to the number of guns in the array (i.e., all else being equal, a 30-gun array will generate twice the amplitude of a 15-gun array)

2) linearly proportional to the firing pressure of the array (a 4000-psi array will have twice the amplitude of a 2000-psi array)

3) proportional to the cube root of the volume of the array (an 8000-in³ array will generate about twice the amplitude of a 1000-in³ array if they contain the same number of guns)

Sound pressure decreases rapidly as the distance from the source increases. At distances in excess of 250

m (known as the far field), individual guns in arrays will look as if they are working as one source because individual pressure peaks will have coalesced into one relatively broad pulse. The array can then be considered a "point source." For distances less than 250 m, particularly within 2-3 array dimensions (75 m or so, aka the near field), pressure peaks from individual guns do not arrive simultaneously because the observation point is not equidistant from each gun. The effect is destructive interference of the outputs of each gun, so that peak pressures in this region will be significantly lower than the output of the largest individual gun. If an array were a point source, then measurements could be made a few hundred meters away and back-calculated to the level of the sound pressure at the exact location of that point source. For typical industry arrays, that *back-calculated source level would be on the order of 100 bar-m* and numbers of that magnitude are what the industry publishes as the *effective output of arrays at great distances*.

Figure 2 shows back-calculated information from a 3397-in^3 array. The peak source level is 50.9 bar-m, or about 102 peak-to-peak bar-m. Because the arrays are not point sources, the back-calculations are very inaccurate in terms of the sound pressure actually encountered within 75 m or so of the center of an array. Actual measured values verify that *maximum zero-to-peak real sound pressure experienced anywhere within the near field is less than 13 bars*.

Figure 2 has two other items of interest. One is that most energy emitted from an array occurs within 10-20 ms (of the firing source). The array is then recharged and the next firing is typically 10-15 s later. The other point of note is that one must specify the frequency band over which the amplitude value is calculated. With regard to the amplitude spectrum plot in the lower right Figure 2:

1) If one measures the area under the yellow curve between 0 and 50 Hz and between 0 and 100 Hz, the amplitude of the latter is about 6 db higher.
2) Because the vertical scale is in dB, it is true that if one calculates the area between 0 and 125 Hz (the first "notch") and compares that to areas under the curve from 0 to any frequency higher than 125 Hz, the difference will never amount to more than about 3 dB for existing air-gun sources.
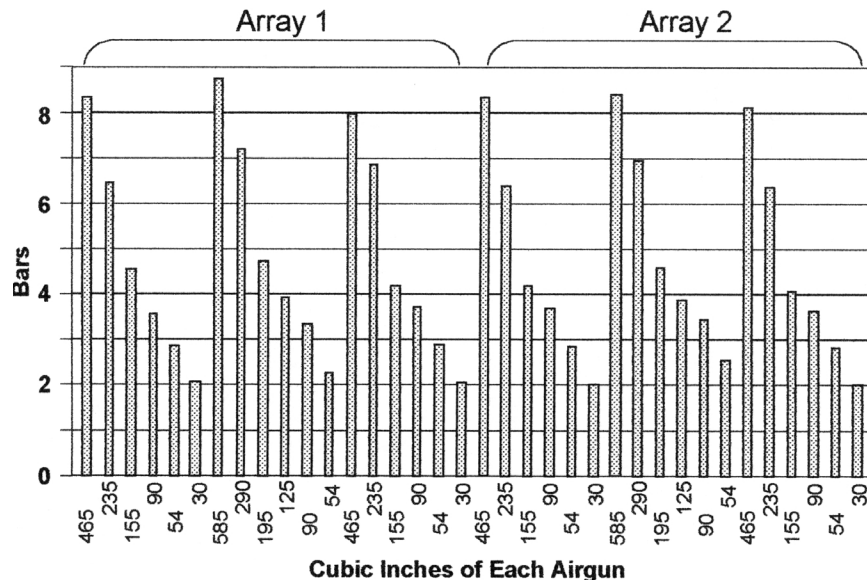

Figure 3. Average maximum output of air guns (dual 3397 arrays, 372 firings of each gun).
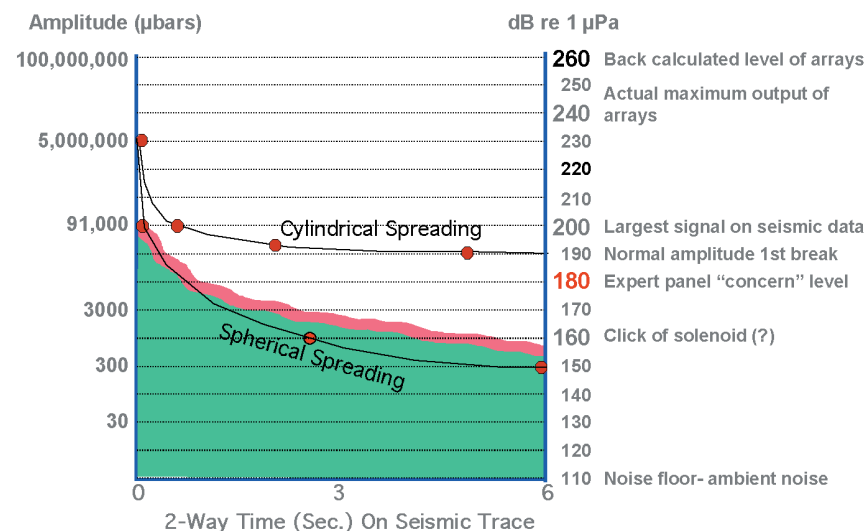

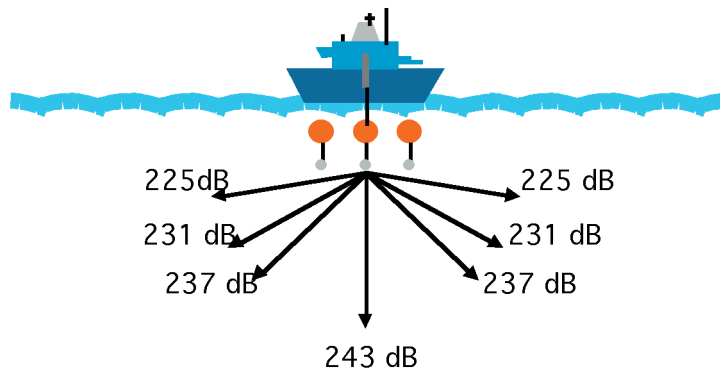Figure 4. Amplitude level for a typical seismic trace.

Figure 5. Vertical radiation pattern of typical array. dB levels re 1μPa-m; rms peak-to-peak maximum of 13.4 bars (absolute P-to-P maximum of 19 bars).

Finally, industry can very accurately calculate the actual amplitude that a source will generate at any point more than 1 m from an air gun. But the method of calculation is not the relatively simplistic back-calculation that assumes a point source, but a more mathematically complex approach that does not assume a point source. This capability has been refined to the point that there is essentially no difference between calculated values and

actually measured values. Figure 6 in the companion article by Dragoset illustrates just how well the more sophisticated modeling mimics an array's measured output.

Measurement of an array's energy output. In typical industry practice, a hydrophone is placed 1 m from each gun to measure actual sound pressure at those points. (These data monitor the performance of each gun and help the computer processing of the data.) Figure 3 shows data recorded by these hydrophones for dual 3397-in^3 arrays in May 1999. Each array has 24 guns; i.e., three subarrays with eight each. Each array is 16 m wide × 15 m long.

Each bar in this graph represents the average maximum pressure amplitude (zero-to-peak) measured by each gun's hydrophone (1 m from the particular gun) for 372 firings of each gun. The number along the bottom indicates gun size. Data from the first array is shown on the left, starting with the first "465" and ending with the second "30" annotation. Data from the second array begins with the third "465" and continues to the right. The maximum average value, 8.8 (zero-to-peak) bars, is generated by the 585-in^3 gun in the first array. The absolute maximum in this data set, not discernable from this plot but observed in the raw data before averaging, is 10.7 bars (zero-to-peak). These data lead to several observations: (1) the output of the two arrays looks very similar; (2) different guns of the same size have very similar outputs; and (3) maximum output actually measured anywhere is less than 11 bars (zero-to-peak).

A good estimate of maximum pressure amplitude emitted from an array can be obtained from this procedure:

1) Determine the largest gun in the array and note its amplitude output at 1 m.
2) Determine nominal spacing between adjacent sources.
3) Assuming spherical spreading, calculate the reduction in amplitude of that largest gun at the midpoint of the nominal spacing.
4) Double that amplitude, and you have an upper bound to the output of that array.

For example, in the 3397 array, the 585-cluster gun is the largest gun. The guns are 3 m apart. Maximum output of the 585 gun is 8.34 bar-m; 8.34 bars at 1 m is 5.56 bars at 1.5 m due to spherical spreading. Doubling that yields 11.12 bars (zero-to-peak),
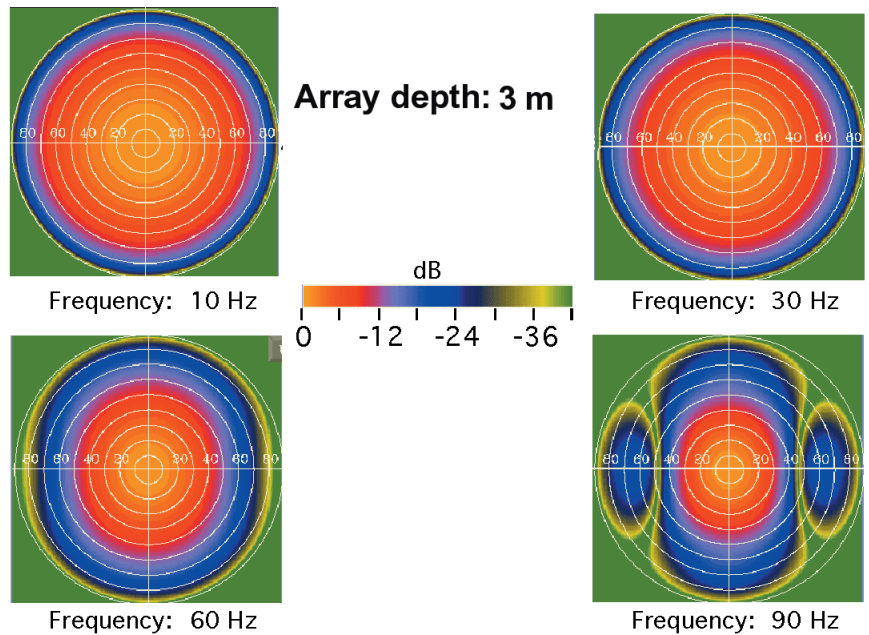

Figure 6. Horizontal plane projection of radiation pattern at 3 m.
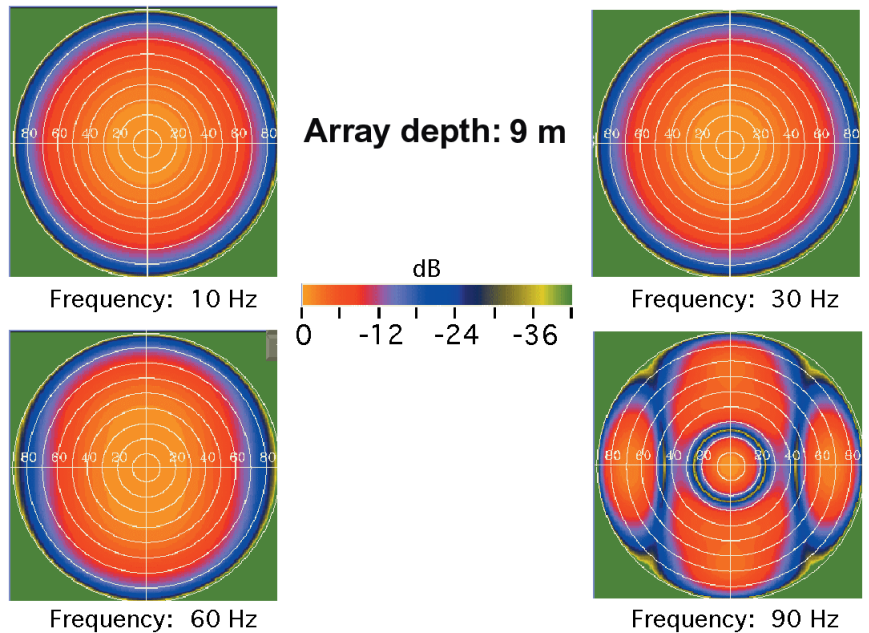

Figure 7. Horizontal plane projection of radiation pattern at 9 m.

which is slightly higher than the 10.7 bars actually observed. This maximum value will lie in the vertical plane containing the central subarray, for a symmetrical array. For a more detailed discussion of the output of arrays, see Dragoset's article.

In actual recording of seismic data, the sound pressure of the first energy from each shot to reach the sensors in the streamers will typically be 40-60 millibars. This is due to the relatively long distance (a few hundred meters, typically) traveled by the energy before reaching the sensors. In good conditions, ambient noise (in-streamer noise such as

vibrations and bulge waves as well as environmental noise such as wind and waves) will be about 2-3 microbars.

Figure 4 shows the amplitude level for a seismic trace as a function of recording time (heavy pink line). Amplitude decay for cylindrical spreading of a pressure pulse is indicated; the decrease is proportional to one over the square root of the distance from the source. Amplitude decay for spherical spreading of a pressure pulse also is indicated; it is proportional to one over the distance from the source. The plot indicates that most seismic traces will decay somewhere

between the spherical spreading case and the cylindrical spreading case. (This is true for energy propagating into the solid part of the subsurface below the water column. Exactly how sound decays depends on the specifics of the area.) Also shown are various reference points: (1) the back-calculated level of arrays (the 260 dB re 1 microPascal at 1 m); (2) the actual maximum level of array output (the 240-246 dB level) corresponding to 10-20 bar-m (peak-to-peak); (3) the current level of caution indicated by mammal experts (180 dB); and (4) the level of the click of a solenoid which initiates the firing of an air gun (160 dB).

Radiation patterns of arrays. Energy generated by arrays is concentrated vertically down (and vertically up). Amplitude levels emitted horizontally will typically be about 20 dB lower than those emitted vertically. Intermediate values will be recorded at intermediate angles. This is true to the left and right (Figure 5) and in and out of the plane as well. The dB levels in this figure are maximum values 1 m from each individual gun (so no assumption is made about the type of geometric spreading); more typical values are 6-10 dB lower. This focusing of energy is done because seismic surveys try to image much deeper in the earth than the near-surface seafloor and water column. Figures 6 and 7 offer another perspective. Vertically down is 0 and the center of each circle. 90, at the edge of each circle, corresponds to horizontally propagating energy. Colors indicate different energy levels in dB. Each array will have its own specific radiation pattern and the pattern will be different for different frequency bands, varying relatively slowly from low frequencies to high frequencies. The radiation pattern also will be different for different depths of tow of the array.

Figure 6 shows radiation patterns for four frequencies for the 3397-in^3 array when towed at a depth of 3 m. Figure 7 shows the patterns when tow depth is 9 m.

Towing depths of arrays. The seismic industry typically tows arrays 5-10 m below the sea surface to ensure that guns fire below the surface of the water, which can be quite rough at times. If guns are bobbing in and out of the water as they fire, energy transmitted into the earth will be quite variable and particularly meager when guns fire above the surface. Another reason that arrays are towed at some
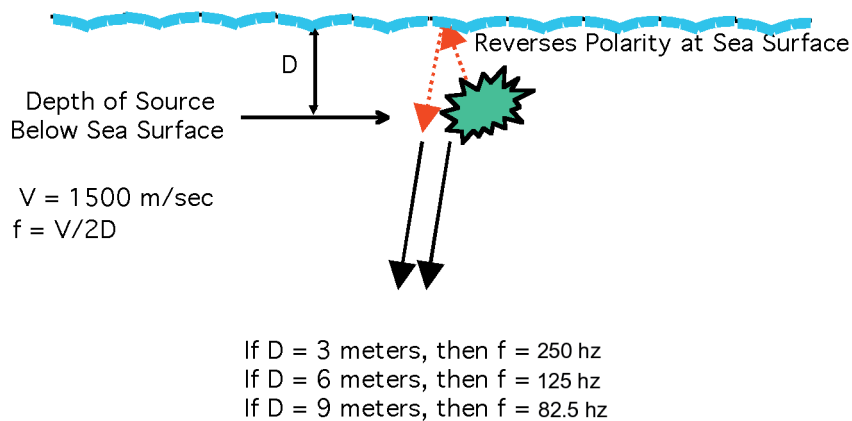

$$V = 1500 \text{ m/sec}$$
$$f = V/2D$$

If D = 3 meters, then f = 250 hz
If D = 6 meters, then f = 125 hz
If D = 9 meters, then f = 82.5 hz
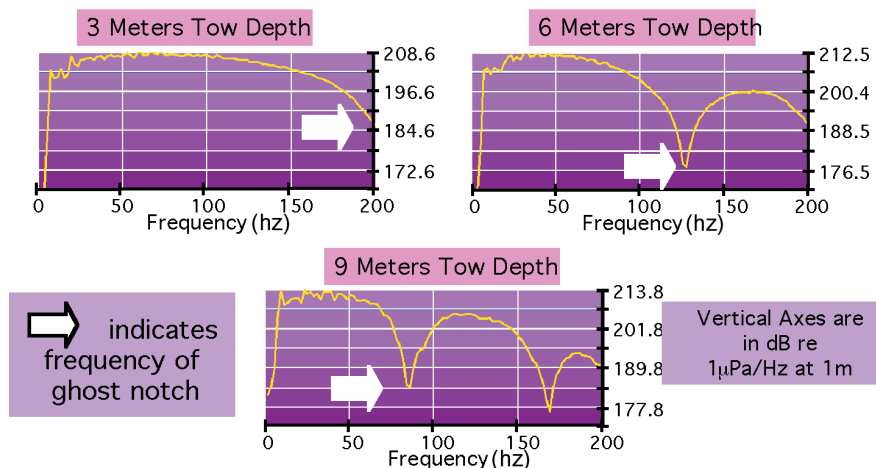
Figure 8. How a ghost notch is formed.

Figure 9. Relationship of depth of tow and ghost notch.

particular depth is to position something called the "ghost notch" outside the frequency band being injected into the earth. The "source ghost" is the energy pulse which travels upward from the gun. It is almost perfectly reflected from the sea surface (i.e., "ghosting" the source pulse), with a reversal in polarity. This ghost will interact with the downgoing energy pulse at a particular frequency that depends on the depth from the source to the sea surface. This is illustrated in Figure 8, which also shows the relationship among the velocity of sound in water, the depth of tow, and the particular frequency that will be missing from energy injected into the earth. Typically, the earth receives and returns (in somewhat usable form) energy in the frequency band of 3-100 Hz. Exact frequencies depend on specific characteristics of equipment and location. But usually, if the ghost notch (that particular frequency, or actually a narrow band of frequencies removed from the downgoing signal) is above 100-125 Hz, everyone is happy. As indicated in Figure 8, if the velocity of sound in water is 1500 m/s, towing an array at 6 m will create a notch at 125

Hz. Towing the array more deeply will cause the notch to descend in the frequency spectrum and towing more shallowly will cause the notch to ascend. Figure 9 shows amplitude spectra associated with a particular array, and what happens to the frequency bandwidth of the data when the array is towed at different depths. Spectra for three tow depths (3 m, 6 m, and 9 m) are shown. One can see clearly the low amplitudes at about 125 Hz for 6 m and about 83.3 Hz for 9-m. At 3 m, amplitudes roll down at 200 Hz but the low point (250 Hz) is off the right side of this display.

Summary. This article has summarized basic information about seismic air-gun arrays, particularly as is applicable to discussions of sound in the oceans and ocean life. It is hoped that this will facilitate understanding and appreciation of the relevance of more "nitty-gritty" details when they are discussed. The most important general points include:

• The radiation pattern of arrays is concentrated downward (and upward), so that amplitude levels

emitted vertically down tend to be at least 15-24 dB larger than levels emitted horizontally.

- Back-calculated values of the output of arrays are just about worthless in the discussion about array effects on marine animals because arrays are not point sources and cannot be treated as such when the issue is the true maximum amplitude of the output.
- More sophisticated modeling is employed by the seismic industry to very accurately model the output of today's arrays.
- Despite the myriad array geometries deployed by the seismic industry, overall output levels (RMS peak-to-peak amplitudes) tend to be 10-20 bar-m, corresponding to 240-246 dB re 1 μPa vertically downward; this means that horizontally emitted amplitudes tend to be 220-230 dB.
- Energy pulse rise-time is 5-10 ms for the positive excursion near the source; during normal operations, arrays are fired every 10-15 s.
- The depth at which an array is towed strongly affects the output spectrum, which means that there is little leeway as to tow depth; generally tow depth will be about 6 m. $\mathbb{E}$

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