AIRGUNS:

Theory and operation

of the marine seismic source

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ABSTRACT

A detailed knowledge of the radiation field of seismic sources is essential to effective source design and source wavefield deconvolution. To understand the principles of airgun theory and operation it is necessary to follow the motion of the air bubble that is produced and released underwater by the airgun. An airgun is a mechanical device that releases a high pressure bubble of air underwater, the expansion of the air bubble generates seismic waves the water that are the source waves of the seismic waves used in reflection seismology.

This monograph is about the motion of the bubble of air in the water that creates the seismic pressure wave called the airgun signature. The relevant physical principles for a single bubble are discussed first, then the dynamic behavior of the bubble is derived from the basic equations of fluid mechanics for the ocean and thermodynamics for the air. The surface ghost reflection part of the signature is derived and its behavior explained.

Once the dynamics of a single bubble is understood, the behavior of an array of airgun bubbles is easy to understand, the reasons for an array are explained and detailed. The discussion then moves on to practical performance specifications in the field.

The different types of airguns are discussed and their mechanical operation explained, this leads to the airgun system, a pneumatic-electrical computer controlled system on board the seismic vessel under the control of the GPS navigation system.

Air Guns: Theory and Operation

by Paul Krail

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Airgun history

To understand the principles of airgun theory and operation it is necessary to follow the motion of the air bubble that is produced and released underwater by the airgun. One of the first theoretical treatments of an underwater air bubble is that of Rayleigh (1917) who was concerned and investigated the bubbles that were created when boiling water for tea. Rayleigh was interested in a description of the sounds emitted by water in a kettle as it comes to the boil, and their explanation as due to the partial or complete collapse of bubbles as they rise through cooler water. The water in Rayleigh's theory was treated as an incompressible liquid. The mental pictures we can form of the bubble in the boiling water and the sounds we hear when the bubble collapses, will be quite instructive when we picture the airgun bubble in the ocean and the seismic sound waves it generates. The sources used in the earliest marine seismic surveys were small explosive charges. The rapidly burning power produced a high pressure bubble in the water. Therefore if we study bubble motion underwater we cover airguns and explosive sources to some extent.

The gas pressure produced by the explosive however is much greater then the airgun. If we assume a spherical charge of dynamite one foot in diameter, to be detonated at its center, we shall have a very rapid conversion of the solid material into high-temperature, high-density gas. The pressure in the interior of the undetonated portion of the solid shell has a peak value of 2 million psi. This is obviously much higher pressure than an airgun and higher than needed to get reflections back from depth in the earth.

During World War II much classified research was done on producing and detecting underwater sound in the ocean which included producing and studying bubble pulses,

and many advances in theory and instrumentation were made. Some of this body of work was subsequently declassified and parts that are of interest to seismic surveying in water covered areas were published by Ewing (1948). Following World War II seismic exploration in the Gulf of Mexico and offshore California were expanded. The source used in these surveys was explosive charges. Use of explosive charges caused environmental concerns and safety problems.

In the mid 1960's Chelminski began manufacturing and testing airguns for use in seismic surveys, and in 1970 he founded Bolt Technology Inc and named his airgun PAR for (pneumatic acoustic repeater), since that time Bolt has continued to improve and develop airguns. In 1975 Chelminski was granted a patent for his airgun design. The need for a replacement for explosive charges was so great that many other marine sources were developed at that time, but none have been found that were as versatile as the airgun.

On the theoretical side advances were also made. Rayleigh had predicted that the next advance in our understanding of the bubble motion would come when the surrounding

water was treated as a compressible liquid. This advance came when Cole's work (1948) was declassified. Keller (1956) succeeded in solving the bubble problem for the incompressible liquid and obtained new predictions from his theory of bubble motion that included the damped oscillations of the gas bubble, that agreed more closely with field measurements. I will cover these advances in more detail in the body of the text.

While the airgun won the competition for most popular marine source it was not without its problems. It was not yet the ideal marine source that the seismic industry desired. Three specific improvements were sought after in airguns; more reliability, more power

and a wider signal bandwidth. Geophysical Services Inc began a development program to address these needs. A radical new design of airgun based on an external sleeve was produced to replace the conventional internal shuttle valve airguns. The prototype field system was tested in March 1984, the first production unit mobilized by mid-year. The innovative design was due to E. R. Harrison and patented by GSI.

Airgun development continues and improved models of the internal shuttle guns have been introduced so that both sleeve guns and internal shuttle guns are popular today.

The SEG recognized the important innovative contributions of both Chelminski and Harrison made to marine source development by awarding Chelminski the Kaufman gold medal in 1975 and the Fessenden award to Harrison in 1998.

Two other innovations in marine pneumatic sources need to be mentioned, both developed by Pascouet and his company Sodara. The first is the watergun, which injects a slug of water into the ocean and produces acoustic energy by the collapse of the air bubble, while airguns rely on the expansion of the bubble. Pascouet was granted a patent

for the hydraulic device to inject a slug of water into the ocean, the patent was granted in 1981. The watergun has the potential to be the ideal marine source but because of engineering difficulties this has not been realized.

The second innovation by Pascouet was the GI gun. The gas injector (GI) airgun first generates a bubble then injects air into the bubble to prevent unwanted bubble oscillations. In 1989 Pascouet presented this new type of source to the seismic industry, and gave a paper Pascouet (1991) explaining his invention and the operation of the GI gun.

A single airgun

Principles of airgun operation

An airgun is a device that releases a high pressure bubble of air underwater as a source of energy to generate the acoustic/pressure waves that are used in seismic reflection surveys. The pressure variation in the water as a function of time caused by the high pressure bubble is called the airgun signature. To understand the nature of the signature of the airgun we must look at the subsequent motion of the bubble following its release, since this controls the detailed features of the signature.

Underwater photographs of the bubble (see Figure 1) show that upon release of the air from the airgun the bubble assumes a nearly spherical shape and maintains that shape throughout its subsequent motion. Thus we are allowed to treat the bubble as a sphere of air.

Since the initial air pressure within the bubble greatly exceeds the hydrostatic pressure in the surrounding water, the bubble expands rapidly. A steep fronted shock wave in the water near the bubble will be generated and radiated by this rapid expansion.

Bubble Motion

As a result of the bubble motion there is a radial displacement of the water from the center of the bubble, and a pressure disturbance is propagated outward in the water. As the bubble expands the pressure of the air in the bubble drops until it falls to that of the surrounding water, but inertia causes it to over expand so that the air pressure in the bubble is now less than the hydrostatic pressure of the surrounding water. Then the greatly expanded bubble begins to contract due to the pressure of the surrounding water. The result is that the bubble is squeezed down to nearly it original volume. The process of expansion and contraction continues so that the bubble oscillates through many cycles. As the bubble oscillates and its pressure varies, pressure waves are transmitted outward into the water.
The terms ‘near-field’ and ‘far-field’ radiation zones are associated with some confusion in terms of seismic source description because different definitions are used. In physics if the source dimensions are of the order d, and the wavelength is L=c/f, where c is the velocity of sound in water, f is frequency and r is distance from source to obsevation point (see Figure 1). Then there are three spatial regions of interest:

The near zone	$d << r << L$
The intermediate zone	$d << r \sim L$
The far zone	$d << L << r.$

If we place a pressure measuring sensor (hydrophone) near the bubble whose position is shown in Figure 1, a near field signature shown in Figure 2 will be recorded. If we examine this near-field hydrophone signature we see that the pressure after reaching a peak falls to negative values below the hydrostatic pressure. The bubble oscillation

amplitude is damped down as time progresses and the bubble period is not constant from one cycle to another. This tells us the bubble motion is not simple harmonic motion. We might guess that as the bubble radiates energy stored in the air into the water the bubble is no longer able to expand as much nor oscillate with the same frequency for each succeeding cycle. The initial release produces the highest amplitude, after that the pressure amplitude and period decrease with time. The surface ghost whose amplitude is very small on the near field signature is due to the location of the near-field hydrophone.

Theory of the bubble motion

In order to predict the airgun signature and its dependence on changes in air pressure, gun volume and depth of tow it is necessary to have a theory that predicts the pressure



Exhaust bubble of a conventional air gun.



Exhaust bubble of a Sleeve Gun.

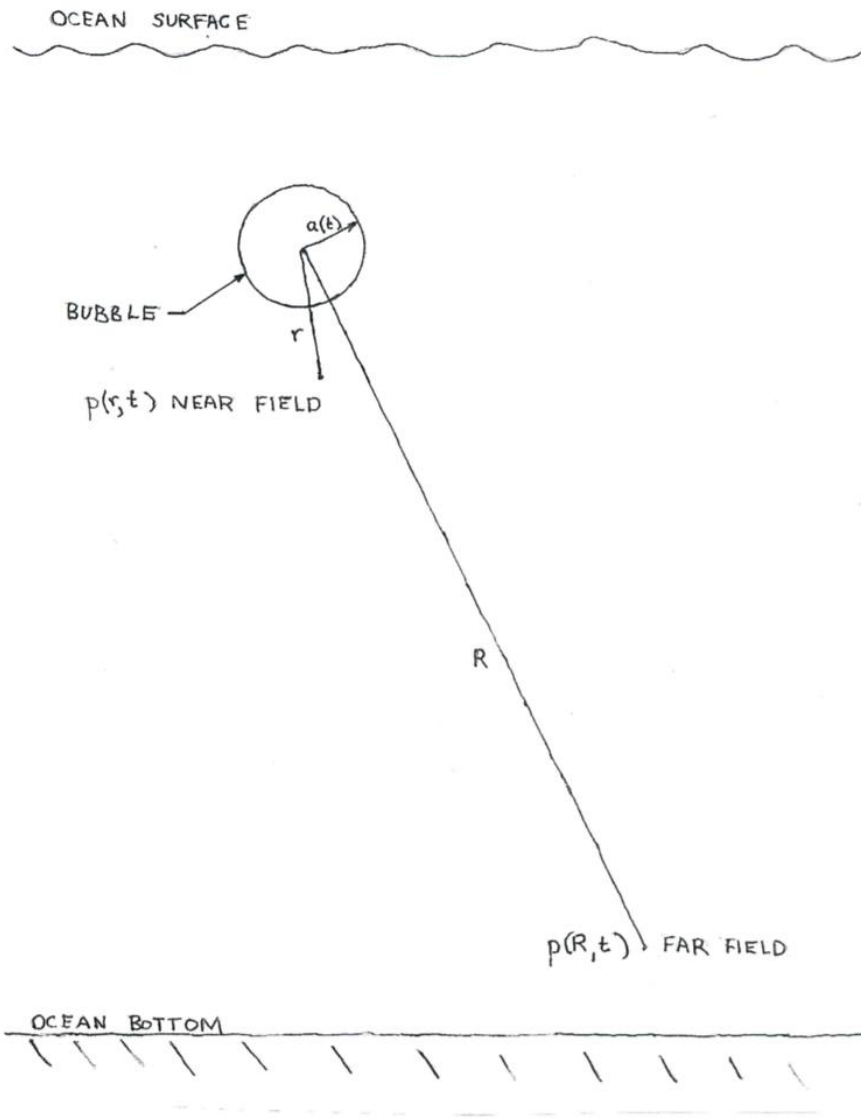


Figure 1. The physical setup

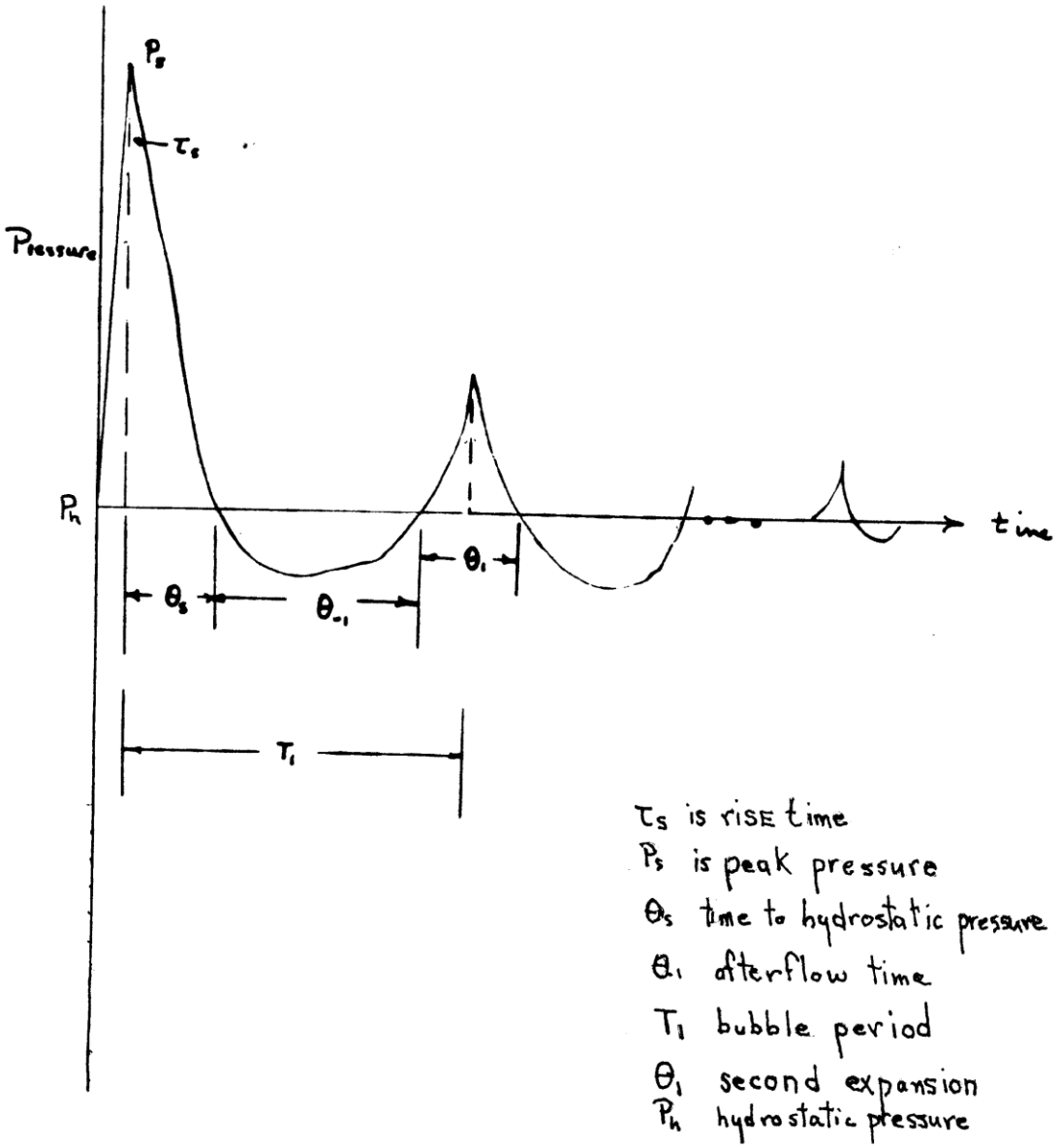


Figure 2. The near field pressure vs. time

signature behavior for given values of the gun parameters. Theoretical treatment of the underwater bubble requires an interesting combination of two branches of classical physics. The gas bubble behavior is treated by thermodynamics and the acoustic waves in the water are treated by hydrodynamics.

The gas behavior

The motion of the air is modeled physically by treating the air as an ideal gas, and because the gas expands so rapidly we can treat the expansion as adiabatic by assuming no heat is transferred between the air and the water. Of course the temperature of the gas changes radically as it expands. This adiabatic assumption is the same one made in the transfer of particle motion in sound propagation. The gas expansion is also assumed quasi-static i.e. the gas at each stage is in an equilibrium state. Since the volume of a sphere of radius a is 4/3pi a^3 we can use the gas law to relate the radius a(t) at any later time to the initial radius a(0).
The state of the gas P,V at every instant is known if its initial pressure P_i and initial volume V_i are known, and by the equation of state for the gas is

$$P_i V_i^g = P_f V_f^g$$

Where g is the ratio of specific heats of the gas (air).

The fluid motion

The motion of the fluid driven by the gas expansion is described by the equations of hydrodynamics. The equation of continuity expresses the relation between the mass of the fluid in a volume and is related to the time rate of change of the density. We shall assume the fluid particles in motion undergo steady flow along streamlines and their motion can be described by Bernoulli's equation. Bernoulli's equation relates the pressure change in a fluid with the resultant change in particle velocity and is Newton's second law applied to a fluid undergoing steady flow.
A major simplification in these equations occurs because we only have to consider motion in one dimension, with the origin of our spherical coordinate system at the center of the gas bubble we only have motion in the radial direction.

The two fluid motion equations together with gas equation constitutes a system of differential equations that describe the gas inside the bubble and the motion of the water particles outside the bubble. However an analytical solution to this system has not been found so we will resort to a numerical solution to the system of equations. We know outside the bubble the two equations for the fluid will reduce to the acoustic wave equation for radial motion

$$\nabla^2\varphi - \frac{1}{c^2}\varphi_{tt} = 0$$

Boundary conditions

At the bubble surface these equations must give the same answer for pressure and particle velocity. In other words the pressure of the gas inside the bubble must equal the pressure in the water at the bubble surface, and velocity of the water particles must equal the rate of change with time of the bubble radius. These conditions at the bubble surface are known as boundary conditions. If we put the solution of the wave equation and the gas equation in the boundary conditions we will obtain a differential equation for the bubble radius as a function of time. Figure 3 shows the equation of motion for the gas bubble and the numerical setup of this equation as input to Mathcad. Figure 4 shows the bubble radius as a function of time, found by solving the equation in Figure 3.
If we plug the radius-time values back into the wave equation we will get a pressure-time plot or a signature:

$$\frac{\partial a}{\partial t} = \varphi_t$$

Signature refers to the wave-shape in a pressure-time recording of a source, and characterizes the output of a particular airgun or array of airguns. We have already described the near and far radiation fields and these definitions apply to the near and far signatures which are the pressure-time measurements made in these zones.

The bubble motion equation
The airgun gas bubble motion in a compressable fluid is described by the following differential equation which we solve by Runge Kutta numerical approximation

$$\left(\frac{dy}{dt} - c\right)\cdot\left[y\cdot\frac{d^2y}{dt^2} + \frac{3}{2}\cdot\left(\frac{dy}{dt}\right)^2 - y^{-3\,g} + 1\right] - \left(\frac{dy}{dt}\right)^3 - (3\cdot g - 2)\cdot y^{-(3\cdot g)}\cdot\frac{dy}{dt} - 2\cdot\frac{dy}{dt} := 0$$

The constants and initial conditions are

$$c := 94.26 \qquad g := 1.33 \qquad y := \begin{bmatrix} 3.6 \\ 0 \end{bmatrix}$$

The second differential equation is expressed as a vector with the two elements the first and second derivatives

$$D(t,y) := \begin{bmatrix} y_1 \\ \dfrac{(3\cdot g - 2)\cdot(y_0)^{-3\cdot g}\cdot y_1 + 2\cdot y_1 + (y_1)^3}{y_0\cdot(y_1 - c)} + \left[\dfrac{\frac{-3}{2}\cdot(y_1)^2 + (y_0)^{-3\cdot g} - 1}{y_0}\right] \end{bmatrix}$$

Evaluate the solution at 9000 points between time zero and 35 units

$$Z := \text{rkfixed}(y, 0, 35, 9000, D) \qquad n := 0 .. 8000$$

Figure 3. The bubble motion equation

The bubble radius as a function of time

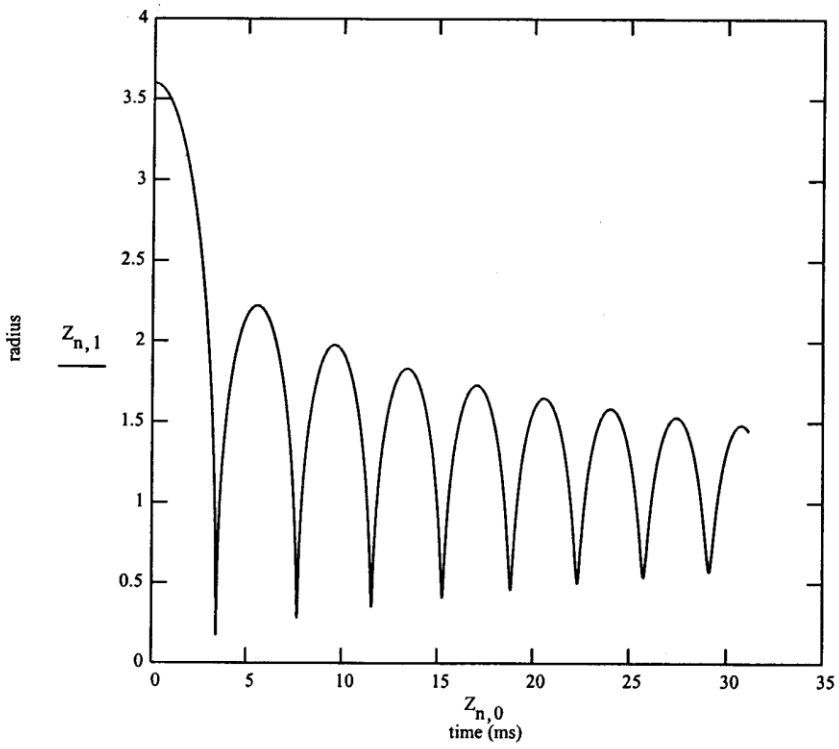


Figure 4. The bubble radius as a function of time

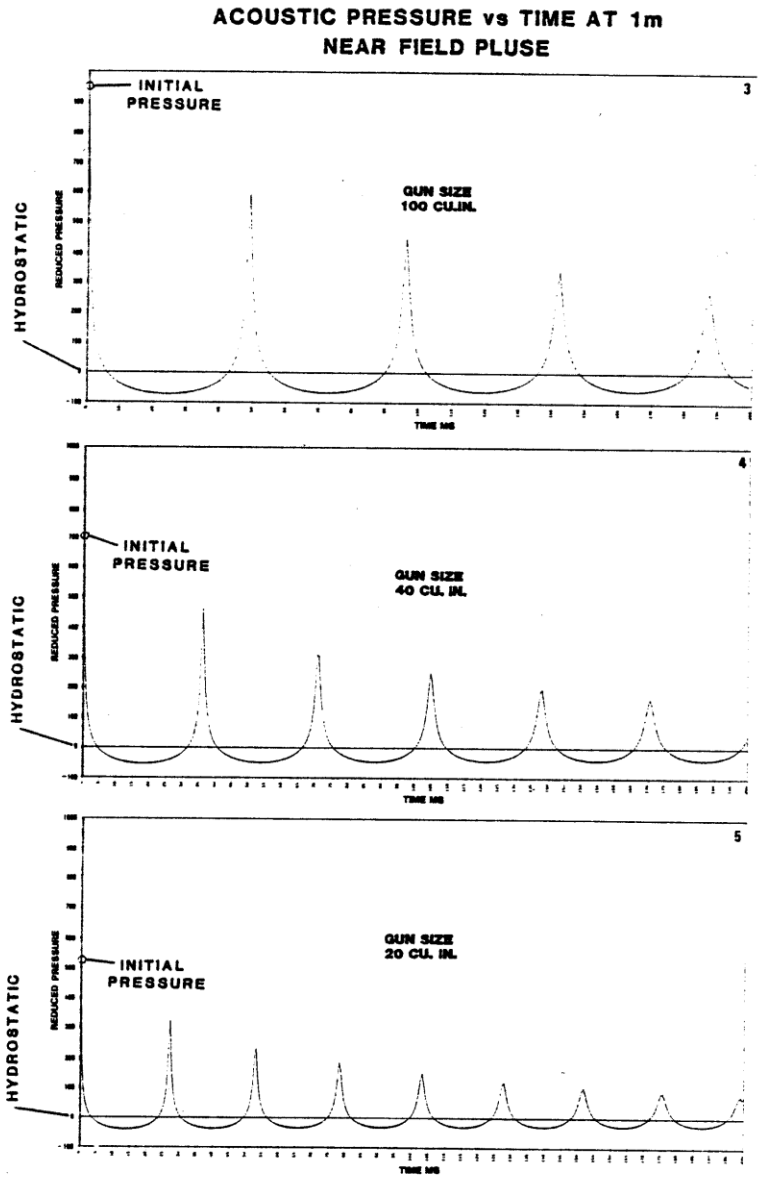
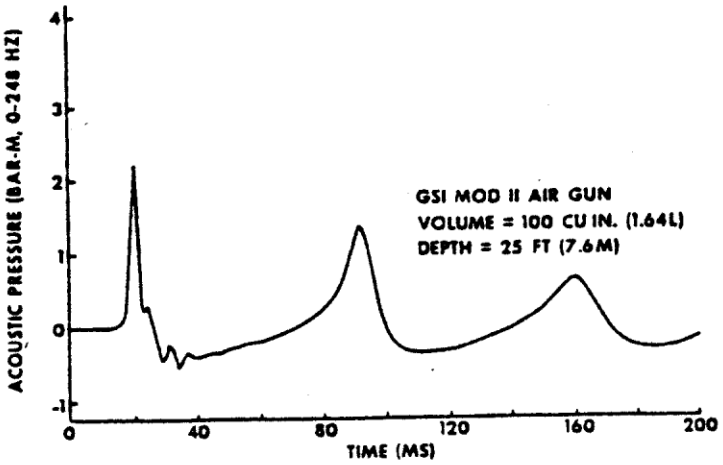
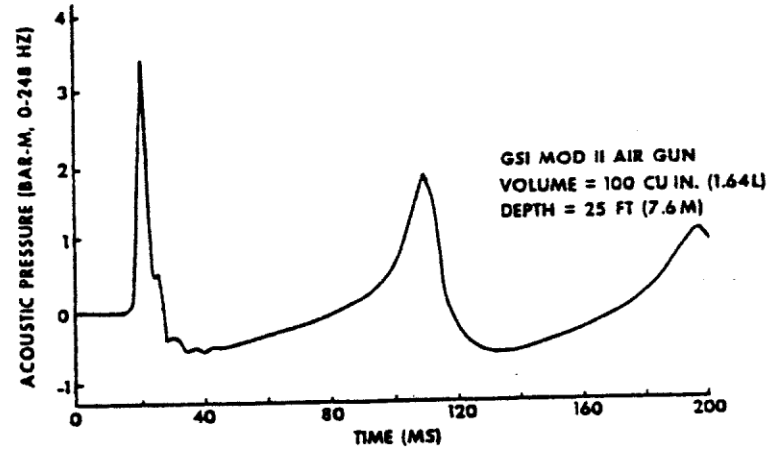


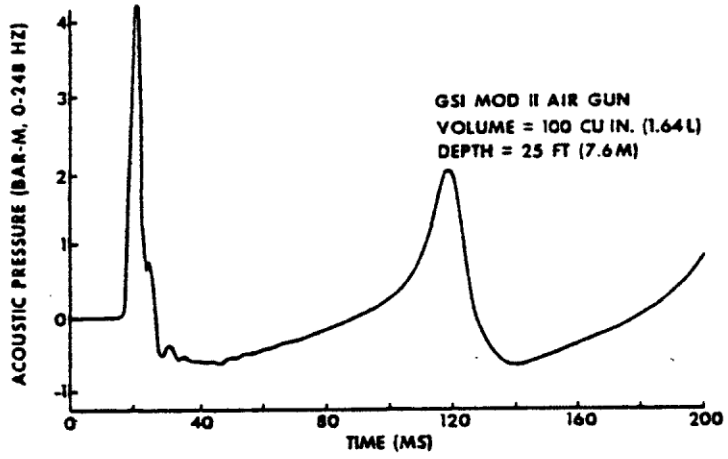
Figure 5. Near-field signature simulation vs. gun volume



Acoustic signature at 2000 psi (13.8 MPa).



Acoustic signature at 4000 psi (27.6 MPa).



Acoustic signature at 6000 psi (41.4 MPa).

Figure 6. Near-field signature measurement vs. gun pressure

Airgun Parametersϕ

The volume of air in the bubble and its pressure depends on the size of the airgun used and the pressure at which it is operated. The pressure signature, likewise show the effects of these two parameters. In Figure 5 we show a simulated near-field signatures of a 20, 40 and 100 cubic inch volume guns. Examination of the figure shows that the larger the volume the larger the initial pressure and the increase in bubble period. In Figure 6 we have near-field measurements of a 100 cubic inch gun operated at 2000, 4000 and 6000 psi. Examination of Figure 6 shows the peak amplitude of the pressure increases with operating pressure but the bubble period does not increase in proportion to the pressure increase.
Airgun design engineers usually study the near field signature to discern details of airgun operation.

The surface ghost

A single source firing below the surface of the ocean emits omni-directional energy until the upward traveling wave is reflected at the air-water interface at the ocean's surface. The initial down-going pulse is followed by a delayed mirror image pulse of opposite amplitude. The surface reflection coefficient is nearly 100% and non-refractive so the delayed pulse's amplitude is nearly equal to the initial pulse at all angles of reflection. The reflection of the source radiation at the sea surface can not be separated from the radiation field, and as such is considered to be a part of the source signature.
The down-going initial pulse and its surface reflection may be treated as emission from a point source at the bubble location and an image source above the sea surface, as in Figure 7. For this reason the image source is sometimes referred to as the surface ghost reflection.
When the hydrophone sensor is placed vertically below, in the far-field radiation zone the recorded pressure-time signature shows clearly the presence of the surface ghost as in the upper graph of Figure 8. The surface ghost has opposite polarity to the primary and is time delayed by its travel path in the sea from the bubble to the surface and back again. The lower graph in Figure 8 is the amplitude spectrum which shows a peak at 10 Hz which is the bubble period and its harmonics, the peak at 60 Hz is electrical leakage from the boats power system (an unusal occurance).
Examination of the far-field signature shows that the surface ghost is superposed over the bubble pulse but it has reversed polarity and is delayed in time with respect to the primary pulse by x/c where c is the velocity of sound in water. The time delay of the ghost T(ϕ), is therefore given by

$$T(\phi) = \frac{2h\cos(\phi)}{c}$$

where h is the source depth. The time delay is a function of the angle ϕ. In fact, the majority of the seismic energy recorded in seismic experiments will have originated at angles very close to the vertical, giving this direction special significance. In the vertical

direction the ghost pulse will be delayed in time by 2h/c. The composite wavelet at any angle ϕ is the sum of the primary and an image pulse delayed in time by $T(\phi)$ and reversed in polarity. The ghost pulse of a vertically traveling far-field signature is delayed in time by 2h/c, in the frequency domain the ghost notch occurs at a frequency $f = 1/T = c/2h$.

The dipole

Measurements of the far-field pulse for a localized source shows that the amplitude of the signature wavelet varies with a directivity dependence like that of $\cos(\phi)$. Thus the primary pulse and its ghost reflection behave like a dipole, and the incident pulse in marine surveys varies in amplitude and in phase with the incident angle.

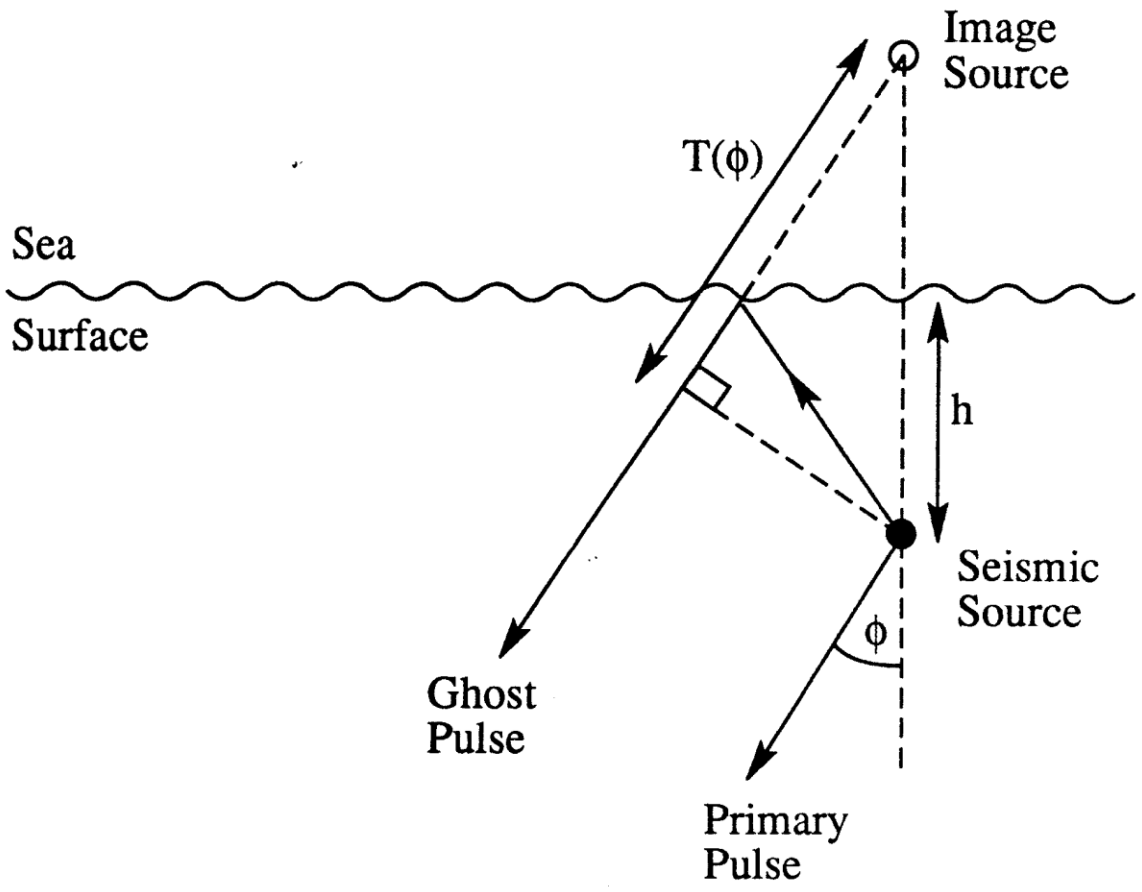


Figure 7. The surface ghost (image source)

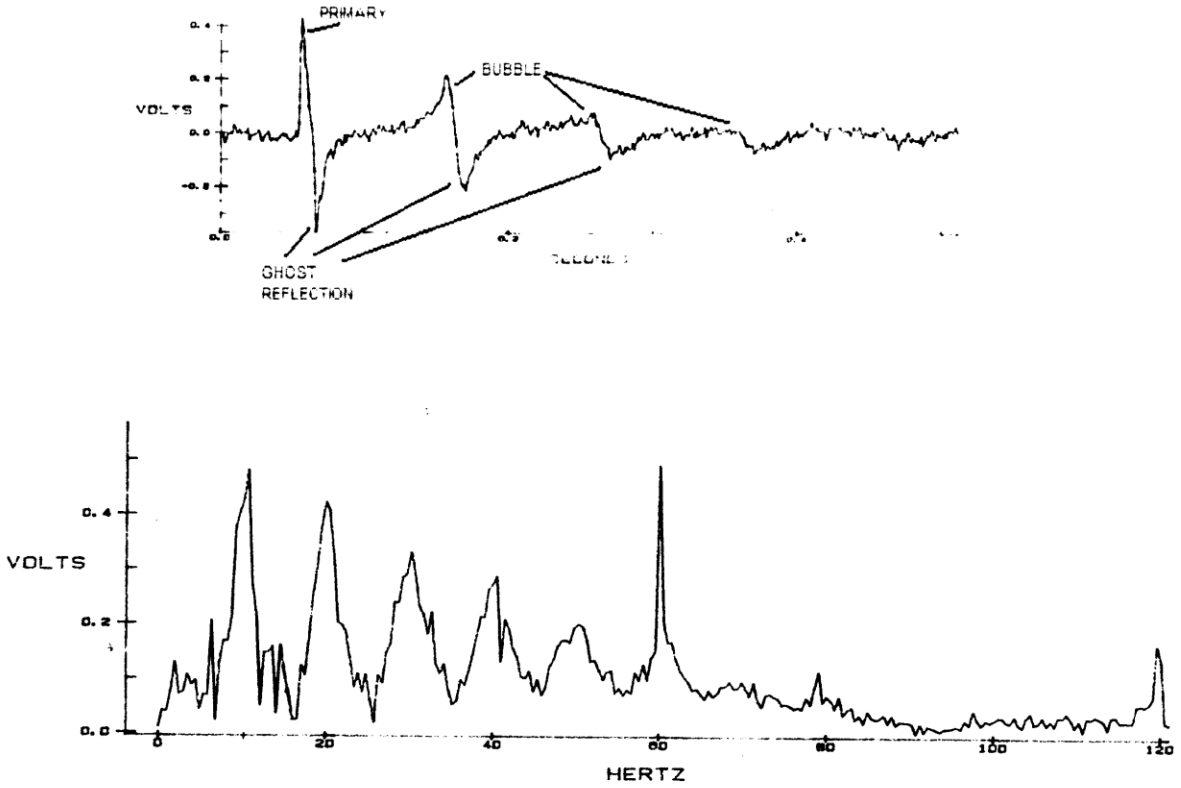


Figure 8. Far-field signature vs. time for 300 cubic inch volume gun

Arrays of airguns

Airgun array performance

The largest single airgun tested by us, with a volume of 2000 cubic inches, does not put out enough energy to get back measurable reflection amplitude from three miles below the surface of the earth. An even more serious drawback to single airgun use as a seismic source is that a single airgun produces a pressure pulse that oscillates through several cycles. Thus, the reflected pulse will oscillate through several cycles and it is impossible to separate the primary from the secondary peaks. What is desired, for seismic exploration is a pressure spike, not a continuous wave train of pressure variation as seen in Figure 8.

The amplitude deficiency and the oscillation problem are both solved by using arrays of airguns. The multi-gun array source has increased amplitude due to the increased number of guns. We have seen that different volume size airguns produce bubbles with different periods of oscillation. Thus if we build a multi-gun array with different volume airguns, and fire all the guns simultaneously, we solve both problems.

The superposition of each guns signature builds up the amplitude of the first peak in the pressure pulse. The subsequent peaks cancel, they are out of phase because each different volume gun has a different period of oscillation.

Figure 9 is a diagram of a six gun array where each gun is a different volume as labeled and deployed in the ocean at 7.5 meters below the surface. Figure 10 shows the pressure pulses of each gun in Figure 9, fired individually and then all guns fired simultaneously to illustrate the above discussion. The far-field signature of an array of airguns looks quite different than a singe airgun. If we compare Figure 10, the far-field signature of the array with Figure 8 for a single gun, we see that the bubble oscillations have been greatly reduced.

The gun signature of the entire array is plotted at the bottom in Figure 10. Examination of this signature shows the cancellation properties of the array to the bubble oscillations in the individual guns and the amplitude buildup in the primary pulse.

The initial large positive pulse is called the primary, the large negative peak is the ghost reflection, the lower amplitude wiggles that follow the primary are referred to collectively as the bubble. Each positive peak is followed by a negative peak because of the reflection at the sea surface, the so called ghost. If the guns and thus the bubbles are of different volumes, then the bubble peaks occur at different times. By a suitable mix of volumes the bubble pulses of the different bubbles can be made to cancel each other in the far-field. In a weakly interacting tuned array the volumes are chosen so that the bubble pulse of one gun is cancelled by the ghost of the bubble pulse of a smaller gun. Because the guns are at the same depth the ghost pulse occurs at the same time in each signature. A gun array designed as described above is said to be tuned to suppress the bubble oscillations.

Efficiency of airguns

It is interesting to consider and compare the efficiency of different types of airgun arrays. Published results indicate that the cost of attenuating the bubble oscillation results in about 60% efficiency for a weakly interacting tuned array and for the GI gun (to be discussed in the section on Types of airguns) . By comparing the primary amplitude of an un-tuned gun with the primary amplitude of a tuned gun we see that the amplitude of the tuned gun is decreased to 60% of the value of the un-tuned gun. What this says is that the cost of tuning that is of getting rid of the bubble oscillation reduces the amplitude of the primary to 60%. This same effect is found in the GI gun also.

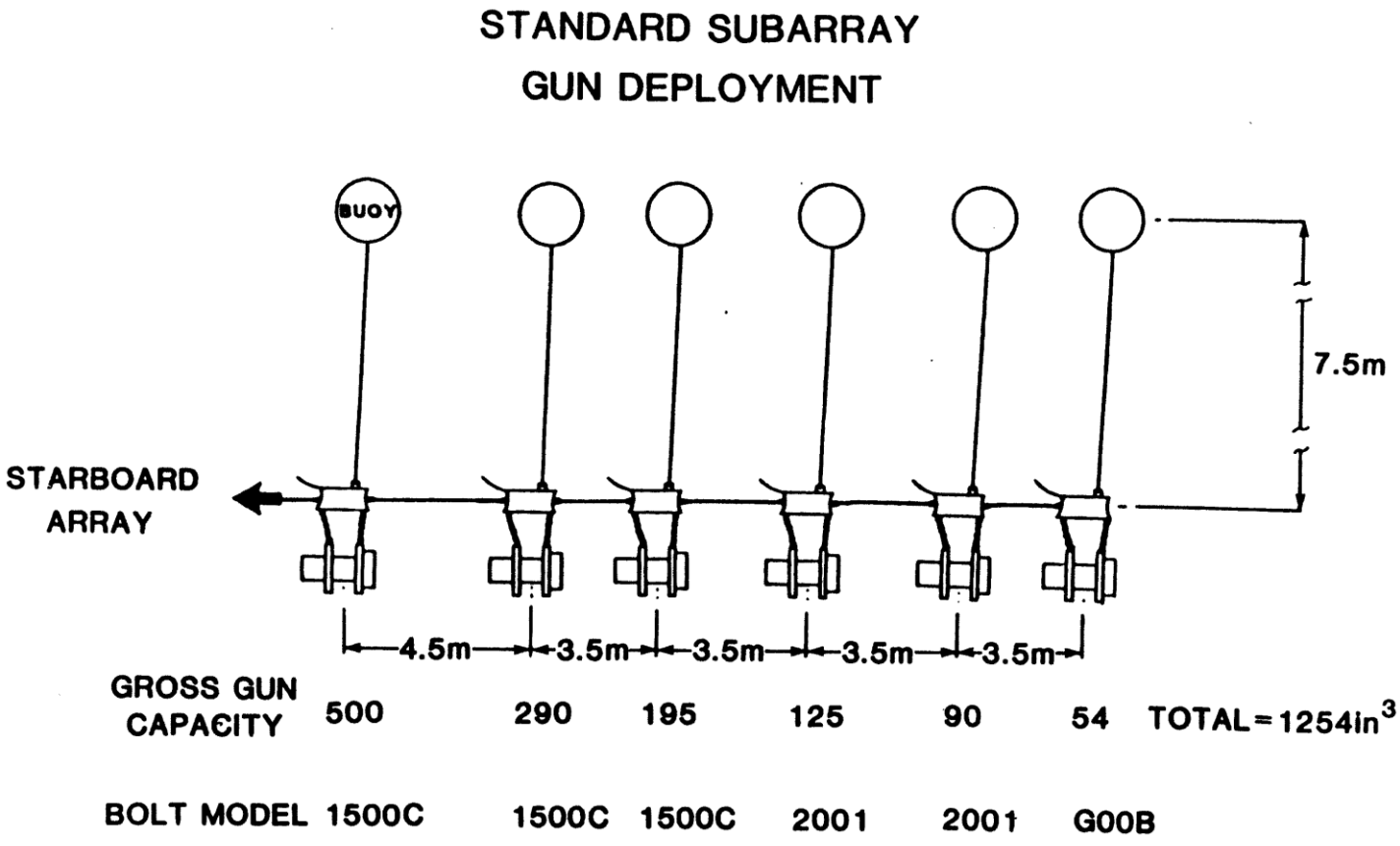
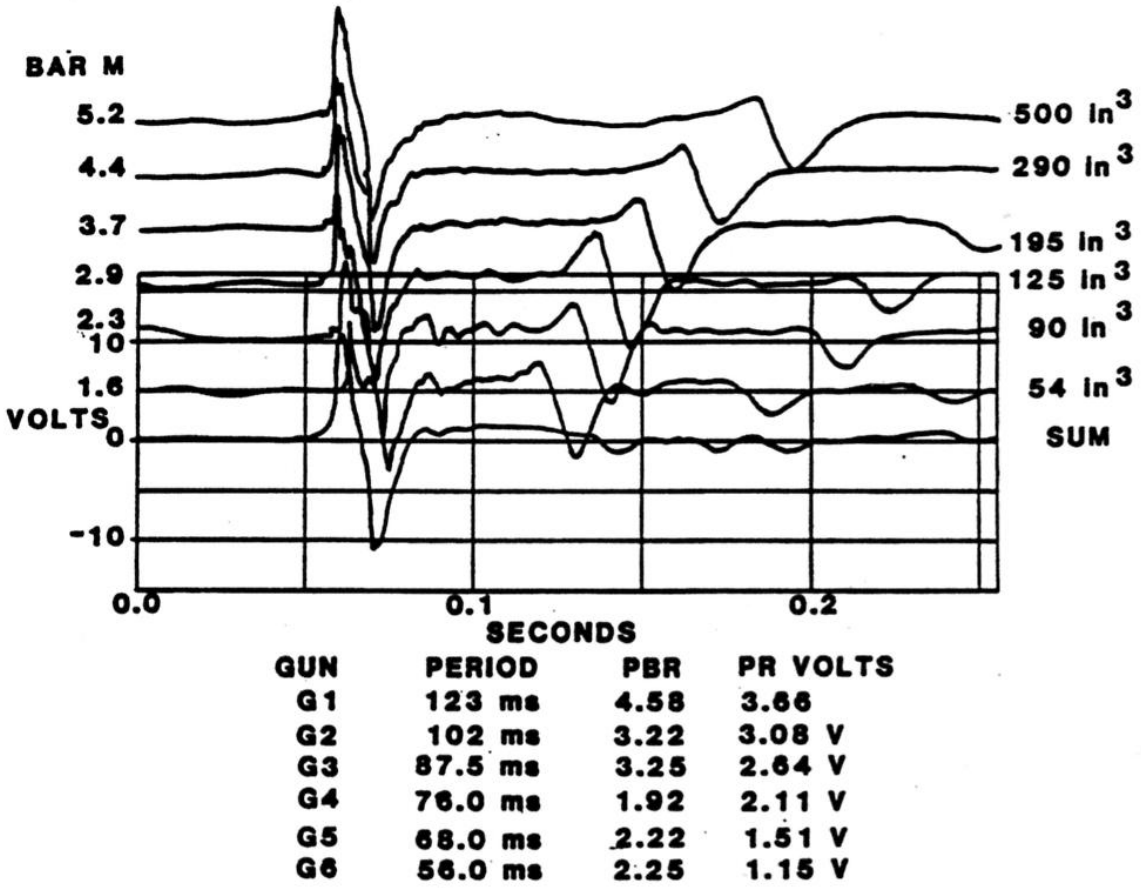


Figure 9. A six gun array of airguns



GUN	PERIOD	PBR	PR VOLTS
G1	123 ms	4.58	3.66
G2	102 ms	3.22	3.08 V
G3	87.5 ms	3.25	2.64 V
G4	76.0 ms	1.92	2.11 V
G5	68.0 ms	2.22	1.51 V
G6	56.0 ms	2.25	1.15 V

Figure 10. The signatures of the guns in Figure 6

FARFIELD SIGNATURE

VESSEL :M/V A.NEMCHINOV
DATE OF TEST :01/05/91
CREW :1006420/231AVGD01
LOCATION :NORTH SEA
TYPE OF SOURCE:SLEEVE GUN
VOLUME :3000CUIN
NUMBER OF GUNS:32
FROM REC. 9999 TO REC. 9999
AVERAGE OF 1 SIGNATURES
DISTANCE SOURCE-PHONE (M) : 1

ENABLED GUN.....
DROP OUT GUN.....

DEPTH OF SOURCE:7.5M
FIRING PRESSURE:2000PSI
RECORDER :SN358DMX
SAMPLING RATE :1MS
LC FILTER :OUT
HC FILTER :154.4HZ 72DB/OCT
HYDROPHONE :REFTEK 17
SENSITIVITY :7.50V/MPA
STRENGTH+P/B RATIO IN P-P MODE
STRENGTH (IN MEGA PA-M) : 9.531
PRIMARY/BUBBLE RATIO : 15.892
BUBBLE PERIOD (IN MS) : 59

NB:.....4xFULL ARRAY(4x750CUIN)
NB:.....

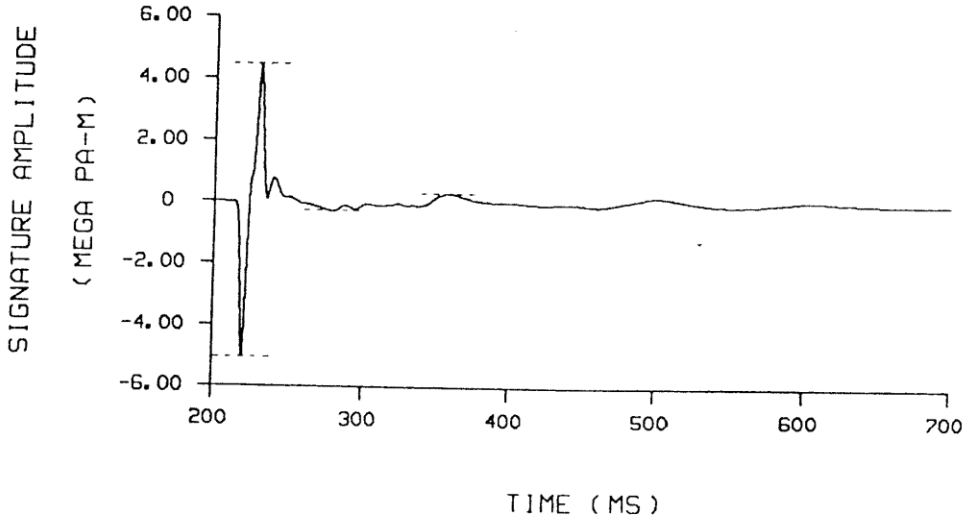


Figure 11. A far-field recorded signature

Performance Specifications

The signature of the marine seismic source depends not only on the characteristics of the individual elements of the source but also on the details of the geometry of the whole source system. The ghost time delay depends on the depth of deployment, as shown in Figure 12, where the negative ghost pulse occurs closer to the primary in time as the tow depth is decreased. On the right of Figure 12 we see in the amplitude spectrum that the ghost notch moves to higher frequency as the tow depth is decreased. Current practice is to tow the guns at about 6m as the places the ghost notch above the seismic frequency. This is another example that if the signature of the array is to be stable, the geometry must be stable. We will assume that the ocean engineering of the towing apparatus has resulted in a stable geometry. There are other factors which control source stability which are:

1. The timing synchronization accuracy of individual elements in an array.
2. The stability of the geometry
3. The repeatability of the individual elements
4. The weather

Time Synchronization

Time synchronization of the individual elements of an array is under the control of the "on-board" computer called the gun controller, which receives input from the internal sensor in the gun and from a near field hydrophone. The mechanical wear on guns of the same type means that two copies the same model gun will fire at different times upon receiving the fire command at the same time. The required accuracy of the timing depends on the gun timing sensor which may be a pressure transducer, hydrophone or magnetic position sensor. In general, the timing errors must be small compared to the duration of the primary pulse of the individual sources. For most of the older sources, the error tolerance is of the order of 1 millisecond or less. The error tolerance is of the order of +/-100 microseconds for the "DigiSHOT" system. The aim of accurate timing is to align the primary peaks in the emitted pulse of each individual element. The gun control computer must compensate for the fact that the fire time and the emission of the pulse may not be the same for each element in the array, even for guns of the same size but different age/wear/temperature/air contamination. There is usually a time delay between triggering a source and that source firing. The time delay between triggering and firing may drift with time/wear/temperature/voltage.
The gun control computer encompasses all the above effects in that it detects the true start times of the primary peaks or zero crossings as some gun vendors use a pressure sensor or position sensor, and time shifts accordingly. Continuous monitoring by the on-board gun control computer makes adjustment corrects for time drift in the actual firing of the guns.

Stability

The stability of the geometry is controlled by its design and ability to maintain planned element spacing and tow depth in different sea states. Marine engineers know that the sea can hold unpleasant surprises for those who are not familiar with her ways. The floatation for the gun arrays and the cables and chains of the suspension harness are subjected to the relentless action of sea surface which pulls and tugs on these, and causes wear and breakage not seen on any engineering design for on-shore use. The electrical cables where they are required to make 90 degree turns are especially sensitive to this constant motion.

The effects of weather

The sea surface changes from flat calm to increasingly larger sea surface waves due to increased wind speed. Increased wave size causes two main effects, 1) source geometry stability deteriorates, and 2) the plane surface approximation that the air-sea surface reflection coefficient is –1 no longer holds.
The variation in the reflection coefficient of the sea surface has a major effect on the source signature. In a vertically traveling far field pulse, about half the energy is from the flat sea surface reflection. The effect of a rough surface will be to produce a composite smoothed out pulse where the amplitude of the ghost reflection is greatly reduced.
In Figure 12A at the top, the far-field signature was made in good weather, with a near flat sea surface. The bottom measurement was made in poor weather. The reduced ghost amplitude is due to the poor reflection properties of the rough sea surface.

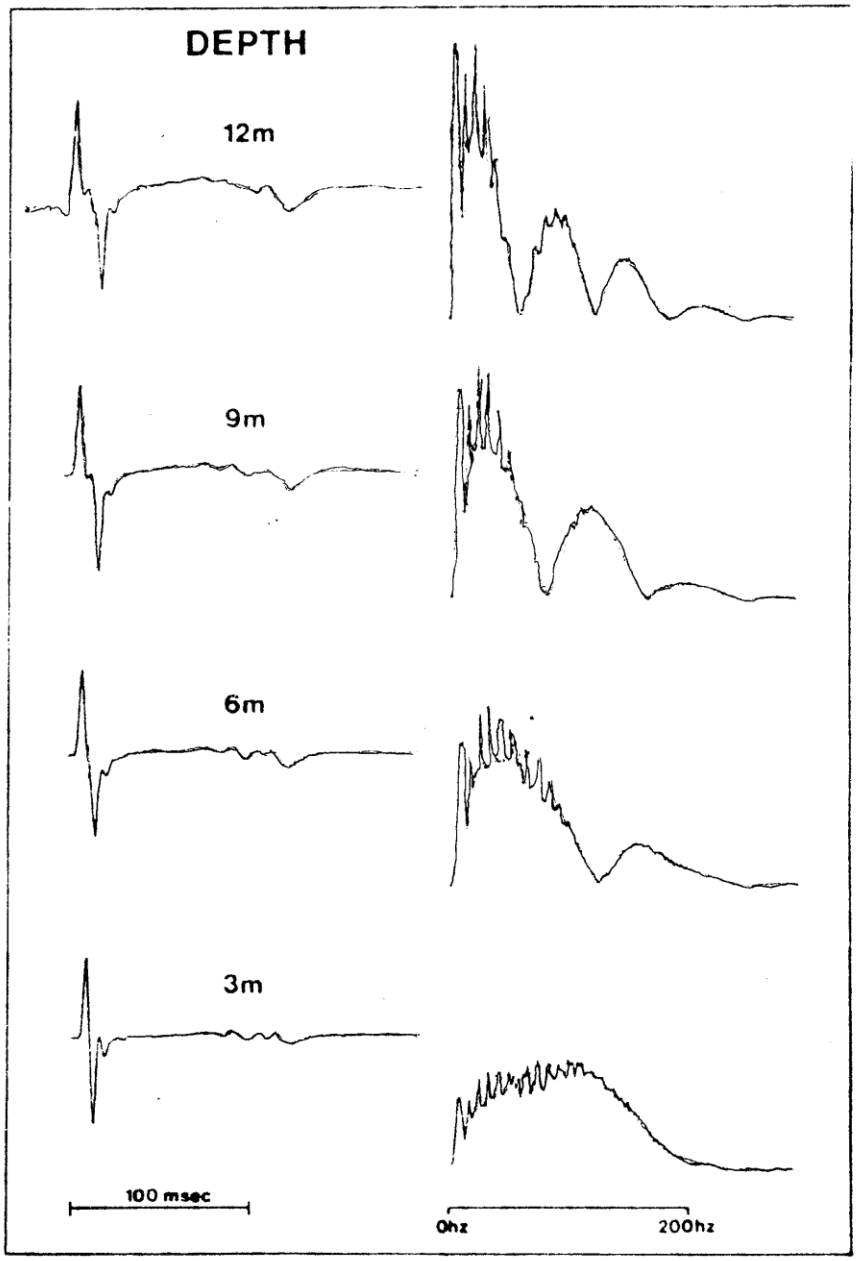


Figure 12. Signature variation with depth of tow

The

24

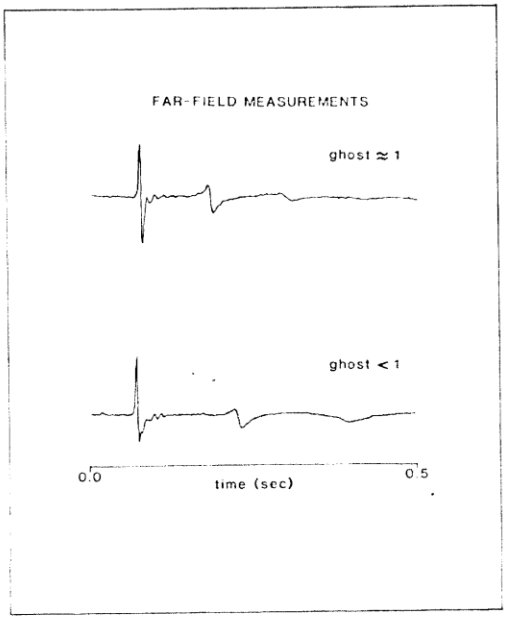


Figure 12A. The effect of weather on the ghost pulse amplitude.

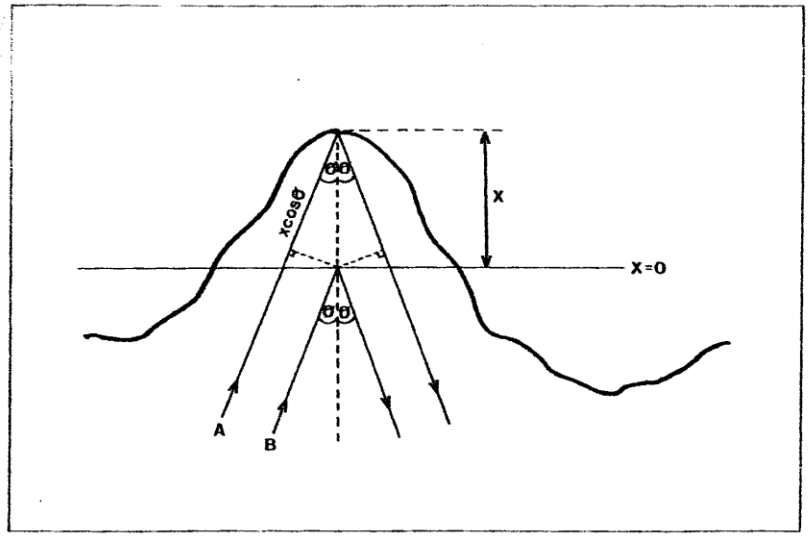
The effect a rough sea surface has on the surface reflection coefficient can be considered by taking two rays, one from a flat surface at mean sea level and the other from a wave of height x (see Figure 12B). The travel path difference between these two rays is 2x cos(0). The phase difference pd, is simply the path difference divided by the wavelength and is given by

$$pd = \frac{-2x\, f \cos(0)}{c},$$

where f and c are the frequency and velocity respectively. Now the wave elevation x, will be assumed to be Gaussian, thus we can derive an average reflection for the sea surface with waves

$$Rave = R0 \exp(-2f\, pd \cos(0)/c).$$

Where pd is the RMS amplitude of the sea wave distribution, and R0 is the flat surface reflectivity.
Lets consider a seismic signature pulse with a center frequency of 20 Hz. This pulse is reflected first by a flat calm sea surface which has a reflection coefficient of -1. Then we want to compare this with the same pulse reflected from a sea surface with 10 foot waves. Substitution of these values in the above equation Rave, reveals that the average amplitude of the ghost reflection is reduced to 45 % of the flat sea reflection by the sea surface with 10 foot waves.



A simple model of a wavy surface in which the path difference between rays A and B equals 2xcos(θ).

Figure 12B A simple model of a wavy surface to compute the path difference

Array Simulation

It is much cheaper to design an airgun array by using computer simulation rather than by performing numerous experiments in the field. However, you must be sure the simulations are accurate. In the literature it is claimed that the use of computer simulation is now well established in the design of conventional, weakly interacting arrays where the airguns are over about one meter apart. We shall discuss airgun interaction in a later section and also discuss strongly interacting airguns when we talk about clustered airguns.
The array simulation is performed by input of the (x,y) location, the gun volume, the air pressure and the tow depth of each gun in the array as shown in Figure 13. The simulation then uses the bubble motion equation discussed earlier to compute the composite of all the guns and outputs the far-field signature. The output signature is shown in Figure 14. The amplitude of the signature is plotted in bar-m. Since the amplitude of a spherical wave decreases as 1/R from the center of the source the amplitude is normalized to that of one meter from the array, thus bar-m (bar is a pressure unit).
The performance of the array is measured by three parameters:

1. The peak to trough amplitude
2. The primary to bubble ratio (called P/B)
3. The frequency spectrum

The peak to trough amplitude is a measure of the energy output by the array. The primary to bubble ratio is a measure of how well the array design cancels out the bubble oscillations. This is said to be how well tuned the array is. The frequency spectrum in Figure 15, shows where the ghost notch lies and allows the designer to judge how broad band the source is and where the high and low frequency cutoff lie.

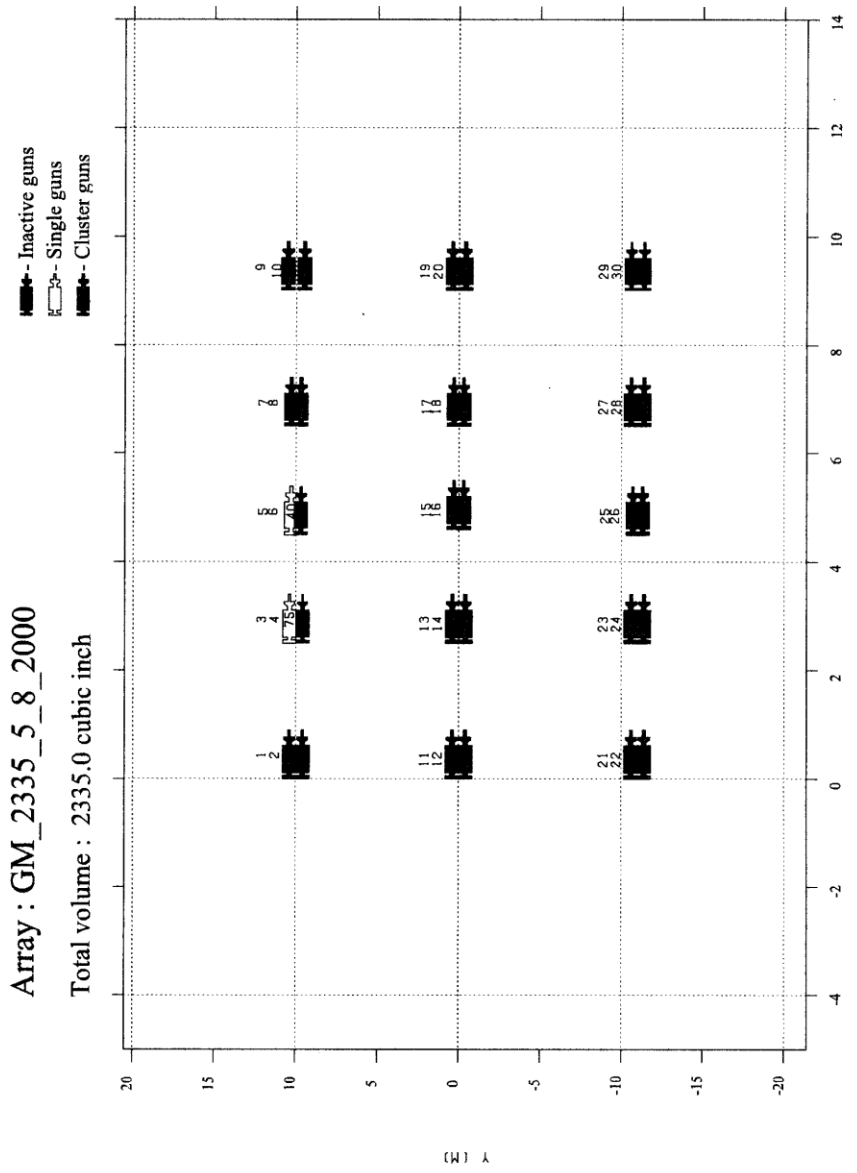


Figure 13. The plan geometry of the airgun array

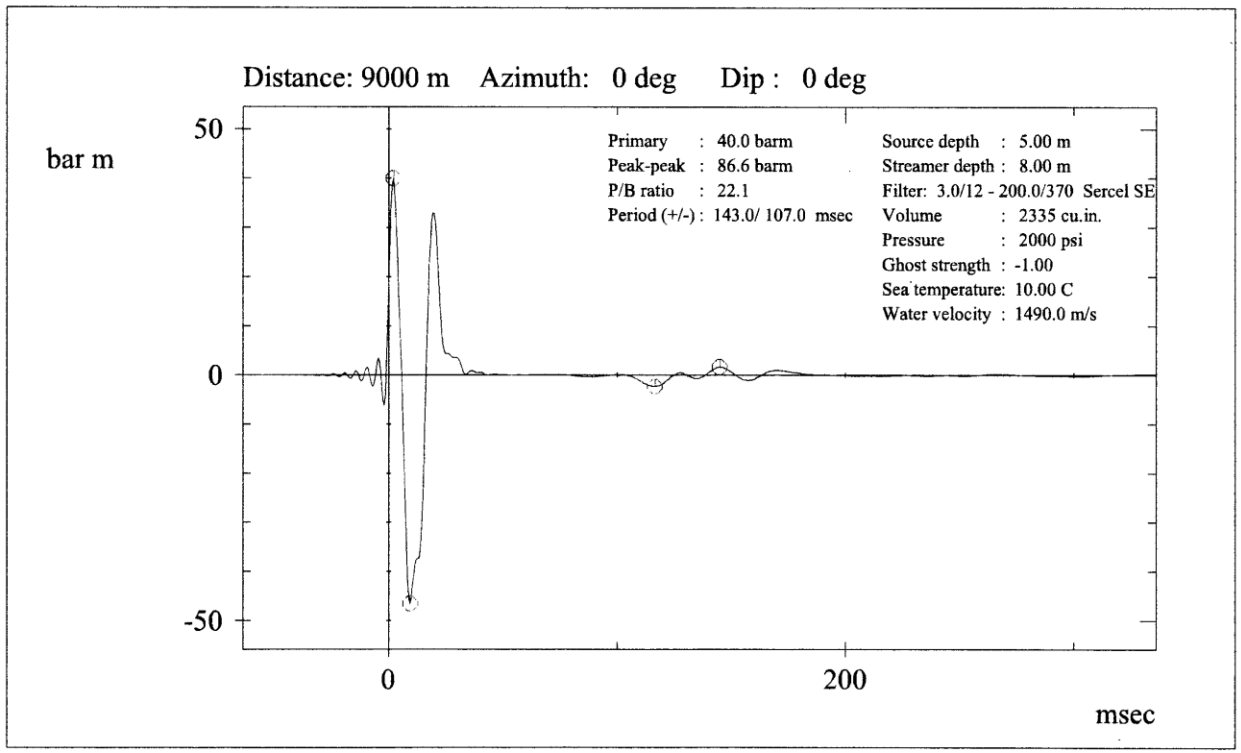


Figure 14. The far-field signature of the array in Figure 10

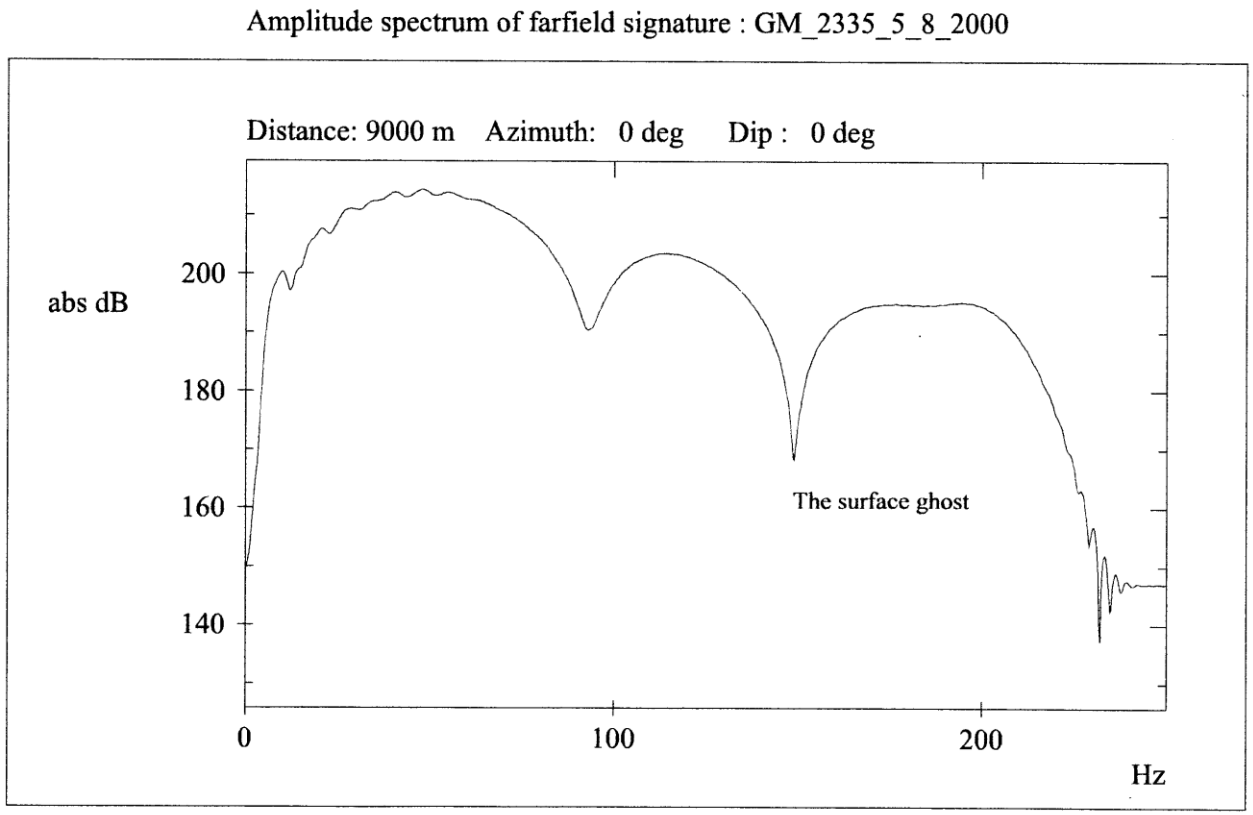


Figure 15. The amplitude spectrum of the far-field signature

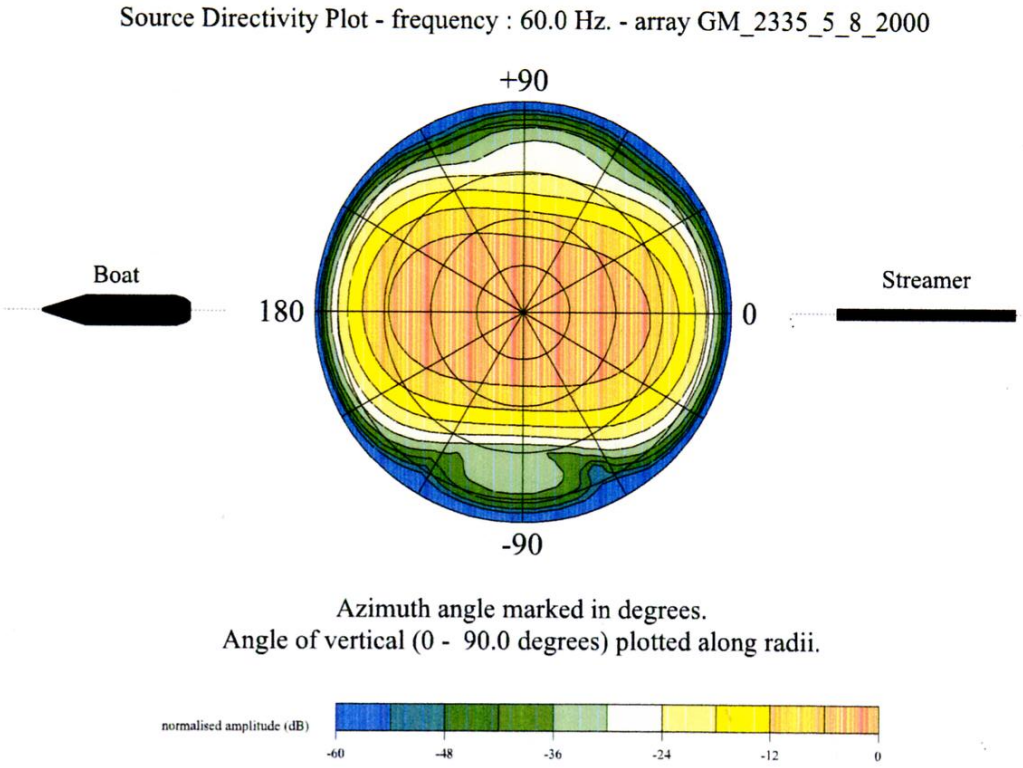


Figure 16. The source directivity plot – horizontal in-line

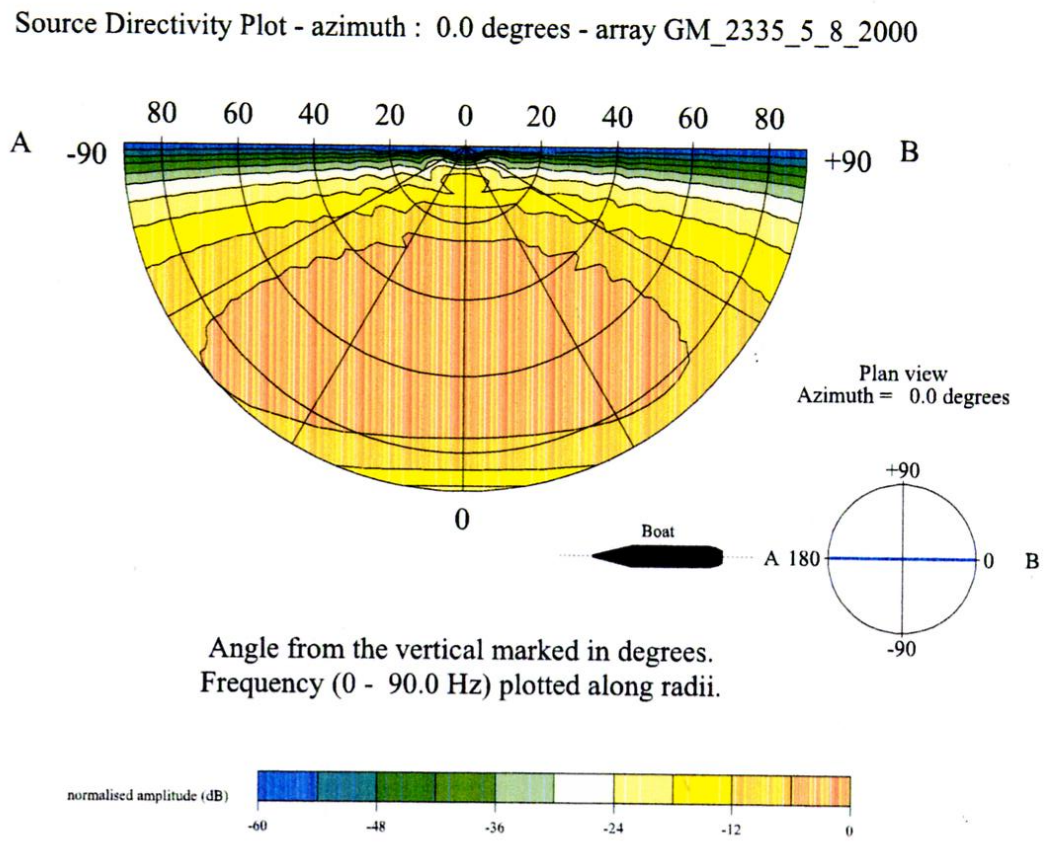


Figure 17. The source directivity plot - vertical

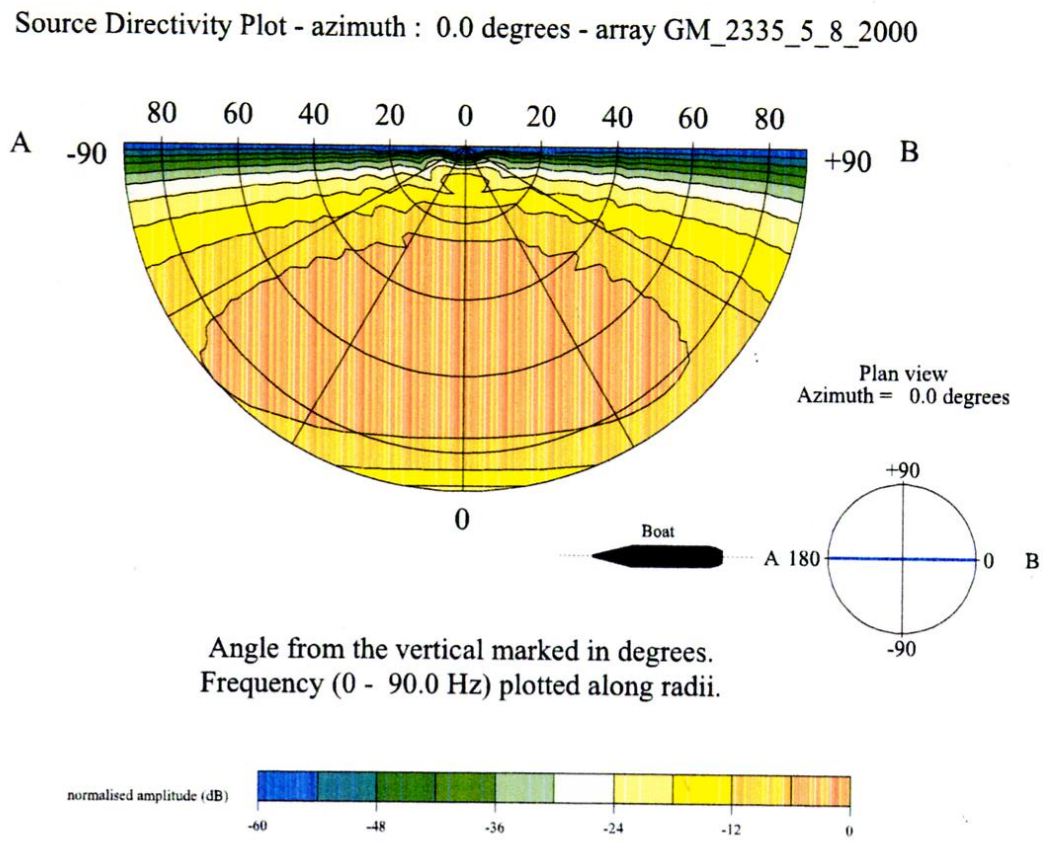


Figure 17. The source directivity plot - vertical

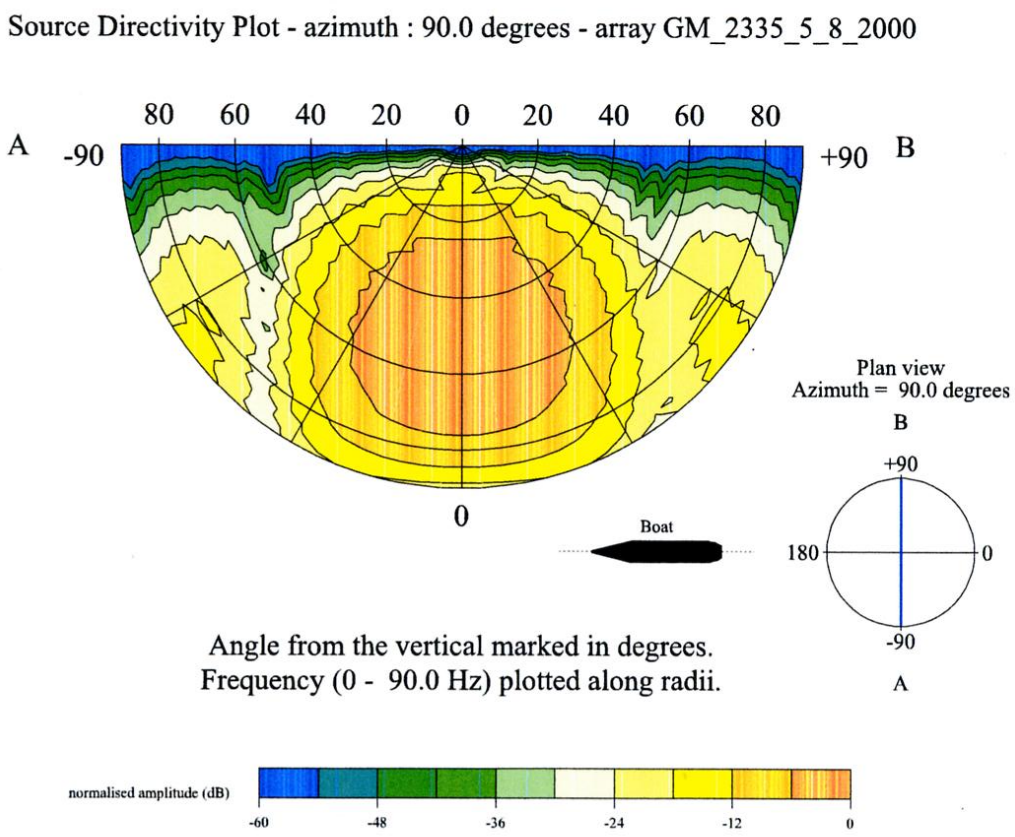


Figure 18. The source directivity plot – horizontal cross-line

The frequency filter applied to the signature should match that which will be used in recording actual data, otherwise an overblown picture of the array amplitude will be given. The source directivity plots show how the source energy is propagating in 3D relative to the sail line of the vessel as shown in Figures 16-18.
Far-field signatures are also directly measured in the ocean. This is done in a test mode because normal seismic operations do not allow a deep tow hydrophone. Far-field measurements allow one to verify the accuracy of the simulation and to get a real world measurement of the output of the designed array. To make the measurement, a single hydrophone is attached to a v-fin depressor or other such device to enable the hydrophone to be towed hundreds of meters vertically below the array while the vessel is sailing. The test must be conducted in deep water so that reflections coming up from the ocean bottom will not arrive during the duration on the source signature and interfere with it.
Airgun simulation for weakly interacting arrays can use the bubble equation as given. For arrays with clusters additional terms are needed. The after-flow term is needed, the actual bulk movement of the bubble is needed and to account for the increased turbulence when the bubbles are close to each other.

Performance specifications in the field

Airgun performance specifications in the field are usually governed by the legal contract between the oil company client and the geophysical contractor. The specifications spell out in a document called, “the dropout specifications” how much degradation of the airgun array performance is allowed before seismic acquisition must cease. Typical dropout specifications look like the following:

1. The dropout signals which have peak to peak amplitude and primary to bubble ratio deviating less than 10% of the full array are allowed.
2. The dropout signals which have a peak to peak amplitude and primary to bubble ratio between 85% and 90% and between 111% and 115% of full array are considered marginal and require discussion with company representative.
3. The dropout signals which have a peak to peak amplitude and primary to bubble ratio less than 85% and more than 115% of full array will result in seismic crew shut down until repaired.

The other malfunctions that cause an airgun array to go out of specifications are specific to the functioning of one or more guns in the array, these include: no-fire where a gun in the array fails to fire, misfire where a gun fires does not fire at all. Auto-fire refers to the fact that the gun fires on its own (once or multiple times). And finally double pop means a gun will fire twice when it is triggered to fire only once. There is a difference between double pop and auto-fire. Double pop is when a second fire occurs within the timing window. An auto-fire is a second or many firings occur after the timing window and before the next normal fire time.

Interaction between airguns

As we have seen, when an airgun fires and the bubble expands it disturbs the hydrostatic pressure in the ocean. If two airguns are fired close together we cannot assume that the hydrostatic pressure around them is ambient hydrostatic pressure. Thus depending on the distance of separation between two airguns we say they are weakly or strongly interacting. Initially, most airgun arrays were of the weakly interacting design. Weakly interacting arrays are characterized by a primary to bubble ratio of between 10-14:1. Now many airgun arrays consisting of clusters of airguns with separations of less than one meter have become popular. One advantage of a cluster is that it can have a significantly higher primary to bubble ratio than a single airgun using the same quantity of air.
When two airguns are fired in very close proximity the two bubbles come into physical contact and partly merge. This is known as coalescence. When two airguns are fired so close that coalescence does not occur but that interaction dominates the motion the bubbles are said to have a strong interaction. One meter of separation seems to define the difference between weak and strong interaction.
The interaction of the pulsating bubbles in such close cluster is much stronger than in weakly interacting tuned arrays because the bubbles are closer together.
Most airgun arrays consist of both strongly interacting clusters and weakly interacting single guns (separation greater than one meter.) Another measure of the bubble separation for strong interaction is to say about one bubble diameter apart for the two guns.

Clustered Airguns

Prior to 1990 most airgun arrays were the weakly interacting type. The effort to get both more power out of an airgun array by adding more guns to the array and by tuning these guns to decrease the primary to bubble ratio had reached its limits. The reason being that a value of 10-14 :1 is about the limit for weakly interacting conventional arrays.
We define a clustered airgun unit as two or more airguns whose distance of seperation is closer than the weakly interacting guns but not close enough to cause bubble coalescence. This was discussed in the section on Interaction where this distance for strong interaction between two bubbles is about one meter.
To explain why clusters of n guns beats a single airgun of the same volume consider the following simple assumptions. In crude terms the primary pulse from an airgun is proportional to the chamber pressure and the cube root of the volume. The primary amplitude of an n gun cluster is

$$A_{cluster} = k\, n(V/n)^{1/3}$$

Whereas the primary amplitude of a single gun of volume nV has an amplitude

$$A_{single} = kV^{1/3}$$

Thus by dividing the same quantity of air into a cluster of n smaller guns we increase the primary amplitude by a factor of $n^{2/3.}$
What about the PBR ? Tests conducted in the late 1980's using two identical sleeve guns at a depth of 5 meters showed that as the separation decreased below one meter three factors were obvious:

1. The primary amplitude was virtually unaffected.
2. The bubble amplitude decreases as separation is reduced.
3. The bubble period generally increases as separation is reduced.

Thus clusters of airguns can be used to both increase the primary amplitude and to increase bubble ratio. We cannot design a tuned cluster because all the bubbles in the cluster oscillate with a single period irrespective of their volumes. We must use tuned arrays of clusters where each cluster has a different total volume.

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