Artificial Seismic Sources

SIO 226
Winter 2012
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These slides are a condensed version of src.pdf, which is on the class web site.

Convolution

$$D(t) = \int G(t-q)S(q)dq$$

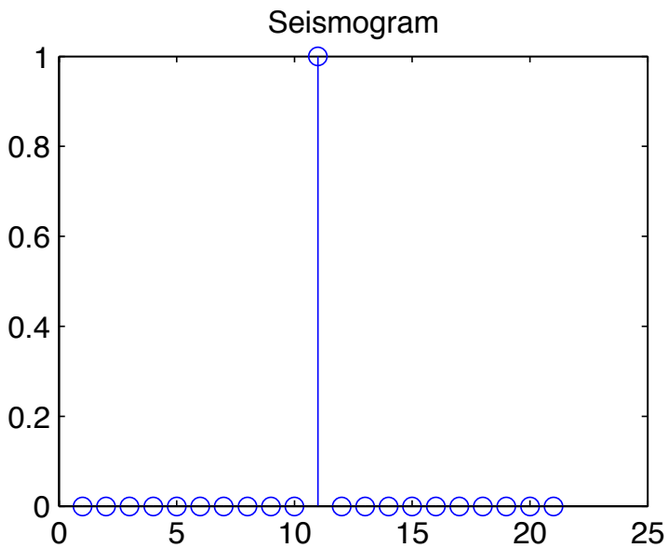
- The seismogram we see, D(t) is the convolution of the Green's function, or seismogram for a simple source, with an actual source S(q)
- This equation differs from the definition of autocorrelation only by the sign of q.
- Next we look at a few simple cases.

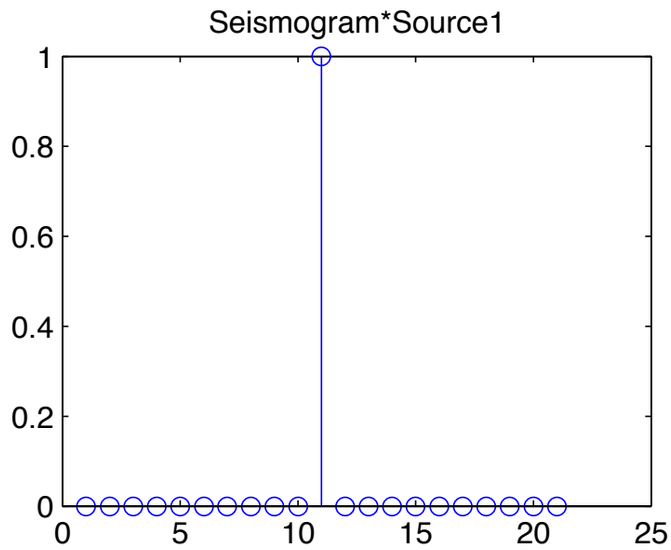
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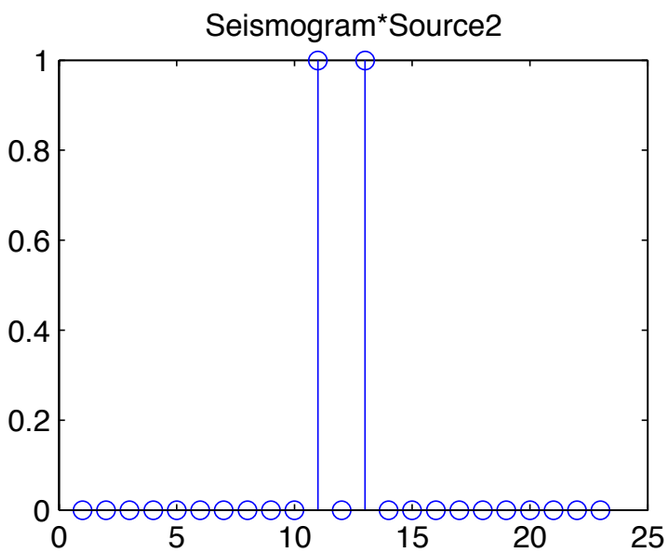
While talking about earthquakes, we concerned ourselves with the geometric aspects of a source signature
Now we will look at the temporal aspects, when a source doesn't happen "all at once".

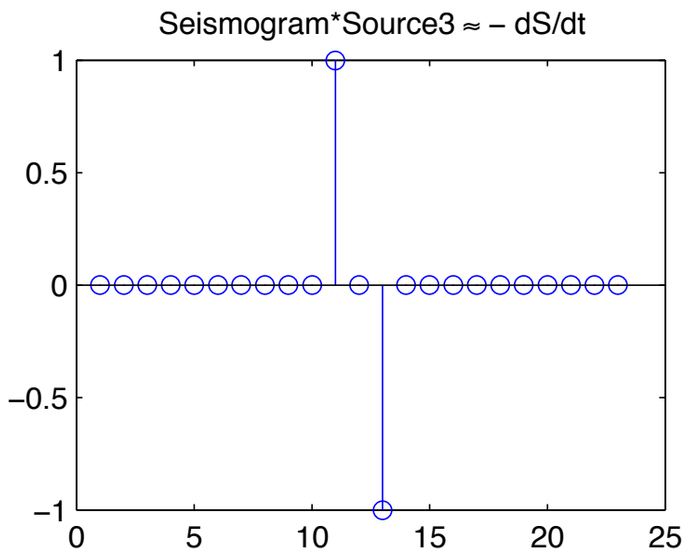
Seismogram convolved with:

- Green's function δ
- Conv with another δ
- Conv with 2 δs
- Conv with +/- δ, approximating differentiation









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Imagine the simplest possible earth, in which the fundamental seismogram, or Green's function (GF) is simply a delta function, as in the upper left panel. Even in a pretty simple earth, a GF can consist of more than one pulse, for example a tt plot with a triplication.
If our source is also a temporal delta, we get the UR panel, (Duh).
If our source is 2 δ we get the LL, if source is +− δ, we get the LR, which is a numerical differentiation,
like calculus, but without going to the limit of small δ.

The bubble as a source

- An explosion or an airgun instantaneously (almost) produces a bubble at high pressure.
- Water is not very compressible, and it is heavy, but the bubble eventually expands.
- When the internal pressure reaches equilibrium, expansion does not stop because of the momentum of the water outside the bubble, so the size oscillates.
- Rayleigh (1917) figured out the period of the oscillation (the bubble pulse period).

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Each oscillation produces a pulse of radiated sound at points of high pressure and bubble wall acceleration.
Inspired by sound or teapot

The Rayleigh-Willis formula

$$T = 1.83 A_m \left(\frac{\rho}{P_0} \right)^{1/2} \tag{2}$$

Here T is the period in seconds, A_m is the maximum radius of the bubble in cm., ρ is the density of the fluid in g/cc, and P_0 is the ambient hydrostatic pressure in dynes cm^{-2}. The English investigator Willis, during the second world war, combined this result with an expression for the potential energy of a spherical void of radius A_m

$$Q = (4/3)\ \pi\ A_m^3 P_0 \tag{3}$$

where Q is in ergs to obtain the Rayleigh-Willis formula

$$T = \frac{.000209\ (KQ)^{1/3}}{(d+33)^{5/6}} \tag{4}$$

where d is the depth in feet of water and K and Q have values from the following table:

K	Units of Q
Ergs	1
10^{10}	KiloJoules
$1.36\ x\ 10^7$	Foot-Pounds
$1.88\ x\ 10^{13}$	Pounds of 60% dynamite.
$1.06\ x\ 10^{13}$	Pounds of TNT
$.717\ x\ 10^{13}$	Pounds of Nitromon "S"
$1.42\ x\ 10^{13}$	Pounds of Nitromon "WWEL" or Tovex
$.70\ x\ 10^{13}$	Pounds of Tovex in barrels

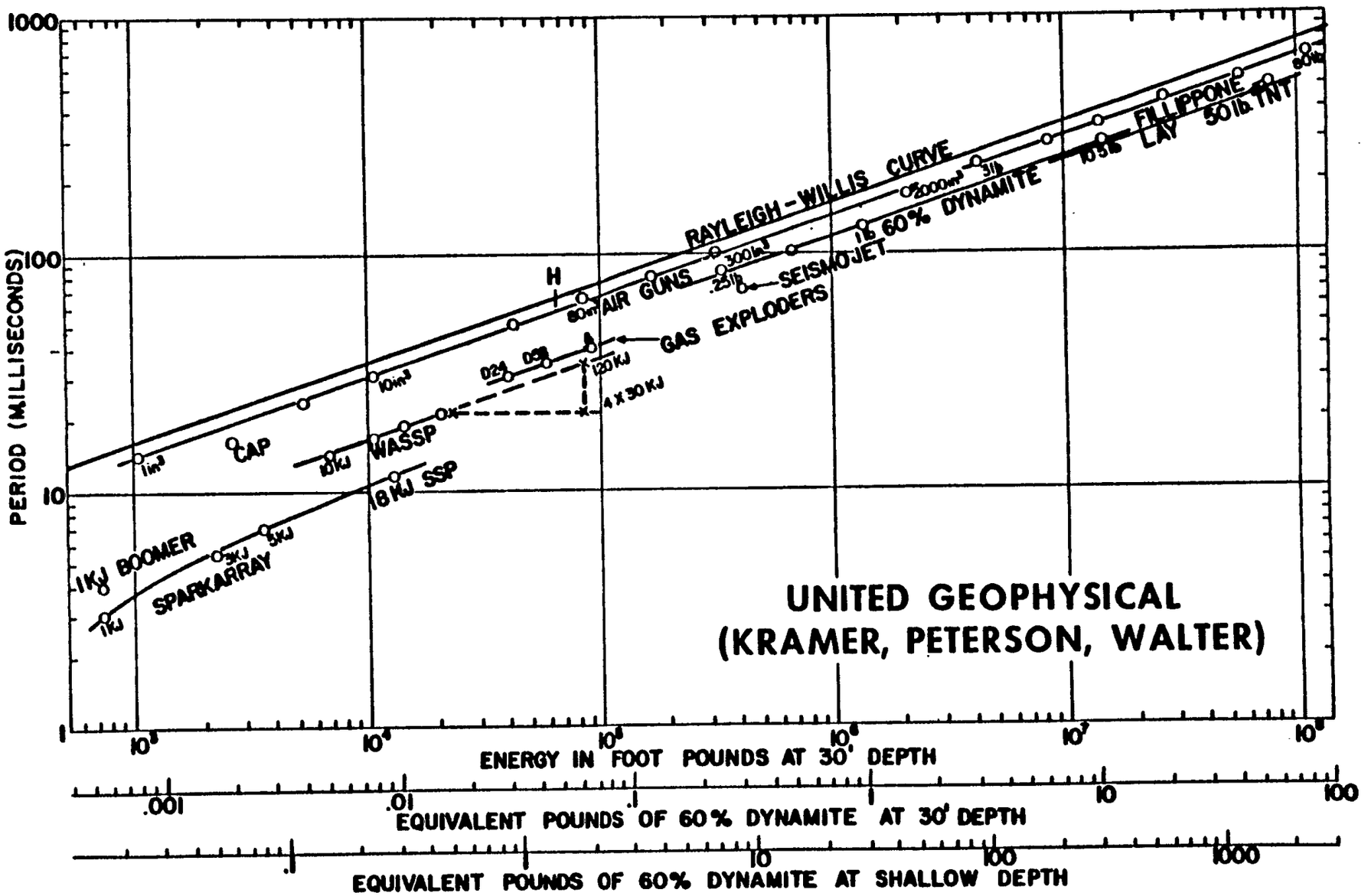
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Exploration industry uses english units, SI not so much.

Assumptions

These results are based on the following assumptions:
1) The water flow is spherical and non-compressive.
2) The internal energy of the gas is negligible.
3) The fluid is unbounded.

Rayleigh-Willis



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Note particularly airgun line, cap, TNT

A common use of the R-W formula is to solve it for depth of a source of known size, as with shooting with burning fuse.

A simple explosive source

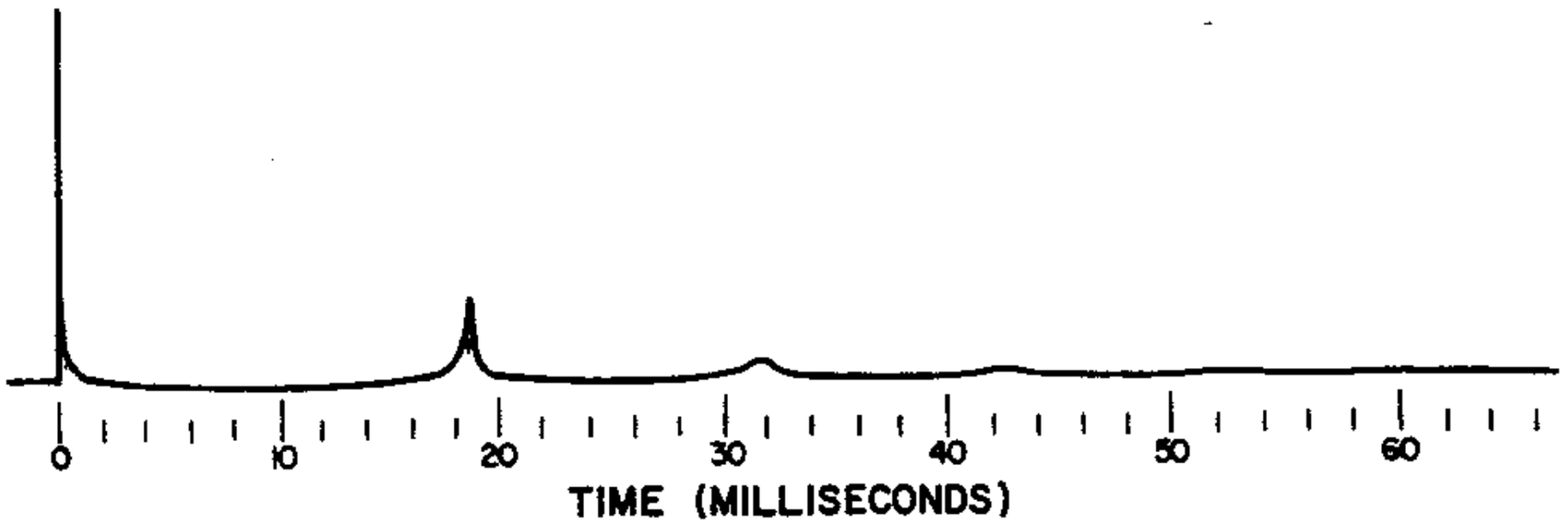


FIGURE 7. Pressure Signature of .5 Pound of TNT at 500′ Depth

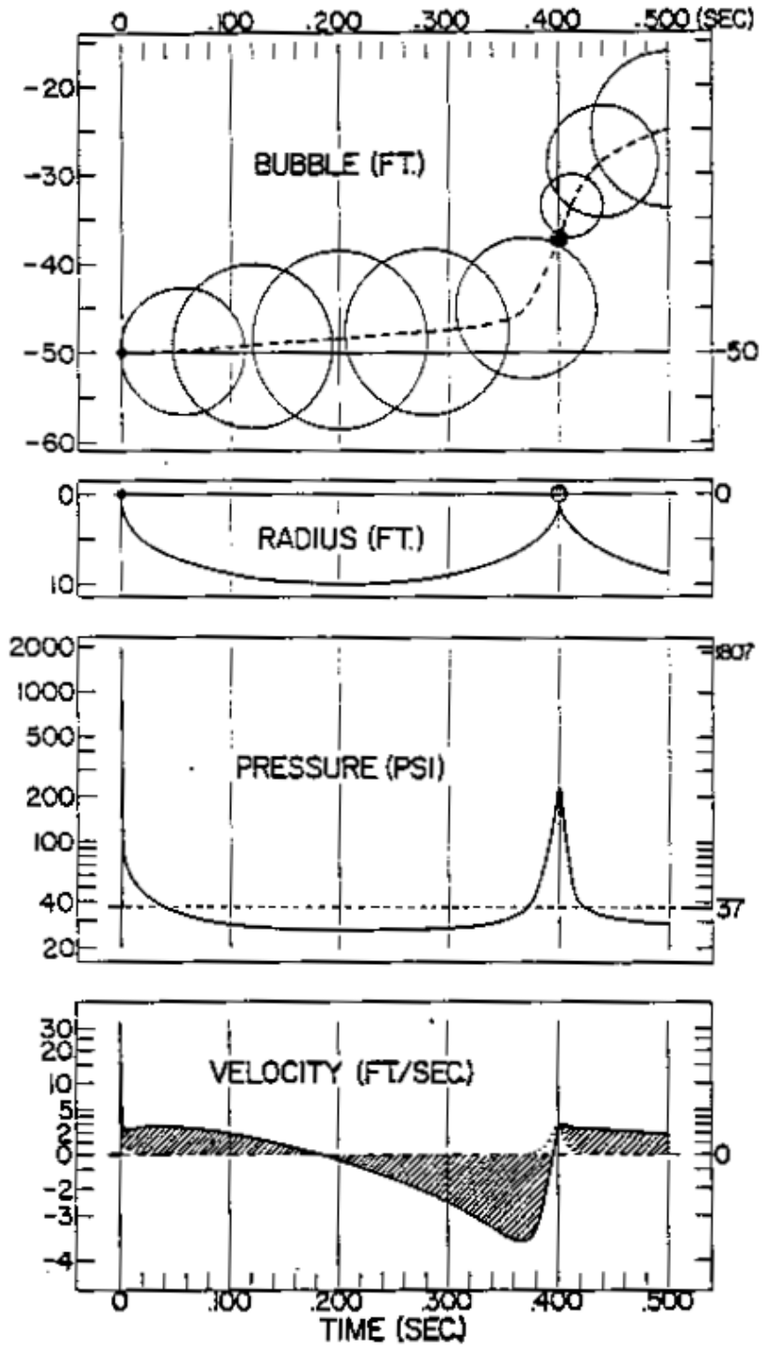
Figure 4.2: Pressure signature recorded at 2.25 feet from a half pound charge of TNT detonated at a depth of 500 feet. From Arons [1948].

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This is not too different from the double impulse source from slide 3 of this lesson.

Bubble evolution in water

- From Kramer et al 1968
- Change with time of:
- Depth
- Size
- Pressure
- Wall velocity



The free surface is important

R-W: dash
box: 6” iron plate
circle: Free Surface
Dot: Bag

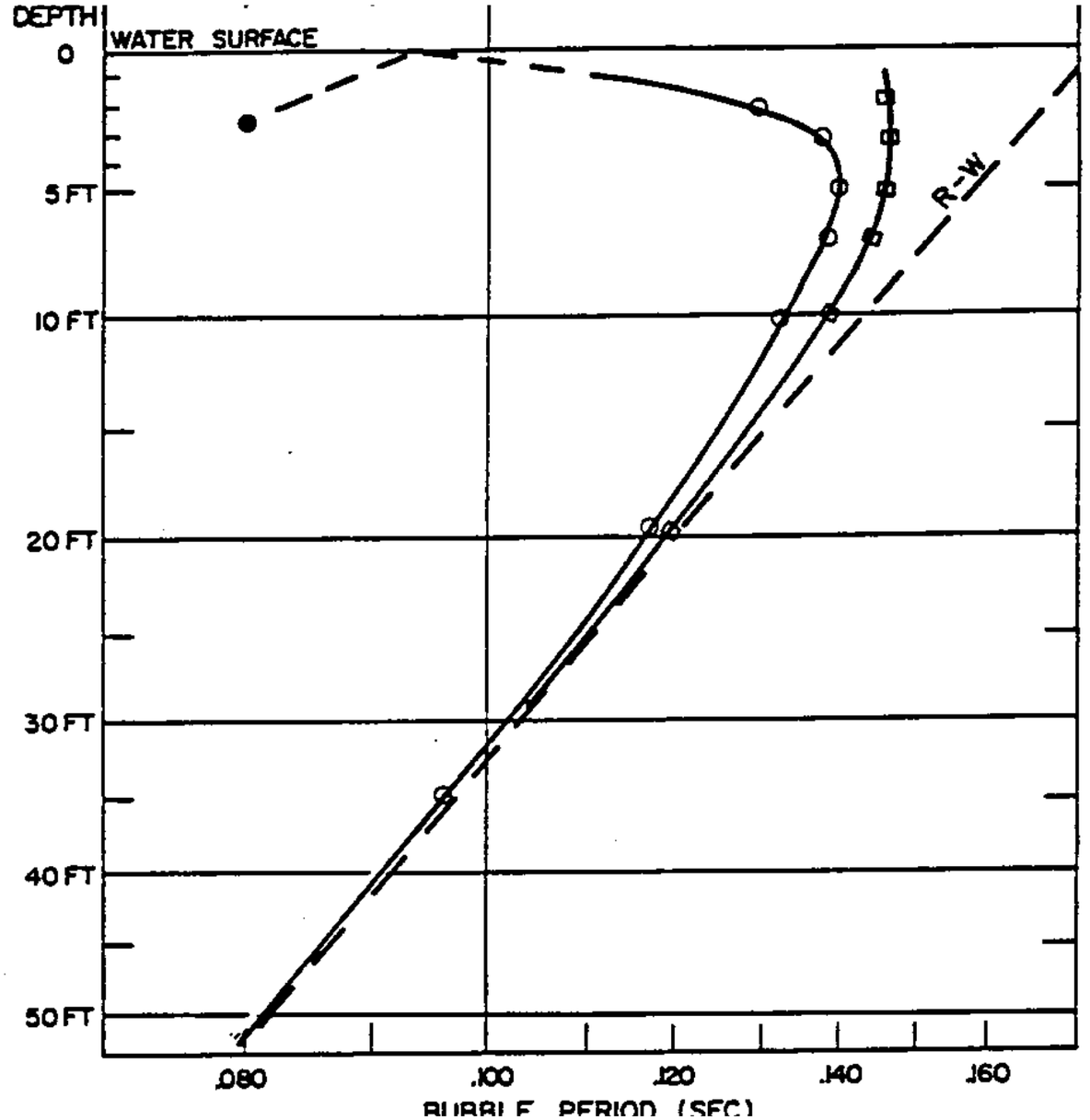
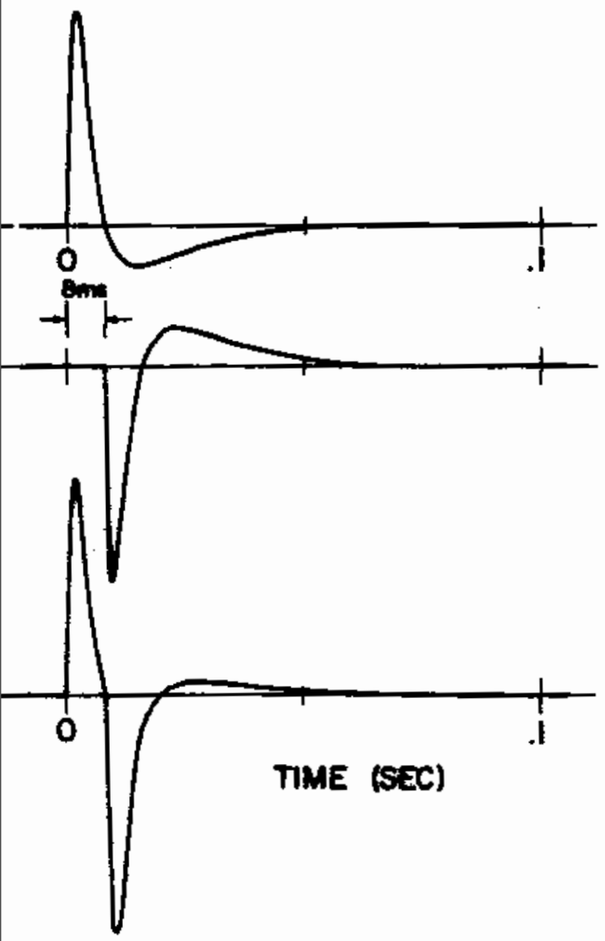


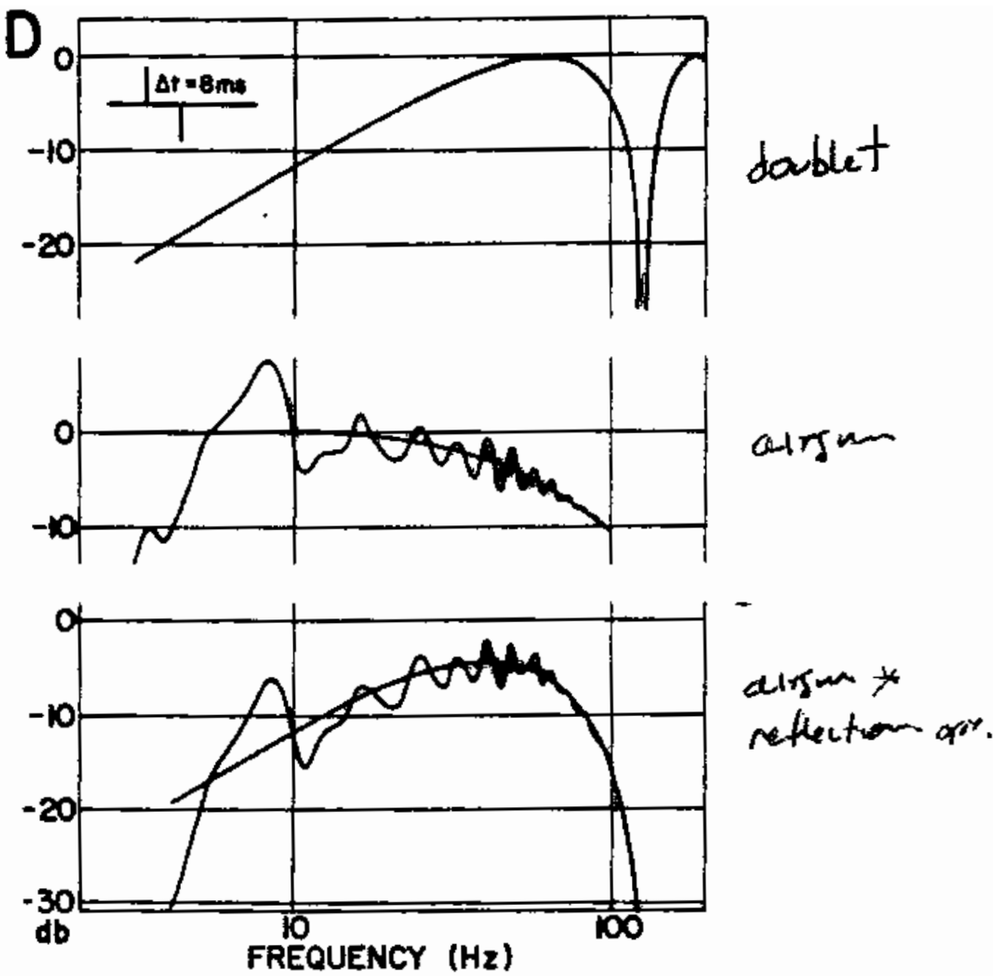
Figure 4.4: Bubble period affected by pressure-release surface. From Kramer et al. [1968].

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The R-W formula does not include surface effects.

Surface reflection



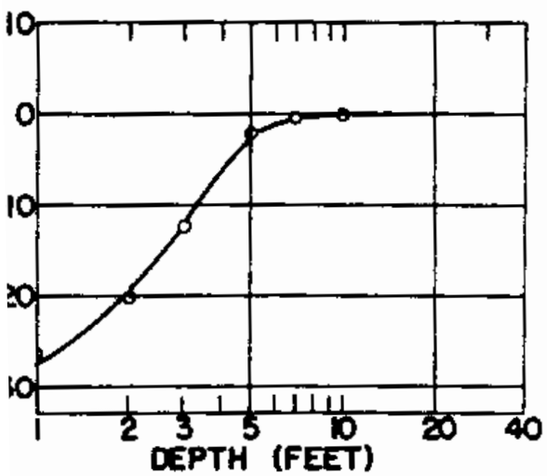


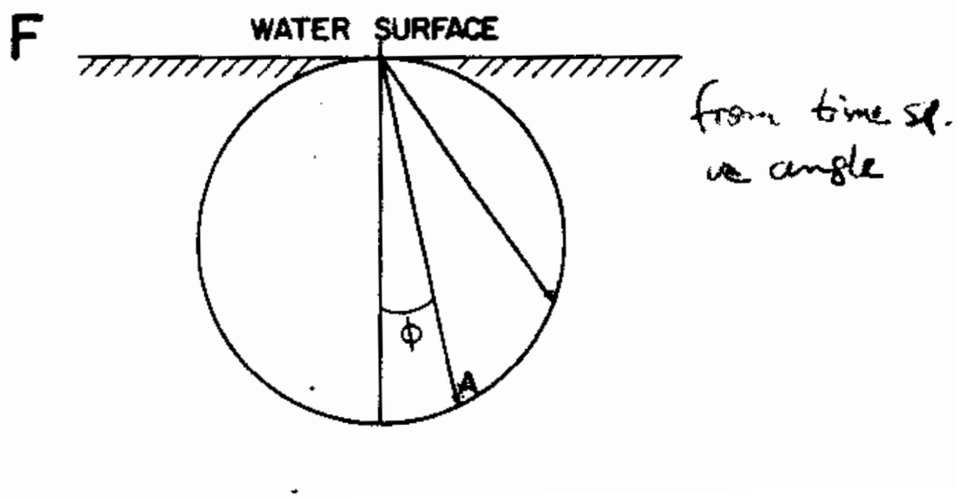
- 8 ms delayed reflection as doublet
- Spectra of doublet, airgun, airgun + reflection

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The delay depends on angle of reflection.
It approximates a derivative at low frequencies.

Impulse and radiation pattern



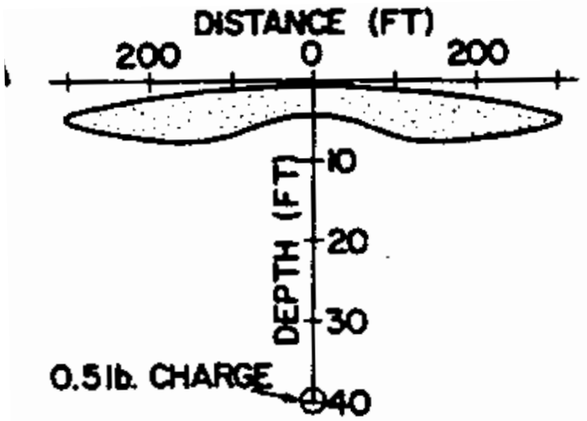


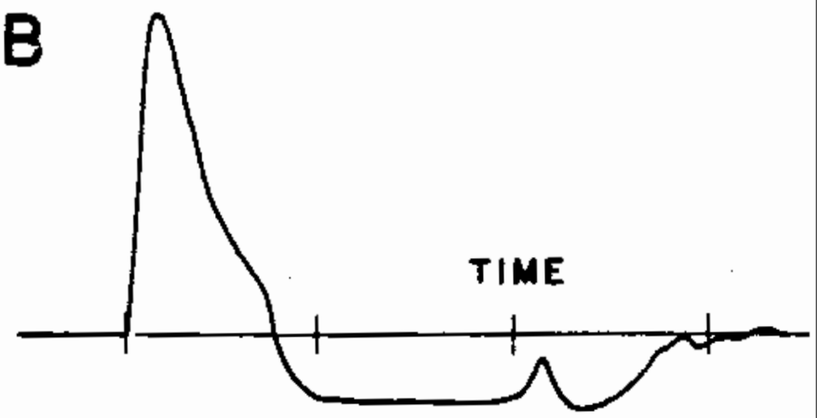
- Left: impulse (dB) due to pulse cancellation
- Right: radiation pattern from angle dependence of delay

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Sometimes called Lloyd's mirror

Other surface effects: Cavitation





- This occurs with explosives, but not usually with airguns (later)

Analytic equations of bubble oscillation

$$\ddot{R}R + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho_\infty}(P - p_\infty)$$

- Rayleigh's solution ignores viscosity and assumes that water is incompressible: or that sound velocity is infinite.
- It includes terms in acceleration and velocity squared.

The equation of Herring

$$\ddot{R}R(1-2\frac{\dot{R}}{c_\infty})+\frac{3}{2}\dot{R}^2(1-\frac{4}{3}\frac{\dot{R}}{c_\infty})=\frac{1}{\rho_\infty}[P-p_\infty+\frac{R}{c_\infty}\dot{P}(1-\frac{\dot{R}}{c_\infty})]$$

- Includes the effects of a constant sound velocity c-inf

F. R. Gilmore and Tait's e.o.s.

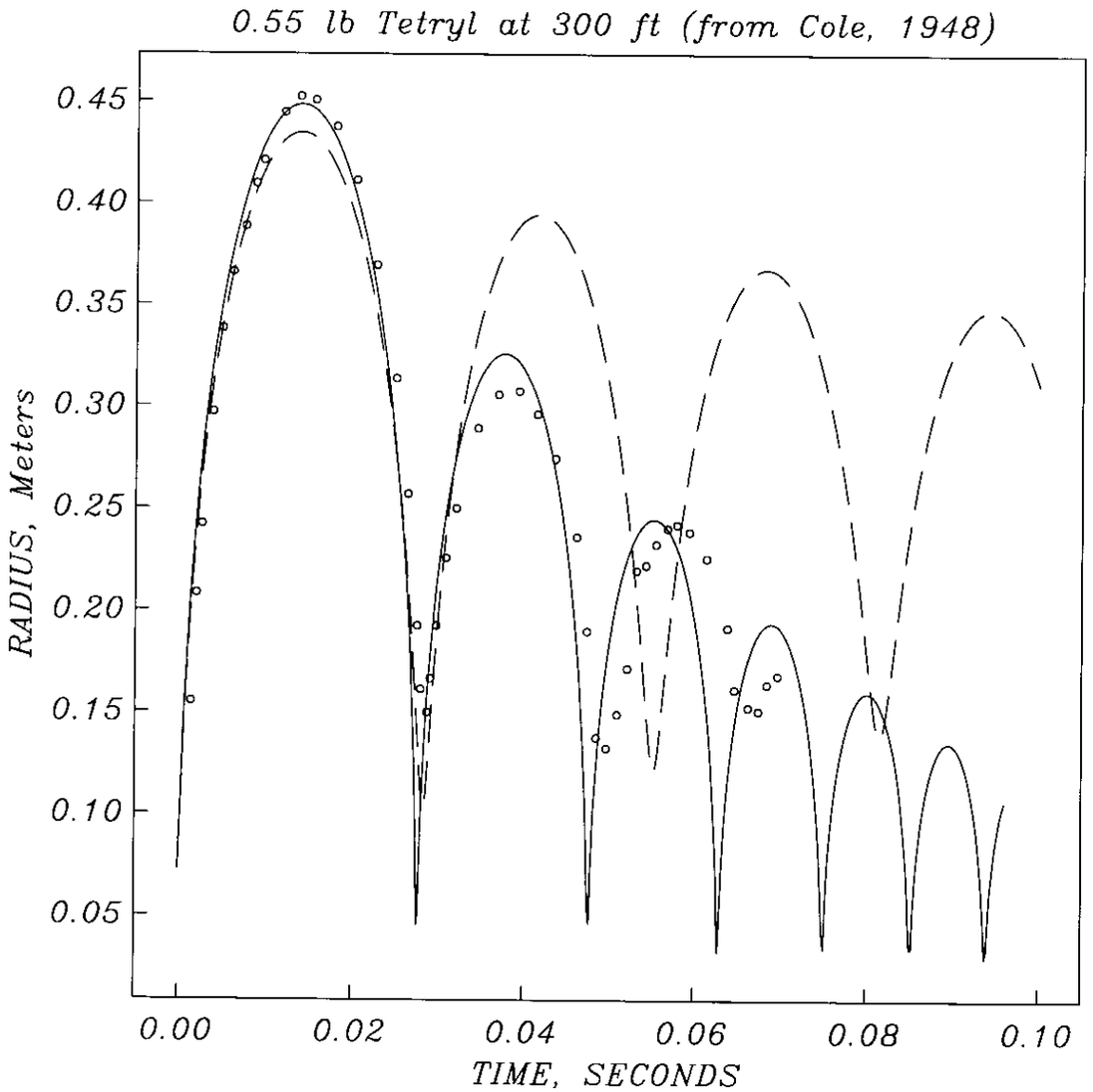
$$\ddot{R}R(1-2\frac{\dot{R}}{C})+\frac{3}{2}\dot{R}^2(1-\frac{1}{3}\frac{\dot{R}}{C})=H(1+\frac{\dot{r}}{C})+\frac{R}{C}\dot{H}(1+\frac{\dot{r}}{C})$$

$$c=c_\infty(\frac{p+B}{p_\infty+B})^{\frac{n-1}{2n}}$$

- allows for pressure-dependent density of water, hence sound velocity
- where B is 3000 Atm. and n=7
- This gives good agreement with hydrocodes.
- Although this is an analytic equation, it must be integrated numerically.

Comparison with data

- Circles are from photos.
- Dashed line is from Gilmore eq and shows radiation damping.
- Solid line includes empirical factor of Pritchett (1971) which includes cooling of gas.



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The correction of Pritchett was based on modeling of nuclear depth charge.
I calculated this using RK code modified from Press et al to disallow negative radius.

Airgun source

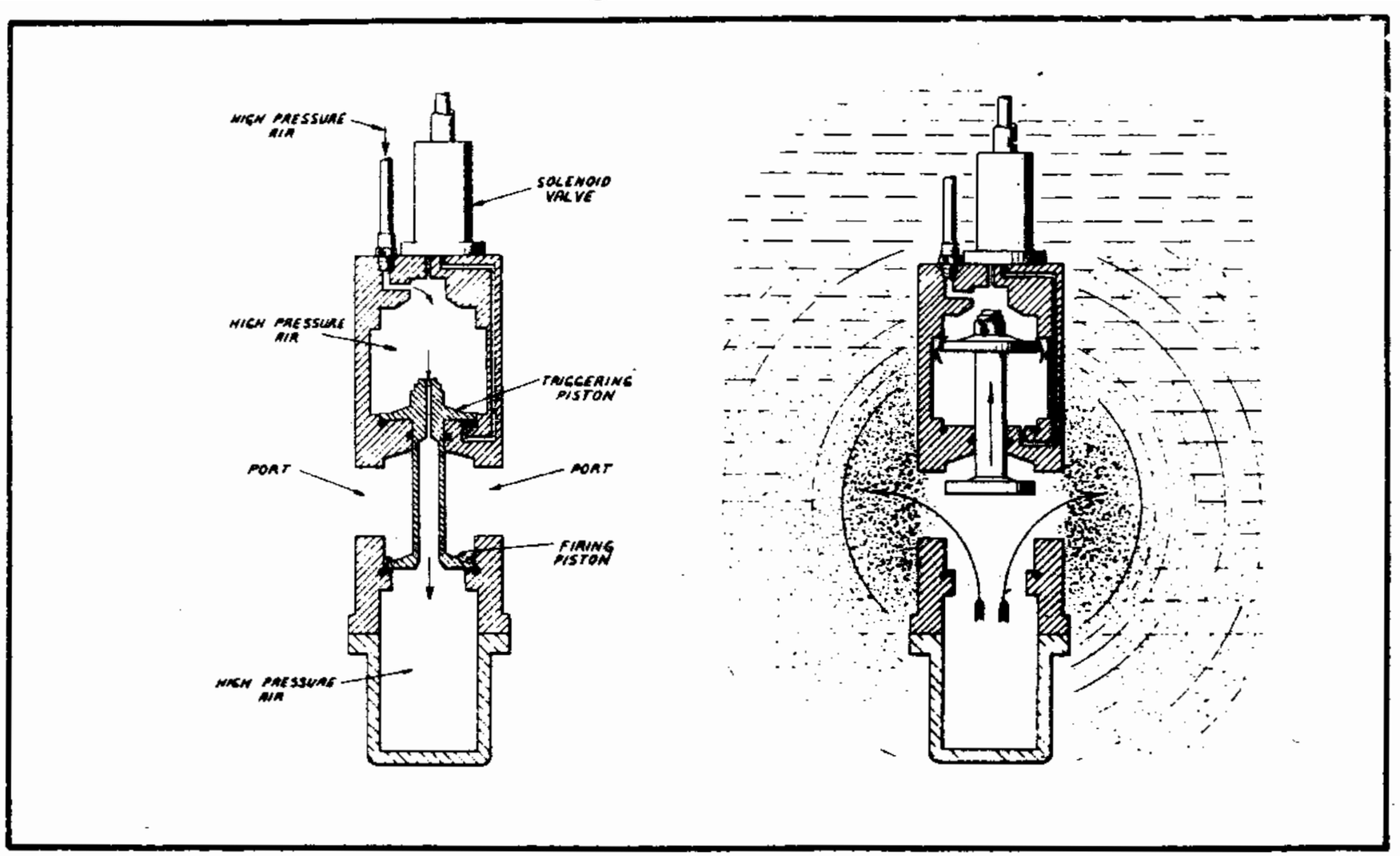


Figure 4.7: Airgun from PAR (Bolt Associates). From Kramer et al. [1968].

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This is the most common source used today. Air pressure is usually 2000 PSI up to 4000 PSI
It produces an air bubble, so has a bubble pulse. Initially, ratio of shuttle surfaces keeps shuttle in closed (down) position. Solenoid valve lets air under triggering piston, then when triggering piston unseals, pressure imbalance is huge, so shuttle accelerates upward. Shuttle stops slowly by shoulder in upper chamber.

Watergun source

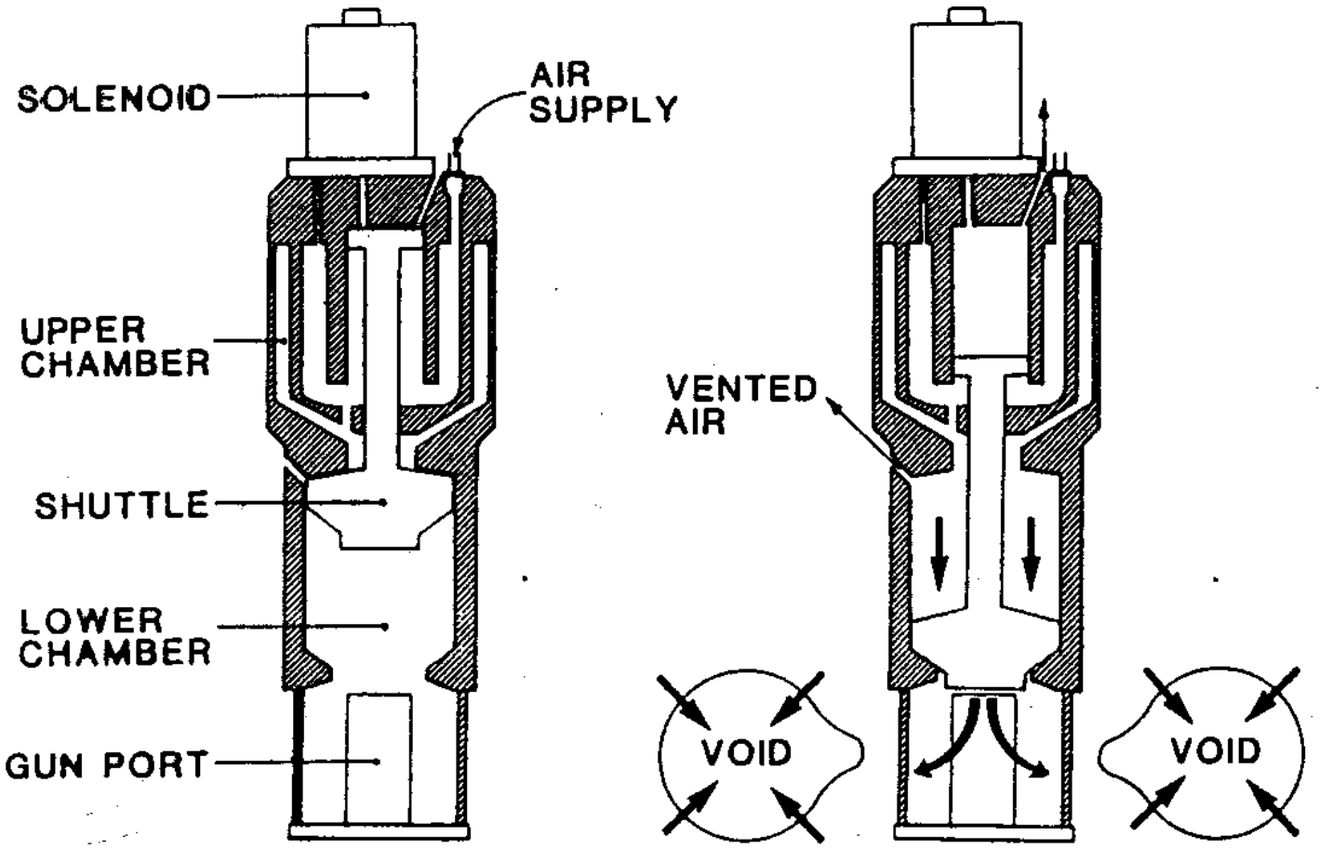


Figure 4.8: Watergun from Sodera. From Safar [1984].

- produces no bubble pulse, but less energy and has a precursor.

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Bubble is created by cavitation, filled with water vapor which collapses to zero volume.

Watergun source signature

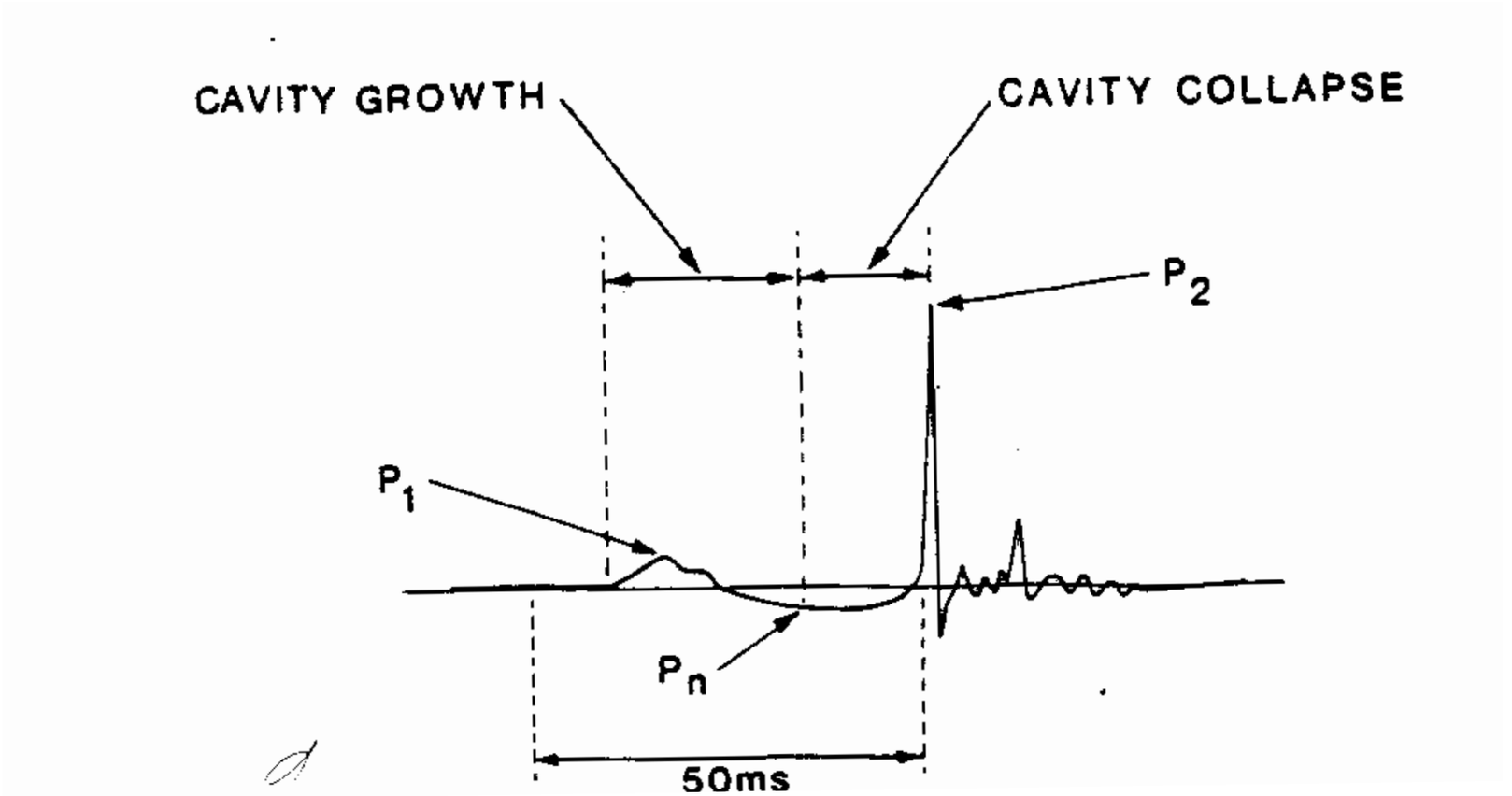


Figure 4.9: Signature of watergun. From Safar [1984].

Watergun source spectrum

- Spectrum is smoother than that of airgun

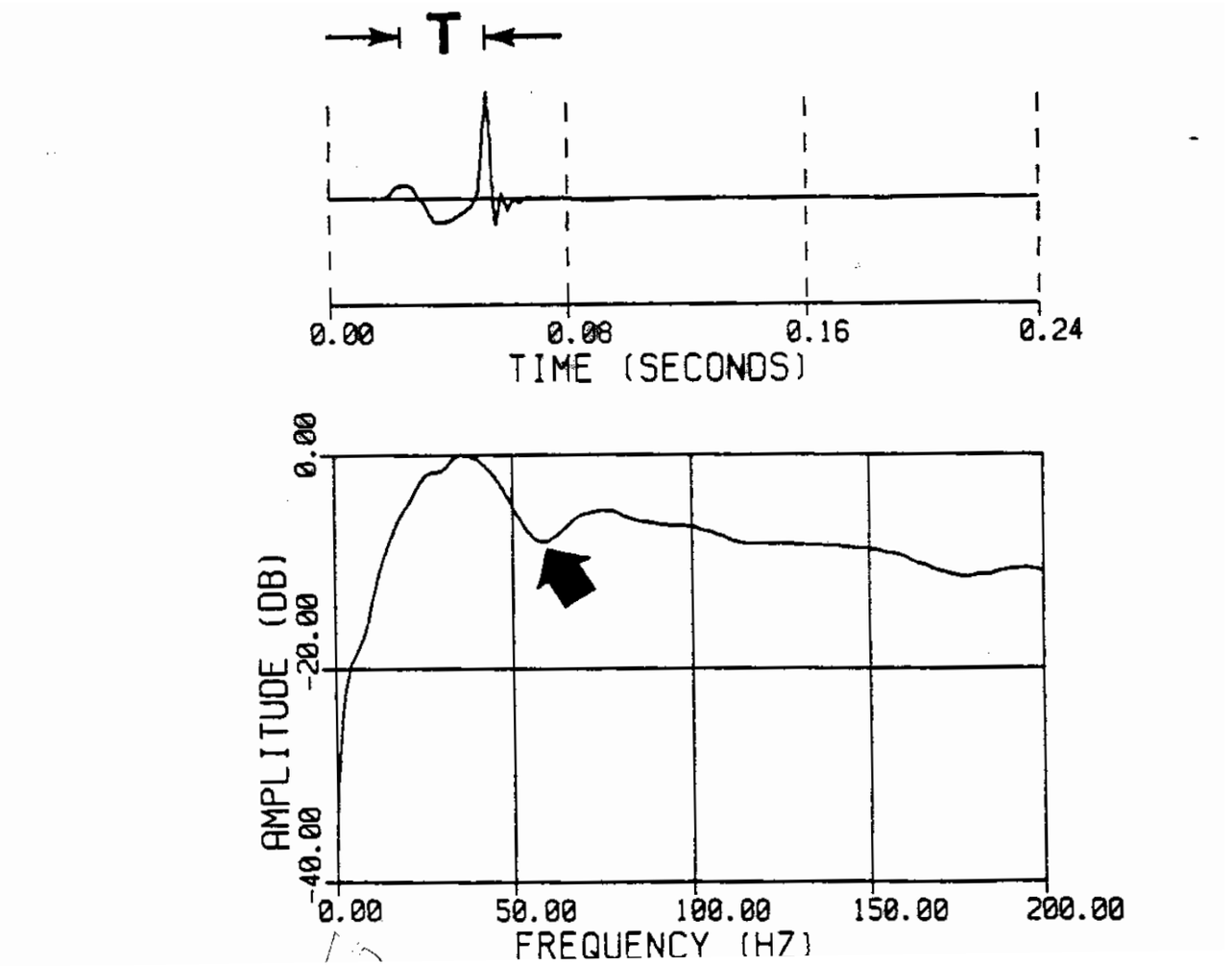


Figure 4.10: Signature and spectrum of watergun. From Safar [1984].

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Which is good.

Comparison of airgun and watergun data

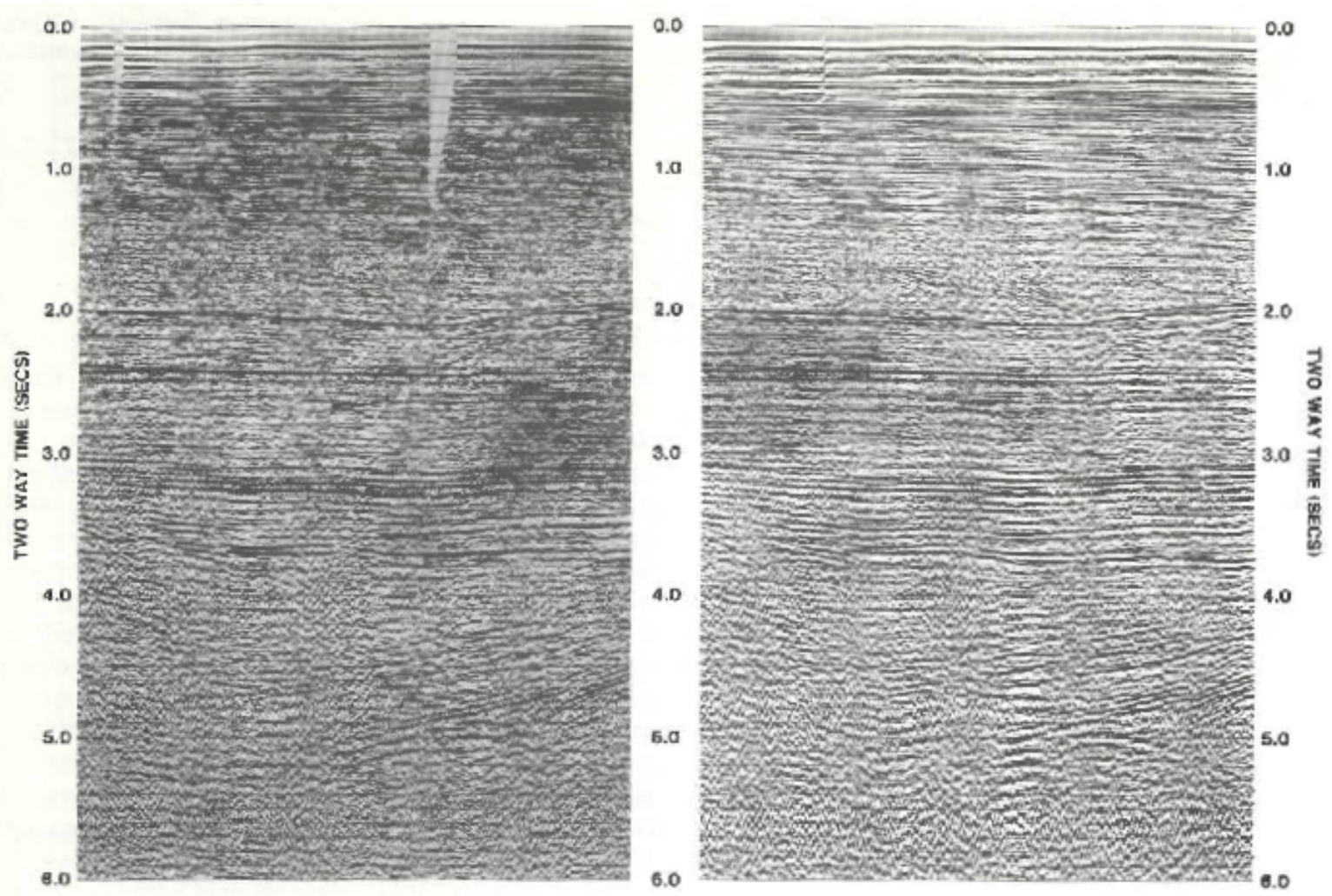


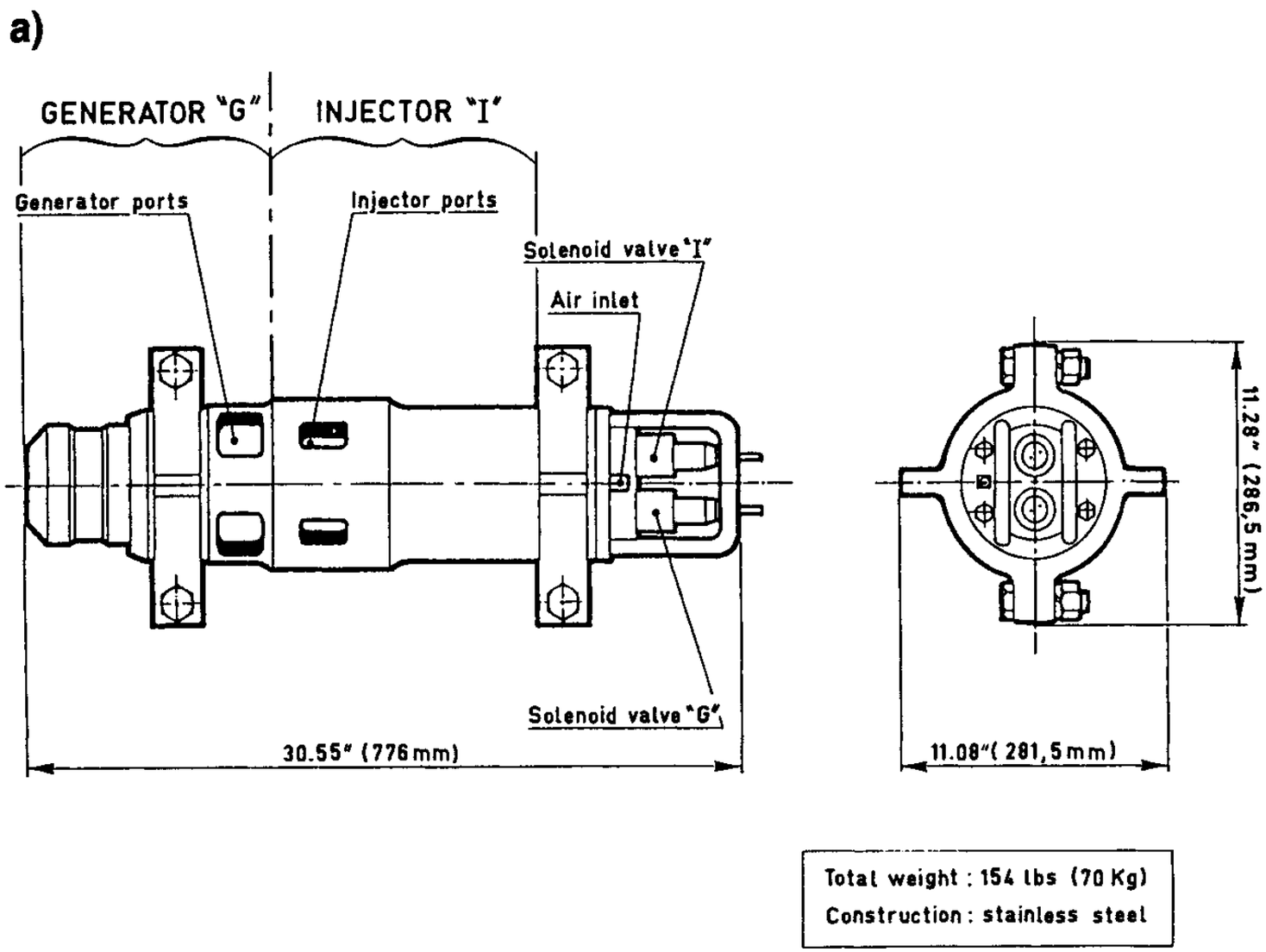
Figure 4.11: Comparison of reflection profiles using airgun (left) and watergun (right) sources. From Safar [1984].

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WG is some better but not remarkably.

The Generator-Injector (GI) gun

- is really two guns, separately controllable
- Can be operated to emphasize initial or first bubble pulse

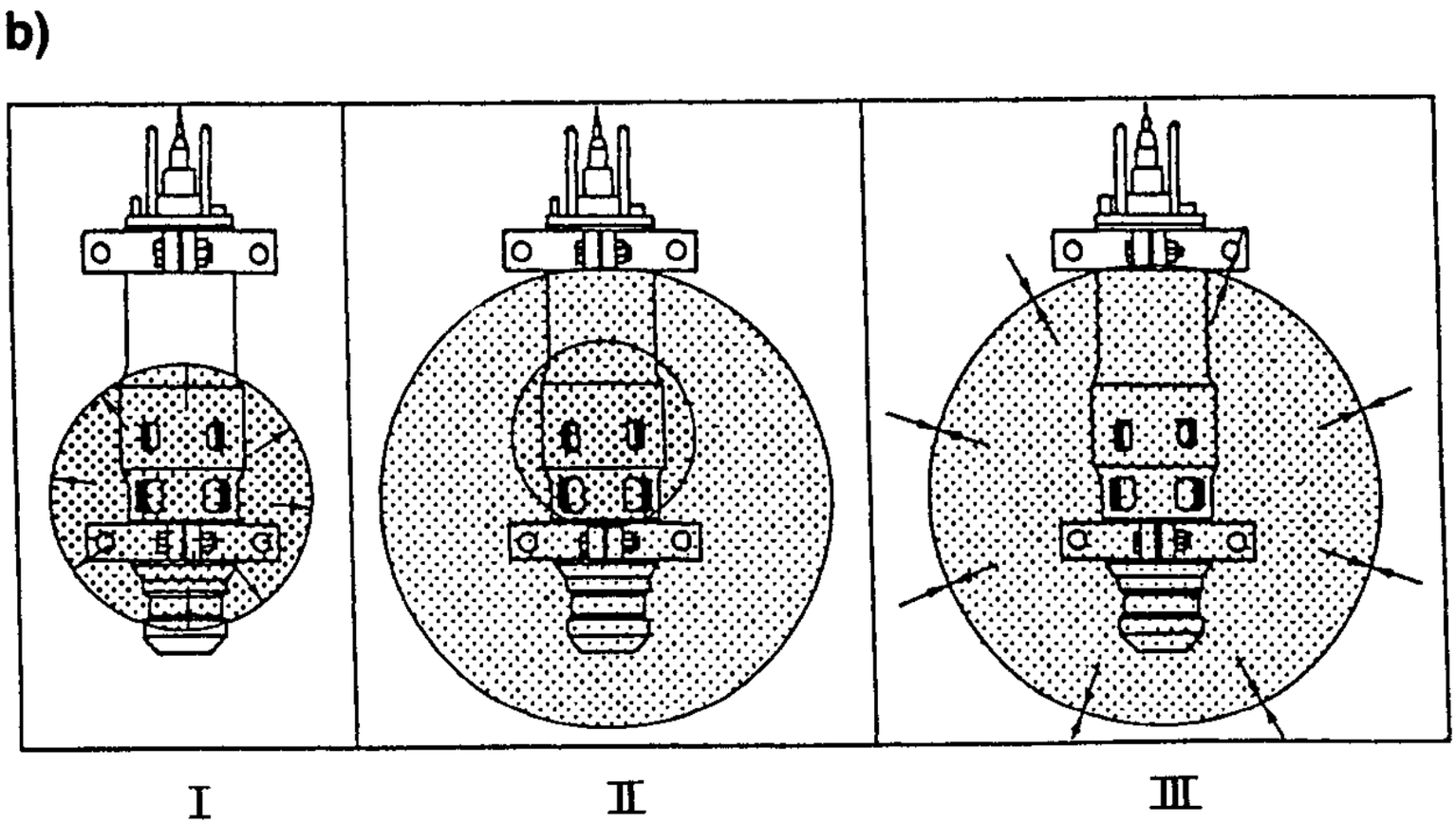


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SIO has.

Operation of GI gun

I-Fire G
II-Fire I at time of max bubble size so that III-bubble pressure equals ambient and does not oscillate



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Single-pulse operation
I fired at bubble maximum.

Bubble-free signature

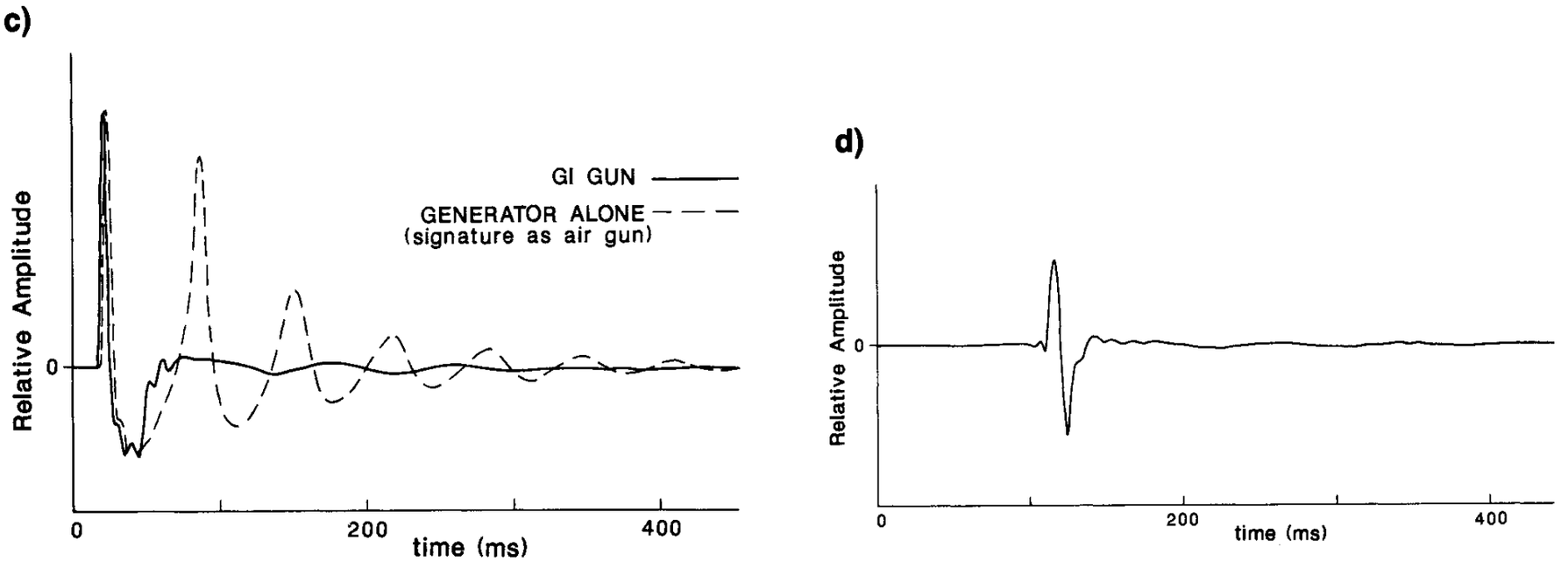


FIG. 8. The GI-150 gun®: the first bubble free air gun. (a) Physical characteristics. (b) Operating principle: I. generator fires; II. injector fires; III. the bubble is stabilized. (c) The GI-150 gun®: "bubble free" near-field and (d) far-field pressure signatures. G = 45 in^3 (0.7 L); I = 105 in^3 (1.7 L); Gun depth: 6 m; Air pressure: 140 bars (2000 PSI) (from Pascouet, 1989).

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Does a pretty good job.
SIO has GI gun available, I think

GI single-bubble operation

- This mode of operation concentrates energy in the 8-64 Hz range rather than the 8-128 Hz range, for better deep penetration.

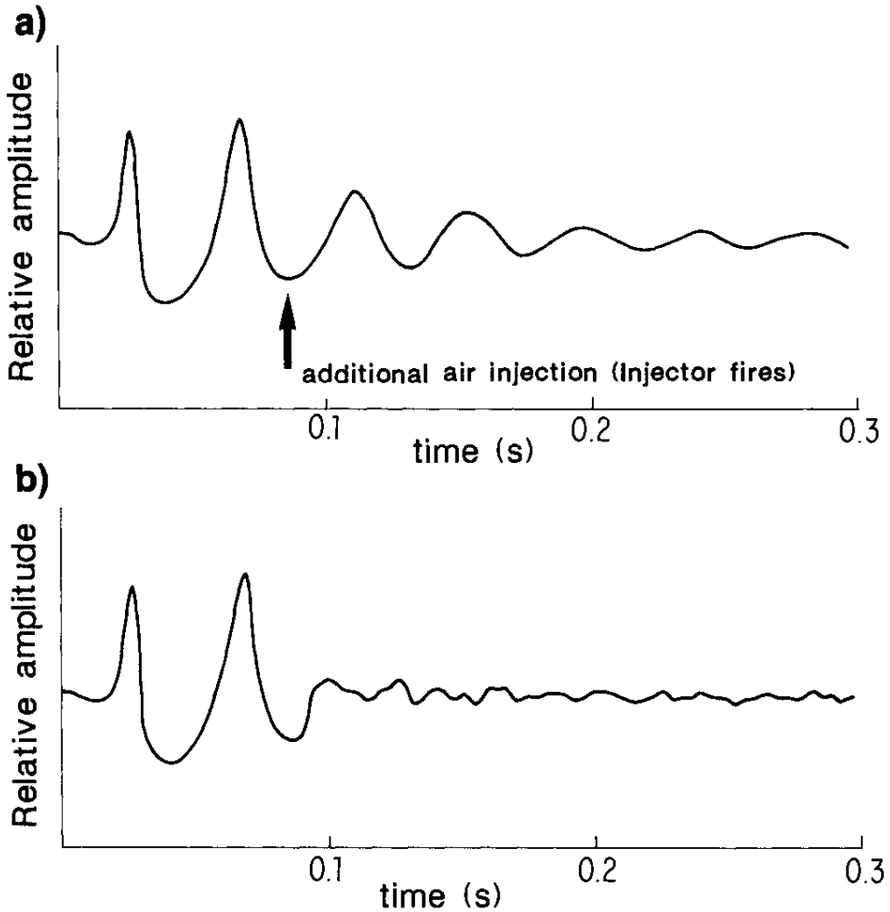


FIG. 10. GI gun as "single bubble air gun": (a) Example of a near field pressure signature when the Generator (G) alone is fired; shows typical air gun signature. (b) Example of a "single bubble" signature obtained when firing the injector after the first bubble pulse to obtain the suppression of the later bubble pulse train. G = 50 in^3 (0.8 L); I = 50 in^3 (0.8 L); Air pressure: 140 bar (2000 PSI); Gun depth: 16 m.

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For example crustal studies rather than for exploration of sediment column.

Array of guns

used for

bubble pulse reduction

Table 1. Dependence of an air-gun signature on gun parameters		
	Strength (S)	Bubble period (T)
Gun volume (V)	$S \propto V^{1/3}$	$T \propto V^{1/3}$
Firing pressure (P)	$S \propto P$	$T \propto P^{1/3}$
Gun depth (D in m)	complicated	$T \propto (10 + D)^{-5/6}$

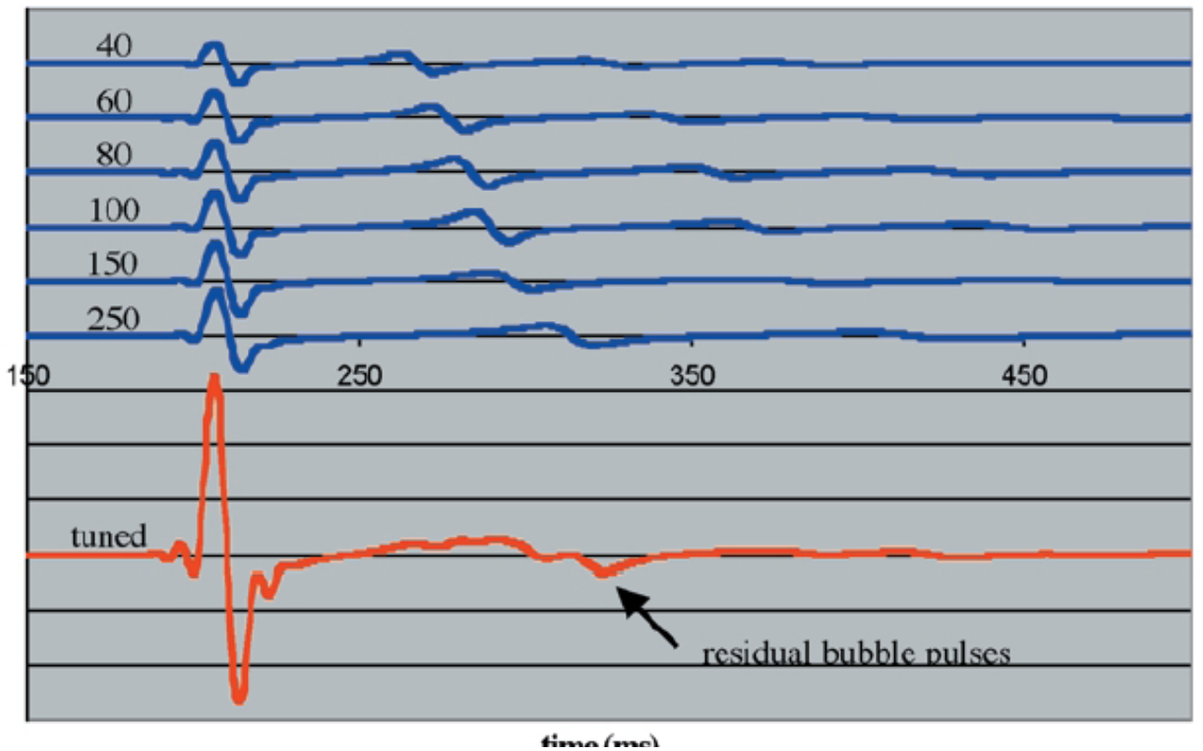


Figure 4.13: Concept of tuned air-gun array. Blue signatures come from individual guns whose volumes, in cubic inches, are on the left. If those six guns are placed in an array and fired simultaneously, they produce the red signature at a hydrophone 300 m below the array. The arrays PBR is 8.6. From Dragoset [2000].

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PBR is primary to bubble ratio, which approaches half for single gun.

What it takes in real life production operation

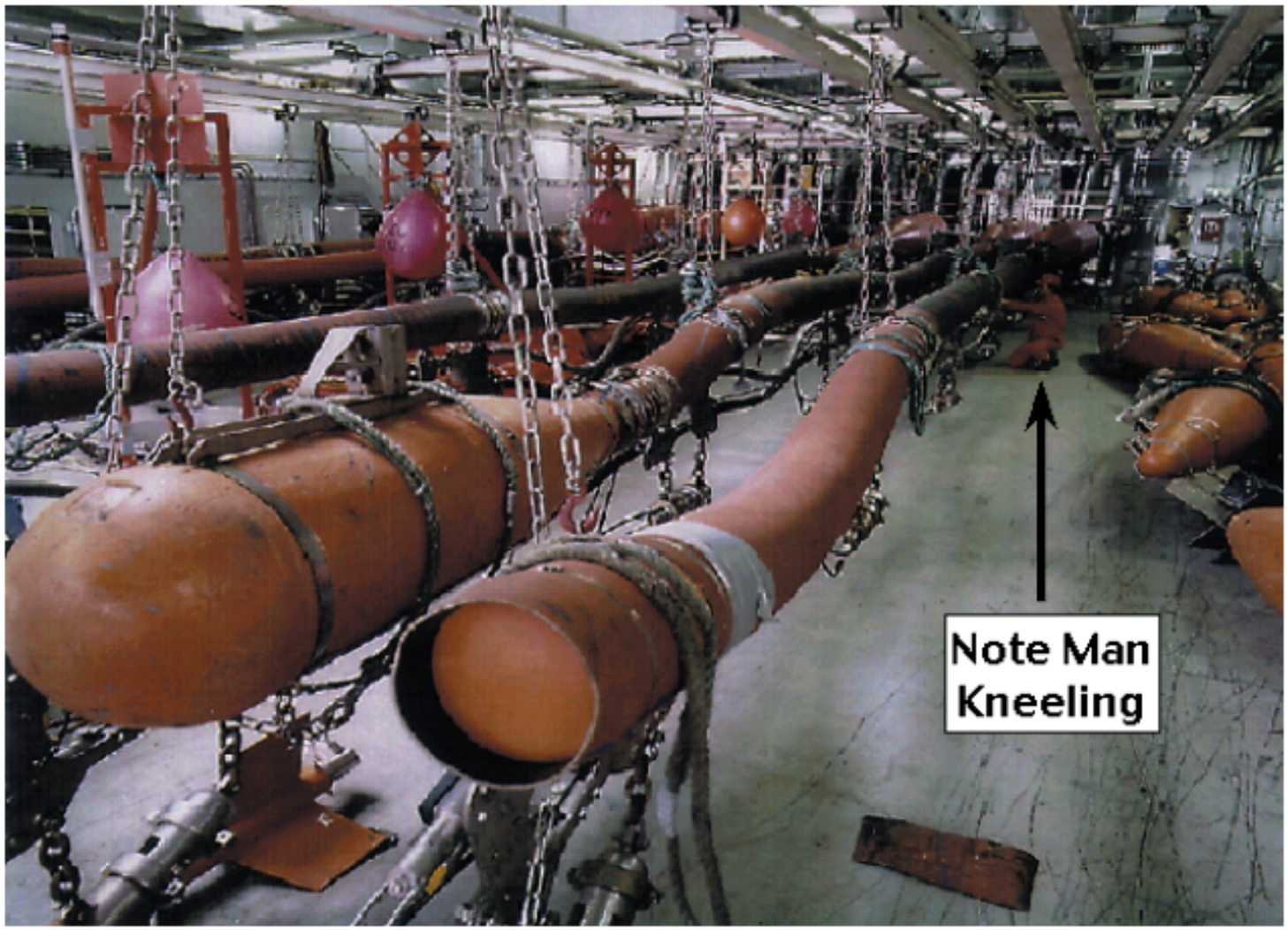


Figure 4.14: An airgun array on the gundeck of a survey vessel. The orange tubes that look like large hot dogs are the floats that support the air guns; the air guns themselves are hanging beneath the floats. From Caldwell and Dragoset [2000].

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These assemblies are suspended from overhead rails to allow them to be moved to the afterdeck for launch.

Deep sources

All the airgun-derivatives, deriving their energy from compressed air, are limited in depth of usage. The air pressure most commonly available is $2000 lbs/in^2$ (about 135 bars), which is equal to ambient pressure at about 1350 meters depth. These guns are usually used at around 10 meters depth.

Explosives can be used at greater depth but the bubble size is governed by the Ideal Gas Law, PV=nRT, so as depth increases the volume of gas produced by the explosion increases.
As the bubble size decreases, the frequency of oscillation increases (Rayleigh-Willis) and low-frequency energy available falls.

What we really need is volume change (proportional to Moment), which can be produced by an implosion just as well as an explosion.

P ressure V olume n umber of moles R product of Boltzmann's constant and Avogadro's number.

Volume source and bubble

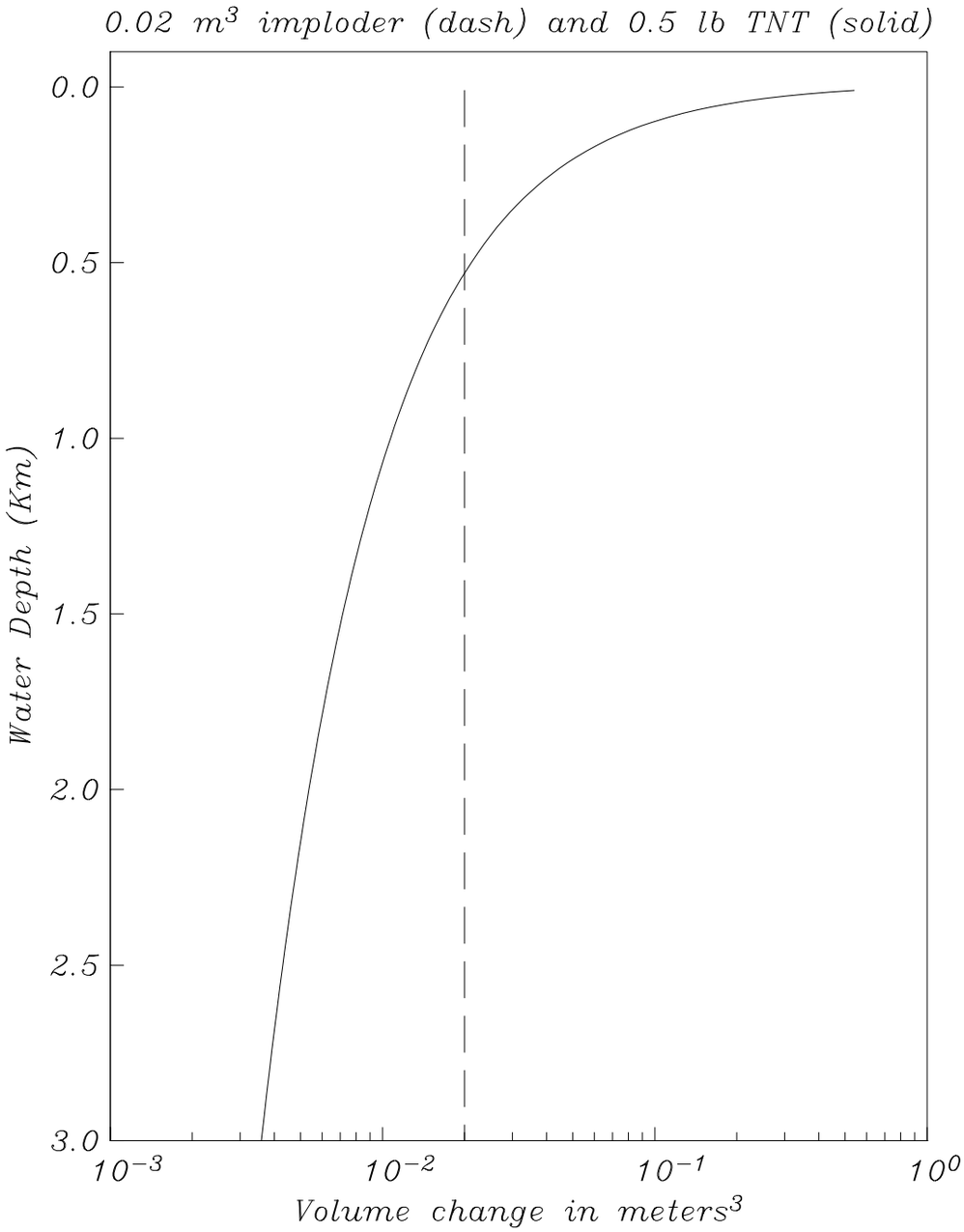


Figure 4.15: Depth dependence of volume change from a half-pound explosive and a volume source. From Dorman and Sauter [2006].

In terms of moment magnitude

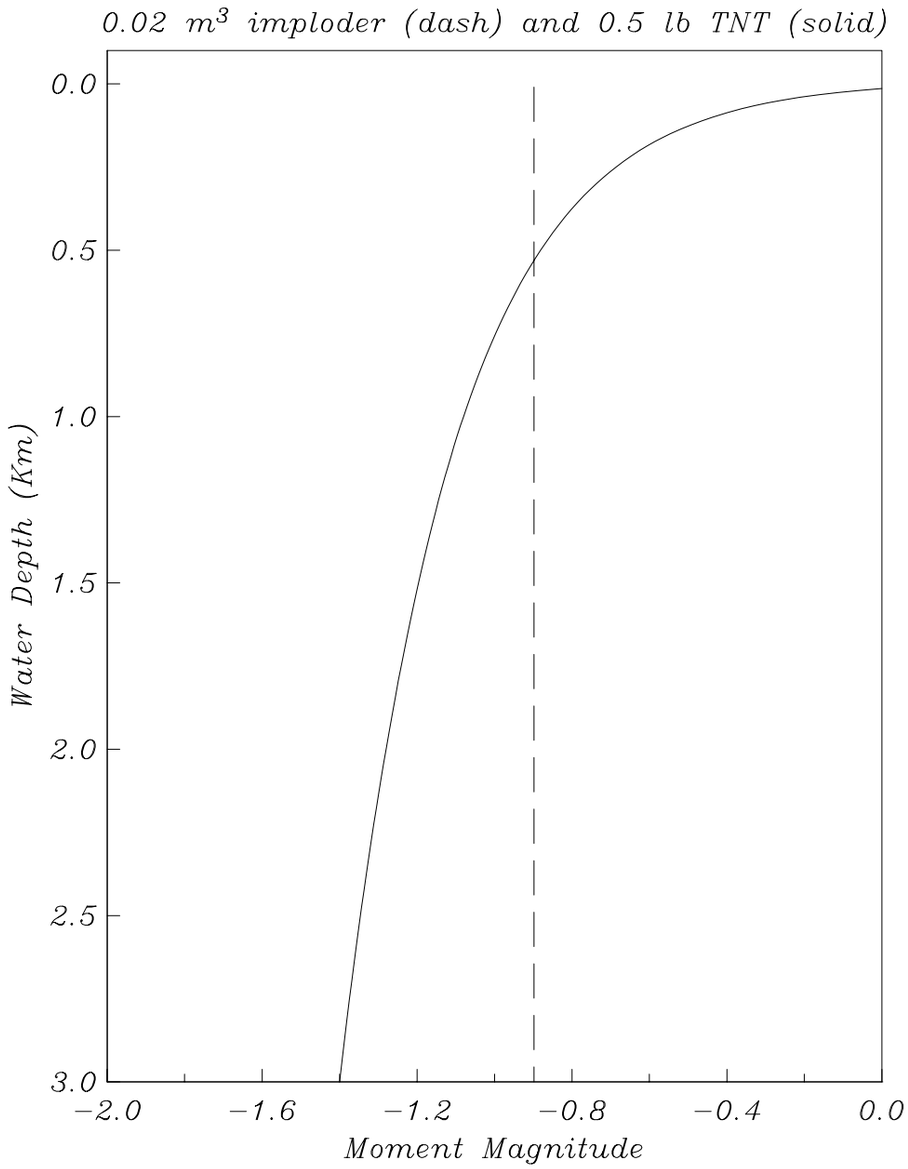


Figure 4.16: Depth dependence of moment magnitude from a half-pound explosive. From Dorman and Sauter [2006].

Principle of operation of single-shot version

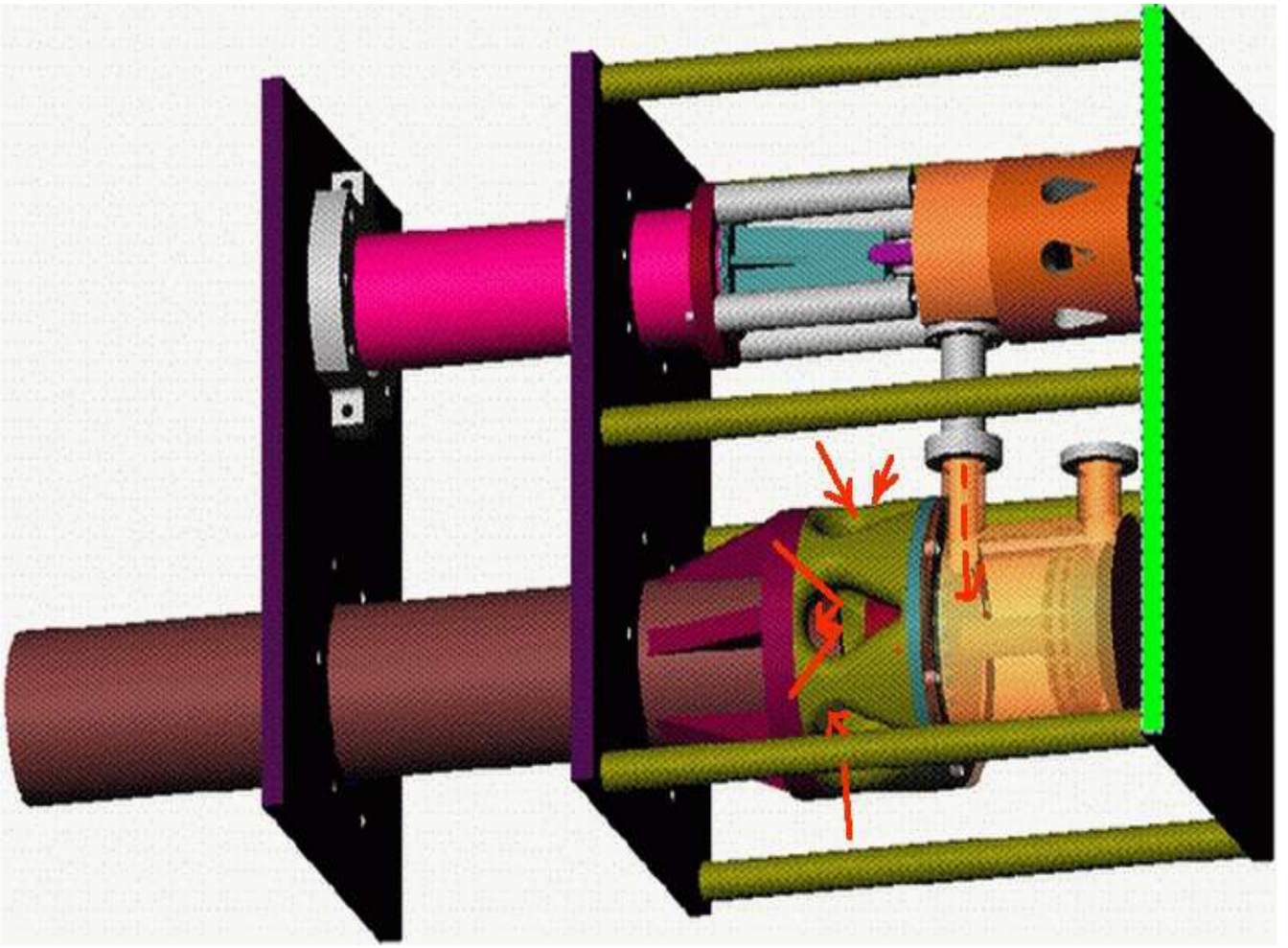


Figure 4.17: Cartoon showing interior of a volume implosive source. At the lower right-hand corner is the operating shuttle, similar to that in an airgun. From Dorman and Sauter [2006].

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Red cylinder is EG&G acoustic release, operated electrically. Brown cyl to its right is valve. Dark cyl to lower left is working volume, shuttle and ports to its right.

Actual device weight is about 600 lbs

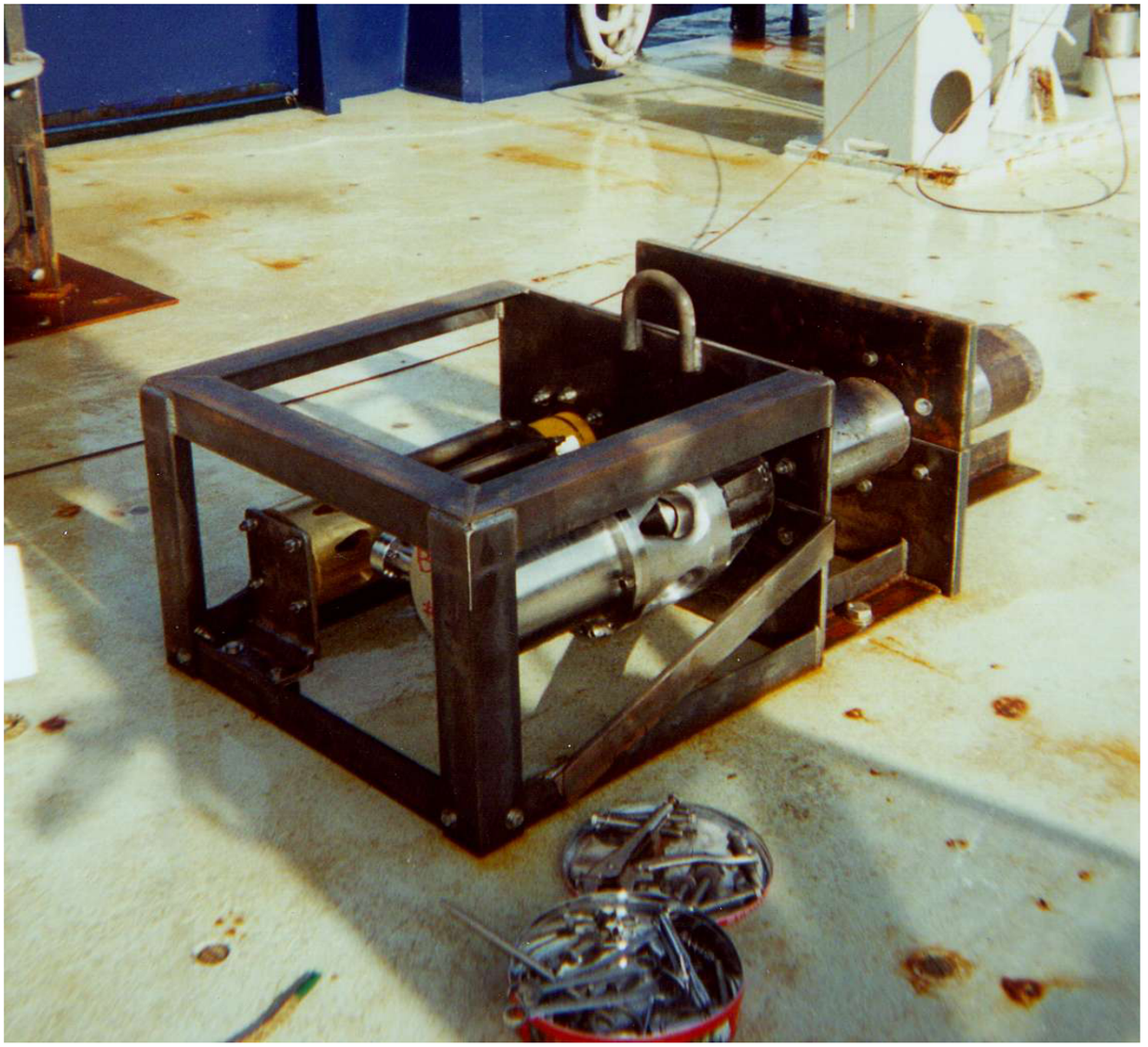
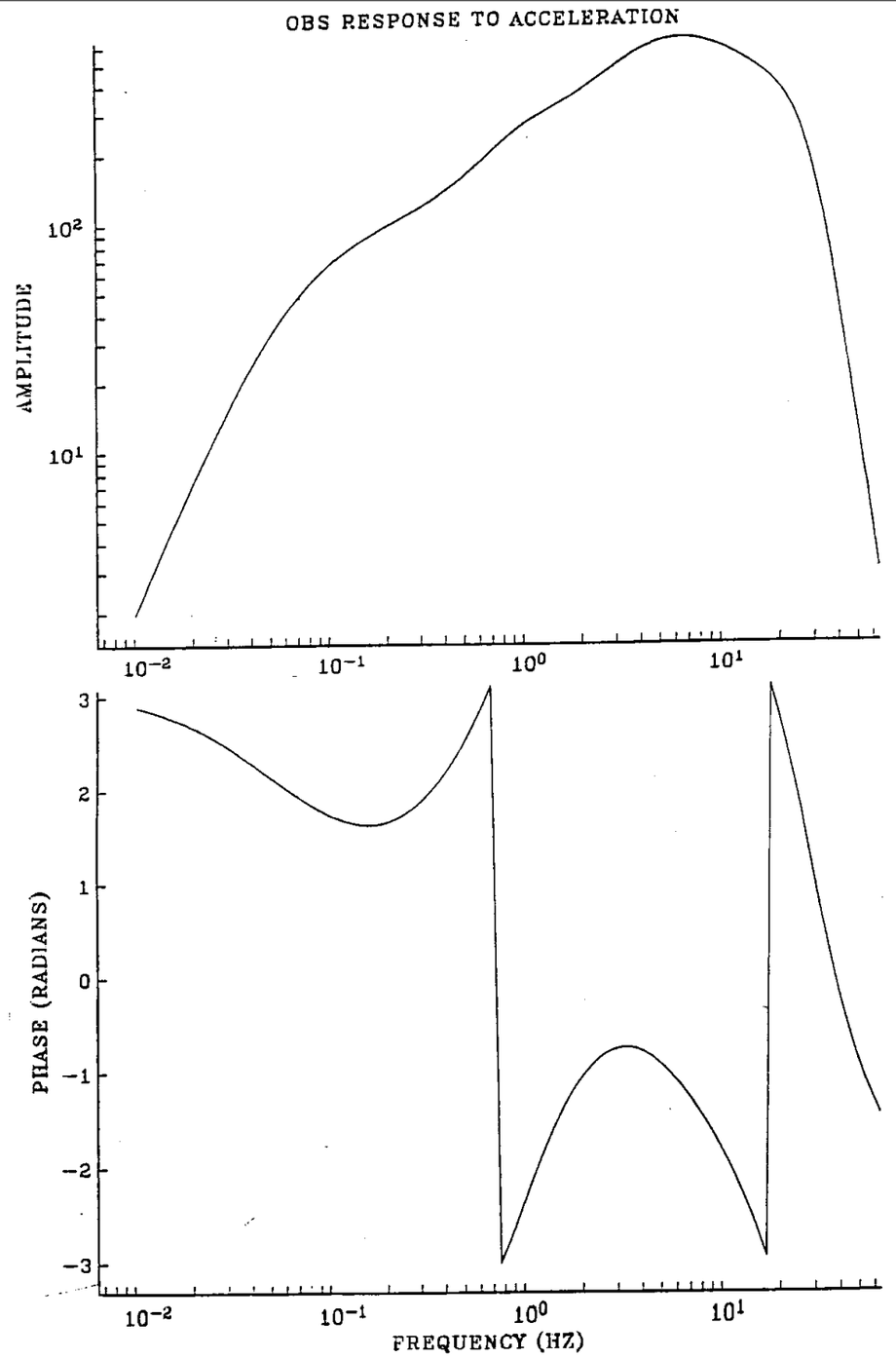


Figure 4.18: Photo of implosive source. Its weight is about 600 lbs. The cookie tin containing tools is about a foot in diameter. From Dorman and Sauter [2006].

Instrument response (OBS)

The instrument amplification increases with frequency to exploit the lower noise at higher frequencies.



OBS Instrument Response

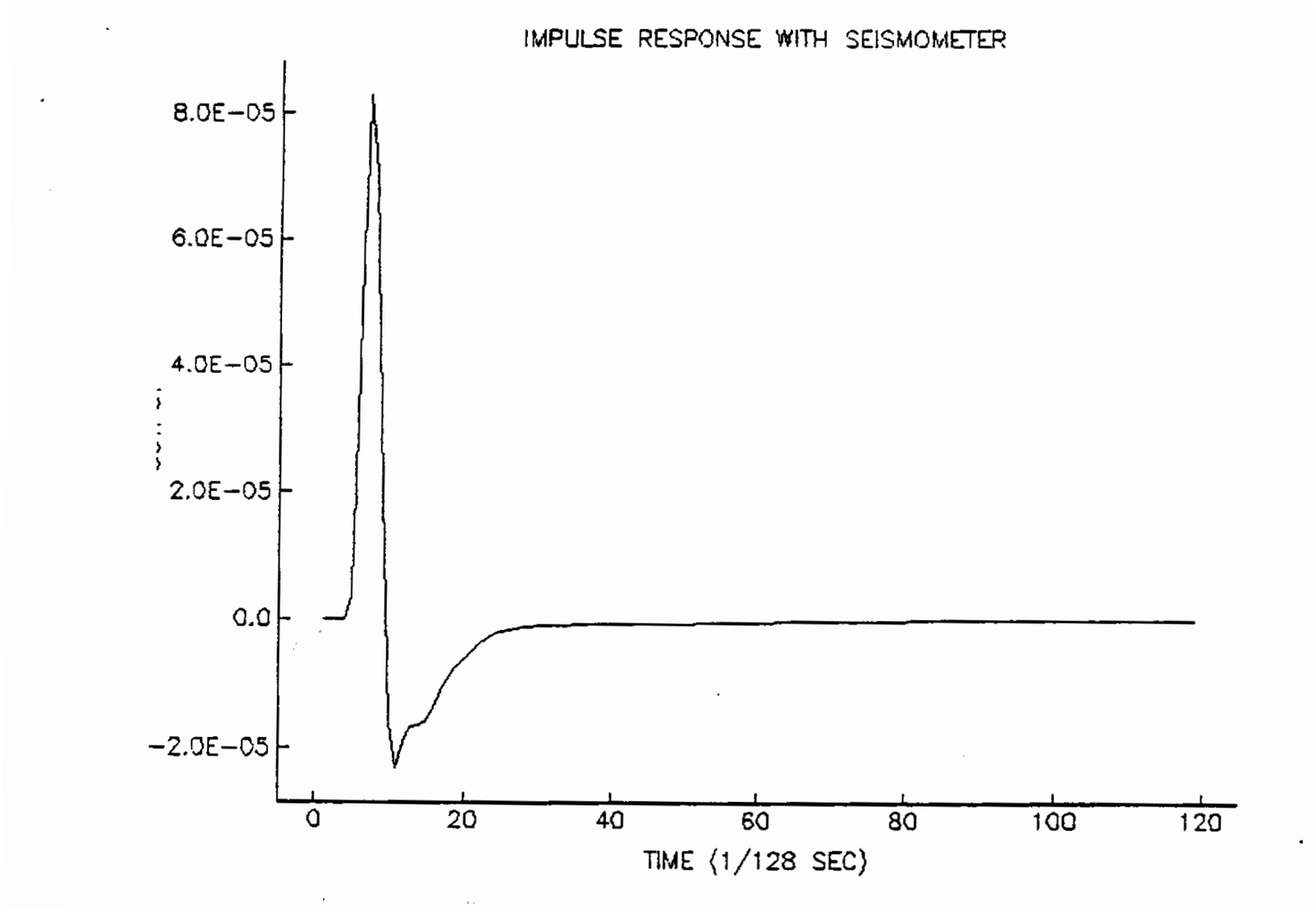


Figure 4.20: OBS impulse response. It is well-behaved in comparison with the complex signatures of many sources. From Moore et al. [1981].

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Somewhat like a differentiation (of acceleration)

Water waves from explosive sources

Distance range (down) out to 40 km.
Reducing Velocity 1.5 km/s

Left traces are direct to OBS.

What are traces to right? Why more complicated?

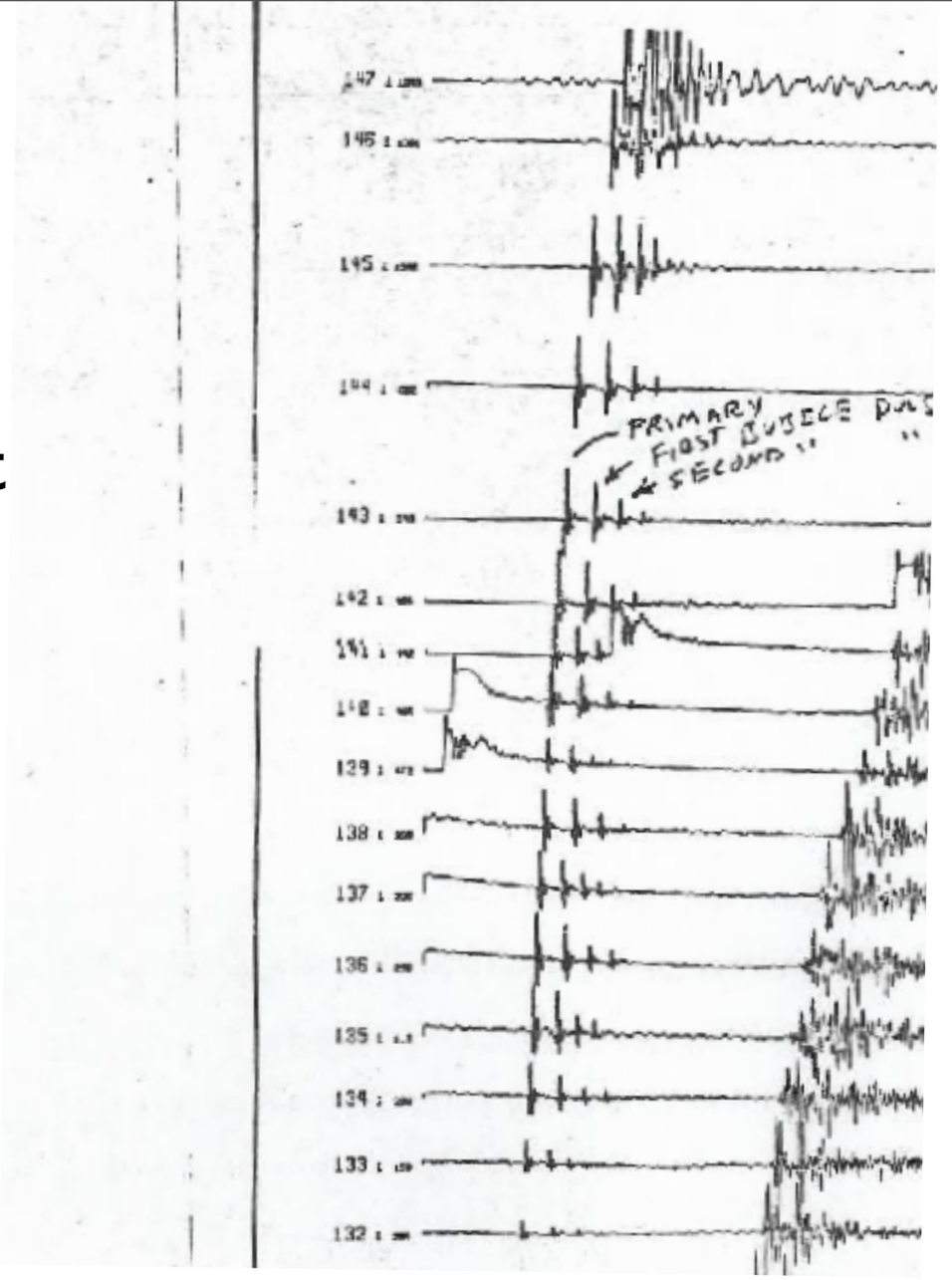


Figure 4.21: Record section of water wave arrivals recorded in West Phillipine Sea Goodman et al. [1989], Goodman and Bibee [1991].