IMPROVED HIGH-RESOLUTION SEISMIC PROFILING

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Abstract

High repetition-rate seismic reflection profiling is a technique used at sea to obtain visual analogues of geologic cross-sections. This thesis reports the development of a high resolution profiling system which has been field-tested in Boston Harbor. The system incorporates several improvements over conventional apparatus.

Visual display of the profiles is produced from playback of magnetic tape-recordings. A tape-recording is used to trigger the sweep and to modulate the beam of a cathode-ray tube; successive traces are recorded across slowly-moving 35 mm. film. Electronic sweep control and optical stacking onto photographic emulsion allow greater flexibility and dynamic range than the mechanical sweep stacking on electro-sensitive paper employed by pre-existing facsimile recorders.

Edgerton's boomer sound source has been modified to eliminate cavitation and to give non-oscillatory acoustic pulses of 118 decibels peak pressure (relative to 1 dyne/cm^2 at 1 meter). The initial impulse (0. 1 millisecond long) is followed by a slow decay which provides low-frequency energy for deeper penetration.

Generation of multiple events from a single echo by reflection from the sea surface above source and receiver can introduce ambiguity which reduces the effective resolution of a short-pulse sound source. The boomer source can be designed and towed so that no surface reflection ambiguity is observed at the source. Surface reflection from above the hydrophone can be reduced by towing it under the bow of the boat.

The combined capability of the improved sound source and the photographic display system is illustrated by a sample profile.

Thesis Supervisor: L. W. Dean, III
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Table of Contents

Appendices

List of Figures

I. INTRODUCTION

1.0 Background. High repetition rate seismic profiling is a technique used in water-covered areas to obtain a pictorial analogue of a geologic structural cross-section. Each time an artifical sound source is fired, a sequence of echoes returns from the acoustical discontinuities of the geologic structure. Each of these sequences is commonly recorded adjacent to the preceding sequence as a variable darkening along a sweep line of a facsimile recorder.

In some applications the goal of seismic profiling is to map deep structures; in others it is to map shallow sedimentary structures in shallow water. To record successfully reflections from great depth requires a powerful low-frequency sound source, since attenuation of sound in geologic materials is less at lower frequencies.

Resolution of fine detail, on the other hand, requires a short-pulse sound source. Since it is difficult to make a short-pulse source which is also very loud, and the requirements of short pulse length and low frequency are conflicting, separate systems are usually employed for high-resolution and deep penetration surveys. A more complete background is presented in Chapter II.

1.1 Goal of this Study. The goal of this study was to develop a high-resolution profiling system which represents an improvement in resolution over existing apparatus and technique, and which reduces ambiguity of interpretation to a minimum hitherto unattained. This goal was achieved by developments in data display, sound source design, and profiling technique.

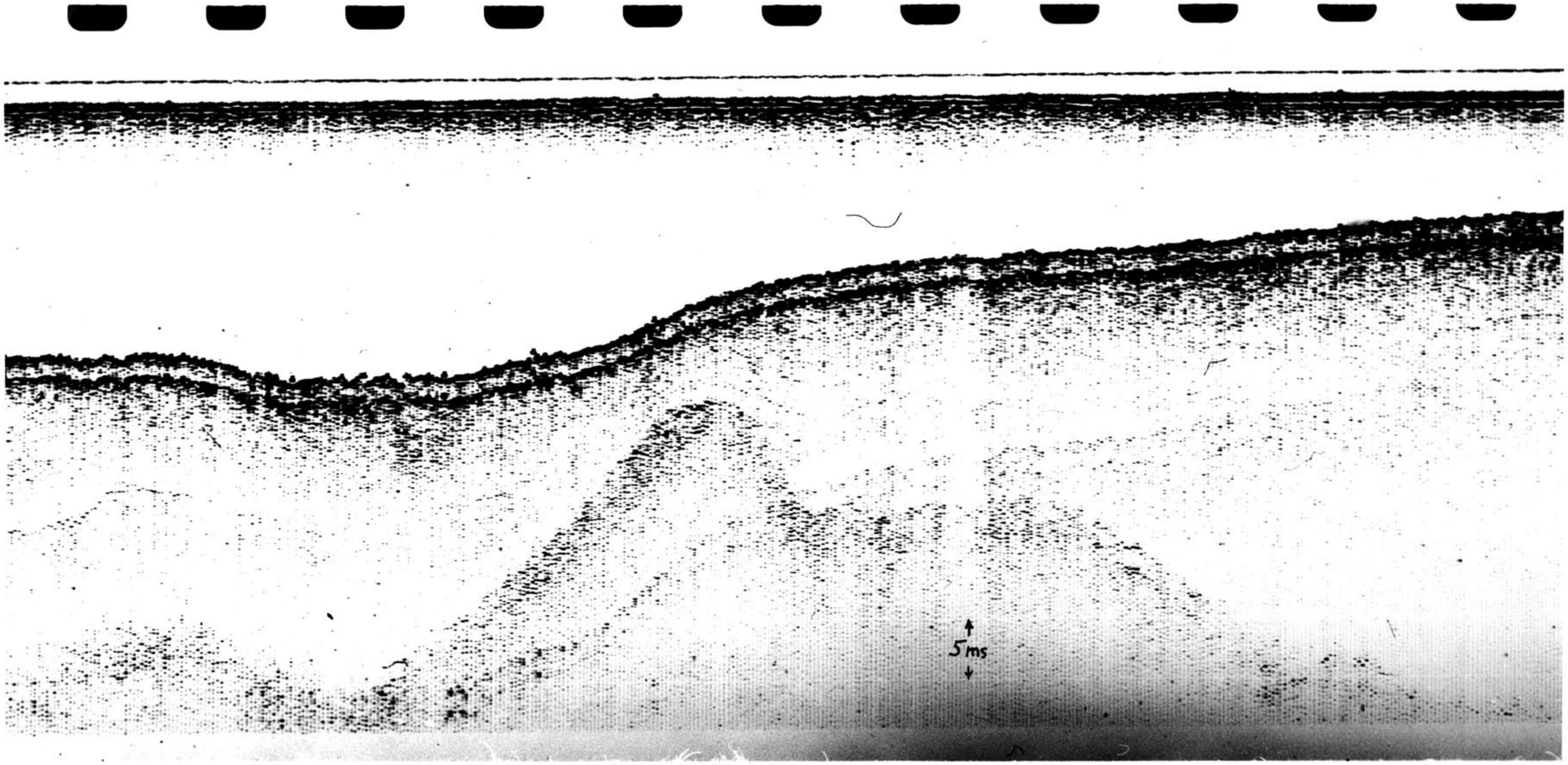
1.2 Data Display. Visual display of acoustic pulse data is essential for analysis. The defects of a system must be recognized before they can be corrected. Although individual pulses can be observed in detail by oscillography, there is so much information in a seismic profile that facsimile-format high-density display is required for complete display. Conventional facsimile recorders are difficult to synchronize in applications where they do not control a data sequence because their sweep has considerable mechanical inertia. They also have a rather narrow dynamic range of reproduction.

The design of an improved facsimile recorder is described in Chapter III. This recorder uses a cathode-ray tube for electronic sweep and modulation, and records on slowly-moving photographic film. The recorder was designed for the display of tape-recorded profiles; direct-writing for immediate readout was not attempted.

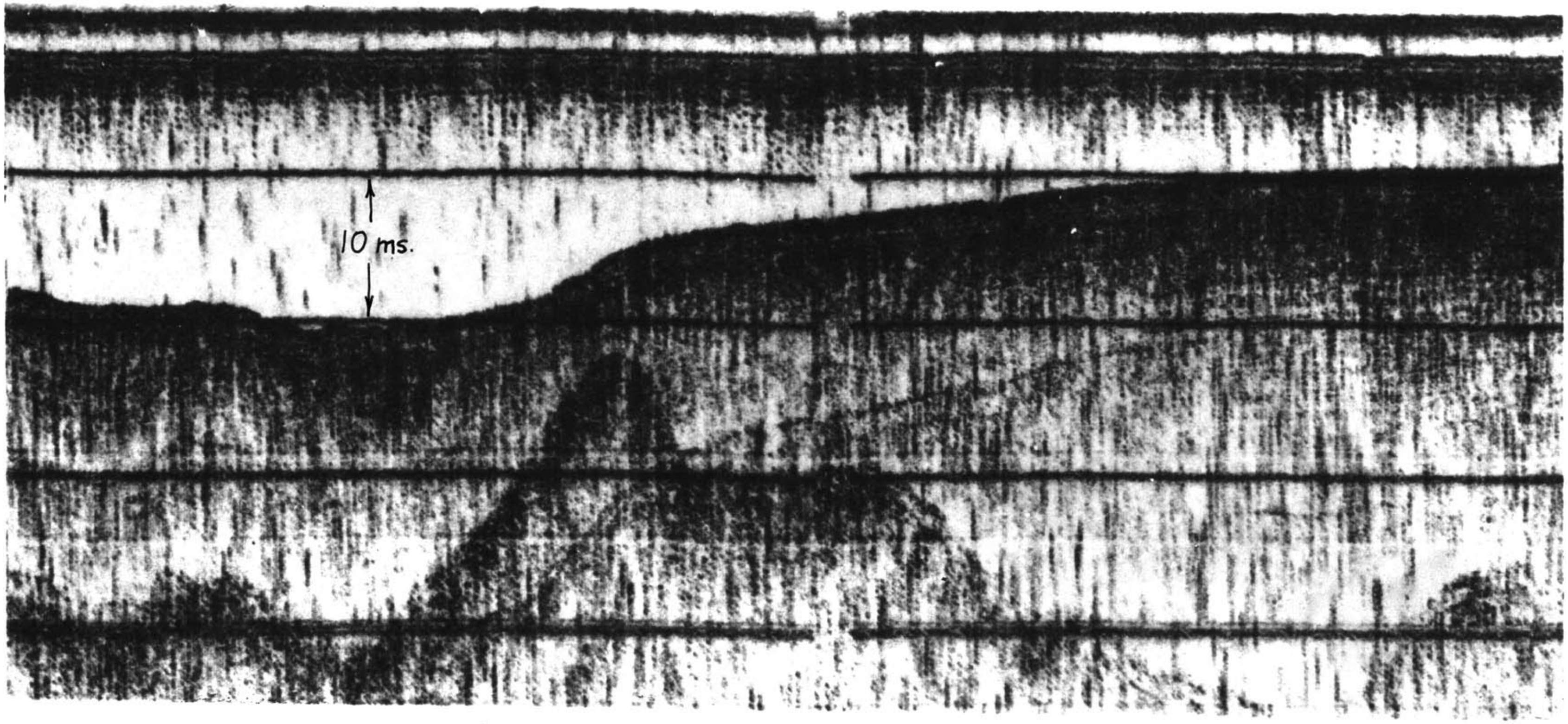
Figure 1--1 shows a film record made early in this study. It can be seen more readily from this record than from the corresponding conventional facsimile record, figure 1--2, that the source pulse is oscillatory, and that the delayed image, inverted by reflection from the sea surface, will introduce ambiguity where there are closely-spaced reflections of nearly equal amplitude.

1.3 Sound Source. A sound source for high-resolution profiling should produce a short pulse of acceptable amplitude. A non-oscillatory pulse is desirable for two reasons. The first is that a low-frequency pulse is desirable because of the increase of attenuation of sound with increase in frequency. An oscillatory pulse must have a higher frequency than a non-oscillatory pulse of the same duration, so it will be attenuated more. An oscillatory pulse also introduces ambiguity if there are closely-spaced reflections.

The design of an improved sound source is described in Chapter IV. It is shown that the initial impulse from this source can be controlled by the electrical design parameters. This impulse is followed by a low-frequency decay, caused by mechanical rebound, which provides energy at low frequency for deeper penetration.



1-1. Film Record of Seismic Profile, 20 June 1965



1-2. Paper Record of Seismic Profile, 20 June 1965 (2X photostat)

1.4 Hydrophone Placement. Seismic profiling is complicated by the air-water interface, which acts as a nearly perfect reflector. If an omnidirectional source and an omnidirectional receiver are suspended underwater near the sea surface, the direct echo from a reflector below them will be followed closely by three echoes from the sea surface above the source and receiver. These multiple events must be eliminated if the full value of high-resolution profiling is to be realized.

The sound sources developed here are flat, and can be towed at the surface, so that surface reflection from above the source does not appear on the acoustical record. Receiving hydrophones present more of a problem because they are omnidirectional. If a receiver is placed near the surface, the reflection ambiguity is confined to a short time-span, but the low-frequency response is cancelled by the negative reflection coefficient of the water-air interface. An alternate solution is to tow a hydrophone beneath the bow of the boat. The convex shape of the hull acts as a diffuse reflector so that the reflection received by a hydrophone some depth below the bow can be much weaker than the direct arrival.

This and other technical problems in seismic profiling are presented in Chapter V.

1.5 Results and Suggested Improvements. Part of a profile across President Roads, Boston Harbor, is presented in Chapter VI. The illustrations show that the profiling system developed here does resolve sedimentary structure and an underlying irregular surface to a depth of about 100 feet (30 milliseconds two-way travel time in the sediment), the greatest depth encountered in this area. Some features of the illustrations demonstrate the 0.1 millisecond resolution capability of the system.

The principal failings of the data display system are loss of resolution at high beam current (the phosphor is probably responsible) balanced against insufficient exposure at low beam current, and uneven film motion at very slow speed due to friction and backlash.

One hydrophone was not mounted on a streamlined towing fish, and was therefore too noisy at minimum boat speed.

The writer suggests that it may be possible to improve the display compromise by using more sensitive photographic materials and by using contact to a fibre-optic CRT face plate instead of a lens system to increase exposure. A different phosphor (e. g. P11) might be more suitable too.

The use of a high-resolution (1000 line) CRT should enable the recording system to compete favorably with conventional facsimile recorders marking on 19-inch paper.

Dual-channel recording from two hydrophones at the same depth on opposite sides of the boat should make it possible to identify side-echoes by stereoscopic viewing of paired photographic records.

II. BACKGROUND

2.0 Evidence in Geology. Geology is both a descriptive science and a logical one. Both aspects of the science require information--as a description, or as evidence to support or refute hypotheses. The traditional source of this information is surface mapping. In modern times aerial methods have greatly increased the amount of surface information accessible to the geologist.

Unfortunately, most of the surface of the earth is covered by water, which is practically opaque to anything but sound, and largely reduces surface methods to blind operation of remote devices. Furthermore, even on land, surface methods only give clues for inference of three-dimensional structures.

Echo-sounding at sea has made available a caricature of aerial photography on land. Seismic reflection surveying has provided information about three-dimensional structure beneath the land surface and the floor of the ocean[1, 2].

Seismic reflection profiling at sea has been born of both echo-sounding[3, 4] and land seismic reflection surveying. The transparence of sea-water to sound and good acoustic coupling of the sea to the earth beneath the sea make seismic profiling at sea much easier than the corresponding operation on land. In seismic profiling, just as in echo-sounding, the picture one gets is only an approximation to the geologic profile, or topographic profile, which is desired. Within this limitation, though, these methods can be used to portray fine structure more effectively than can be done on land.

2.1 Display of Data. Acoustic signals in echo-sounding and seismic profiling are usually transformed into electrical signals by receiving transducers. These time-varying voltage waveforms can be recorded or displayed in oscillographic form; for detailed analysis this is probably the best form of presentation. At high information rates, though, direct visual display is too fast, and strip-chart recordings become unmanageably bulky.

For each out-going sound pulse there is an echo, or a sequence of echoes, which returns at a time delay which is practically the same for adjacent pulses. This correlation can be effectively displayed by light-dark modulated lines immediately adjacent to each other as in facsimile recording. A recording device must be synchronized with the out-going pulse if this correlation is to be achieved.

There are two solutions to the synchronization problem. One is to build a recorder which can be triggered by the firing of a sound source[5]; the other is to use only sound sources which can be fired electrically by a continuously-sweeping recorder[6].

The recorders of both types which are in common use are mechanical devices which mark electro-sensitive paper.

Tape-recording of acoustic data has been introduced into seismic profiling instrumentation because of the narrow dynamic range of the electro-sensitive papers which are available. The tape-recorded information can be played back any number of times at a later date in attempts to improve record quality over those taken at sea.

2.2 <u>Sound Sources.</u> Electrically-fired sound source for continuous seismic profiling[6] can be divided into two categories--high-powered sound sources for deep sea operations and short-pulse devices usually used to delineate sediments in shallow water[8, 9]. None of the high-powered sources in common use have pulse lengths shorter than one millisecond; most have a duration of many milliseconds[6, 9]. Short-pulse sound sources may achieve pulse durations as short as 0. 1 millisecond, but a high resonant frequency must be used which results in a high propagation attenuation in geologic materials[7, 8, 3].

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III. DATA RECORDING AND DISPLAY SYSTEM

3.0 Introduction. It has already been pointed out that the facsimile format of intensity-modulated sweeps laid down parallel to each other on a slowly-moving recording medium is a convenient way to pack large amounts of repetitive information into a compact visual display. The fact that currently available mechanical facsimile recorders have a number of undesirable features, including limited dynamic range, plus the fact that magnetic tape recorders allow playback of data at a later time has led to tape-recording of seismic profile data in the field. Although mechanical facsimile recorders can be synchronized for display of tape-recorded data they require a pre-recorded synchronizing channel, and have to be locked into correct time synchronization with the data. This and other defects of conventional facsimile recorders inspired the development of a photographic facsimile system using an intensity-modulated cathode-ray tube display. Some difficulty was experienced in trying to get direct read-out[1]. In the experiments reported here film records were developed only after removal from the camera at the end of a tape-recording playback.

3.1 The Cathode-Ray Tube. A Tektronix 545B oscilloscope was used to display seismic profile data.

The specifications given for the tube (T5470) state a minimum spot size of about .01 inch for beam currents less than 5 microamperes. Since the spot size of paper-marking facsimile recorders (Alden, for example) is also .01 inch, the 4-inch CRT display should have about the same resolution as a 5-inch paper record.

The z-axis input available on the 545B oscilloscope was unsatisfactory because of differentiation by the capacitive coupling. The grid of the CRT is normally used to turn on the beam during its sweep and to turn it off during retrace and while it is at rest. Unblanking is necessary for the swept display developed here so a method of modulating the beam had to be developed which would not disrupt the unblanking. Because the grid circuit is a high-impedance circuit it is possible to insert a low-impedance transformer secondary winding in the circuit without affecting the unblanking. An acoustic signal connected to the primary winding then adds to the unblanking voltage, and the unblanking voltage is isolated from the signal amplifier by the transformer. The only modification to the oscilloscope was the addition of a three-conductor shorting jack in the unblanking line. The transformer was mounted in a separate chassis.

Grid modulation of the CRT was tested visually as a check on Tektronix' technical data on spot size (Performance Curves, T5470, dated 7/28/64). A modulating signal of 5 volts (peak-to-peak) was acceptable at low low beam intensity (increase in intensity or modulation increases the spot size); modulation of only 0. 2 volts (peak-to-peak) was clearly discernable. The ratio of these voltages gives a dynamic range of 28 decibels. Other evidence seems to indicate that for correlated display on film the minimum visible modulation is considerably smaller. The writer has recorded sixty-cycle noise on film when the noise measured at the modulation input to the CRT was about 50 decibels below the maximum signal (5 volts peak-to-peak). This dynamic range is certainly well within the statistical limitation of the beam current (1 μampere for 100 μseconds equals about 10^9 electrons). The P31 phosphor supplied in the tube has a grain size of 12 μ, or about . 0005 inch, which means that a . 01 inch spot illuminates about 300 grains of phosphor.

3. 2 Optical Recording.

Most photographic emulsions achieve their full dynamic range for resolutions no greater than 10 lines per millimeter[2]. In this application 200 lines must be resolved (400 spot diameters), so a frame width of 20 millimeters on film is required. This can be conveniently achieved by a 5:1 image reduction onto 35 millimeter film.

The camera built for this project uses a two-inch focal length lens to focus on 35 millimeter film wrapped one-half turn around a 24-tooth sprocket wheel. The camera is mounted on a board which is used as a jig to align and position the camera at a fixed focal distance. Ambient light is excluded from the lens field by a cannister light-shield. The camera has no shutter but there are baffles inside it which prevent exposure of the film outside an adjustable slit window.

3. 3 Film Mechanics.

In operation the film is moved slowly past the window by rotation of the sprocket wheel. The film is pulled out of a standard cassett by the sprocket, so the drive must be disengaged before the exposed film can be rewound.

The film transport is a critical part of the data reduction system. It was necessary to exclude compliant elements (rubber belting, for instance) from the drive train and to use a controlled-speed motor to prevent irregularity in the film motion. A dual-winding motor-generator operated by a feedback system with an adjustable reference allows speed control over a 1000:1 range. The motor is coupled to the sprocket by quick-disengage gearing with a step-down of about 10, 000:1. The range of effective image speed at the CRT face is about 0. 01--10 millimeters per second.

3. 4 Oscillography. Although the camera was designed for facsimile-format recording it can also be used to record a sequence of oscillographic traces. The slit baffles in the camera are left opened to accept a two-centimeter image,

so all that is required of the camera is to increase the film advance speed.

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IV. THE SOUND SOURCE

4.0 Introduction. A good pulse source has three requirements: short duration, adequate amplitude, and controlled initiation. A seismic sound source must have considerable amplitude in the low-frequency part of the spectrum, since propagation attenuation in geologic materials is greater at higher frequencies. The conflicting requirements for short duration and low frequency can be best compromised by a half-cycle sine-wave pulse. Devices which are acoustically mismatched to water impedance (e. g., piezo-electric transducers) are naturally oscillatory and cannot be easily adapted to produce such a pulse. Control of delayed rebound (cavitation collapse) pulses is a problem in the case of explosives and underwater spark sources. The boomer sound source[1] in its original form depended on cavitation for its operation.

The improved sound source developed here is a modification of the boomer to eliminate cavitation and the resulting long-duration output signal. The modified boomer can produce an acoustic output closely approximating a half-cycle sine-wave pulse. The following sections of this chapter are devoted to electrical design consideration, design to optimize transduction, and mechanical design considerations. In the final section acoustic pulses from several experimental transducers will be illustrated which approximate the desired pulse, but which also give a novel benefit.

4.1 Electrical Circuit Considerations. The boomer sound source consists of a high-voltage, capacitor-discharge driving circuit connected to a transducer coil which repels a conductive plate when current flows. The capacitor is charged between firings at a rate which is limited by the power rating of the charging circuit. The fully-charged voltage is also usually a fixed design consideration in a given charging circuit. The energy stored in the capacitor

($\frac{1}{2}CV^2$) is proportional to the capacitance, so for a given charging circuit the maximum firing-rate multiplied by the capacitance (or energy) is a constant. Thus, for a particular charging circuit the compromise between firing rate and energy-per-firing will determine a particular value of capacitance.

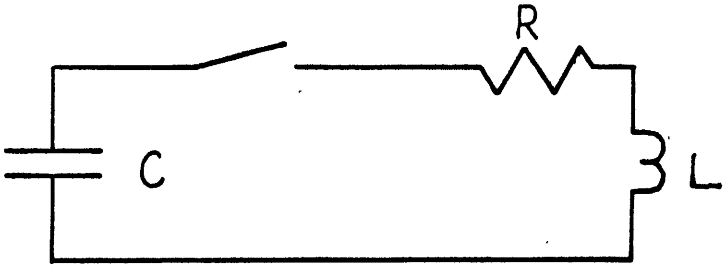
An oscillatory circuit is formed when the air-gap switch is ignited and couples the inductance of the transducer to the capacitance of the driving circuit. The frequency of oscillation can be controlled by the inductance of the transducer (together with the capacitance of the driver), and the damping can be controlled by resistance. A simplified equivalent circuit for the boomer sound source is shown in figure 4--1a.

The shortest current pulse is obtained from a given L--C circuit when it is critically damped. The criterion for critical damping is that the decay constant equal one half-period ($T/2 = \pi\sqrt{LC}$). For a series-damped circuit the decay constant is $\tau = L/R$ (figure 4--1a), for a parallel-damped circuit $\tau = RC$ (figure 4--1b). The peak current of a critically damped circuit is $\frac{1}{e}$ times the value it would have if there were no damping.

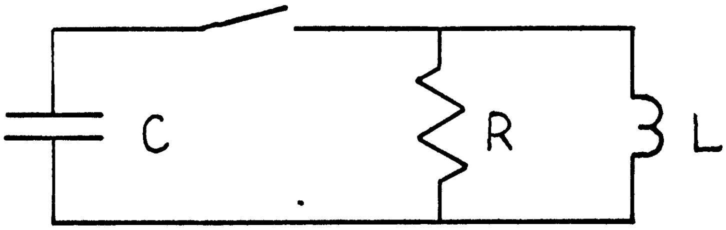
There are circumstances in which an over-damped current pulse form may be useful. Although this can be achieved by resistive damping, the reduction in peak current may be unacceptable. An alternate solution is to use a back-baised, or run-down, diode in the inductive part of the circuit. A simplified equivalent circuit and hypothetical current pulse are shown in figure 4--1c. A reason for experimenting with this configuration is presented in section 4.3; the results of these experiments are presented in section 4.4.

4.2 Transduction. A generalized boomer transducer consists of two current-carrying conductors which repel each other according to Ampere's

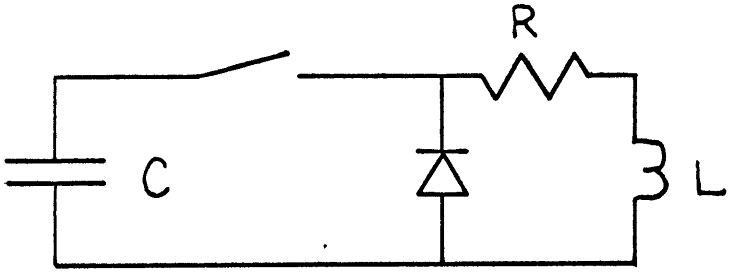
a. Series Damping



b. Parallel Damping



c. Run-down Diode



4-1. Simplified Electrical Equivalent Circuits for the Boomer Sound Source law. Usually one conductor is a flat coil electrically driven by the capacitor-discharge; the other is a conducting plate in which eddy-currents are induced by the magnetic field from the driven coil.

Experiments with two-coil boomers and two-terminal impedance measurement of one of the successful conducting plate prototypes developed here, together with symmetry arguments, indicate that the current induced in a conducting plate in close proximity to a flat coil is a synchronous geometric image of the current in the coil. Ampere's law for the force exerted on a current element i ds by another current element i'ds' at a distance r away in free space is

$$\underset{\sim}{dF} = \frac{\mu_o}{4\pi} \cdot \frac{i\,i'\,(\underset{\sim}{ds} \times [\underset{\sim}{ds} \times \overset{\underset{\sim}{r}}{\cancel{\underset{\sim}{x}}}])}{r^3} \tag{1}$$

in rationalized MKS units. If we assume distributed currents this takes the form

$$\underset{\sim}{dF} = \frac{\mu_o}{4\pi} \cdot \frac{dv\,dv'\,(\underset{\sim}{J}' \times [\underset{\sim}{J} \times \underset{\sim}{r}])}{r^3} \tag{2}$$

while for planar distributed currents the corresponding force equation is

$$\underset{\sim}{dF} = \frac{\mu_o}{4\pi} \cdot \frac{da\,da'\,(\underset{\sim}{j} \times [\underset{\sim}{j} \times \underset{\sim}{r}])}{r^3} \tag{3}$$

where j represents current density in the plane. The force on a unit area of one conductor due to the currents over the entire other conductor is represented by the area integral

$$d\underset{\sim}{F} = da \int_{A'} \frac{\mu_o}{4\pi} \left(\frac{\underset{\sim}{j'} \times (\underset{\sim}{j} \times \underset{\sim}{r})}{r^3} \right) da' \tag{4}$$

Consider two discs of uniform areal distribution of circumferential current in close proximity on a common axis. If we take a test area to compute the above integral which is near neither the edge nor the center of one of the discs, the force on this area will be normal to the discs, and its magnitude will be substantially independent of position.

This is true because of a combination of factors. The vector product contributes only for separations normal to the local current direction. Furthermore, contributions from large separations are oblique, so in the vector addition all but a small normal component is concelled by symmetrical contributions. These effects combined with the $\frac{1}{r^2}$ dependence on separation assure that contributions to the integral will be negligible outside an integration area only slightly larger than the test area. The force distribution on the discs will therefore be uniform except near the centers and near the edges, where near is defined as approximately the separation distance.

The solution to this hypothetical case inspired the full-area coil modification from Edgerton and Hayward's design to achieve uniform force distribution. In light of the arguments presented above the force per unit area should be approximately

$$\frac{|d\underset{\sim}{F}|}{da} = \frac{\mu_o}{4\pi} \cdot \frac{j^2}{d^2} \tag{5}$$

where d is the separation distance and j is the areal current density expressed in ampere-turns per meter of radius. Because of the $\frac{1}{d^2}$ term the coil-to-plate separation must be kept as small as possible. For the same reason the thickness of the conducting plate and of the coil must be kept small (skin depth effects are not significant in the experiments discussed here).

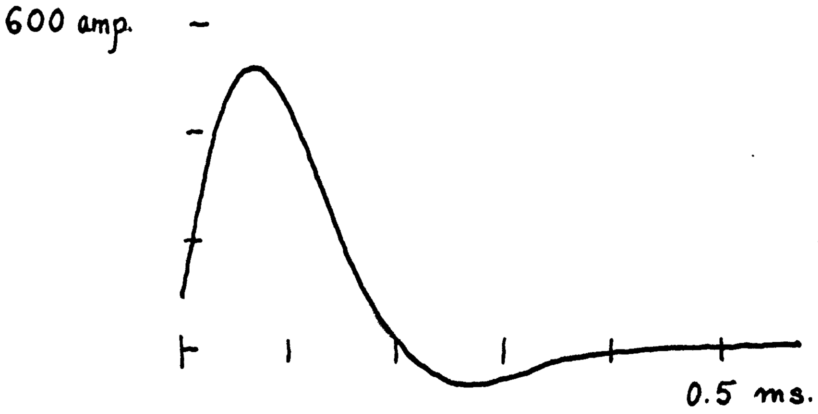
The sensitivity of the transduction to current density suggests increasing the number of turns, but it can be easily shown that this is self-defeating because it increases the inductance by the square of the number of turns (n). Since the energy, $\frac{1}{2} Li^2$, is fixed, ni is fixed, so the current is in exact inverse to the number of turns. No potential gain means conversely that there is no potential loss, so the number of turns may be freely varied as a design parameter to control inductance.

However, difficulty will arise in trying to achieve high inductance, because the more effectively the coil and plate are coupled, the less the measured inductance will be. The run-down diode configuration (figure 4--1c) could in principle enable the production of a long pulse by a low-inductance transducer.

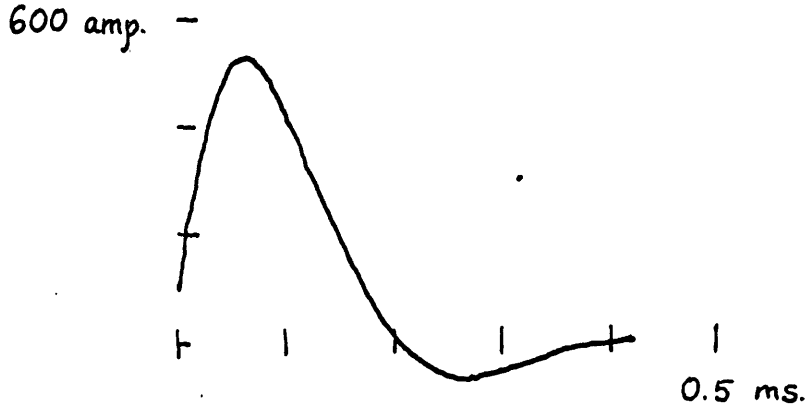
There is experimental justification for the image assumption made at the beginning of this section: that the induced currents are in phase with the inducing currents, and that they form a symmetrical geometric image. Two-coil boomers have been operated with the front coil shorted and with both coils driven in series. The measured current through the discharge circuit was the same in either case (figure 4--2a, b) and the acoustical output was observed to be unchanged. One coil-and-plate boomer (the A-boomer) was measured for impedance as a function of frequency[2]. It was found to have a well-behaved constant inductance over the range of 1--100 kiolcycles.

4.3 Mechanical Design. It has been shown above that a transducer can

a. Front Coil Shorted



b. Coils in Series



4-2. Current Driving a 2-Coil Boomer

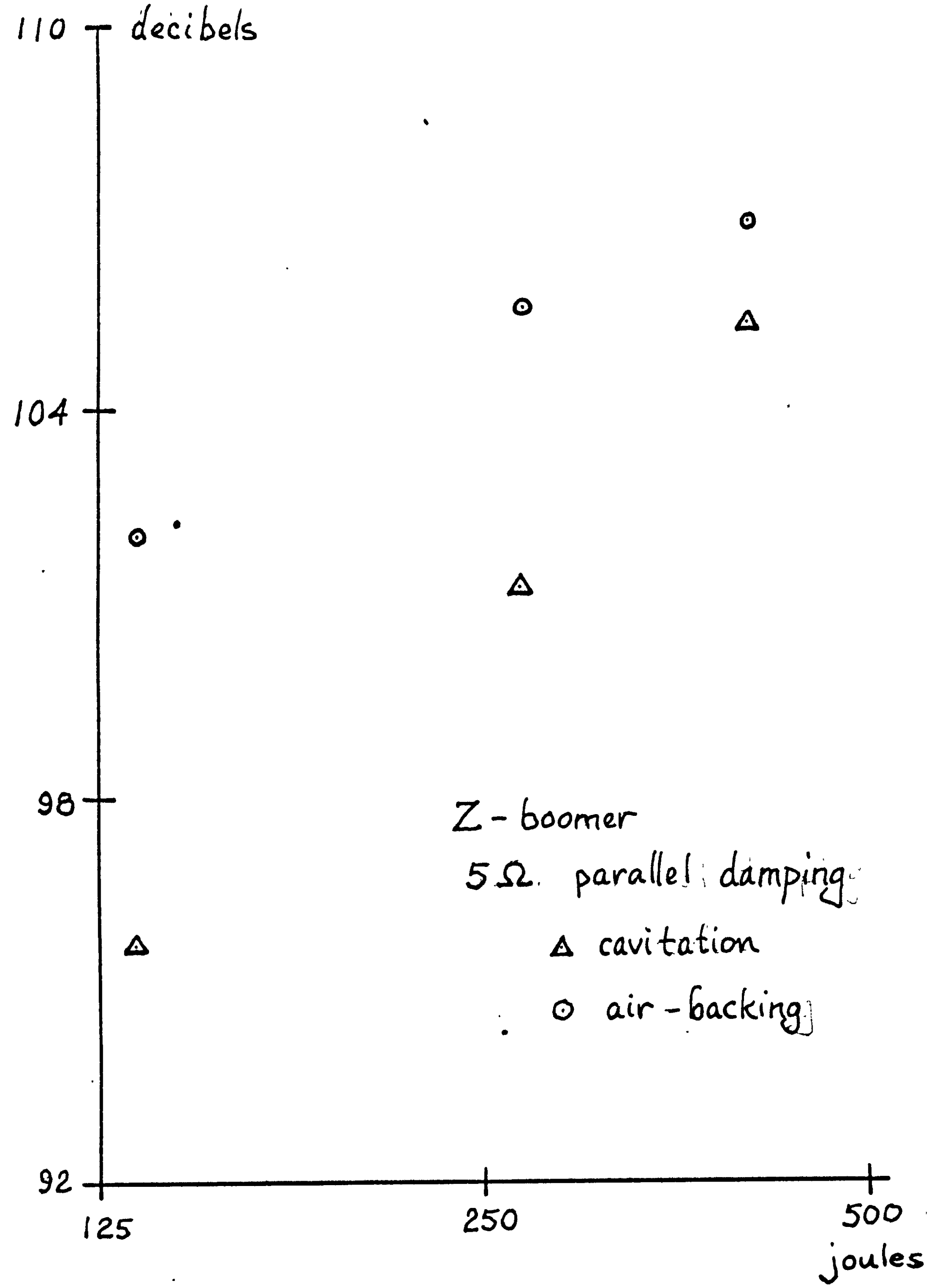
be designed to give a nearly uniform force density over an area. This force is in dynamic balance with inertial and restoring forces. The mass of the conducting plate is negligible compared to the inertia of the water which is pushed by the transducer, so it can be said that the transducer is perfectly coupled to the water; thus there is in principle a one-to-one correspondence between the transduction force and the pressure delivered to the water. In practice restoring forces limit this relation. Edgerton and Hayward's boomer depends on cavitation behind the plate to make up for the volume opened as the plate moves forward. This means that while the cavity exists there is a pressure difference from ambient pressure in front to the vapor-pressure of water behind the plate in addition to the dynamic acoustic pressure. Since the vapor pressure of water at ambient temperatures in the ocean is on the order of only one hundredth of an atmosphere this can be a quite serious defect.

The use of air behind the plate was suggested by Edgerton and Hayward. A transducer was operated "wet" and with air-backing to test the idea. The resulting increase in peak acoustic pressure is shown in figure 4--3. The difference in output is most apparent at low energy. This is probably due to the surface energy loss in creating the surface of the cavitation volume.

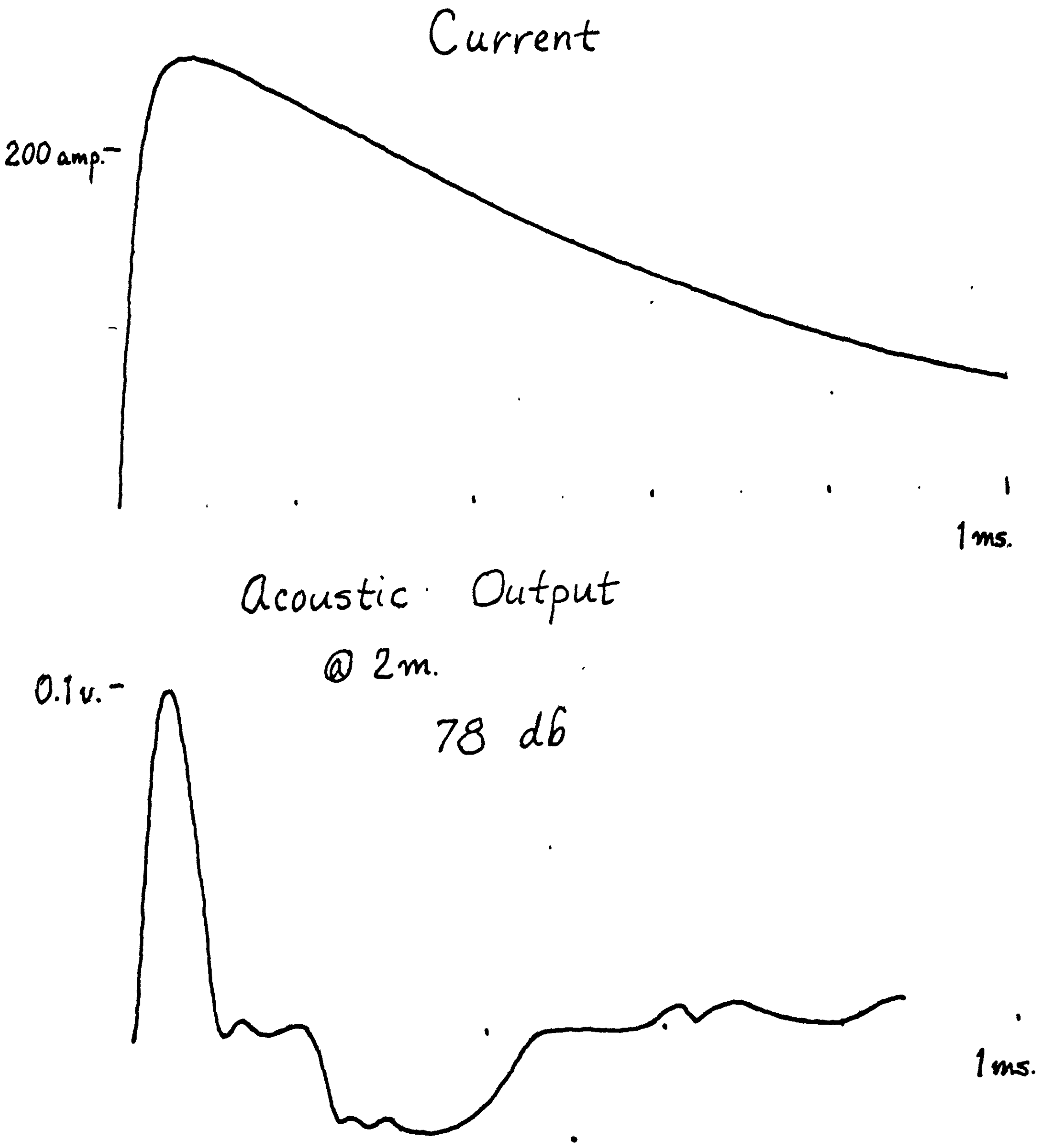
Air-backing does not eliminate restoring force. As the plate moves forward the air pressure decreases in approximate proportionality to the inverse of the increase in volume. The transducers developed here are seriously non-linear due to this effect, which appears as a negative overshoot in the acoustic waveforms.

One use of the run-down diode configuration (figure 4--1c) is to combat this restoring force. An experiment in over-damping a wet boomer showed (figure 4--4) that this current waveform can delay and reduce the amplitude of undershoot caused by restoring force.

The introdcution of the full-area coil into the boomer design eliminates



4-3. Effect of Air-backing on Acoustic Peak Pressure Output



4-4. Over-damping to Hold Undershoot

flexing of the plate, since the force is uniform, and thereby eliminates rebound cavitation at the center of the front of the plate.

Keeping the air in and the water out of an air-backed boomer is a mechanical design problem which is considerably complicated by the need for a compliant suspension of the plate. It seems likely that the negative overshoot observed is partly due to the incompliance of the air seal and the plate suspension of the transducers developed here, since the most compliant (the S2) boomer has the least overshoot.

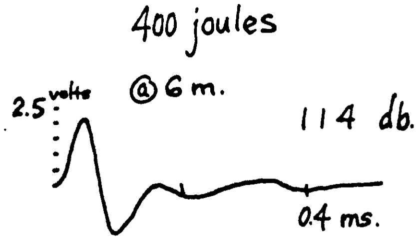
4.4 Acoustic Output. Three transducer designs have been developed in the course of this study. The A-boomer was the first of the full area coil designs. A square plate of 1/8" aluminum was sealed to the coil by a dike of RTV silicone rubber, and held at the corners by bolts used to fasten the transducer to its frame. A symmetrical small two-coil boomer (S2) was sealed around the edge with gum-rubber tubing, split and glued. The pizza-pan boomer (PP) is essentially an aluminum pan containing a coil loosely resting on plastic insulation against the bottom. Water is kept out by a glued-on lid.

Acoustic outputs are shown in figure 4--5. An acoustic output of 118 decibels (referenced to 1 dyne/cm^2 at 1 meter) has been measured for the A-boomer driven by 48 μfd. at 4 kilovolts (400 joules).

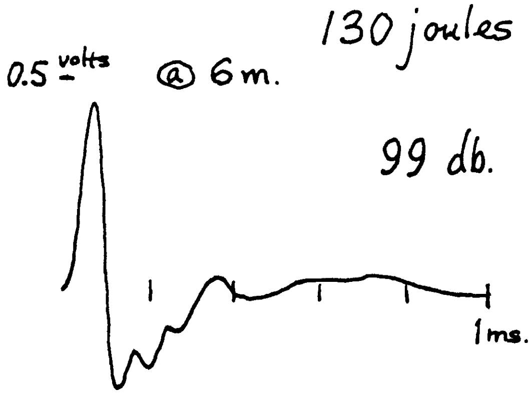
The run-down diode configuration was tested with the pizza-pan boomer in water and with the A-boomer in the laboratory. The run-down of the pizza-pan boomer was very fast because of the high resistance of the coil and cable, but it did reduce the undershoot considerably (figure 4--6).

An alternative to trying to suppress the undershoot is to use the rebound as a source of low-frequency sound. The output of the pizza-pan boomer (figure 4--5c) has a negative-pressure output which is capable of high resolution

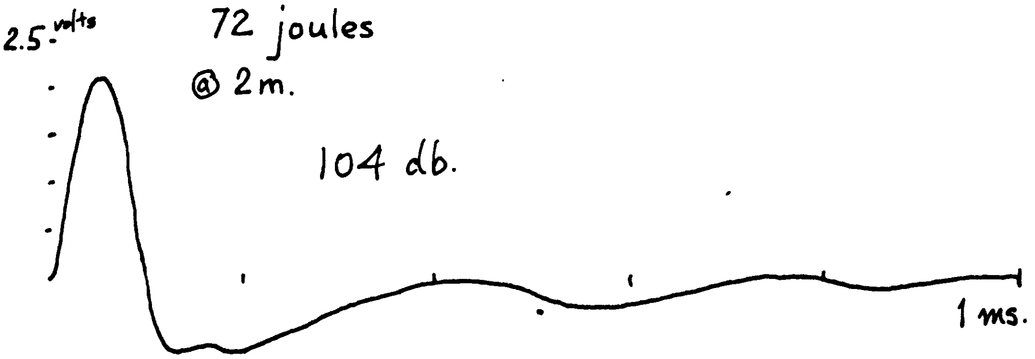
a. A-boomer, parallel damped



b. S2 boomer, parallel damped

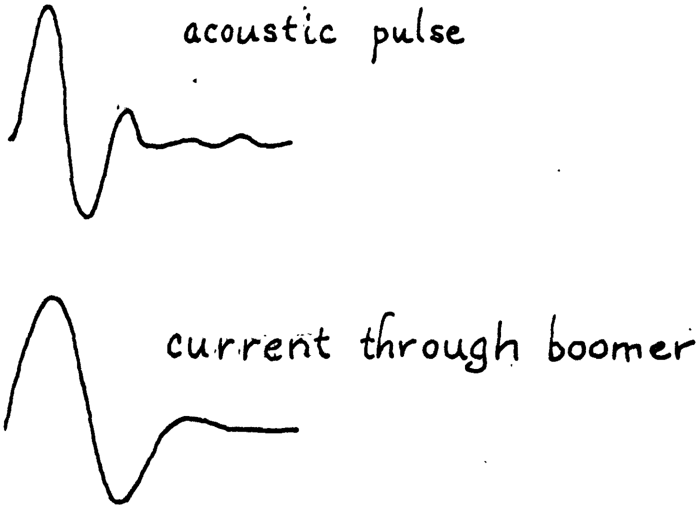


c. Pizza-pan boomer

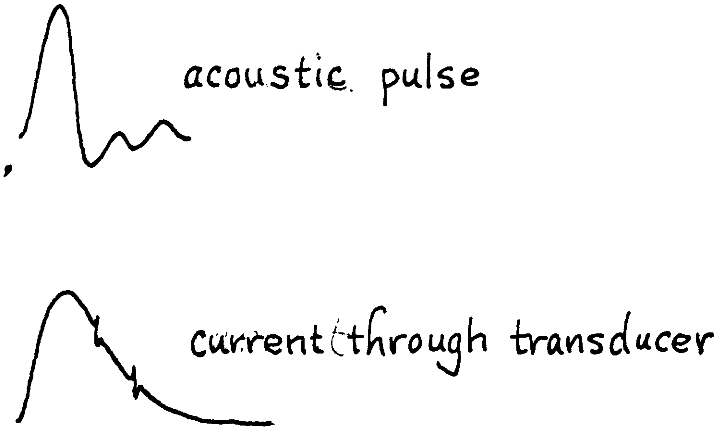


4-5. Acoustic Output of Improved Boomers

a. Before diodes



b. With run-down diode



4-6. Run-down Diode Holds Undershoot

and is less sensitive to high-frequency attenuation than the initial impulse is.

References

1. Edgerton, H. E., and G. G. Hayward, 1964. The "boomer" sonar source for seismic profiling. J. Geoph. Res., 69, 14, 3033--3042.
2. E. P. Shaw, private communication.

V. PROFILING TECHNIQUES

5.0 Introduction. This chapter is a discussion of some of the things which were done to make a given set of building blocks work well as a system. In particular, tape-recording of acoustic pulse data for easy retrieval requires some comment. Two-channel recording from a single hydrophone can be employed in cases where extended dynamic range is desired. Placement of source and receiver, as well as the use of more than one receiving hydrophone to resolve ambiguity are included here. The writer made no attempt to develop high-speed profiling techniques. Single omnidirectional hydrophones were used, rather than arrays, so that no off-angle receiver distortion occurred, but ship speed was kept below about one knot to limit noise caused by water flow around the hydrophone.

5.1 Hydrophone Placement. The impulse response of a seismic profiling system may be thought of as the response to a single sharp reflecting interface. If the source and receiver are omnidirectional and are near the water surface, a single reflection will generally be recorded as four different events: the direct return and three delayed returns involving one or two reflections from the water surface above the source and receiver. Although this is not a serious defect in low-resolution systems using oscillatory source-waveforms, it could completely defeat the purpose of the single-pulse high-resolution system described here.

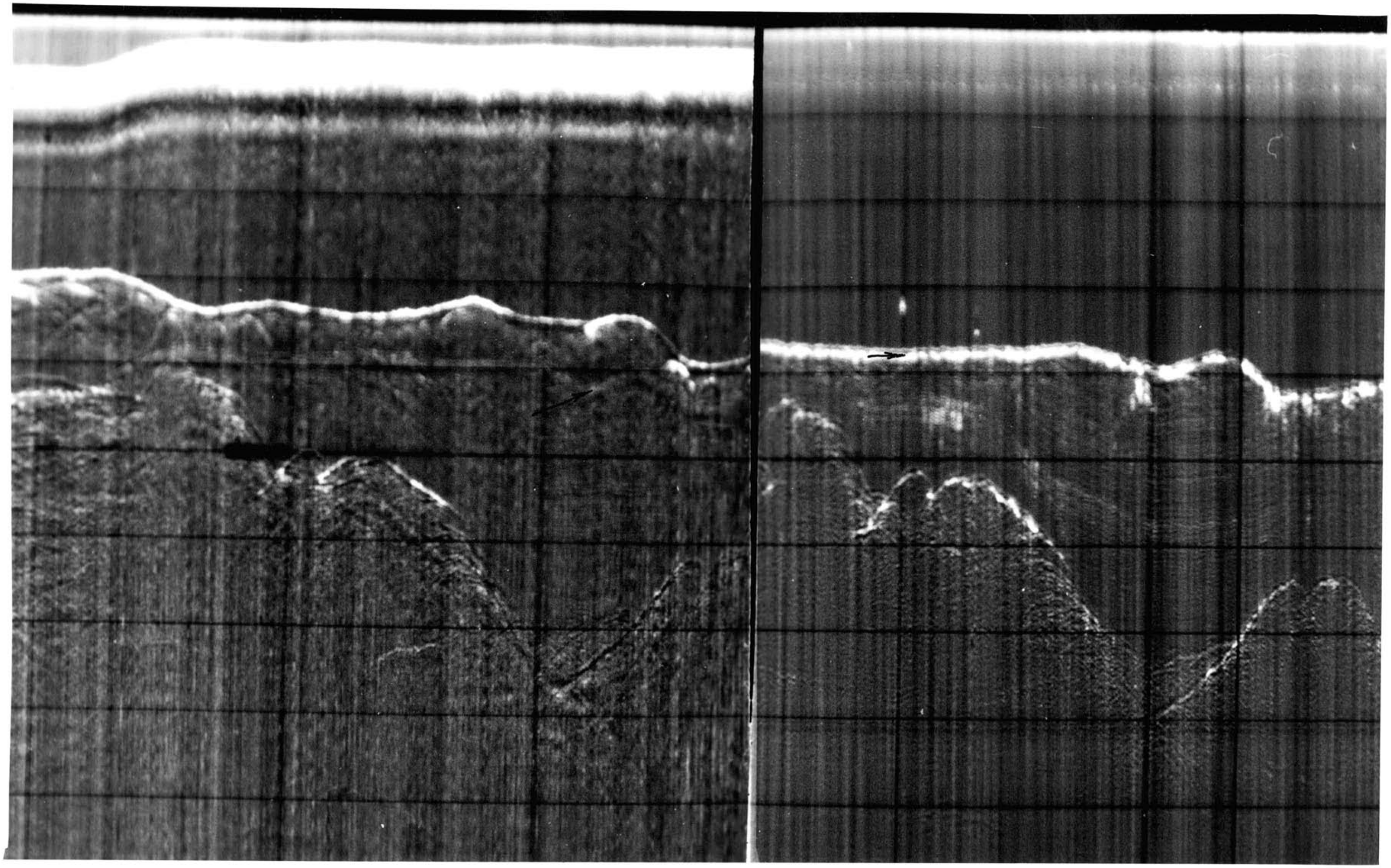
Fortunately, the boomer sound source can be designed to give a directional output with a weak back-wave which can be trapped between the boomer and the surface by towing the boomer only a few centimeters below the surface. The acoustic effect of this geometry probably contributes to the negative overshoot, but at least no confusion is introduced at the impulse frequency (note that the S2 boomer, figure 4--5c, which is the least directional, has the least undershoot).

The surface reflection controlled by the depth of the hydrophones can be delayed by placing the hydrophone at considerable depth. The difficulty of towing a deep hydrophone makes this a somewhat undesirable solution, but if the hydrophone can be lowered far enough to delay the surface reflection beyond all events of interest, this technique completely eliminates overlap ambiguity. Another technique which in principle allows the surface-reflection ambiguity to be resolved is the use of two hydrophones at different depths. If the surface reflection could be completely attenuated, the problem would be entirely solved. Figure 5--1 shows simultaneous recordings made with one hydrophone at a few centimeters depth and a hydrophone at about two meters depth, with a considerably reduced reflection from the convex boat hull above.

5.2 Tape-recording Pulse Data. The first problem the writer encountered in using a tape-recorder at sea was finding a substitute for the accurate sixty-cycle power normally used to drive synchronous capstan motors. The solution here was a vibrator invertor from a lead-acid storage battery.

The next problem was that the dynamic range of signals received by the hydrophone may exceed the dynamic range of the tape-recorder. The strong signals must be clipped at the input of a high-gain channel. Since it is difficult to clip at levels below about 0.5 volt, the signals must be amplified and clipped externally, then coupled to a 1 volt input to the tape-recorder. A difficulty peculiar to asymmetrical pulse data is that a-c coupling capacitors may cause trouble by being charged by a pulse and introducing slow discharge transients into the recorded data. Interstage coupling in the tape-recorder electronics seemed to be less sensitive to this problem, so it was possible to avoid this trouble by using an available d-c coupled input.

5.3 Timing in Data for Easy Retrieval. Retrieval of data on playback is



5-1. Two Hydrophones Record a Seismic Profile largely a problem of timing. A turns-counter on the tape-recorder is of some help, but with delayed readout after photographic processing it is a great advantage to have landmarks in the data which are visible on a photographic record as well as available in real time.

A clock motor-microswitch, operating a relay at one minute intervals to interrupt the triggering of the sound source was used to achieve this.

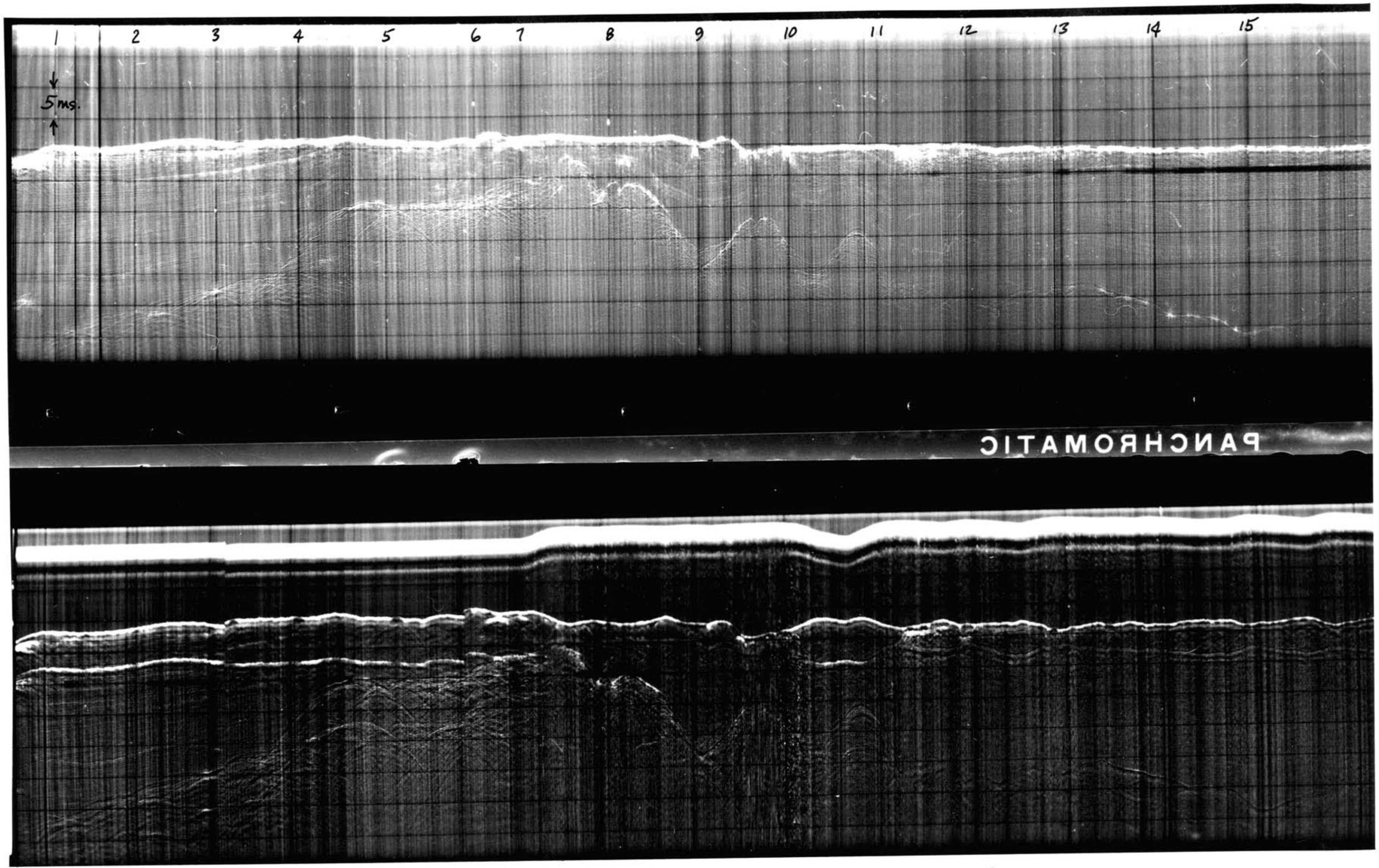
A more fundamental problem of display of repetitive pulse data is synchronizing the display with the data. Mechanical facsimile recorders are commonly used to fire sound-sources in real time applications, and are synchronized for displaying tape-recorded data by using a separate channel of tape-recorded synchronizing signal. A cathode-ray oscilloscope can be triggered from the data itself, but it is advisable to control triggering more dependably in noisy or overloaded data channel by clipping the channel below the overload level, and then mixing in a trigger pulse which is significantly larger than the clipping level.

VI. RESULTS AND CONCLUSIONS

6.0 The Profile. A portion of a profile across President Roads, Boston Harbor, is presented in figure 6--1. The recording was started while the boat was drifting to the northeast into President Roads anchorage. The upper film is a recording made from an 8-ball hydrophone mounted on a "fish" towed just beneath the water surface. The lower record was made from an LC-57 hydrophone hung from the bow of the boat and weighted down in an attempt to keep it from immediately towing up to the surface when the boat got underway. It was lowered from 15 feet to 18 feet after the minute mark 3. The tape transport was stopped for most of minute 6. The boat's engine was started at minute 7, disengaged during minute 10, then operated on an intermittent schedule at its lowest throttle for the rest of the profile. The boat's course, following minute 7, was south southeast across the main channel toward the water tower on Long Island. The average speed over the bottom for the entire profile was somewhat over a knot--about 140 feet per minute. The sound source firing rate was about 180 per minute except before minute 5, when it was slower.

6.1 Profiling Technique. The principal technical problem was that the deep hydrophone was not mounted on a faired fish for towing, so the minimum speed of the boat was too fast: the hydrophone towed aft and up practically against the hull of the boat (minute 9). The intermittent operation of the engine caused the hydrophone to swing back and forth to different depths--resulting in the apparent irregularity of the bottom in the lower film.

A seismic profiling system should be designed to operate well at a speed through the water which can be achieved by the operating vessel. Hydrodynamic noise generated by water flow around hydrophones is often the factor limiting speed through the water, as it was in this case. The obvious solution here is



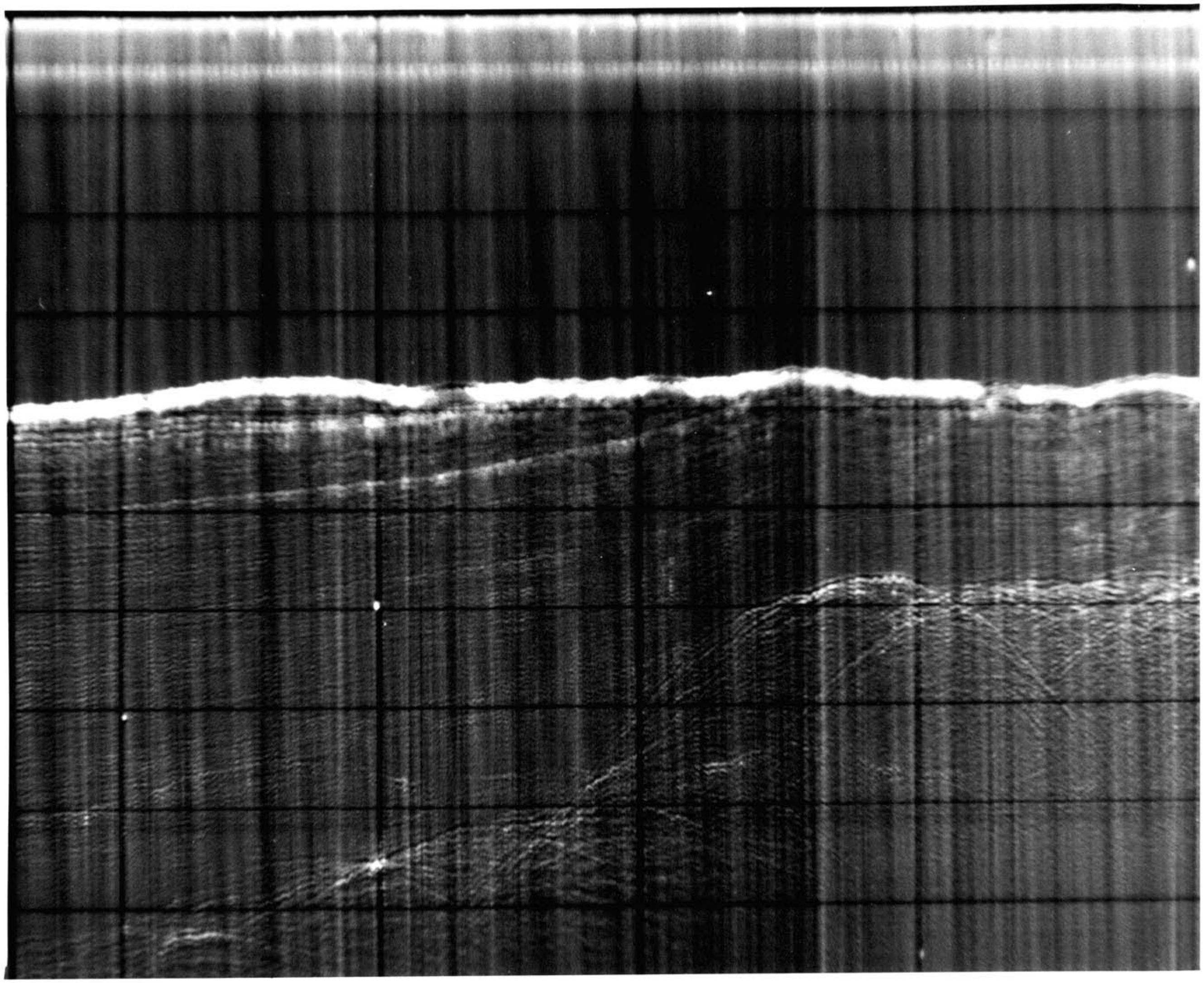
6-1. 16 minutes of Dual-Channel Profile

that a weighted, streamlined body should be designed for towing LC-57, perhaps using fairing on the suspension cable to reduce strumming.

6.2 Sound Source. The pizza-pan boomer was used as the sound source for this profile. A layered sequence, assumed to be blue clay, is resolved to about 0.1 millisecond, and the underlying irregular surface is clearly recorded to a depth of about 100 feet (30 milliseconds two-way travel time in the layered section), the maximum depth observed in this area. This represents an improvement over pre-existing systems: 12 Kc pinger records with 0.1 millisecond resolution do not penetrate the full thickness of layered section[1], while a 6 Kc pinger system which penetrates the full section has a resolution capability of no finer than about 0.5 millisecond[2].

6.3 Data Display. The photographic recording system has several defects in its present form. The upper film of figure 6--1 shows a streaking after minute 9 which is due to irregular film motion. This record was made at a time when the film-sprocket was driven by a rubber-tired gear wheel. It is hoped that the substitution of a positive gear drive will enable recording at the slowest motor speeds without streaking.

Figure 6--2 is an enlargement of minutes 2 to 6 from the same film appearing in figure 6--1, upper. Two defects of the recording are clearly visible in this picture. First, it is somewhat out of focus except near the 6, 7 and 8 cm. lines. The difficulty is caused by the large lens aperature which is required to get adequate exposure. Focussing is very critical at f/2, and the resolution of the lens off-axis is not very good. The second defect which is quite apparent is that the high-amplitude reflection from the top of the sedimentary section is not resolved. The CRT beam current should be kept within a narrower range to avoid this phosphor "bloom." Unfortunately, this



6-2. Enlargement of Drift Profile

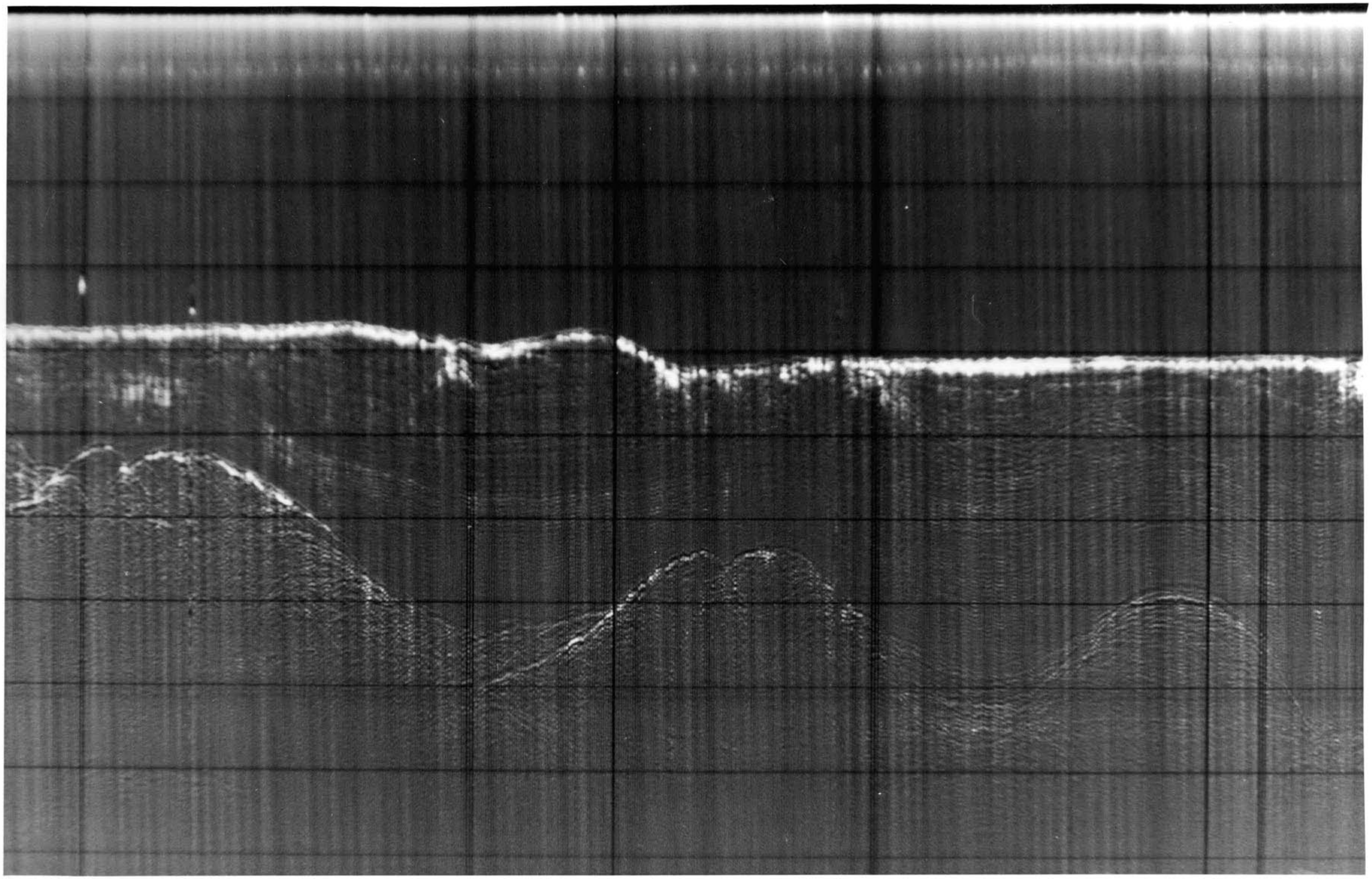
would decrease the sensitivity, so a small amount of blooming probably will have to be tolerated in applications which demand a very wide dynamic range.

An improvement to the present system could be made rather easily by using a more efficient phosphor in the CRT. A P11 phosphor would give about double the light output. A CRT ordered for this application also should be supplied without a graticule to avoid the blanking observed on the 5 cm. line of the lower film of figure 6--1. The divisions are not particularly necessary in a permanent record which can be measured at any time.

6.4 Geologic Evidence. Figure 6--3 illustrates the value of high-resolution profiling as a source of evidence for geologic interpretation. It is apparent that the sediments approximately conform to the topography of the underlying material, but that the valleys in the irregular contact are filled with a less coherent material.

6.5 Extension to Deep-Sea. The writer feels that high-resolution technique in seismic profiling has considerable value in improving the quality of information obtained. The sound source developed here is capable of peak acoustic output equivalent to that of sources currently in use in deep-sea seismic profiling. It is suggested that high-resolution technique be extended to deep-sea seismic profiling. The principal development which would be required is the adaptation of underway receiving techniques for high-resolution.

6.6 Suggested Revisions to the Data Display System. The faults of the display system presented here are the unhappy compromise between low exposure and loss of resolution through phosphor bloom, and the overall limitation in resolution determined by the CRT. The phosphor bloom could be controlled if the beam modulation could be decreased without loss of



6-3. Geologic Evidence

exposure; the overall resolution could be increased by the use of a CRT capable of higher resolution.

The effective exposure could be increased by using more sensitive photographic emulsions. The optical system would have to be redesigned for larger film format if increased film grain should begin to limit the resolution. The efficiency of transfer of light from the phosphor to the film could be increased by the use of fibre-optics instead of a lens. The film could be contact-exposed to a fibre-optic CRT face plate.

References

1. Edgerton, H. E., 1963. Sub-bottom penetrations in Boston Harbor. J. Geoph. Res., 68, 9, 2753--2760.
2. Edgerton, H. E., 1965. Sub-bottom penetrations in Boston Harbor, 2. J. Geoph. Res., 70, 12, 2931--2933.

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Appendix 1.

HYDROPHONES AND MEASUREMENTS OF SOUND SOURCES

An Atlantic LC-57 hydrophone was used for all acoustic measurements reported in this thesis. The hydrophone was calibrated by Atlantic by using a pressure-release cell and ballistic galvanometer. The sensitivity measured for release of 25 psi. was 0. 0365 μc/psi. This and the capacitance of the device (0. 0215 μfd.) can be used to calculate the open-circuit sensitivity of 1. 7 volt/psi, or 26. 2 volts/atmosphere. The standard reference for underwater acoustic pressure measurement is 1 dyne/cm^2, or 10^{-6} atmosphere.

The sensitivity of the LC-57 is therefore expressed as - 92 decibels relative to 1 volt/dyne/cm^2. The frequency response reported by Atlantic is flat to 20 Kc. except for a 3-decible peak near 2 Kc., and the resonance near 20 Kc. where the high-frequency roll-off begins. The low-frequency roll-off is controlled by the impedance connected to the hydrophone. In all the measurements reported here the input impedance of the amplifier connected to the hydrophone was one megohm; this gives a low-frequency roll-off below 50 cps.

The standard reference for measurement of underwater sound output is 1 dyne/cm^2 at 1 meter from the source. The output of a sound source is usually measured at a greater distance so that near-field effects will not influence the measurement. The measured value can be adjusted simply in the case of sound sources which are not large compared to a wavelength of the sound they project. Spherical spreading of energy has a $1/r^2$ dependence on radius, but since energy is proportional to the square of amplitude, sound pressure should decrease as

1/r. Thus an acoustic pressure measured at 6 meters can be adjusted to the standard reference by multiplying it by 6.

Let us do a sample calculation for a real measurement: The A-boomer output was measured on the sixth of February , 1966. A peak signal of 3.5 volts was recorded by the LC-57 six meters away from the face of the transducer. The reciprocal of the hydrophone sensitivity is + 92 decibels relative to 1 dyne/cm^2/volt. The product of measured pressure and distance give gives the pressure adjusted to 1 meter (the "PD" law). The source strength is therefore 92 + 11 + 15.5 db, or 118.5 decibels relative to 1 dyne/cm^2 at 1 meter.

Appendix 2.

THE TAPE-RECORDER

A Crown 700 tape-recorder was used to record seismic profiles at sea, and for playback to the photographic facsimile recorder in the laboratory. It was modified for this project so that the capstan motor could be powered by a separate a-c line from that which provides power to the power supply for the reel motors and the electronics.

The principal trouble encountered in using this tape-recorder was its sensitivity to temperature. During the cold winter months when the temperature in the cabin of the boat was about 50°F. the bias was two to three decibels low when the tape-recorder was turned on. It would rise over a period of hours, as the internal temperature of the tape-recorder rose, until it was practically normal at the end of a day's work. This variation and difference in bias due to different line voltages could be compensated by bias adjustment when the recorder was otherwise in good working order.

The tape-recorder was given a major overhaul and alignment in the course of this work, and a turns-counter was installed.

Appendix 3.

THE PHOTOGRAPHIC FACSIMILE RECORDER

A Tektronix 545B oscilloscope with a T5470 cathode-ray tube coated with P31 phosphor is used for intensity-modulated display. It was modified by inserting a non-grounded three-conductor phone jack in the 100 volt unblanking line to the ground side of the floating CRT grid supply. This line is interrupted only when a plug is inserted in the jack.

The impedance of the grid supply is determined by 470 μμfd. and 2.2 MΩ ties to ground. The unblanking circuits are coupled to this through cathode followers. Up to 1000Ω can be inserted in this line without seriously affecting the unblanking.

Audio modulation of the grid of the CRT is accomplished by inserting a 500Ω coupling transformer (UTC A-20, 10--50,000 cps bandwidth) into the grid line. The inductance of the secondary winding caused overshoot oscillation of the unblanking signal which was reduced by connecting a 500Ω resistor across the winding. With this configuration the peak overshoot is 10 volts; the duration of oscillation is about 100 microseconds.

The display is photographically recorded on slowly-moving 35 mm. film at 1:5 reduction by a 2-inch focal-length lens with a maximum aperature of f/1.5 (Wollensak Cine Anastigmat). Plus-X film is used for its fine grain. The lens must be opened to f/2 to get adequate exposure. The film is developed in 1:1 Dektol for 6 minutes, and printed on contrast-grade 6 paper (Agfa Brovira).

The film-advance sprocket (24-tooth) is driven through 1:12,000 step-down gearing by a speed-controlled motor (Electro-Craft E150). Speed is varied by changing the reference voltage to the feed-back amplifier input; it is monitored by connecting a meter to the output of the motor's feedback (generator) winding.

Appendix 4.

SOUND SOURCE INFORMATION

The boomer sound source consists of a driver connected to a transducer by a cable. The driver is usually powered by sixty-cycle A. C. at 115 volts.

Two drivers were used during this project: The "Black Box" delivers 4 Kv. to 16, 32, or 48 μfd., and has a 5Ω, 200 watt, resistor which can be connected in parallel with the output. The "Tool-Box" delivers 3 Kv. to 4, 12, or 16 μfd.

The cable connecting the driver to a transducer should have an inductance which is considerably smaller than that of the transducer, but the resistance of the cable may be made large to act as series damping.

Three transducers were fabricated following the design considerations presented in this thesis. The first is called the "A-boomer" because it incorporated the first full-area coil. The "S2" boomer is a small symmetrical design using two coils instead of a coil and plate. The "pizza-pan" boomer is named for the spun aluminum dish which is both housing and active face of the transducer.

The A-boomer has an 18" diameter coil potted behind a 1/8" linen-bakelite facing in a 1-1/2" thick block of sanded-epoxy backing. A square plate of soft aluminum 1/8" thick is sealed to the circumference of the coil facing with RTV 108 (G. E. Clear Seal) and bolted at the corners on 16" centers. The coil is 40 turns of three strands in parallel 1/4" × 0.050" cotton-covered copper ribbon. The assembled transducer has an inductance of 37 μhenries.

The S2 boomer consists of two identical coils 8" in diameter externally connected in series. Each coil has more than 50 turns of 1/8" wide cotton-covered copper ribbon and is potted against an 1/8" disc of bakelite which faces the air space between them. The air space is sealed around the edge with 1/4" gum rubber tubing split and glued with RTV 108. The inductance of the assembled unit is 190 μhenries.

The pizza-pan boomer has a 160 turn coil of 0.200 × 0.040" cotton-covered copper ribbon. The 16" coil is not potted; the cotton must be kept dry to insulate adjacent turns. The pizza-pan itself is a 2" deep pan about 18" in overall diameter, including a 1/4" lip. The coil is separated from the bottom of the pan by a 0.010" thick sheet of mylar insulation. Packing material is used as a spacer between the coil and the lid, which passes the cable and is glued to the lip of the pan. The inductance of this transducer is 300 μhenries.