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SACLANT ASW
RESEARCH CENTRE

# ACOUSTIC CALIBRATION OF AN EXPLOSIVE SOUND SOURCE

by

AUDUN SKRETTING

1 AUGUST 1970

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## ABSTRACT

A calibration of the sound output from 180 g TNT explosive sources at depths between 40 m and 90 m is described. No depth effect was observed and the results are in good agreement with earlier published measurements made at single depths.

## INTRODUCTION

Explosive charges are the main sound source used for sound propagation experiments at SACLANTCEN. The characteristics of sound from explosive sound sources have been previously measured, both with respect to peak pressure and to energy spectrum [Refs. 1, 2, 3 and 4]. The energy spectrum reported by those authors has normally been that for the shock wave combined with the bubble pulse and has been analysed by means of band-pass filters.

The digital analysis system now available at SACLANTCEN [Ref. 5] enables a separate examination to be made of small parts of the signal. It is therefore important that the separate energy spectra of the shock wave and the bubble pulse should be known with good accuracy. The purpose of the experiments described was to determine these separate values, and the possible effects of depth.

# 1. SEA TRIAL

## 1.1 Place and Time

A sea trial was conducted in the Western Mediterranean off Sardinia in April 1970. During this trial an experimental set-up was used that, in addition to serving its main purpose, lent itself to a calibration of the explosive-charge measurements.

## 1.2 Sources

The explosive sound sources used at SACLANTCEN contain either 180 g or 500 g of TNT. The 180 g type is made for use down to 100 m depth, and the 500 g type for depths greater than 100 m.

For the present experiment a charge containing 180 g of TNT was selected. This charge is normally fired electrically by means of a pressure device and a seawater-activated battery.

## 1.3 Experimental Work

It was assumed that the acoustic output of the detonation would depend very little on the mechanical behaviour of the explosive charge. Specifically, it was assumed that the acoustic output is the same whether the explosive charge (without its pressure-activated unit) is hung on a wire and detonated electrically from the ship, or whether — as in sound propagation experiments — it is falling freely in the water and is detonated by means of the pressure device and the battery. The advantage of hanging the explosive charge from the ship for calibration purposes is that the range between the source and receiver can be determined with great accuracy.

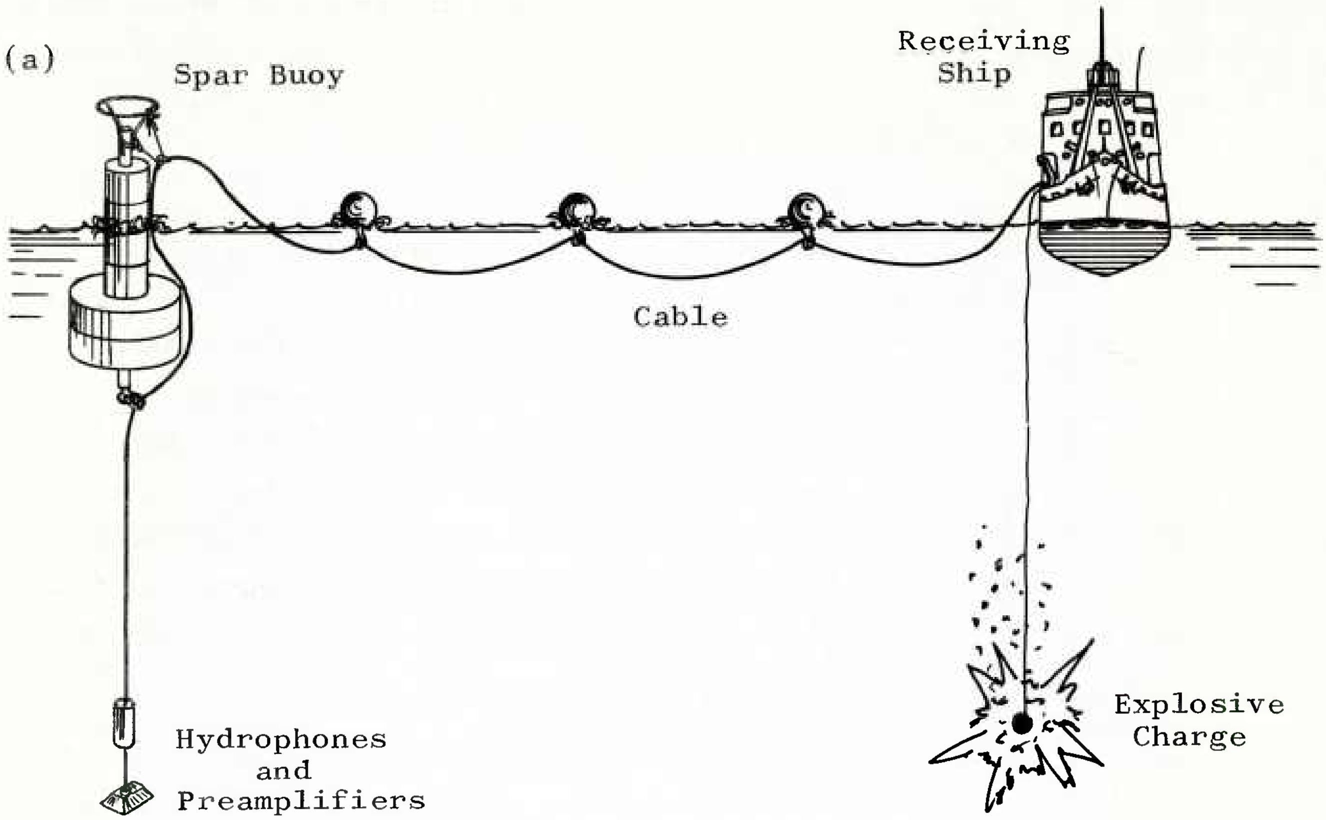


FIG. 1a GEOMETRY OF THE SEA TRIAL

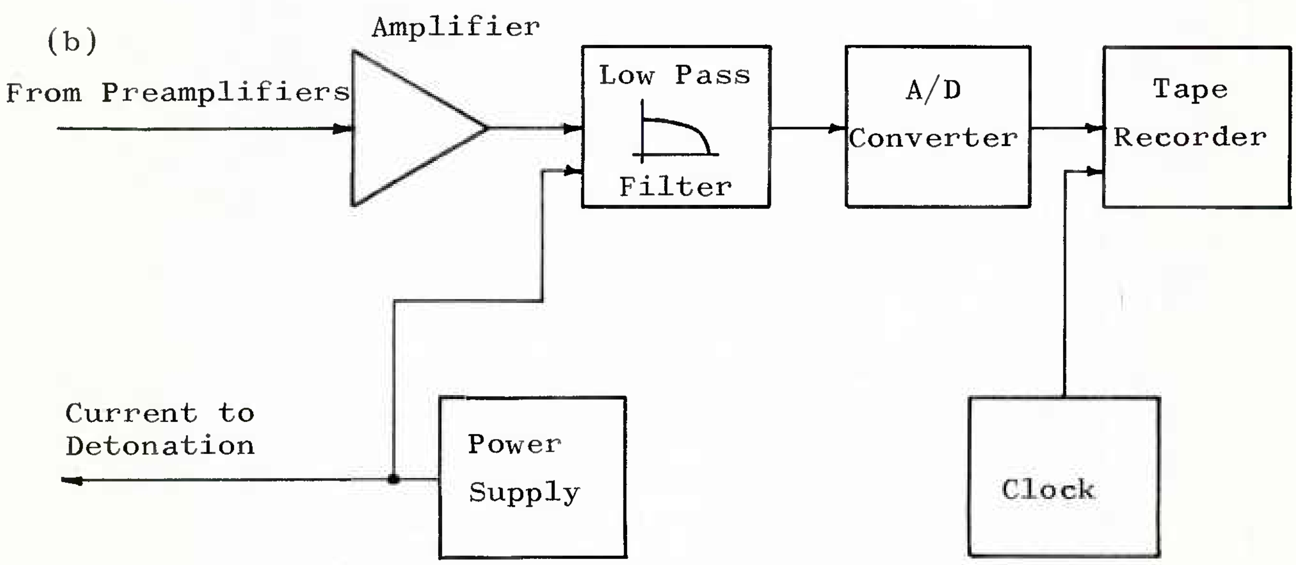


FIG. 1b BLOCK DIAGRAM OF RECEIVING AND RECORDING EQUIPMENT

Figure 1a shows the geometry for the experiment. The hydrophones with the preamplifiers were positioned about 100 m under a spar buoy and connected to the ship by means of an armoured electric cable. The spar buoy was drifted out to a distance of about 200 m from the ship. The explosive charges were suspended at different depths under the ship by means of an electric cable. The propagation path was nearly horizontal.

Figure 1b shows the block diagram of the signal-recording system. All data were recorded on magnetic tape on which were also recorded the signals from a high precision clock. A voltage proportional to the current used to detonate the charge was recorded on the tape so that, at the moment of explosion when this circuit breaks, the voltage falls to zero and there is a precise time mark. The signals received from the hydrophone were amplified, lowpass filtered, and fed to an analogue/digital converter having a 48 kHz sampling rate. The digital values of the samples were then recorded on the magnetic tape.

# 2. DATA REDUCTION

## 2.1 Range Determination

Using the method described in Sect. 1.3, the travel time can be found with great accuracy.

The abnormal sound velocity associated with the shock front occurs within a distance of ten times the radius of the explosive charge. For larger distances the only effect of the finite amplitude propagation is the reshaping of the shock wave, and therefore the influence on the travel time is only a fraction of a millisecond [Refs. 1 and 3].

From the temperature profile recorded, it is easy to determine a mean sound velocity with an accuracy of better than 0.5%. The overall accuracy of range determination is therefore better than 1%, corresponding to an error in the power spectrum level of less than 0.1 dB.

## 2.2 Gain of the Receiving Chain

### 2.2.1 Hydrophones

The signals were received on three spherical hydrophones (made at SACLANTCEN) each comprising two 1-inch diameter (25.4 mm) hemispheres.

A calibration curve for one of the hydrophones used is shown in Fig. 2. Their sensitivity is known to within about ± 0.5 dB. Calibrations have shown that these hydrophones are omnidirectional to better than 0.3 dB in the frequency range considered here.

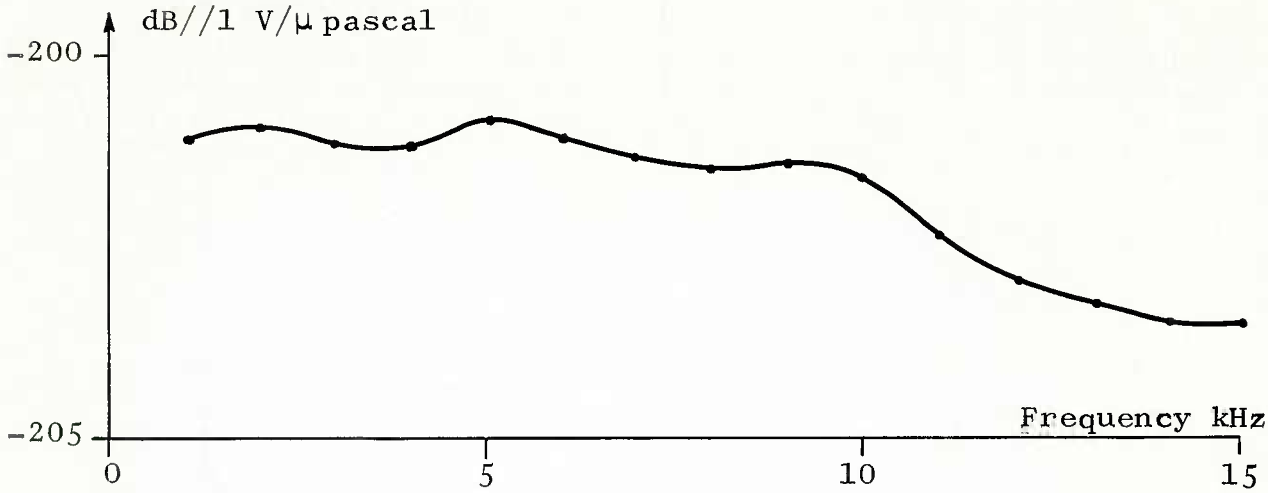


FIG. 2 SENSITIVITY FOR SPHERICAL HYDROPHONE

After the trial, a calibration signal was injected in series with the hydrophones and recorded on magnetic tape. For the data reduction, the calibration signal was treated as a normal signal and thus the gain of the whole electric receiving chain could be determined.

## 2.3 Acoustic Considerations

The ray paths used during the trial were nearly horizontal and thus sensitive to sound velocity gradients.

A bathythermograph taken just after the experiment [see Fig. 3] showed that the water was nearly isothermal. Ray tracings made with this profile have shown that the actual geometric spreading losses are within 0.1 dB from spherical spreading and that they are not very sensitive to changes in depth.

The finite amplitude effect is of small importance for distances larger than 100 m [see Ref. 3] and will not be considered here.

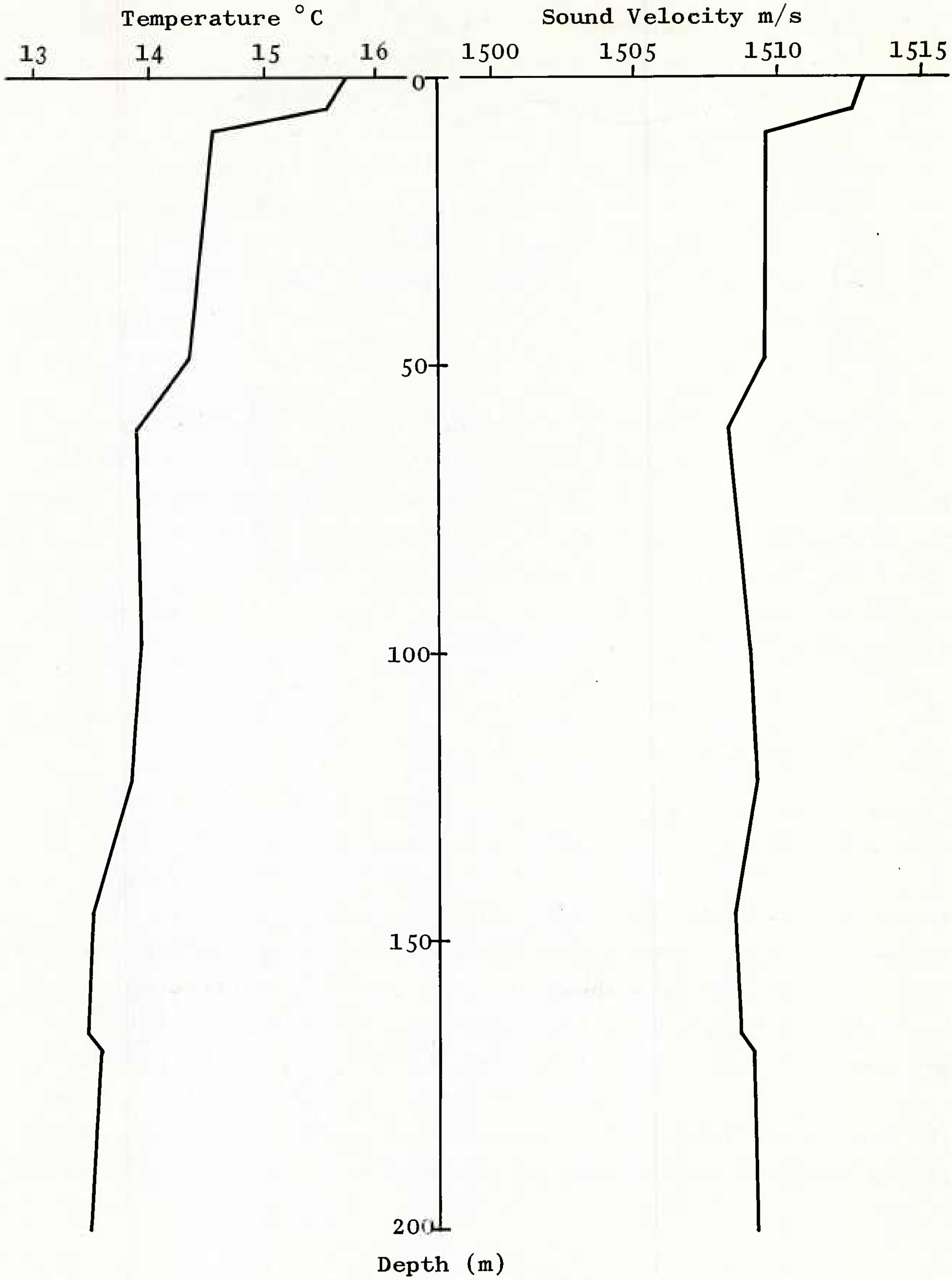


FIG. 3 TEMPERATURE AND SOUND VELOCITY PROFILE

## 2.4 Plotting of the Signals

As the signals are recorded in digital form, the natural way to reduce the data is by means of a digital computer. The signals are first plotted as shown in the example of a signal signature from an explosion at a depth of 80 m, given in Fig. 4. Figure 4a shows the complete signal, Fig. 4b shows an expanded plot of the shock wave, and Fig. 4c shows an expanded plot of the bubble pulse. The expanded plots have been drawn by the computer using a double sin x/x interpolation between the sample. The small oscillation in front of the shock wave in Fig. 4b is due to a numerical inaccuracy that is revealed by the interpolation.

Note the very clean signal obtained: this derives from the technique of digitizing the signal on board the research vessel and thus eliminating tape-recorder noise. The shape of the negative part of the signal has been affected by the RC highpass filter used during the recording.

## 2.5 Computation of Fourier Transform

The discrete Fourier transform of the times series $x_k$ $(k = 0,1 \dots N-1)$ is

$$X_r = \sum_{k=0}^{N-1} x_k \exp(-2\pi j \frac{rk}{N}), \quad r = 0,1 \dots N-1, \qquad \text{[Eq. 1]}$$

which is calculated very efficiently by means of the Fast Fourier Transform.

Equation 1 is valid for a complex input time signal, and the output will normally be complex. It is possible to write a real time series of length 2N samples as a complex time series of length N samples and make the Fourier Transform of this complex signal.

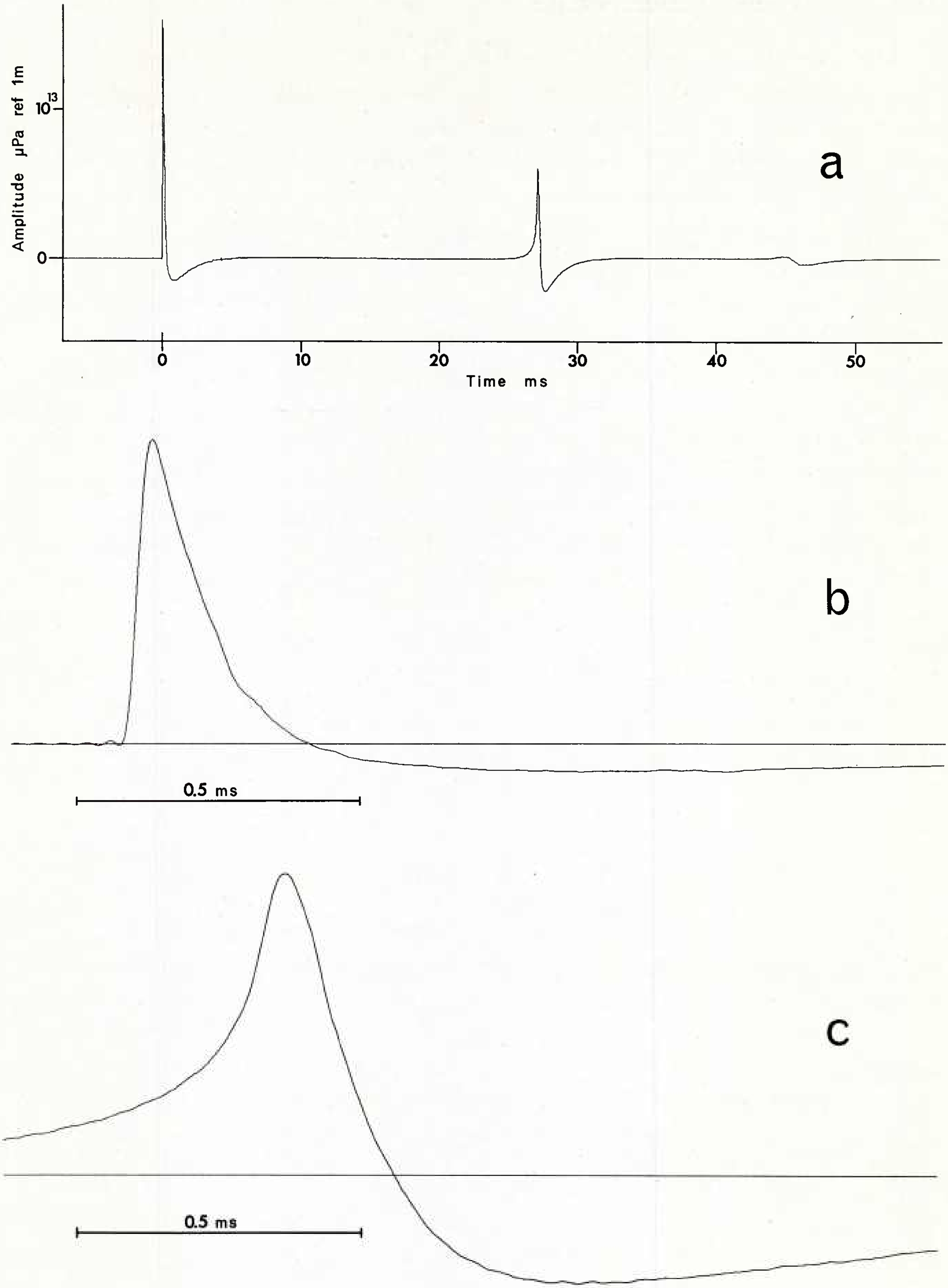


FIG. 4 SIGNAL SIGNATURE FROM AN 80 m SOURCE DEPTH
(a) Complete signal (b) Enlargement of shock wave plot (c) Enlargement of bubble pulse

The Fast Fourier Transform procedure used is made so that for a real signal $x_k$ of length 2N we have:

$$\sum_{k=0}^{2N} x_k^2 = \frac{1}{N} \sum_{r=0}^{N} |X_r|^2 \quad . \qquad \text{[Eq. 2]}$$

We multiply this equation by $\Delta t$ (sampling interval) and then it is easy to see from the left side that an expression for the total energy of the signal is given by

$$\Delta t \cdot \sum_{k=0}^{2N} x_k^2 = E_{tot} = \frac{\Delta t}{N} \sum_{r=0}^{N} |X_r|^2 \quad . \qquad \text{[Eq. 3]}$$

Now every $|X_r|^2$ is proportional to the energy in a frequency band of width $\Delta f = {}^{Fs}/2N$, Fs being the sampling frequency.

We therefore have the energy in a frequency band

$$E\Delta f_r = \frac{\Delta t}{N} \cdot |X_r|^2 \quad . \qquad \text{[Eq. 4]}$$

From Eq.4 we can find the mean one-hertz band energy for frequency band r

$$Eocb_r = \left( \frac{\Delta t}{N} \cdot |X_r|^2 \right) / \Delta f = \frac{1}{N \cdot Fs \cdot \Delta f} \cdot |X_r|^2 = \frac{2}{Fs^2} \cdot |X_r|^2$$

[Eq. 5]

Equation 5 shows us the "gain" of the Fast Fourier Transform procedure used.

## 2.6 Computation of Acoustic Intensity

The gain of hydrophones, electric receiving chain, and the Fast Fourier Transform is known. It is therefore easy to derive the rms pressure received by the hydrophone from the computed Fourier component. The intensity is then found by dividing the rms pressure by the specific acoustic impedance $\rho c$ ($\rho$ = density, c = sound velocity).

## 2.7 Units

The results are given in MKS units, now becoming generally adopted for acoustics. For convenience, Table 1 gives conversion values from the older cgs units.

TABLE 1

| | MKSA | cgs Unit | MKSA to cgs Multiply by |
|---|---|---|---|
| Pressure | pascal(=newton/$m^2$) | microbar(= dyne/$cm^2$ ) | 10 |
| Pressure | μPa | μbar | $10^{-5}$ |
| Density | kg/$m^3$ | g/$cm^3$ | $10^{-3}$ |
| Velocity | m/s | cm/s | $10^2$ |
| Intensity | W/$m^2$ | erg/s.$cm^2$ | $10^3$ |
| Energy per unit area | Ws/$m^2$ = J/$m^2$ | erg/$cm^2$ | $10^3$ |

## 3. RESULTS

### 3.1 Peak Pressure and Energy

The peak pressure was measured after filtering. The filter used was 6 dB down at 16 kHz. The energies are computed by a digital computer and it is therefore easy to correct for the filter curves. The energy is thus the total energy up to 16 kHz, but no correction has been applied for the sensitivity change of the hydrophones at high frequencies [see Fig. 2]. The effects of the RC highpass filter used are corrected both with respect to the peak pressure and the amplitude spectrum.

The results for peak levels and energies are shown in Table 2.

TABLE 2

| Depth m | Shock Wave | | Bubble Pulse | |
|---|---|---|---|---|
| | Peak Pressure dB//1 μPa | Energy dB//1 J/m² | Peak Pressure dB//1 μPa | Energy dB//1 J/m² |
| 87 | 263 | 41.3 | 254.6 | 38.8 |
| 79 | 263.4 | 41.7 | 255.1 | 39.2 |
| 48.5 | 263.2 | 41.4 | 251.2 | |
| 47 | 263.2 | 41.4 | 251.2 | |
| 40 | 263.2 | 41.5 | 251 | |

The results all refer to a distance of 1 m. This is chosen as a convenient reference distance, although it is recognized that the actual values at 1 m distance from the explosion would be different because of finite amplitude effects.

As the surface reflection occurred before the bubble pulse for the three most shallow charges, the corresponding bubble-pulse signals were not analysed by the computer for energy and energy spectra.

## 3.2 Energy Spectra

Figure 5 shows a plot of the energy per unit area per hertz as a function of frequency for the five signals analysed. The curves have been corrected for the filters used but not for the frequency dependence of the hydrophone. All the analysed signals, representing source depths from 40 m to 90 m, are plotted together in Fig. 5.

Only two of the bubble-pulse signals have been analysed, because for all the signals except the two deepest the bubble-pulse signals were disturbed by the surface reverberation.

The amplitude spectra of the bubble-pulse signals are shown in Fig. 6.

## 3.3 Discussion of the Results

The accuracy of this experiment and of the analysis is good. The uncertainity in the final results is, therefore, due to the ± 0.5 dB possible error in the calibration of the hydrophones.

The relative accuracy is very good, and it can be seen from Fig. 5 that the five events fit extremely well together. The small "bump" at about 10 kHz is probably due to reflection from the hydrophone suspension. In fact, experience has shown that without careful hydrophone suspension, reflection can cause "bumps" with amplitudes of some decibels in the high-frequency part of the amplitude spectrum.

Weston [Ref. 3] gives rules for scaling the results for different explosion weights; employing his rules we find that our results are in good agreement with his results and those of Stockhausen

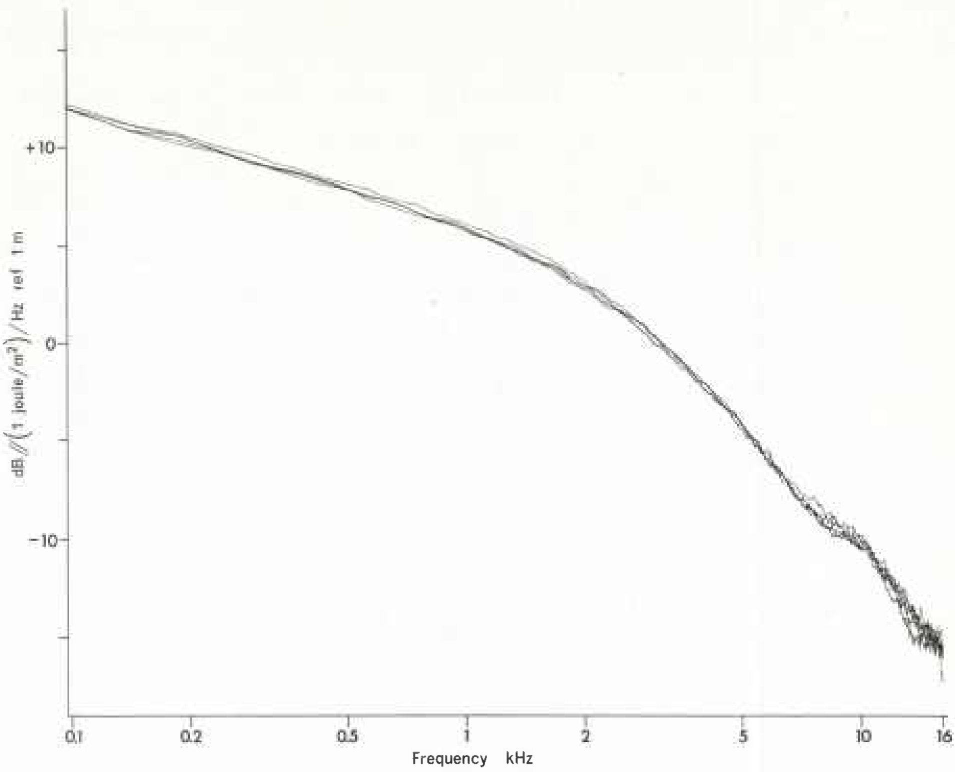


FIG. 5 ENERGY SPECTRA OF SHOCK WAVES

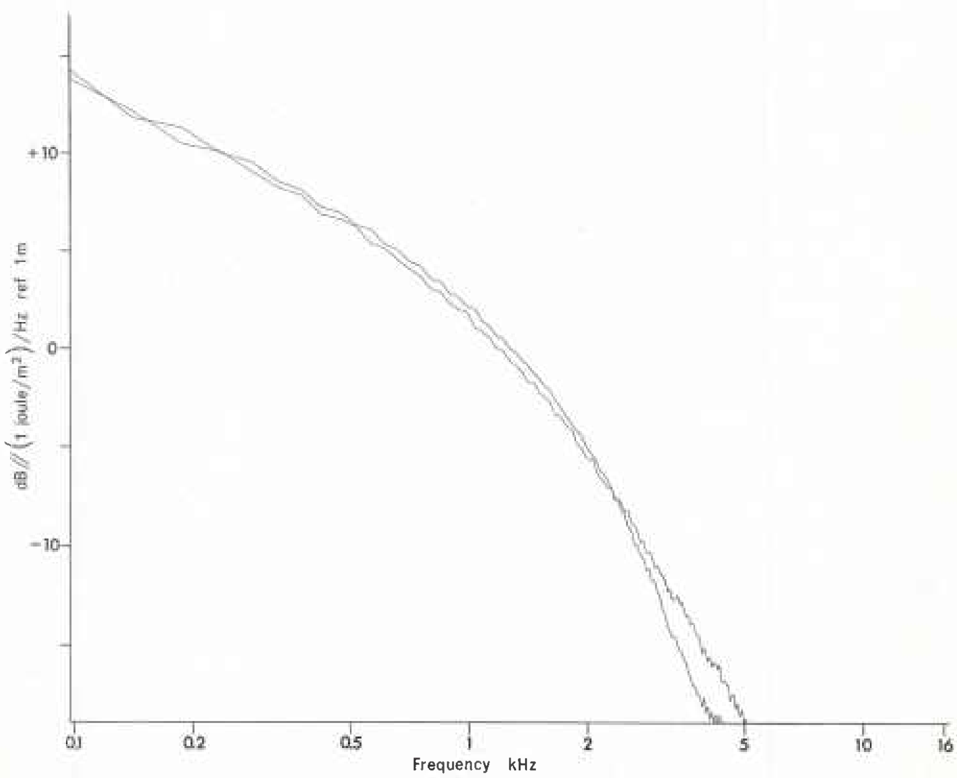


FIG. 6 ENERGY SPECTRA OF BUBBLE PULSES

[Ref. 4]. It should be mentioned that Maples and Thorp [Ref. 6] did not find agreement with Weston or Stockhausen.

The peak values we found are slightly lower than the values found for 100 m distance by using Aron's formula [Ref. 2] and scaling to 1 m distance, but are 0.5 dB higher than the values found by Leroy [Ref. 7].

Using the model of an exponential pulse to describe the explosion, and employing the peak pressure and time constant found from Weston's formula (using 100 m distance and scaling to 1 m distance) one finds the amplitude spectrum illustrated in Fig. 7, together with the calculated amplitude spectra.

It is seen from Fig. 7 that this simple model fits the actual amplitude spectrum reasonably well. The fall-off from the model for frequencies higher than 10 kHz is due to the lower sensitivity of the hydrophone for these frequencies. The points in the figure are those of Stockhausen scaled to the actual weight, and they are seen to fit the results very well. One can especially note that the deviations from Weston's model are the same for the results found here and for those of Stockhausen.

The total energy found for the shock wave is 225 cal/g which seems to fit the results of Cole [Ref. 1, p.145].

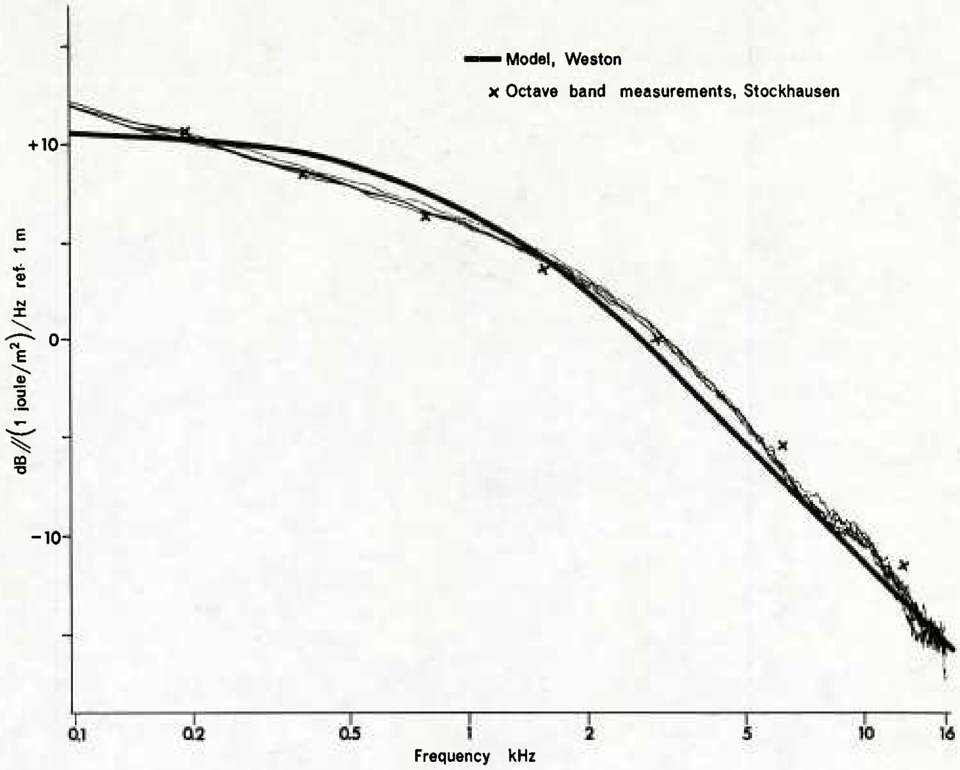


FIG. 7 COMPARISON OF CALCULATED ENERGY SPECTRA OF SHOCK WAVES WITH WESTON's MODEL AND WITH STOCKHAUSEN's MEASUREMENTS

## CONCLUSION

In an experiment conducted to calibrate the sound output from an explosive sound source of 180 g TNT, it was found that the accuracy of the techniques employed is good and that the uncertainty of the results is due to the ±0.5 dB uncertainty in the hydrophone calibration figure.

The following can be concluded:

a. With the sources at 40 m to 90 m depth it was not possible to observe any depth effect for the shock wave.

b. The amplitude spectra show little deviation from each other; for frequencies lower than 6 kHz they are within ±0.25 dB from the mean. This indicates that the explosive sound source gives a more reliable acoustic output than normally anticipated.

c. The results are in good agreement with those published by Weston [Ref. 3] and Stockhausen [Ref. 4].

As the two bubble pulses analysed derive from nearly the same depth, nothing can be said about the depth dependence of the bubble pulse, except that it is known to exist.

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