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UNIVERSITY OF MIAMI

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SURFACE LAYER TRANSMISSION IN THE TONGUE OF THE OCEAN

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by

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ABSTRACT

Signals from a series of explosive shots are analyzed in order to determine the effect of the surface channel sound duct in the Tongue of the Ocean. A simple technique is described for determining sound arrivals via this channel. The frequency spectrum of the sound transmitted through the surface channel is in good agreement with that predicted by normal mode theory.

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SURFACE LAYER TRANSMISSION IN THE TONGUE OF THE OCEAN

I. INTRODUCTION

The purpose of this study was to determine means by which the existence of a reliable acoustic transmission surface duct in the Tongue of the Ocean could be established. The surface duct refers to the sound channel in the top few hundred feet of ocean depth which results from a positive velocity gradient in this surface layer and consequent refraction of sound ray paths, Horton (1959).

II. GENERAL THEORY

When the top layers of water in the ocean are nearly isothermal, usually because of mixing due to turbulence from the surface, the sound velocity increases with depth because of the pressure effect. At some depth this mixing is no longer effective, and the temperature decreases with increasing depth. At this point velocity maximum exists. This is called the "duct 'bottom." Above this axis, sound is refracted up, and below, it is refracted down. For rays emitted from a source at angles less than some critical angle, the combination of this upward refraction and the downward reflection from the surface boundary is manifest in "trapping" of sound energy in the "surface channel," and a useful transmission path can result.

The finite depth of the surface duct causes wave-guide type channeling of the transmitted sound. This results in an optimum transmission frequency band below which transmitted energy is rapidly attenuated with decreasing frequency. Hence, the existence of a surface duct can also be established by analysis of transmitted sound for the frequency content of the signals which arrive via this path.

In this report, sounds from explosive sources which have been transmitted over a 31 kilometer range are analyzed in two ways. First, ray path information is obtained by examination of the arrival times of the various signals, and this is compared with the expected ray paths calculated from BT data. Second, the frequency content of the various signals is analyzed for the wave-guide channeling effect. This is done first by "time-frequency analysis" of the transmitted signals, next by frequency spectrum analysis of some particular signal arrivals, and last by simple filtering of the signals in order to determine their frequency "cut-off" characteristics. The expected transmission characteristic of the surface channel is derived from normal mode theory, and the transmitted signals are compared to this.

III. FIELD PROGRAM

In July of 1959, a series of fourteen explosive shot tests were carried out in the Tongue of the Ocean. The shots were detonated from a small boat off Green Cay and received on another boat off Tinker Rocks (see chart, figure 1). The detonating and listening were done as close as possible to the sharp drop-off into deep water, but close enough to land so that sightings could be obtained for position accuracy of about fifty yards in case future tests were carried out.

In figure 2 a profile in a vertical plane is shown for the path from Green Cay to High Point Cay. The profile from Green Cay to Tinker Rocks should be very nearly identical except for a difference in distance of the order of a mile.

The receiver was an AN/PQM-1A noise measuring set. The output of the noise measuring set was recorded on magnetic tape. A radio link between the detonating and listening boats provided communications and firing time marks. The experimental system is shown in figure 3.

During the runs the ship's batteries supplied power for the equipment. DC to AC inverters were used for obtaining 60 cps AC power. A separate "vibrator" type inverter was used for the magnetic tape recorder. The vibrating reed of this inverter had been adjusted in the laboratory to have a natural frequency as close to 60 cps as possible. This was done by weighting the reed with lead solder and filing the lead off until the reed frequency coincided with the laboratory power line frequency. The reed frequency was stable within about 0.2 cps under widely changing load conditions.

The explosive used was 40% "giant jell" dynamite. The first ten charges were five pounds each, and the last four were one pound each. Electric blasting caps were used to detonate the charges. The charges were set off near the surface in order to minimize bubble pulse interference. The charge depths were not known exactly, but varied between three and six feet below the surface.

IV. BT DATA AND SOUND VELOCITY PROFILE

A series of six BT's were taken at intervals along the range between Green Cay and Tinker Rocks just prior to the explosive tests. The BT's were all nearly identical. A typical BT for this test is shown in figure 4. Using the BT data for the first 250 feet, and other known velocity data for the deeper water, Tschiegg (1959), the sound velocity profile was calculated. This is shown in figure 1.

V. RAY PATH SOLUTIONS

The source receiver distance based on the charts of the area (HO 26b) is 31.6 km. Based on the transmission times of the first signal arrivals (20.32 sec. average), and the velocity of sound in the surface channel (1545 m/sec.) the source to receiver distance is 31.4 km. This gives a discrepancy of about 0.2 km. The initial arrival times were checked with a stop watch for several of the shots. These times averaged 20.4 seconds. The entire sequency from the firing time was recorded on magnetic tape, and these tapes were later used to make the graphic shot records. The tape speed of the magnetic tape recorder used to record the signals was known to be accurate to within 0.25 cps in 60 cps, or about 0.4%. The correct distance from source to receiver is therefore assumed to be 31.4 ± 0.11 km.

Based on the sound velocity data of figure 5, ray paths were plotted for the vertical profile from Green Cay to Tinker Rocks. The ray paths are drawn to scale in figure 6 with straight line approximations. The limiting ray for the surface channel leaves the source at 2° 3' 39" (source at surface, receiver depth meters). The horizontal distance for one full loop of the limiting ray (surface-to grazing duct bottom-to surface) is 5560 meters.

The deep water ray leaves the source at 2° 32'. This path is seen to contain two bottom reflections. Total travel time calculated for this path is 21.05 seconds, thus there should be 0.73 seconds time difference between the surface channel and deep water arrivals.

VI. NORMAL MODE SOLUTIONS

The theory of transmission in layered media has been treated extensively elsewhere, Pekeris (1948), Ewing (1957), Officer (1958) and normal mode theory has been applied specifically to the surface duct, Voorhis (1952), Officer (1953). This theory will be used, but not elaborated on here. In Voorhis (1952) the solution for the sound pressure after transmission through the duct is given as an infinite sum, of orthogonal terms called normal modes, the first of which is here the most important one.

$$P_{(r,z,t)} = P_0 \, R_0 \, \frac{A_i \, e^{-\tau_1 r}}{\sqrt{r}} \, e^{-i(kT - wt)}$$

where r, z, and t are range, depth, and time, τ and k are determined by the duct parameters, and the factor $1/\sqrt{r}$ represents the cylindrical spreading loss. This first mode is graphed as a function of frequency for various duct depths and thermocline gradients in the Voorhis (1952) reference.

In calculating the actual sound pressures to be expected one must also take into account the physical absorption of the sound energy in the water. This is given approximately by

$$\alpha = 0.01 f^2 \quad \text{db/Kyd} \tag{2}$$

over the frequency range of interest here.

The net effect of the combination of the channel transmission loss at low frequencies and greater physical absorption at high frequencies is similar to that of a band pass filter. An optimum transmission frequency band results which is fairly sharply defined.

The results of Voorhis have been used to plot surface channel transmission functions for a duct gradient of +0.02/sec. and thermocline gradient of -0.1/sec. for several duct bottom depths. This is shown in figure 7. This figure represents the theoretical transmission function based on the first mode only. It must be emphasized that it is limited in application.

VII. EXPERIMENTAL DATA AND ANALYSIS

In this section, four types of shot record presentations will be made and discussed individually. First, the straightforward graphic records will be presented. Second, the shots will be played through high and low pass filters onto graphic records. Third, "time-frequency" analyses of some of the shots will be presented. Fourth, a frequency spectrum of an individual signal arrival will be presented. Each method will yield some information about the shots.

Graphic Records

The signals were recorded in the field on magnetic tape, and graphic records of all shots were made in the laboratory for visual observation. The graphic records are shown in figures 8 through 11. These records have been cut and spliced for convenience in presentation. The elapsed times starting from "fire" marks are also noted on the records.

The ray path calculations predict a time difference of 0.73 seconds between the signal arrival from the surface channel and the deep water path. From the graphic records, the average difference between the peaks of the two major signal arrivals is 0.8 sec., which is in reasonably good agreement with the ray path calculations.

Bubble Pulses

All the shot records showed bubble pulses between the two major arrivals. The shots were fired fairly close to the surface. but just deep enough (3 to 6, feet) so that bubble pulses may have occurred. For TNT we have for the bubble radius at a depth, d in feet and for weight, w in lbs.

$$a = 12.6 \left(\frac{w}{d + 35} \right)^{1/3} \qquad (3)$$

Setting a = d to find the marginal depth at which the bubble will vent to the surface, we get for a one-pound charge a = d ~3.75 ft. Bubble pulses can also occur even when the gas bubble does vent to the surface, Knudsen (1958).

For bubbles far from a boundary, the first bubble period for TNT is given by

$$T_1 = 4.36 \frac{w^{1/3}}{(d + 33)^{5/6}} \qquad (4)$$

This equation is not actually valid here because of the proximity of the surface boundary. It is being applied only to get a rough idea of the bubble period. Assuming a one-pound equivalent charge weight and d = L ft., we get T = '_~.215 seconds. For shots and lC, of labs dynamite, the graphic records show the first bubble
period to be 0.21 to 0.22 seconds. Shots 11, 17, and 1L, one 1b. dynamite, had bubble periods of 0.16 to 0.17 seconds.

Graphic Records with Filtering

The simplest method of extracting information about the signal arrivals appears to be graphic recording with the signal played through various combinations of filters. The transmission function for surface channels with duct bottoms less than 200 ft. shows rapid attenuation below 1 kc and signal reductions of more than 20 db below about 500 cps. In figure 12 the magnetic tape recordings were played through 400 cps, 60C cps, and 1 kc low pass filters. The second channel was in all cases played through a 200 cps high pass filter in order to eliminate background noise, although this was not absolutely necessary. The signal peaks are shown with arrows in the figure. The increase in the shock and bubble pulse signals via the surface channel as the low-pass filter cutoff frequency is raised is evident. For a rapid field test, this method appears to be the simplest way of determining that explosive shot signals have been transmitted via a particular "channel."

Time Frequency Analysis

A large amount of information about the shots can be derived from a three-dimensional picture of the frequency-amplitude spectrum versus time. A Panoramic Radio Products "Time-Frequency Analyzer" (TFA) was used to obtain such a presentation for this study.

The TFA presents an oscilloscope display of such an analysis. The x axis is calibrated in frequency, variable from 40 cps to 20 kc. The y axis is calibrated in time, variable from l second to l minute. The intensity of the picture is proportional to amplitude over a dynamic range of about ten db, offering a qualitative frequency analysis.

In using the instrument a tape 'Loop was made of a particular shot arrival sequency and this was played repeatedly while the frequency was slowly scanned. The time sweep was triggered by a signal on the second channel of the magnetic tape loop. This time sweep trigger signal was made to occur just before the first signal arrival from the explosive shot.

Similar methods have been used before for investigations of the normal mode structure of channeled sound, Johnson (191,-21, Hersey and for bubble pulse frequencies, Urick (1959). In these references a Kay Laboratories "Vibrolyzer" was used. The Vibrolyzer displays on teledeltos paper a picture similar to that of the oscilloscope display of the TFA.

Shots 9 and 11 were analyzed in this way and the TFA records are shown in figures 13 and 14. The first display in each figure is for the frequency range 0 to 6 kc. In the second display the low frequencies have , been expanded as shown. The frequency scales are linear in each case.

In figure 14 (shot 11) the secondary pulses are particularly evident. The apparent shift to the lower frequencies of the second and what looks like a third bubble pulse is particularly interesting. Such a shift is predicted on the basis of bubble migration. Whether this is the cause here, is not known. Figure 15 for expected TNT spectra indicates such a shift in the energy of the bubble pulses to lower frequencies.

It is also rather striking to compare the TFA with the graphic shot records. This is done for shot 11 in figure 16. Here, the time scale of the TFA picture was made to coincide with the graphic record time axis.

VIII. QUANTITATIVE ANALYSIS OF INDIVIDUAL SIGNAL ARRIVALS

The frequency characteristics of the signals which arrive at the receiver will be dependent on (1) the frequency spectrum of the source, (2) absorption properties of the transmission medium, the effect of channeling, and (4) the reflection coefficients of the boundaries where reflections occur.

The frequency spectrum near the source was not measured during this study, however this has been done for other explosives. Weston (1957) presents source spectrum levels for 1 pound TNT charges. Those curves are repeated here in figure 15 for comparison with results of this study. Calculations of the source spectra and bubble parameters will be based on those known for TNT. The TNT equivalent weight is undoubtedly greater than one compared to 40~ dynamite, but no figures on this are presently available.

The effect of molecular absorption can be taken into account with the attenuation coefficient. This is given by Horton, (1959).

$$\alpha = \frac{40f^2}{4100 + f^2} + 0.000275f^2 \quad \text{db/Kyd} \tag{5}$$

For frequencies and accuracies of interest here, this can be approximated by equation 12' noted earlier. Any transmission function must include this equation. The Tongue of the Ocean range used in the present study was 31.4 km long, hence a transmission function for this range will include the equation.

$$\alpha = 0.33f^2 \text{ db (note change from km to Kyd)} \tag{6}$$

The effect of channeling was discussed in an earlier section. The effect of surface reflections on the spectrum of the channeled sound did not seem to affect the data and will not be discussed here.

The signal arrivals were investigated in detail by frequency analysis of magnetic tape loops made from just that portion of the tape containing the individual signals. This was a somewhat difficult laboratory procedure since for the 15 inches per second tape speed the loops were about two inches in diameter. The analysis was done with a Panoramic Radio Products Analyzer Model LP-1A. This is a heterodyne-type frequency analyzer with an oscilloscope readout. An oscilloscope camera was used to record the spectra. This analyzer also forms part of the TFA system described earlier. Using this method, the surface channel arrival of the signal from shot 11 was investigated.

The frequency spectrum of the surface channel arrival is shown in figure 17. The shape of the signal which one would expect would be the sum of the transmission function of figure 7 and the expected source spectrum, figure 15. For comparison with the photograph of figure 17, a bandwidth correction factor must also be added because of the variation of bandwidth with frequency of the Panoramic Analyzer, Richard (1955). These factors have all been combined, and the resultant curve is shown as the dashed line in figure 17. In this figure only the shapes of the curves are compared. The absolute levels were not calculated, hence they may not have coincided as shown.

Above 1.5 kc the transmission function is determined chiefly by absorption; below this it is a function chiefly of leakage from the channel as determined by the first normal mode term given in equation 1. The agreement of the dashed curve with the photograph is very good and demonstrates the application of normal mode theory in this case.

It should be noted that the preparation of this report was partially supported by contract Nobsr 72626.

IX. CONCLUSIONS

1. The isothermal surface channel in the Tongue of the Ocean can serve as a useful acoustic transmission path.
2. The frequency range of this duct is clearly defined by the depth of the duct bottom.
3. It is possible to determine the existence and reliability of this channel by the transmission characteristics of standardized explosive shots.
4. The simplest test for the existence of a surface channel appears to be examination of graphic records where the signals are compared with and without frequency filtering.
5. The transmission properties of the surface channel can be predicted with reasonably good accuracy using normal mode theory.

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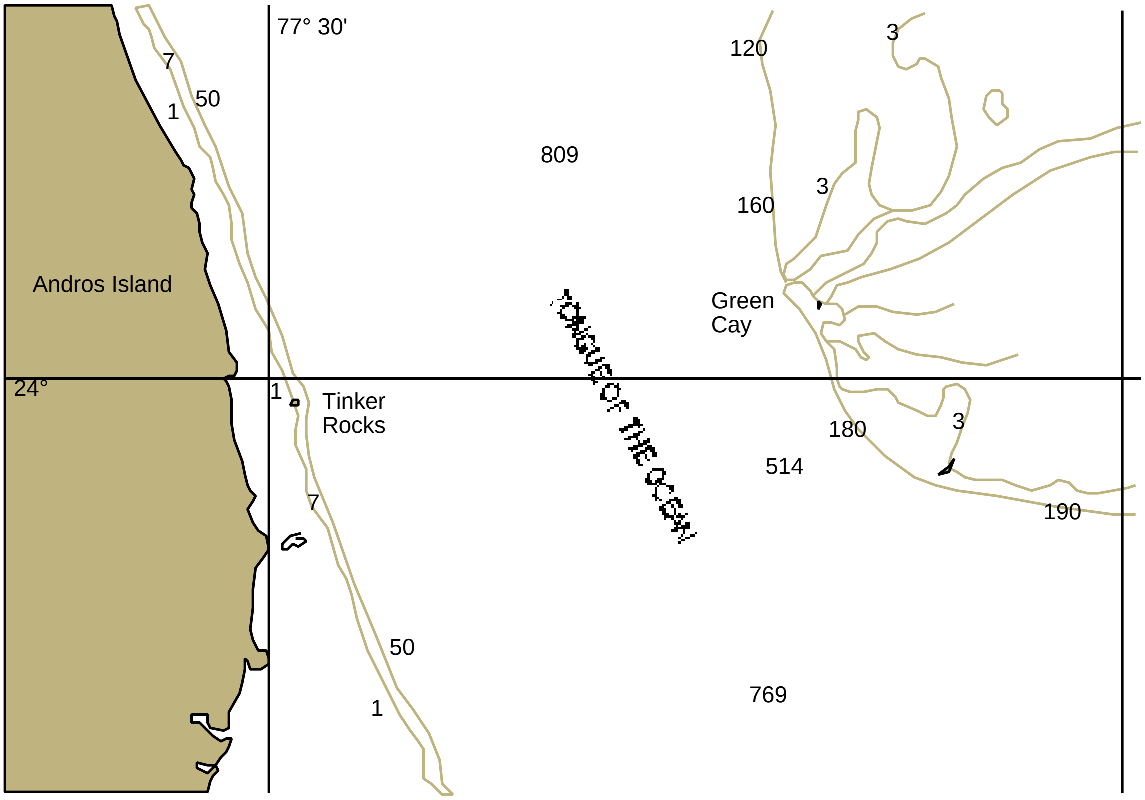


Figure 1. Chart of area of Green Cay and Tinker Rocks.

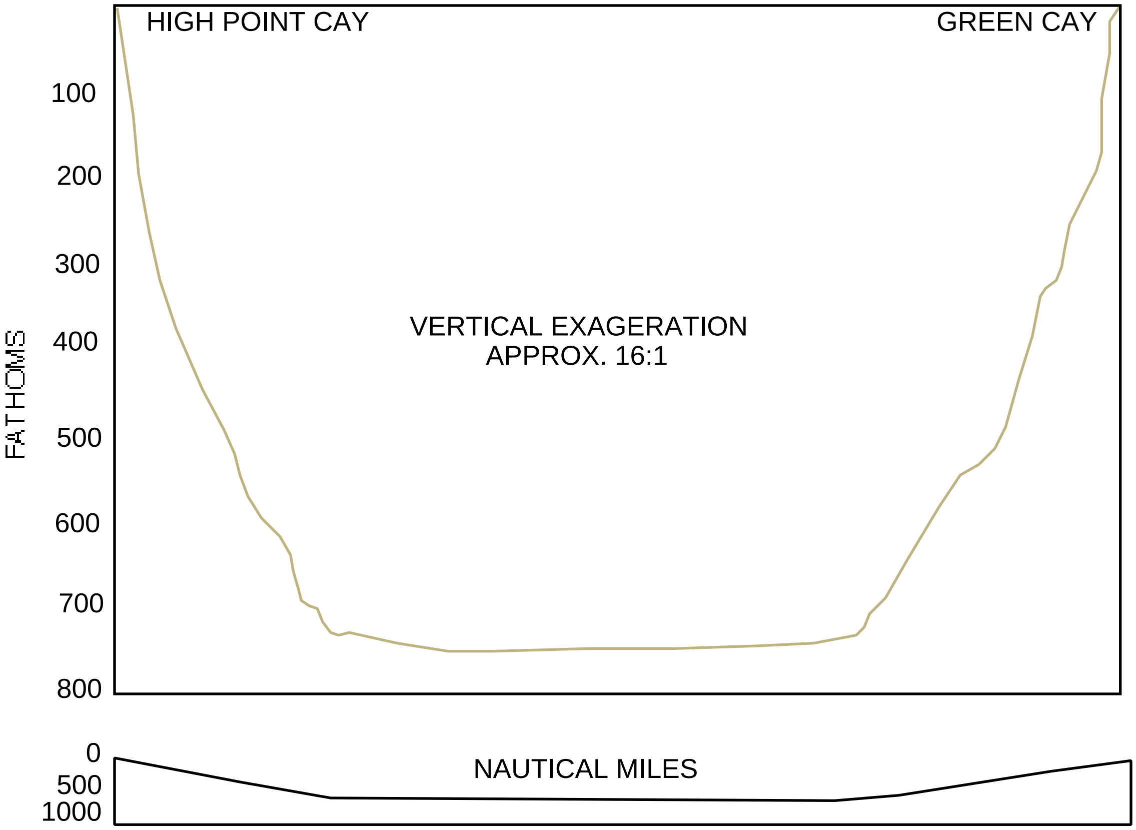


Figure 2. Vertical profile - High Point Cay to Green Cay.

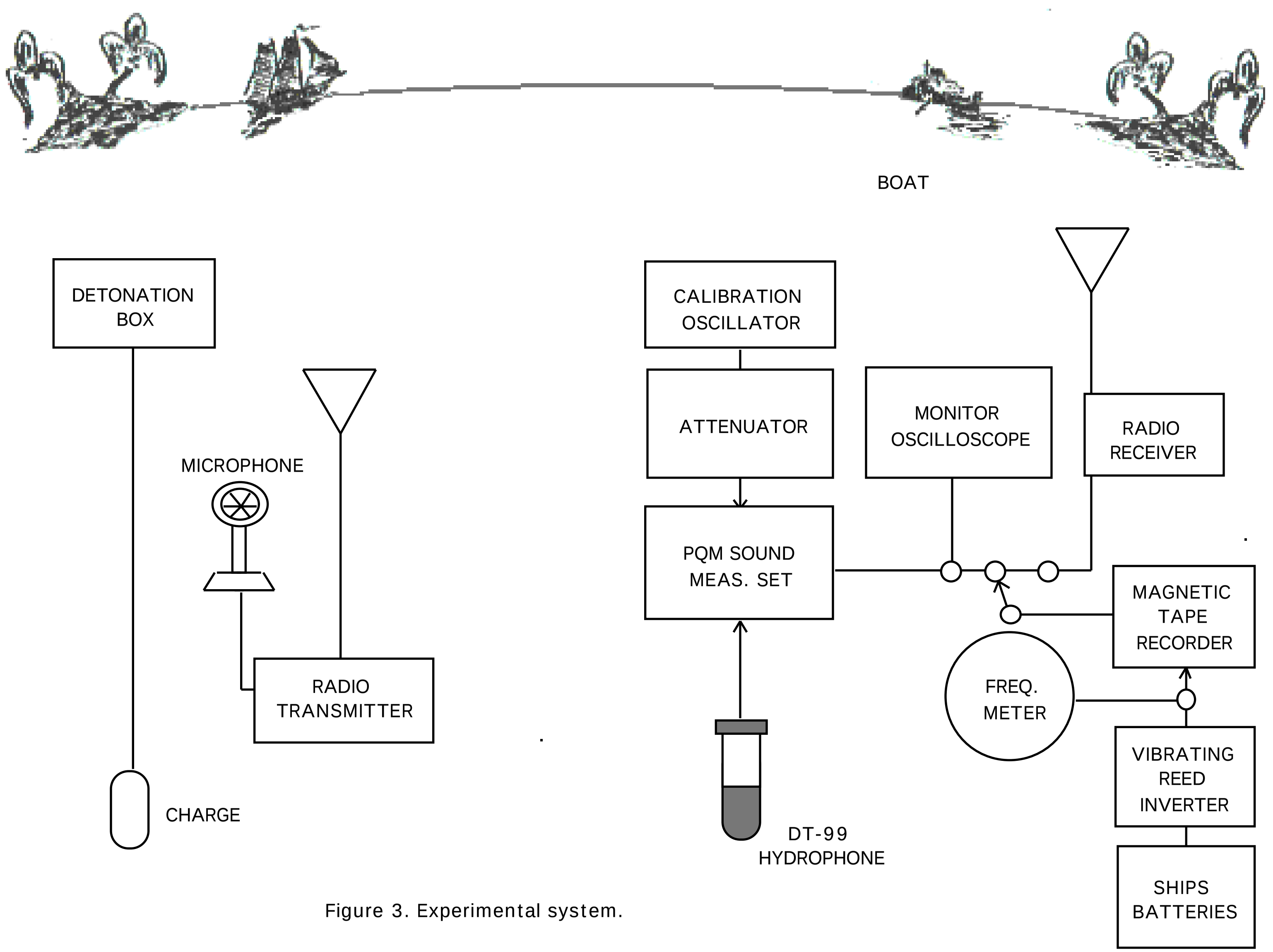


Figure 3. Experimental system.

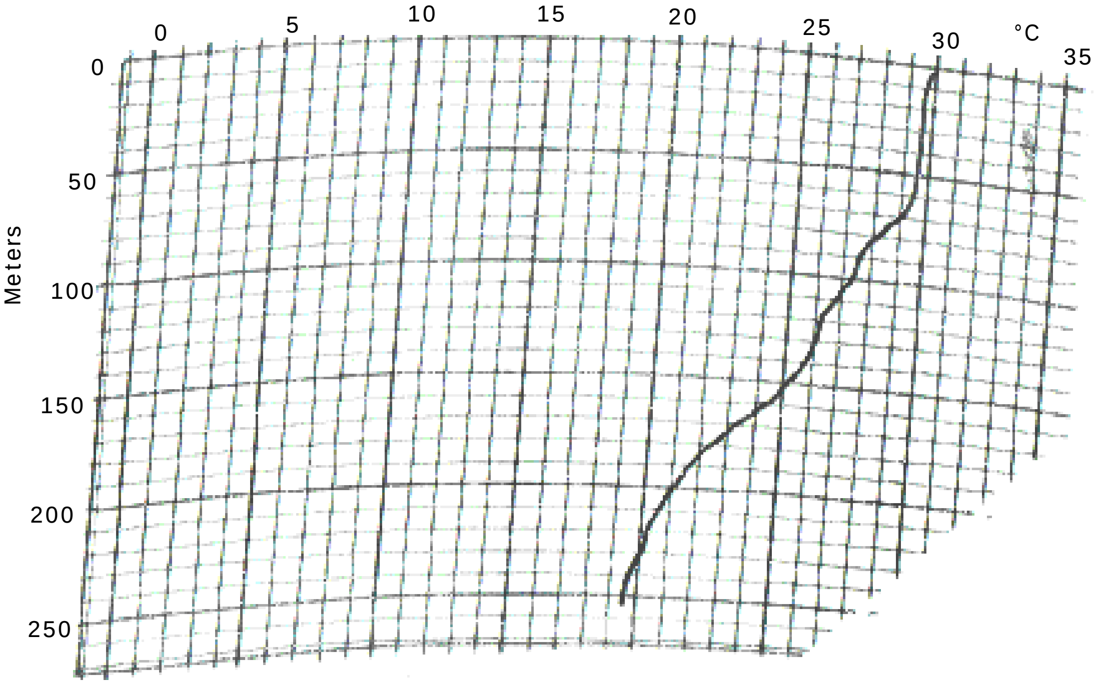


Figure 4. Near-surface BT.

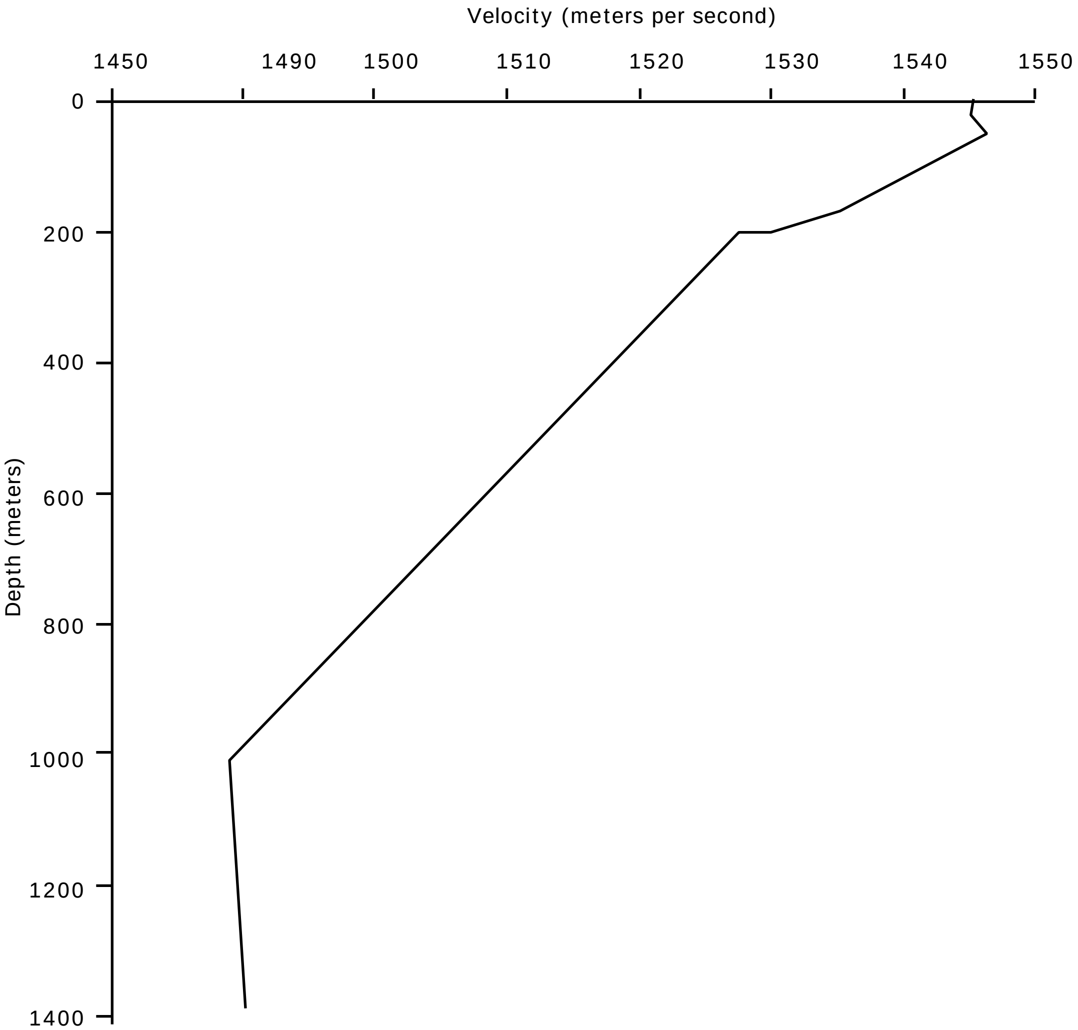


Figure 5. Sound velocity profile.

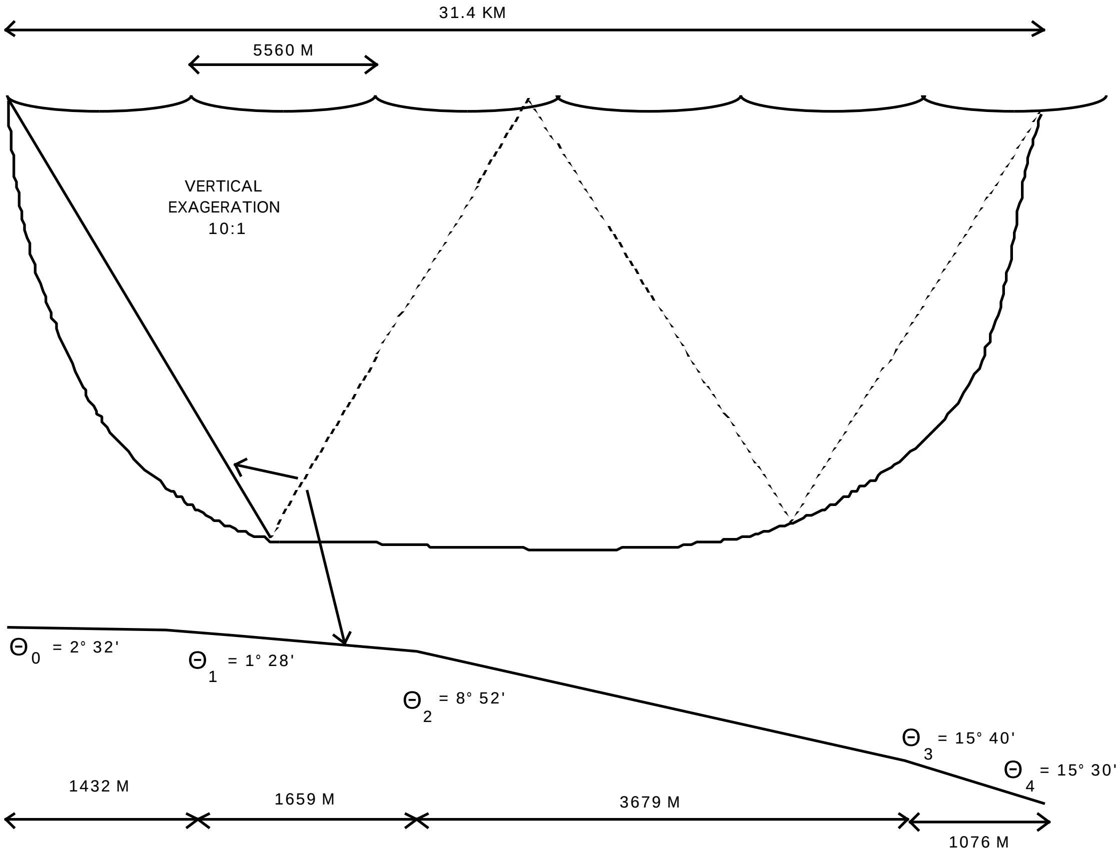


Figure 6. Sound ray paths.

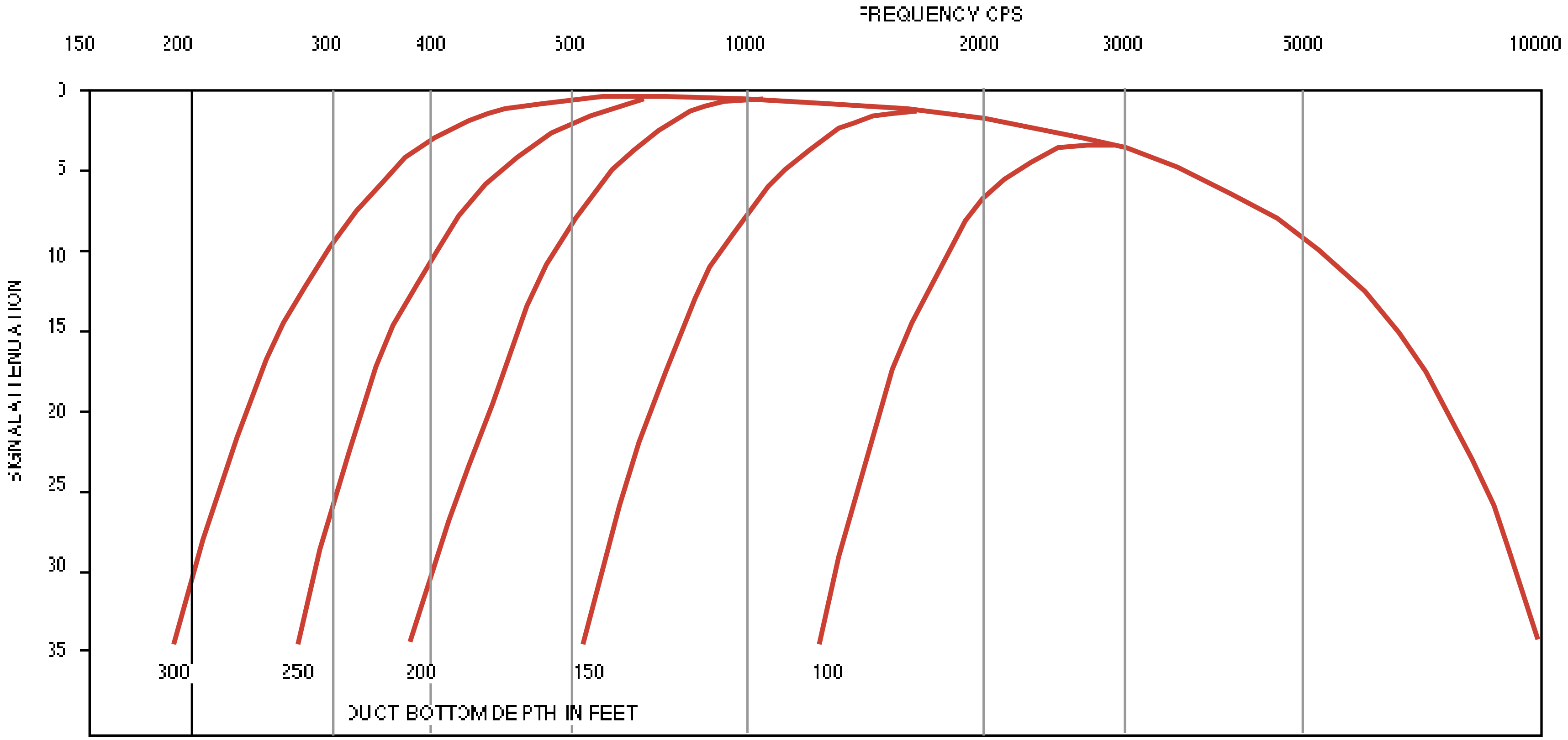
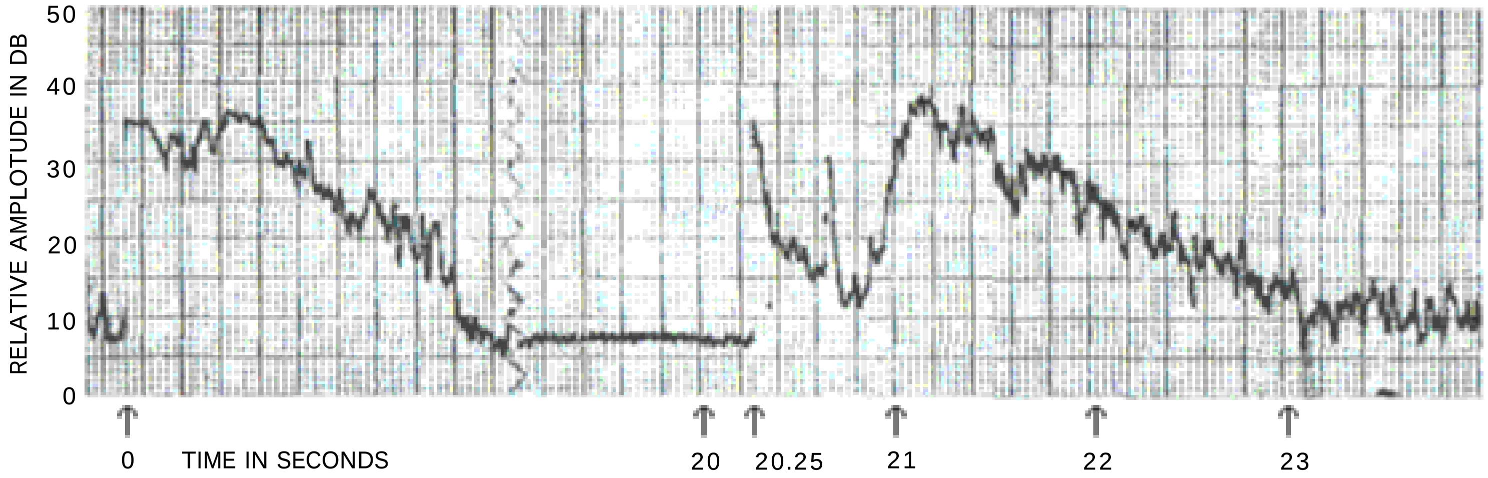
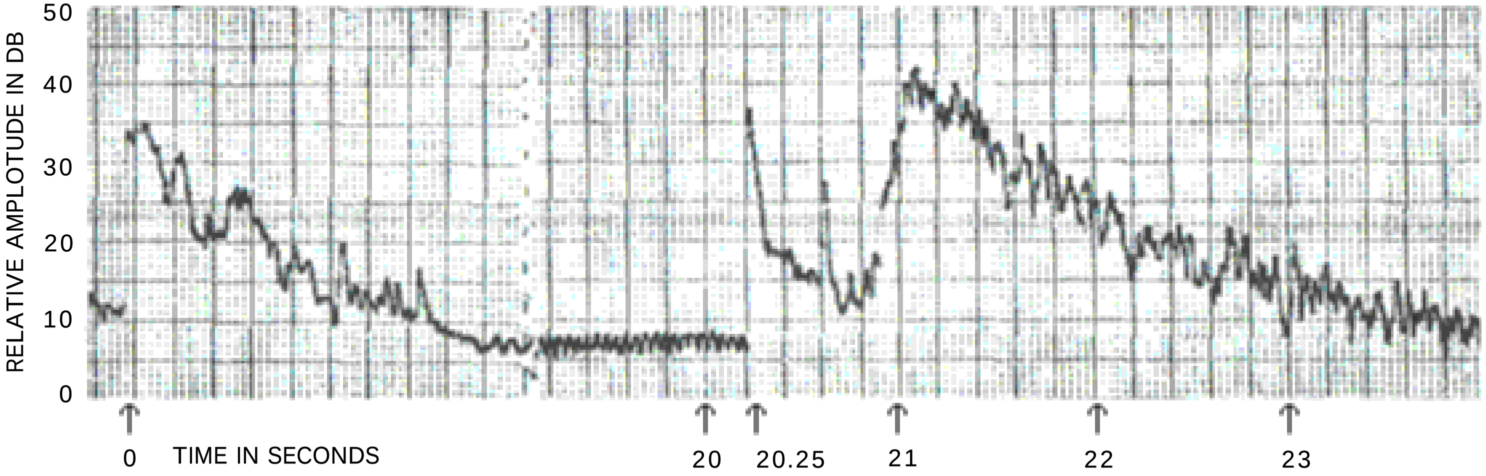


Figure 7. Transmission functions based on first mode.

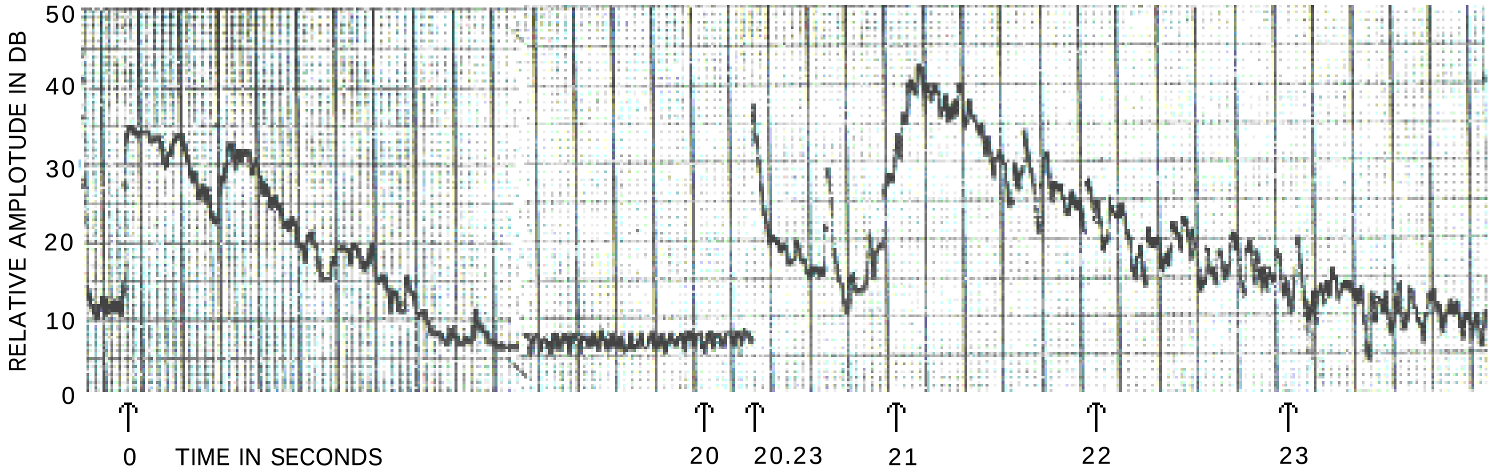


SHOT NO. 4 8/1/59 0800 CHARGE: 5 lb. DYN

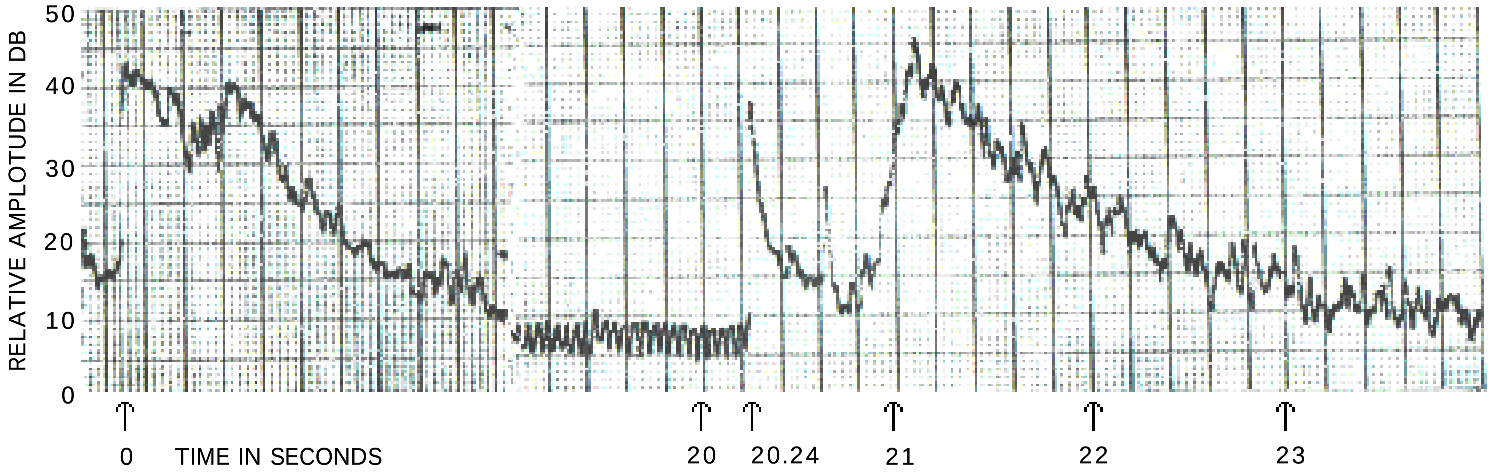


SHOT NO. 5 8/1/59 0815 CHARGE: 5 lb. DYN

Figure 8. Shots no. 4 and 5 run record.

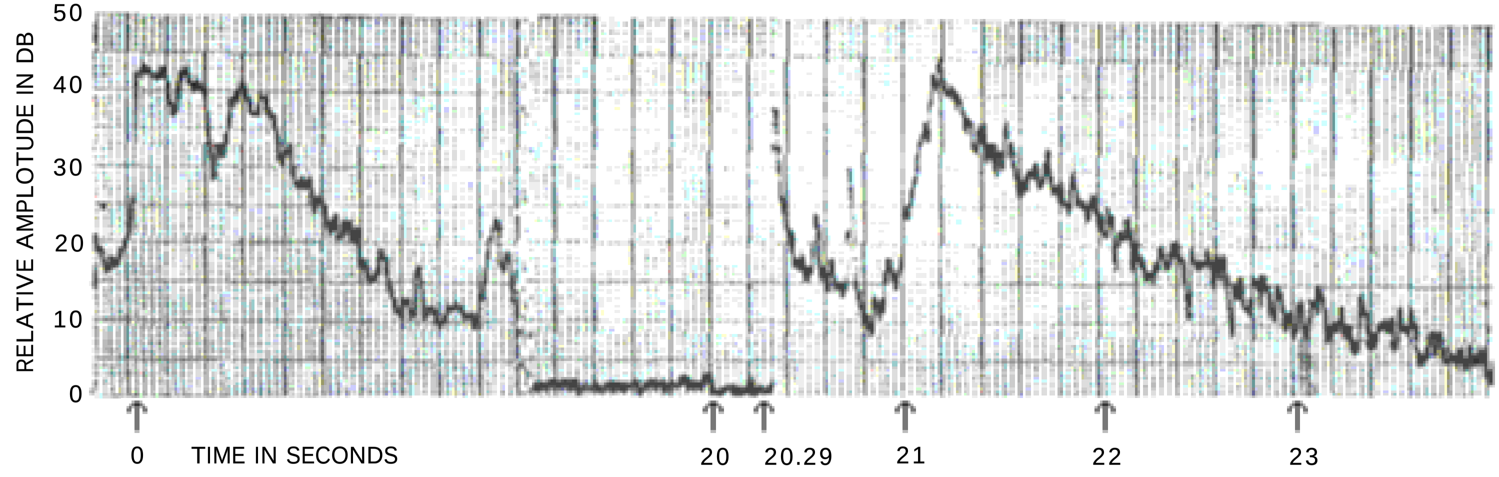


SHOT NO. 7 8/1/59 0845 CHARGE: 5 lb. DYN

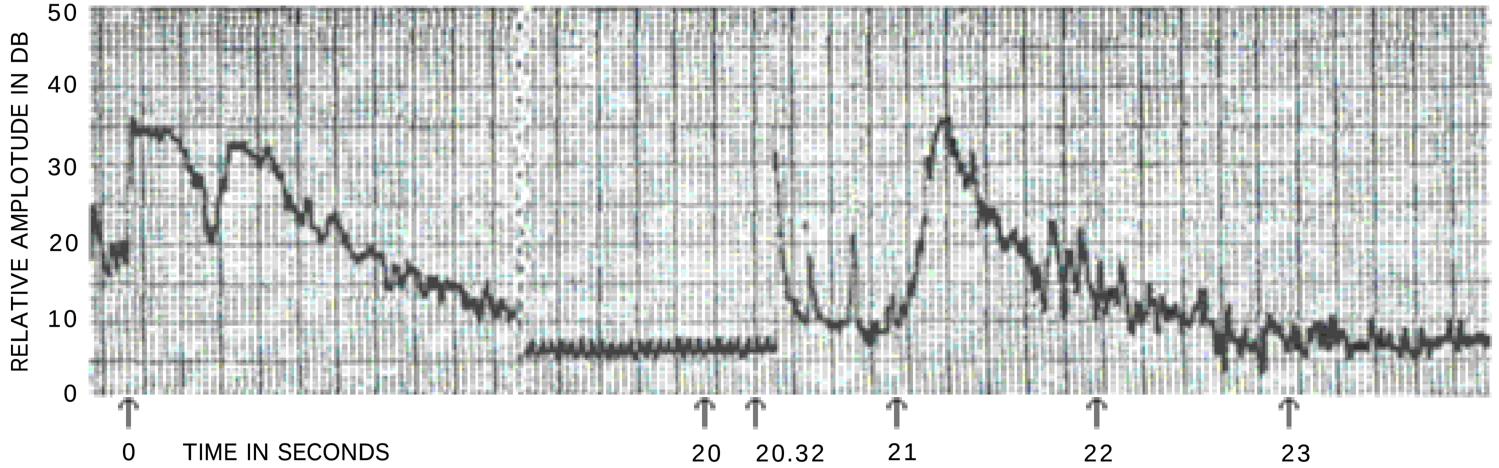


SHOT NO. 9 8/1/59 0925 CHARGE: 5 lb. DYN

Figure 8. Shots no.7 and 9 run record.

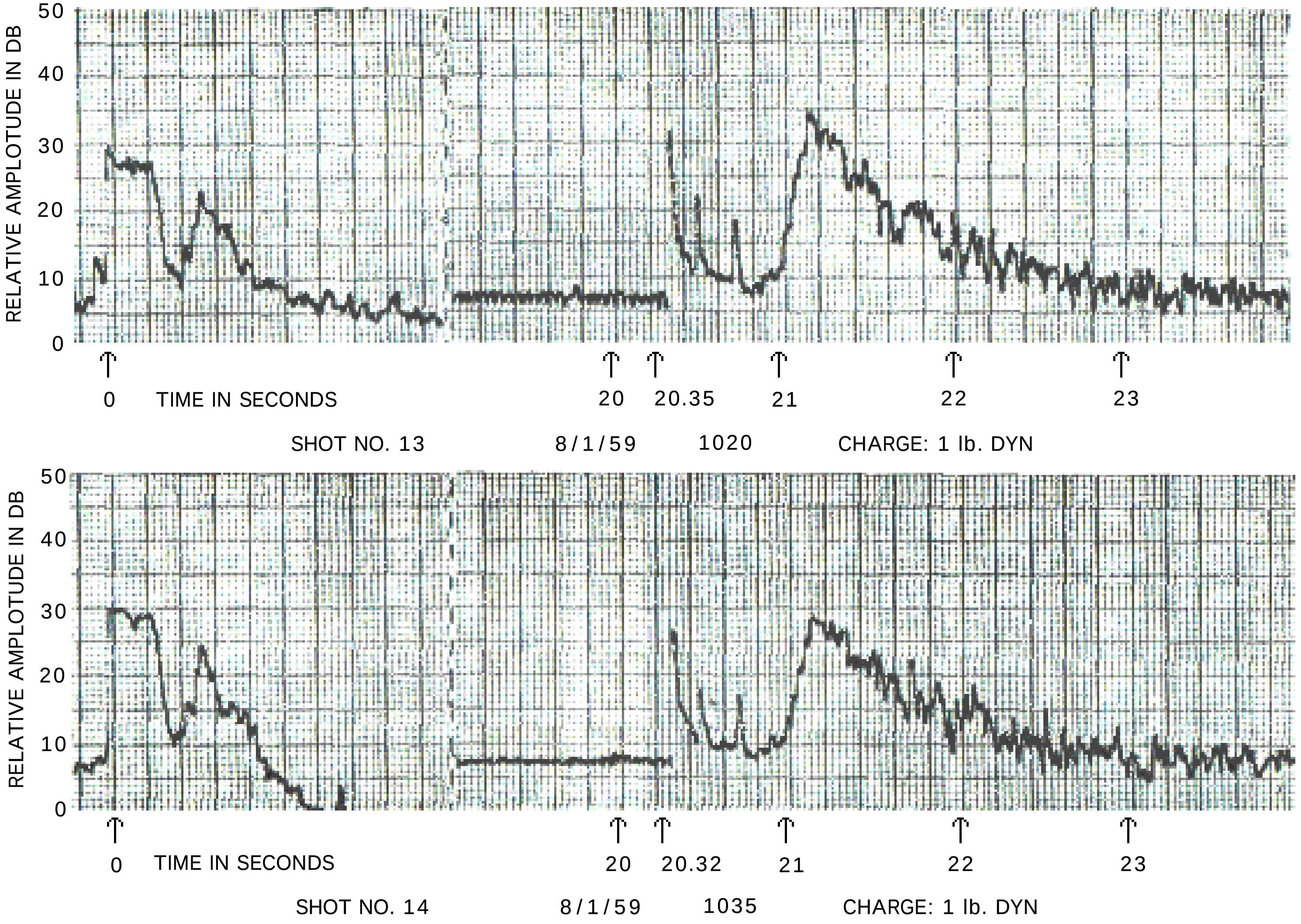


SHOT NO. 10 8/1/59 0940 CHARGE: 5 lb. DYN



SHOT NO. 11 8/1/59 0950 CHARGE:1 lb. DYN

Figure 10. Shots no. 10 and 11 run record.



SHOT NO. 13 8/1/59 1020 CHARGE: 1 lb. DYN

SHOT NO. 14 8/1/59 1035 CHARGE: 1 lb. DYN

Figure 11. Shots no.13 and 14 run record.

Figure 12. [NOT IN ARCHIVE COPY.]

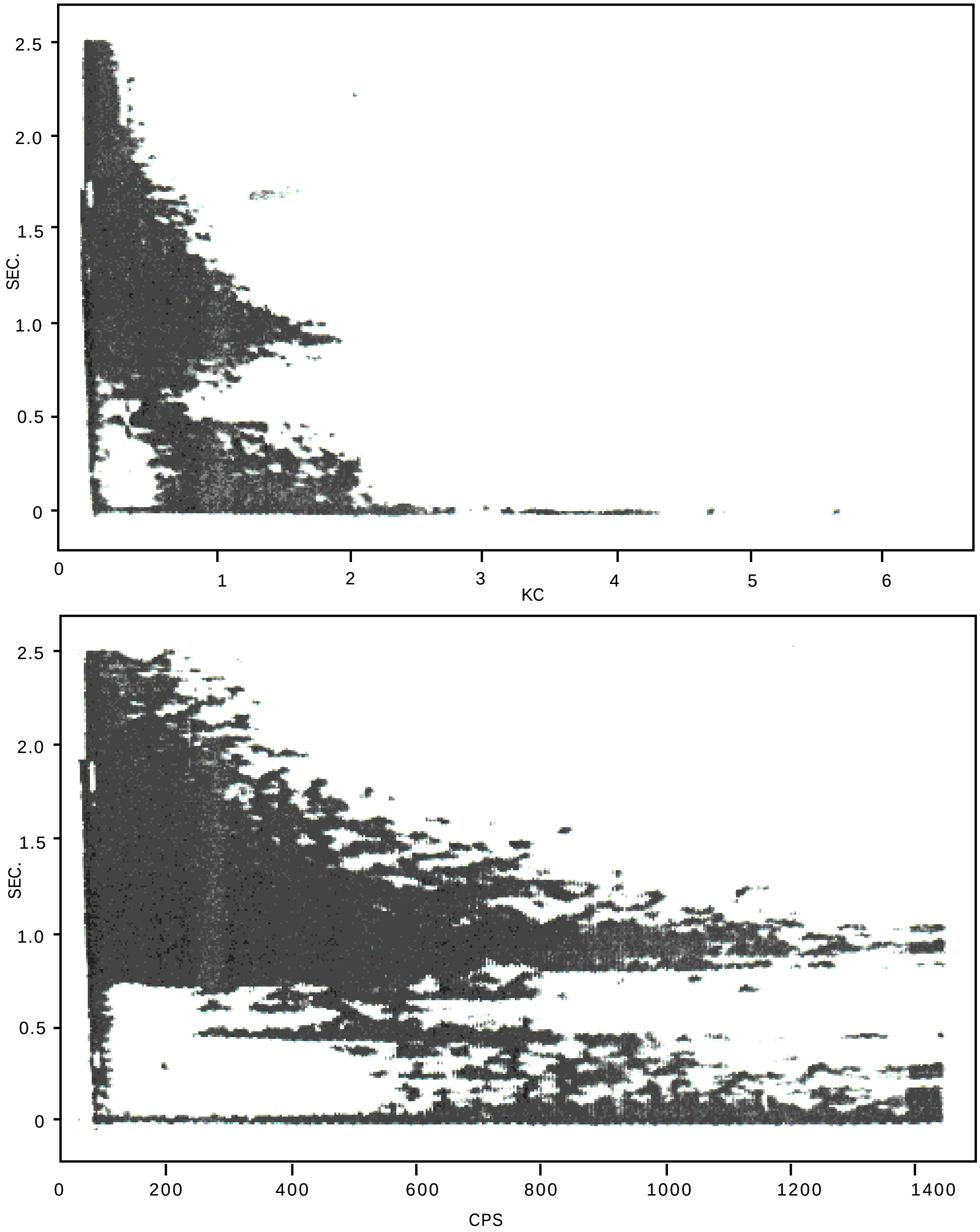


Figure 13 Time frequency analysis of shot 9.

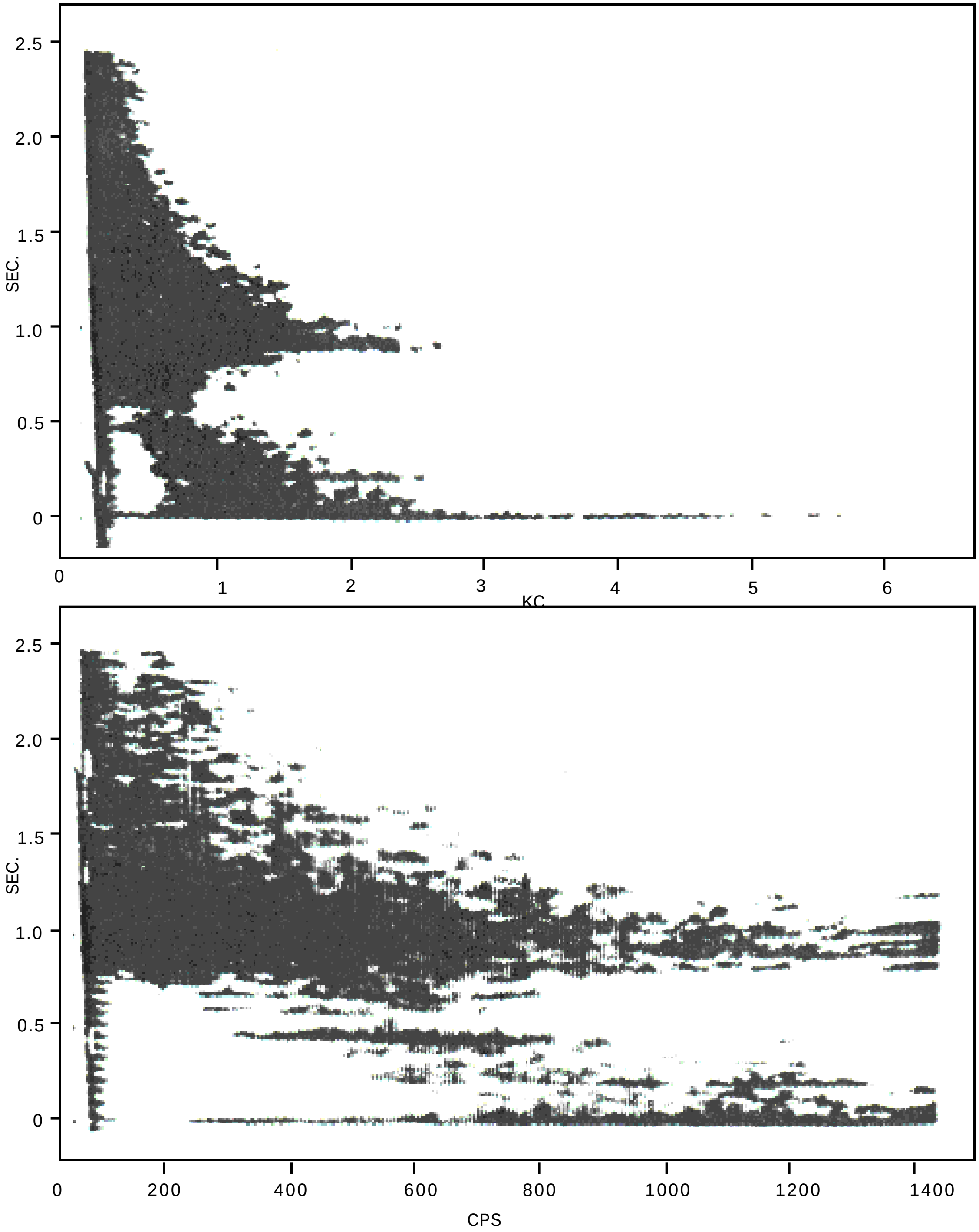


Figure 14 Time frequency analysis of shot 11.

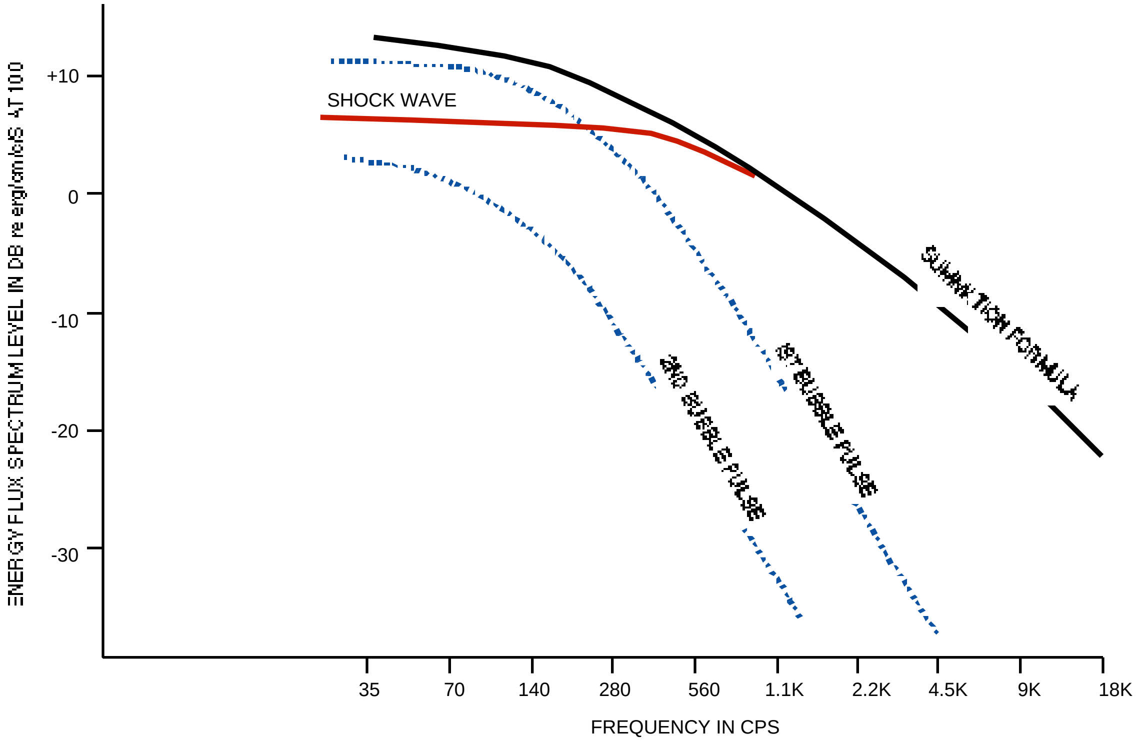


Figure 15. Theoretical free-field source spectrum levels for a one pound charge of TNT at 20 fathoms (after Weston 1957).

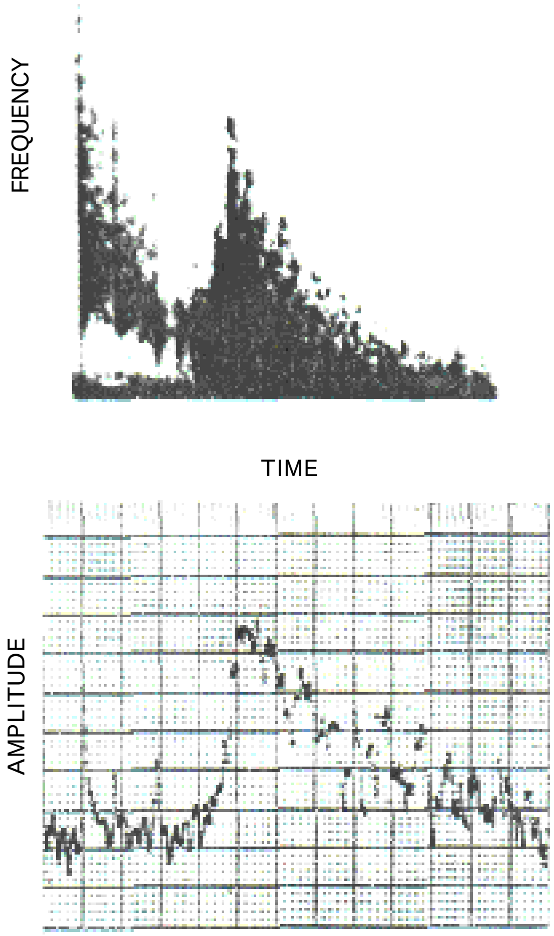


Figure 16. Comparison of TFA with graphic shot records.

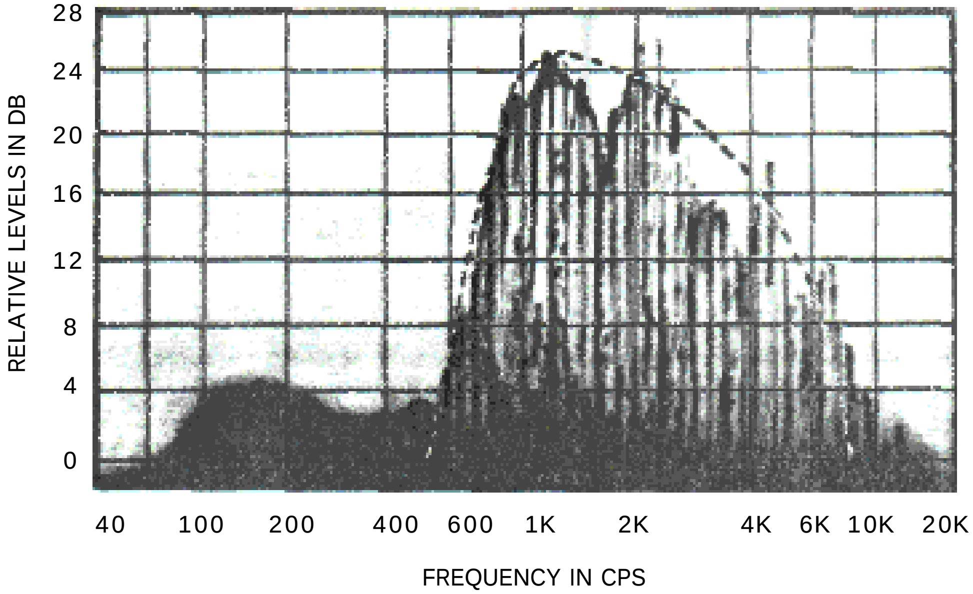


Figure 17. Frequency spectrum of shock wave arrival via surface channel.