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STUDIES OF THE EFFECT OF DEPTH OF FOCUS ON SEISMIC PULSES

Final Report

by

B. F. Howell, Jr. and P. M. Lavin

31 October 1966
Period covered: 1 January 1962 thru 31 October 1966

Contract Monitor: Ker C. Thomson

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Final report

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STUDIES OF THE EFFECT OF DEPTH OF FOCUS ON SEISMIC PULSES

I. Abstract

This report summarizes the conclusions reached in thirty other reports issued in connection with this contract, and lists the individual reports which detail how each of the objectives of the contract was reached.

The principal method used in an attempt to measure depth-of-focus of shallow events is the Watson-Merdler inverse-filtering technique. It is shown that a simplified version of this method which neglects noise also finds ghosts in a seismogram, as does cross-correlation. The three methods frequently but not always find the same ghosts.

Two important factors which make it difficult for all three methods to find ghosts are that short-period seismometers do not record the main part of the energy in most seismic pulses and the ghosts commonly differ greatly from their primaries in waveform and frequency spectrum.

II. Objectives

The objectives of this research are listed below together with reference to the scientific and technical reports which describe each part of the work. Inasmuch as detailed technical reports have already been distributed on most aspects of this research, only the conclusions will be summarized here except for the work of the last three months, which has not been thoroughly reported previously.

Objective 1: To construct seismic scale-models wherein the effects of the earth on seismic pulses can be simulated. The model facilities are described in Technical Report Nr. 2 by R. L. Rothman (1964). Figure 1 shows typical arrangements of some of the equipment. Scientific Report Nr. 2 by Y. Nakamura (1963A) discusses the behavior of some of the model materials. Scientific Report Nr. 3 by B. F. Howell, Jr. (1966) describes a digitizer developped for use in this laboratory.

Objective 2: To study interference patterns in model records and to compare them with patterns observed in real events. Technical Report Nr. 2 by Rothman (1964) is concerned with interference in the model records. Technical Report Nr. 4 by G. Leblanc (1966) discusses the spectra of a real earthquake in detail. This problem has also been discussed by Nakamura (1963B) in Technical Report Nr. 1.

Objective 3: To collect seismograms for the study of depth of focus. A file of over 400 seismograms, most of them in digital form has been assembled as a source of research material.

Objective 4: To try various methods of analyzing seismograms in an attempt to measure accurately the depth of focus of the causitive event. This was the principal objective of the project. It was hoped that accurate depth determination would assist significantly in distinguishing natural earthquakes from blasts. A method of inverse filtering called the Watson-Merdler method was developped, and is described in Technical Report Nr. 3 by S. C. Merdler (1964). The original method was modified and tested on blasts as described in Technical Report Nr. 5 by J. L. Lin (1966) and on earthquakes as described in Technical Report Nr. 6 by Y. Y. Cheng (1966).

A simplified version of this method (known as the deghost method) which neglects noise has also been developped and is described below. Both methods have been compared with two types of cross-correlation analysis.

Objective 5: To construct a two-dimensional scale-model of the earth's crust, to examine the effects of refraction of seismic waves along the Mohorovicic discontinuity in this model and to compare them with results in the real earth. Technical Report Nr. 7 by D. E. Siskind (1966) describes the principal experiment in this series. Other experiments related to this objective are described in Technical Report Nr. 1 by Y. Nakamura (1963) and in Scientific Report Nr. 1 (Nakamura, 1964), Nr. 4 (Howell, 1967) and Nr. 5 (Howell and Baybrook, 1967).

Objective 6: To prepare reports covering all work done. A complete list of all reports prepared, including verbal reports before societies, published reports to which this contract contributed partial support and publications planned which will be completed after the close of this contract are included in Table I.

III. Summary of Conclusions arrived at in Previously Issued Reports.

A. Model materials.

In the early experiments on this project, scale models were made from commercial plastics. These materials were found to absorb elastic waves much more rapidly than metals. The rates of absorption were measured in polystyrene and in Plexiglas. Absorption in these materials was found to be frequency dependent. The absorption coefficient was found to be

$$\alpha = (0.054 \log F - 0.080)/\text{cm} \qquad (1)$$

in Plexiglas and

$$\alpha = 7.3 \times 10^{-5} F^{1.4}/\text{cm} \qquad (2)$$

in polystyrene for 30-180 kc, where F is frequency and α is defined by the equation for amplitude

$$A = A_o e^{-\alpha\Delta} \qquad (3)$$

where Δ is distance. To avoid the effects of absorption, only metal models have been used for the last two years. Absorption is much lower in metals. The variation with frequency was too small to measure in the bi-metallic sheets used in this research.

B. Effect on the frequency spectrum of refraction along boundaries.

Three types of boundary were investigated. Nakamura (1963B) studied the effect of a transition layer in which velocity increased smoothly from the low-velocity material to the high-velocity material. Seismic pulses refracted along such a boundary were attenuated about 12 db/octave above a frequency given by 1.7 times the velocity gradient in the model. Using field data, Nakamura and Howell (1964) and Howell (1966A) found a similar frequency cut-off effect corresponding to a transition-layer of not over 0.5 km thickness under the Gulf of Maine and Lake Superior.

This does not mean that such a transition layer exists in these places. Siskind (1966) found that a thin intermediate-velocity layer could have an effect on the spectrum which could not be distinguished from a Nakamura-type transition layer.

Howell and Daybrook (1966) investigated an irregular (saw-toothed) boundary (Fig. 2), and found that it also produced a decrease in energy at high frequencies (Fig. 3). It thus appears that a wide range of structures can produce the observed effect, which must consequently be expected from many if not nearly all real crustal structures. Critical refraction thru a layered crust or along the Mohorovicic discontinuity will, in this fashion, tend to limit seismic signals to frequencies below 6-10 cps. The peak energy in the spectrum tends to be below this. This filtering effect will have a tendency to obscure any differences in the spectrum of earthquakes and blasts, even if such differences existed at the source.

C. Depth of focus from simple spectral analysis.

Throughout this research the basic principle used in an attempt to measure depth of focus has been the concept that there is a surface-reflected pulse, pP, arriving after an unreflected first arrival, P, and resembling it in waveform. In the frequency domain, the presence of these two pulses will produce maxima and minima, the positions of which are determined by the pP-P delay time. Rothman (1964) sought to measure this delay by examining the interference patterns which resulted from the overlapping of these two pulses. He found maxima and minima in the frequency spectrum at the expected places, as did Siskind (1966) in a more limited test. Rothman showed, however, that even in the case of very simple layering, there were many superposed interference patterns resulting from the presence not only of P and pP, but also from P and other pulses. Because every passage thru an interface potentially produces up to four pulses, the pattern of peaks and troughs in the spectrum of any seismogram from a real structure is complicated. Rothman showed that there is a spectral effect which marks the depth of focus, but that it was not an obvious one which could be measured dependably in any but special, simple cases. Similar results were obtained by autocorrelation analysis.

Leblanc (1966) studied the complexities of the spectrum further and showed that even from one earthquake the spectrum varied greatly from station to station (Figure 4). He demonstrated that the detailed structure of the spectrum can be fully accounted for by the effects of reflection and refraction as a seismic pulse passes thru a layered crust. He showed that this effect on the pulse, called the transfer function of the crust, could be calculated for any segment of seismogram. He developped a method of choosing between different transfer functions to decide which of two or more was the more likely cause of an observed spectrum representing any given seismogram.

If the structure of the earth is accurately known, Leblanc's method will allow the spectrum to be adjusted (thru inverse filtering) until only the effect of depth of focus remains. However, the spectrum is so sensitive to small changes in layer thicknesses and physical properties that more research will have to be done before the effect of the crust at any station can be removed well enough to try Rothman's method of finding focal depth.

D. Watson's focal-depth method.

Since every seismic event except one right at the surface must produce both a P and a pP pulse (except for the special cases of zero P reflection from the surface and nulls in the radiation pattern at the source) the seismogram normally consists of several trains of pulses: 1) the P pulse travelling from the source to the recorder, followed by all the additional pulses generated by reflection and refraction at intermediate boundaries; 2) the surface reflected pP pulse and its train of additional pulses; 3) the surface reflected sP pulse; 4) the S pulse; etc. If only that portion of the seismogram before the arrival of sP is considered, this portion may be treated as the sum of two trains of pulses: P(t) and pP(t). Where the upward-radiated P pulse has the same waveform as the downward-radiated P pulse, where there are no large additional pulses generated by interfaces between the focus and the surface, and where the angle of incidence at the surface is small so that pP and P travel nearly the same path beneath the surface, then the seismogram can be considered to consist of only the sum of P(t), pP(t) and any noise which is present. Since pP(t) is postulated to be of the same waveform as P(t) but delayed behind it by the time, Δt, to rise to the surface and descend again to the focal depth,

$$pP(t) = RP(t-\Delta t) \tag{4}$$

where R is the ratio of amplitudes of pP(t) to P(t). In this case, the seismogram will be

$$S(t) = P(t) + RP(t-\Delta t) + N(t) \tag{5}$$

where N(t) is noise plus the effects of imperfections in any of the approximations assumed above. Knowing S(t), R and Δt, P(t) can be approximated for any noise level.

An approximation of P(t) can be found for any S(t), R and Δt. If R and Δt are known to lie within some range of values, these can be sampled, and $P(t)$'s found for all desired values of R and Δt for any given $S(t)$. Merdler (1964) experimented with different criteria for picking that $P(t,R,\Delta t)$ which was the best approximation to the original pulse radiated from the focus of the seismic event. He postulated, on empirical evidence, that, for the correct values of Δt and R, the value of the quantity C_R would be larger than for any other combination of Δt and R, where

$$C_R = \frac{\sum\limits_{T_{pu}} \left(\left| P(t) \right| - U \right)^2}{\left(\sum\limits_{T_{pu}} t \right) \cdot \left(\sum\limits_{T} P^2(t) \right)} \qquad (6)$$

where T_{pu} is the sequence of time intervals when $P(t)$ exceeds the noise level U, and T is the total length of $P(t)$ tested. C_R is called concentration ratio. C_R was considered to be a measure of the relative simplification of $P(t)$ as compared to $S(t)$.

Lin (1966) and Cheng (1966) tested the Watson-Merdler method on fourteen nuclear-test-blast seismograms and on fourteen earthquake seismograms, respectively. They found that they had to add to Merdler's criterion the requirement that the numerator in equation (4) was less than the corresponding summation for the original seismogram:

$$\sum_{T_{pu}} \left(\left| P(t) \right| - U \right)^2 < \sum_{T_{su}} \left(\left| S(t) \right| - U \right)^2 \qquad (7)$$

They also found no evidence that the largest C_R necessarily occurred for the case sought. By examining all P(t)'s for combinations of R and Δt where C_R was greater than the concentration ratio for the original seismogram, S(t), from which P(t) was derived, they discovered that there seemed to be more than one P(t) which was a simplified version of S(t). Each was suspected of being a case where the inverse filtering used to find P(t) in the Watson-Merdler procedure had removed some real pulse or pulses. Sometimes the removed pulses could be identified as pP, sP or the core reflection, PcP. At other times they could not be identified.

It was also found on checking that the effect of the layering of the crust was to produce many pulses in the seismogram. It was concluded that the most likely explanation for the many combinations of R and Δt which produced reasonably simplified P(t)'s was that each corresponded to a case where one of these crustal internal reflections was removed. Which P(t) was pP was not obvious.

The Watson-Merdler method succeeded in recognizing pulses, but it could not identify them (Figs. 5 and 6). Even in the case of a shallow blast, there were usually several P(t)'s recognized. Hence, the method, in its elementary form, failed as a means of distinguishing between blasts and seismograms. Using many earthquake seismograms, however, there is a good possibility that pP and other pulses can be recognized by their tendency to occur as solutions regularly for a large fraction of the records.

IV. Comparison of the Watson-Merdler method with alternative approaches.

The Watson-Merdler method was able to find values of time delay, Δt, and pulse-strength ratio, R, for which the seismogram, S(t), seemed to consist approximately of two pulses: a P(t), which was simpler than the original seismogram plus an image of itself, RP(t-Δt). Merdler's measure of simplicity, C_R, was largely empirical. In the course of Lin's and Cheng's studies, it became increasingly apparent that the use of C_R as a means of identifying the cases where inverse filtering was removing a real pulse was the weakest part of the procedure. C_R consists of three parts:

$$U_p = \sum_{|P|>U} (|P(t)| - U)^2 \tag{8}$$

where U is the noise amplitude

$$L_p = \Sigma P^2(t) \tag{9}$$

$$T_p = \sum_{|P|>U} t \tag{10}$$

Using this notation, equation (4) can be rewritten

$$C_R(P) = \frac{U_p}{T_p \cdot L_p} \tag{11}$$

There are corresponding quantities for S(t)

$$U_s = \sum_{|S|>U} (|S(t)| - U)^2 \tag{12}$$

$$L_s = \Sigma S^2(t) \tag{13}$$

$$T_s = \sum_{|S| > U} t \qquad (14)$$

$$C_R(S) = \frac{U_s}{T_s \cdot L_s} \qquad (15)$$

To identify cases where inverse filtering simplified the seismogram, Lin (1966) and Cheng (1966) used equation 7 and the following equation in place of the condition that C_R as given by equation 6 be a maximum

$$C_R(P) > C_R(S) \qquad (16)$$

The second test was necessary because in certain cases, inverse filtering produced a P(t) whose amplitude was much greater than that of S(t). It did not seem reasonable that P(t) should represent more energy than the S(t) of which it was presumed to be a part.

Peaks in the Watson-Merdler C_R occur largely when T_p is significantly less than T_s. The two criterion $T_p < T_s$ and $U_p < U_s$ can be combined to give a test criterion

$$C_H = \frac{U_s \cdot T_s}{U_p \cdot T_p} > 1 \qquad (17)$$

This test was proposed late in the research as a substitute for the Watson-Merdler C_R test. It has not been properly tested to see if it is a better test. It was used in place of C_R in testing the simplified version of the Watson-Merdler procedure described below.

The Watson-Merdler method finds P(t)'s which meet certain criteria within a designated noise level, U. If it is assumed that no noise is present, then a P(t) can still always be found for any S(t) for any combination of Δt and R for a finite time after the start of S(t) provided S(t) is zero before time t=0. In this case equation (3) becomes

$$S(t) = P(t) + RP(t-\Delta t) \qquad (18)$$

This can be rearranged, giving

$$P(t) = S(t) - RP(t-\Delta t) \qquad (19)$$

It is simple to write a computer program which will find P(t) from S(t), R and Δt. This was done. This program is called the "deghost" program. This is possible because $P(t) = S(t)$ up to $t=\Delta t$. For every t between Δt and $2\Delta t$, P(t) can, therefore, be calculated from already known values of S(t). After calculating P(t) for the range Δt to $2\Delta t$, the calculation can be extended to $3\Delta t$, and so forth.

Such a program has one major weakness: the errors due to noise can be cumulative, and the pulse can increase in average amplitude with time. An S(t) which gives an unstable P(t) is the continuous signal

$$\begin{array}{rll} & = 0 & 0 \geq t \; \cancel{0 \leq t} \\ S(t) & = \ln(1 + \alpha t) & 0 \leq t \leq \Delta t \\ & = \ln\left(\frac{1 + \alpha t}{1 + \alpha t - \alpha \Delta t}\right) & \Delta t \leq t \end{array} \qquad (20)$$

Solving (18) for P(t) when R=-1 and $\Delta t \leq t \leq 2\Delta t$

$$\begin{aligned} P(t) &= S(t) + P(t-\Delta t) \\ &= \ln\left(\frac{1+\alpha t}{1+\alpha t-\alpha\Delta t}\right) + \ln(1+\alpha t-\alpha\Delta t) \\ &= \ln(1+\alpha t) \qquad (21) \end{aligned}$$

so that

$$\begin{aligned} P(t) &= 0 & t\leq 0 \\ &= \ln(1+\alpha t) & t\leq 0 \qquad (22) \end{aligned}$$

which rises continuously toward infinity as Δt increases. Provided $\alpha\Delta t$, is less than unity, $S(t)$ increases from zero at $t=0$ to $\ln(1+\alpha t)$ at $t=\Delta t$, and thereafter decreases to zero as t approaches infinity. Any noise pulse which resembles this will produce a component of $P(t)$ which steadily increases in size.

The deghost program was tried on the same seismograms used to test the Watson-Merdler program. A similar procedure has been used by Sarmah and Berg (1966), who credit it to Carpenter (1964). Computations by the deghost method are accomplished much faster than by the Watson-Merdler method, using less than one quarter of the computer time.

Tables II and III compare the cases of greatest simplification found by the Watson-Merdler method with those found by the deghost method. C_H was used in place of C_R as a criterion for simplification in the deghost program. For the fourteen earthquake seismograms, the deghost method found that a simplification, as indicated by a peak in C_H, had occurred for Δt's within 0.15 seconds of the greatest simplification found by the Watson-Merdler method in only seven out of the 17 cases of strongest Watson-Merdler simplification, testing over the same range in both cases. (The deghost program was run over a wider range of time delays than the Watson-Merdler method. The largest deghost C_H's occurred in some cases for delays shorter than those tested by the Watson-Merdler method.) Since the P(t)'s found by the deghost method have not been systematically studied, it is unknown which of the two methods is the better at picking the most obvious cases of simplification. Nor is it known to what degree the differences in the results are due to differences between the C_R and the C_H test criteria and to what degree they reflect the failure of the deghost program to allow for the effects of noise.

In the case of the fourteen nuclear blast seismograms, the deghost method indicated simplification in ten out of twelve of the cases of greatest C_R picked by the Watson-Merdler method; and the Watson-Merdler method found simplifications in nine out of fourteen of the cases of greatest C_H found by the deghost method (Table III).

The first parts of the fourteen blast and fourteen earthquake seismograms were also cross-correlated with the whole seismograms, and the cases of strongest correlation are reported in Tables II and III. Strong correlations with the greatest simplifications picked by the Watson-Merdler method occurred in 10 out of 28 cases, and with the deghost largest C_H's in 15 out of 23 cases.

One other test was made. Define a segment of a digitized seismogram from the A'th to the B'th point as $S_{A-B}(t)$.

Define another segment of equal length starting with the C'th point as $S_{C-D}(t)$, where D-C=B-A. Now define $Q_C(t)$ as

$$Q_C(t) = S_{C-D}(t) - RA_{A-B}(t) \tag{23}$$

where R is a multiple of 0.1. The "search" program compares $S_{C-D}(t)$ with $S_{A-B}(t)$ as a function of the variable, C, by finding the largest value of +R or -R where $Q_C(t)$ is simpler than $S_{A-B}(t)$ using condition 17. This method expectably gives very nearly the same results as cross-correlation.

These tests are not conclusive. Examination of the results has, however, led to the suspicion that the basic trouble may not lie in the Watson-Merdler or deghost methods themselves, but in the nature of the seismograms. The seismograms used were all recorded with short-period Benioff or similar high-natural-frequency seismometers. The displacement sensitivity of the Benioff instrument falls off rapidly below its peak sensitivity at 1.67 cycles per second, and is about 24 db down by 0.4 cps. The energy in the earthquake studied by Leblanc (Technical Report Nr. 4, 1966) usually had its peak at or below 0.4 cps. The effect of this is to make the energy in the seismograms sharply peaked in frequency near 1 cps. This is born out by a tendency for peaks in the cross-correlation function to occur at regular one-second intervals. This is true also of the deghost solutions. This was not so apparent in the case of the Watson-Merdler method, but whether this is because of a greater sensitivity of that method, or because the C_R test was poorer than the

C_H test for picking simplifications, or for some other reason is unknown. One thing is apparent, however: the seismic data analyzed should include lower frequencies than the predominant range in the seismograms tested here.

Another reason why the method may have failed to pick pP consistently in seismograms is that the pulse shape of pP is not always the same as that of P. To test this, several earthquakes of presumably known focal depth have been examined. Figure 7 is the first part of the State College, Pa., seismogram of the 11 January 1965 Alaskan earthquake, reported by the Coast and Geodetic Survey to be at 59 km focal depth. This focal depth corresponds to a pP-P delay of about 13.5 sec. There is no clear pulse at this time in the seismogram, but there is a strong pulse beginning at 7.6 sec (corresponding to 31 km focal depth). The deghost program finds this correlation clearly. It also finds a weak correlation at 9.15 sec (38 km). It finds no simplification for R=-0.5 for delays between 9.15 and 25 sec, the largest delay tested.

Figure 8 compares the spectra of the initial P and the pulse at 7.6 sec. Although these are similar, they are far from identical. Leblanc's study (Technical Report Nr. 4) of the crustal transfer function shows that the crust in the epicentral region is capable of introducing enough changes into the pulse shape of pP to cause it to differ substantially from P in the frequency band used here.

There is also the possibility that the ghost intensity coefficient, R, is sometimes positive for pP for earthquakes. The first motion from earthquakes can be a compression in some azimuths, a dilatation in others. Neither Lin nor Cheng tested systematically for positive values of R. Tests using the deghost program found approximately as many cases of $C_H > 1$ for positive R as for negative R in a few trial runs. Large positive cross-correlations also occurred about as often as negative ones.

V. Conclusions and Recommendations

This research has demonstrated that the Watson-Merdler and the deghost methods can find pulses in a seismogram, but that in the frequency range recorded well by short-period seismometers, more pulses are found than can be easily interpreted. The research suggests but has not proven that pulse interference due to the crustal transfer function is a major disturbing factor and may be the principal cause of this difficulty. As a result of this, these methods have failed to provide an easily used means of distinguishing earthquakes from blasts.

One of the major needs in seismology is a means of removing the effects of the crustal transfer function from seismograms. It appears likely that it is the complexities introduced by crustal layering that have prevented these methods from separating blasts from earthquakes and have introduced uncertainties into the depth-of-focus measurements. Leblanc (Technical Report Nr. 4, 1966) has suggested an approach by which this problem may be solved. When means of removing the crustal effect from the seismogram at a recording station have been developped, this whole depth-of-focus experiment should be repeated.

This research has shown also that seismic energy falls off rapidly above 0.4 cps. Any further work done along the lines tried here should use data covering a broader range of frequencies at the low-frequency end.

The methods developped here do show promise of providing a means of selecting the pP-P time interval more accurately than by simple visual inspection of the seismogram. This possibility should be studied in greater detail on longer-period seismograms. Long period seismograms are advantageous also because pulse interference is less prominent than in short-period seismograms.

The Watson-Merdler and deghost methods should be compared more thoroughly to find if the complicated Watson-Merdler method is significantly more sensitive to ghosts in a seismogram than is the deghost method, and to find out if either is better at picking ghosts than cross-correlation or autocorrelation.

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Y. Y. Cheng and T. G. Baybrook were particularly significant, and have resulted in special reports in each case. Dr. R. J. Watson shared in the direction of this work in 1964-65. His ideas, particularly the basic concepts of inverse filtering as used in the Watson-Merdler method and the concept of concentration ratio as a measure of simplicity of a seismogram, have been central to this work since he proposed them.

The friendly and patient help and encouragement of Mr. Ker C. Thomson, our contract monitor, is gratefully acknowledged.

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Table I. Non-Periodic Reports Prepared and Planned, Supported Entirely or Partly by Contract AF19(628)-238

Title of report	Type of report	Published or distributed	Status and approximate probable distribution date
1. Absorption of Simulated Seismic Waves in Plastic Models, by Y. Nakamura (Abstract: Earthquake Notes 33:98)	Verbal before Seis.Soc.Am.	Dec. 1962	
2. Frequency Specta of Refraction Arrivals and the Nature of the Mohorovicic Discontinuity, by Y. Nakamura	Supplement Progress Rpt. 6 (Technical Report Nr. 1)	June 1963	
3. Absorption Measurements of Ultrasonic Waves in Plastic Sheets, by Y. Nakamura (Reprint, J. Ap. Phys. 34:3288-3290)	Scientific Report Nr. 2	Nov. 1963	
4. Model Experiments on Refraction Arrivals from a Linear Transition Layer, by Y. Nakamura (Reprint, Bull. Seis. Soc. Am. 54:1-8)	Scientific Report Nr. 1	Feb. 1964	
5. Model Studies for Focal-Depth Determination at Near-Source Stations, by R. L. Rothman, P. M. Lavin, B. F. Howell, Jr. (Abstract: Trans. Am. Geophys. Union 45:91-92)	Verbal before Am. Geophys. Union	April 1964	
6. On the Inadequacy of Paper Recording of Seismic Data, by B. F. Howell, Jr. (Abstract: Trans. Am. Gph. U. 45:95)	Verbal before Am. Geophys. Union	April 1964	
7. Model Studies for Focal-Depth Determination at Near-Source Stations, by R. L. Rothman	Supplement to 5th semi-annual report (Technical Report Nr. 2)	June 1964	

Table I. - continued

8.	Model Experiments on Refraction Arrivals from a Linear Transition Layer, By Y. Nakamura and B. F. Howell, Jr. Proc. VESIAC Conf. Variation of Earth's Crust and Upper Mantle pp. 14-27, U. Michigan	Verbal and in VESIAC Conference report 4410-75-X	July 1964
9.	Estimation Procedure for Focal-Depth Determination of Seismic Disturbances, by S. C. Merdler	Technical Nr. 3, AFCRL-64-755	Sept. 1964
10.	Optimum Sensitivity for Seismographs, by B. F. Howell, Jr., Earthquake Notes 36:7-8	Published	June 1965
11.	Effect of Truncation on Crustal Transfer Functions, by G. Leblanc	Verbal before Seis.Soc.Am.	April 1966
12.	Spectral Analysis of Short-Period First Arrivals of the 13 April 1963 Peru Earthquake, by G. Leblanc and B. F. Howell,Jr.	Verbal before Seis.Soc.Am.	April 1966
13.	Lake Superior Seismic Experiment: Frequency Spectra and Absorption, by B. F. Howell, Jr. (Abstract: Trans. A.G.U. 47:163)	Verbal before Am.Geophys. Union	April 1966
14.	Simple Digitizer for Paper Seismograms, by B. F. Howell, Jr., (Reprint, Bull. Seis. Soc. Am. 56:605-608)	Scientific Report Nr. 3	June 1966
15.	Spectral Analysis of Short-Period First Arrivals of the 13 April 1963 Peruvian Earthquake, by G. Leblanc	Technical Report Nr. 4	Oct. 1966

Table I. - continued

16.	Frequency Spectra Studies for a Model with an Irregular Boundary, by T. G. Baybrook and B. F. Howell, Jr.	Verbal before Seis.Soc.Am.	Oct. 1966	
17.	Scale-Model Study of Refraction Arrivals in a Three-Layered Structure, by B. F. Howell, Jr. and D. E. Siskind	Verbal before Seis.Soc.Am.	Oct. 1966	
18.	Method for Recognizing Repeated Pulse Sequences in a Seismogram, by B. F. Howell, Jr., P. M. Lavin, R. J. Watson, Y. Y. Cheng, and J. L. Lin	Verbal before Seis.Soc.Am.	Oct. 1966	
19.	A Study of the Watson-Merdler Method for Focal-Depth Determination of Seismic Disturbances from Underground Nuclear Explosions, by J. L. Lin	Technical Report Nr. 5	Oct. 1966	
20.	Study of Modified Estimation Procedure for Focal-Depth Determination of the 10 May 1963 Ecuador Earthquake, by Y. Y. Cheng	Technical Report Nr. 6	Oct. 1966	
21.	Seismic Model Study of Refraction Arrivals in a Three-Layered Structure, by D. E. Siskind	Technical Report Nr. 7	Oct. 1966	
22.	Procedure for Estimating Seismic Focal Depth, by R. J. Watson	Verbal before VESIAC Conference and to be published		In press VESIAC Conference report
23.	Lake Superior Seismic Experiment: Frequency Spectra and Absorption, by B. F. Howell, Jr.	Being published		In press Am. Geophysical Union Monograph 10

Table I. - continued

24.	Lake Superior Seismic Experiment: Absorption Using Smoothed Frequency Spectra, by B. F. Howell, Jr.	Scientific Report Nr. 4	Cancelled
25.	Scale-Model Study of Refraction Along an Irregular Interface, by B. F. Howell, Jr. and T. G. Baybrook	Scientific Report Nr. 5	Submitted to Bull.Seis.Soc. Am. for publication in 1967
26.	Scale-Model Study of Refraction Arrivals in a Three-Layered Structure, by D. E. Siskind and B. F. Howell, Jr.	Scientific Report Nr. 6	Submitted to Bull.Seis.Soc. Am. for publication in 1967
27.	Method for Recognizing Repeated Pulse Sequences in a Seismogram, by B. F. Howell, Jr., P. M. Lavin, R. J. Watson, Y. Y. Cheng, and J. L. Lin	Scientific Report Nr. 7	Submitted to Bull.Seis.Soc. Am. for publication in 1967
28.	Truncated Crustal Transfer Functions and Fine Crustal Structure Determination, by G. Leblanc	To be published	Submitted to Bull. Seis.Soc.Am. for publication in 1967
29.	Sharpness of the Mohorovicic Discontinuity, by B. F. Howell, Jr.	Verbal before Geol.Soc.Am.	Nov. 1966
30.	Spectral Study of Short-Period P-waves, by G. Leblanc and B. F. Howell, Jr.	to be published	To be submitted to Canadian Jour. of Geophysics for publication in 1967
31.	Final Report for Contract AF19(628)-238	Final	Jan. 1967

Table II

Comparison of four different methods of recognizing ghosts in seismograms of the 10 May 1963 Ecuador Earthquake (Cheng's (1966) tests are for $2.5 \leq \Delta t \leq 14$ sec., all others are for $1.0 \leq \Delta t \leq 14$ sec.) Strongest indication is marked with an asterisk in each case. RS means easily recognized simplifcation; SS means some simplification; NS means simplification not recognizable above the noise level.

Recording Station	Cheng's time delays in sec		Time delay by deghost program in secs		Strongest cross correlations in secs		Peaks in search program in secs	
	Time	rating	Time	Strength	Time	Strength	Time	Strength
CGM			*1.0	1.47				
			2.1	1.28			1.95	0.8
	*3.9	SS						
			4.5	1.41	4.9	0.48	4.7	0.5
	5.6	SS					5.75	0.6
	7.9	NS	7.7	1.15	7.7	0.49		
					*11.1	0.56	*11.2	1.0
							12.5	0.5
SCP					1.2	0.67	*1.2	1.0
			*2.2	1.64			2.4	0.9
	*4.9	SS	4.9	1.30	*4.9	0.72	5.0	0.8
			9.5	1.19				
AAM					*1.3	0.7		
							*1.6	1.0
			*4.6	1.05				
					4.9	0.67	4.95	0.7
	*5.6	SS						

Table II - continued

MHT			1.5	1.08	1.7	0.49	*1.8	1.1
			2.8	1.09				
	*4.5	SS			3.6	0.50	3.65	0.5
	4.8	SS	*4.7	1.26	4.7	0.54	4.7	0.7
					5.7	0.46		
							6.85	0.5
			7.7	1.14	7.7	0.56		
	8.8	NS	8.8	1.17	8.8	0.55		
	9.8	SS	9.8	1.08				
			11.0	1.02				
	12.0	NS	12.0	1.03			12.05	0.5
					*14.0	0.59		
LDN			2.3	1.17			*2.1	0.8
	3.8	NS						
	*4.3	SS						
	4.8	SS	*4.8	1.40	*4.8	0.68	*4.7	0.8
	6.5	NS						
	6.9	NS						
	7.8	NS						
	8.3	NS					8.4	0.5
			9.5	1.08	9.6	0.61	9.7	0.8
	11.3	SS			11.1	0.48	11.05	0.5
							12.3	0.7

Table II - continued

VIC			*1.8	1.80	*1.8	0.56	1.8	-1.2
			2.6	1.47				
			3.8	1.16				
	*5.0	SS	5.0	1.18				
			6.0	1.04				
			6.4	1.11				
			8.7	1.03				
			9.7	1.05	9.8	0.47	9.8	0.6
	10.8	SS	10.8	1.02	10.8	0.47	10.8	0.5
			13.0	1.03			13.0	0.5
PHC			1.7	1.23	1.7	0.51	*1.8	0.8
	*3.9	SS						
	4.3	NS						
			5.2	1.04				
	6.4	NS	6.35	1.09				
			7.55	1.13	7.6	0.51		
	8.2	NS						
	8.8	SS	*8.6	1.33	8.6	0.52	8.65	0.5
	9.9	NS	9.8	1.23	*9.8	0.62	9.8	0.6
			10.8	1.12	10.8	0.56		
					11.9	0.58	11.9	0.7

Table II - continued

CMC					2.7	0.47		
			3.5	1.07			*3.7	1.3
			*4.5	1.35	4.5	0.67	4.5	0.9
					5.6	0.46		
					6.6	0.76	6.6	0.8
			7.6	1.30	*7.6	0.97	7.65	1.0
			9.9	1.06			9.85	0.5
PTO	2.8	NS	2.1	1.09				
	3.1	NS						
	*4.1	RS	*4.1	1.24	4.1	0.57	*4.1	0.7
	4.6	NS						
	5.1	NS	5.4	1.08				
			8.0	1.002	*7.9	0.60	*8.0	0.7
	9.2	NS						
	10.1	NS						
	10.4	SS	10.5	1.06				
	11.7	SS						

Table II - continued

RES			3.9	1.10			3.85	0.5
	*4.6	SS						
	5.8	SS	5.8	1.17				
	6.9	NS	6.8	1.05			6.8	0.5
			7.8	1.20	7.9	0.58	7.85	0.6
			9.0	1.06	8.9	0.46		
	9.0	NS						
	*10.0	SS	*10.0	1.34	*10.0	0.69	9.9	0.7
			12.5	1.10				
			13.4	1.15	13.4	0.64	*13.3	0.8
MBC					1.6	0.61		
					2.2	0.58	2.25	0.6
	2.7	NS			2.9	0.67	2.9	0.8
	*3.6	SS	3.7	1.10	3.7	0.71	3.7	0.6
	*4.3	SS					4.4	0.8
	4.6	NS	*4.6	1.24	4.5	0.50		
	4.9	NS						
	5.6	NS	5.9	1.05				
	6.3	NS	6.7	1.07	6.6	0.48	6.6	0.7
	7.0	NS						
			7.8	1.17	*7.9	0.83	7.8	0.9
	8.8	NS	8.5	1.06	8.6	0.60	8.6	0.5
					11.8	0.48	11.8	0.5

Table II - continued

ALE					*2.1	0.60	*2.1	1.5
			3.7	1.01				
			*4.4	1.08				
	*8.5	SS						
	9.8	NS						
	10.1	NS						
	11.5	SS	11.5	1.02				
	12.2	NS					*13.9	0.5
STU			*2.2	1.22	2.3	.6	*2.3	*0.9
			3.5	1.15			3.1	0.5
	*4.1	RS	4.3	1.16	4.2	0.69	4.2	0.6
			*5.4	1.22				
	5.8	NS			6.1	0.53	6.2	0.8
			7.0	1.08	7.0	0.54	7.1	0.5
					*8.1	0.73	8.05	0.7
			10.3	1.03			9.8	0.5
							11.8	0.6

Table II - continued

							*1.0	0.8
WIN								
					*1.2	0.75	*1.3	0.8
			*1.8	1.69				
	2.9	NS						
			4.1	1.09	4.1	0.748	*4.05	0.8
	*4.4	SS	4.6	1.13				
			6.8	1.04	7.4	0.56	7.3	0.6
	*9.3	SS			9.2	0.46	9.1	0.5
							13.8	0.5

Table III

Comparison of ghosts picked as most prominent by the four systems tried for fourteen nuclear blasts. Strongest indication is marked with an asterisk in each case. Strength of the corresponding indication by the other methods is shown if there is a corresponding indication.

Event and recording station	Watson-Merdler		Deghost	Program	Search	Program	Cross-Correlate	
	delay (secs)	strength	delay (secs)	strength	delay (secs)	strength	delay (secs)	strength
Bilby-LZBV	--		--		*4.6	-0.5	*4.75	-0.495
	--		--		*7.35	-0.5	7.35	-0.490
	--		*12.35	1.02	--		--	
Bilby-OONY	1.0	1.26	1.0	1.44	*1.1	-0.9	--	
	*2.2	1.27	*2.15	2.25	2.23	-0.8	*2.15	-0.490
Bilby-SBGR	--	--	*1.0	1.43	*1.0	-0.6	*1.0	-0.524
	*2.1	1.14	2.1	1.20	--		--	
	*12.5	1.14	12.6	1.07	--		--	
Bilby-HWIS	*1.6	1.19	*1.45	1.15	--		--	
	5.0	1.06	--		*4.9	-0.5	--	
	5.8	1.06	--		*5.8	-0.5	--	
Bilby-CPO	*1.0	1.27	*1.05	1.38	--		--	
	--		2.3	1.33	*2.2	-0.7	--	
Bilby-EKA	--		*1.3	1.77	*1.2	-0.9	1.3	-0.724
	*2.3	1.3	*2.25	1.77	2.15	-0.8	*2.25	-0.742

Table III - continued

Bilby-PZPR	1.0	1.06	*1.0	1.56	*1.0	-0.8	--	
	*4.0	1.21	4.0	1.14	4.05	-0.4	--	
	6.8	1.14	6.75	1.31	6.73	-0.5	*6.65	-0.46
Bilby-EWIS	--		*2.45	2.23	--		--	
	--		5.25	1.36	*5.25	-1.0	*5.2	-0.855
	*5.6	2.87	--		--		--	
Bilby-NPNT	--		*1.0	1.35	*1.1	-0.9	--	
	--		2.15	1.14	2.15	-0.3	*2.05	-0.337
Shoal-LZBV	1.7	1.26	--		1.95	-0.5	*1.95	-0.579
	2.7	1.38	*2.55	1.57	*2.7	-0.8	2.75	-0.457
	*8.9	1.62	--		9.05	-0.3	--	
Shoal-DHNY	*1.6	1.50	*1.45	1.09	1.55	-0.4	--	
	--		--		*3.6	-0.6	*3.55	-0.421
Shoal-NPNT	--		--		--		--	
Salmon-NPNT	*1.3	1.89	1.25	1.15	--		--	
	2.7	1.30	*2.75	1.53	2.78	-0.4	--	
	7.7	1.35	7.7	1.40	*7.7	-0.5	*7.65	-0.47
Mississippi at HNME	*3.0	1.92	3.2	1.13	*3.15	-0.5	3.15	-0.401
	4.2	1.54	*4.4	1.58	*4.43	-0.5	*4.35	-0.580

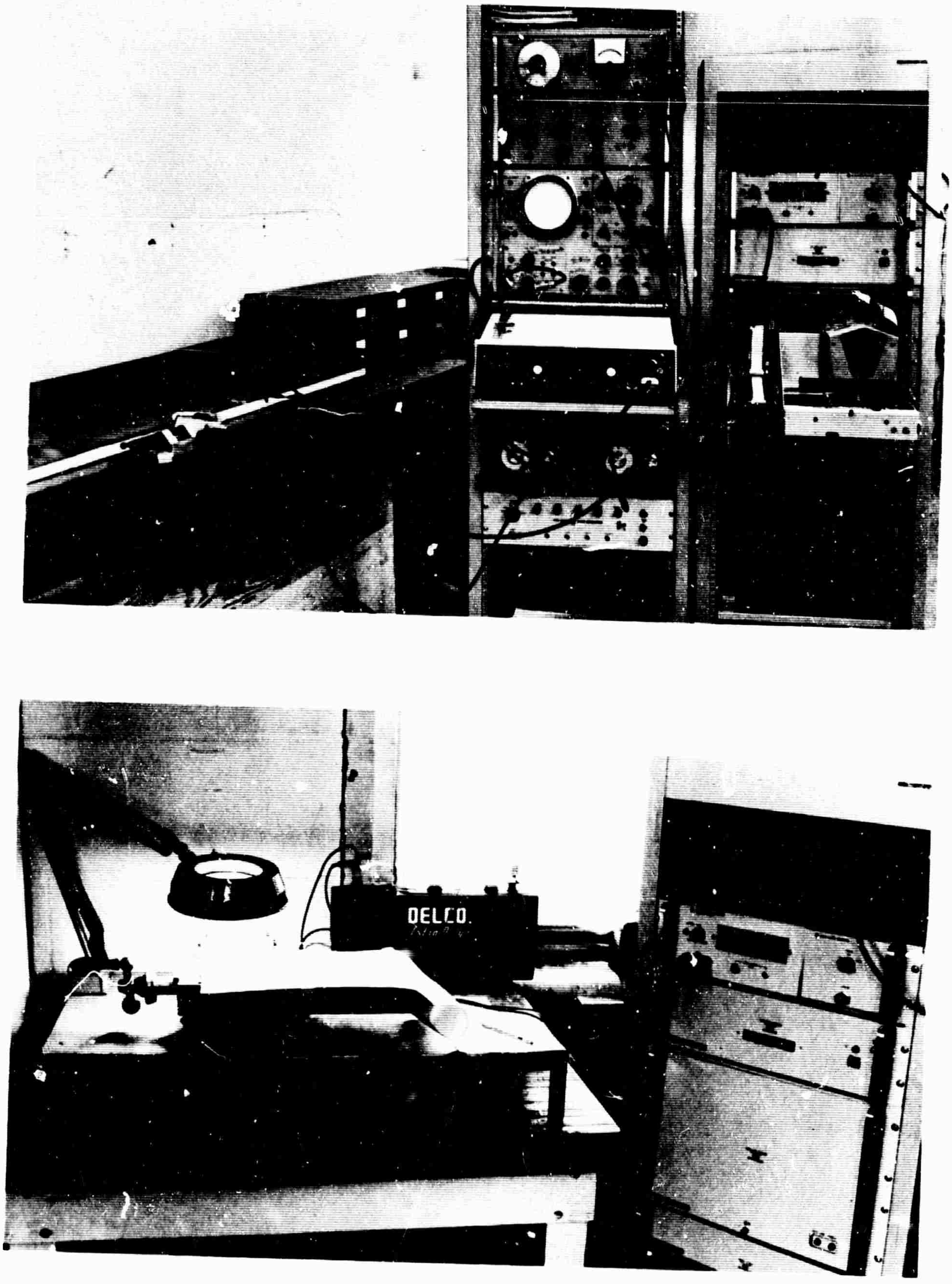

Fig. 1. Two parts of the scale-model laboratory facilities. Upper view: a model in place ready for recording pulses. Lower view: apparatus for digitizing earthquake seismograms.

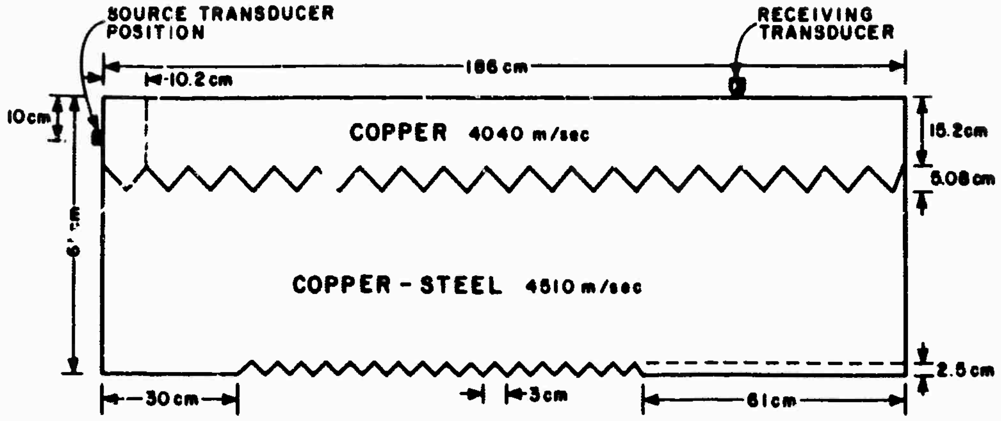

Fig. 2. Model used to investigate irregular Mohorovicic boundary.

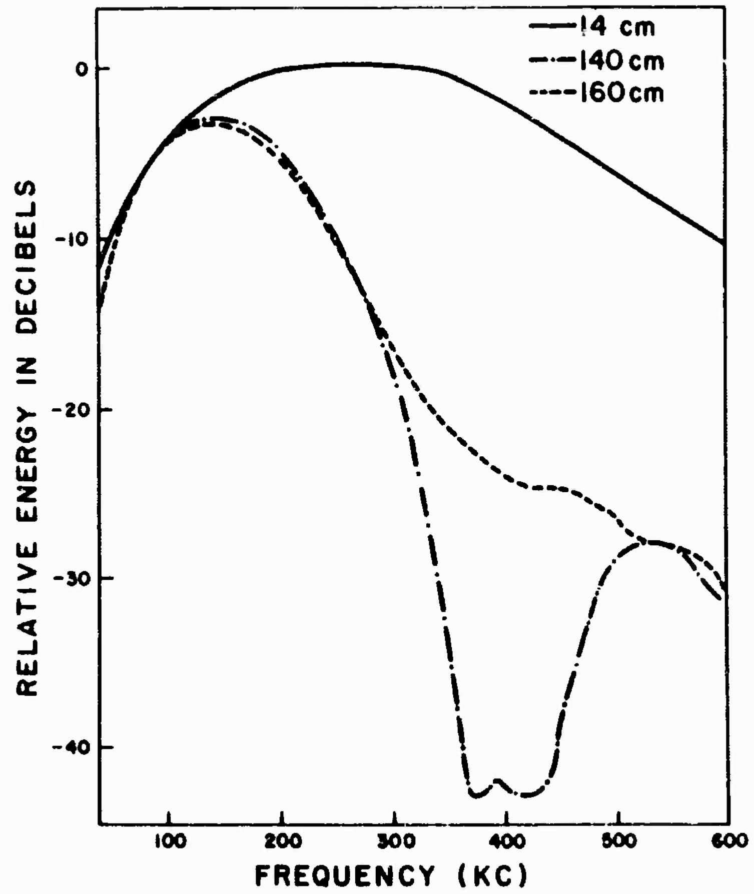

Fig. 3. Spectra of pulses critically refracted at two distances along irregular boundary compared to spectrum of same pulse before refraction (at 14 cm).

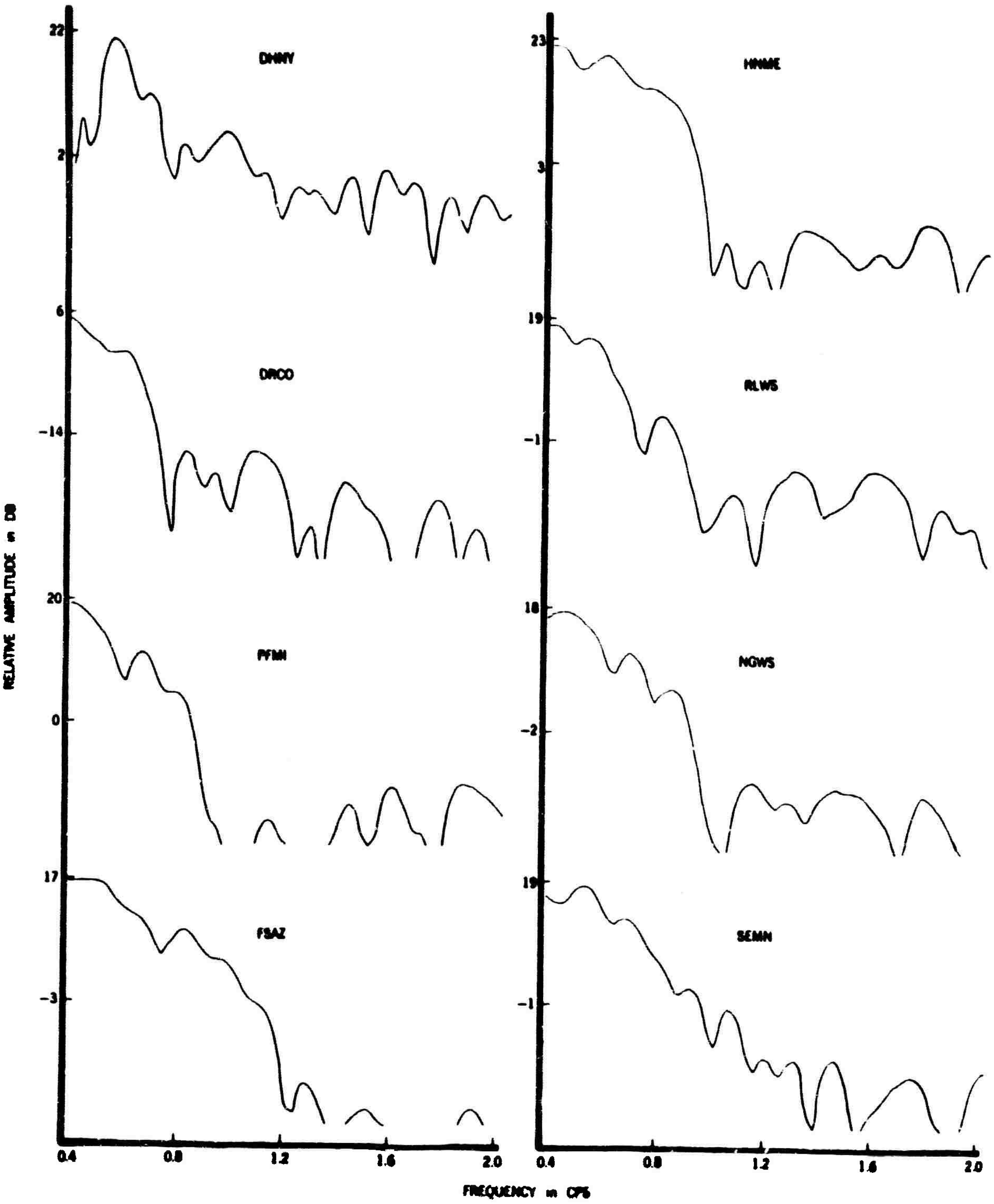

Fig. 4. Spectra of the 13 April 1963 Peru earthquake recorded at 8 different stations.

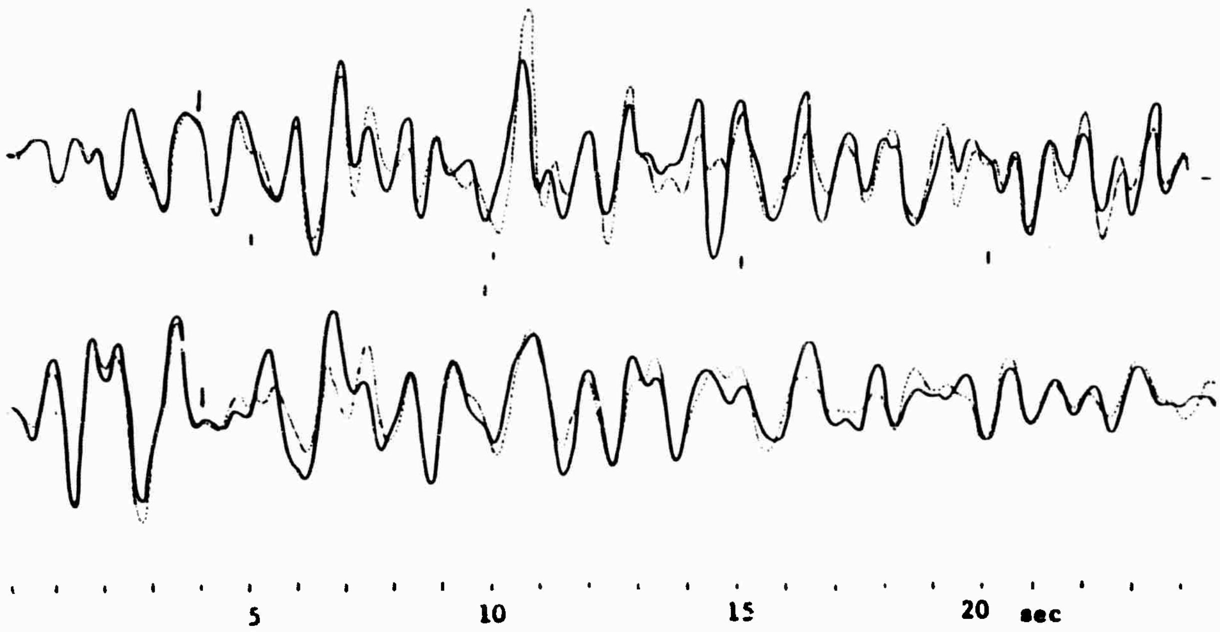

Fig. 5. Original S(t) (solid line) and deconvolved P(t) (dashed line) earthquake seismograms which show simplification of P(t) as compared to S(t). Ecuador Earthquake of 10 May 1963.

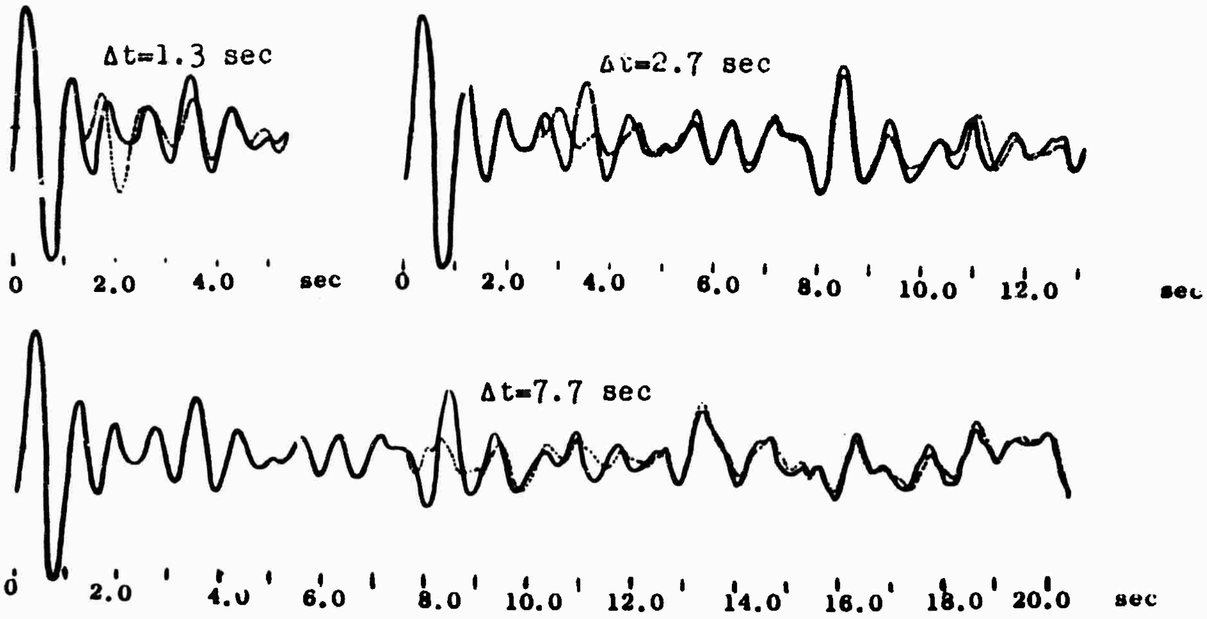

Fig. 6. Original S(t) (solid line) and deconvolved P(t) (dashed line) blast seismograms which show pulse removal by inverse filtering. Salmon blast at Mould bay, Canada.

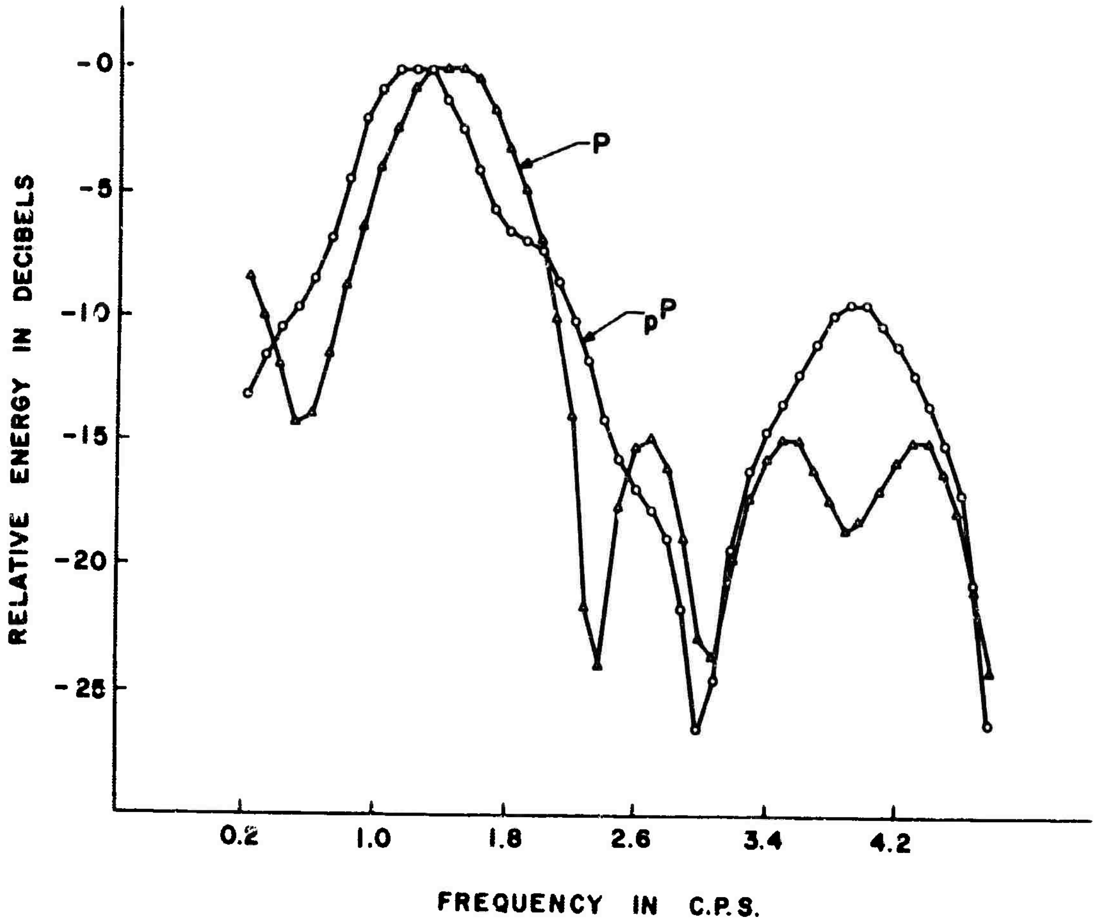

Fig. 8. Spectra of P and pP of the 11 Jan. 1965 Alaska earthquake.

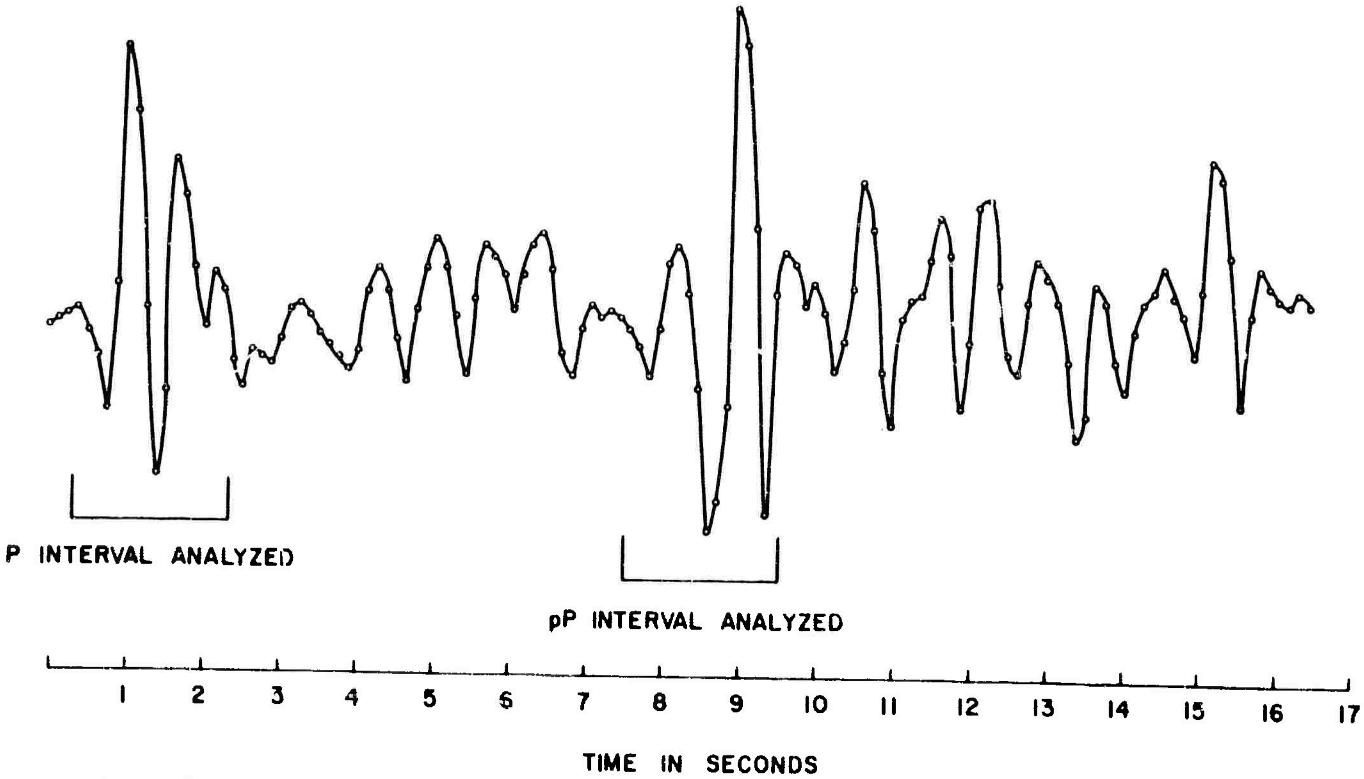

Fig. 7. Initial portion of the seismogram of the 11 Jan. 1965 Alaska earthquake.

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13. ABSTRACT

This report summarizes the conclusions reached in thirty other reports issued in connection with this contract, and lists the individual reports which detail how each of the objectives of the contract was reached.

The principal method used in an attempt to measure depth-of-focus of shallow events is the Watson-Merdler inverse-filtering technique. It is shown that a simplified version of this method which neglects noise also finds ghosts in a seismogram, as does cross-correlation. The three methods frequently but not always find the same ghosts.

Two important factors which make it difficult for all three methods to find ghosts are that short-period seismometers do not record the main part of the energy in most seismic pulses and the ghosts commonly differ greatly from their primaries in waveform and frequency spectrum.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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DEPTH-OF-FOCUS						
FOCAL DEPTH						
NUCLEAR BLASTS						
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