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RADIATION OF SEISMIC WAVES FROM THE BILBY EXPLOSION

17 May 1967

Prepared For

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RADIATION OF SEISMIC WAVES

FROM THE BILBY EXPLOSION

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ABSTRACT

The seismic surface wave and P-wave data generated by the Bilby explosion and the associated cavity collapse are studied comparatively to determine the radiation patterns of these waves. The asymmetric radiation patterns of P and Rayleigh waves as well as the presence of Love waves are explained in terms of a composite source. This consists of an isotropic dilatational component due to the explosion and a double-couple component due to tectonic effects. The relative strength of the multipolar component is 0.47 times that of the explosion. The source time functions of Rayleigh and Love waves from the Bilby are determined. For Rayleigh waves this is a pulse of the form $p(t)=\underline{t}\ \exp(-1.5\underline{t})$. For Love waves the source time function may be a step function with a slow rise time.

I. INTRODUCTION

The underground nuclear explosion Bilby was detonated in the Nevada Test site on 13 September 1963 at 17:00:00 UT. The shot was at a depth of 2314 ft. below the surface and the coordinates of the epicenter were 37° 03' 38" N and 116° 01' 18" W. The geologic medium at the shot was tuff. The assigned magnitude of the event was m = 5.8.

Bilby generated seismic waves which were recorded well at most of the North American stations and especially at the LRSM stations. Furthermore, it was followed by the cavity collapse (assigned magnitude = 4.5) at 17:31: (20.5) U T. The presence of this collapse, the relatively large size of the explosion, radiation of both Rayleigh and Love waves, and the proximity of the site to those of other well-recorded explosions such as Haymaker and Sedan have made Bilby ideally suited for the study to determine the mechanism of generation of seismic waves and the radiation pattern.

In this study we follow a procedure of analysis similar to that used in the earlier studies (Toksöz, et al., 1964, and 1965). To minimize the effects of the propagation we determine radiation patterns of the P-waves and Rayleigh waves of Bilby relative to those of the collapse. Then we use the ratios of the Love and Rayleigh wave amplitudes to determine a source mechanism which is consistent with the Rayleigh wave radiation pattern. The source time function is determined from the amplitude spectra corrected for propagation and instrument effects. Finally, we compare the Bilby results with those of other explosions.

II. RADIATION PATTERNS OF SURFACE AND BODY WAVES

The nuclear explosion Bilby generated Love waves which were recorded well at a number of the LRSM stations shown in Figure 1. Since the long-period horizontal instruments are generally oriented in a radial and transverse direction relative to the explosion site, the Love waves can be identified and separated without much difficulty. Furthermore, for the continental paths, the Love wave group velocities are generally higher than those of Rayleigh waves in the period range of 10 - 40 sec. This also facilitates the study of the Love and Rayleigh waves.

The generation of these transverse waves by Bilby suggests a source mechanism which was more complicated than a theoretical explosive source. The possible sources of the Love waves generated by explosions were discussed in earlier papers (Toksöz, 1966). There is strong evidence that the Love waves are the results of radiation of some tectonic strain energy either because of the explosion-formed cavity or the explosion-induced directional cracking or faulting. (See Press and Archambeau, 1962; Archambeau, 1964; Toksöz, et al., 1965; and Toksöz, 1966, for details). Then, the source must be treated as a combination of a radially symmetric explosion and a multipolar source of tectonic strain release.

A. Absolute Amplitudes

The recorded amplitudes of body and surface waves can be corrected for the seismograph response and the ground displacements can be determined. Under ideal conditions these can be interpreted in terms of the source properties after corrections for the geometric spreading and attenuation. In practice, however, the geologic conditions are complicated and the idealized situation cannot be realized. First, the crustal layering between the source and the station does not remain perfectly uniform and horizontal. Second, the crustal structures under the stations affect the amplitudes, and these structures could vary significantly from one location to another.

With the full realization of these limitations, we made an attempt to test the possibility of determining the radiation pattern from the absolute amplitudes. Figure 2 shows the polar plot of the ground motion amplitudes of the Z component of Rayleigh waves. If the radiation pattern and the structures were uniform, one would expect circular amplitude contours falling off as $(2\pi r)^{\frac{1}{2}}$ away from the center. The figure indicates amplitude discrepancies along a single azimuth. These cannot be explained by the source properties and must be the results of the structures and ground coupling effects at the stations.

Another example of these structure effects are illustrated in Figure 3 where magnitudes (m) are plotted against the azimuth in a polar diagram. The data are from the Bilby shot report, (Teledyne, 1963). Again the scatter is such that no radiation properties can be determined. In the case of body waves, the mantle as well as the crustal structure plays a significant role in controlling the amplitudes. At epicentral distances corresponding to the depths of velocity discontinuities in the mantle, these effects are especially important since the amplitude is a strong function of the velocity gradient (dv/dr) at depth (Asbel, et al., 1966; Chinnery and Toksöz, 1966; Anderson, 1966). Our knowledge of the exact mantle structure along each path is very poor, and, at the present, we cannot hope to compute these effects to make the necessary corrections.

B. Relative Amplitudes of Rayleigh Waves.

Since the effectiveness of using the absolute amplitudes of seismic body and surface waves are limited by the crust and mantle structures, a method of normalization to minimize these effects is considered. Unfortunately, the source and the propagation factors cannot be isolated from each other. Thus, we must consider methods in which one of the variables is held constant while the effect of the other is investigated. In this work we used two methods for the study of relative amplitudes to determine the radiation pattern from Bilby. In the first, we normalized the amplitudes of the Rayleigh and P-waves generated by the explosion to those of the collapse event that followed. In the second we used the ratio of the Love and Rayleigh wave amplitudes to obtain a source function.

The collapse of the cavity (formed by the explosion) seems to provide an excellent reference for normalization. When the amplitude ratios of the explosion-and collapse-generated waves are taken, the propagation and instrument effects completely cancel out, and the ratio directly reflects the source effects. In previous studies, it was found that the radiation pattern from the post-explosion collapse was in general more symmetric. The uniform amplitudes as well as the absence of outstanding Love waves were the results of this radial symmetry (Toksöz, et al., 1965; Toksöz, 1966).

If we assume that this was the case for Bilby (i.e., that the Bilby collapse had a radially symmetric radiation pattern), then the explosion/collapse ratio should show whether the explosion was symmetric. The ratios of peak amplitudes of the Rayleigh waves are shown in Figure 4 as a function of azimuth. The peak amplitudes were directly read from the long-period records of the LRSM stations. In a few instances the spectral ratios were computed, and these in the average gave the same results as the peak amplitudes.

The azimuthal coverage in Figure 4 is far from being complete, but in the north and northeast directions where there is a sufficient number of observations, the deviation from a uniform ratio is clear. If we assume that the radial non-uniformity of the radiation pattern from the explosion was due to some form of tectonic complication (such as the relaxation of the medium due to the cavity or induced rupture- Press and Archambeau, 1962; Archambeau, 1964; Toksöz, et al, 1965) we can include this effect by superimposing a multipolar term to the explosive source. Both seismic model experiments and theoretical studies indicate that at large distances from the source, a double-couple type source function is a good representation for tectonic strain release (Honda, 1962)
Then the displacements observed at a distant station can be written as the vectorial sums of those due to an explosive source and to a double-couple.

Using the notation of Toksöz, et al., (1965), we can write the far-field expressions for the Rayleigh wave ground displacements from a near-surface explosive source.

$$
\begin{aligned}
W_e(\omega) &= \frac{C_1}{(2\pi r)^{1/2}}\, k_R^{1/2} \left(-\frac{\dot{u}_0^*}{\dot{w}_0}\right) A_R(\omega)\, T(\omega)\, \exp(-\gamma_R r)\, \exp[i(\omega t - k_R r - \varphi_t + 3\pi/4)] \\
U_e(\omega) &= \frac{C_1}{(2\pi r)^{1/2}}\, k_R^{1/2} \left(\frac{\dot{u}_0^*}{\dot{w}_0}\right) 2A_R(\omega)\, T(\omega)\, \exp(-\gamma_R r)\, \exp[i(\omega t - k_R r - \varphi_t\, 3\pi/4)] \qquad (1) \\
V_e(\omega) &= 0
\end{aligned}
$$

$W_e(w)$, $U_e(w)$, $V_e(w)$ are the vertical, radial and tangential components of the displacement, k_R is the wave number, r is the radial distance, γ_R is the Rayleigh wave attenuation coefficient. A_R is the medium response for Rayleigh waves due to a vertical force, u_o and w_o are the components of particle velocity at the surface. $T(\omega)$ and $\varphi_t(\omega)$ are the amplitude and the phase spectra of the source time function. The displacements due to an orthogonal, horizontal double-couple source are (Ben-Menahem and Harkrider 1964; Toksöz, et al., 1965):

$$W_{dc}(\omega) = \frac{C_2}{(2\pi r)^{1/2}} \left(\frac{u_0^*}{w_0}\right) A_R(\omega)\, T'(\omega)\, \sin 2\theta\, \exp(-\gamma_R r)\, \exp[i(\omega t - k_R r - \varphi_t' + 3\pi/4)]$$

$$U_{dc}(\omega) = \frac{C_2}{(2\pi r)^{1/2}} \left(\frac{u_0^*}{w_0}\right)^2 A_R(\omega)\, T'(\omega)\, \sin 2\theta\, \exp(-\gamma_R r)\, \exp[i(\omega t - k_R r - \varphi_t' - 3\pi/4)] \qquad (2)$$

$$V_{dc}(\omega) = \frac{C_2}{(2\pi r)^{1/2}} k_L^{1/2} A_L(\omega)\, T'(\omega)\, \cos 2\theta\, \exp(-\gamma_L r)\, \exp[i(\omega t - k_L r - \varphi_t' - 3\pi/4)]$$

The subscript R and L refer to Rayleigh and Love waves, respectively. The angle θ is measured counter-clockwise from the principal plane (i. e. fault plane) of the double-couple.

The far-field displacements of Rayleigh and Love waves from a composite source consisting of an explosion and a double-couple can be written from (1) and (2).

$$\begin{aligned} U_{Rz} &= W_e(\omega) + W_{dc}(\omega) \\ &= W_e(\omega)\left\{1 + F\,\frac{T'(\omega)}{T(\omega)}\,\sin 2\theta\,\exp[i(\delta\varphi_t)]\right\} \qquad (3) \\ U_L &= V_{dc}(\omega) \end{aligned}$$

F is the relative strength of the double-couple, $\delta\varphi_t = \varphi_t' - \varphi_t$ is the phase difference of two time functions. The term with the factor $\sin 2\theta$ gives the azimuthal dependence of the Rayleigh wave radiation.

If we assume that the source time functions are approximately

the same for an explosion and the tectonic strain release (i.e. T=T')
eg. (3) becomes

$$U_{Rz} = W_e\ (1 + F \sin 2\theta) \qquad (4)$$

$$U_L = V_{dc}$$

The motion from the collapse of the cavity can be represented by

$$\left(U_{Rz}\right)_{collapse} = C_3\ W_e\ \exp(i\varphi_c) \qquad (5)$$

where C_3 is the relative amplitude and φ_c is the phase of time function relative to the explosion. From previous studies of explosion and collapse pairs it was found that, for long periods, $\varphi_c \approx \pi$ (Brune and Pomeroy, 1963; Smith, 1963; Toksöz, et al, 1964). This result means essentially that the collapse can be considered an implosion when we are dealing with long period data. With the above formulations and assumptions, the theoretical Rayleigh wave displacement ratios for a given explosion-collapse pair can be written as

$$\frac{\left(U_R\right)_{explosion}}{\left(U_R\right)_{collapse}} = C'[1 + F \sin 2\theta] \qquad (6)$$

In Figure 4 the theoretical curve is computed using (6); choosing C', F, and the orientation of the double-couple to fit the data best, we find C' = 12, F = 0.47, and the reference direction for the double-couple principal plane (i.e.,"fault plane") $\theta = 340^{\circ}$. With these data the fit can be considered to be good. The above figures mean that the explosion-generated surface waves were 12 times larger than those of the collapse, and that the relative strength of the double-couple force was 0.47 times that of the explosion.

The P-wave radiation pattern should be similar to that of the Rayleigh waves. Unfortunately the P-wave data from the collapse are scarce, and the amplitudes not very reliable. The available data (amplitude ratios of explosion to collapse) are shown in Figure 5. It is obvious that the radiation pattern of Rayleigh waves shown in

Figure 4 does not fit the data: the amplitudes are too large, although the shapes of the two curves are similar. A new curve based on equation (6) is computed keeping all the parameters except C' the same. A value of C' = 4.8 seems to fit the P-wave radiation pattern. This implies that the amplitudes of Rayleigh waves relative to the P-waves was larger for the collapse than for the explosion. This can be explained using general observations about source functions. The peak of the source spectrum shifts to lower frequencies with increasing size of the event, whether it is an explosion or an earthquake, (Toksöz, et al., 1964). It has also been observed that in short-period recordings the collapse event seems to have a source spectrum shifted to lower frequencies compared to those of the explosions of equivalent size (Smith, 1963). However, the size effect seems to dominate in this case, and the collapse appears to be richer in high frequencies. When we take collapse/explosion source spectral ratios over a wide frequency range, we would expect a frequency dependence unless the sizes are comparable. This frequency dependence does not affect our assumptions and calculations when we are limited to a narrow frequency band.

C. Amplitude Ratios of the Love and Rayleigh Waves

The Love waves generated by the explosions can also be used to determine the nature of the source mechanism. According to our formulation, the Love waves will be due to the contribution of the tectonic component of the source. The explosion itself will not generate Love waves under ideal conditions.

In determining the radiation pattern, we will again use a normalization scheme to minimize the effects of propagation and recording uncertainities. Since we do not have a pure Love wave source that can be used as a reference, we will normalize to Rayleigh waves. This scheme was successfully applied to explosions and earthquakes by Toksöz, et al. (1965).

The ratio of the Love wave amplitude to the Z component of the Rayleigh waves generated by the explosion can be written using equations (1), (2), (3), and (4).

$$\frac{|U_L|}{|U_{Rz}|} = \frac{F\, k_L^{1/2}\, A_L \cos 2\theta}{(1 + F \sin 2\theta)\, k_R^{1/2}\, A_R\, (\dot{u}_0^*/\dot{w}_0)} \exp[-r(\gamma_L - \gamma_R)] \tag{7}$$

In writing (7) it was assumed that the source time functions T(w) and T'(w) were the same for both the explosion and the double-couple component. Furthermore, as in the previous section, it is assumed that the tectonic contribution can be represented as a double-couple. Thus the Love waves are those generated by a double-couple, and the Rayleigh waves are the vectorial sum of those due to the explosion and due to the double-couple.

In using (7) we must compute k_L, A_L, k_R, A_R, $\left(\dot{u}_o^*/\dot{w}_o\right)$, γ_L, γ_R. These quantities are functions of the frequency for a given structure. Fortunately, $k_L^{1/2}\, A_L/k_R^{1/2}\, A_R$ is nearly unity for the frequency range of our interest. Thus the effect of the structure is minimized by the normalization process, and an imprecise knowledge of structure does not limit the applicability of the method. We took one average structure for the Western United States given by Alexander (1963) and computed the amplitude response for the Rayleigh (A_R) and the Love (A_L) waves. The method and programs of Harkrider (1964) were used in these computations. The results are shown in Figures 6 and 7. k_L, k_R, and $\left(\dot{u}_o^*/\dot{w}_o\right)$ are parameters which are computed by all standard dispersion programs.

In computing the Love/Rayleigh amplitude ratios from the long period recordings on the LRSM stations we used the peak amplitudes. In cases where spectra were computed, they peaked at about T = 18 seconds, and the ratio was nearly constant in the period range of 10 to 30 seconds. These spectral ratios are shown in Figure 8 for four stations, together with the ratio of peak amplitudes. In the average the agreement is good enough to justify the use of peak amplitudes.

All the available U_L/U_{Rz} data from Bilby are shown in Figure 9, as well as the theoretical curve based on equation (7). The reference plane for double-couple orientation (plane of $\theta_o = 340^o$) and the relative strength F = 0.47 are the same values that were determined from the explosion/collapse Rayleigh wave ratios. The agreement between the observed and the theoretical can be considered good.

The consistency of one single source model for both the Rayleigh and the Love wave radiation patterns is encouraging. Although this is not a definite proof, it gives support to our method of synthesizing the source and to our assumptions.

III. SOURCE TIME FUNCTION OF BILBY

The source time function of the explosion can be determined from the recordings of the motion at distant stations by correcting for the instrument response and the response of the propagation medium. For surface waves, we can compute both amplitude (including attenuation) and phase response if the structure is known. In this study we will use an average structure and use only the amplitude spectra, since the accuracy of phase spectra depends very strongly on exact knowledge of the structure.

The Rayleigh waves recorded at three stations are first corrected for the instrument response to obtain the true ground displacement. These stations are Kanab, Utah, Campo, California, and Winnemucca, Nevada; they represent excellent azimuthal coverage at fairly close distances. The filtered Rayleigh wave pulses from two of these are shown in Figure 10 and their Fourier amplitude spectra in Figure 11. Ground displacement spectra (Figure 12) are obtained by correcting the spectra of Figure 11 for the instrument response at each station. They represent the product of the source amplitude spectrum and the response of the layered medium (i.e. propagation path) to Rayleigh waves. The medium response includes the attenuation effect and the source depth.

To determine the source function we must correct the ground displacement for the propagation factor. This was done using the impulse response of the medium (Figure 5) as shown in equation 1.

The effect of attenuation was removed using $\gamma_R = \pi f/UQ$ where U is the group velocity and Q was assumed to be 100, independent of frequency. The corrected spectra are shown in Figure 13. They represent the spectrum of the source pressure function.

The interpretation of amplitude spectra in terms of a time function cannot be done unless we can incorporate either the phase information or some other constraint. We will assume that the pressure pulse has the form $p(t) = P_o\, t \exp(-\eta t)$. This formulation was discussed in an earlier study (Toksöz, et al., 1964). The whole problem now consists of determining parameter η from the spectra. A value of $\eta = 1.5$ seems to agree well with the observations as shown in Figure 13. The corresponding time function is given in Figure 14.

We must note here that the p(t) we determined represents the stress wave form not at the source but some distance from the point of detonation. Since we used a linear theory based on infinitesimal strains to correct for propagation and attenuation effects, our corrections are valid only to the boundary of the region where these conditions are met. This may be at a distance of several hundred or a few thousand meters from the source point. We must clarify one other aspect of Figure 10: the pressure pulse was based on data in the period range of 10 to 40 seconds, so we could not see any of the fine features of the pulse that would be observable primarily in the high frequency components.

It would be of interest to determine the source function of the Love waves generated by Bilby. Choosing four stations where Love waves are well separated from the Rayleigh wave interference, we followed the same procedure as for Rayleigh waves for correcting the spectra for the instrument response, and the response of the layered medium for an orthogonal double-couple source. The resultant spectra of source time function are shown in Figure 15, and their shapes are consistent for all four stations.

From the comparison of Figures 13 and 15 it is obvious that source time function of the explosion-generated Rayleigh waves and the Love waves are quite different. The Love waves seem to be richer in low frequency components. From the available data in a relatively narrow frequency band we cannot determine the time function. It appears to be between a step function and a ramp. For the former, the spectrum would be a linearly increasing function of the period, and for the latter it would increase as T^2. A step function with a slow rise time may be adopted. The source spectra of the Rayleigh and Love waves generated by explosions are important because they contain the information about the mechanism of the Love wave generation. The differences demonstrated above are significant. They indicate that the explosion may trigger the Love wave radiation, but it does not control its time history.

IV. CONCLUSIONS

In this study we determined the source properties of the Bilby explosion from the radiation pattern of seismic waves. We followed the same procedures that were used in our earlier studies of the Hardhat, Haymaker, Sedan and Shoal explosions. Here we will compare the Bilby results with some of the earlier results.

The most significant result is that Bilby, like the Haymaker and Shoal explosions, generated some Love waves. The source mechanism in all cases can be explained in terms of an ideal explosive source superimposed over a tectonic source of double-couple form. The orientation and relative strength of the double-couple seem to be controlled by the properties of the medium and the orientation of the tectonic axes. Bilby (in tuff) and Haymaker (in alluvium) were located about 5 km apart. The radiation patterns of Rayleigh waves are almost identical. In both cases the principal plane of the double-couple is oriented in the direction $\theta = 340^{\circ}$. For the Shoal explosion, which was fired in a completely different area, the orientation of the double-couple was in very good agreement with those of earthquakes in the area (Toksöz, et al., 1965). These facts suggest that multipolar contributions to the radiation patterns are controlled by the general tectonic features ov the region.

The relative strength of the tectonic (double-couple) contribution to the radiation pattern seems to be controlled by the properties of the medium in which the explosion is detonated. This can be justified by the fact that for explosions in salt domes (Gnome and Salmon) and loose alluvium (Sedan) the source functions did not have multipolar components (i.e., F = 0). For Shoal, which was buried deep in alluvium, a value F = 0.33 was determined. For Bilby (in tuff) F was 0.47, and for Haymaker, which was fired in granite, F was equal to 0.9. These indicate an increase of F with increasing rigidity and shear strain energy capacity of the medium. From these examples we may be able to conclude that the multipolar component of the seismic energy radiation is due to release of some of the strain energy accumulated in the medium. This may be due to the relaxation because of the cavity formation, and/or the cracks formed in the medium.

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FIGURE CAPTIONS

Fig. 1. Distribution of the LRSM stations which received Bilby signals.

Fig. 2. Observed ground motion amplitudes (mμ/sec) of the vertical component of Bilby Rayleigh waves as a function of azimuth and distance from the source.

Fig. 3. Polar plot of the Bilby magnitudes as determined at vatious stations (Radial scale is magnitude m).

Fig. 4. The radiation pattern of normalized Rayleigh waves for Bilby. The points are the ratio of the amplitudes of explosion-generated to collapse-generated Rayleigh waves. The curve is the theoretical radiation pattern for a composite source consisting of an explosion and an orthogonal double-couple.

Fig. 5. The radiation pattern of P waves from Bilby. Points are normalized amplitudes (ratio of explosion to collapse). Theoretical curve is the radiation pattern of a composite (explosive plus double-couple) source. Outer curve is same as that of Fig. 4, included for comparison.

Fig. 6. Rayleigh wave amplitude response of the layered medium to an explosive source near the surface, with impulsive time function.

Fig. 7. Love wave amplitude response of the medium to a double-couple source near the surface.

Fig. 8. Love wave to Rayleigh wave vertical component Fourier amplitude spectral ratio at four stations. Dashed lines are the ratios of peak amplitudes measured in time domain.

Fig. 9. Amplitude ratios of the explosion-generated Love and Rayleigh waves U_1/U_{rz}). The theoretical curve is for the composite source described in Fig. 4.

Fig. 10. Rayleigh wave pulses at two stations plotted from digitized data.

Fig. 11. Fourier amplitudes spectra of the pulses shown in Fig. 10.

Fig. 12. Ground displacement spectra obtained from those of Fig. 10 after correction for instrument response.

Fig. 13. Amplitude spectra of source time function after correction for propagation effects. Circles indicate data uncorrected for attenuation; triangles indicate the data corrected taking Q=100.

Fig. 14. The Bilby pressure function at the boundary of the linear zone.

Fig. 15. Amplitude spectra of source time function for Love waves after correction for propagation effects. Circles are uncorrected; triangles are corrected for attenuation.

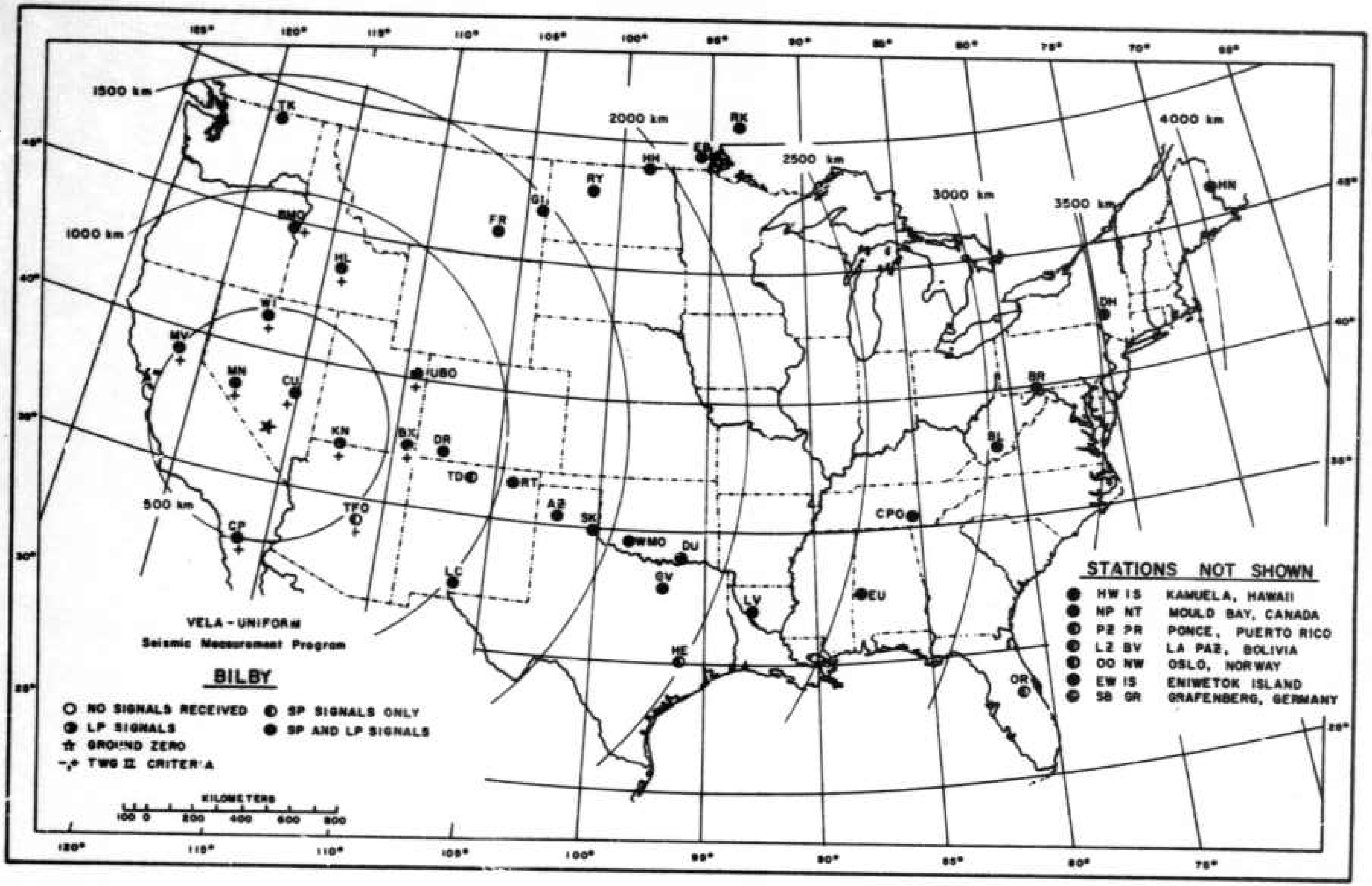

Figure 1. Distribution of the LRSM stations which received Bilby signals.

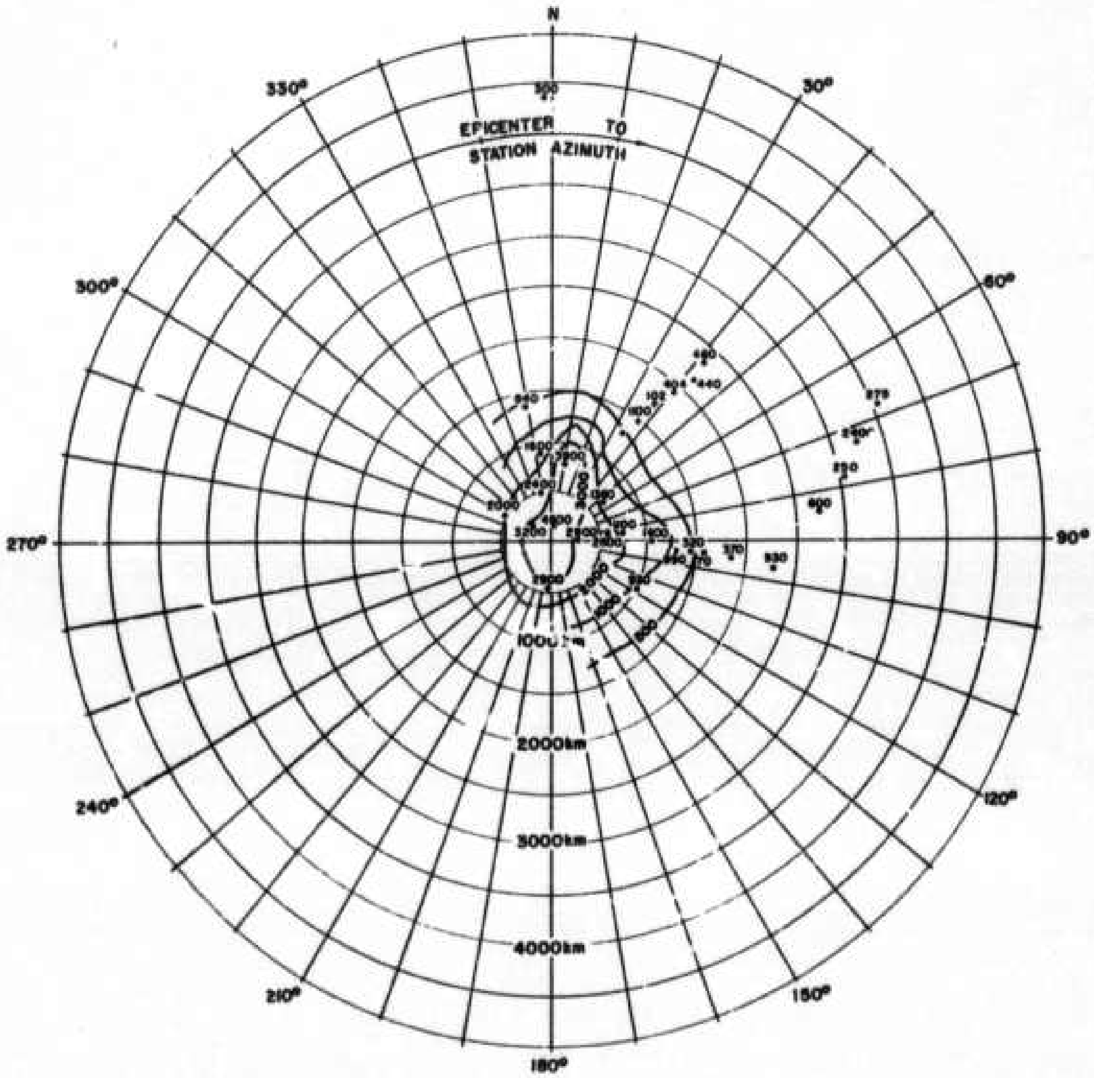

Figure 2. Observed ground motion amplitudes (mμ/sec) of the vertical component of Bilby Rayleigh waves as a function of azimuth and distance from the source.

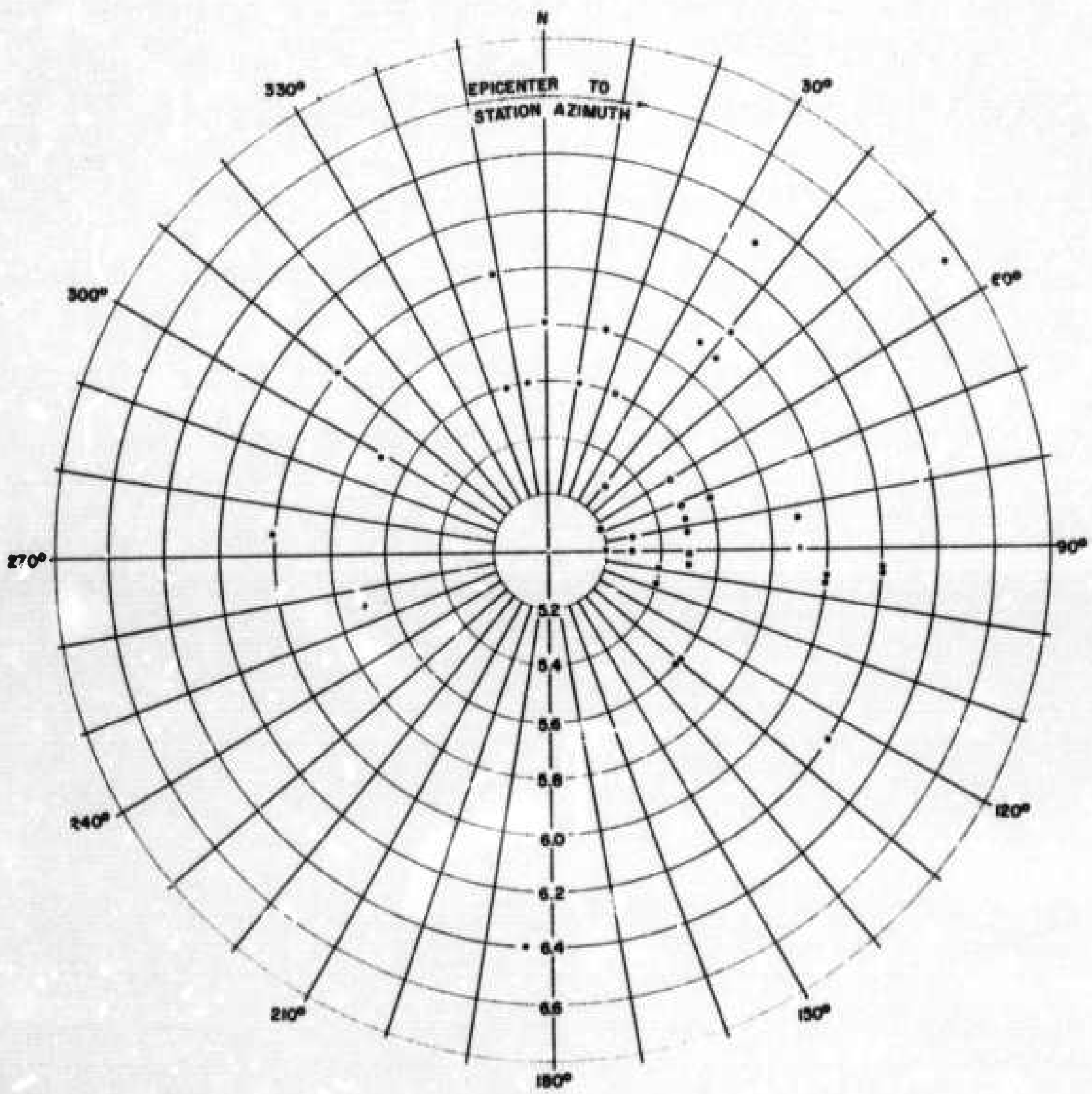

Figure 3. Polar plot of the Bilby magnitudes as determined at various stations (Radial scale is magnitude m).

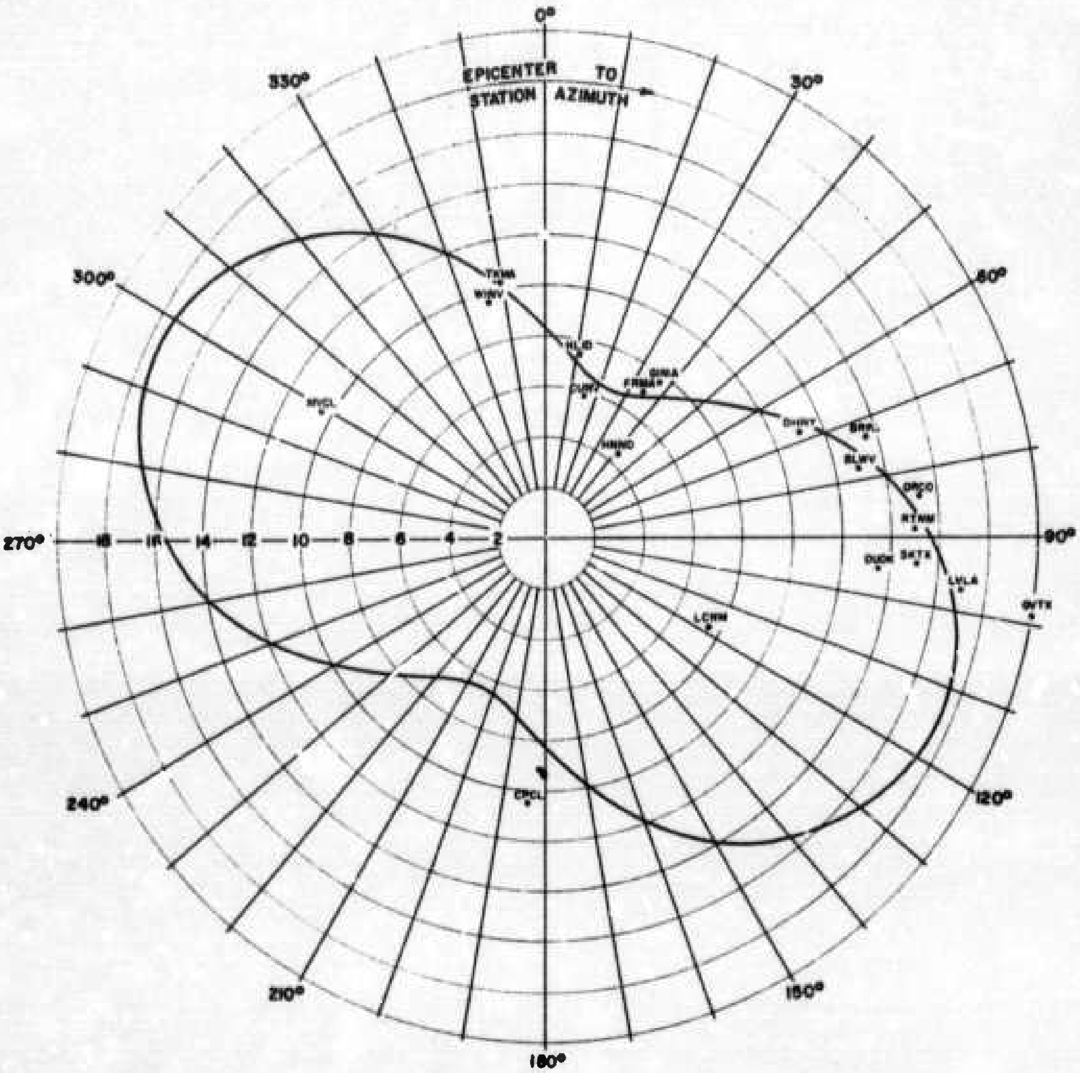

Figure 4. The radiation pattern of normalized Rayleigh waves for Bilby. The points are the ratio of the amplitudes of explosion-generated to collapse-generated Rayleigh waves. The curve is the theoretical radiation pattern for a composite source consisting of an explosion and an orthogonal double-couple.

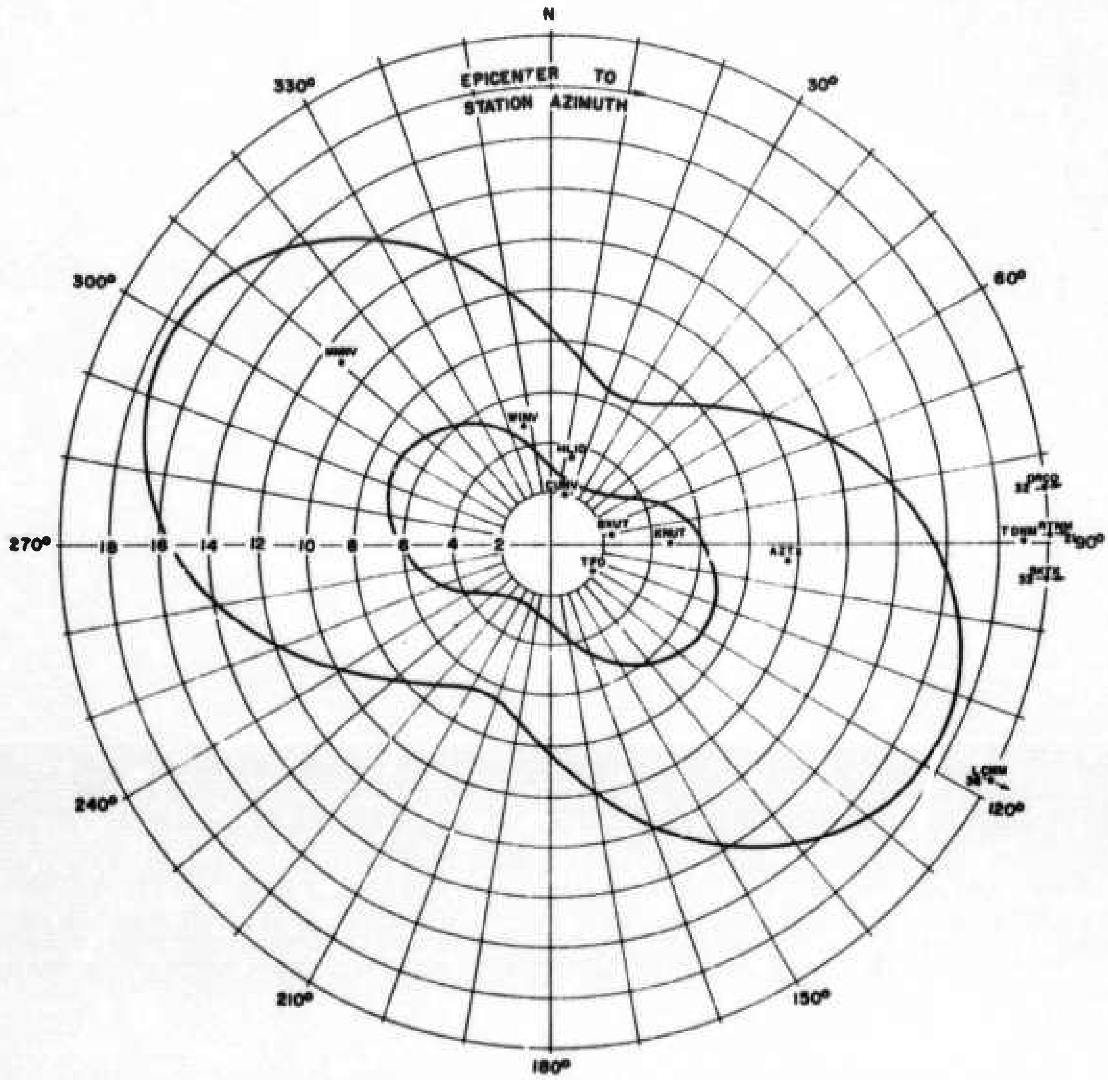

Figure 5. The radiation pattern of P waves from Bilby. Points are normalized amplitudes (ratio of explosion to collapse). Theoretical curve is the radiation pattern of a composite (explosive plus double-couple) source. Outer curve is same as that of Figure 4, included for comparison.

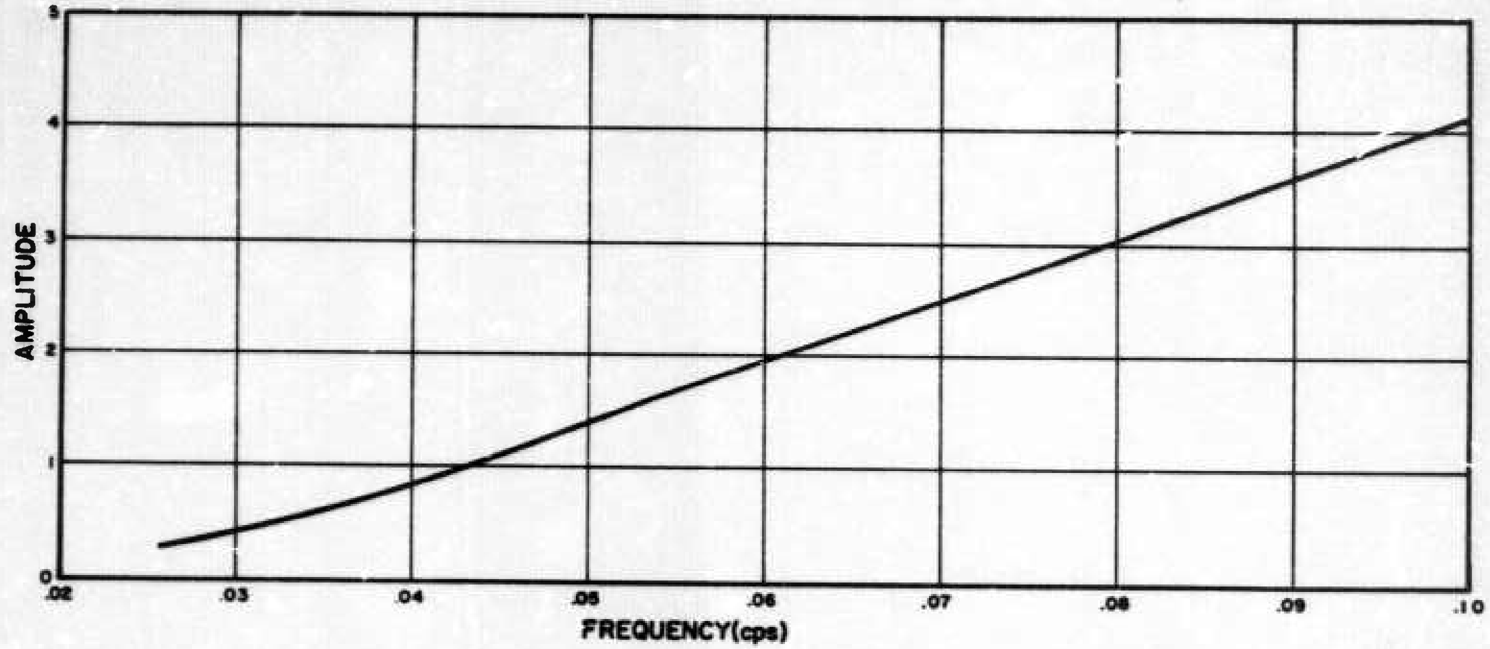

Figure 6. Rayleigh wave amplitude response of the layered medium to an explosive source near the surface, with impulsive time function.

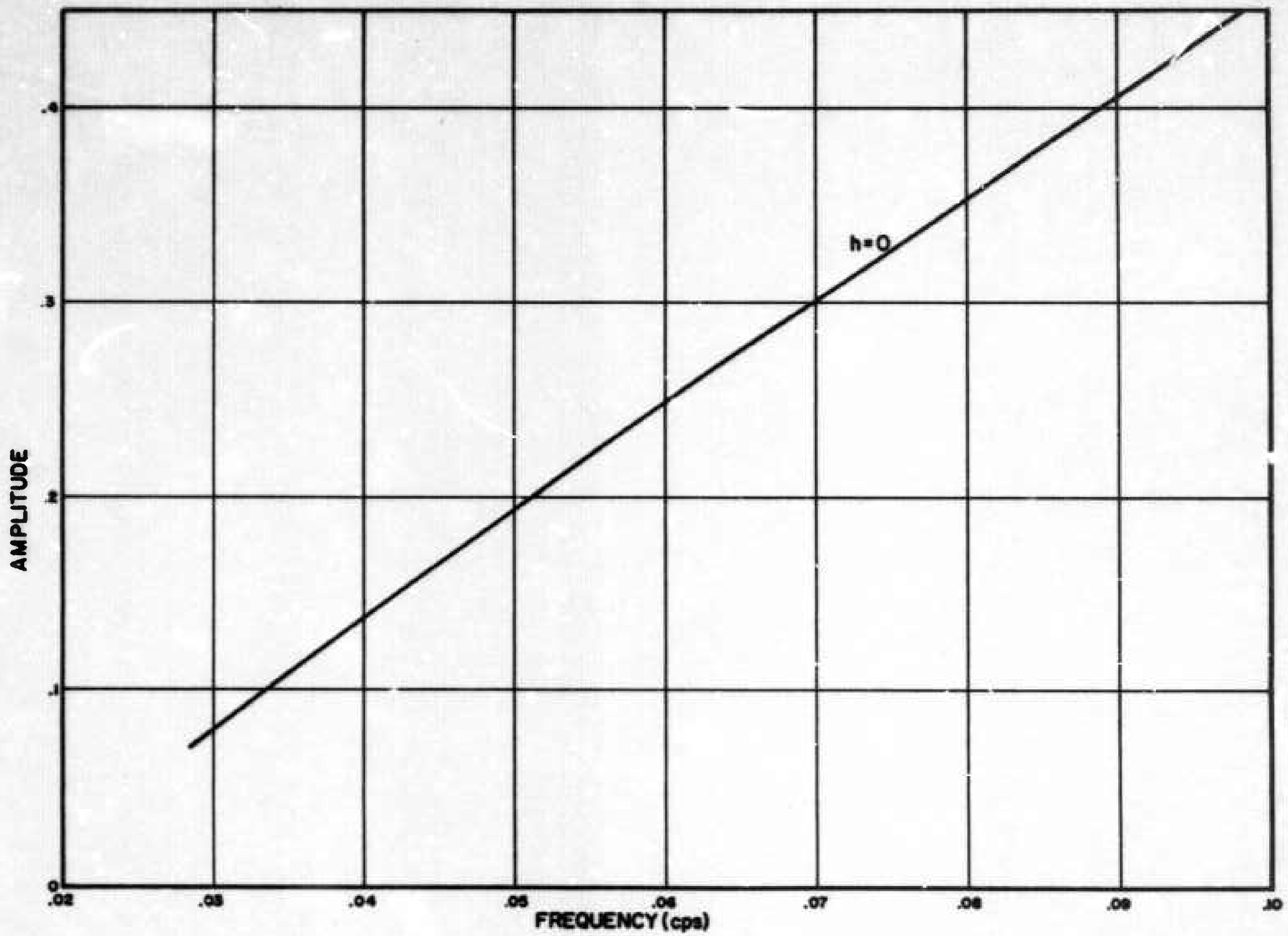

Figure 7. Love wave amplitude response of the medium to a double-couple source near the surface.

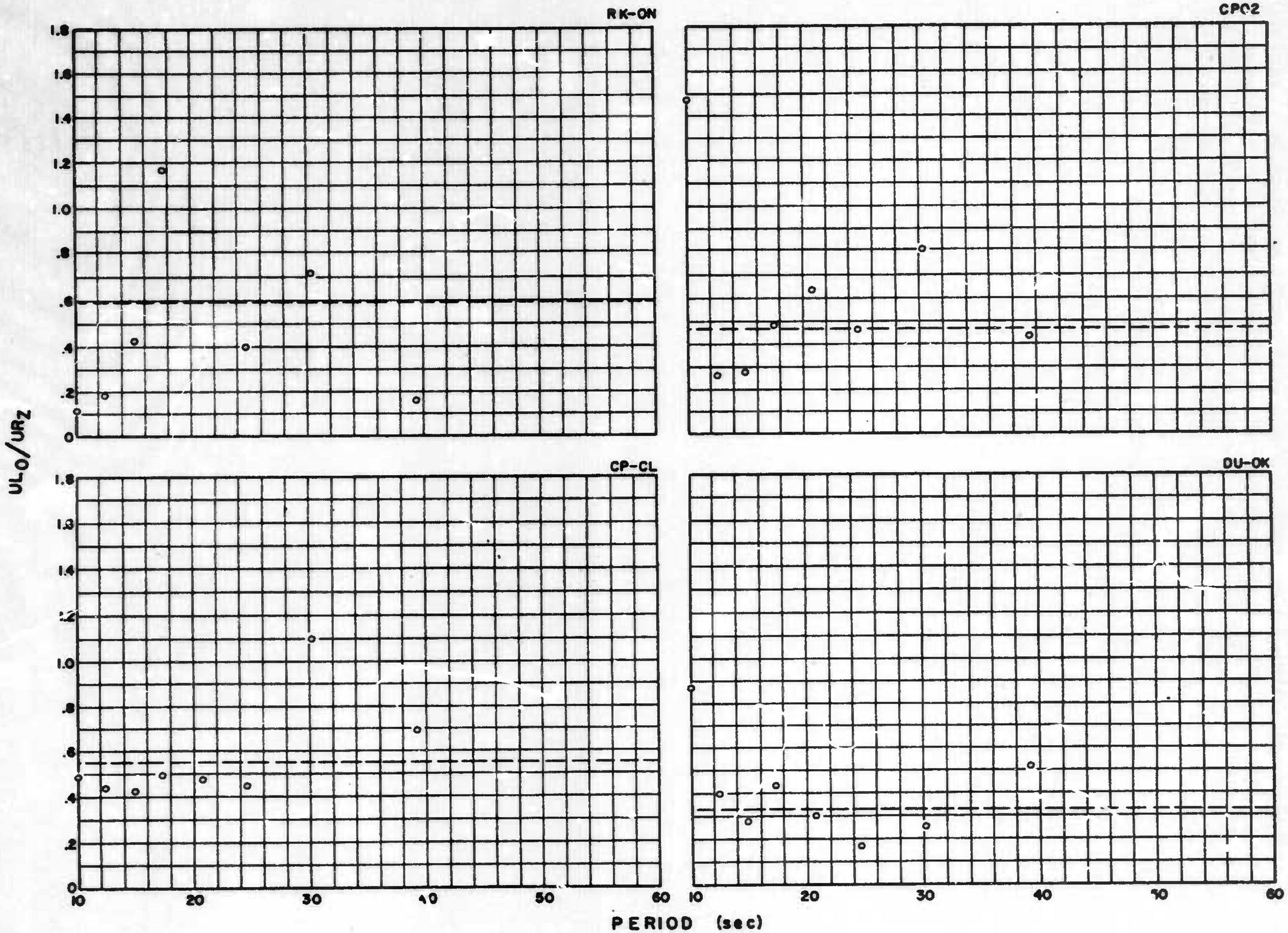

Figure 8. Love wave to Rayleigh wave vertical component (U_L/U_{Rz}) Fourier amplitude spectral ratio at four stations. Dashed lines are the ratios of peak amplitudes measured in time domain.

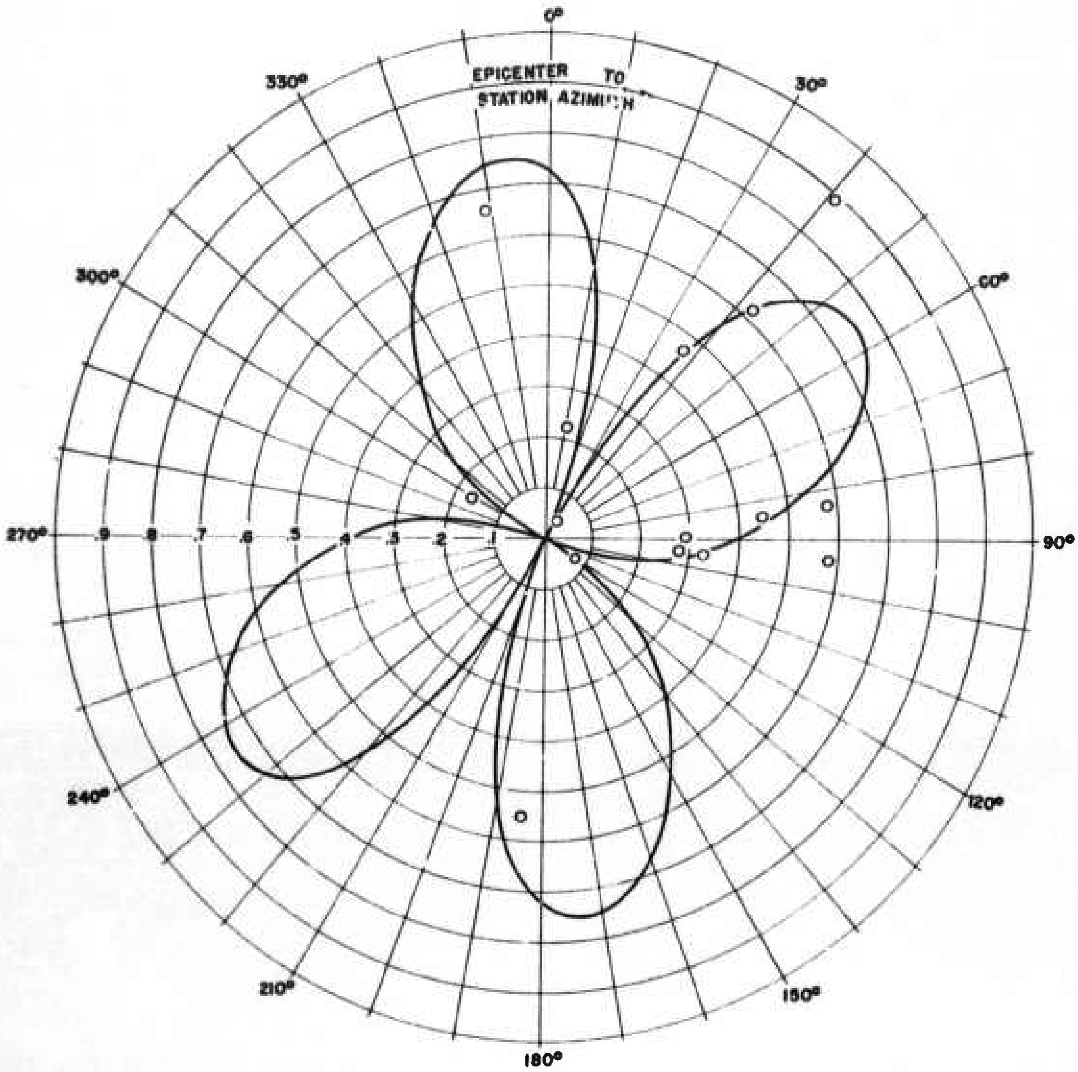

Figure 9. Amplitude ratios of the explosion-generated Love and Rayleigh waves (U_L/U_{Rz}). The theoretical curve is for the composite source described in Figure 4.

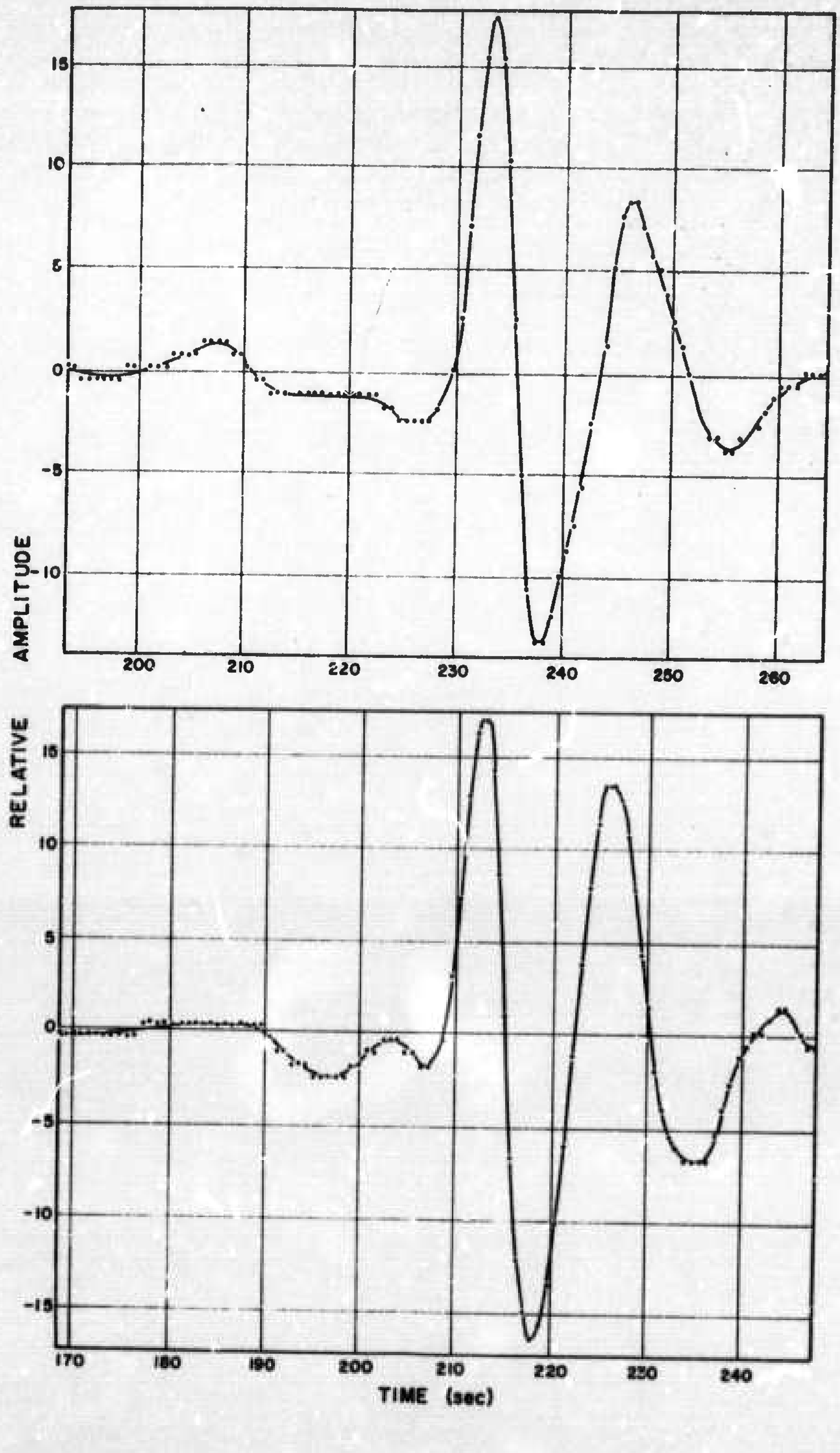

Figure 10. Rayleigh wave pulses at two stations plotted from digitized data.

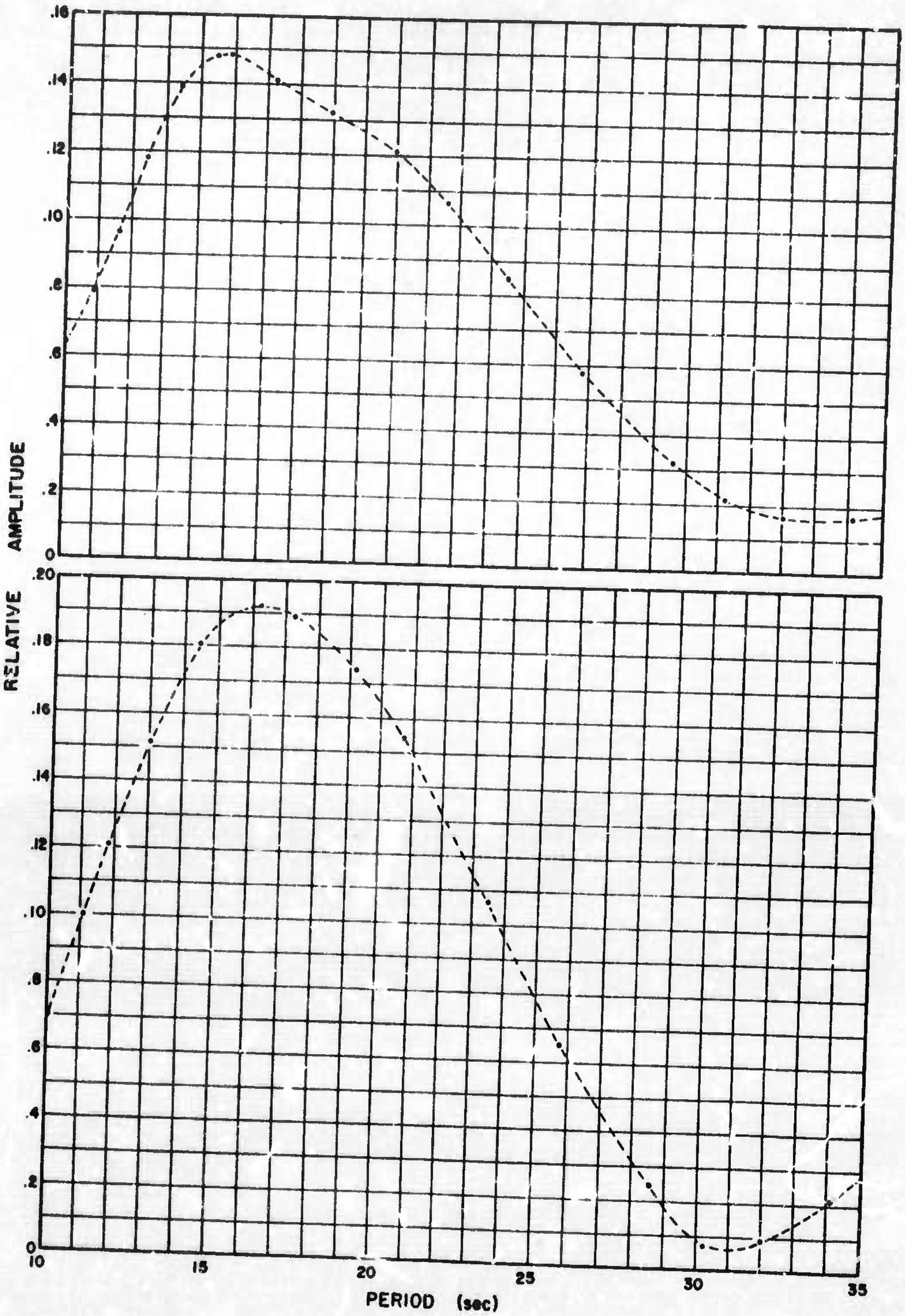

Figure 11. Fourier amplitude spectra of the pulses shown in Figure 10.

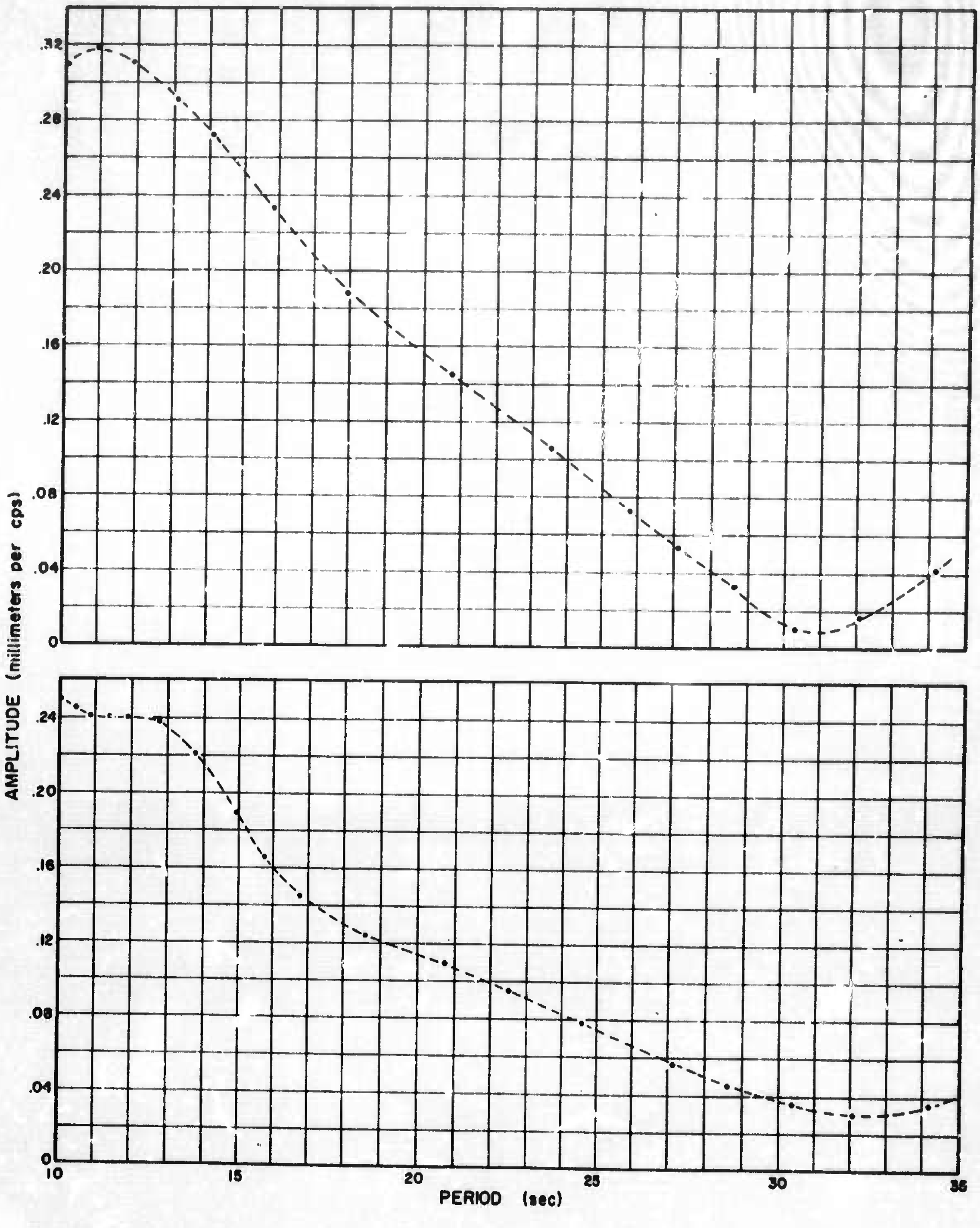

Figure 12. Ground displacement spectra obtained from those of Figure 10 after correction for instrument response.

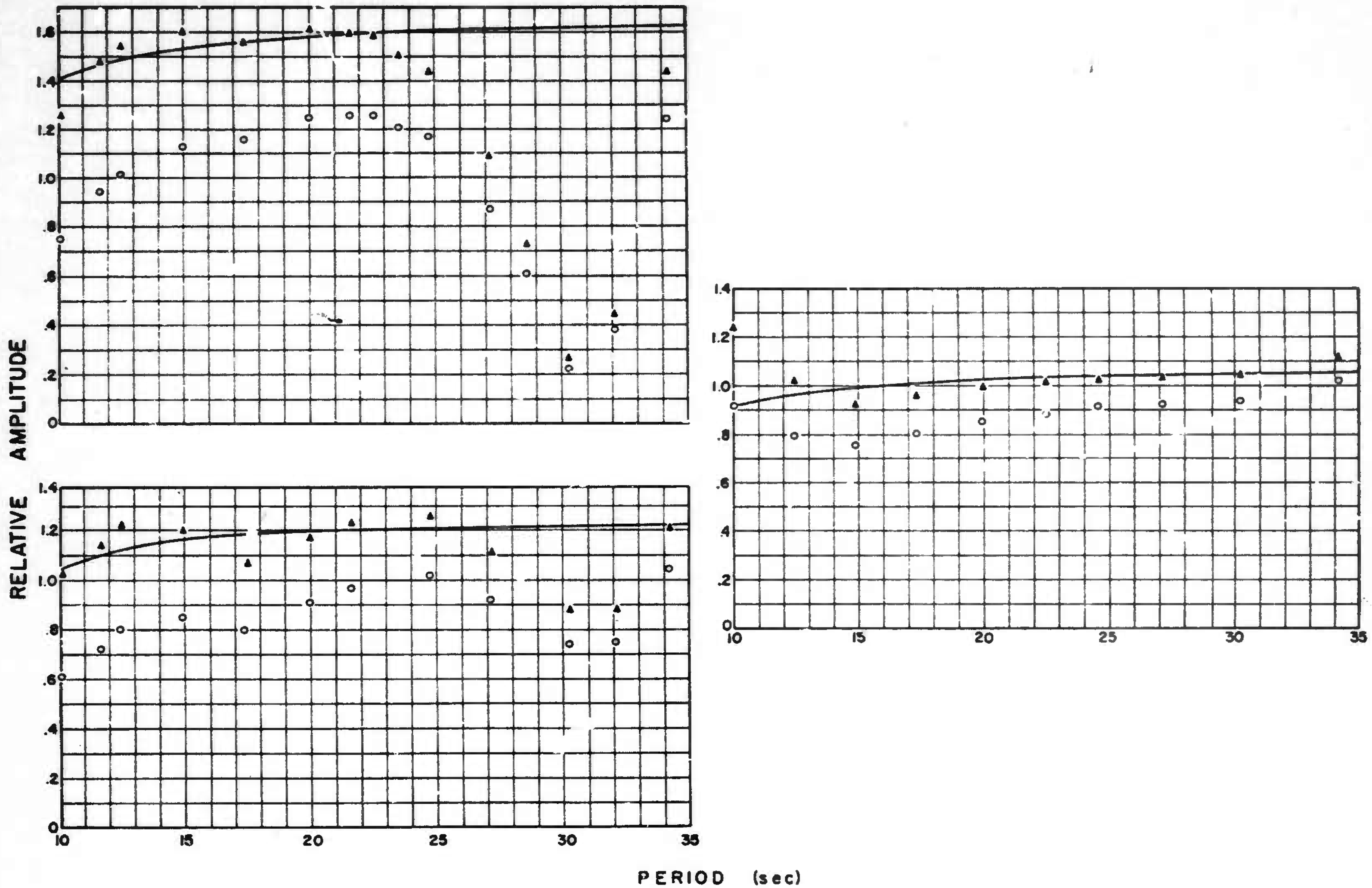

Figure 13. Amplitude spectra of source time function after correction for propagation effects. Circles indicate data uncorrected for attenuation; triangles indicate the data corrected taking Q=100.

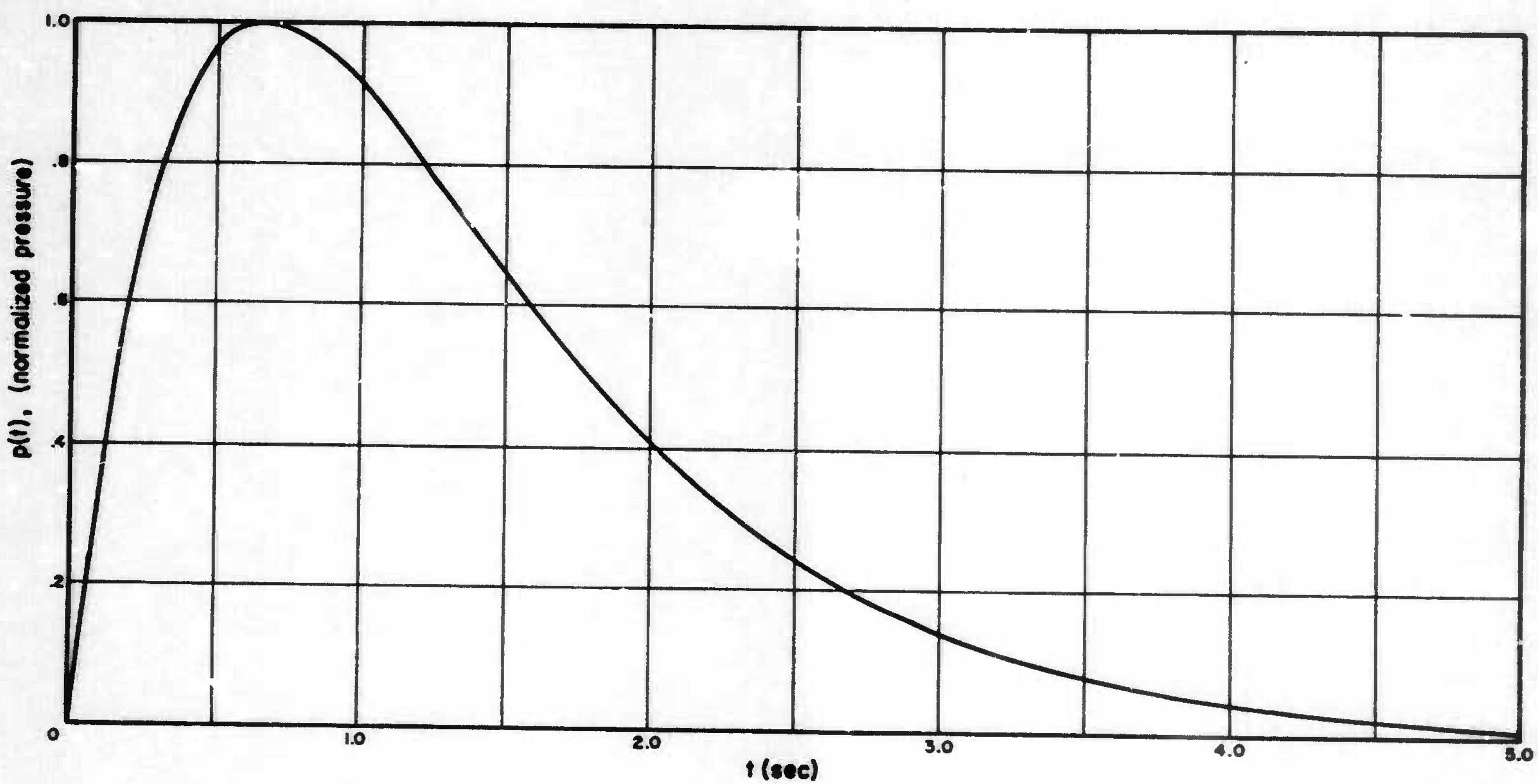

Figure 14. The Bilby pressure function at the boundary of the linear zone.

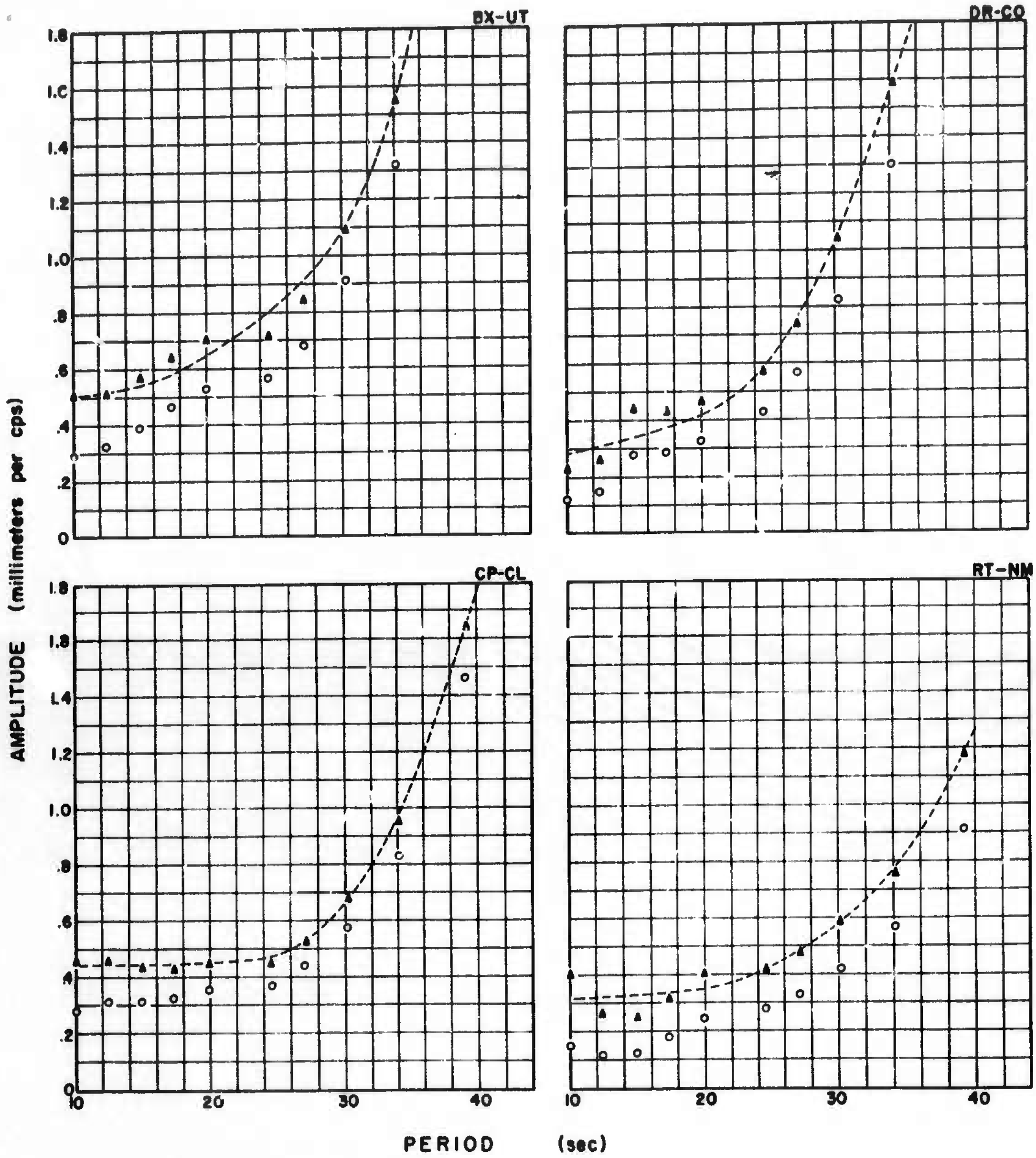

Figure 15. Amplitude spectra of source time function for Love waves after correction for propagation effects. Circles are uncorrected; triangles are corrected for attenuation.

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13. ABSTRACT

The seismic surface wave and P-wave data generated by the Bilby explosion and the associated cavity collapse are studied comparatively to determine the radiation patterns of these waves. The asymmetric radiation patterns of P and Rayleigh waves as well as the presence of Love waves are explained in terms of a composite source. This consists of an isotropic dilatational component due to the explosion and a double-couple component due to tectonic effect. The relative strength of the multipolar component is 0.47 times that of the explosion. The source time functions of Rayleigh waves this is a pulse of the form $p(t)=\underline{t}\ \exp(-1.5\underline{t})$.
For Love waves the source time function may be a step function with a slow rise time.

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