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COMPARISON OF LOVE- AND RAYLEIGH-WAVE MULTIPATH PROPAGATION AT LASA*

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ABSTRACT

An analysis was made of the multipath propagation of Love waves by using data obtained from the array of three-component instruments located at the Large Aperture Seismic Array (LASA). These data were analyzed by means of a high-resolution analysis technique, which provided a greater angular resolution and accuracy than was previously possible for the analysis of the multipath propagation of Love waves. The measurement of this phenomenon was made for the Love waves of six events distributed at various azimuths and distances from LASA. These measurements were used to make conjectures about the actual propagation paths for Love-wave groups in the 20 to 40-sec-period range. In addition, these paths were compared to the corresponding ones for Rayleigh waves, which were obtained previously. It is shown that in most cases, for both Love and Rayleigh waves, these propagation paths can be associated with refractions and reflections at the continental margins.

Introduction

It has been shown that a valuable discriminant for distinguishing between natural seismic events and underground nuclear explosions is based on the relationship between the surface-wave magnitude (M_s) and the body-wave magnitude (m_b) (cf. Press *et al.*, 1963; Brune *et al.*, 1963; Liebermann *et al.*, 1966; Marshall *et al.*, 1966; Evernden, 1969; Capon *et al.*, 1969). Thus, the fundamental-mode Rayleigh wave of an event is extremely important for the problem of seismic discrimination.

Since the group and phase velocities for continental regions differ from those of oceanic regions (Oliver, 1962 and Brune, 1969), the refraction, as well as reflection, of fundamental-mode Rayleigh waves at continental margins will lead to extremely complex propagation paths for these waves. This fact seems to have been first established in a definitive manner by Evernden (1953), (1954). In a recent paper, Capon (1970) analyzed the multipath propagation of fundamental-mode Rayleigh waves at the Large Aperture Seismic Array (LASA) located in eastern Montana. This measurement provided both angle of arrival and group delays for the 20-, 25-, 33- and 40-sec-period groups, so that reasonably good conjectures could be made about the actual propagation paths for these period groups during the 800-sec time interval following the onset time of the fundamental-mode Rayleigh wave. It was found that, in almost all cases for the 26 events which were analyzed, the propagation paths could be associated with refractions and reflections at the continental margins. The reflection of a group was found to usually take place at a continent-to-ocean boundary and the angle of incidence usually exceeded the critical angle for the period of the group.

It is known that the particle motion associated with fundamental-mode Rayleigh-wave propagation should be retrograde elliptical in the plane containing the lines which are vertical and radial to the propagation path. Thus, the phase of the signal observed on a seismometer oriented in the radial direction will lead that of a signal observed on a

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seismometer oriented in the vertical direction by approximately 90°. The precise value of this phase angle will be determined by the particular crustal structure at LASA. In particular, there will be no signal output, due to the fundamental-mode Rayleigh wave, observed on a seismometer which is oriented in the direction which is transverse to the propagation path.

In the present work we will consider, primarily, Love waves. The particle motion for fundamental-mode Love waves is transverse to the direction of the propagation path. Thus, there will be a signal output, due to the fundamental-mode Love wave, only on the horizontal seismometer which is oriented transverse to the direction of propagation. As yet, the fundamental-mode Love wave has not been found to be as important as the fundamental-mode Rayleigh wave for the purposes of seismic discrimination. The diagnostic capabilities of the Love wave are about as good as those of the Rayleigh wave for discriminating between earthquakes and underground nuclear explosions. However, it is more difficult to observe the fundamental-mode Love wave on the horizontal seismometers, at low surface-wave magnitudes, than it is to see the fundamental-mode Rayleigh wave on the vertical seismometer. The reason for this is that, while the signal for the Love wave is approximately the same as that for the Rayleigh wave, the noise power on the horizontal seismometers is usually more than 10 db greater than that on the vertical seismometer (cf. Capon, 1969a). This larger noise-power level is apparently due to local ground tilting caused by atmospheric pressure fluctuations which affect the long-period horizontal seismometers but do not affect the long-period vertical component.

The analysis of Love waves is important for several reasons, in spite of the fact that they have not, as yet, been found to be as useful as the Rayleigh wave for the purpose of seismic discrimination. One reason is that it is important to know how any possible multipath propagation of Love waves will contaminate the Rayleigh wave when observed on a horizontal seismometer oriented in the radial direction. Another reason is that the measured dispersion curves of Love waves can be used to determine crustal structure (cf. Aki and Kaminuma, 1963). In addition, it is possible that the noise, due to local tilting of the Earth's surface, on the long-period horizontal seismometers may be reduced. In this case the fundamental-mode Love wave may play a much more important role in seismic discrimination in determining the source type at low surface-wave magnitudes.

The theory describing the propagation of Love waves in a horizontally layered medium is also well understood (cf. Ewing *et al.*, 1957). These waves propagate in a dispersive medium, and the group and phase velocities are determined by the elastic parameters of the medium. An analysis similar to that for Rayleigh waves, shows that Love waves are also refracted across a boundary according to Snell's Law for the respective phase velocities. In addition to this refraction, some of the energy of the dispersive wave train is reflected at the boundary such that the angle of reflection is equal to the angle of incidence. The travel time along a path which crosses the boundary is determined essentially by the group velocities in the respective media.

The group and phase velocities of fundamental-mode Love waves for continental regions differ from those of oceanic regions (Oliver, 1962 and Brune, 1969), so that the refraction, as well as reflection, of Love waves at continental margins will lead to extremely complex propagation paths for these waves, as was the case also for Rayleigh waves. The multipath propagation of both Love and Rayleigh waves was analyzed by Aki and Kaminuma (1963) using a network of stations located in Japan. They found a discrepancy between the observed dispersion curve of Love waves and the theoretical curve based on the Gutenberg mantle which coincides best with the observed Rayleigh-wave dispersion. They attempted to explain this discrepancy by postulating the existence of anisotropic layers in the upper mantle. It is interesting that, except for this work, very little has been done on investigating the multipath propagation of Love waves.

The purpose of the present work is to investigate the multipath propagation of Love waves using observations obtained from the LASA. These results will then be compared to those obtained by Capon (1970) for Rayleigh waves. At the time that the experiments were performed, the LASA consisted of 21 subarrays of 25 short-period vertical seismometers as indicated in Figure 1 of Capon (1970). At the center of each subarray, there was a three-component set of long-period seismometers oriented in the vertical, north-south and east-west directions. The long-period vertical (LPZ), north-south (LPNS) and east-west (LPEW) instruments will all be considered. The frequency response of these instruments is shown in Figure 2 of Capon (1970). A detailed description of the LASA has been given by Green *et al.* (1965).

The LASA data were analyzed by means of the high-resolution frequency-wave number-spectrum analysis program described previously by Capon (1969b) and used by Capon (1970). The use of this program provided measurements for the direction of approach of Love waves with very high angular accuracy and resolution. Thus, it was possible to determine the angles of arrival of various frequency groups, arriving simultaneously at the array, during each of four successive 200-sec time intervals starting at the onset time of the Love wave. Hence, it was possible to measure group delays as well as directions of approach. The group delay was known only in multiples of 200 sec. However, this information appeared, in many cases, to be adequate for allowing a reasonably good conjecture to be made concerning the actual paths taken by various Love-wave group arrivals at LASA. These propagation paths were compared with the corresponding ones obtained by Capon (1970) for Rayleigh waves. As expected, in many cases, the multipath propagation can be associated with refractions and reflections at the continental margins. However, in some cases the multipath propagation appears to be caused by other factors, for example, tectonic features such as ridges.

High-Resolution Analysis for Love Waves

The frequency-wave number power spectrum provides the information concerning the power as a function of frequency and wave number for propagating waves. Hence, this spectrum can be used in the present work to determine the direction of approach, as well as the phase velocity and relative power of various frequency groups of a Love wave. The high-resolution (HR) method, described in detail by Capon (1969b), was used to measure the frequency-wave number spectrum over four successive non-overlapping 200-sec intervals, starting at the onset time of the Love wave, so that a total of 800 sec was considered. The measurement was made at 0.025, 0.030, 0.040, 0.050 Hz, corresponding to period groups of 40, 33, 25 and 20 sec, respectively. The details of the measurement are the same as given by Capon (1970), with the only exception that the rotated long-period horizontal components are analyzed as well as the LPZ components. This particular aspect of the measurement will now be described in greater detail.

The HR method is first applied to the array of LPZ components. This provides estimates of power and phase velocity at each frequency for the Rayleigh waves. The HR method is then applied to each array of long-period radial (LPR) and long-period transverse (LPT) components which are obtained by rotating the LPEW and LPNS components. This rotation is done as follows.

$$R = -EW \sin \theta - NS \cos \theta$$

$$T = -EW \cos \theta + NS \sin \theta$$

where θ is the azimuth of the event and R, T, EW, NS represent the instantaneous amplitudes of the radial, transverse, east-west and north-south components, respectively. For each set containing appreciable Love and Rayleigh energy, two peaks will usually appear, one giving Love-wave power contribution and phase velocity, and the other yielding the analogous horizontal Rayleigh-wave estimates. The identification and separation of Love waves by this method may be obtained by matching horizontal Rayleigh-wave peaks one-to-one with those obtained from the LPZ components. The remaining peaks, therefore, represent Love-wave contributions. This method is applicable if the propagation directions for Love and Rayleigh waves are sufficiently different so that the HR method can resolve separate peaks for each wave type. When the directions coincide, the phase-velocity differences may not be sufficient for the HR method to resolve two distinct peaks. In this case, we can still identify the different wave types as follows.

We assume that the Love and Rayleigh waves are propagating from azimuths of θ_L, θ_R, respectively, and that a transverse component is obtained for an azimuth of $\theta_L + \Delta\theta = \theta$, by rotating the LPEW and LPNS components. The azimuths θ_L, θ_R are assumed to be close enough in value so that the HR method provides only a single peak for both wave types using the LPT components. If θ_R is equal to $\theta_L + \Delta\theta$ then, of course, there will be no contribution on the LPT components due to the Rayleigh wave. The instantaneous amplitudes of the EW and NS components are

$$EW = -R' \sin \theta_R - L \cos \theta_L$$

$$NS = -R' \cos \theta_R + L \sin \theta_L$$

where R' and L are the instantaneous amplitudes of the radial Rayleigh, and Love wave, respectively. Hence, the instantaneous amplitude of the transverse component for the direction $\theta = \theta_L + \Delta\theta$ is

$$T = -EW \cos (\theta_L + \Delta\theta) + NS \sin (\theta_L + \Delta\theta)$$

$$= L \cos (\Delta\theta) + R' \sin (\theta_R - \theta_L - \Delta\theta).$$

Thus, assuming for simplicity that the radial Rayleigh and transverse Love-wave particle motions, for a particular frequency group, are approximately sinusoidal, and are in phase with each other, then the instantaneous amplitude of the Love wave is

$$L = [T - R' \sin (\theta_R - \theta_L - \Delta\theta)] \sec (\Delta\theta).$$

This equation may be rewritten as

$$20 \log L = 20 \log [T - R' \sin (\theta_R - \theta_L - \Delta\theta)] + 20 \log \sec (\Delta\theta).$$

It can be assumed that R' and θ_R are known from HR analysis of the LPZ sensors on which we can obtain only pure Rayleigh particle motion. This assumes that the particle motion of the Rayleigh wave is retrograde circular so that the instantaneous amplitude of the radial component is the same as that of the vertical component, after an appropriate 90° phase shift is introduced. An amplitude reduction factor of 0.8 may be closer to reality, but this is not taken into account in the present analysis. It should also be noted that $\Delta\theta = \theta - \theta_L \cong \theta - \theta_R$, since $\theta_R \cong \theta_L$. Thus, using these measurements, the Love-wave power, as measured using the LPT components, may be obtained by subtracting out the Rayleigh-wave contribution as indicated above.

The procedure given above provides a good approximation for the Love-wave power when the phase angle between the Love- and radial Rayleigh-wave components is

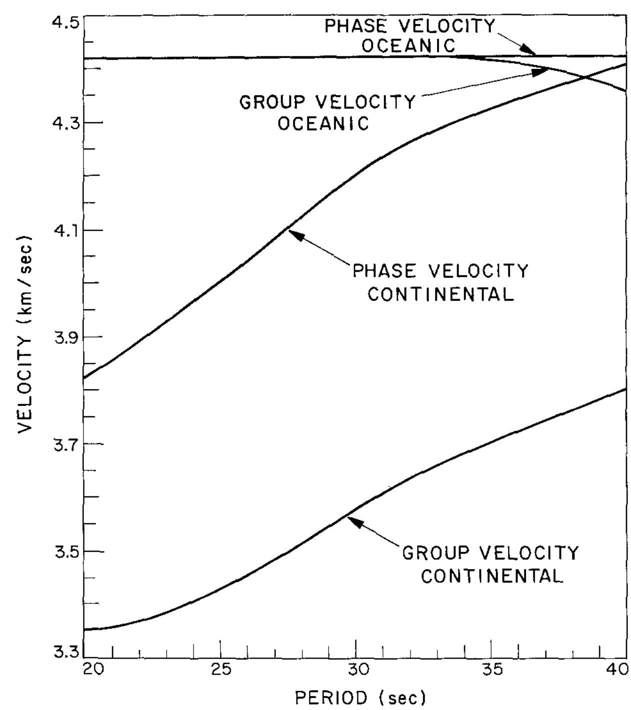

FIG. 1. Fundamental-mode, Love-wave dispersion curves in the 20- to 40-sec-period range.

close to 0°. The approximation may be quite crude if this phase angle deviates significantly from 0°. In practice, this phase angle is rarely known and is usually assumed to be 0°. However, if R' is small relative to T, or if $\theta_R - \theta_L - \Delta\theta$ is small, say less than 10°, then the Rayleigh component may be neglected in computing the Love-wave power. This latter condition can always be satisfied by rerotating the LPEW and LPNS components using a rotation angle $\theta' = \theta_R$. Hence, using the above procedure, it is possible in almost all cases to identify the Love-wave component.

Propagation of Love Waves Across A Boundary

A brief discussion will now be given for the way in which a dispersive Love-wave train propagates across a boundary. An analysis similar to that given by Capon (1970) shows that the dispersive Love-wave train is refracted across a boundary according to Snell's Law for the respective phase velocities. In addition, the travel time along a path which crosses the boundary is determined essentially by the group velocities in the respective media.

It is also known that the ray path must satisfy Fermat's principle; that is, the ray path must be a stationary-time path. For Love waves, this means that the path for the initial arrivals will be a minimum-time path while later arrivals propagate along paths which, while not minimum-time paths, are stationary-time paths. In other words, there are usually many possible paths, as will be seen subsequently in the interpretation of the experimental results for the multipath propagation of Love waves.

The phase- and group-velocity curves for fundamental-mode Love waves for continental and oceanic regions are shown in Figure 1, and were obtained from Brune (1969). It is seen from this figure that both the phase and group velocities for oceanic regions are larger than those for continental regions at all periods. In addition, the phase velocity for the longer periods, about 40 sec, is almost the same for both conti-

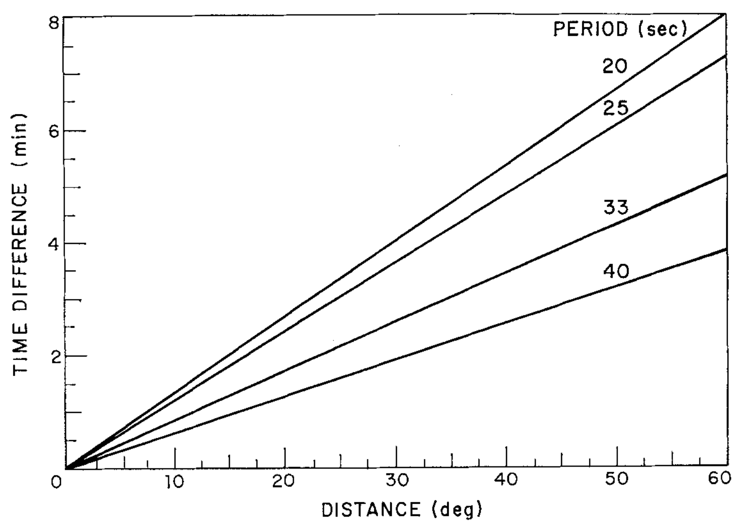

FIG. 2. Time difference for propagation of Love waves in oceanic region relative to continental region.

nental and oceanic regions, so that very little refraction of these longer-period groups would be expected. This is also brought out by the experimental results to be presented below. The data in Figure 1 were used to compute the amount of time saved by a Love-wave group by traveling an oceanic path, of a certain distance, relative to a continental path of the same distance, and the results are depicted in Figure 2. This figure corresponds to Figure 10 given by Capon (1970) for Rayleigh waves, and will be important subsequently in the attempt to correlate specific paths with observed angles of arrival and group delays.

In addition to the refraction at a boundary, there is also energy which is reflected in such a way that the angle of reflection is equal to the angle of incidence. A critical angle of incidence is reached at a continent-to-ocean boundary and is the angle at which much of the energy is reflected. The critical angle is given by

$$\theta_c = \sin^{-1}\left(\frac{c_c}{c_o}\right),$$

where c_c, c_o are the continental and oceanic phase velocities, respectively. The data in

Figure 1 were used to compute the critical angle versus period and the results are depicted in Figure 3.

The exact solutions for the reflected and transmitted Love waves are difficult to obtain, as was the case for the Rayleigh waves. The mathematical formulation of the problem is complicated by the difficulty of finding an elementary coordinate system in which to describe both the solutions of the wave equation and the boundary conditions.

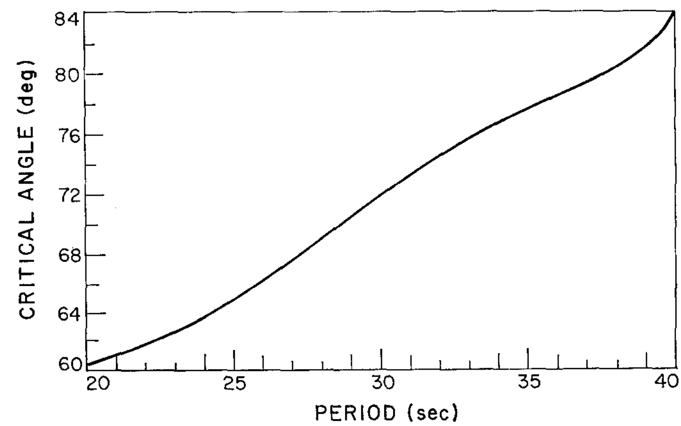

FIG. 3. Critical angle of reflection versus period for Love waves at a continent-to-ocean boundary.

TABLE 1

LIST OF EVENTS

Event No.	Date	Region	Origin Time (GMT)	Latitude (deg)	Longitude (deg)	Distance (deg)	Azimuth (deg)	Depth (km)	Body-Wave Magnitude (USCGS)
1	21 Nov 66	Kurile Islands	12:19:27	46.7 N	152.5 E	64.3	311.5	40	5.6
6	27 May 67	Kashmir-Sinkiang Border Region	19:05:49	36.1 N	77.8 E	97.5	356.7	35	5.4
10	4 Aug 67	Central Mid-Atlantic Ridge	06:01:10	7.4 N	36.3 W	70.9	99.7	33	5.0
12	8 Sep 67	Near Coast of Northern Chile	08:59:59	23.4 S	70.7 W	76.8	146.8	33	5.5
17	22 Sep 67	Central Mid-Atlantic Ridge	08:08:04	0.7 S	20.1 W	87.8	93.3	33	5.3
22	19 Jan 68	Solomon Islands	06:04:38	9.4 S	158.4 E	100.4	267.4	33	6.0

The basic difficulty arises because of the complex geometry of a free surface with relatively sharp corners. However, approximations may be used for the special case of normal incidence to obtain reflection and transmission coefficients for Love waves (cf. Knopoff and Hudson, 1964 and Alsop, 1966).

ANALYSIS OF MULTIPATH PROPAGATION OF LOVE WAVES

The HR method which was described previously was used to analyze the multipath propagation of the Love waves of six events. These events were observed on the LPZ, LPNS, and LPEW seismometers at LASA and the data were recorded in digital format on magnetic tape. The locations, origin times and other parameters obtained from USCGS for the six events used in the study are presented in Table 1. These six events correspond to a subset of the 26 events considered by Capon (1970), and

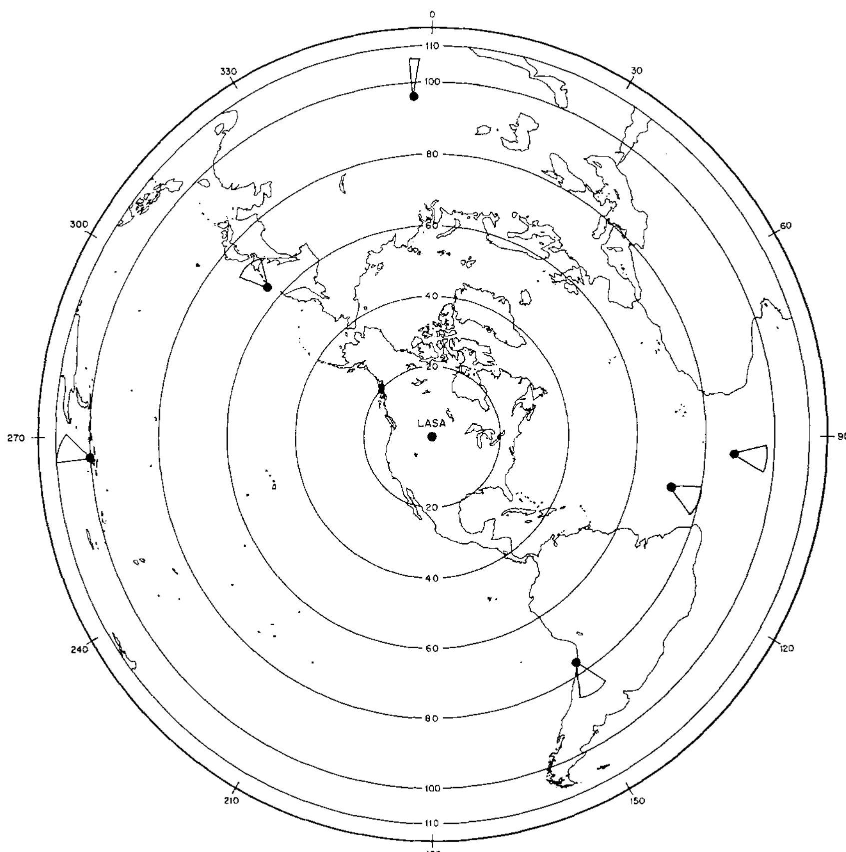

FIG. 4. Variations in azimuth of arrival of Love waves at LASA.

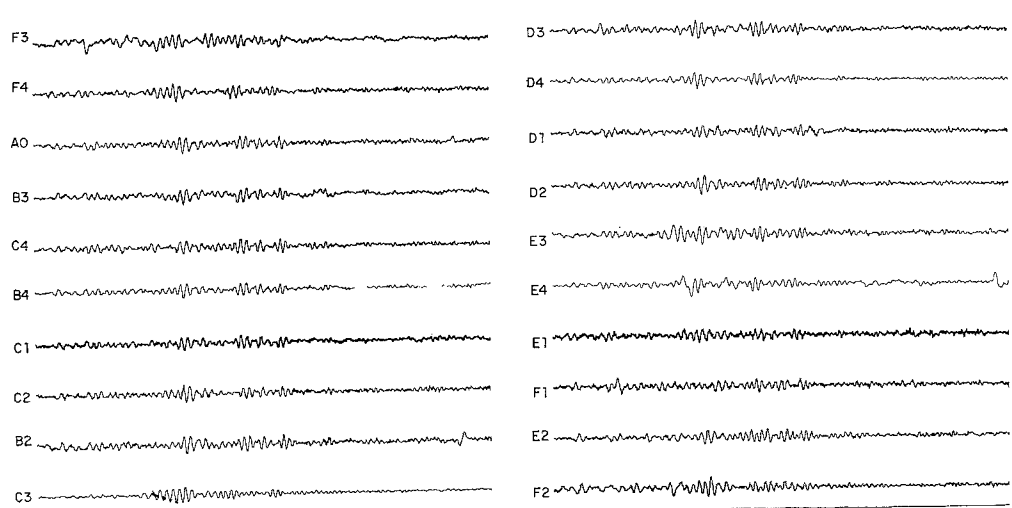

FIG. 5. The long-period transverse wave forms for the November 21, 1966, Kurile Islands event.

the previous numbering system used there is retained in the present work to facilitate the comparison of results. The locations of the epicenters of these events are shown in Figure 4 along with the observed variations in azimuth of arrival for Love waves. The map given in this figure is an equidistant azimuthal projection with LASA as the projection point, so that all great circle paths passing through LASA appear as straight lines and all points at the same distance from LASA lie on a circle centered on LASA.

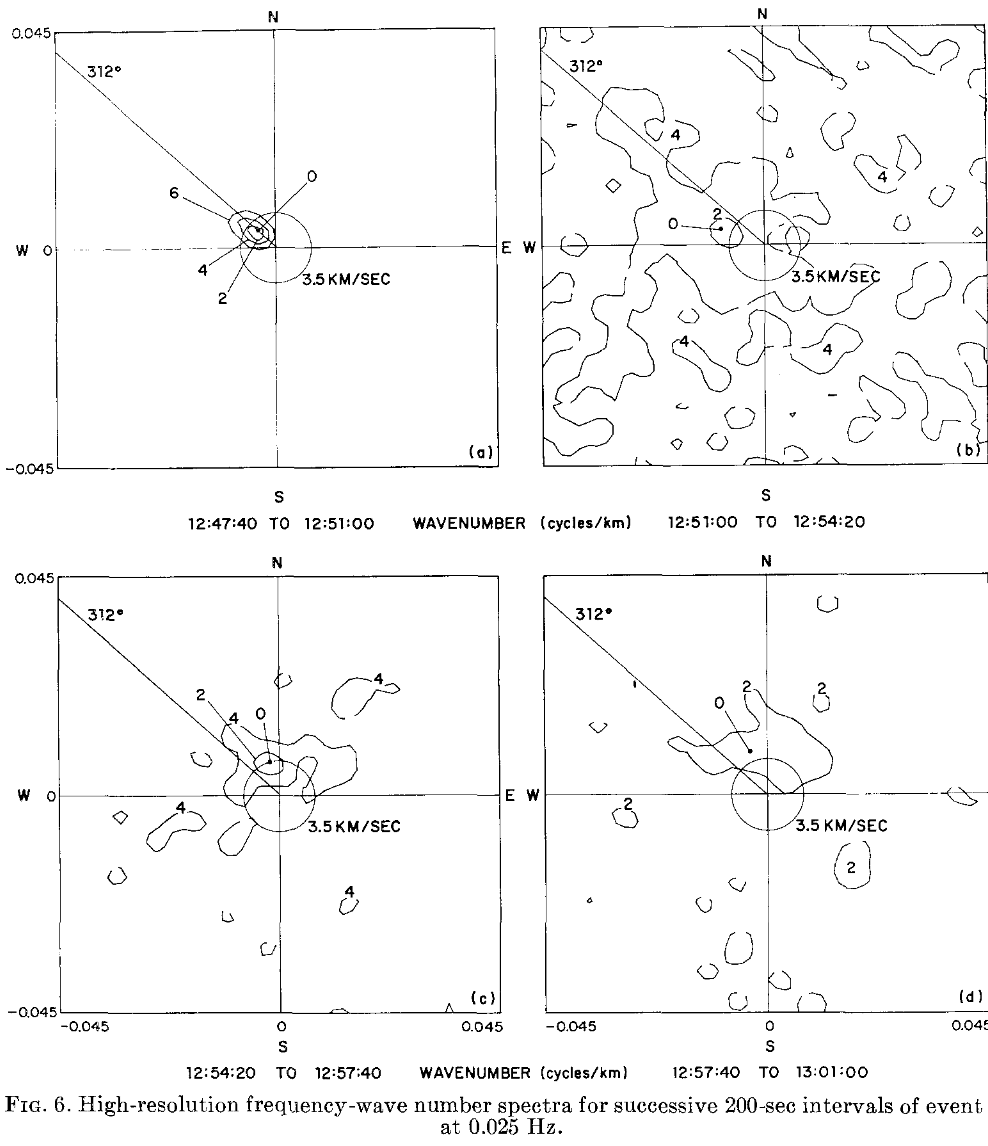

FIG. 6. High-resolution frequency-wave number spectra for successive 200-sec intervals of event 1 at 0.025 Hz.

The wave forms for event 1, which occurred on November 21, 1966 in the Kurile Islands, as observed on the LPT sensors are shown in Figure 5. It should be noted once again that the LPT wave forms are obtained by rotating the LPEW, LPNS traces in the direction corresponding to the azimuth of the event, as described previously. The results obtained for the processing of the LPT wave forms for this event with the HR method are shown in Figures 6, 7, 8, and 9 for the period groups of 40, 33, 25 and 20 sec, respectively. The occurrence of frequency windowing in Figures 6 (b, c, and d) and 7 (d) should be noted. This windowing was described in detail by Capon (1970).

The measurements made on the six events, such as shown in Figures 6, 7, 8 and 9 for the LPT wave forms, as well as the measurements using the LPZ and LPR wave forms, were analyzed to obtain the data in Table 2. This table lists the deviation of the

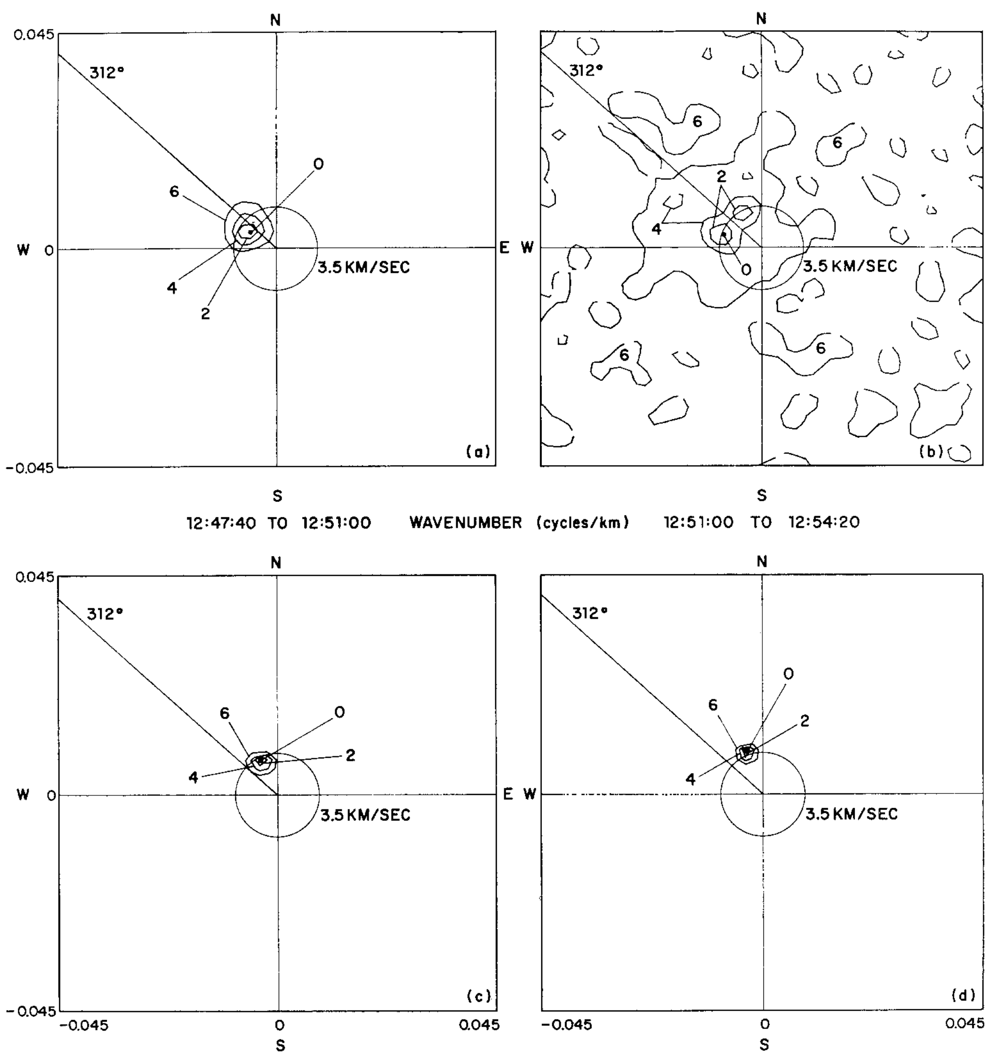

FIG. 7. High-resolution frequency-wave number spectra for successive 200-sec intervals of event 1 at 0.03 Hz.

azimuth of arrival from the true azimuth, in degrees, of the four groups considered, during successive 200-sec intervals of time starting with the onset time of the 40-sec-period group of the Love wave. In all cases, this onset time was in agreement with the known origin time of the event and the propagation time computed from the group velocity and distance appropriate to the propagation path for the 40-sec-period group of the Love wave. In Table 2 the power levels of the Love-wave groups are given in decibels relative to the power level of that frequency group which had the largest power level observed during the entire 800-sec analysis time. This power level is measured as the power output of a narrow-band filter whose selectivity function corresponds to the Bartlett window shown in Figure 3 by Capon (1970). Thus, the power levels given in Table 2 enable us to determine the relative energies of the various Love-wave group arrivals at LASA. A dash in Table 2 indicates that the group was not

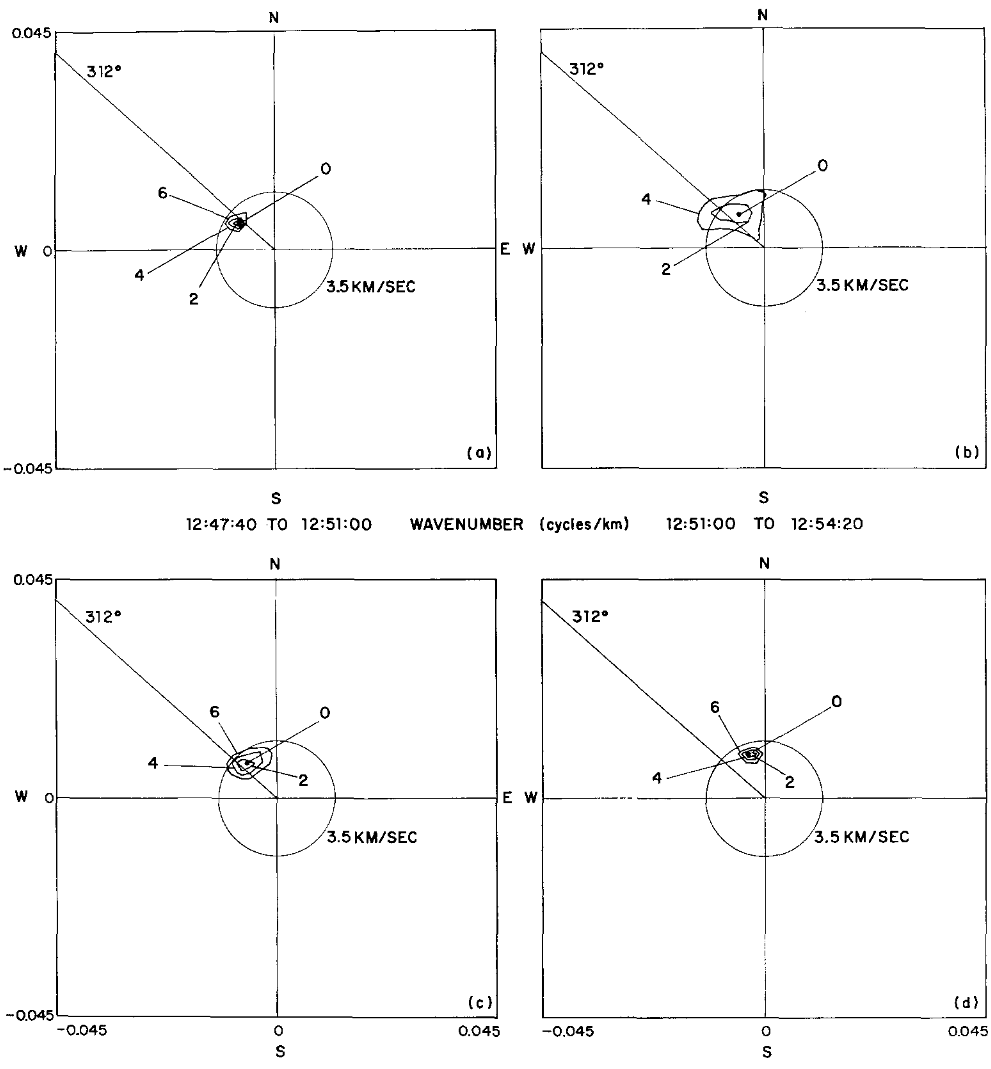

FIG. 8. High-resolution frequency-wave number spectra for successive 200-sec intervals of event 1 at 0.04 Hz.

detected during that time interval. The data in Table 2 will be used below to make conjectures about the actual ray paths for the multipath propagation of Love waves, and a comparison with Rayleigh waves will be made.

It should be stressed that the analysis of the multipath propagation of Love waves entails the application of the HR method to three different arrays of data, namely LPZ, LPR and LPT. This represents a great complication over the case for Rayleigh waves where only the LPZ array was analyzed. Thus, three times as much computer time is required for Love waves than for Rayleigh waves. In addition, there are complications involved in the identification of Love waves which have been contaminated by Rayleigh waves that propagate along multiple paths. These complications do not arise in the analysis of Rayleigh waves using the LPZ array. However, as described

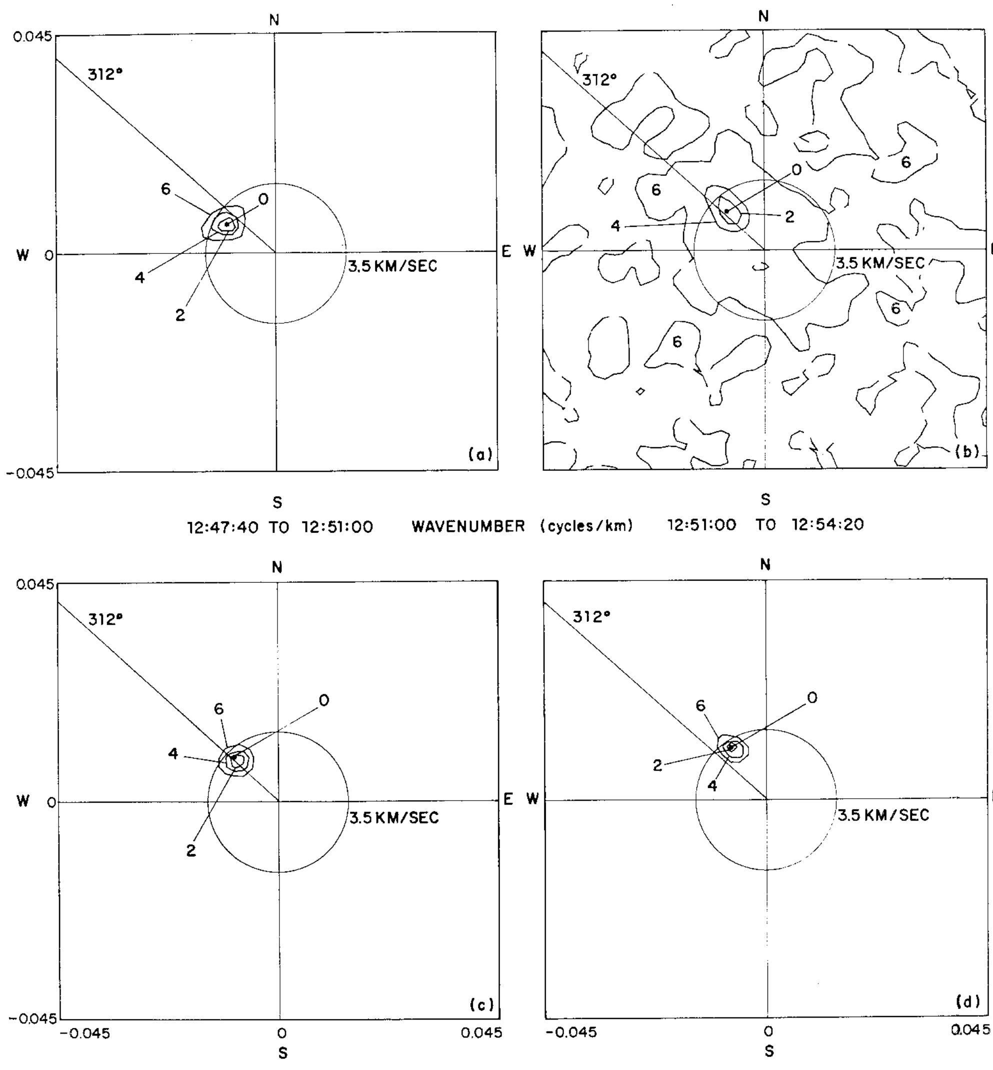

FIG. 9. High-resolution frequency-wave number spectra for successive 200-sec intervals of event 1 at 0.05 Hz.

previously, it is possible in most cases to identify Love-wave groups using the present method of analysis.

The azimuthal variations observed for the Love waves of the events are listed in Table 3. The average azimuthal difference between the extremes observed is about 53°. This should be compared with the corresponding figure of about 39° for the Rayleigh waves of these same events (cf. Table 3 of Capon, 1970). In Table 4, there is listed the maximum observed Love-wave power relative to the maximum observed Rayleigh-wave power, in decibels, for the six events considered. These data indicate that the peak power of the Rayleigh wave tends to be about 6 db larger than that of the Love wave.

Propagation Paths for Love and Rayleigh Waves

We will now use the experimental data in Table 2 to make conjectures about the actual propagation paths for the various Love-wave groups. It should be clear that

TABLE 2

Measured Variations in Azimuth of Arrival, and Power Levels at Various Times for Events

Event No.	Time (secs)	Azimuthal Deviations*				Power Levels†			
		At 40 sec (deg)	At 33 sec (deg)	At 25 sec (deg)	At 20 sec (deg)	At 40 sec (db)	At 33 sec (db)	At 25 sec (db)	At 20 sec (db)
1	0–200	0	−7	−8	−12	10	9	7	12
	200–400	—‡	−22	10	5	—	6	4	11
	400–600	—	20	10	5	—	3	0	5
	600–800	—	—	28	14	—	—	1	3
6	0–200	0	0	3	3	8	13	16	20
	200–400	0	0	3	—	3	3	13	—
	400–600	—	8	3	—	—	0	5	—
	600–800	—	—	12	3	—	—	1	2
10	0–200	0	0	−5	—	1	0	7	—
	200–400	—	12	−5	−10	—	4	2	4
	400–600	45	12	28	—	6	8	3	—
	600–800	—	—	28	22	—	—	2	3
12	0–200	0	9	—	—	0	1	—	—
	200–400	0	9	−18	30	4	2	3	3
	400–600	—	—	−18	−25	—	—	0	2
	600–800	—	—	−18	−25	—	—	3	5
17	0–200	10	10	−3	—	4	3	8	—
	200–400	—	—	−18	−3	—	—	2	2
	400–600	—	—	25	—	—	—	0	—
	600–800	—	—	—	—	—	—	—	—
22	0–200	0	0	3	—	0	0	0	—
	200–400	—	0	—	3	—	1	—	0
	400–600	—	50	—	—	—	0	—	—
	600–800	—	—	—	—	—	—	—	—

* Azimuthal deviations are differences between measured azimuth of arrival and true azimuth of epicenter of event.

† Power levels in decibels relative to maximum power.

‡ Dash indicates that group was not detected during indicated time interval.

the data in Table 2 are insufficient to determine unequivocally the propagation paths, so that the results to be presented represent guesses about the structure of the propagation paths. However, it is believed that there is sufficient evidence to support these conjectures as being reasonably accurate indications of actual propagation paths.

The trial-and-error procedure which was used to determine the propagation paths for Love waves is similar to that described previously for Rayleigh waves by Capon (1970). Three examples of such propagation paths are shown in Figures 10, 11 and 12 for both the Love and Rayleigh wave of an event. The timing sequence for the group arrivals is not shown in any of these figures, but this information can be obtained from Table 2 and Table 2 of Capon (1970). Any two propagation paths whose azimuthal angles of arrival at LASA are within 3° of each other are usually merged into a single path. In addition, all propagation paths in these figures are drawn as straight-line segments. All refractions and reflections are depicted as taking place at the geographic boundaries for the continents, although it is more likely to take place at the continental margins. The difference is, in most cases, very small and may be neglected. Only one refraction or reflection is taken into account on each epicenter-to-LASA path.

The propagation paths for event 1 located in the Kurile Islands are shown in Figure 10. We see that initially, for both Love and Rayleigh waves, the longer-period groups

TABLE 3

VARIATION IN AZIMUTH OF ARRIVAL OF LOVE WAVES AT LASA

Event No.	Azimuth (deg)	Azimuthal Variation (deg)	Azimuthal Difference (deg)
1	311.5	290–340	50
6	356.7	357–9	12
10	99.7	90–145	55
12	146.8	122–177	55
17	93.3	75–118	43
22	267.4	267–317	50

TABLE 4

COMPARISON OF MAXIMUM LOVE-WAVE POWER WITH RESPECT TO MAXIMUM RAYLEIGH-WAVE POWER

Event No.	Maximum Love-Wave Power Relative to Maximum Rayleigh-Wave Power (db)
1	−7
6	5
10	−5
12	−1
17	−11
22	−15

arrive at LASA along the great circle path between LASA and the epicenter, or slightly refracted versions of this path. These groups are followed by shorter-period groups which are refracted and reflected at the continental margin. In addition, the multipath propagation of the Love waves is strikingly similar to that of the Rayleigh waves. However, the two sets of paths are sufficiently different from each other that it would be difficult to predict one set from the other, except for the gross details. These conclusions are also brought out by the propagation paths depicted in Figures 11 and 12.

We observe that reflection of a Love-wave group usually takes place at a continent-to-ocean boundary and that the angle of incidence usually exceeds the critical angle for the period of the group. This is seen by comparing Figure 3, which shows the critical angle versus period, with Figures 10, 11 and 12. This result is to be expected, since it is at these angles of incidence that reflection of large amounts of energy would be expected. A similar result has been found for Rayleigh waves by Capon (1970).

It should also be mentioned that analysis of the LPZ array, during time intervals prior to the onset time of the Rayleigh wave, has shown that fundamental-mode Rayleigh waves of relatively low power levels can be detected. These early arrivals of fundamental-mode Rayleigh waves may ebe caused by either body-wave-to-Rayleigh-wave or Love-wave-to-Rayleigh-wave conversion at boundaries.

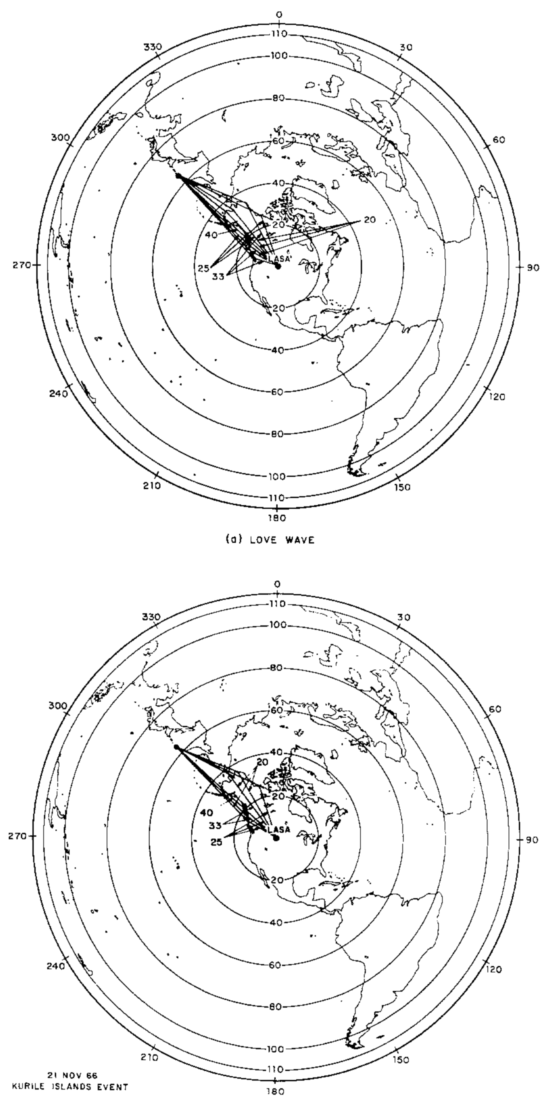

FIG. 10. Propagation paths for the Love and Rayleigh waves of event 1.

CONCLUSIONS

The analysis of Love-wave multipath propagation has been performed at LASA using the HR method. This analysis had to be performed on the LPZ, LPR and LPT arrays and has allowed a greater angular resolution and accuracy to be attained than was previously possible.

It was possible to obtain data which provided information about path length differences. This in turn has enabled us to make reasonably good conjectures about the actual propagation paths. In most cases for the six events analyzed, these propagation paths could be associated with refractions and reflections at the continental margins. It is interesting that the reflection of a group usually takes place at a continent-to-ocean boundary and the angle of incidence usually exceeds the critical angle for the

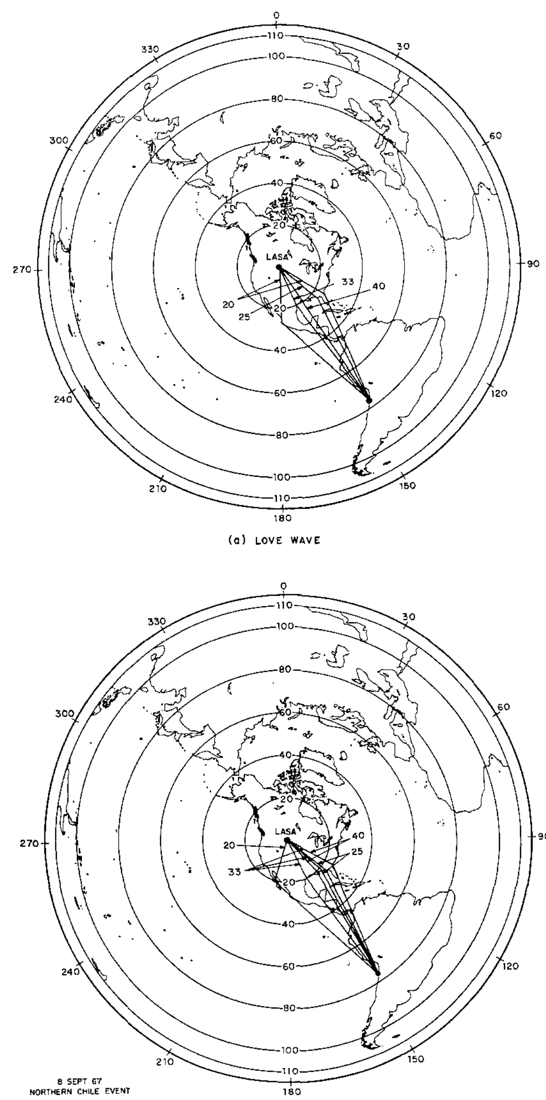

FIG. 11. Propagation paths for the Love and Rayleigh waves of event 12.

period of the group. There were some exceptions, however, in which the multipath propagation was caused by other major tectonic features of the Earth, such as ridges (cf. Figure 12).

We mention also that the present method of analysis has provided a means for identifying Love and Rayleigh waves by essentially using an array of LPZ, LPEW and LPNS sensors. It would appear that the unequivocal identification of these wave types, which propagate along complex multiple paths, requires an array of three-component instruments such as is available at LASA. Thus, the use of only a single three-component instrument does not appear to be sufficient for identifying unequivocally Love and Rayleigh waves.

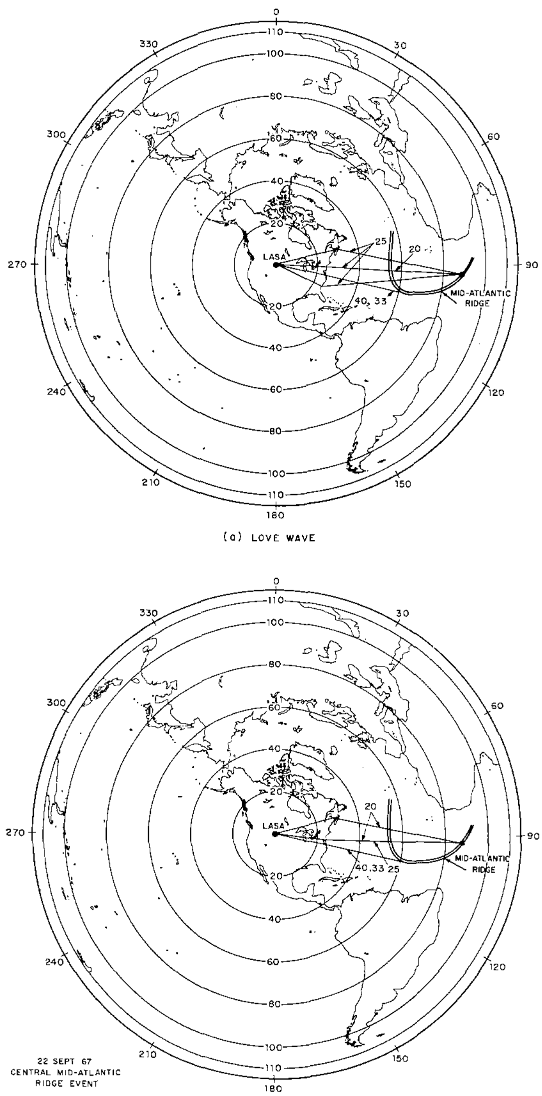

FIG. 12. Propagation paths for the Love and Rayleigh waves of event 17.

It is mentioned, finally, that the present method of analysis is also applicable for identifying noise sources as being of Rayleigh- or Love-wave type, provided that most of the noise is propagating from a single direction. Several such analyses were performed and showed that seismic noise in the 20- to 40 sec-period range consists of both Love waves and Rayleigh waves. In addition, in most cases the Love-wave noise power tended to exceed the Rayleigh-wave noise power (cf. Haubrich and McCamy, 1969).

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