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MULTITAPER CROSS-SPECTRAL ANALYSIS OF CLOSELY LOCATED NTS EXPLOSIONS

Indra N. Gupta
Peter Davis
Thomas W. McElfresh

Teledyne Geotech Alexandria Laboratories
314 Montgomery Street
Alexandria, VA 22314-1581

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I. N. Gupta, J. P. Davis, and T. W. McElfresh

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Location relative to a reference event is often more useful and precise than absolute event location. Such location requires relative times for pairs of events observed at a common station, which can be obtained with high precision for similar events by waveform cross-correlation. The precision can be further boosted by applying the cross-spectral analysis method, which can provide relative delay times with resolution up to an order of magnitude better than the seismogram sampling interval. Software for cross-spectral analysis based on use of both single cosine taper and the significantly more sophisticated multitaper was developed and tested on real data. Analysis of data from six closely-located Yucca Flat explosions provided relative locations with mean location error of only about 1 km; an impressive result if one considers the large epicentral distances and the complex geology of the Nevada Test Site. Mean velocities along the four source-receiver paths were found to be stable and significantly different, suggesting considerable anisotropy. The cross-spectrum method was also applied to regional data from two pairs of closely located NTS explosions recorded at common stations. Our results indicate that the analysis can detect small differences (of the order of 0.1%) in the propagation velocities of regional phases generated by the two shots.

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1. SUMMARY

Location relative to a reference event is often more useful and precise than absolute event location. Such location requires relative times for pairs of events observed at a common station, which can be obtained with high precision for similar events by waveform cross-correlation. The precision can be further boosted by applying the cross-spectral analysis method, which can provide relative delay times with resolution up to an order of magnitude better than the seismogram sampling interval. Software for cross-spectral analysis based on use of both single cosine taper and the significantly more sophisticated multitaper was developed and tested on real data. Analysis of data from six closely-located Yucca Flat explosions recorded at the four broadband digital stations, ELK, KNB, LAC, and MNV provided relative locations with mean location error of only about 1 km; an impressive result if one considers the large epicentral distances (about 200 km to 320 km) and the complex geology of the Nevada Test Site. Inter-source coherence for Pn was found to be significantly greater when the two sources lay along the direction of wave propagation than when perpendicular to it. Mean velocities along the four source-receiver paths were found to be stable and significantly different, suggesting that propagation velocities may vary considerably from one path to another. It seems therefore that at least a part of the observed location errors are due to the assumption of a uniform path-independent velocity model in the computation of location. The cross-spectrum method was also applied to regional data from two pairs of closely located NTS explosions recorded at common stations. Our results indicate that the analysis can detect small differences (of the order of 0.1%) in the propagation velocities of regional phases generated by the two shots. A knowledge of these differences may be useful in a comparison of the near-source characteristics of closely located explosions.

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2. INTRODUCTION

Location relative to a known reference event is often more useful and precise than absolute event location. The use of relative location compensates for most of the errors arising from path effects. Such location requires relative arrival times for pairs of events observed at common stations, which can be obtained with high precision for similar events by waveform cross-correlation. This estimate of the relative time based on the full waveform is generally more precise than that based on rather subjective picks of the initial phase arrival. Conventional cross-correlation slides one waveform past another, and the lag with the optimum correlation coefficient is taken as the relative time. However, the cross-spectral analysis method can yield relative delay times with resolution up to an order magnitude better than the seismogram sampling interval.

A considerable amount of effort was devoted to developing the software for cross-spectral analysis based on use of both single cosine taper and the significantly more sophisticated multitaper. An application to the available data from Yucca Flat explosions demonstrated significant improvement in relative locations when the multitaper is used. A combined use of cross-spectral analysis and the multitaper constitutes a significant improvement over all previous studies of cross-spectral analysis based on the use of a single taper. The cross-spectrum method was also applied to regional data from two pairs of closely located NTS explosions recorded at common stations. Our results indicate that the analysis can detect very small differences (of the order of 0.1%) in the propagation velocities of regional phases generated by the two shots. A knowledge of these differences may be useful in a comparison of the near-source characteristics of closely located explosions.

3. CROSS-SPECTRAL ANALYSIS WITH MULTITAPER

Single taper cross-spectral analysis of regional data from Yucca Flat explosions with precisely known locations provided relative locations that were accurate to within about 1 km. However, locations based on arrival times determined by alignment of the first peaks were found to be somewhat better (Gupta and Davis, 1992). A possible reason for this disappointing performance was suspected to be the use of a cosine taper on rather short signal windows. We therefore applied the multitaper method of spectral analysis which has been shown to yield better results than standard single-taper procedures (Park *et al.*, 1987; Zhu *et al.*, 1989).

We employed the multitaper method, based on a family of tapers which are resistant to spectral leakage, by mainly following the procedure described by Park *et al.* (1987) and Vernon *et al.* (1991). A set of k tapers $v_n^k(n,w)$ are generated which are functions of the time series length n and the specified inner bandwidth w. The tapers are the eigenvectors of the Toeplitz matrix with associated eigenvalues λ_k. Following Park *et al.* (1987), w was selected to be 4, and only those tapers with λ_k greater than 0.9 were used. With these two restrictions, k was found to be equal to 7, independent of the number of points in the signal window.

Consider two signals A and B represented by the time series $f_a(t)$ and $f_b(t)$, respectively. The signals are windowed (e.g. 64 or 128 samples of data), calibrated, demeaned, and detrended, providing the signals $X_a(n)$ and $X_b(n)$, respectively, where n is the number of samples in the selected window. Let $Y_a^k(N)$ and $Y_b^k(N)$ represent the Fourier transforms of $v_n^k X_a(n)$ and $v_n^k X_b(n)$, where $N = \frac{n}{2}+1$, respectively.

An adaptive spectral estimate of $f_a(t)$, $\hat{S}_a$ is formed by

$$\hat{S}_a = \frac{\sum_k |d_a^k(N)\ Y_a^k(N)|^2}{\sum_k |d_a^k(N)|^2} \tag{1}$$

where the weights d_a^k, which depend on frequency (N) and on the taper order k, are chosen to reduce bias from spectral leakage. An initial spectral estimate is made by assuming

$$\hat{S}_a = \frac{|Y_a^1|^2 + |Y_a^2|^2}{2} \tag{2}$$

The first guess for weights is then made by

$$d_a^k(N) = \frac{\sqrt{\lambda_k}\ \hat{S}_a}{\lambda_k\ \hat{S}_a + (1-\lambda_k) \sum_{i=1}^{n} [X_a(i)]^2} \tag{3}$$

A new spectral estimate of $\hat{S}_a$ is made by inserting the weights from equation (3) into equation (1) and using this new value into equation (3) to compute the corresponding new weights. This process is repeated until the relative error between two successive $\hat{S}_a$ is less than 0.0001. Once the weights have been determined, the multitaper cross-spectrum is computed from:

$$Y_{ab} = \frac{\sum_k (\lambda_k)^{-1} \sum_k \lambda_k\ d_a^k(N)\ Y_a^k(N)\ d_b^k(N)\ [Y_b^k(N)]^*}{k\ [\sum_k d_a^k(N)^2\ ]^{1/2}\ \ [\sum_k d_b^k(N)^2\ ]^{1/2}} \tag{4}$$

where * indicates the complex conjugate. If Y_{ab} is expressed as

$$Y_{ab}(N) = Re(N) + i\ Im(N), \tag{5}$$

the phase spectrum $\phi(N)$ is

$$\phi(N) = \tan^{-1} \frac{Im(N)}{Re(N)} \tag{6}$$

If the two seismograms are identical in shape but have different amplitudes and are shifted in time by τ, then

$$f_b(t) = k\ f_a(t+\tau), \tag{7}$$

and by the application of the shift theorem, the phase spectrum becomes

$$\phi(N) = 2\,\pi\,N\,\tau \tag{8}$$

Thus the delay time τ can be obtained simply by fitting a straight line through the phase of the cross-spectrum with zero intercept. In fitting this slope, the values are weighted based on the coherence γ_{ab}:

$$\gamma_{ab}^2 = \frac{|Y_{ab}|^2}{Y_{aa}\,Y_{bb}} \tag{9}$$

The weighting factor, W(N) in the linear fit is based on the Hannon-Thomson processor (Knapp and Carter, 1976), *i. e.*

$$W(N) = \frac{\gamma_{ab}^2(N)}{1 - \gamma_{ab}^2(N)} \tag{10}$$

The slope of the line has a continuum of possible values, rather than discrete values, with the result that estimates of delay time for highly coherent pairs can actually be an order of magnitude more precise than the sample rate. This technique has been applied successfully to local sequences of earthquakes with impressively precise locations (Ito, 1985; Fremont and Malone, 1987).

Regional data from six closely spaced underground nuclear explosions at the Nevada Test Site (NTS), recorded at the four broadband digital stations, ELK, KNB, LAC, and MNV (Table 1 and Figure 1), have been analyzed to determine how the cross-spectral method may best be used to improve relative locations. For these explosions, with precisely known locations, the near-source geological and geophysical properties are also known so that the influence of parameters such as shot depth and geological environment can also be investigated. Software for determining the delay time between two waveforms has been developed and tested. The relative arrival times between two events recorded at a common station may be determined with a precision as small as 0.001 sec. As an example, results from the

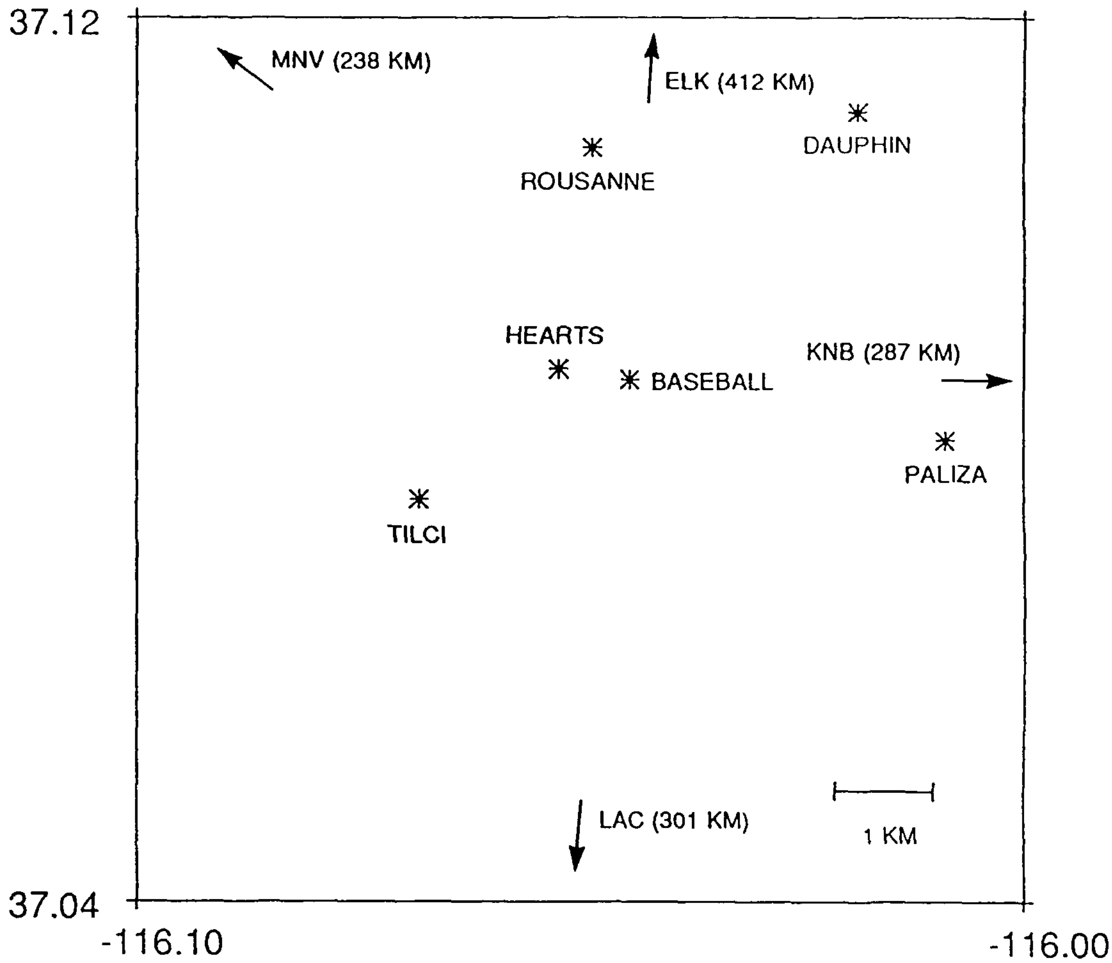

Figure 1. Map of six Yucca Flat explosions used in the study. Azimuthal directions and distances from BASEBALL to the four recording stations are indicated.

vertical component ELK records of the Yucca Flat explos[illegible] and PALIZA are shown in Figure 2. The digital data are sampled at 42 samp[illegible] signal window is 64 points (about 1.5 sec). Figure 2 (bottom) shows the [illegible] which may be selected to be of any desired duration. The signal window over which a cosine taper applies is also variable. The top plot shows the phase of the cross-spectrum varying between $-\pi$ and $+\pi$ whereas the lower plot shows the coherency, varying between 0 and 1, derived by using a bandwidth of 2.0 Hz. The delay time of 0.0477 (0.0473) sec is simply the slope of the phase of the cross-spectrum over the specified range of 0.5-5.0 Hz and is obtained by fitting a slope through 0, using a weighting scheme based on coherence of the cross-spectrum (equation 10); the quantity within parentheses denotes one standard deviation.

TABLE 1

6 YUCCA FLAT EXPLOSIONS USED IN STUDY

No.	DATE	NAME	m_b	P-WAVE VEL (KM/S)	SHOT DEPTH (KM)	DEPTH OF WT (KM)
1	06 Sep 1979	HEARTS (B)	5.892	1.763	0.6400	0.5070
2	14 Nov 1980	DAUPHIN (A)	4.554	1.420	0.3200	0.5800
3	15 Jan 1981	BASEBALL (B)	5.725	1.970	0.5639	0.5120
4	01 Oct 1981	PALIZA (A)	5.115	1.497	0.4724	0.5300
5	11 Nov 1981	TILCI (A)	5.035	1.600	0.4450	0.4940
6	12 Nov 1981	ROUSANNE (B)	5.458	1.580	0.5182	0.4950

Note: B and A denote shots below and above the water table, respectively.

Figure 3 shows results of cross-spectral analysis when the signal window is doubled to 128 points. A comparison with Figure 2 shows a decrease in the average coherency and an increase in the delay time. Results when the cosine tapers in Figures 2 and 3 are replaced by multitaper are shown in Figures 4 and 5, respectively. Note the significant improvement in

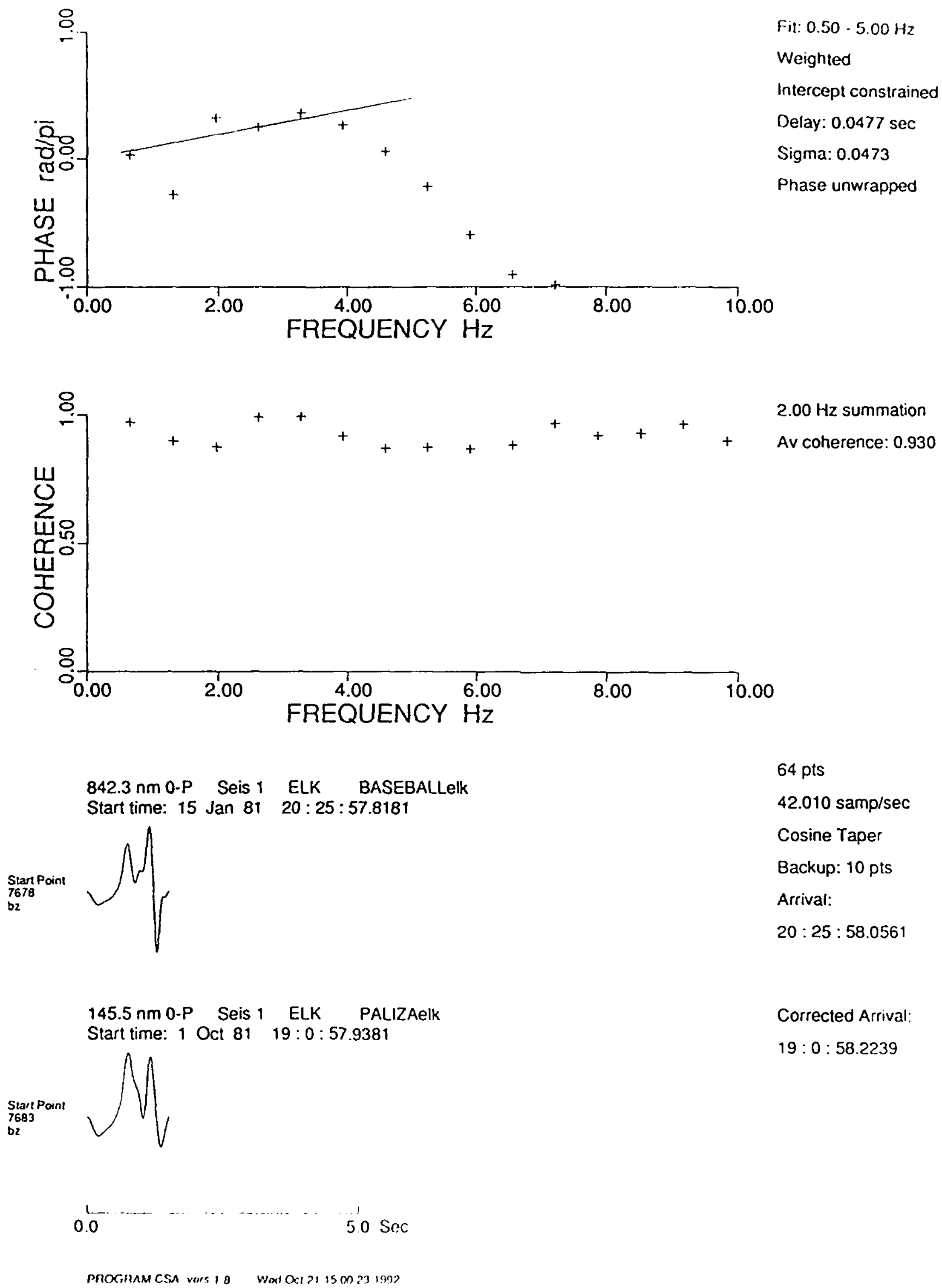

Figure 2. Cross-spectral analysis for measuring delay times based on use of the cosine taper. The two input waveforms at ELK (bottom), each 64 points long, provide the phase of the cross-spectrum (top) and coherence based on bandwidth of 2.0 Hz for frequencies up to 10 Hz. Mean slope of the phase spectrum, averaged over the indicated frequency range of 0.5-5.0 Hz, provides the delay time used to obtain the corrected arrival time for PALIZA.

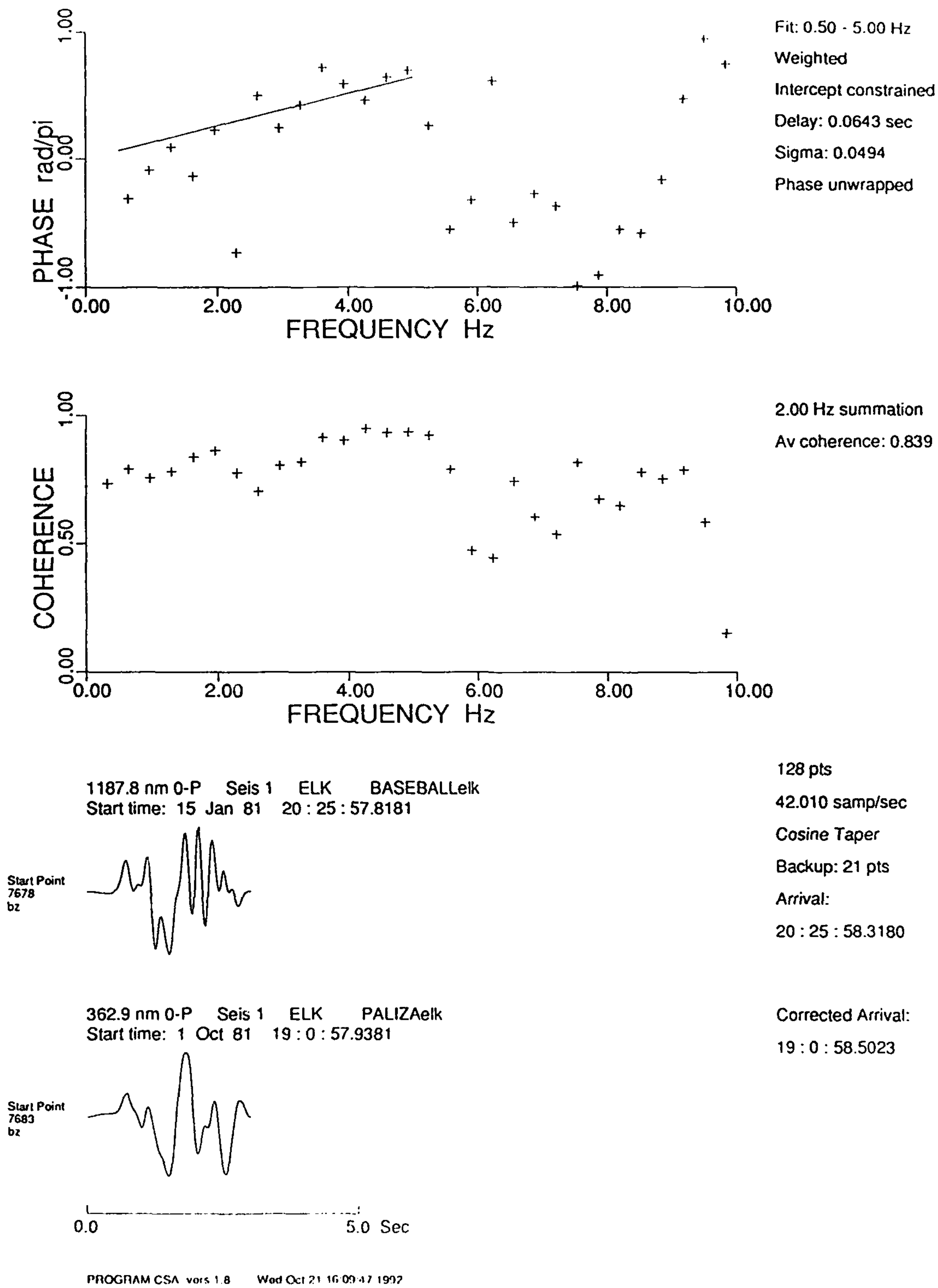

Figure 3. Similar to Figure 2 for signal windows of 128 points.

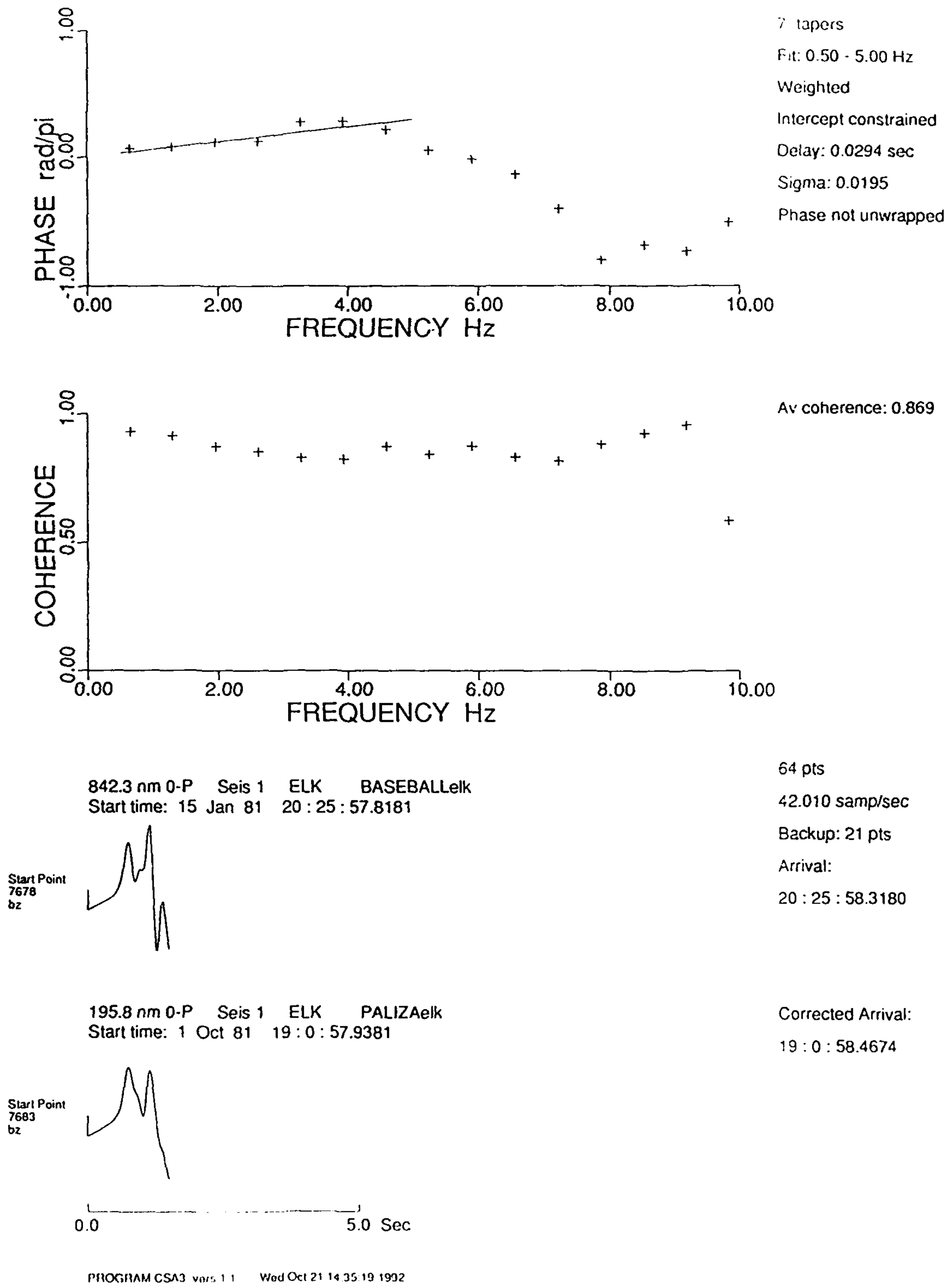

Figure 4. Similar to Figure 2 based on use of the multitaper (seven tapers).

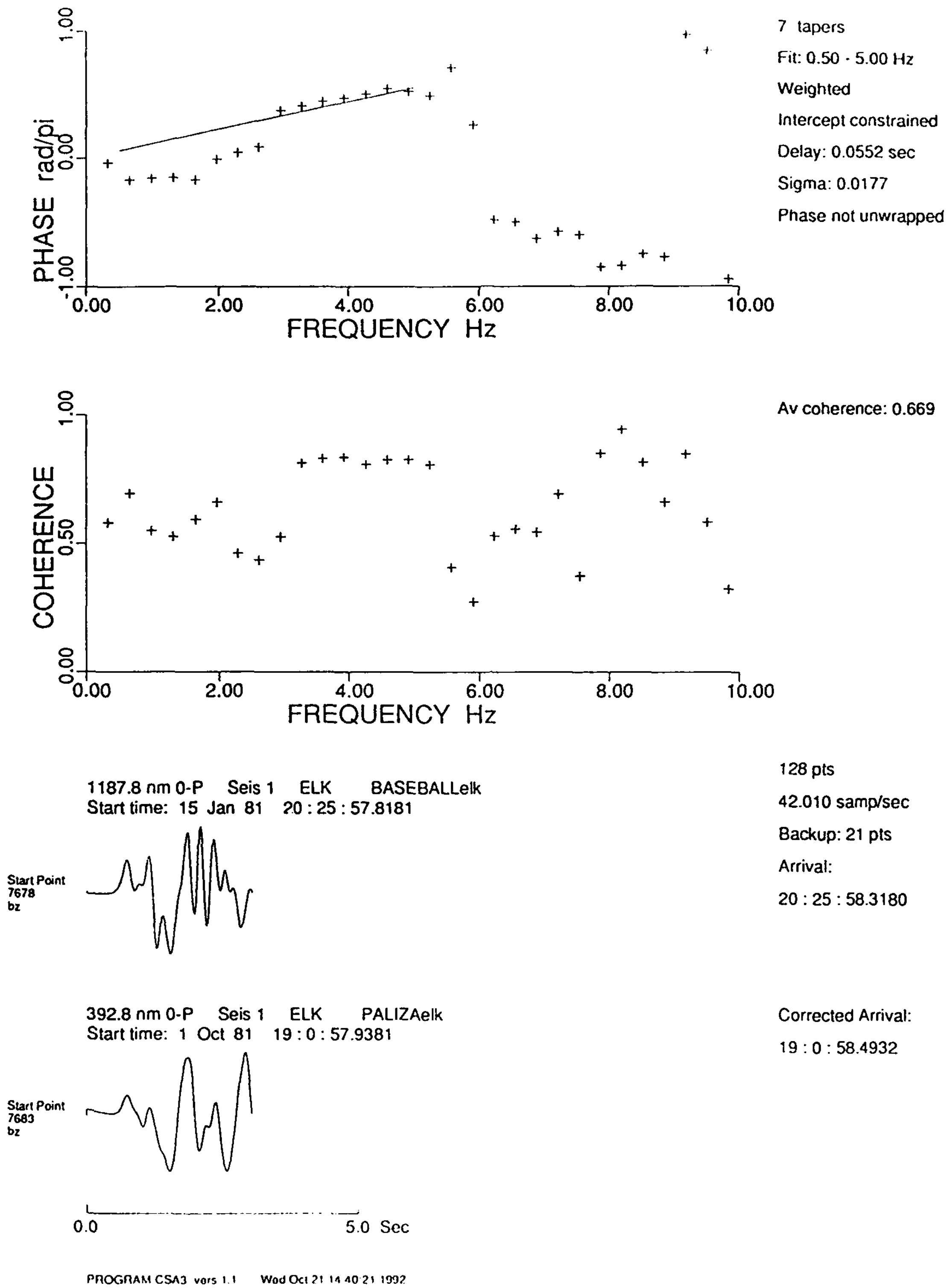

Figure 5. Similar to Figure 2 based on use of the multitaper and signal windows of 128 points.

the determination of delay times as indicated by the improved fits of mean slope and the reduced values of standard deviation.

Assuming BASEBALL to be the reference shot with known location and its first peak at each station as the reference time, cross-spectral analysis was carried out to obtain the corrected arrival times (such as those indicated on Figures 2, 3, 4, and 5) for each explosion recorded at the four stations. Results based on use of the cosine taper and signal windows of 128 points were first determined. For each explosion, the four arrival times are used as input to the LOCATE feature of the Analyst Review Station (ARS) to obtain the epicentral location and the origin time. The arrival times (without any delay correction) for BASEBALL recorded at the four stations are also used to compute the corresponding ARS location. The ARS computed locations and the actual (known) locations of six explosions are shown in Figure 6. The ARS computed locations for the five shots (paired with BASEBALL) are shifted by the amount of shift between the ARS computed and actual locations of BASEBALL. A comparison of the shifted locations of each of the five shots with its actual location provides the location error associated with each shot (Figure 6). The mean location error is only 1.32 (0.61) km. Cross spectral analysis based on the use of longer (256 points) windows was also carried out for the same six explosions. Using a bandwidth of 1.0 Hz for deriving coherency and a frequency range of 0.5-5.0 Hz for computing the delay time, the location results were found to be very similar to those in Figure 6 in both the magnitude and azimuthal direction of the location errors; the mean location error was 1.22 (0.61) km.

Locations based on the use of arrival times determined by simple alignment of the first peaks at common stations are shown in Figure 7. A comparison with locations derived by using the cross-spectral analysis (Figure 6) shows significant improvement, especially for the

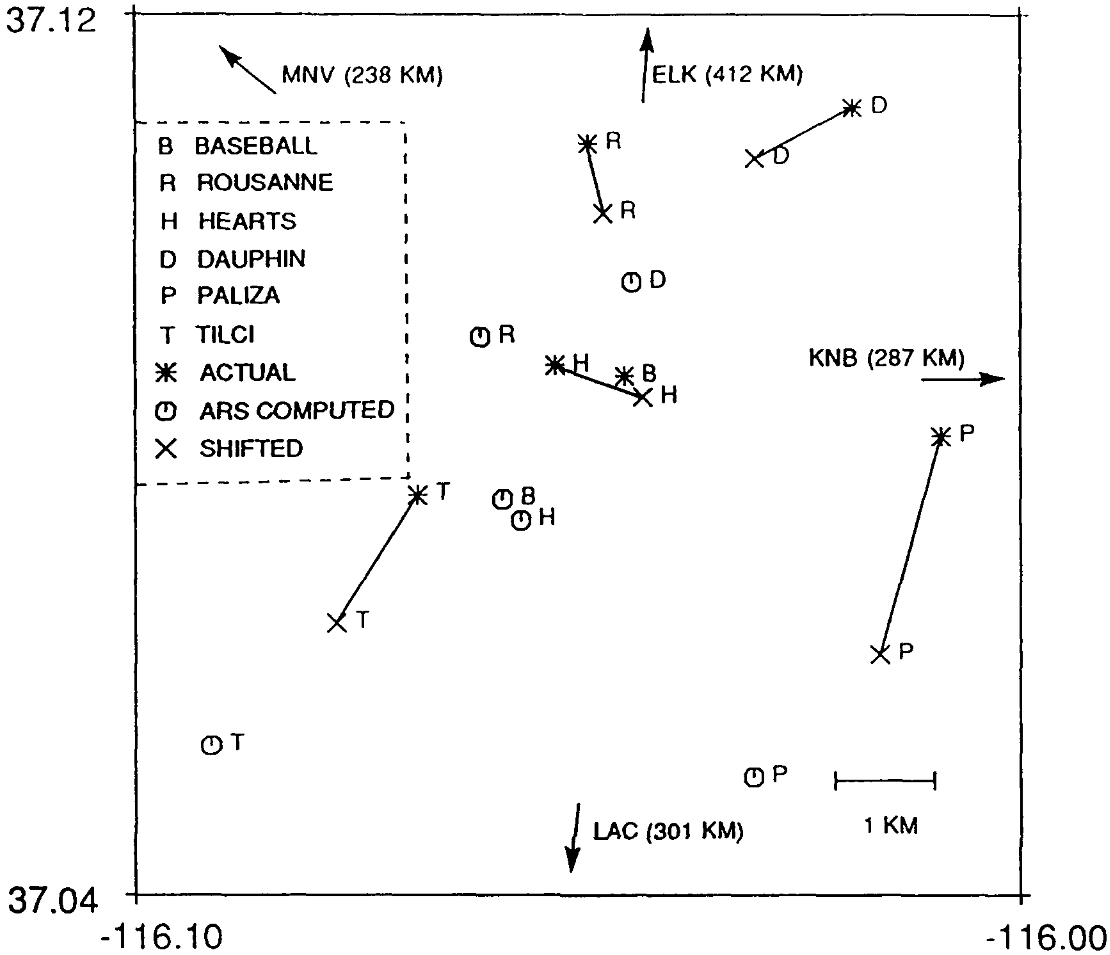

Figure 6. Location results for six Yucca Flat explosions based on arrival times derived from cross-spectral analysis using the cosine taper and signal windows of 128 points. Actual locations, ARS computed locations, and locations with shift based on BASEBALL are shown; the five lines indicate the error between the actual and computed locations. Mean location error is 1.318 (0.614) km.

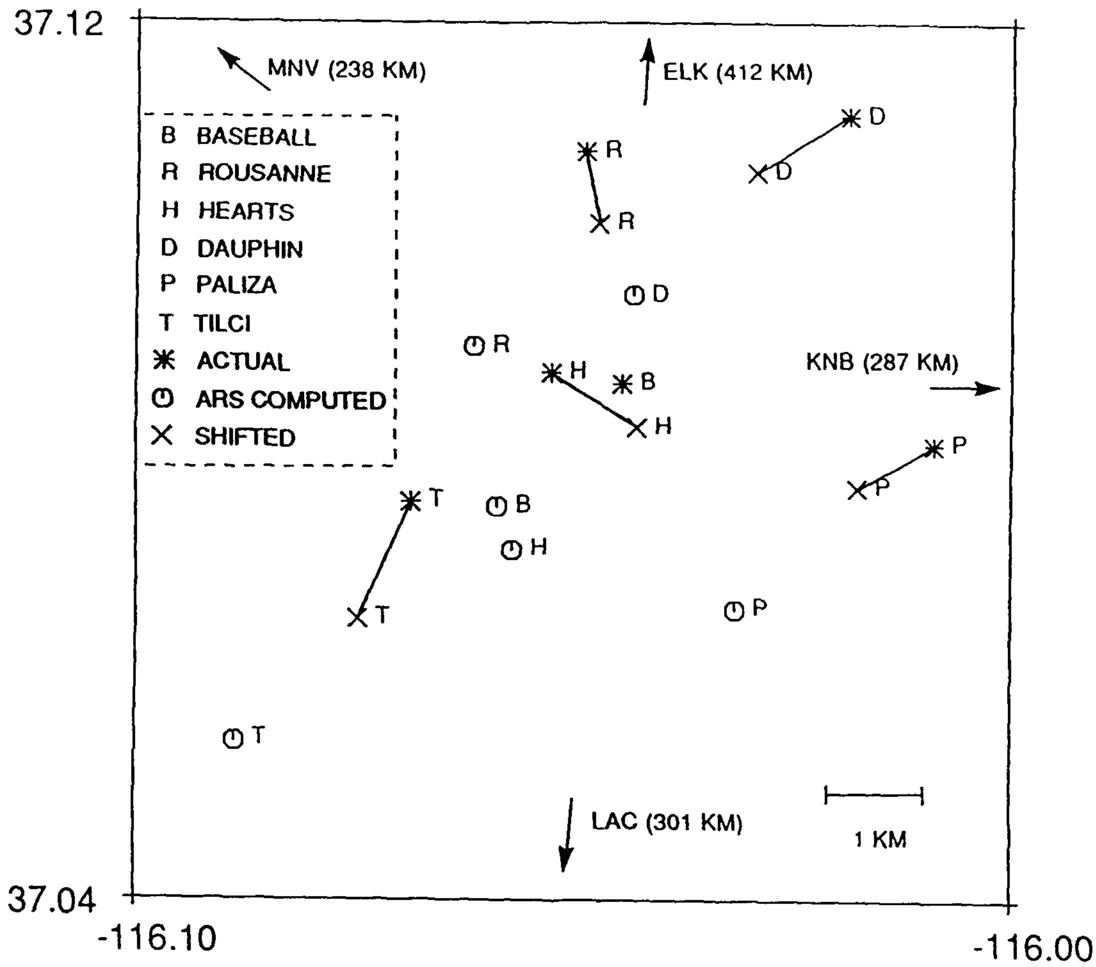

Figure 7. Similar to Figure 6 but derived from simple alignment of the first peaks of all explosions recorded at the four recording stations. Mean location error is 1.017 (0.218) km.

two shots PALIZA and TILCI. The mean location error is only 1.017 (0.218) km. Possible reasons for the smaller accuracy of the cross-spectral analysis are the spectral leakage and variability for the estimates expected when cosine taper is used on rather short time series (Vernon *et al.*, 1991).

Location results based on use of the multitaper and signal windows of 64 points are shown in Figure 8. There is significant improvement compared to the results with cosine taper (Figure 6); the mean location error is 1.010 (0.221) km. These results appear to be impressive if one considers the large epicentral distances (about 200 km to 400 km) and the complex geology of the Nevada test site.

Analysis of regional data from Yucca Flat explosions also provides valuable information regarding inter-source coherence of closely located explosions recorded at common stations. A comparison of the coherency plots in Figures 2 and 3 or Figures 4 and 5 indicate that the shorter signal windows of Pn have significantly better coherency over a much larger range of frequency than the longer windows. This implies that the first arrivals in Pn are considerably more similar than the later arriving phases, perhaps due to greater contamination by later-arriving scattered energy. Furthermore, inter-source coherence for Pn appears to be significantly greater when the two sources lie along the direction of wave propagation than when perpendicular to it. This is illustrated by comparison of coherence at ELK and KNB for two pairs of explosions BASEBALL and ROUSANNE (Figure 9) and BASEBALL and PALIZA (Figure 10). These results were based on use of the multitaper and signal windows of 128 points. For BASEBALL and ROUSANNE, ELK and KNB are nearly along and perpendicular to the direction of wave propagation, respectively. On the other hand, for BASEBALL and PALIZA, ELK and KNB approximate directions perpendicular to and along the

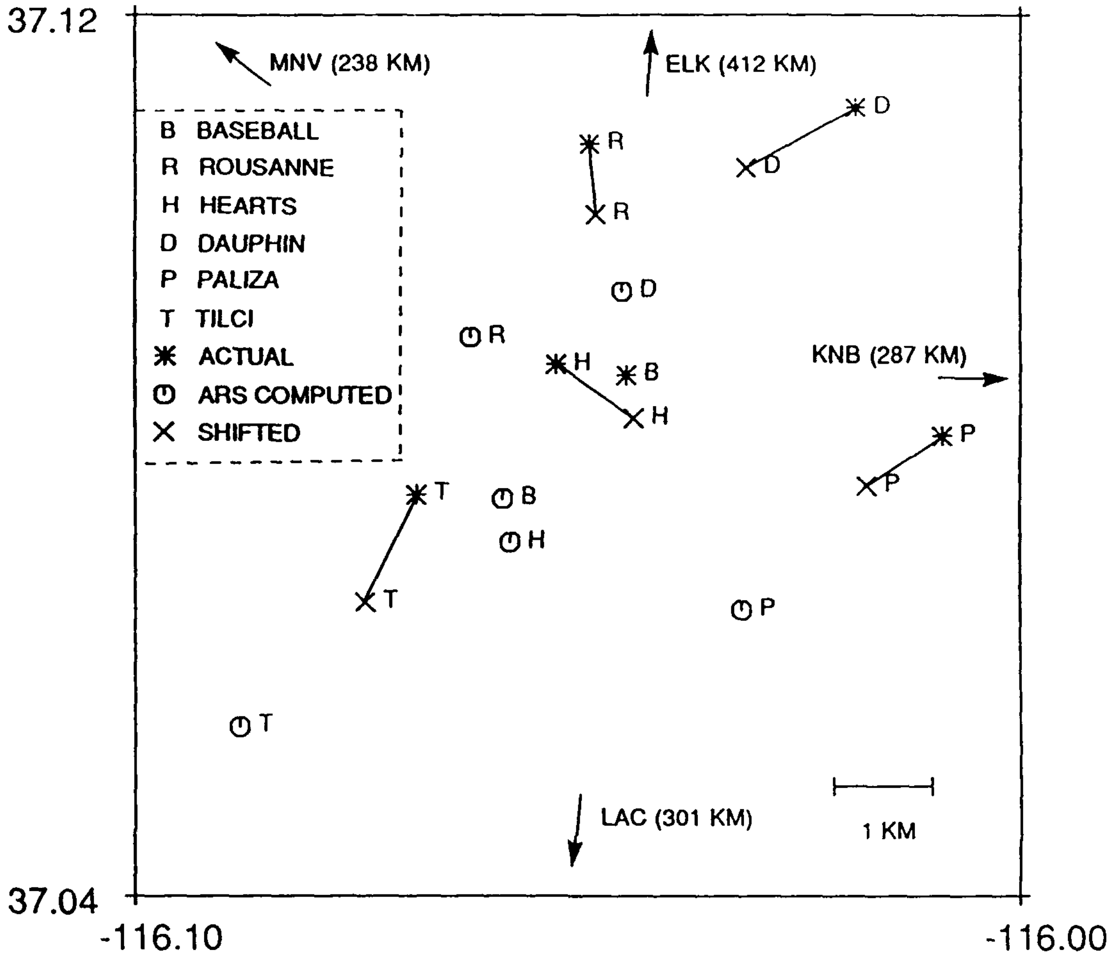

Figure 8. Similar to Figure 6 but derived from cross-spectral analysis based on use of the multitaper and signal windows of 64 points. Mean location error is 1.010 (0.221) km.

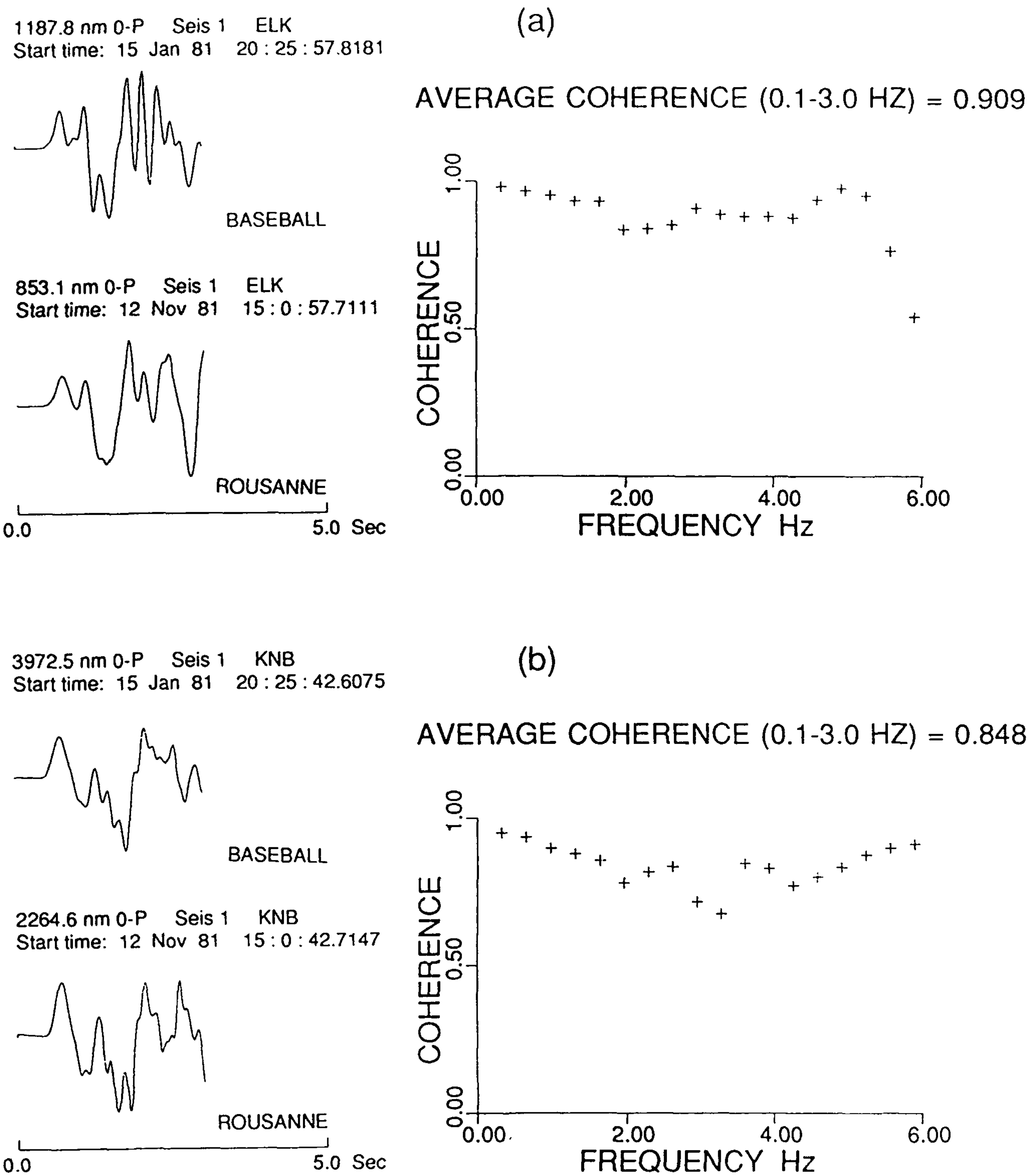

Figure 9. Waveform and coherency plots for BASEBALL and ROUSANNE recorded at ELK and KNB showing the inter-source coherency for Pn (over the frequency range of 0.1-3.0 Hz) to be larger when the two sources lie nearly along the direction of wave propagation than when approximately perpendicular to it.

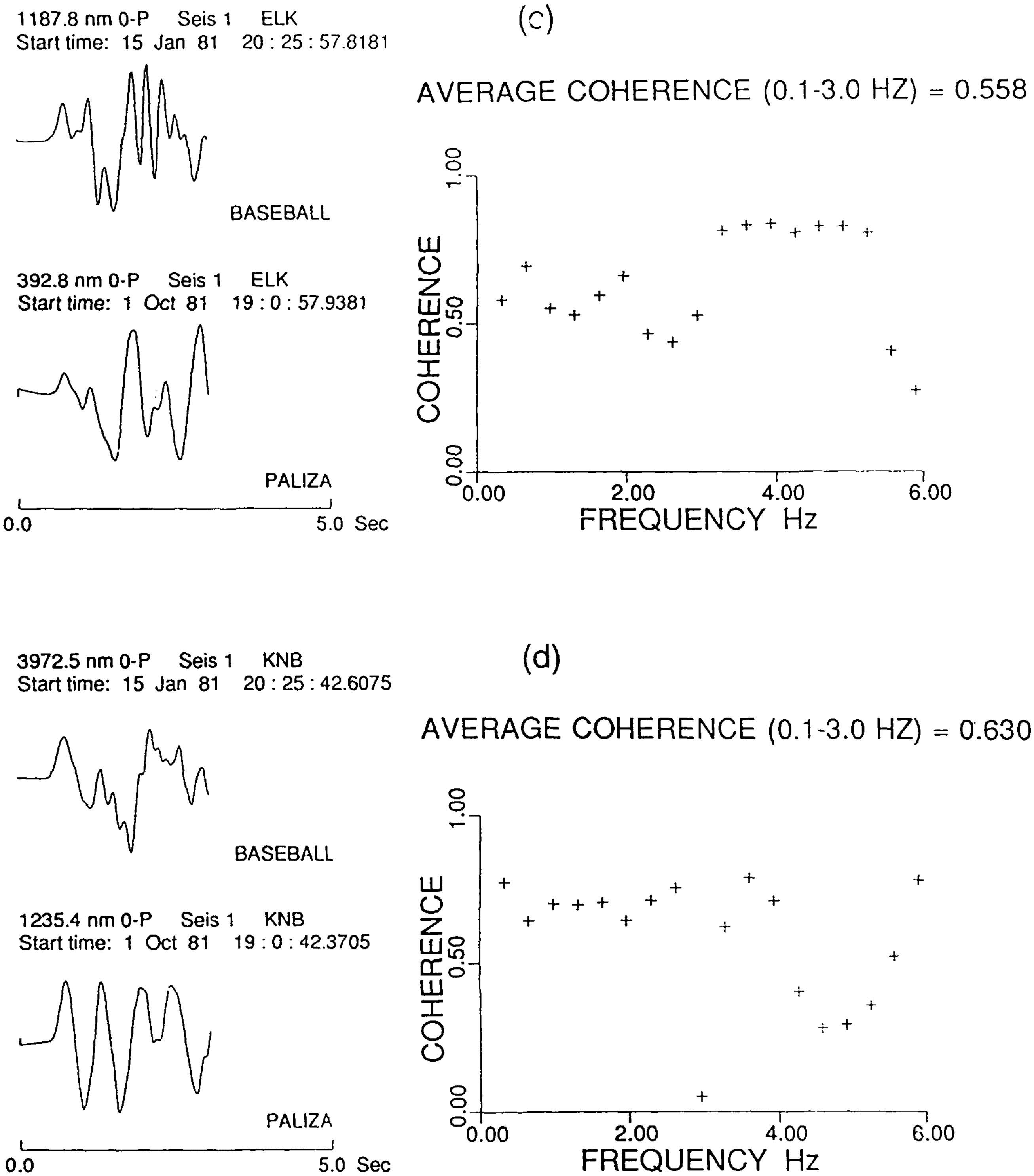

Figure 10. Waveform and coherency plots for BASEBALL and PALIZA recorded at ELK and KNB, again showing the inter-source coherency for Pn (over the frequency range of 0.1-3.0 Hz) to be larger when the two sources lie nearly along the direction of wave propagation than when approximately perpendicular to it.

wave propagation. These results, based on use of the multitaper and signal windows of 128 points, are similar to the inter-sensor coherence of regional phases generally observed to be greater along the radial direction than along the transverse direction. An attempt will be made to exploit these coherency differences to improve locations. Analysis of the Lg phase showed the inter-source coherence to be significantly smaller than for Pn, again similar to the observed inter-sensor coherence results for Lg and Pn. Also, coherency appeared to vary significantly from one station to another.

In order to understand what causes the discrepancy between the actual locations and those computed from observations of Pn from the Yucca Flat explosions, we examined the lateral variations in the Pn velocity under the test site. Pn arrival times from closely spaced explosions can be used to estimate average velocities to various stations if the spatial locations of the explosions are precisely known and data from at least two shots are available.

Consider a number of closely located sources, S_i recorded at a number of well-separated receivers, R_j. Let the average P-wave velocities from the limited source region to the relatively distant receivers be α_j. If r_{ij} represents the distance from source S_i to the receiver R_j and z_i are the origin times of the various sources, then the P-wave arrival times, T_{ij} are given by

$$T_{ij} = \frac{r_{ij}}{\alpha_j} + z_i \qquad (11)$$

Having data from two or more sources at two or more receivers, we can solve for α_j by using the method of least squares.

Using Pn arrival times, based on alignment of the first peaks, from six explosions (Table 1) recorded at the four stations, the mean velocities to the four stations ELK, KNB, LAC, and

MNV were determined to be 7.051 (0.006), 6.636 (0.007), 6.767 (0.007), and 6.469 (0.008), respectively. The quantities within parentheses, denoting one standard deviation of the mean, are remarkably small so that the velocity differences are significant and outside the margin of error. The large differences in mean velocities (maximum about 9%) along the four source-receiver paths suggest that propagation velocities may vary considerably from one path to another. Moreover, our results indicate velocities along the north-south direction to be somewhat larger than those along the east-west direction, in general agreement with the tectonics of the region and the velocity measurements of Harmsen (1992). It seems therefore that at least a part of the observed location errors are due to the assumption of a uniform path-independent velocity model.

4. COMPARISON OF DATA FROM CLOSELY LOCATED SHOTS

Cross-spectrum analysis has been used to provide a high-precision method for measuring temporal velocity changes in the earth's crust (Poupinet *et al.*, 1987). The method compares the scattered wave portions, or coda, of two highly similar waveforms, generated by a pair of nearly identical sources (called doublets), recorded at the same receiver at different times. By analyzing progressive relative phase delays between the two doublet signals as a function of elapsed time, velocity changes on the order of 0.01% could be measured. The high precision of the doublet method is possible because coda waves from colocated sources will sample the same regions and generally follow paths that increase in length with elapsed time. Thus a small decrease in velocity occurring within the sampled region during the time period between the doublet origin times will produce a relative delay that increases with elapsed time over some portion of the scattered waves. If the velocity change is pervasive, the relative delay may increase linearly over the entire coda. This trend of increasing delay is easier to detect and measure than an isolated delay based on a single arrival. Using active, repeatable sources instead of natural earthquakes, Roberts *et al.* (1992) used the doublet method for measuring small velocity and attenuation changes in solids.

A significant improvement to Poupinet *et al.*'s (1987) method of measuring velocity changes was made by Roberts *et al.* (1992) who took full advantage of the principal assumption that, as long as dispersion and mixed wave type effects are negligible, the cross-spectral phase is linear with a value of zero at the intercept. This assumption makes it possible to eliminate the intermediate phase-versus-frequency regression steps so that, instead of estimating a single delay point for each time window, all phase data may be converted to units of equivalent time delay as:

$$\tau(t, f) = \frac{\phi(t, f)}{2 \pi f} \tag{12}$$

All phase-derived delay times are then plotted directly versus elapsed time. In this way all usable phase data may be fit simultaneously to obtain velocity changes in one step rather than two. This allows trends in the measured delay times to be derived from the cross-spectral phase directly rather than from intermediate measurements based on the slope of the ϕ-versus-f curves. This is particularly useful for reducing errors caused by erratic phase data at lower frequencies when dealing with narrow-band data. This approach, designated as the "one-step-regression technique" by Roberts *et al.* (1992), also minimizes the influence that spurious outlying phase data have on the delay estimates and eliminates the need for visual inspection of intermediate ϕ-versus-f plots.

The Pahute Mesa explosions BUTEO (12 May 1965, shot depth 696 m, yield 0.7 kt) and DURYEA (14 April 1966, shot depth 544 m, yield 65 kt) were closely located (probably in the same hole) and generated similar records at two common LRSM stations, MN-NV and KN-UT at epicentral distances of 201 and 321 km, respectively (Blandford, 1976). Using 20 samples/sec data at MN-NV, equivalent time delays were derived (by using equation 12) for overlapping 64-point (3.2 sec) windows incremented by 5 points (0.25 sec). The results are shown in Figure 11 in which the range of frequencies is 1.0-3.0 Hz and only those points satisfying the conditions (1) coherency at least 0.8 and (2) S/N power ratio of at least 2 in the spectra of each of the two waveforms are plotted. A comparison of delays in the first several windows (Figure 11) shows a gradual increase with elapsed time, followed by a gradual decrease to nearly 0. The increase over the first 1.5 sec of the elapsed time has a mean slope of 0.0286, indicating a relative decrease in mean velocity of about 2.9% for DURYEA versus BUTEO. This result implies that for the P waves arriving at MN-NV in the first few seconds,

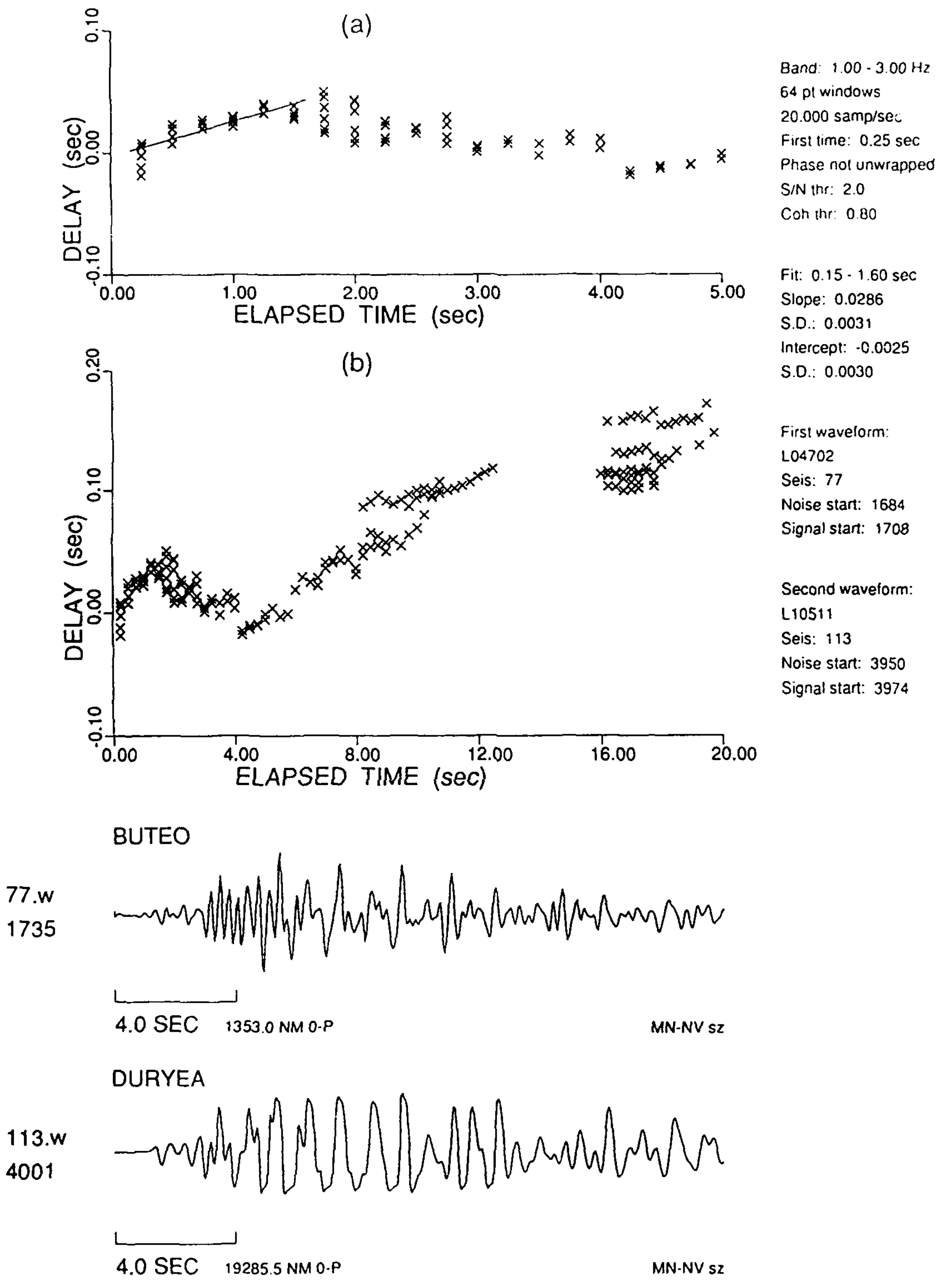

Figure 11. Cross-spectral analysis of the vertical component MN-NV records of BUTEO and DURYEA (shown at bottom) indicating delay time versus the elapsed time. Results for the first 5 and 20 sec, shown in (a) and (b), respectively, are based on the use of 3.2 sec long windows with incremental shift of 0.25 sec and the frequency range of 1.0-3.0 Hz. Delay time over the first 1.5 sec of elapsed time has an average slope of about 0.029.

the average near-source velocity for DURYEA is about 3% lower than that for BUTEO. Seismic reflection surveys before and after a nuclear detonation (e.g. Miller and Steeples, 1992) have indicated velocity differences of about 10% in the vicinity of the shot points. The zone of intense fracturing typically occurs out to a radius of about three times the cavity radius, which in turn varies approximately as the cube-root of the explosive yield (Lamb *et al.*, 1991).

Gupta *et al.* (1991) proposed that near-source scattering of the explosion-generated fundamental-mode Rayleigh waves (Rg) into P (referred to as Rg→P hereafter) may be responsible for the large arrivals immediately following P and pP on NORSAR records of Nevada Test Site (NTS) shots. Theoretical studies of near-source scattering by explosion sources in the Yucca Flat (NTS) region by McLaughlin *et al.* (1987) and Stead and Helmberger (1988) also demonstrated that locally scattered Rayleigh waves may be responsible for arrivals immediately following P and pP. Therefore, it seems likely that the first several seconds of Pn include a significant amount of the low-frequency Rg→P arrivals due to near-source scattering and these scattered waves pass through the near-source lower velocity region associated with the fracture zone. Since the larger explosion DURYEA will have a much larger lower velocity zone than the much smaller shot BUTEO, the scattered arrivals from DURYEA will be somewhat more delayed than those from BUTEO. Other aspects of the scattered waves from the two shots should be nearly identical because of common epicentral region and propagation paths. The initial gradual increase in delay time with elapsed time (Figure 11) may therefore be due to progressive scattering of Rg→P as Rg propagates outwards in all directions from the epicentral region and the scattered P pass through a greater volume of lower velocity medium for DURYEA than for BUTEO. The relative delays start diminishing when the Rg→P waves from DURYEA have gone beyond its lower velocity (or the fracture) zone and the propagation media for Rg→P waves from both shots have become almost identical. A possibility for the second round of relative delays, starting near the onset of Pg, is the contribution of Rg to Pg, perhaps by scattering into S since Pg is expected to include significant amount of P derived from near-source scattering of S (Kennett, 1989). The second cycle of relative delays appears to be significantly longer than the first cycle and a possible explanation is the observation (Carroll, 1981) that, in the near-source fracture zone, S-wave velocity is generally reduced by a much larger amount and over a larger volume than the P-wave velocity.

Results of similar processing of data from the same two explosions recorded at KN-UT are shown in Figure 12. The mean slope in Figure 12, averaged over the first 2.5 sec of elapsed time, has a mean slope of about 0.0136, suggesting a velocity decrease of about 1.4%. These results are qualitatively similar to those in Figure 11 but quantitatively different, perhaps because of the expected anisotropic characteristics of scattered waves.

Figures 13 and 14 show results of similar analyses of regional data from another pair of closely spaced normal and overburied explosions. BASEBALL and BORREGO have the same shot depth and are less than 500 m apart. On the basis of their m_b values, the yield of the overburied shot, BORREGO is at least a factor of 50 smaller than that of BASEBALL. The general similarity of the previous results (from BUTEO and DURYEA) to those from this pair of shots recorded at the two digital stations, KNB and LAC suggests that our analysis provides a systematic method of detecting and measuring small differences in the velocities of the near-source media of closely located explosions.

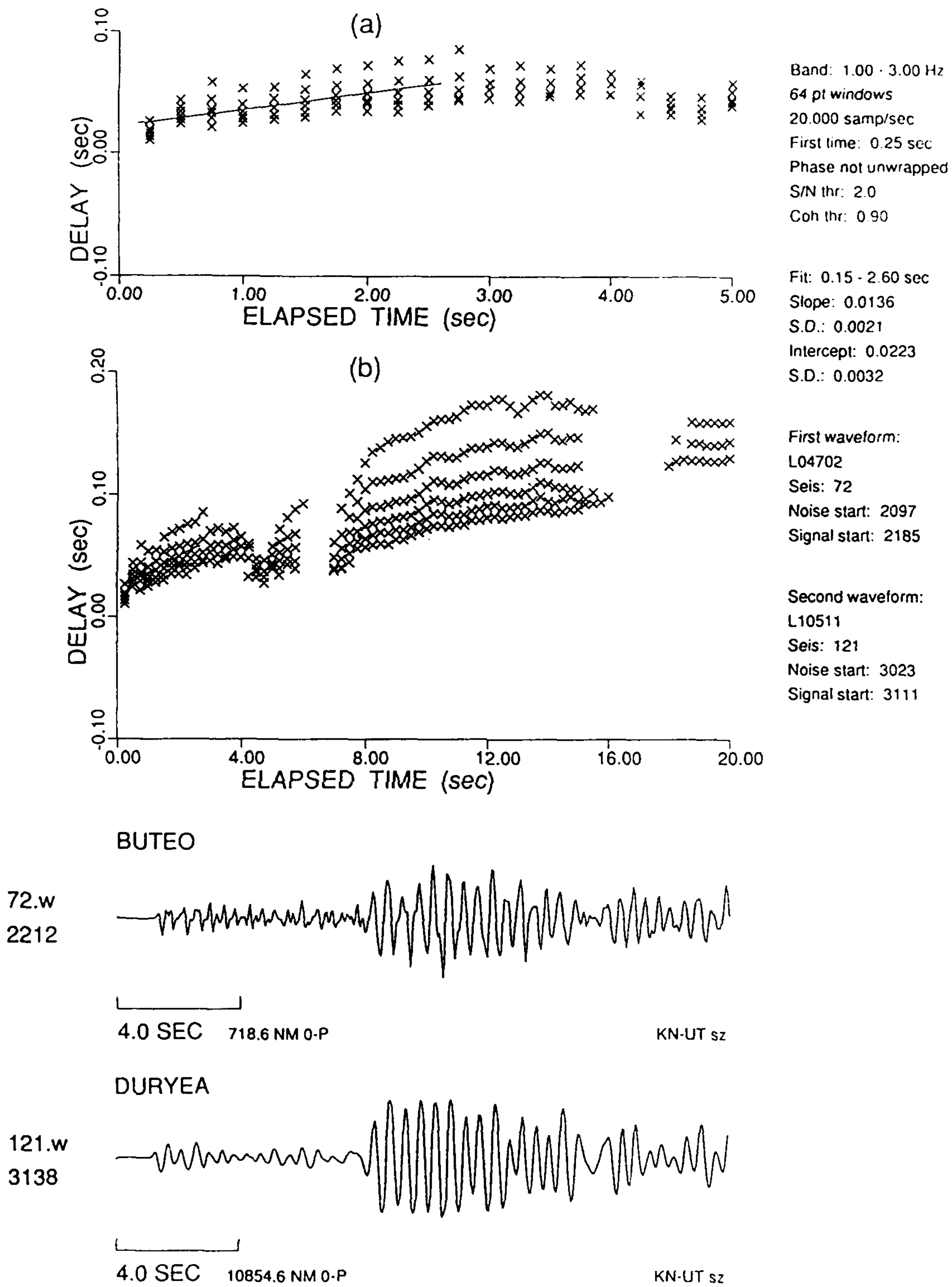

Figure 12. Similar to Figure 11 but derived from the vertical component KN-UT records of BUTEO and DURYEA (shown at bottom). Delay time over the first 2.5 sec of elapsed time has an average slope of about 0.014.

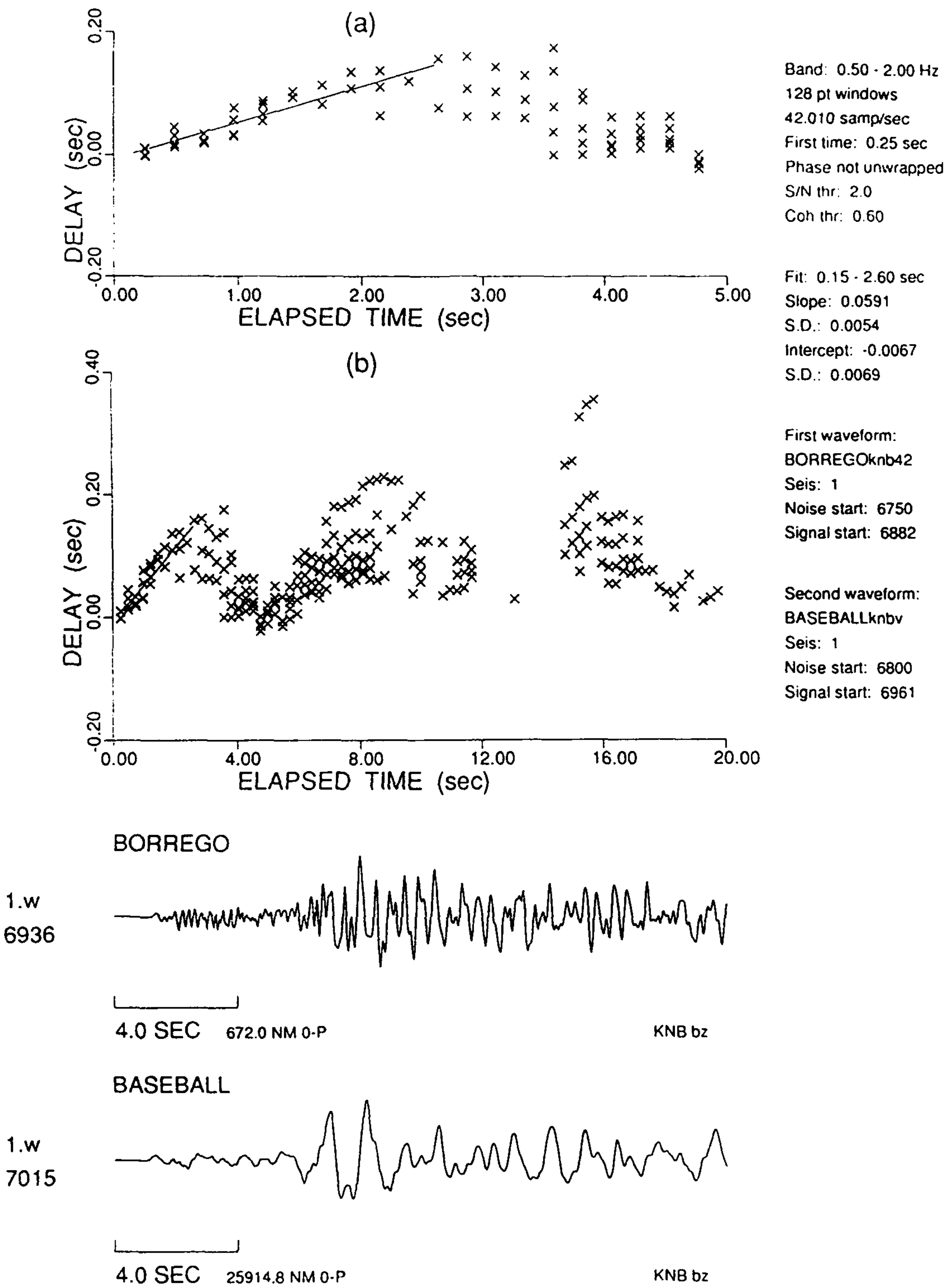

Figure 13. Similar to Figure 11 but derived from the vertical component KNB records of BORREGO and BASEBALL (shown at bottom). The frequency range is 0.5-2.0 Hz and the windows are about 3.05 sec (128 points) long with incremental shift of about 0.24 sec (10 points). Delay time over the first 2.5 sec of elapsed time has an average slope of about 0.059.

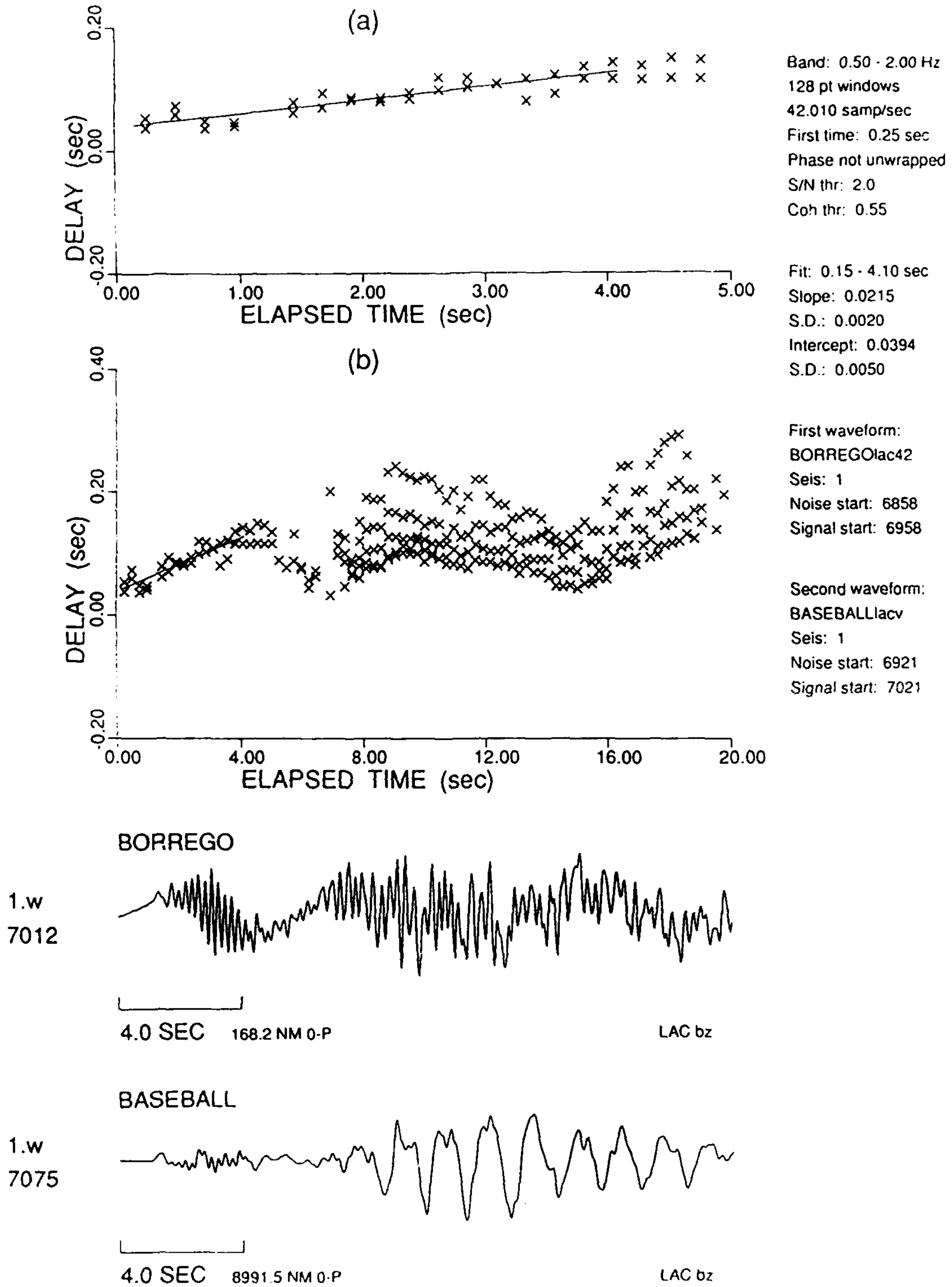

Figure 14. Similar to Figure 11 but derived from the vertical component LAC records of BORREGO and BASEBALL (shown at bottom). The frequency range is 0.5-2.0 Hz and the windows are about 3.05 sec (128 points) long with incremental shift of about 0.24 sec (10 points). Delay time over the first 4.0 sec of elapsed time has an average slope of about 0.022.

5. CONCLUSIONS

A comparison of relative locations based on application of a single taper versus the multitaper to cross-spectral analysis of regional data from Yucca Flat explosions shows significant improvement when the multitaper is used. An accuracy of about 1 km has been achieved; an impressive result if one considers the large epicentral distances (about 240 and 410 km) and the complex geology around the Nevada Test Site. Inter-source coherence for Pn is found to be significantly greater when the two sources lie along the direction of wave propagation than when perpendicular to it. Mean velocities along paths from the Yucca Flat source region to four stations are found to be stable and significantly different, suggesting that propagation velocities may vary considerably from one path to another. This means that at least a part of the observed location errors are due to the assumption of a uniform path-independent velocity model. Analysis of regional data from two pairs of closely located shots suggests that the cross-spectral method may also be used to determine very small differences (of the order of 0.1%) between the near-source media velocities of closely spaced explosions.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Blandford, R. R. (1976). Experimental determination of scaling laws for contained and cratering explosions, *SDAC-TR-76-3,* Teledyne Geotech, Alexandria, Virginia.

Carroll, R. D. (1981). Seismic velocity and postshot properties in and near chimneys, *LA-9211-C, vol. 1* Los Alamos National Lab, 379-396.

Fremont, M. J. and S. D. Malone (1987). High precision relative locations of earthquakes at Mount St. Helens, Washington, J. Geophys. Res. 92, 10223-10236.

Gupta, I. N. and J. P. Davis (1992). High-precision relative event location with cross-spectral analysis and related studies, *Proc. 14th Annual PL/DARPA Seismic Research Symposium,* 146-152.

Gupta, I. N., T. W. McElfresh, and R. A. Wagner (1991). Near-source scattering of Rayleigh to P in teleseismic arrivals from Pahute Mesa (NTS) shots, in *Explosion Source Phenomenology,* S. R. Taylor, H. J. Patton, and P. G. Richards, Editors, Geophysical Monograph 65, American Geoph. Union, Washington, D.C., 151-159.

Gupta, I. N. and R. A. Wagner (1992). Evidence for Rg-to-P scattering in teleseismic P-coda of East Kazakh explosions, *Bull. Seism. Soc. Am. 82,* 2139-2152.

Harmsen, S. C. (1992). Regional-scale velocity anisotropy inferred from Nevada Test Site nuclear test P-arrivals, *Seismol. Res. Lett. 63,* 39 (abstract).

Ito, A. (1985). High resolution relative hypocenters of similar earthquakes by cross-spectral analysis method, *J. Phys. Earth 33,* 279-294.

Kennett, B. L. N. (1989). On the nature of regional seismic phases-I. Phase representations for Pn, Pg, Sn, Lg, *Geophys. J. 98,* 447-456.

Lamb, F. K., B. W. Callen, and J. D. Sullivan (1991). Yield estimation using shock wave methods, in *Explosion Source Phenomenology,* S. R. Taylor, H. J. Patton, and P. G. Richards, Editors, Geophysical Monograph 65, American Geoph. Union, Washington, D.C., 73-89.

Knapp, C. H., and G. C. Carter (1976). The generalized method for estimation of time delay, *IEEE Transactions on Acoustics, Speech, and Signal Processing 24,* 320-327.

McLaughlin, K. L., L. M. Anderson, and A. C. Lees (1987). Effects of local geologic structure on Yucca Flats, Nevada Test Site, explosion waveforms: two-dimensional linear finite-difference simulations, *Bull. Seism. Soc. Am. 77,* 1211-1222.

Miller, R. and D. Steeples (1992). Seismic reflection surveys before and after BEXAR at the Nevada Test Site, *LAUR-92-244,* Los Alamos National Laboratory, Los Alamos, New Mexico.

Park, J., C. R. Lindberg, and F. L. Vernon III (1987). Multitaper spectral analysis of high-frequency seismograms, *J. Geophys. Res.* 92, 12675-12684.

Poupinet, G., W. L. Ellsworth, and J. Frechet (1984). Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras Fault, California, *J. Geophys. Res. 89,* 5719-5731.

Roberts, P. M., W. S. Phillips, and M. C. Fehler (1992). Development of the active doublet method for measuring small velocity and attenuation changes in solids, *J. Acoust. Soc. Am. 91*, 3291-3302.

Stead, R. J. and D. V. Helmberger (1988). Numerical-analytical interfacing in two dimensions with applications to modeling NTS seismograms, *PAGEOPH 128*, Nos. 1/2, 157-193.

Thomson, D. J. (1982). Spectrum estimation and harmonic analysis, *Proc. IEEE 70*, 1055-1096.

Vernon, F. L., J. Fletcher, L. Carroll, A. Chave, and E. Sembera (1991). Coherence of seismic body waves from local events as measured by a small-aperture array, *J. Geophys. Res. 96*, 11981-11996.

Zhu, T., K. Y. Chun, and G. F. West (1989). High-frequency P-wave attenuation determination using multiple-window spectral analysis method, *Bull. Seism. Soc. Am. 79*, 1054-1069.

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