MAXIMUM SPECTRAL ENERGY ARRIVAL TIME OF RAYLEIGH WAVES FOR ACCURATE EPICENTER DETERMINATION AND LOCATION ERROR REDUCTION

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ABSTRACT

Maximum spectral energy (MSE) is defined as the most energetic signal in prescribed frequency and velocity windows characteristic to a seismic phase and is computed by means of the Fast Fourier Transform (FFT) and the Multiple Filter Analysis (MFA). MSE arrival times for Rayleigh waves are computed in the period window 17 to 23 seconds and in the velocity window 2.8 to 3.2 kilometers/second (km/sec). These arrival times and a constant velocity model of 3.0 km/sec are used in a hypocenter computer program to evaluate location error, *i.e.*, mislocation vector.

Epicenter locations for selected nuclear explosions from the Nevada Test Site (NTS) are determined by the Rayleigh waves MSE arrival times. The same explosions are also located by the conventional P-wave first-break arrival times, listed in the International Seismic Center (ISC) Bulletin. Explosion selection is restrained by the availability of both arrival times from the same set of stations common to each explosion. This limited the study to only seven nuclear explosions; each has 12 or more digital seismograms with corresponding P-wave first-break arrivals listed in the ISC Bulletin. The study is confined to NTS explosions, since for these there are published locations against which to compute the location errors. All such errors of epicenter location computed from MSE arrivals are less than those of epicenter locations from first-break arrivals. The location error for the seven explosions, calculated by the MSE arrivals, is half that calculated by the P-wave first-break arrivals.

INTRODUCTION

The conventional seismic event location is based on measuring the arrival times of impulsive phases with sharp, clear onsets at several stations. The goodness of a determined epicenter depends on factors including the velocity model, the sharpness for the P-wave first break, and the accuracy of measuring the first break onset time. Velocity models are subject to error due to the unaccounted variations of geological structures and rock physical properties along the propagation path. Such variations are more apparent at regional distances where the body wave path is confined to the earth's crust, as pointed out by Herrin and Taggart (1962). At teleseismic distances velocity variations over the propagation path are minimized for body waves because of the short distances travelled by these waves in the earth's crust. This facilitated the development of global travel time tables for body-waves, such as the IASPEI (International Association of Seismology and the Physics of the Earth's Interior) Tables, Herrin 68-Tables, JB (Jeffrey-Bullen) Tables, etc. The availability of these tables makes teleseismic body waves the primary tool for locating seismic events.

Surface waves, and some regional phases, are non-impulsive and propagate along or through the earth with nearly constant velocities much slower than P-wave velocities. For surface focus seismic sources, the apparent P-wave velocity ranges from 8.2 to 24.4 km/sec in the distance range 10 to 100 degrees. These velocities are 3 to 8 times faster than the 3.0 km/sec of Rayleigh waves propagating through continental and shallow oceanic crusts. A similar argument applies to Love waves. The Lg regional phase travels with a velocity of about 3.5 km/sec (Nuttli, 1972, and Ewing *et al.*, 1957), which is less than half the apparent velocity for P-wave at 10 degrees. The constant and low velocities of these phases simplifies the location procedure. However, these phases show no onset time and cannot be used for epicenter determination by current methodologies.

The first attempt to locate seismic events using Rayleigh waves was done by von Seggren (1970). By cross-correlating a Rayleigh wave train with another Rayleigh wave train of a well-located event (reference event) from the same region, he was able to determined the relative travel-time based on the correlation trace peak. He used three pairs of US nuclear explosions: Jorum-Boxcar, Faultless-Boxcar, and Milrow-Long Shot. For example, the mislocation vector magnitude for the Boxcar explosion using the Jorum explosion as the reference event is 34.4 km based on Rayleigh waves, and 29 km based on body waves which was reduced to 8.3 km by using relative travel times, *i.e.*, travel time residuals. Similar results were obtained for the other pairs.

A timing method is proposed that replaces onset arrival times in the hypocenter determination procedure with the arrival times for seismic signal amplitudes. These amplitudes are functions of the source's energy, and are used in detection, source characterization, magnitude measurement, attenuation, etc., but not in source location. MSE reflects the most energy for a seismic phase, and is measured within its characteristic frequency and velocity windows. Yacoub (1982) used amplitude averaging for the maximum energy of Rayleigh waves within the period range 17 to 23 seconds to estimate Rayleigh wave spectral magnitudes. Although the method was successful in magnitude estimation, as reflected by the reduction in the network magnitude standard deviation, the arrival times for these averaged magnitudes failed to reduce the location error. Yacoub (1994a, 1996, and 1998b) forsakes amplitude averaging for the most energetic signal in frequency and velocity windows characteristic to the seismic phases. This proved to be successful in measuring Rayleigh wave spectral magnitudes which showed lower network magnitude standard deviation than the corresponding time domain magnitude, M_s (Yacoub, 1998b). MSE was also successful in locating nuclear explosions using Rayleigh waves (Yacoub, 1994b, 1996, and 1999), and P-waves (Yacoub, 1997, 1996, and 1998b). The average location error against the ground truth computed by the spectral timing, either for Rayleigh wave or for P-waves, is reduced to half that computed by P-wave first-break timing.

Seven nuclear explosions, from NTS, are located using arrival times for the Rayleigh wave maximum energy, assuming constant velocity model of 3 km/sec. These explosions are located by the conventional method using P-wave first-break arrival times listed in the ISC Bulletin, and the Herrin (1968) travel-time tables for surface focus. In both methods of timing the location parameters are determined by the same computer program for epicenter estimation using arrival times as recorded by stations from the World Wide Seismic Station Network (WWSSN), Global Seismic Network (GDSN), and the Canadian Seismic Network (CSN).

MAXIMUM SPECTRAL ENERGY

Maximum spectral energy is defined as the most energetic signal in prescribed frequency and velocity windows which uniquely characterize a seismic phase. For example, the P-wave energy peaks in a bandpass 0.7 to 1.4 Hertz (Hz), and in a velocity window ±3 to 5 seconds from P-wave travel-time table predicted arrival. For the regional Lg phase, the energy peaks in a frequency window 0.8 to 1.2 Hz, and a velocity window 3.4 to 3.6 km/sec (Nuttli, 1972, and Ewing *et al.*, 1957). For the Rayleigh and the Love waves, the energy peaks in a period range 17 to 23 seconds, and a velocity window 2.8 to 3.2 km/sec for Rayleigh waves, and 3.3 to 3.7 km/sec for Love waves (Yacoub, 1998b).

MSE is computed by means of the Fast Fourier Transform (FFT) and the Multiple Filter Analysis (MFA), developed by Dziewonski *et al*. (1969). MFA is performed by passing seismogram spectra through a set of narrow-band Gaussian filters at selected center frequencies within the frequency window for the seismic phase. Inverse Fourier Transform (IFT) is applied to each center frequency which produces a complex time domain function. The sum of the squares for the real and the imaginary parts defines the spectral energy. The most of these energies is the maximum energy for the center frequency of the Gaussian filter, and the maximum of these maxima characterizes the MSE whose arrival time is computed and, is used in the hypocenter location.

VELOCITY MODEL

Reliable velocity models are required to locate seismic sources. Since body waves are the primary phase for seismic location, their velocity models are continuously updated with the availability of new data. However, this is not the case with surface waves. The most extensive work done to establish global group velocity models is the classical work by Oliver (1962), which is based on earthquake-generated surface waves. He showed that in the period range 17 to 23 seconds Rayleigh waves travel with a group velocity of 3.0 km/sec through continental crusts and 3.5 km/sec through oceanic crusts.

Yacoub (1994a) used Multiple Filter Analysis techniques to study velocity and frequency characteristics of surface waves maximum spectral energy. Over 5000 long period digital seismograms generated by 215 nuclear explosions at US, Peoples Republic of China (PRC), and the former Union of Soviet Socialist Republics (USSR) test sites were processed. These seismograms are recorded by stations from the WWSSN, the CSN, GDSN, and the US Atomic Energy Detection System (USAEDS). The study showed that maximum spectral energy propagates with a velocity between 2.8 and 3.2 km/sec for Rayleigh waves and between 3.3 to 3.7 km/sec for Love waves, and occurs in the period range 17 to 23 seconds for both waves with the energy dropping by more than an order of magnitude outside the period window 15 to 30 seconds. Propagation paths, for these waves, cover the Northern Hemisphere and cross most types of crustal structures with the exception of very deep oceanic crusts. Yacoub (1998b) developed a travel time curve for Rayleigh waves that propagated in continental, tectonic, and oceanic crusts. Figure 1 shows an azimuthal-equidistant projection for some of the stations used and their great circle paths from NTS. Note the various crustal structures crossed by the propagation paths. The travel time distance scatter diagram, shown in Figure 2, is based on 500 arrivals generated by nuclear explosions at various test sites. The correlation model, where both variables have equal error, gives a slope of 3.0 ± 0.017 km/sec, which is an average group velocity for all paths, including paths shown in Figure 1. The correlation coefficient for the data is 0.998, which is reflected by the low scatter around the correlation line. Note that the scatter of the data around the correlation line is very small at distances below 4000 km and becomes more pronounced beyond that distance. The increase in the scatter could be attributed to multipath effect or propagation in higher velocity layers, or both, since it is equally distributed on both sides of the correlation line.

EPICENTER DETERMINATION

Rayleigh wave long period digital seismograms, for selected nuclear explosions from the NTS, are processed to compute the arrival times of their MSE, within the period window 17 to 23 seconds and the velocity window 2.8 to 3.3 km/sec. The same explosions are located by the conventional P-wave first-breaks arrival times, listed in the ISC Bulletin. Explosion selection is conditioned by the availability of P-wave arrival times and digital LP seismograms from the WWSSN, CSN, and GDSN common to each explosion. This limited the study to only seven nuclear explosions; each has 12 or more digital LP seismograms with corresponding P-wave first-break arrivals. The study is confined to NTS explosions, since for these there are published locations against which to compute the location errors.

These arrival times are used in a hypocenter computer program to determine the source epicenter. Velocity models used by the program are a constant velocity model of 3.0 km/sec for Rayleigh wave location and the Herrin (1968) Travel Time Tables for P-wave location. In cases for stations with large travel time residuals for either P- or Rayleigh-waves, the station is restrained from both data sets to maintain identical networks. Following is an example of epicenter determination.

The Hearts nuclear explosion, 6 September 1979, Yucca Flat, NTS, has 42 digital seismograms. Twenty of these have first-break arrival times listed in the ISC Bulletin. However, one station, ALE, was rejected by the program because of high residuals, so the station is restrained from both solutions. Figure 3a depicts a sample of the original seismograms from stations PHC, STJ, KBS, and KEV. Plotted on the seismograms are the velocity window 2.7 to 3.3 km/sec and the 3.0 km/sec Rayleigh waves velocity marker. This sample represents a typical dispersed Rayleigh wave, shown by PHC, and highly contaminated seismograms as shown by the rest of the seismograms. The use of these noisy seismograms demonstrate the robustness of the MFA to extract the proper signal and allow for measuring the arrival time for the maximum spectral energy as depicted in Figure 3b. This figure shows the filtered seismogram at the period with the most energy. The arrival time for maximum spectral energy is annotated above the red inverted arrow, on top of the velocity window box. Azimuthal distribution for the network is shown in Figure 4a, and Figure 4b depicts the mislocation vector for the determined epicenters. The ground truth is shown with the red star, P-wave determined epicenter and the mislocation vector are shown by the green square and the green line, respectively, and the MSE determined epicenter and the mislocation vectors are shown by blue circle and blue line, respectively. The location error is 18.32 km for the P-wave onset timing, and 11.15 km for Rayleigh waves MSE timing.

Figures 4, 5, 6, 7, 8, and 9 depict in a similar manner the results for the determined epicenters for nuclear explosions Backbeach, Scantling, Lowball, Mizzen, Strake, and Sheepshead.

RESULTS

Results for Rayleigh wave and P-wave location errors for the seven explosions are shown in Table 1 and by the bar chart in Figure 10. The table and the figure depict the mislocation vector magnitudes between the determined epicenters and the actual locations as determined from Rayleigh wave MSE timing and P-wave onset timing. The location error determined from Rayleigh wave MSE timing shows a reduction in the location error of between 40 to 70 percent of that determined from P-wave first-break timing. On the average the mislocation vector magnitude determined by the Rayleigh wave MSE timing is 13 km, and that determined by P-wave onset timing is 29 km, which is about a 55-percent reduction.

CONCLUSIONS

Robustness of the maximum spectral energy timing method for Rayleigh wave seismic location is manifest in its consistently greater location accuracy compared to the P-wave onset timing method.

Maximum spectral energy arrival times allow for the use of non-impulsive phases such as Rayleigh waves to locate epicenters without resort to the relative location method.

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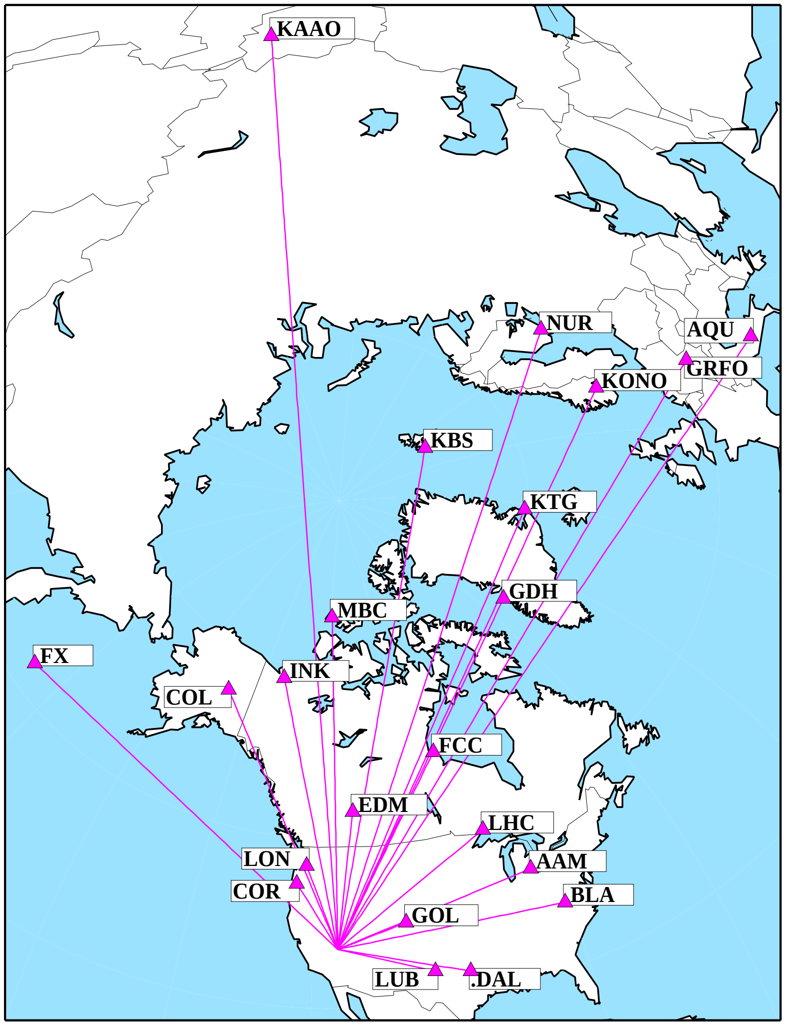

Figure 1. Azimuthal-Equidistant projection for the propagation paths between the Nevada Test Site and some of the seismic stations used in the study of the group velocity of Rayleigh wave maximum spectral energy. Note the various crustal structures crossed by the propagation paths such as the path to station KAAO and FX. No digital data are available from South America or South Pacific. From Yacoub (1998b).

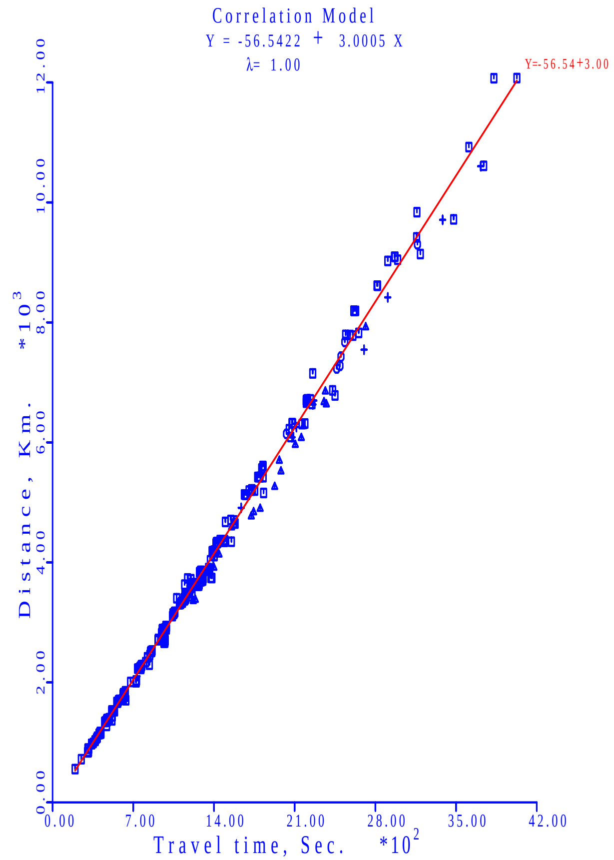

Figure 2. Scatter diagram for Rayleigh wave maximum energy travel time versus distance. Five hundred travel times at several seismic stations from various test sites are shown with different symbols. The travel times represent the arrivals for the maximum spectral energy in the period window 17 to 23 seconds. Note the slight increase in the scatter with distance, which could be attributed to longer path other than the assumed great circle, and the excellent fit at distances less than 4000 km. The slope for the curve is 2.99 ± 0.02 which represents the average group velocity. The different symbols represent the different test sites: squares for

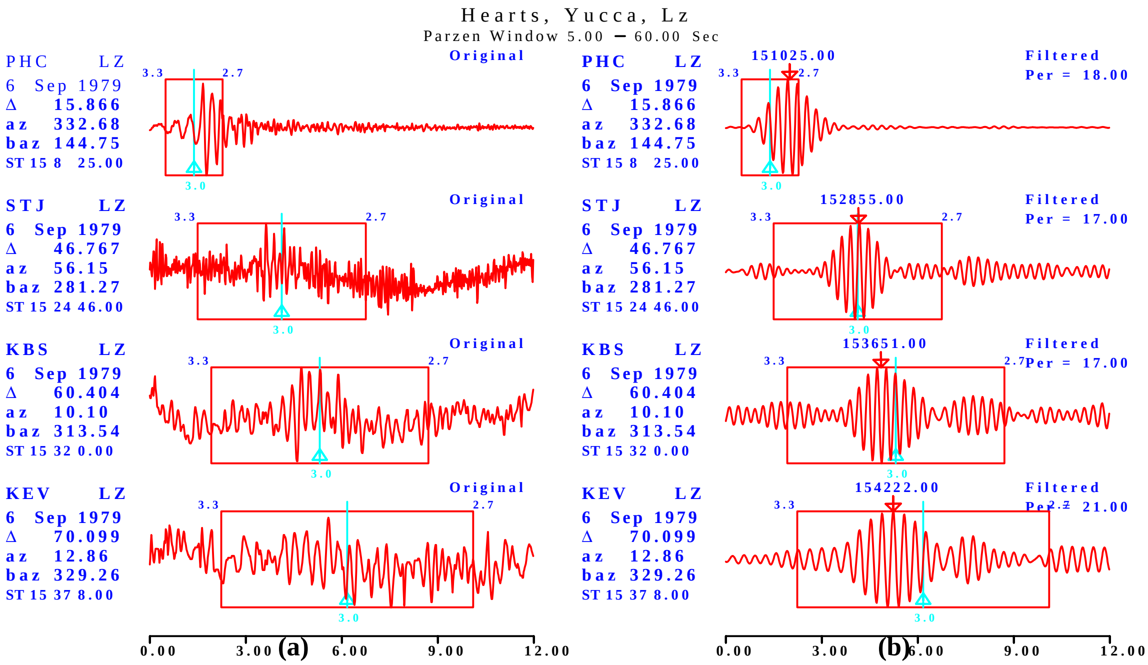

Figure 3. (a) Shown are sample seismograms generated by Hearts nuclear explosion. Each seismogram shows the velocity windows that encompass the Rayleigh wave and the 3.0 km velocity arrival. (b) Shown are the filtered seismograms with the most energy in the period range 17 to 23 seconds. The maximum energy is

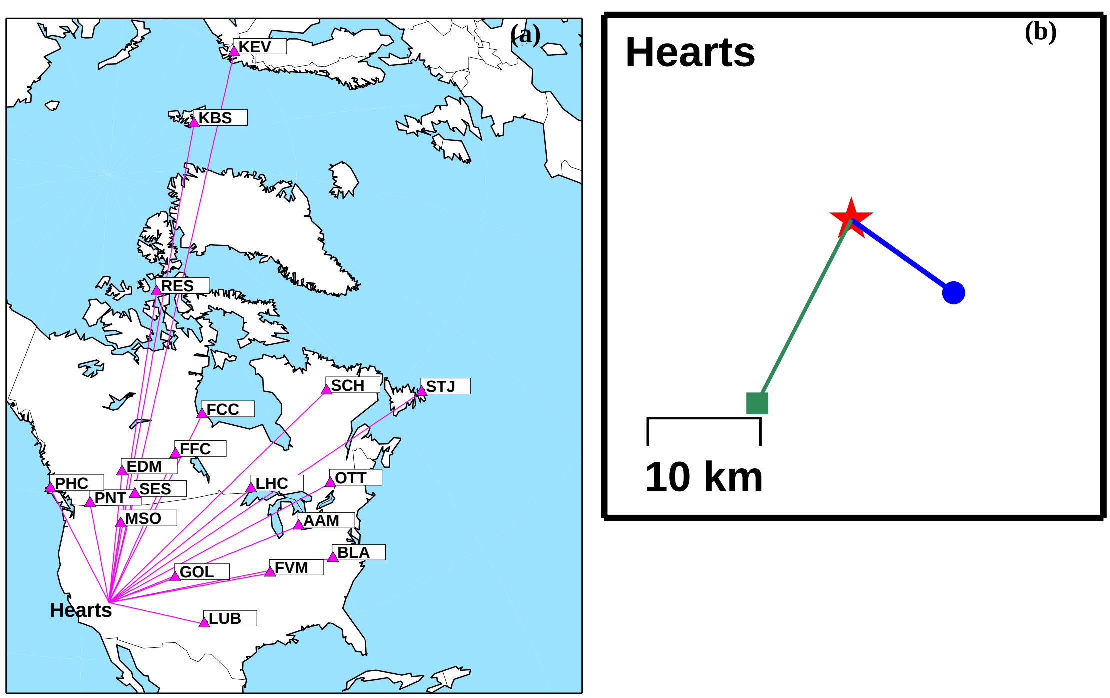

Figure 4. Nuclear explosion Hearts, 6 September 1979. Figure (a) depicts the azimuthal distribution for the network and their great circle path to the actual location for the explosion used to determine the epicenter by P-wave arrival times and Rayleigh waves maximum spectral energy arrival times. Figure (b) depicts the mislocation vectors for the determined epicenters. ★ shows the actual location, ■ shows the P-wave location, and ● shows the Rayleigh wave location. Here the location error for P-wave is 18.32 km and for Rayleigh MSE is 11.2 km.

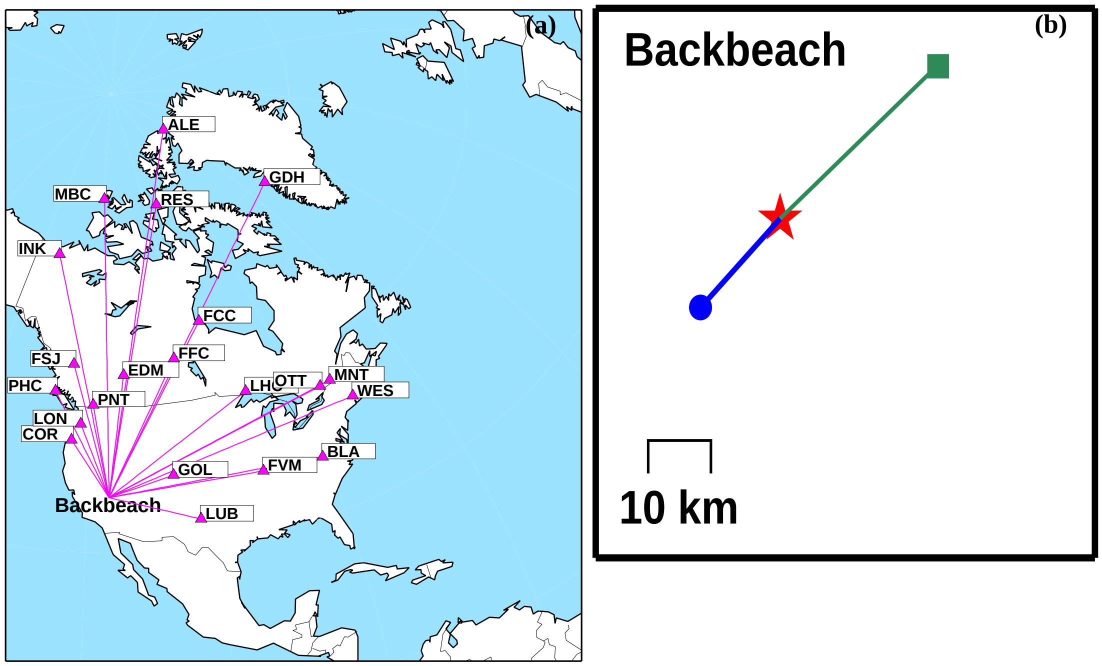

Figure 5. Nuclear explosion Backbeach, 11 April 1978. Figure (a) depicts the azimuthal distribution for the network and their great circle path to the actual location for the explosion used to determine the epicenter by P-wave arrival times and Rayleigh waves maximum spectral energy arrival times. Figure (b) depicts the mislocation vectors for the determined epicenters. ★ shows the actual location, ■ shows the P-wave location, and ● shows the Rayleigh wave location. Here the location error for P-wave is 33.1 km and for Rayleigh MSE is 9.7 km.

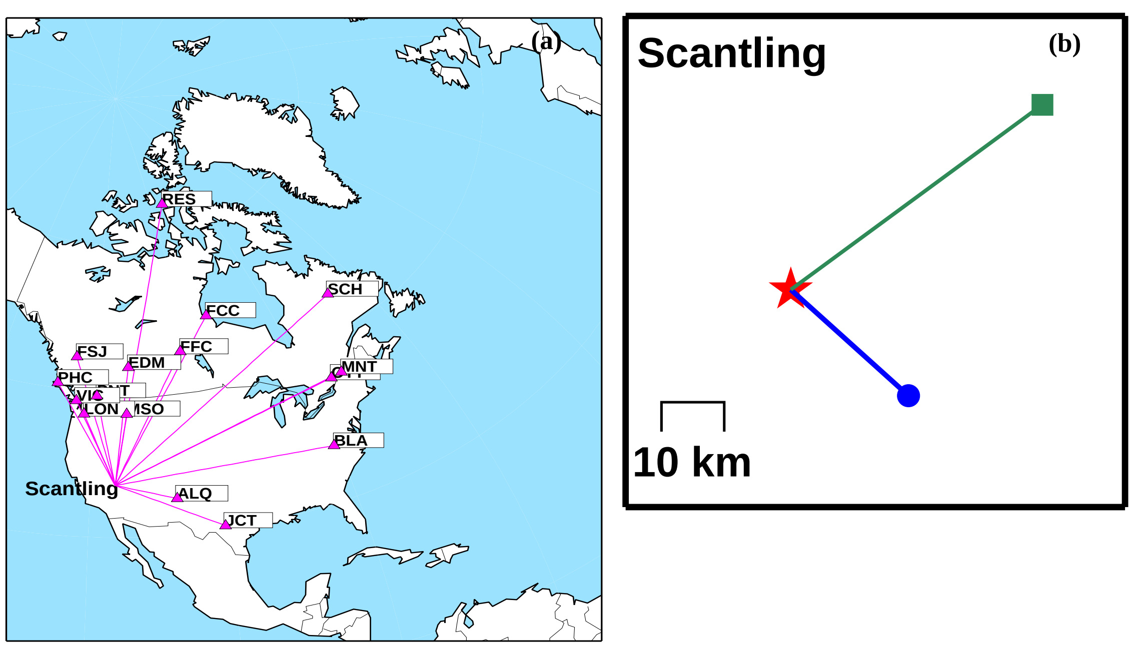

Figure 6. Nuclear explosion Scantling, 19 August 1977. Figure (a) depicts the azimuthal distribution for the network and their great circle path to the actual location for the explosion used to determine the epicenter by P-wave arrival times and Rayleigh waves maximum spectral energy arrival times. Figure (b) depicts the mislocation vectors for the determined epicenters. ★ shows the actual location, ■ shows the P-wave location, and ● shows the Rayleigh wave location. Here the location error for P-wave is 49.9 km and for Rayleigh MSE is 25.1 km.

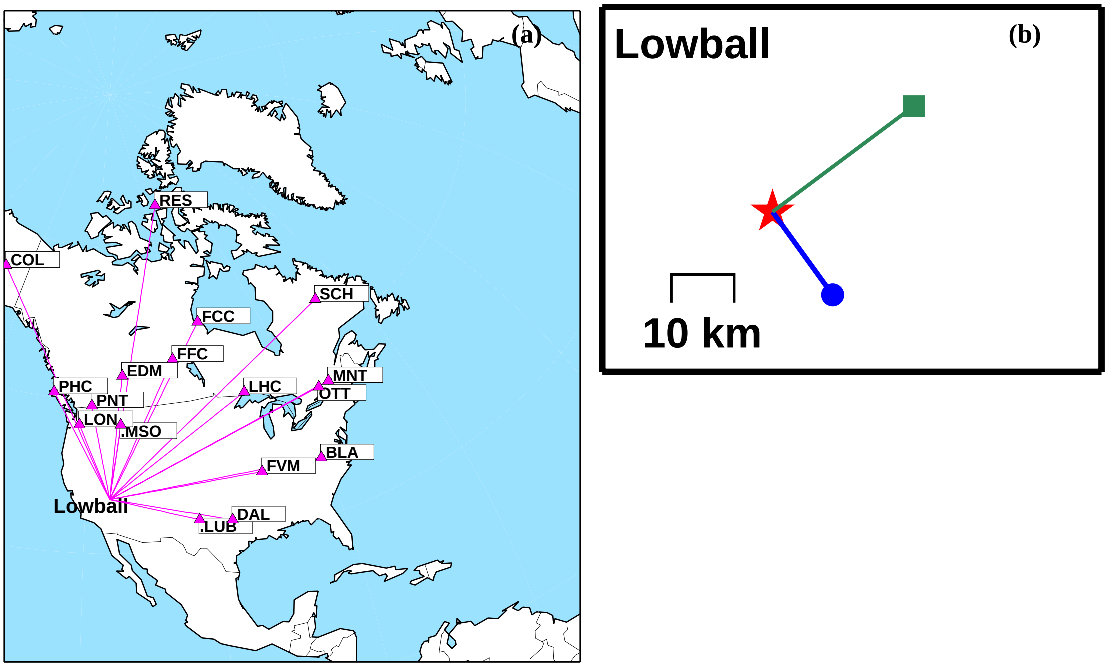

Figure 7. Nuclear explosion Lowball, 12 July 1978. Figure (a) depicts the azimuthal distribution for the network and their great circle path to the actual location for the explosion used to determine the epicenter by P-wave arrival times and Rayleigh waves maximum spectral energy arrival times. Figure (b) depicts the mislocation vectors for the determined epicenters. ★ shows the actual location, ■ shows the P-wave location, and ● shows the Rayleigh wave location. Here the location error for P-wave is 28.3 km and for Rayleigh MSE is 16.3 km.

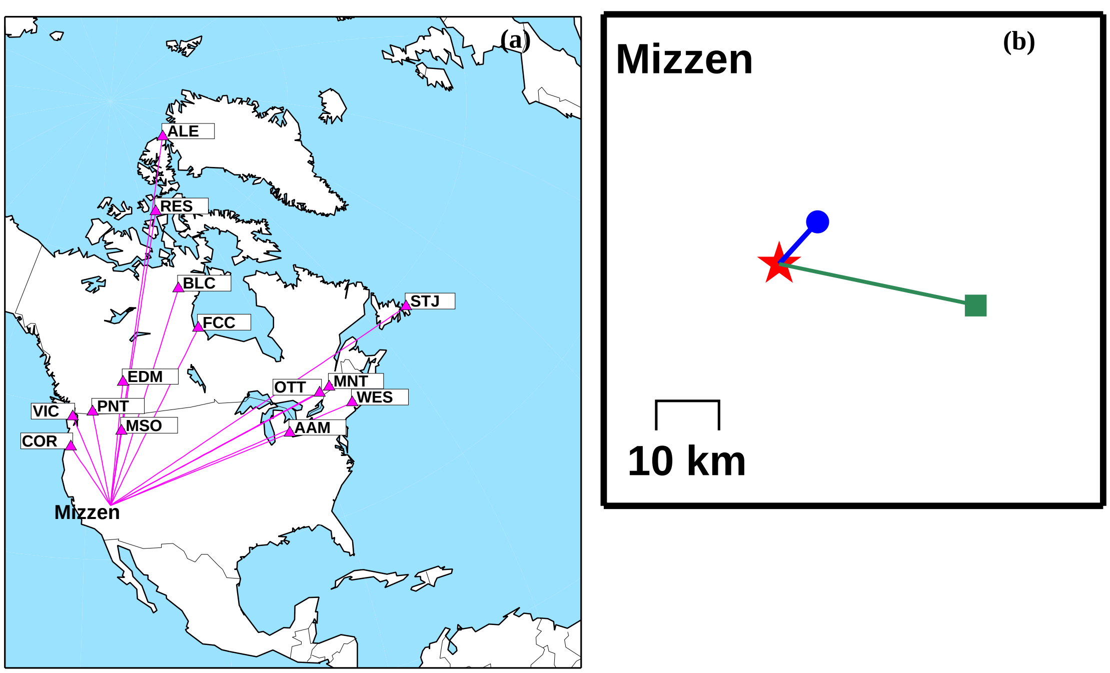

Figure 8. Nuclear explosion Mizzen, 3 June 1975. Figure (a) depicts the azimuthal distribution for the network and their great circle path to the actual location for the explosion used to determine the epicenter by P-wave arrival times and Rayleigh waves maximum spectral energy arrival times. Figure (b) depicts the mislocation vectors for the determined epicenters. ★ shows the actual location, ■ shows the P-wave location, and ● shows the Rayleigh wave location. Here the location error for P-wave is 32.0 km and for Rayleigh MSE is 9.3 km.

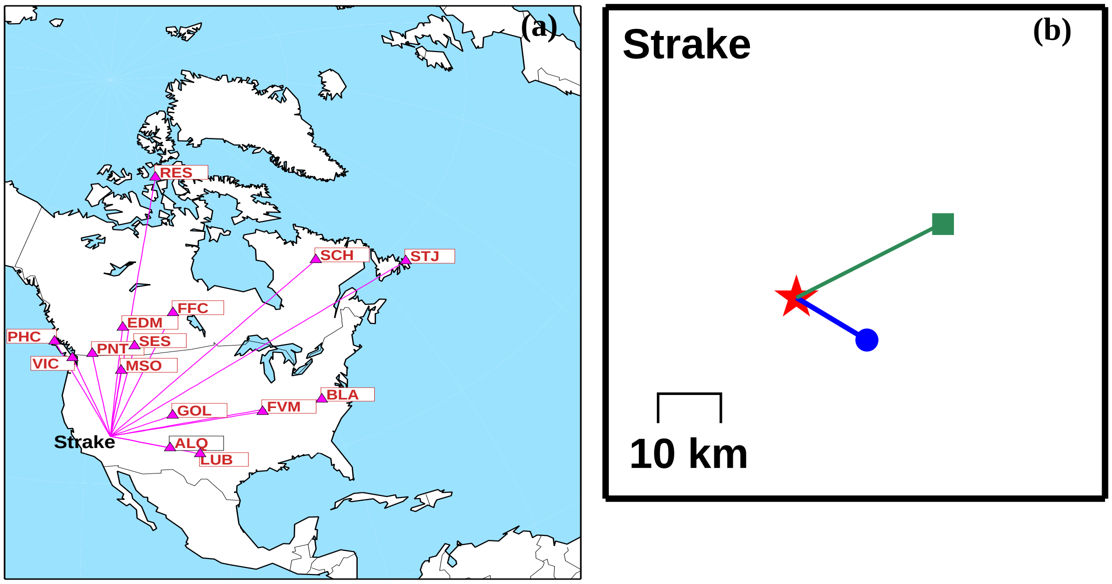

Figure 9. Nuclear explosion Strake, 4 August 1977. Figure (a) depicts the azimuthal distribution for the network and their great circle path to the actual location for the explosion used to determine the epicenter by P-wave arrival times and Rayleigh waves maximum spectral energy arrival times. Figure (b) depicts the mislocation vectors for the determined epicenters. ★ shows the actual location, ■ shows the P-wave location, and ● shows the Rayleigh wave location. Here the location error for P-wave is 26.1 km and for Rayleigh MSE is 13.0 km.

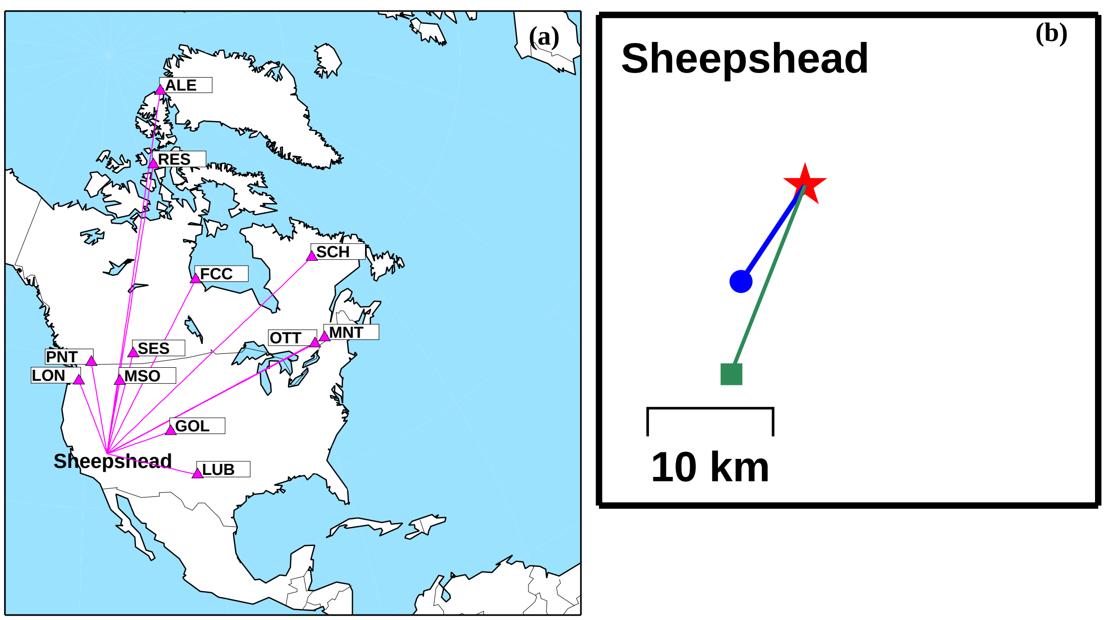

Figure 10. Nuclear explosion Sheepshead, 16 September 1979. Figure (a) depicts the azimuthal distribution for the network and their great circle path to the actual location for the explosion used to determine the epicenter by P-wave arrival times and Rayleigh waves maximum spectral energy arrival times. Figure (b) depicts the mislocation vectors for the determined epicenters. ★ shows the actual location, ■ shows the P-wave location, and ● shows the Rayleigh wave location. Here the location error for P-wave is 16.1 km and for Rayleigh MSE is 9.2 km.

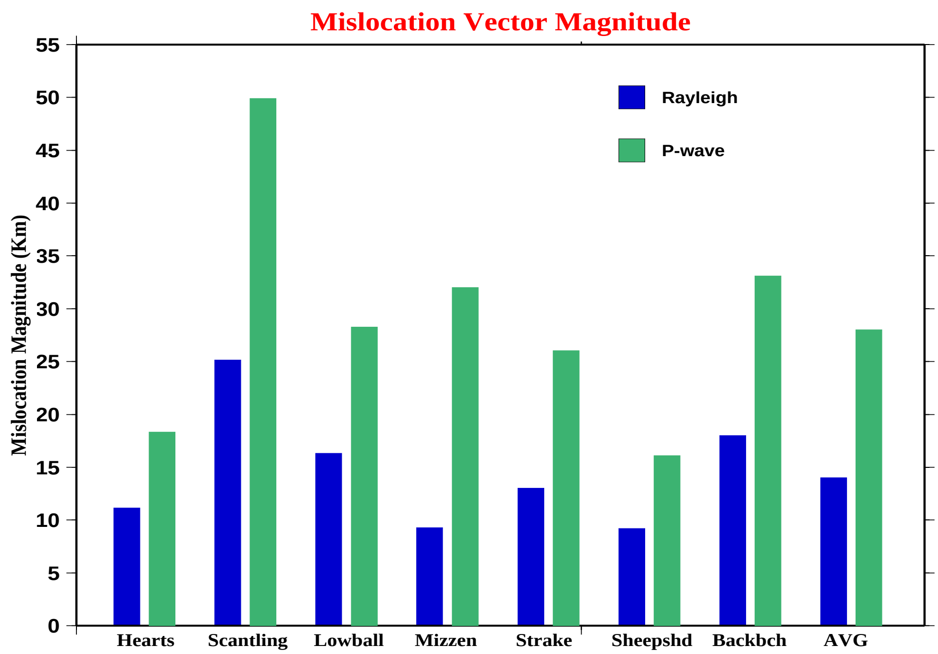

Figure 11. Bar chart showing mislocation vector magnitudes for six presumed nuclear explosions from Yucca, Pahute Test Site, and their averages, as indicated under each group of bars. Numerical values are given in Table 3.

■ Represents location error for epicenters computed from P-wave conventional timing method.

■ Represents location error for epicenters computed from Rayleigh wave maximum energy spectral timing method.

Table 1: Mislocation Vector Magnitudes

Event	No STA	Location Error, Km		Reduction%
		LR	P	
Hearts	**19**	**11.2**	**18.3**	**39%**
Backbeach	**19**	**9.7**	**33.1**	**71%**
Scantling	**18**	**25.1**	**49.9**	**49%**
Lowball	**17**	**16.3**	**28.3**	**42%**
Mizzen	**14**	**9.8**	**32.0**	**71%**
Strake	**14**	**13.0**	**26.0**	**50%**
Sheepshead	**12**	**9.2**	**16.1**	**42%**
Averages		**13±6**	**29±11**	**55%**