Improved resolution of earthquake source parameters from long-period surface wave inversions

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ABSTRACT


Source centroid location optimization improves moment tensor inversions of long-period fundamental mode surface wave spectra. Joint inversions of Rayleigh and Love wave spectra are used to find source moment tensors for the 18 October 1989 Loma Prieta, California, earthquake (M~L = 6.9) and the 22 April 1991 Valle de la Estrella, Costa Rica, earthquake (M~L = 7.6). For the Loma Prieta event, the focal mechanism at the optimal centroid location is consistent with that at the epicenter, and both agree with independent information. For the Costa Rica event, the solution at the optimal centroid location is consistent with geodetic and body wave observations, whereas the solution found for the epicenter is not. We conclude that optimizing for centroid location in spectral inversions is possible and improves the determination of long-period surface wave source parameters.

1. Introduction

Every seismic wave analysis procedure used to study earthquakes involves model assumptions which affect resulting source parameters. For example, Wallace et al. (1991) and Velasco et al. (1992) have shown that estimates of seismic moment, source depth, and rupture duration obtained from long-period surface wave analyses are dependent upon the propagation, attenuation, and source excitation structures assumed in the processing. Synthetic tests have also shown biases in seismic moment tensor estimates for surface wave spectral methods (Patton and Aki, 1979) and normal mode techniques (Dziewonski and Woodhouse, 1983a). Long-period surface wave spectral analyses are also very sensitive to the assumed location of the source (Zhang and Lay, 1990; Velasco et al., 1992); this sensitivity has not been allowed for in most investigations.

Sensitivity to the source location is a complicated problem. Body wave inversions are typically desensitized to source location by aligning the traces on the first arrival. However, this is not possible for surface waves, as the phase information helps constrain the source model. Despite recent progress in developing aspherical velocity models, propagation corrections will continue to be for only approximate Earth models. There are several options to overcome this. One can use the body wave travel time location, assuming this does not bias the solution (i.e. errors in the model are random). This assumption is demonstrably flawed, as shown by comparison of inversions that use different spherically symmetric or aspherical models (e.g. Wallace et al., 1991). Alternatively, one can try to determine the best source location given an assumed Earth model, recognizing that this location may be biased as a result of the model errors and may therefore not correspond...
to the location used in analysis of other data from the same event.

The very successful centroid-moment tensor (CMT) inversion procedure (Dziewonski et al., 1981; Dziewonski and Woodhouse, 1983a,b) includes a simultaneous time-domain inversion for source moment tensor and optimal centroid location using three-component long-period body waves and surface waves. The set of wave groups included in CMT inversions is sufficient to obtain a stable moment tensor in many cases. One should not expect the centroid location found by the CMT inversion to correspond to the actual physical source location, nor should it necessarily apply to either short-period body waves or very long-period fundamental modes and free oscillations outside of the passband emphasized by the CMT inversion (45–175 s). Why centroid optimization tends to project model errors into the source location rather than the moment tensor (e.g. Dziewonski and Woodhouse, 1983a) remains somewhat enigmatic. We attribute this to the stabilizing effect of varying trade-offs between location and mechanism for different wave types, with the low-order terms introduced by incorrect Earth models preferably mapping into source location. This may not occur in all cases.

In this paper, we develop a method of centroid location optimization appropriate for long-period surface wave frequency-domain inversions. We use a recently developed aspherical Earth model, MPA (Wong, 1989) for phase propagation corrections, as this model is found to yield very good source locations and reliable source parameters. Although our method has some similarities to the CMT procedure, it yields results specifically appropriate for long-period surface waves. We obtain very compatible moment tensors with the CMT results, but different centroid locations.

2. Source duration and surface wave epicentral location

We develop our procedure using the 18 October 1989 Loma Prieta, California, earthquake ($M_w = 6.9$) and the 22 April 1991 Valle de la Estrella, Costa Rica, earthquake ($M_w = 7.6$). The analysis procedure is the moment tensor inversion method developed by Kanamori and Given (1981), as modified to a two-step procedure which isolates source finiteness effects from the determination of the centroid depth and moment tensor (Romanowicz and Guillemant, 1984; Zhang and Kanamori, 1988). This inversion is applied to long-period (157–288 s) fundamental mode spectra.

The first step in the surface wave spectral inversion technique obtains a point source duration, $\tau$, for a trapezoid source function by minimizing the normalized r.m.s. error, $\sigma$, between the calculated and observed phase delay in the inversion (see Zhang and Kanamori, 1988). Surface wave source duration estimates are strongly affected by the choice of phase velocity model used in the propagation corrections, and are not sensitive to the details of the rupture process. We obtain duration estimates for the Loma Prieta event varying from $\tau = 30$ s ($\sigma = 0.488$) for the Preliminary Reference Earth Model (PREM), and $\tau = 18$ s ($\sigma = 0.333$) for the model M84C, (Woodhouse and Dziewonski, 1984) to $\tau = 12$ s ($\sigma = 0.349$) for MPA, as was previously found by Velasco et al. (1992). The duration results for MPA are compatible with duration estimates from short-period waves. For the Valle de la Estrella earthquake, we find similar dependence on the propagation model; $\tau = 48$ s ($\sigma = 0.369$) for PREM, $\tau = 44$ s ($\sigma = 0.324$) for M84C, and $\tau = 40$ s ($\sigma = 0.316$) for MPA. MPA again gives a duration consistent with other data (Goes et al., 1992).

By mapping $\sigma$ as a function of point source position near the epicentral location, we can establish any dependence of $\tau$ on assumed source location. This process can be visualized as locating the effective source position with a 'best' point source trapezoidal source time function. We create a grid of point source locations near the epicenter of each earthquake and invert for the point source duration at each grid point. The spectra are corrected to each source location, with the origin time held fixed at the National Earthquake Information Center (NEIC) value. For the Loma Prieta earthquake a 112 km x 112 km grid with 225 point source locations was considered. Using MPA for the propagation correc-
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tions, we contour $\sigma$ obtained at each source location (Fig. 1(a)). The optimal location for a point source, at $\sigma_{\text{min}}$, is directly on the epicenter. Other phase velocity models yield $\sigma_{\text{min}}$ at different locations. PREM gives a source location approximately 35 km northeast of the NEIC epicenter, whereas M84C locates the source 8 km north of the epicenter. Within the region over which $\sigma$ varies by less than 5% from the minimum, the duration is found to vary by only 1–2 s for all models.

For the Valle de la Estrella event, the grid is 100 km x 130 km and has 154 points (Fig. 1(b)). For this earthquake, MPA again yields $\sigma_{\text{min}}$ directly on the epicenter (Fig. 1(b)). Using PREM shifts the source location 80 km to the NE, off the grid. M84C locates the source 23 km from the epicenter. Again, the duration varies by only a second or two across the grid for a given model. MPA does an excellent job of locating the sources using the surface waves alone for both events.

The variation in duration estimates with source location for a given model is much smaller than the variation in duration estimates between propagation models, so for a given propagation model we can use a single value of source duration in the moment tensor inversion as we scan the source location grid for the best moment tensor and centroid location.

3. Centroid location, depth, and the moment tensor solution

The concept of the centroid location as the optimal point source moment tensor location for the seismic energy release from an earthquake is intrinsically model dependent, as this location will depend on the Earth model used in the inversion. Source location affects moment tensor inversion of long-period surface waves through the phase variation caused by propagation and minor amplitude effects related to attenuation (Zhang and Lay, 1990; Velasco et al., 1992). Thus, phase velocity, source velocity structure, and attenuation model uncertainties all map into the second-step moment tensor inversion that we use, and different models will give different optimal

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Fig. 1. Contours of the residual error in the source duration inversion for different assumed point source locations for the Loma Prieta (a) and the Valle de la Estrella (b) earthquakes. The minimum error gives the optimal epicentral location for a point source based on phase data alone. The model MPA is used in the inversions. The best locations are directly on the epicenter for both earthquakes and duration estimates vary by only a few seconds over the grid. These plots correspond to locating the sources using long-period surface waves alone, and demonstrate the quality of MPA.
centroids. Our philosophy, like that of the CMT procedure, is to define the optimal centroid location for a particular Earth model and a given data set as that position which gives the lowest residual error in the moment tensor inversion. The foregoing analysis has shown that this inversion is independent of the source duration model, as long as the appropriate duration for the given propagation model is used.

The centroid location is found by inverting for depth and moment tensor over a grid of point source locations. The advantage of the spectral inversion is that we can easily consider many Earth models to test their effect on the resulting inversions. We evaluate the significance of the centroid optimization by comparing the inversion errors over the grid, but it is straightforward to include explicitly centroid relocation parameters in the inversion, as is done in the CMT procedure. Velasco et al. (1992) showed that the global $Q$ and source velocity models used in the inversion do not have a dramatic effect on the resulting centroid location, but the phase velocity model can affect the centroid location. In the moment tensor inversions we use the global $Q$ model of Dziewonski and Stein (1982), and excitation functions for the average ocean model of Regan and Anderson (1984) for both earthquakes. We use the source durations and dispersion corrections determined for each earthquake for the phase velocity model MPA.

Using the same grid of source locations as described in Section 2, inversions were performed at each location for a series of depths. We contour the residual variance in this second-step inversion, $\rho$ (Fig. 2(b)). As $\rho$ is a measure of how well the data are fitted by the associated moment tensor for that source position and depth, the location of $\rho_{\text{min}}$ gives the optimal centroid location. For the Loma Prieta event $\rho_{\text{min}}$ is located approximately 24 km west of the epicenter, outside the rupture area (Fig. 2). The variation in residual error over the grid is 50%, but the region near $\rho_{\text{min}}$ is broad and flat. The major double-couple focal mechanisms determined from the moment tensors at several locations are shown in

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**Fig. 2.** (a) Map illustrating, for the Loma Prieta earthquake, the sensitivity to centroid location for simultaneous Rayleigh and Love wave moment tensor inversions. The focal mechanism at the epicenter has a strike ($\phi$) = 112°, dip ($\delta$) = 60°, and rake ($\lambda$) = 114°, whereas the solution at the minimum error, $\rho_{\text{min}}$, gives $\phi$ = 122°, $\delta$ = 66°, and $\lambda$ = 126°. (b) Contours of the residual error in the inversion for the full moment tensor as a function of source location. The minimum error, $\rho_{\text{min}}$, gives the optimal centroid location approximately 30 km west of the epicenter. The overall error reduction over the grid is 50%, but the region around the minimum is broad and flat and encompasses the NEIC hypocenter. The focal mechanisms in the vicinity of $\rho_{\text{min}}$ demonstrate the stability of the solution.
Fig. 2(a). In the area near \( P_{\text{min}} \) the major double-couple is very stable, demonstrating the stability of the solutions. The NEIC epicenter lies within the broad, flat region of the error surface, and the moment tensor inversion is very similar to that at the optimum centroid, with both being consistent with first-motion and body wave mechanisms for the event. This indicates that in this case there is little bias incurred by assuming the source location derived from body waves in the surface wave inversion. For other model combinations this is not always the case (Velasco et al., 1992). The CMT centroid location lies about 28 km east of the NEIC epicenter, and if we use that location we obtain an incorrect moment tensor, illustrating the data dependence of the centroid location.

For the Valle de la Estrella earthquake \( P_{\text{min}} \) is located approximately 30 km northeast of the NEIC epicenter, and the minimum is well defined and has a greater relative error reduction over the grid (approximately 100%) than for the Loma Prieta earthquake (Fig. 3(b)). The focal mechanisms near \( P_{\text{min}} \) demonstrate the stability of the solution near the optimum centroid (Fig. 3(a)), but locating the point source at the epicenter results in a significant difference in focal mechanism (approximately 50° change in dip). The solution at the centroid location is consistent with first motions, body waves and geodetic observations (Goes et al., 1992). In this case, the shift in source location is necessary to obtain a stable source model. Although some model deficiency probably contributes to the centroid shift in this case, the location of the centroid is consistent with the observed coastal uplift and the small tsunami produced by this event. Although we cannot resolve directivity in the long-period waves for this event, it is likely that at least some of the centroid location corresponds to an up-dip shift of the true physical centroid relative to the NEIC hypocenter. The CMT centroid location is 60 km northeast of the NEIC location, near the edge of our grid and beyond the actual rupture zone. Using that location to invert our data gives similar moment tensor results, but the moment

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Fig. 3. Same as Fig. 2, but for the Valle de la Estrella earthquake. (a) The focal mechanisms in the region near \( P_{\text{min}} \) demonstrate the stability of the solution, whereas locating the centroid at the epicenter results in a dramatic 50° change in dip of the focal mechanism. The focal mechanism at the epicenter has \( \phi = 106°, \delta = 60° \), and \( \lambda = 73° \), whereas the solution at the minimum error, \( P_{\text{min}} \), gives \( \phi = 107°, \delta = 21° \), and \( \lambda = 55° \). (b) \( P_{\text{min}} \) is located approximately 30 km northeast of the epicenter. In this case, the minimum is steep and has a relative error reduction which is much greater than for the Loma Prieta earthquake (approximately 100%).
tensor at our optimal centroid is virtually identical to that from the CMT inversion. This indicates that centroid optimization works in both cases to project model deficiencies out of the moment tensor determination, but gives different centroid locations.

4. Discussion and summary

Inclusion of centroid location optimization in long-period source parameter determinations appears to improve source moment tensor inversion. The centroid location procedure primarily affects the phase, and projects small, low-degree azimuthal patterns out of the data. The moment tensor is then rather robustly derived from the complex spectra of the Love and Rayleigh waves. This process is stable because of the significant differences in the radiation patterns for these spectra, and centroid optimization may not converge to the correct solution if only Rayleigh waves are used, as noted by Zhang and Lay (1990). The CMT inversion is similarly stabilized by the differences in the radiation patterns of the body wave and surface wave arrivals in the wave trains that are inverted. As the centroid optimization reduces to some extent the dependence on the model parameters, we are able to establish more realistic confidence bounds on source parameter estimates by comparing the suite of results for different model combinations (Velasco et al., 1992).

When we invert for the moment tensor and depth at the optimal centroid location for a particular model combination, the separate moment tensor elements for the Love and Rayleigh waves are found to be essentially identical, whereas they are increasingly different away from the optimum centroid. The centroid optimization thus brings into agreement the least constrained moment tensor terms for surface waves for shallow events, $M_{xx}$ and $M_{yy}$, stabilizing the moment tensor estimates.

Improved aspherical propagation models are also critical for improving the resolution of earthquake source parameters from long-period surface wave inversion. We have found that the model MPA gives duration results that are consistent with those of other studies for both earthquakes considered here, indicating improved average velocities as well as aspherical structure in this recent spherical harmonic degree 12 model. As Earth models become more accurate the optimal centroid location will become a better approximation to the actual centroid of the energy release, but at present the models are not reliable enough for us to attach much significance to the centroid position. In general, any investigation of surface waves or free oscillations should strive to determine the centroid location appropriate for the phases being used, rather than assume a model- and data-dependent centroid obtained from different wave types for the same event.

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References


