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A Double-Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, California

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Abstract We have developed an efficient method to determine high-resolution hypocenter locations over large distances. The location method incorporates ordinary absolute travel-time measurements and/or cross-correlation *P*-and *S*-wave differential travel-time measurements. Residuals between observed and theoretical travel-time differences (or double-differences) are minimized for pairs of earthquakes at each station while linking together all observed event-station pairs. A least-squares solution is found by iteratively adjusting the vector difference between hypocentral pairs. The double-difference algorithm minimizes errors due to unmodeled velocity structure without the use of station corrections. Because catalog and cross-correlation data are combined into one system of equations, interevent distances within multiplets are determined to the accuracy of the cross-correlation data, while the relative locations between multiplets and uncorrelated events are simultaneously determined to the accuracy of the absolute travel-time data. Statistical resampling methods are used to estimate data accuracy and location errors. Uncertainties in double-difference locations are improved by more than an order of magnitude compared to catalog locations. The algorithm is tested, and its performance is demonstrated on two clusters of earthquakes located on the northern Hayward fault, California. There it collapses the diffuse catalog locations into sharp images of seismicity and reveals horizontal lineations of hypocenters that define the narrow regions on the fault where stress is released by brittle failure.

Introduction

Seismicity analysis for the study of tectonic processes, earthquake recurrence, and earthquake interaction requires knowledge of the precise spatial offset between the earthquake hypocenters. This is particularly the case for crustal faults that are most readily investigated using microseismic activity. The location uncertainty of routinely determined hypocenters is typically many times larger than the source dimension of the events itself, thus putting limits on the study of the fine structure of seismicity.

The accuracy of absolute hypocenter locations is controlled by several factors, including the network geometry, available phases, arrival-time reading accuracy, and knowledge of the crustal structure (Pavlis, 1986; Gomberg *et al.,* 1990). The use of a one-dimensional reference velocity model to locate the earthquakes limits the location accuracy, since three-dimensional velocity variations can introduce systematic biases into the estimated travel times. One can partially account for the velocity variations by including station and/or source terms in the location procedure (e.g., Douglas, 1967; Pujol, 1988; Hurukawa and Imoto, 1992; Shearer, 1997) and/or by jointly inverting the travel-time data for hypocenters and velocity structure (e.g., Crosson, 1976; Ellsworth, 1977; Roecker, 1981; Thurber, 1983; Michael, 1988; Kissling *et al.,* 1994).

The effects of errors in structure can also be effectively minimized by using relative earthquake location methods (Poupinet *et al.,* 1984; Fréchet, 1985; Frémont and Malone, 1987; Got *et al.,* 1994) (for a discussion on relative location errors see Pavlis [1992]). If the hypocentral separation between two earthquakes is small compared to the event-station distance and the scale length of the velocity heterogeneity, then the ray paths between the source region and a common station are similar along almost the entire ray path. In this case, the difference in travel times for two events observed at one station can be attributed to the spatial offset between the events with high accuracy. This is because the absolute errors are of common origin except in the small region where the raypaths differ at the sources.

We can further improve location precision by improving the accuracy of the relative arrival-time readings using waveform cross-correlation methods. Two earthquakes produce similar waveforms at a common station if their source mechanisms are virtually identical and their sources are colocated so that signal scattering due to velocity heterogenei-