High resolution from an earthquake seismologist's point of view

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abstract

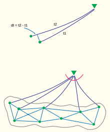
Two challenges face earthquake seismologists: one) we don't know where the earthquakes are and two) we don't know the origin times of the events. These factors limit the extent that natural sources can be used to image the earth and also our understanding of earthquake source processes. Our data is often sparse and noisy as compared to other fields. The earth is a complex, non-transparent medium which often contributes noise in unknown ways to our seismograms. For the astronomer, the electromagnetic waves travel through a vacuum and so the signal is contaminated little along the journey, especially if the recording instruments are placed outside the earth's atmosphere. In the medical community, there is excellent control of the sources and receivers used to produce a CAT scan image of the brain. In our field, we have no control over the distribution of seismicity and the global, regional, and local networks are comparatively sparse. The oil industry, conversely, produces startling 3D images of the earth from its dense geophone arrays and controlled source explosions. We overcome many of the unknowns in earthquake seismology by setting up the problems in a relative sense. In this way we are able to remove much of the two main sources of error in locating earthquakes -- pick measurement error and velocity model error.

Technique

Model Error

Consider two nearby events (top) with travel times *t2* and *t1*. Much of their ray paths travel through similar earth structure. Taking the travel time difference *dt=t2-t1* gives information on the relative position of the events and is most affected only by the velocities close to the events (*dt*=**dr.dn**, position vector dotted with slowness vector, slowness is inverse velocity).

To locate many events (bottom) station corrections are often employed to account for a static shift due to topography or sediments. The red arc illustrates this graphically where all the ray paths sample approximately the same volume. If travel time differences are used instead, much more of the unknown velocity structure can be differenced out, so that the locations are influenced by velocity variations only local to the events (gray region). Note that events on the ends are located relative to each other only through the connectivity of closer events.



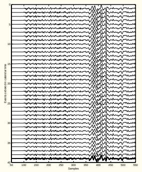
Double difference method of Waldhauser and Ellsworth [2000]

Measurement Error

Another major source of error in earthquake location comes from inaccurate arrival time picks for the events. If nearby events are similar enough, cross-correlation can be used to align the waveforms and significantly improve the relative arrival time measurement. These *dt* values can be directly inverted for earthquake locations and origin time in the double difference approach.

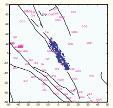
At right is a special case of a repeating event cluster on the Calaveras fault. Displayed are the waveforms of 39 different events recorded at station JST. The bottom trace shows all the events superposed. To create such a plot the relative *dt* computed by cross-correlation can be inverted for absolute time adjustments following *Van Decar and Crosson* [1990].

$$\begin{pmatrix} -1 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ -1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{pmatrix} = \begin{pmatrix} dt_{21} \\ dt_{31} \\ dt_{41} \\ dt_{32} \\ 0 \end{pmatrix}$$

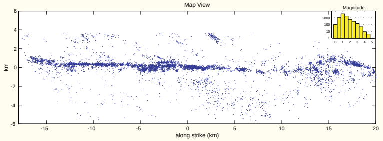


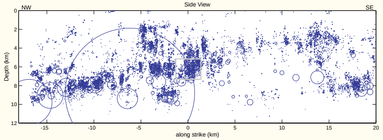
Application

Below are 7857 events on the Calaveras Fault in Northern California before and after relocation. The top panels are in map view rotated along the strike of the fault and the middle panels are depth sections. Overall reduction of hypocentral errors ranges from one to two orders of magnitude. The greatest improvement is in depth. Average catalog location errors are 1.5 km horizontal and 3 km vertical. Improved locations have errors on the order of 10s of meters or for repeating events occuring at a point, meters. Circles represent approximate source dimensions. The 1984 M 6.2 Morgan Hill earthquake is the largest event. The bottom panels display seismograms for about 3500 of the events (enclosed in green snake) ordered by distance along strike recorded at station CCO on the fault (see map at right). On the left, the arrival times are the original catalog picks and on the right the waveforms are aligned by cross-correlation. These record sections correspond to single receiver gathers and are not stacked. The time axis in samples is reduced to the P-wave arrival time. The strong amplitude arrival coming in later with a different apparent velocity is the S-wave. To maximize visual coherence the sections were plotted by event order and not true distance. The S-wave moveout appears more linear on a true distance plot. The strong variations of the S minus P time, seen here, are a consequence of different distances and event depths. Arrivals coming in prior to the S-wave but with the same moveout are most likely S to P conversions. Larger magnitude events are clipped at this close station, however, the zero crossings and phase are preserved. Surprisingly structures deeper into the records from weaker events correlate with and are enhanced by these larger events.

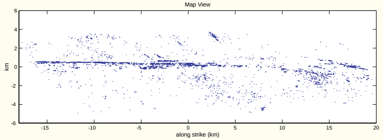


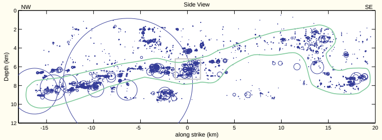
Catalog locations



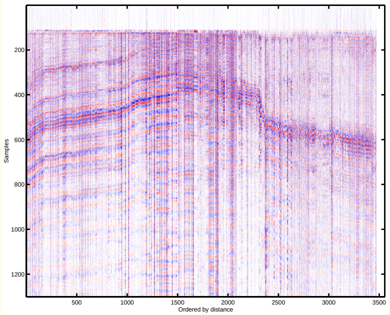


Relocated

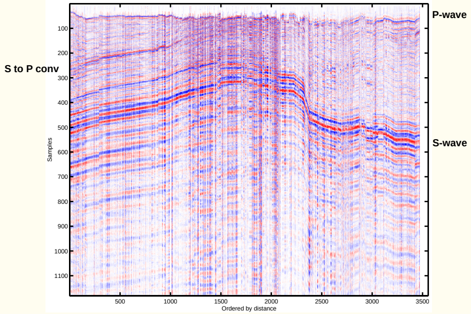




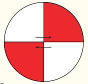
Catalog P-wave picks



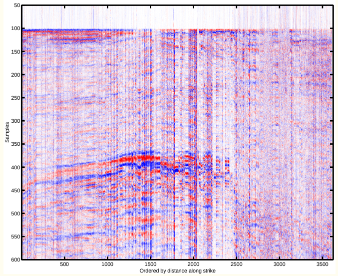
Cross-correlation



The same events and order, but now the seismograms from station JST (located off the fault) are displayed. The sense of slip on the Calaveras Fault is the same as the San Andreas Fault, right-lateral strike slip. This can be represented schematically with a beachball diagram at right, where the P-wave compressional quadrants are in red and the dilatational quadrants are white. Interestingly, from the record section most of the aftershocks of the 1984 Morgan Hill earthquake and the background seismicity also seem to exhibit right-lateral strike slip motion. The polarities of the P-waves change from down (blue) to up (red) as JST traverses from the dilatational to the compressional quadrant of the events. Near the middle where the P-wave becomes nodal, The S-wave is at its strongest amplitude, which is expected from the double-couple source mechanism for an earthquake.



JST



Reflection Seismology	Earthquake Seismology
known source location and origin time	unknown source location and origin time
explosion source	shear source (S-waves)
common mechanisms	variable focal mechanisms
ground roll	surface waves
sources at surface	sources at depth (less ground roll)
common source size	range of magnitudes (M [0.5 6.2])
more receivers	more sources
regular spacing	irregular distribution
high fold	less redundancy of event/station pairs
statics	correlation alignment
CMP gathers used	Common reciever gather best b/c of distr.
***	***
earth is the signal	earth is noise
source is noise	source is the signal!

Conclusions

The saying, "One man's signal is another man's noise," certainly applies to earthquake and reflection seismologists. Most earthquake seismologists look at event waveforms, individually, to try to understand more about the source. Since recorded seismograms are the convolution of both source and earth structure, both groups can profit by considering the other half of the equation, perhaps more than is typically done. For example, we may glean more information for large earthquakes if smaller aftershocks could be used to derive empirical green's functions for the earth. The availability of lots of earthquake data recorded now by the permanent networks permits a station centered view. Reflection seismology may also benefit, if problems can be set up in a relative sense to diminish the effect of unknowns -- such as the velocity model.

Waldhauser, F. and W.L. Ellsworth, A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, Bull. Seismol. Soc. Am., 90, 1353-1368, 2000.

VanDecar, J.C., and R.S. Crosson, Determination of teleseismic relative phase arrival time using mulit-channel cross-correlation and least squares, Bull. Seismol. Soc. Am., 80, 150-169, 1990.