Improving the measurement side of the double-difference equation: double whammy high-resolution earthquake locations

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Study Area for Relocation
Overview

Motivation
For Calaveras fault one to two orders of magnitude improvement

Theory
2 independent sources of error:
velocity model error (double difference)
pick measurement error (cross correlation)

Technique
waveform cross correlation
quantifying the quality

Application
local
regional
teleseismic
Velocity Model Error

station corrections
3D tomography
difference out (double difference)

\[ t_1 = t_{1c} + t_m \]
\[ t_2 = t_{1c} + t_m + dt \]
\[ dt = t_2 - t_1 \]
\[ d = G_m \]

Waldhauser and Ellsworth [2000]
Measurement
Error

38 different events

events superposed
Correlation Measurement Techniques

- Time domain
- Frequency domain
Correlation Data Quality?

Connectivity plot

- obs >= 5
- obs >= 10
- obs >= 30
Comparison of Measurement Error

Two runs
1) catalog only
2) correlation only

299,642 identical observations (model error fixed)
Inter-event distance dependence

- at zero distance: measurement error
- increasing distance:
  - catalog: model error
  - correlation: measurement + model error
Fine-scale structure
Comparison of two streaks

Characteristic vs. random

Seismic vs. aseismic slip

Triggering vs. minimal earthquake interaction
Complementarity with Morgan Hill Slip Model
Slip directions and fault planes known.

Maximum compressive stress is at a high angle to the fault implying that it is weak.
Two Clusters in China

Regional and Teleseismic
Regional Lg waves 750 km away
Telesismic example in China

SS phases at 51 degrees
Relocation of Underground Nuclear Explosions

Lop Nor Test Site

Phase picks @ ISC/ABCE stations

X-corr @ IRIS/array stations

X-correlation at ULHL.HHZ

Aligned on DOE P-wave picks

Selected Phase Pairs

Aligned by cross correlation

100 samples/sec, unfiltered (aligned from 0.5 to 2)
Double-difference Locations of Lop Nor Shaft Explosions

Most events are GT1

Absolute locations identified from satellite imagery.
Conclusions

Examples with order of magnitude improvement in measurement error
local -- interevent distances up to 2 km, 1 to 10 Hz band
regional -- interevent distances 5 to 10 km, 0.5 to 5 Hz band
teleseismic -- interevent distances 20 to 30 km, 30 to 10 sec band
1/4 wavelength rule more or less holds

Double whammy is when both model and measurement error can be reduced resulting in up to two orders of magnitude improvement in earthquake locations.

The new degree of resolution obtained enables more detailed studies.
Calaveras Fault
Lop Nor explosions

Double-difference approach is preferred for correlation data because it directly inverts the measured differential travel times.
Future Directions

Differential Tomography
  model error
  measurement error

Record sections for Calaveras Fault
  converting relative travel times to absolute

Northern California correlation database
  250,000 events
  2.5 billion correlation measurements
  10 million correlations per hour
Northern CA correlation database

250,000 events

2.5 billion measurements