Final Technical Report

USGS/NEHRP Award No: G09AP00018

REAL-TIME DOUBLE-DIFFERENCE LOCATION AT THE CISN: IMPLEMENTATION AND DD CATALOG MAINTENANCE

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ABSTRACT

This grant was in support of a larger project with the goal to integrate the real-time double-difference location software, DDRT, in routine CISN monitoring procedures at the Northern California Seismic Network in Menlo Park. Under this grant we have made progress towards this goal in two areas. 1) We have adapted our DDRT software package and underlying databases to recent changes that took place in routine CISN procedures at the NCSN in Menlo Park. These modifications are necessary in order to prepare the DDRT software for migration to USGS computers this summer. These changes also affected our procedures to compute and update the double-difference earthquake location catalog. 2) We have updated the original double-difference earthquake catalog for northern California, wich includes events between 1984-2003 (Waldhauser and Schaff, 2008; NCAeqDD.v2003), with events up to Decemeber 2008 (NCAeqDD.v200812.1.1). The new catalog is now based on a simultaneous re-analysis of 25 years (1984-2008) of the digital seismic archive of Northern California, including 445,493 earthquakes. Cross-correlation and double-difference methods were used to reduce measurement uncertainties and model errors, respectively, resulting in orders of magnitude improvement in location precision. Because the new DD catalog will likely find many applications in the Earth sciences, we made it available to the scientific community. Integrated in the DDRT system, the DD catalog will allow for monitoring spatio-temporal changes in seismogenic properties of active faults with unprecedented resolution and therefore has considerable social and economic impact in the immediate evaluation and mitigation of seismic hazards. This study also shows that the precision with which new events are located using these techniques will improve with time, helped by the continued increase in density of recorded earthquakes and growth of the digital seismic archives.

1. Overview of Investigations

This final report covers the activities performed between January 1, 2009 (start date of the project) and December 31, 2009. The initial project was for one year, but has been extended by an additional year at no cost to the end of 2010 to accommodate delays that arise from handling the large amount of data associated with the project. The work described in this report is being undertaken by the principle investigator Felix Waldhauser and by co-PI David Schaff.

This grant was in support of a longer-term goal to bring real-time double-difference location and continuous updates of the northern California DD catalog to USGS computers in Menlo Park. Under this grant we have made progress towards this goal in two areas.

1) We adapted our software system for real-time double-difference (DD) relocation, DDRT (Waldhauser, 2009), and procedures for comprehensive DD catalog computation (Waldhauser and Schaff, 2008), to reflect recent changes in routine CISN monitoring procedures at the Northern California Seismic Network (NCSN) in Menlo Park. These changes were necessary to prepare the software for migration to USGS computers, work that is ongoing and funded under a different grant.

2) We have updated our original DD catalog for northern California (NCAeqDD.2003; Waldhauser and Schaff, 2008), which included events between 1984-2003, to include all events up to 2008. The new catalog, including 445,493 high-precision earthquake locations, was released to the community in June 2010 (NCAeqDD.v200812.1.0), followed by a minor revision in July 2010 (NCAeqDD.v200812.1.1).

2. Investigations undertaken

2.1 Changes to the DDRT system

The DDRT system automatically and in near-real-time computes double-difference hypocenter solutions for earthquakes recorded in northern California and routinely processed at the Northern California Seismic Network (Waldhauser, 2009). The DD-RT process currently runs at Lamont and relocates new earthquakes relative to a high-resolution DD catalog of background seismicity by using differential times between the new event and its neighboring (reference) events in the DD catalog. Routinely determined parametric data of new events, such as phase picks and hypocentral information, are automatically sent to LDEO by the NCSN in Menlo Park and waveforms are accessed from the real-time DART server at the Northern California Earthquake Data Center in Berkeley. Data associated with the reference events are accessed from a locally stored copy of the entire Northern CA seismic archive. DDRT results are posted and can be accessed in near-real-time at http://www.ldeo.columbia.edu/~felixw/DDrtCISN.

We have adapted the current DDRT software and related archives and data bases to the following two main changes that recently took place at the CISN: changes in NCSN event IDs for a few thousand of events, adoption of SNCL, the new station naming convention, SNCL. These modifications required work on almost every piece of DDRT software and underlying archives, including some 3 billion cross correlation delay times. At the same time, in 2009, we have also started rewriting parts of the DDRT system to make it platform independent. The prototype system has been developed under SUN Solaris on a SPARC platform, using MATLAB functions to carry out several tasks of the real-time computations, including the cross-correlation measurements.

2.2 Update of the DD earthquake catalog for northern California

We have update the original double-difference earthquake catalog for northern California, wich included events between 1984-2003 (Waldhauser and Schaff, 2008; NCAeqDD.v2003), with events up to Decemeber 2008 (NCAeqDD.v200812.1.1). The new catalog is now based on a simultaneous re-analysis of 25 years (1984-2008) of the digital seismic archive of Northern California (Figure 1a). Billions of correlations were carried out on pairs of seismograms between new events and between new and old events separated by less than 5 km (see Schaff and Waldhauser, 2008, for details). The correlation data base now has nearly 600 million P-wave and 350 million S-wave delay times measured from pairs of seismograms that correlated at a correlation coefficient of 0.7 or higher. Approximately 3.5 million cross-correlation delay times were combined with delay times computed from NCSN phase picks and inverted for precise hypocenter locations for some 445,493 earthquakes. Compared to the 2003 catalog this represents a 35% increase in the number of events. About 90% of the earthquakes have correlated P- and S-wave trains at common stations (Figure 1b), which is similar to the 2003 catalog. 12% are co-located repeating events. Correlation characteristics and location improvement are remarkably similar across most of Northern California (Figure 1b), implying the general applicability of these techniques to image high-resolution seismicity caused by a variety of plate-tectonic and anthropogenic processes.

The relocated catalog is able to image the fine-scale structure of seismicity associated with active faults, with median relative location uncertainties of ~30 m for events constrained with correlation data and ~70 m for those constrained by phase picks only. Figure 2 shows before and after relocation results for four regions in northern California.

The DD catalog grew at an average annual rate of ~20,000 events and ~500,000 phase picks over the last few years. Figure 3 show the cumulative annual increase in the number of correlated events and the number of correlation measurements (Cf>=0.7) for various tectonic regions.

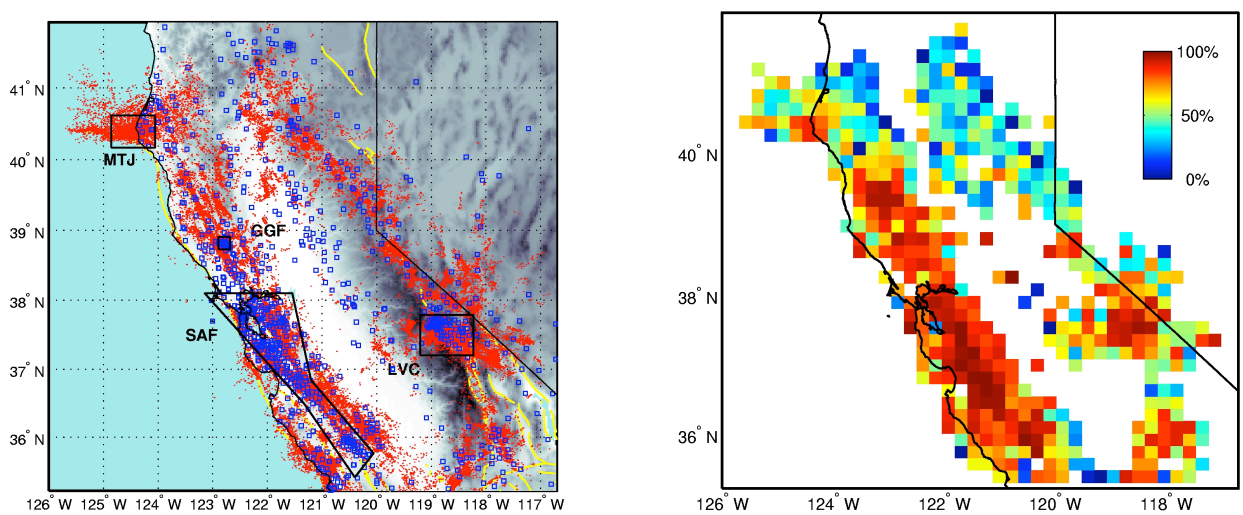

Figure 1 Distribution of 445,493 relocated earthquakes (red dots) between 1984-2008 and NCSN station locations (blue squares) (left panel). Right panel: Distribution of the percentage of correlated events within bins of 20x20 km.

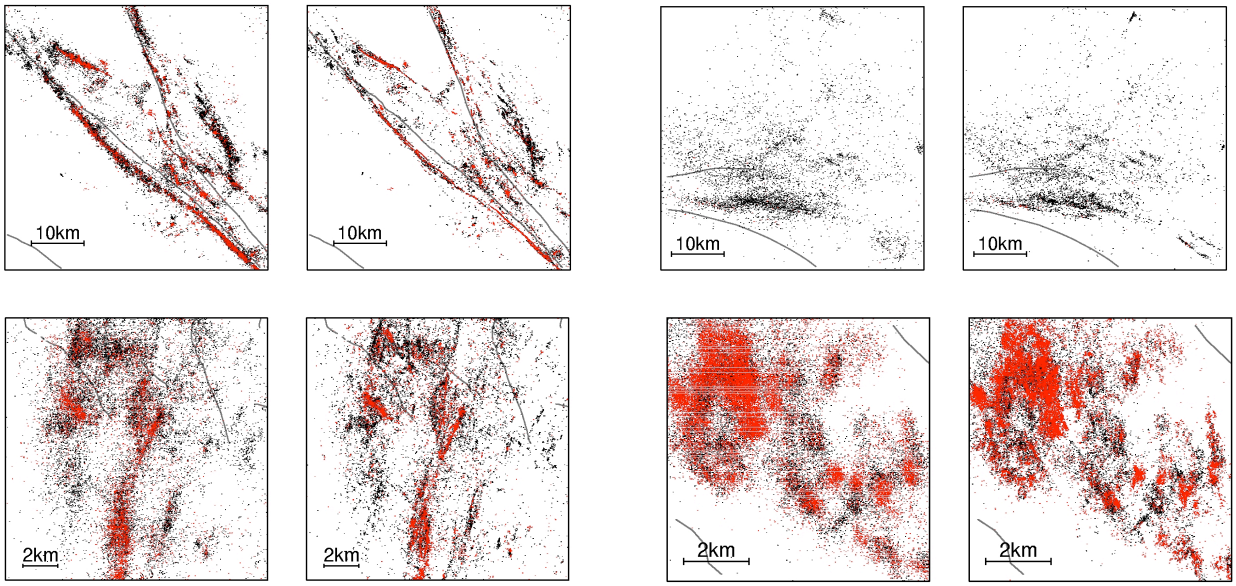

Figure 2 Map view of earthquake locations before (left panel in each subfigure) and after relocation (right panel in each subfigure). Top left: San Andreas/Calaveras Fault. Top right: Mendocino Triple Junction. Bottom left: Long Valley Caldera. Bottom right: Geysers Geothermal Field. Events in red occurred between 2004-2008 and are new since to the 2003 catalog.

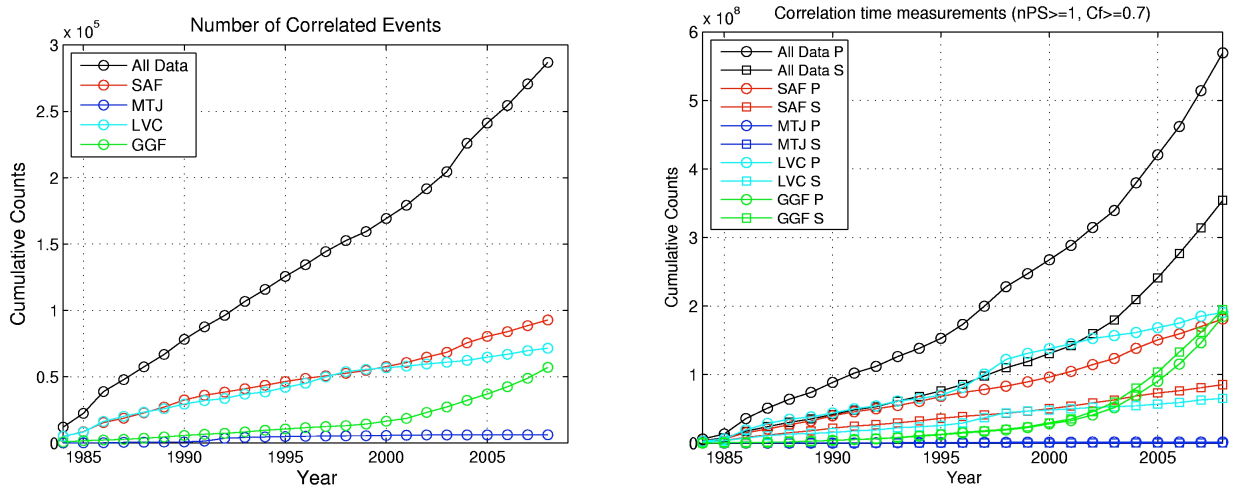

Figure 3 Cumulative increase in the number of correlated events (left panel) and the number of correlation measurements (right panel), shown for various tectonic regions in northern California.

4. References

Schaff, D.P. and F. Waldhauser (2005), Waveform cross-correlation-based differential travel-time measurements at the Northern California Seismic Network, *Bull. Seism. Soc. Am.*, *95*, 2446-2461.

Waldhauser, F. and D.P. Schaff (2008), Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods, *J. Geophys. Res.*, 113, B08311, doi:10.1029/2007JB005479.

Waldhauser, F. (2009), Near-real-time double-difference event location using long-term seismic archives, with application to Northern California, *Bull. Seism. Soc. Am.*, 99, 2736-2848, doi:10.1785/0120080294.

5. Reports published related to this project, or previous related projects

Peer-reviewed journal publications:

Waldhauser, F. (2009), Near-real-time double-difference event location using long-term seismic archives, with application to Northern California, *Bull. Seism. Soc. Am.*, 99, 2736-2848, doi:10.1785/0120080294, 2009.

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McCrory, P.A., J.L. Blair, and F. Waldhauser, Mapping the Juan de Fuca slab beneath the Cascadia margin, GSA Annual Meeting, Portland, October 18-21, 2009.

Waldhauser, F., and D. Schaff, Near-real-time double-difference earthquake locations for Northern California, 6th Annual Northern California Earthquake Hazards Workshop, Menlo Park, CA, January 20-21, 2009.

6. Available Data and Products

The 2008 DD catalog for northern California (NCAeqDD.v200812.1.1) is available from http://www.ldeo.columbia.edu/~felixw/NCAeq_DD/. The near-real-time double-difference hypocenter solutions for earthquakes in Northern California produced by the DD-RT method developed under this grant are continuously being made available at www.ldeo.columbia.edu/~felixw/DDrtCISN on a beta-test basis.

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7. Final Remarks

We are close to completing the work of updating the 2008 DD catalog to include all events until the end of 2009. We will then be replacing the current (2003 edition) DD base catalog in the DD-RT system with the new, updated DD catalog. An additional update to include the 2010 events is planned for this Summer.

Under a separate NEHRP grant, G10AC00040, we, in collaboration with P. Friberg (ISTI), will be installing an adapted DDRT software package on a dedicated workstation at the USGS in Menlo Park. The DD-RT process will be integrated into the real-time system at the California Integrated Seismic Network (CISN) to allow a more seamless interaction with the existing databases and archiving systems.