

Final Technical Report

USGS/NEHRP Award No: G10AC00040

Implementation of a Real-Time Double-Difference Earthquake Location System at the CISN and Maintenance of a Continuous DD Catalog for Northern CA

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ABSTRACT

We have completed DD-RT 1.0, a software package for real-time double-difference earthquake location. The DD-RT procedure uses cross-correlation and double-difference methods to rapidly relocate new earthquakes in Northern California relative to nearby reference events found in a high-resolution double-difference (DD) earthquake catalog. The DD-RT software is implemented and runs on a newly acquired Linux cluster at the Lamont-Doherty Earth Observatory (LDEO), using near real-time parametric and waveform data feeds from the Northern California Earthquake Data Center (NCEDC) for new events, and a locally stored archive of seismic data for past events. The DD-RT system updates the currently employed DD base catalog, which includes events between 1984-2009, with the most recent events in Northern California. All results are made available in near-real-time from a dedicated web server at <http://ddrt.ldeo.columbia.edu>. The DD-RT software has been installed on an Intel-based SUN-Solaris workstation at the USGS in Menlo Park, and a modul, `ddrt2aqms`, has been developed to interface with the AQMS system and databases used for routine seismic monitoring at the Northern California Seismic Network. Real-time double-difference location allows 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 demonstrates that the precision with which new events are located using this technique 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, 2010 (start date of the project) and September 15, 2011. The work described in this report is being undertaken by the principle investigator Felix Waldhauser (Columbia U), co-PI David Schaff (Columbia U), Paul Friberg (ISTI), and Ben Engebretth (Columbia U).

Within the scope of this project we completed the following two main tasks: 1) Adaptation and implementation of the real-time double-difference earthquake location software DD-RT for routine operation at the CISN in Menlo Park; 2) Production and maintenance of a continuous high-precision double-difference earthquake catalog for Northern California, made openly available at <http://ddrt.ldeo.columbia.edu>. The availability of continuously updated double-difference earthquake catalogs in near real-time is expected to have considerable social and economic impact in the evaluation and mitigation of seismic hazards, and the catalogs are particularly valuable to the research community as they provide fundamental data in the geophysical sciences. For example, rapid knowledge of precise aftershock locations may be useful to delineate the rupture area of the mainshock, which may help scientists assess the potential for and size of future aftershocks as well as provide critical source information for strong ground motion prediction. Changes in the recurrence intervals of repeating events can be monitored to infer changes in the loading rate, or the short-term evolution of stress concentrations can be tracked in near-real-time to better assess the potential occurrence of future events. Monitoring fine-scale changes in seismogenic behavior is particularly important along hazardous faults with well-characterized spatio-temporal behavior of past seismicity like the Hayward, Calaveras, and Central San Andreas faults.

2. Investigations undertaken

2.1 DD-RT 1.0: A software package for real-time double-difference earthquake location

We have completed a version 1.0 of the DD-RT (double-difference in real-time) software package, a prototype version of which has been developed under previous NEHRP grants. DD-RT computes automatically, and in real-time, high-precision hypocenter locations for earthquakes in Northern California. It uses near-real time data feeds from earthquakes recorded at stations of the Northern California Seismic System (NCSS). The NCSS, which assimilates data from 13 seismic networks (among them NC, NN, WR, CI, PG & UW), records an average of ~50 earthquakes on 1200 channels each day. The DD-RT system is built around real-time versions of the *hypoDD* software package (Waldhauser, 2001) and the correlation code *correl* (Schaff et al., 2004), and includes numerous additional programs for collecting, selecting, and processing the data, controlling the process flow, and generating a dynamically updated web site, <http://ddrt.ldeo.columbia.edu>, for displaying and accessing the relocation results over the internet (Figure 1).

A detailed description of the DD-RT method is given in Waldhauser (2009). Here we give a brief summary. The DD-RT procedure relocates new events relative to the high-resolution double-difference (base) catalog (Waldhauser and Schaff, 2008) by computing differential times from routine phase picks and/or from waveform cross-correlation at common stations between a new event and its neighboring (reference) events in the base catalog (Figure 2). The differential times are simultaneously inverted in an iterative weighted least-squares procedure for

adjustments in the location of the new event relative to its reference events in the DD catalog, using a real-time version, *hypoDD-RT* (Waldhauser, 2009), of the double-difference algorithm *hypoDD* (Waldhauser and Ellsworth, 2000; Waldhauser, 2001). *HypoDD-RT* uses only the equations that constrain a new event, i , relative to its $nref$ reference events, j , in the DD catalog:

$$\frac{\partial t_k^{i=1}}{\partial \mathbf{m}} \Delta \mathbf{m}^i - \frac{\partial t_k^{j=1,nref}}{\partial \mathbf{m}} \Delta \mathbf{m}^j = dr_k^{ij} \quad (1)$$

where dr_k^{ij} is the residual between observed (dt^{obs}) and predicted (dt^{cal}) phase travel-time difference between a new event and its reference events observed at a common station, k (see also Eq. 18 in Waldhauser and Ellsworth, 2000). $\Delta \mathbf{m}$ are changes in the vector connecting their hypocenters through the partial derivatives of the travel times, t , for each event with respect to the vector, \mathbf{m} , of the four unknowns.

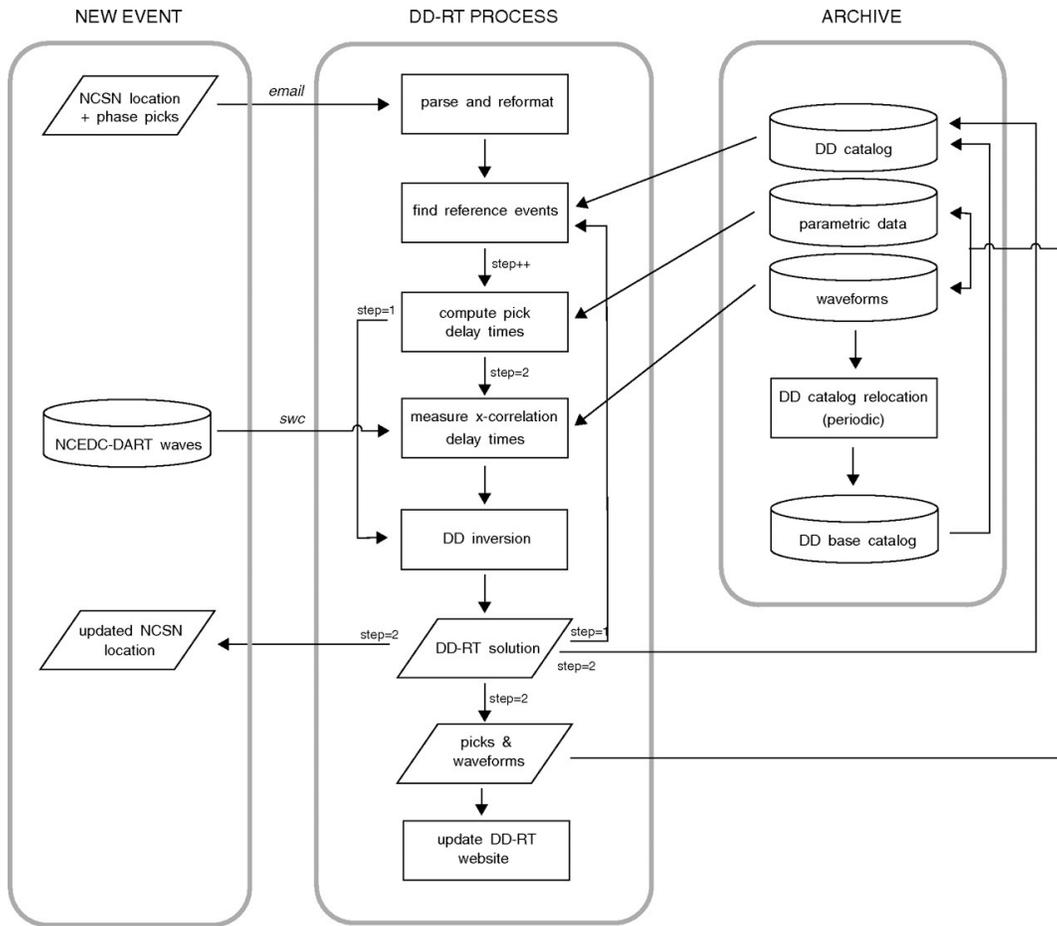


Figure 1 Detailed flow chart of the DD-RT procedure as implemented at LDEO for relocation of earthquakes in Northern California with real-time data feeds from the USGS in Menlo Park (NCSN) and UC Berkeley (NCEDC). *swc*: Simple Waveform Client (Doug Neuhauser, pers. comm., 2008). From Waldhauser (2009).

Event ID = 71667366

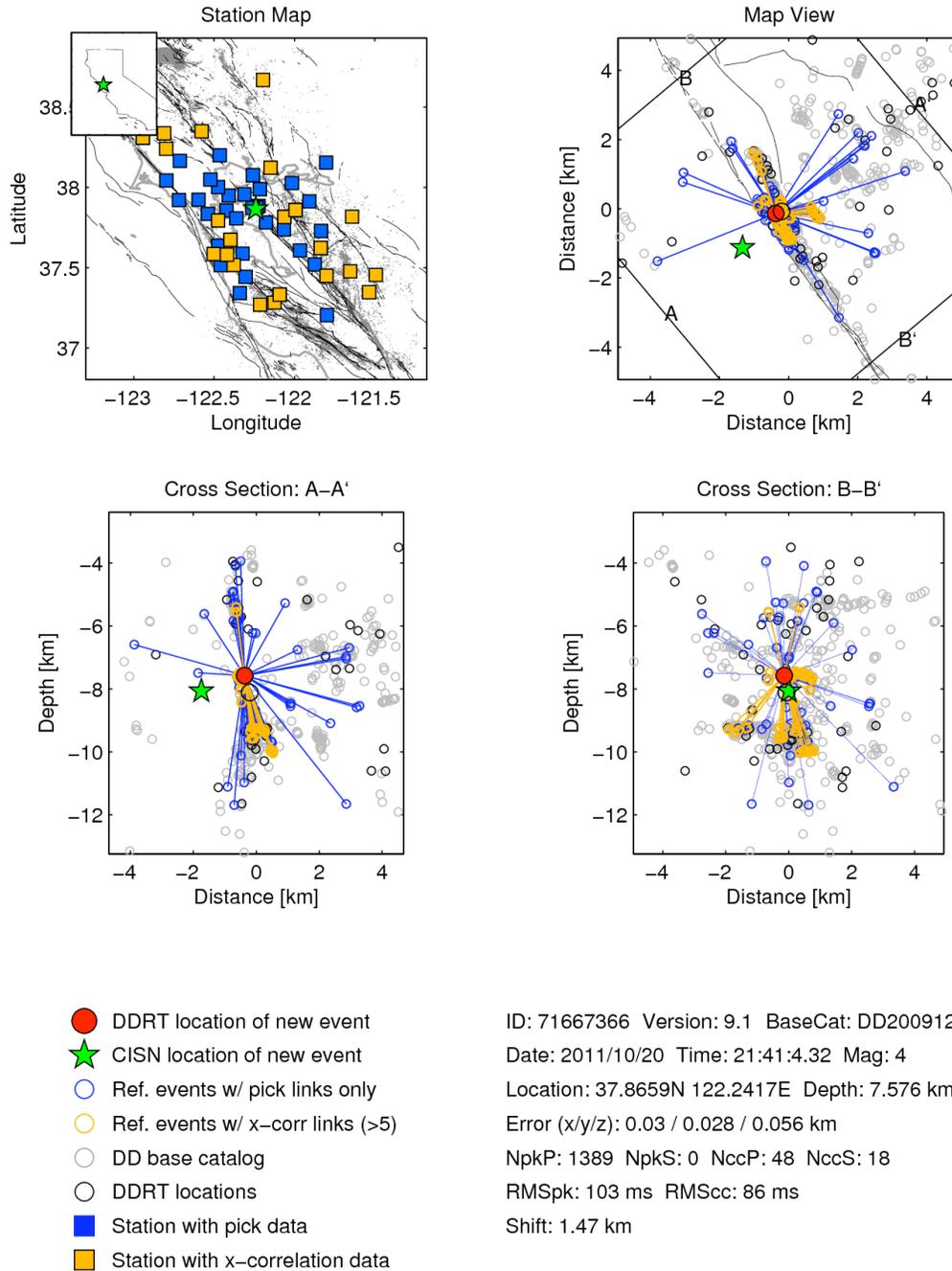


Figure 2 Example of automatically generated figure displaying and summarizing the DD-RT relocation performance and results for each event relocated. The event shown is the October 20, 2011, $M_L=4.0$ earthquake beneath Berkeley (from <http://ddrt.ldeo.columbia.edu>).

The real-time DD algorithm has some similarity to the master event location method (e.g., Evernden, 1967), except that in the master event approach many slave events are relocated relative to one master event, while here we relocate one slave event (new event) relative to a set of master events (reference events). We note that this procedure significantly improves the precision of a new event's location relative to the background seismicity. The accuracy of the absolute location depends on the location accuracy of the reference events in the DD base catalog. We refer to Waldhauser and Schaff (2008) for a detailed description and location error analysis of the DD base catalog for Northern California.

2.2 Update of the DD base catalog, 1984-2009

An integral part of the DD-RT system is the underlying DD base catalog with associated parametric and waveform archive. The DD base catalog is computed from a simultaneous relocation of all events, involving the cross-correlation of waveforms between each event and all neighboring events within 5 km distance (see Schaff and Waldhauser, 2005 and Waldhauser and Schaff, 2008 for details). During real-time operation, new events are relocated relative to only a selected number of reference events in the base catalog. Their locations, therefore, are of lower quality compared to locations in the base catalog. For this reason the base catalog requires periodic (yearly, as of now) updating by simultaneous relocation of all events. As part of this project we have generated the 2009 edition of the DD earthquake catalog for northern California, including 457,114 earthquakes from 1984 to the end of 2009. The DD catalog grows at an average annual rate of $\sim 20,000$ events and $\sim 500,000$ phase picks. Figure 3 displays the exponential increase in the number of correlation measurements and the linear increase in the number of correlated events. We have implemented the 2009 DD catalog and archives in the DD-RT v1.0 system.

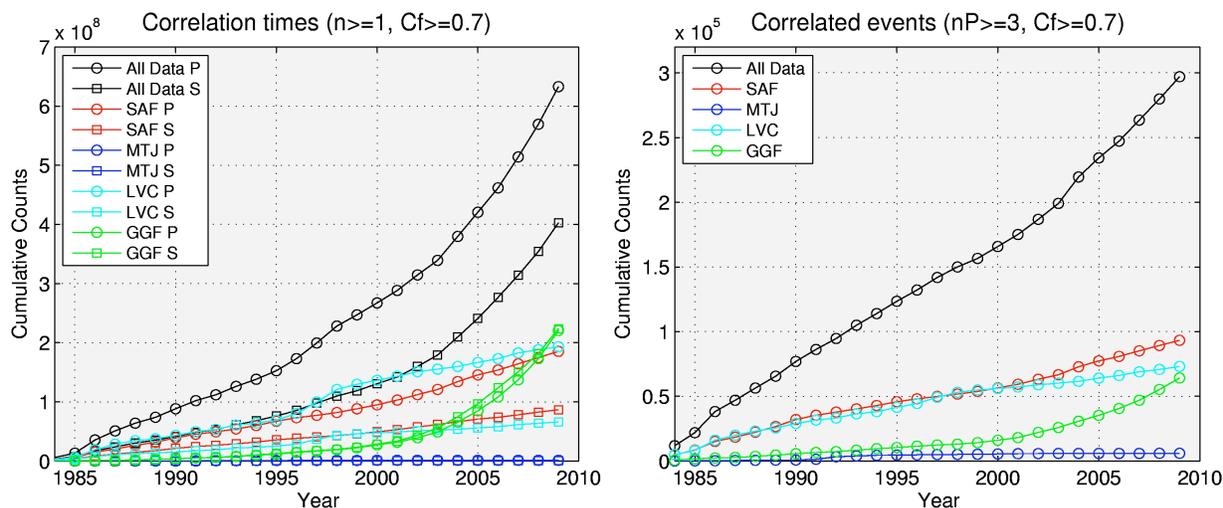


Figure 3 Year-over-year increase in the number of cross-correlation measurements (left) and number of correlated events ($C_f \geq 0.7$) (right) for various tectonic regions. SAF: San Andreas Fault; MTJ: Mendocino Triple Junction; LVC: Long Valley Caldera; GGF: Geysers Geothermal Field; P: P-waves; S: S-waves.

2.2 Implementation of the DD-RT software and dissemination of results

As part of this project we have installed and are running the DD-RT system on a newly acquired Linux cluster here at Lamont. We are now producing a continuously updated high-precision earthquake catalog for Northern California, fulfilling task 2 of the project. Parametric data of new events in Hypoinverse archive format (including phase picks, hypocenter location and origin time, and magnitude estimates) (Klein, 2002) are automatically being sent to the LDEO server via email and seismograms, two minutes long and starting 10 s before the origin time, are automatically requested from the NCEDC using the program *swc* (Simple Waveform Client; Doug Neuhauser, pers. communication; Romanowicz et al., 1994). The *swc* program access the Simple Wave Server (SWS) at the NCEDC which stores the real-time DART waveforms, and downloads the seismograms of new events in miniSEED format to the local disk. Parametric and waveform data for the reference events are retrieved from a locally stored copy of the entire NCSN archive from 1984-2009 (the period for which we currently have a DD base catalog), totaling about 1.5 Tb in size. The archive consists of ~10 million NCSN phase arrival time picks (mostly P-phases) and some 25 million waveforms recorded at 800 stations. Pick based DD-RT solutions are computed within a few tens of seconds after receiving the initial location and phase information, and final DD-RT solutions computed using cross-correlation data (if available) are typically available in less than a minute. Having the DD-RT process run locally at Lamont allows us to monitor its performance of the system and trouble-shoot it. Furthermore, it will serve as a platform to improve existing software and develop and test new procedures.

The DD-RT process automatically generates figures and tables that summarize key parameters describing the solution quality and characterize the hypocenter's location relative to the past seismicity. Figure 2 displays DD-RT results for the recent M4.0 Berkeley earthquake of October 20, 2011. It indicates the final DD-RT location (red dot) relative to its routinely determined solution (green star), and relative to the historic seismicity as present in the DD base catalog (gray dots). The example illustrates how the hypocenter of the event, initially located about 1.5 km to the south-west of the Hayward fault, falls onto the main fault after relocation. The DD-RT solutions as well as associated figures and solution parameters are automatically being posted to a dedicated web site (<http://ddrt.ldeo.columbia.edu>) from which they can be openly accessed. The website also contains links that allow the search of both the DD base and the DD real-time catalogs.

Finally, we have adapted the DD-RT software to run on the Intel-based SUN-Solaris workstation *mnlodd1*, a machine dedicated for DD-RT processing at the Northern California Seismic Network in Menlo Park. We have installed the DD-RT software on *mnlodd1* and have completed all necessary tests to run DD-RT in single event and batch mode. Paul Friberg from ISTI wrote the script *ddrt2aqms*, which launches the DD-RT process from AQMS, the CISN routine monitoring software, and writes the DD-RT solution into the AQMS database (Figure 4). Before DD-RT can become part of the AQMS routine processing at the NCSN, the specifics on how to store DD-RT results in the NCSN database and how to report them to the public still need to be defined. Discussions including personnel at USGS and Berkeley towards this goal are ongoing.

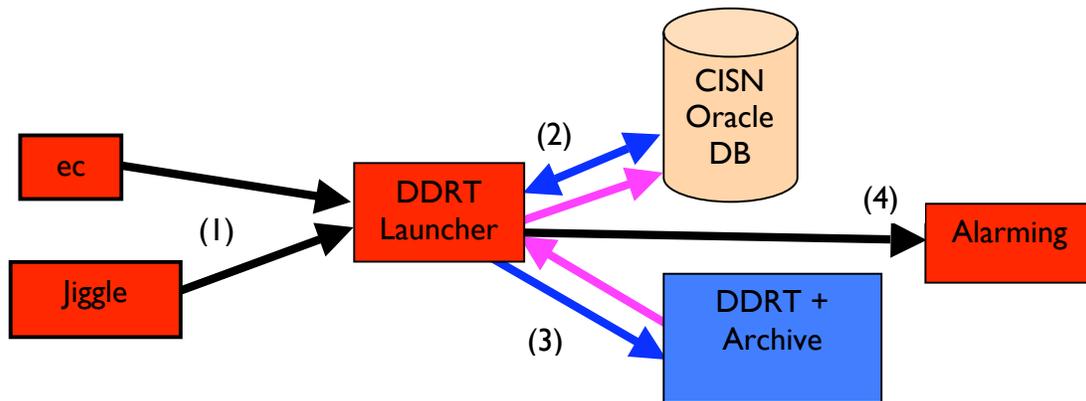


Figure 4 A flow diagram of DDRT Launcher ddr2aqms showing data processing pathways between various components of the system as integrated into the CISN software. Blue arrows represent earthquake location, phase, and waveform data, pink arrows signify updated location data, and black arrows represent CISN messages with the event identifier. Numbers in parenthesis (1) indicate the sequence in which actions occur.

3. References

- Evernden, J.F. (1969). Identification of earthquakes and explosions by use of teleseismic data, *J. Geophys. Res.* **74**, 3828-3856.
- Klein, F. W. (2002), User's Guide to HYPOINVERSE2000, a Fortran Program to Solve for Earthquake Locations and Magnitudes, *U. S. Geol. Surv. Open-File Rep, 02-172*, 123pp.
- Romanowicz, B., D. Neuhauser, B. Bogaert and D. Oppenheimer (1994), Accessing Northern California Earthquake Data Via Internet, *EOS Trans A.G.U.* **75**, 258-261.
- 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 W. L. Ellsworth (2000), A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, *Bull. Seism. Soc. Am.*, **90**, 1353-1368.
- Waldhauser, F. (2001), HypoDD: A computer program to compute double-difference hypocenter locations, *U.S. Geol. Surv. open-file report*, 01-113, Menlo Park, California.
- Waldhauser, F. and D.P. Schaff, 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, 2008.
- Waldhauser, F., 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.

4. Reports published related to this and previous DD-RT projects

Peer-reviewed journal publications:

- Waldhauser, F., 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.
- Waldhauser, F. and D.P. Schaff, 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, 2008.

Conference abstracts:

- 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.
- Waldhauser, F., D. Schaff, B. Engebret, P. Friberg, Towards Real-Time Monitoring of Fine-Scale Seismogenic Properties in Northern California, 8th Annual Northern California Earthquake Hazards Workshop, Menlo Park, CA, January 24-25, 2011. (KEYNOTE)
- Waldhauser, F., D. P. Schaff, Real-Time Cross-Correlation and Double-Difference Algorithms for Event Detection and Aftershock Screening (INVITED), Abstract S51D-06, Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec, 2010.
- Waldhauser, F., and D. Schaff, Real-time double-difference location and monitoring of fine-scale seismic properties, SSA Annual Meeting, *Seism. Res. Lett.* 81, 2, p.377, 2010.
- Waldhauser, F., and D. Schaff, Towards real-time double-difference event relocation at the CISN, 6th Annual Northern California Earthquake Hazards Workshop, Menlo Park, CA, January 26-27, 2010.

5. Available Data and Products

The near-real-time double-difference hypocenter solutions for earthquakes in Northern California produced by the DD-RT system developed under this grant are continuously being made available at <http://ddrt.ldeo.columbia.edu>. The current DD catalog (NCAeqDD.v200912.1) can be downloaded via a link available from the same website, as will future updates of the catalog.

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6. Final Remarks

We will continue to maintain the DD-RT system both at Lamont and at the USGS, including the regular updating of the DD base catalog, as well as trouble-shoot the system when problems arise. Future work is also aimed at improving the performance of the DD-RT system and the accuracy of the results it produces.