Improving Real-time Earthquake Determination with GPS Geodetic Observations

D Ray Baxter, Mark H Murray, Doug S Neuhauser, Lind S Gee, Barbara Romanowicz
Berkeley Seismological Laboratory, UC Berkeley (mmurray@seismo.berkeley.edu)

Overview

Geodetic observations of ground deformation caused by an earthquake can be used to infer the fault location and geometry, and the distribution of slip on the fault. We are developing methods for rapidly measuring coseismic displacements using continuously operating, permanent Global Positioning System (GPS) networks, such as BARD, in order to determine finite-fault characteristics of earthquakes. We plan to incorporate this methodology into the REDI project in order to enhance hazard mitigation and emergency management in the immediate aftermath of a major earthquake.

BARD

The Bay Area Regional Deformation (BARD) network of permanently installed GPS stations continuously monitors crustal deformation in northern California, with a particular focus on the San Andreas fault system in the San Francsico Bay Area. The BARD network is a collaborative effort of UC Berkeley, the US Geological Survey, and several other university, government, and commercial institutions.

10 BARD stations are co-located with the seismic instrumentation of the Berkeley Digital Seismic Network (BDSN) and use digital frame relay connections for continuous telemetry to the Berkeley Seismological Laboratory. 2 additional sites have continuous radio communication. Data from the remaining stations in northern California are collected once per day via dial-up phone lines.

Map of the BARD network in northern California (top) and detail of the San Francisco Bay Area (bottom). Red triangles indicate operational sites and blue triangles indicate planned installations. Circles indicate stations where frame relay connections provide continuous telemtry to UC Berkeley. About 30 receivers are currently operating in northern California, some not shown here. Approximately 8 additional stations are planned to be installed in 1998.

REDI

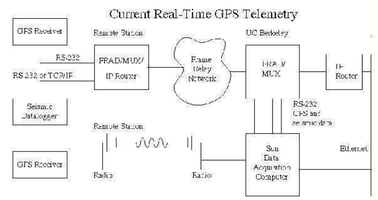
The Rapid Earthquake Data Integration (REDI) project is a system for the determination of earthquake parameters in northern and central California at UC Berkeley.

The Berkeley Seismological Laboratory and the USGS operate a joint notification system that integrates multi-stage processing at both institutions. Earthquake parameters are broadcast to government, utility, and emergency response agencies within minutes of the event via commercial pagers, electronic mail, and the WWW.

Depending on the event size, earthquake analysis can include:

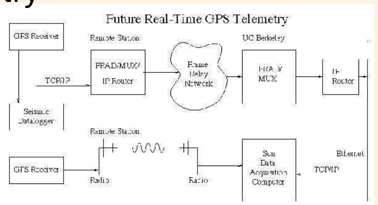
- event association and preliminary location, performed by the USGS within seconds of the event
- improved location and coda magnitude, provided by the USGS within 2-4 minutes
- local magnitude, from analysis of waveform data by UCB within 3-5 minutes
- observations of peak ground motions from UCB accelerometers within 5-7 minutes
- moment magnitude and moment tensor determination within 9–10 minutes
- at the highest magnitudes, finite-fault parameters estimated from GPS measurements of coseismic displacements

Telemetry



UC Berkeley receives real-time data from 12 BARD GPS sites. Most of these sites are co-located with Quanterra seismic dataloggers, and utilize existing FRADs (Frame Relay Access Device) and frame relay connections to transmit both real-time seismic and GPS data. The Motorola FRADS support multiple X.25 VCs (virtual circuits), which allows simultaneous data transmission of GPS and seismic data on different ports across a single digital frame relay line. The seismic and GPS data are received on different ports at UC Berkeley and are archived on disk independently.

Several GPS stations utilize either direct radio transmission or a hybrid path of radio to frame relay to UC Berkeley.



In the future, GPS stations co-located with Quanterra dataloggers will transmit real-time data directly to the Quanterra. The Quanterra will:

- Log GPS data into circular disk buffers (and optionally tape), providing long-term reliable onsite storage.
- Integrate GPS data into Quanterra's reliable telemetry protocol for real-time data transmission to one or more central processing sites.
- Allow data retrieval from disk via dialup or network link.

GPS will be encapsulated in MiniSEED format, transmitted to the central site, and logged to disk along with the seismic data in MiniSEED format. Utilities will extract the raw GPS data from the MiniSEED format for real-time processing.

Frame Relay benefits

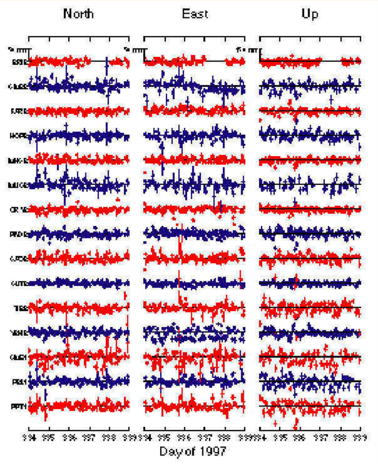
- Faster communication (56Kbit to 1.5MBit) and more reliable digital telemetry than analog modems.
- Robust networking infrastructure instead of point-to-point links. Traffic can be rerouted within a network to bypass damaged lines.
- Each site with a single frame relay connection can directly communicate with multiple sites on the frame relay network using multiple Permanent Virtual Circuits (PVCs).
- FRADs can support multiple connections over serial lines, ethernet, and TCP / IP sockets or UDP / IP datagrams.
- Frame relay has flat-rate pricing for intra-LATA connections instead of mileage-based rates for point-to-point links.

Real-Time GPS Processing

Current Strategy

Continuous GPS data are binned into one hour files and processed beginning at 15 minutes after the hour. Each hour is processed independently using fixed IGS predicted orbits, which are available before the beginning of the UTC day; processing takes about 10 minutes.

The figure at right shows the variations in site position of the hourly solutions for 5 days in early December. Scatter is approximately 1-cm in horizontal and 3-cm in vertical, suggesting that offsets 3 times these levels can be reliably detected. 24-hr solutions with much smaller scatter clearly show that CMBB moved 2 cm west between days 335 and 337; this offset is marginally detectable in the hourly solutions. The cause of this anomaly is not known at this time.



Future Strategy

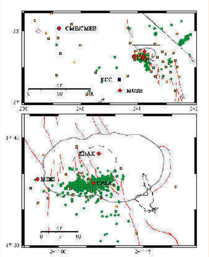
We plan to test Kalman filtering techniques, using GIPSY / OASIS, to estimate epoch-by-epoch position updates. Differentiating between cycle slips due to loss of lock and earthquake displacements is a potential difficulty. One possible solution is to use the REDI information about seismic events to estimate when the coseismic displacement should have occurred at the station.

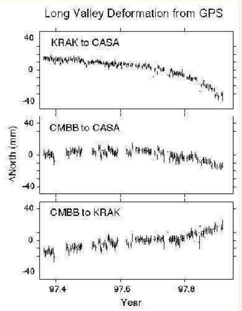
Real-time monitoring of Natural Hazards

Volcanoes

Rapid estimates of deformation are useful for monitoring volcanic areas, because the surface deformation caused by the movement of magma at depth often can be detected geodetically.

The Long Valley caldera near Mammoth Lakes, California, has experienced increased rates of moderate seismicity and accelerated deformation since August 1997. This recent unrest is being closely monitored by an array of geophysical instruments, include permanent GPS receivers at CASA directly above the most recent seismicity and at KRAK on the resurgent dome. The north-south line between these stations has lengthened by more than 5 cm since August, as determined by two-color laser ranging measurements. Our automatic processing of daily GPS measurements show similar rates of deformation, and also show that CASA is moving south and KRAK is moving north relative to a distant stable site, such as CMBB in the Sierra Nevada foothills. These absolute displacements provide useful constraints on the tectonic sources responsible for the deformation within and near the caldera.





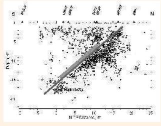
Earthquake faults

Deformation prior to major earthquakes has not been measured geodetically, but GPS can be used to determine the location, extent, orientation, and slip on a fault caused by an earthquake. We are developing techniques to rapidly determine finite-fault parameters from coseismic displacements, which is a non-linear inverse problem. We are currently testing several Monte Carlo approaches, such as random cost and simulated annealing, possibly combined with gradient methods to find the most rapid and reliable approach.

Fault Geometry and Ground Motion

Rapid finite-fault determination is most useful in areas where the fault geometry is not well known prior to the event.

For example, recent earthquakes in the Los Angeles basin provide dramatic evidence that the region is underlain by a complex set of poorly known blind thrust faults. The 1971 M=6.7 San Fernando earthquake occurred on a *north*-dipping thrust fault that ruptured to the surface. The 1994 M=6.7 Northridge earthquake occurred just west of the San Fernando earthquake and had a similar focal mechanism, but it ruptured on a blind *south*-dipping thrust fault.



Cross section showing fault plane models and aftershock locations for the Northridge earthquake. Slip was distributed on the thin black line, but was concentrated on the thick gray line. Modified from *Hudnut et al.* (1996).

Because the Northridge earthquake did not rupture to the surface and the initial pattern of aftershock locations was diffuse, it was not immediately clear whether the north- or south-dipping fault plane had slipped. However, within one week the displacements measured by campaign-style GPS surveys were able to unambiguously show that the south-dipping plane had ruptured.

Stations in the permanent GPS network operating at that time were too far away from the epicentral region to help much. However, recent expansions of the network should make determination of fault geometry in the LA region feasible within minutes of an earthquake.

Once the fault slip and geometry are determined, strong ground motion can be predicted.

The figure at right shows peak ground velocity estimated by a point-source summation method, assuming the rupture initiates at the hypocenter and propagates uniformly on the fault plane. It shows that the strongest shaking due to the Northridge earthquake was focused in the Santa Susanna Mountains, in general agreement with the observed ground motion.

We are developing methods to combine rapid measurements of ground motion with finite-fault predictions to provide a more robust and accurate map of strong ground shaking for emergency response management.

Coseismic displacements (95% confidence) measured within 1 week of the Northridge earthquake used to determine the finite-fault geometry (rectangle), and predicted horizontal ground velocity (cm / s contours) determined by point-source summation assuming 3 km / s rupture on the fault initiating at the hypocenter (star).