Introduction

Moment magnitudes for large earthquakes ($M_w > 7.0$) derived in real-time from near-field seismic data can be underestimated due to instrument limitations, ground tilting, and saturation of frequency/amplitude-magnitude relationships. Real-time high-rate GPS resolves the build-up of static surface displacements with the S-wave arrival, thus enabling the estimation of slip on a finite fault and the event's geodetic moment. Here, we present the first operational system for real-time GPS-enhanced earthquake early warning as implemented at the BSL and currently running on data for Northern California. Using synthetic and real-data test cases, we explore its sensitivities to disturbances of a priori constraints (origin time, location, fault strike/dip). The work presented here is a continuation of Grapenthin et al. (2013a,b).

Data processing

The BSL generates real-time position estimates operationally using data from 62 GPS stations (BARD, PBO, USGS) in Northern California (Figure 2.30.1). A fully triangulated network defines 170+ station pairs for processing with the software trackRT (Herring et al., 2010). The BSL uses G-larmS, the Geodetic Alarm System, to analyze the positioning time series, and determine static offsets and pre-event quality parameters. G-larmS derives and broadcasts finite fault and magnitude information through a least-squares inversion of the static offsets for slip based a priori fault orientation and location information. This Python implementation tightly integrates seismic alarm systems (CISN ShakeAlert, ElarmS-2) as it uses their P-wave detections to trigger its processing; quality control runs continuously.

Figure 2.30.1: Snapshot during a real-time test of G-larmS (second solution, five seconds after event); the red line on the right side shows the timing of the snapshot. Top right figure shows the estimated earthquake magnitude for the slip model in magenta on the left. Test is based on a simulated $M_7.0$ earthquake. G-larmS begins estimating co-seismic offsets (blue and black symbols) after the S-wave arrival. Offsets are updated and input into an inversion for distributed fault slip every second. Testing was run in true real time; synthetic offsets were added to GPS position time series on-the-fly in order to capture true real-time noise and data availability.
Sensitivity Tests

To linearize the finite fault inversion step to increase processing speed we make assumptions about fault orientation and location. We test G-larmS’ sensitivity to these assumptions using synthetic tests in which we add modeled ruptures at the Hayward Fault to real-time data (Figure 2.30.1). In individual tests, we randomly perturb pre-defined fault strike and dip, and the event epicenter and origin time, which are derived from a seismic alarm message that triggers our processing.

Here, we show only the impact of misestimates in fault geometry is shown in Figure 2.30.2 (more details in Grapenthin et al., 2014). We vary strike and dip of the model inversion fault by ±20 degrees and ±45 degrees, respectively. The upper row (Hayward 0 km) uses the same forward model as shown in the offset time series in Figure 2.30.1 (rupture from 0-12 km depth) and demonstrates that magnitude recovery (blue) and model fit (red) degrade quickly with small deviations from the nominal values.

The lower row in Figure 2.30.2 (Hayward 5 km) uses a forward model that slips only between 5 and 12 km depth. In the inversion, however, slip over the entire fault width along dip is assumed. While the model fits (red) are generally good for the full range of values, the magnitude recovery (blue) is poor. Asymmetries are due to asymmetries in the network (dip of 140 and 45 degrees are towards West and East, respectively which then constrained the inverse model to have lower overall magnitude.

Conclusions and Outlook

From the tests presented here, and others summarized by Grapenthin et al. (2014), we suggest, that slip for an earthquake occurring within small bounds of our assumptions, i.e. strike=320±5 degrees, dip=90±3 degrees, mislocation within 3 km orthogonal to surface trace, and surface rupture, will be well recovered for earthquakes within the network (depending on station distribution). Outside of these bounds, however, we may face unphysical slip models and poor magnitude recovery at relatively good fit of the model to the data.

While dense station coverage provides high resolution and, most importantly fast observations, it requires us to sample the parameter space for the non-linear finite slip inversion problem more thoroughly. The most problematic issue is choosing any parameter such that individual (near field) stations end up on the wrong side of the model fault. As the parameter space exploration in real-time cannot be exhaustive unless heavily parallelized, we have to exploit this property in the future. As real-time GPS is sought to contribute improved magnitude estimates within ±0.3 magnitude units and an approximate fault length for ground motion prediction to earthquake early warning, two simplifications are possible: (1) ignoring/down-weighting near-field data at single outlier stations in a dense network that produce significant misfits, (2) placing model faults between station pairs with highest strain. These can be combined and both reduce the complexity of the solution while providing approximate solutions. The trade off between speed and accuracy of the solutions is the subject of future investigation.