RAPID DETERMINATION OF EARTHQUAKE MAGNITUDE AND DISPLACEMENT FIELD FROM GPS-OBSERVED COSEISMIC OFFSETS FOR TSUNAMI WARNING

H.-P. Plag, G. Blewitt, [*]

University of Nevada, Reno
Nevada Bureau of Mines and Geology
and Seismological Laboratory
Mail Stop 178; Reno, NV 89557, USA

Y. Bar-Sever[†]

Jet Propulsion Laboratory,
4800 Oak Grove Drive
Pasadena, CA 91109-8099, USA

1. INTRODUCTION

The rapid assessment of the tsunamigenic potential of an earthquake is crucial for reliable tsunami early warning. For ocean-wide tsunamis, knowing the tsunami potential within an hour of the event is critical. For coastal areas in the vicinity of seismogenic faults, warning times are on the order of ten minutes. For great earthquakes, initial estimates of the magnitude from seismological observations tend to be too low due to a saturation [1], although recent improvements in rapid magnitude estimation have addressed this problem (e.g., [2]). Estimates of the seismic moment magnitude M_w are used to assess the order of the tsunamigenic potential. The generation of tsunamis depends on the potential and kinetic energy transferred to the ocean by rapid co-seismic displacement of the ocean bottom [3]. In order to improve prediction of the likely propagation of a tsunami, the surface displacement field of the earthquake needs to be known with latencies of a few minutes after the earthquake. Coseismic surface displacements determined from displacement time series measured at GNSS (Global Navigation Satellite System) tracking station in real-time can be used to improve early estimates of earthquake magnitude and displacements and thus support the assessment of the tsunamigenic potential of an earthquake and also helps to improve predictions of the propagation pattern of the tsunami.

Real-time and low-latency processing of GPS observations has reached a level of precision sufficient for the determination of coseismic permanent displacement at the GPS sites with low latency [4]. Real-time stations are increasingly available, thus opening the opportunity for operational use of GPS displacement time series in tsunami early warning.

We have developed a fingerprint methodology for the rapid estimation of M_w, and the determination of the surface displacement field from GNSS-determined displacements. This method depends on *a priori* knowledge of the faults potentially involved in a rupture. The procedure is implemented in a prototype system, which is run in real time as a component of a comprehensive early warning system. The prototype is part of the *GPS-aided Real-Time Earthquake and Tsunami (GREAT) Alert System* [5]. The prototype can also be used for delayed-mode studies.

2. THE FINGERPRINT METHOD

To our knowledge, a theory for the full inversion of the coseismic permanent displacements observed by GNSS tracking stations for a source model is currently not available. Available inversion methods for the slip distribution on predefined fault elements

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using a Green's function approach (in the strict mathematical sense of this term, see below) tend to be cpu-time intensive (Wang, 2011, personal comm.). Therefore, they are currently not implemented for real-time use, and they require well-defined constraints in the fault geometry.

In order to minimize the requirements for *a priori* knowledge of the rupture area and direction, we have developed a regression approach for the determination of the slip distribution on the ruptured fault area, which we denote as *fingerprint method*. In many geographical areas, the location of seismogenic faults are known, and these faults can be approximated by a sequence of predefined fault elements. For each finite fault element we compute the 3D surface displacement field due to a unit slip. We denote these displacement fields as *fingerprints*, since they are for finite elements and hence not Green's functions. Fingerprints for dip-slip and strike-slip are needed in order to represent all possible slip directions, resulting in six scalar fingerprints each fault element.

The displacement $\vec{X}$ (given as $(\delta e, \delta n, \delta u)$ where e, n, u are east, north, and up-displacements) observed at a GNSS tracking station on the Earth's surface at location $\vec{r}$ and time t is modeled by

$$\vec{X}(\vec{r}, t) = \sum_{j=1}^{N} \left\{ \alpha_j \vec{A}_j(\vec{r}) + \beta_j \vec{B}_j(\vec{r}) \right\} H(t - t_{0j}(\vec{r})) + \delta \vec{X}_{\mathrm{s}}(\vec{r}, t) \; , \tag{1}$$

where $\vec{A}_j$ and $\vec{B}_j$ are the fingerprint displacement vectors at location $\vec{r}$ for the j-th fault element for dip-slip and strike-slip, respectively; H is the Heaviside function; t_{0j} the predicted arrival time of the permanent displacement caused by element j at location $\vec{r}$, and $\delta\vec{X}_s$ the predicted displacements caused by seismic waves or other disturbances [6]. In the regression, the scaling factors α_j and β_j for dip-slip and strike-slip, respectively, at the j-th fault element are determined in a least-squares fit of eq. 1 to a set of observed displacement time series.

Based on the approximate location of the epicenter as provided by seismological methods, the set of fault elements potentially participating in the rupture can be determined, and the set of GPS stations potentially having experienced a detectable coseismic static displacement can be identified. The model space for the regression analysis contains all physically reasonable combinations of fault elements, which could have ruptured together during the earthquake. A search is being performed in order to determine the "best fit" combination. Several statistical parameters of the fit are used to identify the "best fit" combination.

3. FINGERPRINT DATABASE

Computation of the fingerprints using a forward-modeling approach is demanding in cpu-time and cannot be done as part of a real-time warning system. In order to apply the fingerprint method, we have populated a database of fault elements with fingerprints sampled with sufficiently high spatial resolution so that the displacements can be interpolated to the GNSS. We used the fault database of the NOAA's Center for Tsunami Research [7], which ensures consistency with NOAA's tsunami warning model. This database comprises 573 fault elements for most major tsunamigenic faults. The fault segments have a length of 100 km. Each segment is represented by a pair of connected shallow and deep elements [7], resulting in a total of 1,146 fault planes. We computed fingerprints using the algorithm of [8]. The elastic Earth model used in the computation is derived from PREM. The uncertainty in the dip of the elements is accounted for by computing fingerprints for several dip values. The total number of available fingerprints is currently about 4,500.

The requirement that the interpolation error at GNSS sites should be $< 1\%$ necessitates a high spatial resolution in the near-field of a fault element and a much lower resolution in the far-field. We chose to sample the fingerprints for a set of circles centered around the midpoint of the element, and an azimuth resolution of 2 degrees (180 points per circle) was found to be sufficient. For the radius r_i of the i-th circle, the relation $r_i = (x_0 + i \cdot \delta x)^3$; $i = 1, K$, with $x_0 = 0.3$, $\delta x = 0.03$, and $K = 112$ is sufficient to keep the interpolation error below 1%. The total area covered by a fingerprint sampled with these parameters ranges from a radius of about 3 km to about 5,400 km.

4. INTEGRATION OF THE GPS-COMPONENT INTO A TSUNAMI EARLY WARNING SYSTEM

The overall architecture of a tsunami early warning system integrating a GPS-based component for the determination of earthquake magnitude and displacement field is sketched in Fig. 1. The GPS-component provides refined magnitude estimates to the decision makers as well as estimates of magnitude and displacement field to a modeling component for tsunami propagation predictions.

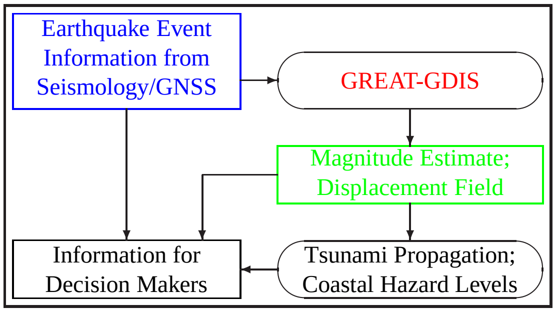

Fig. 1. High-level architecture of a tsunami early warning system integrating GPS-determined displacements. For event detection, seismological observations are used, and the approximate epicenter location and time are provided to the component for the GPS-based magnitude and displacement field estimation (GREAT-GDIS). This component requires displacement time series from a sufficiently dense regional GPS network. The estimates of the magnitude and coseismic permanent displacement field for the ocean bottom are used in the prediction of tsunami amplitude and propagation pattern in support of the decision for which coastal areas to issue a tsunami warning. From [6].

The implementation of the GPS-component is sketched in Figure 2. Real-time GPS displacement time series with 1 s temporal sampling are computed by the Jet Propulsion Laboratory (JPL) for a global network with currently about 130 stations. These time series are transferred to the GPS-component with a time delay < 10 s, where the program *capture* updates the data archive. The quality of the time series in the archive is constantly improved by eliminating infrequent spikes and applying a sidereal filter (*cleaner*). Alert messages based on seismic observations are also provided by JPL. These messages have time delays of 8-12 minutes. The alerts trigger *earthquake* to issue a notice for *geqdis* to initiate a fingerprint analysis. *geqdis* identifies the relevant GPS sites and the time window to be used in the analysis. A request for time series is sent to *gnss-server*. While waiting for the response, *geqdis* computes all parts of the normal equations that are independent of the displacement time series. In case the event notice was for a synthetic earthquake, e.g., in delayed-mode sensitivity studies and assessments, *earthquake* also provides the synthetic offsets to *gnss-server*. *gnss-server* extracts the requested time series from the archive. In case of a synthetic earthquake, *gnss-server* adds the synthetic offsets to the time series before delivering these to *geqdis*. *geqdis* then embarks on a search for the "best fit" element combination. After completing the search, it produces a message file for the tsunami propagation component, which includes the magnitude estimate and the displacement field.

The main time-limiting factors are the delay of the initial alert message and the requirement for sufficient data after the onset of the earthquake to capture the co-seismic permanent displacement at a sufficiently large number of stations. The network density close to the rupture area is a critical design parameter for the overall system.

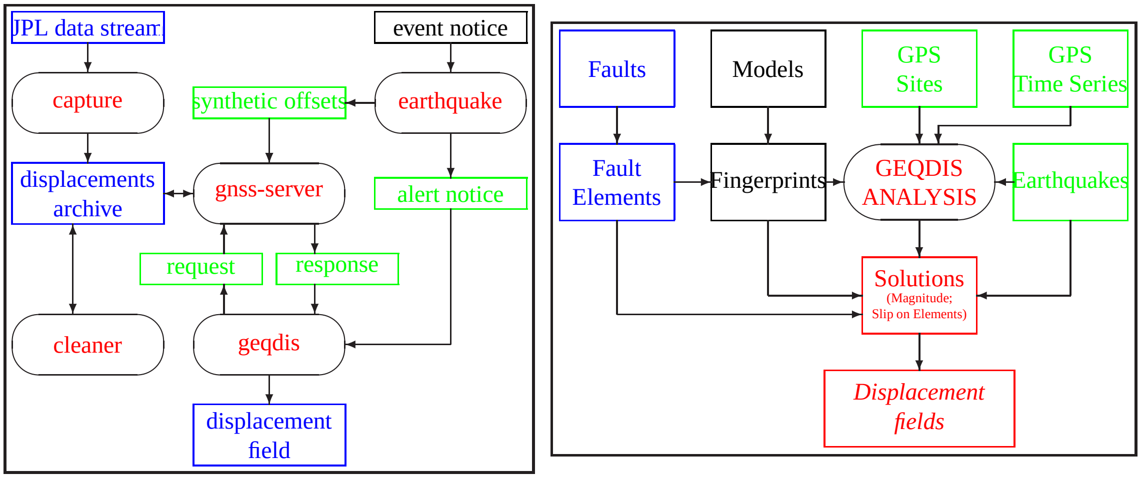

Fig. 2. Architecture of the GPS-component of the GREAT alert system (left) and structural elements of the Fingerprint analysis (right). For details, see text. From [6].

5. CONCLUSIONS AND PERSPECTIVE

The fingerprint method is a fast and efficient method for using real-time or low-latency GNSS displacement time series to rapidly determine the moment magnitude and coseismic permanent displacement field. Compared to currently available inversion methods, the fingerprint method has the advantage of being much faster in terms of computation time. The applicability of the fingerprint method depends on the quality of the fault database. The currently available database of off-shore faults does have gaps that can cause problems for some earthquakes.

The prototype has been running in a semi-operational mode since April 2009. Based on the available experience, the main issues limiting the quality and accuracy of the results are the station density of the real-time network, and the quality of the displacement time series with 1 s sampling interval. For some regions such as the Pacific Northwest, additional stations are being added to increase the station density. New algorithms for time series with 5-minute sampling rates are under test, which would still allow rapid determination of the static offsets.

The prototype is designed to allow for an easy exchange of the fitting procedure. It is planned to implement also an inversion based on Green's function (Wang, 2011, personal communication). Different geophysical models are under comparison to assess the impact of model assumptions. The largest earthquakes since 2004 are being used for validation and system-sensitivity studies.

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