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G-larmS - An Infrastructure for Geodetic Early Warning and Rapid Response

1 PROJECT MEMBERS

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2 ABSTRACT

The simplest, most effective way to quickly evaluate large magnitude(M>6) earthquakes is to leverage GPS measurements. As such, geodetic data are invaluable to earthquake early warning. As a result of the funds provided by this proposal we have made major steps in creating, deploying, and testing a West coast wide geodetic algorithm (G-larmS) that can directly contribute to earthquake early warning. In this report we will highlight the main accomplishments and point to the relevant areas for future expansion and work. Originally deployed in Northern California, G-larmS now receives data and produces source models for the entire West coast and it is capable of more complex inversion geometries than when it was first created. Importantly, we have developed a coherent framework for generating realistic rupture scenarios in both subduction and strike-slip environments and for synthesizing realistic 1Hz GPS waveforms that can be used to test the performance of the code. We have also found areas of synergy with other hazards projects such as the joint NASA/NOAA venture to utilize GPS data and algorithms for tsunami early warning.

3 BRIEF BACKGROUND AND PROJECT ACCOMPLISHMENTS

Earthquake early warning (EEW) exploits the differential propagation velocities of seismic body waves. By detecting the less destructive P-Wave (pressure wave) rapidly in real-time, a warning is issued before the damaging S-Wave (shear wave) arrives (Allen and Kanamori, 2003). Location and moment magnitude estimates derived from P-wave records of a few seismometers are key inputs into models that, for example, predict ground shaking at specific locations or forecast tsunami threats (Blewitt et al., 2006; Melgar et al., 2016a). Rapid estimation of magnitudes for large events from seismic data alone is known to fail as empirical frequency/amplitude-magnitude relationship saturate and instruments may not resolve the full dynamic range of the event in the near field (Hoshiba and Ozaki, 2014). While real-time GPS suffers from poor resolution of small events (Mw<6) and requires additional time to wait for static displacements, which arrive with the S-wave, it has demonstrated great potential to reliably determine large magnitudes through finite fault models (Crowell et al., 2012; Colombelli et al., 2013)

Over the last 3 years, we have developed G-larmS (the Geodetic alarm System) to analyze GPS time series in real-time and estimate co-seismic offsets and finite fault models when triggered by a seismic alarm, with the intention of rapidly providing magnitude updates for large earthquakes in Northern California. This project addresses the space geodetic enhancement of earthquake early warning through real-time fault rupture extent estimation and geodetic moment determination for large earthquakes (Mw > 6.5); building on 2 years of NEHRP funding and 3 years of development funding from the Gordon and Betty Moore Foundation.

For this project we focused on the contributions of space geodesy to earthquake early warning in general and in particular to the west-coat wide ShakeAlert EEW effort. The main accomplishments of the project (further discussed in the "Detailed Results Section" were as follows:

1. Software enhancement of the G-larmS algorithm for compatibility with seismic data protocols
2. Expansion of G-larmS from a single northern California instance to full West coast-wide coverage
3. Expansion of G-larmS to 2D discretization and inversion
4. Creation of a coherent framework for synthetic simulations
5. Exploration of the UCERF3 set of fault models
6. Synergy with NASA/NOAA tsunami warning project

A brief note on the project participants. During the duration of this award project members, Dr. Grapenthin and Dr. Johanson left the Berkeley Seismological Laboratory for jobs at New Mexico Tech and the Hawaii Volcano observatory, they remained collaborators of the project after their departure and routinely contributed to the project goals and accomplishments. Dr. Diego Melgar (preparer of this report) stepped in after their departure.

4 Detailed Results

4.1 Software enhancement of the G-larmS algorithm for compatibility with seismic data protocols

A major milestone of this project was making the adjustments to enable G-larmS to utilize geodetic data in standard seismic protocols, namely Earthworm data formats (tracebuf2) and structures (rings) in which seismic data is routinely made available. Efforts in this regard were driven by close collaboration between ShakeAlert geodesy committee participants and algorithm developers. Roughly speaking, before the beginning of this award the state of G-larmS (and of all geodetic algorithms) was such that they used custom protocols and formats for data exchange and processing. This heterogeneity was in striking opposition to the standardization and homogeneity of protocols and formats in the seismic EEW data and algorithms.

Thus, it was recognized early on in this award, and in consensus with other algorithm developers and data providers, that this was detrimental to the overall progress of geodesy based EEW algorithms. After some discussion it was decided to expend effort in migrating geodetic algorithms and data to the Earthworm framework. Data providers to ShakeAlert such as UC Berkeley, Central Washington University and the USGS now provide geodetic data in formats that can easily be transformed into Earthworm tracebuf2 in Earthworm rings. In parallel UC Berkeley members of this award refactored G-larmS to be able to accept Earthworm tracebuf2 data packets from Earthworm rings for its waveform processing. After considerable development effort this task is now complete.

4.2 Expansion of G-larmS from a single northern California instance to full West coast-wide coverage

The initial development of G-larms (Grapenthin et al., 2014b) focused on Northern California (NorCal polygon in Figure 4.1). This worked well as a test bed for the system which behaved as designed during theM_w6.1 Napa earthquake in 2014 (Grapenthin et al., 2014a). However, with the homogenization of protocols and formats expansion to West-coast wide coverage (Figure 4.1) became possible. As of the writing of this report we have effectively achieved coverage of the entire West Coast with the following strategy. The G-larms workload is split into three separate instances running on three separate machines, a Cascadia instance, a Northern California (Norcal) instance, and a Southern California instance (Socal). The Cascadia and Norcal instances run in-house at UC Berkeley machines and the Socal instance is hosted on a computer at the California Institute of Technology (Caltech).

Of fundamental importance to this expansion were modifications to the code to enable ingestion of both relative positions (baselines) and absolute or precise point positions (PPP). The original Norcal instance of G-larms only handled baselines, however the expansion to the code that allows it to handle PPP data is now complete. G-larms can invert just baselines, just PPP, or a mixed data set. Following the original design of Grapenthin et al. (2014b) the general workflow for G-larms is as follows. Each G-larms instance has an event

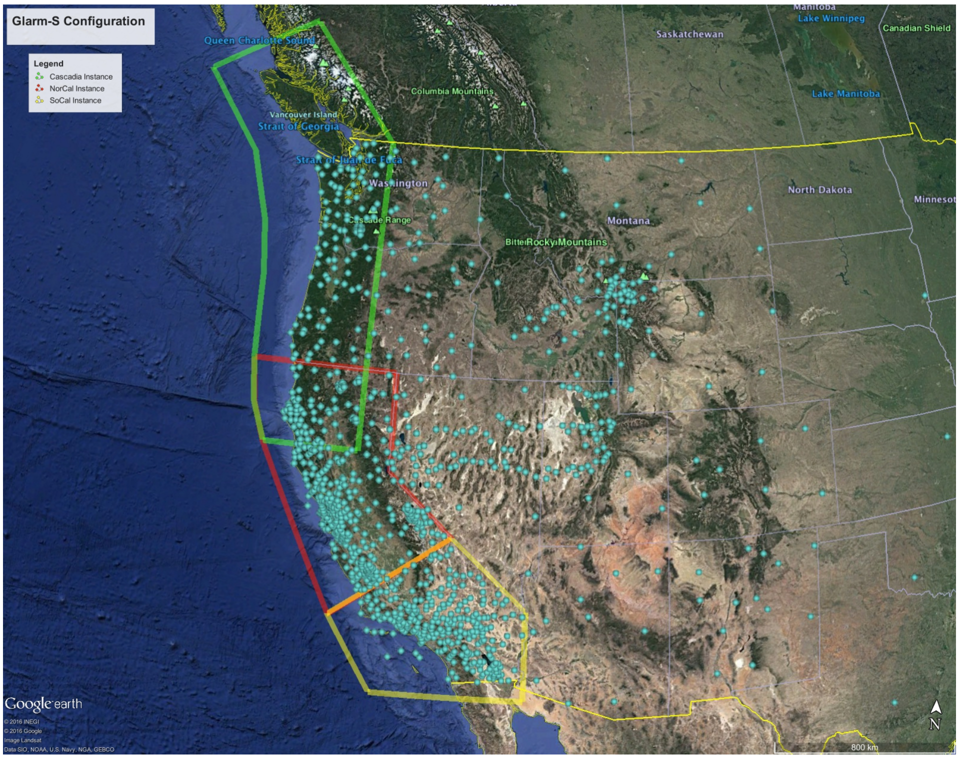

Figure 4.1: Configuration of the G-larms instances. Events with hypocenter in the green polygon are handled by the Cascadia instance. Events in the red polygon are handled by the NorCal instance. Events in the yellow polygon are handled by the SoCal instance. Blue circles are real-time enabled stations that can contribute to G-larms. The actual number of stations contributing at any given moment is usually about half of what is shown here and depends on each network operator.

listener, when the algorithm receives a notification from ShakeAlert that an event has happened inside it's region of influence (defined by the polygons in Figure 4.1) it begins the process of estimating offsets from whatever real-time GPS data is available and calculating the finite fault. G-larms tests a number of different inversion geometries at every epoch, and determines the "correct" one to be that one which best fits the data. In the Norcal instance 3 inversion geometries are tested, San Andreas parallel, San Andreas conjugate and a Mt. Diablo thrust geometry. In the Socal instance, which has a more complex tectonic setting, four geometries are tested, San Andreas parallel, Big Bend parallel, Garlock fault parallel and Northridge thrust parallel. In the Cascadia instance we use a single megathrust 2D geometry (see Section 4.3).

The Norcal and Socal instances of G-larms have been stable for some time now. The Cascadia instance with the 2D megathrust geometry was implemented only recently and is performing well. As a result of the work done for this award we are now in the position to consider migrating to a single West Coast wide instance rather than 3 separate ones. We are studying the computational demands of the algorithm and of each instance to develop the steps necessary for this migration. This is an important objective of the efforts at the BSL going forward. For example, each instance right now inverts on the order of a few geometries per epoch. If this proves to be well under the computational limit of the hardware we will expand to include the UCERF3 fault geometries which are already being used for the synthetic scenario database (See Section 4.4).

4.3 Expansion of G-larmS to 2D discretization and inversion

The original design of Grapenthin et al. (2014b) emphasized speed as the G-larms inversions were to be conducted each epoch. As such it utilized simple one-dimensional geometries with subfaults extending from the surface to a pre-defined seismogenic depth. This works well for California were seismicity is constrained to a fairly narrow cross section of the shallow crust. However as the expansion to Cascadia was considered it was evident that simple line sources would not be sufficient. Significant effort was dedicated to expanding the inversions to 2D sources. These modifications to the code are now complete and running in the Cascadia instance.

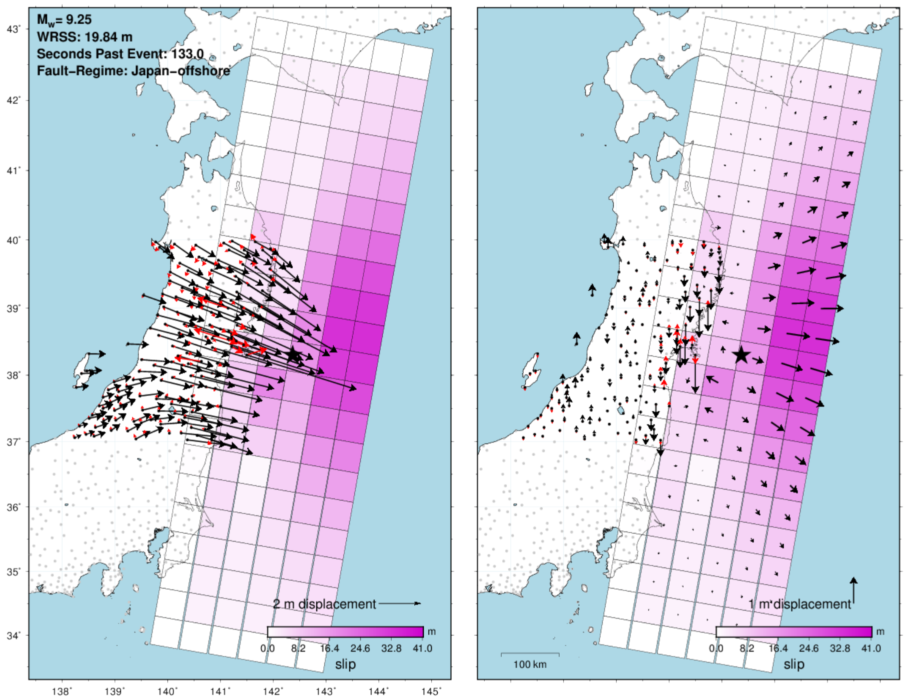

Figure 4.2: Example of a 2D G-larms inversion. Using the dataset from the m_w9.0 Tohoku-oki event in Japan as a guide G-larms can now invert for a 2D distribution of slip. Shown are surface offsets from the 1Hz GPS data and the resulting slip model at a given epoch (t=133s after origin time).

GPS data from the 2011 M_w9 Tohoku-oki event was very useful when developing the algorithm (Figure 4.2). As with the 1D case the algorithm allows the fault to grow along strike and dip up to a certain maximum length determined by fault length scaling (Grapenthin et al., 2014b). With an increasing number of model parameters the inverse problem becomes ill-posed, adaptive Tikhonov Regularization based on L-curves (Melgar et al., 2013) is used for this. In the Tohoku-oki example (Figure 4.2 the problem is still tractable growing the event by a few rows and columns at a time takes 6 seconds. This can be sped up with pre-computed Green's functions for a fault catalog for subduction zones, which is work in progress and will reduce the computation to well under one second. As noted, this has only recently been implemented and its stability and performance is still being tested. While it performed well in the Tohoku-oki replay we are exploring realistic scenarios (see Section 4.4) to further assess the performance of this expansion to the algorithm.

4.4 Creation of a coherent framework for synthetic simulations

The 2-5cm sensitivity of GPS to ground motions means it is only of use, roughly, for events larger than $M_w 6$. These are infrequent in California and even more so in Cascadia. The result of this is that it is difficult to assess how well an algorithm is doing and what effect changes to it have. Other large events recorded worldwide are useful guides (as shown in Section 4.3) but they do not necessarily reflect how the code will do with a different configuration of stations and with different tectonic settings and rupture characteristics.

We designed a framework for generating stochastic kinematic ruptures on pre-defined fault geometries and for synthesizing 1Hz displacement data that capture the general characteristics of GPS waveforms, namely, they include, in addition to long period shaking, static offsets. We refer to this code and algorithm as *FakeQuakes* and details of it have been published in Melgar et al. (2016b). For the initial development of the FakeQuakes technique we focused on the Cascadia instance of G-larms, since we expect that this is where GPS will have the most impact in the case of a recurrence of an $M_w 9$ event like the 1700 earthquake. An example of FakeQuakes ruptures can be seen in figure 4.3 where 4 events in the $M_w 8.4$-9.2 range are shown. Synthesized GPS waveforms for 3 stations from one of those events are shown in Figure 4.4, note that we capture both the long period strong shaking and the static offsets.

A key challenge in generating these scenarios was and still remains, validation. Assessing that the waveforms compare favorably to reality is challenging. In rupture simulation this is generally done by comparison to ground motion prediction equations (GMPEs), however modern GMPEs do not contemplate displacement based metrics such as peak ground displacement (PGD). Thus in developing FakeQuakes we relied on the only existing (to our knowledge) GMPE for PGD developed by Melgar et al. (2015). This produced favorable results for the Cascadia simulations but exposed that more work is necessary with respect to displacement GMPEs.

With the favorable results from Cascadia we are now exploring simulations for California events. We rely on the current fault model for the state from UCERF3 (Field et al., 2014) and selected 25 faults from that database and generate 150 FakeQuakes rupture of varying magnitudes on each one (3750 events). We are now generating synthetic displacements for these ruptures and exploring other waveform validation techniques in addition to PGD. For example, we are studying whether long period spectra accelerations (Sa) from the NGA-West 2 GMPEs (Bozorgnia et al., 2014) can be used to this end.

We are making progress with the scenarios and converging on strategies for validation. It is straightforward to create many events and waveforms. For example, for Cascadia

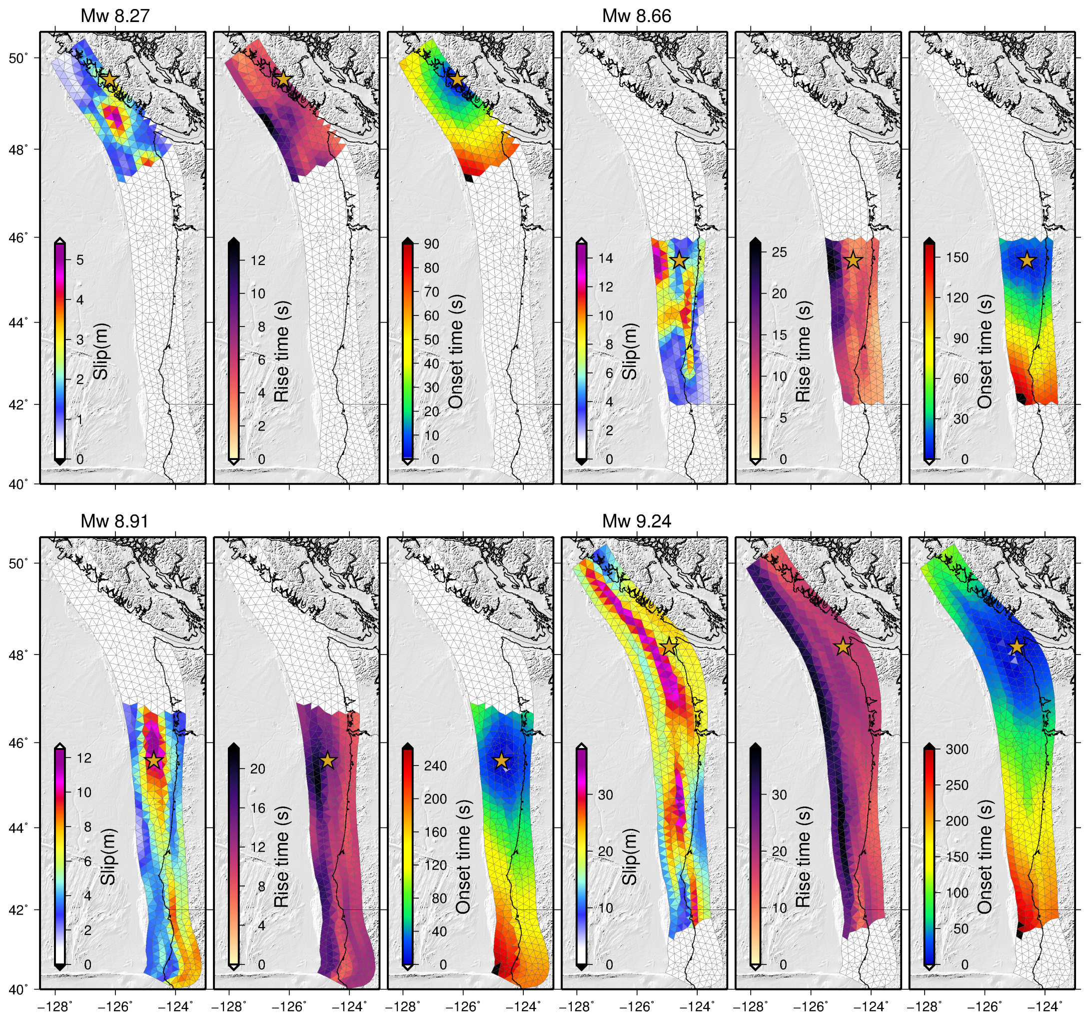

Figure 4.3: Sample scenarios. Plotted are the slip, rise times, and onset times for each scenario. The star denotes the position of the hypocenter.

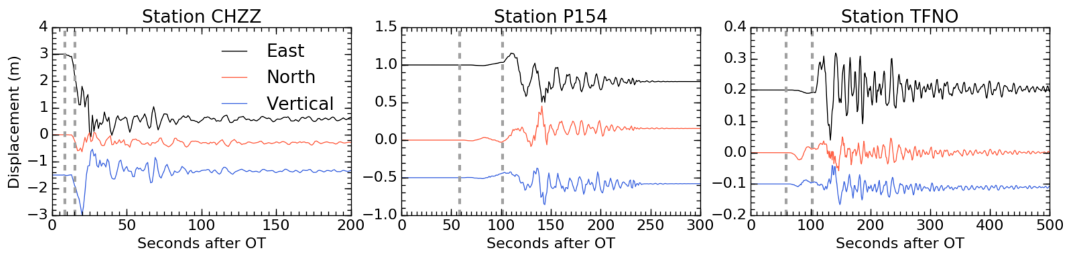

Figure 4.4: Sample waveforms for 3 stations for the M_w8.6 event of Figure 4.3. Dashed lines are the P- and S-wave arrivals determined from ray-tracing. The waveforms are offset for clarity.

we created 1300 scenarios, while for California we currently have 150 scenarios for each one of the 25 faults selected. The remaining technical challenge is to convert the scenario waveforms into Earthworm-ready replay files. We are making progress in this regard as

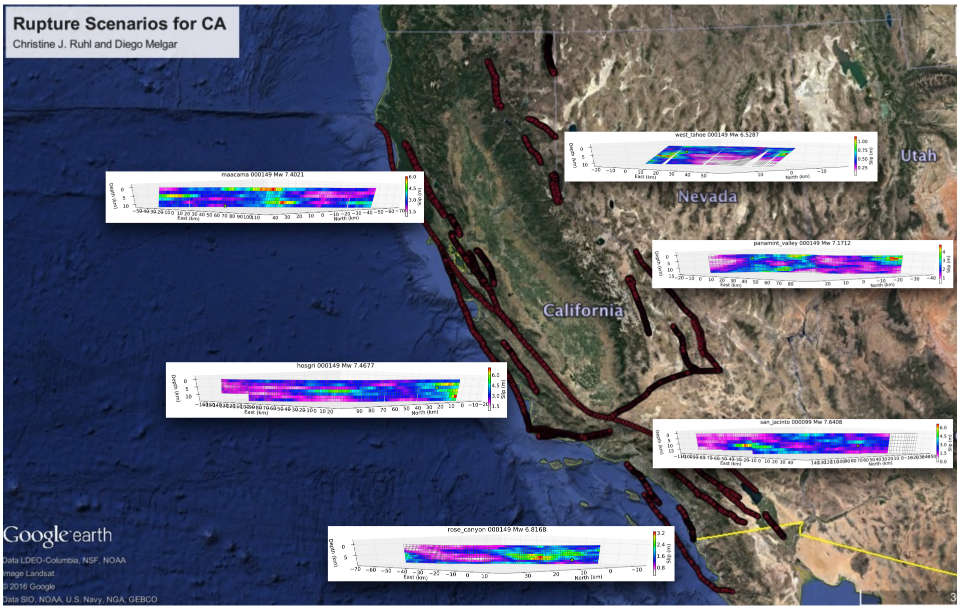

Figure 4.5: Sample FakeQuakes ruptures for California events. Red lines denote the 25 large faults from the UCERF3 database selected for simulation. Shown here are ruptures for the Maacama, Hosgri, Rose Canyon, San Jacinto, Panamint Valley, and West Tahoe faults.

well. Earthworm has a replay infrastructure through Tankplayer and Tankfiles, collaboration with other partners (See Section 4.6) has led to progress in this area as well. Once we finalize this we can systematically test the performance of G-larmS by studying how well it estimates magnitudes and fault dimensions when compared to the input ruptures.

4.5 Exploration of the UCERF3 set of fault models

As noted in Section 4.3 G-larmS relies on assumed faulting styles or "tectonic regimes" (Grapenthin et al., 2014b). Thus when an event is recorded these faulting geometries are tested and the best fitting one selected as the "correct" model. The driver behind this approach is computational speed, simple and few geometries lead to stable calculations on an epoch by epoch basis. This has worked well. However, it limits the complexity of potential solutions to only a few and disregards previous knowledge about where earthquakes are expected to occur and what their geometries should be.

To ameliorate this we have explored the incorporation of the UCERF3 fault and ruptures database (Field et al., 2014) into the G-larmS framework. The California synthetic scenarios (Section 4.4, Figure 4.5) are built on this, and in fact, we have discretized all of the faults in the database. With this work complete the plan now is to first determine the stability of the full West coast wide instance running on a single machine and then to begin slowly testing the introduction of UCERF3 geometries as solutions to be considered in the epoch by epoch inversion.

4.6 Synergy with NASA/NOAA tsunami warning project

In Melgar et al. (2016a) we studied the potential contributions of rapid source products, such as those produced by ShakeAlert, to local tsunami warning. Particularly we argued by retrospectively analyzing large events that were measured by GPS, strong motion and tsunami gauges that algorithms such as G-larmS could have a lasting impact in how tsunami earl warning is performed. While tsunami monitoring and warning was never a goal of the work conducted under this grant, synergies developed naturally thanks to the progress on the G-larmS algorithm. Parallel to the development of ShakeAlert a collaboration between NASA and NOAA started to deliver high-rate GPS data to the tsunami warning centers. The initial focus of this project is the Cascadia subduction zone and UC Berkeley has been involved in this effort. Both TWCs are now receiving GPS data from the west coast and are in need of algorithms that produce rapid source products. The TWCs have expressed interest in running G-larms locally, both in Hawaii and Alaska. With the expansion of G-larms to include 2D sources we are now in a position to do so and are continuing our involvement and collaboration in this project.

5 Publications and Conference Presentations

Journal Articles

1. Grapenthin, R., Johanson, I., and Allen, R. M. (2014a). The 2014 Mw 6.0 Napa earthquake, California: observations from real-time GPS-enhanced earthquake early warning. *Geophys. Res. Lett.*, 41(23), 8269-8276.

2. Grapenthin, R., Johanson, I. A., and Allen, R. M. (2014b). Operational real-time GPS enhanced earthquake early warning. *J. Geophys. Res.*, 119(10), 7944-7965.

3. Melgar, D., LeVeque, R., Dreger, D., and Allen, R. (2016b). Kinematic rupture scenarios and synthetic displacement data an example application to the Cascadia subduction zone. *J. Geophys. Res.*, in press.

Recent Conference Abstracts

1. Seismological Society of America Meeting, 2015, *Elarms and G-larms, UC Berkeley's Earthquake Early Warning Algorithms in CISN Shakealert*, Hellweg, M., Allen, R. M., Henson, I., Johanson, I., Neuhauser, D., Grapenthin, R.

2. Seismological Society of America Meeting, 2016, *Rapid Finite Faults With Real-Time GPS: The Geodetic Alarm System*, Grapenthin, R., Aranha, M., Melgar, D., Allen, R. M.

3. Seismological Society of America Meeting, 2016, *Local Tsunami Warnings: Perspectives From Recent Large Events*, Melgar, D., Allen, R. M.

4. American Geophysical Union, 2016, *Investigations on Real-time GPS for Earthquake Early Warning*, Aranha, M.A., Grapenthin, R., Melgar, D., Allen, R.M.

5. American Geophysical Union, 2016, *Connecting earthquake source products to local tsunami warning*, Melgar, D., Allen, R. M.

6. Japan Geoscience Union, 2016, *Local Tsunami Warnings and the role of high-rate GNSS in Earthquake Early Warning*, Melgar, D., Allen, R.M., Barrientos, S., Grapenthin, R. and Aranha, M.

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Melgar, D., Allen, R. M., Riquelme, S., Geng, J., Bravo, F., Baez, J. C., Parra, H., Barrientos, S., Fang, P., Bock, Y., et al. (2016a). Local tsunami warnings: Perspectives from recent large events. *Geophysical Research Letters.*

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