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SYSTEM DESIGN FOR A GPS COMPONENT OF REAL-TIME EARTHQUAKE SOURCE DETERMINATION AND TSUNAMI WARNING SYSTEMS

Collaborative Research with University of Nevada, Reno and Northwestern University

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ABSTRACT

We report on our preliminary study toward a longer-term goal, which is to enable the use of GPS data for real-time assessment of great earthquakes, particularly those capable of generating damaging tsunamis. The specific objective of this task was to identify the key design aspects of a GPS-based system that could contribute to early warning systems. Our approach has been based on models of both transient and permanent displacement of GPS stations caused by large earthquakes, and based on GPS errors as they affect sensitivity to earthquake source parameters. Our main conclusions are that (1) the pattern, magnitude, and timing of permanent displacement of GPS stations is the key signal to be exploited, in that it can be inverted for the earthquake source and so predict the displacement field of the ocean bottom, and (2) there are no inherently limiting factors arising from real-time orbit and positioning error, provided sufficient near field GPS stations are deployed. This signal could be readily exploited by GPS networks currently in place in the Cascadia region. In fact, the geometry of the (non real-time) GPS network in the Pacific Northwest is already sufficient to resolve within minutes great earthquakes in the Cascadia subduction zone that are capable of generating oceanwide tsunamis. As a result of this preliminary work we are now collaborating with various federal agencies (NASA, NOAA, and USGS) toward developing a practical real-time system.

Introduction

This project proposed the following research question: "What are the key design specifications of a GPS-based system that would enable near-real time determination of great earthquake source models with sufficient accuracy and resolution for tsunami warning systems?" Shortly after the proposal for this project was submitted, we published results that demonstrated how GPS could have been used in real time to accurately determine the magnitude of the 2004 Sumatra earthquake using data up until 15 minutes after the origin time [*Blewitt et al*. 2006]. These time series are summarized in Figure 1. This naturally led to the idea that permanent GPS stations might contribute to early warning systems, which in turn provided motivation for studying aspects system design.

Various aspects of system design have been considered, including (1) the physics of how "permanent" displacement arrives with seismic waves, as it affects the timing of the signal that GPS is using to invert for source parameters, (2) GPS network geometry, which must be sufficient to

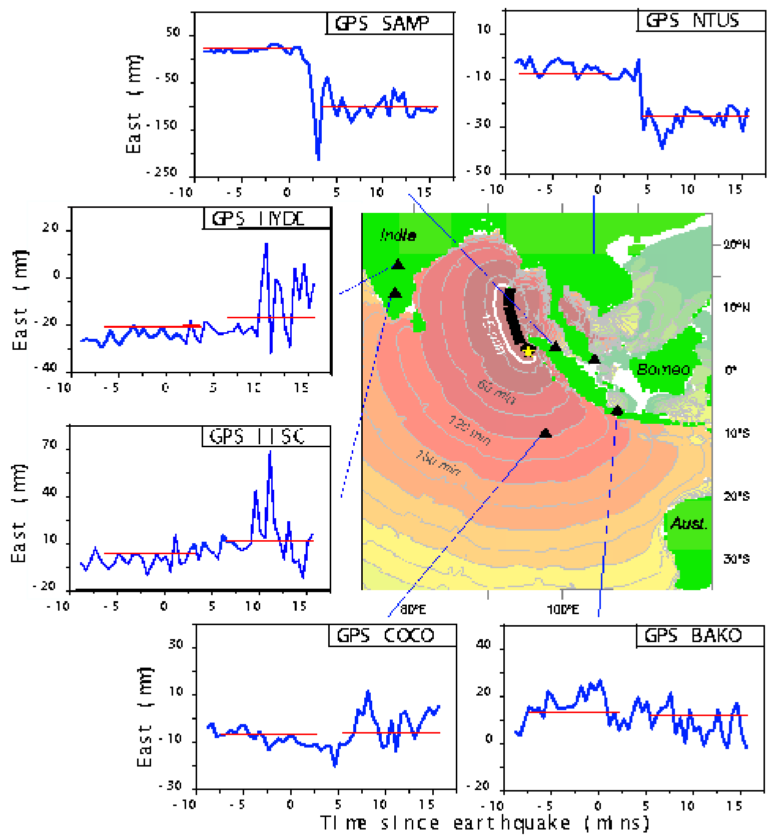


Figure 1: GPS permanent displacement observed during the Mw 9.2 2004 Sumatra earthquake, demonstrating that within minutes (1) permanent displacements can be resolved with ~1 cm accuracy (by comparison with long term monitoring), and (2) the earthquake magnitude can be clearly resolved to be in the range capable of generating an oceanwide tsunami.

sense the spatial pattern of ground displacement in order to resolve the earthquake source model; (3) real-time GPS positioning error, both current, and what might be possible given real-time IGS orbits; and (4) broader design aspects from the point of view of providing information that is useful to decision makers, with traceability of system specifications to early warning requirements.

Timing of Permanent Displacement

We invested considerable time in trying to decide how to synthesize GPS data for receivers close to a large thrust earthquake. Most approaches can predict either the traveling waves that would be observed on a seismogram or the final static offset that would be observed on a GPS receiver. However, to simulate real time data we want to predict how the combined displacement field evolves. We expected to do this using normal mode summation, but this proved computationally impractical.

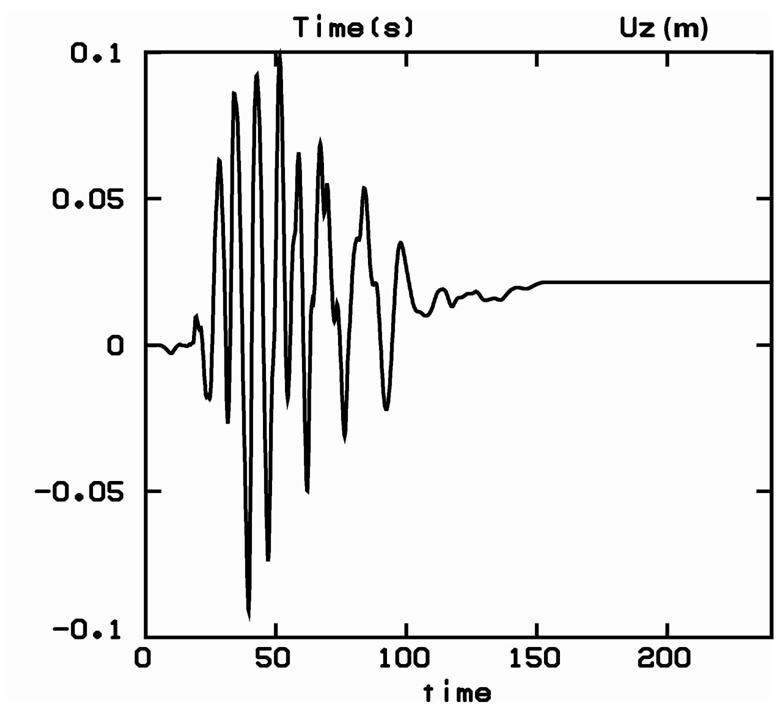


Figure 2: Vertical displacement seismogram 75 km from the epicenter of a M 7.8 subduction thrust event showing the transient wave field evolving into the static displacement.

Instead, we adopted a new Green's function approach developed by R. Wang of the GeoForschungs-Zentrum Potsdam. Our initial tests of this computer code show that it can produce the combined displacement field showing how the traveling wave evolves to the static term. Figure 2 shows an example of simulated ground motion illustrating the timing of the arrival of permanent displacement, which is the key signal that GPS needs to extract. We are now synthesizing records from large trench earthquakes for analysis.

These simulations confirm that, in theory, the permanent displacement emerges as seismic waves arrive, and should be resolvable within minutes. In principle faster resolution could be achieved by averaging through the oscillations, which would require high rate GPS (~1 Hz). This may be an argument for high rate GPS to enable more timely warnings for the case of near-field tsunamis. Otherwise, for oceanwide tsunamis, it is clear from these simulations that the current "standard" rate GPS (15 or 30 sec intervals) would be sufficient to resolve the permanent displacement, as we proved for the 2004 Sumatra earthquake.

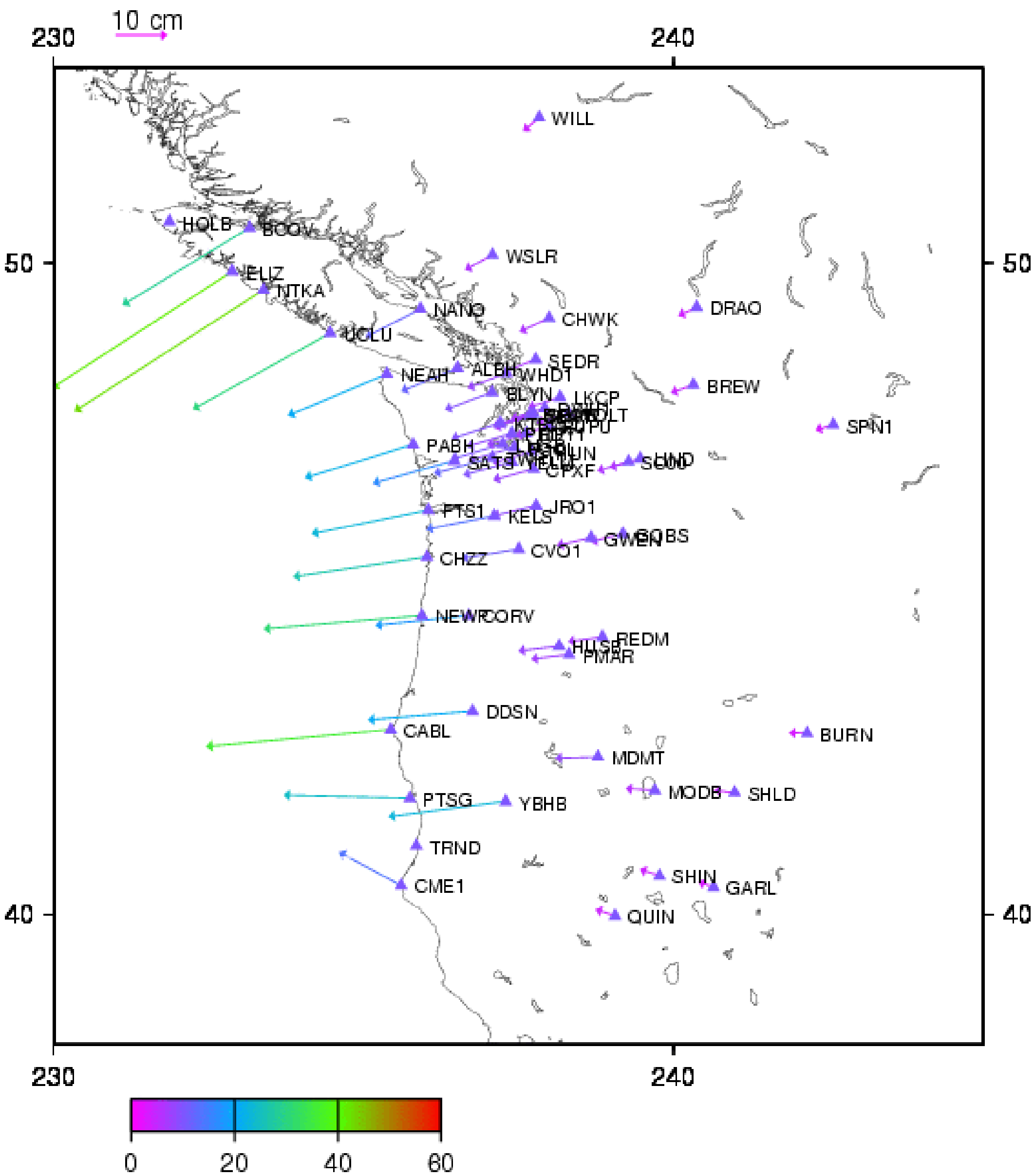


Figure 3: Example of simulated permanent displacements at GPS stations as a result of an Mw 9.0 earthquake in the Cascadia subduction zone. Thus displacements near the coast are several decimeters, which *Blewitt et al.* [2006] demonstrates is an order of magnitude more than sufficient to resolve the source parameters.

Network Geometry

We have developed simulations for hypothetical scenarios in Cascadia, where great earthquakes are certainly capable of generating damaging tsunamis, and where already there are many permanent GPS stations that could in future serve as part of a real-time warning system. Figure 3 illustrates the simulated spatial pattern of permanent displacement mapped to the locations of current permanent GPS stations. The observed displacements would then be used to resolve the earthquake source parameters, as demonstrated in *Blewitt et al.* [2006].

As we know that 1 cm level resolution can be achieved (assuming sufficient control over GPS errors, the topic of the next section), we conclude that current network design in Cascadia is already more than sufficient to serve the purposes of an oceanwide tsunami warning system. However the issue of local tsunamis from smaller earthquakes would benefit from extra spatial density of stations near the coast (a conclusion consistent with the workshop recommendations presented later). Furthermore, given the deformation signal arrives first at the coast, and that the near-field stations carry most of the information needed for source inversion, the time required to resolve the static displacements, and thus invert for the source, can be reduced by installation of more coastal stations.

Taking this and the previous study together, we conclude that it is the permanent displacement signal in the time/spatial domain measurement of ground motion that GPS should be extracted for purposes of earthquake source inversion. This approach has the advantage that it makes GPS maximally complimentary to the frequency-domain approach taken by seismology, thus providing an extra layer of robustness in a multi-technique warning system.

Real-Time GPS Error

The objective of this aspect of the study was to elucidate the critical specifications, as they relate to real-time orbit and clock accuracy, parameter estimation strategy, and multipath mitigation strategies. Of specific interest was how errors in real-time orbits currently distributed by the International GNSS Service (IGS) propagate into GPS station position time series, and how that propagates into the inversion for the earthquake source parameters.

In exploring the potential of GPS for tsunami warning systems, *Blewitt et al.* [2006] used an “best possible” procedure where simultaneously estimated parameters included satellite orbit state vectors (initialized using the Broadcast Ephemeris acquired prior to the earthquake), stochastic solar radiation pressure on the satellites, satellite and station clocks at every 30-s epoch, the Earth's pole position and drift rate, the Earth's rate of rotation, random-walk variation in zenith tropospheric delay and gradients at each station, carrier phase biases and cycle slips, and station positions. Given the computationally intensive nature of orbit determination, it would be valuable to know if the problem can be partitioned (with sufficient accuracy) by using real-time orbits computed by a third party.

Here we also test alternative options for real time orbits, including the Broadcast Ephemeris, and the IGS Ultra-Rapid orbits. In all cases, satellite clocks were estimated as white noise at every epoch (equivalent to double differencing). The IGS ultra rapid orbits are published 4 times per day, each with an initial latency of 3 hours. As a consequence, the actual latency in real time falls in the range 3-9 hours. In this particular case, the latency was 7 hours, meaning that the orbits were actually predicted ahead 7 hours until the time of the earthquake. To test whether the systematic drifts

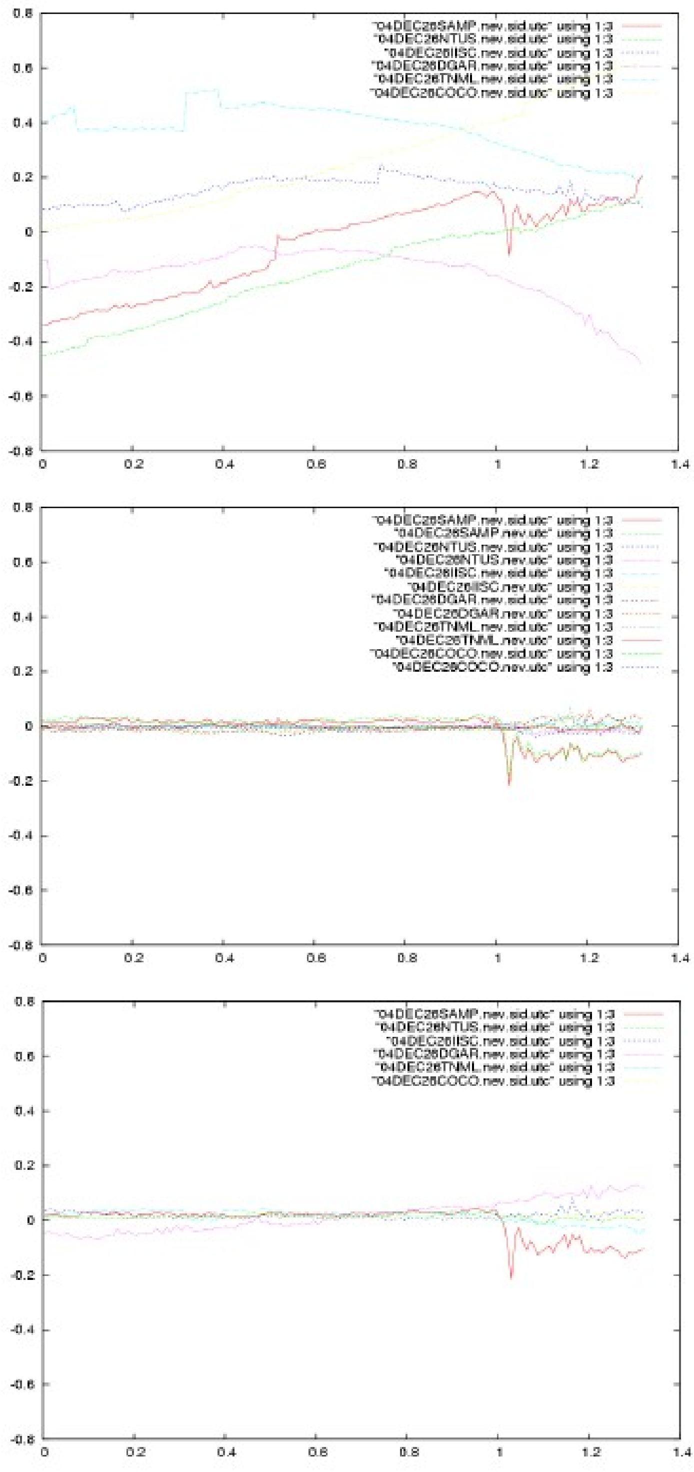


Figure 4. Coordinate time series (30 sec) on 26 December 2004 using (Top) Broadcast Ephemeris, (Middle) estimated orbits, and (Bottom) IGS ultra-rapid orbits. In all cases, satellite clocks were estimated.

evident in Figure 6 (Bottom) were due to errors in prediction, we also tested the IGS ultra-rapid orbits published 6 hours later, with 1 hour latency. Very similar drifts were evident, thus prediction does not appear to be the main cause of the drifts.

To test the performance of the IGS rapid orbits, we followed the procedure detailed in *Blewitt et al.*, [2006] to estimate displacements from the time series (with a 15 minute deadline) and then computed the goodness of fit for the entire variety of northward rupturing models with a range of M_w 8.0–9.5 (Figure 4). An *F*-statistic was computed relative to the best-fitting model to assess the range of M_w for models that are not significantly different in quality than the best-fitting model. The results were then compared to those for the estimated orbits presented in *Blewitt et al.* [2006].

The resulting time series (Figure 4) show that solutions using the Broadcast Ephemeris are dominated by systematic drifts and jumps. In contrast time series using estimated orbits are very flat until the seismic waves arrive at each station (at ~01:00 UTC), after which the stations are permanently displaced. *Blewitt et al.* [2006] shows each time series in more detail. The IGS ultra-rapid orbits produce results with slight systematic drifts as compared to the case using estimated orbits.

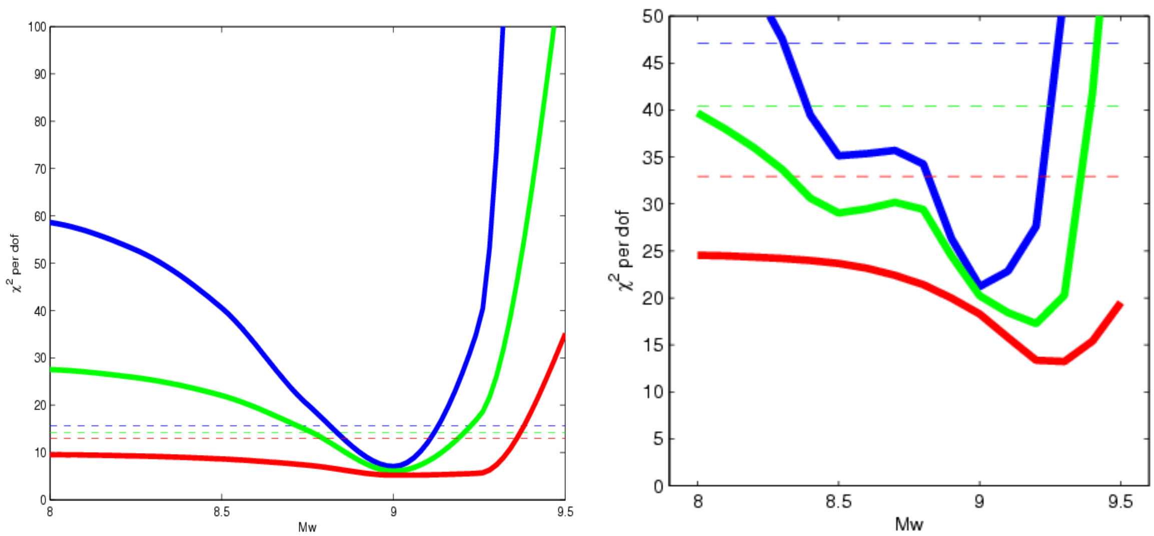


Figure 5. Reduced chi-square summarizing the misfit of displacements as a function of M_w (Left) using estimated orbits [*Blewitt et al.*, 2006]; (Right) using IGS ultra-rapid orbits. For each plot, three cases are shown: all stations (blue), all except nearest (300 km) station SAMP (green), and all except SAMP and next nearest (900 km) station NTUS (red). The dashed lines indicate 95% confidence intervals.

Whereas for the estimated orbits M_w is constrained with 95% confidence to the range 8.8–9.1, for the IGS ultra rapid orbits M_w is only constrained to the range 8.3–9.3. As it stands, the results for the IGS ultra rapid orbits are not sufficiently precise for purposes of tsunami warning, because of the problem of false alarms. One possible way forward is to modify the displacement estimation algorithm by estimating a low-order polynomial to the time series, though this has not been attempted here. A more robust way forward is to install more sites in the near field. Figure 5 confirms that near-field sites are critical to constrain the range of earthquake models.

Broader Design Aspects

As current geodetic techniques approach the ability to monitor ground movements with millimeter accuracy over the broadband range of ~1 second to ~10 years, it becomes apparent that the Global Geodetic Observing System (GGOS) [*Plag*, 2006; *Plag et al.*, 2008] should be exploited for geohazard prediction and early warning systems [*Plag and Zerbini*, 2008]. Hazards that can be addressed by geodesy include earthquakes, tsunamis, landslides, and volcanic eruptions, and of course geodesy can also address global climate change and coastal inundation associated with sea level rise and land subsidence.

Broadly speaking, successful prediction and early warning require two very different system designs. On the one hand, prediction systems are characterized by high accuracy measurements, detailed modeling and understanding, and long term stability to provide a standard frame of reference as a basis for prediction. On the other hand, early warning systems are characterized by real-time sensitivity and automatic response to events, and robustness against false alarms.

Since geohazards are often associated with long-term cumulative processes leading to precipitously damaging events, there is an obvious advantage if the two systems being used for prediction and early warning are developed within a self-consistent framework, as could be provided by GGOS. This way, the early warning system design can be better informed by the understanding gained from the prediction system. Prediction also helps to target the warning systems more efficiently. Precise positioning using GPS/GNSS can be done at high rate in real-time, and so can bridge the bandwidth from seconds to decades, enabling an early warning capability, while providing a connection to the more long-term stable components of GGOS required for prediction.

Recommendation 1: *So that early warning can be better informed by prediction, real-time GPS infrastructure development and deployment should be designed to play a dual role both for early warning (real-time, higher rate data) and prediction (lower rate data with latency, with a strong tie to ITRF as part of GGOS).*

As for specific early warning and disaster management applications where real-time GPS could make a big difference, consider the 26 December 2004 Sumatra earthquake (Mw 9.2–9.3), which generated the most deadly tsunami in history. Within minutes, displacements of >10 mm were detectable as far away as India, consistent with results using weeks of data after the event (Figure 1). These displacements implied Mw 9.0 ± 0.1, indicating a high tsunami potential.

Thus GPS infrastructure could enable more accurate and timely assessment of the magnitude and mechanism of large earthquakes, as well as the magnitude and direction of resulting tsunamis. Real-time GPS could add significant value to existing data types (1) to improve tsunami warnings by NOAA's Pacific Tsunami Warning Center (PTWC), and (2) to enhance post-earthquake damage assessment for emergency response produced operationally by USGS (ShakeMap). NASA's potential contributions to this effort includes the research and development required to make real-time GPS operational with sufficient accuracy, precision, reliability, and low latency. To realize the full potential of NASA's contributions requires coordination with other federal agencies (NOAA and USGS in particular), and international programs (GEO/GEOSS, and of course, GGOS/IGS).

Table 1: Recommendations developed at the Real Time GPS Science Requirements Workshop

Science/Hazards Goals (high level goal statements/questions)	**Science/Hazard Objectives** (stretch and baseline objectives)	**Measurement Requirements** (to achieve the science/hazard objectives)	**Instrument/Real-time GPS Requirements** (to make the needed measurements)	**Implementation Requirements**
Understand tsunami genesis Rapidly provide useful information to early warning decision-makers Prevent false alarms Provide confirmation of tsunami waves (later time scale)	Provide stream of station displacement time series and static offset estimates to decision makes. Characterize offshore earthquake sources for M>7.0 (to 9.5) within 3 min of origin time. Continue to update source characterization (important for M>8.5 earthquakes and oceanwide tsunamis) Estimate tsunami magnitude Observe and describe tsunami propagation	Seismology for locating source, initial magnitude estimates, and providing initial trigger for further analysis. GNSS (not only GPS) for real-time sampling of the displacement field every second within 1 rupture length, within 3 min. Tide gauges and DART buoys (bottom pressure, deep and surface water velocity field) and GPS/GNSS (for ionosphere) to confirm and measure tsunami propagation	Initial seismic information within 2 min of origin time 1 sample per second GPS/GNSS with ~50km spacing near coast, and increasingly broader spacing out to 1000 km from the source 1 cm real-time GNSS displacement accuracy in global reference frame within 3 min 1-cm precision of ionospheric delay by multi-frequency, real-time GNSS.	Real-time satellite orbits and clocks of sufficient accuracy to enable 1 cm positioning. Global real-time GPS network and data analysis centers to generate orbit/clocks. Consistent software for real-time estimation of GPS station positions. Dislocation models using database of potentially tsunamigenic faults Ionospheric models. Tsunami models

Recommendation 2: *Real-time GPS system requirements should be based on the value added to current components (seismic systems, ShakeMap, etc.) of post-earthquake response and tsunami warning systems. Effective implementation requires coordination between NASA, NOAA, USGS, GEO/GEOSS, and GGOS/IGS.*

A major part of the problem has already been solved by JPL. NASA's operational Global Differential GPS (GDGPS) System is currently delivering real-time GPS corrections to enable real-time positioning with few-cm accuracy. This could be further developed into a system enabling centimeter-level real-time positioning.

Recommendation 3: *NASA's GDGPS System should be exploited as a national/international resource for early warning of geohazards, and should be further developed to enable centimeter-level real-time positioning.*

We presented our recommendations above at the Real Time GPS Science Requirements Workshop on held at Leavenworth, Cascadia, September 2007. In addition they were presented at the International Geohazards Workshop at ESRIN, Frascati, Italy, in November 2007 (see http://geodesy.unr.edu/ggos/ggosws_2007/). In January 2008, we began collaboration with NASA/JPL, NOAA, and USGS on a project to develop a GPS component of a real-time tsunami warning system and earthquake response system, funded at this stage by NASA.

At the Cascadia workshop, experts in GPS geodesy, earthquake source physics, and tsunami modeling worked together to determined requirements for GPS networks in order to provide data that useful to decision makers. Table 1 summarizes the recommendations regarding tsunami warning.

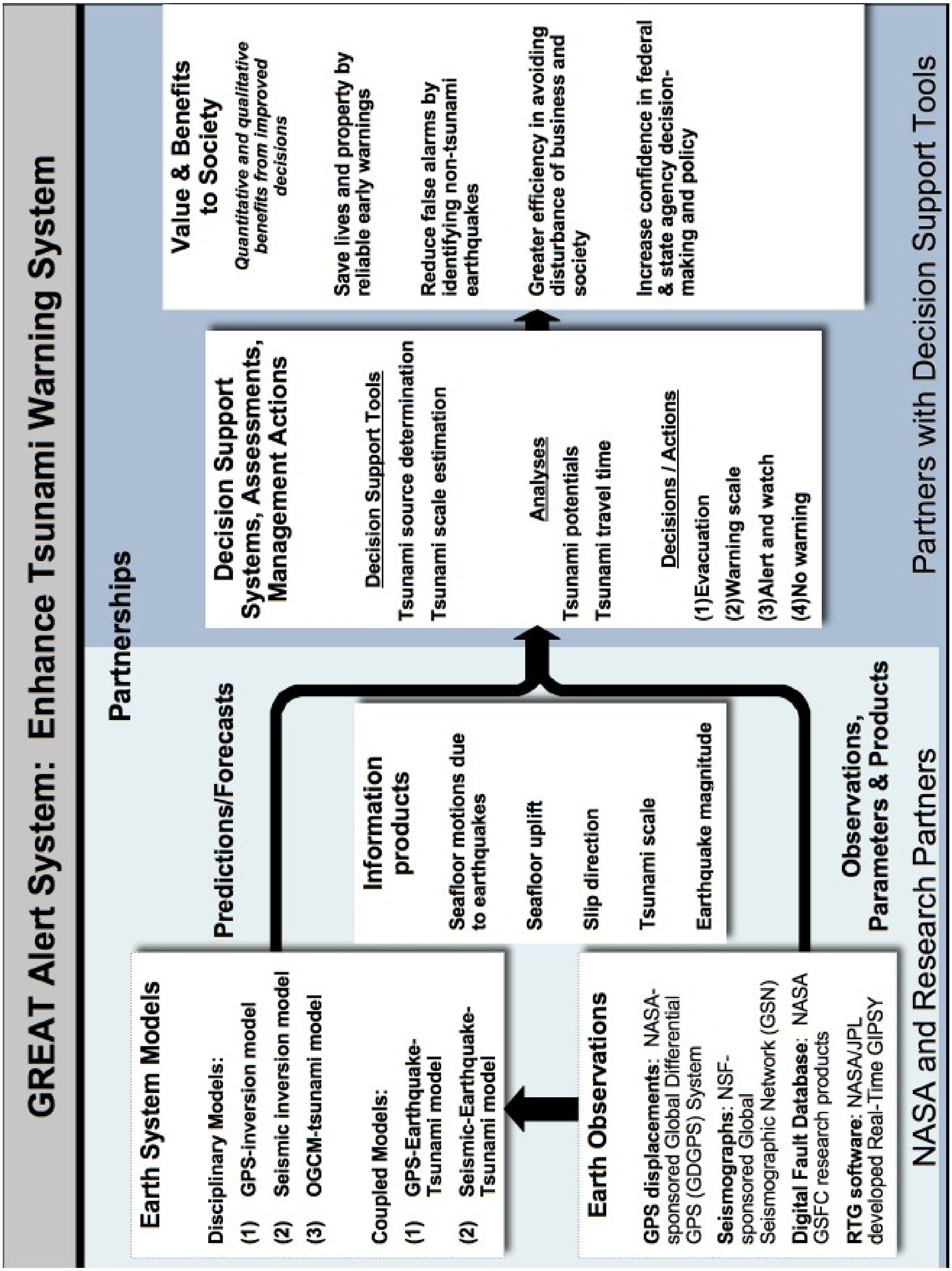
Conclusions

The pattern, magnitude. and timing of permanent displacement of GPS stations is the key signal to be exploited, in that it can be inverted for the earthquake source, which in turn provides the ocean bottom displacement field that can drive tsunami initiation models. We find no inherently limiting factors arising from real-time orbit and positioning error, provided sufficient near field GPS stations are deployed.

The permanent displacement signal could be readily exploited by GPS networks currently in place in the Cascadia region. In fact, the geometry of the (non real-time) GPS network in the Pacific Northwest is already sufficient to resolve within minutes great earthquakes in the Cascadia subduction zone that are capable of generating oceanwide tsunamis. Faster inversions would benefit from having a greater density of stations near the coast as possible, preferably with high rate GPS in order to better average down the oscillations as the permanent deformation arrives. Greater station density would also better address the problem of local tsunamis that can be initiated by smaller earthquakes.

This system design project provides a crucial first step in incorporating GPS into real-time earthquake source determination and tsunami warning systems, which can be implemented via real-time GPS data transmission. Real-time tsunami models are being developed by NOAA/PMEL for implementation by the Pacific Tsunami Warning Center [*Titov et al.*, 2005]. Such models require initialization using real-time earthquake source parameters that can come from a combination of

Table 2: Proposed System (in collaboration with NASA/JPL, NOAA, and USGS)



seismology and geodesy. Note that geodesy provides not only the predicted 3-D displacement field through the source model inversion, but also direct evidence of the For oceanwide tsunamis, the far-field tsunami wave height predictions are only critically sensitive to the seismic moment and the location of the extended source. The longer term significance of this project would be the eventual implementation of an operational system to provide real-time tsunami models with critical earthquake source information as quickly as possible. This would contribute to reducing future losses caused by oceanwide tsunamis that will hit Hawaii and the U.S. west coast.

As a result of this preliminary work we are now collaborating with various federal agencies (NASA, NOAA, and USGS) toward developing a practical real-time system (Figure 2). We are also working with GEO (the intergovernmental Group on Earth Observations who is coordinating international efforts to build a Global Earth Observation System of Systems), GGOS, and IGS in order to improve the availability of real-time GNSS data worldwide.

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