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ORIGINAL ARTICLE

GPS for real-time earthquake source determination and tsunami warning systems

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Abstract We identify the key design aspects of a GPS-based system (and in the future, GNSS-based systems) that could contribute to real-time earthquake source determination and tsunami warning systems. Our approach is based on models of both transient and permanent displacement of GPS stations caused by large earthquakes, while considering the effect of GPS errors on inverted earthquake source parameters. Our main conclusions are that (1) the spatial pattern, magnitude, and timing of permanent displacement of GPS stations can be inverted for the earthquake source and so predict the 3D displacement field of the ocean bottom, thus providing the initial conditions for tsunami models, and (2) there are no inherently limiting factors arising from real-time orbit and positioning errors, provided sufficient near-field GPS stations are deployed. This signal could be readily exploited by GPS networks currently in place, and will be facilitated by the IGS Real-Time Project as it comes to fruition.

Keywords GPS · GNSS · Real-time · Earthquake · Tsunami · Warning system

1 Introduction

As current geodetic techniques approach the ability to monitor ground movements with millimeter accuracy over the broadband range of ∼1 s–∼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 et al. 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 (Blewitt et al. 2006a; Dixon et al. 2006). Here we focus on the application of the Global Positioning System (GPS), and (in future) the application of Global Navigation Satellite Systems (GNSS), to the earthquake source determination in near real-time, and to the problem of tsunami warning. We also identify how the International GNSS Service (IGS) is likely to play an important role in such applications.

The first hour is critical for early warning of ocean-wide tsunamis. Fundamental to the generation of tsunamis is the potential and kinetic energy imparted to the ocean by rapid co-seismic displacement of the ocean bottom (Song et al. 2008). Ocean-wide tsunamis require the earthquake to have a sufficiently large seismic moment, which is proportional to the multiple of fault slip and the area of the rupture plane. Given that the moment magnitude M_w of an earthquake is defined in terms of the seismic moment M_0 (Hanks and Kanamori 1979) using the relation $M_w = (\log M_0/1.5) - 6.07$ (for M_0 in SI units), the moment magnitude M_w is a critical indicator as to whether an ocean-wide tsunami is indeed possible. In fact, damaging ocean-wide tsunamis are extremely unlikely unless $M_w > 8.5$ (Fig. 1).

Yet, underestimation of M_w for great earthquakes compromises early tsunami warning (Kerr 2005; Menke and Levin 2005). The problem relates to the various types of earthquake magnitude scales that can be derived within a short period following the earthquake, which can saturate for great earthquakes (Fig. 1). This was the case of the 2004 Sumatra M_w9.2 earthquake, which generated the most deadly

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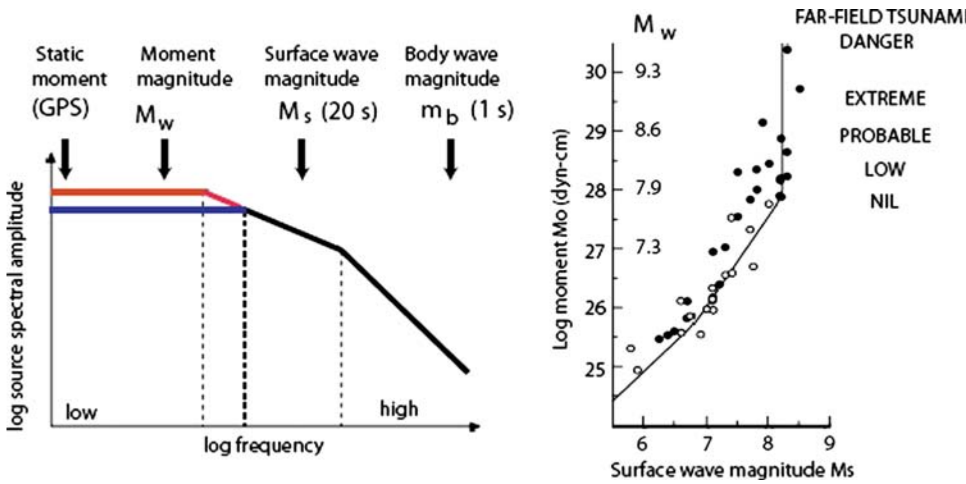


Fig. 1 (*Left*) Illustration of earthquake spectra showing corner frequencies (*dashed vertical lines*) and different magnitude determinations. The earthquake whose spectrum is shown in red has larger M_w than the one with spectrum shown in blue, even though they have the same surface and body wave magnitudes, as shown by the black part of the spectra that are the same for both earthquakes. GPS samples the lowest frequency part of the spectrum, and as a time-domain measurement system, can readily sample static offsets. (*Right*) Due to surface wave magnitude saturation, earthquakes of the same M_s can have very different seismic moments (Geller 1976) and thus risk of generating an ocean-wide tsunami

ocean-wide tsunami in history. Using a method known as M_{wp}, an initial magnitude estimate of 8.0 was derived within 11 min of the earthquake. Within 1 h, using surface wave data, estimates were raised to M_s8.5. Within 5 h the estimate was again raised to M_w9.0. Days later, it was determined from free-oscillations of the Earth that the true magnitude was M_w9.2 (Stein and Okal 2005; Park et al. 2005). While these magnitude estimates were being revised, within 3 h, the tsunami had raced across the ocean at the speed of a jet aircraft, and had devastated the coasts of Thailand, Sri Lanka, and India.

According to earthquake source theory, a plot of the logarithm of amplitude of the radiated waves versus the logarithm of the frequency (Fig. 1) is flat at low frequency (long period) and then decays for frequencies above (periods shorter than) "corner" frequencies proportional to 1 over the times needed for the rupture to propagate along the length of the fault and for slip to be completed at a point on the rupture. The larger the earthquake, the more the corner frequencies move to the left of the plot. Different measures of "earthquake magnitude" use the seismic energy radiated at different periods. The conventional short-period body wave magnitude m_b is determined at a period of 1 s, whereas the surface wave magnitude M_s is determined at a period of 20 s. A problem with both types of magnitude is that they saturate (i.e., remain constant) once earthquakes exceed a certain size. This happens because of destructive interference between individual source components at frequencies greater than the corner frequencies of the source. When the earthquake size grows, the source takes more time to occur, the corner frequencies decrease below those used for the standard m_b and M_s measurements, and eventually, no matter how large the moment, these magnitudes saturate around values of $m_b \sim 6.3$ and $M_s \sim 8.2$ (Geller 1976).

On the other hand, GPS can measure the permanent co-seismic deformation of the Earth's surface (Blewitt et al. 1993; Bock et al. 1993), and so can be used to estimate the seismic moment (hence M_w) without any problems of saturation (Fig. 2). The fundamental requirements are that (1) the GPS network has sufficient near-field stations (within 1 rupture length) to capture the permanent displacement signal, (2) the GPS network has sufficient far-field stations to provide a reference frame and an upper bound on the seismic moment, (3) GPS stations transmit their data in (near) real-time, and (4) GPS analysis systems are in place to handle near real-time data, including the precise estimation of GPS orbits, as well as the estimation of GPS displacements. The first condition requires specific consideration for regions that can potentially generate mega-thrust earthquakes (Fig. 3). The IGS global network already naturally takes care of the second condition. The IGS Real-Time Pilot Project is a valuable step toward meeting requirements (3) and (4), though much work remains to develop real-time analysis systems. It is possible to partition requirement (4) into two parts: the generation of real-time orbit and clock parameters, and the generation of real-time GPS station positions. In this partitioned model, IGS might consider the role of providing the real-time orbits and clocks. One question we address here is the requirement on accuracy of real-time orbits in such a partitioned model.

Blewitt et al. (2006b) demonstrated that GPS observations could have been used in real time to accurately determine the magnitude of the 2004 Sumatra earthquake using only data within 15 min after the origin time. The time series for the two near-field GPS stations of that study are summarized

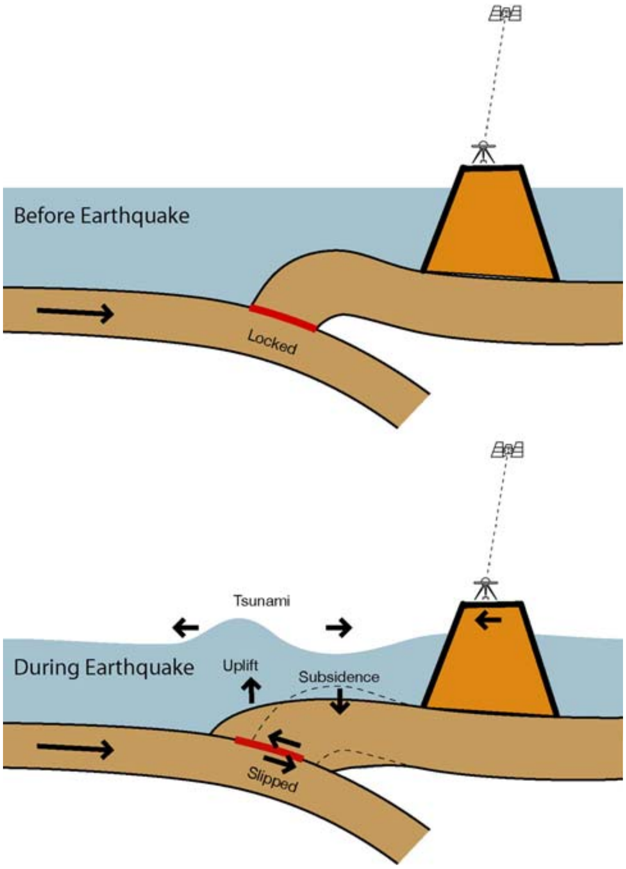


Fig. 2 Cartoon illustrating the concept of using GPS permanent displacement as a means to model the initial conditions for tsunami genesis, by inversion of the rupture plane parameters, hence predicting the displacement of the ocean bottom. Note that it is the horizontal displacement of the GPS stations on land that provide most information to predict the 3D displacement of the ocean bottom

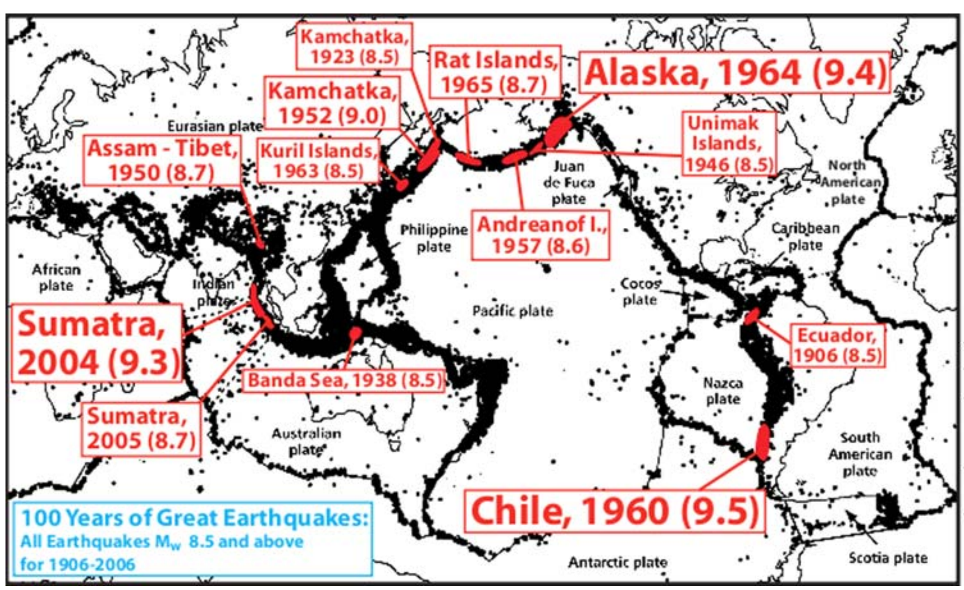
in Fig. 4. This naturally led to the idea that permanent GPS stations could contribute to early warning systems (Blewitt et al. 2006b; Song 2007; Sobolev et al. 2007), which in turn provided motivation for studying aspects of system design. Here we pose the following research question: "What are the 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?"

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 a GPS-based method would use to invert for source parameters; (2) GPS network geometry, which must be sufficient to sense the spatial pattern of ground displacement in order to resolve the earthquake source model; (3) real-time GPS positioning errors, both current, and what might be possible given real-time orbits from the IGS; 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.

2 Timing of permanent displacement

We first considered 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.

Fig. 3 Great earthquakes of $M_w > 8.5$ (*in red*) occurring in the period 1906–2006. Smaller earthquakes are shown as black dots, which delineate the boundaries of major tectonic plates



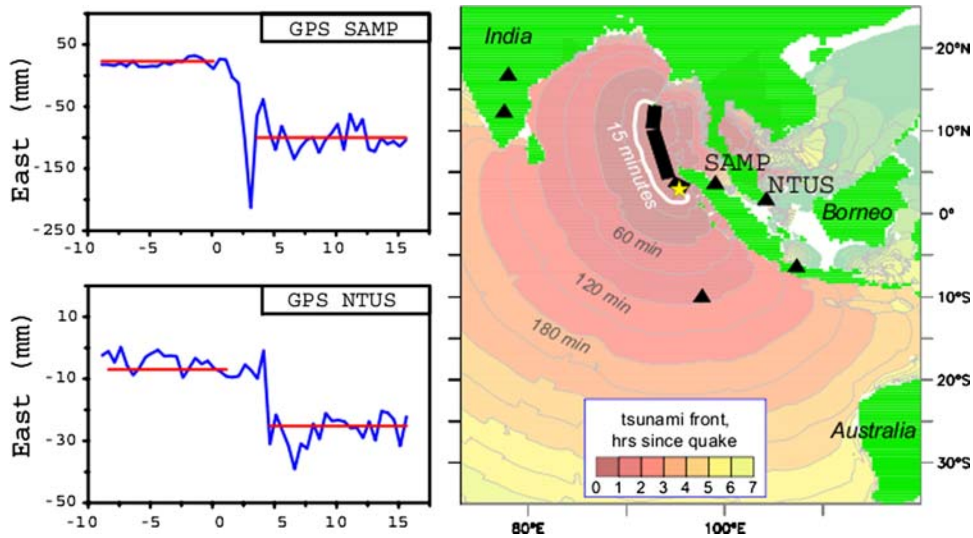


Fig. 4 GPS permanent displacements observed during the Mw 9.2 2004 Sumatra earthquake demonstrated that, within minutes, permanent displacements can be resolved with ∼10 mm accuracy. Sites SAMP and NTUS in the near-field (within ∼1 rupture length) provide a statistically significant offsets from which earthquake magnitude can be resolved (Fig. 2) as being in the range capable of generating an ocean-wide tsunami (Fig. 8). Adapted from Blewitt et al. (2006b). Yellow star is the earthquake epicenter

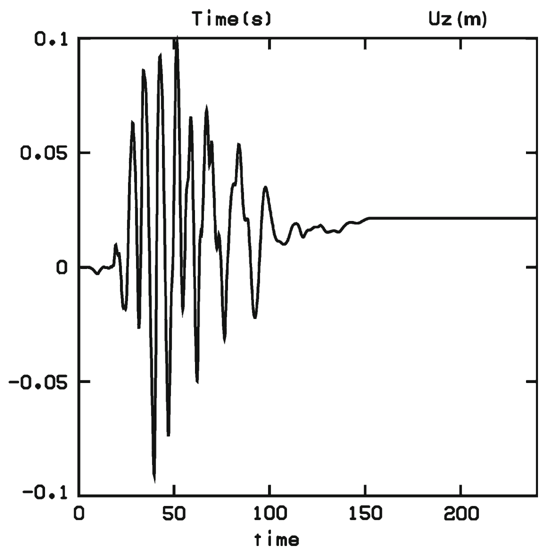


Fig. 5 Example of a vertical displacement synthetic seismogram 75 km from the epicenter of a M 7.8 subduction thrust event showing the transient wave field evolving into the static displacement

Instead, we adopted a new Green's function approach developed by Wang (2003). 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 5 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 ocean-wide tsunamis, it is clear from these simulations that the current "standard" rate GPS (15 or 30 s intervals) would be sufficient to resolve the permanent displacement, as was proven for the 2004 Sumatra earthquake (Blewitt et al. 2006b).

3 Network geometry

We have developed simulations for hypothetical scenarios in the region of the Cascadia subduction zone, western North America, where great earthquakes are certainly capable of generating damaging tsunamis (Mazzotti et al. 2003), and where already there are many permanent GPS stations that could in future serve as part of a real-time warning system (Dragert et al. 2005). Figure 6 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 (Blewitt et al. 2006b), and thus provide the initial conditions for tsunami models (Titov et al. 2005), as illustrated in Fig. 2. Alternatively, a "tsunami magnitude" approach can be applied more directly from the coastal GPS displacement data, as suggested by Song (2007). Although the time is likely too short to aid significantly in warning communities along the Cascadia coast, the results would be valuable for warning more distant sites.

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 ocean-wide tsunami warning system. However, the issue of local tsunamis from smaller earthquakes would benefit from extra spatial density of stations near the coast.

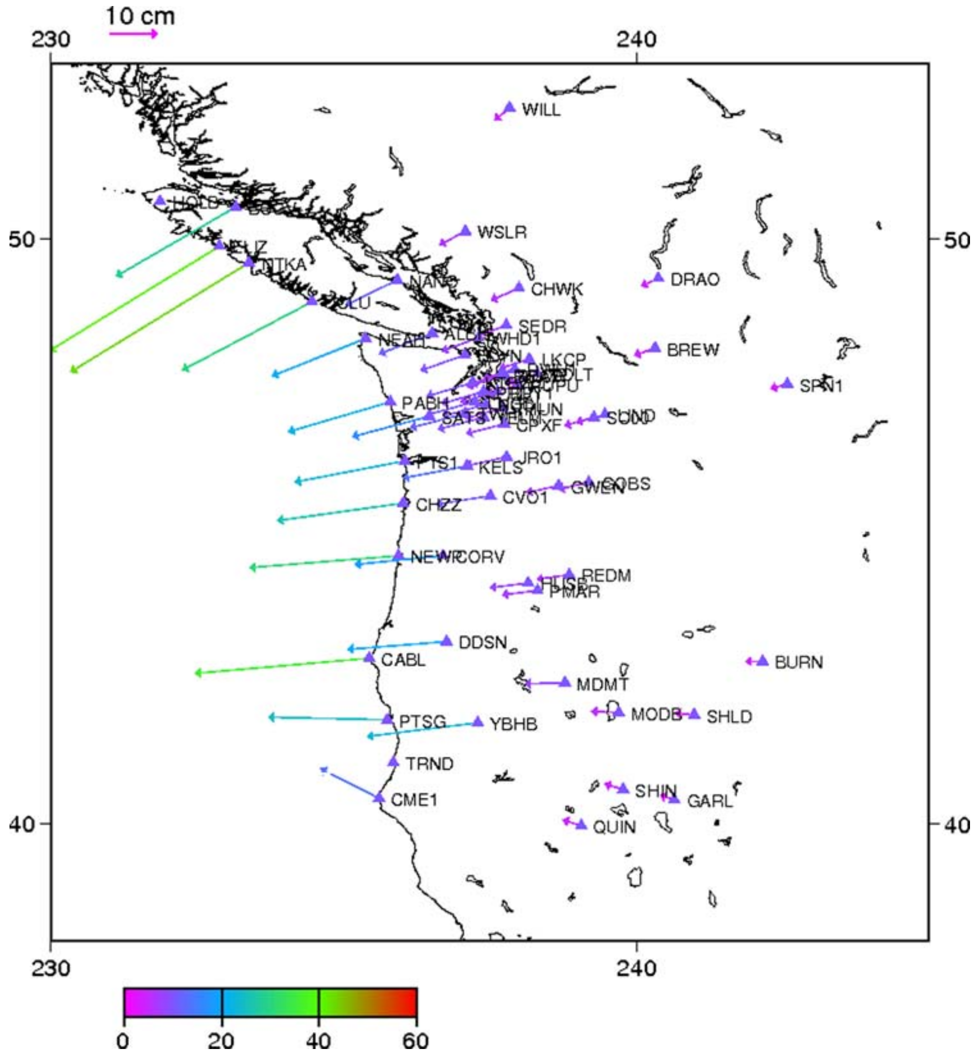


Fig. 6 Example of simulated permanent displacements at GPS stations as a result of an Mw 9.0 earthquake in the Cascadia subduction zone. Thus displacements near the coast are several decimeters, which Blewitt et al. (2006b) demonstrates is an order of magnitude greater than the uncertainties in the offsets inferred using GPS after 15 min

Furthermore, given that 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 the permanent displacement signal in the GPS records of ground motion should be extracted for purposes of earthquake source inversion. This approach has the advantage that it makes GPS maximally complimentary to the transient waveform approach taken by seismology, thus providing an extra layer of robustness in a multi-technique warning system.

4 Real-time GPS errors

The objective of this aspect of the study was to elucidate the critical specifications, as they relate to real-time orbit accuracy and parameter estimation strategy. Of specific interest was how errors in real-time orbits currently distributed by the 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. 2006b), we had previously used a "best possible" procedure that simultaneously estimated parameters including 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 (Fig. 7, bottom). 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.

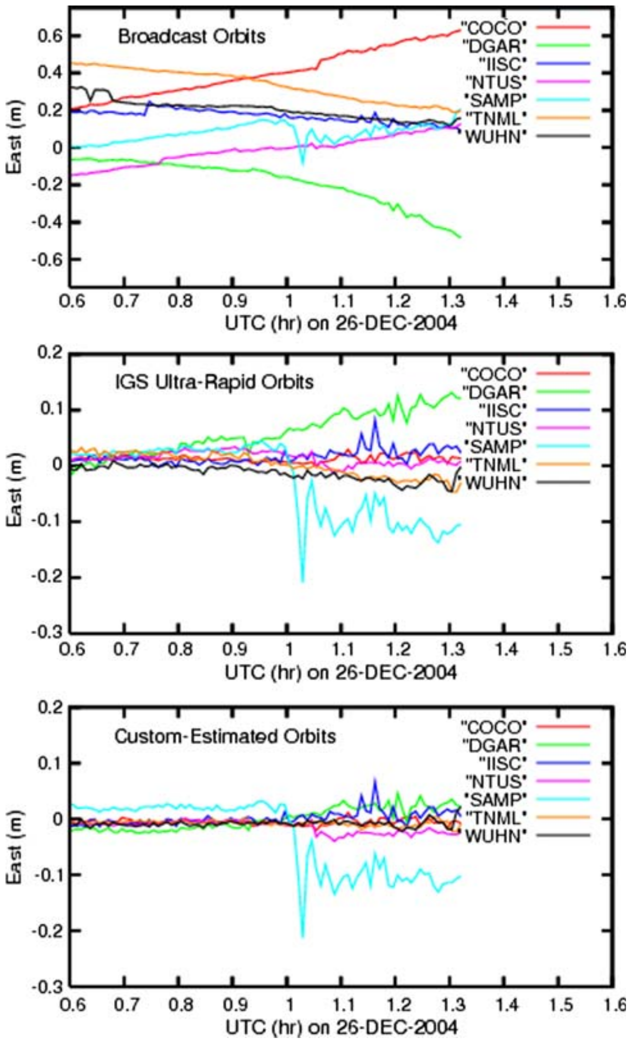


Fig. 7 East coordinate time series (30 sec) on 26 December 2004 estimated for permanent GPS stations (within a few rupture lengths) using (*Top*) broadcast orbits, (*Middle*) IGS ultra-rapid orbits, and (*Bottom*) custom-estimated orbits. Note that the y-scale for broadcast orbits is 3 times larger. In all cases, satellite clocks were estimated

Here we tested alternative options for real time orbits, including the Broadcast Ephemeris and the IGS Ultra-Rapid orbits, by applying them to the analysis of the 2004 Sumatra earthquake. In all cases, satellite clocks were estimated as white noise at every epoch (equivalent to double differencing), and sidereal filtering was applied to mitigate multipath (Choi et al. 2004). The IGS ultra rapid orbits are published 4 times per day, each with an initial latency of 3 h. As a consequence, the actual latency in real time falls in the range 3–9 h. In this particular case, the latency was 7 h, meaning that the orbits were actually predicted ahead 7 h until the time of the earthquake. To test whether the systematic drifts evident in Fig. 7 (middle) were due to errors in prediction, we also tested the IGS ultra-rapid orbits published 6 h later, with 1 h latency (not shown). Very similar drifts were evident, thus prediction does not appear to be the main cause of the drifts.

The resulting time series show that systematic drifts and jumps dominate solutions using the Broadcast Ephemeris (Fig. 7, top). In contrast, time series using estimated orbits (Fig. 7, bottom) are very flat until the seismic waves arrive at each station (at ∼01:00 UTC), after which the stations are permanently displaced. The IGS ultra-rapid orbits produce results with slight systematic drifts as compared to the case using estimated orbits (Fig. 7, middle).

To test the performance of the IGS rapid orbits, we followed the previous procedure (Blewitt et al. 2006b) to estimate displacements from the time series (with a 15 min 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 (Fig. 8). 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. (2006b). Note that, as was the case in Blewitt et al. (2006b), F tests easily rules out other hypothetical scenarios, such as a southward propagating rupture, a strike slip event, or normal faulting event (which can occur in subducting slabs). For all scenarios we assessed a broad range of rupture lengths in increments of 200 km.

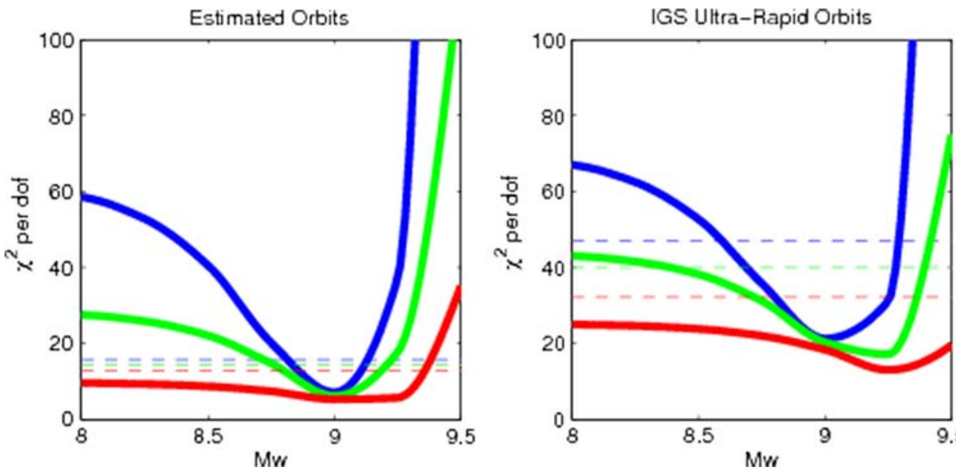
Whereas for the estimated orbits M_w is constrained with 95% confidence to the range 8.8–9.1, for the IGS ultra rapid orbits M_w is only constrained to the range 8.6–9.3. In this case, the results for the IGS ultra rapid orbits are not sufficiently precise for purposes of tsunami warning, because of 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. We tested this idea using polynomials over a variety of time spans prior to the earthquake origin time (to predict the time series after the earthquake). None of the test cases narrowed the acceptable range of earthquake magnitudes, and in some cases degraded the results, leading us to conclude that the slight drifts in the time series of Fig. 7 (most apparent for station DGAR) are not a limiting problem. Another possible reason for the poorer chi-square statistic for the case of IGS ultra rapid orbits is that the larger orbit errors cause greater jumps in the time series whenever a satellite sets or rises. However, such jumps would be relatively small compared to the earthquake-induced displacement for stations in the near field and therefore a more robust way forward is simply to install more sites in the near field. Figure 8 confirms that near-field sites are critical to constrain the range of earthquake models.

5 Broader design aspects

Broadly speaking, successful prediction and early warning require two very different system designs. On the one hand,

Fig. 8 Reduced chi-square summarizing the misfit of displacements as a function of M_w (*left*) using estimated orbits, adapted from Blewitt et al. (2006b); (*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



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, 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 (and in the future, 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 we have already discussed, 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 centers including NOAA's Pacific Tsunami Warning Center (PTWC), and (2) to enhance post-earthquake damage assessment for emergency response produced operationally (for example in the United States, USGS ShakeMap). Potential contributions to this effort include 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 these contributions requires coordination between national agencies and with international programs including Group on Earth Observation (GEO), Global Earth Observation System of Systems (GEOSS), and of course, GGOS and IGS.

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 at both the national and international levels. (For example in the United States, coordination is required between NASA, NOAA, USGS, GEO/GEOSS, and GGOS/IGS).*

Progress is now being made by several groups to develop precision real-time GPS and its application to warning systems. For example in the United States, NASA's operational Global Differential GPS (GDGPS) System developed by JPL (Muellerschoen et al. 2001) 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. Similarly the IGS Real-Time Pilot Project in principal has the potential to demonstrate precise real-time positioning, and enable such a capability by third party users. In Canada, a pilot project is underway to measure in real-time the displacement of coastal GPS stations relative to stations further inland in real-time (Dragert et al. 2005). In Japan, the Earthquake Research Institute has developed tsunami warning buoys that are tracked by GPS (Kato et al. 2005), and of course, Japan's Geographical Survey Institute already has GEONET, a very dense GPS network with a real-time capability (Yamagiwa et al. 2006). In Europe, GeoForschungsZentrum (GFZ) has developed a concept known as "GPS Shield" (Sobolev et al. 2007), which also includes coastal GPS stations, as well as GPS-tracked buoys to observe the tsunami directly.

Recommendation 3 *Systems based on precise real-time GPS 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 recommendations similar to those above at the Real Time GPS Science Requirements Workshop, which was held at Leavenworth, Washington, USA, in 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 collaborating 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 Leavenworth 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 are useful to decision makers. Table 1 summarizes the recommendations regarding tsunami warning.

6 Conclusions

The spatial 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 (Titov et al. 2005), or tsunami magnitude estimators (Song 2007). 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 detected and 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 ocean-wide tsunamis. Faster inversions would benefit from having a greater density of stations near the coast, 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.

Table 1 Recommendations developed at the real time GPS science requirements workshop

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

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 PTWC (Titov et al. 2005). Such models require initialization using real-time earthquake source parameters that can come from a combination of seismology and geodesy. For ocean-wide 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 ocean-wide tsunamis that will hit Hawaii and the US west coast.

As a result of this preliminary work we are now collaborating with various US federal agencies (NASA, NOAA, and USGS) toward developing a practical real-time system. We are also working with GEO, GGOS, and IGS, in order to improve the availability of real-time GNSS data worldwide.

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