Real-time, reliable magnitudes for large earthquakes from 1 Hz GPS precise point positioning
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Real-time, reliable magnitudes for large earthquakes from 1 Hz GPS precise point positioning: The 2011 Tohoku-Oki (Japan) earthquake

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The early warning issued after the onset of the Mw 9.0 Tohoku-Oki earthquake significantly underestimated its magnitude, saturating, 120 seconds after the earthquake began, at Mw 8.1. Here we investigate whether real-time deformation data from Japan’s dense network of continuously-recording Global Positioning System (GPS) stations could have been used to provide a more reliable rapid estimate of the earthquake’s magnitude, and ultimately a more robust tsunami forecast. We use precise point positioning in real-time mode with broadcast clock and orbital corrections to give station positions every 1 s. We then carry out a simple static inversion on a subset of stations to determine the portion of the fault that slipped and the earthquake magnitude. Unlike most previous methods, our method produces estimates of seismic moment before the earthquake rupture has completed. We find that the deformation data allow a robust magnitude estimate just ~100 s after the earthquake onset. We also investigated the density of stations required for a robust moment magnitude estimate. Fewer than 1 station every 100 km are needed. We recommend that GPS data be incorporated into earthquake early warning systems for regions at threat from large magnitude earthquakes and tsunamis. Citation: Wright, T. J., N. Houlié, M. Hildyard, and T. Iwabuchi (2012), Real-time, reliable magnitudes for large earthquakes from 1 Hz GPS precise point positioning: The 2011 Tohoku-Oki (Japan) earthquake, Geophys. Res. Lett., 39, L12302, doi:10.1029/2012GL051894.

1. Introduction

The successful early warning [Yamada, 2011; Hoshiba et al., 2011] issued after the onset of the Mw 9.0 Great Tohoku-Oki Earthquake of 11 March 2011 [Simons et al., 2011; Ozawa et al., 2011] undoubtedly saved lives. Yet it significantly underestimated the earthquake’s magnitude, saturating, 120 seconds after the earthquake began, at Mw 8.1. Here, we investigate whether deformation data recorded during the earthquake could have been used to rapidly determine its magnitude more reliably than existing seismic methods, and more rapidly than GPS methods previously proposed. In addition, we explore the number of GPS stations that are required for such magnitude estimation.

Several countries, including Japan, now have operational earthquake early warning systems (EEW) based on seismic methods [Allen et al., 2009]. These systems are able to detect and estimate the location and magnitude of earthquakes, and to transmit this information to places yet to be shaken. To provide the longest warning times, most EEW systems attempt to estimate earthquake magnitude from the earliest P-wave arrivals. The methods developed use empirical relationships to magnitude, for either the predominant period [Nakamura, 1988; Allen and Kanamori, 2003; Kanamori, 2005; Hildyard et al., 2008; Hildyard and Rietbrock, 2010], the peak amplitudes of the early P-wave [Wu and Zhao, 2006; Zollo et al., 2006], or a combination of these methods [Wu et al., 2007].

Currently, a key limitation in earthquake early warning systems is the reliability of magnitude estimations [Yamada and Mori, 2009]. In particular, the relationships may saturate for large magnitudes. For peak displacement, Wu and Zhao [2006] and Zollo et al. [2007] demonstrate saturation effects above Mw 6.5–7. For period-based methods, saturation effects above Mw ~ 6.5 have been demonstrated from theoretical considerations [Kanamori, 2005; Hildyard and Rietbrock, 2008]. Saturation is likely in part due to the short length of the time window used, and also due to insufficient data in the very large magnitude range. Both amplitude- and period-based estimates improve with a larger time window [Zollo et al., 2007; Yamada and Mori, 2009] although this may then include S-wave arrivals.

Deformation data from the Global Positioning System (GPS) have long been used to determine source parameters for earthquakes [e.g., Lisowski et al., 1990; Clarke et al., 1997] using simple elastic dislocation theory [Okada, 1985]. After the 2004 Mw 9.3 Indonesian earthquake and tsunami, several teams investigated methods for using GPS data in real time with a particular focus on tsunami warnings [Blewitt et al., 2006; Sobolev et al., 2007; Blewitt et al., 2009; Crowell et al., 2009; Behrens et al., 2010]. Similar methods were employed after the 2010 Mw 7.2 El Mayor-Cucapah earthquake [Allen and Ziv, 2011]. These previous studies have all relied on estimating the final static displacements for the earthquake, usually after the transient motions have died down. These methods therefore typically take ~10 minutes to produce estimates of earthquake magnitude. Instead, like Ohta et al. [2012], we attempt to speed up the magnitude estimation by determining an evolving slip model (and magnitude estimate) while the earthquake rupture is still progressing. The data available for the Tohoku-
Oki earthquake provides an unprecedented opportunity to test these methods using real data from a Mw 9.0 event.

In this manuscript we do not attempt to resolve the details of the earthquake slip distribution or rupture process, which have been the focus of numerous studies [e.g., Ozawa et al., 2011; Simons et al., 2011; Yokota et al., 2011; Loveless and Meade, 2011; Yue and Lay, 2011; Jinuma et al., 2011; Yagi and Fukahata, 2011]. Instead, we exploit the dense data available in Japan [e.g., Grapenthin and Freymueller, 2011] to test the utility of sparse GPS networks for real-time earthquake early warning, by testing the resolving power of small subsets of the available data. Such networks could be set up with minimum cost in countries at risk from great earthquakes but without Japan’s resources.

2. GPS Data

The Tohoku-Oki event is the best recorded great earthquake in history. Deformation from the earthquake was recorded on 1200 sites from Japan’s extensive GPS Earth Observation Network (GEONET) [Sagiya, 2004]. We post-processed the 1 Hz GEONET data from 414 sites in the range 138–143 E, 34.5–42.5 N, centred on the Tohoku district of Japan. We used the Real-Time Network (RTNet) software [Rocken et al., 2004] in real-time mode using a precise point positioning strategy [Zumberge et al., 1997]. We applied a very loose kinematic constraint of 100 m/s, allowing us to retrieve any rapid motions at stations. Clock errors and satellite orbits were adjusted using corrections from the VERIPOS service based on global GNSS network that were also available in real time and every 5 seconds [Rocken et al., 2011]. We have confirmed that for 1 s GPS data, the temporal resolution of the satellite product is optimal at 5 s; degradation of the coordinate solution is negligible compared to solutions using 1 s corrections. Furthermore, real-time generation and transmission of the satellite products is possible at 5 s. We note that these positions could be produced in real time with a 1–2 second delay for data transmission and processing.

The positional accuracy (1-sigma) for any individual site is found to be 2.7 cm (east–west), 4.2 cm (north–south), and 12.2 cm (vertical) based on an analysis of 144 minutes (0.1 day) of data before the earthquake event for all the stations used here. Accuracy of the height solution is a little worse than the nominal accuracy declared by APEX (10 cm). The primary contributor to the noisy height solution is likely to be water vapor variations in the relatively humid climate over Japan.

The sites closest to the epicentre begin to move significantly about 30 seconds after the earthquake onset (Figures 1 and 2). Displacements for coastal sites near the

Figure 1. GPS displacements for the 11 March 2011 great Tohoku-Oki earthquake. Arrows show horizontal displacements (a) 50 s, (b) 100 s and (c) 300 s after the earthquake onset. Thin black lines outline the model fault geometry, with inverted slip values given by the colors. Major plate boundaries are thick lines. The white star is the USGS epicentre. Time histories for labelled GPS stations are given in Figure 2.

Figure 2. Measured (black) and modelled (red) east–west displacements as a function of time at 5 selected GPS sites. The site locations are given in Figure 1.
[10] Although solving for the slip on a fault with pre-defined geometry is a linear inversion, determining its geometry is non-linear. We restrict range of possible fault geometries by forcing it to occur on a pre-defined Japan trench, following the simple geometry used in the USGS finite fault seismic inversion [Hayes, 2011]. We use a subduction interface that is a plane dipping at 15 degrees, striking at 195 and intersecting the USGS earthquake hypocentre (lat/lon/depth). Although the earthquake only ruptured 300 km of the subduction interface, we extend it for 400 km on either side of the hypocentre.

[11] For simplicity, we treat the displacements recorded at each epoch as if they were the final, static displacement field, and model the earthquake as a series of eight rectangular dislocations, each 100 km long, embedded in an elastic half space [Okada, 1985]. We solve for the slip on each dislocation, the down-dip extent of faulting, and a single fault rake by minimising the square misfit between the predicted displacements and those observed at ten different selections of ten coastal stations spaced by ~100 km. We note that we are not attempting to determine the most accurate slip model for the earthquake, but are more interested in the stability of the inversion when relatively few data are available.

[12] For Japan, where there are no islands near the trench, land-based geodetic observations have very little sensitivity to slip in the shallowest (and most distal) part of the subduction interface [Loveless and Meade, 2011]. We therefore fix the up-dip limit of faulting to 10 km below the surface. Inversions without this, or similar, constraint collapse to very narrow line sources with very high slip, but have near-identical $M_w$ to sources with more normal aspect ratios.

[13] This simple non-linear inversion is solved using a hybrid downhill simplex, Monte-Carlo inversion scheme [Clarke et al., 1997; Wright et al., 1999] and takes less than 1 second to run on a standard desktop computer.

[14] Because of the relatively high noise levels in the real-time GPS precise point positions in comparison to post-processed static offsets, we do not attempt to solve for an earthquake magnitude until at least one site has moved by more than 8 cm. This value was found by trial and error to be sufficient to avoid false alarms, but restricts the utility of GPS early warning for earthquakes on the subduction interface to those larger than $M_w \sim 7$, if used independently of seismology.

4. Results

[15] We are first able to detect the Tohoku-Oki earthquake with GPS 35–45 seconds after its onset (Figure 3a). Our GPS magnitude estimate quickly rises from $M_w$ 7.5 at 40 seconds to $M_w$ 8 at 60 seconds, before reaching its maximum value ($M_w$ 8.8) at 90–100 seconds.

[16] By comparison, the first early warning from seismic data ($M_w$ 7.1) was issued at 28 s, rising to $M_w$ 7.7 at 60 seconds, and saturating at $M_w$ 8.1 at ~120 seconds (Figure 3a). Subsequently, the Japanese Meteorological Agency increased their estimate to $M_w$ 8.4 after ~75 minutes and to $M_w$ 8.8 after nearly three hours. The initial USGS earthquake notification service alert (issued about 30 minutes after the earthquake) had $M_w$ 7.9.

[17] For this earthquake, it appears that the maximum GPS $M_w$ is reached before the earthquake has finished propagating - an initial dynamic overshoot of displacements at sites closest to the epicentre appears to balance slip yet to have occurred on fault patches at larger distances and later times (Figure 2). The ongoing movements due to the continued passage of seismic waves is a second order effect when estimating $M_w$. Dynamic displacements do not affect the moment estimate, presumably because the signals are different at each station. They are likely to have a bigger effect for smaller earthquakes, but we believe that in general the effect will be second order.

[18] We note that our GPS magnitude estimate of $M_w$ 8.8 still underestimates the final seismic moment $M_w$ 9.0. We believe the discrepancy is primarily due to our simplified geometry and the insensitivity to shallow slip near the trench. We tested whether the results of the inversion were sensitive to size of the fault patch used. For this earthquake and station spacing, near-identical moments were found with 50 km and 200 km patches, although there was significantly more noise for 50 km patches with 100 km station spacing, particularly in the first 50 s.

[19] We also explored how many stations were needed to make a reliable forecast. To do this, we divided the GPS data set into 100 km bins along strike and varied the number of stations used in each bin. For each of these station densities, we picked 50 random sets of stations and examined the range of magnitudes found. We found that the magnitude...
could be determined with fewer than 1 site every 100 km (Figure 3b). However, additional stations would leave the inversion less susceptible to outliers and be valuable for discriminating between subduction zone thrusts and earthquakes in the upper plate or outer rise, for example.

5. Discussion and Conclusions

[20] Our results demonstrate the utility of real-time GPS deformation data for earthquake early warning for large subduction zone earthquakes. Unlike existing seismic methods, the magnitude estimates derived from deformation data do not saturate. Unlike most previous GPS studies, our method can be applied while the earthquake is still propagating, before the permanent displacements have set in. For the Tohoku-Oki earthquake, this gives a reliable moment in under 2 minutes (compared to ~10–15 minutes in previous studies). This speed could be critical for the evacuation effort.

[21] Ohta et al. [2012] carried out a similar analysis to that presented here, but used positions based on Real-Time Kinematic (RTK) GPS processing. As these authors pointed out, the Precise-Point Positioning method that we use has the advantage over RTK that it does not require the use of a reference station, which might itself be subject to shaking. We also note that our simpler inversion scheme, and the use of a subset of GPS sites, means that our scheme more rapidly reaches a maximum moment estimate.

[22] The lack of islands above the shallowest part of the plate boundary that slipped limits the ability of GPS data to determine the exact distribution of slip on the plate interface and the resultant seafloor deformation [Sobolev et al., 2007]. The details of resultant tsunami predictions will therefore be inaccurate. Nevertheless, the moment magnitude from GPS is robust, whereas existing seismic methods can underestimate the tsunami danger of great earthquakes [Blewitt et al., 2009]. Seafloor geodetic data [Sato et al., 2011] would be essential in Japan to improve the accuracy of inversions for slip distributions and therefore for tsunami forecasts.

[23] We note that for an operational system, a careful definition of subduction zone interfaces and other potential sources would be required. Seismic early warning locations, or P-wave picks from the GPS data themselves, could be used to limit the source faults in the early warning system. We recommend that further work be carried out to assess the optimum configuration of a GPS network that is able to distinguish, for example, earthquakes on the subduction interface from those occurring with different mechanisms in the upper plate or outer rise.

[24] In the near future, it is unlikely that most countries at threat from great earthquakes and tsunamis will be able to afford a GPS network with the density of Japan’s GEONET. However, for earthquake early warning, we have shown that a station spacing of ~100 km would be adequate. Furthermore, updated position vectors every 30 s could be used, significantly reducing the required bandwidth for telemetry if this was an issue (N. Houlié, Low sampling rate GPS earthquake early warning system, manuscript in preparation, 2012). Therefore, we support the arguments for incorporating GPS into tsunami warning systems [Sobolev et al., 2007]: A relatively modest investment in infrastructure (say ~400 sites for the whole Pacific rim) could provide an early, accurate warning for vulnerable communities at threat from future great earthquakes and tsunamis.

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