Long-baseline quasi-real time kinematic GPS data analysis for early tsunami warning

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Real time monitoring of wave height in the ocean far from the coast can contribute to mitigation of a tsunami disaster. Here we demonstrate that early detection of a damaging tsunami can be achieved using a new long baseline kinematic GPS method, by tracking the anomalous changes in sea surface heights. The movement of a GPS buoy relative to a base station with a baseline length of 500 km has been monitored in quasi-real time mode, and the tsunami waves caused by the 5 September 2004 Off Kii Peninsula earthquake, Japan, have been successfully resolved. Based on the continuous analysis of GPS buoy data for 8 days, the average scattering of the low-pass filtered 1-Hz GPS buoy heights after tidal correction are about 3.4 cm and 1.2 cm for typhoon and calm weather, respectively. That is precise enough to detect tsunami waves with an amplitude of over 30 cm even under typhoon conditions. The long baseline can ensure an adequate evacuation time for people living on the coast.

Key words: Long baseline kinematic GPS, GPS buoy, tsunami sensor, real time tsunami monitoring, 2004 Off Kii Peninsula earthquake.

1. Introduction

The December 2004 Sumatra-Andaman earthquake generated the most devastating tsunami ever recorded, causing more than 200,000 casualties (Satake *et al.*, 2006). The tragedy has been blamed on the initially underestimated earthquake magnitude and the lack of a tsunami warning system in the Indian Ocean (Kerr, 2005). The first information bulletin issued by the PTWC (Pacific Tsunami Warning Center), 15 min after the quake, stated a magnitude of 8.0 that there could be a local tsunami. An hour later, a second bulletin was issued by PTWC, stating a larger magnitude of 8.5 and announcing a worldwide alert, but by that time, it was too late. If people had been informed about the incoming tsunami wave with enough time for evacuation, the great devastation would have been greatly decreased. Thus, the establishment of modern and robust tsunami early warning systems is an urgent need for many countries.

In the current tsunami warning system operated in Japan, for example, earthquake source parameters, such as hypocenter location and magnitude, are estimated from seismic observation and function as key information to predict the coastal distribution of tsunami height. However, the 1896 Sanriku earthquake, the 1998 Papua New Guinea earthquake, and the recent July 2006 Java earthquake generated unexpectedly large tsunamis, which were difficult to anticipate from seismic observation (Kanamori, 1972; Kawata *et al.*, 1999; Fritz *et al.*, 2007). These examples clearly indicate that current seismology-based tsunami warning systems are inadequate and may fail to issue a successful alarm in some cases.

Another approach to early tsunami warning is to directly monitor the fluctuation of sea surface changes in the open sea. Since this approach is to detect the tsunami wave itself, the prediction of coastal tsunami height is more straightforward.

The monitoring of sea surface fluctuation is possible with several different techniques. For example, NOAA has deployed the Deep Ocean Assessment and Reporting for Tsunami (DART) network with ocean bottom pressure gauges along the circum-Pacific region and the U.S. coast to detect tsunami waves. In Japan, the ocean-bottom pressure gauge installed southeast off Hokkaido successfully detected tsunami waves associated with several earthquakes (Hirata *et al.*, 2003; Watanabe *et al.*, 2004; Baba *et al.*, 2004). However, operating an ocean-bottom pressure gauge is much more expensive than operating a GPS buoy (Kato *et al.*, 2000). What is needed is a far less expensive system with a greater geographic coverage over oceanic regions that will detect the physical manifestations of a tsunami's occurrence. In the case of the 2004 Sumatra-Andaman earthquake, satellite altimetry with TOPEX/Poseidon and JASON-1 satellites has resolved a sea surface fluctuation associated with the tsunami propagation in the Indian Ocean (Hirata *et al.*, 2006; Gower, 2007). This measurement was made only along satellite tracks and cannot provide a full picture of the event.

In this paper, we investigate a potential use of a GPS buoy for the purpose of tsunami early warning. A special

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buoy has been designed and installed south off Shikoku Island, southwestern Japan. With this GPS buoy, Kato *et al.* (2005) successfully detected a tsunami wave caused by the 2004 Off Kii Peninsula earthquake (M_w 7.4). However, the buoy location is only 13 km from the coast, and the tsunami detection was made 8 min before the coastal arrival of the first wave, which is far from enough time for successful evacuation. In order to secure a longer evacuation time, we need to install the GPS buoy further offshore, requiring a new feasibility study of the GPS buoy with a long-baseline kinematic GPS analysis. To that end, we have developed a new quasi-real time long-baseline kinematic analysis method and tested it on a 500 km long baseline to resolve the motion of the GPS buoy (see Section 3 for details on this method). We also investigate the noise level of the GPS buoy height measurement under various weather conditions. Based on these results, we discuss the applicability of the GPS buoy system for tsunami warning.

2. GPS Tsunami Buoy Observation

The GPS tsunami buoy was installed and anchored about 13 km off Cape Muroto in April 2004 (Fig. 1), where the water depth is about 95 m. One-second GPS data were transmitted in real time by radio to the ground base located at the Muroto Meteorological station, of the Japan Meteorological Agency (JMA). The system uses a real-time kinematic (RTK) GPS technique to estimate the buoy position. The RTK software, called R(everse)-RTK (Kato *et al.*, 2001), was specially developed based on commercial RTK software to allow real-time data transmission from a rover (GPS buoy) to the ground base station.

As already mentioned, on September 5, 2004, a M_w 7.4 earthquake occurred southeast off the Kii Peninsula, southwest Japan, and the GPS tsunami buoy successfully resolved the resulting tsunami wave. The amplitude of the tsunami wave was about 20 cm, and the detection time was 8 min before its arrival at the nearest Muroto tide gauge.

In order to investigate the applicability of the GPS buoy system for earlier warning, we need to examine the sensitivity and stability of the GPS buoy movement determined relative to a more distant base station. To this end, we used GPS observation data collected at 1 Hz at the International GNSS Service (IGS) station at Usuda, in central Japan, situated about 500 km away from the GPS buoy (Fig. 1).

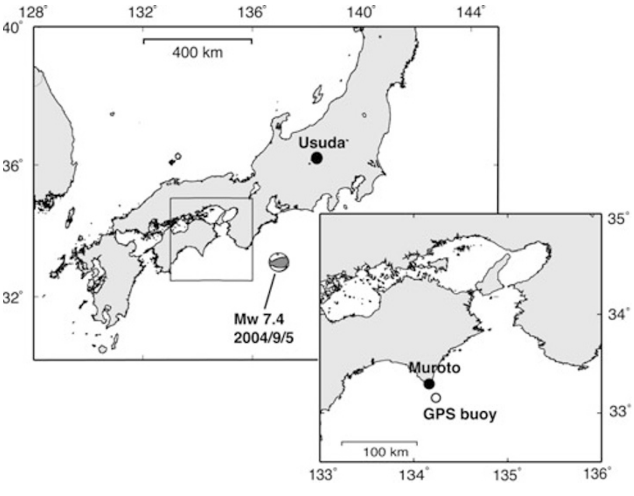

Fig. 1. Location map of the 2004 Off Kii Peninsula earthquake and GPS stations. The hypocenter and focal mechanism of the earthquake are determined by JMA. The GPS stations are denoted by solid circles and GPS buoy is shown by a circle.

3. Kinematic GPS Processing Approach

We used the Bernese 5.0 software (BSW) for our GPS data analysis. In order to conduct a long-baseline quasi-real time kinematic GPS analysis, especially with a moving object, such as a GPS buoy, we have developed a new methodology, called the "windowing-processing method", to allow automatic processing at preferred intervals using the Bernese Processing Engine (BPE) Module within BSW. In this method, we use information that is available in real time only. To put it more concretely, we used the predicted GPS satellite orbits (ultra-rapid orbit) provided by IGS. The ultra-rapid orbit consists of an observed and a predicted part. The observed part is calculated based on actual observation data, while the predicted part is calculated by forward integration of the equations of motion for each satellite. Nominal accuracies of satellite ephemerides and satellite clocks of the IGS ultra-rapid orbits are about 10 cm and 5 ns, respectively (International GNSS Service, 2008). These values are better than those of the GPS Navigation Message broadcast orbits (satellite ephemerides accuracy of 160 cm, and satellite clock accuracy of 7 ns (International GNSS Service, 2008)), which is essential for obtaining the necessary positioning accuracy with a long baseline. We estimated various parameters, such as the satellite and station clocks, zenith tropospheric delays, carrier phase biases, and cycle slips, together with the time-dependent coordinates of the GPS buoy.

Since a tsunami wave has a frequency of 10–30 min, we have applied our windowing-processing method to do automatic processing at 10-min intervals. We have enforced continuity between the successive 10 min segments for 24 h of observations. It takes about 3–3.5 min to complete processing data (including data transfer) for each 10 min segment, yielding a latency of 3–13 min for each segment.

We processed GPS tsunami buoy data for two baselines with two different baseline lengths, 13 km and 500 km. The short baseline of 13 km is the same as that in Kato *et al.* (2005), and we validated our processing strategy through a comparison with their results, which we also used to study the dependence of GPS processing on baseline length. For the long-baseline solutions, the L1 and L2 carrier phase were double-differenced between the buoy and the land base receivers, and then combined to form the ionosphere-free observable Lc. The Lc biases (a linear combination of the L1 and L2 ambiguities) were estimated as real numbers (floated) (Colombo *et al.*, 2000; Ohta *et al.*, 2006). Kinematic coordinates were estimated using the epoch-wise pre-elimination and the backward substitution algorithm (Hugentobler *et al.*, 2006).

We processed the data for eight consecutive days from September 4–11, 2004. The 2004 Off Kii Peninsula earthquake occurred on September 5. The aim of this processing was, firstly, to investigate the potential of our long-baseline kinematic GPS analysis to monitor fluctuations of the sea surface as well as to retrieve tsunami signals caused by the earthquake. A continuous record for 8 days enabled us to investigate the long-term stability and consistency of the long-baseline kinematic GPS method under various meteorological conditions.

4. Tsunami Detected by Long-baseline Kinematic GPS Solution

On 5 September 2004, two large earthquakes occurred southeast off the Kii peninsula. The main shock occurred at 14:57:16.9 UTC with a moment magnitude (M_w) of 7.4 preceded by a M_w 7.1 foreshock at 10:07:7.5 UTC. Both earthquakes triggered tsunamis. The main shock generated a larger tsunami, whose recorded peak-to-trough tsunami amplitude was about 1 m at the Muroto tide gauge (Koike *et al.*, 2005). In this study, we first focus on this main shock event to retrieve tsunami waves using long-baseline kinematic GPS data analysis.

The original GPS analysis result of the vertical movement of the buoy from 14:30 to 17:00 UTC of 5 September is dominated by high-frequency fluctuations with an amplitude of about 4 m the tsunami signal is not visible at all (Fig. 2(a)). We applied a running average with a boxcar window of 150 s to the raw GPS buoy height-time series as a low-pass filter to eliminate the short-term fluctuations due to ordinary waves. We also approximate the tidal component by fitting a polynomial function of order 5, and we remove the tides from the original records (Satake *et al.*, 2005). Figure 2(b) shows the comparison of the resultant time series for the period of 14:30 h to 17:00 h (UTC) of September 5, 2004. The first time series is the filtered record of the long baseline, and the second time series is for the short baseline. As shown in Fig. 2(b), the filtered records clearly reveal the tsunami signal with a period of a few to 10 min and an amplitude of about 15 cm. The filtered record of the long-baseline solution closely resembles that of the short baseline, with an RMS of 3.4 cm over 2.5 h.

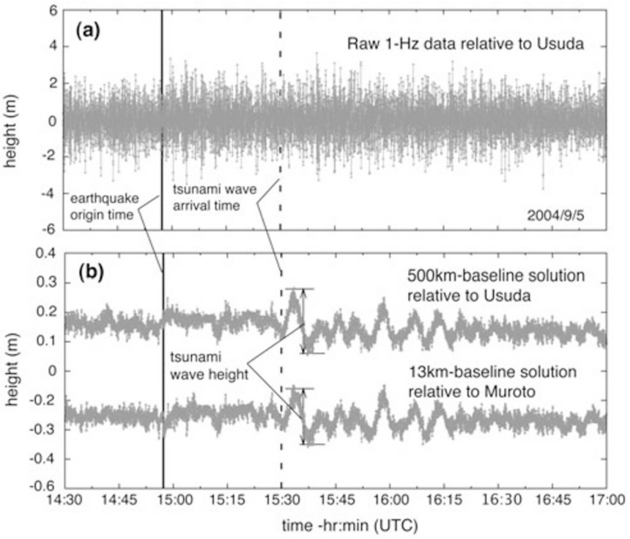

Fig. 2. Time series of GPS buoy heights recorded for the period of 14:30–17:00 h, September 5, 2004 (UTC). Solid and dash lines represent the 2004 Off Kii Peninsula earthquake origin time and arrival time of tsunami wave, respectively. (a) Original 1-Hz records of GPS buoy heights determined from the Usuda GPS station located 500 km away. (b) The resultant time series of GPS buoy heights. The first time series is the filtered record of the long baseline (Usuda) and the second time series is one for short baseline (Muroto).

Our long-baseline result agrees quit well, most of the time, with the short-baseline result between the Muroto and GPS buoy. It also resembles the result of Kato *et al.* (2005). Kato *et al.* (2005) already demonstrated that their GPS buoy result is consistent with the sea level change computed using a tsunami model. These results indicate that we can monitor GPS buoy motion with our long-baseline quasi-real time kinematic analysis. With this new analysis technique, we can reduce the restriction around the GPS buoy location and place buoys far offshore for early detection of tsunamis.

5. Stability and Consistency

In order to test the robustness of our GPS analysis method as well as to investigate the noise level under different weather conditions, we conducted a GPS tsunami buoy data analysis continuously for 192 h (8 consecutive days) to monitor the motion of the GPS buoy. We divided the original GPS data into 10-min segment, and processed each segment one after another just as in real-time processing. As is usual for September in Japan, several typhoons hit the target area in September 2004. During the 8-day period from September 4 to September 11, the first half was under typhoon conditions, while the weather became calm in the latter half.

We applied the same smoothing technique discussed above to the original time series and suppressed the high-frequency wind waves. Figure 3 shows the whole 8-day long-time series of GPS buoy motion during September 4–11.

Figure 3 clearly shows the consistency of the long-baseline kinematic GPS solution during both a major typhoon and under calm weather conditions. However, the amplitude of the fluctuation does change under different weather conditions. The RMS error for the typhoon period is 3.0–3.8 cm, while that for the calm period is 1.4–1.6 cm. The 2004 Off Kii Peninsula earthquake occurred under typhoon conditions, so we can barely identify the tsunami signal. In the filtered record, there are many trains of large-amplitude, long-period waves, marked by dashed squares, which do not correspond to any reported seismic activity or tsunami. Such fluctuations may be due to small-amplitude, long waves, also known as "*infragravity waves*", often caused by a major or distant storm (Rabinovich and Stephenson, 2004). Therefore, it is actually very difficult to automatically detect tsunami waves of 15 cm amplitude under typhoon weather. It should be noted that this difficulty has nothing to do with the GPS baseline length but originates from the behavior of the ocean. On the other hand, based on the statistics of the GPS results, we are quite sure that the present GPS analysis technique is precise enough to detect a tsunami wave with similar amplitude under a calm weather condition.

Also, we emphasize that a tsunami wave of 15 cm is not what the tsunami early warning system should be designed for. Actually, the 2004 Off Kii Peninsula earthquake

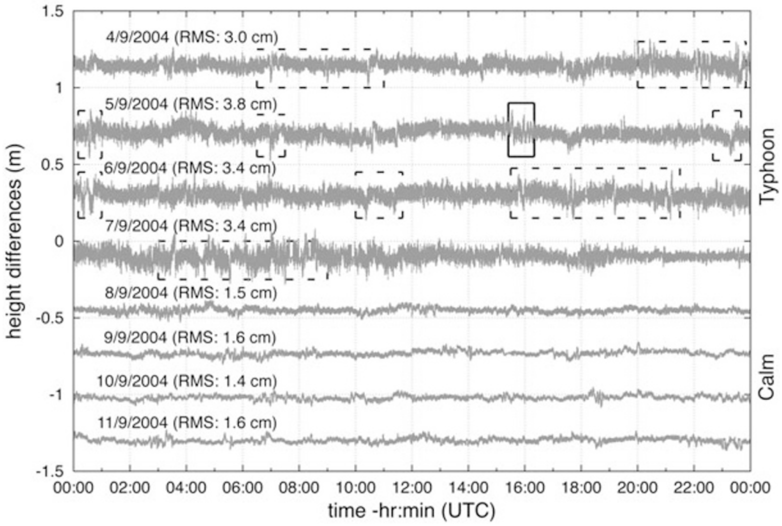

Fig. 3. The time series of GPS buoy heights determined from 500 km baseline length for the period of September 4–11, 2004. GPS buoy heights are filtered by the 150-s running mean through the period. Typhoon was close to Japanese Islands on September 4–7 and since then it was calm. The periods of tsunami and "*infragravity wave*" caused by a major typhoon are shown by solid and dash squares, respectively.

tsunami did not cause any severe damage along the coast. We can validate that our long-baseline GPS technique can detect tsunami waves over 30 cm in amplitude far offshore. For example, satellite altimetry observations revealed that the 2004 Sumatra-Andaman tsunami had a wave height of about 44 cm in the Indian Ocean (Gower, 2007). GPS buoys anchored more than 100 km offshore can resolve the arrival of such a tsunami wave, and we can make use of the information for evacuation, with plenty of time before the tsunami arrival on the coast.

6. Discussion and Conclusions

We have developed a quasi-real time kinematic GPS analysis strategy for a long baseline and have applied it to GPS buoy data. We have demonstrated that we can monitor the GPS buoy heights with a standard deviation of about 1.4–1.6 cm and 3.0–3.8 cm under both calm and typhoon weather conditions, after performing a running average with a boxcar window of 150 s. This accuracy is good enough to be applicable to a tsunami early warning system. Since our long-baseline kinematic GPS analysis is applicable to a long baseline up to 500 km, we can place a GPS buoy far offshore, which ensures an adequate evacuation time, even for people living on the coast.

Although our long-baseline analysis yielded virtually the same result as that of the previous study with a short (13 km) baseline, the signal of the 2004 Off Kii Peninsula earthquake tsunami was only barely visible in the continuous monitoring record of the sea level change because of the typhoon weather conditions, which made it difficult to detect the signal in an automated manner. However, since the tsunami was not damaging along the coast, it was not an actual target of an early tsunami warning system. The continuous record of the GPS buoy heights for 8 days clearly shows we can detect larger tsunamis with amplitudes of 20–30 cm with the current technology. Also, if the 2004 tsunami waves had come under calm weather conditions, it would have been clearly detected.

The amplitude of a tsunami wave is rather small in the deep ocean, but it drastically increases near the coast with decreasing water depth. There, with a specific sensitivity level, the applicability of the GPS buoy system with the long-baseline kinematic analysis heavily depends on the bathymetry. However, there are some places where this method will be very effective. For example, along the western coast of Thailand and Malaysian Peninsula, the continental shelf, with a water depth less than 200 m, extends no less than 100 km from the coast. In such a situation, we can expect a GPS buoy installed far offshore to work effectively for early tsunami detection.

To implement the long-baseline kinematic GPS method in the tsunami warning system, a real-time data transfer system from GPS buoy to an inland facility needs to be developed. In addition, a GPS buoy system is not the only device for the early detection of tsunami waves. Others systems, such as a good seismological network to determine the hypocenter location and earthquake magnitude very quickly, an ocean bottom pressure sensor network as another monitoring system, and an effective information transmission system to issue the warnings, must be properly integrated to make the early warning system effective and to save people's lives.

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