Strong ground motion recorded by high-rate sampling GPS at the closest site to the 2003 Tokachi-oki earthquake

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The Mw 8.1 earthquake occurred on September 25, 2003, off the southeast coast of Hokkaido, Japan. Since 2000 we have conducted high-rate sampling GPS measurements and precise gravity surveys in Erimo Peninsula, the closest site to the source region of the 2003 event. Strong ground motion recorded by GPS at the point of Erimo Peninsula, located just above the second asperity of the earthquake, shows two major pulses as large as about 56 cm on the EW component. Displacements obtained from the integration of accelerograms very close to our GPS site are consistent with each other, showing the absolute displacement field generated by the magnitude 8-class earthquake. Synthetic seismogram from a similar fault model by Yamanaka and Kikuchi (2003) would predict the amplitude of the second pulse to be about one half of that observed. Synthetic NS component from the GSI fault model (2003) is not consistent with our observations both on amplitude and polarity. The amplitude of ground motions detected by our GPS observation is more than one order larger than the noise level of the GPS survey, so this discrepancy is not due to insufficient GPS observation. We rather think that this suggests that our observations closest to the earthquake would give an insight into the detail of the source processes of the earthquake, which cannot be resolved from observations away from the source region. Static deformation at the point of Erimo Peninsula is consistent with the GSI fault model but not with the Yamanaka and Kikuchi model. The static analysis of our GPS measurement evidently describes the continuous post-seismic deformation as well as the co-seismic displacement in the source region until November.

Key words: Strong ground motion, high-rate sampling GPS, Tokachi-oki earthquake.

1. Introduction

Erimo Peninsula, Hokkaido, Japan contains the Hidaka mountain chain due to the collision between the Kurile and Northeast Japan Islands. The region is located over the subduction zone of the Pacific plate. The geophysical investigation in this region has the particular concern to elucidate the crustal deformation and seismic activity in such a complicated tectonic area with respect to the plate dynamics (Moriya *et al.*, 2001). The structure of this region has also been studied in relation to the seismicity derived from the highly-dense seismic array (Katsumata *et al.*, 2003).

The Geographical Survey Institute of Japan (GSI) has established a nationwide continuous GPS observation network, GEONET (Miyazaki and Hatanaka, 1998). Crustal deformation of Japan detected by GEONET has advanced the research and observation to the prediction of natural disasters in Japan. Co-seismic and post-seismic deformations have been also detected quantitatively, showing the peculiar time history of earthquake sources (Tsuji *et al.*, 1995; Heki *et al.*, 1997).

In addition to GEONET, we started GPS measurement in Erimo Penunsula in 1998. We have installed a high-rate sampling GPS receiver at the point of Erimo Peninsula in order to measure the kinematic and static behaviors of ground motions (Kaneso *et al.*, 2001). Other geophysical surveys have been conducted since 2000, including GPS campaign measurements and absolute/precise gravity surveys in and around Erimo Peninsula at least twice per year (Taira *et al.*, 2002). Our high-rate sampling GPS is to test the ability of GPS to retrieve information on crustal deformation in a frequency range from several Hz to permanent deformation without a limit to the dynamic range.

At about 19:50 (UT) on September 25, 2003, a Mw8.1 earthquake occurred off the southeast coast of Hokkaido and our survey area is very close to the source region. Since we made repeated surveys at the end of August, 2003, about four weeks before the earthquake, our own data set would provide the precursory, if any, co-seismic and post-seismic displacements accompanied by the earthquake. This is the first report to describe high-rate sampling GPS data in relation to the focal mechanism of the earthquake.

2. GPS Measurement at KAZE

High-rate sampling GPS measurement has been made since 1998 at the point of Erimo Peninsula, Kazenoyakata (station code KAZE). KAZE is the GPS station closest to the source region of the 2003 Tokachi-oki earthquake. The research project in this area also includes absolute gravity and precise gravity measurements (Taira *et al.*, 2001). Fig-

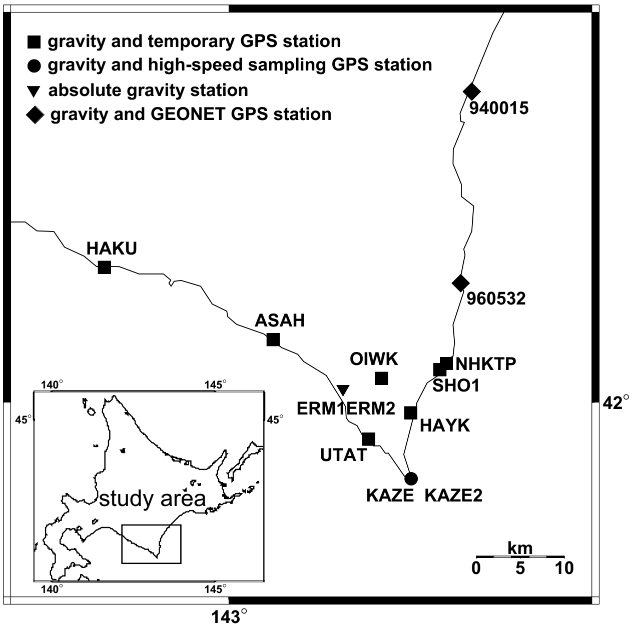

Fig. 1. Location of gravity and GPS stations in the vicinity of Erimo Peninsula. GPS Temporal surveys and precise gravity measurements have been repeated twice a year since 2000.

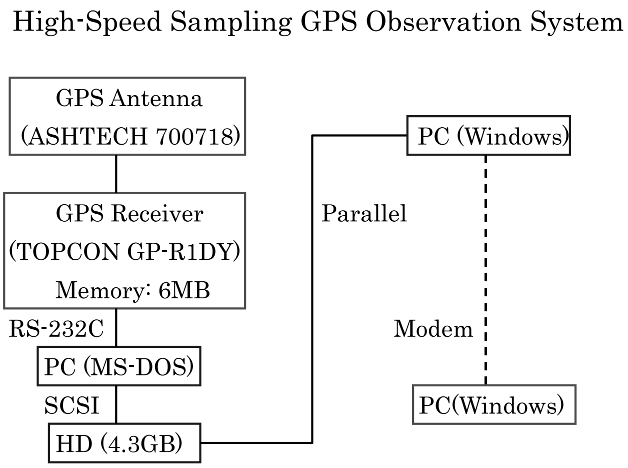

Fig. 2. Block diagram of the system for high-speed sampling GPS observation in Kazenoyakata (KAZE, Erimo Peninsula) using two personal computers with telephone-line telemetry.

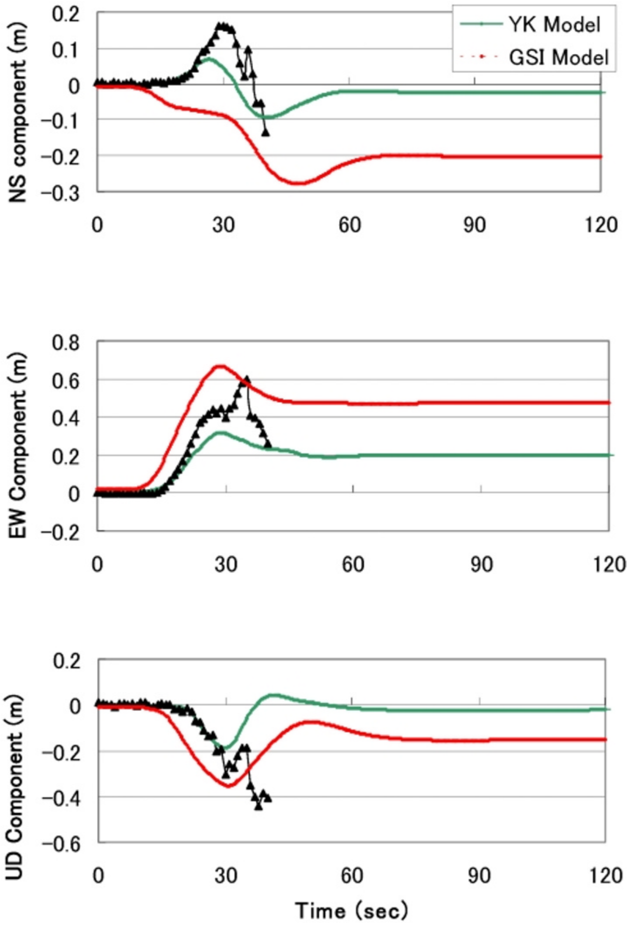

Fig. 3. Kinematic displacements retrieved from GPS pseudo-kinematic analysis at KAZE. The data terminated at 19:50 51″, September 25 due to a power failure. Synthetic seismograms are also plotted from simplified source models of Yamanaka and Kikuchi (2003; YK Model) and GSI (Geographical Survey Institute, Japan, 2003; GSI Model). Time axis starts from the origin time of the main shock at 19:50 7″. Time axes of GPS results are shifted 20 sec in advance to match the synthetics calculated from the simplified YK Model. This is due to an initial minor breakage in the main shock, which is not considered in the simplified model.

ure 1 shows the location of 13 observation sites on Erimo Peninsula. TOPCON GP-R1DY, LEGACY-H and LEICA 500 receivers powered by dry batteries were used in the campaigns, sampling GPS data every 30 sec for about 12 to 24 hours at each site. The high-rate, 1 sec interval at KAZE is our own development (Kaneso *et al.*, 2001). Figure 2 shows a block diagram of our GPS system installed at KAZE. The observation system consists of two PC's, hard disk (HD) and a modem. Since one epoch data of GPS is about 300 bytes, the 1-sec sampling data of one day is about 26 Mbytes. The receiver has a memory of 6 Mbytes and we divide one-day's observations into 10 sessions, each of 2.4 hours. The HD of 4.3 Gbytes can store backup data of about 4 months. The system is so designed that the data of a particular session can be collected through a telephone line via the attached modem. We describe the KAZE data in this report and the campaign result will be discussed elsewhere.

Bernese GPS Software Version 4.2 (Hugentobler *et al.*, 2001) and IGS (International GPS Service for Geodynamics) precise ephemeris were used for the static and pseudo-kinematic analyses. Tsukuba of the GSI is always used for the reference station on ITRF97 and the coordinates of Wakkanai of the GSI, Hokkaido and KAZE have been calculated. Figure 3 shows the pseudo-kinematic result projected on NS, EW and UD components. Two analyses were made: One was to calculate the deviation of the coordinates of NS, EW and UD components from those of the first epoch of 19:50.0, where the coordinates were determined with respect to Wakkanai. The other was to correct NS, EW and UD coordinates with respect to those by the same analysis on the previous day (267). The former analysis is better to correct for the ambient atmospheric effect on the kinematic result compared to the latter. In order to remove noises due to multipath effects on the kinematic analysis (Heki *et al.*, 1997), the latter analysis would be better. We did an ad-

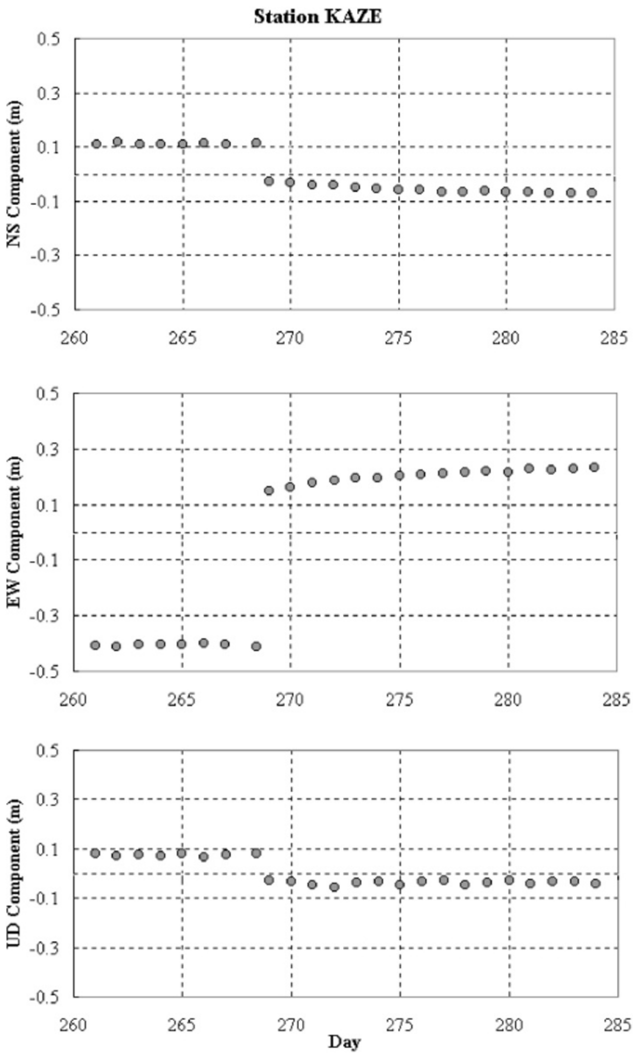

Fig. 4. Static displacements retrieved daily from 30 sec sampling data at KAZE by GPS static analysis. They represent the coordinate variations with respect to Tsukuba, GSI. Jumps on day 269 are co-seismic deformations by the 2003 Tokachi-oki earthquake and as much as 20% of the co-seismic deformation was observed in the following days as post-seismic deformation.

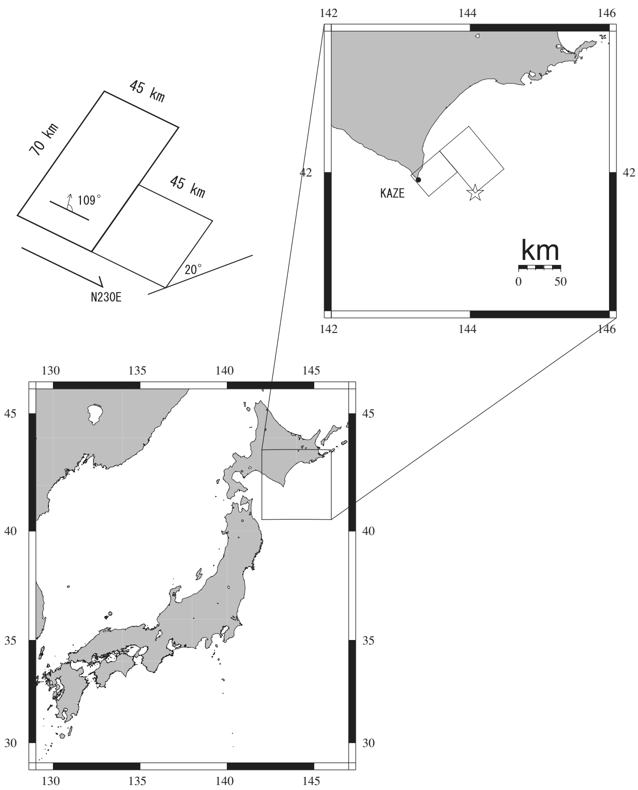

Fig. 5. Fault model to calculate the synthetic seismograms. The model is simplified from the original Yamanaka and Kikuchi (2003) so as to enhance the seismic waves from the first and second asperities.

ditional analysis to crosscheck the pseudo- kinematic result by comparing the relative positioning of KAZE with respect to Wakkanai. Since we find no significant differences (less than 5 mm) from the above two analyses, the first result is presented in Fig. 3. The high-rate samping GPS observation terminated at 19:50 51″ due to a power failure caused by the strong ground motions and came back again after 2 hours. Unfortunately, the largest aftershock at 21:08, September 25 was not recorded because of this power failure.

Figure 4 shows the daily variation of KAZE coordinates with respect to Tsukuba from day 261 to 284. Coordinates on day 268 were calculated from the data before the earthquake, while the others used 24-hour data. Co-seismic displacements of about 14, 56 and 11 cm on NS, EW and UD components, respectively were observed. Since day 269 a post-seismic deformation has been clearly observed. The amount of post-seismic deformation at KAZE is about 5, 8 and 2 cm on NS, EW and UD components, in about three weeks. Since the observation is closest to the source region of the earthquake, this data will also give an insight into the temporal variation of the total seismic moment released by the earthquake.

3. Seismic Source of the Tokachi-oki Earthquake

Although KAZE GPS observation is single station data, it gives information on the seismic source process of the Tokachi-oki earthquake. Yamanaka and Kikuchi (2003) proposed the faulting mechanism (YK Model) of the earthquake from the inversion analysis of world broadband seismic records. A fault model in Fig. 5, which is simplified from the YK Model, is used to calculate synthetic seismograms by the discrete wavenumber method in an infinite frequency band (Honda and Yomogida, 2003). Kinematic and static displacements calculated from the model are plotted in Fig. 3, marked by YK Model. The first (larger) asperity is characterized by the dislocation of 5 m and by its rupture velocity of 2.8 km/s, while the second (smaller) one is of 4 m and 3 km/s broken up after 13 seconds. Rise times of both asperities are assumed to be 10 sec. Other parameters such as strike and dip of the fault plane and rake of the slip as well as the origin time of 04:50 7.6″ are the same as those of the YK Model. Since we have assumed the dislocation on the fault, the seismic moment of the simplified model is about 1.3×10^{21} Nm. The value falls between 1.0×10^{21} by the YK Model and 1.6×10^{21} Nm by the USGS (2003).

Time axes of observations are shifted about 20 seconds in advance to match the synthetics in Fig. 3. We compare the integrated accelerograms at HKD112 with KAZE displacements in Fig. 6. HKD112 is a K-net station (National Re-

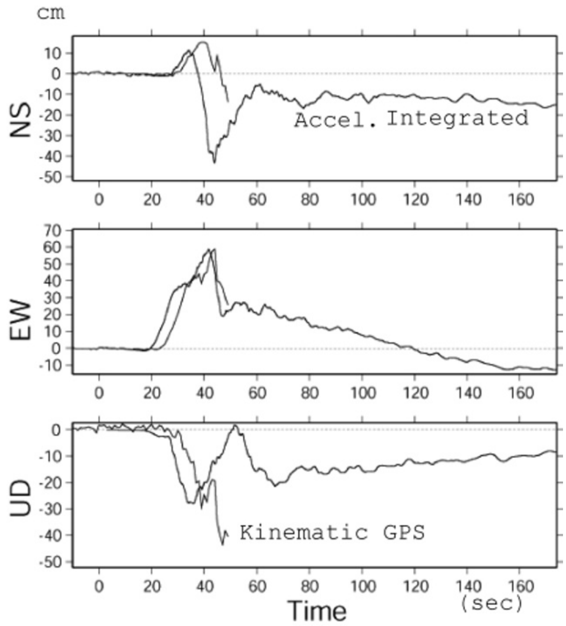

Fig. 6. Kinematic displacements retrieved from GPS observation at KAZE and accelerograms at HKD112 (K-net station, National Research Institute, for Earth Science and Disaster Prevention, Japan) integrated twice numerically. HKD112 is about 1.5 km from KAZE and is located on similar site conditions to those at KAZE. Time axis starts from 19:50 11″.

search Institute for Earth Science and Disaster Prevention, Japan), which is about 1.5 km away from our KAZE site. They are in good agreement with each other. This proves the validity of GPS and acceleration observations for great earthquakes and shows the absolute displacement field generated by the magnitude 8-class earthquake. This also indicates that the time correction in the above is not due to the GPS timing error. Although the synthetics start from the origin time of the earthquake due to the assumption of the dislocation on the fault, the large-amplitude strong ground motion comes from the asperity where the large seismic moment is released. Therefore, this time difference is partly due to the disadvantage of our forward modeling to calculate the synthetic seismograms and not due to the error in GPS observation. Inversion by the YK Model reveals the above time difference quantitatively, where there were several seconds at first with little seismic moment release and another several seconds with a very little moment release. The large seismic moment release of the main shock by the YK Model is about 15 sec from the origin time.

Strong ground motion at KAZE generated by the 2003 Tokachi-oki earthquake is characterized by two strong pulses. The amplitude on the EW component is as large as 58 cm and is about 16 cm on the NS component. The amplitudes are one order of magnitude larger than the stationary noise level we have previously observed at KAZE (Kaneso *et al*., 2001). Although there have been large-amplitude spiky noises observed at KAZE, their patterns are not like the waveforms in Fig. 3. The significance of strong ground motion observed at KAZE over the noise level can also be confirmed by the two different analysis methods mentioned previously to retrieve the kinematic displacements.

The simplified YK Model predicts two pulses coming from two major asperities. The synthetic amplitude of the first pulse is consistent with the observation, the amplitude of the second pulse is less than one half compared to the observation. The first asperity of the simplified YK Model is far from all the stations, while KAZE is very close to the second asperity. The difference in amplitudes between observed and synthetic would result from the reason that the observation at KAZE recorded every detail of the source processes, which cannot be reflected on far-field / rather long-period observations.

Synthetic seismograms from the GSI Model (2003) which has been derived from the co-seismic deformations derived from GPS observations in Hokkaido, Japan, are also plotted in Fig. 3 marked by GSI Model. The model being composed of a single fault, only a single pulse is generated from the model. Since KAZE is located just above the western half of the fault plane (second asperity), the observed displacements are very sensitive to the fault geometry close to the site. In this analysis, the NS component of the synthetic ground motion did not agree with the observation not only in amplitude but in polarity. This suggests that the fault plane of the 2003 Tokachi-oki earthquake is not so simple as the single fault plane derived from the static deformation in the vicinity of the earthquake by GSI.

4. Discussion

Our analysis of GPS in this study is restricted to the KAZE data. Nevertheless, we find a lot on the 2003 Tokachi-oki earthquake. The time difference of about 20 sec in Fig. 3 is understood to be partly due to our simplified parameters on the faulting process to calculate the synthetic seismograms and not the timing error of the GPS. It is common in nature that there is an initial minor breakage with some build-up time necessary to grow into a large failure, especially for great, shallow earthquakes (Koyama, 1997). The simplification of the faulting model would not generate such an initial minor breakage and the actual faulting process of the 2003 Tokachi-oki earthquake has been characterized by a small amount of seismic moment in the first 15 to 20 seconds, as the YK Model predicted. This also suggests that the simplified fault would also be responsible to some extent for the deficiency in the synthetic amplitude. It is possible to assume much more seismic moment release of the second asperity than that in this analysis, while the net seismic moment is the same. There is also a GPS station deployed by the GSI in Erimo, which is about 10 km away from KAZE station. The 1-sec sampling records retrieved from Erimo of the GSI show two pulses, but they are not so clear as at KAZE. Since KAZE observation is the closest to the source region, the data is essential to constrain the detail faulting process of the 2003 Tokachi-oki earthquake, not only on its geometry but also displacement distribution.

The data also indicates a static horizontal displacement in KAZE as large as 58 cm (Fig. 4). The value is a little smaller than the displacements obtained at the GSI stations nearby. Erimo and Erimo2 of the GSI registered horizontal displacements of 60 and 87 cm, respectively. This is partly because KAZE station is fixed to bed rock along the Hidaka mountain chain, Hokkaido, while Erimo is anchored in park ground in Erimo town and Erimo2 is located on the bank of the Saruru River, very close to the shore line. Kinematic and static time histories of KAZE displacements are not completely consistent with the kinematic YK Model nor the static GSI Model, suggesting the complexity of the source process of the 2003 Tokachi-oki earthquake.

Post-seismic deformation observed at KAZE is evident, as much as 20% co-seismic deformation in just three weeks after the main shock. The deformation is still continuing on the GSI and our GPS observations. Since this large amount of post-seismic deformation occurring continuously with the co-seismic slip is peculiar, and none of the theories has described such a slip history on the fault of a magnitude 8 earthquake.

At first we were conscious that 1-sec sampling GPS data must be heavily contaminated by the aliasing effect due to high-frequency seismic waves. In our observations, displacements retrieved from accelerations at HKD112 and Erimo of GSI, all suggest that the effect is small and negligible. This would be partly because the source spectrum of this size of earthquake has, in general, a spectral intensity of about 50 sec, which is 100 times larger than that of about 1 sec (Koyama, 1997).

5. Summary

This is the first time that GPS observation provides data on strong ground motion generated by magnitude 8 earthquake in a very short distance. The remarkable consistency between GPS displacements and integrated accelerograms is another type of evidence that describes the accelerations and displacements of strong ground motion and shows the absolute displacement field generated by a large earthquake. We point out that there is a gap that still remains to be explained, the large amplitude strong ground motion and static deformation in such a short distance by a faulting model of the 2003 Tokachi-oki earthquake. The observations require further analysis using only the data in the near field to elucidate the detailed source process of the earthquake, since the source inversions so far estimated are based on rather long-period and far-field data. In addition, it should be noted that a simultaneous observation with GPS and strong motion acceleration is important to retrieve the high-frequency source process in relation to the general sketch of the earthquake source from standard analyses.

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