Coseismic and postseismic crustal deformation after the M_w 8 Tokachi-oki earthquake in Japan

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(Received February 9, 2004; Revised June 11, 2004; Accepted June 11, 2004)

The permanent Global Positioning System (GPS) array in Japan detected coseismic and postseimic deformation of the 2003 Tokachi-oki earthquake (M_w 8). We estimate the time evolution of its postseismic slip, together with its coseismic slip distribution. The result shows that the postseismic slip has been occurring mainly in an area adjacent to the coseismic slips, propagating to the northeast and southwest. This suggests that, as of March 6, 2004, the postseismic slip of the strongly coupled area neighboring the coseismic rupture partly released seismic moment, equivalent to an earthquake of M_w 7.8.

Key words: Tokachi-oki earthquake, coseismic deformation, afterslip, postseismic deformation.

1. Introduction

The Pacific Plate is subducting westward beneath the North American or Okhotsk Plate at a rate of 10 cm/year at the Kurile Trench southeast of Hokkaido, Japan (Fig. 1). This area has been repeatedly struck by large offshore thrust earthquakes (Fig. 1(b)). The segment off the Tokachi area ruptured in the 1952 M_w 8.2 earthquake, and the probability of the next earthquake within a 30 years period from 2003 has been estimated to be ∼60% (Earthquake Research Committee, 2004). An earthquake of M_w 8 occurred on September 26, 2003 (local time) with the ruptured area similar to the 1952 event. The strike, dip, and rake angles of the coseismic rupture are inferred to be 230°, 20°, and 109°, respectively, indicating that this was a typical interplate thrust earthquake (Yamanaka and Kikuchi, 2003). At GPS stations near the epicenter, postseismic displacement had exceeded 10 cm by March 6, 2004, following the coseismic displacement up to ∼1 m. It is important to investigate where and how the postseismic slip has been occurring, because it provides information on the stress change over time and frictional characteristics of the plate interface (e.g., Heki *et al.*, 1997; Nishimura *et al.*, 2000; Yagi *et al.*, 2001). In this study, we investigate the coseismic slip distribution and compare it with the spatiotemporal evolution of the afterslip obtained using the time-dependent inversion method (Segall and Matthews, 1997).

2. Data and Analytical Procedure

The dense GPS array (GPS Earth Observation Network; GEONET), with dual-frequency P-code receivers, of the Geographical Survey Institute of Japan (GSI) has been in operation since 1994. GPS data are analyzed using the Bernese GPS software version 4.2 with precise ephemerides and Earth orientation parameters from the International GPS service for Geodynamics (IGS). Tropospheric delays are estimated at each station every three hours (Hatanaka, 2003).

Since the raw data include periodic (largely annual) and secular components, we estimated them using the data between 1999 and 2002 and removed them as described in Ozawa *et al.* (2004). Figure 1(b) shows the velocities during the period 1999–2002 relative to 950241 (Fig. 1(a)). Coseismic crustal movements were estimated as offsets in the de-trended coordinate time series.

Figure 2(a) shows the coseismic displacements relative to 950241 (Fig. 1). Southeastward horizontal motion up to ∼1 m and subsidence up to ∼20 cm are observed near the epicenter. Postseismic movements seem to have started immediately after the earthquake (Fig. 3). Postseismic movements, which are also relative to 950241, are larger in the areas surrounding the epicenter rather than in the epicentral region (Fig. 3), suggesting that afterslip occurred mainly in the fault area surrounding the coseismic rupture. Figure 4 shows postseismic vertical movements of GPS sites relative to 950241 in the period from September 26, 2003 to March 6, 2004. The Pacific coastal area shows uplift of up to 3 cm. Considering a systematic spatial pattern of uplifting in this region, we think the observed upheaval reflects true crustal deformation, though such a small uplift might be within the range of vertical observation uncertainties of GPS. This may suggest the occurrence of postseismic slip in a deeper part of the plate interface. Figure 5 shows the de-trended time series at selected GPS sites shown in Fig. 3(a) after the removal of coseismic offsets. GPS sites show postseismic movements that decay with time.

Using the coseismic deformation data, we estimated the coseismic slip distribution following the method of Ozawa *et al.* (2001) based on Yabuki and Matsu'ura (1992). We used the plate interface configuration given in Katsumata *et al.* (2003) (Fig. 1(b)). By representing the fault slip as a superposition of B-spline functions on the plate boundary, we estimated the optimal slip distribution by balancing the good-

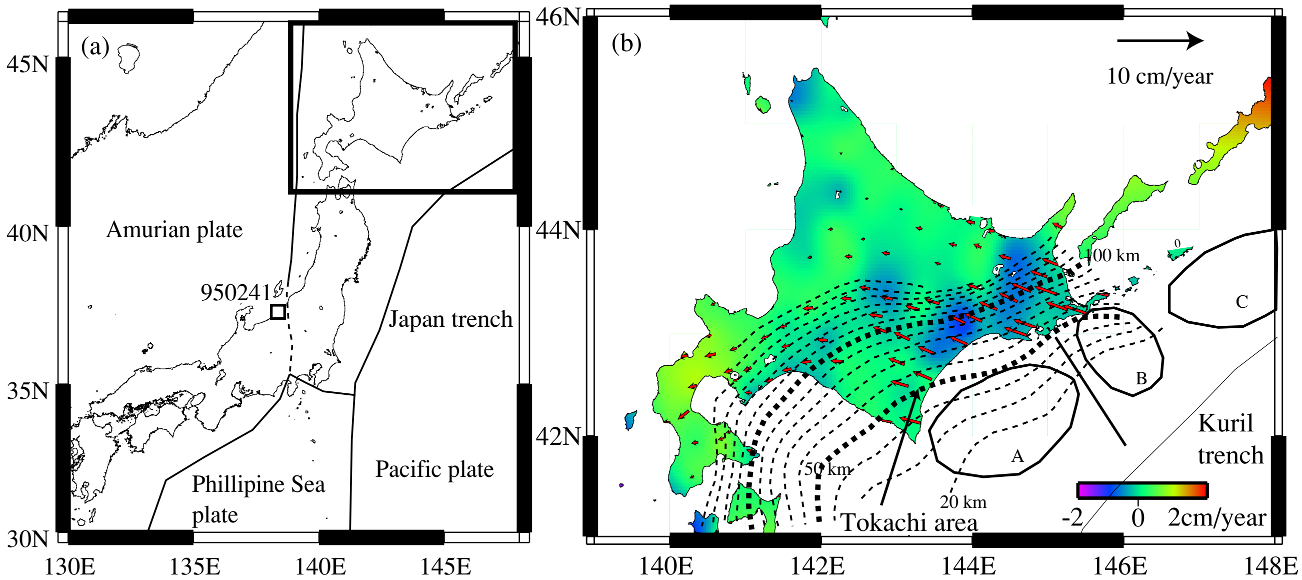

Fig. 1. (a) Tectonic setting of Hokkaido, Japan. Open square shows the location of 950241 which is used as a reference point for ground motion. (b) Enlarged map of the rectangular area in (a). Large offshore earthquakes have repeatedly occurred off the east coast of Hokkaido. A: 1952 Tokachi-oki earthquake (M_w 8.2), B: 1973 Nemuro-hanto-oki earthquake (M_w 7.8), C: 1969 Chishima earthquake (M_w 8.2). Segmentation along the trench axis is approximately shown by solid lines. Red arrows show interseismic horizontal displacements while color represents vertical motion relative to 950241 (1999–2002) in cm/year. Broken lines show isodepth contours of the plate boundary between the subducting and the overriding plates (Katsumata *et al.*, 2003). Isodepth contour interval is 10 km.

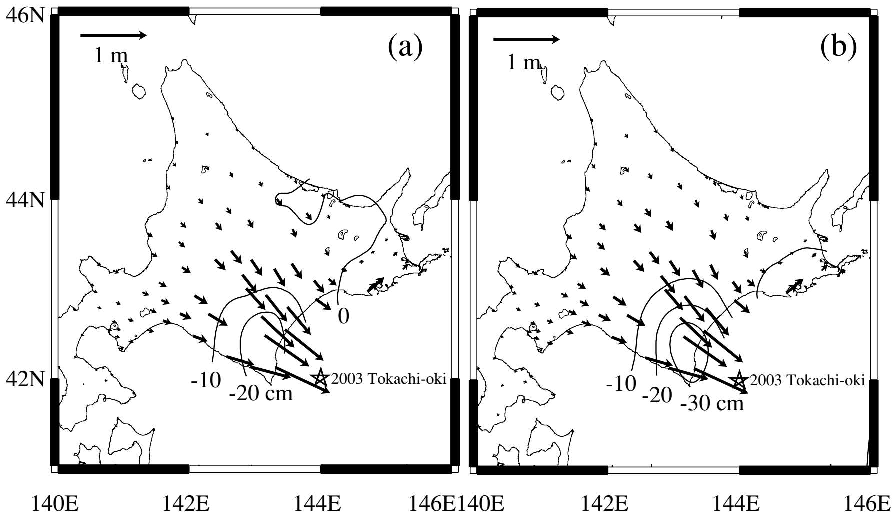

Fig. 2. (a) Observed coseismic deformation from the 2003 Tokachi-oki earthquake relative to 950241. Contours show vertical coseismic motion with an interval of 10 cm with relative to 950241. Star shows the epicenter of the 2003 Tokachi-oki earthquake as identified by the Meteorological Agency of Japan. (b) crustal deformation calculated using the model in Fig. 6(a).

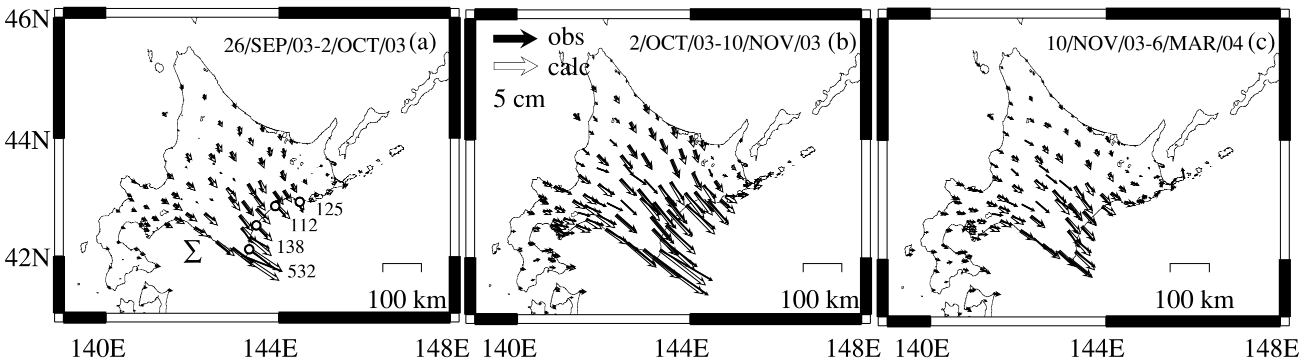

Fig. 3. Observed postseismic deformation relative to 950241. Open circles show the location of the selected GPS sites whose time series are shown in Fig. 5. (a) September 26–October 2, 2003. (b) October 2–November 10, 2003 (c) November 10, 2003–March 6, 2004. Solid arrows show observations, while white arrows represent values calculated using the model in Figs. 6(b)–(d).

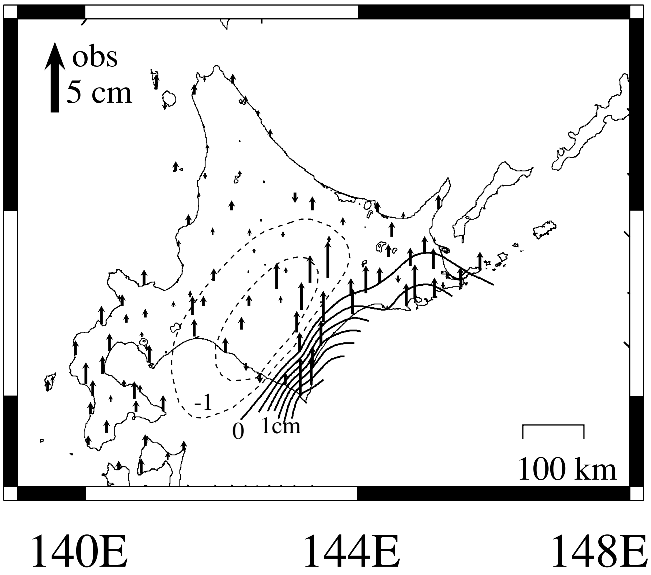

Fig. 4. Observed postseismic vertical deformation for the period between September 26, 2003 and March 6, 2004 relative to 950241. Solid arrows show observations, while contours show values calculated using the model in Figs. 6(b)–(d). Broken-line contour indicates subsidence, whereas solid-line contour shows uplift.

ness of fit to the data and the smoothness of fault distribution based on the Akaike's Bayesian Information Criteria (ABIC) (Akaike, 1974; Yabuki and Matsu'ura, 1992). We imposed non-negative constraints of the slip components assuming eastward and southward slips positive. Green's functions of surface deformation are taken from Yabuki and Matsu'ura (1992). We used east-west (EW), north-south (NS), and up-down (UD) components at the 85 GPS sites shown in Fig. 2(a).

After estimating the coseismic slip distribution, we applied square-root information filtering (see Appendix) based on the time-dependent inversion technique for the time series in Fig. 5 for the period between September 4, 2003 and March 6, 2004. In this inversion analysis, we set the constraint that aseismic fault motion is eastward and southward, as was the case for the coseismic slip estimate, using the hard constraint method of Simon and Simon (2003). Figure 3 shows the GPS sites used in the filtering analyses.

3. Results and Discussion

The estimated coseismic slips are mainly located off the coast of the Tokachi area, Hokkaido, with the epicenter determined by the Meteorological Agency of Japan (JMA) at its eastern edge (Fig. 6(a)). Our model reproduces the observed crustal movements well (Fig. 2(b)), and is consistent with past reports of coseismic slip distributions fronm seismological (e.g., Yamanaka and Kikuchi, 2003; Yagi, 2004; Honda *et al.*, 2004; Kamae and Kawabe, 2004; Koketsu *et al.*, 2004) and tsunami waveform (Tanioka *et al.*, 2004) studies.

With regard to afterslip distribution, the slip mainly occurs in an area adjacent to the coseismic slip region over the entire time interval (Figures 6(b)–(d)). From September 26 to October 2, the afterslip is distributed surrounding the coseismic slips (Fig. 6(b)). The afterslip expanded toward the northeast

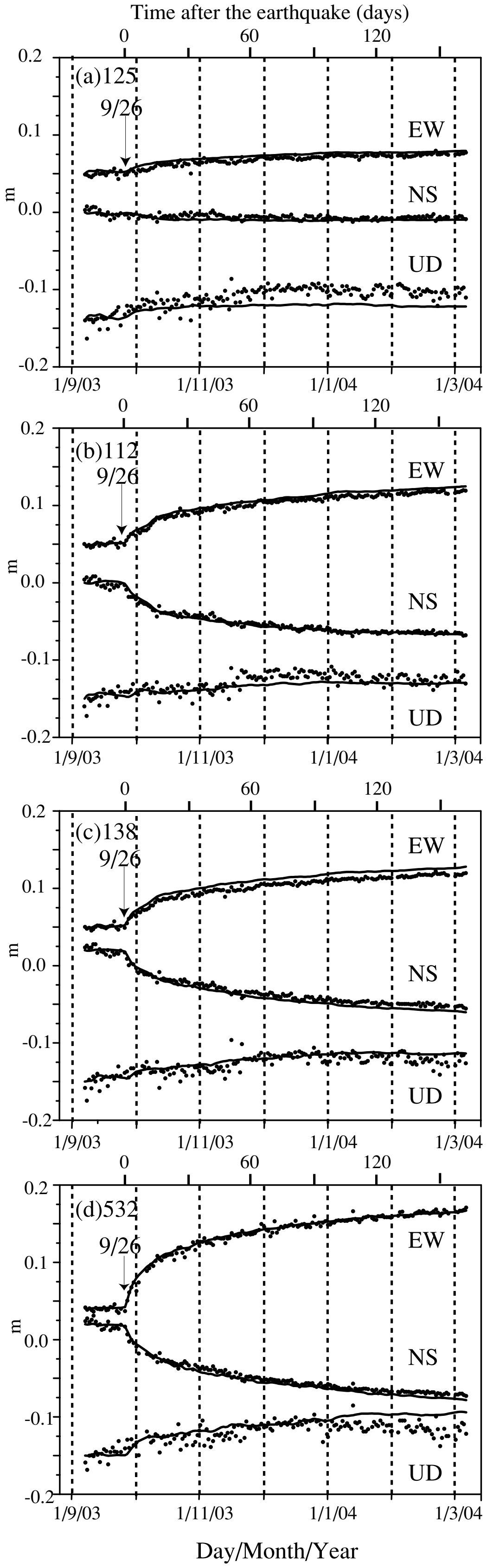

Fig. 5. De-trended time series at the selected GPS sites in Fig. 3(a) without coseismic jumps of the 2003 Tokachi-oki earthquake, relative to 950241. EW, NS, and UD represent east-west, north-south and up-down components with east, north, and up being positive. Solid lines indicate values calculated using the estimated model in Figs. 6(b)–(d). Labels 0–120 indicate number of days from September 26, 2003. (a) 125, (b) 112, (c) 138, (d) 532.

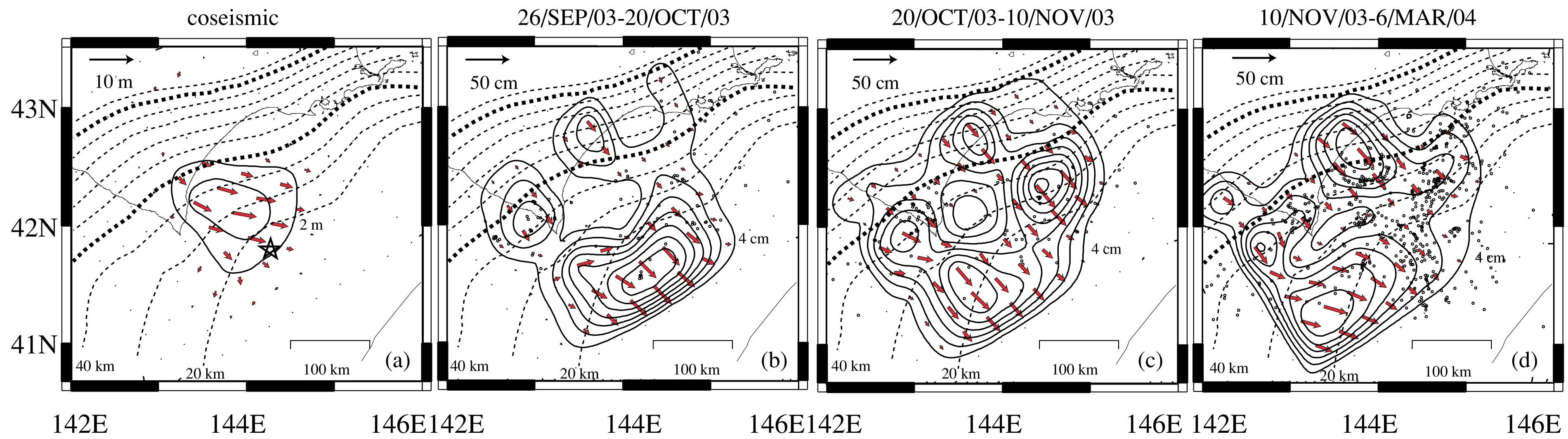

Fig. 6. Estimated coseismic and postseismic slip distributions. Open circles represent aftershocks (Data from the Meteorological Agency of Japan). Broken lines represent isodepth contours of the plate boundary with 10 km intervals. (a) Coseismic slip distribution. The star represents the epicenter of the 2003 Tokachi-oki earthquake as identified by the Meteorological Agency of Japan. Contour interval is 2 m. (b) Postseismic slip for the period September 26–October 2, 2003. Contour interval is 4 cm. (c) Postseismic slip for the period October 2–November 10, 2003. Contour interval is 4 cm. (d) Postseismic slip for the period November 10, 2003–March 6, 2004. Contour interval is 4 cm.

and southwest in the period between October 2 and November 10 (Fig. 6(c)). After November 10, a part of it seems to have come back to the coseismic slip areas (Fig. 6(d)). Such a temporal evolution of the afterslip is consistent with the distribution of aftershocks that mainly occurred in a peripheral area of the coseismic slip region (Shinohara *et al.*, 2004; Ito *et al.*, 2004). In particular, the northeastward propagation of the aftershock distribution is in good agreement with the afterslip migration in Fig. 6(c). In accordance with the decay of aftershocks over time, the moment release rate of the afterslip decreases from September 26, 2003 to March 6, 2004. Figures 3, 4, and 5 show that the observed and modeled crustal movements are highly consistent. The present result supports past works (e.g., Yagi and Kikuchi, 2003) that afterslip and coseismic slip distributions are complementary.

In our study, aseismic slip is suggested to have extended to a relatively deep part of the plate boundary. This suggests that the coupling area in Hokkaido extends deeper (∼70 km) than the down-dip end of the slip deficit (30∼50 km) suggested in past studies (e.g., Ito *et al.*, 2000; Mazzotti *et al.*, 2000). In fact, Murakami and Ozawa (in preparation) proposed a coupling model, where slip deficits extend to a deeper portion of the Hokkaido area slab (∼100 km), based on GPS data. According to their result, the slip deficits beneath the Cape Erimo and the Tokachi area are estimated to be around 4 cm/year. This implies that the cumulative slip deficit amounts up to ∼2 m for the period 1952–2003. The present study shows afterslip of 40∼60 cm, much less than 2 m, in these areas. This imbalance is also seen in a fact that postseismic uplift of 3 cm cannot compensate for the cumulative interseismic subsidence (Fig. 1(b)) and the coseismic subsidence in the Tokachi/Erimo area (Fig. 2(a)). However, since the postseismic movements still go on and there exist uncertainties of ∼2 cm/year in the slip deficit rate in these areas, we cannot rule out the possibility that the current afterslip may eventually release the energy accumulated over the interseismic period. It would be at least reasonable to say that the part deeper than the presently believed seismogenic depth had accumulated strain before the 2003 earthquake, because this earthquake is now releasing the strain. From this viewpoint, the present results suggest that interplate coupling occurs deep beneath the Cape Erimo and the Tokachi region, though the quantitative comparison of the slip deficit and the entire afterslip requires further studies.

Although the northeastern part of the coseismic slip area is thought to be coupled strongly during an interseismic period, it remained intact over the coseismic period of the 2003 Tokachi-oki earthquake. Consequently, the northeastern part of section A in Fig. 1(b) requires some mechanism to release strain energy, part of which is now being compensated by afterslip of the 2003 earthquake. Since energy equivalent to that of the main shock is often released by postseismic slip in interplate thrust earthquakes (e.g., Heki *et al.*, 1997; Nishimura *et al.*, 2000), this area may release enough strain energy by the on-going afterslip, i.e this section may not rupture as an ordinary earthquake. At present, the moment magnitude of the postseismic slip of the 2003 Tokachi-oki earthquake is around 7.8. Since the moment release rate is becoming roughly constant as of March 2004, it will probably take more time for postseismic slip to come to an end, and this will enable us to grasp overall understanding of the 2003 Tokachi-oki earthquake and its postseismic behavior.

Acknowledgments. We used focal mechanism solutions published by the Meteorological Agency of Japan on its web site. We are grateful to Dr. Munekae of the GSI for helpful discussion.

Appendix.

We used square-root information filter (Bierman, 1977) instead of ordinary Kalman filtering scheme, incorporating spatial smoothing equations that are shown later and slightly different from those in Ozawa *et al.* (2004) in a transition equation. We adopt the following state vector

$$x_{n|n} = (u, v, p_1, p_2, \ldots, p_L), \tag{A.1}$$

where u, v, and p_i represent fault slip, slip velocity, and a random walk of GPS site with station number of i, respectively. In this representation, GPS site is assumed to move as Brownian over time. We modify the transition equation in square-root information filtering by adding spatial smoothing equations that are in the third and fourth rows of the following description:

$$\begin{bmatrix} W^{-1} & 0 & 0 \\ -R_1^{-1}F^{-1} & 0 & R_1^{-1}F^{-1} \\ 0 & -R_2^{-1} & R_2^{-1}MJ \\ 0 & \frac{\alpha}{t}I & 0 \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ x_{n+1|n} \end{bmatrix} = \begin{bmatrix} 0 \\ R_1^{-1}x_{n|n} \\ R_2^{-1}MJx_{n|n} \\ 0 \end{bmatrix}, \tag{A.2}$$

where ω_1, ω_2, $x_{n+1|n}$, and $x_{n|n}$, represent system noise of an ordinary transition equation in time, system noise of spatial smoothing, the one-step-ahead predicted state, and a state at time n. M, J, and F represent the smoothing matrix in space, the matrix used to select the slip component from a state, and the transition matrix in an ordinary transition equation, respectively. The variables t, α, and I represent the lapse time between step n and step $n+1$, the smoothing parameter in space, and the identity matrix, respectively. W^{-1} is the upper triangular matrix with WW^T equaling the covariance of system noise in time, where the superscript T means a transpose matrix. R_1^{-1} is the upper triangular matrix with $R_1R_1^T$ equaling $V_{n|n}$ which is the covariance of $x_{n|n}$. R_2^{-1} is a matrix with $MJV_{n|n}JM^T = R_2R_2^T$ with only diagonal components. Fixed interval smoothing is described by Ozawa *et al.* (2004). In this research, we adopted Simon and Simon's method of hard constraints (2003) to incorporate inequality constraints. We use the conventional formula of the log likelihood of Kalman filtering without adding terms related to the initial state, as discussed by Ozawa *et al.* (2004). Computation of the log likelihood under inequality constraints is described by Ozawa *et al.* (2004).

References

Akaike, H., A new look at the statistical model identification, *IEEE, Trans. Auto. Control,* **AC-19**, 716–723, 1974.

Bierman, G. J., *Factorization methods for discrete sequential estimation,* Academic Press, New York, 1977.

Earthquake Research Committee, Long term evaluation of the seismic activity along the Chishima trench, Rep. Earthquake Res. Committee, 2004 (in press).

Hatanaka, Y., Improvement of the analysis strategy of GEONET, *Bull. Geograph. Survey Inst.*, **49**, 11–37, 2003.

Heki, K., S. Miyazaki, and H. Tsuji, Silent fault slip following an interplate thrust earthquake at the Japan Trench, *Nature,* **386**, 595–598, 1997.

Honda, R. *et al.*, Ground motion and rupture process of the 2003 Tokachi-oki earthquake obtained from strong motion data of K-NET and KiK-net, *Earth Planets Space,* **56**, 317–322, 2004.

Ito, T., S. Yoshioka, and S. Miyazaki, Interplate coupling in northeast Japan deduced from inversion analysis of GPS data, *Earth Planet. Sci. Lett.*, **176**, 117–130, 2000.

Ito, Y. *et al.*, Spatial distribution of moment tensor solutions of the 2003 Tokachi-oki earthquake (MJMA=8.0) and aftershocks, *Earth Planets Space,* **56**, 301–306, 2004.

Kamae, K. and H. Kawabe, Source model composed of asperities for the 2003 Tokachi-oki, Japan, earthquake (MJMA=8.0) estimated by the empirical Green's function method, *Earth Planets Space,* **56**, 323–327, 2004.

Katsumata, K., N. Wada, and M. Kasahara, Newly imaged shape of the deep seismic zone within the subducting Pacific plate beneath the Hokkaido corner, Japan-Kurile arc-arc junction, *J. Geophys. Res.*, **108**, 2565, doi:10.1029/2002JB002175, 2003.

Koketsu, K., K. Hikima, S. Miyazaki, and S. Ide, Joint inversion of strong motion and geodetic data for the source process of the 2003 Tokachi-oki, Hokkaido, earthquake, *Earth Planets Space,* **56**, 329–334, 2004.

Mazzotti, S., X. L. Pichon, H. Pierre, and S. Miyazaki, Full interseismic locking of the Nankai and Japan-west Kuril subduction zones: an analysis of uniform elastic strain accumulation in Japan constrained by permanent GPS, *J. Geophys. Res.*, **105**, 13159–13177, 2000.

Nishimura *et al.*, Distribution of seismic coupling on the subducting plate boundary, in northeastern Japan inferred from GPS observations, *Tectonophysics,* **323**, 218–238, 2000.

Ozawa, S., M. Murakami, and T. Tada, Time-dependent inversion analysis of the slow thrust event in the Nankai trough subduction zone, southwestern Japan, *J. Geophys. Res.*, **106**, 787–802, 2001.

Ozawa, S., S. Miyazaki, T. Nishimura, M. Murakami, M. Kaidzu, T. Imakiire, and X. Ji, Creep, dike intrusion and magma chamber deflation model for the 2000 Miyake eruption and the Izu islands earthquakes, *J. Geophys. Res.*, 2004 (in press).

Segall, P. and M. Matthews, Time dependent inversion of geodetic data, *J. Geophys. Res.*, **102**, 22391–22409, 1997.

Shinohara, M. *et al.*, Aftershock observation of the 2003 Tokachi-oki earthquake by using dense ocean bottom seismometer network, *Earth Planets Space,* **56**, 295–300, 2004.

Simon, D. and D. L. Simon, Aircraft turbofan engine health estimation using constrained Kalman filtering, ASME Turbo Expo 2003, Atlanta, GA, paper GT2003–38584, 2003.

Tanioka, Y., K. Hirata, R. Hino, and T. Kanazawa, Slip distribution of the 2003 Tokachi-oki earthquake estimated from tsunami waveform inversion, *Earth Planets Space,* **56**, 373–376, 2004.

Yabuki, T. and M. Matsu'ura, Geodetic data inversion using Bayesian information criteria for spatial distribution of fault slip, *Geophys. J. Int.*, **109**, 363–375, 1992.

Yagi, Y., Source rupture process of the 2003 Tokachi-oki earthquake determined by joint inversion of teleseismic body wave and strong ground motion data, *Earth Planets Space,* **56**, 311–316, 2004.

Yagi, Y. and M. Kikuchi, Partitioning between seismogenic and aseismic slip as highlighted from slow slip events in Hyuga-nada, Japan, *Geophys. Res. Lett.*, **30**, 1087, doi:10.1029/2002GL015665, 2003.

Yagi, Y., M. Kikuchi, and T. Sagiya, Co-seismic slip, post-seismic slip, and aftershocks associated with two large earthquakes in 1996 Hyuga-nada, Japan, *Earth Planets Space,* **53**, 793–803, 2001.

Yamanaka, Y. and M. Kikuchi, EIC SEISMOLOGICAL NOTE: No. 139, 2003.

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