Real-Time GNSS Positioning System REGARD for Rapid Earthquake Moment Estimates

Satoshi KAWAMOTO, Basara MIYAHARA, Yohei HIYAMA, Yudai SATO, Tomoaki FURUYA, Yusaku OHTA, Takuya NISHIMURA, and Masaru TODORIKI, Japan

Key words: Earthquake early warning, GNSS, GPS, Real-time kinematic (RTK) positioning

SUMMARY

Recent rapid advances in earthquake early warning (EEW) have been achieving great improvements in promptness and reliability of earthquake information which is utilized for disaster prevention and mitigation. The further improvements involve a prevention of saturation problem in estimating moment magnitude (Mw) for large earthquakes, especially those of Mw larger than eight. The saturation ca also result in an underestimation of following tsunami forecasts. GNSS real-time kinematic positioning technique has enabled rapid estimation of coseismic deformation and estimation of a finite fault model for a large earthquake without any saturation. Such advantage of finite fault modeling can improve the weakness of current EEW system, which experienced the saturation at the 2011 off the Pacific coast of Tohoku Earthquake. A new real-time fault modeling system based on GNSS Earth Observation Network (GEONET) is collaboratively developed by Geospatial Information Authority of Japan (GSI) and Tohoku University. The new system consists of real-time GNSS positioning, automatic detection of earthquake events, and quasi real-time finite fault model inversion routines. The tests of the system for past three large earthquakes with moment magnitude larger than eight, which includes the 2011 off the Pacific coast of Tohoku Earthquake, demonstrate that the system stably estimates appropriate moment magnitudes within three minutes. Furthermore, the Mw estimates are not saturated for all the case. Therefore, the Mw estimate with GNSS augmentation employed in such a system should be utilized for improving an initial Mw estimate for better tsunami forecasts. This system would be one of the realizations of the 2015 International Union of Geodesy and Geophysics (IUGG) resolution 4.

Real-Time GNSS Positioning System REGARD for Rapid Earthquake Moment Estimates

Satoshi KAWAMOTO, Basara MIYAHARA, Yohei HIYAMA, Yudai SATO, Tomoaki FURUYA, Yusaku OHTA, Takuya NISHIMURA, and Masaru TODORIKI, Japan

1. INTRODUCTION

The 2011 off the Pacific coast of Tohoku earthquake (the 2011 Tohoku earthquake; Mw 9.0) occurred on March 11, 2011. The following tsunamis have attacked the coastal area of northeast Japan causing catastrophic damages. Japan Meteorological Agency (JMA) issued a tsunami warning 3 minutes after the earthquake. However, the initial magnitude used for the tsunami warning was saturated at Mj 7.9, which resulted in underestimation of tsunami heights in the tsunami forecast (Ozaki, 2011). The initial magnitude estimated by JMA was based on a seismometer-based Earthquake Early Warning (EEW) and thus had a risk of saturation problem for large earthquakes of Mw > 8. One of the keys to improve the tsunami warning is to prevent the saturation problem occurred on the real-time moment magnitude estimates. This limitation can be improved by real-time GNSS kinematic (RTK) positioning technique, which provides real-time land surface displacement data. Moment magnitude estimates derived by finite fault model inversions using geodetic measurements never saturate even for a large earthquake (Blewitt et al., 2006; Allen et al., 2009), and also could provide the size and length of an earthquake fault that is enormously variable information for tsunami simulations (Blewitt et al., 2009). Ohta et al. (2012) demonstrates unsaturated Mw estimate of 8.7 is derived at 3 minutes after the 2011 Tohoku earthquake by utilizing the combination of real-time GNSS positioning and real-time fault model inversion. In order to realize such a robust GNSS-based warning system, a robust GNSS observation network covering wide range of the nation is essential. The GNSS-based tsunami warning system should be implemented as fast as possible to reduce damages due to future large earthquakes especially in nations vulnerable for natural disasters such as Japan.

The Geospatial Information Authority of Japan (GSI) has operated a nationwide GNSS network, GEONET (Yamagiwa et al., 2006), which consists of over 1300 real-time stations. As a reaction to the 2011 Tohoku earthquake, GSI and Tohoku University have jointly developed a real-time GNSS analysis system in GEONET: Real-time GEONET analysis system for Rapid Deformation monitoring (REGARD) in order to provide real-time Mw estimates based on real-time RTK positioning as fast as possible (Kawamoto et al., 2015). One of the basic components of the system is real-time GNSS positioning utilizing the RTKLIB 2.4.1 program package (Takasu, 2011). Earthquake events are detected by the RAPiD algorithm (Ohta et al., 2012) or EEW issued by JMA. Once an earthquake event is detected by the system, automated fault model inversion routines are launched, finite fault models are estimated from the displacements of the real-time GEONET analysis, and the Mw estimates are distributed to GSI members. The basic procedures for the quasi real-time fault model inversions are proposed by Kawamoto et al. (2015).

In the present study, we describe the overview of the prototype system of REGARD and how the fault model inversion routines are implemented. We also assess the performance of the system using data of past large earthquakes following Kawamoto et al. (2015).

2. System description

2.1 Overview Of REGARD

The prototype system of REGARD is currently processing ~600 stations all over Japan, processing 1Hz real-time GNSS observation data in order to calculate 1Hz real-time positions (Fig. 1). Once an earthquake event occurs, displacement fields are extracted repeatedly and they are approximated by a single rectangular earthquake source fault model and slip distribution model every minute. REGARD updates the Mw estimates once per minute because the first tsunami warning is issued by JMA at 3 minutes after an origin of an earthquake. The fault models are updated repeatedly and the final result is issued 5 minutes after the origin (Fig. 2).

REGARD consists of three subsystems: real-time positioning subsystem, event detection subsystem and fault model inversion subsystem (Fig. 3). The data used for the real-time positioning are the real-time GNSS data from the half of GEONET stations and the predicted half of Ultra-rapid orbit provided by International GNSS Service (IGS). The real-time positioning subsystem receives the real-time data and 1Hz displacements are calculated in real-time by RTKLIB 2.4.1 software, which offers kinematic baseline solutions. The zenith tropospheric delay, as well as its gradient and the ionospheric delay are estimated epoch-by-epoch. The event detection subsystem monitors the real-time displacements with RAPiD algorithm (Ohta et al., 2012), in which a discrepancy of the short term average (STA) and the long term average (LTA) of the displacement time-series is continuously monitored as a threshold for the event detection. An earthquake event is detected in the Event detection subsystem in case that the discrepancy, |STA-LTA|, exceeds 0.03m. If an earthquake of Mw > 7 is issued by EEW, then an event is also considered to be detected. The fault model inversion subsystem approximates a displacement field by a rectangular fault model and a slip distribution model. The displacement field is extracted from the real-time displacement time-series. Firstly a time-series is filtered with a 20 s-moving average filter to smooth the disturbance due to seismic waves. Finally a displacement field is derived subtracting the reference position 5 minutes before the event detection from the current position. The displacement fields are extracted for 5 minutes and two fault model inversion routines are launched simultaneously. Mw are estimated with a rigidity of 30 GPa from the derived fault models. The detail of the modeling procedures is described in the following section.

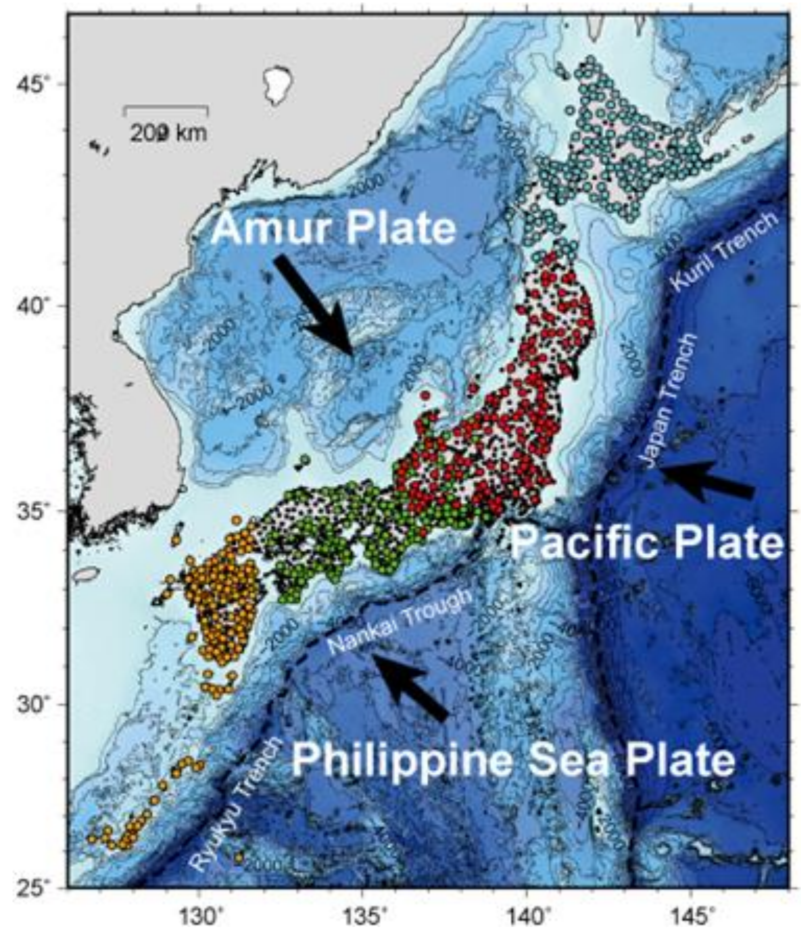

Fig. 1 Distribution map of real-time stations used by REGARD.

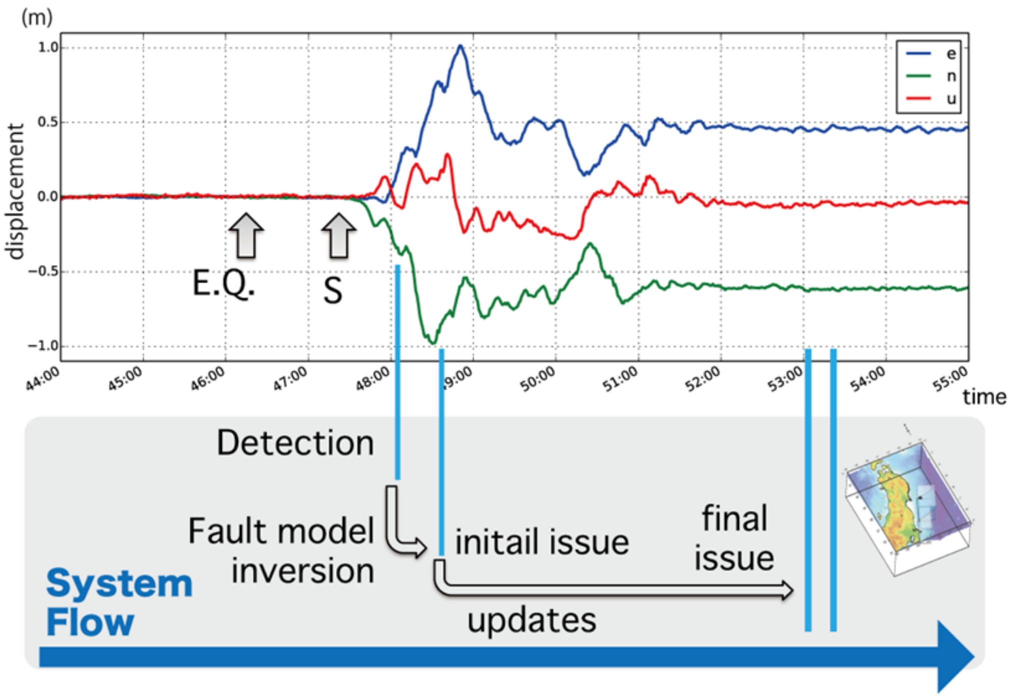

Fig. 2 Work flow of the real-time Mw estimation in REGARD.

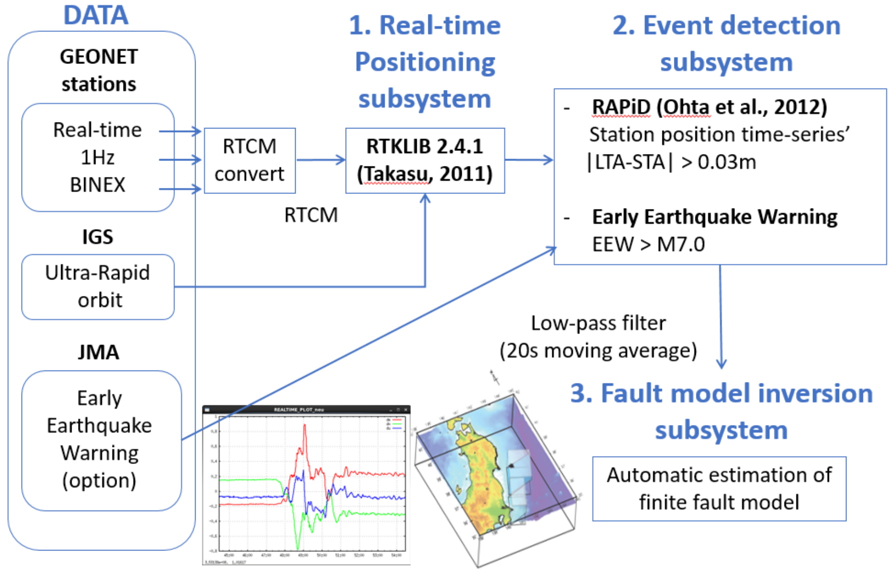

Fig. 3 Schematic diagram of REGARD.

2.2 Two fault model inversion routines

Two fault model inversion routines are implemented in the Fault model inversion subsystem (Kawamoto et al., 2015). The fault model inversion routines must be quick and automated in order to satisfy the demand from the tsunami warning that is issued at 3 minutes after a large earthquake. Therefore, each inversion is required to be finished within 10 – 30 s. We designed the Fault model inversion subsystem so that both uniform and heterogeneous slips using two different inversion routines: single rectangular fault modeling routine and fault slip distribution modeling routine. The slip distribution model was also implemented to improve the performance for modeling heterogeneous slips because possible large earthquakes strike Japan would involve the Nankai trough earthquake, in which shape of the fault cannot be expressed in simple rectangular plane along the trench. Mw estimates are calculated using a rigidity of 30 GPa in both routines.

The single rectangular fault modeling routine estimates nine fault parameters (latitude, longitude, depth, length, width, strike, dip, rake angles, and slip amount) and a translation parameter that accounts for common mode noise in three directions. A dislocation model in a homogeneous half-space (Okada, 1992) was used to calculate the Green's functions. We solved the nonlinear system using a nonlinear optimization method proposed by Matsu'ura and Hasegawa (1987), which assumes a normal prior distribution on the model.

The initial parameters are assumed from EEW or maximum displacement of a station. The initial latitude, longitude and depth are taken from EEW, but otherwise the initial location of fault is roughly approximated to be at the station where the largest displacement is detected in case that EEW is not available. The other initial fault parameters are pre-determined as a moment tensor database in each 0.5 × 0.5 degree grid (Fig. 4a). The standard deviation of the fault model parameters are assumed to be [0.02L (in deg.), 0.02L (in deg.), 5 (km), 2L (m), 2L (m), 10 (deg.), 10 (deg.), 10 (deg.), 10 (m)], which correspond to latitude, longitude, depth, width, strike, dip, rake and slip respectively. The initial fault length L is approximated by the moment magnitude taken from the EEW using a scaling law: W = 0.5L and S = 0.0001W, in which W denotes the fault width and S is slip amount. The 12 model parameters are optimized with the initial parameters described above. The fault model is updated to reflect the ongoing rupture process. The consecutive inversion is carried out with updated initial parameters replaced with the model parameters derived by the previous inversion. This sequence of inversions continues for 5 minutes that is long enough to get stable permanent ground displacements.

The second fault modeling routine estimates a slip distribution on the plate boundaries along the Japan Trench, the Sagami Trough, the Nankai Trough, and the Ryukyu Trench (Fig. 4b). Shape of the fault surfaces was prepared in advance by discretizing commonly used plate boundary models (Nakamura and Kaneshiro, 2000; Baba et al., 2002; Nakajima and Hasegawa, 2006; 2007; Hirose et al., 2008; Kita et al., 2010; Cabinet Office, 2013) into ~2000 elements. We used triangular meshes to approximate the curvature of the plate boundaries and a dislocation model for a triangular element in a homogeneous half space (Meade, 2007) is used to calculate the Green's functions. A slip distribution model is estimated using the plate boundary model nearest to the epicenter. We smoothed the slip distribution by a second-order Tikhonov regularization (e.g., Aster et al., 2012) with the linear least squares problem minimizing L2 norm:

$$min. \|\mathbf{Gm} - \mathbf{d}\| + \alpha\|\mathbf{Lm}\|,$$

where **G** is the Green functions, **m** is the model parameters, **d** is the observation data vector, **L** is the Laplacian matrix, and α is the hyper parameter that controls the spatial roughness of the fault parameters. A global optimization of the hyper parameter α takes long computation time and is not suitable for the real-time situations. Therefore, we optimized the hyper parameter α for each plate boundary model in advance for a synthetic earthquake with Mw of 8.5 (Fig. 5). The synthetic earthquakes were assumed the strongly coupled region where large earthquakes repeatedly occur in history. The best roughness parameters were estimated based on the L-curve criterion (Hansen, 1992) using the static displacements due to the assumed synthetic earthquakes.

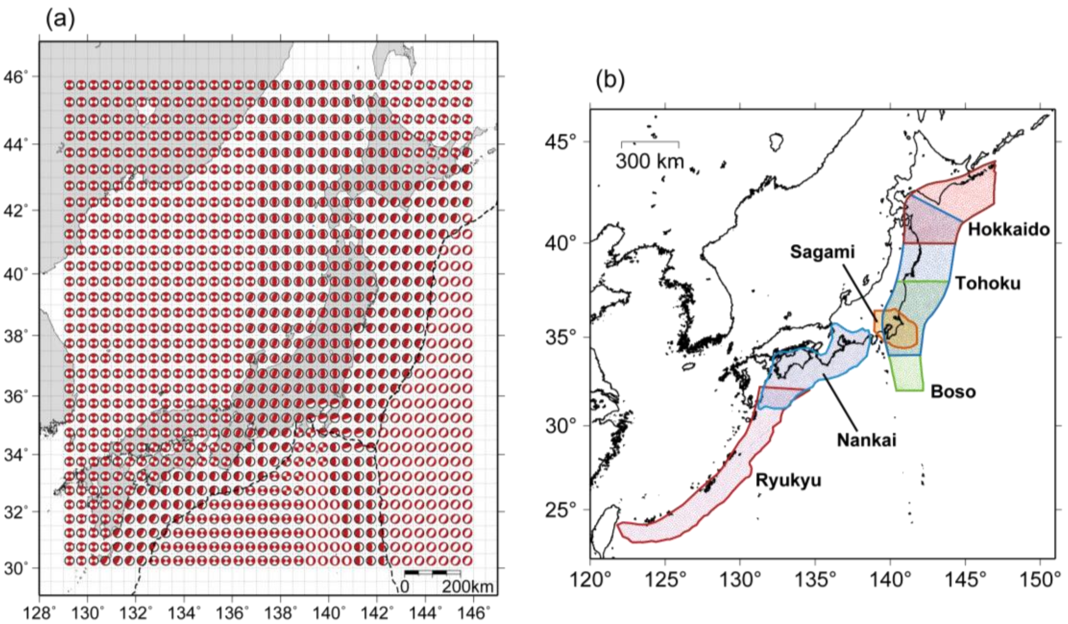

Fig. 4 (a) Pre-determined moment tensor database and (b) Pre-determined triangular meshes mapping on the plate boundaries (from Kawamoto et al., 2015).

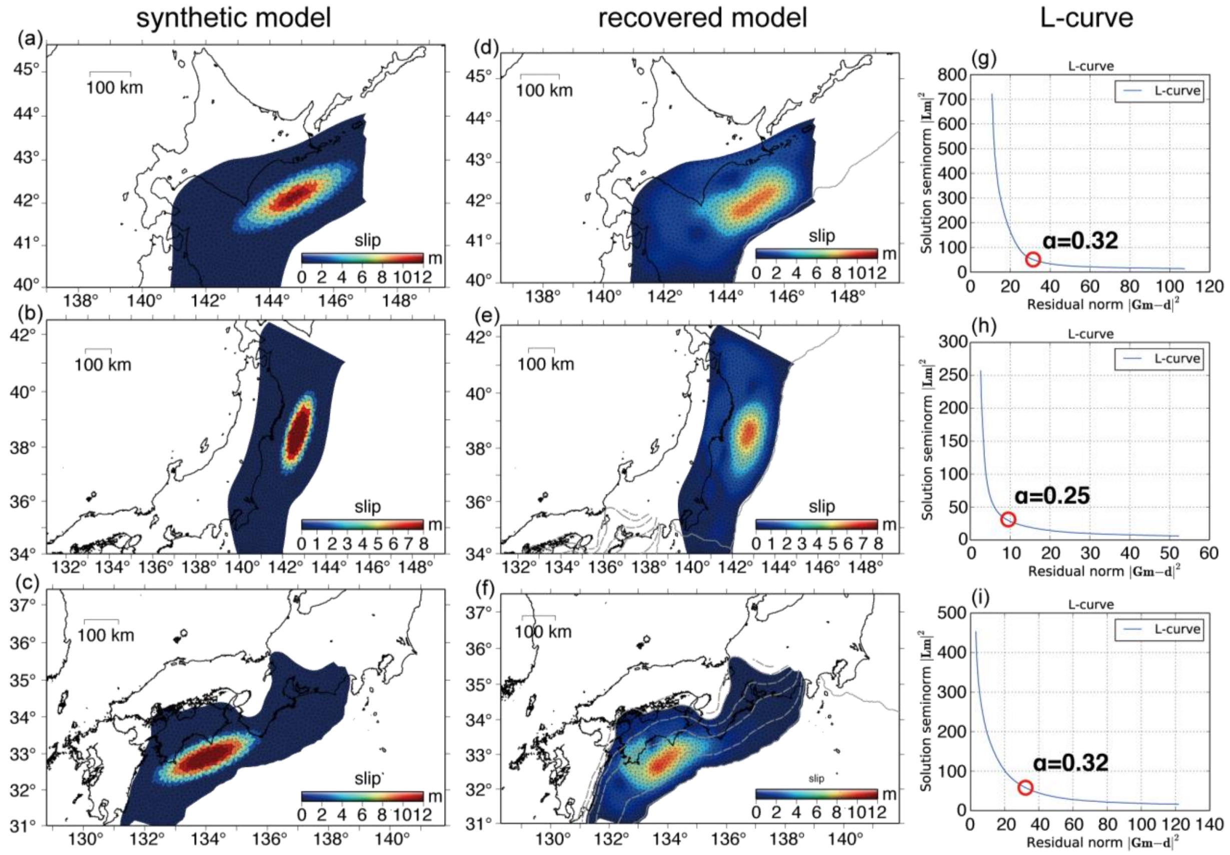

Fig. 5 (a-c) Synthetic models for the optimization of the roughness parameters, (d-f) recovered models using the best roughness parameters, and (g-i) the best roughness parameters at the corner of the L-curve. The figures on top, middle, and bottom correspond to the plate boundary around Hokkaido, Tohoku, Nankai trough respectively (from Kawamoto et al., 2015).

3. ASSESSMENT OF REAL-TIME FAULT MODELING ROUTINES

3.1 2003 Tokachi-oki Earthquake (Mw 8.3)

The 2003 Tokachi-oki earthquake occurred on September 26, 2003. The epicenter was ~ 50 km east offshore from Cape Erimo, northern island Hokkaido of Japan. The fault slip ranges from 4.0 to 9.0 m with a Mw from 8.0 to 8.3 (Yagi, 2004; Miyazaki et al., 2004; Ozawa et al., 2004; Yamanaka and Kikuchi, 2003; Crowell et al., 2012; Global Centroid Moment Tensor (GCMT; Dziewonski et al., 1981; Ekström et al., 2012)).

The Mw estimates from the single rectangular fault model and the slip distribution model were Mw = 7.94 and Mw = 8.21 for the time = 180 s. Both models were derived with high variance reduction (VR) over 90 %. The slip distribution model was slightly better than the rectangular model in VR by 1 %, and also consistent well with the Mw from GCMT with Mw = 8.3 and the model of Crowell et al. (2012) with Mw = 8.23. The time variation of the Mw estimates was also stable until around 200 s where massive communication blackout occurred.

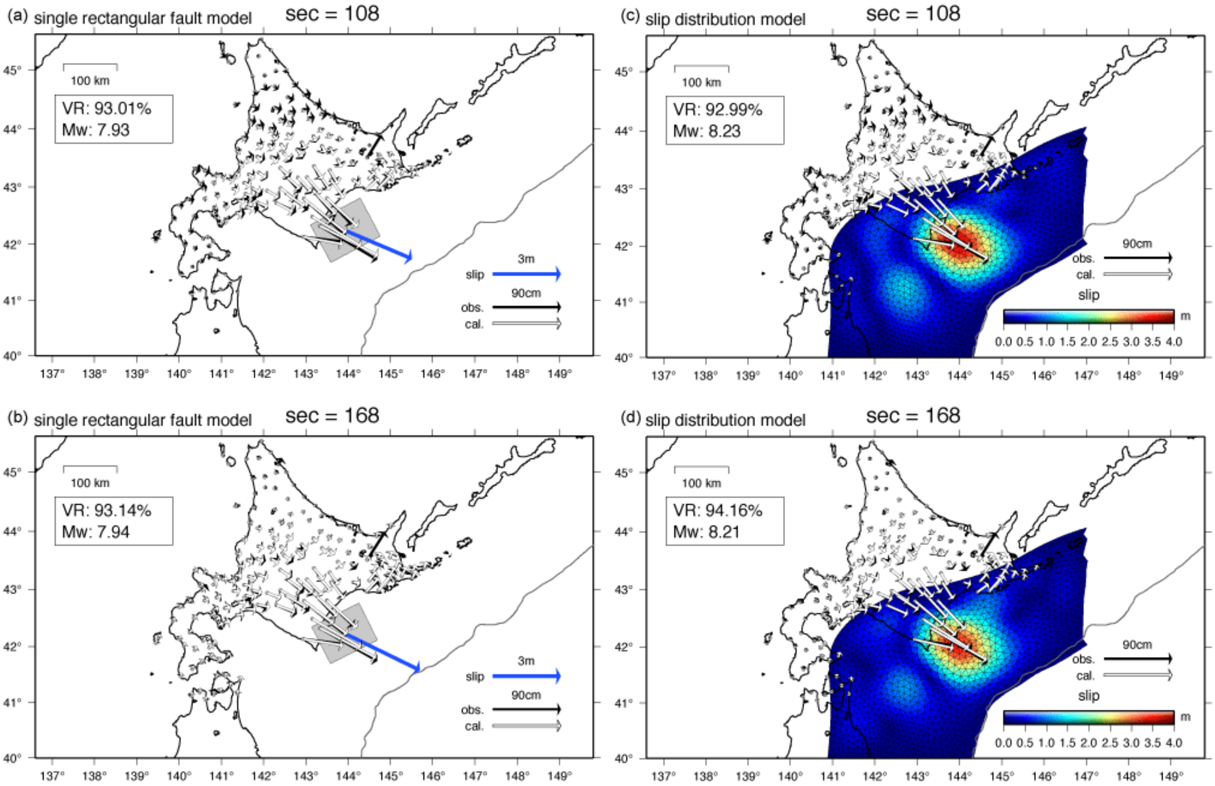

Fig. 6 Comparison between the fault model inversion result from the single rectangular fault modeling routine (a, b) and the slip distribution modeling routine (c, d) obtained by the time = 120 s and 180 s after the 2003 Tokachi-oki earthquake (Mw 8.3; after Kawamoto et al., 2015).

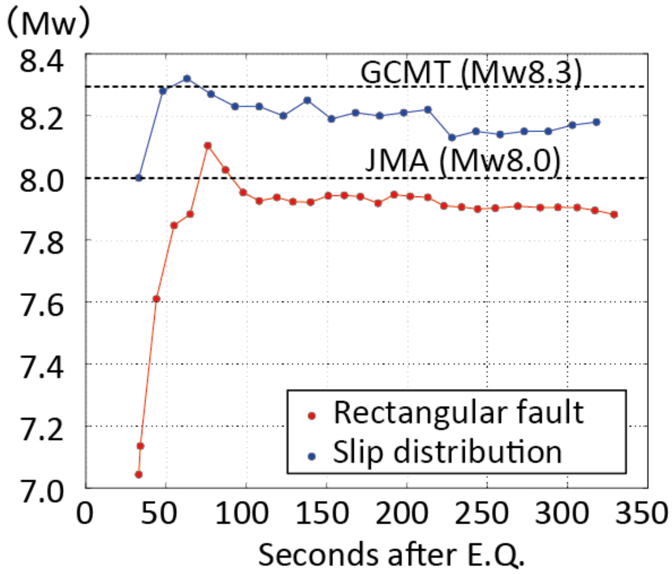

Fig. 7 Time variation of the Mw estimates from the single rectangular fault modeling routine (red) and the slip distribution modeling routine (blue). The Mw estimates determined by JMA and the GCMT project are shown in dotted lines (after Kawamoto et al., 2015).

3.2 2011 Tohoku Earthquake (Mw 9.0)

The 2011 Tohoku Earthquake (Mw 9.0) occurred on March 11, 2011. The epicenter was ~150 km east from the coastline of Tohoku region. The fault rupture is over 300 km long along the Japan Trench (e.g., Nishimura et al., 2011; Ozawa et al. 2011; 2012; Simons et al. 2011). The fault models estimated using onshore geodetic observations show the maximum slip of 25 m (Ozawa et al., 2011), and over 50 m with sea-floor observations (Ozawa et al., 2012; Simons et al., 2011). There is also large slip near the trench (Ide et al., 2011).

The Mw estimates derived with significantly high VR: Mw = 8.75 with VR = 98.8 % for the single rectangular fault model, Mw = 8.83 with VR = 99.4 % for the slip distribution model at 180 s. The variation of Mw estimates became stable after 150 s, and the Mw estimates were clearly unsaturated though the Mw estimates from EEW saturated at Mw = 8 (Fig. 9). The slip distribution model was consistent well with the result of Ozawa et al. (2011), which model is inferred only from onshore displacements. On the other hand, the Mw estimate from single rectangular fault model was ~0.2 underestimated because the fault location was converged to closer to the coastline. From the results above, the slip distribution model was better for the case of the 2011 Tohoku earthquake. The coseismic fault is not uniform for the 2011 Tohoku earthquake, thus the slip distribution models were more stable.

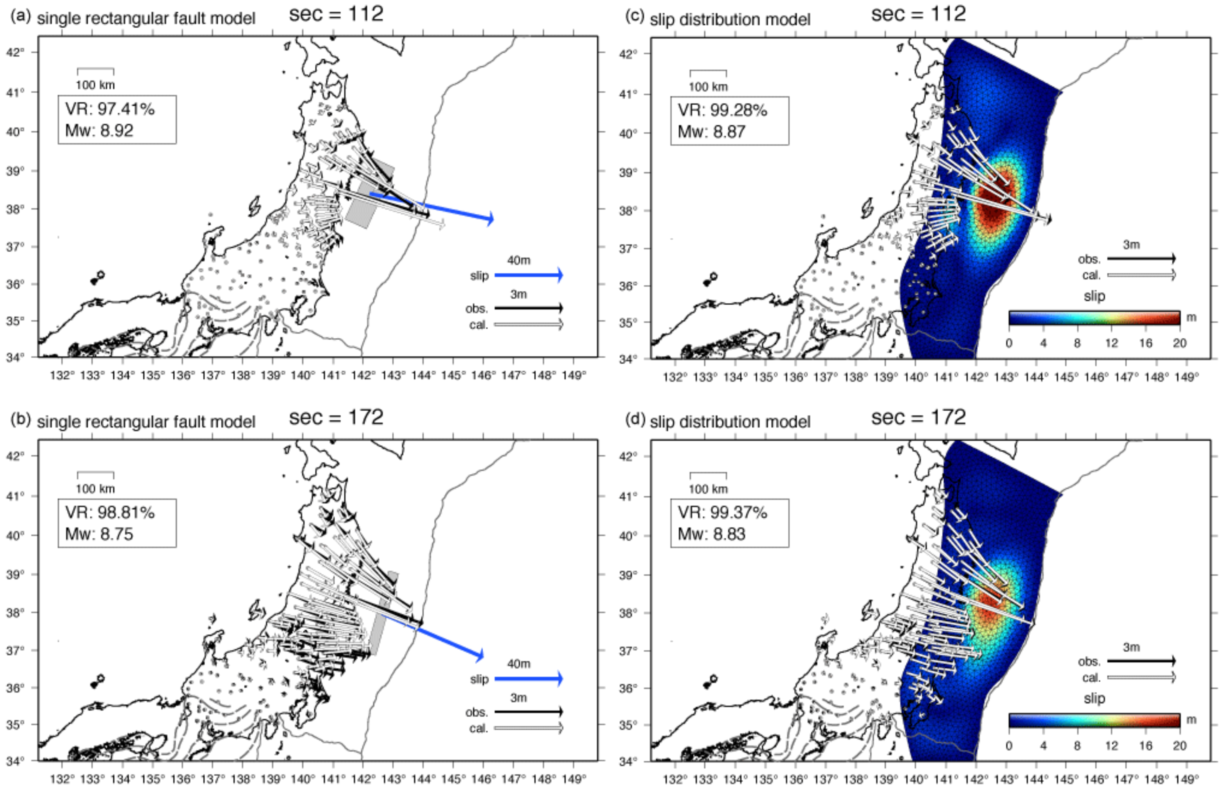

Fig. 8 Comparison between the fault model inversion result from the single rectangular fault modeling routine (a, b) and the slip distribution modeling routine (c, d) obtained by the time = 120 s and 180 s after the 2011 Tohoku earthquake (Mw 9.0; after Kawamoto et al., 2015).

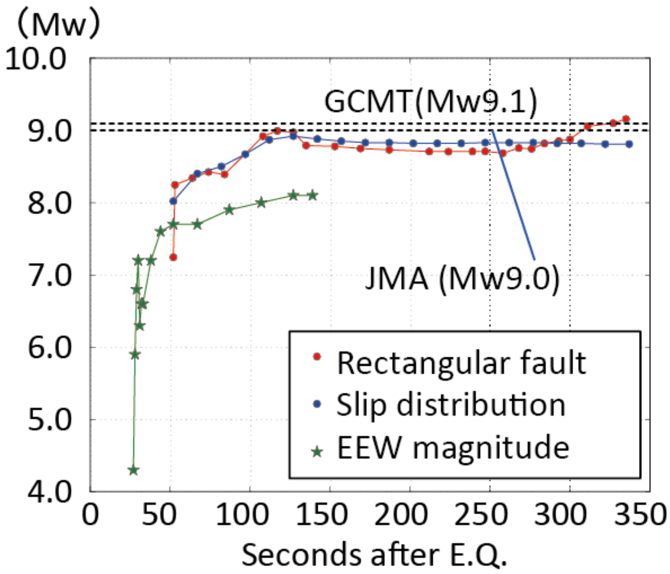

Fig. 9 Time variation of the Mw estimates from the single rectangular fault modeling routine (red) and the slip distribution modeling routine (blue). The moments by EEW are also shown

(green). The Mw estimates determined by JMA and the GCMT project are shown in dotted lines (after Kawamoto et al., 2015).

3.3 Simulated Nankai Trough Earthquake (Mw 8.7)

Large earthquakes repeatedly occur along the Nankai Trough, which corresponds to the plate boundary between the Philippine Sea Plate and the Amur Plate. A future large earthquake should involve this area. The fault surface of the expected earthquake is curved and the strike direction is not uniform along the trench. We used a simulated displacement time-series due to a Nankai Trough Earthquake (Todoriki et al., 2013), which were estimated based on the 1707 Hoei type earthquake (Furumura et al., 2011), for testing the fault model inversion routines. The assumed model consists of 10 fault segments, in which input slips are 5.6, 7.0, 5.6, 9.2 and 9.2 m from Suruga Bay to Hyuga-nada.

The inversion results showed that the slip distribution model of Mw = 8.75 with VR > 93% derived before 3 minutes (Fig. 10c, 10d). The variation of Mw estimates became stable after ~160 s, which is enough faster than the timing of the initial tsunami warning at 3 minutes (Fig. 11). However, the single rectangular fault model poorly recovered the true model: Mw = 9.69 with VR =70.31 % (Fig. 10a, 10b). The Mw estimates by the single rectangular fault were very unstable with Mw of 8.5 - 9.8 (Fig. 11). The major causes of the instability are non-uniform plate boundary and complexity of the fault rupture separated to several subfaults, which cannot be approximated with a single uniform slip.

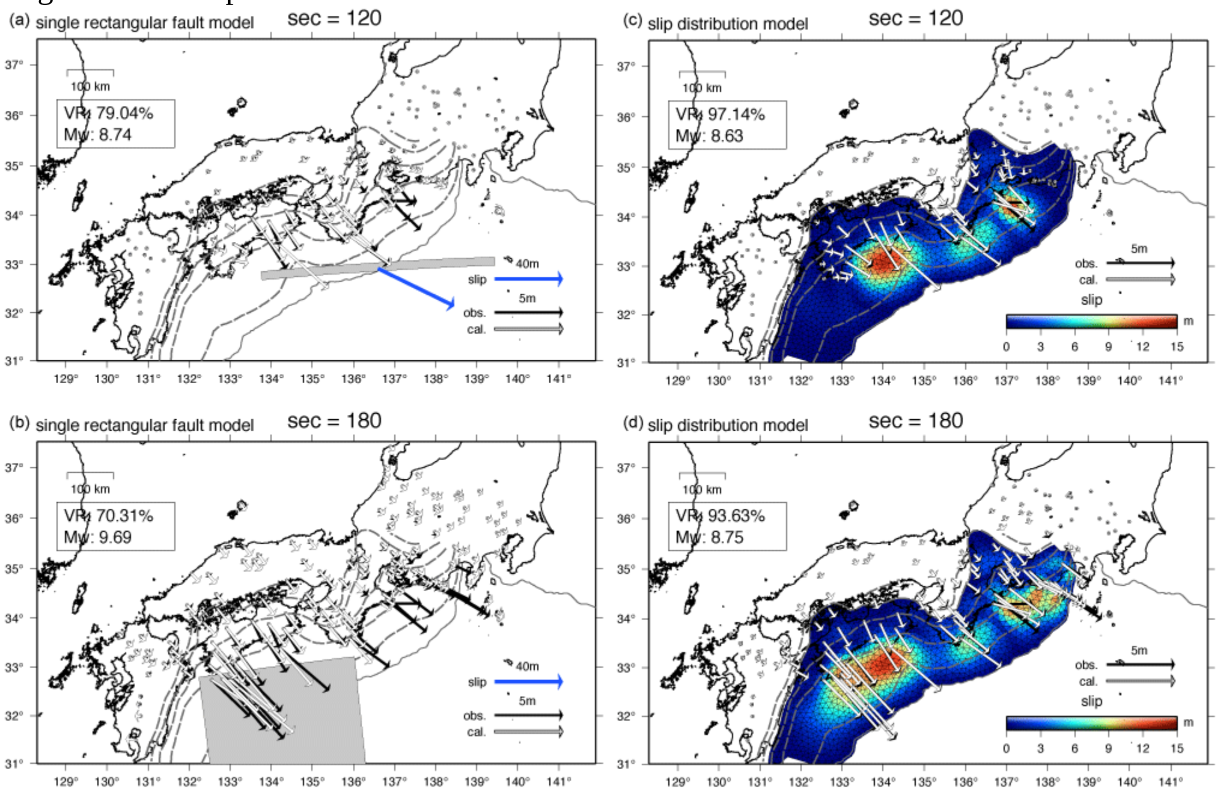

Fig. 10 Comparison between the fault model inversion result from the single rectangular fault modeling routine (a, b) and the slip distribution modeling routine (c, d) obtained by the time = 120 s and 180 s after the simulated Nankai Trough earthquake (Mw 8.7; after Kawamoto et al., 2015).

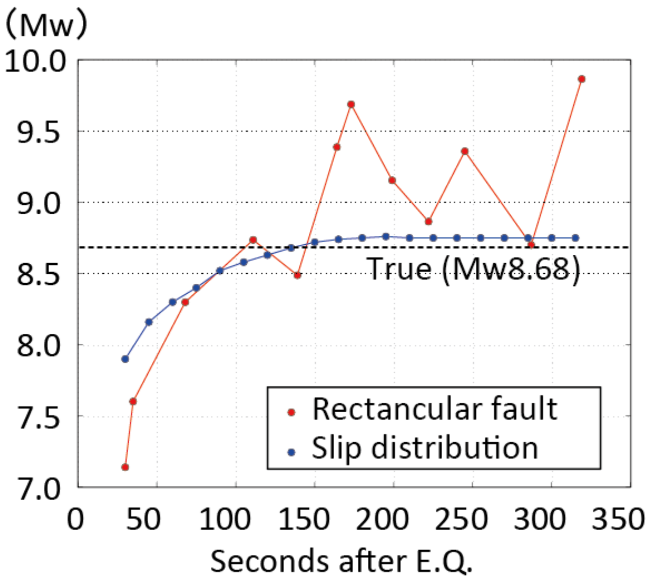

Fig. 11 Time variation of the Mw estimates from the single rectangular fault modeling routine (red) and the slip distribution modeling routine (blue). The Mw estimates determined by JMA and the GCMT project are shown in dotted lines (after Kawamoto et al., 2015).

4. DISCUSSION AND CONCLUSION

In this paper, we described the overview of a GNSS based system for rapid earthquake moment estimates, which provides earthquake fault models in real-time: REGARD. The 1 Hz displacement data from the system record long-period ground motion without any saturation, thus finite fault models can appropriately be estimated from the data without no saturation of magnitudes of events. We developed and tested the two fault model inversion routines for the past large earthquakes including the 2003 Tokachi-oki earthquake (Mw 8.3), the 2011 Tohoku earthquake (Mw 9.0), and the simulated Nankai Trough earthquake (Mw 8.7). All of the displacements due to the earthquakes were appropriately approximated with high VR without any saturation using our inversion routines. This reveals the efficiency of the REGARD for estimating the size of large earthquakes with Mw > 8, which is the upper limit of rapid detection capability for earthquake size by current EEW. Therefore, REGARD should be further utilized for improving the robustness of current seismometer based magnitude estimates. In addition to this, the results of the fault model inversions can be utilized for estimating seafloor deformation that could directly be used for a simulation of tsunami inundation.

The resolution 4 of the 2015 International Union of Geodesy and Geophysics (IUGG) encourages the use of GNSS for robust tsunami warning system (IUGG, 2015). The scheme of

REGARD should also be efficient for the regions where dense real-time GNSS network exists and a detailed plate boundary model, which is developed from observation of repeated tsunamigenic earthquakes, is already available. We strongly believe REGARD will be one of the basic designs of GNSS augmentation of tsunami early warning systems.

REFERENCES

Allen RM, Gasparini P, Kamigaichi O, Boese M (2009) The status of earthquake early warning around the world; an introductory overview. Seismological Research Letters 80(5): 682-693

Aster RC, Borchers B, Thurber CH (2012) Parameter Estimation and Inverse Problems, 2nd edn. Academic Press

Baba T, Tanioka Y, Cummins PR, Uhira K (2002) The slip distribution of the 1946 Nankai earthquake estimated from tsunami inversion using a new plate model. Phys. Earth Planet. Inter. 132:59–73. doi:10.1016/S0031-9201(02)00044-4

Blewitt G, Kreemer C, Hammond WC, Plag HP, Stein S, Okal E (2006) Rapid determination of earthquake magnitude using GPS for tsunami warning systems. Geophysical Research Letters 33: L11309. doi:10.1029/2006GL026145

Blewitt G, Hammond WC, Kreemer C, Plag HP, Stein S, Okal E (2009) GPS for real-time earthquake source determination and tsunami warning systems. Journal of Geodesy 83(3–4):335–343. doi:10.1007/s00190-008-0262-5

Cabinet Office, Government Of Japan (2013) Report on the fault models of M7 class earthquake beneath the capital and M8 class earthquake on Sagami Trough, and seismic intensity distribution and tsunami height (in Japanese). http://www.bousai.go.jp/kaigirep/chuobou/senmon/shutochokkajishinmodel. Accessed 22 October 2015

Crowell BW, Bock Y, Melgar D (2012) Real-time inversion of GPS data for finite fault modeling and rapid hazard assessment. Geophysical Research Letters 39(9): L09305. doi:10.1029/2012GL051318

Dziewonski AM, Chou TA, Woodhouse JH (1981) Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. J. Geophys. Res. 86: 2825-2852. doi:10.1029/JB086iB04p02825

Ekström G, Nettles M, Dziewonski AM (2012) The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes. Phys. Earth Planet. Inter. 200-201: 1-9. doi:10.1016/j.pepi.2012.04.002

Furumura T, Imai K, Maeda T (2011) A revised tsunami source model for the 1707 Hoei earthquake and simulation of tsunami inundation of Ryujin Lake, Kyushu, Japan. J. Geophys. Res. 116:B02308. doi:10.1029/2010JB007918

Hansen PC (1992) Analysis of discrete ill-posed problems by means of the L-curve. SIAM review 34(4):561–580

Hirose F, Nakajima J, Hasegawa A (2008) Three-dimensional seismic velocity structure and configuration of the Philippine Sea slab in southwestern Japan estimated by double-difference tomography. J. Geophys. Res. 113:B09315. doi:10.1029/2007JB005274

Ide S, Baltay A, Beroza GC (2011) Shallow dynamic overshoot and energetic deep rupture in the 2011 Mw 9.0 Tohoku-Oki earthquake. Science 332(6036):1426–1429. doi:10.1126/science.1207020

International Union of Geodesy and Geophysics (2015): The IUGG 2015 resolutions. http://www.iugg.org/resolutions/IUGGResolutions2015.pdf. Accessed 22 October, 2015

Kawamoto S., Miyagawa K., Yahagi T., Todoriki M., Nishimura T., Ohta Y., Hino R., Miura S. (2015) Development and Assessment of Real-Time Fault Model Estimation Routines in the GEONET Real-Time Processing System. International Association of Geodesy Symposia, doi:10.1007/1345_2015_49

Kita S, Okada T, Hasegawa A, Nakajima J, Matsuzawa T (2010) Anomalous deepening of a seismic belt in the upper-plane of the double seismic zone in the Pacific slab beneath the Hokkaido corner: Possible evidence for thermal shielding caused by subducted forearc crust materials. Earth Planet. Science Lett. 290:415–426. doi:10.1016/j.epsl.2009.12.038

Matsu'ura M, Hasegawa Y (1987) A maximum likelihood approach to nonlinear inversion under constraints. Phys. Earth Planet. Inter. 47:179–187. doi:10.1016/0031-9201(87)90076-8

Meade BJ (2007) Algorithms for the calculation of exact displacements, strains, and stresses for triangular dislocation elements in a uniform elastic half space. Computers & Geosciences 33(8):1064–1075. doi:10.1016/j.cageo.2006.12.003

Miyazaki S, Larson KM, Choi K, Hikima K, Koketsu K, Bodin P, Haase J, Emore G, Yamagiwa A (2004) Modeling the rupture process of the 2003 September 25 Tokachi-Oki (Hokkaido) earthquake using 1-Hz GPS data. Geophys. Res. Lett. 31:L21603. doi:10.1029/2004GL021457

Nakajima J, Hasegawa A (2006) Anomalous low-velocity zone and linear alignment of seismicity along it in the subducted Pacific slab beneath Kanto, Japan: Reactivation of subducted fracture zone?. Geophys. Res. Lett. 33:L16309. doi:10.1029/2006GL026773

Nakajima J, Hasegawa A (2007) Subduction of the Philippine Sea plate beneath southwestern Japan: Slab geometry and its relationship to arc magmatism, J. Geophys. Res. 112:B08306. doi:10.1029/2006JB004770

Nakamura M, Kaneshiro S (2000) Determination of subducted Philippine Sea Plate in the Nansei islands deduced from hypocenter data. Bull. Fac. Sci. Univ. Ryukyus 70:73–82 (in Japanese with English abstract)

Nishimura T, Munekane H, Yarai H (2011) The 2011 off the Pacific coast of Tohoku Earthquake and its aftershocks observed by GEONET. Earth Planets Space 63:631–636

Ohta Y, Kobayashi T, Tsushima H, Miura S, Hino R, Takasu T, Fujimoto H, Iinuma T, Tachibana K, Demachi T, Sato T, Ohzono M, Umino N (2012) Quasi real-time fault model estimation for near-field tsunami forecasting based on RTK-GPS analysis: Application to the 2011 Tohoku-Oki earthquake (Mw 9.0). Journal of Geophysical Research: Solid Earth (1978–2012) 117(B2):B02311. doi:10.1029/2011JB008750

Okada Y (1992) Internal deformation due to shear and tensile faults in a half-space. Bulletin of the Seismological Society of America 82(2):1018–1040

Ozaki T (2011) Outline of the 2011 off the Pacific coast of Tohoku Earthquake (Mw 9.0) -Tsunami warnings/advisories and observations. Earth Planets Space 63:827-830

Ozawa S, Kaidzu M, Murakami M, Imakiire T, Hatanaka Y (2004) Coseismic and postseismic crustal deformation after the Mw 8 Tokachi-oki earthquake in Japan. Earth Planets Space 56:675–680

Ozawa S, Nishimura T, Suito H, Kobayashi T, Tobita M, Imakiire T (2011) Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake. Nature 475(7356):373–376. doi:10.1038/nature10227

Ozawa S, Nishimura T, Munekane H, Suito H, Kobayashi T, Tobita M, Imakiire T (2012) Preceding, coseismic, and postseismic slips of the 2011 Tohoku earthquake, Japan. Journal of Geophysical Research: Solid Earth (1978–2012) 117(B7):B07404. doi:10.1029/2011JB009120

Simons M, Minson SE, Sladen A, Ortega F, Jiang J, Owen SE, Meng L, Ampuero JP, Wei S, Chu R, Helmberger DV, Kanamori H, Hetland E, Moore AW, Webb FH (2011) The 2011 magnitude 9.0 Tohoku-Oki earthquake: Mosaicking the megathrust from seconds to centuries. Science 332(6036):1421–1425. doi:10.1126/science.1206731

Takasu T (2011) RTKLIB: An Open Source Program Package for GNSS Positioning. http://www.rtklib.com. Accessed 22 October 2015

Todoriki M, Furumura T, Maeda T (2013) 3D FDM Simulation of Seismic Wave Propagation for Nankai Trough Earthquake: Effects of Topography and Seawater. AGU Fall Meeting, 9–13 December, San Francisco, USA

Yagi Y (2004) 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

Yamagiwa, A, Hatanaka Y, Yutsudo T, Miyahara B (2006) Real-time capability of GEONET system and its application to crust monitoring. Bulletin of the Geospatial Information Authority of Japan 53:27-33

Yamanaka Y, Kikuchi M (2003) Source process of recurrent Tokachi-oki earthquake on September 26, 2003, inferred from teleseismic body waves. Earth Planets Space 55:e21–e24

BIOGRAPHICAL NOTES

Satoshi Kawamoto is a chief researcher of the Geography and Crustal Dynamics Research Center, Geospatial Information Authority of Japan, Tsukuba, Japan. His current research interests include GNSS kinematic positioning and it's application to disaster mitigation. He received his M. Sc. degree in Geophysics from Nagoya University, Nagoya, Japan in 2006.

CONTACTS

Satoshi Kawamoto
Geospatial Information Authority of Japan
Kitasato 1, Tsukuba, Ibaraki
JAPAN
Tel. +81-29-864-4767
Fax + 81-29-864-1802
Email: kawamoto-s96tf@mlit.go.jp
Web site: http://www.gsi.go.jp/ENGLISH/index.html