

On the realtime monitoring of the long-period seismic wavefield

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Abstract

A possibility of monitoring the long-period seismic wavefield in realtime is suggested. The seismic wavefield below 0.1 Hz may be consistently modeled by the earthquake activity field defined by a point source moment tensor on 10 km-mesh grid points. With the current level of personal computers, it should be possible to perform moment tensor inversions for all the mesh points to find the best moment tensor every second. A sparse regional broadband seismometer network appears suffice to perform such realtime monitoring, which may eventually enable us to predict the short-period ground motion in realtime as well.

Introduction

As a result of continuous activities of the earth - earthquakes and volcanoes are familiar examples for geophysicists, but flows in the mantle, ocean and atmosphere are also such manifestations (e.g., Suda et al., 1998) - the solid part of the earth elastically vibrates to generate the seismic wavefield (SWF). Owing to the great advances in the global seismology, led by the deployments of global digital seismic networks (e.g., IDA, GDSN, GEOSCOPE, POSEIDON etc...), the very-long-period part of the seismic wavefield is now well understood, and corresponding activities of the earth (let us call this "the earthquake activity field (EAF)") is now routinely determined by various institutes in the world (e.g., Dziewonski et al., 1981; Sipkin, 1993; Kawakatsu, 1995). In the view of seismic source analysis, the eternal goal of seismology may be defined as to monitor in realtime the seismic wavefield to infer the corresponding earthquake activity field. The purpose of this short note is to suggest that such realtime monitoring of long-period seismic field may be now possible using data from sparse broadband seismic network in a regional scale.

Long-period seismic wavefield vs. seismic activity field

Seismic moment tensor determination for regional earthquakes is now becoming a common approach for monitoring regional seismicity (e.g., Dreger and Helmberger, 1993; Romanowicz et al., 1993; Thio and Kanamori, 1995; Fukuyama et al., 1998). At the Earthquake Research Institute, we have developed an automated scheme using data from the regional broadband seismic network deployed in Kanto area (Fig. 1). The system is initiated by an e-mail

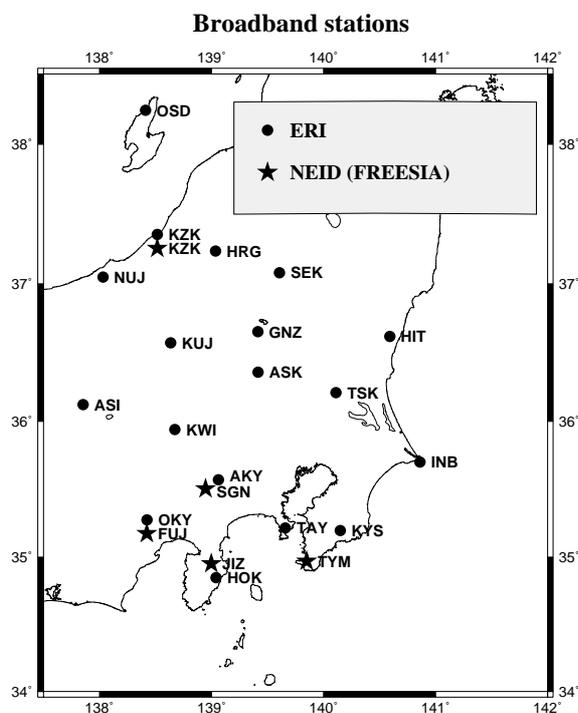


Fig. 1 Location of regional broadband seismic stations available in the Kanto area, Japan. The closed circles indicate the stations operated by the Earthquake Research Institute, and the stars indicate the stations of FREESIA network.

from JMA (Japan Meteorological Agency) when JMA detects an earthquake in the area. For the actual moment tensor inversion, broadband data are lowpass filtered at 0.1Hz, and a laterally homogeneous flat layer structure is assumed to calculate Green's function. JMA's initial location can be off as large as 10km from the final JMA location, but such location error usually does not alter the inverted moment tensor solutions significantly (Fig. 2; Ito & Kawakatsu, 1997; Ito, 1997). This observation indicates that the seismic wavefield below 0.1Hz may be consistently modeled by a point source moment tensor located on one of the grid points of 10 km-mesh: i.e., the seismic wavefield below 0.1Hz can be modeled by the seismic activity field represented by a 10 km-mesh. So the question is now whether or not such modeling can be done in realtime, and we suggest in the following that it is possible.

Mechanism variation

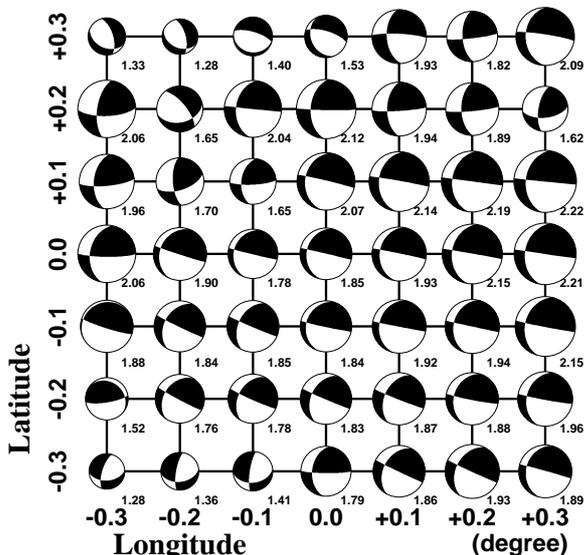


Fig2 (a) Moment tensor solutions of an intermediate depth earthquake (1996/10/12 21:40 $M_w=4.2$) obtained on each grid point of 10km-mesh. Numbers next to the focal mechanisms are estimated seismic moment ($\times 10^{15} Nm$). Only the best double couple component is shown. The location (0.0, 0.0) corresponds to the preliminary location given by JMA (after Ito, 1997).

Realtime monitoring

Let us think a moment tensor inversion problem when the origin time and the source location are given. The observation equation to be solved for a source s and station k is

$$\sum_i G_i^{sk}(t) m_i^s = d^k(t), \quad (1)$$

where $G_i^{sk}(t)$ and $d^k(t)$ are theoretical and observed seismograms at k th station (superscript k is used to represent all

three component seismograms of a station k) respectively, and m_i^s is the i th component of the moment tensor. The normal equation based on (1) is

$$\sum_i A_{ji}^s m_i^s = b_j^s, \quad (2)$$

where

$$A_{ji}^s = \sum_k A_{ji}^{sk}, \quad A_{ji}^{sk} = \int G_j^{sk}(t) G_i^{sk}(t) dt,$$

$$b_j^s = \sum_k b_j^{sk}, \quad b_j^{sk} = \int G_j^{sk}(t) d^k(t) dt$$

(for simplicity we omit the superscript s when it is not confusing). Thus the least squares solution for the moment tensor is given in the vector form by

$$\hat{m} = A^{-1}b. \quad (3)$$

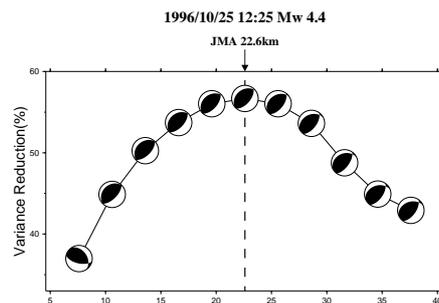


Fig2 (b) Variance reduction as a function of depth of a shallow event (1996/10/25 12:25 $M_w=4.4$). The epicenter is fix at the best location. Corresponding moment tensor solutions (best double couples) are also shown. The variance reduction has a peak at the depth near the JMA's final depth estimate (22.6km), although the mechanisms are not so dependent on the depth. Therefore, the variance reduction, which is a fuction of the residual (4), should allow to locate earthquakes.

Since A is a cross-correlation between Green's functions, it can be readily calculated and stored once the structure model is chosen. Therefore the moment tensor \hat{m} can be obtained by a simple matrix multiplication if b is determined. This shows that the procedure of estimating a moment tensor when a source location is given is almost equivalent with the calculating the cross-correlation between Green's functions and data. It can be further shown that model prediction error (residual between data and synthetic seismograms calculated for the estimated \hat{m}) is

$$Res = \left(\sum_k \int d^k(t)^2 dt \right) - b^t A^{-1}b, \quad (4)$$

which can be also easily calculated if we have b .

It should be now clear that in order to monitor EAF from long-period SWF, we only need to be able to calculate the cross-correlation b for all possible source points on the 10 km-mesh (hereafter referred as to “virtual sources”). For this can be done in realtime, there are two conditions to be satisfied: (1) all Green’s functions can be stored in the computer memory, (2) the cross-correlation b can be calculated within a certain short time (the first can be considered as a necessary condition for the second).

For the region of our interest (Kanto area ($34^\circ-38^\circ, 138^\circ-142^\circ$), Fig. 1), these conditions appear to be satisfied. For stations with an epicentral distance of at most 400 km, all the major phases arrive within the first two minutes. Considering that we are dealing long-period wavefield above 10 sec., with one sample per two-second, each waveform contains 60 points. If the horizontal and vertical grid sizes are taken 0.1° and 10km respectively, there will be $40 \times 40 \times 10 = 16000$ virtual source points in $4^\circ \times 4^\circ \times 100\text{km}$ size area. The total size of the Green’s function for each station to “memorize” is

$$60(\text{points}) \times 3(\text{components}) \times 16000(\text{grids}) \\ \times 5(\text{moment tensors}) \times 4\text{bytes} \approx 57\text{Mbytes},$$

which can fit in some decent PC memory. As to the second condition, for one station, calculating b_j^k ($j = 1, \dots, 5$ for a deviatoric moment tensor) for all virtual sources ($s = 1, \dots, 16000$) takes only a second with recent fast PCs. It should be therefore possible to monitor the long-period wavefield for every second, if we assign one PC for each station.

The best moment tensor solution (in the least-squares sense) for each virtual source s is

$$\hat{m}^s = (A^s)^{-1} \cdot \sum_k b^{sk} \quad (5)$$

and the corresponding prediction error is (4). \hat{m}^s which gives the smallest prediction error is the “earthquake activity” most consistent with the long-period seismic wavefield of the time.

Seismometer as a cross-correlator

In the view of monitoring the long-period SWF presented above, a seismometer (or seismic station) can be considered as a machinery to correlate the long-period vibration with the vibration predicted by virtual sources: Conceptually speaking, the role of a seismic station is now said to estimate b^{sk} for all possible s every second, and to send them to the central computer, where b^{sk} from different stations are summed to estimate $b^s = \sum_k b^{sk}$ for all s . The central computer multiply $(A^s)^{-1}$ to b^s to obtain \hat{m}^s for all s , and choose the best one using (4). This “solution” may be visually shown on a display which then give the EAF of the time (with few minutes delay). Off course, this whole process can be done on a single main-frame machine, not necessarily in the way suggested above by assigning a PC to each station.

Discussion

As shown above, it appears feasible to monitor the EAF in realtime using data from a sparse regional broadband network. It should be then also possible to “predict” in **real-time** the shorter period wavefield (if an earthquake occurs, it becomes a so-called strong motion wavefield) everywhere consistent with the estimated EAF. Thus we may be able to say that we have a realtime strong motion prediction machine based on the data from a sparse regional broadband network. Of course, at first, the predicted strong motions may be quite different from the actual observations. But the system can be improved as our understanding of the each step of the above procedure advances in the future: e.g., the better knowledge of the regional structure improves the Green’s function, which may result in a smaller mesh size; the better knowledge of the site effect improves strong motion prediction; advanced source analysis such as attempted by Kaverina et al. [1997] improves the estimation of the effect of rupture propagation, etc... What seems important is to realize that seismology is now at the stage to be able to start such realtime monitoring and prediction.

The realtime monitoring of long-period SWF need not to be restricted to the regional scale problem. Instead of the Green’s function, we can correlate observed wavefield with incoming plane waves. With this kind of monitoring, we may start seeing exotic seismic events which might have been overlooked by the conventional method of event detection, in which seismic events are “detected” when coherent short-period signals are observed within a seismic network. For example, Kawakatsu et al. (1993) reported 10 sec period volcanic signals observed at remote broadband seismic stations. Reports on longer-period signals on a global scale can be also found in many geophysical literatures (Kanamori and Given, 1980; Kawakatsu, 1989; Rouland et al., 1992; Shear, 1994).

Finally, we note that the realtime monitoring of the long-period seismic wavefield suggested in the present paper seems even practical at Aso volcano, where long-period tremors of 15 sec period is continually emitted from a known source (Kaneshima et al., 1996). Legrand et al. (1998) performed the grid-point moment tensor inversion (of 100 m-mesh), and Kawakatsu et al. (1998) suggests the possibility of the realtime monitoring of the volcano using long-period waveforms.

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