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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 motions 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 vibrates elastically to generate the seismic wavefield (SWF). Due to the great advances in 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)") are now routinely determined by various institutes around the world (e. g., Dziewonski *et al.*, 1981; Sipkin, 1993; Kawakatsu, 1995). From the view point 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 the long-period seismic field may now be possible using data from sparse broadband seismic network on a regional scale.

Long-period seismic wavefield vs. earthquake activity field

Seismic moment tensor determination of 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 the Kanto area (Fig. 1). The system is initiated by an e-mail from JMA (Japan Meteorological Agency)

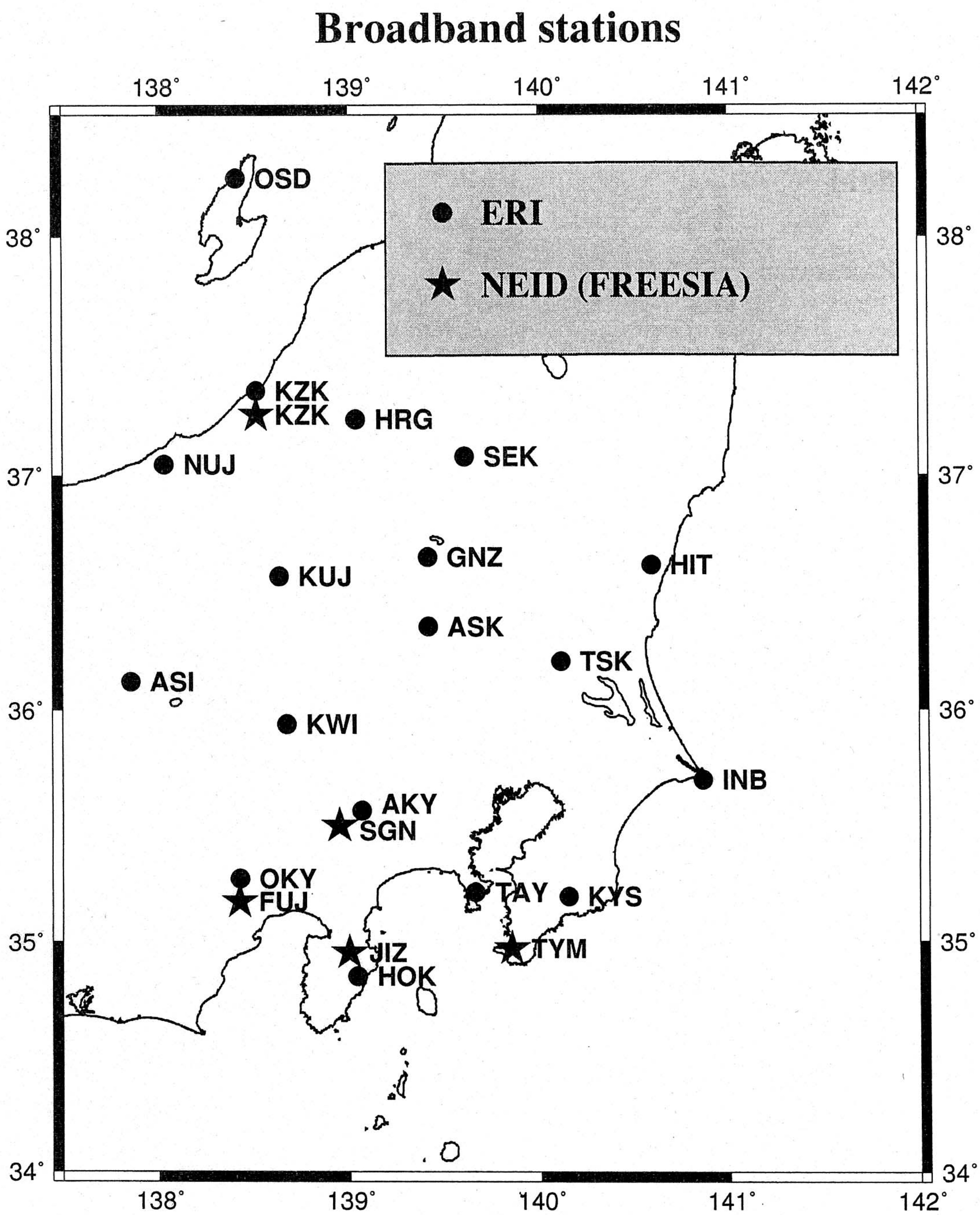
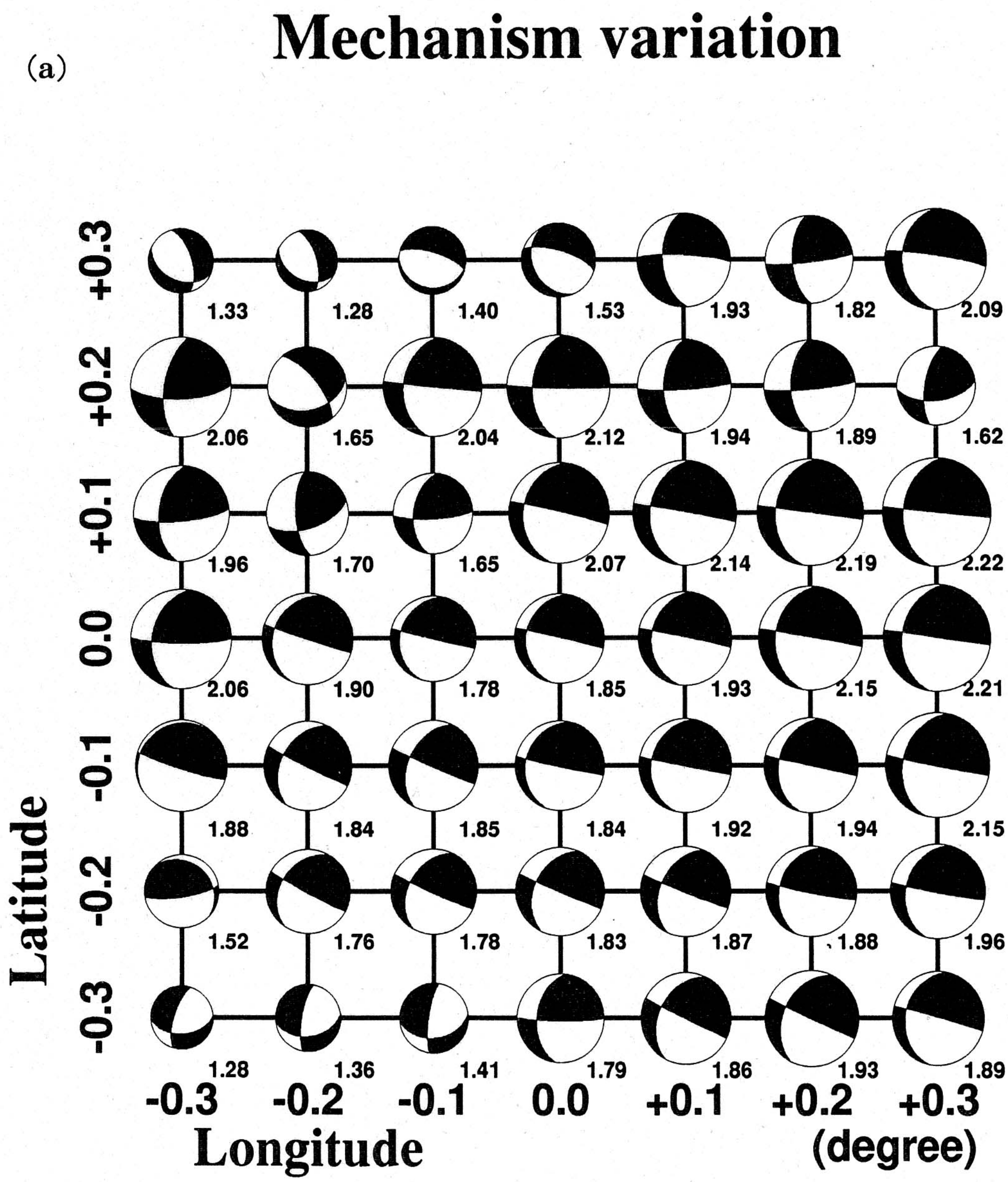


Fig. 1. Location of regional broadband seismic stations available in the Kanto area, Japan. The closed circles indicate the stations operated by the Earthquake Research Institute, and the stars indicate the stations of FREESIA network.

when JMA detects an earthquake in the area. For the actual moment tensor inversion, broadband data are lowpass filtered at 0.1 Hz, and a laterally homogeneous flat layer structure is assumed to calculate Green's function. JMA's initial location can be off as large as 10 km from the final JMA location, but such a 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 0.1 Hz 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 0.1 Hz 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.

(a)



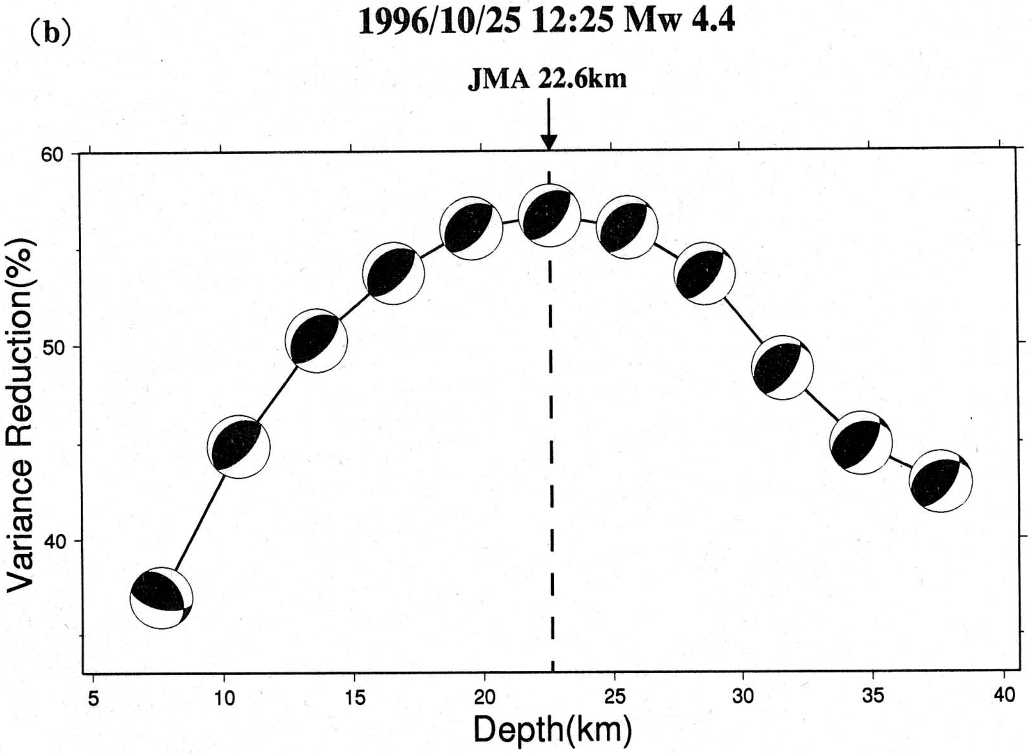


Fig. 2. (a) Moment tensor solutions of an intermediate depth earthquake (1996/10/12 21: 40 Mw=4.2) obtained on each grid point of 10 km-mesh. Numbers next to the focal mechanisms are estimated seismic moment ($\times 10^{15}$ Nm). Only the best double couple component is shown. The location (0.0, 0.0) corresponds to the preliminary location given by JMA (after Ito, 1997). (b) Variance reduction as a function of depth of a shallow event (1996/10/25 12: 25 Mw=4.4). The epicenter is fixed 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 (22.6 k), although the mechanisms are not so dependent on the depth. Therefore, the variance reduction, which is a fuction of the residual (4), should allow earthquakes to be located.

Realtime monitoring

Let us think about 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

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

where $G_i^{sk}(t)$ and $d^k(t)$ are theoretical and observed seismograms at kth station (superscript k is used to represent all three component seismograms of a station k) respectively, and m_i^s is the ith component of the moment tensor. The normal equation based on (1) is

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

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 vector form by

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

Because $\boldsymbol{A}$ 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 $\hat{\boldsymbol{m}}$ can be obtained by a simple matrix multiplication if $\boldsymbol{b}$ is determined. This shows that the procedure for 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 $\hat{\boldsymbol{m}}$) is

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

which can be also easily calculated if we have $\boldsymbol{b}$.

It should now be clear that in order to monitor EAF from long-period SWF, we only need to be able to calculate the cross-correlation $\boldsymbol{b}$ for all possible source points on the 10 km-mesh (hereafter referred as to "virtual sources"). For this to be done in realtime, two conditions must be satisfied: (1) all Green's functions can be stored in the computer memory, (2) the cross-correlation $\boldsymbol{b}$ 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°-38°, 138°-142°), 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 with a long-period wavefield above 10sec., with one sample per two-second, each waveform contains 60 points. If the horizontal and vertical grid sizes are taken to be 0.1° and 10 km respectively, there will be $40 \times 40 \times 10 = 16{,}000$ virtual source points in $4° \times 4° \times 100\,km$ size area. The total size of the Green's function for each station to "memorize" i s

$$60\,(points) \times 3\,(components) \times 16{,}000 (grids) \times 5\,(moment\ tensors) \times 4\ bytes \approx 57\,Mbytes,$$

which can fit in the memories of some recent PCs. As for the second condition, for one station, calculating $b_j^k = \int G_j^k(t) d^k(t) dt$ ($j = 1, \cdots, 5$ for a deviatoric moment tensor) for all virtual sources ($s=1,\ldots,16000$) takes only a second with recent fast PCs. It should, therefore, be 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

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

and the corresponding prediction error is (4). $\hat{\boldsymbol{m}}^s$ 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, the role of a seismic station is now said to be to estimate $\boldsymbol{b}^{sk}$ for all possible s every second, and to send them to the central computer, where $\boldsymbol{b}^{sk}$ from different stations are summed to estimate $\boldsymbol{b}^s=\Sigma_k \boldsymbol{b}^{sk}$ for all s. The central computer multiplies $(\boldsymbol{A}^s)^{-1}$ to $\boldsymbol{b}^s$ to obtain $\hat{\boldsymbol{m}}^s$ for all s, and chooses the best one using (4). This "solution" may be shown visually on a display, which then gives 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 then also be possible to "predict" **in realtime** 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 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., a better knowledge of the regional structure improves the Green's function, which may result in a smaller mesh size; a better knowledge of the site effect improves strong motion prediction; advanced source analysis such as that attempted by Kaverina *el al.* [1997] improves the estimation of the effects of rupture propagation, etc. What seems to be important is to realize that seismology is now at the stage where it is possible to start such realtime monitoring and prediction.

The realtime monitoring of long-period SWF need not be restricted to the regional scale problem. Instead of the Green's function, we can correlate an 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.* (1994) reported 10sec period volcanic signals observed at remote broadband seismic stations. Reports on longer-period signals on a global scale can also be found in many geophysical literatures (Kanamori and Given, 1980; Kawakatsu, 1989; Rouland *et al.*, 1992; Shearer, 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 15sec period are continually emitted from a known source (Kaneshima *et al.*, 1996). Legrand *et al.* (1999) performed the grid-point moment tensor inversion (of 100 m-mesh), and Kawakatsu *et al.* (1999) suggests the possibility of the realtime monitoring of the volcano using long-period waveforms.

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