GRiD MT (Grid-based Realtime Determination of Moment Tensors)
monitoring the long-period seismic wavefield

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Abstract

We have developed and implemented a new grid-based earthquake analysis system that continuously monitors long-period seismic wave-field of 20 to 50 seconds recorded by broadband seismometers. The new analysis system automatically and simultaneously determines the origin time, location and seismic moment tensor of seismic events within three minutes of their occurrence. This system has been in operation since 2003 at the Earthquake Research Institute (http://www.eri.u-tokyo.ac.jp/GRiD_MT/), and the locations and origin times are usually obtained within 3s and 20km away from the earthquake catalog values determined by the Japanese Metrological Agency (JMA). In addition, moment tensor solutions are comparable to the network solutions manually obtained. This new system enables us to monitor long-period seismic wavefield continuously further to help identifying long-period (or low-frequency) events which are undetectable by the conventional monitoring of short-period seismic wavefields.

Key words: Seismic sources, automated real-time system, moment tensor inversion

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1 Introduction

Until now, many automated waveform data processing systems have been developed that use waveform inversion techniques to determine earthquake source mechanisms (i.e., CMT solutions). For earthquakes with moment magnitude larger than 5, moment tensors are routinely determined by several institutes using long-period waveforms observed by the world-wide seismic networks (Dziewonski et al. (1981); Sipkin (1994); Kawakatsu (1995)).

For regional earthquakes, there are several attempts to estimate moment tensors using regional broadband networks. For example, Thio and Kanamori (1995) analyzed moment tensors of local earthquakes using TERRA-scope regional broadband surface waveforms. Dreger and Helmberger (1993) developed a broadband body wave inversion to estimate regional earthquakes using three-component sparse network data. Moment tensors of regional earthquakes in various countries and areas are now determined using this algorithm.


As all of these systems are started after receiving informations about earthquake occurrences, they basically process data that are already saved on hard disks, rather than a real-time data flow of waveforms. For this reason, it is difficult to reduce the time lag between the earthquake occurrence and determination of the earthquake mechanism, as these solution systems must wait until they receive information concerning the earthquake’s origin time and location.

To circumvent this situation, Kawakatsu (1998) suggested a possibility of monitoring the long-period wavefield in realtime using a grid-based search algorithm. Tajima et al. (2002) have applied this approach to Berleley Digital Seismic Network (BDSN) data with a 0.25 degree mesh grid points. Recently, Ito et al. (2006, 2007) employed a similar technique that lead them to report very-low-frequency earthquakes occurring in the transition zone of the subducting plate interface along the Nankai subduction zone in the southwest Japan. Auger et al. (2006) presented a comprehensive processing tool which performs by 62 node of a Linux cluseter for the real-time analysis of the moment tensor of very long period to monitor the activity of the Stromboli volcano. Although these researches are the approaches which do not use prior earthquake informations, they use the waveform data stored on hard disks, rather than the actual flow of data.

In this study, we introduce a new analysis system that use a waveform data on
a network or a memory and developed the system that continuously monitor long-period seismic wavefield. Kanamori et al. (1999) pointed out that such a continuous monitoring of waveforms enhances the reliability of the system because of minimizing of the workload.

2 Method

2.1 Inversion algorithm

A moment tensor inversion is considered for cases where the origin time and the source location are given. The observation equation of such an inversion is provided below, with s denoting the source and k the station:

\[ G_{sk}^i(t)m_{is} = d^k(t) \]  

(1)

where \( G_{sk}^i(t) \) is the theoretical waveform (Green’s function) for \( i-th \) component moment tensor, and \( d^k(t) \) the observed waveform, and the summation convention is assumed for subscripts. This equation covers for all three of the component waveforms obtained at station \( k \), and \( m_{is} \) refers to the \( i-th \) component of the moment tensor at a source \( s \). The corresponding normal equation is:

\[ A_{ji}^s m_{is} = b_j^s \]

(2)

where \( A_{ji}^s = \sum_k A_{ji}^{sk}, b_j^s = \sum_k b_{sk} \), \( A_{ji}^{sk} = \int G_{sk}^i(t)G_{sk}^j(t)dt \), and \( b_{sk} = \int G_{sk}^k(t)d^k(t)dt \).

Hereafter, the superscript for the source, \( s \), is omitted from equations when not confusing. The least squares solution of the moment tensor is then given by:

\[ \hat{m} = A^{-1}b \]

(3)

In this equation, \( A \) is given once a structural model is specified as it can be provided solely by the Green’s functions. The inversion solution can therefore be obtained if \( b \) can be estimated from the Green’s function and the observed waveform. In addition, the prediction error of the observed waveforms for the obtained moment tensor is also easily calculated:

\[ \text{res} = \left( \sum_k \int d^k(t)^2 dt \right) - b'A^{-1}b \]

(4)
Thus, for a given “virtual” source $s$, both the moment tensor (3) and the residual (4) can be easily estimated. This allows us to perform a grid-search type approach to find a moment tensor solution and a location of a virtual source which is most consistent (i.e., gives the least prediction error) with the observed wavefield. Kawakatsu (1998) suggested a possibility to do such a grid-search in realtime for every one second to monitor the regional long-period seismic wavefield.

To search for the best solution, in the present approach, instead of the quantity estimated in (4), a variance reduction (VR)

$$VR = \left[ 1 - \frac{\text{res}}{\sum_k \int (d^k(t))^2 dt} \right] \times 100(\%) \quad (5)$$

has been used in the actual monitoring. $VR$ is an indicator of the fit between the observed waveform and the theoretical waveform.

### 2.2 Realtime analysis system

#### 2.2.1 Outline of the system

Our system consists of programs that perform the following tasks: (1) receiving of data (recvt, order), (2) filtering and conversion of data from the shared memory into the standard output (shmdump), (3) moment tensor inversion (rmtinv), (4) detection of an earthquake (EventDetect.pl), (5) visualization (mtplot, shmx, mtx) and dissemination programs (e-mailing, www). All these programs work together to form the system. Programs (1) and (2) were prepared using those from the WIN system (Urabe (1994)). Programs (3) to (5) were developed in the current study. Since all of these programs have been developed for clearly-defined functionality, the system is capable of flexibly accommodating changes and modifications. Fig. 1 shows how these programs are interrelated. The programs have also been developed to facilitate offline processing of data as well as real-time processing.

#### 2.2.2 System configuration

As this earthquake analysis system requires a high level of computational performance and computers with large memory resources, we used PCs with the specifications shown below for the actual monitoring: CPU: Intel Xeon 3.06 GHz; Mother board: Chipset ServerWorks GC LE; Memory: 1 GB PC2100 DDR SDRAM. For both the system and memory, bandwidth is 4.2 GB/s. A system with insufficient memory bandwidth, such as a Pentium III (1.06
GB/s), is not capable of real-time processing. Each of the PCs is connected to a broadcast segment to which data from the satellite or terrestrial is distributed, so the PCs can easily share seismic waveform data.

2.3 Monitoring details

2.3.1 Period range

In ordinally moment tensor inversions, the frequency band used for analysis may be modified to adjust for the earthquake magnitude. Our system, however, employs a fixed frequency band because it performs continuous real-time processing. Considering the degree of seismic activity in the monitored area, long-period wavefields of 20 to 50 seconds are used in this study. A recursive digital filter (Saito, 1978) is used as the band-pass filter for the waveform, as such a digital filter works well with real-time processing. The broadband seismometers installed at Japanese stations produces velocity records. To reduce processing time, velocity records are used as in the inversion, instead of displacement records.

2.3.2 Time length, station number and grid size

The time length of the analysis, number of stations, and number of virtual sources need to be set in such a way that enables real-time processing. Considering that F-net determines a solution at three stations close to the hypocenter (Fukuyama et al., 1998), it is considered herein that the monitoring area is where real-time processing is possible at three stations. For a seismic wave that travels 400km distance, P, S, surface, and other major waves arrive at stations within 2 minutes. For this reason, the time length covered by the analysis is set for 2 minutes. As re-sampling of data is performed every second, the system collects 120 data points in total. As we used long-period waveforms (20 s to 50 s), there is no need for the high resolution required in determining hypocenter. Thus, virtual sources are located every 0.1 degree horizontally and every 9 km vertically (depth). Under these conditions, our tests show that real-time data processing is possible for up to some 7,000 virtual sources. A single PC is therefore able to cover an area of 2.4 degrees x 2.4 degrees x 90 km (= 25 x 25 x 11 = 6875 virtual sources,) in maximum. While more stations should be used to improve the reliability of the obtained solutions, monitoring with three stations is conducted for two reasons. Firstly, this particular inversion provides comparatively stable solutions even with a small number of stations. Secondly, improved computer performance enables us to increase the number of stations in the future.
2.4 Earthquake detection algorithm

As this system does not depend on a preliminary report of the seismic event occurrence, the system itself is required to detect the earthquake. Thus, the system monitors the $VR$ of every $\hat{m}^s$, which is determined every second. Supposing that the maximum value of $VR$ over a time period of $w$ seconds is $T_i$, where $i$ denotes the time step in second, in a case where this $T_i$ meets the condition below, this system decides that an earthquake has occurred.

$$T_{i-1} \leq T_i \geq T_{i+1}, T_i \geq VR_0$$

(6)

where $VR_0$ is the event detection threshold, which is set to 65.0. As $w$ is set to 20 seconds, the system recognizes an earthquake occurrence on average 30 seconds after $VR$ takes a maximum value.

3 GRiD MT

We have implemented the realtime monitoring system based on the procedures described above to monitor the seismicity of the Pacific ocean side of the northeast Japan, and have been operating the system since April of 2003. The analysis system is termed GRiD MT (Grid-based Realtime Determination of Moment Tensors), and realtime solutions have been available at the following URL: http://www.iec.eri.u-tokyo.ac.jp/GRiD_MT/.

3.1 Monitoring area

All the broadband stations used in the present study are shown in Fig.2. All the data are collected and distributed in realtime using a satellite telemetering system (Takano et al., 2001), which is recently changed to a terrestrial telemetering system. In terms of the area to be monitored, there is a restriction on the number of virtual sources that enables computation of (3) and (5) within a period of one second. Three different monitoring areas are defined, each containing 25 x 25 x 11 = 6875 virtual sources, as shown in Fig. 2. In the actual monitoring, small parts of these three areas are overlapped. The details of each area are given below:

- **R0010**: 140.8 - 143.2E, 35.8 - 38.2N, 5 to 95 km depth (Stations used: N.KSKF, N.YMZF, E.TSK)
- **R0015**: 139.5 - 141.9E, 34.1 - 36.5N, 5 to 95 km depth (Stations used: N.YMZF, N.ONSF, N.JIZF)
3.2 Green’s functions and moment tensors

For computation of the Green’s function, eight-component seismograms are computed in advance, namely $T_{SS}$, $T_{DS}$, $R_{SS}$, $R_{DS}$, $R_{DD}$, $Z_{SS}$, $Z_{DS}$, and $Z_{DD}$ (for the notation of these terms, see Herrmann and Wang (1985)), for depths at every 9 km from 5 km to 95 km and for epicentral distances at every 5 km from 30 km to 500 km, covering the first 300 seconds from the origin time (which is counted as second 0). We use Saikia’s (Saikia, 1994) frequency wave number integration method. The obtained components were then saved onto a disk. The velocity structure used to compute the Green’s function is the same as the one used by the Japanese F-net moment tensor inversion (Fukuyama et. al., 1998) as listed Table 1.

The current GRiD MT solves only for the deviatoric components of a moment tensor, and the 8 component synthetic seismograms stored on the disk are converted to Green’s functions corresponding to the 5 deviatoric components which are stored in the memory.

4 Results and performance

GRiD MT has been monitoring the area R0010 starting from April, 2003, Fig. 3 shows the monitoring results obtained from January 2004 to December 2006. In all, 550 earthquakes are detected, including some overlaps. Table 2 lists the determined source parameters of selected events with moment magnitude larger than 5.0, and Fig. 4 shows an example for an earthquake, $M_w = 6.2$.

4.1 Comparison with JMA catalog

As GRiD MT does not rely upon a preliminary report of the earthquake information, it is important to check the location and origin time with catalogues determined by dense short-period seismic networks. We compare GRiD MT results with the earthquake catalog data provided by the Japan Meteorological Agency (JMA). Fig. 5 shows the differences between the locations obtained by GRiD MT and those derived from the JMA catalogue. The horizontal grid size for the virtual sources is 0.1 degree, and the results show horizontal differences that are generally less than two grids (averaged differences and standard
deviations are 19.4km ± 11.9 km). There appears to be a systematic bias in the estimate of the epicentral longitude; earthquakes are located further offshore. We attribute this to the inadequacy of the used structural model. The seismic velocity in the frontal arc region is likely to be slower than the main island arc part. The usage of a faster reference model should result in mislocation earthquakes offshore. The vertical (depth) differences are also within two grids. The usage of a more appropriate structural model or a 3-D model would reduce these mislocations.

Fig. 6 shows differences of origin time of GRiD MT and JMA catalogue. The differences of origin times are three seconds or less (averaged differences and standard deviations are -0.3sec ± 3.2sec). As GRiD MT is performed in a frequency band of 20 to 50 seconds, these results are considered to be of high precision.

Fig. 7 compares computed magnitudes with those from the catalog data. Although both are in agreement in general, differences and variations are greater and scattered for smaller earthquakes. The maximum differences in magnitude between the two methods are 0.6 (averaged differences and standard deviations are 0.00 ± 0.27). It is well known that the magnitude estimated by JMA tend to be larger than the corresponding moment magnitudes for large earthquakes (Takemura, 1990). Although the average difference is 0.00, for relatively large events (Mj>4.5), Mj is about 0.1 larger on the average than Mw of GRiD MT. The scattered estimate of Mj for smaller events appears to make the average difference reduced.

All in all, we conclude that GRiD MT obtains origin time and locations with a high level of precision both in time and space.

4.2 Comparison with F-net solutions

The broadband seismic network F-net operated by the National Research Institute for Earth Science and Disaster Prevention (NIED) provide their moment tensor solutions. Although the F-net solutions assume an preliminary epicenter provided by JMA, they do estimate the depth of earthquakes. We compare GRiD MT solutions with the manually determined F-net solutions available on the internet. Fig. 8 shows a comparison of the obtained moment magnitudes. The magnitudes obtained by the two methods have differences of approximately 0.1 or less (averaged differences and standard deviations are 0.03 ± 0.08), and are very similar. Differences in depth estimated by the two methods are shown in Fig. 9; again the similarity is strong, with differences being less than 2 grids. With respect to depth, the R0010 and R0100 monitoring areas results tend to be shallower than the corresponding F-net results. We
attribute this trend to the fact that F-net solutions use the assumed epicenters obtained by JMA.

We next compare earthquake mechanisms estimated by the two methods. In comparing mechanism solutions, we use an index of similarity of two moment tensors introduced by Kuge and Kawakatsu (1993). The index value is 1 if the two mechanisms are identical, and -1 if they are completely different. The index value is not affected by the size of the earthquake. The comparison results are shown in Fig. 10. The similarity is 0.8 or higher for most of the data, indicating that the obtained mechanisms are very similar.

4.3 Threshold of the VR

The VR threshold is set at $VR = 65.0$ for this study. This setting enables the detection of earthquakes with a magnitude of larger than approximately 4.5, as defined by JMA magnitude (note that $M_j$ is larger than $M_w$ by about 0.2). To detect smaller earthquakes, we need to lower the threshold value; however, a lower threshold value results in more false detections. Fig. 11 shows the relation between VR threshold and the number of false detections. The vertical axis indicates the ratio of the number of actual earthquakes detected by JMA to that of earthquake detected by GRiD MT. With the VR threshold at 65.0, this ratio is 73.6%, meaning that 26.4% of the detected cases are false detections. We have examined the possibility that some of these events are actually real “unusual” events, but could not identify any. The presence of unusual (e.g., very-low-frequency) earthquakes are not established along the Pacific coast of northeastern Japan.

Although a larger VR threshold reduces the number of false detections, it also results in the fewer earthquakes detections. Also VR can became as high as 50 due to the teleseismic earthquake. To detect as many earthquakes as possible while reducing the number of false detections, GRiD MT might need to cooperate with a system that determines by dense short-period networks. The use of a larger number of stations might solve this problem of teleseismic events.

In Fig. 12, the vertical axis indicates the ratio of the number of earthquake determined by JMA to that detected by GRiD MT, and the horizontal axis refers to the JMA magnitude. The three lines show cases that correspond to three different VR thresholds, 50 ($\Delta$), 65 (o), and 70 (+). With the threshold set at 65, the value chosen for our monitoring, GRiD MT detects 90% of earthquakes of magnitude 4.5 or more. For the rest 10 percent of events, the long-period wavefield was contaminated by surface waves of large teleseismic earthquakes.
5 Discussion

5.1 Remaining problems

Missing data  The most important problem to consider at this point is how to deal with missing waveform data. In such a case, our system is unable to correctly detect an earthquake. As this problem arises from the fact that data is currently being used from three fixed stations, we need to consider building and employing a new algorithm that monitors three stations out of more where data are collected.

Multiple-PC processing  In addition, to expanded the coverage area (e.g., entire Japan), multiple PCs will be needed in distributed processing. The analysis results from all PCs would then need to be integrated effectively and correctly. In the present study, two or more different monitoring areas partially overlap each other, and multiple sets of information are detected for same earthquakes. This overlapping of information must be avoided.

Monitoring period range  The current system is more-or-less successful in monitoring the period range of 20 to 50 seconds. This is so because the largest earthquake occurred during the study period is of Mw6.5. The system may not be able to properly detect an earthquake larger size, as the assumption of a point source does not hold true for such a large earthquake. The monitoring period range would need to be adjusted depending on actual monitoring purposes. For larger earthquakes, it will be necessary to use longer period and far station data (Fukuyama and Dreger, 2000).

Monitoring “long-period” events  Seismolgy has now experienced plenty examples of “long-period” seismic events (e.g., Kanamori and Given (1982), Kawakatsu et al. (1994), Ekström (2003)) which may not be detected using conventional monitoring of short-period seismic networks. Recently, Ito et al. (2007) added new such an example by employing a grid-based approach to discover ultra-low frequency earthquakes in the deeper portion of the seismogenic zone beneath southwest Japan, where major interplate earthquakes are expected in the near future. With GRiD MT monitoring a long-period wavefield, such “long-period” events can be also regularly monitored. Although in our current system, the isotropic moment tensor and the single force component are not monitored, such inclusion is possible and is planned in the near future which should further expand our ability to detect “long-period” events in realtime.
6 Conclusions

The GRiD MT described in this paper utilizes realtime broadband seismic waveform records collected and distributed by a satellite or terrestrial telemetering system. It continuously monitors long-period wavefields of 20 to 50 seconds to automatically determine earthquake origin times and locations as well as mechanisms (moment tensor solutions). GRiD MT is the first of its kind in the world, and after three years of monitoring we reached the following conclusions: (1) GRiD MT detects earthquakes and determines the source parameters with a high level of precision and complete automation within three minutes of the earthquake occurrence. (2) The origin time and locations obtained using our system are very similar to those of JMA catalogue. (3) The mechanism and moment magnitude obtained by our system are very similar to the corresponding F-net solutions determined by NIED.

The above conclusions suggest that GRiD MT can be highly effective in the further development of new seismic analysis systems that are able to monitor long-period earthquakes that none of the conventional short-period wavefield monitoring systems are able to detect. Our monitoring results also prove the feasibility of continuously monitoring of the long-period seismic wavefield. Incorporation of more accurate structural models (e.g., 3-D), and/or the usage of different period data, should result in more accurate description of the earthquake activity field in realtime.

Acknowledgments

We used the F-net data provided by the National Research Institute for Earth Science and Disaster Prevention. We also used FKRPROG, developed by Saikia, for the computation of the Green’s function.

References


at regional distances with single station or sparse network data, *J. Geophys. Res.*, 98, 8107-8125.


Takano, T. et al., Development of the national real-time distribution system of high sensitivity waveform data *Program and Abstracts, Seismological Society of Japan, No. 2*, B57.

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<th>S velocity (km/s)</th>
<th>Density (kg/m³)</th>
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<th>Qs</th>
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Table 2. Detected event list larger than $M_w=5.0$.

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Fig. 1. Outline of the real-time earthquake analysis system used in this study.
Fig. 2. Locations of stations (filled triangle) and virtual sources (plus). Three monitoring regions (R0010, R0015, R0100) are showed.
Fig. 3. Monitoring results from January 2004 to December 2006. The focal mechanisms are lower hemisphere projection and are scale by the moment magnitude.
Fig. 4. Example of the monitoring result for an earthquake 2005/Oct/19 20:44:44 Mw=6.2. The moment tensor shows thrust faulting. The solid lines and dashed lines represent the observed and synthetic waveforms, respectively.
Fig. 5. Horizontal and depth differences of the GRiD MT locations and the Japan Meteorological Agency (JMA) catalogues. The difference pairs of longitude and latitude are plotted (top). There appears a systematic bias in the longitude difference. Histogram of the longitude difference (bottom left), latitude difference (bottom center) and depth difference (bottom right).
Fig. 6. Origin time of differences of GRiD MT and JMA catalogues.
Fig. 7. Left: Correlation of the magnitude of GRiD MT and JMA catalogues. Right: Histogram of the difference in magnitude by GRiD MT and JMA catalogues.
Fig. 8. Left: Correlation of the moment magnitude of GRiD MT and F-net catalogues by NIED. Right: Histogram of the difference in moment magnitude by GRiD MT and F-net catalogues.
Fig. 9. Histogram of the depth differences of GRiD MT and F-net catalogues.
Fig. 10. Histogram of the mechanism resemblance of GRiD MT and F-net catalogues. Resemblance is the cross-correlation of P-wave radiation patterns. The index value is 1 if the two mechanisms are identical, and -1 if they are completely different.
Fig. 11. Probability that a signal is an real earthquake. The vertical axis indicates the ratio of the number of actual earthquakes detected by JMA to that of earthquake detected by GRiD MT. With the $VR$ threshold at 65.0, this ratio is 73.6%, meaning that 26.4% of the detected cases are false detections.
Fig. 12. Detection Rate of events for JMA catalogue. The vertical axis indicates the ratio of the number of earthquake determined by JMA to that detected by GRiD MT, and the horizontal axis refers to the JMA magnitude. The three lines show cases that correspond to three different $VR$ thresholds, 50 ($\triangle$), 65 (○), and 70 (+).