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Automated near-realtime CMT inversion

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Abstract.
The Earthquake Research Institute (ERI) of the University of Tokyo has completely automated the process of determining source mechanisms of earthquakes using waveform data. The solutions are automatically distributed using the Internet without being checked. The process is initiated by receipt of e-mail giving the origin time and location of an earthquake. To determine the source mechanism, we apply the Harvard centroid moment tensor (CMT) inversion method to long-period body wave data (the portion of the seismogram from the first arrival to the initial surface wave). The method has been successfully applied since October 1993 to all of the major earthquakes in the world for which we received event e-mail. 108 of the 242 CMT solutions in 1994 were determined within 6 hours of the event, with an average delay of 3.8 hours. For local events (e.g., events around Japan), it is also possible to determine CMT solutions within 30 minutes from the occurrence of the earthquakes, using an efficient dialup data retrieval system operated by ERI.

Introduction

Due to advances in seismology in the last 15 years, reasonably accurate earthquake source mechanisms can now be determined within several hours of the occurrence of an earthquake. The moment tensors of world major earthquakes ($m_b > 5.4$) are now being routinely determined by several institutes using long-period waveforms [e.g., *Ekström*, 1993; *Sipkin*, 1994]. The success of these efforts suggests that it may be possible to obtain such solutions quickly and accurately enough so that they can be used to issue warnings soon after the occurrence of large earthquakes [*Kanamori and Given*, 1981]. However, it is necessary to automate the process of determination of moment tensor solutions in order to be able to issue such warnings.

At the Earthquake Research Institute (ERI) of the University of Tokyo, we have completely automated the process of determining source mechanisms of earthquakes. We apply the Harvard centroid moment tensor (CMT) inversion method to long-period body wave data. The method has been successfully applied since October 1993 to all of the major earthquakes in the world for which we received event e-mail from the U.S. National Earthquake Information Center (NEIC). Solutions have been distributed to the seismological community via e-mail since January 1994. This report presents our procedure for determining automated CMT solutions (AUTOCMT hereafter), as well as some statistics for the AUTOCMT solutions.

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Procedure

The AUTOCMT process consists of the following four parts. (1) Initiation by receipt of e-mail which gives the origin time and location of an earthquake (at present NEIC event e-mail is used). (2) Retrieval of waveform data through SPYDER of IRIS DMC or the POSEIDON Data Center of ERI. Since at both data centers, data retrieval using a dialup system is started much earlier than our receipt of e-mail from NEIC, we can usually find several records from worldwide stations; the number of available stations depends on the interval between the event and the receipt of the NEIC e-mail. (3) CMT inversion. (4) Distribution of the AUTOCMT solutions by e-mail to the seismological community. The entire process is executed by several SHELL scripts on a UNIX machine without human intervention.

CMT inversion The CMT inversion method developed by the Harvard group [*Dziewonski et al.*, 1981] is a powerful technique for determining the moment tensor of earthquakes. It utilizes the entire waveform from the beginning (usually the P-wave arrival) until just before the arrival of the first surface waves; this portion of the waveform contains the arrivals of many different body waves, each of which departs from a different part of the focal sphere. The use of this portion of the waveform significantly increases the coverage of the focal sphere and thus the resolution of the moment tensor. This reduces the number of stations necessary to determine a moment tensor; sometimes records from only one station are sufficient to obtain a solution [*Ekström et al.*, 1986]. The moment tensors determined from this portion of the waveform are less susceptible to the well-known indeterminacy of certain moment tensor components of shallow earthquakes than moment tensors determined from surface wave data [*Kanamori and Given*, 1981]. We use long-period body wave data recorded at teleseismic distances ($\Delta > 30^o$) bandpass filtered between 22mHz and 10mHz (i.e., 45-100sec) for the AUTOCMT solutions.

The AUTOCMT inversion basically follows the procedure described by *Dziewonski et al.* [1981], using a program developed locally [*Kawakatsu*, 1989]. Since the procedure is automated, we cannot visually investigate the quality of the waveform data to discard bad quality records (e.g., those with glitches). We instead prepare data as follows. (1) The station response is deconvolved from each seismogram, and a bandpass filter (22-10mHz) is applied. (2) We then estimate the root mean square (RMS) amplitude of each seismogram; when the ratio of the maximum to minimum RMS amplitudes is too large we discard some of the records so that the ratio stays below 300. (The median RMS value is use as a reference, and the records which have the largest RMS ratio relative to the reference value are discarded). Those records which happen to have glitches are usually discarded at this stage, because they have unacceptably large amplitudes after filtering. In the final iterative least squares inversion, each record is weighted by the inverse of its power for the first two iterations and by the inverse of the power of the differential seismogram afterwards. This weighting scheme also helps to stablize the solution by reducing the weighting of "bad" records.

Performance

The above method has been successfully applied since October 1994 to all of the major earthquakes in the world for which we received NEIC event e-mail. In this section, we present some of the statistics of AUTOCMT solutions determined in 1994.

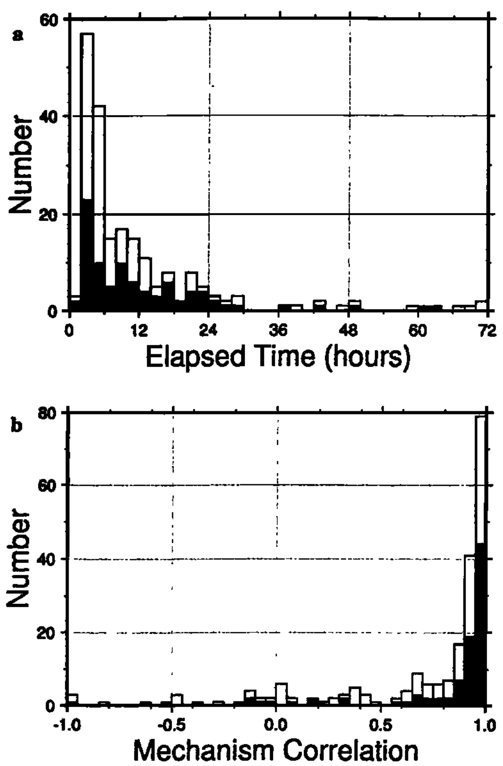

Figure 1. Histograms of (a) elapsed time for determining AUTOCMT solutions, and (b) mechanism correlation coefficient between the AUTOCMT and Harvard CMT solutions. The white and gray bars in the histograms correspond to all events in 1994 and events after August 1, respectively.

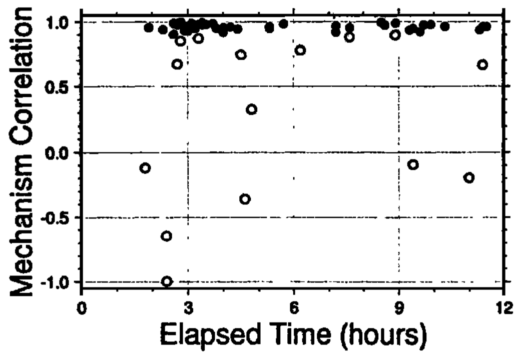

Figure 2. Mechanism quality vs. elapsed time. Closed symbols denote good quality solutions (correlation coefficient > 0.9).

Time performance Figure 1a shows a histogram of the elapsed time between the occurrence of an earthquake and the AUTOCMT determination. For 108 events out of 242 (45%) for which solutions were determined, the AUTOCMT solutions were obtained within 6 hours of the occurrence, with an average of 3.8 hours. This statistic compares with those of the other two routine (manual) determinations of moment tensor solutions, namely the Harvard quick CMT [*Ekström*, 1993] and USGS rapid MT [*Sipkin*, 1994]: 74 out of 178 (42%) with an average delay of 4.5 hours for the Harvard solutions, and 29 out of 152 (19%) with an average delay of 3.7 hours for the USGS solutions.

Of the four parts of the AUTOCMT procedure, the most time consuming part is the first part. The last two parts usually take less than ten minutes; and the second part depends on how many stations we need to use. At the moment, it is difficult to determine an AUTOCMT solution within two hours of the occurrence of an earthquake, but it is quite possible to do so within three hours of the occurrence.

Mechanism Quality We measure the mechanism quality of AUTOCMT solutions by the correlation coefficient of P-wave radiation pattern with the final Harvard CMT solutions [e.g., *Dziewonski and Woodhouse*, 1983], which are more reliable, as the latter are determined several months later when a large number of records have become available. When the coefficient is above 0.9, the two solutions may be considered very similar. Figure 1b shows the histogram of the correlation coefficients. Since August 1994, the AUTOCMT program was upgraded so that records from a larger number of stations can be used for the analysis. The gray bars in the histogram show results for events after August 1. Until the end of July, only 49% of the AUTOCMT solutions had a correlation coefficient larger than 0.9, while after the upgrade, 67% have correlation coefficients over 0.9. Thus in the following, we discuss the mechanism quality of the AUTOCMT solutions for events which occurred after August 1, 1994.

Figure 2 shows the mechanism quality in relation to the elapsed time. The solid symbols depict good quality (correlation coefficient > 0.9) solutions. It can be seen that the elapsed time is not the major factor which controls the quality of solutions. Three hours appears to be sufficient to obtain good quality solutions. In Figure 3 we compare the mechanism quality against the size of events. On the top, the quality index (the number of records used for the inversion multiplied by the square of the variance reduction) is given on the vertical axis. For the larger events ($M_w > 6.1$), the quality of the AUTOCMT solutions appears to be very good. For smaller events, when the quality index is above ~ 5, the quality is usually high. When it is below 5, some of the AUTOCMT solutions are not reliable.

Finally in Figure 4, we compare the seismic moment (of the best double couple [*Dziewonski and Woodhouse*, 1983]) of the AUTOCMT solutions against that of the Harvard CMT solution. We only compare those solutions whose correlation coefficient is above 0.9. On the average, the seismic moment of the AUTOCMT solutions is 20% smaller than that of the Harvard solutions. For large events this is partly due to the fact that we do not take into account the effect of the source finiteness in AUTOCMT, while the Harvard CMT solutions do include finiteness effects by simultaneously inverting body wave and surface wave data. If the misfit comes from the phase delay (or advance) of body wave phases, the estimated moment should scale with the square root of the variance reduction. The actual situation does not seem to be so simple, but a positive correlation appears to exist.

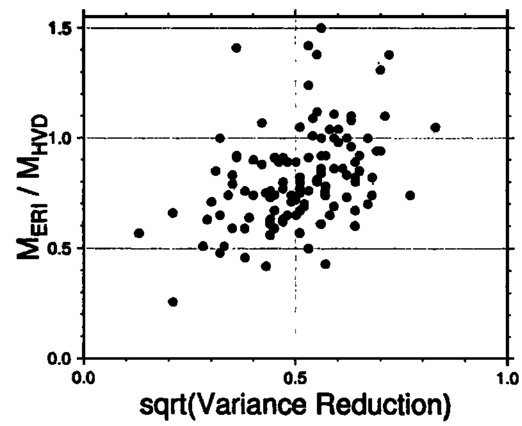

Figure 4. The ratio between the seismic moment of the AUTOCMT solutions and that of the Harvard CMT solutions is compared with the waveform variance reduction.

Discussion

Figure 1b shows that three AUTOCMT solutions in 1994 converged to the reversed solution (i.e., the mechanism correlation coefficient is ~ -1). These solutions correspond to some of the largest events which took place in 1994, including the deep Bolivian event. For such very large events, the centroid time shift can be so large compared to the period of the waves used in the analysis that the inversion procedure tries to fit the troughs of waves instead of the next peaks for which it should really fit. This situation can be remedied if we use longer period surface waves for the inversion as the Harvard group does [*Dziewonski and Woodhouse*, 1983].

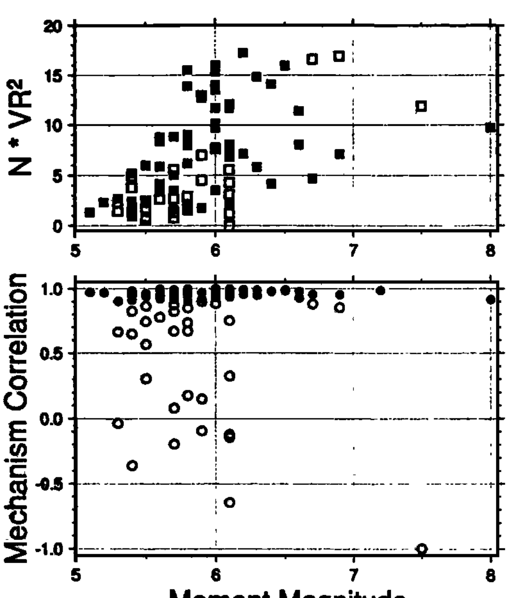

Figure 3. Mechanism quality vs. size of earthquakes. Closed symbols denote good quality solutions.

On the average it is now possible to automatically determine earthquake source mechanisms within three hours after the occurrence. This elapsed time is currently constrained by the time delay for receiving the NEIC event e-mail. However, if we "tune-up" the whole process, it should be possible to determine mechanisms within one or two hours with the system currently available; for example, SPYDER at the IRIS-DMC retrieves data "considering" azimuthal distribution of stations, and when it finishes obtaining data from, say, five stations with good azimuthal coverage, AUTOCMT should be initiated. Such cooperation will certainly be beneficial for our community. Also the quality of the AUTOCMT solutions for small size earthquakes (M_w 5.5 $\sim$ 6.1) would be improved, if SPYDER did not impose a size dependent record collection algorithm on its data retrieval.

For a station whose epicentral distance is less than 1000km, all major seismic phases, including body waves and surface waves, arrive within five minutes of the occurrence of the earthquake. If we could obtain event information within 10 minutes (say from the Japan Meteorological Agency), we could use the currently available dialup system at ERI (which is called ERIOS [e.g., *Tsuboi*, 1995]) to collect data within the next 10 minutes. So, we should be able to determine CMT solutions within about 30 minutes for local Japanese earthquakes. The application of the CMT inversion method to local events is straightforward [e.g., *Fukushima et al.*, 1989], and currently being tested at ERI. Figure 5 shows two AUTOCMT (global and local) solutions obtained for an earthquake off the east coast of Honshu on Feb 23, 1995, as well as some of the Harvard CMT solutions for this region. It took more than 5 hours to obtain the

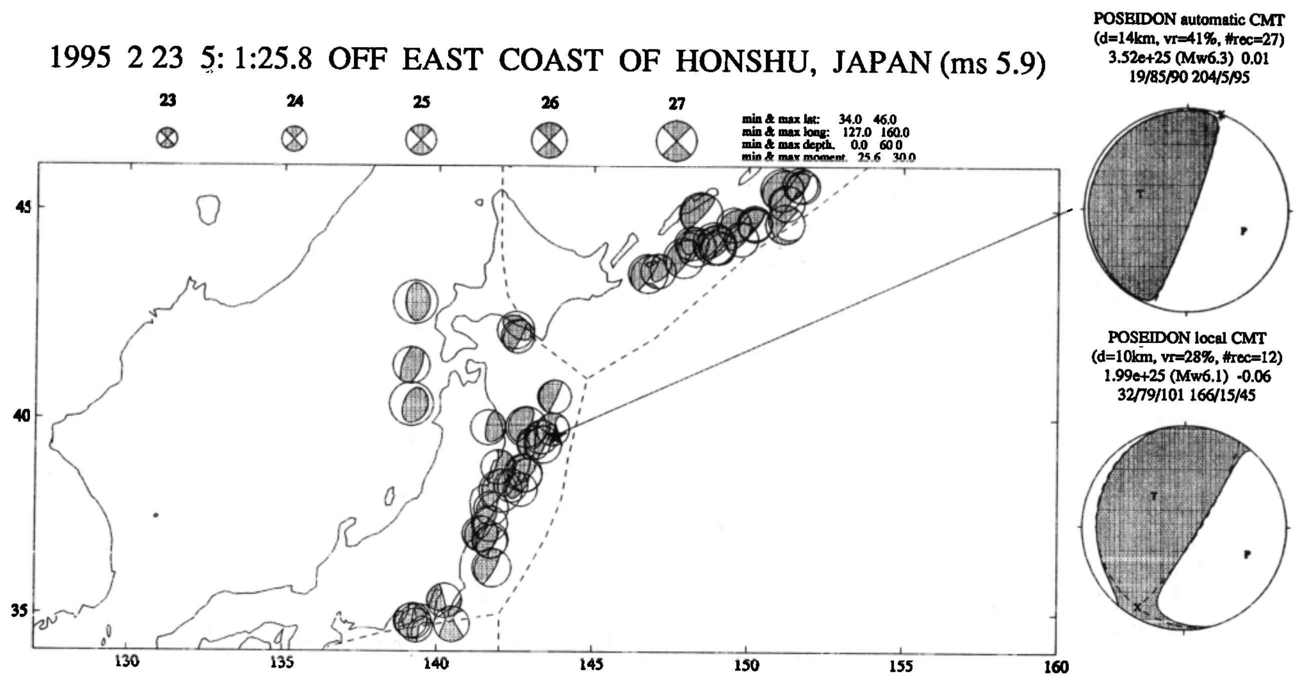

Figure 5. Global (right top) and local (right bottom) AUTOCMT solutions for the event on Feb. 23, 1995.

global solution, while the local solution was obtained 45 minutes after the occurrence. In the near future, with a completely automated process, we should be able to determine CMT solutions for local events within 30 minutes of their occurrence.

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