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Automated Reporting of Earthquake Parameters to the NEIC

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ABSTRACT

This report describes developments in the implementation of strategies that would make it possible for our research group to deliver automatically derived earthquake parameters to the NEIC a short time after a moderate or large earthquake has occurred in the US or elsewhere in the world. The specific information products that we discuss are epicenters and magnitudes for moderate ($M \geq 5.0$) earthquakes worldwide, derived from long-period surface waves, and moment tensors for large ($M \geq 5.5$) earthquakes.

1. Introduction

Rapid detection and location of seismic events worldwide is needed for timely assessment of potential earthquake impact and identification of seismicity patterns before, during, and after major earthquakes. More detailed source parameters, such as focal mechanisms, add important information that can allow for identification of active geologic structures and make it possible to consider the earthquake in a broader tectonic framework, including its potential interaction with other active faults and structures. These source parameters are especially valuable for loss reduction when they are available within a short time following an earthquake.

The great $M_W = 9.0$ Sumatra earthquake of December 26, 2004 occurred a week before our funding from the USGS started on January 1, 2005. In spite of not yet having a fully automated procedure in place, we were able to provide the NEIC with a very good estimate of the magnitude ($M = 8.9$) and the source mechanism within a few hours of the earthquake, and our revised $M = 9.0$ estimate, obtained within 24 hours, became the official NEIC magnitude of the event. The main objective of our project was to develop and improve our analysis and reporting systems to make sure that accurate earthquake parameters can be provided to the NEIC without unnecessary delays.

The Sumatra earthquake, and the intensive aftershock activity that has followed, demonstrate the importance of rapid determination of basic earthquake parameters. The sequence has also identified aspects of our approach that could be further improved. For example, while our long-period, full-seismogram approach will never be able to generate very rapid (i.e., within minutes) results, we believe that it would be possible to achieve a significant reduction in time of analysis such that we can have robust moment-tensor results within one to two hours.

2. Results

In the following two subsections we describe in some detail the current capabilities of the two earthquake-analysis algorithms that have been refined as part of this project, with the objective of establishing a robust flow of event information to the NEIC. In each subsection we have included observations concerning the performance of our algorithms during the great Sumatra earthquake and its aftershock sequence. The description below is focused on describing technical capabilities, and is not intended to give the full theoretical background of the methods. As the focus is on practical results, we have not included an extensive list of references.

Surface-wave locations. The background seismic noise spectrum has a pronounced low in the period range 30–500 s, which makes it possible to observe long-period surface waves at teleseismic distances even for earthquakes of moderate size. Surface waves are frequently the largest-amplitude signals in long-period seismograms, but they have so far not been exploited routinely for event detection or event location. This is due in part to the large variations in phase and group velocity exhibited by these waves at shorter periods. Also, the detection of surface waves and the determination of an arrival time is more complicated than for body waves, owing to the dispersive character of the waves. Instead, surface waves have so far mainly been used to determine M_S, a longer-period estimate of the event size, but this is done only after the event has been located.

The surface-wave detection and location algorithm that we have developed utilizes the global network of stations in an array-processing mode. A global grid of target locations is monitored continuously for detection of coherent surface-wave energy. The tuning of the array for each target location is accomplished by calculation of path corrections using global phase-velocity maps [*Ekström et al.*, 1997]. The quality of the detection and the size of the event are determined using a matched-filter technique. Several components of the current algorithm build on experience gained in earlier studies. *Shearer* [1994] used known earthquakes and a stack of long-period seismograms from the IDA network to develop a matched filter for surface-wave detection. He then applied the matched filter to seismograms from the same network to locate events on a grid of points on the Earth's surface, separated by approximately $10°$. *Ihmlé and Jordan* [1996] used a similar grid-search technique to match long-period ($T>$80 s) Rayleigh waves or their envelopes in a search for slow earthquakes. Both of these earlier studies reported successful detections of moderate-size ($M_S\sim$5.0) earthquakes. In our algorithm, we have developed a method to analyze shorter-period surface waves, which allows us to detect smaller events and to determine the locations and origin times of the events with some precision.

In the method we have developed, a dense grid of test locations covering the surface of the Earth is analyzed for detections using continuous seismic data [*Ekström et al.*, 2003]. An initial detection of coherent surface-wave energy is made by considering points on a 4-by-4-degree global grid. Each grid cell that generates a potential detection is then subdivided into four 2-by-2-degree cells, and

the detection is recalculated. The subdivision is continued, with the smallest grid cell considered having a size of 0.5 degrees. In a cluster of detections (i.e., adjacent grid cells that all show a detection), the one with the greatest correlation is selected as the best event location and time. The timing is determined using a sampling interval of 4 seconds.

In the development of the surface-wave detection and location algorithm, it was applied to archived data. We have also implemented the algorithm in an operational mode, as part of our real-time data analysis. Briefly, we collect real-time data from the GSN and other broadband networks using the internet, and perform various standard analyses on the waveforms, including calculating surface-wave detections and locations using the algorithm described above. We currently analyze data from approximately 150 stations in this way.

Experience from the great 2004 Sumatra earthquake. The numerous aftershocks that followed the December 26, 2004 Sumatra earthquake provided a very intense trial period for the near-real-time surface-wave detection algorithm. The detection and location algorithm was found to be excellent at disentangling overlapping events. This was best demonstrated during the unique aftershock swarm that occurred east of Great Nicobar Island one month after the mainshock. More than 150 $M \sim 5.0$ earthquakes occurred in this area over three days, probably the most intense earthquake cluster ever observed. During January 27 and 28, a $M \sim 5.0$ earthquake occurred approximately every 20 minutes. The table below show the output from our analysis during the first 12 hours of January 27, 2005.

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SWEA 2005  1 27  1 15 12.00   7.3100   93.9400  10.0 0.0 4.9 NICOBAR ISLANDS, INDIA REGION
SWEC 2005  1 27  2 26  8.00   7.6300   93.8800  10.0 0.0 4.8 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  3 17 20.00   7.5600   94.1900  10.0 0.0 4.8 NICOBAR ISLANDS, INDIA REGION
SWEC 2005  1 27  3 43 44.00   7.8800   93.8800  10.0 0.0 4.9 NICOBAR ISLANDS, INDIA REGION
SWEE 2005  1 27  3 56 56.00  27.3800  141.3800  10.0 0.0 5.1 BONIN ISLANDS, JAPAN REGION
SWEA 2005  1 27  3 58 48.00   7.5600   93.9400  10.0 0.0 5.4 NICOBAR ISLANDS, INDIA REGION
SWEB 2005  1 27  4 21  4.00   7.5600   94.0600  10.0 0.0 4.9 NICOBAR ISLANDS, INDIA REGION
SWEB 2005  1 27  4 38 40.00   7.3800   93.8800  10.0 0.0 4.9 NICOBAR ISLANDS, INDIA REGION
SWEC 2005  1 27  4 56 24.00   7.7500   93.7500  10.0 0.0 4.9 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  5  3 12.00   7.4400   93.9400  10.0 0.0 4.9 NICOBAR ISLANDS, INDIA REGION
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SWEB 2005  1 27  5 35 28.00  13.5600   92.8100  10.0 0.0 5.0 ANDAMAN ISLANDS, INDIA REGION
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SWEB 2005  1 27  6 14 32.00   7.6900   93.9400  10.0 0.0 5.0 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  6 44 48.00   7.6300   93.8800  10.0 0.0 5.1 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  6 57  4.00   7.8100   93.9400  10.0 0.0 5.6 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  7 20 24.00   7.5600   93.9400  10.0 0.0 5.1 NICOBAR ISLANDS, INDIA REGION
SWEB 2005  1 27  7 26  0.00   7.8800   93.8800  10.0 0.0 5.2 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  7 35 52.00   7.8100   94.0600  10.0 0.0 5.3 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  8 19 12.00   7.7500   94.2500  10.0 0.0 5.6 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  8 31 20.00   7.2500   94.2500  10.0 0.0 5.3 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  8 42 24.00   7.2500   94.2500  10.0 0.0 5.4 NICOBAR ISLANDS, INDIA REGION
SWEC 2005  1 27  8 58  0.00   7.7500   93.7500  10.0 0.0 5.0 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  9 11 36.00   7.7500   94.2500  10.0 0.0 5.1 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  9 25 36.00   7.7500   94.2500  10.0 0.0 5.2 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  9 52 24.00   7.7500   94.2500  10.0 0.0 5.3 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27  9 59 28.00   7.2500   93.7500  10.0 0.0 5.2 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27 10  8 24.00   7.7500   94.2500  10.0 0.0 5.2 NICOBAR ISLANDS, INDIA REGION
SWEB 2005  1 27 10 16  8.00   7.8100   93.9400  10.0 0.0 5.0 NICOBAR ISLANDS, INDIA REGION
SWEC 2005  1 27 10 25 12.00   8.5000   94.5000  10.0 0.0 5.0 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27 10 42 40.00   7.2500   94.2500  10.0 0.0 5.0 NICOBAR ISLANDS, INDIA REGION
SWEC 2005  1 27 10 50  8.00   7.2500   94.7500  10.0 0.0 4.9 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27 10 58  8.00   7.7500   94.2500  10.0 0.0 5.4 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27 11 14 56.00   7.8100   94.0600  10.0 0.0 5.0 NICOBAR ISLANDS, INDIA REGION
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SWEA 2005  1 27 11 47 44.00   7.7500   94.2500  10.0 0.0 5.6 NICOBAR ISLANDS, INDIA REGION
SWEA 2005  1 27 11 56 56.00   8.0600   94.1900  10.0 0.0 5.0 NICOBAR ISLANDS, INDIA REGION
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Our surface-wave location algorithm was able to keep up with this activity very well, and we were able to provide timely and useful epicentral and magnitude information to the NEIC. The grid-search algorithm has few problems with overlapping events, and the computational burden does not increase significantly with the number of earthquakes during a given time period. Later analyses of the initial epicenters, including comparisons with PDE hypocenters and CMT centroids and moment magnitudes, indicate that the automatic results were highly accurate.

Automatic CMT solutions. The Centroid-Moment-Tensor (CMT) algorithm of *Dziewonski et al.* [1981] has proven to be a very robust method for determining seismic moments and focal mechanisms for earthquakes with magnitudes $M > 5.5$. Under favorable conditions (good station distribution and low seismic noise), the standard CMT method can be used for events as small as $M = 5.0$. The method has been applied systematically to all significant earthquakes since 1976, and the CMT catalog currently contains nearly 23,000 moment-tensor solutions.

In addition to the maintenance and generation of the monthly addition of solutions to the Harvard CMT catalog, our group routinely calculates so-called 'quick CMTs'. The quick CMTs are calculated in the same way as the CMT solutions that become part of the catalog, but they are based on the subset of seismic data available to us in real time via the internet. Just as the regular CMTs, the quick CMTs require the involvement of an analyst, who determines that an earthquake has occurred, collects and edits the associated waveforms, makes decisions about the success of the waveform inversion, and prepares and mails out the results to interested parties.

Over the last few years, we have experimented with and introduced various schemes to allow a computer program to decide which waveform data should be included in the analysis. This is a complicated problem, for a number of reasons. First, since we wish to analyze as many earthquakes as possible with the techniques at hand, most of the earthquakes that we attempt to analyze will only be well recorded on a subset of stations. The automatic editor therefore has to be able to distinguish signal from noise. Second, while the quality of seismic instrumentation and information about the seismograph response functions have generally improved over the last several years, it is not uncommon to have one or a few stations with incorrect polarity or dramatically incorrect gain in the data set for any given earthquake. The automatic editor has to be able to remove such faulty data, even though the signal may appear to be earthquake generated. Any software that aims to select good data and discard bad data has to consider a number of both predictable and unexpected problems, and tends to become quite complex.

Notwithstanding these technical difficulties, it seems reasonable that an automatic editor could be designed that, in most cases, could make decisions similar to those of a trained analyst, even for relatively small events. Following a long testing period, during which a number of quality-assessment parameters were introduced and tuned, we have now developed and tested an automatic waveform editor that meets many of our desired goals. Starting with earthquakes that occurred in January 2004, we have introduced this tool in our routine CMT analysis of earthquakes, with great success. The automatic editor seldom makes choices that lead to an erroneous focal mechanism. For marginal earthquakes the algorithm is more likely to fail completely than to produce a bad result, which is the preferred situation.

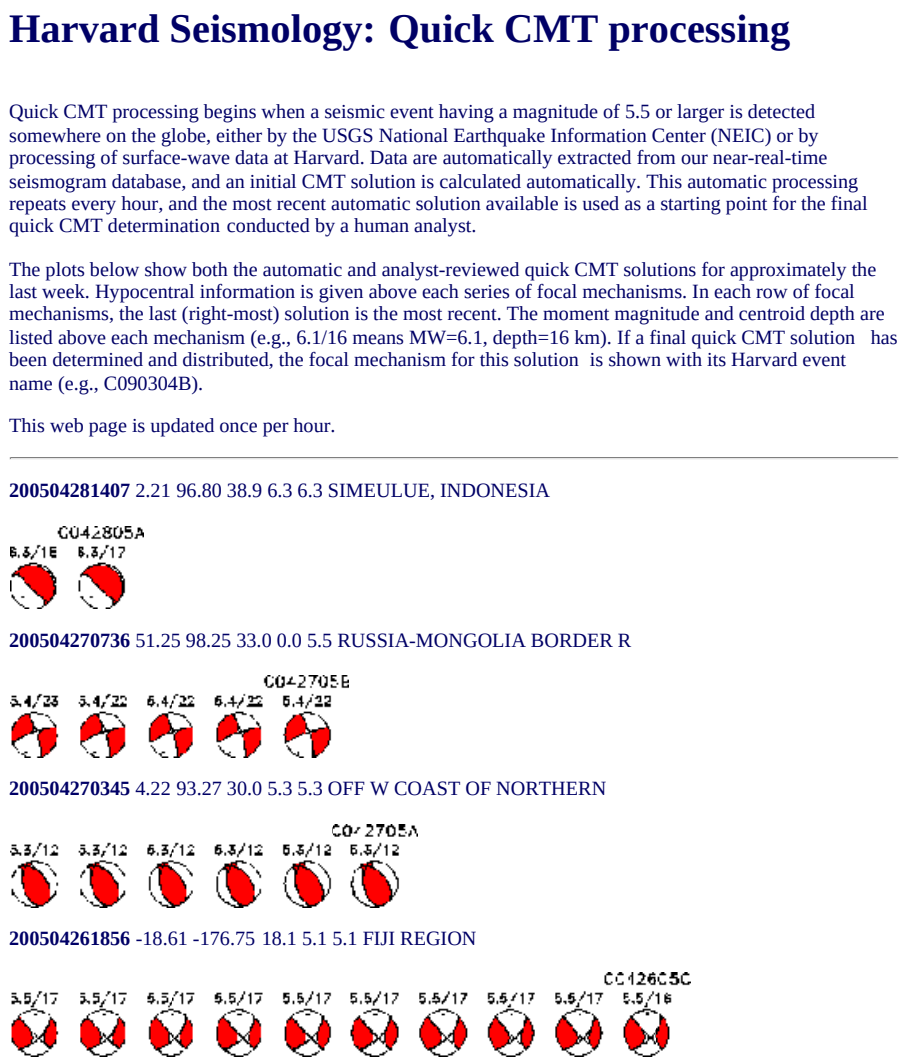

Figure 1: Examples of automatic CMT results on our prototype internal web page.

During the last year, we have implemented the automatic editor in an automatic CMT analysis. Once a hypocenter for a recent earthquake is obtained (usually from the NEIC, but sometimes from our own surface-wave location algorithm), a sequence of programs and scripts prepares all the necessary files, and executes the automatic CMT analysis. The results are posted on an internal web page, and form the starting point for the analyst-assisted CMT analysis. Figure 1 shows an example of the internal web page, which is updated whenever a new earthquake is analyzed.

At the present time, we only attempt an automatic CMT analysis for events with $M \geq 5.5$. For such events, it is very rare that the final, analyst-reviewed CMT differs significantly from the initial automatic CMT. We are currently working on the fine tuning of this algorithm. In particular, more work is needed to identify erroneous solutions; i.e., better criteria and tests have to be included to identify automatically a failed analysis.

Experience from the great 2004 Sumatra earthquake. The 2004 Sumatra earthquake and the aftershock sequence that followed presented a dramatic challenge to all groups involved in global

earthquake monitoring. Figure 2 shows the CMT focal mechanisms of the largest events in the sequence, including the great December 26, 2004 $M_W = 9.0$ and the great March 28, 2005 $M_W = 8.6$ mainshocks.

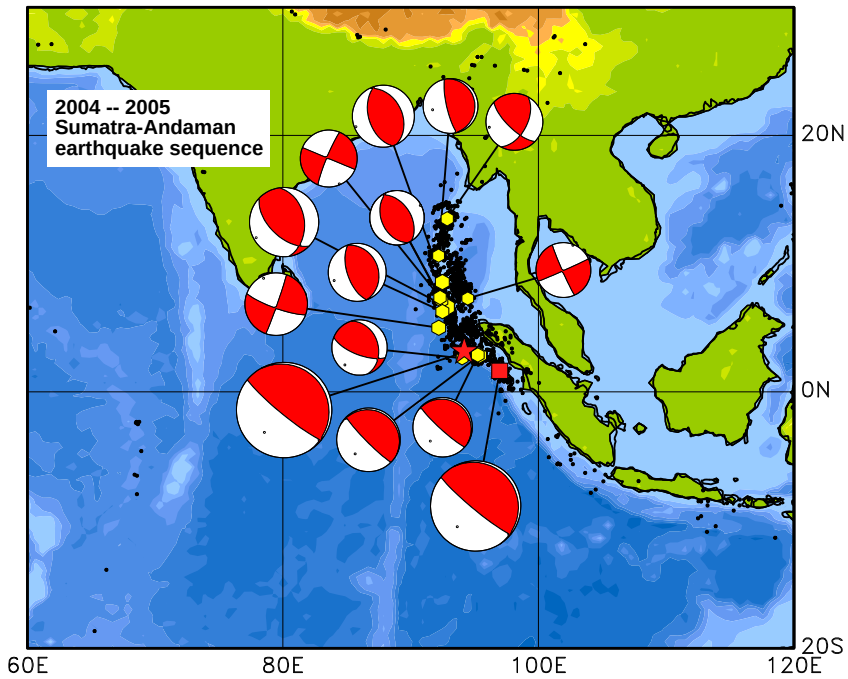

Figure 2: Map of the December 26, 2004 great Sumatra earthquake source area. The CMT focal mechanisms (best double couples) for earthquakes of $M > 6.0$ occurring during the three months following the mainshock are shown together with epicenters of additional aftershocks. The strike-slip earthquake in the back arc is located near the swarm of more than 150 $M \sim 5.0$ earthquakes mentioned in the text.

One of the experiences from the great 2004 Sumatra earthquake is that our automatic algorithm needs to be more adaptive to the size of the event, in particular for very large earthquakes. In the initial stages of development, we had not addressed the possibility that the event had a duration greater than 300 seconds, which poses some technical challenges.

Our prototype automatic CMT algorithm did not obtain an accurate focal mechanism for the mainshock in the earliest attempted automatic analysis. In fact, the initial analysis resulted in a completely reversed mechanism (i.e., with compressional and dilatational quadrants interchanged). This occurred because of the long duration of moment release, and the correspondingly large shift in the centroid time. The analysis found a local minimum with a smaller centroid time with all waveforms shifted by one half cycle. By design, the algorithm adjusts the band-pass filter of the data to include only periods longer than the corner period in order to avoid this problem. However, the maximum high-pass corner that we had envisioned was 200 seconds, which is adequate for most events. For example, the algorithm obtained an essentially perfect result for the March 28, 2005 $M_W = 8.6$ earthquake using the 200-second filter. It is interesting to note, however, that although the initial mechanism was reversed for the December 26 earthquake, the magnitude estimate was still quite good, $M = 8.9$.

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