INCLUSION OF A BODY WAVE SEISMIC MOMENT TENSOR ESTIMATOR IN THE CTBTO/IDC PROCESSING SUITE

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ABSTRACT

The experimental SEL0 system of the CTBTO's Preparatory Commission (Le Bras et al., 2006) now includes a moment tensor (MT) and moment magnitude estimate. The SEL0 system rapidly detects and locates events. The effort to include further processing of large natural events, and get a better size estimate for large natural events than the *mb* magnitude was started in the summer of 2005. The basic scientific software that performs the MT inversion was acquired from Y. Yagi from Tsukuba University, Japan. It performs a time-domain, long-period body-waves MT inversion soon after an event is automatically detected and located, within about 20 minutes after its occurrence. We wrote signal processing scripts to prepare the broad-band International Monitoring System (IMS) vertical seismic data for MT inversion, including deconvolution of the complete instrument responses. We included the scientific software into the Commission's environment and have now achieved its seamless integration through the web page displaying the results of the SEL0 bulletin.

The addition of the moment tensor inversion module allows us to estimate the size and focal mechanism of the detected events, which is of interest for better characterization of the event in a limited time frame. This is important since the only available measure of the size of the earthquake for SEL0 events was the *mb* scale, which saturates for larger events. We have been able to interactively run a number of inversions and we present case examples and statistics from selected events since December 2006.

OBJECTIVES

The objective of this project is to integrate an MT and moment magnitude M_w (Hanks and Kanamori, 1979) measurement in the International Data Centre (IDC) processing system to take advantage of the broadband data sent to the CTBTO IDC. For the following reasons, this additional processing item will be of use to the IDC and the monitoring community in general:

- The additional module will be of use in the prototype processing pipeline using the IMS network that can produce a timely bulletin useful as input for agencies charged with warning the general public about impending disasters such as tsunamis.
- The IDC automatic bulletins measure the size of events using the *mb* magnitude which is known to saturate for events larger than about magnitude 6.5 (e.g., Abe, K, 1995). It is therefore necessary to develop other methods of assessing the size of large events in a timely manner. For large events, the focal mechanism also provides additional information for the tsunamigenic potential of the event.
- The focal mechanism for seismic events is mentioned in Annex 2 of the Protocol to the CTBT as a potentially useful attribute for event screening.
- The method may be applied to data archived at the IDC and used to calibrate the IMS network at low frequencies for large events whose seismic moments have been estimated by other agencies such as the Harvard University centroid moment tensor (CMT) or the National Earthquake Information Center (NEIC) of the U.S. Geological Survey (USGS).

RESEARCH ACCOMPLISHED

Interactive Inversion from the SEL0 Web Page

The IDC operates an experimental processing pipeline to obtain a global bulletin within about 20 minutes of the occurrence of the event (Le Bras et al., 2006). This bulletin, and therefore, the processing pipeline have been named SEL0 in line with the naming convention for the other three automatic bulletins (SEL1, SEL2, and SEL3) published by the IDC for distribution to the member states of the preparatory commission for the CTBTO. These later bulletins are available in a database visible to authorized users 1 hour 50 minutes, 6 hours, and 12 hours, respectively, after the occurrence of the events.

The SEL0 bulletin has proven useful for locating events over magnitude 6 worldwide in a very timely fashion. A drawback, however, has been that the estimates of the size of the events were based on the *ML* and *mb* magnitudes, which saturate rapidly for large events. The *mb* saturation threshold is particularly low for the specific *mb* calculation used at the IDC (Kebede and Koch, 2003). The amplitudes are measured on vertical channels in a relatively narrow 5.5-second window around the first arrival picks, which leaves out larger amplitudes that may occur later in the coda for large events. The frequency band for *mb* is also limited to 0.8 to 4.5 Hz. Since one of the main purposes of the IDC *mb* magnitude is to screen out natural events using the *mb/Ms* ratio, this does not cause any severe problems for the mission of the IDC. To better estimate the size of larger events it is desirable to measure the moment magnitude (Hanks and Kanamori, 1979). The moment magnitude samples lower frequencies and is correspondingly measured in larger time windows. This can be achieved through several means, including modeling the low frequency body waves for the event. To obtain the moment tensor (MT) solution from body waveform (P-wave), we assumed a simple triangle source time function and 5 elementary moment tensor components (Kikuchi and Kanamori 1982), and varied the duration of source time and the centroid depth. The Green's function is calculated by the method of Kikuchi and Kanamori (1991). To remove the effects of detailed source process and detailed 3D structure, we apply a low-frequency band-pass filter on the waveforms before the moment tensor inversion. The estimated magnitude range of the event determines the bounds on the band-pass filter.

The web interface for the SEL0 bulletin has been upgraded to allow MT inversion for any event once it is visible on the web page. Another, more general web interface is also in development to allow access to the IDC archive database. The back-end processing called through both these interfaces involve an experimental program, called *gparse*, a command-line system with an expandable set of alphanumerical and graphical I/O as well as signal processing commands, which can also be used in batch mode.

An example of inversion for a SEL0 event with comparison to other sources, the Celebes Sea event of December12, 2006

Figure 1 shows the waveform fit obtained for this event. The fit was obtained semi-automatically from the SEL0 web page, with the user selecting a magnitude range, a depth range and identifying the event as an offshore event. The fit is quite acceptable (variance of 0.37) given that no editing was done on the station list and that the quick automatic epicenter was used as input to the process. This solution was available a few minutes after the event was written to the SEL0 bulletin. The geographical distribution of the stations is shown on Figure 2, a global map centered on the event. Note that more IMS stations would be available to refine the solution if non-associated stations were used in the inversion. Table 1 shows a comparison of this quick solution with two other published solutions (USGS and Harvard.)

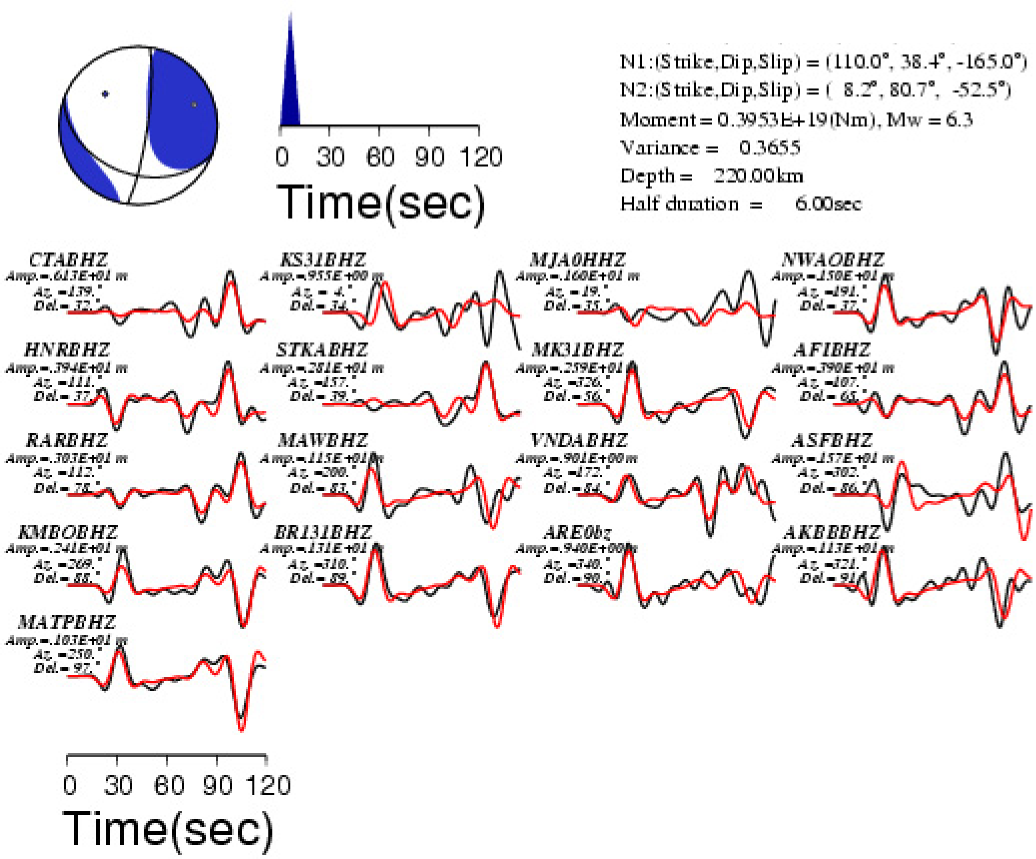
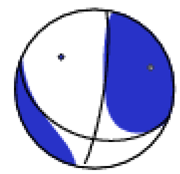
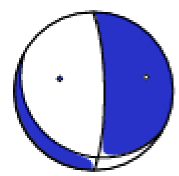
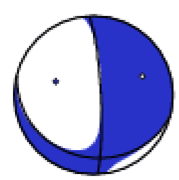


Figure 1. Example of waveform fit for an event in the Celebes Sea on December 12, 2006. The data (black line) and synthetic waveforms (red line) are filtered in the band (0.008–0.095) Hz. The fit is acceptable with a variance of about 0.37. Note the very clear depth phases for this event, whose hypocenter is estimated to be at 220 km depth.

Figure 2. Map centered on the Celebes Sea event (red star) showing the location of the broadband stations (blue triangles) used in the MT inversion. Only associated SEL0 stations were used in this case. This result was obtained shortly after the event was written to the SEL0 database table.

Table 1. This table shows the comparison of the CTBTO MT inversion results for the Celebes Sea event with two other sources (USGS and Harvard.) Note that the agreement is good with both sources, bearing in mind that no editing of the stations list has taken place and that only stations associated by SEL0 have been used in the inversion.

Celebes Sea event of December 12, 2006 (MT components in units of 10^{19} N-m)				
CTBTO (Mw 6.3)				
Epicenter	[3.72, 124.82]	**Mrr**	**-1.04**	
Depth	220 km	**Mtt**	**-1.13**	
		Mpp	**2.17**	
		Mrt	**-0.06**	
Time	15:48:04.58	**Mrp**	**-2.90**	
		Mtp	**-2.12**	
USGS (Mw 6.3)				
Epicenter	[3.72, 124.72]	**Mrr**	**-1.27**	
Depth	208 km	**Mtt**	**-0.04**	
		Mpp	**1.32**	
		Mrt	**-0.16**	
Time	15:48:03.42	**Mrp**	**-3.32**	
		Mtp	**-1.12**	
Harvard (Mw 6.3)				
Epicenter	[3.90, 125.01]	**Mrr**	**-0.91**	
Depth	212 km	**Mtt**	**0.38**	
		Mpp	**0.53**	
		Mrt	**-0.16**	
Time	15:48:06.20	**Mrp**	**-3.19**	
		Mtp	**-1.25**	

Interactive Inversion Generalized to Other Bulletins and Additional Inversion Options

A new web interface has been developed which allows additional options to be used in the inversion process and most importantly allows inversion on the analyst-generated reviewed bulletin (REB). The additional options added when compared to the SEL0 web page are the ability to choose the bulletin from which the event is selected and choose whether the inversion should use the associated stations or all stations in the broad-band vertical seismic network.

The Mozambique event of February 22, 2006

Figure 3 shows the waveform fit obtained using this interface where all stations are selected rather than only associated stations and the noisy stations are eliminated through a manual process. Figure 4 shows the distribution of the stations used in the inversion on a map centered close to the epicenter, and Table 2 shows a comparison with the USGS and Harvard solutions. Note that our solution is slightly closer to the Harvard solution for this event.

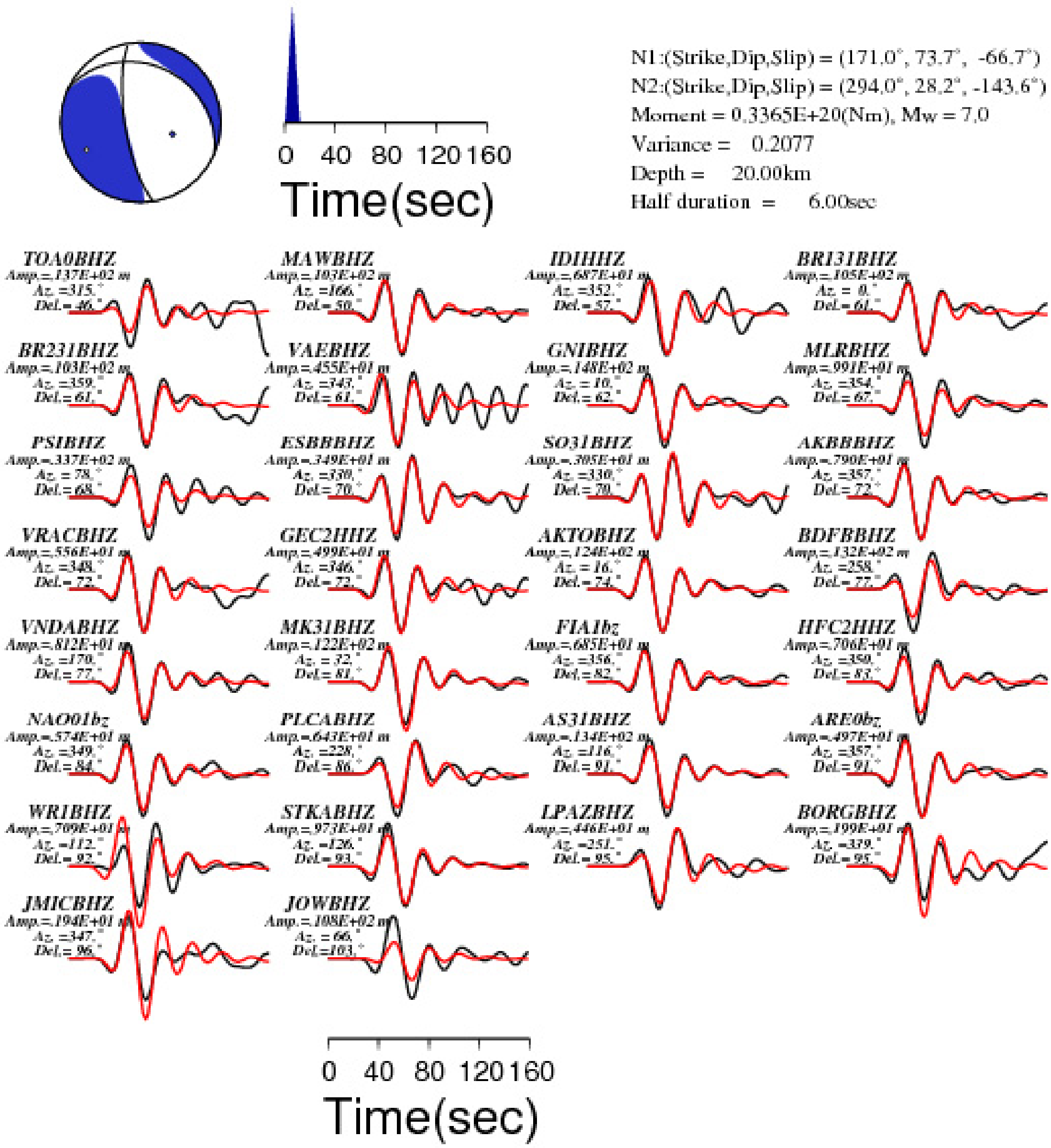
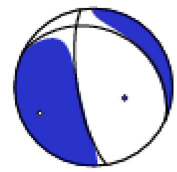
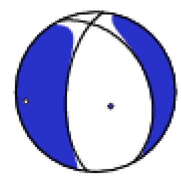
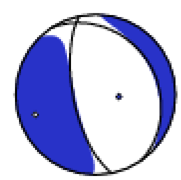


Figure 3. Example of waveform fit for the normal rift-style event of February 22, 2006, in Mozambique. The data (black line) and synthetic waveforms (red line) are filtered in the band (0.005–0.05) Hz. The fit is good with a variance of about 0.21.

Figure 4. Map centered on the Mozambique event (red star), showing the location of the broadband stations (blue triangles) used in the MT inversion. Note that the map shows only one of the broadband elements for arrays BRAR (BR231 shown as BRAR, BR131 not shown) and ESBB (ESBB shown, SO31 not shown.)

Table 2. This table shows the comparison of the CTBTO MT inversion results for the Mozambique event with two other sources (USGS and Harvard.) Note that the agreement is quite good with both sources, with a slightly better proximity to the Harvard solution for the focal mechanism.

Mozambique event of February 22, 2006 (MT components in units of 10^{19} N-m)				
CTBTO (Mw 7.0)				
Epicenter	[-21.18, 33.51]	**Mrr**	**-1.53**	
Depth	20 km	**Mtt**	**0.11**	
		Mpp	**1.42**	
		Mrt	**-0.28**	
Time	22:19:05.06	**Mrp**	**2.56**	
		Mtp	**-1.53**	
USGS (Mw 7.0)				
Epicenter	[-21.22, 33.32]	**Mrr**	**-3.62**	
Depth	23 km	**Mtt**	**-0.63**	
		Mpp	**4.25**	
		Mrt	**0.75**	
Time	22:19:08.11	**Mrp**	**2.11**	
		Mtp	**-0.92**	
Harvard (Mw 7.0)				
Epicenter	[-22.20, 33.33]	**Mrr**	**-2.88**	
Depth	12 km	**Mtt**	**-0.14**	
		Mpp	**3.02**	
		Mrt	**-0.49**	
Time	22:19:15.00	**Mrp**	**3.10**	
		Mtp	**-1.46**	

Statistics on the variance of the semi-automatic solutions as a function of the magnitude of the events

We have collected statistics on the variance of the waveform fit as a function of the moment magnitude. It is clear that for events of moment magnitude with approximately Mw > 6.0, the variance is usually below 0.4, which constitutes an acceptable fit. Figure 5 shows the scatter plot for a few events processed semi-automatically through SEL0. It is likely that the reason for the generally bad performance at lower magnitudes is due to an insufficient signal to noise ratio in the low frequency ranges used in the inversion. It may be possible to refine the definition of the frequency ranges to be used for these lower magnitude events.

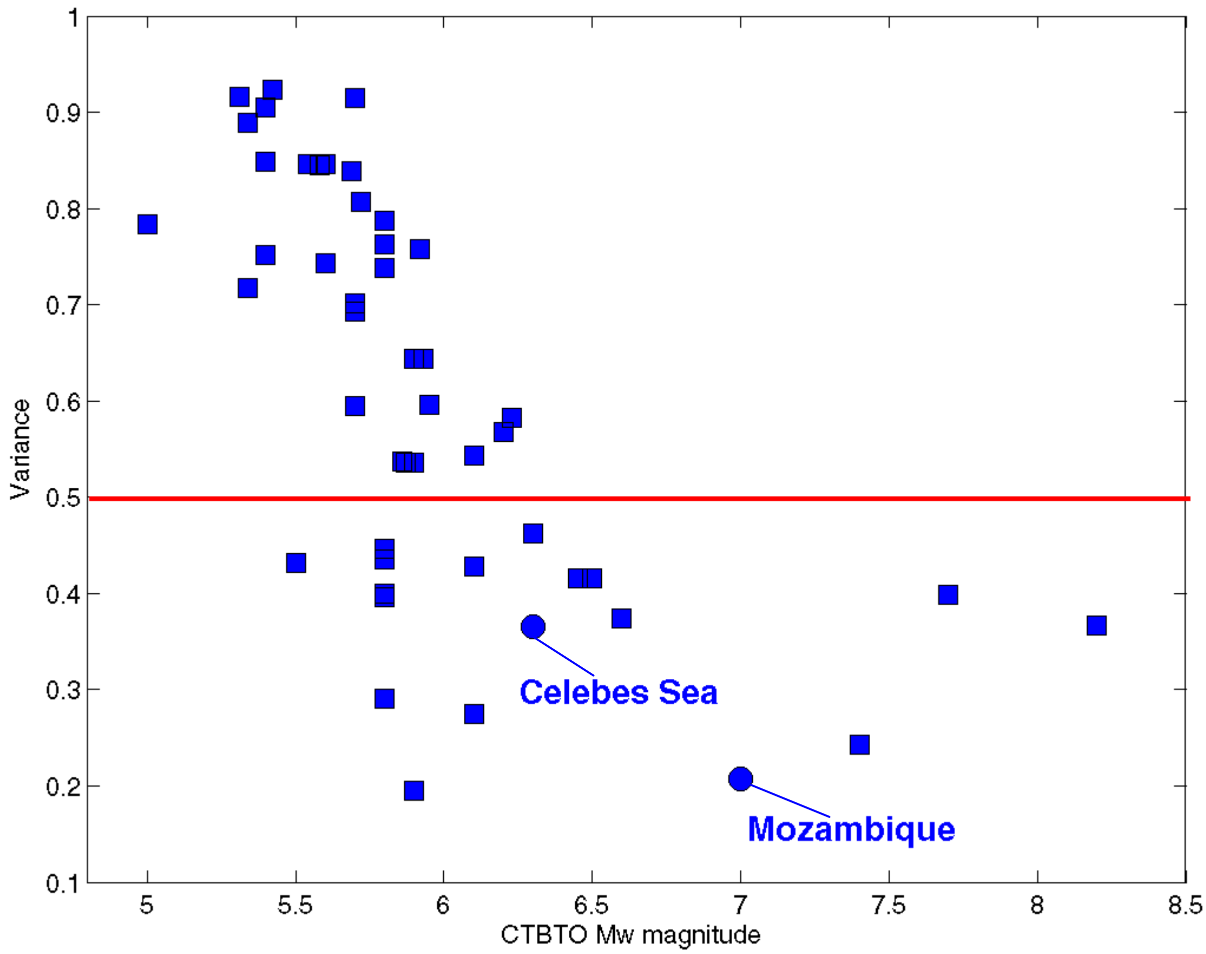


Figure 5. Scatter plot showing the relationship between the variance obtained from the MT inversion and the magnitude of the event for a sample of the SEL0 events processed semi-automatically. For comparison, the circles show the values for the two events (Celebes Sea and Mozambique) detailed in this paper. It is clear that, on this sample, we obtain consistently better results at the higher end of the magnitude spectrum (above about $M_w = 6.5$).

CONCLUSIONS AND RECOMMENDATIONS

We have integrated body-wave MT inversion software into the IDC processing environment on an experimental basis. The inversion is integrated with the SEL0 (Le Bras et al., 2006) web page. At present, an experienced user can obtain a fast and accurate MT with a few mouse clicks and within a few minutes.

Several challenges lie ahead to make the MT inversion process more automated, faster and robust for smaller magnitude events. To fully automate the MT process, good automatic estimates of the following inputs are required:

- Automatic determination of water depth at epicenter, if the event is offshore.
- Reliable initial depth range for the event.
- Reliable magnitude estimate to choose the appropriate frequency range for the inversion.

- Beam forming at stations where several broad-band stations are available.

Some criteria are being developed in terms of the minimum number of associated/non-associated stations that need to be included into the inversion process, as well as the quality of the waveform fit as measured by the total variance. A pre-processing of the amplitude data between the P and PP phases using newly developed methods to obtain fast order of magnitude for the event should be useful as input to the process in terms of assigning a magnitude range to the event. We are currently experimenting along these lines (Bormann and Wylegalla, 2005; Lomax, 2005; Guilbert et al., 2005). These criteria could be implemented and integrated into our signal processing environment, *gparse*.

To refine the solution after analyst review, an interactive tool to select the best channels would be useful to replace a tedious manual preparation as is the case currently, especially for smaller magnitude events where low frequency waveforms are often contaminated by noise.

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Disclaimer

The views expressed in this paper are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.

REFERENCES

Abe, K. (1995). Magnitudes and Moments of Earthquakes, in *Global Earth Physics, A Handbook of Physical Constants*, AGU Reference Shelf 1:206, 213.

Bormann, P. and K. Wylegalla (2005). Quick estimator of the size of great earthquakes, *Eos Trans. AGU* 86: 464.

Guilbert J., J. Vergoz, E. Schisselé, A. Roueff, and Y. Cansi (2005). Use of hydroacoustic and seismic arrays to observe rupture propagation and source extent of the M_w= 9.0 Sumatra earthquake, *Goephys. Res. Lett.* 32: L15310, doi:10,1029/2005GL022966.

Hanks, T. C. and H. Kanamori (1979). A moment magnitude scale. *J. Geophys. Res.* 84: 2348–2350.

Kebede, F. and K. Koch (2003). Comparison of IDC and ISC bulletins for the year 2000, IDC Internal technical report CTBT/IDC/SR/2003-1.

Kikuchi, M. and H. Kanamori (1982). Inversion of body waves, *Bull. Seismol. Soc. Am*. 72: 491–506.

Kikuchi, M. and H. Kanamori (1991). Inversion of complex body waves—III, *Bull. Seismol. Soc. Am*. 81: 2335–2350.

Le Bras, R., T. Hampton, J. Coyne, and A. Boresch (2006). SEL0: A fast prototype bulletin production pipeline at the CTBTO in *Proceedings of the 28th Annual Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-06-5471, Vol. 2, pp. 1007–1015.

Lomax, A. (2005). Rapid estimation of rupture extent for large earthquakes: Application to the 2004, M9 Sumatra-Andaman mega-thrust, *Geophys. Res. Lett.* 32: L10314, doi:10.1029/2005GL022437.