WANTED: A Strategy for the Rapid Determination of the
Magnitude of Great Earthquakes

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In the initial hours following the event's origin at 00:58:53 on Dec. 26, 2004, the Bay of

Bengal earthquake was widely reported as having a magnitude of about 8, and thus its

potential for generating a damaging teletsunami was considered minimal. Only after more

than four and a half hours had passed, when a moment estimate based on 2.5 hours of

data became available from the Harvard group (Nettles and Ekstrom, 2004), was its size

shown to be approximately ten times larger. This estimate placed its magnitude at

$M_w \approx 9.0$, in the range capable of generating a damaging teletsunami (ocean-crossing

tsunami). Actually, the earthquake had caused a teletsunami, one that by that time had

already killed more than *a hundred thousand people*. Kerr's (2005) account of difficulties

that seismologists encountered in those first hours is gripping – and damning! The poor

seismologists couldn't get right the magnitude of the most important earthquake to occur

in over forty years. This is pretty serious criticism, and seismologists everywhere ought

to be outraged. But more importantly, we should all start thinking about how to get it

right the next time - even though we'll all probably be retired by then.

We show here that a reliable magnitude estimate – one that identifies the Bay of Bengal

earthquake as capable of causing a damaging teletsunami – can be achieved using only

data collected within one half hour of its origin and using only a magnitude-based (as contrasted to a moment-based) approach. Such a determination, had it been made in first hour after the event's origin, could have been used to issue a timely preliminary alert. It's not an intractable problem, at all.

The size of an earthquake can be objectively quantified by its seismic moment, m_0, (the product of fault area, average slip, and the rigidity of the surrounding rock) or, equivalently, the moment-magnitude, M_w, a quantity directly computed from moment using the standard formula $M_w=2\log10(m_0)/3-10.73$. Moment estimation is based on laborious, wiggle-for-wiggle matching of observed and predicted seismograms. Routine magnitude determination techniques use only the peak amplitude of the observed seismograms, and produce quicker results. They are very widely used, even though they have a tendency to underestimate the size of the very largest earthquakes (a fact well-known amongst seismologists since the 1970's) (Aki, 1972; Geller, 1976). The problem is that the slip that occurs on a long fault is not instantaneous. Slip on a thousand kilometer long fault, such as the one in Bay of Bengal, occurs over about 500 seconds, because the rupture front propagates at a speed of about 2 km/s from one end of the fault to the other. Consequently, the seismic waves that radiate from the fault are systematically deficient in energy at periods shorter than this characteristic time scale. Routine techniques typically are optimized for estimating magnitudes of small earthquakes. That's because magnitude 6's and 7's pop off many times each year, and everyone wants to know their magnitude! These routine methods use seismic waves with periods in the 1 to 20 second range – much less than 500 seconds - because the signal-to-

noise ratio is highest in that band. This approach yields a systematic downward bias when applied to the rare magnitude 9. The upper magnitude limit of these techniques can be extended by attempting to correct for the bias (Sipkin, 2003). For very large earthquakes, longer periods must be used in the magnitude-estimation procedure. However, the longer the period, the more data that must be collected before a magnitude estimate can be made, explaining any delay in issuing a public announcement of the earthquake's magnitude.

That the Bay of Bengal earthquake had a magnitude *much* greater than 8.0 is apparent even at the 50-200 second period band. As an example, we compare the vertical ground displacement of this earthquake with the smaller, magnitude M_w=8.1 Macquarie Island earthquake of Dec. 23, 2004, both observed at station ANMO (Albuquerque, New Mexico) (Figure 1). The displacement of the Bay of Bengal earthquake is about ten times larger than that of the Macquarie Island earthquake, even though two events are roughly the same distance from ANMO. Because magnitude is proportional to the $\log_{10}$ of displacement, the factor of 10 difference in displacement implies that the Bay of Bengal earthquake is about one magnitude unit larger than the Macquarie Island (thus $M_w \approx 9.1$). Furthermore, the Bay of Bengal earthquake has a displacement at ANMO that is roughly 50 times larger than that of the November 2, 2002 magnitude M_w=7.2 earthquake that occurred in roughly the same region. Given the logarithmic relationship between displacement and magnitude, we would expect the magnitude difference to be $\log_{10}(50)$=1.7, and thus the magnitude of the Bay of Bengal Earthquake to be $M_w \approx 8.9$. There's nothing tricky here.

This example suggests an approach to rapidly determine the magnitude of great earthquakes: First determine the location of a candidate earthquake, C, using standard means (e.g. Geiger's method) and then systematically compare the long-period (e.g. 50-200 second) displacement with that of a reference event, R (located in the same general geographic region as C) and observed on the same seismometer. A station-magnitude, M^s, is then estimated as $M^s_C = M_R + \log_{10}(r^s)$, where r^s is some measure of the ratio of displacement amplitudes at station, s. An overall magnitude is then estimated from an average of all available station-magnitudes. Our choice of the 50-200 second period band is somewhat arbitrary, but trades off data collection time with the tendency to underestimate the magnitude of the very largest events (downward bias starts at about magnitude 8.6 in this case). Thus this method is designed primarily to evaluate if the magnitude of the candidate earthquake at least 8.6, which is to say large enough to cause a damaging teletsunami. That is, after all, *the* question that needed to be answered on the morning of Dec 26th.

In the cases we examine here, we use an actual, previously-occurring earthquake as the calibration event, choosing the nearest magnitude $M_w \sim 7$ event for which data are available from the Incorporated Research Institutions for Seismology (IRIS) Data Management System. An alternative idea that we have not explored is to use synthetic seismograms, either drawn from a database of previously-computed examples or calculated on-the-fly (though this idea, pursued to its extreme, just reinvents the moment-estimation method). Ideally, the candidate and reference events should be co-located.

However, events separated by up to a few hundred kilometers will suffice, given the long periods that are used. They should also have similar focal mechanisms. In practice, the range of plausible focal mechanisms for a great earthquake in a particular tectonic setting is pretty limited (e.g. most great subduction-zone events are low-angle thrusts), so this requirement is not much of a problem, either.

The purpose of the reference event is two fold: First, it provides a way to normalize the amplitudes of the many distinct seismic phases (e.g. PKP, P, SS, R, G, etc.) that contribute to the seismogram, and to correct for the decrease in amplitude with distance. Second, it provides a readily-understandable standard by which a decision-maker can judge the reliability of the magnitude estimate. In our opinion, the most compelling check on the validity of the output of an automated magnitude-determination system is the examination of the actual ground displacements and the verification that they are in the size range expected for an earthquake of that magnitude.

We apply this method to estimating the magnitude of both the 2004 Great Bay of Bengal and 2004 Macquarie Island earthquakes (magnitudes 9.0 and 8.1, respectively). We use high-quality, broadband seismic data from a representative selection of 25 globally-distributed IRIS Global Seismic Network station. Only data starting at the onset of the first arriving wave (P or PKP) and ending 30 minutes after the origin are used. Station-magnitudes (Figure 2), computed from amplitude ratios (Figure 3), have means of 8.77±0.02 (1σ) and 8.27±0.09 (1σ) for Bay of Bengal and Macquarie Island, respectively. Thus the method correctly singles out the Bay of Bengal earthquake as

having the potential to generate a damaging teletsunami. The choice of a 30 minute window is arbitrary, but trades off our interest in using sufficient data (that is, including at least three or four oscillations of 200 second period at every station) and yet being able to complete the estimate in a timely fashion, so as to allow the possibility of issuing an early alert.

Since the Bay of Bengal earthquake, and especially since President Bush's Jan. 10, 2004 announcement of the US's intent to participate in an expanded global tsunami warning system, attention has been focused on the technical and human resources needed to make such a system reliable. We assert that seismic methods have a very critical place within such a system. They must, however, be optimized towards answering the *right questions* in the *shortest amount of time*. They must be explicitly designed to work well for the very largest of earthquakes, and be easily verifiable by the decision-makers tasked with issuing alerts.

Figure 1. Vertical displacement seismograms, bandpass filtered between periods of 50 and 200 seconds, for A) the moment magnitude M_w=9.0 Great Bay of Bengal earthquake, B) a nearby M_w=7.2 event occurring on Nov. 11, 2002, C) the M_w=8.1 2004 Macquarie Island earthquake, D) a nearby Mw=6.7 event occurring on Mar. 20, 1998. All moment magnitudes are from the Harvard Centroid Moment Tensor catalogue.

Figure 2. Map of global distribution of magnitude residuals for the Bay of Bengal (top) and Macquarie Island (bottom) earthquakes. Numbers indicate the deviation of the

individual station-magnitudes from the overall mean. The location of the candidate event and reference event are indicated by large and small squares, respectively. Station-magnitudes for the Macquarie Island event show the greater scatter, possibly due to its strike-slip mechanism, which caused a greater geographic variability of displacement amplitude.

Figure 3. Instantaneous magnitude for the Bay of Bengal (bold) and Macquarie Island (solid) earthquakes observed at the station ANMO located in Albuquerque, NM. Estimated are based on the logarithm of the ratio of root mean square amplitudes of the candidate and reference events, calculated in 3 minute time windows. The values scatter around the overall averages of 8.77 for Bay of Bengal and 8.27 for Macquarie Island, respectively (horizontal lines).

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10
microns

1000
microns

10
microns

1000
microns

D.

C.

B.

A.

20 minutes

ANMO

M average 8.77

M average 8.27