Hydroacoustic identification of tsunamigenic events based on the shape of the T-phase spectrum

David H. Salzberg and *Peter N. Mikhalevsky*
Science Applications International Corporation, Acoustic and Marine Sciences Operation
M/S 1-11-15, 1710 SAIC Drive, MCLEAN, VA 22102

Introduction

SAIC has identified three areas where T-phases recorded at hydrophone stations provides information that is useful for tsunami warning. They are:

T-Phase Observation	Parameter determined
Duration	Estimate of source duration
Direction	Estimate of lateral extent
Spectral Content	Estimate of source depth

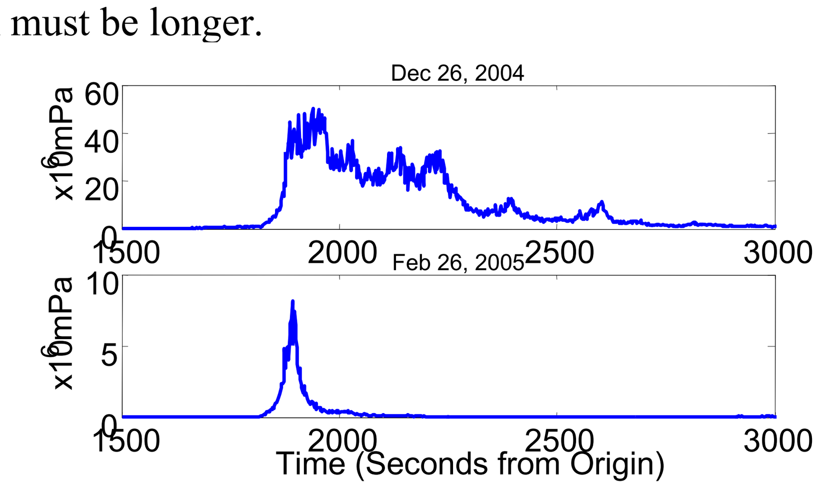
In this poster, we will present examples of each of the observations, and the theory behind the parameters.

T-Phase duration

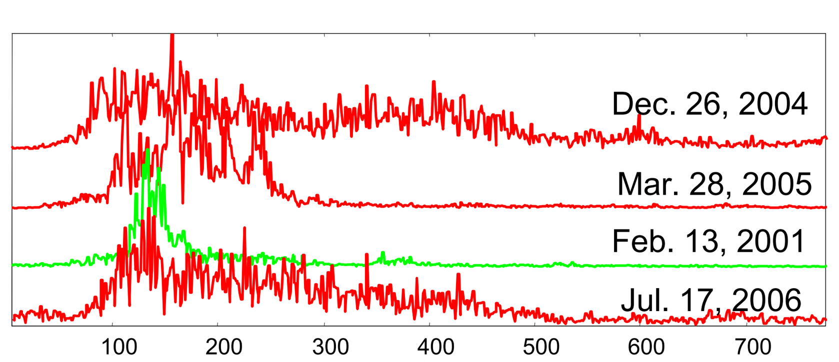
Extended T-phase means extended source duration

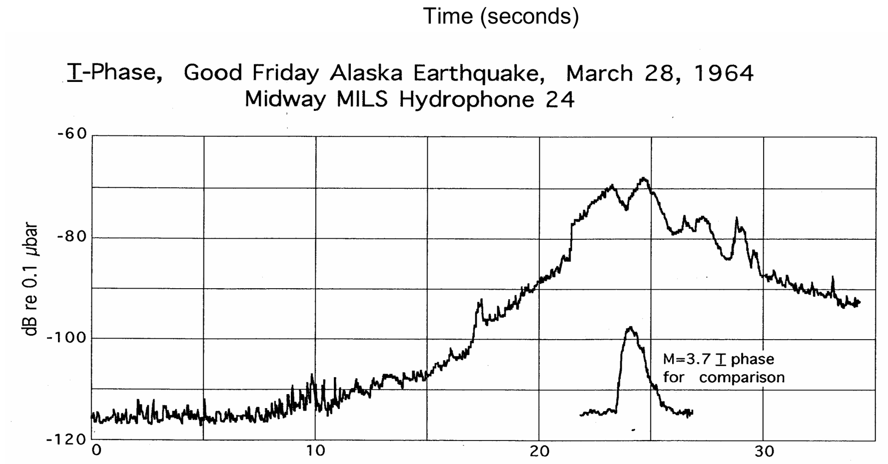
Observed(t) = Source(t) * Propagation(t)

Two events near by should have nearly the same propagation. Therefore, if one has a significantly longer duration. The source duration must be longer.



Using an aftershock as an empirical Green's Function indicates a T-phase duration of 1-3 minutes for the aftershock, compared with 12-15 minutes for the mainshock.



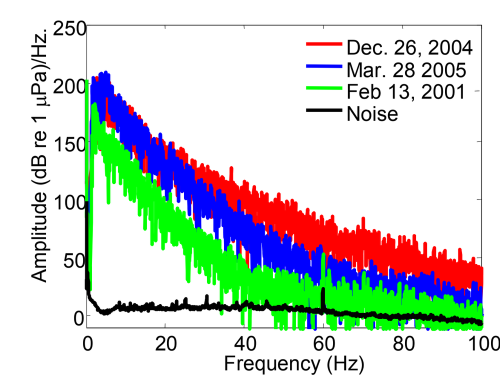


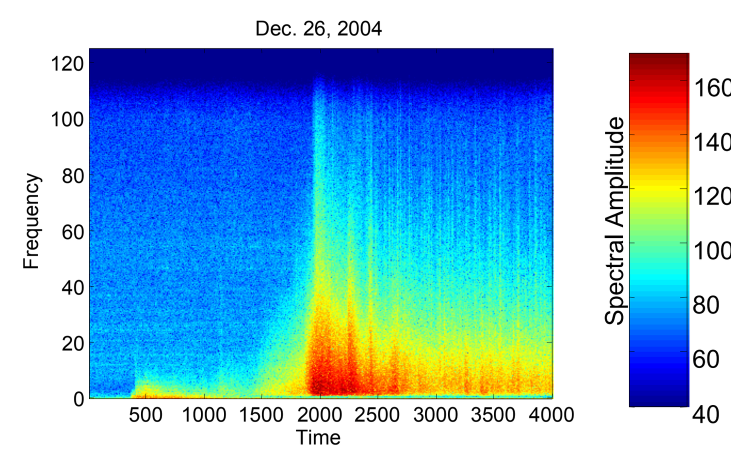
The figures above show the T-phase from 5 events. The upper figure shows events recorded at Diego Garcia from Indonesia; the three in red produced a Tsunami, the green did not. The lower figure shows the T-phase from the 1964 Alaskan earthquake recorded at Wake Island. Note that the tsunami events all had longer durations than the event that did not excite a tsunami.

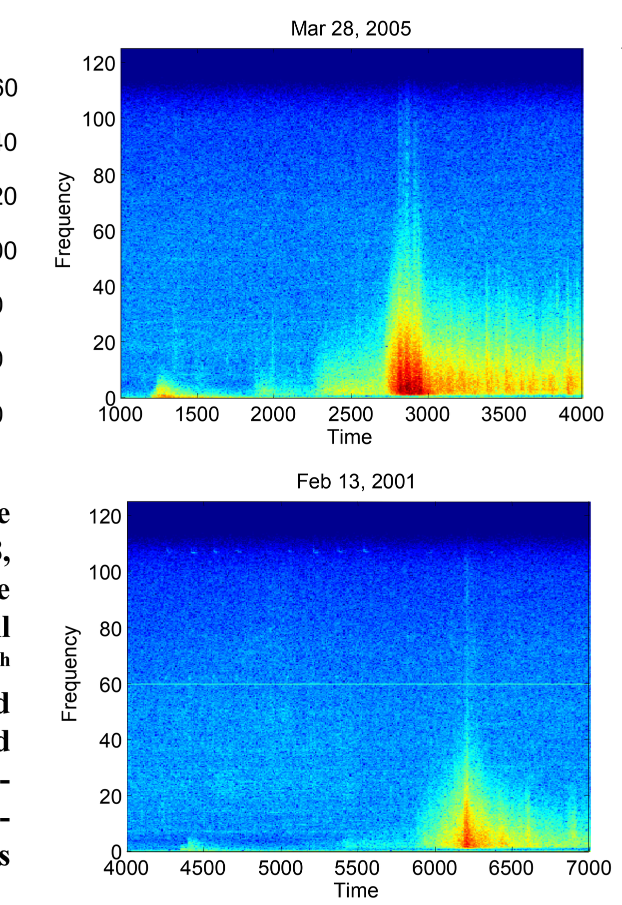
T-Phase Spectral Content

We have observed that the T-phase from the Tsunamogenic Earthquakes recorded at IMS Hydrophones are much richer in high frequency (f >50 hz) than typical events, as shown below and to the right.. Walker et al [1992] analyzed the T-phase from 28 events in the Pacific region using data recorded at the Wake Island bottom mounted hydrophone. Using data sampled at 80 samples per second, they found that the T-phase from tsunamigenic earthquakes were richer in frequency energy than the T-phases from other events.

The high-frequency T-phase energy from tsunamigenic energies is somewhat counterintuitive, as the long source duration for the tsunami events should result in less high frequency energy relative to the low frequency energy. Walker et al explained this by invoking ad hoc secondary sources , such as land slides.





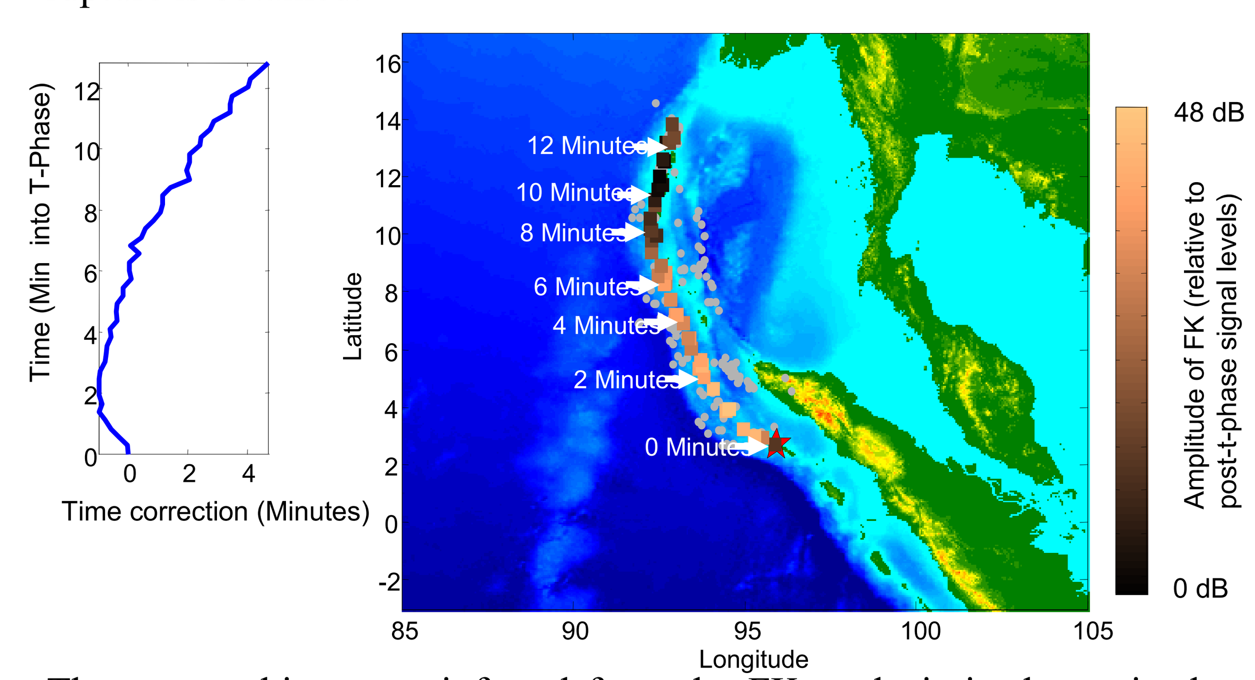


A comparison of the spectral content of the T-Phase for three events: Dec. 26, 2004, (above); Mar. 28, 2005 (above right), and Feb. 13, 2001 (right). The Dec. 26th and Mar. 28th events both produced well documented Tsunamis. In contrast, the Feb. 13th event was not associated with any observed Tsunami. The two tsunamigenic events had significant signal at frequencies up to the anti-aliasing roll off frequency, whereas, the non-tsunamogenic event has little signal at frequencies above 50 Hz.

Studies of the December 26, 2004 event show little evidence for secondary sources; the observed tsunami wave be explained by the coseismic deformation associated the mega-thrust event. Thus, secondary sources probably were not responsible for the high-frequency T-phase energy. We propose an alternate hypothesis to explain the high-frequency T-phase of tsunami earthquakes: *The high frequency energy is a result of less anelastic attenuation because of the short solid-earth propagation path*. That means that, the apparent abundance of high frequency energy relative to other earthquakes is because of the additional attenuation in the other signals.

T-phase direction

Use time delays to estimate the direction of energy arrival (Frequency-Wavenumber Processing). For each time window in the T-phase, and independent estimate of direction is obtained. By back projecting that to a probable T-phase conversion point, an image of the source extent and rupture is obtained.



The rupture history as inferred from the FK analysis is shown in the shaded boxes. The numbers to the left represent the time into the rupture. Note that the rupture speed slows down as the rupture propagates to the north.

This type of analysis (though with a different approach) is the subject of Catherine deGroot-Hedlin's poster. As such, we will not present more detail here.

Theory of the T-phase attenuation

In the solid earth, the signal loss (attenuation) is a fraction of the energy per wavelength (and thus frequency dependant [e.g., Lay and Wallace, 1995]) whereas in the SOFAR channel, there is minimal attenuation in the 3-200 Hz frequency band [Urick, 1983]. Below 3 Hz, the SOFAR wave guide breaks down. Thus, all of the observed attenuation (i.e., the spectral slope) in the 3-200 Hz frequency band relates to attenuation in the solid earth, which can be written as:

$$A(x) = A_o \cdot e^{-\pi f \frac{x}{cQ}}$$

Where, A_o is the reference amplitude, f is the frequency, x is the distance traveled, and Q is the fractional loss of energy per wavelength. The rupture depth for this hypothetical point source can be determined by taking the log of both sides of equation 1, which is

$$\log_e(A(x)) = \log_e\left(A_o \cdot e^{-\pi f \frac{x}{cQ}}\right) = \log_e A_o - \pi f \frac{x}{cQ}$$

Since large tsunamigenic earthquakes are typically not point sources, it is useful examine an extended, line source. Assuming a two-dimensional solution where the observed energy in one small time window emanates uniformly from a variety of depths, the, then impact of the attenuation can be computed by integrating Equation 1 over the displacement from the conversion point, which is:

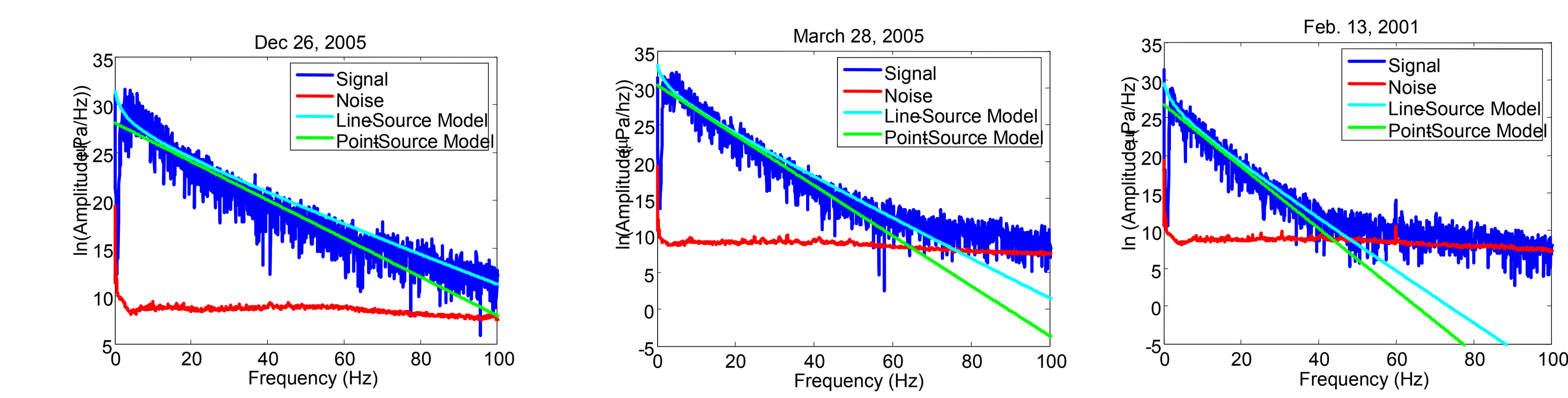
$$A(x) = \int_{x_{min}}^{x_{max}} A_o \cdot e^{-\pi f \frac{x}{cQ}} dx = A_o \frac{e^{-\pi f \frac{x_{min}}{cQ}} - e^{-\pi f \frac{x_{max}}{cQ}}}{\pi f}$$

Where, x_{min} is the minimum (shallowest) point of the rupture, and x_{max} is the deepest point of the rupture.

Applications of the technique

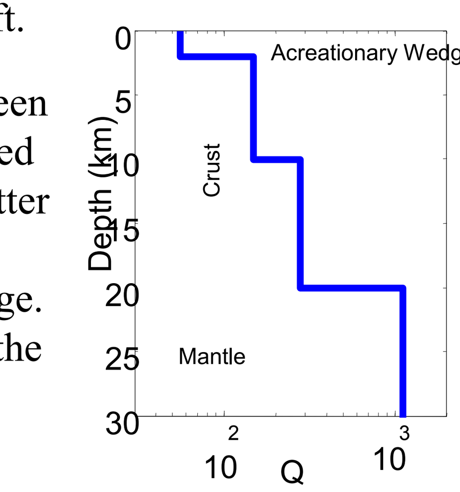
The hydroacoustic signals from three Indonesian events were processed using the spectral analysis approach, with the results shown in in the three figures below. The first event occurred on the Dec. 26, 2004 event produced a significant tsunami throughout the Indian Ocean. This event had significant high-frequency T-phase energy, as shown in the spectrum on the left. The point and line source models indicate that the rupture was very shallow, with a point-source rupture depth of about 6 km.

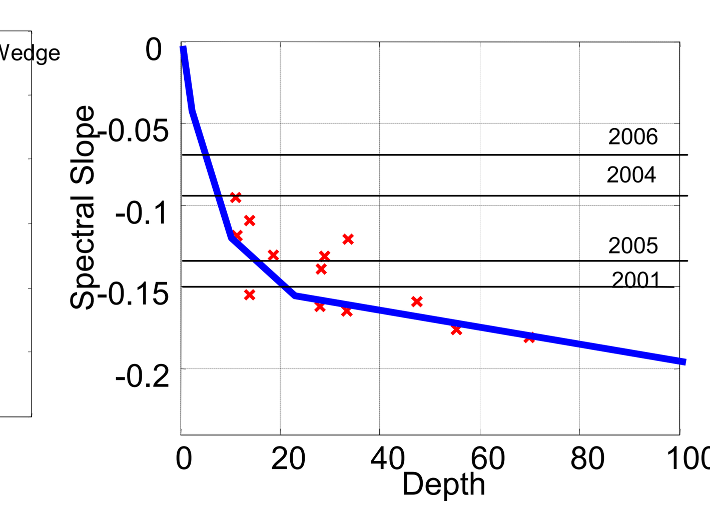
The second event examined occurred on March 28, 2005 and produced a smaller, but noticeable tsunami. This event also had high-frequency energy, as shown in in the center, but not as much as the Dec. 26th event. The rupture depth inferred from the spectral shape was about 16 km for the point source model. Thus, the energy from this event appears to have been generated from a deeper source than the Dec. 26th event. Furthermore, while the peak amplitude of the T-phase for this event was greater than the Dec. 26th event, the duration of the rupture was much shorter (200 vs. 600 seconds). The final event, an M_w=7.4 event occurred on Feb. 13, 2001, and did not produce any observable tsunami. The T-Phase had more decay with frequency, as shown on the right, indicating an even deeper rupture of about 20 km.



Applying this approach to a series of well-located aftershocks (depth error < 2 km) for events with clear T-phases and conversion in the accreationary wedge, we compare the spectral slope to the reported depth, shown below right. In addition, the the blue line is the expected slope based on the attenuation model shown below left.

There is a general agreement between the measured slopes and the Q-based slopes, with some scatter. The scatter may result from using a uniform thickness of the accreationary wedge. As geophysical databases provide the sediment thickness for a given location, that information could be



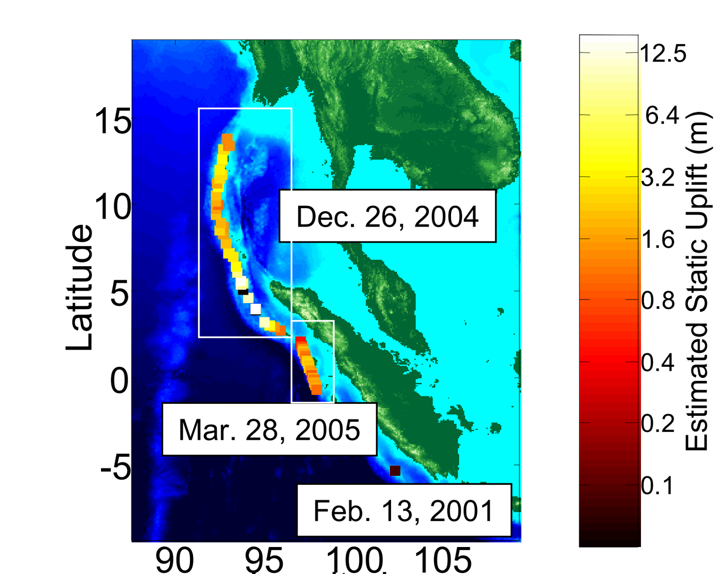


used to provide estimates of the event depth based on spectral slope and attenuation model, and may provide a mechanism for obtaining real time estimates of the rupture depth.

Summary

We have demonstrated three potential markers for identifying which earthquakes are likely to produce tsunamis. Those markers are outlined below:

Measurement	Derived Parameter
T-phase duration	Source Duration
T-Phase azimuth	Source Extent
T-Phase spectral slope	Source Depth



Assimilating these terms with seismic parameters may lead to the ability to predict seafloor deformation in real time, yielding results shown on the right.

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