Tsunami Detection with HF radar

Tsunamis are very long ocean waves generated by catastrophic events such as the undersea earthquake in the Indian Ocean on December 26th 2004. The purpose of this document is to begin to explore the feasibility of using HF radar systems to detect tsunamis. The work is only preliminary and by no means exhausts all the problems that need to be addressed or the way in which the properties of tsunami-HF radar interaction can be encapsulated into a robust detection algorithm. Nonetheless the analysis below suggests that it may be possible to detect tsunamis using HF radar with a warning time and precision that would depend on coastal bathymetry and radar configuration.

The US-French satellites, called TOPEX/Poseidon and Jason-1, passed over the Bay of Bengal two hours after the massive earthquake struck just off the coast of Indonesia. The satellites saw the first two wavefronts produced by the main quake, spaced 500 to 800 kilometres apart. These waves reached a maximum height of 50 centimetres in the open ocean, only reaching their full devastating height when entering the shallow waters of the coast.

The average depth of the Indian Ocean is 3,890 m. Ocean wave theory tells us that when the depth to wavelength ratio is very small (here <1% over the range of observed wavelengths in the deep ocean and much less as the wave moves into coastal areas) the phase speed of the tsunami (i.e the speed at which the crest moves) equals $\sqrt{gd}$ m/s where g is acceleration due to gravity and d is depth. This is about 700km/hr in the deep Indian Ocean, slowing to about 100km/hr at 100m depth. The waveheight in the deep ocean is small but increases as the wave moves into shallow water, $h_{shallow} \sim h_{deep}\sqrt[4]{\frac{d_{deep}}{d_{shallow}}}$. If this is detected by the radar as a moving target the associated Doppler shifts will be large ~3Hz at 200m depth reducing to ~1Hz at 25m depth.

For an HF radar detection algorithm it is probably the speed of the water (i.e the induced current) beneath the wave that is more important. For these very long waves the water is more or less moving forward (under the peak) and backward (under the trough) with little vertical motion. The shorter Bragg waves that are detected by a radar feel this as an oscillating current which is given by $u = h\sqrt{\frac{g}{d}}\sin 2\pi(\frac{t}{T} - \frac{x}{L})$ where h is the amplitude of the Tsunami wave, T is its period and L its wavelength. The wave period stays the same as the wave propagates across the ocean but the wavelength varies with depth as $L = T\sqrt{gd}$ metres. In the analysis below I have taken an intial depth, wave period and amplitude of 4000m, 20 seconds and 50cm respectively. The maximum value of this current (under the Tsunami wave peak) is shown in figure 1. In deep water this is less than 5cm/s and would be very difficult to detect. As the waves come into shallower water this speed increases and becomes more detectable but, because the wavelength decreases there will be more variation in the current over a radar measurement cell. Figure 2 shows the mean and standard deviation of this current given a 10km range cell size (assuming the wave moves directly towards the radar). Where the Tsunami wavelength is greater than 10km, the average has been calculated over consecutive 10km lengths shown with different colours. This gives some indication of differences over neighbouring range cells which might be used in a detection algorithm. The standard deviations are important because they indicate the extent of velocity smearing that might either cause problems to, or make possible, a detection algorithm. Figure 3 shows the mean and standard deviation converted into radar frequency resolution bins (assuming values typical for a Pisces radar).

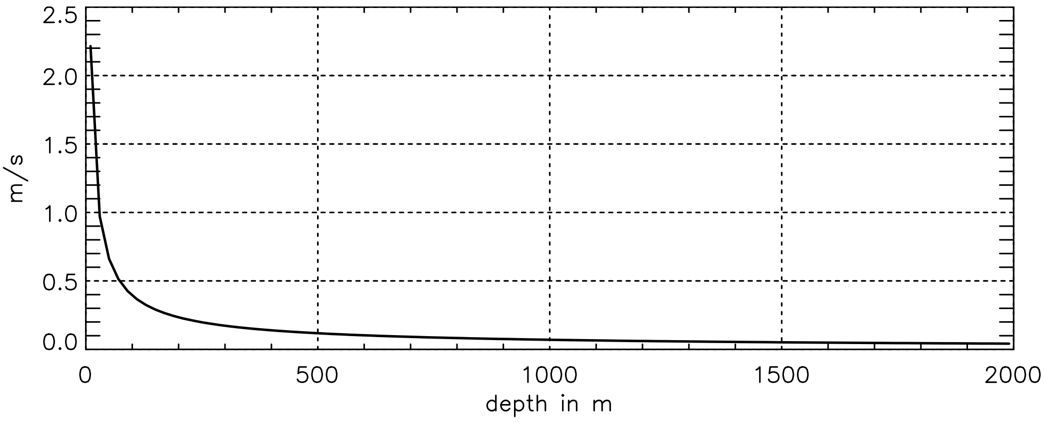

Figure 1. Wave induced current under the crest

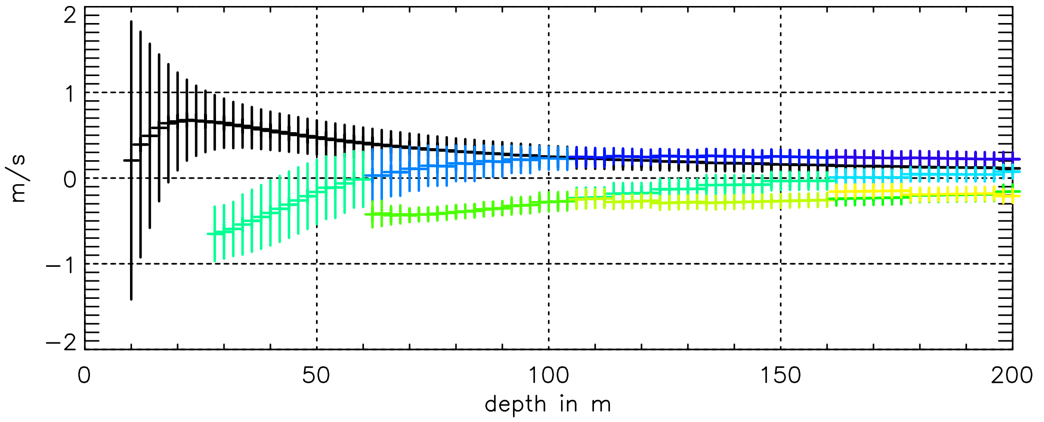

Figure 2. Mean and standard deviation of the current over 10km sections of the tsunami wave as it moves into shallow water.

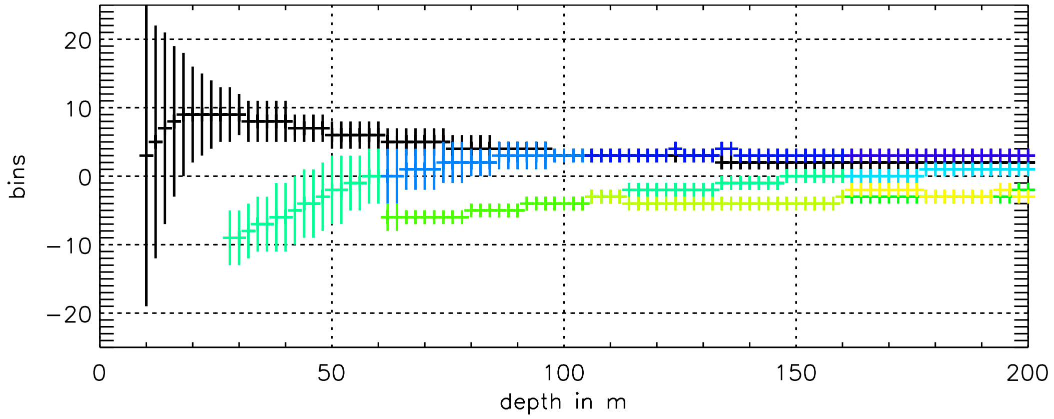

Figure 3. Number of frequency bins corresponding to the mean and standard deviation of the current over 10km sections of the tsunami wave.

The above analysis assumes that the Tsunami wave is frozen during the period of the radar measurement. Figure 4 shows the timescales that are involved. If an averaging time for the radar data of the order of or longer than the time taken for the wave to move through the bin is used, the standard deviations will increase and the means decrease. The times required are shorter than those conventionally used to provide wave and current measurements (10-20minutes typically). At depths of the order of 50m it is not much larger than the typical time for one un-averaged measurement (~7 cf 3.4mins for Pisces, 2.2mins for WERA). A trade off between current resolution (bearing in mind figure 2) and measurement time may be required.

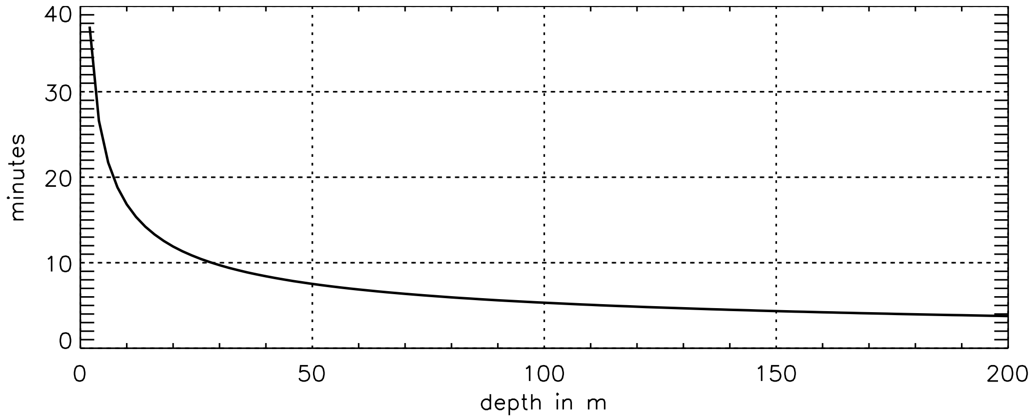

Figure 4. Time taken for one tsunami wave to move through 10km