

SEASONDE DETECTION OF TSUNAMI WAVES

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I. INTRODUCTION

We here report on preliminary results of a study to assess the capability of a SeaSonde to detect tsunamis well before their arrival and estimate their parameters. This study was of course inspired by the disastrous tsunamis generated by an earthquake off Sumatra, December 26, 2004, and the numerous enquiries we have received thereafter.

Barrick [1] first proposed using HF radar systems for tsunami detection. Since then (1979) the range of measurement has been extended to 200 km, potentially increasing the time from detection until the tsunami strikes the shore.

This paper is organized as follows: Section II outlines the theoretical equations used in the study and their limitations. Section III describes simulated tsunami observations from a Long-Range SeaSonde. Section IV discusses observations/timing that would have been provided by SeaSondes at locations that were in the path of the Indian Ocean tsunamis.

II. TSUNAMI PARAMETERS

In the open ocean, a tsunami has a low height and an extremely long wavelength and can be detected in real time only by bottom-mounted pressure sensors. When a tsunami moves into shallower water, the height and the orbital velocity increase and the wavelength decreases, while the wave period remains invariant. Barrick [1] assumed linear wave theory and expressed these quantities in terms of their values in deep water, which he took to have depth 4000 m. For tsunami waves, the wavelength is always far greater than the water depth d . The equations describing the tsunami can be simplified by expanding them as Taylor series in $\frac{d}{\lambda(d)}$, where $\lambda(d)$ is the wavelength in water of depth

d . Retaining only the first term in the series, the defining equations used in this study can be written as follows:

The phase velocity is given by:

$$v_{ph}(d) = \sqrt{gd} \quad (1)$$

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where d is the water depth (m) and g is the gravitational acceleration (m/s^2).

The maximum surface orbital velocity for water of depth d is given by:

$$v_o(d) = v_{ph}(d) \left(\frac{h_{4000}}{d} \right) \left(\frac{4000}{d} \right)^{1/4} \quad (2)$$

where h_{4000} is height of the tsunami wave in water of depth 4000 m. The relationship between the wave period P and wavelength is given by the shallow-water dispersion equation, which defines how the wavelength changes with depth:

$$\lambda(d) = P\sqrt{gd} \quad (3)$$

The time for the tsunami to cover a distance L terminating at the radar site is given in terms of the phase velocity by

$$T = \int_0^L \frac{dx}{v_{ph}(d)} \quad (4)$$

where the phase velocity is given by (1). Note that for shallow-water waves like tsunamis, phase velocity and group velocity of the wave are equal, much faster than orbital velocities but slowing down in shallow water as square root of depth, as in (1).

The above equations use linear wave theory to represent the tsunami. When linear wave theory breaks down in shallow water, currents become stronger and hence more detectable. In the nonlinear regime, wave energy is converted to massive water transport or surge. There are then no simple equations to describe the tsunami.

Expanding the equation for the surface height as a perturbation expansion in $\frac{a}{\lambda(d)}$,

where a is the surface amplitude, as in [2], and then invoking the small-argument limit for hyperbolic functions in $\frac{d}{\lambda(d)}$, we retain the linear term and the first nonlinear term for the

wave profile. Linear wave theory breaks down when the magnitude of the nonlinear term approaches that of the linear term. We assume that linear wave theory becomes invalid when the nonlinear term exceeds 50% of the linear term, which can be shown to occur at a depth defined by:

$$d_{thresh} = 1.383 \left(\frac{4000}{h_{4000}} \right)^{1/5} h_{4000} \quad (5)$$

For depths less than this threshold, higher-order wave nonlinearities become non-negligible based on this definition of the linear domain.

III. SIMULATED TSUNAMI RADIAL VELOCITY MAPS

The SeaSonde is a compact HF radar device that produces maps of the radial component of the ocean surface current velocity using radar echoes from short wind-driven waves. Standard-range SeaSondes operate with a transmit frequency in either the 13 MHz band or the 25 MHz band, with ranges up to 40 km and 80 km respectively. Long-Range SeaSondes operate with a transmit frequency close to 5 MHz and have ranges up to 200 km with coarser spatial resolution. Fig. 1(a) shows an example of a typical radial current map measured by a Long-Range SeaSonde located at Tuckerton, New Jersey.

We now describe simulations of the radial current map that would have resulted from the Indian Ocean tsunami of 2004, should it have struck the New Jersey coast near Tuckerton. Satellite measurements made by US-French satellites, (TOPEX/Poseidon and Jason-1) reported by Lee-Lueng Fu, project scientist for the satellites at NASA's Jet Propulsion Laboratory [3] indicate that in deep water (about 4000 m in depth), the wave amplitude was approximately 50 cm and the wavelength was between 500 and 800 km. From (3) the period of the wave in deep water is about 50 minutes. As already stated, wave period is independent of depth.

As discussed by Barrick [1], a sinusoidal tsunami wave appears as a periodic surface current over the radar coverage area. Its wave orbital velocity at the surface transports the far shorter waves seen by the radar by an extra amount that adds to the ambient current field and can be seen by the radar. In the present simulation, we assume that the water depth is constant at 40 m over the radar coverage area, which is typical of the continental shelf close to Tuckerton (see Fig. 1). At this depth, (2) gives a maximum orbital velocity of 78 cm/s and (3) shows that the wavelength is 60 km. Fig 1(b) shows the radial map that would be produced by the tsunami wave coming directly onshore when it is 100 km from the radar (i.e. one half the radar range) and Fig 1(c) shows the radial map just before landfall. In practice, this radial pattern would be superimposed on the background radial velocities of Fig 1(a). It is clear from Fig. 1 that in this case, the tsunami radial velocities dominate the background radials, and straightforward analysis will yield the strength of the tsunami and its direction. From (4), 84 minutes will elapse from detection at 100 km until the tsunami reaches the radar.

We then apply (5) to find the water depth at which linear wave theory breaks down for this tsunami. For a 50 cm deep-water amplitude the threshold depth is only 4.2 m; the above equations will therefore apply over most of the radar coverage area, allowing tsunami parameters to be obtained reliably until the first surge is only moments away from the shore. As the wave moves into shore and the water depth decreases from this threshold value, the water velocity seen by the radar will increase as the wave crest/trough forward speed decreases. There are no simple formulas to predict this velocity increase, however.

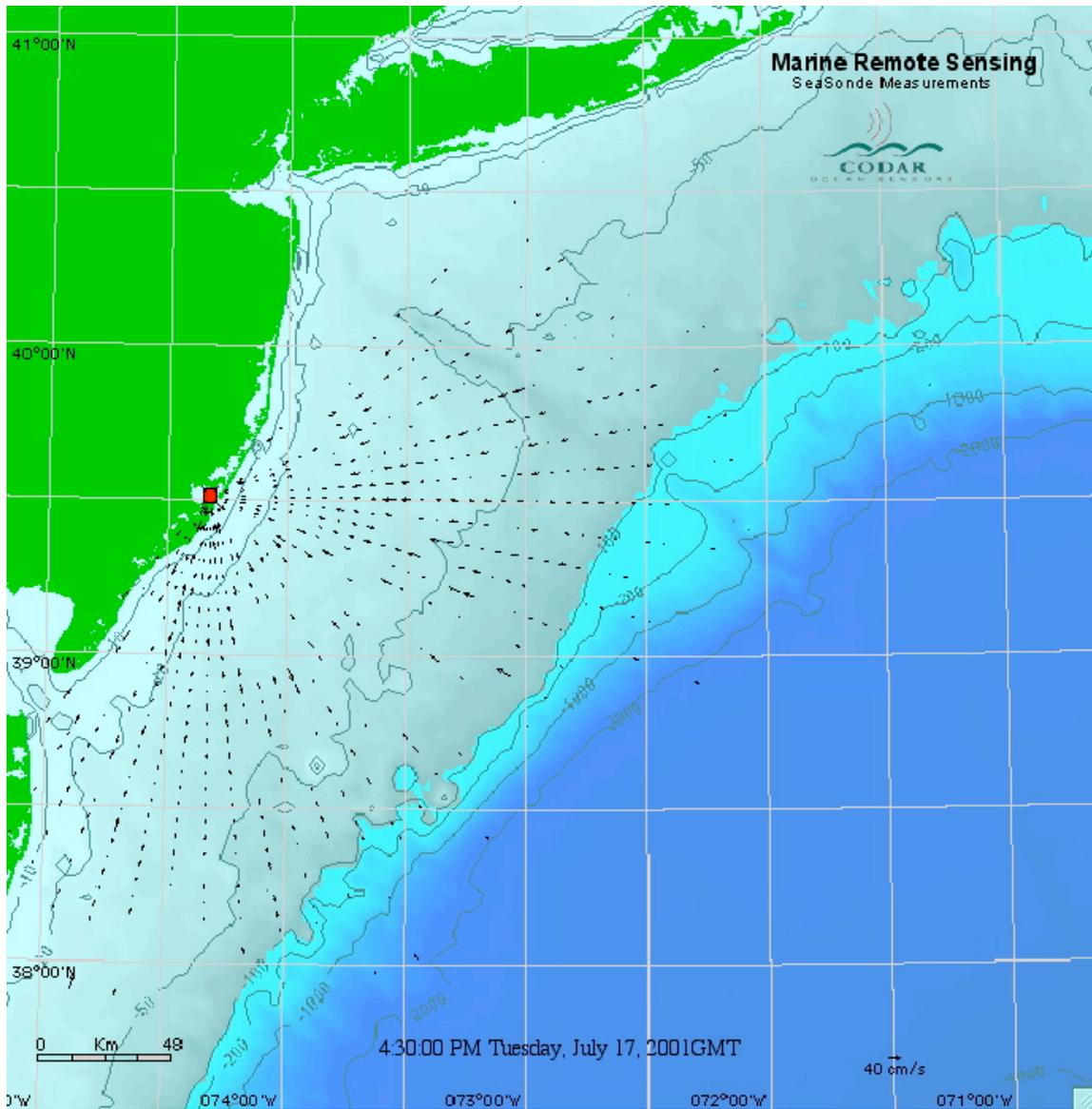


Fig. 1(a) Typical radial vector map measured by a long-range Seasonde located at Tuckerton, New Jersey. Depth contours are labeled in meters.

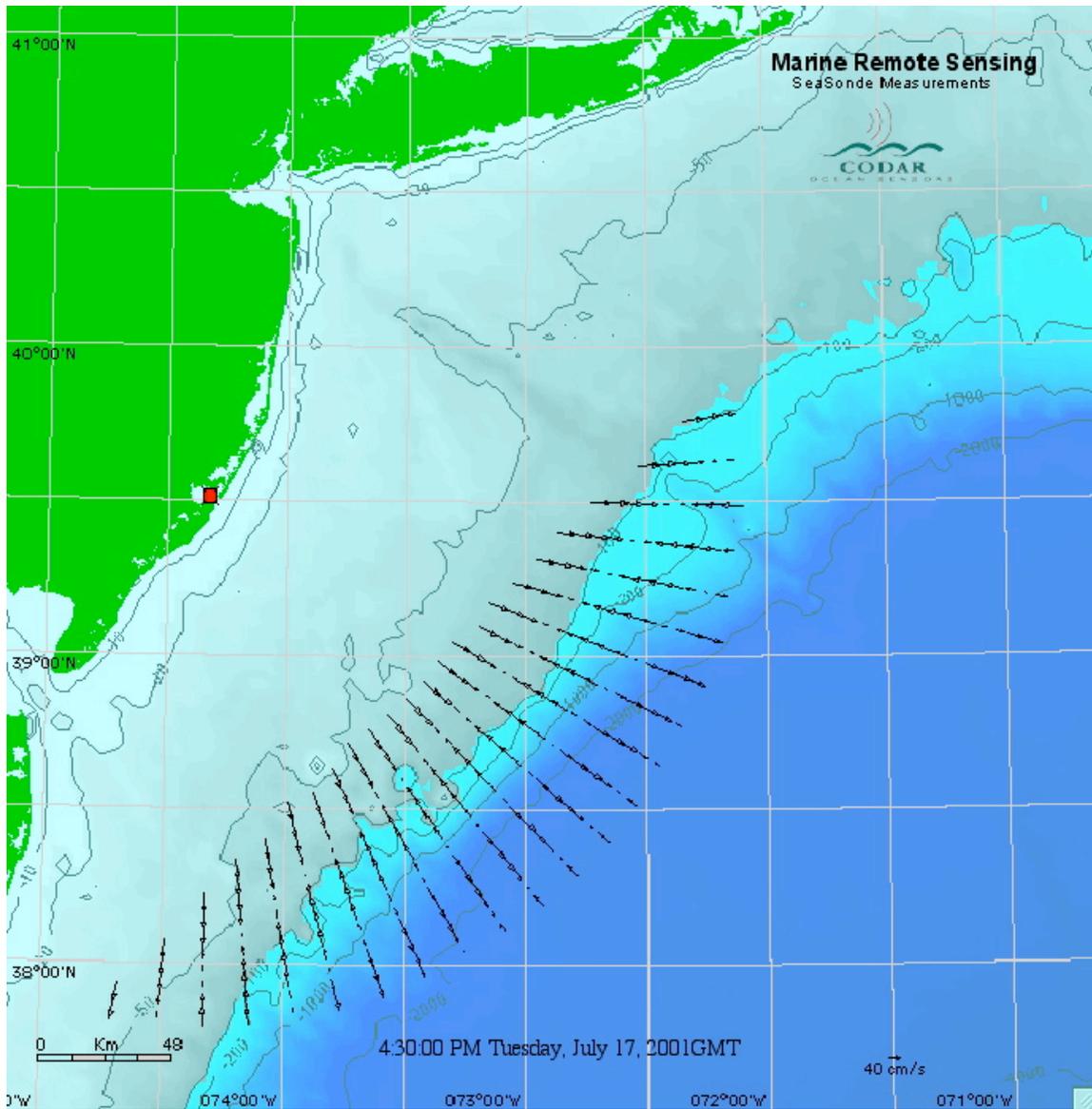


Fig. 1(b) Radial vectors due to a tsunami that has proceeded to within 100 km of the coastline. It is assumed that the tsunami signal; will be detected at the full range of the Long-Range SeaSonde i.e. 200 km.

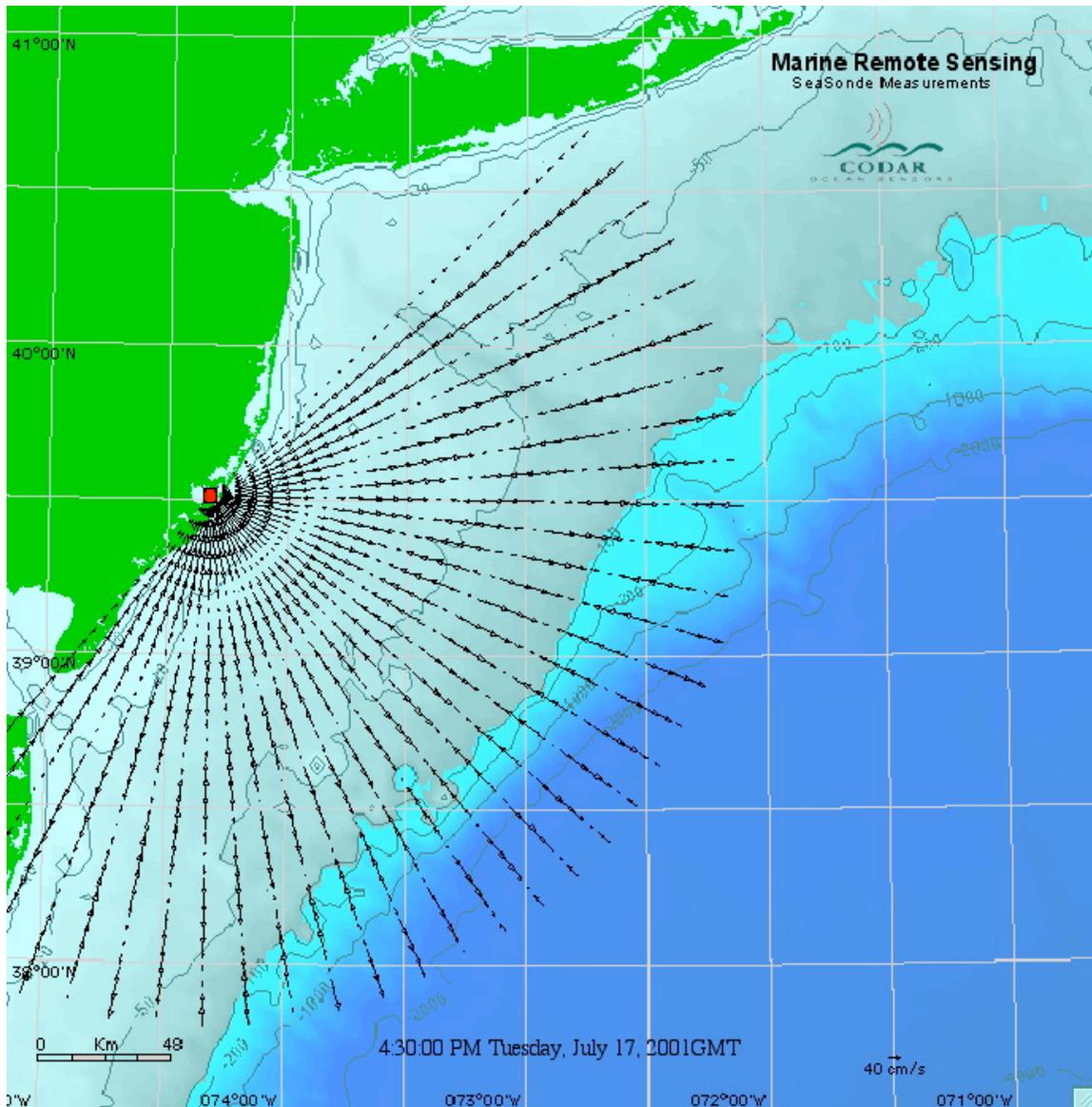


Fig. 1(c) Radial vectors produced by the SeaSonde as the tsunami reaches the coast.

IV WARNING TIMING

What is the time delay after detection before the tsunami strikes the shore? This is to large degree dependent on the water depth over the radar coverage area. We illustrate this by calculating the time delay from detection to arrival at the coast for the Indian Ocean Tsunami approaching hypothetical Long-Range SeaSondes at two locations: Penang, Malaysia and Chennai, India. Bathymetric charts for the two locations are shown in Fig. 2. It can be seen that these two cases represent examples of shallow and deep-water conditions. Fig. 3 shows the water depth plotted as a function of range toward deep water. We here assume that the tsunami signal is detectable in the Long-Range SeaSonde radial velocity map at ranges of 100 km from the radar, as for

Tuckerton, New Jersey (see Fig. 1). The maximum orbital velocities and times-of-arrival follow from (2) and (4) using the depth profiles shown in Fig. 3.

In reality a feasibility study needs to be performed for each location, based on the type of SeaSonde in use (Long-Range or Standard-Range) and taking into consideration typical current regimes for the location, in addition to the bathymetry.

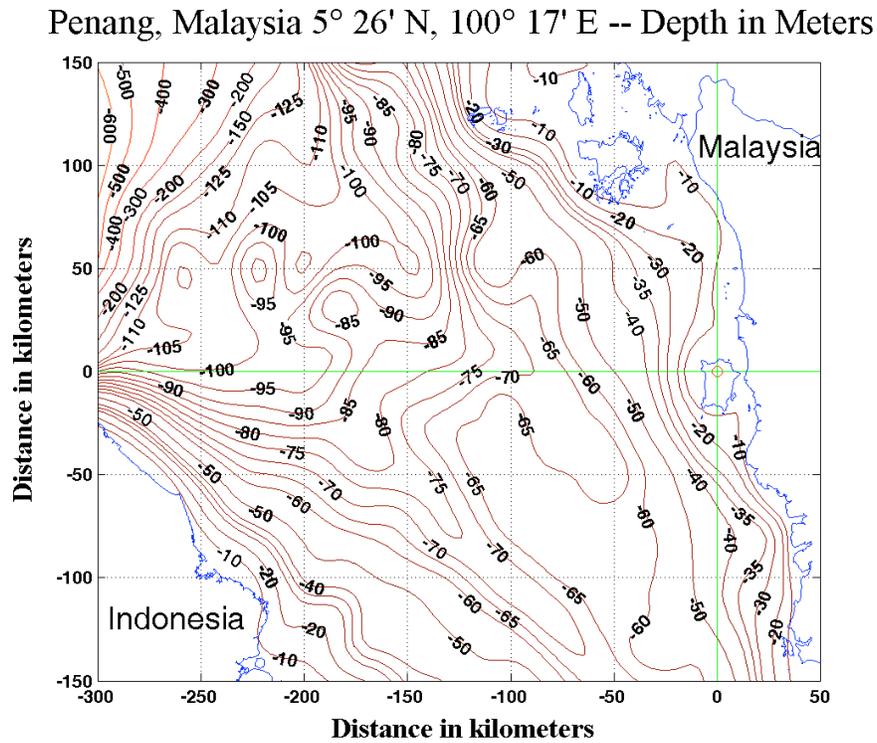


Fig. 2(a) The bathymetry near Penang, Malaysia. Coastlines are marked in blue. The simulated radar position is shown by a red circle at the junction of the green lines.

Chennai, India $13^{\circ} 05.4' N$, $80^{\circ} 16' E$ -- Depth in Meters

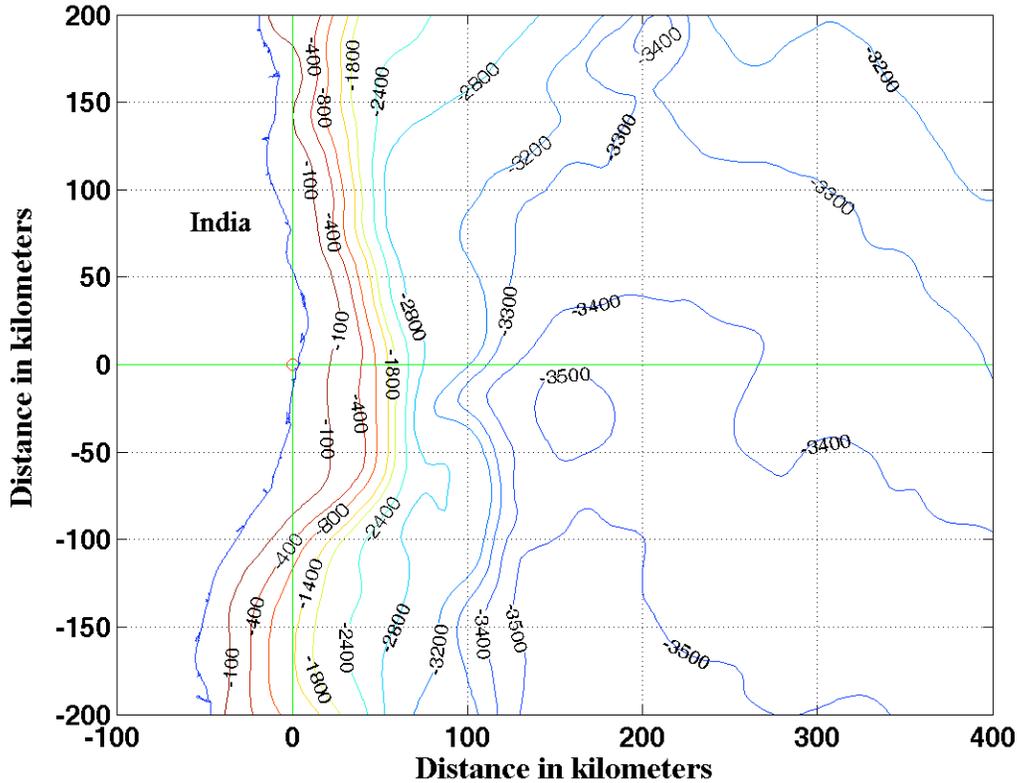


Fig. 2(b) The bathymetry near Chennai, India. . Coastlines are marked in blue. The simulated radar position is shown by a red circle at the junction of the green lines.

A. Penang

At Penang, water depth in the Straits of Malacca is less than 100 m within the SeaSonde range. From the equations of Section II, assuming the tsunami parameters described above, and a detection range of 100 km, the time delay before the tsunami strikes the shore is 96 minutes and the maximum orbital velocity is 54 cm/s, which should be clearly detectable against the ambient current background.

B. Chennai

At Chennai, the continental shelf is narrow, and the water depth exceeds 2000 m at distances greater than 60 km. As a result the maximum orbital velocity 100 km from the radar is far less (2.9 cm/s) which will make the tsunami more difficult to detect. If this weak signal can be detected, the time delay before the tsunami strikes the shore would be 23 minutes. We plan to do simulations to determine if this weak tsunami signal can be detected, based on typical current field for the region.

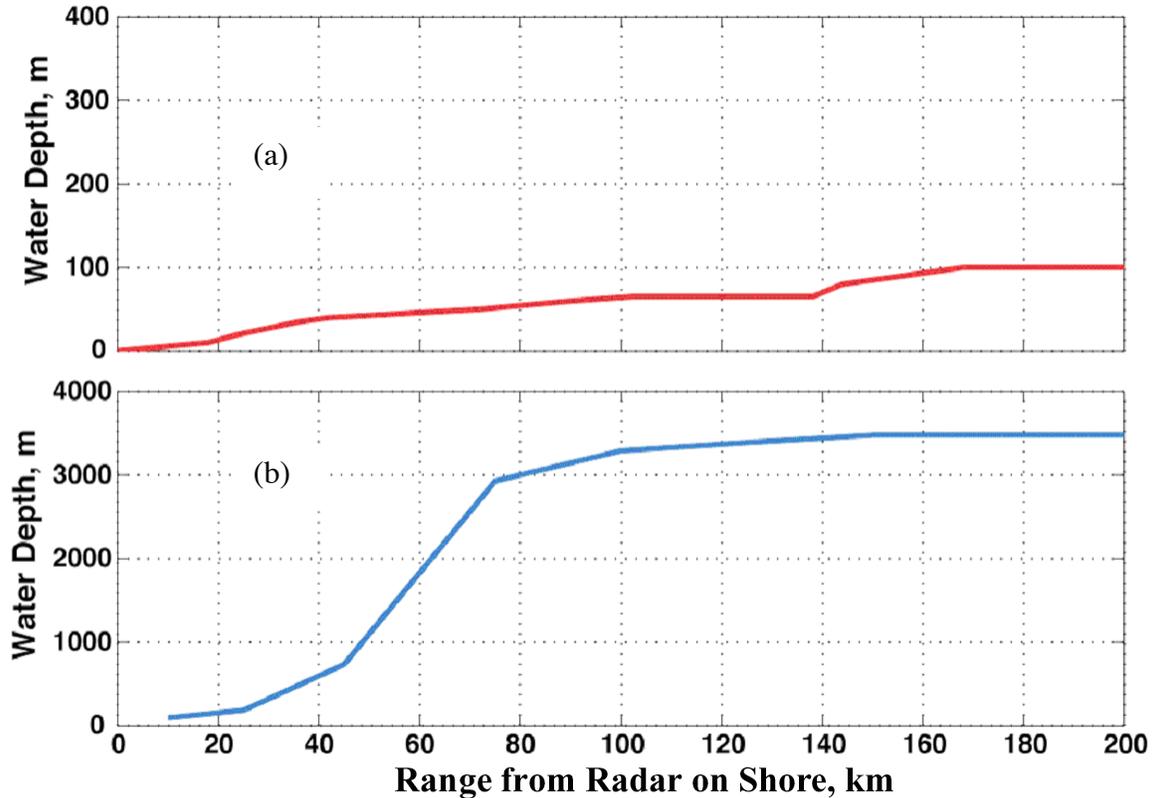


Fig. 3 The depth plotted as a function of range from the radar toward deep water. (a) Penang, Malaysia (b) Chennai, India. Note that the vertical scales for (a) and (b) differ by a factor of 10.

V. CONCLUSION

This preliminary study indicates that with shallow water bathymetry in the radar coverage areas, the SeaSonde is capable of measuring the strength and direction of a tsunami wave and providing vital information well before impact. Fig. 4 shows that shallow-water bathymetry applies over much of the area of South-East Asia that was devastated by the recent tsunami: large portions of Indonesia, Malaysia, Thailand, all of Cambodia and a good portion of southern Vietnam all are surrounded by shallow waters. This would suggest that vast areas of the Indo-Malaysian shores form an ideal region for the use of SeaSondes to monitor tsunamis. This region includes Singapore and Bangkok, both of which are of great commercial importance. The analysis described above indicates that SeaSonde installations in such locations could provide vital capability for the detection and measurement of approaching tsunamis.

We plan further studies on the effects of nonlinear tsunami dynamics on SeaSonde observations. In addition, simulations will be performed to determine limits on tsunami information available from a SeaSonde. A tsunami will be more difficult to detect if it is small or if the background current velocities are high and rapidly varying. It is therefore necessary to simulate the SeaSonde output for each location to determine how well the signal can be utilized to detect and characterize tsunamis.

Penang, Malaysia 5° 26' N, 100° 17' E Depth: Meters

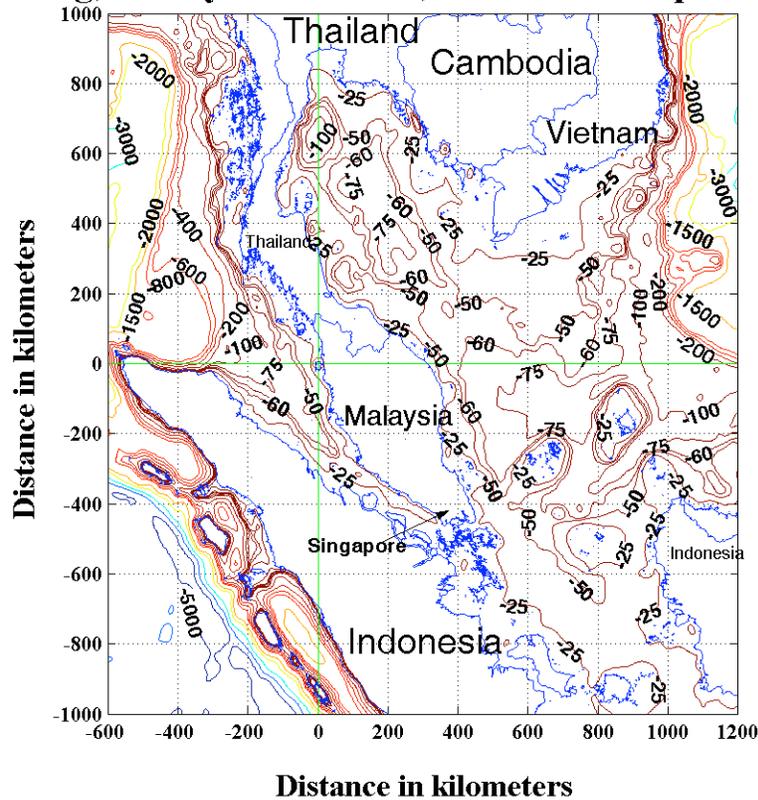


Fig. 4 Bathymetry map of area in South East Asia, showing extensive shallow water.

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