Near-Field HFSWR Detection/Warning of Tsunamis — Fact and Myth

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1 Background

The mechanism whereby HF radars see tsunamis was discovered four decades ago (Barrick, 1979). These very long waves in shallow water generate a back-forth orbital velocity of the short Bragg waves that shows up as a component of current. It was not until the catastrophic Banda Aceh earthquake and tsunami of 2004 -- in which a quarter million perished -- that significant attention focused on how to recognize these tsunami signals in the Bragg Doppler echoes. But no radars were operating that could have captured those tsunami signals from that event. Following the 2011 Tohoku Japan tsunami, a number of radars on several continents recorded raw data from which tsunami detection algorithms could be developed and optimized. CODAR SeaSondes saw this and subsequent weaker tsunami signals in 26 distinct cases.

2 Technical Approach to Tsunami Detection

Our approach has been to use only a single site's radial velocity pattern for detection. Several papers have been published (listed on the poster) that describe a "q-factor" pattern-recognition algorithm. This must find the unique, usually weak tsunami signature in a stronger background surface-flow field. Our post-processed results have shown possible warnings between 4 and 45 minutes. Detections of course are limited to the radar's coverage area. Detection comes from orbital velocity strength which depends on depth, further restricting range to the continental shelf. Within the tsunami community, this coincides with what is called the "near field" with respect to the coastal impact zone. Excluding the radar's first range cell, the math of a tsunami wave is"linear" in this near field, simplifying the model we developed. We use our model to forecast warning time and relate the radar-observed velocity to the tsunami height desired by warning centers. Our simple but adequate linear model that runs on a laptop computer contrasts with the worldwide "far-field"tsunami forecast models like "MOST", used by NOAA's Tsunami WarningCenters.

2.1 Synopsis of Understanding -- True and Not So True Factoids

Much activity, workshops, presentations, and proceedings have ensued over the past five years. Our purpose in this poster is to summarize what we know, separating facts from anecdotal speculation and simply erroneous statements.

2.1.1 A "shallow-water" tsunami wave is unique, in that its orbital velocity is essentially constant vs. depth, i.e., no vertical shear.

2.1.2 Two velocities are associated with tsunamis: orbital velocity (tens of cm/s) and profile velocity (hundreds of km/h). Orbital velocity is like a particle velocity, and transports the Bragg-scattering waves.

2.1.3 The tsunami orbital velocity sensed by the radar depends on depth to the inverse three-quarters power law. This is a strong depth dependence, increasing HF tsunami observability rapidly as it moves toward shore over the continental shelf.

2.1.4 Tsunami height has a weaker depth dependence, i.e., inverse one-quarter power.

2.1.5 Tsunamis have two sources: seismic subsea events (earthquakes) and atmospheric fronts moving across the sea surface (generating what are called meteo-tsunamis). After initiated, their propagation laws are the same.

2.1.6 An atmospheric front or storm passing across the sea surface often generates a flow pattern due to wind stress. Usually this wind-driven change in surface flow is not a meteo-tsunami, although frequently it has been erroneously called that.

2.1.7 Such an atmospheric front moving across the ocean can generate an actual meteo-tsunami when the frontal velocity is near equal to the shallow-water wave velocity for a given depth. This is known in this community as "the Proudman resonance effect. From that point on, it propagates according to the shallow-water dispersion relation.

2.1.8 Why is this an important distinction? Because a tsunami model useful for forecasting gives the both orbital and profile velocities. But a wind-stress-driven surface flow does not follow this relation -- it moves at the speed of the atmospheric low-pressure storm event.

2.1.9 Our model for near-field tsunami propagation is based on two simple equations: Newton's second law (force = mass x acceleration) and incompressibility of water. It leads to the following linear second-order partial differential equation that is easily solved with MATAB:

$$\nabla\nabla\cdot\left(d\tilde{v}\right) - \frac{1}{g}\frac{\partial^2\tilde{v}}{dt^2} = \tilde{0}$$

where $\boldsymbol{v}$ is the horizontal tsunami orbital velocity; d is water depth; and g is the gravitational constant.

2.1.10 To solve this, one specifies an initial condition (tsunami wave farther out) and boundary condition at the coast (e.g., reflecting). Example solutions are shown in the poster and in movies.

2.1.11 It remains linear in the velocity solution for a tsunami, until water depth is less than about four meters (within the first range cell). Shoreward of that point, the wave crests and breaks as its energy is dissipated into other forms (e.g., as it runs up onto the beach, between trees and buildings).

2.1.12 Scales for tsunamis that are mathematically important (both time and space) for modeling and radar observations are large. E.g., spatial scales of hundreds of kilometers for its wavelength; tens to hundreds of kilometers per hour for its profile propagation velocity; and time scales of tens of minutes. Hence bathymetry resolution scales required for modeling can be quite coarse for tsunami waves, time increments for Doppler processing can be 2 – 4 minutes.

2.1.13 It is often incorrectly claimed that long phased-array receive antennas are more useful than compact single-mast SeaSonde antennas for tsunami detection. But for sea echo the higher directive gain of a narrow phased-array beam is exactly cancelled by the larger surface-scatter area contained in the broad-beam pattern of the compact antenna. This has been confirmed by measurement and theory. Their average maximum ranges are the same.

2.1.14 Several have speculated that the HF radar can best observe tsunami waves far out, at the edge of the continental shelf, because fine-scale surface and short-time features appear there, due to nonlinear interactions. This is unsupported speculation that is easy to disprove; there are no such features. The strongest observable tsunami features occur close in, at the shallowest depths.

2.1.15 The tsunami pattern-recognition algorithmic module (called q-factor for SeaSondes) is the first step in an end-to-end procedure to generate robust warnings for effective use by national tsunami warning centers. Other required steps include filtering and correlations with other information. These additional required steps are outlined in our poster. CODAR has patents pending on this end-to-end system.

2.1.16 Metrics to optimize any end-to-end HF radar tsunami alert system are: false alarm rate and probability of detection. Of these two metrics, the goal is to optimize all software algorithms in this chain (introduced in prior bullet) so as to minimize the former while maximizing the latter.

References

- Barrick, D., 1979: A coastal radar system for tsunami warning, *Remote Sensing of Environment*, vol. 8, pp. 353-358.
- Barrick, D. et al., 2016: Coastal HF radar system for tsunami warning, U.S. Patent Application 15/140,325.