How HF Radars See Tsunamis

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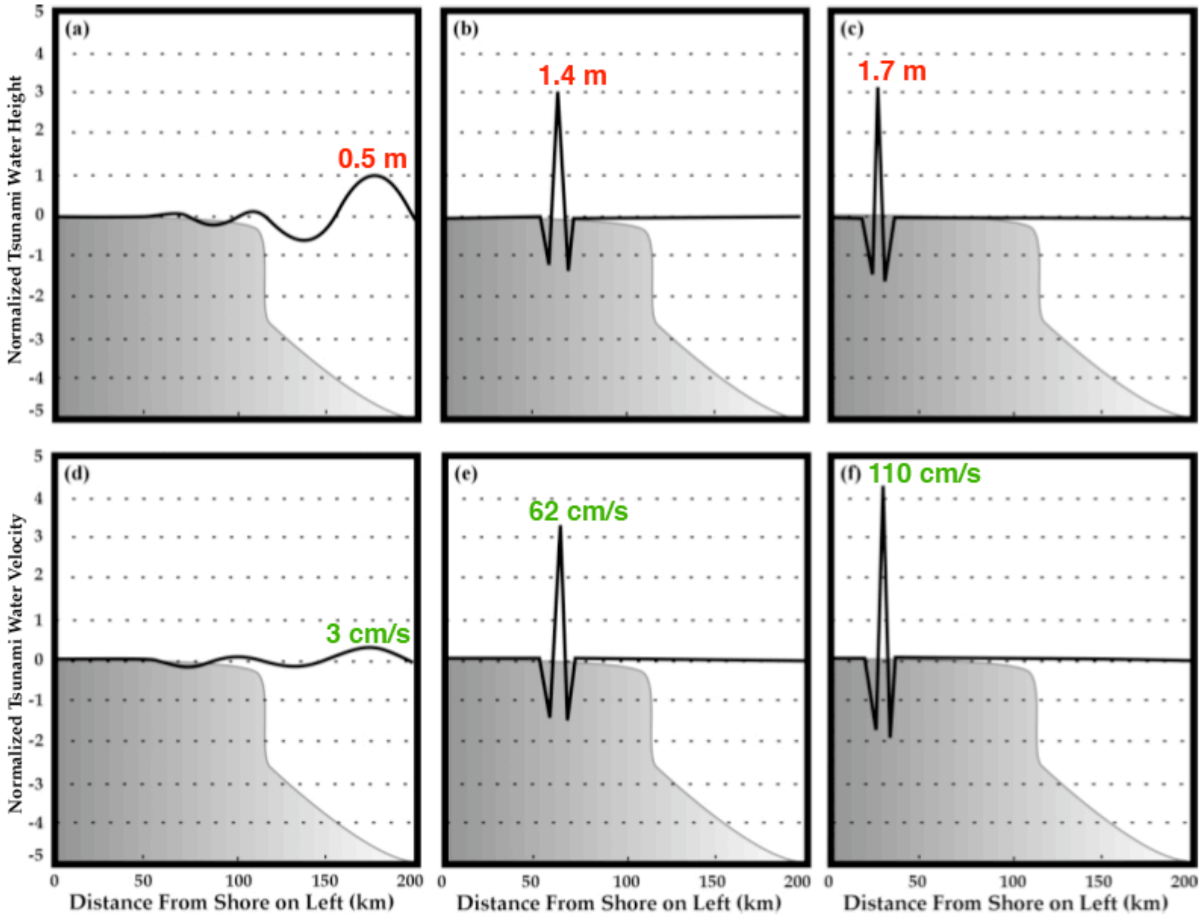
- **What is a tsunami?** A tsunami is a shallow-water ocean wave, caused by an undersea seismic event like an earthquake, volcanic explosion, or landslide at a seamount. Even though it may travel across the deepest ocean basins, it is called "shallow water" because it is always feeling and responding to the bottom depth. Typical tsunami periods might be 30 minutes, wavelengths in deep water of 600 km, and propagation speeds as high as 700 km/hour (nearly supersonic). However, in deep water, the height of a killer tsunami is only 50 cm, not enough to ever be felt by someone sitting in a boat while the tsunami passes over the course of a half hour.

- **What causes the horrible damage?** Everything changes as this tsunami moves up onto the continental shelf, into shallow water. The wave slows down. Its wavelength decreases. And its height gently increases, inversely as depth to the one-quarter power -- very slowly indeed. However, as the depth changes from 4000 m to 2 m, the height increases from 50 cm to ~3.5 m. As the depth gets shallower yet, called its "run-up phase", nonlinear energy/momentum transfers can cause this wave to rise up to 10 meters or more, a catastrophically damaging event.

- **What does the radar see?** The HF radar ***does not*** see the tsunami wave itself. However, every shallow-water wave has a "particle current" attached to it. In deep water, the particle of water at the surface orbits around in a circle whose radius is the amplitude of the water wave. In shallow water, the particle translates back and forth, as though the circular orbit were squashed down to a straight horizontal line. Short Bragg waves that the radar observes are the same as particles: they are translated toward the shore on top of the tsunami crest, and back away from the shore in its trough.

- **How does the radar measurement relate to the tsunami height?** The radar measures the velocity of these particle-like Bragg waves arrayed over the surface of the tsunami wave. While the tsunami height increases slowly as depth decreases, the particle/Bragg velocity increases much faster: as the inverse three-quarters power of the depth. Therefore as the water gets shallower, the velocity seen by the radar begins to stand out from the background circulation in that region.

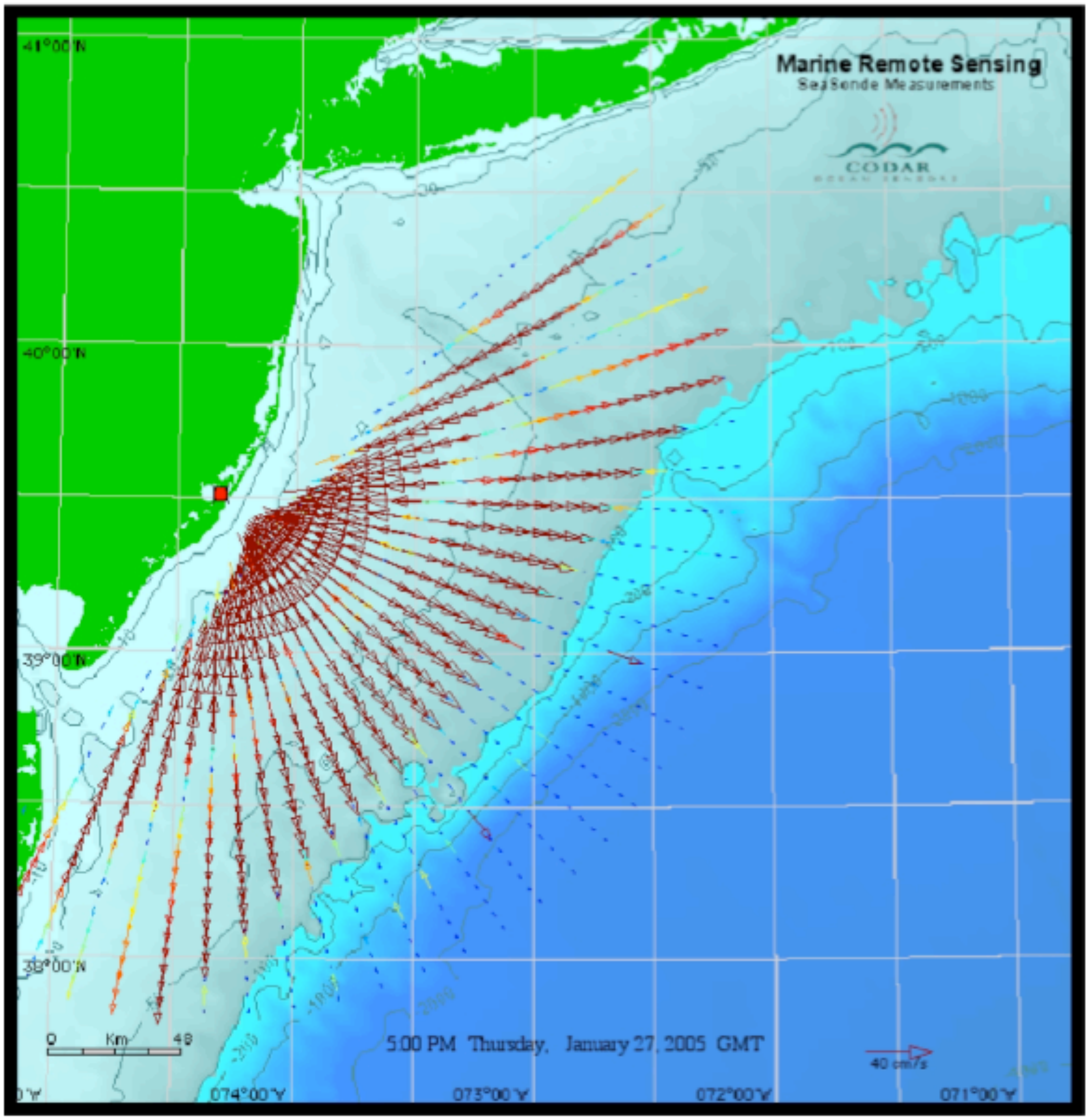
- **An example.** We show a picture of the height and radar-detected velocity as the wave propagates to the left, into shallow water (gray shading). The depth starts at about 4000 meters on the right; it represents the bathymetry off the East coast of the U.S.



The three panels across the top are the tsunami heights at three different positions as the wave moves up onto the shelf. The corresponding heights in meters (representing the magnitude of the 2004 Banda Aceh disaster) are shown in red. Directly below these are the Bragg/particle currents at the same positions. Indeed, the radar-observable current magnitude increases much more rapidly than the height. The 3 cm/s velocity would not be detectable above the background and noise. However, the currents at the other two positions stand out clearly. Anything greater than about 20 cm/s should be detectable with a good pattern recognition algorithm

- **What does the spatial pattern of an approaching tsunami wave look like?** Any wave that moves into very shallow water refracts, so that it advances very nearly perpendicular to the bottom contours, or isobaths. In most cases, these isobaths are parallel to the coast. Small features in the isobath contours do not matter. Because the tsunami wavelength even in shallow water is tens of kilometers, a bathymetry feature must be at least 30 - 40 km to cause much of a deviation in direction.

- **Do we need two radars to see the tsunami?** No, one radar is sufficient. The radials will show a distinct, recognizable pattern, such as that in the figure below. In this case, the bottom contours are nearly parallel to shore, seen as the green/gray contours.



This is a pattern of radial currents seen by a single radar on the New Jersey coast that would be produced by an approaching tsunami. The band of vectors closer to shore ride on the crest of the tsunami wave, while those further out accompany the trough.

- **Is it really this simple?** No, because what is missing in the above picture are the "background" currents. That is, before the tsunami occurred, there was the naturally occurring circulation pattern, dominated by tides, wind-driven flows, and the strong Western Boundary current called the Gulf Stream. All of these current contributors are added in, on top of the tsunami pattern. So how does one "find the tsunami"?

- **A Pattern Recognition Challenge.** Finding the tsunami pattern within the obscuring background is facilitated by capitalizing on two factors:

- The background currents don't change very much over time periods of 1 - 2 hours, while the tsunami currents change a lot over that time. Therefore we calculate continuously an average background flow and subtract it from the latest incoming radial pattern.
- Devise an algorithm that looks for onshore vectors that are nearly constant within strips parallel to the bathymetry contours, but are allowed to vary with distance from shore. This should extract the tsunami pattern that would be more difficult to detect if the view were restricted to a small cell on the ocean.

- **How does it all work?** After subtracting out an average "background" pattern, take the residual radial velocities (illustrated in above figure) and convert to a total onshore velocity that produced it. This is just simple trigonometry. Then average all these velocities (i.e., their absolute values) within each strip (perhaps 15 km wide in the offshore direction). But this average should be divided by the standard deviation of the currents within that same strip; this will account for the remaining random fluctuations that did not get cancelled in the background subtraction. We call this dimensionless ratio indicator for each strip a "Q" factor.

- **When do you sound the alarm and transmit potential tsunami data?** We suggest that when the Q-factor exceeds unity, a "watch" might begin. Above three, one might move into a "warning" mode. And finally, one should observe the pattern of Q with distance from shore; it should not be random from point to point, but should exhibit a recognizable pattern, similar to that in the radial map figure above.

- **Can we do tsunami detection while the radar is mapping normal circulation and monitoring waves? Are there any conflicts?** At first, there might seem to be conflicts, but that's not the case. In normal current mapping, radial output files are produced every hour, or even longer for some long-range radars. That seems much too long to wait if a tsunami is approaching, and indeed it is. Minutes are of the essence! Therefore, we create separate tsunami-detection radial current files at shorter intervals in parallel, while the normal current and wave extraction is running in the background. These separate files are used by the tsunami-detection algorithms.

- **Are there tradeoffs in sampling times for tsunamis?** Yes there are. One would like very rapid updates of our Q-factor tsunami detector. However, since the latter is based on determining a velocity pattern very accurately and with high resolution, a very short processing time is detrimental. Velocity resolution increases with longer processing times. So how well does the pattern recognizer work with short processing times, based on the accompanying poorer velocity resolution? See the next paragraph.

- **Do I need to make a tradeoff decision that I may regret?** No you don't. The field systems will be processing data in parallel with different spectral time samplings. They will simultaneously be calculating Q-factor detection indicators for all of these processing times. Therefore, you don't need to second-guess the unknowns: i.e., the parameters of the tsunami itself. All of this parallel-processed information can be examined for tsunami presence and its relevant details.

- **How does one optimize settings and decision processes?** No one can afford to wait for a major tsunami in order to have relevant data sets for analyses. Hence we must use simulations for continuing optimization efforts, as well as for examining new processing, pattern-recognition, and decision-making algorithms. These should be ongoing at CODAR, and most importantly, in partnership with our customer/users of the tsunami software. This will ensure the best, most relevant outcomes.

- **Are there other parts of the tsunami processing that can be improved?** Yes, the approximation of the natural irregular bottom contours by parallel strips should be replaced by smoothed, curved fits to these isobaths. This is very site specific, of course. For that reason, it is desirable here also to have customer scientists involved in this effort, in partnership with the CODAR software creators. Accompanying this will be extension of the simple parallel-strip propagation model to the actual curving geometry situation. This is -- in effect -- a 2-D model for the tsunami rather than our 1-D version.