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Tsunami Physics and Conflicting WERA Chile 2011 Tsunami Observation

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Introduction

It was recognized 36 years ago [1] that tsunamis could be detected via their orbital velocities by coastal HF radars. This "near-field" measurement contrasts with the deep-ocean DART buoy observations of their height as the wave passes overhead. It was not until after the catastrophic Tohoku Japan March 11, 2011 event that there were sufficient HF radars in place that these tsunami signals were captured at close and distant locations, from data recorded and processed off line. Since that time, SeaSonde-type radars have captured tsunami observations at 26 times and locations [2, 3, 4, 5], and the WERA phased-array type system has partially observed a tsunami once [6].

Recently, Heron et al. [7] have interpreted the single observation of the Japan event from a WERA system in Chile. He discusses a paradox, in that the radar observations did not follow accepted linear tsunami physics, which he calls "Green's Law." These accepted physical principles dictate a strong dependence of radar-observed orbital velocity on water depth (with a weaker dependence of height on depth).

The next section summarizes the Chile tsunami observation, and Heron's [7] interpretation of the disagreement with expectations. Then in the third section we summarize results of linear tsunami shallow-water physics that are analyzed in greater detail in the appendix. The fourth section discusses the problems with Heron's interpretation of the Chile observations, as attributed to inapplicability of tsunami physics that underlies accepted models such as NOAA's MOST [8, 9]. This puts into question the relevance and adequacy of his optimization method for HF radar design and siting presented therein, as these are predicated on the validity of the Chile findings in lieu of accepted tsunami physics and models. Finally, we give the most likely explanation for the puzzling observation, namely a known system malfunction.

The Chile Observation

The single radar was set up to record tsunami signals in the hours before its arrival at a site near Concepcion, Chile. This operated at 22 MHz, which has a typical range (for the power radiated) of 40 km for currents. Current components pointing toward/away from the radar are captured within beams formed by the receiving antenna array. The orbital velocity of the shallow-water tsunami wave is therefore part of the current signal, which also includes other background contributions (tides, geostrophic flow, etc.). The echoing mechanism is Doppler shift of Bragg-scattered spectral peaks from short waves (i.e., ~7 m) that are half the radar wavelength. The tsunami component of these currents is identified from their typical periods that lie between 20 – 45 minutes. They are clearly recognizable when one plots them as velocity (in color) vs. elapsed time and range from the radar. We repeat Fig. 3 from [6] of the Chile radar tsunami observation to facilitate this discussion.

Dashed lines in the adjacent Fig. 3 [6] give the depths within the main radar beam pointed offshore. The first dominant tsunami peak can be seen as the vertical stripe (red at the bottom, trailing off to yellow vs. range) at ~05:07 UTC on March 12, ~22 hours after the Japan earthquake (as confirmed by NOAA's MOST model).

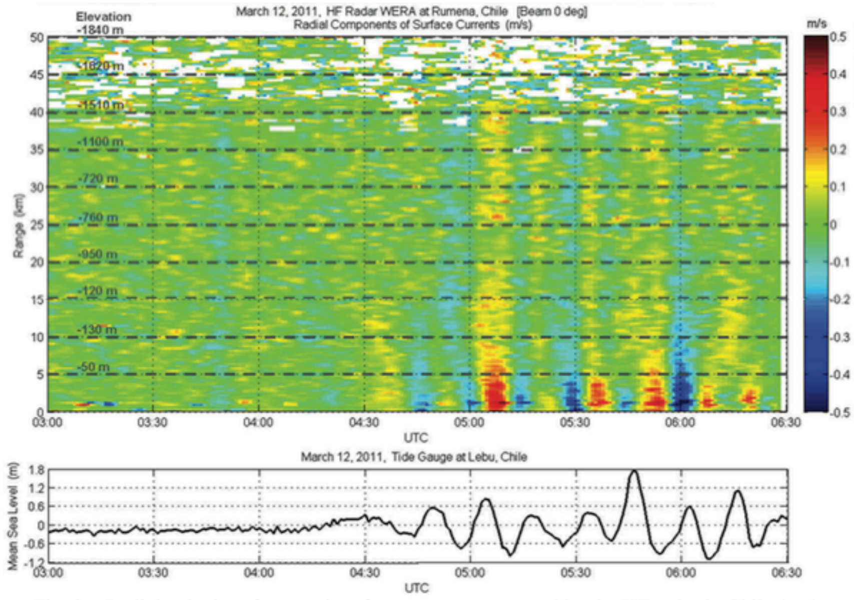


Fig. 3. Radial velocity of tsunami surface currents measured by the HF radar in Chile (top); mean sea level measured by the tide gauge in Lebu, Chile, during the tsunami hitting the Chilean coast (bottom).

The depth contours define a short continental shelf, followed by a steep slope. From a depth about 50 m at 5 km, depth drops to 1000 m at distance of 34 km, i.e., a steeply sloping region within a ~29 km span. From there, depth decreases slowly with distance beyond the shelf/slope region. However, the tsunami orbital velocity between these ranges (5 km @ 50 m depth and 34 km @ 1000 m depth) varies between ~0.2 m/s and ~0.12 m/s. ***That the tsunami was seen is not in contention; the periodicity of tens of minutes clearly confirms this.***

Tsunami Propagation Physics and Water Depth

It is long accepted that a tsunami is a shallow-water wave that propagates under the restoring force of gravity. For a typical 30-minute period, its wavelength varies between tens and hundreds of kilometers. When depth is considerably less than wavelength (maximum ocean depths are ~4000 m), the water is "shallow" by definition, and wave propagation speed is $\sqrt{gd}$, where g is the acceleration of gravity and d is water depth (i.e., several hundred km/h).

A simple "ray-optics" depiction of tsunami wave height and orbital velocity variation with depth was given in [1] and is referred to as Green's Law in [7]. This approximation, while not perfect, provides insight to basic expected tsunami depth dependence, and is invoked by the NOAA MOST model developers [8, 9] as a ***rough*** guideline for their expected outputs. By this approximation, the tsunami wave will refract so that it always comes in perpendicular to bathymetry contours (isobaths). Its height and orbital velocity change with depth as $d^{-1/4}$ and $d^{-3/4}$, respectively. (Orbital velocity is what the radar observes.) In order to be strictly valid (i.e., not an approximation), depth must change slowly with respect to tsunami wavelength. When this is true, there is no reflection from steep subsea depth changes such as a sharp shelf edge or a seamount.

In practice, an adequate model cannot be built on this simple ray-optics approximation. Subsea reflections from sharp depth changes, as well as failure to follow Snell's Law for ray refraction, necessitate a model that accounts properly for these effects. NOAA's MOST model, as well as ours and those of others, are predicated on a simple linear equations (and their numerical solution). These are discussed in more detail in our Appendix, as well as numerical outputs that are important to interpreting the unexpected Chile observations.

Heron's Interpretations of the Radar Observations and Problems with It

As we saw from the above figure, the tsunami orbital velocity between these ranges (5 km @ 50 m depth and 34 km @ 1000 m depth) varies between ~0.2 m/s and ~0.12 m/s, a ratio of 1.7:1 (at time 05:07 UTC). Heron et al. [7] observed this from their observations, and were concerned. The Green's Law cited above would have predicted a ratio of $\left(\frac{d_2}{d_1}\right)^{3/4} = \left(\frac{1000}{50}\right)^{3/4} = 9.5:1$. This is a huge difference! Heron's interpretation is that their radar observations have proven that the linear Green's Law for tsunami physics is inadequate. Indeed, Green's Law (the ray optics approximation) does not explain their radar observation. Heron speculates that this is due to nonlinear reflection from the steep subsea continental shelf, that blocks the stronger velocity from farther out from reaching coast. Or the converse: this type of phased-array radar can see detectable velocities in very deep water (greater than 1000 m it is claimed), well off the continental shelf, whereas less capable systems like SeaSondes need the shallow water of a continental shelf for detection.

First of all, all applicable models, including NOAA's MOST, are based on linear equations in the regions over which HF radars observe. This is detailed in our Appendix. There we run a model with these same equations (movie is discussed in Appendix); we also give an independent result based on the NOAA MOST equations. In both cases, a sharp shelf going from 1000 m to 50 m was modeled. One occurs over a 26 km distance, the other from the MOST equations was a vertical escarpment going from 1000 m to a shelf of 50 m. Indeed, there is a velocity reflection of the incoming wave at the shelf that cannot be predicted by the ray-optics model. However, the velocity ratios from these linear equations underlying the models are 7.5:1 (our model) and 7.3:1 (NOAA steep escarpment). These are less than the Green's Law 9.5:1, but far from the WERA ratio of 1.7:1. As stated in the NOAA references, their outputs have behavior that is close to Green's Law, meaning that depth is indeed important as the tsunami wave moves onto the shelf in shallow water, even with reflections properly included. Thus their observed radar velocities that have a very weak dependence on depth cannot be explained by any of the existing, long-accepted tsunami propagation theories or models.

Additional factors in the above figure mitigate against the claimed observations and their interpretation at great distances (45 km) and great depths (1000 m).

a. Beyond the shelf, where depths change more slowly, from 760 m at 25 km to 1510 m at 40 km, "observed" velocity is nearly constant. By the simple Green's Law or ray optics (which should apply here), velocity should change by the three-quarter power of the depth ratios, i.e., ~1.7:1. Their radar data does not vary with depth, showing no change at all.

b. By far the overwhelming argument showing the impossibility of a tsunami observation at 40 km originating from that distance is simple causality. The perfect vertical nature of the observed tsunami stripe at ~05:07 UTC means the tsunami velocity surge wave would have taken "zero time" to travel between 40 km and the coast. Yet even the most conservative estimate for phase velocity of the wave propagating over the varying depth says it should take at least 12 – 15 minutes. The scale is expanded sufficiently to show that there is not even a couple minutes difference. If this were an actual tsunami observed by their radar at greater distance, the "vertical" stripes would be visibly slanted to the left as one goes upward.

Alternative Interpretation of Chile Contradictions: Radar Malfunction

The contradictions enumerated above clearly show that tsunami echoes claimed and shown as having come from far out deep water cannot possibly be real. And hence this negates the conclusions Heron et al. draw therefrom: that tsunami theory that underlies not only ray-optics (Green's Law) but also all accepted linear propagation theories including NOAA's MOST model, are in serious error because this radar shows that depth matters very little. Such a conclusion flies in the face of long accepted practice. Rather, all of these contradictions seen in Chile are explained by a system malfunction that many have been aware of: signal aliasing resulting from WERA's transmit-while-receive operation.

- Five groups worldwide today have designed, build, and market HF radars that use FMCW signals for backscatter. Only WERA operates in a mode that transmits while receiving with a simple baseband sweep demodulation scheme. The other four either pulse while sweeping the signal so as to avoid this dilemma (i.e., they do not transmit while receiving). Or, they digitize at a much higher frequency than baseband, eliminating the possibility of "range aliasing." The other four groups account for over >90% of the HFSWRs in the world today.

- All of these four groups have tried the non-pulsing mode, most of us decades ago. Everyone but WERA abandoned it because of the aliasing problem.

- The "Aliasing Problem" Explained: Simple radar physics (e.g., propagation path loss) shows that strong Bragg echo from nearest range cells (which includes tsunami signals) can exceed that in outermost cells where one wants to analyze current/tsunami information by 120 dB (twelve orders of magnitude).

- System dynamic range greater than 80 dB is difficult to maintain over time, under varying environmental, systematic, or aging conditions. When system dynamic range is exceeded, nonlinearities and/or imbalances cause strong close-in echoes and other strong spurious signals to "alias", or be spread into far-out weaker cells, leading to a false interpretation. We often refer to this negative impact as "ringing."

- WERA does attempt to mitigate this problem somewhat. The transmit antenna is designed to "focus a null" in the direction of the receive antenna, to limit the intensity of the strong signal being swallowed. Such cancelling techniques can rarely maintain a null greater than 10 – 20 dB over an extended time. That is not enough.

- As a result, strong Bragg signals close to the radar appear at the same Doppler shifts at farther out ranges, where Bragg echoes could never have occurred. This is exactly what is seen in the above Fig. 3 from [6].

- This undesired phenomenon cannot be predicted from day to day, or system to system. Sea echo and environmental conditions change. Old hardware will naturally deteriorate over time. Many of us have tried to "beat this", and realized long ago that sound practice simply dictates that one avoids transmitting while receiving with backscatter geometries. When it occurs, "far-out" false aliases can appear perfectly valid. One must use other known physics to determine when this happens, as we have done here. But it is often tempting to believe distant observations that appear "too good to be true." That is the case here.

Conclusions

The WERA HF radar data that observed the 2011 Japan tsunami from Chile found a very slow variation in the tsunami orbital velocity vs. depth offshore. This differs drastically from the ray-optics (Green's Law) explanations for tsunami propagation. It also differs nearly as drastically from the linear theory that underlies model outputs, that is the basis, for example, of NOAA's MOST that is used worldwide. These models (including ours here) are in agreement with each other, and predict a significant increase in velocity as the tsunami propagates from 1000 m to 50 m depth, even over short horizontal scales where there reflection from the subsea shelf slope is included. Finally, this solitary, their unexpected tsunami observation differs in this respect from 26 other HF radar tsunami observations [2 – 5].

Heron [7] draws the conclusion, therefore, that the existing linear theories do not explain tsunami propagation. He then uses these results in an attempt to optimize phased-array-type radar performance for tsunami warning. He claims that large phased array radars such as WERA can detect the tsunami far offshore, in water greater than 1000 m deep, whereas the prevailing compact design (with crossed-loop antennas) cannot; see also [10]. We disagree with this assessment that effectively would overturn accepted tsunami theory, models, and many measurement findings. What's more, even simple causality abnegates his conclusion: WERA saw the tsunami far offshore at the same time it was observed to arrive at the coast (with no time delay that must occur due to its finite propagation speed). This is impossible!

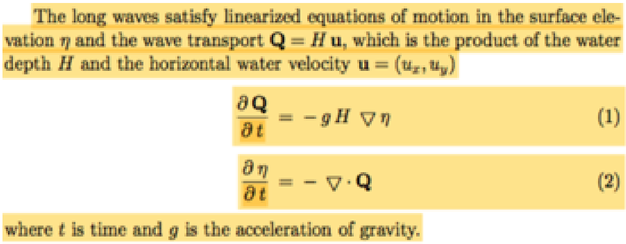
But even if it were true, what then would be the value of a coastal HF radar for tsunami warning? If it saw the tsunami at the same time far out as when it arrived at the coast, then there would be no warning.

The remaining explanation for this observational contradiction is system malfunction. It is perfectly explained as aliasing that results when echoes from close in spill out into distant range cells where no echo could have been observed. It happens because their system transmits while receiving. This causes the dynamic range of the receiver to be exceeded, a phenomenon others discovered decades ago. It has led the others to abandon this simpler choice in favor of pulsing/gating the FMCW signal to avoid transmitting while receiving. Therefore, his optimization based on this instance of faulty Chile radar performance is meaningless.

Appendix: Linear Theory and Tsunami Modeling

Within "near-field" coastal zones over which HF radars measure (1 – 100 km), the equation basis that predicts tsunami propagation is linear. The NOAA scientists who developed the basis for the world-accepted MOST model that predicts worldwide tsunami propagation from its source and arrival at distant continents make this clear in their publications over the past two decades [8, 9]. Nonlinear effects come into play only during the run-up phase onto the shore. Coriolis and spherical earth effects are important only when traversing ocean basin-wide distances.

Two simple equations form the basis for NOAA's MOST model (as well as our own and that of others). These are copied from [9] by Mofjeld, Titov, et al. These NOAA scientists make the point that although the equations below are critical for accurate tsunami models, the simpler Green's Law approximation serves as a rough, simple guide for depth variation of height and velocity.


The long waves satisfy linearized equations of motion in the surface elevation η and the wave transport $\mathbf{Q} = H\,\mathbf{u}$, which is the product of the water depth H and the horizontal water velocity $\mathbf{u} = (u_x, u_y)$

$$\frac{\partial \mathbf{Q}}{\partial t} = -g H \nabla \eta \qquad (1)$$

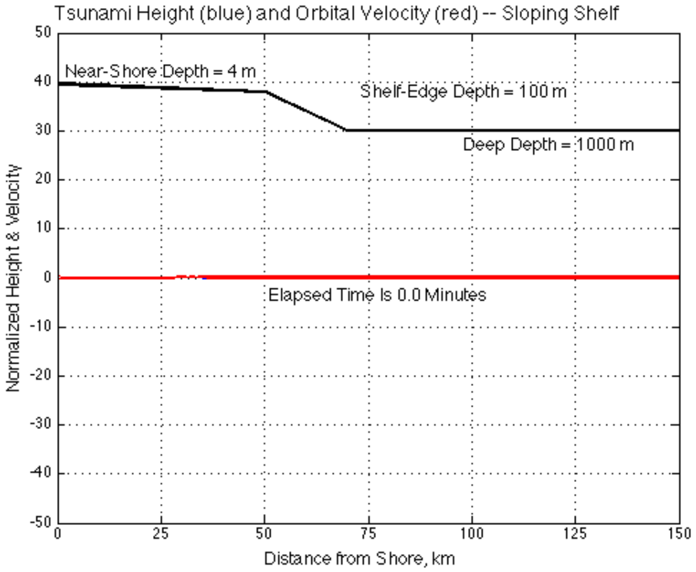
$$\frac{\partial \eta}{\partial t} = -\nabla \cdot \mathbf{Q} \qquad (2)$$

where t is time and g is the acceleration of gravity.

The first equation is merely Newton's second law, while the second gives the incompressibility of water. These linear equations are solved using simple partial differential equation tools, employing the actual bathymetry (depth) of the sea: $H = d$. Such models include reflections both from subsea bathymetry features as well as the coast, which the simple Green's Law approximation misses. Heron apparently believes in MOST model outputs because he uses archived versions to study tsunami propagation. What he apparently misunderstands is that those models are linear, because he dismisses linear models as being unable to account for the contradictory Chile radar observations: minimal orbital velocity change with depth as the tsunami passes across subsea shelf edges. To illustrate this point and study propagation across sharp shelf edges as found on the West coast of the Americas, we use these equations in our own model to produce estimates of velocity change as the shelf is crossed. We follow this with an independent confirmation from Mofjeld,Titov et al. [9] of reflection and transmission across a subsea vertical escarpment (even more severe than a sloping shelf).

- **Linear-equation model outputs for steep continental shelf.** We solve the linear equations behind the NOAA MOST model shown above using a standard MATLAB PDE tool-box solver. For simplicity, we show one-dimensional profiles for a generic shelf-edge bathymetry that goes from 1000 m to 100 m over 20 km distance. This roughly represents the situation off Chile, and also for a meteo-tsunami we observed off the New Jersey coast in 2013 [5]. This allows us to study reflection and transmission across the shelf. Features to note in the movie model output are:

- Velocity and height waves come in from the right toward the left. Each is normalized to unity on the right where depth is constant at 1000 m. The movie can be viewed by going to: https://www.youtube.com/watch?v=LXDq69Aadk8



- The heavy black profile at the top is a depiction of the water depths, showing the shelf to the left, the slope, and deep-water region to the right.

- Red is velocity and blue is height. Note that velocity grows much quicker than height as depth decreases on the shelf, following the classical behavior of the earlier "Green's Law", even though this law is not specifically used here because the linear equations are solved exactly.

- Elapsed time in minutes is given in each frame of the movie.

- A Neumann boundary at the coast on the left ensures that normal velocity is zero there. (We can also use partially absorbing boundary conditions at the coast.)

- Hence, height remains positive after coastal reflection, while the sign of velocity reverses for the outgoing wave. Although it is below the visibility threshold in the movie, the same is true for reflection at the shelf-edge ridge: reflected velocity is negative to the right of the shelf.

- After reflection at the coast, one observes another strong backward reflection to the left, as the wave propagates outward across the shelf edge. In fact, this backward-reflected wave explained the "meteo-tsunami" as it impacted the coast, seen in 2013 off New Jersey by SeaSonde, with only a 4 – 5 cm/s orbital velocity [5]. The original tsunami was launched via the Proudman mechanism by a fast-moving weather system traveling offshore West to East. This is confirmed in our model (above) as well as in NOAA's and another model.

- **Application to Chile Observed Velocities and Offshore Bathymetry.** To study the puzzling results observed at 22 MHz off Chile, we refer to Fig. 3 of [6] repeated earlier. It shows velocity (color intensity) vs. time in minutes and distance offshore. Also shown are water-depth dashed-line markers vs. range offshore along the radar beam.

- Observe the first strong tsunami peak seen at about 05:07 UTC. At 5 km where the depth is 50 m, the tsunami velocity is about 0.2 m/s. Going outward in range at the same time along this band, the velocity is ~0.12 m/s at 34-35 km where depth is about 1000 m. The velocity ratio at these depths is 1.67.

- Now, apply the Green's Law approximation. The velocity change should have been the ratio of depths, 1000/50 to the three-quarters power. That would be 9.55. Clearly this departs greatly from their radar observation. Heron [7] also called attention to this conundrum, making the point that Green's Law cannot explain their observation. Indeed it cannot.

- Using the linear model outputs behind the movie, examine now the ratio of the velocity at 1000 m depth (far right in movie) to that at 50 m (at a distance of 25 km), up on the shelf. This ratio is about 7.5. Compared to Green's Law (no reflection), this implies that the shelf-edge reflection removes a bit of the forward velocity, so that the transmitted on-shelf value at this point is less than that for the no-reflection Green's Law. This makes sense. However, it is still greatly different than the puzzling Chile radar observation.

- As a final check, compare to the example considered by the NOAA MOST developers, Mofjeld, Titov, et al. [9]. Their Section 3 treats lineal escarpments. This is an underwater vertical cliff. We consider a case where the depth contrast is 50:1000. Using the same linear equations behind their MOST model, they obtain a closed-form transmission coefficient for velocity that gives 7.31. Meaning it is close to that found from our movie model output for a steep (but not vertical) shelf. The two are in close agreement.

- The their observed radar behavior is far from these three calculations that are all based on linear tsunami propagation physics. Again, the their observation implies that velocity changes very little with depth when going between 1000 m and 50 m. Their conclusion is that linear tsunami propagation physics behind both Green's Law and the full differential equation models (that include NOAA's MOST) are incorrect. It also gives a false hope that HF radar is much more capable than has been known for years, namely it says that depth matters little and HF radars (of the WERA type, [10]) can observe a tsunami much farther than previously believed possible.

- Examine further their Fig. 3 above from [6]. Follow the velocity at this time (05:07 UTC) but farther out. At 1500 m depth, the velocity remains essentially constant from its value at 1000 m. In other words, where the bottom slope is now small and Green's Law should apply and change by a factor of 1.35, there is no velocity change. This defies all accepted tsunami understanding.

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