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DONALD E. BARRICK

NOAA / ERL / Wave Propagation Laboratory, Boulder, Colorado 80302

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A Coastal Radar System for Tsunami Warning

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NOAA/ERL/Wave Propagation Laboratory, Boulder, Colorado 80302

A high-frequency radar system which has been used at coastal locations for measurement of surface current and wave fields is suggested and analyzed as a tsunami detection and warning system. This system would detect the presence and magnitude of a tsunami as it approaches the shore by observing the to-fro current pattern produced by the orbital velocity of the tsunami wave. For the radar system presently in existence, typical warning times exceeding 45 min are shown to be possible for Pacific United States coastal locations.

Introduction

A tsunami, sometimes incorrectly called a "tidal wave," is produced by an earthquake near or within an ocean basin. Official tsunami reports filed at the International Tsunami Information Center in Hawaii show that, on the average, 20 tsunami-genic earthquakes occur per year; of these, about four to six tsunamis of sufficient magnitude occur to cause varying amounts of destruction and loss of life. An example is the tsunami of March 28, 1964, which was generated at Prince William Sound in Alaska. Fatalities totaled 122, and over $104 million in damage resulted as far south as Crescent City, California (Spaeth and Berkman, 1967). Whereas the wave height at Crescent City exceeded 4 m (the exact excursion was unknown because the tide gauge was broken by this wave), the wave height on the open ocean for this tsunami was only 25 cm. As a result of such low wave heights on the deep ocean, Harvey (1978) notes that no tsunami has ever been detected in the deep sea.

A functional tsunami early warning system is presently nonexistent. When an earthquake occurs and its epicenter is located, a tsunami watch is initiated. The switch is made to a "warning" mode only after coastal tide gauges record the onslaught of the first wave; these instruments are often rendered inoperative by the force of the wave. Although some warning can then be afforded to other coastal regions, this "system" (or lack thereof) provides too little, too late. It yields little quantitative information as to the parameters (e.g., energy) of the tsunami for use in prognoses of its impact on other coastal areas.

Tsunami detection on the open ocean is not possible with known observation techniques from ships, aircraft, or satellites. Bottom pressure sensors have long been known to be able to detect a tsunami, but an effective ever-ready network of such sensors—coupled to a real-time readout and analysis system—is

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deemed beyond the realm of practicality because of cost considerations (Shinmoto and Vitousek, 1978). These authors describe an air-deployable pressure-transducer system which would be installed after occurrence of an earthquake; studies as to aircraft siting scenarios versus system effectiveness need to be completed, followed by a considerable commitment of resources. Detection of fluid motion based on electric field measurements at the sea bottom is in the research stage (Larsen and Daniel, 1978); details and costs of a workable system using this principle are not yet available.

We suggest a coastal hf (high frequency) radar system which can provide, typically, a 45-min warning, along with relevant parameters (e.g., wave height, period, direction) that can be used in tsunami propagation and run-up predictive models [See Symposium on Tsunamis (1978), for several summaries of the latest studies on this subject]. This radar system has the advantage that it would be installed along the coast of the continental United States, Alaska, and Hawaii for monitoring of coastal current and wave field patterns; only minor additional software would be required to switch this system (when already in place) to a "tsunami warning" mode after the occurrence of an earthquake.

Technique

Barrick et al. (1977) have described a small, low-powered, inexpensive coastal hf radar system which measures and maps near-surface currents in near-real time. This system can monitor such currents to a distance of ~70 km from shore, with an areal resolution grid as fine as 1×1 km. The system measures currents by observing the Doppler frequency change of the sea echo scattered from ocean waves one-half the radar wavelength. At 25 MHz radar frequency, this corresponds to scatter from ocean waves 6-m long. The phase velocity of these relatively short ocean waves is affected by currents lying within the upper 50 cm of the mean ocean surface. As little as 128 sec of radar observations can provide sufficient data for a map of the current field. Recent processing improvements (Barrick et al., 1978) show that the radar-deduced rms current accuracy is of the order of 10 cm/sec (possibly better, but we are presently limited by the inaccuracy of the technique used for comparison). We therefore assume here that currents having 10 cm/sec or more departure from the mean ambient current field can be detected by the system at a range of ~60 km (allowing for processing and confirmation time).

As the tsunami wave approaches shore, propagating into ever shallower water, several things happen. While the wave's temporal period remains fixed (e.g., 20–30 min), its height increases, its spatial period decreases, its phase and group velocities (which are equal) decrease. As a result, the tsunami-induced orbital velocity of the water underlying various parts of the surface wave increases. Over distances comprising several radar resolution cells (i.e., >2–3 km), this orbital water velocity near the surface is indistinguishable from a surface current, and it will alter the phase velocities of the 6-m waves being observed by the radar. A sketch of the pattern of such a tsunami wave train approaching shore is shown in Fig. 1. When v_M, the maximum orbital velocity, exceeds 10 cm/sec, it will be detectable by the radar if it is within 70

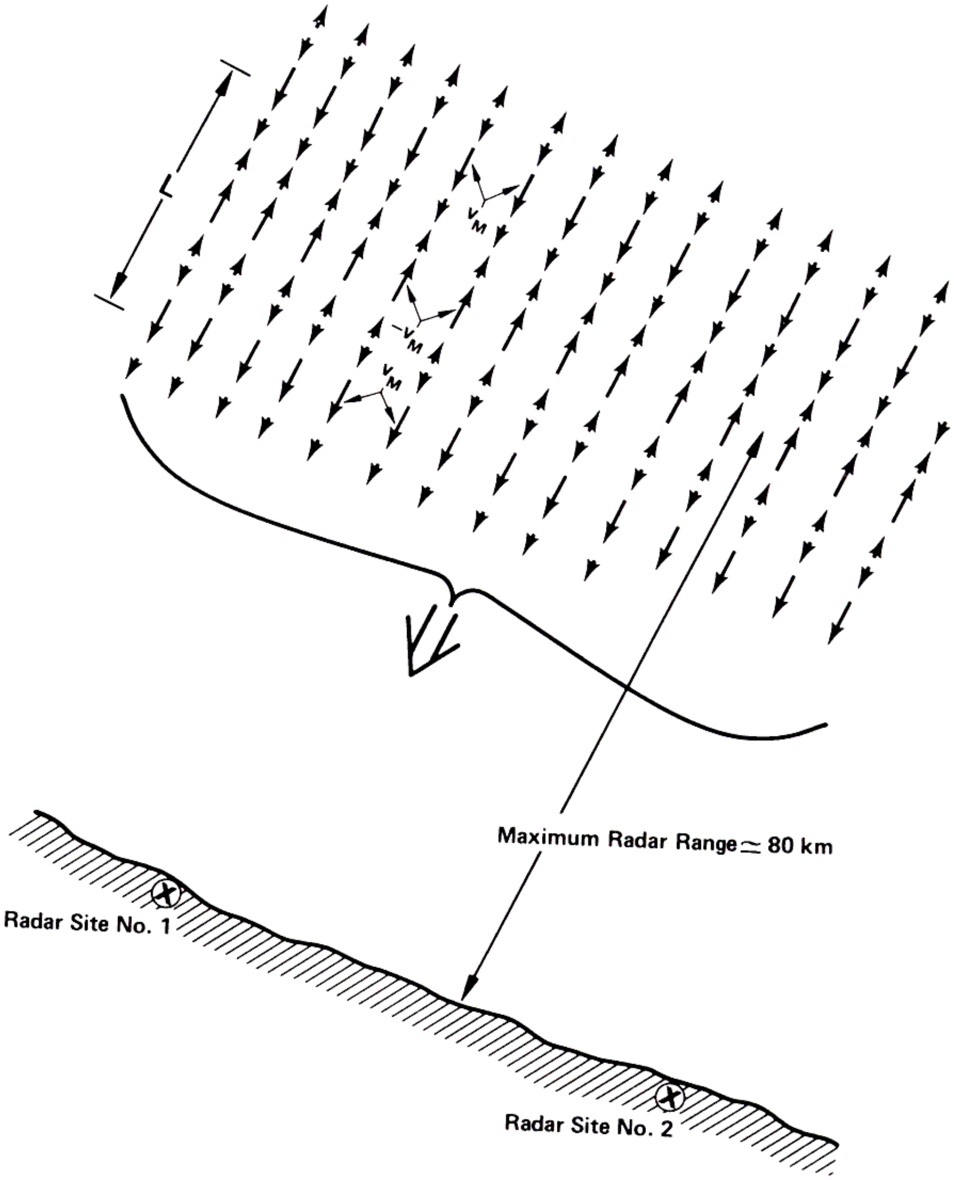

FIGURE 1. Sketch showing surface currents induced by orbital velocity of tsunami wave approaching coast line, as it would be observed with NOAA hf current-mapping radars. (For a tsunami wave with typical temporal period of 20 min, spatial period in water 100-m deep is $L = 30$ km.)

km of shore. The spatial period and direction of the tsunami wave will then be evident in the radar output maps.

To analyze the technique further, we employ simple ray theory for waves in shallow water; although more sophisticated models for propagation are presently being developed (Symposium on Tsunamis, 1978), these first-order equations are accurate enough for the limited coastal regions of interest. We assume that the sinusoidal tsunami wave originates on the "open ocean" (4000-m deep) with amplitude a_d at that depth. Next, we assume that it approaches from a direction nearly perpendicular to the shore. (Results for directions within ± 45° of perpendicular will not be appreciably different.) At a 4000-m depth, the typical tsunami wave is already feeling the bottom; hence shallow-water propagation theory (Kinsman, 1965) shows that its propagation speed is ~700 km/hr, independent of its period.

Relevant propagation equations are given here, and several that are needed for the tsunami detection problem are provided graphically in Fig. 2. The velocity of the tsunami wave is $v_t = \sqrt{gD}$, where D is the depth and g is the acceleration of gravity; this relation is shown graphically as the dashed curve in Fig. 2. The height of the tsunami wave as it comes into water D meters deep from a depth of 4000 m is given by $a = a_d(4000/D)^{1/4}$ (Kinsman, 1965); the factor in parentheses can be considered a wave-height growth factor, and is given by the solid curve of Fig. 2. Finally, the maximum tsunami-wave orbital velocity in water of depth D is then given by

$$v_M = a\sqrt{g/D} = a_d g^{1/2} 4000^{1/4} D^{-3/4}, \tag{1}$$

where again, a_d is the tsunami wave amplitude in deep water (4000 m).

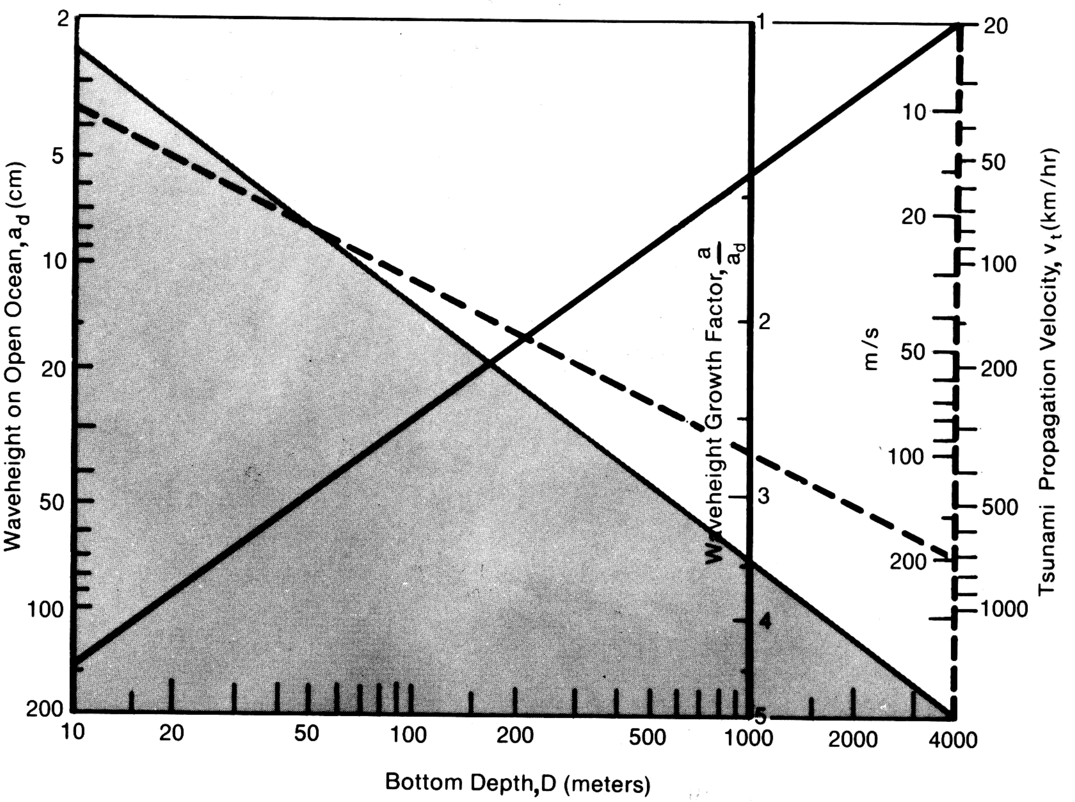

FIGURE 2. Dashed curve and axis give tsunami-wave velocity versus bottom depth. Solid curve and axis give wave height increase factor as tsunami moves into water of depth D from 4000 m depth. Shaded curve and region give shallow-water depths, D, for radar detection of tsunami with amplitude, a_d, on open ocean (4000 m deep).

Setting Eg. (1) equal to 10 cm/sec, we can solve for the amplitude of the tsunami wave, a_d, in deep water (4000 m) necessary for radar detection in shallower water D meters deep. We would typically take D to be the depth 60-km offshore, an estimated detection/confirmation range for the radar. This "detection curve" is shown in Fig. 2 in gray. Thus the shaded portion of Fig. 2 can be considered a radar detectability region; a wave of amplitude a_d on the open ocean will be detectable at depths, D, falling in this shaded region.

Sample Application

From the above equations, one can see that the further a shallow-bottomed shelf extends from shore, the greater the warning time afforded. Thus around the United States, longest warning times would be obtained off the Atlantic and Gulf of Mexico coasts, reasonably good warning time in the Gulf of Alaska, Aleutian, and Northwest Pacific coasts, with decreasing warning time off California, and the least time afforded for the Hawaiian islands. By tracing through an example, we show that adequate warning time is available even for California. The example here will illustrate how warning times can be calculated for other areas by using the simple shallow-water ray theory discussed above.

We select a location approximately 40-km south of San Francisco, on the California coast. A linear model for depth versus distance from shore is quite reasonable for this location, with a bottom slope or lapse rate of approximately 3 m per kilometer distance from shore. Assuming that the position of the peak orbital velocity, v_M, (see Fig. 1) of the first approaching tsunami crest is 60 km from shore at detection and confirmation, we see that the depth at this point is 180 m. From the detection curve of Fig. 2 it is evident that any tsunami with amplitude greater than 20 cm in deep water (4000 m) will be detectable, i.e., have an orbital-velocity-related current greater than 10 cm/sec.

We now estimate the time, T, between detection at 60 km and impact of the first wave crest on shore, assuming propagation directly toward the coast. We employ the shallow-water first-order wave propagation speed, $v_t(x)=\sqrt{gD(x)}$ in the equation

$$T=\int_0^L \frac{dx}{v_t(x)}, \tag{2}$$

where x is distance from shore, and for the linear model with bottom lapse rate, s, we have $D(x)=sx$. L is the distance from shore at which detection is made (60 km in this case). Substituting this into the above, we obtain $T=2\sqrt{L/gs}$. With $L=$ 60 km and $s=3$ m/km, we obtain $\mathrm{T}\simeq 47$ min.

Hence, even for a coastal region which is thought of as having little continental shelf, we obtain a reasonable warning time before impact. More sophisticated tsunami propagation models might be expected to refine this estimate somewhat, but should not change it or its implications appreciably. Warning times could of course be increased to some extent by increasing the detection range; one way is to increase the radar power or effective radar system signal-to-noise ratio. Furthermore, other details of the tsunami wave, as it is distorted by the bottom topography within the detection region, will actually be observed by the radar as the wave moves into shallower water, aiding in the prognosis of impact damage by providing more accurate input to run-up models.

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