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MODELLING & ANALYSIS OF LF SCATTER FROM THE SEA USING SURFACE WAVE RADARS FOR TSUNAMI SIGNAL DETECTION

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ABSTRACT

Tsunamis are an ever-present threat to lives and property along the coasts of the most world's ocean. Sumatra tsunami of 26 December 2004 reminded the world that we must be more proactive in developing ways to reduce their impact on our society. It is a general purpose and object of the present invention to provide a tsunami detection system that can detect very long wavelengths in ocean waves in real time and can distinguish shallow water waves from wind-generated waves having much smaller wavelengths. In addition to the tsunami wave, wind-generated waves will also be detected by the tsunami wave detection system. Signal processing methods are used to separate the two types of waves in spectral space to eliminate the wind generated waves from consideration and thereby avoid false positives. Mathematical Modelling using shallow water wave equations is the best method of propagation of tsunami detection system that can detect very long wavelengths in ocean waves in real time and without a high false alarm rate. For that low-frequency surface wave radars can be used.

KEYWORDS: *Tsunami, Shoaling' Effect, Coriolis Force, Shallow Water Wave, Surface Wave Radars*

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INTRODUCTION

The internal dynamics of the water allows all the motion in the waves to go up and down, or in the same circular patterns correlated with the direction of the wave. Nonlinear wave equations are very important at the shore where most of the damages by the tsunami are experienced while the Coriolis effects must be considered for teletsunami. A teletsunami is nothing but a distant tsunami that originates from a faraway source, generally more than 1,000 km away. Less frequent, but more hazardous than regional tsunamis, are ocean-wide or distant tsunamis. These waves cause additional casualties and destruction on shores more than a 1,000 km from the source and travel across an entire ocean basin with sufficient energy and. In the last 200 years, there have been at least 21 destructive ocean-wide tsunamis. The worst tsunami catastrophe in history occurred in the Indian Ocean on the 26th December 2004, when a magnitude 9.1 earthquake off of the northwest coast of Sumatra, Indonesia produced an ocean-wide tsunami that also hit Thailand and Malaysia to the east, and Sri Lanka, India, the Maldives, and Africa to the west as it traversed across the Indian Ocean. Over 225,000 people lost their lives, and more than 1 million people were displaced, losing their homes, property, and their livelihoods. That led to the development of the Indian Ocean tsunami warning and mitigation system in 2005.

To describe the generation, propagation and interaction of tsunami wave with complicated topography such as bays or harbors and the resulting flooding have advanced to the stage where the development of numerical models are useful tools for determining the tsunami hazard in local regions. The linear, shallow water, long wave model is the most common model used to describe tsunami generation, propagation, and flooding that neglects both the shoaling effect of the shore and the Coriolis effect during a long tsunami travel. Since as the depth of the water decreases, the speed of the tsunami reduces. As a resulting tsunami leaves deep waters and propagates into the shallow waters, it transforms its characteristics. But since the change of total energy of the tsunami remains constant, with the decrease in speed, the height of the tsunami wave grows. A tsunami which was imperceptible in deep water may grow too many meters high and this is called the **'shoaling' effect**. Coriolis force does not have much effect on a tsunami because it does only affect moving masses. Coriolis force in fact, isn't a force but a movement pattern looking as though a force were involved. It is nothing but a result of inertia that "drives" the moving masses towards a constant direction in space and at the same time the earth's rotation taking place. However, while a tsunami travels across the globe there is little water moving, instead what actually is moving is its energy. But in contrast, in the case of hurricanes, there is actually a huge amount of air moving which is affected by Coriolis force.

DESCRIPTION OF THE PRIOR ART

The distributed nature of tsunami waves i.e. with very long periods and wavelengths make detection difficult even though tsunami waves contain tremendous energy. A satellite radar detection of the tsunami wave created by the 2004 Indian Ocean earthquake was made hours after the tsunami wave originated and occurred far too late to provide any practical warning of the event. Detection of tsunami waves ideally needs to occur in real time. The Deep Ocean Assessment and Reporting of Tsunamis (DART), a system by the National Oceanic and Atmospheric Administration, attempts to detect tsunami waves via point measurements of pressure changes due to surface waves. However, given the long tsunami wavelengths, the DART point measurements will have a greater false alarm rate than a distributed measurement. Currently, there is a need for a tsunami detection system that can detect very long wavelengths in ocean waves in real time and without a high false alarm rate.

KNOWLEDGE OF TSUNAMI

As tsunami waves are long period waves with the wavelength of 200-250kilometers and their height in the open sea cannot be distinguished by people traveling on a ship in an open sea and may range between few centimeters to a meter. The speed of the tsunami wave is related to the depth of the ocean, greater the water depth higher the speed. Like in Indian ocean or Bay of Bengal, for an average depth of 4km, the speed of tsunami can go up to 720km/hr. or about the speed of a jet airliner. As the tsunami waves approach the shore, the water depth becomes shallower, waves slow down, the wavelength becomes shorter and waves gain larger amplitude or heights and become destructive and can be distinguished by people. A tsunami is considered a "shallow water wave", having a large wavelength compared to the ocean depth. A tsunami can have wavelengths ranging from 100 to 500 km, and amplitudes up to 60 cm (i.e., a pressure signal of up to 1 psi). The tsunami wave will have a propagation speed of $v=\sqrt{gd}$ where g is the gravitational acceleration, and d is the water depth. The tsunami wave will have a travel time of $t = 2D/\sqrt{gH}$, where H is the shelf break depth and D is the distance to shore.

There is a huge difference between wind-generated surface waves and tsunamis or tidal waves, in which the first one is not strongly affected by ocean bottom topography, but the second one is almost invisible out in the ocean depths at an average of 4 km deep, travel at speeds up to 1000 km/hour, and have wavelengths on the order of 500 km as well as periods of one-half hour, and more than those on-shore heights up to 40 meters. Tsunamis and tides are markedly affected by bathymetry, i.e., the ocean bottom structure, depth, basins, seamounts, continental shelves, bars, canyons, etc. Generally, long-wavelength waves for example tsunami signals travel faster out at sea than shorter wavelengths; that is why the long storm surge affords early warning of a distant storm at sea before the shorter, higher waves come crashing in against the cliffs. For all kinds of waves, as the waves approach the shore, resulting in slowing down of the wave velocity, increase in wave height, shortening of the wavelength, and no change in frequency. For water waves, there are different mechanisms, for example for wind, but if we throw a rock in glass-smooth water pond, the very small ripples happens that flow is dominated by gravity, thus these are called "gravity waves" and the speed C_G depends on depth h and constant of gravity g by the formula $C_G=\sqrt{gh}$. The frequency is not changed thus the wavelength gets longer as depth is increased since the wavelength λ is: $\lambda = \frac{C_G}{f} = \frac{\sqrt{gh}}{f}$. The waves you see on the surface of the Ocean do not depend on the depth of the water, unless that depth is less than the amplitude of the wave in which case it will "break". Tsunami waves do depend on water depth, and its speed is proportional to the square root of depth. So a Tsunami wave at sea may have an amplitude of 10 cms but a wavelength of 50 kilometers. As the speed decreases in shallow water, the wave gets bunched up and Height increases from 10 cm to 50 km long.

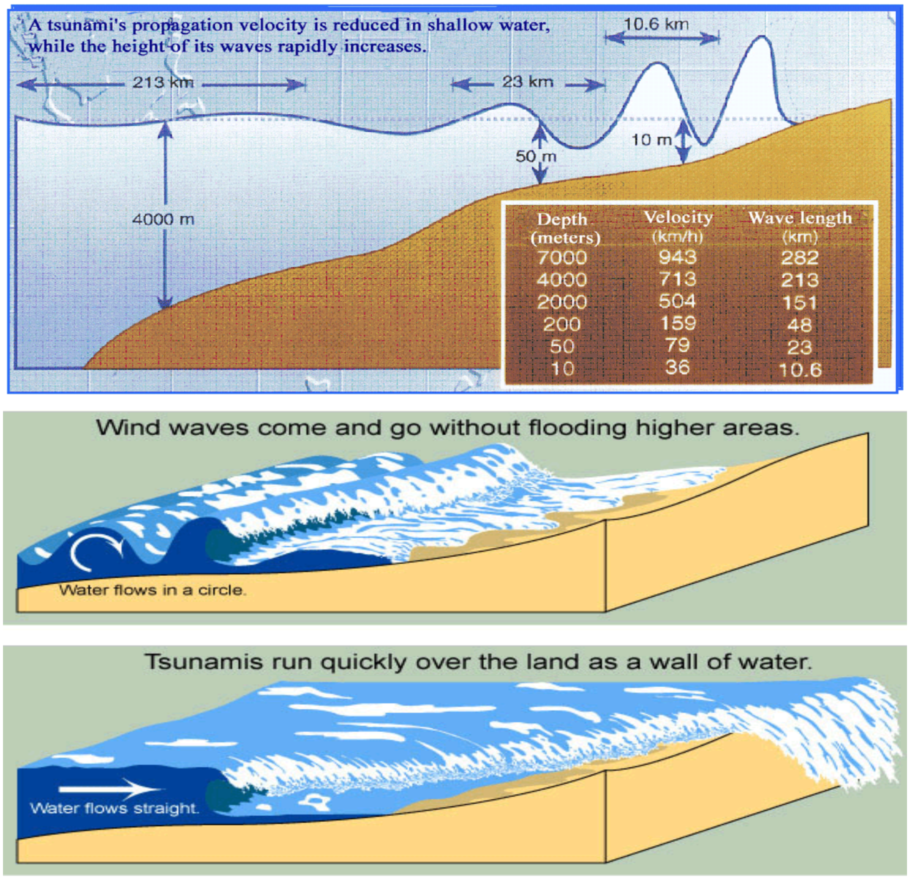

Figure 1

SURFACE WAVES

A mechanical wave that propagates along the interface between differing media is called a **surface wave**. A common example for the surface wave is gravity waves that travel along the surface of liquids, such as ocean waves. A ground wave propagates close to the surface of the Earth in the case of radio transmission. Several types of surface waves are encountered in nature. Surface waves are classified as either Love waves (L waves) or Rayleigh waves. A seismic wave is a wave that travels through the Earth, usually as the result of an earthquake or explosion. Love waves have transverse motion (movement is perpendicular to the direction of travel, like light waves), whereas Rayleigh waves have both longitudinal (movement parallel to the direction of travel, like sound waves) and transverse motion. In practical radio transmission systems, several different types of propagation are used. One type of propagation is Line-of-sight propagation that travels in a straight line from the transmitting antenna to the receiving antenna. A line of sight transmission is used in some applications such as cell phones, cordless phones, wireless networks, FM radio and television broadcasting and radar, and satellite communication, such as satellite television. This type of transmission is limited to the distance to the visual horizon that is nothing but the height of transmitting and receiving antennas and this is possible only at microwave frequencies and above. At microwave frequencies, even moisture in the atmosphere can degrade transmission. The radio waves can bend over obstacles like hills at lower frequencies due to diffraction and can travel beyond the horizon as surface waves which follow the contour of the Earth. These waves are called ground waves. A typical application is AM broadcasting stations which use ground waves to cover their listening areas. As the frequency gets lower, the attenuation with distance decreases. Moreover very low frequency (VLF) and extremely low frequency (ELF) ground waves can be used to communicate worldwide effectively. So VLF and ELF waves can penetrate significant distances through water and earth, and these frequencies are used for mine communication and military communication with submerged submarines.

Surface waves can span over a wide frequency range, and 10 seconds or longer period of waves are most damaging in nature. It can travel around the globe many times from the largest earthquakes. Lower frequency radio space waves that is below 3 MHz travel efficiently as ground waves. That may be medium frequency (MF), low frequency (LF), very low frequency (VLF), ultra low frequency (ULF), super low frequency (SLF) or extremely low frequency (ELF) waves. Due to their long wavelengths, lower-frequency waves are more strongly diffracted around obstacles allowing them to follow the Earth's curvature and so ground propagation works. The Earth has one refractive index and the atmosphere has another, that supports the guided wave's transmission by constituting an interface. Vertical polarization, with their magnetic field horizontal and electric field (close to) vertical is applicable for Ground waves propagation. The ionosphere and earth's surface act as a waveguide for VLF waves.

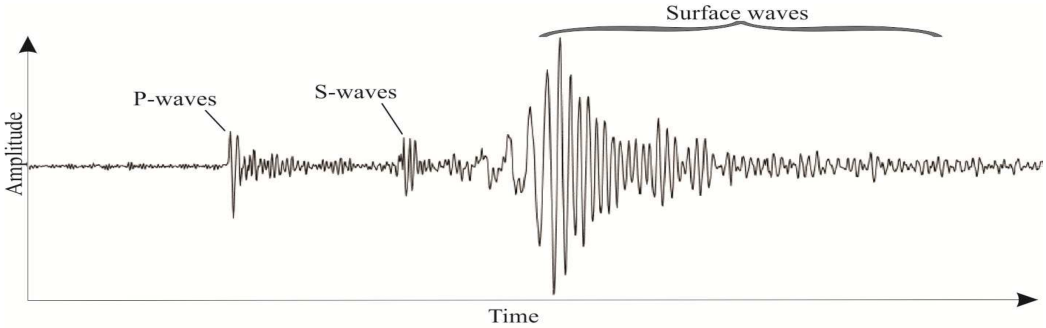

Figure 2

Generally speaking, waves are oscillations (or disturbances) of the water surface that can be observed in any water basin like rivers, lakes, seas, and oceans. For a wave to exist there must be an initial equilibrium state, which is perturbed by an initial disturbance and compensated by a restoring force. Generating mechanisms are primarily originated by local wind, seismic oscillations of the Earth during earthquakes, atmospheric pressure gradients, and gravitational attraction between the Earth, Sun, and Moon. Normally, these forces are compensated by gravity. However, surface tension plays a more substantial role for very short (capillary) waves, while very long perturbations such as the ones produced by gravitational attraction (i.e., tides) tend to be restored primarily by the Coriolis force. The different origin and nature of surface oscillations affect the waveform in terms of height and period (and associated wavelength), generating a large variety of waves. In this regard, it is worth mentioning that the water surface acts as an interface separating two fluids of different density: the air with a density of 1 kg/m3 and water with a density of 1000 kg/m3. As the former is negligible with respect to the latter, any disturbance propagating on the water surface (i.e., at the air-sea interface) is defined as the surface wave. This opposes the concept of an internal wave (Sutherland, 2010), which refers to oscillations traveling within layers of a stratified fluid such as, for example, layers of different temperature and/or salinity in the ocean.

Characteristics of Waves

- Wave crest and trough: The highest and lowest points of a wave are called the crest and trough respectively.
- Wave height: It is the vertical distance from the bottom of a trough to the top of a crest of a wave.
- Wave amplitude: It is one-half of the wave height.
- Wave period: It is merely the time interval between two successive wave crests or troughs as they pass a fixed point.
- Wavelength: It is the horizontal distance between two successive crests.
- Wave speed: It is the rate at which the wave moves through the water, and is measured in knots.
- Wave frequency: It is the number of waves during a one second time interval.

Since the wavelength is far longer tsunami waves do not resemble normal undersea currents or sea waves. A tsunami may initially resemble as a rapidly rising tide rather than appearing as a breaking wave. Because of this, it is often referred to as a "tidal wave", even though this usage is not favored by the scientific community since it might give the false impression of a causal relationship between tides and tsunamis. Tsunamis are nothing but a series of waves, with periods ranging from minutes to hours, arriving as an "internal wave train". Even wave heights of tens of meters can be generated by large events. The destructive power of tsunamis can be enormous even though the impact of tsunamis is limited to coastal areas,, and they can affect entire ocean basins.

Shallow Water Waves

A wave which has a wavelength much greater than the depth of the water it is propagating through, then it is termed as shallow water wave. For example, tsunamis, which have very long wavelengths, always, travel as shallow water waves even in deep oceans. Although there are several causes of tsunamis, about 90% of tsunamis of the world are bound up with underwater earthquakes (Jaiwal et al., 2008). Three stages of tsunami development are usually distinguished: (a) formation of a localized initial disturbance and its evolution near the source; (b) propagation of waves in the open ocean; (c) method of propagation of waves in shallow water and on the shore. Tsunamis are created oceans by an impulsive disturbance and they are a series of waves of very long wavelengths and period. Tsunamis are different from the wind-generated waves which usually have a period of five to twenty seconds. Tsunamis behave as **shallow-water waves** because of their long wavelengths. They have a period in the range of ten minutes to two hours and a wavelength exceeding 500 km. The rate of energy loss of a wave is inversely related to its wavelength. So tsunamis lose little energy as they propagate because of their very large wavelength. So in deep waters, they will travel at high speeds and travel great distances at the same time losing little energy. A tsunami that occurs 1000 meters deep in water has a speed of 356 km per hour. At 6000 m, it travels at 873 km per hour. It travels at different speeds in water that is slow in shallow water and fast in deep water.

MODELLING & PROPAGATION OF TSUNAMI

Basically, a tsunami commonly has three stages, i.e., generation, propagation, and inundation. In the generation stage, Okada's finite fault deformation model is widely used as the initial method to predict the initial sea surface displacement of a tsunami (Okada, 1985). This method assumes that an earthquake can be regarded as the rupture of a single fault plane. This fault comprises dip angle, strike angle, rake angle, fault width, fault length, and fault depth etc. Okada's vertical displacement is used (e.g., Satake 1995), to drive the model at a specific rupture time (e.g., Yamazaki et al., 2012). The former application is likely to underestimate tsunami wave height because the earthquake energy release is a sustained process, instead of an instant process (Wen et al., 2011). The sensitive tests, focused on seismic rupture parameters, are reliable approaches to improve the simulation performance because they can evaluate the initial condition of the models (Yamazaki et al., 2011). Recently, tsunami-wave generations independent of the Okada's assumption are also developed and evaluated, in which a 3D Finite Element Model is employed (Grilli et al., 2012). In the propagation stage, two main types of governing equations had been employed in previous research, the Boussinesq equations (Chawla and Kirby, 2000; Tappin et al., 2001; Zhang et al., 2010), or the nonlinear shallow-water equations (Kilinc et al., 2009; Tang et al., 2009; Kowalik and Proshutinsky, 2010; Olabarrieta et al., 2010). In the inundation stage, two-way nested models are frequently employed since they are of high efficiency and precision when resolving the near-shore processes (e.g., Tang et al., 2009; Chen et al., 2012). Precise simulation of the inherent processes over the shelf interacted with the topography would be useful in hazard assessment and tsunami warning (Yamazaki et al., 2012).

Tsunamis are usually generated by the movement of the sea bottom due to long waves of earthquakes. The impulsive sea floor movement in the earthquakes region causes the water surface region instantaneously. The sudden gain in potential energy converts to kinetic energy by the gravitational force which serves as the restoring force of the system. Generally, tsunamis are treated as shallow water waves. Tsunami is a Japanese word that is the combination of two words: "tsu" means harbor and "nami" means wave. Therefore, tsunami literally means "harbor waves". The word was originally created to describe large amplitude oscillations in a harbor under the resonance condition. The most common cause of a tsunami is undersea earthquakes. We can use shallow water equations (SWEs) to model water wave propagation in one dimension. We obtain the SWEs from Euler's equation of mass and momentum considering a long wave approximation. In the case of SWEs water wave's the wave length is much longer than the depth of water. Therefore, we have modeled tsunami wave using SWEs.

Shallow Water Equations (SWEs)

Shallow Water Equations (SWEs) are a system of hyperbolic partial differential equations (PDEs) governing the flow of fluid in the rivers, channels, oceans and coastal regions. We have investigated SWEs from mass and energy conservation principle expressed in the Navier-Stokes equations. SWEs give the idea about the flow of water waves, especially those water waves whose wavelength is much longer than the depth (basin) of water. The wavelength of tsunami waves is far longer than the normal waves. A tsunami wave initially resembles a rapidly rising tide for this reason they are often referred to as tidal waves. The average depth of ocean nearly 5 Km, which is compared with the wavelength long waves or tsunamis, which may exceed 100 Km. The destructive power of tsunami can be enormous although its impact is limited to coastal areas, and they can affect entire ocean basins; in 2004 Indian Ocean tsunami was among the deadliest natural disasters in human history with over 230,000 people killed in 14 countries bordering the Indian ocean. One can get SWEs by neglecting the bottom friction and assuming long wave approximations from the Euler equations of mass and momentum.

Mathematical Modelling of Tsunami Propagation

The shallow water wave equations describe a number of physical features including wave dynamics where disturbances in the sea surface height are moving as waves. The basic linear shallow water wave equation of' tsunami generation by small bottom deformations inhomogeneous ocean of constant depth H neglecting the stresses at the surface and bottom, the Coriolis force, and the viscous terms are given as[21]:

$$\frac{\delta U}{\delta t} + gH\frac{\delta \eta}{\delta x} = 0 \qquad (1)$$

$$\frac{\delta V}{\delta t} + gH\frac{\delta \eta}{\delta y} = 0 \qquad (2)$$

$$\frac{\delta \eta}{\delta t} + \left(\frac{\delta U}{\delta x} + \frac{\delta V}{\delta y}\right) = 0 \qquad (3)$$

$\boldsymbol{\eta}$ is the vertical displacement of the water surface above the equipotential surface, t is elapsed time, U and V are the horizontal and vertical components of the water surface, x and y are the spatial coordinates of the wave and g is the gravity acceleration. Combining these equations it can be shown that

$$\frac{\delta^2 \eta}{\delta t^2} - gH\nabla^2 \eta = 0 \qquad (4)$$

The corresponding equation in one-dimension derived from equation (4) is:

$$\frac{\delta^2 \eta}{\delta t^2} - gH\frac{\delta^2 \eta}{\delta x^2} = 0 \qquad (5)$$

This equation has a waveform and we thus introduce a wave solution in the form

$\eta \approx e^{i(kx-\omega t)}$. Inserting this expression into equation (5) we find that $\eta \approx e^{i(kx-\omega t)}$ is a solution if and only if:

$$\omega = \sqrt{gHk} \qquad (6)$$

Where ω is the wave frequency in radian and k is the wave number. Equation (6) is the dispersion relation and characterizes how the frequency must be related to the wave number in order to fulfill equation (5). Using ordinary theory for surface waves, the dispersion relation is therefore:

$$\omega^2 = gk\,tanh(kH) \tag{7}$$

For the results of the treatment of tsunami as shallow waves to be valid equation 7 shows that the tsunami waves must be considerably longer than the depth of the ocean. If the water depth is much less than the wavelength (λ) then only this Shallow water approximation is valid. In this case, H << λ, kH << 1, and tanh (kH) = kH and nonlinear effects can be neglected. As the long wave with small amplitude enters shallow coastal waters, the solution contradicts the assumptions of the shallow water wave equation. Tsunami wave propagating over the continental shelf towards the shoreline is transformed mainly by shoaling, refraction and reflection. In this region, nonlinearities cannot be neglected anymore and the full nonlinear shallow water equations must be applied to solve the problem. They have set the limit of shallow-water and deep-water dispersion relations at H < λ /11 and H > λ/ 4 respectively.

Detailed bathymetric information and assumed wavelength at the shore are required to set these boundaries in the ocean. Tsunami evolution is very important near shore where the waves are dangerous and destructive. The assumptions underlying the tsunami wave equations at the open sea fail near the shore and the bottom topography must be considered. To obtain a solution we assume a simple form for the bottom topography such that

$$h(x) = -ax \tag{8}$$

Where h(x) is the variable depth of the basin, x-axis is directed to the shoreline and a is a constant.

Under this condition the tsunami wave takes the form of nonlinear wave equation:

$$\frac{\delta\eta}{\delta t} + u\frac{\delta u}{\delta x} + g\frac{\delta\eta}{\delta x} = 0 \tag{9}$$

$$\frac{\delta\eta}{\delta t} + \frac{\delta}{\delta x}\{(h+\eta)u\} = 0 \tag{10}$$

Tsunami Equations with Coriolis

The equations that neglect the Coriolis acceleration can be regarded as valid only as long as the tsunami travel distance remains insignificant in relations to the earth's complete rotation time. When a tsunami propagates over long distances, the Coriolis acceleration terms must be introduced to account for the fact that the earth, frame of reference with respect to which the wave is propagating, is rotating. The rotation of the earth can strongly affect the tsunami characteristics near the region of formation of tsunamis. Owing to the rotation of the earth, each moving particle of the water is under the influence of a Coriolis force. Therefore, tsunami generation is generally accompanied by the formation of internal waves and vertical motions. During this process, some part of the energy, which is transmitted to the ocean with the seismic bottom motions, accumulates in the region of the disturbance. This leads to a reduction of the barotropic wave energy and tsunami amplitude. The direction of the tsunami radiation varies and the energy flow transferred by the waves is redistributed. The integrated equations for linear long waves with Coriolis force in the spherical coordinate system (longitude ϕ and latitude θ) can be shown to be

$$\frac{\delta Q_{\emptyset}}{\delta t} = \frac{gH}{Rsin\theta}\frac{\delta\eta}{\delta\emptyset} - fQ_{\theta} \tag{11}$$

$$\frac{\delta Q_{\theta}}{\delta t} = \frac{gH}{R}\frac{\delta\eta}{\delta\theta} - fQ_{\theta} \tag{12}$$

$$f = 2\Omega cos\theta$$

where R is the radius of the earth, Q is the flow rate and Ω is the rotation vector of the earth.

It is also important to consider the group velocity of tsunami waves since it is the velocity of wave energy propagation.

For the non-dispersive waves, the phase velocity $C_0$is given as

$$C_0^2 = \left(\frac{g\lambda}{2\pi}\right) tanh\left(\frac{2\pi H}{\lambda}\right) \qquad (13)$$

Since H << λ

$$C_0 = \sqrt{gH} \qquad (14)$$

Group velocity by definition

$$C_g = \frac{\delta\omega}{\delta k} \qquad (15)$$

By using the approximation for the dispersion relation, we obtain:

$$C_g = \frac{\delta\omega}{\delta k} = C_0 \qquad (16)$$

The group velocity which here is equal to the phase velocity is independent of the wave number k; so we find that tsunami waves are non-dispersive. Accordingly, we see that all waves travel at the same speed irrespective of the wave number or frequency. This implies that any given form of an initial disturbance in the sea surface will preserve its form. One notable feature of tsunami waves is therefore, that their speed depends only on the depth of the ocean. Thus when reaching shallow water the waves reach an area with slower propagation speed. The waves will tend to bend towards areas with shallow water since according to Snell's law; waves tend to bend towards areas with lower propagation speed. Thus, when long ocean waves enter a coastline the wave propagation will change direction such that the waves more or less will come in perpendicular to the coastline. For this reason, capes usually receive more wave power that bays.

The amplitude of shallow water waves is approximate:

$$\frac{A_s}{A_d} = \sqrt{\frac{C_d}{C_s}}$$

Where A_s and C_s are shallow water amplitude and velocity, and A_d and C_d are deep water amplitude and velocity. This approximation fails for breaking waves otherwise the amplitude would increase to infinity as water depth approaches zero. In order to keep their frequency constant, their wavelength decreases. The energy of the wave is transmitted as kinetic energy and potential energy. The kinetic energy is tied up in the motion of the water while the potential energy is tied up in the gravitational potential that is the amplitude of the wave. However, when the wave approaches the shore and enters shallow water, the kinetic energy of the water near the bottom is converted into potential energy of the water at the top and this actually explains why the height of the tsunami wave increases as the wave approaches the shore.

Tsunami propagation can be treated in two separate phases for the accurate prediction of the tsunami that is: linear shallow water waves in the open sea and as nonlinear wave near the shore. Bathymetric data are required to set the boundary between the constant depth of the open sea and the variable depth near the shore. Whereas Coriolis effects may not be considered as important in local tsunamis, these effects must be integrated into the treatment of teletsunamis to ensure a more accurate determination of their point of arrival.

RESULTS & CONCLUSIONS

Advance prediction and accurate simulation of the tsunami wave in terms of wave amplitude and arrival time are very important to tsunami forecast and warning. This paper presents the modeling of tsunami waves using shallow water equations and the propagation of waves using low-frequency surface wave radars. Through this, we can develop a tsunami detection system that can detect very long wavelengths in ocean waves in real time and without a high false alarm rate.

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