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Future Contribution of HF Radar WERA to Tsunami Early Warning Systems

High-frequency (HF) surface wave radars provide a unique capability to detect targets far beyond the conventional microwave radar coverage but also could contribute to the development and improvement of Tsunami Early Warning Systems. The HF radar system WERA is an oceanographic radar placed at the coast and providing simultaneous wide area measurements of ocean surface current fields and sea state parameters. This paper describes the simulation of tsunami related signatures observed by HF radar at long ranges in case of a tsunami travelling towards the coast. A tsunami event is modeled using the oceanographic HAMburg Shelf Ocean Model (HAMSOM), which has high spatial and temporal resolution and gives the ocean surface currents induced by an approaching tsunami. The tsunami current velocity is converted into modulating signals and superimposed on measured antenna signals of the WERA radar. The possible ocean surface current changes due to a tsunami event are evaluated using fast update of the radar backscattered spectra. The proposed tsunami detection technique is based on the ordered-statistics constant false alarm rate (CFAR) detection algorithm applied to the entropy filed of surface currents. It gives an opportunity to issue an automated tsunami alert during the real-time monitoring by the WERA radar.

1. Introduction

A tsunami is a series of waves that can be generated when earth plate boundaries abruptly move and vertically displace the overlying water. Not every earthquake generates a tsunami. For this reason it must be determined at sea whether or not an earthquake has actually triggered the deadly wave.

A tsunami has a much smaller wave height offshore and a very long wavelength (hundreds of kilometers long), that is why they generally pass unnoticed at sea. This wave travels at a speed over 800 km/h, but due to the enormous wavelength the wave has a typical amplitude less than 1 m. This makes tsunamis difficult to detect over deep water. As the tsunami approaches the coast and the water becomes shallow, the wave is compressed due to wave shoaling and its speed slows down to 80 km/h. Its wavelength diminishes to less than 20 km and its amplitude grows enormously, producing a distinctly visible wave.

No system can warn of a sudden tsunami, which happens very close to the coast. Only if a tsunami is gen-

erated in the deep ocean and the shelf edge is far enough off the coast then sufficient time remains and warning systems could be effective. The newly implemented German Indonesian Tsunami Early Warning System (GITEWS) for the Indian Ocean goes into operation and now enters its final phase of optimization [1]. The high frequency (HF) surface wave radar could contribute to the development and improvement of Tsunami Early Warning Systems. The HF radar, which is based on surface wave propagation along salty water, provides a unique capability to detect targets far beyond the conventional microwave radar coverage. HF radars use the frequency band of 3-30 MHz to provide a large coverage that could extend to more than 200 kilometers in range. These maximum range values are of high interest for many applications including ship detection, tracking, and guidance, as well as search and rescue, distribution of pollutants, fishery and research in oceanography. These radar systems recently became an operational tool in coastal monitoring worldwide.

HF radar uses over-the-horizon radar techniques and could identify a tsunami wave travelling towards the

coast at long ranges. Bragg-resonant backscattering by ocean waves with half of the electromagnetic wavelength allows measuring the radial components of ocean surface currents at far distances. If these radar systems have already been installed at the coast then it is just a software package to be added to enable support for tsunami detection. As no HF radar measurements of a real tsunami exist, the ocean current signature generated by a tsunami is simulated by an oceanographic HAMburg Shelf Ocean Model (HAMSOM). The ocean model output is then used as an input to simulate what HF radar would actually observe. Based on these results, an algorithm to detect a tsunami signature in the ocean current maps measured by HF radar is proposed.

2. HF Radar WERA in Coastal Monitoring

The HF radar system WERA (WEllen RAdar) was developed at the University of Hamburg, Germany, in 1996 to allow a wide range of working frequencies, spatial resolution, and antenna configurations in order to operate as a low power oceanographic radar providing simultaneous wide area measurements of surface currents, ocean waves and wind parameters [2]. This HF radar is a tool for synoptic on-line mapping of surface current fields and the spatial distribution of the wave directional spectrum. WERA is based on a modular design that can be easily adopted to the requirements of an actual application.

Conventional oceanographic radars use long coherent integration time (10 minutes to 30 minutes) to collect long-term data and to obtain sea parameters. The tsunami scenario applied to conventional oceanographic processing results in disappearing of the fast changing tsunami signatures due to the non-stationarity of the process. The WERA system has been set to a continuous data acquisition mode during the ship detection and tracking campaign for several months [3]. The WERA system installation includes the transmitting and the receiving antenna arrays which are placed at the coast and are shown in Fig. 1. We propose to monitor the potential tsunami areas in the same operation mode, which provides a quick update of the radar backscatter spectra, e.g. at a 2-minute rate. Thus we can use the measured data to investigate the tsunami signatures.

WERA transmits a low power of 30 watts totally but can achieve a detection range up to 200 kilometers, which is far beyond the conventional microwave ra-



Fig. 1. The HF radar WERA system installation. a) the transmitting array; b) the receiving array.

dar coverage. It uses a frequency modulated continuous wave (FMCW) mode for range measurements and resolution; hence the transmitter and the receiver are operated simultaneously. WERA transmits linear frequency chirps, where the frequency shift between the transmitted and received echo determines the range. The range cell is related to the bandwidth of the chirp signal. The azimuthal angle covered by WERA is $\pm 60^{\circ}$ perpendicular to the linear receive antenna array that consists of M = 16 antenna elements located along the seashore as shown in Fig. 1b. The received signal is a superposition of HF waves, which have been backscattered at different distances from the radar:

$$r(t) = \int \alpha(\tau) \sin\left(2\pi \left(f_0 + \frac{b}{2T}(t-\tau)\right)t - \tau\right) + \varphi(\tau) d\tau$$

where τ is the propagation time from the radar to the scattering ocean surface area and back. The amplitude α (t) and the phase (t) change slowly with the time t due to the variations of the scattering surface waves but they can be assumed to be constant during a chirp period. After phase-coherent demodulation with the transmitted chirp, the in-phase and quadrature-phase time series form complex series:

$$z(t) = \int \frac{\alpha(\tau)}{2} \exp\left(-i\left(2\pi \frac{b\tau}{T} - \varphi(\tau) + \phi(\tau)\right)d\tau\right).$$

Range resolution is performed by a windowed Fourier transform of each single chirp. Thus the range resolution is defined as $R = \frac{c}{2b}$ where c is the speed of light, b is the transmit signal bandwidth. The complex Fourier amplitudes of the chirps determine the samples of the slowly varying modulation of the backscattered signal, which contains the information about the ocean surface variability.

After sorting into range cells the received signal of antenna elements can be written as

$$\mathbf{Z}(t) = \left\| \zeta_{n,m}(t) \right\|, \quad \zeta_{n,m}(t) = \alpha_m(n\Delta R, t)e^{i\phi_m(n\Delta R, t)}$$
(1)

where m = 1, 2, ..., M corresponds to each antenna in the array, n = 1, 2, ..., N corresponds to the number of range cells.

After applying the conventional windowed beamforming technique to the received signals (1), the measured WERA signals are defined as follows:

$$\mathbf{Y}(t) = \mathbf{Z}(t) \cdot \mathbf{B} \tag{2}$$

where $\mathbf{B} = \|B_{m,k}\|$, $B_{m,k} = \gamma_m e^{2\pi i \frac{(m-1)d}{\lambda} \sin \theta_k}$, (m=1,2,...,M, k=1,2,...,K) are defined for a uniform linear antenna array with *M* elements and *K* beamformed angles, γ_m is the window coefficient, λ is the radar wavelength, *d* is the distance between antenna elements, θ_k is the *k*-th azimuthal beam angle.

The range-Doppler power spectrum maps are obtained using further windowed FFT processing. An example of a measured range-Doppler power spectrum for a specified beam direction is shown in Fig. 2. The coherent integration time of a single snapshot was set to 133 s for each range cell. The range-Doppler maps are updated every 33 s.

It can be seen in Fig. 2 that several kinds of specific clutter and targets are present, e.g. ocean surface backscattering, moving ships and aircrafts, radio and ionosphere interferences. The main contribution for the WERA system is due to the ocean surface echo signals. As ocean waves are moving targets, they cause Doppler shifts to any radiation which is scattered from them.

The first-order HF scattering cross section theory introduces the sea surface as a time-varying quantity based on Bragg scattering as the physical mechanism responsible for electromagnetic scatter from the ocean surface. The dominant contribution of the HF radar backscatter is produced by scattering from ocean waves having half of the radar wavelength and moving towards and away from the radar site. In a range-Doppler map the Bragg lines are observed permanently and provide the radar capability of current measurements [4].

Besides the strong first-order Bragg peaks, the Doppler spectrum of electromagnetic backscattering from the ocean, such as shown in Fig. 2, contains a continuum beyond and between the first-order Bragg peaks. Second-order scattering is caused by the interaction between crossing sea waves, which leads to side bands around the Bragg lines, also referred to as the secondorder continuum [5]. Therefore, the ocean surface can be characterized as a distributed, non-directional source of scattering.

Fig. 2. Example of a measured range-Doppler power

spectrum with several kinds of interference and targets.



The software package developed at the Institute of Oceanography by Gurgel et al. [2] uses the information about the first-order and second-order ocean backscattering to reconstruct ocean surface currents, wind directions and significant wave heights within the area observed by the WERA radar. It allows continuous monitoring of oceanographic environment.

While the tsunami wave is approaching the beach, the surface current pattern changes in the shelf area. This strong change of the surface current can be detected by WERA system in real-time monitoring.

3. Simulation of a Tsunami Event Using HAMSOM and WERA Data

To identify regions at risk where the HF radar can contribute to an Early Warning System it is important to have information about the width and depth of the ocean shelf, as well as the location and strength of the earthquake, thus allowing an early warning time of 30 minutes and more. The HAMSOM model was developed at the Institute of Oceanography, University of Hamburg [6]. It was designed to allow the simulation of ocean/shelf dynamics. Model input data include bottom topography and friction, wind forcing, tides, etc. Model output data result in ocean surface currents, surface elevation, as well as water salinity and temperature fields.

In the present application HAMSOM was downgraded to a barotropic two-dimensional model. The modified HAMSOM model is evaluated in a special high-resolution mode. This high spatial and temporal resolution is necessary to be able to acquire the dynamics of the propagating tsunami wave and its signature in the current field correctly, as the propagation speed is up to 800 km/h at an ocean depth of 4000 m.

Figure 3 shows the simulated radial component of the ocean surface current at about 19 minutes after the underwater earthquake. The modeled bottom topography represents a typical shape from the deep ocean towards the shelf with the shelf edge being located 100 km off the coast. The underwater earthquake is represented by an initial ocean elevation disturbance of 2 metres, 180 km off the coast. The ocean surface current field induced by a propagating tsunami is calculated at spatial scales of 1 km covering an area of 250x250 km² extension and temporal scales of 1 second. The total time of the tsunami



Fig. 3. Simulated radial velocities of tsunami induced currents using HAMSOM.

event simulation covers a one-hour time frame since the earthquake has happened. The white lines indicate the area which the radar covers at 250 km range and an azimuthal angle of ± 60 degrees. Due to the decreasing water depth, the tsunami wave speed is reducing and it takes about 40 minutes until the tsunami reaches the coast. That is why HF radar should be located at the coast where the shelf extends to approximately 100 km. The tsunami induced surface current reaches up to 1.3 m/s, which is well above the ocean current due to tides, density gradients, and wind.

In order to simulate the signals seen by an HF radar in case of a tsunami travelling towards the coast, we suppose that as the tsunami moves into shallower water we could see stronger currents with shorter spatial periods as the tsunami wave gets closer.

The ocean backscattering effect on the received monostatic radar Doppler spectrum produces two large peaks at frequencies of $\frac{1}{\sqrt{2gk}}$, where g is the gravity acceleration and k is the radio wavenumber. The ocean surface currents lead to the additional frequency modulation in the radar spectrum with the deviations from the theoretical values, i.e. to the additional Doppler shift of the first-order Bragg peaks shown in Fig. 4. Tsunami currents would cause extra shifts in the Bragg frequencies comparing to normal oceanographic situation. Thus they can be laid over the obtained spectrum using real measured signals from the WERA antennas.



The modulating tsunami current signal can be written for a range cell and an azimuthal beam angle as follows:

$$\Xi(t) = \exp\left\{2\pi i \int_{0}^{t} \mathbf{F}_{curr}(\tau) d\tau\right\}$$
(3)

where $\mathbf{F}_{curr}(t) = \|f_{currn,k}(t)\|$ is the Doppler frequency shift, which corresponds to fast changing tsunami current velocities in space and time.

The final signal $\mathbf{X}(t)$ is obtained using the Hadamard product of the derived signals (2) and (3)

$$\mathbf{X}(t) = \mathbf{Y}(t) \otimes \mathbf{\Xi}(t)$$

Further it has to be processed with a standard signal processing scheme with windowed FFT to get the power spectra of the signals that include the superimposed tsunami currents.

A typical measured HF radar range-Doppler spectrum obtained during the integration time of about 2 min is shown in Fig. 5 (left). We superimposed the ocean surface currents caused by a moving tsunami as they were shown in Fig. 3. The situation was simulated based on the measured radar antenna signals and it is shown in Fig. 5 (right).

Figure 6 presents an example of measured radial ocean surface currents using the WERA system. Vectors of surface currents were evaluated from the beamformed range-Doppler power spectra. The grid spacing is 1.5 km with maximum range of 250 km off the coast. Arrows show the direction of the radial current compo-

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nent. The colour scale corresponds to the ocean currents velocities in m/s. Specific tsunami current signatures are clearly observed in this map. The appearance of such signatures can be monitored early enough to issue a warning message about an approaching tsunami.

4. Proposed Tsunami Detection Technique

The tsunami detection technique is based on the statistical approach. The ocean current velocity values are mapped into an entropy field using the Shannon's entropy filtering for a single snapshot, i.e. about 2 min of integration time, collected by the HF radar. The current velocity map statistics may vary from snapshot to snapshot, therefore we have to detect the tsunami event against a background clutter and noise, which has an unknown distribution of entropy values.

We apply the detection technique to the range-angle ocean current entropy map using a conventional constant-false-alarm-rate (CFAR) algorithm. The probability of detection is a measure of the likelihood that a target with a given signal-to-clutter ratio will be detected. Variations in both signal strength and the contending noise or clutter level determine the probability that a signal on the threshold boundary will be registered as detection. The probability of false alarm is determined by the likelihood that the noise or clutter signal amplitude exceeds a given level.

Detection of a tsunami event can be expressed with hypotheses

CFAR methods usually formulate a test statistic for each cell of interest and compare it to some threshold. The CFAR threshold calculation is usually based on the Neyman-Pearson criterion with a fixed probability of false alarm and a maximum probability of target detection. A detection decision must be made for each entropy map individually.

The adaptive threshold $\epsilon_{\rm thr}$ at the specified test cell can be selected according to the ordered-statistic CFAR (OS-CFAR) detector [7]. The test cell value ϵ is compared to the threshold $\epsilon_{\rm thr}$ using the test rule

$$\varepsilon \gtrsim \varepsilon_{th}$$



The threshold is always calculated as the product

$$\varepsilon_{thr} = C \cdot \varepsilon_{a}$$

where *C* is the scaling factor used to adjust the probability of false alarm $P_{fa'} \varepsilon_{\alpha}$ is the entropy distribution quantile of the α -th order.

When the local entropy exceeds this threshold, we detect a tsunami area and issue a tsunami warning. The detection result for the OS-CFAR with $P_{ia} = 10^4$ is a



Fig. 5. Measured HF radar spectrum at WERA site (left) and HF radar spectrum with the superimposed tsunami currents shown in Fig. 3 at 19 min after the underwater earthquake (right).

basis of the tsunami alert map shown in Fig. 7, where the colour scale gives the importance of the tsunami event. It gives the location of tsunami, which is possible to detect in time.

Fig. 7. Tsunami alert map.



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5. Conclusions

The HF surface wave radar could contribute to the development and improvement of Tsunami Early Warning Systems. Sufficient time to detect approaching tsunamis and issue an early warning message can be achieved when these radars are located at the coast with a shelf edge of about 100 km.

A tsunami event is modeled using the HAMSOM model, which provides high spatial and temporal resolution and gives the ocean surface currents induced by an approaching tsunami.

The simulated tsunami current velocity is converted into modulating signals and superimposed on the measured antenna signals of the WERA system. The measured range-Doppler spectra with the superimposed tsunami currents have a specific "zigzag" signature that changes from snapshot to snapshot according to the tsunami movement. The reconstructed ocean surface current map based on the radar spectra shows a pattern, which changes very quickly in the shelf area before the tsunami wave approaches the beach. Specific radial tsunami current signatures are observed in these maps clearly.

The tsunami detection technique is based on the OS-CFAR detection algorithm applied to the entropy field of surface currents. This gives an opportunity to issue an automated tsunami alert during the real-time monitoring by the WERA radar.

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