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High-frequency ocean radar support for Tsunami Early Warning Systems

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Abstract

A high-frequency (HF) ocean radar system is a shore-based remote sensing system to simultaneously monitor ocean surface currents, waves and wind far beyond the horizon. The system operation is based on electromagnetic wave propagation coupling to salty water. Depending on operational frequencies, which are usually chosen between 5 and 30 MHz, a radar coverage of ocean surface may be extended up to 300 km offshore. The primary output of these radar systems is well used for various applications such as ocean current and wave mapping, vessel traffic service, search and rescue, monitoring of pollutants drift, and ocean sciences. Observations of the 2011 Japan tsunami event and recent meteotsunami events by HF radar technology confirmed that ocean radar systems are capable to measure tsunami-induced surface current velocity in real time. If the shelf edge width extension occupies tens of kilometers then the first appearance of specific tsunami currents can be monitored by an HF radar system in advance, already starting at the shelf edge. Hence, the radar measurements may be utilized to raise a tsunami alert. Moreover, the ocean radar can be a valuable tool to support Tsunami Early Warning Systems. The National Multi-Hazard Early Warning System in Oman launched in 2015 already includes a network of phased-array WERA® ocean radar systems to provide real-time tsunami monitoring. The radar measurements are considered to confirm a tsunami pre-warning from seismic, tide gauge and buoy components of the system.

Introduction

A tsunami is a series of waves that is mainly generated when earth plate boundaries abruptly move and vertically displace the overlying water. Earthquakes related to subduction zones generate the majority of all tsunamis; however, not every earthquake is able to generate a tsunami. For this reason, it should be determined at sea whether or not an earthquake has actually triggered a tsunami wave. Although a tsunami cannot be prevented, it is feasible to mitigate the impact of a tsunami through community preparedness, timely warnings, and effective response. The Tsunami Early Warning Systems (TEWS) meet the challenge of near-field warning with extremely short warning time. If a tsunamigenic earthquake originates close to the shore, the time between a seismic event and the issue of a tsunami warning is limited to a few minutes only.

While everyday ocean waves have a wavelength (from crest to crest) of up to 100 m and a height of typically up to 3 m, a tsunami in the deep ocean has a wavelength of about 200 km and travels large transoceanic distances with limited energy losses. Such a wave travels at a velocity of more than 200 m/s, has an enormously large wavelength and usually an amplitude much less than 0.5 m. This makes tsunamis difficult to detect over deep water and they are usually not noticed by vessels on the open ocean.

It is supposed that tsunami disturbances propagate in the deep ocean as shallow water gravity waves with zero dispersion, so their phase velocity is approximated by linear wave theory as $\sqrt{gd}$, where g is the gravity acceleration and d is the water depth. The phase velocity dependency is shown in Fig. 1a. As the tsunami approaches the coast and the waters become shallower, the wave is compressed due to wave shoaling and its speed slows down to about 20 m/s (see Fig. 1a). Its wavelength diminishes to less than 20 km and its amplitude grows and produces a distinctly visible wave.

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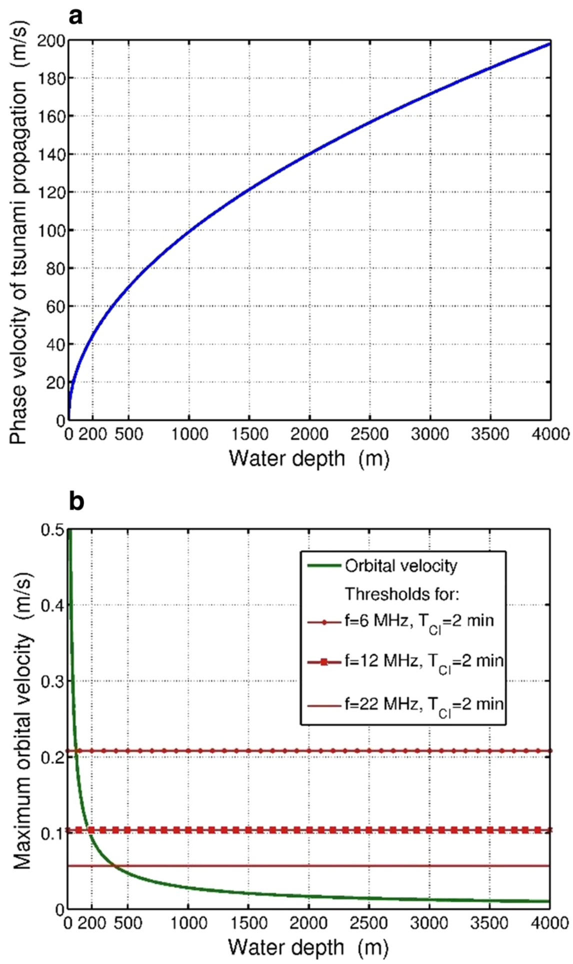

Fig. 1 Linear wave theory results: **a** Tsunami phase velocity of propagation. **b** The maximum orbital velocity (surface current velocity) of surface particles in a tsunami wave. Red lines are the radar velocity resolution thresholds for different radar operating frequencies, which define the detectability of tsunami-induced currents

The orbital motions of surface particles, as the shallow water gravity wave propagates past a point, are horizontally elongated ellipses with the semi-major axis corresponding to water elevation as described in Kinsman (1965). The application of linear theory for the maximum orbital velocity (surface current velocity) as a function of depth is shown by a green line in Fig. 1b for a tsunami wave with an initial elevation of 0.2 m in deep ocean. It can be easily seen that surface current velocities induced by a tsunami are smaller scales than the phase velocity of tsunami propagation. Nevertheless, these current velocities would be accurately measured with high spatial and temporal resolution using the high-frequency (HF) ocean radar technology. The sensitivity of the radar in resolving the surface current velocities strictly depends on its operating frequency f (between 5 and 30 MHz) and coherent integration time T_{CI} for signal processing as it is shown in Fig. 1b by red lines. These lines are velocity resolution thresholds. It should be noted that using either a radar frequency of 6 MHz with 4-min integration time or 12-MHz frequency with 2-min integration time would deliver the equivalent velocity thresholds. Generally, the lower the operating frequency, the longer integration time is necessary to obtain the necessary tsunami velocity resolution. All tsunami current velocities above these thresholds are detected offshore. Although the HF ocean radar does not directly measure the wave height of an approaching tsunami, it is able to contribute to the development and improvement of TEWS, most of which are overviewed in Joseph (2011), by measuring surface current velocities.

Propositions on HF ocean radar to support TEWS

Until the last decade of the twentieth century, measurements of tsunami waves were obtained mostly by coastal tide gauges. During the past decades, the engineering made a step forward and reached a level of development that provides a possibility of tsunami registration in deep ocean, e.g. DART® real-time tsunami monitoring systems (Gonzalez et al. 1998) or continuous GNSS buoys (Schoene et al. 2011). The HF radar systems are usually deployed at the coast for oceanographic purposes. Their operation is based on electromagnetic wave propagation coupling to salty water and utilizes the interaction between the transmitted electromagnetic wave and moving ocean waves. The main contribution for the HF radar system is given by the ocean surface echo signals, which are measured and converted into the ocean surface current velocity at far distances offshore. Therefore, HF radar could identify a tsunami wave travelling towards the coastline early and follow ocean surface current changes caused by a tsunami event using fast update of the measured radar spectra. The ocean backscatter effect on the received radar Doppler spectrum produces two large resonant power peaks containing information about velocities of incoming and outgoing surface currents. Bragg-resonant backscattering process by ocean waves with half of the electromagnetic wavelength allows measuring the ocean surface current velocity at far distances, e.g. 300 km offshore with a 6-MHz system. Tsunami-induced surface currents would cause additional shifts in the peak frequencies compared to normal oceanographic situation. While the tsunami wave is approaching the shore, the surface current pattern changes slightly in deep water and significantly in the shelf area as it was shown in Gurgel et al. (2011).

The capability of ocean current monitoring far beyond the horizon is helpful for tsunami detection. If ocean radar systems have already been installed at the coast then their upgrade for tsunami monitoring is relatively easy and not expensive. In case of an approaching tsunami, an increasing ocean current signature may be observed by the radar when the tsunami wave enters the shelf edge and travels into shallower water. Depending on the width and depth of the shelf, it could take up to 1 h from the first detection of the tsunami velocity signature until the tsunami wave hits the coast.

The HF ocean radar does not measure the approaching wave front (wave height) of a tsunami; however, it can detect the surface current velocity signature, which is generated when tsunami reaches the shelf edge and propagates in the shallow water region. Assuming that a tsunami is generated in the deep ocean and the shelf edge is far enough off the coast, there is enough time remaining and a warning system could be effective. The HF ocean radar could provide valuable information to increase the reliability of TEWS under fulfillment of certain conditions:

- The extension of the shelf within radar coverage should be significant to allow time for issuing and transmitting a tsunami alert.
- The bathymetry within the radar coverage has to be known in detail to plan an ocean radar installation with a maximum effectiveness for tsunami monitoring.
- The temporal resolution of the radar must be high enough to pick up the fast changing surface velocity and tsunami wave period. The potential tsunami areas should be monitored in a fast acquisition mode, which provides a quick update of the ocean surface current fields, for example at a 2-min rate. Based on this mode, an algorithm to identify a tsunami signature in the HF radar measurements has already been implemented.
- The spatial radar resolution must be sufficient to resolve the current signature. It is necessary for the radar system to achieve high signal-to-noise performance and narrow beam directivity. For example, these features can be obtained using a phased-array radar system with multiple channels and fast beamforming technique.
- The radar system should be equipped with an additional uninterrupted power supply unit to account for a power outage and the transmission link between a radar site and the central server of TEWS should be stable and independent of local communication networks.
- The output data of ocean radar should be easily integrated into existing TEWS using a flexible data format, fast update rate and quality control of measurements; additionally they may be a part of systems, which provide simulations and assimilation for different tsunami scenarios.

More detailed information can be found in Dzvonkovskaya (2018). Beyond any doubt, an optimization process is necessary for each radar site individually due to different geometries of the continental shelf and radar operating frequency. Nevertheless, by measuring only surface current velocities, ocean radar systems are able to contribute to the development and improvement of TEWS.

The final decision about a tsunami alert is done automatically by the tsunami-alert software within three levels, i.e. no tsunami, a possible tsunami, and a tsunami alert. The alert decision should be immediately transmitted to the nearest TEWS server via a text or bit message. The term "early warning" is not used to describe the information delivered by HF radar, because an actual tsunami warning is issued by local authorities, who are responsible for population and evacuation processes. All sensors, including HF ocean radar systems integrated into TEWS, deliver only advisable information regarding a tsunami threat.

Presently, three main HF ocean radar systems have delivered a significant contribution to HF surface wave radar technology for tsunami observation, namely these systems are the frequency-modulated continuous waveform (FMCW) phased-array radar system with software beamforming WERA® by Helzel Messtechnik GmbH in Germany (e.g. see Fig. 2), the frequency-modulated interrupted continuous waveform (FMICW) direction-finding radar system with cross-looped antenna SeaSonde® by CODAR Ocean Sensors Ltd. in USA, and FMICW

Fig. 2 The WERA ocean radar phased-array antennas near Dibab, Oman

phased-array radar system with digital beamforming by Nagano Japan Radio Corporation (NJRC, Japan).

Examples of seismic tsunami and meteotsunami observations by HF ocean radar

On March 11, 2011, a 9.0-magnitude submarine megathrust earthquake occurred 130 km off the east coast of Sendai, Honshu, Japan (The U.S. Geological Survey (USGS) web site 2011). The earthquake produced a major tsunami, which brought destruction along the Pacific coastline of Japan's northern islands. Moreover, the tsunami propagated across the Pacific Ocean and many countries issued evacuations along the coasts because of the predicted tsunami waves. However, while the tsunami was widely felt, in many of these places, it caused only relatively minor effects. Chile's section of Pacific coast is one of the furthest from Japan, at about 17,000 km away but still was hit by tsunami waves of more than 2-m height (The NOAA National Geophysical Data Center (NGDC) web site 2011).

The propagation of the 2011 Japan tsunami was estimated by the National Oceanic and Atmospheric Administration (NOAA) Center for Tsunami Research, USA, using the MOST (Method of Splitting Tsunami) model (Titov and Gonzalez 1997) with the tsunami source inferred from special tsunami buoy data. As the tsunami started from Japan, after 22 h it had propagated throughout the entire Pacific Ocean, reached the coast of Chile and was an extremely complex wave train due to the structure of the sea bottom. One WERA system was in operation on March 11–12, 2011, when the tsunami waves reached the Chilean coast. The 22-MHz phased-array radar system was located near Rumena, Chile, and was continuously providing ocean surface monitoring in that region. The radar measurements were recorded and archived every 5 min during several hours while the tsunami wave train was hitting the Chilean coast.

The surface current pattern changes in the shelf area were identified in the radar measurements and originally reported in Dzvonkovskaya et al. (2011). To obtain the pure tsunami-induced currents, a filtering technique was applied to eliminate the background surface current field, which included tidal components. Figure 3a shows an example of measured radial velocities of tsunami currents in the west–north–west (WNW) direction. The color scale corresponds to the velocities in meters per second and shows the current intensification while tsunami waves were approaching shallower waters. In the figure, clear periodic disturbances in surface currents due to the Japan tsunami can be seen. The positive and negative velocity values correspond to crests and troughs of the tsunami waves with a clear periodicity and also show that the first tsunami wave was not the highest in the tsunami train. The velocity measurements achieved accuracy of a few cm/s, which means the sensitivity of radar measurements was good enough to catch the small changes caused by tsunami. Moreover, it can be clearly observed that the tsunami current velocity becomes higher during the wave propagation towards the coastline as it was previously suggested in Gurgel et al. (2011). Figure 4 shows a bottom relief along the radar look to WNW. Although the shelf width within the radar coverage is only 10–20 km, a slight inclination in the estimated tsunami currents shows that tsunami waves crossed the shelf within several minutes.

Additionally, the observed radar results were compared with water level measurements by the tide gauge located 50 km to the south from the radar site. Figure 3b shows the measurements of mean sea level in meters recorded by the tide gauge located at Lebu, Chile (The UNESCO/IOC oceanographic data website 2011). Obvious tsunami signatures are found for both types of measurements; although the measurements correspond to different sea surface parameters and were obtained utilizing different equipments. The analysis of the data produced by the WERA system and the tide gauge indicates a high correspondence during the tsunami event. The tsunami wave periodicity from the radar was examined further. Wave periods were scaled off in Fig. 3 using time between positive peaks and negative troughs of tsunami waves. There is no significance difference between the wave periods at the different depths of the water column. This is consistent with linear theory, where the wave period is invariant through shoaling.

Wave periods of 14 and 32 min were estimated for both tide gauge and radar measurements. Due to these values of tsunami period, it should be stated that the potential tsunami areas have to be monitored by the ocean radar in a continuous operation mode with a fast update of the ocean surface current measurements, e.g. at least about 5 min and preferably at much faster rate.

An example of tsunami detection and alert map is shown in Fig. 5 for the case of the 2011 tsunami measured in Chile. It should be mentioned that the detection of tsunamis by HF radar is first considered using a direct inversion of tsunami currents from the radar spectra as described in Gurgel et al. (2011) and the technique is typically limited to areas where such currents are significant, i.e. exceed 5 cm/s. In case of the WERA system, the tsunami detection technique is always based on a statistical approach to deliver a tsunami alert scale as a probability of detecting a tsunami. The estimation at a particular time is based on residuals of measured radial velocity detrended from tidal components. This is done by applying a moving polynomial regression spanning the previous 45–60 min of measurements as a trend estimation.

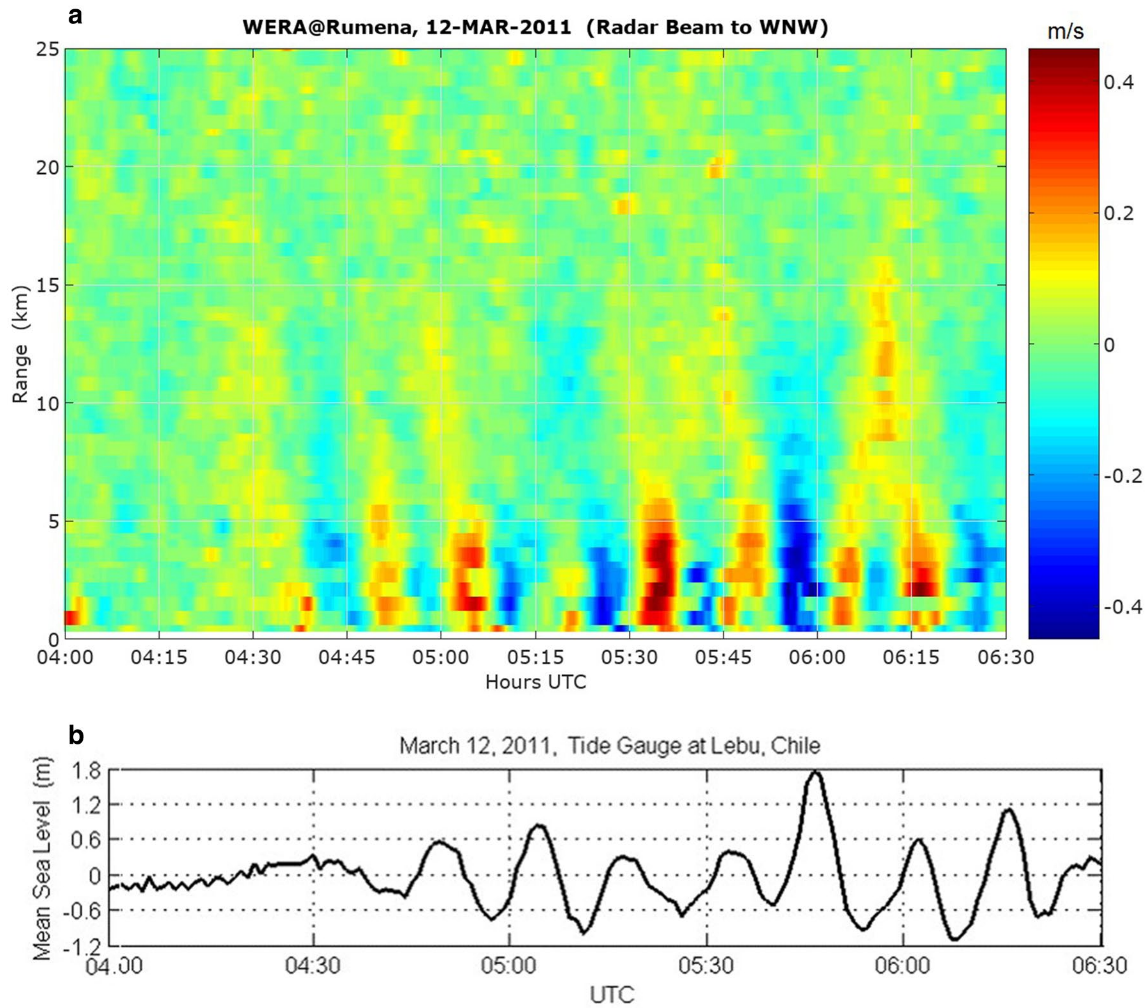

Fig. 3 The 2011 Japan tsunami measurements in Chile: **a** Radial velocity of tsunami surface currents measured by the WERA radar in Chile. **b** Mean sea level measured by the nearby tide gauge in Lebu, Chile

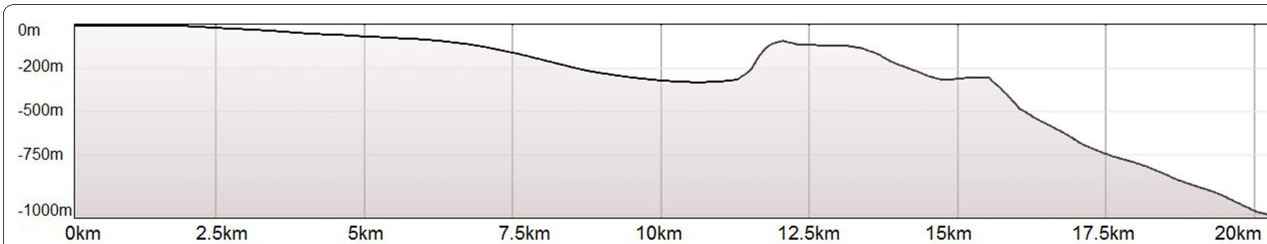

Fig. 4 The seafloor profile along the radar beam to WNW

As described in Dzvonkovskaya (2018), the probability of a detected tsunami may be simultaneously calculated in each grid point within radar coverage, assuming Bernoulli distribution of residual values. The final alert decision is based on the ordered-statistics estimation for the probability map. This approach is already implemented in the WERA tsunami-alert software and delivers spatial information regarding an alert every 33 s.

Following the Japan tsunami event in 2011, direction-finding CODAR SeaSonde radar systems recorded

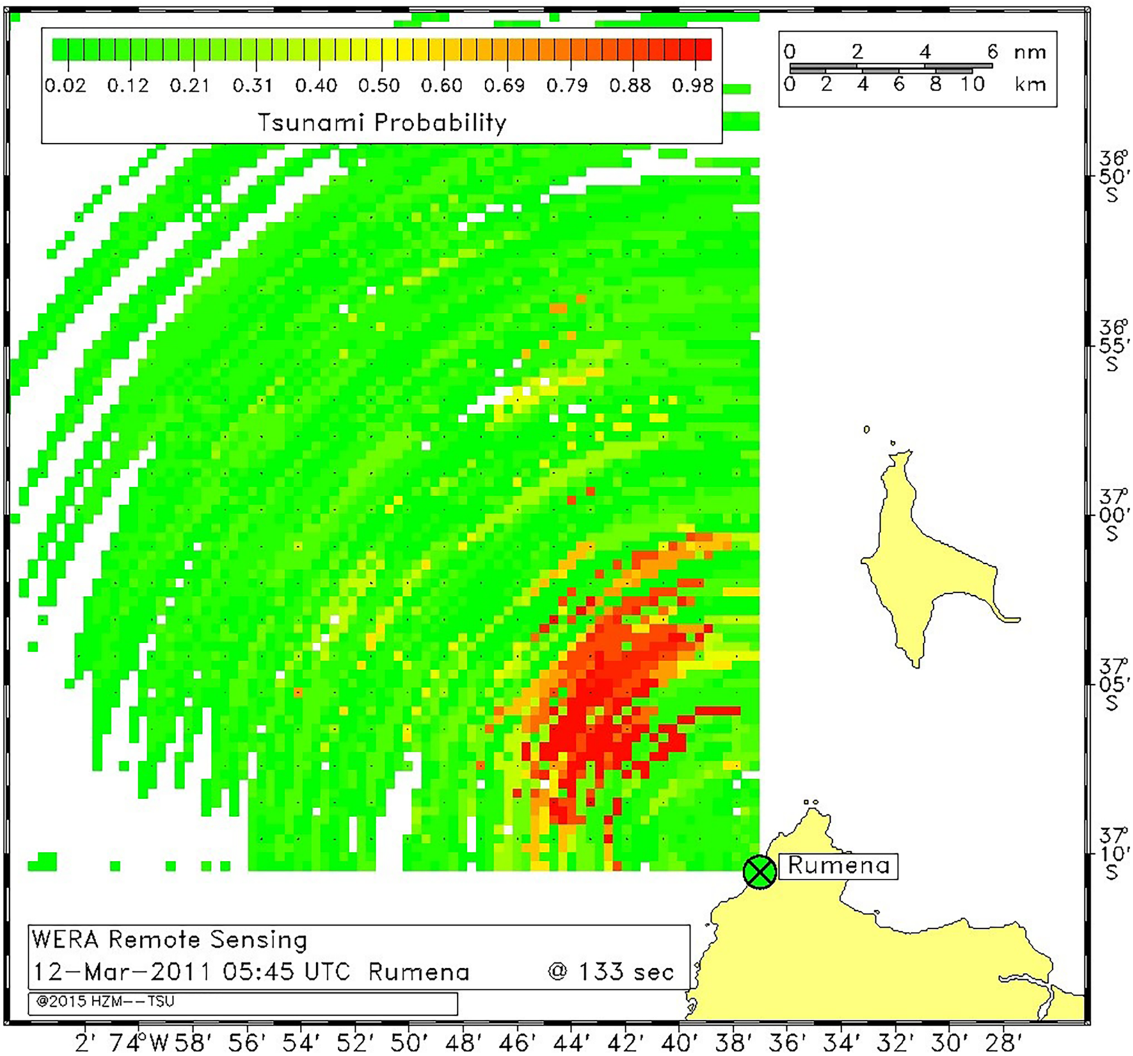

Fig. 5 Real-time visualization of tsunami alert based on retrieved tsunami current velocity from the WERA measurements in Chile

strong tsunami signals. Several radars on two continents 8200 km apart obtained the distinctive tsunami signatures in the 42-MHz radar system in Hokkaido, Japan, and 13-MHz and 5-MHz systems in California, USA (Lipa et al. 2011). Signals from the tsunami waves induced by the 2011 earthquake and from subsequent resonances were also detected as radial velocity variability by an NJRC HF ocean radar (Hinata et al. 2011). Both types of radar systems proposed an empirical approach, different from the WERA technique, to get a possibility for tsunami detection. It uses a cross-correlation between distant observation points/range bands on a coverage grid in which 60-min data streams of filtered current velocities in time and space were cross-correlated. When the cross-correlation increased significantly together with the passage of the first tsunami wave, it was judged that the ocean radar had detected the tsunami.

Since the 2011 Japan tsunami, the WERA system was further developed to follow the TEWS requirements and installed as a part of the Ocean Networks Canada (ONC) Tsunami Project, the initiative to develop a near-field tsunami alert network consisting of different types of pressure and seismic sensors as well as ocean radar systems.

On 14 October 2016, the 13-MHz WERA system on Vancouver Island, Canada, automatically detected strong changes in measured currents at distances up to 60 km off the coast and triggered an automatic alert immediately. The system tracked the unusual current pattern for 1.5 h in real time following the wave propagation coincided with an atmospheric frontal passage [see detailed event description in Dzvonkovskaya et al. (2017)]. A

Fig. 6 A video evidence of the Dutch meteotsunami wave propagation on 29 May 2017 (Retrieved from The Dutch Meteotsunami (2017))

jump in surface current velocity was observed simultaneously with air pressure development; thus the event may be identified as a meteotsunami (a type of non-seismic tsunami).

On 29 May 2017, another meteotsunami was generated in the North Sea by an air pressure disruption and reached the southwestern coast of the Netherlands (see Fig. 6). There are two 16-MHz WERA radar systems installed in that area, which are operated in a standard non-tsunami mode and provide sea current information around the port of Rotterdam. After re-processing, the acquired raw radar measurements from both systems, the original WERA tsunami detection software identified tsunami-like currents more than 40 km offshore [see detailed event description and comparison with tide gauges in Dzvonkovskaya et al. (2018)]. For comparison, one can observe in Fig. 7 that the wave front has a similar slope to the coastline as it is seen in Fig. 6. Thus, a high spatial resolution acquired via phased-array HF radar may be used to track the tsunami wave front.

HF radar network for TEWS in Oman

The newly established Multi-Hazard Early Warning Center in Oman is shown in Fig. 8. It is responsible to issue warnings for natural disasters such as tsunamis and tropical cyclones and is one of the most sophisticated tsunami-warning systems worldwide applying a mix of well-proven state-of-the-art subsystems together with newest technologies. It serves as a basis for the integration of HF radar data into the tsunami-warning procedure as shown in Fig. 9. This becomes possible since any WERA system is capable of detecting changes of the surface current in real-time monitoring via specially developed signal processing and tsunami detection software. This fact gives an opportunity to issue an automatic tsunami alert message by the radar system to TEWS and also to provide data assimilation for real-time tsunami simulations. The tsunami simulations can be validated using a comparison between simulated and measured oceanographic data including HF radar measurements of surface currents. The core of the TEWS is the seismic real-time analysis system SeisComp3 described in Hanka et al. (2010) and used in most tsunami-warning centers globally. The tsunami simulation and decision support system is based on the Tsunami Observation and Simulation Terminal (TOAST) system developed by gempa GmbH (Global Earthquake Monitoring Processing Analysis 2018), which is a commercial software for tsunami simulation and confirmation giving a quick hazard assessment. Oceanographic sensors such as tide gauges and buoys may verify the results. While conventional TEWS are based on huge databases of pre-calculated scenarios, TOAST uses a real-time simulation approach. Following this approach, TOAST can react on any atypical events, for example, an epicenter location in an unexpected area or an earthquake with untypical rupture mechanisms.

Most TEWS rely on a hydrodynamic detection network, which mainly consists of coastal tide gauges, since offshore buoys are rare due to their high costs. In addition, the Omani TEWS also integrates measurements of a modern network of WERA phased-array radar comprising of 13-MHz and 9-MHz systems (see radar coverage in Fig. 10). It is used to verify simulations in TOAST giving additional scenario quality information and confirmation to the decision support. The CAPS (Common Acquisition Protocol Server) developed by gempa GmbH greatly simplifies the integration of multi-sensor data in TOAST. CAPS allows the acquisition of data from many different sensor systems including seismic stations, continuous GPS (CGPS) buoys, tide gauges and HF radar systems in one acquisition system providing access to all sensor data through a common interface and disseminating tsunami information via mass media (as shown in Fig. 9). The ocean radar allows continuous offshore monitoring while providing valuable input for the tsunami verification. If the tsunami origin is far away, the SeisComP3 and TOAST systems would already be alerted and the HF radar data would serve as a confirmation of timing and severity of the hazard. If the tsunami is generated nearby, the HF radar data would take a dominant role in the warning system. In some cases, a shore-based HF radar may be used as an alternative to expensive buoys maintained offshore.

While tide gauge data are integrated as conventional water level measurements, the radar tsunami data are integrated in TOAST as a chain of “virtual”

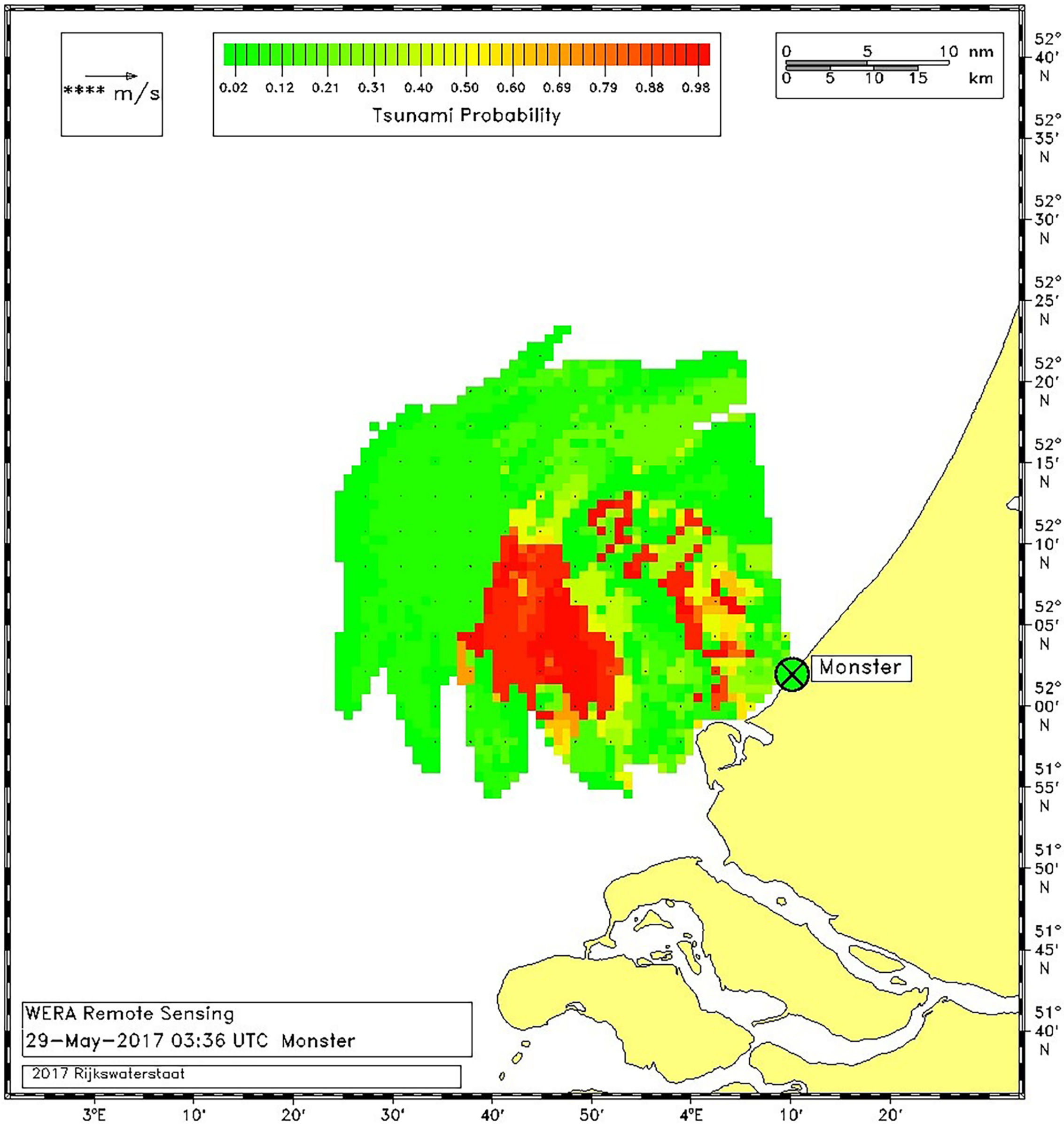

Fig. 7 Meteotsunami signatures (red color) in WERA tsunami alert maps generated on 29 May 2017 for the radar site at Monster, the Netherlands

oceanographic sensors located at the shelf edge. The data are displayed in the form of velocity streams estimated at the specific virtual sensor positions, which are grid points of radar coverage, and further they are treated in a similar way as tide gauge or buoy data. HF radar systems measure surface orbital velocity within the waves of passing tsunami wave-trains and can be used for picking the tsunami onset time to confirm wave amplitudes using the linear transform to calculate amplitude as a function of maximum velocity and water depth (Kinsman 1965). Since the current velocities can be accurately measured with high spatial and temporal resolution using the phased-array HF ocean radar technology, these onsets are used to verify arrival times of the simulated scenarios and give additional information about the exact location of the rupture area.

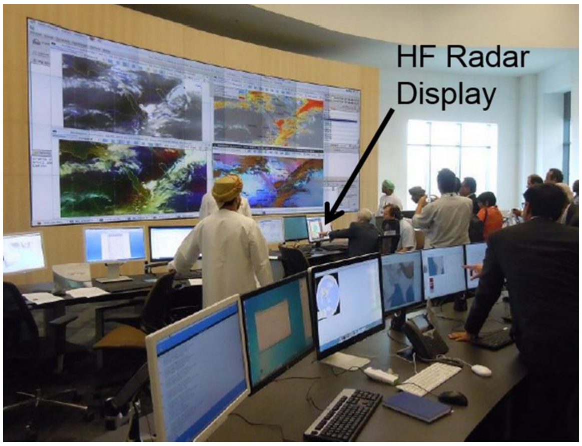

Fig. 8 The launch of the National Multi-Hazard Early Warning System in Oman

Conclusions

HF ocean radar has a unique capability to monitor the ocean surface far beyond the horizon. The remote observation of a real seismic and non-seismic tsunami events using HF radar systems showed that phased-array radar systems are capable of measuring tsunami surface current velocity in real time while tsunami waves are crossing the shelf edge and moving in shallow water areas. If the shelf edge has a significant extension from the coast then the first appearance of such currents can be identified by an HF radar system early enough, thus having time to issue an alert message.

Based on tsunami measurements, a set of requirements for ocean radar systems has been identified to give an opportunity to bridge them to existing TEWS. The requirements include a high spatial and temporal resolution of an ocean radar system, a fast data update mode and flexible output to provide a possibility of offshore tsunami detection in real time. The radar measurements are applicable to confirm a tsunami pre-warning. The capability of phased-array HF radar systems to observe tsunami signatures already at the edge of the continental shelf provides a useful element in assessing the impact of an approaching tsunami as well as it might be beneficial for local tsunami-warning decision-makers and authorities.

The integration of radar data into a tsunami-warning system is demonstrated in case of the operational Multi-Hazard Early Warning System in Oman. The radar

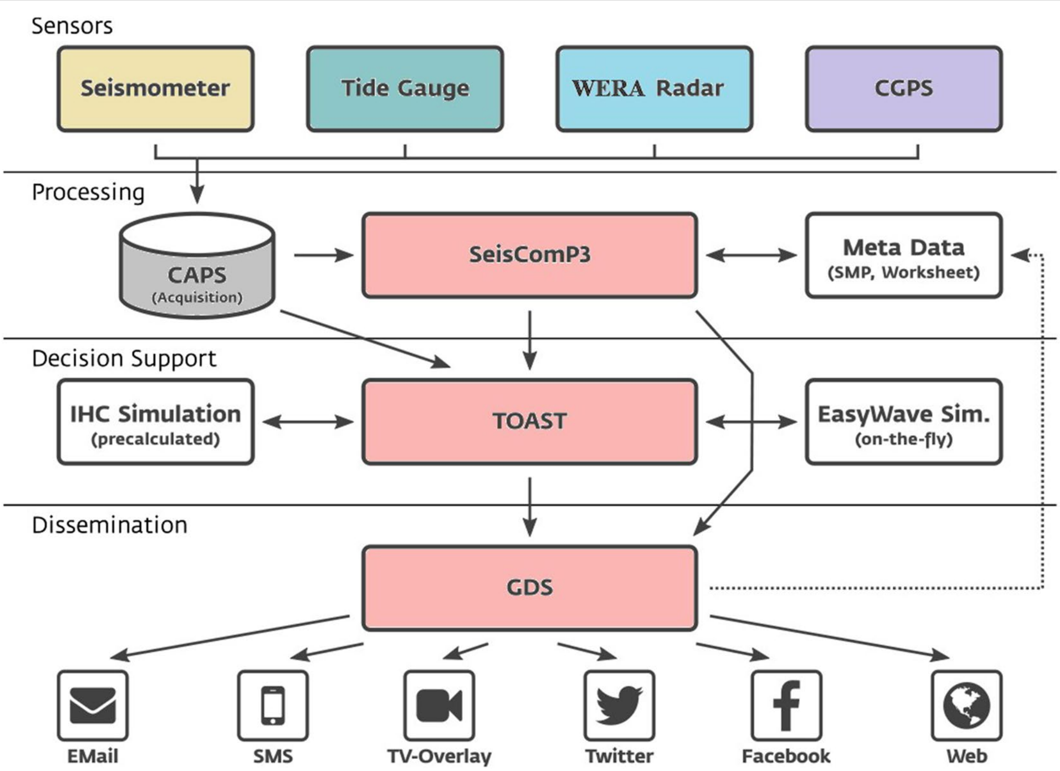

Fig. 9 Architecture and data flow of the TEWS, which includes seismic, tide gauge, WERA ocean radar and CGPS data

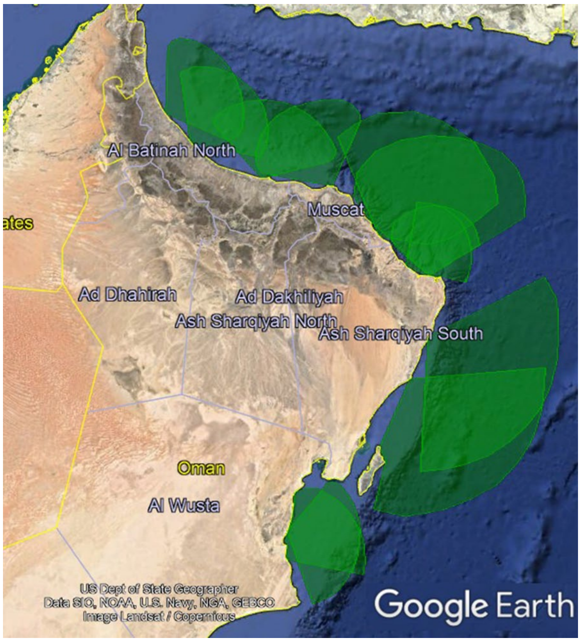

Fig. 10 The WERA system network to support the Tsunami Warning System in Oman (green sectors show the radar coverage of multiple WERA systems)

measurements may be also used to validate the timing and magnitude of the tsunami while following pre-warning from the seismic, tide gauge and buoy components of the system.

Authors' contributions

AD performed the data analysis and developed "Introduction", "Examples of seismic tsunami and meteotsunami observations by HF ocean radar" and "Conclusions" sections, and was a major contributor in writing the manuscript. LP and TH elaborated "Propositions on HF ocean radar to support TEWS" section. LP and MK contributed to "HF radar network for TEWS in Oman" section. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The water elevation datasets generated and analyzed during the current study are available in the UNESCO/IOC oceanographic data repository, http://www.ioc-sealevelmonitoring.org/. Some datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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