Wave profiles derived from Nautical X-Band Radar as data source for Ship Motion Prediction

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Abstract

Nautical X-Band radars used for navigation can be utilised to determine spectral and individual wave properties. The sea surface reflects the incident radar beams. In this process, wave fronts become visible as stripe like pattern of high back scatter. When connected to a conventional nautical X-Band radar, the Wave Monitoring System WaMoS II exploits this imaging of waves to detect full directional wave spectra and to derive statistical sea state parameters as well as surface currents. WaMoS II is continuously improved: New features are developed for high-resolution current measurements, estimation of the water depth as well as for single wave detection. In particular, the sea surface elevation maps derived by WaMoS II allow to investigate and describe the spatial and temporal development of 3D ocean surface waves. The European *Joint Industry Project 'On board Wave and Motion Estimator (OWME)'* used this measurement technique to provide the wave information that is required to predict periods of quiescent vessel motions. A task that offers valuable support for various offshore operations like e.g. the tensioning of a tanker or the landing of a helicopter. This contribution gives an overview of the OWME system design and the results of a first validation campaign, focussing on the method to derive wave trains using the WaMoS II system.

Introduction

Many offshore operations are critically dependent on the prevailing sea state. Regarding safety of loading and crew, the development of systems to detect dangerous sea states automatically, and to provide a decision guidance for the navigation is discussed more and more within the shipping community.

Also the ability to predict vessel motions in real time is of critical importance in the shipping and offshore industry. Certain types of operations, such as float-over-installation, ROV handling and helicopter landing depend heavily on wave impact or wave induced motions. In many cases a short time quiescent period in vessel motions is sufficient to conduct the operation. So far, go/no-go decisions can only be made on the basis of eye observations of the incoming waves by experienced crew. Also numerical extrapolation from the vessel motions history can only predict the motions up to some 10 seconds ahead. To extend the prediction times of such quiescent periods, the Joint Industry Project 'On-board Wave and Motion Estimator' (OWME) was set-up.

The project run by a partnership consisting of MARIN, TU-Delft and OceanWaveS GmbH focussed on offshore applications in mild sea states. The requirement of the project was the development of a system capable to determine the vessel motions some two minutes ahead (Naaijen et al. 2009).

In this paper, emphasis is laid on the first of the three tasks described above, i.e. the development of a measurement technique to provide the wave information needed for the OWME system. The overall OWME approach is briefly described, as well as the wave measuring method. Finally, some results of the sea trial are reported.

The OWME concept

Regardless of the actual design, a motion prediction system has to solve three main tasks: It needs to account for the actual sea state and weather condition, either by measurements or forecasts. The development of the sea state has to be predicted for the time horizon that is needed for the motion prediction. And finally, the system has to estimate the vessels response to this predicted wave environment. These three tasks have to be solved with high update rates and low processing times, otherwise the prediction arrives to late to be useful.

In OWME, solutions for these three tasks were developed, mainly by improving existing technologies and integrating them into a working wave motion predictor. The aim of OWME was to predict quiescent periods for a time horizon of up to two minutes, which is enough time to carry out some critical offshore operations.

Figure 1 shows the design and data flow of the OWME motion predictor and the set-up used for its validation. The OWME predictor uses wave radar to measure the waves in a distance of several 100 meters off the vessel. The individual waves are extracted from the radar images, then a numerical propagation model is used to predict the waves at the vessel location. From the full polar radar images , pre-chosen spots from the quadrant that points towards the waves, one-dimensional sea surface elevation time series are produced, that are fed into the wave propagation model. The propagation model then computes the wave elevations at the location of the vessel up to two minutes ahead. By this approach, the time that the recorded waves need to cover the distance to the vessel determines the prediction horizon of the system. Finally, the predicted wave elevation is fed into a numerical model to estimate the vessels response. Applying ship motion theory on these waves, the vessel motions in all six modes are computed. After its development the OWME approach was successfully tested aboard a vessel under real conditions.

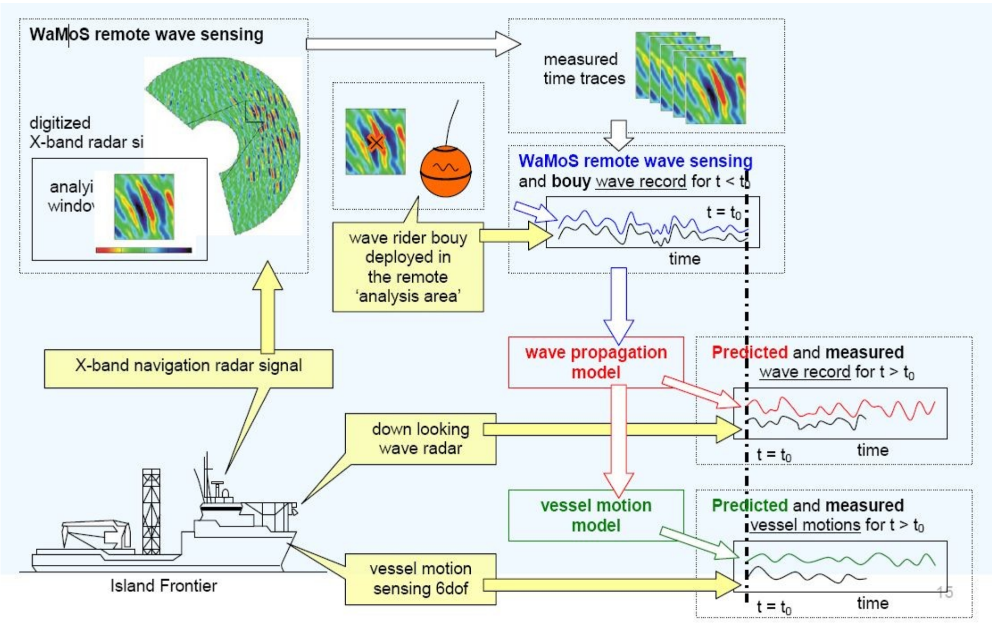

Figure 1: OWME real time prediction scheme. Sea surface elevations are retrieved from X-band radar data. A 1-D wave height series is then fed into a wave forecasting model, which then is used as input to the vessel motion prediction model.

Most critical in this approach is the computational time required to conduct the data processing – the longer the data processing takes, the shorter the prediction time will be. All of the data processing was completed by the CPU in just 13 seconds on a quad-core PC leaving approx. 2 minutes prediction time.

Criteria for a wave sensor

The OWME on-board vessel motion predictor requested a wave sensor that had to fulfil several criteria: It had to be fully functional while the vessel was travelling. This restricts the choice of sensors to remote sensing techniques as it is for instance impractical to deploy wave rider buoys to monitor the sea state for a moving vessel. Preferably, the sensor should be mounted on the vessel itself. Alternatives like e.g. airborne or satellite remote sensing do not provide the full temporal coverage needed and are too costly to support operations on a day-to-day basis. Suitable existing on board remote sensing techniques are altimeters (down looking radar or lidar) which can provide point measurements close to the vessel or scanning systems that are capable to monitor a larger area. The main advantage of scanning a larger area is the capability to detect the waves in some distance to the vessel, thus exploiting the wave propagation time to extend the prediction time.

From the range of existing measurement techniques, the use of marine radar is one of the best options to fulfil all above listed criteria. Nautical radars are designed to monitor larger areas in the vicinity of the vessel and can operate under harsh weather conditions. They are not effected by daylight, fog or heavy ship motions. The Wave Monitoring System WaMoS II exploits these properties with the standard data output being wave spectra and statistical sea state parameters ((Ziemer and Günther, 1994). New functionalities were included to retrieve 3D-sea surface elevation maps (Nieto et al 2004). Therefore, within the OWME project, WaMoS II was chosen to provide the required sea surface elevation data.

Sea surface elevation maps

In addition to the standard spectral analysis, individual waves can be determined from radar images. To retrieve the so-called sea surface elevation maps, sequences of nautical radar images are 'inverted' by applying a method proposed by Nieto et al. (2004). This approach allows to reconstruct the wave field from the radar signatures. It considers shadowing to be the main imaging mechanism of ocean gravity waves in nautical radar images and is based on linear wave theory. It is assumed that the sea surface elevation consists of a linear superposition of several individual sinusoidal waves, each fulfilling the dispersion relation. By means of a FFT, a band pass filter based on the gravity wave dispersion relation, and the application of a transfer function, the imaging process of waves can be inverted as sketched in Figure 2 by a inverse FFT.

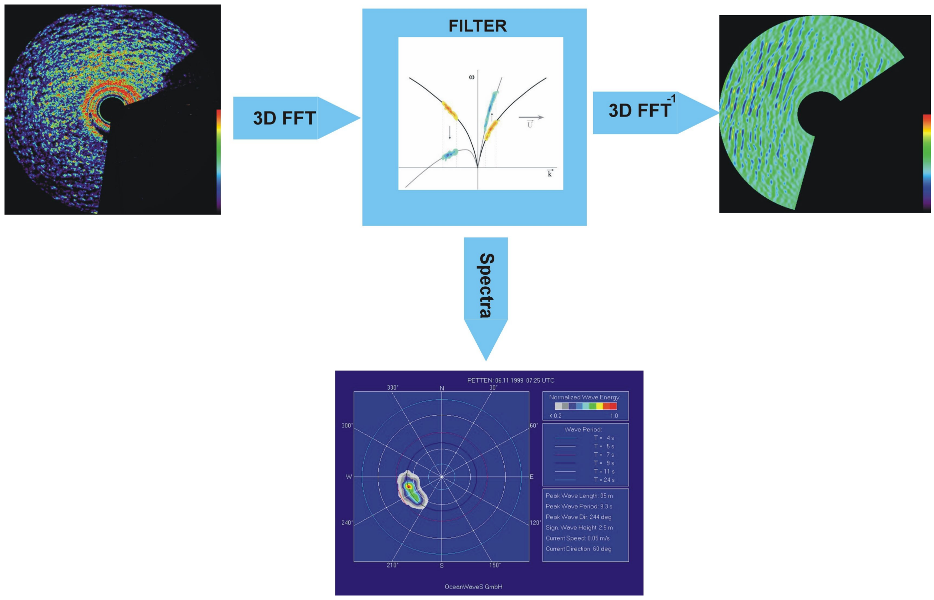

Figure 2: Deriving the sea surface elevation from radar images.

With this procedure, it is possible to retrieve the local wave elevation for each point in the radar field of view (Figure 2, right) in addition to the also available wave spectra (Figure 2, bottom). The resulting sea surface elevation map has the same spatial and temporal resolution as the input radar image. The performance of this measurement technique was applied in several research projects at different locations with good results (Hessner and Reichert ,2007).

For the particular task of the motion predictor, this kind of data product fulfils the main requirements for a ship motion predictor as listed in Section 2: It is the result of a remote sensing technique that allows to cover an extended area over time with good resolution. The measurement is fully continuous. Still, there were some modifications needed to comply also with the required fast data processing and update rate.

Modifications of WaMoS measurement technique for OWME

For the OWME system continuous wave measurements and real time data processing are essential. Therefore the standard WAMOS II software modules have been revised to ensure fast and secure data storage and analysis with minimum time delay between subsequent cycles. This was achieved by separating the raw data acquisition and data analysis while fully integrating the inversion module into the analysis module.

When using a standard PC, the various filters and transforms involved in the data analysis needed too much time when applied to full radar images. In extreme cases, the inversion of the radar images might take more than a minute, i.e. the computation time would be in the same order as the planned prediction horizon for the whole system.

One option is to reduce the observed area and by this minimize the amount of data that needs to be processed, thus reducing the entire processing time considerably. This approach has two advantages: Only those waves, that will approach the vessel within the next minutes will have an impact on its movement, while waves passing by are of no interest for the prediction. Therefore only the part directed into the waves, of the whole radar image contains relevant information for the purpose of vessel motion prediction. In addition, those waves that are approaching the radar show the strongest backscatter, as the radar beams are strongly reflected by the wave front. This yields the clearest raw signal and thereby most accurate wave elevation maps.

Due to the fact, that the wave information from the whole area is in principle available, an automatic tool can be designed to select a suitable sub area and restrict the time consuming full analysis of the whole image to a smaller 'window.' When facing multi modal sea states, more than one of those areas might be needed as it is crucial not to miss the important features of the wave field. Therefore, in the OWME wave measurement software, a recursive window positioning tool was implemented.

The location of the sub area is identified from the statistical wave parameters available from the WaMoS II standard analysis. The positioning algorithm uses the peak wave direction of the actual spectral measurement to choose the window position for the next calculation cycle. As all recursive procedures might become unstable with time, this selection is cross checked using a fixed 'control window'. The reference system used to place an analysis area is the ships heading.

Figure 3 shows an example of the window placement and gives an impression of the results of this procedure. The shown radar image covers a full 360 degree view around the radar antenna located in the centre. The radius of this example image is about 2km, the wave signatures are clearly visible. Within the example radar image, two frames are marked. The red frame represents an analysis area that is placed automatically into peak wave direction, while the green control window is fixed in front of the bow of the vessel. Both analysis windows have a size of 960 x 960 km^2 (128 x 128 pixels), and are placed in this example at a distance of 690m (referring to the inner boundary) from the antenna.

For both windows, the wave spectra are calculated. A 30 minute average of the peak wave direction is used to calculate the position of the analysis window for the next measurement. Only the red analysis window is used to derive the sea surface elevation. In Figure 3, the map of sea surface elevation is colour coded, blue indicating wave troughs, wave crests are displayed in red. In this example, the individual waves are clearly visible. The orientation of the wave fronts show, that the wave field is approaching the vessel, a sequence of such maps contains the unambiguous wave travel direction.

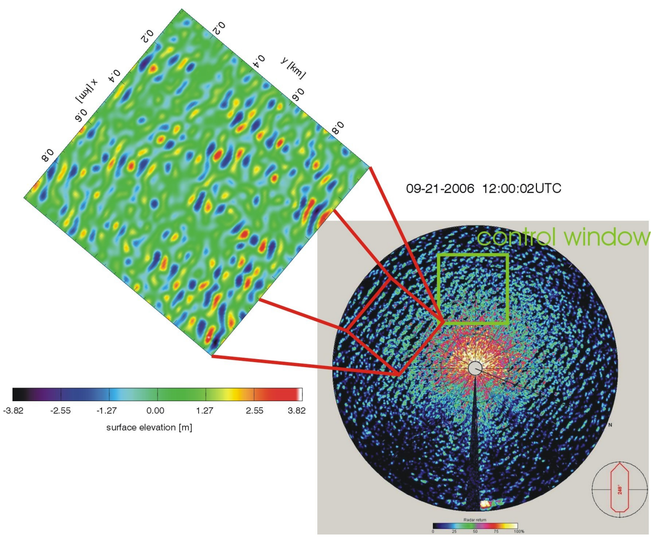

Figure 3: The window positioning algorithms focuses the wave analysis to areas with approaching waves.

Real time testing and data verification

Once the wave surface elevations at the remote location ahead of the vessel were known, a wave propagation model was required to predict the wave surfaces at the location of the vessel. The Ship Hydromechanics department of Delft University of Technology developed a linear wave propagation model based on the dispersion relation of waves. This method is a straightforward superposition of cosine waves with different frequencies travelling in different directions.

The OWME concept was verified against scale model tests both in long crested and short crested waves. Extensive short crested model tests were conducted in MARIN's Seakeeping & Manoeuvring Basin which measures 170 x 40 x 6m. In this basin, a sea area of 1.2 x 1.2nm including the vessel could be modelled at scale 1:70. The model tests proved the feasibility of the concept and the accuracy of the wave propagation and vessel motion prediction model. The modelling approach will not be further discussed in this paper, details are described by Naaijen et al ,2009.

For the final validation and demonstration of the developed OWME system, dedicated sea trials have been performed in September 2008 offshore Norway. The vessel which was selected for these offshore trials was the light well intervention vessel Island Frontier (IFO). This vessel is operated by Island Offshore and was at the time working for StatoilHydro at the Gulfaks-field. All activities on board were conducted in close co-operation with Seaflex, Island Offshore and StatoilHydro.

For the trial the IFO was equipped with a WaMoS II wave recording system, a down looking wave radar underneath the helideck at the bow of the vessel and an advanced on board network for data acquisition and storage. Also compact motion sensor units measuring the vessel motions in 6 DOF were deployed. These sensor systems were tied into the data acquisition system. This advanced monitoring system comprised a direct link with the internet which enabled remote review of the measurements and control of the monitoring software. In this way extensive data sets were recorded prior to the actual trials and parallel to the development of the OWME system. These data sets were used to develop and test the WaMoS wave elevation data processing and the ship motion modelling.

For the final trial, one buoy was deployed and moored in 150 m water depth in the centre of the window of the WaMoS wave detection area. The wave elevation measured by this buoy enables a deterministic verification of the WaMoS wave elevations as well as deterministic time domain test of the wave propagation model using the wave buoy data as input and comparing the output with the wave elevation measured by the radar level gauge on the bow of the vessel.

It should be noted that due to its flexible mooring and the changing wind, wave and current conditions, the wave buoy did not maintain position but exhibited a track as shown in the Figure 4. At the same time the WAMOS window also moved in time due to the automatic control of this window in WAMOS on the basis of the recorded dominant wave direction.

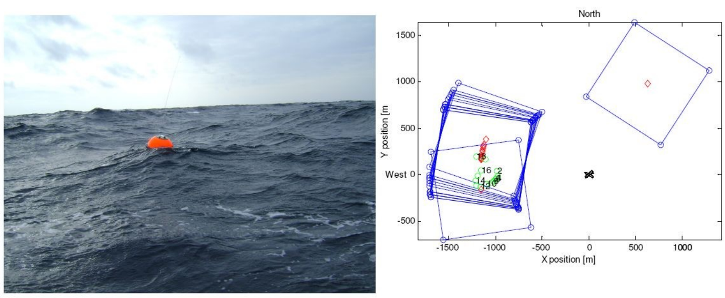

Figure 4:Drifting wave rider buoy and radar analysis window are shifted to the same positions. The exact positions of both sensors and the timing is very relevant to carry out any data comparisons.

When assessing the Hs computed by the various systems, a very close match was obtained. However the important next step for OWME was a deterministic comparison of the sea surface elevations as shown in Figure 5. The correlation between the buoy and WaMoS sea surface elevations showed reasonable results which gave confidence to proceed with the overall OWME approach.

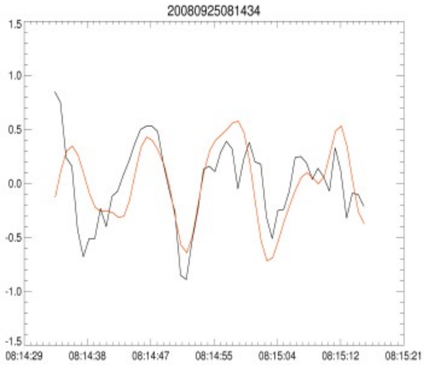

Figure 5: Comparison between wave elevation derived from WaMoS (red) and buoy (black).

Utilising the wave elevations from the WaMoS as input for the wave propagation, the output of the propagation model can be compared to the measured wave elevations by the Down Looking Radar (DLR) at the bow of the vessel. Also by measuring the remote wave elevations with a directional wave rider buoy, the local waves with a level gauge radar and the vessel motions by means of a motion sensor unit, a solid reference data set was obtained for validating the system. By this, each of the components of the OWME concept i.e. the wave sensing, the wave propagation and the vessel motion prediction could be tested separately as well as in combination.

The final test was to compare the advance predicted vessel motions with the actual measured vessel motions. Predictions of the vessel motions were made for 42, 60, 90 and 120 seconds ahead and compared with the actual vessel motions as measured (Figure 6). The general outcome for all four forecasting periods was, that despite significant deviations in the actual amplitudes and phasing, the envelope of the motions was predicted correctly.

The below results show that the OWME system is capable of predicting quiescent periods of vessel motions up to two minutes in advance and can thus, contribute to the workability of offshore operation in otherwise limiting sea states.

It is however noted that the OWME system was developed for and is so far only tested in mild sea states.

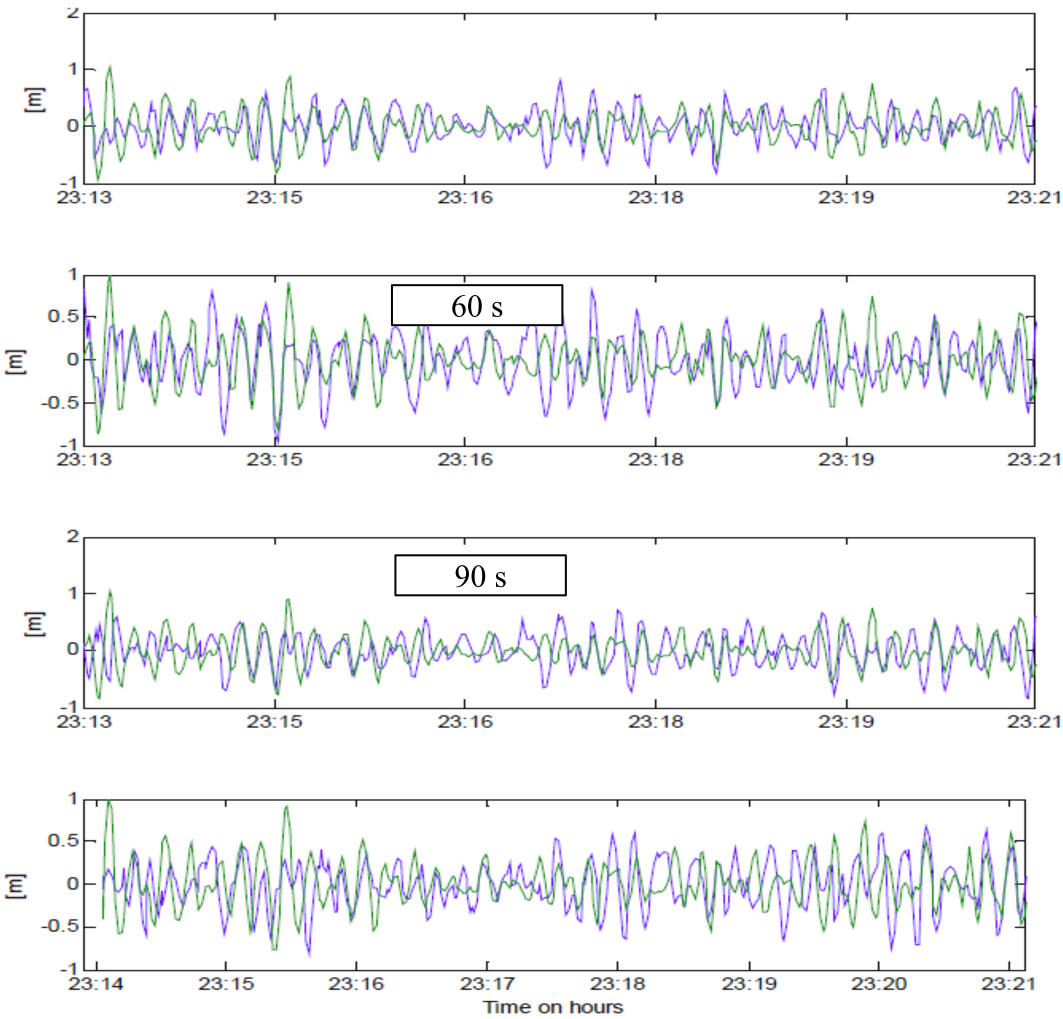

Figure 6: Vessel heave motion predicted 42, 60, 90 and 120 seconds in advance by OWME system compared with the measured on board heave motion (trials on an Offshore Support Vessel at Gulfaks field, September 2008). The green lines represent the measured heave motions, the blue lines the predicted motions.

Outlook

With these promising results, the OWME partners lead by MARIN plan to continue the work on the OWME concept, refine and enhance it, to make offshore operations safer and more efficient. At the same time, OceanWaveS will continue the verification of the sea surface elevation data within the coming years in a large experiment off the coast of California.

The technology is in particular relevant for smaller vessels of the type that are increasingly undertaking operations such as well intervention, drilling, survey and installation, operations for which safety and workability are paramount. The concept is also of interest for trading ships to avoid severe wave impacts and excessive motions by warning for severe incident wave elevations and excessive motions and loads.

Acknoweledgement

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