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On-Board Real-Time Wave & Current Measurements for Decision Support

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Abstract

Accurate information about ocean waves, surface currents, and the Speed Through Water is of great interest in many applications. These include fuel optimization, hull stress monitoring, as well as systems improving cargo safety and passenger comfort. During the recent decades, sensors and systems based on radar remote sensing principles have become increasingly more widespread, due to considerably improved accuracy and reliability. In addition, challenges and costs related to installing and maintaining in-situ or underwater equipment are avoided. This paper presents some of the principal radar-based sensors for wave and current monitoring.

1. Introduction

Digitalization is currently transforming many aspects of the modern society. This also holds true for shipping where easy access to data from a multitude of sources is fueling a wave of innovation that is changing the way vessels are designed, operated and maintained. The ship operation process used to be largely based on manual observations and retrospective analysis based on incomplete data sets. This is now rapidly shifting towards having access to detailed, accurate information in real-time. The information can be made available both on the vessels and at onshore operational centers and enables a wide range of improvements.

Situational awareness is key to unlocking the potential of digitalization. One area that has seen significant improvements recently is within real-time sea state measurements. Recent developments within radar-based technologies have given access to accurate sea state data that can be used to optimize ship operations. Radar-based sea state measurements can now provide both ocean wave and current data accurately under widely varying conditions. Both waves and currents can have a significant effect on ship performance. One example is ocean current measurements which can be used to accurately calculate the Speed Through Water (STW) of seagoing vessels.

A vessel has an optimal speed which in simple terms depends on the speed vs. fuel relationship of the vessel and the efficiency of the propulsion configuration (propellers etc.). Ocean currents of up to several knots can exist on the oceans which means STW might be quite different from Speed Over Ground (SOG). It is therefore STW and not SOG that should be used as the basis for speed optimization. Thus, STW is a very relevant parameter in ship performance optimization.

A number of applications are relevant in the light of accurate STW measurements. The most obvious is speed optimization taking STW as an input parameter which has the potential to lead to significant savings in fuel. However, there are also other foreseeable applications. Hull performance is one such example. With accurate STW measurements it is possible to benchmark the current performance of a vessel with respect to hull resistance and particularly the influence from hull fouling. With such information it is possible to have more accurate information about the state of the hull. This can be used to improve planning of hull cleaning or to investigate the effectiveness of hull cleaning procedures or hull coatings. Further use cases might also be possible such as studies of the performance degradation of parts of the drivetrain.

Ocean surface current measurements from moving vessels by traditional underwater (in-situ) instrumentation are associated with challenges and data heavily influenced by noise. Systems measuring the STW are equally influenced by similar disturbances affecting the vessel speed log, *Antola et al.*

(2017), Baur (2016), Bos (2016), Fritz (2016). Wave measurements from underwater instrumentation are only available on rare occasions. The following items are relevant for both acoustic Doppler current profilers (ADCPs), *Flagg et al. (1998), King et al. (1993), New (1992)*, and other instruments based on traditional in-situ measurement principles.

- Underwater equipment generally involves installation and maintenance procedures being both time-consuming and expensive.
- Underwater equipment is exposed to fouling, *Carchen et al. (2017), Goler et al. (2017), Kelling (2017)*.
- Measurements are disturbed by air bubbles, turbulence, and inhomogeneous hydrodynamics caused by the vessel motion and propellers, *Bos (2016), Carchen et al. (2017), Brown et al. (2001)*.
- Measurements are disturbed by other instruments, for instance acoustic echo sounders and vessel speed logs.
- The surface current itself is considerably affected by the vessel motion.
- Sensors are frequently inadequately calibrated, *Antola et al. (2017), Bos (2016)*, giving systematic errors in certain speed ranges, *Antola et al. (2017)*.

Thanks to considerable work and progress within the field of radar remote sensing during the recent decades, reliable ocean surface measurements can now be obtained using radar sensors. There are radars based on various technologies available on the market, and some of them are more suited than others for measuring from moving vessels. Systems based on imaging radar, Fig.1, using the on-board X-band radar, is probably the radar-based technology which is most suited for moving vessels, *Miros AS (2017c), Gangeskar (2014,2017)*. Microwave Doppler radars, Fig.2, can provide very accurate wave and current measurements from fixed installations and slowly moving vessels, but they are typically not recommended for vessels in transit, *Miros AS (2017a), Grønlie (2004,2006)*. Various sorts of vertical microwave radars, Fig.3, can provide very exact air gap time series that can be used to estimate the non-directional wave spectrum and parameters like the significant wave height, *Miros AS (2017b), Martín et al. (2001), Bushnell et al. (2005)*. By compensating the air gap measurements using data from a co-located motion reference unit (MRU), wave information can also be derived from moving installations. Such sensors can, however, neither provide directional wave information nor surface current measurements when used as single sensors, and they are typically not recommended for wave measurements during transit.

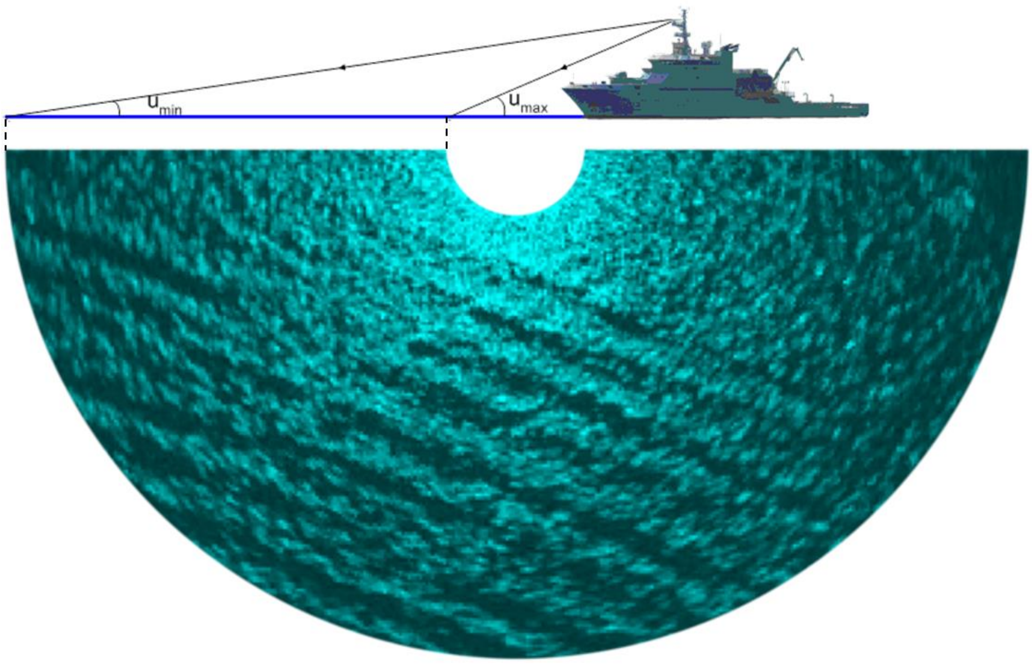

Fig.1: Imaging radar

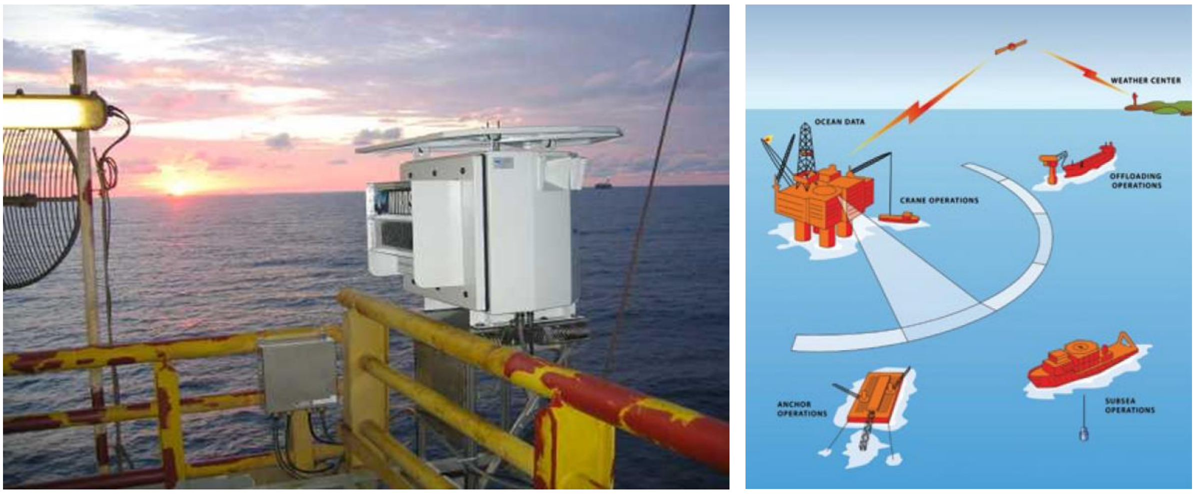

Fig.2: Microwave Doppler radar providing wave and surface current data

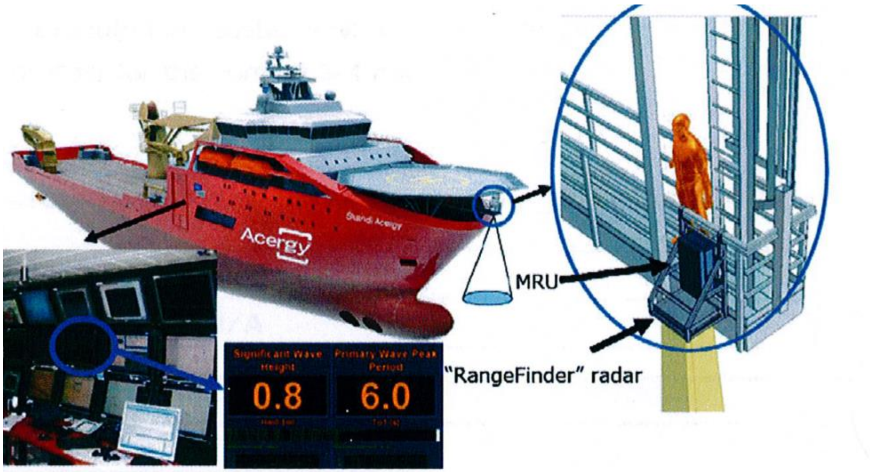

Fig.3: Example of vertical microwave radar in combination with an MRU

In the rest of this paper, we shall focus on a system based on imaging X-band radar that can provide reliable wave and current measurements from moving vessels during transit, as well as the STW. The system is type approved by DNV GL.

2. Measurement principle for system based on imaging X-band radar

Raw radar images are acquired from a marine navigation X-band radar and digitized by DNV GL type approved hardware especially developed for this application, Fig.4. Digitized images can also be acquired directly from radars with digital data feed, commonly known as IP (Internet Protocol) radars, eliminating the need for additional digitalization hardware.

In the context of wave and current measurement by radar, signals refer to gravity wave patterns visible to the radar, given the radar's spatial resolution in range and azimuth. To obtain optimum performance, an unfiltered signal from a radar operating in short pulse mode is required. In addition, a wind speed of at least 2-3 m/s is required to get sufficient electromagnetic backscatter from the ocean surface, *Skolnik (1980)*.

Measurement areas called Cartesian image sections, Fig.5, defined through system software configuration, are extracted from the digitized radar images and processed by dedicated algorithms. This provides the user with real-time wave spectra, as well as integrated wave parameters and surface current vectors. The measurement area can be changed by software reconfiguration at any time.

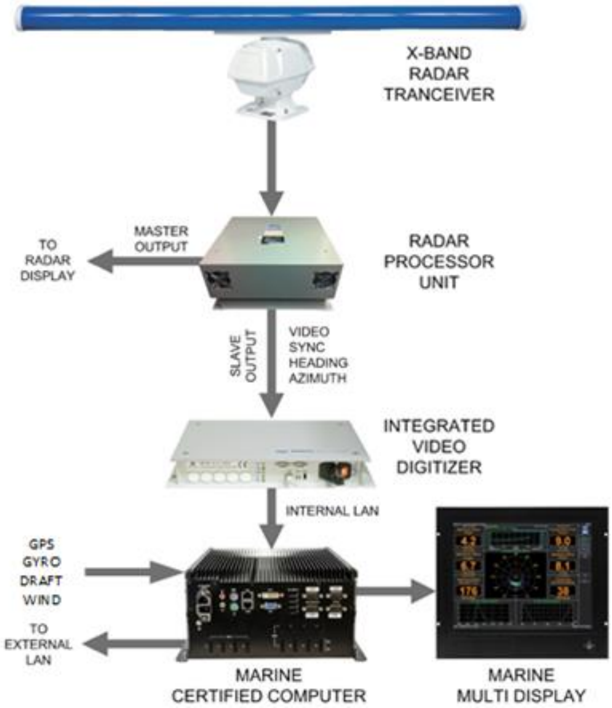

Fig.4: Schematic diagram of system based on imaging X-band radar

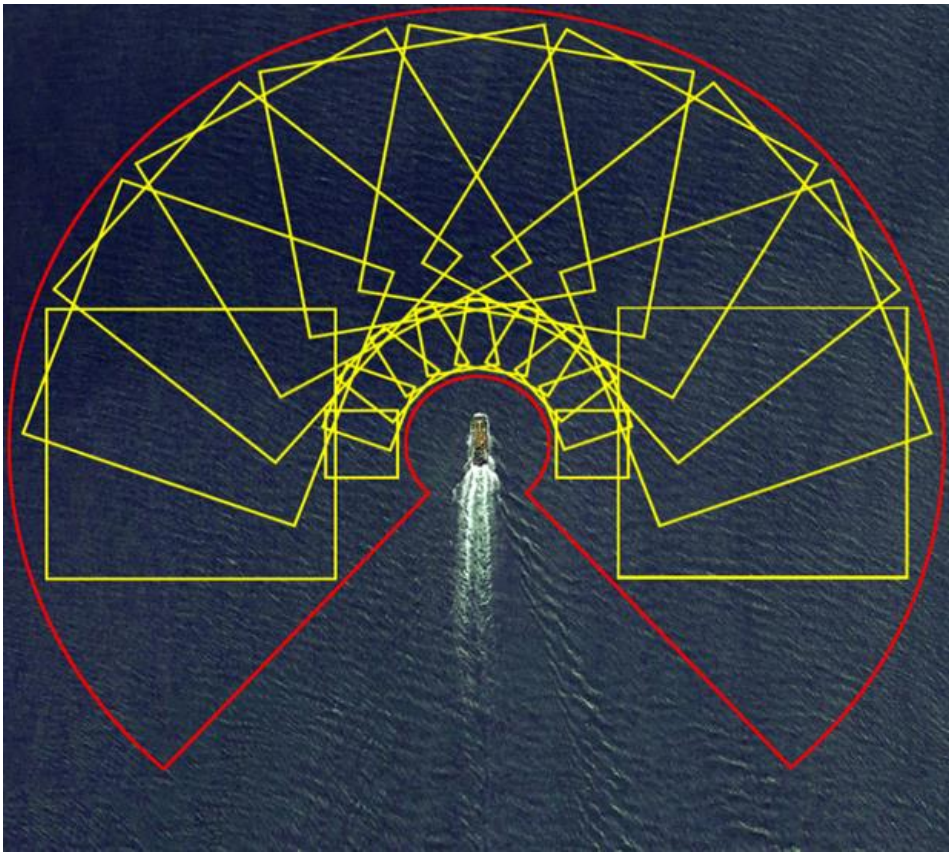
Fig.5: Illustration of how Cartesian image sections are extracted from polar radar image

3-D fast Fourier transforms (FFTs) are applied to time series of Cartesian images, giving 3-D spectra with information about the power present at various wavenumbers and frequencies, *Young et al. (1985)*. Ocean image spectra are obtained from these wavenumber-frequency spectra by integrating over frequency. Various sorts of noise filtering are also applied. The dispersion filtering, for instance, is based on knowledge about the relation between wavenumbers and frequencies, as explained below.

A transfer function is applied to the image spectrum to obtain a calibrated directional wave height spectrum. The transfer function is relatively complex, relying on several fundamental sub-methods, ensuring that the final wave height spectrum correctly describes the actual ocean surface, both with respect to shape and scaling. Integrated wave parameters are calculated from the calibrated wave height spectrum.

Ocean surface currents are estimated from the wavenumber-frequency spectra obtained by 3-D FFTs using a novel method recently developed by Miros. The method is, as previously known methods, based on our already existing knowledge about the relation between wavenumbers and frequencies of ocean gravity waves for zero current, i.e. the dispersion relation, *Pond et al. (1983)*:

$$\omega_0^2 = g\left|\vec{k}\right| \tanh\left(\left|\vec{k}\right| d\right)$$

where ω_0 is the wave frequency, $\vec{k}$ is the wavenumber vector, d is the water depth, and g is the gravity of Earth. If there is a surface current $\vec{U}$ relative to the radar, a Doppler frequency shift is introduced in the wave frequency:

$$\omega = \omega_0 + \vec{k} \cdot \vec{U}$$

This Doppler shift causes the energy in the 3-D spectra frequency planes to be located on ellipses, rather than circles. Based on the power distribution in the wavenumber-frequency spectra, the current vector can be estimated.

Miros has recently developed further improvements to the method used for estimating ocean surface currents from X-band radar images. This includes an improved method utilizing the full power distribution properties, improved motion compensation, as well as several improvements increasing performance under conditions with high current speeds and low signal-to-noise ratios. The method also includes various functionalities to automatically detect and tag data with respect to quality.

Based on kinematic data and the measured surface current, the STW can be calculated, Alternatively, the STW can be directly estimated from the radar images because they already contain sufficient information to directly determine the relative motion between the vessel and the water.

3. Data examples

Calibrated directional wave spectra and integrated wave parameters can be presented in many ways. Fig.6 shows one possibility, with the directional wave spectrum, integrated wave spectra with respect to direction and frequency, and some of the corresponding parameters for wave height, period and direction.

During the recent years, large amounts of data from the system have been acquired from various sites and geometries, using various radar types. For wave measurements, four principal test sites have made the basis for testing and verifying the system reliability and accuracy, *Gangeskar (2017)*. Data have been acquired for months at each of these sites, both from imaging X-band radar systems and reliable reference sensors. For convenience, some previous results are also provided here.

The four principal test sites, Fig.7, span a wide range of properties relevant for the measurements, Table I. Time series and scatter plots of the significant wave height look reasonable, Fig.8, Fig.9, and the statistics show that RMS deviations are well within 0.5 m and correlations close to unity for all sites, also without performing any sort of site-specific calibration, Table II. All available data are used in the studies, apart from data automatically tagged by built-in data quality controls relying on the signal-to-noise ratio and other parameters deduced from the data.

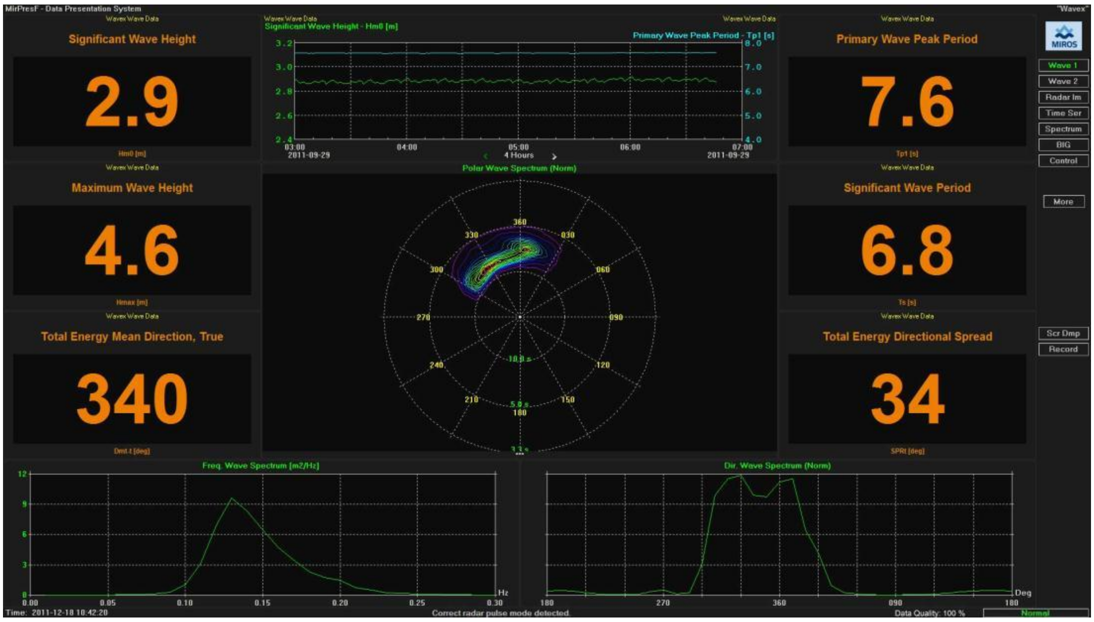

Fig.6: Presentation of calibrated directional wave spectra and integrated wave parameters

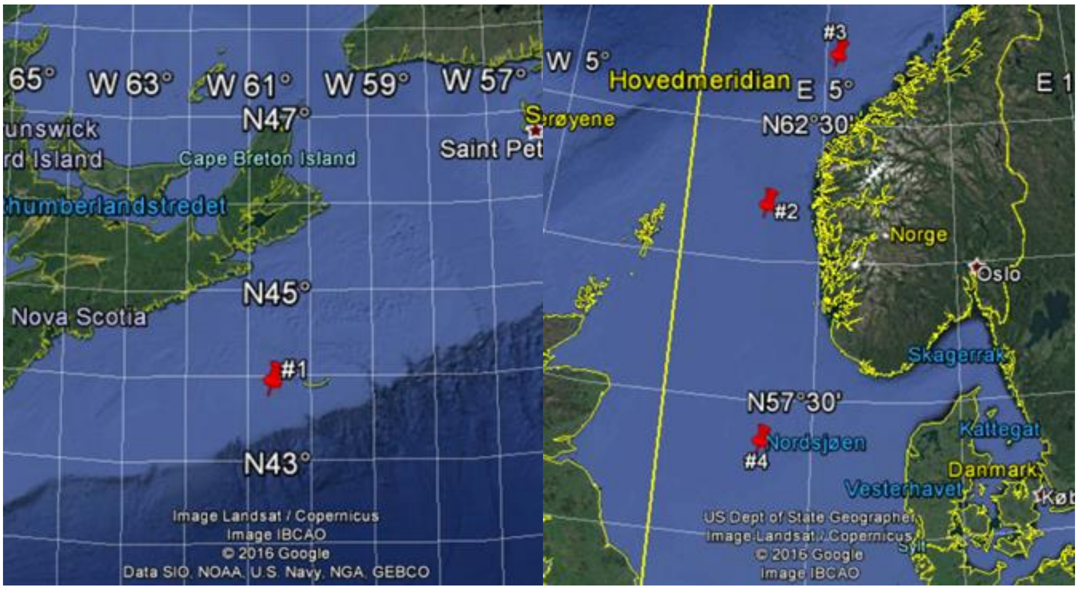

Fig.7: Four principal test sites indicated in Google Earth

Table I: Essential parameters related to four principal test sites

	#1 Deep Panuke (fixed)	#2 North Sea (fixed)	#3 West Navigator (moving)	#4 Ekofisk (fixed)
Radar brand	Furuno FAR 2117	Sperry Bridge-master II	Sperry Bridge-master II	Terma Scanter 5202
Antenna height	26.0 m	43.5 m	23.0 m	92.0 m
Antenna length	6.5 ft	4 ft	6 ft	12 ft
Antenna rotation speed	42 rpm	29 rpm	29 rpm	18 rpm
Range resolution in short pulse mode	10.5 m	7.5 m	7.5 m	3.0 m
Water depth	45 m	185 m	850-1100 m	70 m
Reference, at distance	Buoy, < 5 km	RangeFinder, < 1 km	Buoy, < 1 km	RangeFinder, 7 km

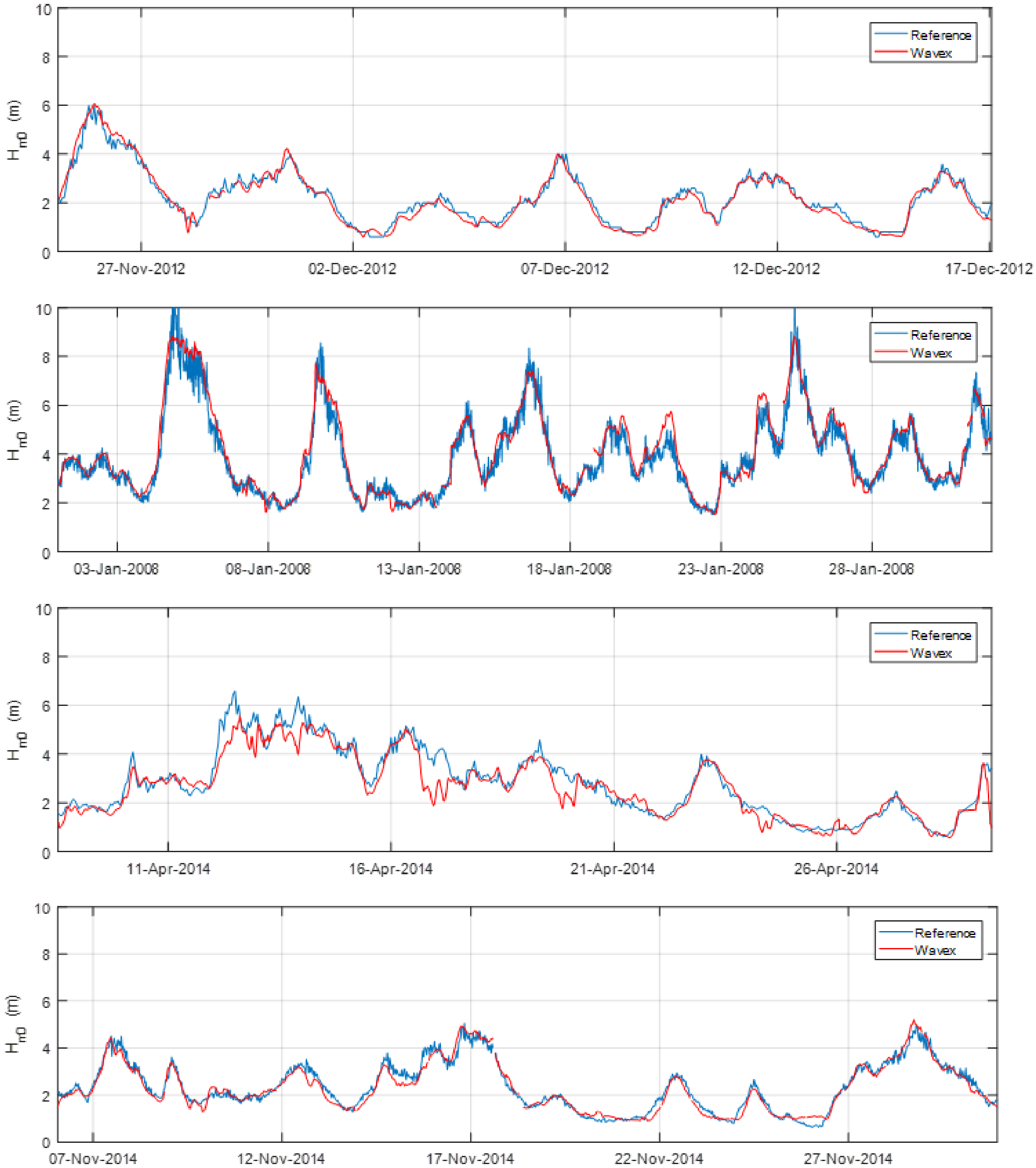

Fig.8: Time series from sites #1 - #4 (#1 on top), comparing significant wave height H_{m0} from imaging radar system and references

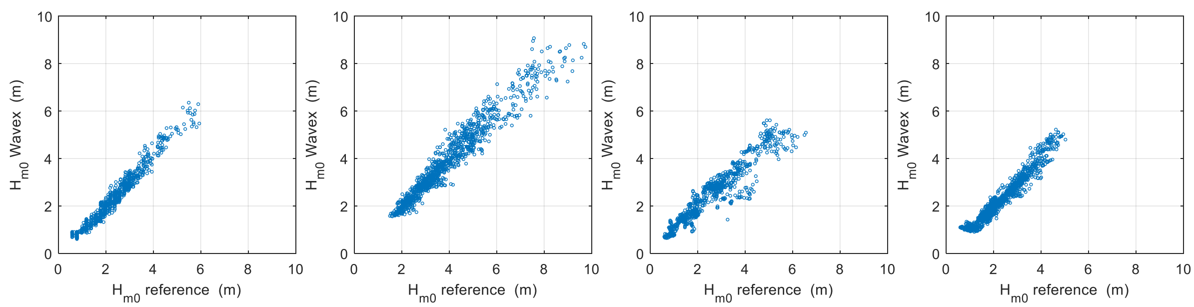

Fig.9: Scatter plots from sites #1 - #4 (#1 to the left), comparing Hm0 from imaging radar system and references. Data are decimated to improve the readability

Table II: Statistics of performance: Correlation, mean deviation, and RMS deviation between significant wave height H_{m0} from imaging radar system and references. Numbers in parenthesis represent statistics after performing site-specific calibration.

	#1 Deep Panuke	#2 North Sea	#3 West Navigator	#4 Ekofisk
Correlation	0.98 (0.98)	0.97 (0.97)	0.94 (0.94)	0.97 (0.97)
Mean deviation (m)	0.04 (0.00)	0.15 (0.00)	0.19 (0.00)	0.13 (0.00)
RMS deviation (m)	0.22 (0.19)	0.42 (0.38)	0.50 (0.46)	0.26 (0.22)

The reference sensors are based on measurement principles very different from the imaging radar system. This also includes spatial and temporal averaging strategies used in the sensors, implying that some differences must be expected due to the statistical properties of the ocean surface itself. Furthermore, the exact accuracy of the reference sensors is not known.

Imaging radar systems can also provide reliable surface current measurements. Recent field trials have shown that a high accuracy can be obtained from both fixed sites and moving installations, *Gangeskar (2018)*. Fig.10 shows a period of data acquired at the Ekofisk platform in the southern part of the North Sea. RMS measurement errors of 0.032 m/s and 9.1° for magnitude and direction, respectively, were estimated based on the entire trial during November and December 2015, as well as correlation coefficients of 0.93 and 0.94 for East-West and North-South current components, respectively, *Gangeskar (2018)*.

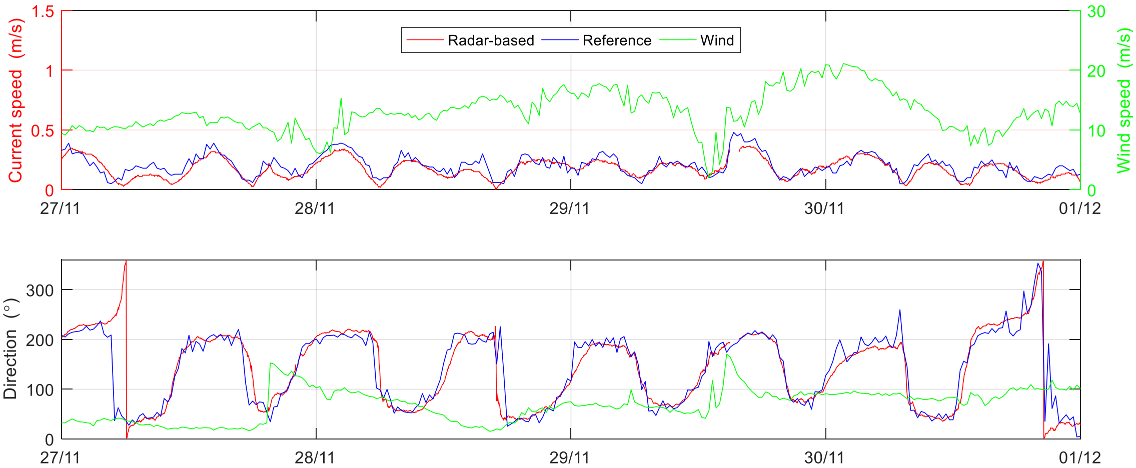

Fig.10: Time series of surface current and wind data from Ekofisk, comparing imaging radar system and reference Aquadopp

Convincing surface current measurements have also been obtained from moving vessels, and this also makes the basis for accurate STW measurements by imaging radar systems, avoiding challenges and noise associated with traditional underwater instrumentation, as discussed above. Fig.11 - Fig.13 show examples of STW data from an imaging X-band radar system installed at the Norwegian research vessel G.O. Sars. Data were acquired during a sea trial in the Norwegian Sea and the Barents Sea in November 2016, in close cooperation with the Institute of Marine Research (IMR) in Norway. In Fig.11, the vessel is moving back and forth, as can be seen from the direction (red). Data are rather smooth and in accordance with our expectations based on how the vessel was maneuvered. In Fig.12, the vessel is alternately moving and at rest to perform various experiments. Data still look reasonable and smooth. Direction estimates are less stable only when the magnitude is close to zero, which is, of course, as expected. The oscillatory changes in direction during the first period with magnitude close to zero are, however, related to actual small movements as the vessel was kept on an approximate constant position. Fig.13 shows another period in which the vessel is in transit along the Norwegian coast, occasionally changing the course.

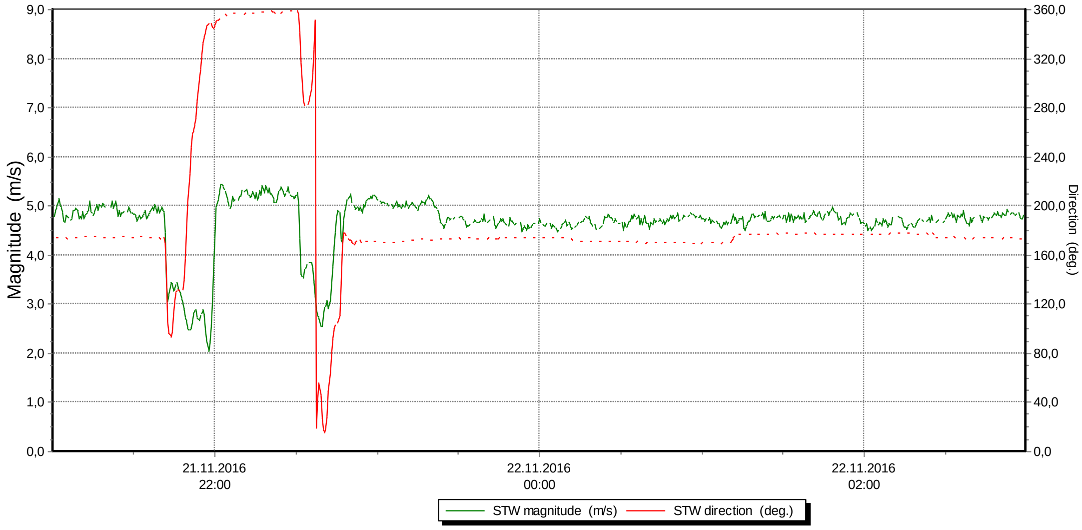

Fig.11: STW data from imaging radar system. Vessel is travelling back and forth during a sea trial

Fig.12: STW data from imaging radar system. Vessel is alternately moving and at rest to perform various experiments during a sea trial

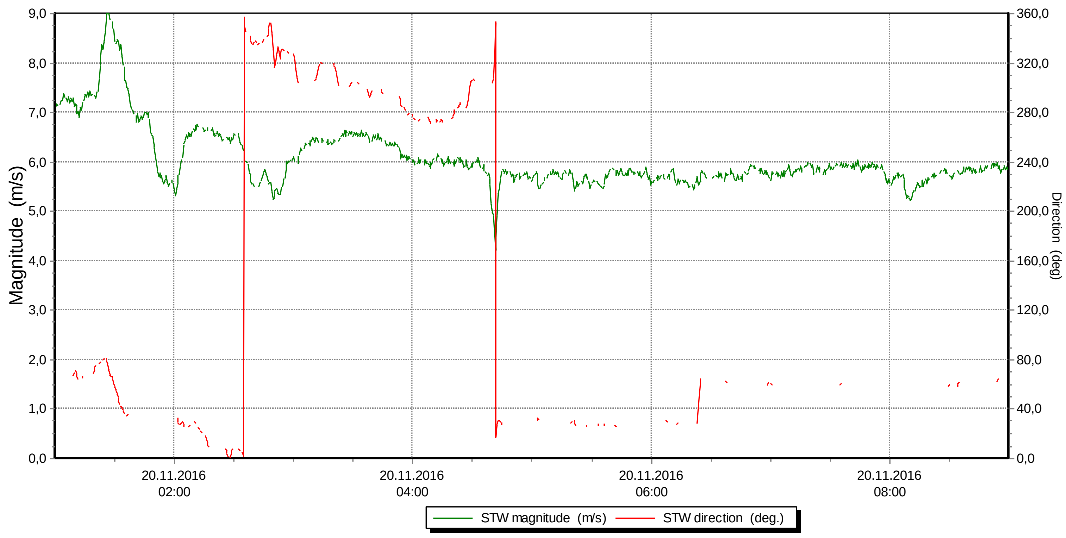

Fig.13: STW data from imaging radar system. Vessel is in transit along the Norwegian coast, changing the course from time to time

4. Conclusion

Information about ocean waves, surface currents, and the Speed Through Water can be of great value to applications such as fuel optimization, hull stress monitoring, and systems improving cargo safety and passenger comfort. Thanks to considerable work and progress within the field of radar remote sensing during the recent decades, such ocean surface measurements can now be performed with a high reliability and accuracy using radar sensors. Hence, challenges like data heavily influenced by noise and costs related to installing and maintaining traditional underwater equipment can be avoided. By means of radar remote sensing techniques, the user can measure the current in the water of interest, sufficiently far away from structures and the chaotic conditions close to a vessel hull that would otherwise disturb the measurements.

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