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Distributing Real-Time Measurements of Speed Through Water from Ship to Shore

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Abstract

This paper describes how latest generation radar-based remote sensing solutions give high-quality information about ocean wave parameters such was wave heights, directions and periods, surface current magnitude and direction and ship Speed Through Water (STW). Combining the sensing technology with Internet-of-Things technologies allows making accurate sea state data available in real-time both onboard and onshore. This enables significant improvements in such applications as hull fouling estimation and speed optimization. This paper will present such a solution in detail together with some examples from testing on vessels.

1. Introduction

The shipping industry is currently undergoing a transformation due to digitalization. A strong focus on cost of operations, operational efficiency and on the environmental aspects associated with shipping are some of the main driving forces behind this development.

Situational awareness is a necessary ingredient in the digitalization process. One area that has seen considerable 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, *Gangeskar (2017,2018a,2019), Gangeskar et al. (2018).* State-of-the-art radar-based sea state measurements can measure both ocean waves and ocean currents accurately under widely varying conditions and with high availability, reliability and accuracy.

Sea state has a significant impact on ship performance. This holds true for both ocean waves and ocean currents. There are intricate relationships between waves and ship performance requiring advanced models that take into account such factors as 3D hull properties and loading conditions. The situation is somewhat simpler when it comes to ocean currents. Currents coming against the direction of ship motion means that more water needs to be displaced per time unit compared to a situation with no current. Similarly, currents travelling in the direction of ship motion means that less water needs to be displaced per time unit. Hence, the current component going in the direction parallel or antiparallel to the vessel heading has a major influence on vessel performance. Currents travelling perpendicular to the ship motion might also lead to a need to spend energy to counter the forces inflicted by the currents. Thus, the presence of ocean currents has a profound influence on the performance of the vessel.

The Speed Through Water (STW) parameter is the vessel speed with respect to the water. STW is equal to the Speed Over Ground (SOG) when there is no ocean current present. SOG is easily measured by means of a GPS receiver. STW, however, has not been easily measured in an accurate and reliable way until now, *Gangeskar (2019).*

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 speed through water (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).*

A vessel has an optimal speed which in simple terms depends on the speed vs. fuel relationship of the vessel and the efficiency characteristics of the propulsion configuration (e.g. the propellers). Ocean currents of up to several knots can exist on the oceans which means STW might be quite different from SOG. It is therefore STW and not SOG that should be used as the basis for vessel performance calculations, i.e. how fast is the vessel moving with a given supply of fuel. Thus, STW is a very important parameter in ship performance optimization.

There are several vessel applications that will benefit from accurate STW measurements. Hull performance is often analyzed by investigating the amount of fuel consumed at a given speed. Hull fouling will lead to increased friction and thus increased fuel consumption at a specific speed. This is typically based on SOG measurements from a GPS or heavily filtered STW measurements from underwater sensors. Hull cleaning can be a very expensive process and thus it is important to estimate the actual hull condition as accurately as possible. Thus, accurate STW measurements can be used to improve planning of hull cleaning or to investigate the effectiveness of hull cleaning procedures or hull coatings. Related use cases might be related to performance degradation of parts of the drivetrain, e.g. the propellers.

While hull performance estimations can be made in retrospect with historical data of medium to low time resolution, there is another very important application that benefits from having access to real-time STW measurements. A vessel has an optimal speed where the fuel consumption is the lowest. The optimal speed is measured relative to the water, i.e. accurate STW measurements are required. Whenever possible, there is a significant potential for fuel savings by making sure that the vessel STW is optimal. The fuel savings potential can range up to tens of tons per day for large vessels in areas with currents of 1-2 knots. Due to the accuracies required, it is in most cases not feasible to rely on theoretical models of surface current. The actual speed optimization can be done either manually by the crew or automatically by an autopilot system.

Traditionally, speed control or autopilot systems have been based on GPS input as the STW sensors have not been reliable enough. With the recent STW solution from Miros it is now possible to have access to STW measurements that are reliable and accurate enough to be used in real time for speed optimization, *Gangeskar (2018,2019),* https://www.miros-group.com/wp-content/uploads/2017/11/Wavex-v5.7-Datasheet.pdf.

Traditionally, information from sensors and automation systems onboard ships have been available mainly for local use by various onboard systems and users. Remote connections have been limited in bandwidth and functionality, complex to install, manage and use and connected to highly proprietary platforms with limited usability for end customers. This no longer needs to be the case. An abundance of cloud platforms, modern communication technologies and Internet-of-Things solutions makes it considerably easier to build end-to-end solutions that are cost-efficient and easy to use. A powerful example of such a technology platform is Microsoft Azure, which offers a very wide set of services and functions to enable seamless integration of sensors, data handling, processing, visualization and distribution, both locally (i.e. on the Edge) and remotely (i.e. in the Cloud). Particularly, the strong combination of Edge and Cloud computing, often referred to as hybrid computing, means that Microsoft Azure is a very attractive platform to build applications related to the Internet-of-Things and digitalization.

In the rest of this paper, we shall focus on describing the system based on imaging X-band radar that can provide reliable STW measurements. Furthermore, the results from a verification study onboard a vessel will be presented in detail. Finally, the integration aspects will be discussed with focus on how modern IoT technologies can simplify the distribution of STW data from ship to shore.

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

Wavex provides current measurements with high accuracy, *Gangeskar (2018a,b,c)*. Measuring the STW has much in common with measuring currents, and the two measurements are generally based on the same physical principles. The major difference is what the measured water speed is referred to: the vessel when measuring the STW, and a fixed position when measuring currents.

The vessel's velocity through water and current velocity are related through:

$$\vec{v}_{STW} = \vec{v}_{SOG} - \vec{U}, \quad (1)$$

where $\vec{v}_{SOG}$ is the vessel's velocity over ground. Therefore, obtaining reliable current measurements implies that also STW measurements will be reliable, as they are related to each other (at the same depth) through the speed over ground (SOG), which can easily be extracted from GPS data.

Fig.1 shows the basic components in a Wavex system on a moving vessel. Specialized, DNV type approved hardware is connected to the analog video signal output from a marine navigation X-band radar. This hardware digitizes the analog radar video and outputs a radar image timeseries. Each radar image includes a sector covering the STW measurement area.

Digitized images can also be acquired directly from radars with digital data output, commonly known as IP (Internet Protocol) radars. This eliminates the need for additional digitalization hardware.

The Wavex system requires certain radar image meta-data from a GPS and a gyro compass.

To provide STW estimates, all required data are collected, synchronized and processed on the system computer.

Optimum STW measurement performance requires radar images with sufficient spatial resolution. The radar's range resolution is determined by the radar pulse width, and the azimuth resolution is determined by the radar antenna beamwidth. For optimal accuracy, the radar should be operated in short pulse mode. (If a solid-state X-band radar, utilizing pulse compression techniques, is used, the spatial resolution in the STW measure area can be sufficient without compromising the radars navigation performance.) In addition, a wind speed of at least 2 – 3 m/s is required. At this wind speed, the sea surface gets sufficiently rough to create sufficient electromagnetic backscatter, *Skolnik (1980)*. Gravity waves modulate the ocean surface backscatter. A radar image with a clearly visible wave pattern is shown in Fig.2.

Wavex bases its measurements on radar images covering local areas of interest, in a reasonable distance from any disturbing structures, including the vessel hull. Fig.3 shows how the STW measure areas are extracted from the radar images. The measure areas are called Cartesian image sections and are defined during system commissioning through software configuration. Dedicated algorithms process these images to provide the user with real-time STW data. The measure areas can be changed by software reconfiguration at any time.

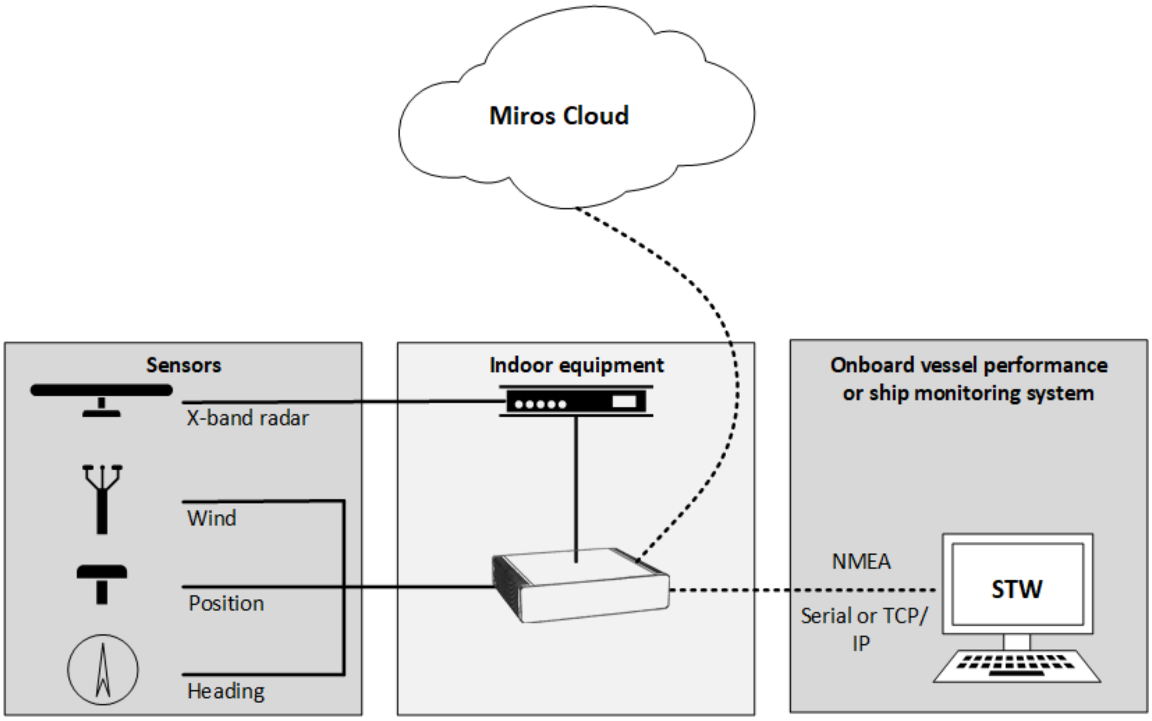

Fig.1: Schematic diagram of system based on imaging X-band radar

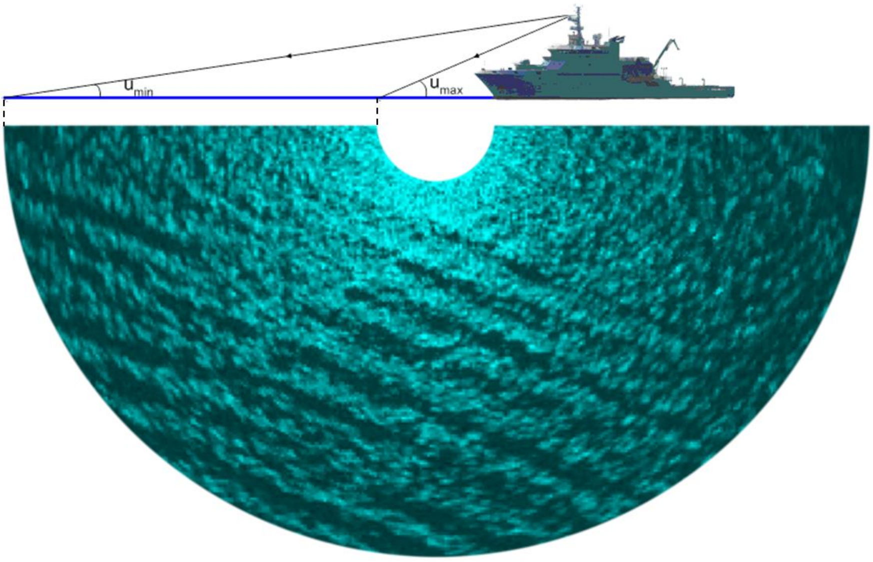

Fig.2: Imaging radar

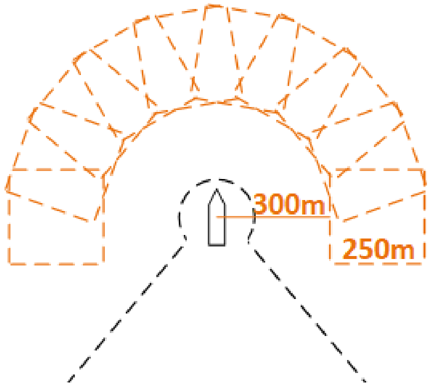

Fig.3: How Cartesian image sections for STW estimates are extracted from a radar image.

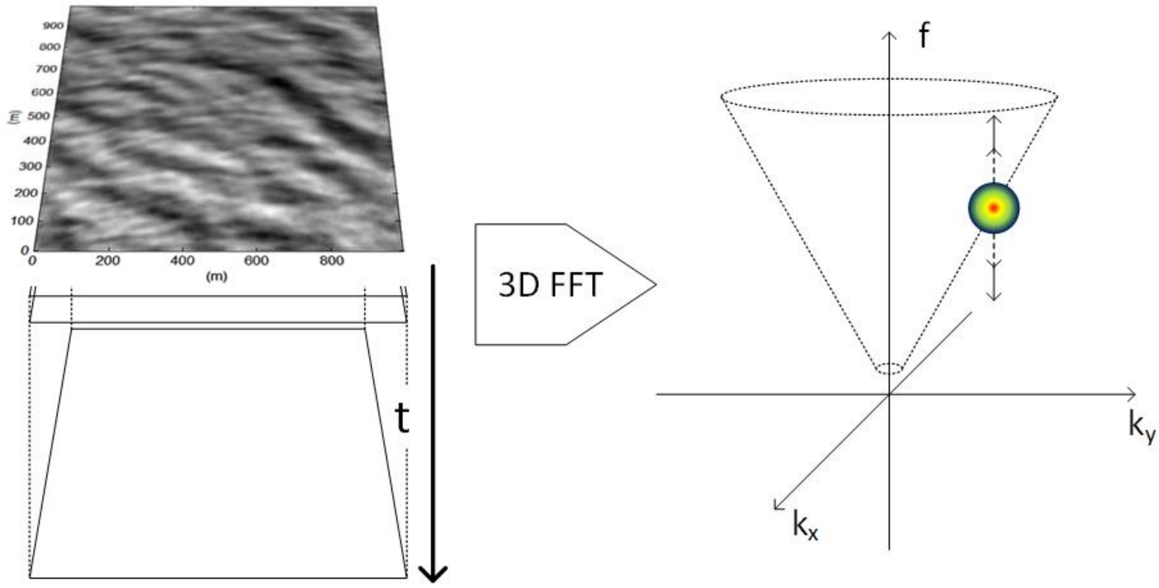

Fig.4: Cartesian image section time series are transformed into a wavenumber-frequency spectrum.

Fig.4 illustrates how 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)*. Various sorts of noise filtering are applied before STW is estimated from the wavenumber-frequency spectra using an improved method 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)*:

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

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:

$$\omega = \omega_0 + \vec{k} \cdot \vec{U} \quad (3)$$

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.

3. Pilot verification of speed through water functionality at Arctic Lady

A number of Wavex pilot systems have been installed on various vessels using various sorts of X-band radars. The system reliability and the accuracy of radar-based STW measurements have been examined and verified by comparing with theoretical models and standard speed logs over large geographical areas in a wide range of weather conditions and sea states.

3.1. Data acquisition

The following examples, based on data acquired from the LNG carrier Arctic Lady, were published in *Gangeskar (2019)* in agreement with the vessel's owner Höegh LNG. With help from the crew, months of data were made available from their travels between Hammerfest in Norway and Marseilles in France. In addition to Wavex measurements, simultaneous data were acquired from the on-board acoustic speed log, from the Norshelf model by the Norwegian Meteorological Institute, and from the Irish Marine Institute Northeast Atlantic Model. Fig.5 shows the route during a period of simultaneous data from all sources, from September 15 to October 31.

The **acoustic speed log** on Arctic Lady is a JLN-550 Doppler Sonar (SDME) provided by JRC, http://www.jrc.co.jp/eng/product/lineup/jln550/pdf/JLN-550.pdf, which is an advanced and widely used instrument for measuring the STW from vessels. It is a two-axis, four-beam pulse Doppler Sonar with optional rate of turn gyro, operating at 2 MHz (for water tracking), measuring a few meters below the hull bottom. Information about the STW longitudinal component is obtained via the VBW (dual ground/water speed) NMEA string. This is the STW component parallel to the vessel heading, with positive values when the vessel moves forward relative to the water.

The **Norshelf model**, *Röhrs et al. (2018)*, provides ocean current data for the Norwegian Shelf Sea. The model has been set up at the Norwegian Meteorological Institute (MET) and includes the Skagerak in the southeast, the northern parts of the North Sea, the shelf sea off western Norway including the shelf slope, and parts of the Barents Sea in the north, that is, a considerable part of section 1 of the route, Fig.5. The model provides data at a horizontal resolution of 2.4 km at a temporal resolution of 1 hour. Data are available from MET Norway Thredds Service, http://thredds.met.no/thredds/fou-hi/norshelf.html, in NetCDF files. Model data representing 5 m depth were chosen because this is close to the effective measurement depth of the radar-based system.

The dataset **Irish Marine Institute Northeast Atlantic Model** provides surface current vectors for the Irish waters in the northeast Atlantic, *Dabrowski et al. (2016)*, that is, a considerable part of section 2 of the route, Fig.5. The ROMS hydrodynamic model (Regional Ocean Modeling System) uses a mean horizontal resolution of 1.9 km and provides data at a temporal resolution of 1 hour. Data for the last week are available via Thredds and ERDDAP servers in various formats, https://erddap.marine.ie/erddap/griddap/IMI_NEATL.html. Older data were ordered from and delivered directly by the data steward at the Irish Marine Institute in Matlab format.

3.2. Statistics and time series

Current data from the models were extracted at times and positions of interest, indicated by the route in Fig.5, using time and position data from the vessel and linear interpolation. This is partly similar to what was done in *Gangeskar (2018a)* when defining a dynamic tidal model following the vessel's route. As already stated above, the accuracy of STW measurements is closely linked to the accuracy of current measurements, defined by (1). Hence, for convenience, as the models and the Wavex system already provides current data, we chose to consider current values as the basis for statistical measures (Table I). The STW longitudinal component output from the speed log was simply converted to the current longitudinal component using (1).

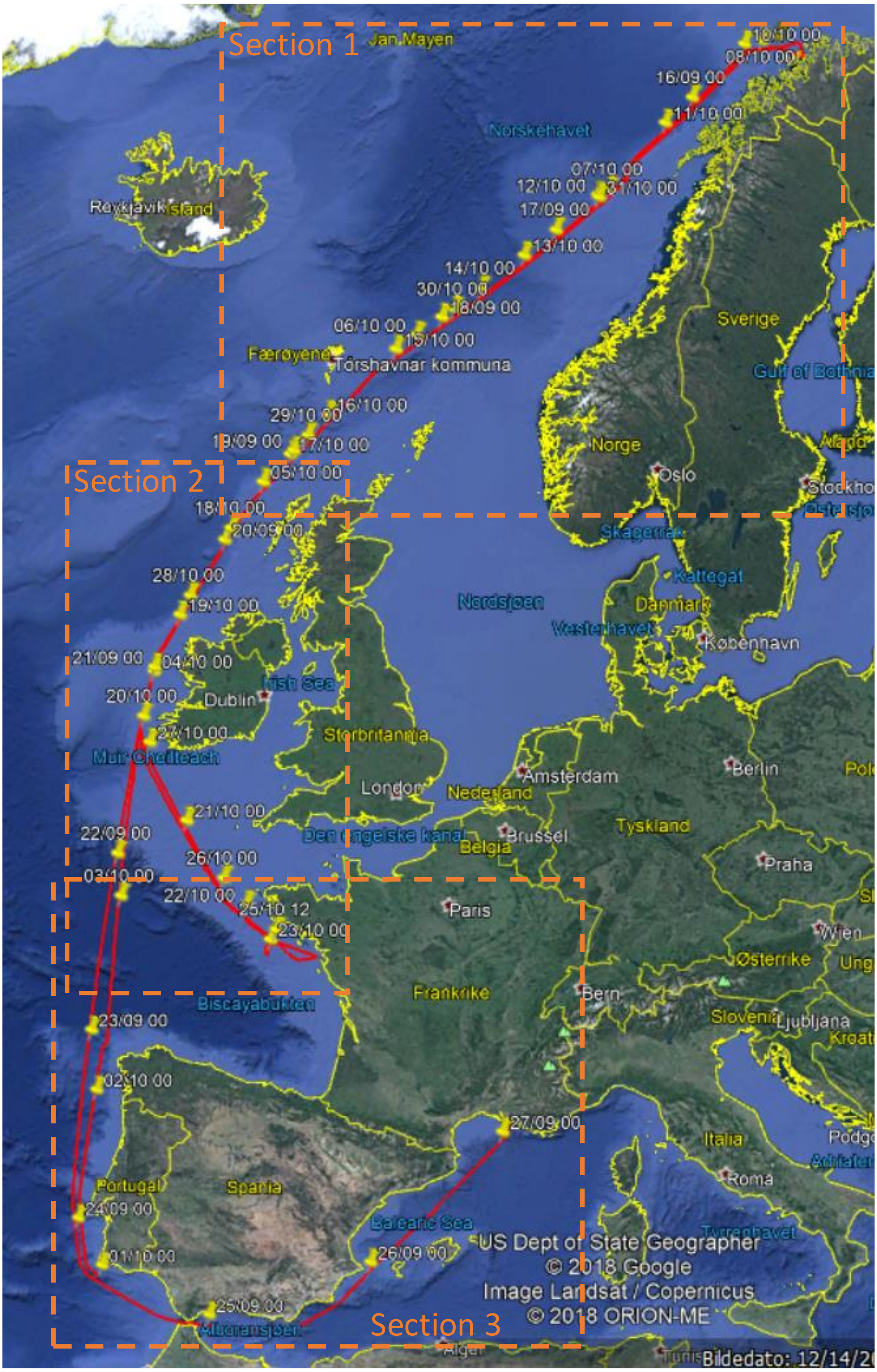

Fig.5: Route from September 15, 2018 to October 31, 2018, indicated by red lines in Google Earth

In order to compensate for different averaging strategies, to make statistical comparison more balanced, to smooth out any minor temporal offsets between various data sources, and to make measured data more comparable to model data, an additional temporal averaging of measured data was performed before calculating statistics. For this purpose, a 40-min centered average filter was applied to the time series. Mean and root-mean-square (RMS) deviations between individual data sources were calculated.

Fig.6 provides an overview of longitudinal current components and STW during the entire route shown in Fig.5. No additional averaging is applied to these data. Data are missing in three periods because most of the measurement systems were turned off when the vessel was at rest in Hammerfest (Norway), Marseilles (France), and Saint-Nazaire (France). Apart from these periods, the data capture is complete. The rate of defined STW data from the Wavex system is 99.94 % during the periods with available radar images. In the following, we will look further into the details for a couple of shorter periods.

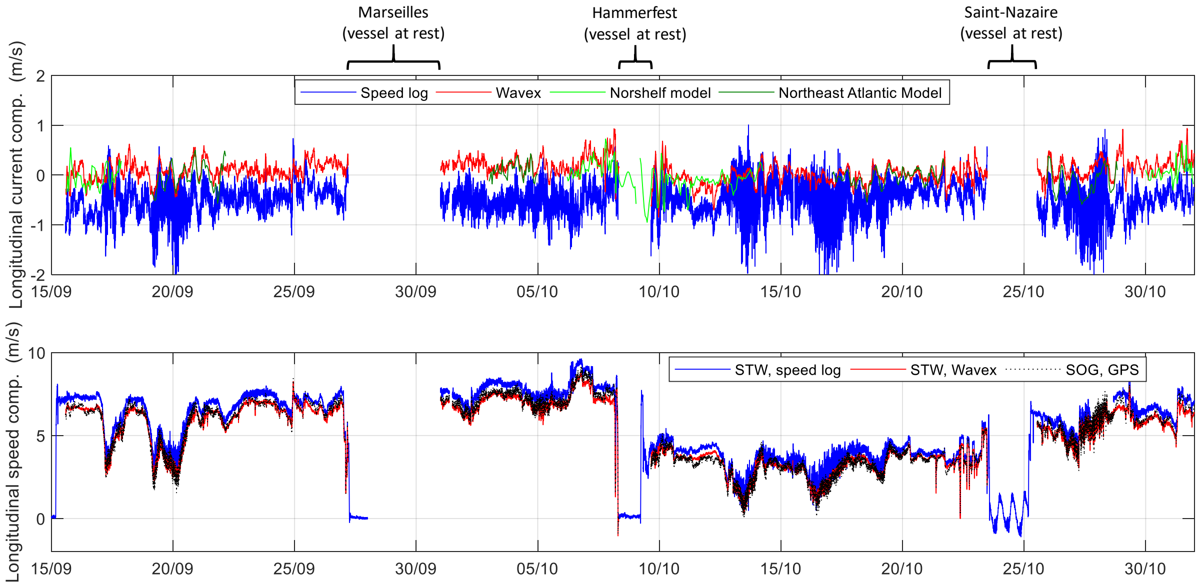

Fig.6: Overview of longitudinal current components and STW during the entire route shown in Fig.5 No additional averaging.

Table I: Deviations between longitudinal current components from radar-based system, speed log, and models, based on all available data

	Radar-based vs.		Speed log vs.		Radar-based vs. speed log
	Norshelf model	Northeast Atlantic Model	Norshelf model	Northeast Atlantic Model	
Offset (m/s)	-0.08	-0.11	0.49	0.46	-0.56
RMS dev. (m/s)	0.24	0.20	0.55	0.49	0.59

Fig.7 shows five days of current and wind data from a period covered by the Northeast Atlantic Model. The wind speed varies from 0 to 15 m/s, and the surface current in the area is dominated by the tidal contribution, making it easy to visually observe the agreement between model data and measurements. Currents in this area are more homogeneous and stable, with less eddies and stronger tidal dominance, than for instance in the region covered by the Norshelf model. This may make this model more accurate, and it makes comparison easier, because different averaging strategies and possible remaining temporal and spatial offsets will make less influence on the results. Table I (based on all available data) shows that measurements agree slightly better with the Northeast Atlantic Model than with the Norshelf model.

Fig.8 shows the longitudinal current component and the STW during the same period, without any additional averaging. It is evident that the radar-based system produces considerably smoother data than the speed log. The reason for the varying amount of noise observed in speed log data is not known. It is also clear that the speed log measurements are systematically erroneous, with an offset of approximately 0.5 m/s. This can also be observed from the statistics in Table I (despite additional averaging before calculating statistics), in which data from the radar-based measurements are considerably more consistent with model data (comparing green and red columns). Current magnitudes in the range 0–0.5 m/s are expected in this region and period. In the context of fuel optimization, the observed offset in speed log data could mean an additional fuel cost corresponding to tens of tons of fuel a day for one ship.

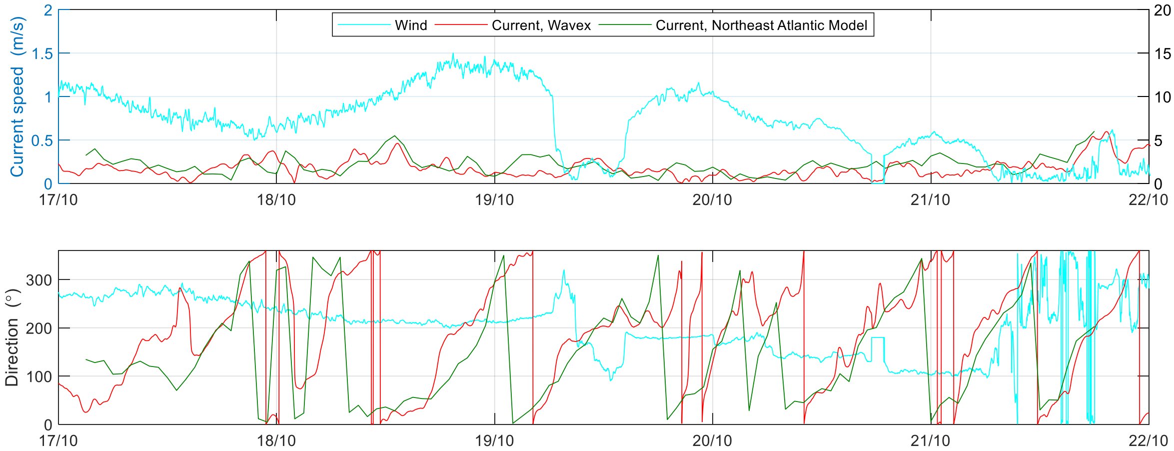

Fig.7: Time series of current and wind data from Arctic Lady, during a period covered by the Northeast Atlantic Model; radar-based compared to Northeast Atlantic Model.

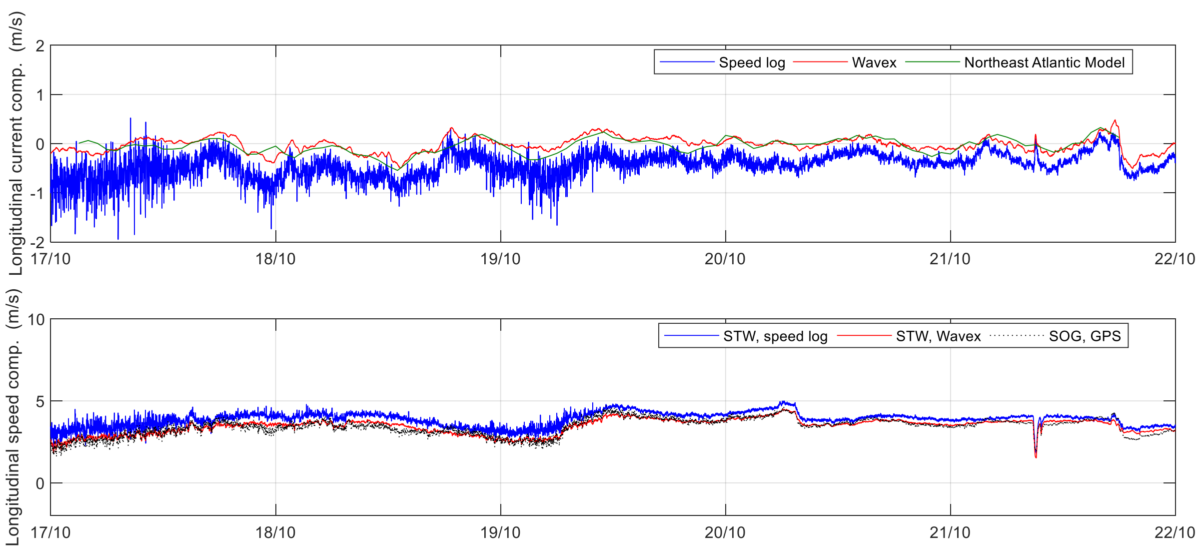

Fig.8: Time series of longitudinal current components and speeds, during a period covered by the Northeast Atlantic Model; radar-based compared to Northeast Atlantic Model, speed log, and GPS (partly covered by radar-based). No additional averaging.

Fig.9 shows the longitudinal current component and the STW during a period covered by the Norshelf model, without any additional averaging. The wind speed varies from 1 to 19 m/s. Less homogeneous currents and more local eddies, combined with different averaging strategies, make comparison more difficult, because both model data and measurements vary relatively quickly with position and time. Still, clearly the radar-based system produces considerably smoother data than the speed log; the speed log data are influenced by an offset-like error, though the covariance between the two sensors looks relatively consistent. Current magnitudes in the range 0–0.5 m/s are expected in this region and period.

Some possible explanations for observed deviations between various data sources are:

- differences in spatial and temporal averaging strategies;
- differences in effective measurement depth;
- minor temporal offsets between various data sources;
- inaccurate environmental data input to models;
- finite resolution and accuracy in models;
- measurement errors in sensors.

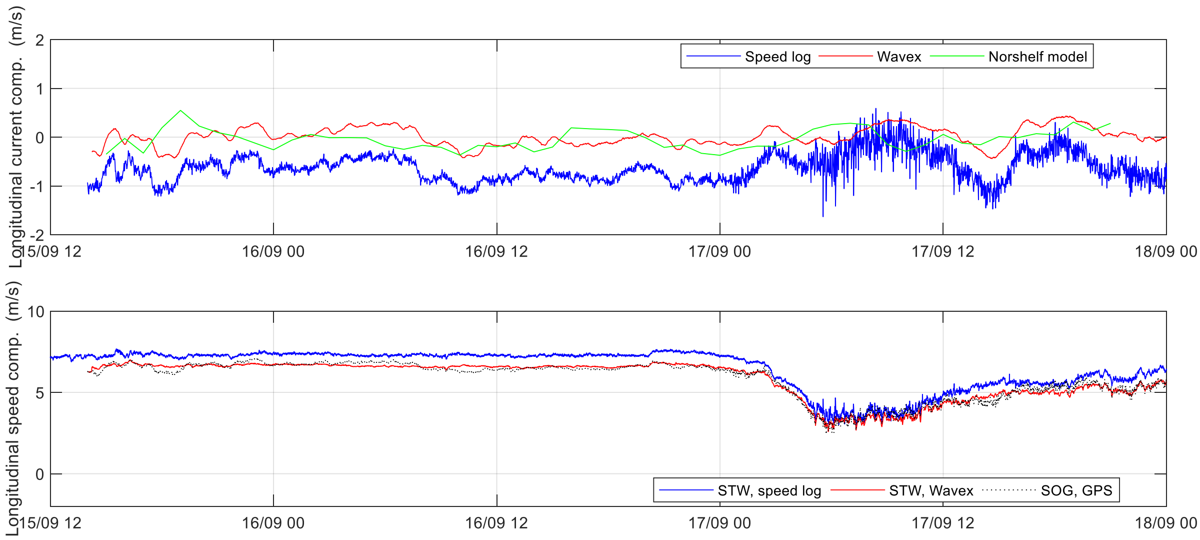

Fig.9: Time series of longitudinal current components and speeds, during a period covered by the Norshelf model; radar-based compared to Norshelf model, speed log, and GPS. No additional averaging.

4. Making STW data available onboard and onshore

Easy access to vast amounts of data from a multitude of sources is currently driving a wave of innovation that impacts how vessels are designed, built, operated and maintained. Processes that used to be largely based on manual observations and retrospective analysis based on incomplete data sets can now be improved and automated with the access to detailed, reliable and accurate data. Modern technologies make sure that the information can be made available both on the vessel and onshore and thus enables a wide range of improvements.

In order to support the various application use cases mentioned above, *Gangeskar (2019)*, there is a need to have a flexible solution that allows easy access to the STW data both onboard the vessel and onshore. The onboard requirement is particularly related to real-time usage for speed optimization. The onshore requirement is related to hull and propeller performance estimations and the optimization of hull cleaning activities. In addition, there are use cases for fleet management, including comparing and optimizing vessel fleets, as well as reporting.

4.1. Access to STW data onboard

The STW data from a system such as the Miros system discussed in this paper can easily be made available onboard the vessel either on dedicated displays, on web displays or via integration into a 3rd party system onboard, *Miros AS (2017)*. Traditionally, such integration has been based on simple transmission of NMEA (National Marine Electronics Association) formatted data on serial links or embedded in TCP or UDP transmissions on an Ethernet connection. A UDP transmission can be seen as a simple push type of communication whereas a TCP connection can be seen as a pull connection as it has to be initiated by the receiver. Sending NMEA data over a serial or Ethernet connection is still a very common way to integrate sensors and systems.

Modern technologies facilitate integration between sensors and systems. One common technology found in this domain is the MQTT (Message Queuing Telemetry Transport) protocol. MQTT is a publish-subscribe type of protocol where a sensor (MQTT client) can send data to a server (often called an MQTT broker). The broker is then responsible for distributing the information. Any MQTT client can both send and receive data from the broker. MQTT is one of several commonly used IoT protocols. One of the major advantages of MQTT over legacy solutions is that the sensor does not have to know who the receivers of the data are, it only needs to relate to the broker. This increases reliability as the remaining system continues to work when a client (receiver) goes down or has intermittent connectivity. MQTT communication can be set up to buffer data in case of connectivity issues or other periods with downtime on the receiver side. MQTT is a bandwidth-efficient protocol. The core MQTT protocol is using TCP ports 1883 and 8883 which typically might be outbound blocked by firewalls. A good solution is therefore to use MQTT over Websockets which is using TCP port 443. This port is commonly open outbound or can easily be opened as it is typically used by many secure services based on TLS (Transport Layer Security) communication, e.g. secure https websites, online banking etc.

Traditionally, it has been challenging to get access to real-time data from distributed assets. This has been due to many factors including limited connectivity, lack of suitable protocols, lack of suitable interfaces to send and receive data from and lack of platforms that can handle data efficiently and seamlessly. Particularly, for seagoing vessels the lack of connectivity with sufficient and reliable bandwidth has been a serious hinderance. This has changed in recent years due to a number of factors, including:

- satellite connections with reliable and cost-efficient connectivity;
- efficient and modern communication protocols suitable for real-time transmission of telemetry data across the internet;
- data platforms that can handle large amounts of incoming data in a cost-efficient manner;
- scalable and flexible processing platforms that can process incoming telemetry data;
- security solutions utilizing mechanisms such as Public Key Infrastructure (PKI) encryption (e.g. https);
- authentication and authorization mechanisms based on Active Directory.

4.2. Access to STW data onshore

The STW data from a system, such as the Miros system discussed in this paper, can easily be made available onshore via web displays or via integration into 3rd party system using push or pull functionality. The described solution is based on using Microsoft Azure to collect, store, visualize and distribute the data from the vessels in a secure manner.

The communication of STW data from the vessel to Microsoft Azure is made via secure communication using modern protocols such as MQTT over Websockets, as described above. The STW system onboard the vessel will initiate a secure connection to Microsoft Azure. Both sides (the vessel STW system from Miros and the Miros environment in Microsoft Azure) is authenticated and authorized to avoid any possibility for illegal access to data or tampering with data. Communication is established outbound from the vessel, thus there is no need to open inbound ports in firewalls. Depending on the vessel network configuration, there might be a need to open outbound firewall ports. If needed this can be set up to only allow communication with Microsoft Azure to avoid any other services to utilize this outbound open port.

On the receiving side the access to data is governed by Microsoft Azure security mechanisms based on Active Directory. This means that only authorized personnel will be able to access the data via download mechanisms or web displays. Furthermore, any automated data transfer will be secured in a similar fashion.

Utilizing Microsoft Azure means that the STW data can be combined with other types of information, such as data from other types of instruments and systems, sea state forecasts from weather providers etc. It is also easy to get an overview of the status and history for a fleet of vessels.

Device management can also be supported by utilizing the functionality found in Microsoft Azure. In this way it is possible to remotely configure the STW system and provide firmware update features. This dramatically simplifies the commissioning and maintenance of the solution. With a transparent solution it is straightforward to identify possible issues related to the configuration or the maintenance of the physical equipment. This results in improvements in data quality and data availability. Software updates and configuration changes can be implemented in several ways. One common use case is to trigger a software update or configuration change from a remote location, i.e. by the equipment vendor (Miros in this case). Microsoft Azure then makes sure that this change is applied in the most seamless way. Software updates are then downloaded from the vessel via https communication which is again authenticated, authorized and encrypted.

The various options for how to integrate the Miros STW solution is shown in Fig.10, starting with using the STW solution as a standalone system onboard, via integrating the STW solution into an onboard system to integrating the STW solution to an onshore party via Microsoft Azure. The onboard system could be a vessel performance system or the vessel control system containing functionality such as an autopilot or automated speed optimizer.

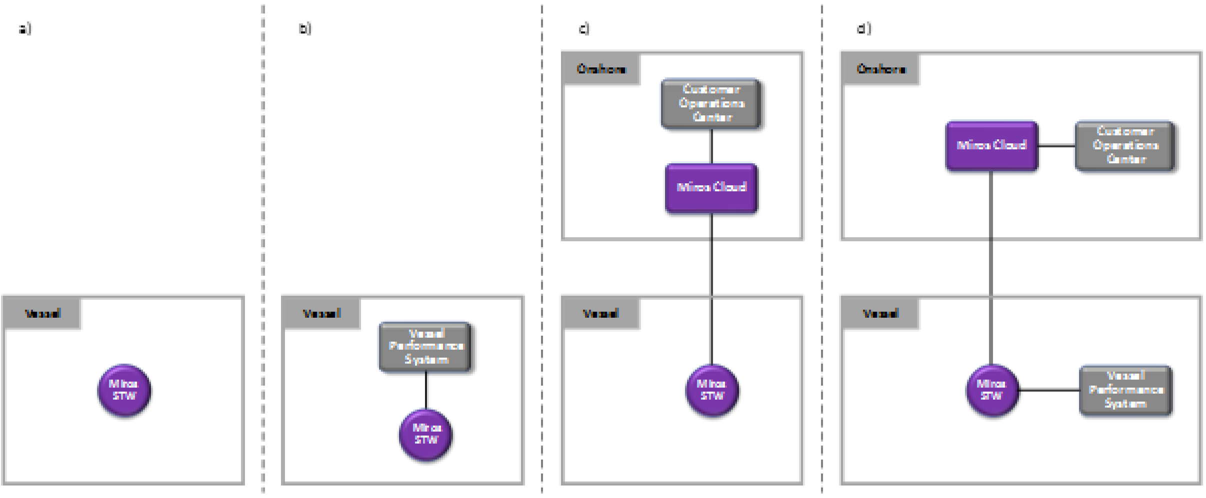

Fig.10: Various options for how to use the Miros STW solution. a) Miros STW system used as a standalone solution onboard a vessel, b) Miros STW system integrated into vessel performance system onboard, c) Miros STW system integrated with an onshore customer system via the Miros Cloud, d) combining options b) and c).

5. Conclusion

Information about surface currents and STW is of great value for many purposes, for instance as input to fuel optimization systems and hull performance estimation (detection of fouling). 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 and the STW 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. Combining the sensing technology with technologies from the Internet-of-Things domain means that the data can be made easily and securely available anywhere in real time.

Acknowledgements

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