

Wind waves in the North Atlantic from ship navigational radar: SeaVision development and its validation with Spotter wave buoy and WaveWatch III

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20 **Abstract**

Wind waves play an important role in the climate system, modulating the energy exchange between the ocean and the atmosphere and effecting ocean mixing. However, existing ship-based observational networks of wind waves are still sparse limiting therefore the possibilities of validating satellite missions and model simulations. In this paper we present data collected on three research cruises in the North Atlantic and Arctic in 2020 and 2021 and the SeaVision system for
25 measuring wind wave characteristics over the open ocean with a standard marine navigation X-band radar. Simultaneously with the SeaVision wind wave characteristics measurements we also collected data from the Spotter wave buoy at the same locations and we ran the WaveWatch III model in a very high-resolution configuration over the observational domain. SeaVision measurements were validated against co-located Spotter wave buoy data and intercompared with the output of WaveWatch III simulations. Observations of the wind waves with the navigation X-band radar were found to be in good
30 agreement with buoy data and model simulations with the best match for the wave propagation directions. Supporting datasets consist of significant wave heights, wave directions, wave periods and wave energy frequency spectra derived from

both SeaVision and the Spotter buoy. All supporting data are available through the PANGAEA repository – <https://doi.pangaea.de/10.1594/PANGAEA.939620> (Gavrikov et al., 2021). The dataset can be further used for validation of satellite missions and regional wave model experiments. Our study shows the potential of ship navigation X-band radars (when assembled with SeaVision or similar systems) for the development of a new near-global observational network providing a much larger amount of wind wave observations compared to e.g. Voluntary Observing Ship (VOS) data and research vessel campaigns.

1 Introduction

Ocean wind waves play a critically important role in air-sea energy and gas exchanges (Gulev and Hasse 1998; Andreas et al. 2011; Blomquist et al. 2017; Ribas-Ribas et al. 2018; Cronin et al. 2019; Xu et al. 2021 among many others) and in ocean surface mixing (McWilliams and Fox-Kemper 2013; Buckingham et al. 2019; Studholme et al. 2021), thus being an important active component of the coupled climate system (Cavaleri et al. 2012; Fan and Griffies 2014). At the same time, massive long-term observations of wind waves over global oceans still have insufficient coverage and quality compared to other surface variables (e.g. air and sea surface temperatures). Wind waves are wind-driven ocean surface gravity waves. Visual wave observations from Voluntary Observing Ships (VOS) while providing the longest time coverage (formally going back to the mid- 19th century) suffer from space- and time- dependent sampling biases as well as from both random and systematic biases, and require continuous validation (Gulev et al. 2003). Remote sensing datasets of wind waves go back to 1985 (Ribal and Young, 2019), when the first satellite radar altimeter missions (Seasat in 1978 (the first satellite to provide data) and Geosat in 1985) were launched and started to provide ocean surface elevations with high temporal and spatial resolution. However, remote sensing data have to be validated against *in situ* measurements, typically available from buoys (such as NDBC buoys, Swail et al. 2010 or NOWPHAS, Nagai et al. 2005). Buoys measure vertical and horizontal displacements of the ocean surface (such as Spotter or Datawell buoys with up to 2.5 Hz sampling frequency, Raghukumar et al., 2019) and provide highly accurate estimates of wind waves characteristics, effectively now assimilated into Numerical Weather Prediction (NWP) models. Assimilation of the significant wave heights from wave buoys in operational wave model decreases root-mean-square error in significant wave height forecasts by 27% on average (Smit et al., 2021). However, buoy networks are sparse with most deployments being in the coastal regions and can only effectively serve for verification of all other datasets rather than for developing global or regional climatologies.

Starting from the 1980s, considerable progress in wind wave modelling (WAMDI, 1988; Hasselmann et al., 1985; Cavaleri et al., 2020) resulted over the last decade in the development of multiple global and regional wind wave hindcasts generated by spectral wave models such as WAM (WAMDI 1988) or WAVEWATCH (WW3DG 2019) forced by atmospheric reanalyses or climate models, and providing multidecadal wind wave fields with high temporal and spatial resolution (Casas-Prat et al., 2018; Semedo et al., 2018; Morim et al. 2020, 2022; Sharmar et al. 2021 among others). Being currently a widely accepted source for estimating long-term climate variability in wave characteristics, wind wave hindcasts also suffer from

the inaccuracy in the modelling of many aspects of wind wave dynamics, including e.g. extremely high wave peaks at high
65 wind speeds during the storm passage (Cavaleri et al., 2020).

Summarizing, all three sources of global wind wave information (VOS, satellite data and model hindcasts) require data for
extensive validation. Existing wave buoys deployed in a few locations cannot solve this problem to the full extent. Thus,
investigating alternative sources of massive wind wave data remains a challenge. In this respect, ship navigation radars
represent an option whose potential, especially in open ocean regions, is not yet explored to its fullest extent. Here, we
70 present the results of the development and validation of the SeaVision system for wind wave observations in the open ocean
using standard navigation marine X-band radars which allows for real time monitoring of wind wave characteristics along
the commercial ship tracks.

Applicability of the navigation radars for measurements of the wind wave characteristics was first noted by Young et al.
(1985). Radar images of the ocean surface, known as sea clutter, are generated by the Bragg scattering (Crombie, 1955) of
75 the electromagnetic signal by the ripples on the ocean surface produced by the wind. Being emitted from the radar, an
electromagnetic signal reaches the ocean surface and further, being reflected by ripples on the ocean surface, and is received
back by the radar antenna when the ocean surface is rough enough (i.e. ripples are developed). Under a wind speed of > 3
m/s and waves height > 0.5 m, the surface waves field becomes detectable on the radar image of the sea clutter (Hatten et al.,
1998; Hessner and Hanson, 2010). Time sequences of these images are further analyzed for estimating the wind wave
80 characteristics. The associated retrieval procedures can be based on various approaches, which include signal-to-noise ratio
derived from the image spectrum (Nieto-Borge et al., 1999; Neito-Borge et al., 2008; Seemann et al., 1997), statistical
analysis of the island-to-trough ratio on the sea clutter images (Buckley and Alter, 1997; Buckley and Alter, 1998), analysis
of the image texture (Gangeskar, 2000), wavelet technique (Huang and Gill, 2015), the least square approach (Huang et al.,
2014) and shadowing analysis (Gangeskar, 2014). Methodologies may also be based on the combination of these methods
85 with the use of artificial neural networks (Vicen-Bueno et al., 2012). This may also include the analysis of the Doppler shift
of the received radar signal that is based on the well-defined relationship between orbital velocities and wave height for
linear gravity waves (Plant, 1997; Plant et al., 1987; Johnson et al., 2009; Karaev et al., 2008; Hwang et al., 2010; Hackett et
al., 2011; Chen et al., 2019). There are many aspects of the sea clutter radar images analysis: Nieto Borge and Guedes Soares
(2000) for example proposed an approach considering superpositions of swell and wind sea components, that allowed to
90 derive wind waves and swell contributions to the total wave field, along with directional characteristics. There are also
attempts to use images of the sea clutter revealed from X-band radars for estimating the current-depth profiles with a
Eulerian approach (Campana et al., 2017), to retrieve wind speed and wind direction (Chen et al., 2015; Dankert and
Horstmann, 2007; Dankert et al., 2003; Vicen-Bueno et al., 2013), and to derive surface characteristics (Senet et al., 2001).

On this basis, several commercial systems such as WaMoS II (<http://www.oceanwaves.de>), SeaDarQ (Greenwood et al.,
95 2018) and WaveFinder (Park et al., 2006) were developed. The most widely used system nowadays is WaMoS II (software
and hardware details provided in Reichert et al., 1999); it is focused on the operational monitoring of the sea state (wind

waves and surface currents) and operational management of oil platforms and ships using nautical X-band radars. Derkani et al. (2021) provided a dataset of the wind, waves and surface currents over the Southern Ocean collected with WaMoS II.

100 In combination with other sources of the data (altimetric wave radar, vessel hydrodynamic simulator), wind waves estimates from navigational radar can be used to manage security of the offshore systems, assess ship fatigue due to mechanical environmental influence (Drouet et al., 2013), or for the real-time prediction of ship rolling (Hilmer and Thornhill, 2015).

We present the design and pre-processing methodology of the SeaVision system along with the dataset collected during three research cruises (Figure 1). SeaVision was developed in collaboration between the Shirshov Institute of Oceanology of the Russian Academy of Sciences (IORAS, <https://ocean.ru/>) and the Joint stock company "Marine Complexes and Systems" 105 ("MC&S" J.S.C., <https://www.mcs.ru/>). SeaVision is developed on the basis of the sea ice monitoring system with navigational marine radar – IceVision (<https://ice.vision/en>). The pilot version of SeaVision was tested and validated in two North Atlantic cruises in 2020 and 2021 and in the Arctic cruise in 2021 (Figure 1). The major advantage of the presented dataset is the provision of the co-located Spotter wave buoy data with SeaVision records at almost 50 locations and outputs of WaveWatch III (WW3) model experiments forced by ERA5 reanalysis (Hersbach et al., 2020) for the corresponding 110 domains. We present in this study the SeaVision system and dataset of the measurements of the wind waves in the open ocean and its comprehensive analysis.

The paper is organized as follows. In Section 2 we provide details of the research cruises, technical specifications of the SeaVision system, data collection and analysis principles as well as the description of the WW3 model setup. Section 3 presents the results of the analysis and validation of the SeaVision dataset against Spotter buoy data and the comparison with 115 the WW3 model output. The concluding section 4 summarizes the results and discusses the perspectives of the use of ship navigation radars for a massively enhanced collection of wind wave information in the open ocean.

2 Data collection and analysis

We provide definitions of all parameters included in the published dataset in Appendix C. For wind and wave directions we use meteorological convention implying that both wind and waves are coming from the specified direction (blow into 120 compass).

2.1 Ship cruises

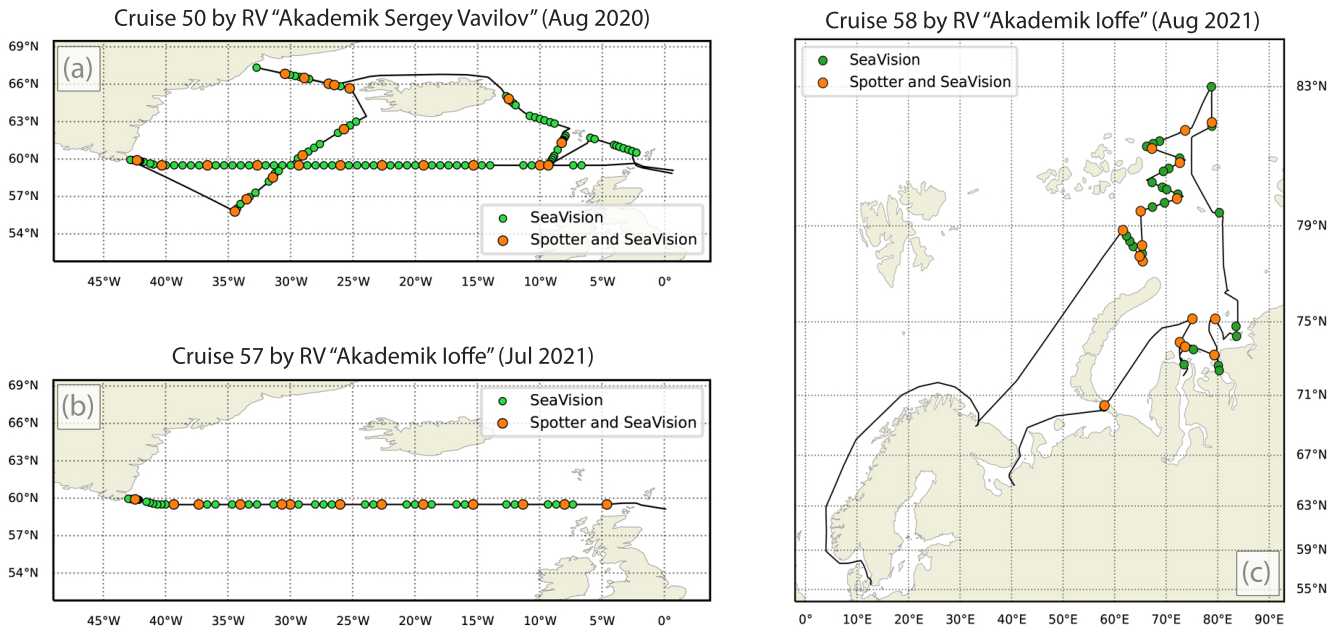


Figure 1: Ship tracks of the three cruises of the research vessels (R/V) “Akademik Sergey Vavilov” (a) and “Akademik Ioffe” (b,c). Green dots indicate locations where only SeaVision radar data were collected, orange dots show the locations for which SeaVision records were co-located with Spotter wave buoy measurements. Cruise numbers are counted from the beginning of the R/V operation.

Figure 1 demonstrates ship tracks of the three research cruises, during which wind wave data were collected. Research cruises were carried out by IORAS research vessels (R/Vs) “Akademik Sergey Vavilov” and “Akademik Ioffe”. Table 1 provides a general information about the cruises and detailed information on the coordinates and dates and is provided in Appendix A. The two cruises in the subpolar North Atlantic (Figure 1a, b) were focused on the regular survey of the 59.5°N oceanographic trans-Atlantic cross-section and cross-sections in the Denmark Strait (Verezemskaya et al., 2021). During these cruises the R/V makes full-depth CTD profiling. The distances between the hydrographic stations vary from ~30 km in the open ocean to a few kilometers near the East Greenland coast with the time allocated for each station (ship is drifting) varying from 2 to 6 hours. Here and later in the manuscript we determine stations as the locations where wind wave observations were carried out (Table A1). Between the stations the R/V travels at a speed of approximately 6 to 10 kn. During the cruise of R/V “Akademik Ioffe” in the Kara Sea (Figure 1c), stations were somewhat shorter in time (2-3 hours). During all cruises wave observations were carried out after completing hydrographic profiling. For operating solely SeaVision, the R/V position was strictly stationary being controlled by bow and stern thrusters of the R/V. When SeaVision was used together with the free drifting Spotter buoy, the thrusters were off to provide also free drifting of the R/V. This allowed for measurements of the background wave field by both SeaVision and the Spotter buoy. At each station we first

released the Spotter buoy with a supplementary floating buoy dumping cable vibrations. Such design allows for the maintenance of at least 300 m distance between the buoys and the R/V. Then, both buoys were in the free-floating mode for at least 30 min during which the recording was performed by both SeaVision and the Spotter buoy (Figure 4a). Lastly, both buoys were pulled back onboard. The Spotter buoy measured vertical and horizontal displacements starting from its release until being retrieved back onboard. After completing measurements at each station, only the data recorded during the free-floating mode were used for the joint analysis of SeaVision and Spotter buoy records. During all SeaVision and Spotter buoy measurements, standard meteorological parameters were measured using the onboard meteorostation.

Table 1: Research cruises during which the wind waves observations were carried out by research vessels (R/Vs) “Akademik Sergey Vavilov” (ASV) and “Akademik Ioffe” (AI). Adjacent numbers in the first column correspond to the R/V cruise numbers counted from the beginning of the R/V operation.

Cruise	Start date and location	End date and location	Distance sailed	Number of stations (with Spotter buoy)
ASV50	08/08/2020 Kaliningrad Russia	08/09/2020 Kaliningrad Russia	10465 km	21
AI57	27/06/2021 Kaliningrad Russia	02/08/2021 Kaliningrad Russia	7745 km	11
AI58	08/08/2021 Arkhangelsk Russia	06/09/2021 Kaliningrad Russia	10611 km	16

2.2 SeaVision system

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2.2.1 Ship navigation radar signal retrieval and preprocessing

Development of the SeaVision system was based on a commonly accepted approach of the recording and analysis of the sea clutter images. Using a similar approach, commercial systems such as WaMoS II (<http://www.oceanwaves.de>), SeaDarQ (Greenwood et al., 2018) and WaveFinder (Park et al., 2006) were developed. These commercial systems provide customers with their original software and hardware. In our approach we are focused on the development of an independently operating, low-cost and easy to install system compatible with the existing ship navigation radars.

Research vessels “Akademik Sergey Vavilov” (R/V ASV) and “Akademik Ioffe” (R/V AI) are equipped with the standard navigation X-band radars JRC JMA-9110-6XA and JMA-9122-6XA. Technical details of radar transmission and backscattering characteristics are given in Table 2. Both radars operate at 9.41 GHz frequency (wavelength ~ 3 cm), and are equipped with a 6 feet antenna with the directional horizontal resolution of 1.2° (Table 2). Radars can optionally operate at the pulse lengths of 0.08 μ s, 0.25 μ s, 0.5 μ s, 0.8 μ s, 1.0 μ s. For our purposes we used the smallest possible pulse length of

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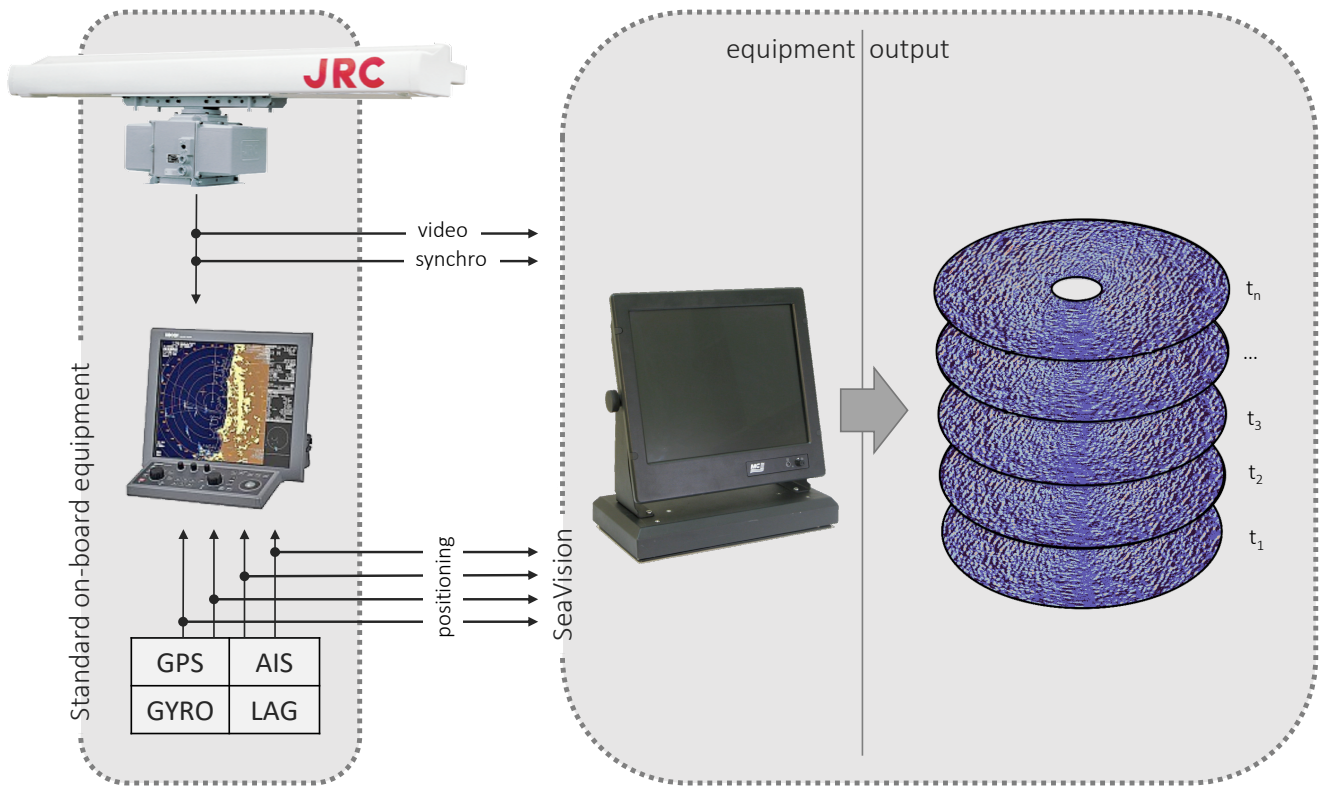
0.08 μs (at the so-called “short-pulse” mode - SP1), providing the highest possible resolution of the image (thus the best resolution of the ocean surface). Our X-band radars are characterized by a 3.18 cm wavelength of the emitted electromagnetic waves (Table 2). The pulse length is the emission time of the wave beam, thus, the number of the emitted waves and the area of reflection at the ocean surface (defining spatial resolution) increase with increasing pulse length.

The SeaVision system (Figure 2) is connected to the radar via a splitter. It provides digitizations and further recording of the directionally stabilized (northward) radar sea clutter image resulting from each single full turn of the radar antenna. By doing this, SeaVision converts the sea clutter image into a digital format and records the data onto the external storage. SeaVision is also connected to the ship navigation package and simultaneously records geographical coordinates from GPS, speed over ground (SOG), and course over ground (COG). Each full turn of antenna results in ASCII file (~16 MB) consisting of a 4096x4096 matrix (1.875 m discretization at 4096 beam directions) representing the sea clutter digitized image with GPS information, SOG and COG in the file header. These files are further consolidated and converted into NetCDF format at the post-processing stage.

Table 2: JRC JMA-9110-6XA radar (R/V ASV) and JMA-9122-6XA (R/V AI) transmission and reception characteristics.

Research vessel	<i>“Akademik Sergey Vavilov”</i>	<i>“Akademik Ioffe”</i>
Radar type	JRC JMA-9110-6XA	JMA-9122-6XA
Radar frequency/Wave length	9.41 GHz / 3.18 cm	9.41 GHz / 3.18 cm
Antenna rotation speed	27 rpm	24 rpm
Impulse power	10 kW	25 kW
Antenna size	6 ft	6 ft
Pulse length mode	0.08 μs (short pulse)	0.07 μs (short pulse)
Analog-digital converter (ADC) frequency/size of output matrix for one antenna turn	80 MHz / 4096x4096	80 MHz / 4096x4096
Azimuthal coverage/resolution	0 – 360°/1.2°	0 – 360°/1.2°

Distance range	231.5 – 2778 m	231.5 – 2778 m
Range resolution	12 m	10.5 m
Analog-digital converter (ADC) frequency/size of output matrix for one antenna turn	80 MHz / 4096x4096	80 MHz / 4096x4096
Calibration coefficients A and B	A = -0.4042, B = 1.0034	A = -0.4042, B = 1.0034



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Figure 2: SeaVision integration to the ship's navigational equipment together with an example of the series of the geographically stabilized (northward) sea clutter images, one for each antenna turn (right column). Image of the JRC radar scanner (top left) is taken from the <http://www.jrc.co.jp/eng/index.html>.

190 2.2.2 Analysis of the sea clutter images

After the sea clutter images are collected and digitized, the next step is the postprocessing focused on the computation of significant wave height (H_s), wave period (T_{m01}), wave energy spectrum (S_w) and wave direction (D_s). Here we provide a short condensed description of the algorithm with the full details given in Appendix B. The subset collected at each station
 195 (Figure 1) consists of the 20-minute SeaVision record, which is equivalent to at least 540 images of the sea clutter (27 antenna full turns per minute for JRC JMA-9110-6XA radar).

The methodology for estimation of wind wave characteristics relies on a well established Fourier Transform (FT) technique (Nieto-Borge and Guedes Soares, 2000; Borge et al., 2004; Borge et al., 2008 among others). For each station, preprocessing of the data begins with the choice of the processing squared area (squared area of 720×720 m). For now, we locate the
 200 processing area visually by taking the area of the most apparent wave signal in the image and requiring this area to be distanced from the ship by 300 m to avoid a potential impact of the ship on the wave field and the effects of the reflection and modulation of the radar signal by the ship superstructure. When the processing area is selected, we consolidate the data captured in this area from all 540 images for further analysis. Note that the data initially sampled in polar coordinates are re-
 gridded at this step to a Cartesian grid of 384×384 grid points with 1.875 m spatial resolution for each subset.

The sequence of 540 matrices with 384×384 grid points each is then split into 16 sectors (22.5° width each). Further, to
 205 obtain the directional spectra estimates, we transformed the data into a 3D spectral domain by using the Fourier transform and applying the Welsh method with a half-width overlapping Hanning window (48 points, Figure 3). This returns for each sector, the three-dimensional spectrum $S_{3d,image}(k_x, k_y, f)$, where $f = \omega/2\pi$ is the frequency (Hz) and ω is the angular frequency, k_x and k_y (rad/m) are the components of the wave vector $\vec{k}(k_x, k_y)$. Then, for each sector we capture the
 210 spectrum power within the band along the line satisfying the linear dispersion relation for ocean waves (Figure 3):

$$\omega = \sqrt{gk} + kU\cos\theta, \quad (1)$$

where k is the wave number (rad/m), g is gravity (m/s²), U is the surface velocity (m/s) which includes surface current
 215 velocity and ship drift, and θ is the angle between the wave vector \vec{k} and velocity vector \vec{U} . This procedure is applied to the bands corresponding to the first and the second spectral harmonics (see Appendix B for the definition of band width). The spectral power outside the bands for the two harmonics is assumed to be a background speckle-noise ($\omega_{speckle}$) (Kanevsky, 2009). Integrated spectral power outside of the bands matching the wave dispersion relation (1) is further used for estimating of the signal-to-noise ratio (SNR) as described in Appendix B and outlined in many works (Nieto-Borge et al., 1999; Hessner
 220 et al., 2002; Young et al 1985, Nieto-Borge and Guedes Soares 2000, Ivonin et al. 2016). Following Nieto-Borge et al. (1999, 2004) SNR is then converted to significant wave height $H_{s,SeaVision}$ using the linear regression equation:

$$H_{s,SeaVision} = A + B \sqrt{SNR}, \quad (2)$$

225 where A and B are empirical calibration coefficients which are specific for each radar. In this study, these coefficients were computed by fitting a linear regression (2) to the significant wave height measured by the Spotter wave buoy. Derived numerical values of A and B coefficients are given in Table 2 for both X-band radars. Wave period $T_{m01,SeaVision}$ was estimated conventionally using zeroth and first spectral moments:

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$$T_{m01,SeaVision} = \frac{m_{0,SeaVision}}{m_{1,SeaVision}}, \quad (3)$$

$$m_{0,SeaVision} = \int_0^{\infty} S_{w,SeaVision}(f) df, \quad (4)$$

$$m_{1,SeaVision} = \int_0^{\infty} S_{w,SeaVision}(f) f df \quad (5)$$

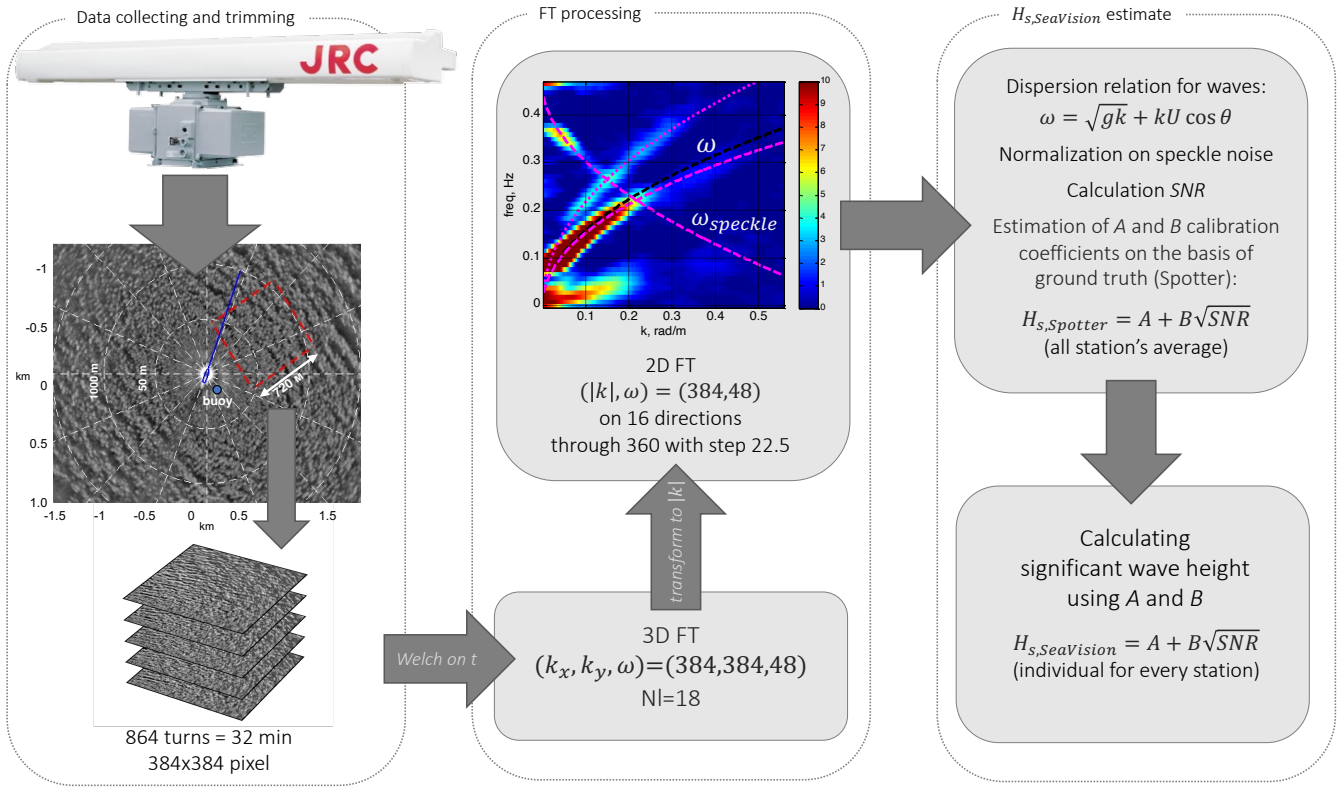
where $S_{w,SeaVision}(f)$ is the estimate of the wave energy spectrum from SeaVision:

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$$S_{w,SeaVision}(f) = \left(\frac{H_{s,SeaVision}}{H_{s,image}} \right)^2 S_{image}(f) \quad (6)$$

and $H_{s,image}$ is $H_{s,image} = 4\sqrt{m_{0,image}}$, thus being the estimate of significant wave height using the raw sea clutter image before calibration.

240 We note that local weather conditions, specifically rain events, can potentially affect the electromagnetic radar signal as the raindrops absorb and scatter radar signal. However, the analysis of current weather has shown that no rain events were observed during observations.



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Figure 3: Organigram of the data processing for estimation of wind waves parameters from the sea clutter images. JRC radar scanner (top left) is taken from the <http://www.jrc.co.jp/eng/index.html>.

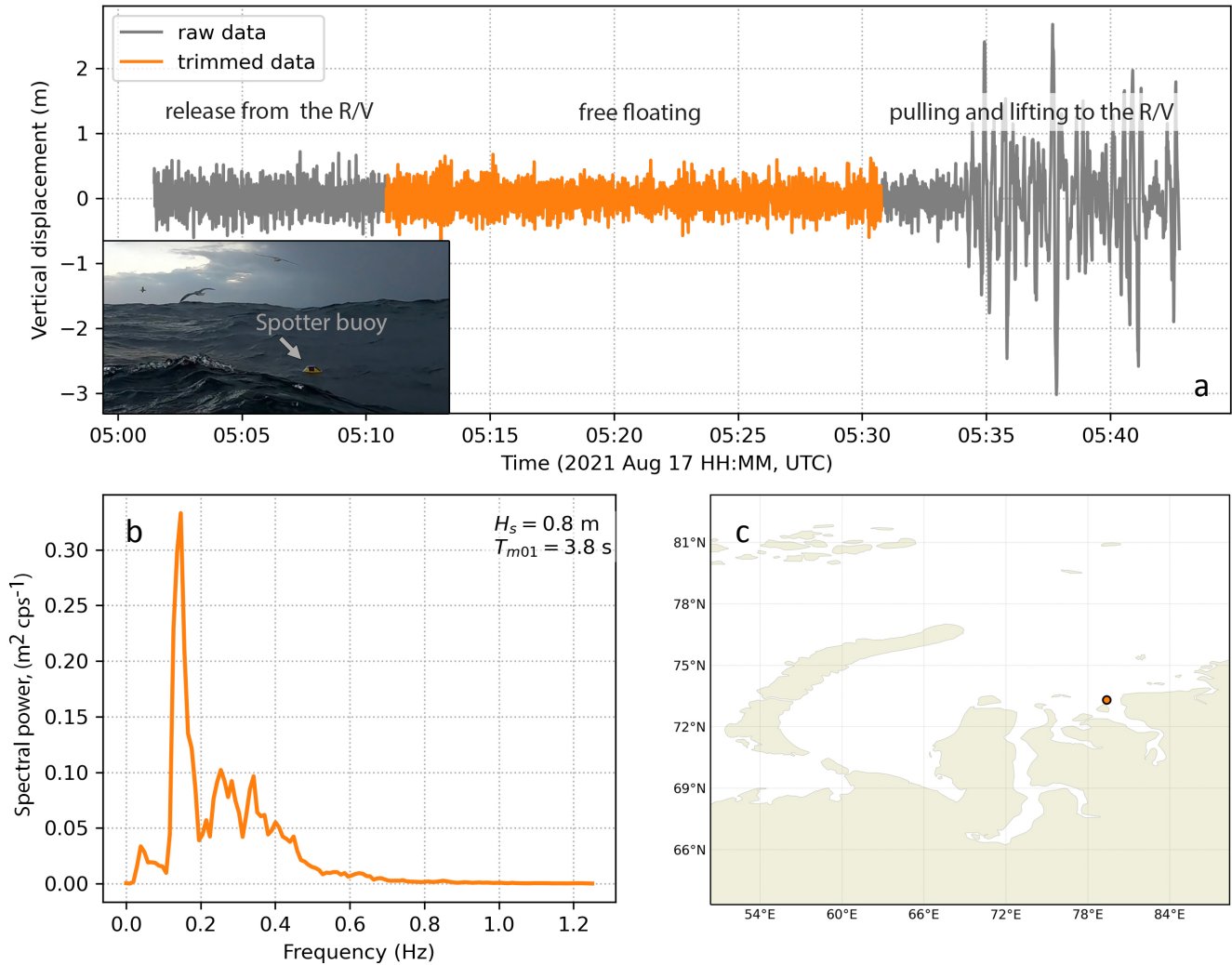
2.3 Spotter wave buoy data

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To calibrate and validate SeaVision wave observations, we performed simultaneous measurements with the Spotter wave buoy (<https://www.sofaroccean.com/products/spotter>) in the locations shown in Figure 1 and specified in Table A1. Once the ship is drifting at the location of the measurements, the Spotter buoy was deployed and started drifting away from the ship. Note that the ship drift is always faster compared with that of the buoy, thus, the distance between the buoy and the ship progressively increase. When the distance between the ship and the buoy reached at least 300 m, the “free floating” mode of SeaVision and Spotter buoy operation was initiated for at least 30 minutes as described in section 2.1. The longest free floating mode time period at some stations reached up to 1.5 hours. To ensure homogeneity of the analysis we used 20-minute segments from the “free floating” mode time series for further computations of significant wave height, wave spectra and directional moments: $H_s = 4\sqrt{E}$, where $E = \int_{0.01 \text{ Hz}}^{1.25 \text{ Hz}} E(f)df$ - the surface elevations variance in the frequency range of the wind waves. Further, we used wave parameters derived from the Spotter buoy as a “ground truth” for the calibration of

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SeaVision data and derivation of A and B calibration coefficients in (2) (Table 2). Example of the wave energy spectrum for 20-minute Spotter buoy record is shown in Figure 4b.



265 **Figure 4: Spotter wave buoy timeseries of vertical displacements at the station #3946 in the AI58 cruise (a), corresponding wave energy spectrum (b) and location of the station #3946 (c).**

2.4 Meteorological data

270 During all cruises, the AIRMAR WeatherStation 220WX was installed on the main ship mast at 30 m height above the sea. The weather station provided an output consisting of standard output parameters (barometric pressure, wind speed and

direction, air temperature and relative humidity). Wind characteristics were recalculated from the relative wind to the true wind in real-time mode.

275 2.5 WaveWatch III model experiment

We ran the WaveWatch III (WW3DG, version 6.07, WW3) spectral wave model forced by ERA5 reanalysis (Hersbach et al., 2020) over the domain and the time period of the research cruises (Table 3). The experiments were performed for the outer domain at 0.1° spatial and 1-hr temporal resolution and for the inner domain with 0.03° (~1 km) spatial (see Table 3) and 1-hr temporal resolution. The outer domain solution was used for setting lateral boundary conditions for the inner domain. These experiments returned two-dimensional wave spectra co-located with SeaVision and Spotter buoy observations. In the WW3 experiments we used the ST6 parameterization (Bababin, 2006; Bababin, 2011; Rogers et al., 2012; Zieger et al., 2015) for wave energy input and dissipation and the discrete interaction approximation (DIA) scheme for nonlinear wave interactions (Hasselmann and Hasselmann 1985).

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Table 3: WW3 model configuration over the domains of expeditions.

Cruise	ASV50	AI57	AI58
Region	North Atlantic polygon	North Atlantic polygon	Arctic polygon
Grid type	Regular, nested grid	Regular, nested grid	Curvilinear grid
Outer domain spatial resolution	30°-75°N and 80W-10E 0.1°x0.1°	30°-75°N and 80W-10E 0.1°x0.1°	36°-90°N and 0°-360° 0.1°x0.1°
Inner domain spatial resolution	54°-68°N and 45°W-1°E 0.03°x0.03°	54°-68°N and 45°W-1°E 0.03°x0.03°	-
Time coverage	2020.08.01-2020.09.06	2021.06.01-2021.07.12	2021.08.01-2021.09.30

3 Results of validation of SeaVision measurements

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Validation of SeaVision data was provided for wind speeds from 2 to approximately 20 m/s and for significant wave heights from few tens of centimeters to 4.2 meters. Figure 5 demonstrates the results of the intercomparison of significant wave height (H_s) estimates retrieved from SeaVision data and those measured by the Spotter buoy and simulated with WaveWatch III. The H_s differences ‘Spotter minus SeaVision’ (Figure 5a) and ‘WW3 minus SeaVision’ (Figure 5b) are plotted as a function of wind speed recorded by the ship weather station (Table A1). Table 4 provides comparative estimates of differences in H_s for the three cruises. On average WW3 yields lower wave heights than SeaVision H_s by 28 cm, while the agreement between SeaVision and the Spotter buoy data is better with H_s measured by Spotter being around 10 cm higher

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than that retrieved from SeaVision. For low wind speeds SeaVision tends to underestimate H_s up to 60 cm and for moderate and strong winds the analysis shows an overestimation of SeaVision H_s compared to buoy and model data. This can be explained by better developed ripples (affecting the signal to noise ratio) at the ocean surface under stronger winds.

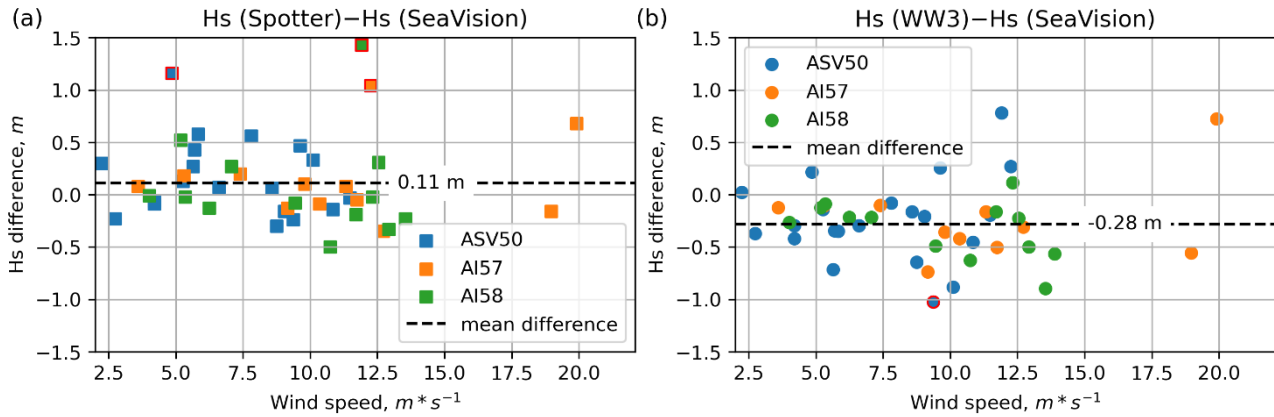


Figure 5: Difference in the significant wave height (H_s) estimates for all stations as a function of the wind speed: Spotter buoy (“ground truth”) minus SeaVision (a), WW3 minus SeaVision (b). Dash lines mark the mean difference across all data points. Red squares and circles mark differences higher than 1 m.

We also identified three locations (2901, 2928 and 2937, see Table A1) for which the differences between the Spotter buoy data and SeaVision reach more than 1 m (for 5 and 13 m/s winds). Weather conditions for these cases were not associated with severe weather and H_s values were in the range between 1.5 and 2 m. However, in these cases we recorded a strong drift of the vessel due to the local current that potentially impacted the angle of the electromagnetic signal reflection from the surface and hence affected the accuracy of the radar images. Thus, strong ship drift may influence the SeaVision results and the data collected under strong ship drift should be considered with caution. These cases, in the future, can be identified by analysis of speed over ground (SOG parameter). For ‘WW3 minus SeaVision’ there is only one station #2841 where this difference reaches 1 m.

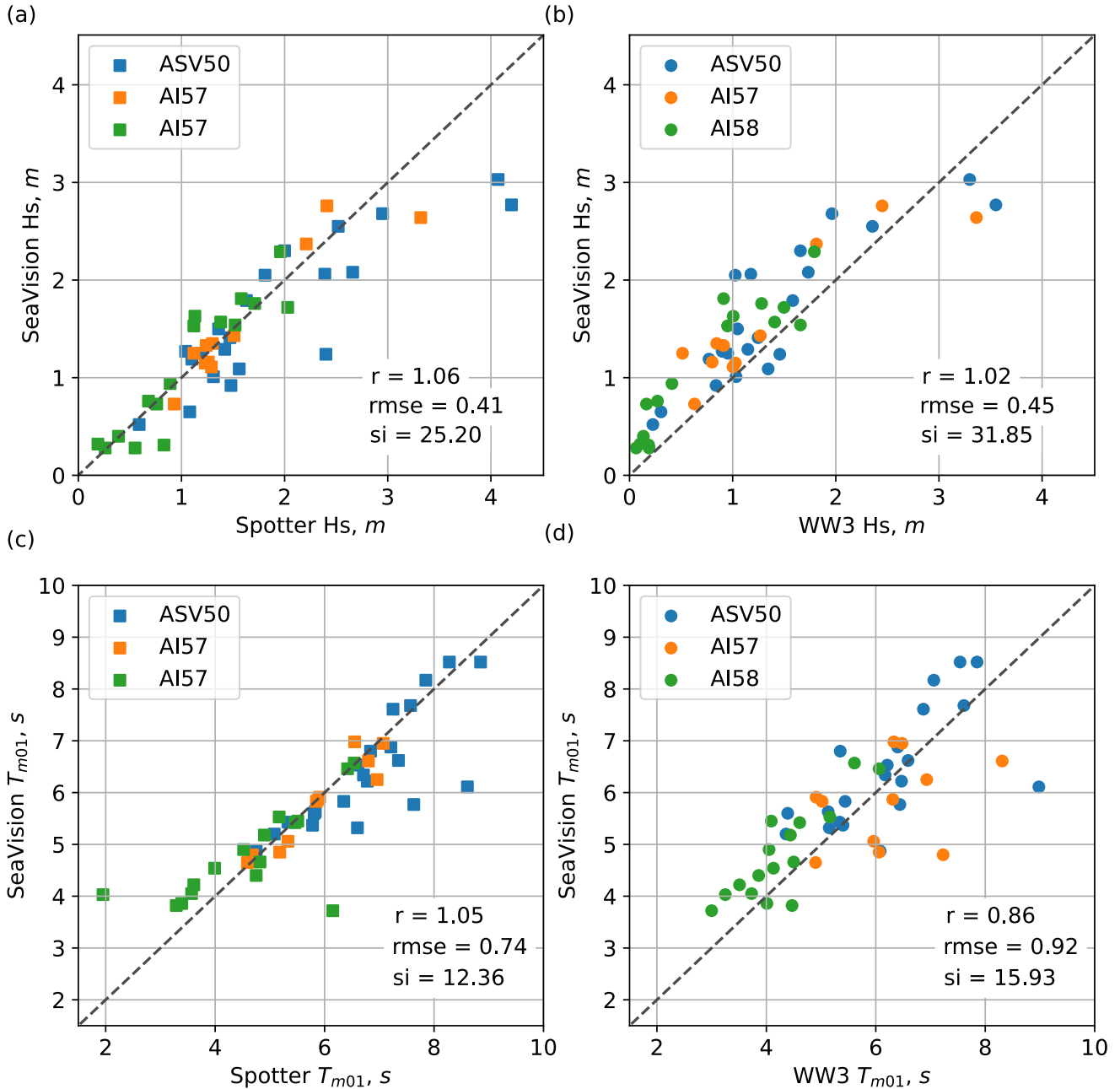
Table 4: Differences in significant wave height estimates for the three cruises.

Mean difference in H_s (m)	ASV50	AI57	AI58
Spotter - SeaVision	0.27	0.05	-0.06
WW3 - SeaVision	-0.24	-0.24	-0.36

Scatterplots for the H_s and wave period (T_{m01}) demonstrate generally a better agreement between different data sources for H_s (1.06 and 1.02 regression coefficients) than for T_{m01} (1.05 and 0.86 regression coefficients) (Figure 6). There is no robust

evidence of the dependence of the magnitude or sign of H_s and T_{m01} differences on the magnitude of parameters themselves.

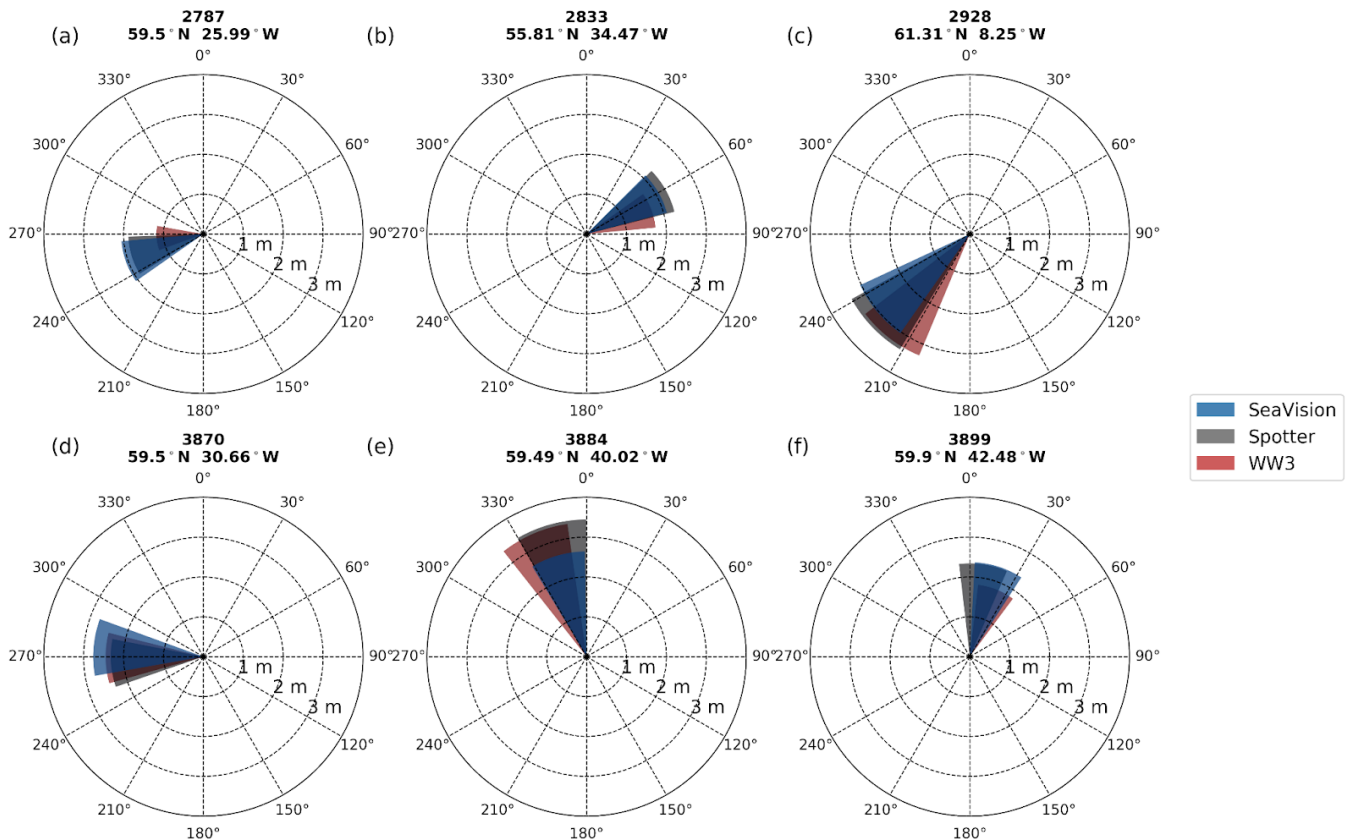
320 We also note that both SeaVision and Spotter show higher waves and slightly longer periods compared to WW3 (Figure 6). We note, however, that simulated wind waves with WW3 strongly depend on the atmospheric forcing (choice of reanalysis). Difference in climatological mean values over the North Atlantic obtained with WW3 but with different forcing functions can reach few tens of centimeters (Sharmar et al. 2021).



325 **Figure 6: Scatterplots of the significant wave height (H_s) and wave period (T_{m01}) revealed by SeaVision and measured by Spotter (a,c) as well as revealed by SeaVision and simulated with WaveWatch III (WW3, b,d) for all stations. Together with Root Mean Square Error (RMSE) and Scatter Index (SI) statistics.**

Overall, the analysis of significant wave heights among these three sources of data (Spotter, SeaVision and WW3) shows
 330 that the highest H_s values are measured by the Spotter buoy, lowest are simulated by WW3, with SeaVision being in between. These results are intuitively correct as wave buoys measure the actual elevations of ocean surface, SeaVision provides a proxy of local wave conditions from image analysis (thus imposing averaging over the domain) and is not expected to be as accurate as wave buoy data.

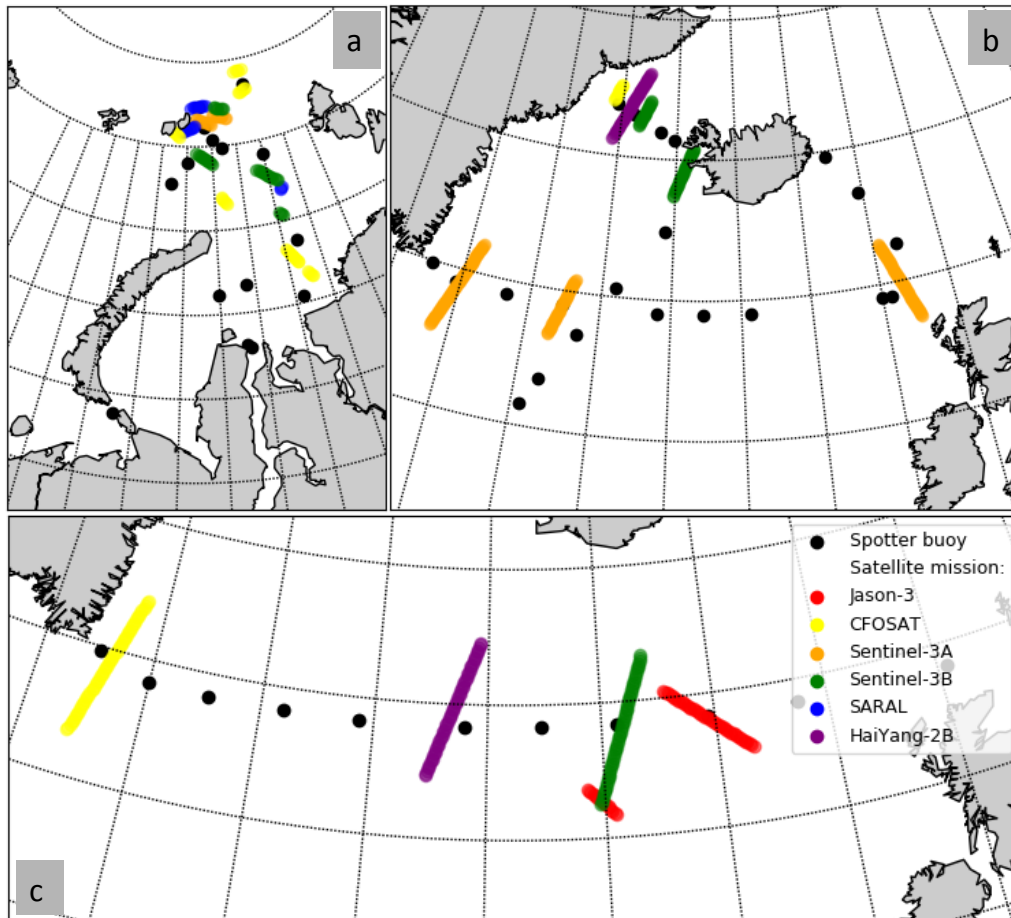
Figure 7 shows comparisons of wave directions (D_s) along with corresponding significant wave height (H_s) values
 335 (simplified approximation of directional spectra) for six stations (see Table A1). Generally, all three data sources demonstrate very good agreement on directions (differences in waves direction do not exceed 10°) with corresponding wave height estimates being underestimated in model simulations as already mentioned above (Figures 5 and 6).



340

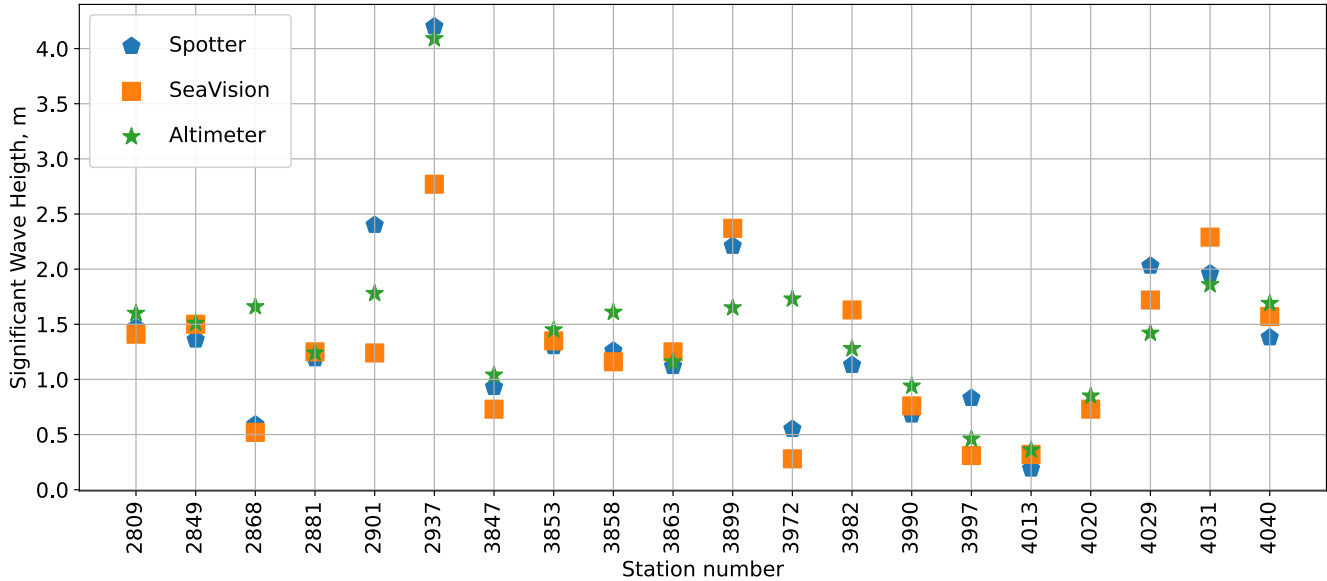
Figure 7: Diagrams (roses) of mean wave direction (D_s , from) and significant wave height (H_s) on the basis of the three data sources: SeaVision (blue), Spotter (gray) and WaveWatch III (WW3, red) at the stations: #2787, #2833, #2928, #3870, #3884, #3899 (see Table A1).

345 We also performed comparisons of SeaVision and Spotter H_s estimates with satellite altimeter missions (Figures 8, 9). Figure 8 shows overpasses of all available satellite tracks of Jason-3, CFOSAT, Sentinel-3A, Sentinel-3B, SARAL and HaiYang-2B which are suitable for comparisons with our dataset. Altimeter data were used for comparisons when they satisfied two conditions: an overpass was within 2° latitude and within ± 30 minutes from the measurement time (Table A1). In total we selected 20 cases that satisfied these conditions.



350 Figure 8: Overpasses of satellite altimeter missions (Jason-3, CFOSAT, Sentinel-3A, Sentinel-3B, SARAL or HaiYang-2B) over the observational domains. Black dots indicate locations where wave parameters were measured simultaneously with Spotter wave buoy and SeaVision (Table A1).

355 The average H_s for these 20 locations measured by satellite altimeters is 1.47 m, with the Spotter buoy giving 1.38 m and SeaVision giving 1.26 m. There is a general agreement for most stations among these three sources of data and differences do not exceed 50 cm except for two cases: stations 2937 and 2901, where H_s is underestimated by SeaVision comparing to Spotter and altimeter by more than 100 cm. These two outliers were already mentioned above (Figure 5) and large differences were attributed to a very strong drift of the ship for these locations.



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Figure 9: Significant wave height estimates for the locations of satellite altimeter overpasses for three research cruises. Numbers on the horizontal axis correspond to the station numbering in Table A1.

Conclusions

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To broaden the avenue for widely needed broad-scale high-quality observations of ocean wind wave estimates we used a conventional navigation X-band ship radar equipped with a SeaVision recorder and software package. Here we present the evaluation of the instrument package for measuring wind wave parameters and comparing them with in-situ observations and model results. The data were collected on three cruises in the subpolar North Atlantic and in the Kara Sea. All SeaVision records were co-located with in-situ Spotter buoy measurements, which were used for validation. We demonstrate an overall agreement of the estimates of significant wave height and wave period measured by SeaVision with the Spotter buoy measurements and with simulations using the WW3 spectral wave model. Estimates of significant wave height between SeaVision, WW3 and the Spotter buoy are in a better agreement than those for the wave periods. In the ranges of H_s up to 4.2 m the average difference between the Spotter buoy and SeaVision is around 10 cm for H_s , while WW3 simulations are lower than SeaVision H_s by 28 cm. We note, however, that comparisons with WW3 should be considered with caution, as the model results are significantly dependent on the choice of forcing function (atmospheric reanalysis). SeaVision tends to

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underestimate mean wave periods by ~ 0.5 s compared to the Spotter buoy while the differences in periods with WW3 simulations may amount to more than 2 sec. Also, a very good agreement was found for the wave directions whose spread across all three data sources does not exceed 10° .

380 We present the newly developed SeaVision system for digitizing and recording the analog signals from navigation radars, and further providing quantitative estimates of wind wave characteristics. A broad implementation of SeaVision opens a potential for enhancing massive observations of wind waves over the open ocean. SeaVision is currently mounted onboard two R/Vs operated by IORAS, but in 2022 five more IORAS R/Vs will be supplied with SeaVision systems. Data records will become operationally available at an open source web page. In 2023 we also plan to develop a portable and cheaper
385 version of SeaVision that can be easily mounted onboard of any commercial ship with navigational radar operating in the open ocean, as well as on the platform, lighthouse or any coastal infrastructure. After further validation in different sea state and weather conditions we plan to upgrade SeaVision to portable device and to incorporate all post-processing procedures into the internal software package that will make it possible for commercial ships on which the system is installed to provide real-time reporting of wind wave parameters through the Global Telecommunication System (GTS). Theoretically the
390 estimated data flow is formally one estimate per 2-3 seconds (1 full turn of the radar antenna). Even with a reporting frequency once per minute, the potential of the SeaVision data flow exceeds the current VOS data flow by hundred times. Contrasting to existing commercial systems for wind waves monitoring with navigational marine radars, such as WaMoS II (<http://www.oceanwaves.de>), SeaDarQ (<http://www.seadarq.com/>) and WaveFinder (Park et al., 2006), SeaVision is representing potentially a low-cost, portable and easy to install alternative. Wide use of such a system on commercial ships
395 can drastically increase the amount of sea state observations available to users, including the National Meteorological Offices using this information as data assimilation input for NWP models and reanalyses. The Global Climate Observing System (GCOS) and associated Global Ocean Observing System (GOOS) are considering the sea state to be a critical climate variable highly demanded by global observing modules. We hope that SeaVision with its perspective to provide exceptionally high global coverage with on-line wave measurements will meet this urgent demand
400 and help to satisfy GCOS given its mandate for systematic observations under the UN Framework Convention on Climate Change (UNFCCC), including also GCOS and GOOS responsibilities under the Subsidiary Body for Scientific and Technological Advice (SBSTA) and the Subsidiary Body for Implementation (SBI).

Data availability

405 Datasets that contains significant wave heights, wave periods, wave directions, wave energy frequency spectra, meteorological data and other related parameters from both SeaVision and the Spotter buoy at the locations of every station (Table A1) is available through the PANGAEA repository - <https://doi.org/10.1594/PANGAEA.939620> (Gavrikov et al., 2021). In this dataset we provide wind waves statistics disregarding separation of the swell and wind waves at this stage of
410 the SeaVision development. We plan to include this procedure into the next studies. At the same time, we provide one

dimensional spectrum that potentially allows to see first and seconds peaks associated with winds waves and swell (an example is shown in Figure 4b). Users interested in the analysis of the raw radar dataset or in the wave characteristics in the locations where measurements were carried out only with SeaVision are welcome to request access from Alexander Gavrikov (gavr@sail.msk.ru).

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Appendix A: List of the locations (stations) of the wind waves measurements during three research cruises

Table A1: Stations list: geographical locations and time of all stations where the wind waves measurements were performed simultaneously with SeaVision and Spotter buoy. In the last column letters stand for the name of the research vessel (ASV – “Akademik Sergey Vavilov”, AI – “Akademik Ioffe”) and numbers stand for the sequence number of reseach cruise since the beginnig of the reseach vessel operation.

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#	Station #	Start UTC time	End UTC time	Latitude° N	Longitude° E	Cruise #
1	2868	27.08.2020 13:53	27.08.2020 14:13	65.67	-25.26	ASV50
2	2881	28.08.2020 10:45	28.08.2020 11:05	66.49	-28.89	ASV50
3	2885	28.08.2020 19:05	28.08.2020 19:25	66.84	-30.43	ASV50
4	2763	11.08.2020 11:25	11.08.2020 11:45	59.50	-10.00	ASV50
5	2777	13.08.2020 18:15	13.08.2020 18:35	59.50	-19.32	ASV50
6	2782	14.08.2020 18:42	14.08.2020 19:02	59.50	-22.66	ASV50
7	2787	15.08.2020 18:10	15.08.2020 18:30	59.50	-25.99	ASV50
8	2797	17.08.2020 10:12	17.08.2020 10:32	59.50	-32.67	ASV50
9	2803	18.08.2020 12:17	18.08.2020 12:37	59.50	-36.67	ASV50

10	2809	19.08.2020 13:26	19.08.2020 13:46	59.50	-40.34	ASV50
11	2821	20.08.2020 13:44	20.08.2020 14:04	59.90	-42.32	ASV50
12	2833	22.08.2020 15:26	22.08.2020 15:46	55.81	-34.47	ASV50
13	2841	23.08.2020 12:31	23.08.2020 12:51	56.78	-33.53	ASV50
14	2849	24.08.2020 14:06	24.08.2020 14:26	58.53	-31.43	ASV50
15	2856	25.08.2020 12:42	25.08.2020 13:02	60.30	-29.04	ASV50
16	2863	26.08.2020 11:45	26.08.2020 12:05	62.40	-25.73	ASV50
17	2901	30.08.2020 13:05	30.08.2020 13:25	65.94	-26.49	ASV50
18	2903	01.09.2020 13:05	01.09.2020 13:25	64.82	-12.49	ASV50
19	2913	02.09.2020 10:17	02.09.2020 10:37	63.35	-10.38	ASV50
20	2928	03.09.2020 19:24	03.09.2020 19:44	61.31	-8.25	ASV50
21	2937	04.09.2020 21:16	04.09.2020 21:36	59.50	-9.31	ASV50
22	3831	29.06.2021 19:49	29.06.2021 20:09	59.50	-4.60	AI57
23	3841	01.07.2021 09:26	01.07.2021 09:46	59.49	-11.33	AI57
24	3847	02.07.2021 10:33	02.07.2021 10:53	59.50	-15.33	AI57

25	3853	03.07.2021 12:35	03.07.2021 12:55	59.50	-19.33	AI57
26	3858	04.07.2021 11:38	04.07.2021 11:58	59.50	-22.67	AI57
27	3863	05.07.2021 10:05	05.07.2021 10:25	59.50	-26.00	AI57
28	3870	06.07.2021 16:29	06.07.2021 16:49	59.50	-30.67	AI57
29	3875	07.07.2021 15:57	07.07.2021 16:17	59.52	-33.98	AI57
30	3880	08.07.2021 17:32	08.07.2021 17:52	59.50	-37.33	AI57
31	3884	09.07.2021 13:51	09.07.2021 14:11	59.50	-40.00	AI57
32	3899	11.07.2021 12:45	11.07.2021 13:05	59.90	-42.48	AI57
33	3911	12.08.2021 13:27	12.08.2021 13:47	70.37	58.04	AI58
34	3929	14.08.2021 21:43	14.08.2021 22:03	75.15	75.09	AI58
35	3930	15.08.2021 06:40	15.08.2021 07:00	73.98	72.66	AI58
36	3939	16.08.2021 12:40	16.08.2021 13:00	73.75	73.66	AI58
37	3946	17.08.2021 04:53	17.08.2021 05:13	73.31	79.35	AI58
38	3956	18.08.2021 12:52	18.08.2021 13:12	75.14	79.54	AI58
39	3972	21.08.2021 12:27	21.08.2021 12:47	82.14	78.88	AI58

40	3982	22.08.2021 15:48	22.08.2021 16:08	81.93	73.70	AI58
41	3990	23.08.2021 14:43	23.08.2021 15:03	81.44	67.25	AI58
42	3997	24.08.2021 08:02	24.08.2021 08:22	81.04	72.66	AI58
43	4013	25.08.2021 19:28	25.08.2021 19:48	79.93	72.11	AI58
44	4020	26.08.2021 13:20	26.08.2021 13:40	79.51	65.06	AI58
45	4025	27.08.2021 03:05	27.08.2021 03:25	78.28	65.33	AI58
46	4029	27.08.2021 12:39	27.08.2021 12:59	77.67	65.45	AI58
47	4031	27.08.2021 18:30	27.08.2021 18:50	77.86	64.85	AI58
48	4040	28.08.2021 11:11	28.08.2021 11:31	78.84	61.62	AI58

Appendix B: Methodology for the computation of wave parameters from sea clutter images

425 We stated above (section 2.2.2) that to relate the signal to the wind waves, we assume that components of the spectrum outside of the dispersion relation are related to the background speckle-noise and components of the spectrum that satisfy the dispersion relation (1) related to the signal, associated with the wind waves. Eq. (1) presents the dispersion relation for the first harmonic and can be also easily extended to the second harmonic as follows:

$$430 \quad \omega_{n,z}(k) = \sqrt{2gk} + 2k \cdot U \cdot \cos \theta_n \quad (\text{B.1})$$

Here and later index n refers no the number of directional sector (22.5° width each). The curve associated with the second harmonic is clearly seen in Figure 3. The rest of the signal lying in the spectral domain outside the bands associated with dispersion curves and attributed to speckle-noise (Kanevsky, 2009) is needed to be properly quantified. This depends on the
435 algorithm used for the quantification of bands associated with dispersion relation curves. Speckle-noise is used for

normalization of the radar spectrum and removing the impulse power impact on the radar signal modulations by the sea waves (Kanevsky, 2009). The 2D normalized spectrum $S_{n,2d,norm}(k, f)$ of the signal at each wavenumber k can be calculated as:

$$440 \quad S_{n,2d,norm}(k, f) = \frac{S_{n,2d,image}(k, f)}{\int S_{n,2d,image,\omega\ speckle}(k, f) df} - 1 \quad (B.2)$$

where the speckle frequency is:

$$\omega_{speckle} = (f \notin \omega_{n,1}/2\pi \text{ and } f \notin \omega_{n,2}/2\pi) \quad (B.3)$$

445 Then the full image spectrum $S_{n,1,\omega}(f)$ needs to be filtered to obtain the power corresponding to the band capturing the first $\omega_{n,1}$ harmonic for the direction n :

$$S_{n,1,\omega}(f) = \int_{k_{n,1}-\Delta k}^{k_{n,1}+\Delta k} S_{n,2d,norm}(k, f) dk \quad (B.4)$$

Here $k_{n,1}$ is the dispersion relation (1) solution for the first harmonic $\omega_{n,1}(k_{n,1}) = 2\pi f$ and Δk is related to the size of the processing area (720 m) as $\Delta k = 0.02 \approx 2 \cdot 2\pi/720$ (rad/m). Similarly for the second harmonic $\omega_{n,2}$ we obtain:

$$450 \quad S_{n,2,\omega}(f) = \int_{k_{n,2}-\Delta k}^{k_{n,2}+\Delta k} S_{n,2d,norm}(k, f) dk \quad (B.5)$$

where $k_{n,2}$ is the dispersion relation (B1) solution for the second harmonic $\omega_{n,2}(k_{n,2}) = 2\pi f$.

The total power $S_{n,\omega}(f)$ falling in the bands along dispersion relation curves yields:

$$S_{n,\omega}(f) = S_{n,1,\omega}(f) + S_{n,2,\omega}(f) \quad (B.6)$$

455 Given that this procedure is applied to all 16 sectors of the image (see section 2.2.2), the omnidirectional image frequency spectrum $S_{image}(f)$ can be derived as follows:

$$S_{image}(f) = \frac{1}{16} \sum_{n=1}^{16} S_{n,\omega}(f) \quad (B.7)$$

Further integration over the frequency domain returns the zeroth moment $m_{0,image}$ of the $S_{image}(f)$ spectrum:

$$460 \quad m_{0,image} = \int_{fr^8}^{fr^{48}} S_{image}(f) df, \quad (B.8)$$

which provides us with the estimate of SNR being:

$$SNR \equiv m_{0,image} + 1.$$

The limits of the integration in (B.8) are $fr^8 = 8\Delta f$ and $fr^{48} = 48\Delta f$, where $\Delta f = \frac{rpm}{60 \cdot 48}$ is defined by the antenna rotation speed rpm (rotations per minute, Table 2) and the 48-points size window of FT in the time domain.

465 Formally, considering the $S_{image}(f)$ spectrum as a modulation analog of the real sea wave spectrum, $S_w(f)$, the zeroth moment $m_{0,image}$ can be further converted to the magnitude of signal modulations H_{image} on the radar image which stands as a provisional measure of H_s :

$$H_{image} = 4\sqrt{m_{0,image}} \quad (B.9)$$

470 Further the transform of the omnidirectional SeaVision image frequency spectrum $S_{image}(f)$ to the sea wave frequency (wave energy) spectrum $S_{w,SeaVision}(f)$ visible by SeaVision is performed by applying the standard technique described in section 2.2.2 and resulting in Eq. (2) returning significant wave height $H_{s,SeaVision}$ estimate based on the radar calibration coefficients A and B along with estimate for the wind wave period (3) derived from the zeroth and the first moments of the spectrum.

475 The mean wave direction $D_{s,SeaVision}$ is estimated with the centroid method

$$D_{s,SeaVision} = \frac{180}{\pi} \arg \left(\frac{\sum_{n=1}^{16} \exp(i\frac{\pi}{180}\theta_n) D_n}{\sum_{n=1}^{16} D_n} \right), \quad (B.10)$$

$$D_n = \int_{f_r^{48}}^{f_r^{48}} S_{n,\omega}(f) df, \quad (B.11)$$

where \arg is the argument of the complex number, D_n is the zeroth moment of the spectrum $S_{n,\omega}(f)$ in the direction n .

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Appendix C: Definition of all the parameters in the manuscript and dataset.

Parameters	Short name	Definition	Range	Name in netcdf
Meteorological variables				
Wind Speed ($m \cdot s^{-1}$)	U_{10}	-	-	meteo_wspd
Wind Direction ($^{\circ}$)	θ_{10}	-	0 – 360° (from)	meteo_wdir
Atmospheric Pressure (hPa)	p	-	-	meteo_pres
Atmospheric Temperature ($^{\circ}C$)	T	-	-	meteo_temp
Humidity (%)	H	-	0 – 100 %	meteo_humd
Spotter wave buoy variables				
1-D wave energy spectrum ($m^2 \cdot Hz^{-1}$)	$S_{w,Spotter}$	$\int_{f^4}^{f^{127}} S(f) df$	0.01 – 1.25 Hz	buoy_Szz, buoy_freq
Significant Wave Height (m)	$H_{s,Spotter}$	$4\sqrt{m_{0,Spotter}}$	0.2 – 4.2 m	buoy_hs
Energy Wave Period (s)	$T_{m01,Spotter}$	$\frac{m_{0,Spotter}}{m_{1,Spotter}}$	1.85 – 8.85 s	buoy_ts

Mean Wave Direction (°)	$D_{s,Spotter}$	270° $-\frac{180^{\circ}}{\pi} \arctan 2(b_1, a_1)$	0 – 360° (from)	buoy_ds
SeaVision variables				
1-D wave energy spectrum ($m^2 \cdot Hz^{-1}$)	$S_{w,SeaVision}$	Eq. 6	0.0423 – 0.4069 Hz	radar_Szz radar_freq
Significant Wave Height (m)	$H_{s,SeaVision}$	$4\sqrt{m_{0,SeaVision}}$	0.3 – 3 m	radar_hs
Energy Wave Period (s)	$T_{m01,SeaVision}$	$\frac{m_{0,SeaVision}}{m_{1,SeaVision}}$	3.7 – 8.5 s	radar_ts
Mean Wave Direction (°)	$D_{s,SeaVision}$	Eq. B.10	0 – 360° (from)	radar_ds

Author contributions

485 NT, AG, DI, VS, AS, LS, VS and PS participated in research cruises and data collection. The leading role in field work program development and implementation belongs to AG and VS. DI made preprocessing, postprocessing and analysis of the radar (SeaVision) dataset, VS developed the configuration and ran the WW3 model for the period of cruises, AG analysed all Spotter buoy data. EE, AG and VS did validation with satellite missions. VF, BT and SB provided hardware development and mounting of the SeaVision to the research vessels. VT, OR and AS provided operational support for the research cruises. NT has a leading role in the project set up and manuscript writing. The initial idea of the research belongs to SG. The scoping of the manuscript was developed by NT, SG and KPK. All authors contributed to the discussion, interpretation of the results and writing.

Competing interests

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The authors declare no conflict of interests.

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