Deltares

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Summary

Using satellite data in our work can help improve our wave models and wave knowledge, allowing for more accurate hydraulic boundary conditions and wave forecasts. Thus, ensuring safe and habitable deltas for now and in the future.

With a new generation of satellite sensors and processing methods, new possibilities emerge to use wave information from satellite data. Until now, the use of wave information derived from satellite data was limited to offshore areas and one parameter: the significant wave height. However, due to new technologies, wave information becomes increasingly reliable closer to the shore.

In this project - part of the Rijkswaterstaat Corporate Innovation Program (CIP) - a technology scan is performed on existing technologies and analysis methods to derive wave information from satellite data. The objective is to provide an overview of these technologies and to determine which ones are most promising to improve and validate the RWsOS SWAN North Sea wave models. Moreover other applications of wave information derived from satellite data are explored, such as filling in nearshore knowledge gaps (for instance for BOI and navigation), satellite data in addition to in-situ measurements and quantifying the effect of offshore wind parks on wave propagation. Through this study, we aim to lower the threshold for applying satellite data for wave applications in Deltares and Rijkswaterstaat projects by building knowledge and expertise.

Three relevant satellite technologies are radar altimetry, SAR imagery and optical satellite imagery. Several datasets/products that make use of one or more of these technologies were analysed in more detail. In the SWAN-North Sea case study it was shown that processed satellite data from radar altimetry can provide accurate wave field information (significant wave height and wave spectra) in the deeper parts of the North Sea.

Recommendations for further research and application of wave information, derived from satellite data, are given for two questions: 1) which satellite techniques and data products to apply in the SWAN North Sea project and 2) which satellite missions and techniques are promising and worth further investigation for nearshore applications.

1. For the application of satellite data in SWAN North Sea models the following is recommended:
    - The CMEMS (Copernicus Marine Environmental Monitoring Service) significant wave height product provides accurate information at 100 km or more distance from the coastline. The product is derived from radar altimetry. The product can be used for model validation of SWAN-North Sea (SWAN-NS), sensitivity studies, to improve the SWAN (RWsOS) forecasts using Machine Learning (ML) or data assimilation. The CMEMS data set is user friendly and can be relatively easy implemented depending on type of application. It is recommended to apply the use of this product within the SITO-PS Model schematizations program.
    - CFOSAT (radar altimetry) and Sentinel-1 (SAR Imagery) can be used for wave spectra validation within the SWAN-NS model domain and at its model boundary. It is recommended to explore the use of this product within the SITO-PS Model schematizations program.
2. For application of satellite data nearshore, the following recommendations are made:
    - With some additional effort, SWOT data (the Surface Water and Ocean Topography satellite mission) is useful for insights nearshore and/or to capture wave fields in a

large area. The technologies used in SWOT are radar altimetry and interferometric SAR. It is recommended to further explore this satellite mission in the CIP satellite follow-up project.

- The processing of optical Sentinel-2 imagery (optical satellite imagery) offers the generation of local image spectra in the nearshore and thereby a proxy for 2D wave spectra. Such spectra do not directly include wave energy/heights, but provide nearshore wave direction statistics of dominant wave periods. Wave heights could possibly be derived using in-situ measured wave spectra for scaling/assimilation. It is recommended to further explore this satellite mission in the CIP satellite follow-up project.
- Finally, it is recommended to explore the processing techniques for waves from SAR imagery, for example Sentinel-1 or from commercial satellites in the CIP satellite follow-up project.

Contents

1 Introduction

1.1 Background and motivation

With a new generation of satellite sensors and processing methods, new possibilities emerge to use wave information derived from satellite data for applications in the North Sea. Until now, the use of wave information derived from satellite data was limited to offshore areas and one parameter: the significant wave height. However, due to new processing technologies and satellite sensors, wave information becomes increasingly reliable closer to the shore. In addition, various satellite missions facilitate the determination of wave spectra. Moreover, a push in imaging techniques makes it possible to extract wave directions from satellite images. The knowledge and expertise to use satellite data for wave applications needs to be built up within Deltares and Rijkswaterstaat. Therefore, it is time to examine how wave information from satellites could meet our knowledge questions and measurement needs for various applications.

Within the Rijkswaterstaat Operational Systems (RWsOS), the SWAN North Sea wave models are used to provide wave forecasts for the Dutch coast. These forecasts are essential for safe navigation and safety precautions during highwater conditions. The SWAN North Sea models are one application for which satellite data could be useful. Not only for model validation and calibration, but also as input for Data assimilation or Machine Learning models. Another application is to (partly) replace the wave measurements that are being done at oil platforms in the North Sea, as these platforms are bound to disappear in the future (for example K13 platform). Note that satellites cannot completely substitute in-situ measurements as these are required for calibration of the satellite products. Finally, current knowledge gaps like the effect of wind farms on waves or the wave directions in the Western Scheldt and Eems-Dollard could be filled with satellite information. All these applications of satellite data are briefly touched upon in the present report.

1.2 Objective

In this project - part of the Rijkswaterstaat Corporate Innovation Program (CIP) - a technology scan is performed on existing technologies and analysis methods to derive wave information from satellites. The objective is to give an overview of these technologies and to identify which have the most potential for the improvement and validation of the operational SWAN North Sea wave models. In addition, other applications of satellite wave information (nearshore) are explored. Through this study, we aim to lower the threshold for applying satellite data for wave applications in Deltares and Rijkswaterstaat projects by building up knowledge and expertise.

1.3 Set up of the report

In chapter 2, the focus is on the potential of satellite data for the SWAN North Sea models. Different techniques have been assessed, from mainstream CMEMS products to research products like CFOSAT. More information on the relevant satellite technologies can be found in Appendix A. In chapter 3, a quick scan is performed of using wave information derived from satellite data in other application areas. Finally in chapter 4 the conclusions and recommendations are given. In addition, a plan of approach for follow-up studies has been provided. A glossary and insight in some of the acronyms, that have been used in this study, is provided.

2 SWAN North Sea case

2.1 SWAN North Sea wave models

Within the Rijkswaterstaat Operational Systems (RWsOS), the SWAN North Sea wave models (SWAN-North Sea (SWAN-NS) and SWAN-Kuststrook (SWAN-KS)) are used to provide wave forecasts for the Dutch coast, see Figure 2.1. In the evaluation for both models (Deltares, 2023) it can be observed that the overall performance of SWAN in the North Sea is generally good. However, for the more extreme events the significant wave height H_{m0} and the swell wave height (H_{E10}) are often underestimated, see for example Figure 2.2, the scatterplot of the computed swell wave height of the SWAN-North Sea model versus in-situ observations at location A12.

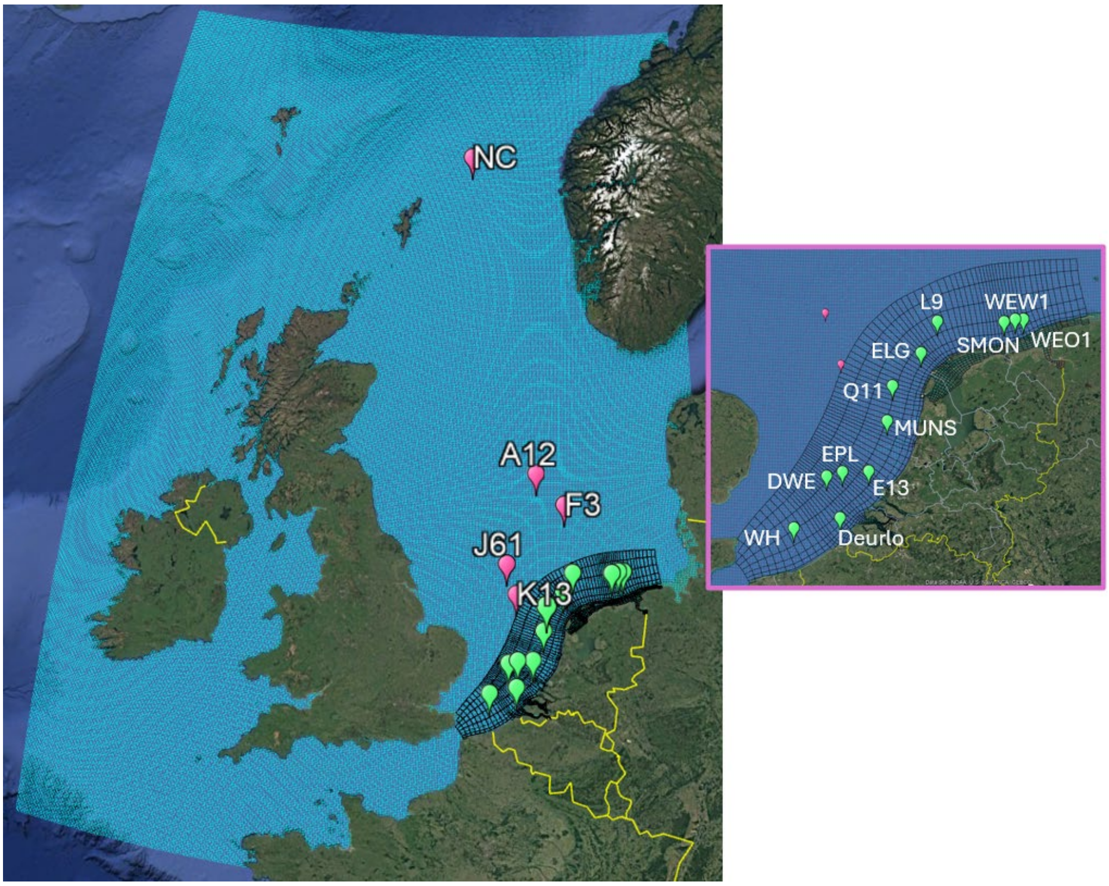


Figure 2.1 SWAN North Sea models with a selection of wave measurement locations ("offshore" and "nearshore" locations in pink and green respectively), in blue the grid of SWAN-NS in black the grid of SWAN-KS (every 10th gridline), Google Earth image.

For the calibration, validation and model developments of the SWAN-North Sea models, wave measurements are used, usually from a wave buoy or other wave measuring device. Although there is a fair amount of wave measurement data available for the North Sea, most wave measurements are concentrated near the Dutch coast.

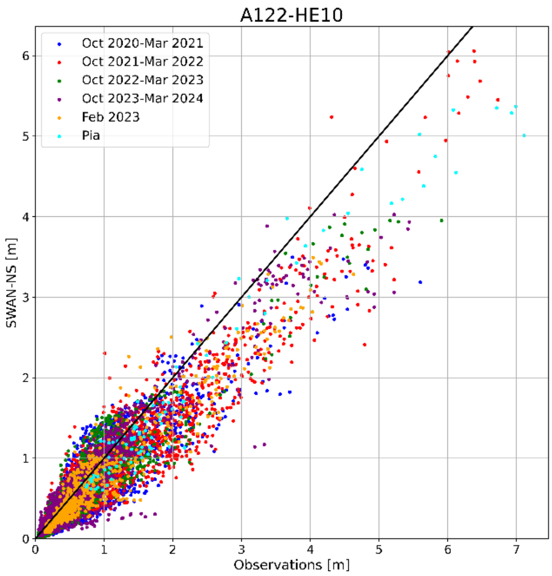


Figure 2.2 Scatter plot computed swell wave height H_{E10} SWAN-NS versus observations at location A12 for four storm seasons.

Satellite wave data could be beneficial for several purposes:

- Providing more wave data, especially in parts of the model domain in which wave measurements are sparse. In these areas, it would be favourable to have not only the wave height, but also more wave parameters or the wave spectrum.
- Providing spatial wave information in the domain of the two wave models. To understand for example why swell waves are often underestimated by our operational models, spatial wave information from satellite data could be beneficial in addition to point wave measurements. Spatial satellite data may be used for the calibration and validation of the wave models, but also to gain system knowledge, which helps to understand how the wave models can be improved.
- Improving the wave models with data assimilation or machine learning models by using available satellite data.

2.2 Introduction satellite technologies

Satellite operators and space agencies like e.g. ESA, CNES and NASA are involved in preparing the space missions, see Figure 2.3. Raw satellite products L0 products are subject to limited distribution, L1 has had radiometric and geometric corrections and L2 has undergone atmospheric corrections and contains the so called geophysical variables, which are the parameters of our interest, such as significant wave height. L3 products typically contain mapped geophysical variables that are quality controlled and validated. L3 altimetry products are often harmonised multi-mission products. There are several upstream data providers that host L2 products such as EUMETSAT, which can be a natural starting point for developing post-processing algorithms. The mapped L3 products are commonly used for validation, data assimilation and would therefore be the most natural starting point for wave model validation. L4 products are often already interpolated or assimilated. CMEMS (the Copernicus Marine Environmental Monitoring Service) is a typical downstream data provider that hosts these L3 and L4 products.

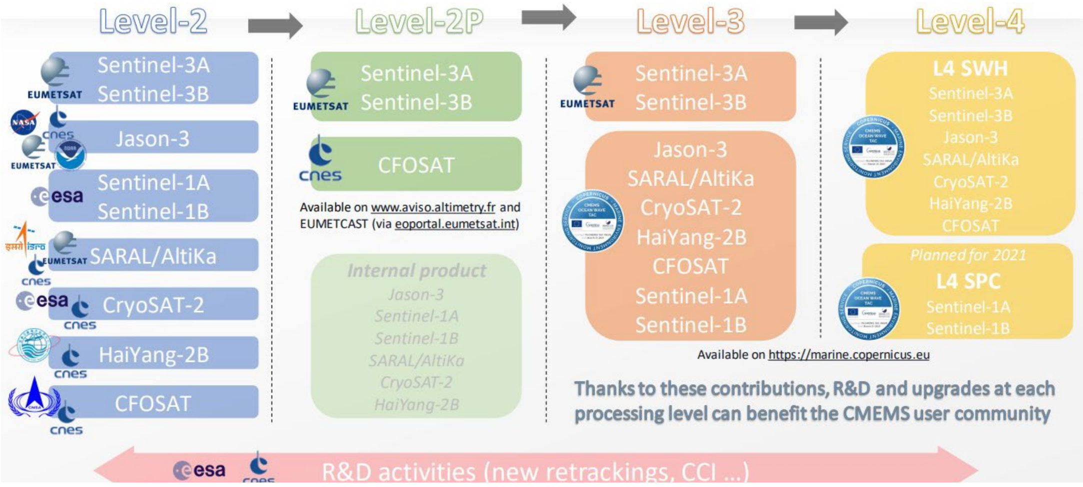


Figure 2.3 Overview of satellite operators and downstream providers (Source: presentation CCI Sea State User Consultation Meeting 23-25 March 2021)

Typically, data from three different satellite technologies are used to derive wave fields:
- Radar altimetry (RA); directly measuring the heigh of the Earth's (sea) surface. This can be done for example in low resolution mode (LRM) or unfocussed Synthetic Aperture Radar (SAR)-mode. A new method of processing SAR-mode altimetry data, fully focussed processing, results in a higher resolution.
- SAR Imagery; acquiring 2- or 3-D images of the Earth's (sea) surface;
- and optical satellite imagery; acquiring information making use of the spectrum of visible light (colours) but also the near-infra red.

Appendix A provides more information on these technologies.

Recently, technologies were combined and Delayed-Doppler (DD) altimetry and nadir (down-looking) SAR-mode altimetry has become available, with increased along-track resolution. Another new generation altimeter is using an Interferometric SAR (InSAR) wide-swath mode and is used in the Surface Water Ocean Topography Mission (SWOT). Apart from this, the China France Oceanography Satellite (CFOSAT) is a scanning-beam Real Aperture Radar (RAR) with a Surface Wave Investigation and Monitoring (SWIM) sensor and a scatterometer that was designed to extract wave spectra and collocated surface wind speed measurements. Appendix A provides more information on these technologies.

In this case study a selection of satellite products/ processing methods have been studied:
- The CMEMS L3 significant wave height product (Radar altimetry)
- The level 4 WAVERYS product of significant wave height peak period (Radar altimetry)
- CFOSAT (Radar Altimetry; RAR with SWIM sensor) provides data to derive wave spectra
- Sentinel-1 (SAR imagery) provides data to derive wave spectra
- SWOT data high resolution satellite (Radar altimetry and interferometric SAR)
- A new way to process altimetry from Sentinel-6 (Radar altimetry with fully focussed SAR-mode processing) to derive significant wave height (SWH)

All these products/ processing methods have become available in the last couple of years and are therefore relatively new.

2.3 Level 3 CMEMS wave height (RA – (P)LRM and SAR)

2.3.1 Product description

The Copernicus Marine Services (CMEMS) hosts the Wave Thematic Assembly Center (WAVE TAC). CMEMS is a downstream data provider that hosts Level-3 (L3) and Level-4 (L4) products, as can be seen in Figure 2.3. The service oversees production of nadir altimetry, SAR (Sentinel-1) and off-nadir altimetry (SWOT and CFOSAT SWIM). For altimeters, Level-3 SWH products are delivered along the tracks of the different altimeters. L4 products are merged altimeter or SAR products on a spatial grid with a daily time step. Available products in WAVE TAC are (in brackets the dates available and the spatial resolution):

1. WAVE_GLO_PHY_SWH_L3_NRT_014_001 (1 Jan 2021 to today; 7kmx7km)
2. WAVE_GLO_PHY_SWH_L3_MY_014_005 (15 Jan 2002to 1 Jan 2021; 7km x7km)
3. WAVE_GLO_PHY_SWH_L4_NRT_014_003 (1 Jan 2020 to today; 2°x2°)
4. WAVE_GLO_PHY_SWH_L4_MY_014_007 (15 Jan 2002 to 21 Dec 2020; 2°x2°)
5. WAVE_GLO_PHY_SPC_L4_NRT_014_004 (1 Nov 2021 to today; 1°x1°)
6. WAVE_GLO_PHY_SPC_L3_MY_014_006 (14 April 2016 to 31 Dec 2020)
7. WAVE_GLO_PHY_SPC_L3_NRT_014_009 (1 Nov 2021 to today; 70kmx70km)
8. WAVE_GLO_WAV_L3_SPC_NRT_OBSERVATIONS_014_002 (28 May 2018 to today)

SPC refers to spectral wave data but is only available for open ocean. NRT refers to Near Real Time and MY is the Multi Year product. Data is accessible through https://data.marine.copernicus.eu/product/WAVE_GLO_PHY_SWH_L3_NRT_014_001/description. Appendix B provides a link to a python toolbox to process the satellite data.

For the model validation of the SWAN-NS SWH, the first two datasets WAVE_GLO_PHY_SWH_L3_NRT_014_001 and WAVE_GLO_PHY_SWH_L3_MY_014_005 are most relevant considering the resolution of the product and direct availability of SWH and collocated wind speed measurements from upstream L2 products. In this chapter the first product (*014_001) is further elaborated as this data period matches recent storm(period)s analysed by Deltares (2023) and contains a relatively large set of ten different satellite missions which is necessary for sufficient temporal and spatial coverage in the North Sea.

Table 2.1 shows all altimetry missions involved in 014_001 and relevant characteristics. Technology types are: Low Resolution Mode (LRM), Pseudo Low Resolution Mode (PLRM) and Synthetic Aperture Radar (SAR). PLRM means that the radar emits bursts of pulses rather than a continuous stream of pulses. Note that cycle duration refers to a return time of one track on the same location. We would expect 2 tracks per day for Jason-3 somewhere in the North Sea for example. The beam limited footprint is the area of the target surface. If this overlaps with land, the result (wave height for example) can be contaminated.

One file containing valid SWH is produced for each mission and for a 3-hour time window. It contains the filtered SWH (VAVH), the unfiltered SWH (VAVH_UNFILTERED), the wind speed (wind_speed) and the time, latitude and longitude.

*Table 2.1 : CMEMS WAVE_GLO_PHY_SWH_L3_NRT_014_001 altimetry missions and characteristics. *SSC= Sunsynchronous*

Mission	Start date till present	Cycle Duration (days)	Latitude Range (°N)	Number of Tracks per Cycle	Inter-track Distance at Equator (km)	SSC	Technology	Beam Limited Footprint [km]
Jason-3	01/01/2020	10	±66	254	~315	No	LRM	~29
Sentinel-3A	01/01/2020	27	±81.5	770	~104	Yes	SAR+PLRM	18-19
Sentinel-3B	01/01/2020	27	±81.5	770	~104	Yes	SAR+PLRM	18-19
SARAL/ AltiKa	01/01/2020	Non-cyclic (since July 2016)	±81.5	1002 (per pseudo cycle)	~80	Yes	LRM	8-9
CryoSat-2	01/01/2020	29 (sub cycle)	±88	840	~98	No	LRM+SAR +InSAR	~15
CFOSAT	01/01/2020	13	±83	394	TBC	Yes	LRM (nadir + off nadir)	<13
HaiYang2B	07/07/2020	14	±81	386	~210	Yes	LRM	~21
Sentinel-6A	17/12/2020	10	±66	254	~315	No	LRM	~30
HaiYang2C	29/11/2022	10	±66	274	293	Yes	LRM	~21
SWOT nadir	29/11/2023	28	±77.6	584	120	No	LRM	unknown

Quality and calibration L3 SWH
The quality of the significant wave height is controlled via a standard CMEMS processing chain. L2P (Level 2 'Plus') files contain along track L2 altimeter data and flags. Based on various criteria such as quality flags and parameter thresholds reliable L2P data is selected. Following, L2P data is calibrated in two steps. First, a long reference mission (now Jason-3, once there is enough data Sentinel-6A will serve as the reference mission) is calibrated against in-situ data. The used in-situ data is stored in the product 'Global Ocean- In-Situ Near-Real-Time Observations'. Second, other satellites are cross-calibrated with the reference mission. This calibration step reduces the inter-mission bias. Next at L3, filtering developed by IFREMER experts (Quilfen et al., 2018) is applied to the L2P data. This step mainly reduces the standard deviation of the crossover differences.

2.3.2 Exploring CMEMS applications: comparison with SWAN-NS and in-situ observations
In this paragraph the CMEMS altimeter product (*014_001, see Table 2.1) is explored to identify the potential of the CMEMS product for (improving) North Sea wave modelling. First, the availability and performance of the altimeter wave heights in the North Sea is discussed. Second, the altimeter product is compared with SWAN-North Sea (SWAN-NS) in hindcast mode. To quantify and illustrate this analysis, 4 (storm)periods are selected; storm Pia (December 19 – 24, 2023), Eunice (February 16 – 23, 2022) and the periods February 2023 and January-February 2022.

Satellite altimeter missions provide the wave height along its track. This means that a track is present in a specific region, such as the North Sea and wave heights are not measured hourly, but in intervals. Figure 2.4 shows all satellite tracks of all missions of the CMEMS product for storm Pia. It can be seen that in these 5 days, more than 12 thousand altimeter wave heights are measured and the North Sea domain is covered quite well.

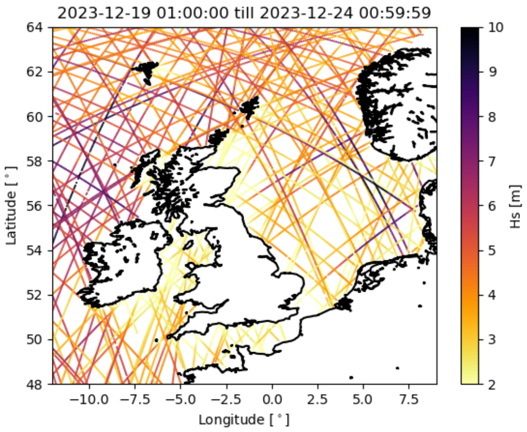


Figure 2.4 Storm Pia satellite tracks within SWAN-NS domain for 5 days.

To quantify the performance of the CMEMS altimeter product, the statistics of the satellite wave heights versus in-situ observations is calculated for offshore and nearshore locations (see Figure 2.1). Since the probability of a satellite track crossing exactly an observation station is very low, maximum distances between the track and station is applied. Since less spatial differences in wave conditions are expected offshore, this maximum distance is larger (< 15 km) than nearshore (< 7.5 km). For a two-month period and five offshore stations this results in a total of 169 datapoints for the statistical analysis (Table 2.2). Using the same time points and locations from SWAN-NS, the performance of both SWAN-NS and CMEMS can be compared (Table 2.3).

Table 2.2 Performance statistics of SWAN-NS and the CMEMS altimeter data product within 15 km distance in comparison with offshore in-situ observations for four periods.. With N the number of points, relBias the relative Bias, SCI the scatter index and RMSE the root mean square error.

Offshore (distance<15 km)	**N**	**relBias [-]**		**SCI [-]**		**RMSE [m]**	
		SWAN	CMEMS	SWAN	CMEMS	SWAN	CMEMS
Pia	21	-0.12	-0.02	0.06	0.04	0.45	0.15
Eunice	50	0.1	-0.03	0.16	0.07	0.71	0.27
Feb2023	122	0.05	0.01	0.12	0.09	0.3	0.22
JanFeb2022	169	0.05	-0.01	0.14	0.07	0.49	0.24

Table 2.3 Performance statistics of SWAN-NS and the CMEMS altimeter data product within 7.5 km distance in comparison with nearshore in-situ observations for four periods.. With N the number of points, relBias the relative Bias, SCI the scatter index and RMSE the root mean square error.

Nearshore (distance<7.5 km)	**N**	**relBias [-]**		**SCI [-]**		**RMSE [m]**	
		SWAN	CMEMS	SWAN	CMEMS	SWAN	CMEMS
Pia	18	0.14	-0.02	0.08	0.08	0.43	0.22
Eunice	27	0.04	-0.06	0.2	0.19	0.68	0.67
Feb2023	71	0.08	0	0.18	0.2	0.23	0.24
JanFeb2022	107	0.06	-0.03	0.16	0.16	0.35	0.34

For the offshore locations (>100 km distance from the coastline, Table 2.2) it can be seen that CMEMS performs generally better (matches in-situ observations better) than SWAN-NS. It is expected that the altimeter product performs well as it is (cross-)calibrated with in-situ observations. Nearshore the performance of SWAN-NS and CMEMS is similar. Reasons why CMEMS performs less near the coast could be due to the influence of land (beam limited footprint is larger than the distance between the in-situ station and the land boundary); processing techniques not being able to capture shallow water wave heights; or lack of nearshore observation stations (less calibration near the coast).

Spatial analysis
CMEMS and SWAN-NS can also be compared spatially. Figure 2.5 visualises the percentual difference between CMEMS and SWAN-NS significant wave heights at similar times (max 30 minute difference, hourly SWAN computations) and locations (nearest SWAN grid point) for storm Pia. It can be seen that at some locations the difference is remarkably large (>30%). During storm Pia large differences between the SWAN model and observations were observed, so this difference is not completely unexpected.

Knowing that the performance of "offshore" CMEMS is quite good, this kind of analysis can give insights into the spatial performance of SWAN. It can show if/in which areas SWAN systematically over- or underestimates (red lines and blue lines respectively in Figure 2.5) significant wave heights.

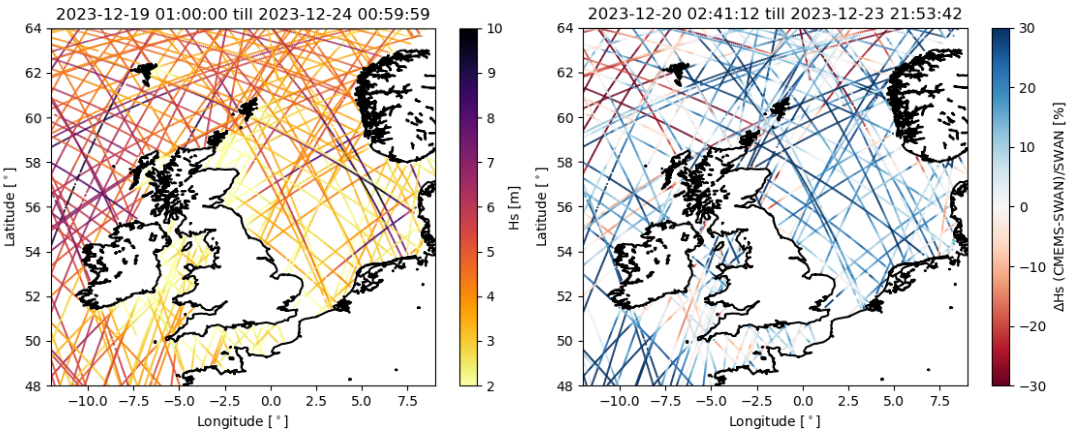


Figure 2.5 Storm Pia satellite tracks within SWAN-NS domain. The CMEMS significant wave height (left) and the percentual difference between CMEMS and SWAN (right). (The period covered differs slightly.)

Table 2.4 presents the statistics of the analysed storm periods.

Table 2.4 Statistics of CMEMS versus SWAN significant wave heights. With N the number of points, SCI the scatter index and RMSE the root mean square error.

All points CMEMS versus SWAN	N	relBias [-]	SCI [-]	RMSE [m]
Pia	12627	0.07	0.24	1.04
Eunice	25293	0.04	0.12	0.55
Feb2023	85239	0.06	0.11	0.42
JanFeb2022	SWAN maps not analysed			

The results for one point in time can be analysed spatially, see Figure 2.6. This figure shows the significant wave height SWAN-NS map output with the CMEMS altimeter data plotted on top. If SWAN and CMEMS would have given the exact same results, the stripes (altimeter data) could not be identified from this plot. It is noted that not for every time step (hour) altimeter data is available. This type of analysis gives for specific times and events insights where (and perhaps also gives a lead as to why) wave heights are over- or underestimated.

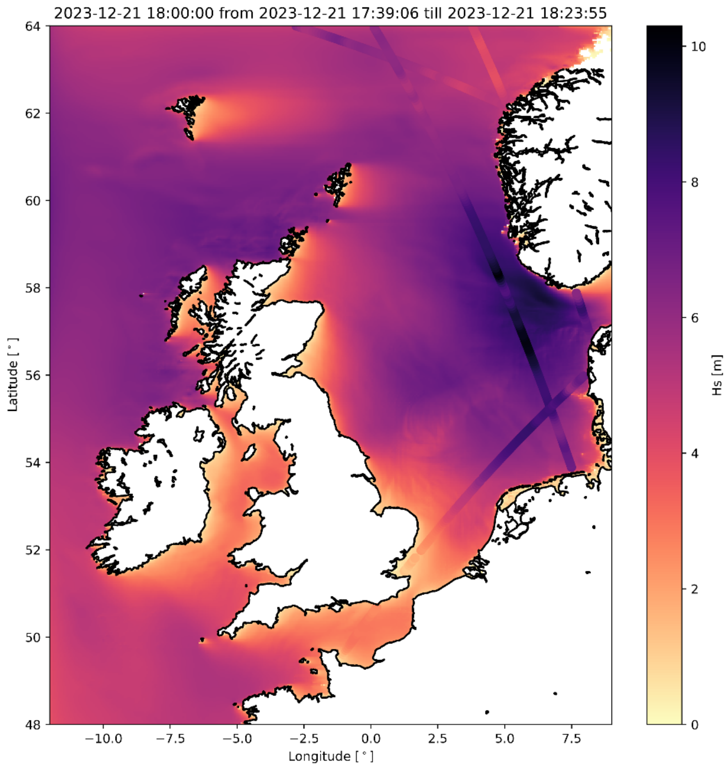


Figure 2.6 SWAN-NS Hs output map of Storm Pia on 18:00 21st of December. The (darker) stripes present the Hs from satellite tracks that passed 20 minutes before and after 18:00.

2.3.3 Conclusion, CMEMS applications for SWAN-NS

It is shown that the performance of CMEMS offshore (>100 km distance from coastline) is quite good. Offshore, CMEMS has on average for the analyzed periods a RMSE of 0.22 m, a relative Bias of -1% and a Scatter index of 7%. There is still some spread (SCI and RMSE) in comparison with in-situ observations, therefore it is necessary to include in-situ observations if possible and available. Overall it is expected that the offshore altimeter measurements meet reality sufficiently well to be used/tested for the following applications:

- General SWAN model validation:
  - Sensitivity analyses of various physical/parameter SWAN model settings for the entire SWAN-NS domain and/or parts of it can be performed. With different model settings, different error statistics will be obtained (see Table 2.4 with one set of settings). The settings with the least errors gives the best results.
  - Using CMEMS wave products, it is also possible to quantify the uncertainty of the offshore SWAN-NS results for specific areas and/or conditions.
- Improvement of operational model (forecast) results:
  - Similar to the machine learning (ML) correction that is now applied to SWAN forecasts at a few specific locations, ML could be applied for the whole offshore SWAN-NS domain. It is noted that the method to implement this needs to be developed, tested and validated. One potential approach is to divide the domain in tiles of specific size or characteristics. For each tile a correction is calculated with ML. Once this correction is implemented this might lead to improved SWAN-KS (Kuststrook) boundary conditions that in its turn might also lead to improved wave heights near the coast. See also Paragraph 2.9 for additional ML and data assimilation applications to improve the model results.

2.4 Level 4 WAVERYS (RA, SAR imagery and WAM model)

2.4.1 Product description

The Level 4 product WAVERYS is also known as the CMEMS GLOBAL_MULTIYEAR_WAV_001_032 product for global wave reanalysis and describes past sea states since the year 1993. The product can be downloaded from https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_WAV_001_032/description
The WAVERYS multi-year wave reanalysis product provides global wave data with a grid resolution of 1/5° and disseminates 3-h integrated wave parameters describing the sea state at the ocean surface. WAVERYS is based on the MFWAM[1] wave model, driven by 10-m wind provided by the atmospheric reanalysis ERA5. WAVERYS includes the assimilation of 1) altimeter wave (SWH) data and 2) directional SAR wave spectra from Sentinel-1 and the SWIM (Surface Wave Investigation and Monitoring) instrument on CFOSAT. The wave reanalysis includes wave-current interactions by using 3-hourly surface current forcing provided by the ocean reanalysis GLORYS. The wave spectrum is discretized in 24 directions and 30 frequencies starting from 0.035 up to 0.58 Hz. A minimum water depth is set at 5 m (Law-Chune et al.2021a; Law-Chune et al., 2021b).

2.4.2 Comparison

Wave statistics of significant wave height (H_{m0}), and peak period (T_p) from WAVERYS were extracted at point TWL_N (Figure 2.7). The WAVERYS data show reasonable agreement with buoy measurements of significant wave height lower than 1.5 metres, see Figure 2.8, covering nine years of data. However, the extreme wave heights are significantly underestimated by WAVERYS. This is most likely due to the coarse time and spatial resolution of the MFWAM model, which is the basis of the product. For the T_p we see huge scatter , which is the disadvantage of using this discrete parameter.

The conclusion is that the Level 4 product WAVERYS does not provide any advantage over the SWAN-North Sea model data. The wave model limitations, for example the underestimation of the more extreme wave heights is also present in the WAVERYS product, like it is in the SWAN-North Sea results. It is more beneficial to directly assimilate the satellite products into the SWAN-North Sea models, either in a reanalysis or in a forecast.

[1] Product of Meteo France: https://dcpc-nwp.meteo.fr/openwis-user-portal/srv/en/main.home

Figure 2.7 Location TWL_N, at lat. 52.545889 and lon.4.161414, where the timeseries of WAVERYS results were extracted, and the buoy IJmuiden Munitiestort (MUNS).

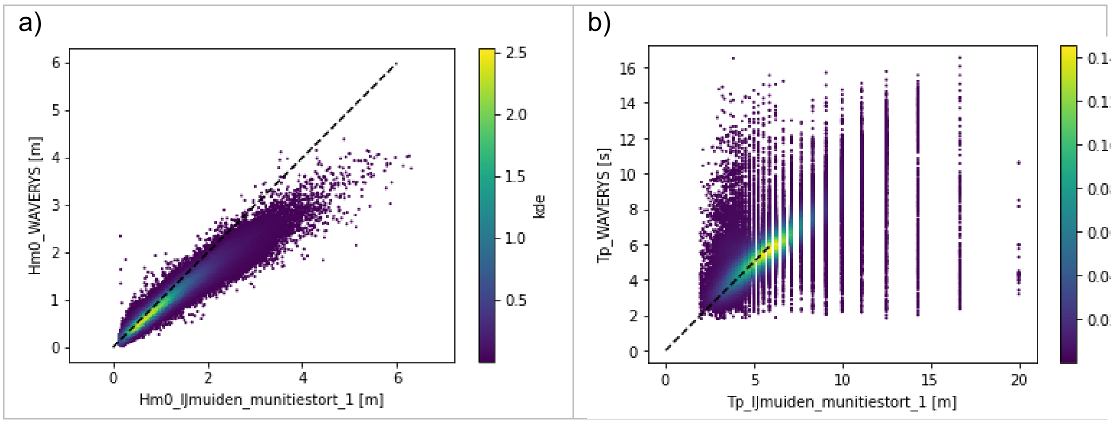


Figure 2.8 Direct comparison of WAVERYS date extracted at TWL-N and buoy data of (a) H_{m0} and (b) T_p, from 01-01-2013 until 31-12-2021 at IJmuiden Munitiestort 1 close to TWL-N. Colorbar indicates the kernel density estimation.

2.5 CFOSAT (RA – RAR with SWIM sensor)

2.5.1 Product description

The CFOSAT mission was launched in 2018 and was planned to finish in 2020, but it is still operating until today and unknown when it will finish. The CFOSAT satellite data is offered by data providers CNES and CLS. The CNES product offers processed wave directional slope spectra[2] in 70 by 90 km boxes on both sides of the nadir that are used to calculate an

[2] The relation between the directional slope spectrum and the frequency spectrum is as follows:

$$E = \int S_f(f)\mathrm{d}f = \iint \frac{S_s(k,\theta)}{k}\mathrm{d}k\mathrm{d}\theta$$

averaged wave spectrum for the boxes based on the 10-degree beam only. The 10-degree beam is considered the best beam after validation (Li., et al., 2023). The CLS product is more complex, has directional slope spectra estimates for different beams and within the boxes. The cases in this study are based on the CNES product, using the mean spectra in the 70 by 90 km boxes. The data in this study has been downloaded from: https://www.aviso.altimetry.fr/en/missions/current-missions/cfosat/access-to-data.html. Appendix B provides a link to a python toolbox to process the satellite data.

The wave spectra are provided in 12 equal discrete directions from 0 degrees to 180 degrees and 32 unequal discrete wavenumber bins from k_0=0.0126 rad/m to k_n=0.2789 rad/m. The range of wavelengths CFOSAT measures is between 70 m and 500 m, so the tail of the wave spectrum cannot be resolved. This makes it more suitable for bigger storms and longer swell waves.

To compare CFOSAT directional slope spectra and buoy frequency spectra, a conversion is needed. The dispersion relation is typically used to translate the direction slope spectra to frequency spectra. We followed Li., et al. (2023) for this conversion. The water depth in this conversion for each location was derived from the GEBCO bathymetry. After the conversion the directional spectrum was integrated to the frequency spectrum.

Buoy measurements, SWAN model output and CFOSAT measurements can be matched with the following procedure. First, the reference cycle of CFOSAT needs to be determined based on the closest date before the date of interest. Next the tracks with offset times from the references cycle can be selected (from a .kml file) that cross wave buoy locations. Then boxes that overlap with the wave buoys are selected from this particular track and the netcdf with the corresponding time stamp can be downloaded. In this case the date of interest is determined by the available measured buoy spectra (or storm of interest). Since the currently available buoy wave spectra measurements were not abundant, matches are scarce. We matched buoy spectra within the boxes or very close, within a max. window of 15 minutes.

2.5.2 Earlier validation work

Li et al. (2023) did a comprehensive global validation study (1st of January 2020 to 31st of December) of CFOSAT wave frequency spectra with wave buoys ranging from nearshore to offshore locations. Figure 2.9 shows the mean annual correlation coefficient R for an empirically fitted function to Hs derived from the CFOSAT spectral boxes and reconstructed buoy spectra. R-values of 0.3 - 0.7 are found in the North Sea, with R-values decreasing closer to the coast. This is a first indicator of the reliability of CFOSAT wave spectra for the North Sea. However, Li et al. (2023) did not find strong correlation between the error and distance to the coast, or wind speed. In contrast, the error is mainly correlated with Hs, where Hs < 2 m is detrimental to the accuracy. From this it seems that CFOSAT reliability is mainly determined by the theoretical cut-off wavelength (70 m - 500 m). This is a result of the noise effects that make it more difficult to measure smaller waves.

Here E is the total energy of the wave spectrum, S_f is the frequency spectrum, f the frequency component and $S_s(k,\theta)$ is the slope spectrum, with the wave number component k and the directional component θ.

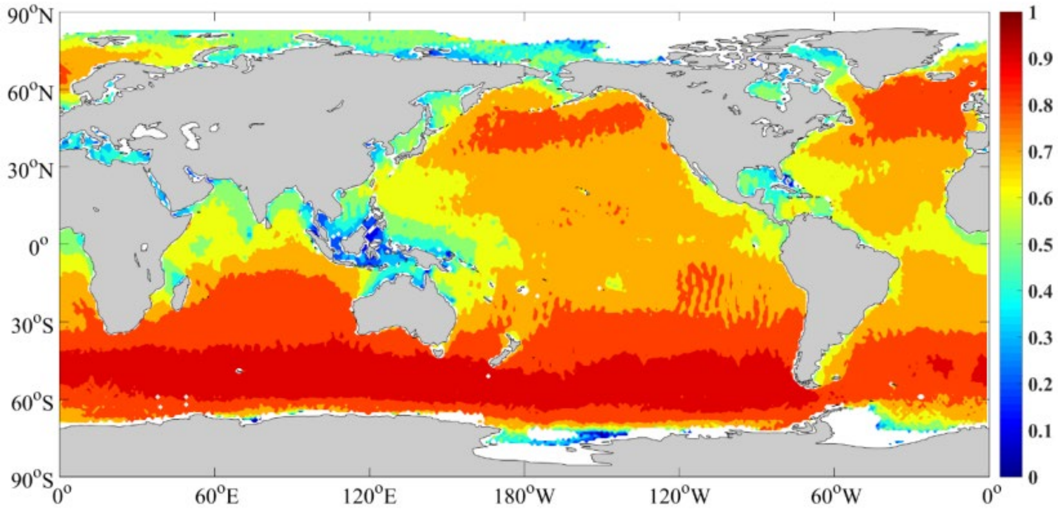


Figure 2.9 Annual mean correlation coefficient R based on the empirically fitted relationship between CFOSAT wave spectra derived Hs and buoy derived Hs (from Li et al. 2023).

2.5.3 CFOSAT 2D Wave Spectrum

The CFOSAT wave spectra are provided as directional slope spectra. Figure 2.10 shows the raw slope spectra for box 511 (left side) that matches with location North Cormorant on 2022-01-30 18:01:01.

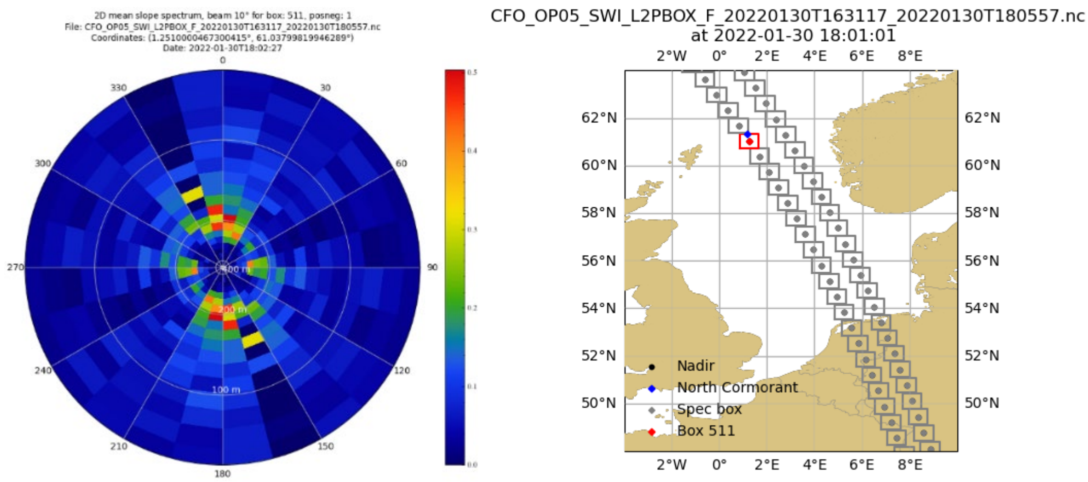


Figure 2.10 CFOSAT directional wave slope spectrum and CFOSAT track with selected box for modulation spectrum and measurement location at North Cormorant

After conversion of the slope spectrum to the frequency spectrum, an interpolation is performed to match the grid of the SWAN spectrum. The SWAN and CFOSAT converted frequency wave spectra are displayed in Figure 2.11. The CFOSAT wave spectra contain the full directional slope spectra, but they have a 180-degree ambiguity. Currently there is no automated processing to derive the correct directional bins. Commonly one can estimate the true shape of the directional spectrum by comparing with the wave model spectrum. The two partitions in the SWAN spectrum are more pronounced but can be matched with the partitions in the CFOSAT spectrum, although the latter is more diffuse. Based on this the ambiguity could be removed by defining the cutoff between 225 and 45 degrees. Note that the wave energy is divided by 2 to compensate for this ambiguity.

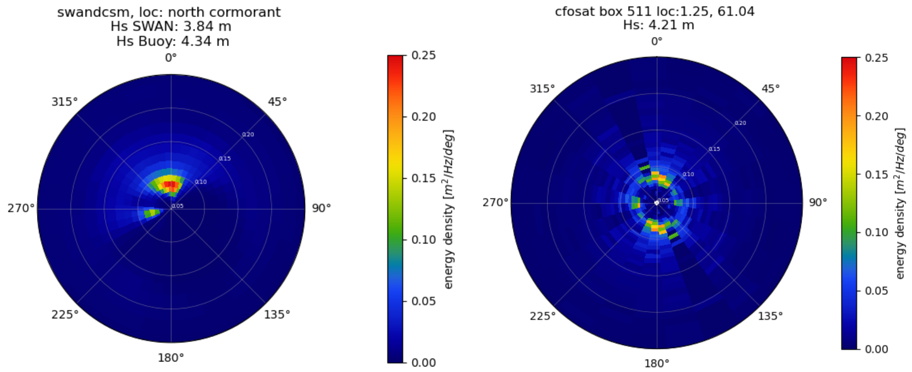


Figure 2.11 SWAN (left) and CFOSAT (right) frequency wave spectra. No measured buoy wave spectrum was available for this match, but the Hs buoy measurement was available indicated in the titles together with the CFOSAT and SWAN Hs.

Despite the absence of directional wave buoy measurements for this case, the CFOSAT Hs (4.21 m) is closer to the wave buoy Hs measurement (4.34 m) at North Cormorant, compared to SWAN Hs (3.84 m). The integrated frequency spectra of both SWAN-North Sea and CFSOAT are shown in Figure 2.12.

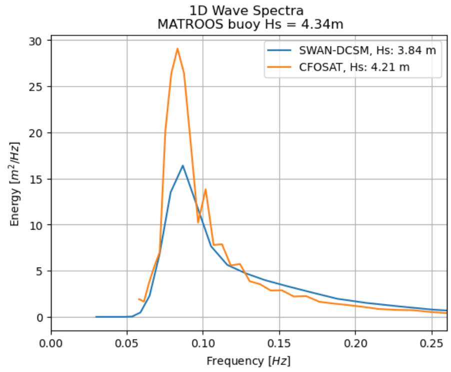


Figure 2.12 Comparison of 1D wave spectra for CFOSAT and SWAN at 2022-01-30 18:00 for North Cormorant

Since the wave buoy spectra are reconstructed as 1D wave spectra, we proceeded by comparing 1D wave spectra from wave buoys, SWAN and CFOSAT.

2.5.4 Comparison 1D Wave Spectra

We matched 1D wave buoy spectra, SWAN spectra and CFOSAT spectra between 26-11-2021 and 05-12-2021. Below, four of these matches are shown with varying performance of SWAN and CFOSAT relative to buoy measurements at North Cormorant, A12 and K13. The time differences between satellite and buoy measurements are in the order of minutes and are indicated in the title of the figures.

Figure 2.13 shows the first match were SWAN underestimates the spectrum and H_s compared to the wave buoy North Cormorant. CFOSAT approximates the spectrum measured by the wave buoy better, showing the potential benefit of CFOSAT.

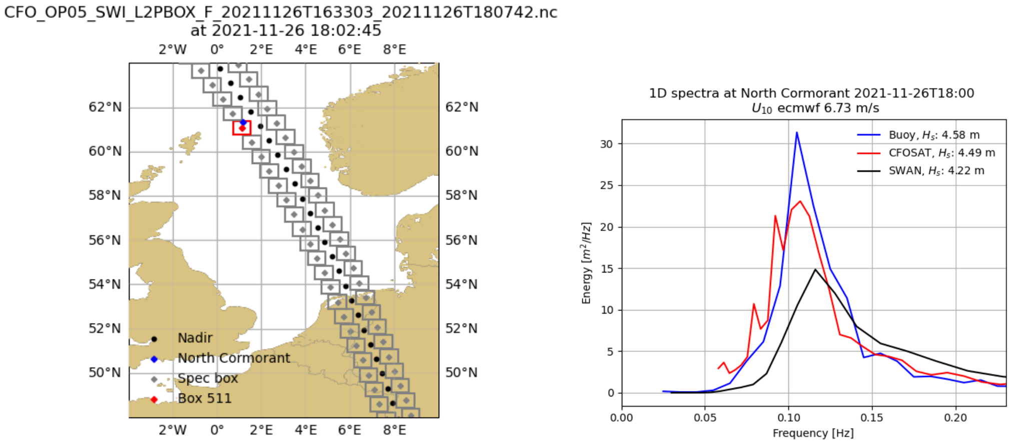


Figure 2.13 Comparison of 1D wave spectra for CFOSAT, buoy and SWAN at 2021-11-26 18:00 for North Cormorant

For illustration, Figure 2.14 displays the directional frequency spectra for SWAN and CFOSAT to illustrate the differences in directional space. Because the direction in which waves are travelling cannot be detected by the satellite, the spectrum will display energy for two opposite directions separated by 180 degrees. There is currently no automated way of masking the correct partition of the wave spectrum, but this can usually be determined by comparison with model data. The energy displayed on the color bar and the Hs values are already corrected for this. The CFOSAT 1D wave spectrum was derived from the directional wave spectrum by integration. Unfortunately, we cannot validate the directional spectrum, as wave buoy directional spectra were not available.

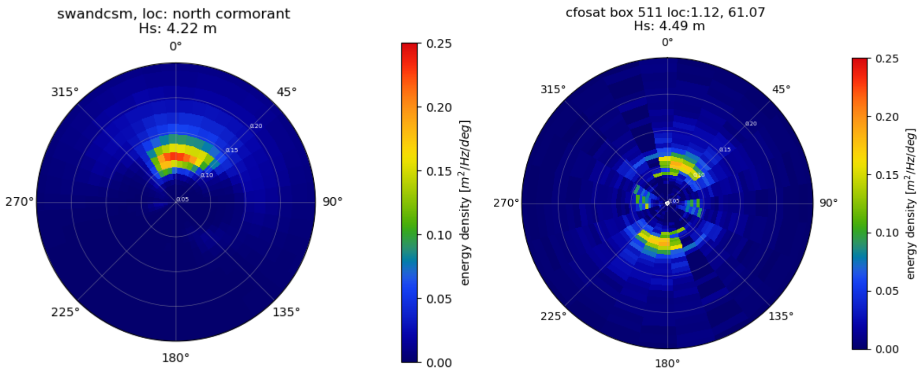


Figure 2.14 Directional frequency wave spectra for SWAN and CFOSAT at North Cormorant at 2021-11-26 18:00

Similarly, but for another moment and location, Figure 2.15 shows that SWAN underestimates the in situ observed spectrum and H_s. Interestingly CFOSAT is able to reconstruct a wave spectrum that is close to the wave spectrum observed by the wave buoy A12.

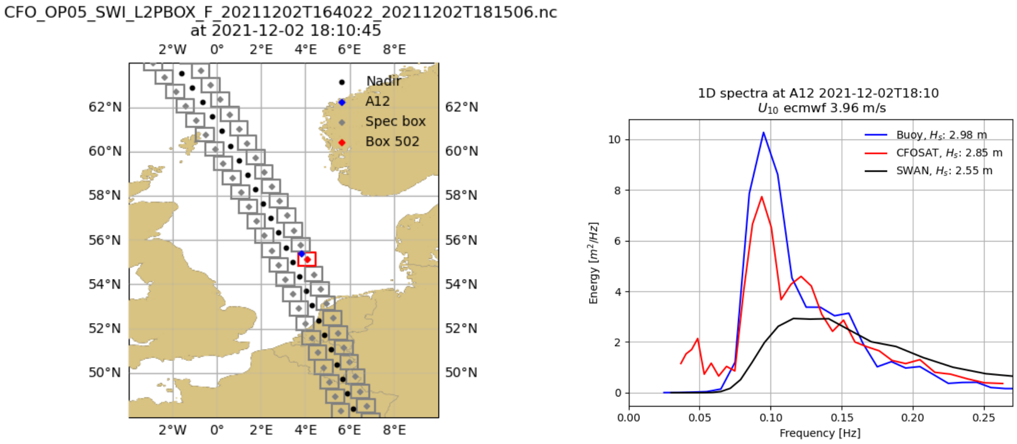


Figure 2.15 Comparison of 1D wave spectra for CFOSAT, buoy and SWAN at 2021-12-02 18:00 for A12

However, Figure 2.16 shows that for another moment in time CFOSAT is not able to closely match the wave buoy spectrum at location A12. The SWAN spectrum is a better match. It is known that CFOSAT wave measurements have low correlation with buoys when H_s is lower than 2.0-2.5 m, mainly due to the low frequency part having noisy peaks (Tourain et al., 2020; Xu., et al. 2022). This could be an explanation for the poor match.

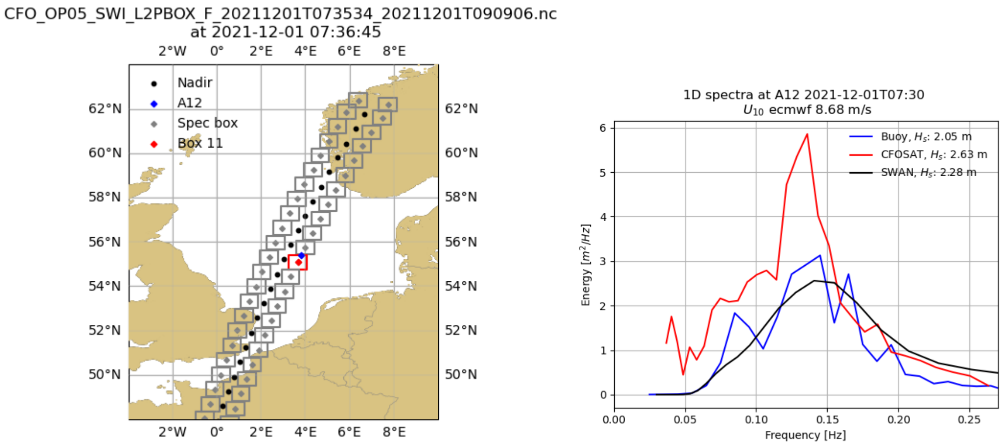


Figure 2.16 Comparison of 1D wave spectra for CFOSAT, buoy and SWAN at 2021-12-01 07:30 for A12

Finally, Figure 2.17 shows a match for station K13, where CFOSAT reconstructs the peak in the spectral shape, but still underestimates the wave energy mainly between 0.12 and 0.16 Hz. This can also be seen in the H_s comparison. Despite, the CFOSAT peak energy matches the in situ observed peak, whereas SWAN underestimates the peak energy. However, SWAN approximates the buoys significant wave height well.

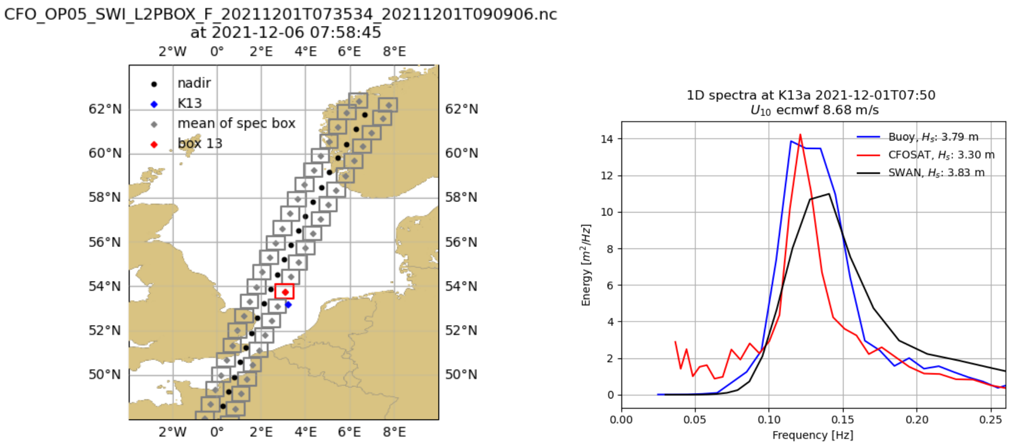


Figure 2.17 Comparison of 1D wave spectra for CFOSAT, buoy and SWAN at 2021-12-01 07:50 for K13

2.5.5 Outlook CFOSAT

CFOSAT provides a unique way of measuring directional wave spectra from space. The largest potential of CFOSAT data will be during bigger storms, swell systems and cyclones approximately 100 km from the coast. This is mainly due to the following limitations: i) we cannot derive the high frequency part of the spectrum (> 0.26 Hz); ii) poor performance typically at H_s < 2.0-2.5 m; iii) presumably not suitable near the coast (but mainly indirectly, because of ii and 70 x 90 km boxes necessary to derive wave spectra). Despite these limitations, we illustrated the potential benefit CFOSAT can offer in the North Sea, also with some examples where the wave model is less capable to resolve the spectra. CFOSAT data could be used to further study problems that occur from the SWAN-North Sea offshore boundaries. In addition, CFOSAT is actively used in the latest research for wave data assimilation and machine learning. However, to understand the limitations of the processed CFOSAT data better, it is recommended to study the instants that the CFOSAT performance compared to measurements is less.

2.6 Sentinel-1 standard ocean (OCN) wave products (SAR Imagery)

2.6.1 Product description

Satellite products from which a wave spectrum or integral parameters can be derived, are validated for open ocean (OCN) conditions, but not for the North Sea. A very limited set of standard Ocean Swell Wave (OSW) products from wave (WV) acquisition mode for the global ocean was found on the EU and ESA (2024) Copernicus Data Space Ecosystem, see Figure 2.18. The OSW component is a two-dimensional ocean surface swell spectrum and includes an estimate of wind speed and direction per swell spectrum (Figure 2.19). The swell spectra (OSW) are provided at a spatial resolution of 5 m by 5 m in 20 km by 20 km vignettes. The data can be downloaded from: https://browser.dataspace.copernicus.eu/.

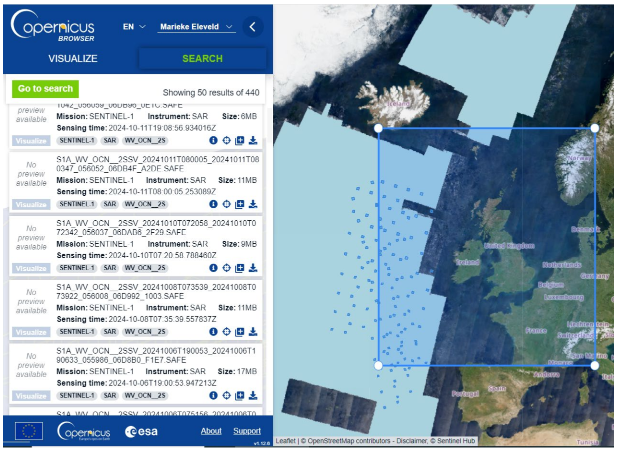


Figure 2.18 Overview of all WV products (Oct 2014-Oct 2024) from the Copernicus dataspace browser intersecting the box in the North-East Atlantic South of Iceland – North of Spain. The blue squares indicate the 20 x 20 km wave mode vignettes.

Other Level-2 Ocean (OCN) products for wind and currents applications as Ocean Wind field (OWI) and Surface Radial Velocity (RVL) are also available from the main, Interferometric Wide (IW) acquisition mode, so that many more products are available for these parameters. The OWI component is an estimate of the surface wind speed and direction at 10 m above the surface.

The wind fields (OWI) and surface radial velocity (RVL) components have a spatial resolution of 1 km by 1 km (for SM/IW/ Extra Wide Swath (EW) modes). For WV, the results are averaged on the 20x20 km grid, giving only 1 value (Sentinel-1 SAR user guide in ESA, 2024 and ESA, 2024a).

2.6.2 Application

Storm Pia (21-22 Dec 2023) was just missed, but spectra from the day after are given in Figure 2.19. Other ocean surface wave (OSW) data in the file are: estimated swell spectrum (m^4) on log-polar grid (based on 60 x 74 pixels), estimated swell spectrum Normalised Variance (on log polar grid), wave partition numbers, and real and imaginary part of the cross spectra $(m/rad)^2$ log-polar grid.

Although the OCN products are only available for the Atlantic Ocean and not for the North Sea, the products could still be valuable to check the waves at the boundary of the SWAN North Sea model.

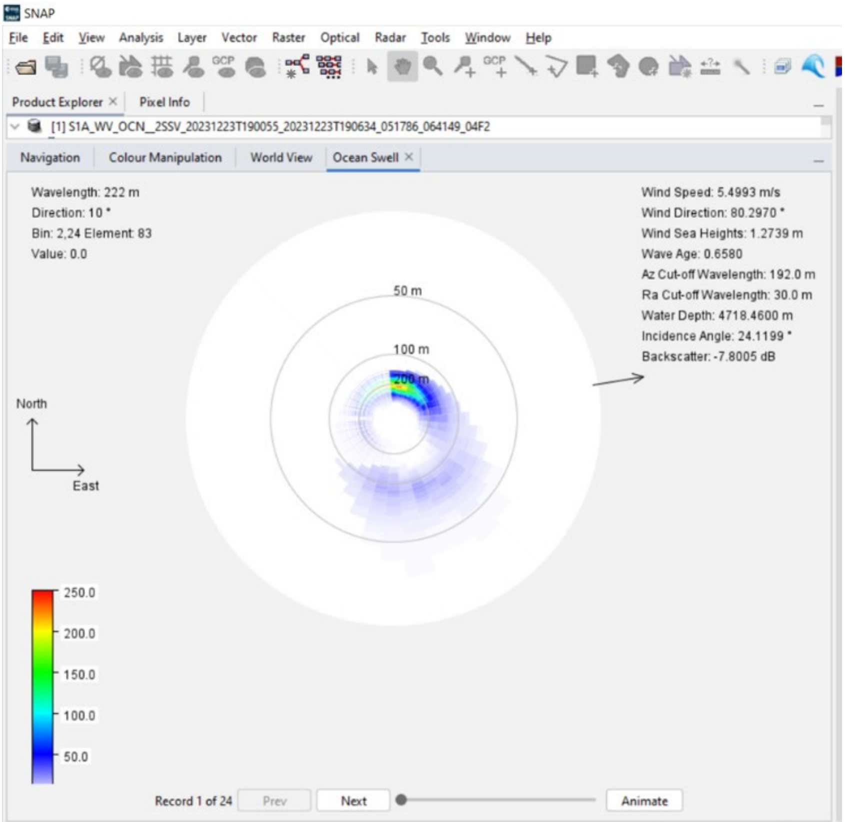


Figure 2.19 Example of a swell wave spectrum from a Sentinel 1 wave (WV) vignette the day after Pia, plotted with ESA SNAP. Colourbar shows the spectral energy, grey circles indicate the wave length.

Sentinel-1 also offers a combination of forward and inverse modelling to produce a limited number of wave products (S1*_WV_OCN) for the open ocean. Kwant (2017) applied this method for the North Sea to derive a number of long ocean swell wave spectra from SAR images. The standard OSW method for IW data at 5 m x 20 m single look complex (SLC) of the North Sea was adapted by Kwant (2017). Figure 2.20 shows cases where the swell peak from the SAR image matches the wave buoy measurements direction. However, not all results compared very well. Further work on the method that Kwant (2017) used, could be interesting to also derive wave spectra from Sentinel-1 for the North Sea.

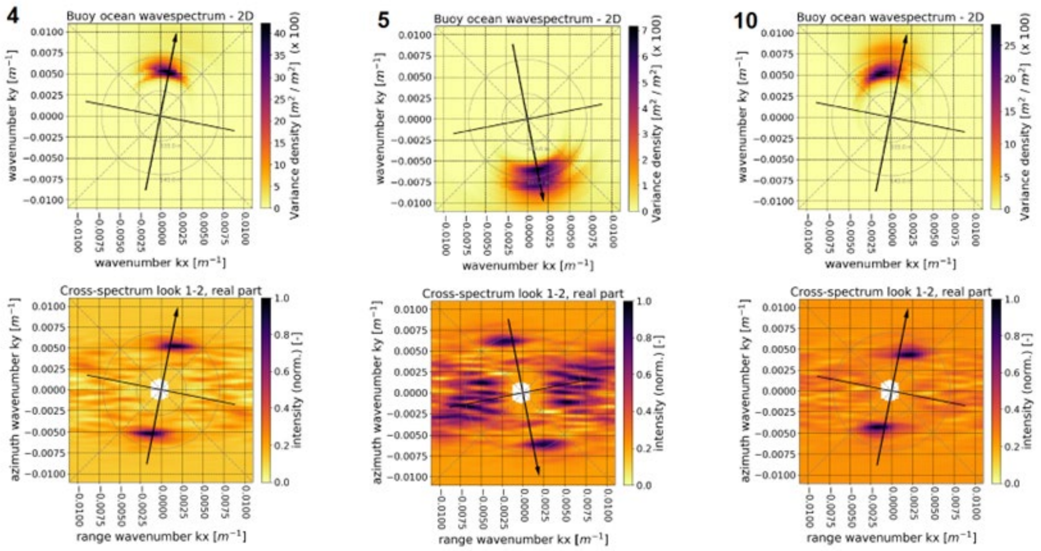


Figure 2.20 Top images show wave buoy spectra, bottom images retrieved SAR cross-spectra in the North Sea for three images 4 (30-10-2016), 5 (31-10-2016) and 10 (16-01-2017). The arrows indicate different orientation for satellite ascending pass (4 and 10) and descending pass (5). (Kwant, 2017).

2.6.3 Outlook: Near-Future Earth Explorer 10 Harmony

In the near future, North Sea research can benefit from Harmony. Earth Explorer 10 mission Harmony will consist of two satellites with a design life of (at least) five years that are expected to be launched in 2029, and will fly in formation with a Sentinel-1 satellite. Each Harmony satellite will carry two instruments on board. When operational, Harmony will help to map and quantify upper ocean surface processes including winds, currents and swell to improve our knowledge and models of the ocean and thus improve our forecasting ability.

The primary instrument is a receive-only C-band SAR (Synthetic Aperture Radar) that will detect C-band radio waves emitted (and also received) by the SAR of a Sentinel-1 satellite. The secondary instrument is a multibeam thermal-infrared instrument. When clouds are present, it will measure vertically resolved cloud movements. When clouds are not present, the instrument will measure the ocean surface temperature to complement the data collected by the SAR.
Sentinel-1 emits a signal and then receives a signal that is backscattered from earth. By flying the two Harmony satellites alternately in different formations close to Sentinel-1, Harmony will receive valuable signals of the ocean that would otherwise have been lost in space, and by having three lines-of-sight, Harmony not only enhances the retrieval of the ocean-wave spectrum, but it also enhances the retrieval of surface-current vectors by constraining the wave Doppler (Kleinherenbrink et al., 2024).

The North Sea would be a challenging calibration and validation site for Harmony, in addition to a benchmark Atlantic site (near Brest). Deltares is already part of the Harmony network led by TU Delft, Paco Lopez Dekker. This brings the future opportunity to benefit from the availability of satellite data that fits our shallow water work.

2.7 SWOT (RA - InSAR)

2.7.1 Product description

The primary instrument in the Surface Water Ocean Topograhy Mission (SWOT) is the Ka-band Radar Interferometer (KaRIn) synthetic-aperture radar (SAR). Designed to be uniquely appropriate for measuring water surface elevations and inundation extents, it measures the elevation of the surface across a 120 km (75 mi) wide swath. It effectively provides range measurements across two 50 km swaths from 10 to 60 km on each side of the nadir ground track, as shown in Figure A.3. KaRIn transmits Ka-band pulses from one of two antennas separated by a baseline length of approximately 10 m. The relative delay, or phase difference, between the reflected signals received by each of the two antennas with their known baseline length provides measurements of the water surface height, in effect through triangulation, see the SWOT Science Data Products User Handbook (JPL D-109532, 2024). A Dual-frequency (Ku- and C-band) pulse-limited Nadir Altimeter (NAlt) is also flown, as was done on the Topex/Poseidon, Jason series, and SARAL missions (Figure A.3). The other instruments on the platform help with positioning and atmospheric correction.

The data have been downloaded from: https://www.aviso.altimetry.fr/en/data.html. Appendix B provides a link to a python toolbox to process the satellite data.

SWOT KaRIn processing over the ocean is in low resolution (LR). Significant wave height (SWH) information is available in:

- The WindWave subcollection from SWOT Level 2 LR altimetry (SWOT_L2_LR_SSH), with a resolution of 2 km;
- The Expert subcollections from SWOT Level 2 LR nadir altimetry (SWOT_L2_NALT_GDR).

500 m resolution unsmoothed files are also available, but they do not provide significant wave height.

SWOT Level 3 (L3-SSH-Expert) data do (currently) not provide SWH or wind, but they do contain sigma0, the backscattering coefficient that indicates roughness and that is subsequently used to characterise and derive wind fields, sea state and waves (Figure 2.21).

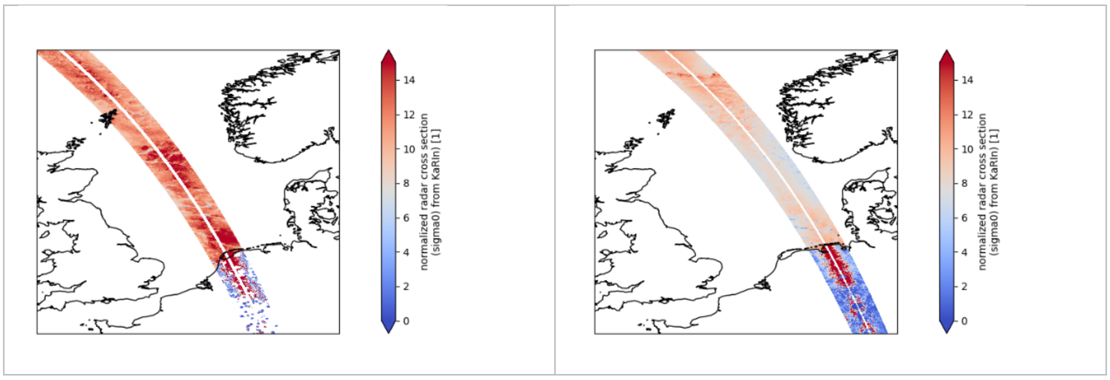


Figure 2.21 SWOT L3 roughness (sigma0) for different wave bands, (left) during and (right) after Pia. Land masks were not yet overlaid.

2.7.2 Comparison/ application example

To test SWOT for the North Sea the analysis focussed on Storm Pia. Plots of Level-2 (Expert) data show that wave heights during Pia were higher than before or after (Figure 2.22). Note that no cross-calibration (which is standard for SSH) or (land) flags were applied. Here all tracks in an area and period were plotted. The primary tracks in Figure 2.22 middle and right (that were also plotted in Figure 2.21) deviate from extreme values (the thinner entirely red and blue tracks) in the other tracks. This needs further attention, also the landmask should still be applied. The current state of the art of customised SWOT for wave extraction was given by Ardhuin et al. (2024). It might be interesting to test this for the North Sea.

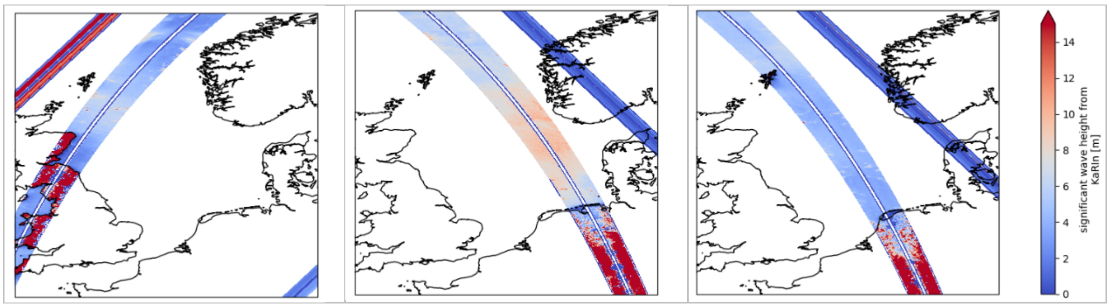


Figure 2.22 Significant wave height from LR KarIn (left) before, (middle) during, and (right) after Pia.

The nadir Sensor Geophysical Data Record 'SWOT_L2_NALT_GDR_SGDR_2.0' offers 1Hz, 6 km resolution, and 20 Hz, 300 m resolution data from the two radar systems – C band, with wavelength of ca 5.7 cm, and Ku band with wave lengths of ca. 2 cm) is plotted in Figure 2.23. We show the full track as is, but can zoom into the North Sea and apply the land mask in a next iteration.

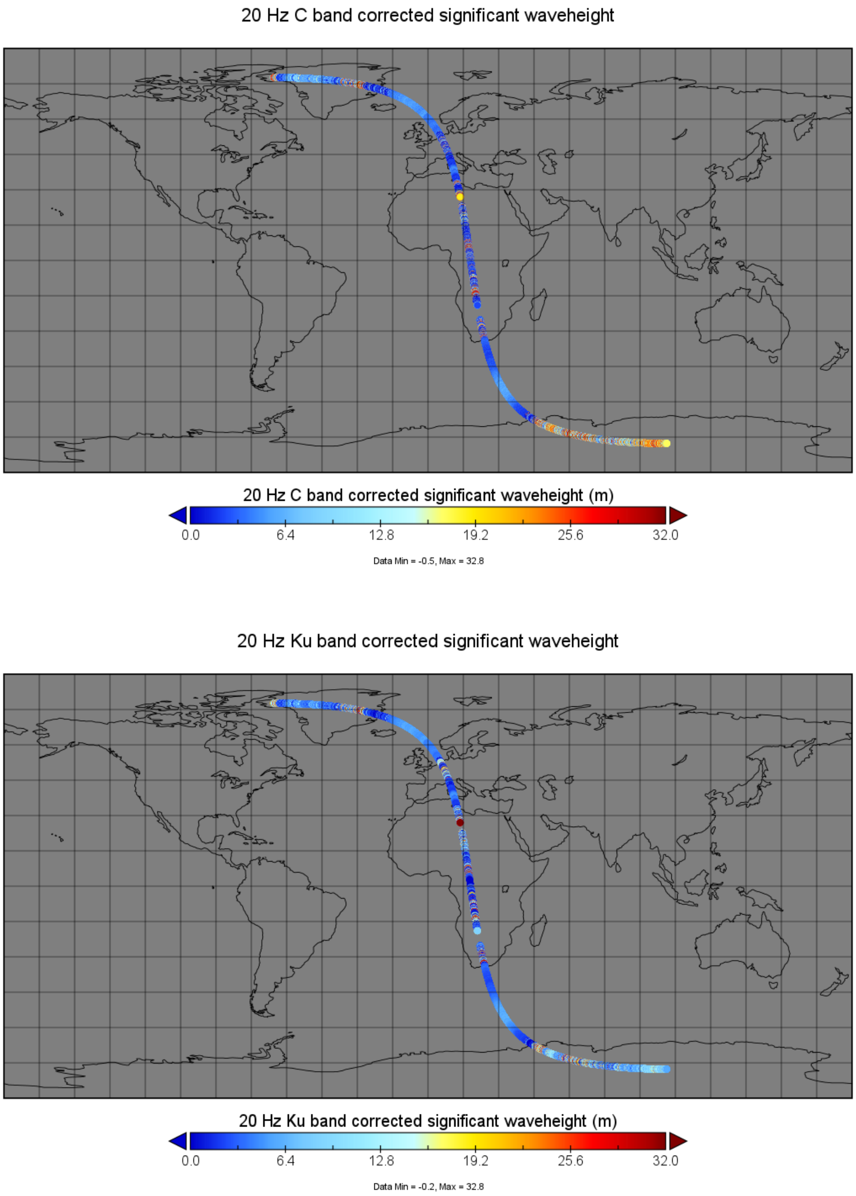
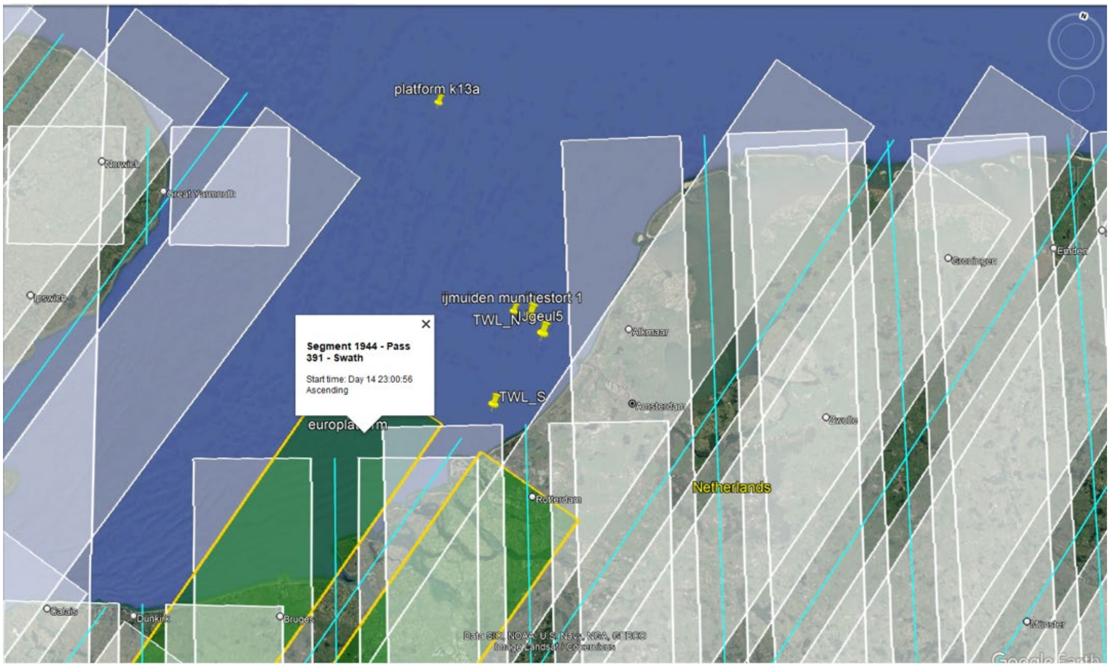


Figure 2.23 Significant wave height from nadir 20Hz C and Ku band on 22 Dec 2023 at_16:19: 24_UTC

2.7.3 SWOT outlook

SWOT surface water ocean topography processing proceeds along two disparate lines: high resolution hydrology (HR, for land) and low resolution (LR, for ocean). We recommend investigating whether any information from coastal waves could be retrieved from the HR hydrology products that also cover the coastal zone as shown in Figure 2.24.



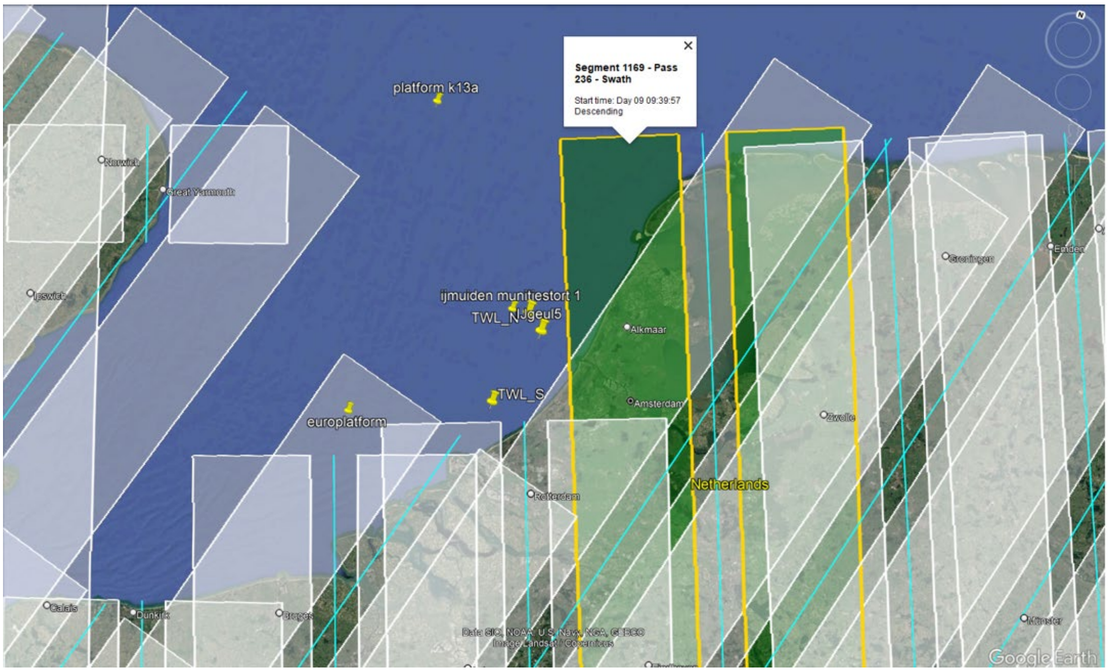


Figure 2.24 Example of high resolution SWOT for the KaRIn and Nadir sensors capture part of the coastal North Sea.

2.8 Sentinel-6 Michael Freilich (RA - Fully Focussed SAR)

2.8.1 Product description

Satellite data would also be interesting to further develop and validate the North Sea models at distances 1-30 km from the Dutch coast, as an addition to the existing wave measurement locations. However, coastal observations from satellite altimetry are seen as unreliable, for example due to resolution, coastal waveforms (e.g. wave breaking), land or objects with a different backscatter near the coast. In recent years some progress has been made in the processing of the satellite data. One example is the use of Fully Focussed (FF) SAR-mode Altimetry, see also section Appendix A.2.

Schlembach et al. (2023) assessed the applicability of FF-SAR-processed Sentinel-6 Michael Freilich (S6-MF) coastal altimetry data to obtain significant wave height (SWH) estimates as close as possible to the coast. They processed the data with a multi-mission FF-SAR processor which they developed themselves. Subsequently, the coastal retracking algorithm CORALv2 was used to estimate SWH. The data included 161 overpasses from five passes, covering the Dutch coast and the German coast along the East Frisian Islands in the North Sea, and 38 cycles, corresponding to the year 2021.The results were compared to unfocussed (UF) SAR, a Level-2 product from EUMETSAT and the results from the SWAN-Kuststrook model.

2.8.2 Results as reported in Schlembach et al. (2023)

Schlembach et al. (2023) show that more accurate results can be achieved with fully focused SAR up to 1-3 kilometres from the coast than with the conventional products, see an example in Figure 2.25. The FF-SAR (140 Hz) dataset exhibits the highest similarity to the SWAN-Kuststrook model, showing a correlation coefficient of ~0.8 with 45% of valid records for the 0–1 km from the coast and 80% of valid records for 1–3 km from the coast.

However, FF-SAR systematically overestimates SWH compared to SWAN-Kuststrook, which is a common issue when processing SAR altimetry and mainly comes from wave motions. The FF-SAR-processed datasets exhibit, across all passes, a median offset of ~32 cm for up to 3 km from the coast and ~27 cm for closer than 3 km from the coast compared to SWAN-KS. The Level-2 product from EUMETSAT has the lowest offset offshore (5-10 cm), but does not yield data near the coast. The precision of FF-SAR near the coast is 37% higher than with UF-SAR.

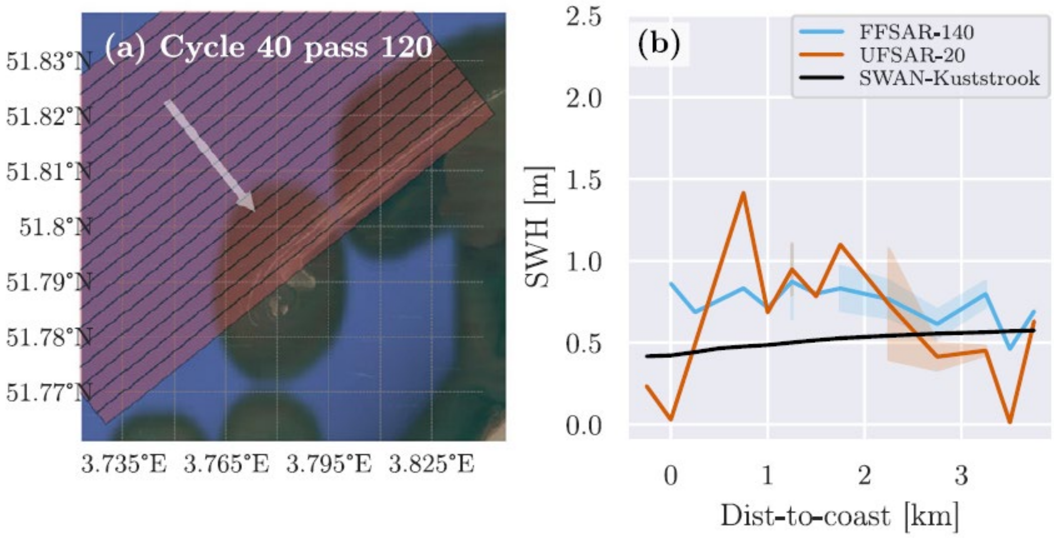


Figure 2.25 Example of one pass of Sentinel-6 with FF-SAR (140Hz) and UF-SAR (20Hz) compared to SWAN-Kuststrook. Schlembach et al. (2023)

Although the fully focussed processing of Sentinel-6 data offers more data and with more accuracy at distance of 0-3 kilometres from the coast, the offset of FF-SAR data may still be a problem for use in the SWAN North Sea models.

2.9 Wave data assimilation or machine learning

2.9.1 Data assimilation

Data assimilation offers several ways to combine observations and models in an optimal way. It gives the opportunity to use satellite (and buoy) measurements in a physically consistent manner.

Most large forecasting centres have mainly relied on relatively simple algorithms like Optimal Interpolation (OI) and the three-dimensional variational scheme (3DVAR) that require assumptions on the shape of the spectrum, when only significant wave measurements are available. Ensemble methods like the Ensemble Kalman Filter (EnKF) do not require this assumption and are superior in representing realistic wave physics. This comes at a computational cost, but there are several research directions that are promising to reduce the computational burden (e.g. Machine Learning).

Current PhD research by Elias de Korte (TU Delft and Deltares) is focussed on the potential benefit of using satellite data for wave data assimilation, using EnKF methods. A first synthetic study for the North Sea using synthetic altimeter measurements with real pass-over times and signatures, shows the potential added value of assimilating satellite altimeter measurements.

2.9.2 Synthetic Wave Data Assimilation Study (PhD)

Figure 2.26 shows a timeseries during storms Corrie and Malik (2022-01-27 to 2022-02-02), where we model the uncertainty in the wave fields by modelling uncertainty in the wind forcing. The EnKF corrects the entire wave spectrum and all integral variables based on only significant wave height measurements (using covariances between model state variables and observed variables). We can clearly see the relationship between growing uncertainty and decreased satellite measurement availability (dashed lines). Despite this, the EnKF improves the estimate (in blue) compared to the synthetic truth (in black) and the original model run (in green).

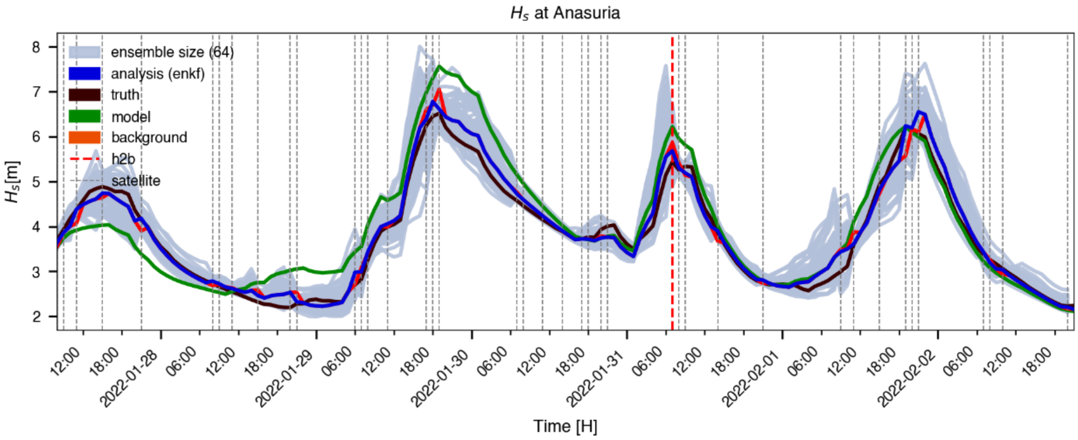


Figure 2.26 Wave height timeseries during storms Corrie and Malik (2022-01-27 to 2022-02-02)

The red dashed line marks the overpass of satellite Haiyang-2B and Figure 2.27 shows the correction at that particular moment in time on the wave spectrum (1D for more convenient visualization of the ensemble spread).

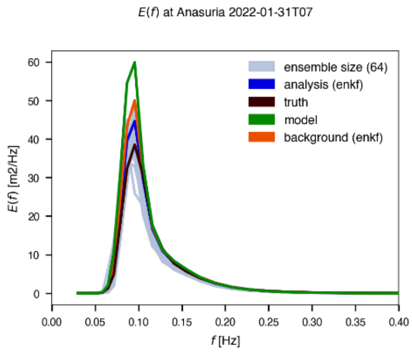


Figure 2.27 Wave spectrum correction during the overpass of Haiyang-2B in time

The results of this synthetic study have been submitted as a scientific paper. The work will continue with an observation impact study to assimilate satellite data over a longer period of time and assess the performance.

2.9.3 Machine learning

We see different ways in which Machine Learning is or can be used with satellite data:

1. The processing of satellites dataset to wave parameters. This has been applied for various datasets: for example, SAR wide-swath deep learning IFREMER (Maillard et al, 2024), CWAVE-family algorithms Pleskachevsky et al. (2022, 2024).
2. Training a Machine Learning model with satellite data to use as hybrid model to correct the results of the numerical wave model. For SWAN-Kuststrook a hybrid model is already used, which has been trained on wave measurement data, see Bieman (2023). However, satellite data could benefit the training as it offers spatial data for the training data instead of point measurements.
3. Possibilities of a surrogate wave model in combination with wave data assimilation, where buoy and satellite data is used to improve the surrogate model results.

3 Quickscan other applications

3.1 Introduction

Whereas the previous chapter focussed fully on applying satellite observations for SWAN-NS improvements, this chapter mentions three other applications for which more or spatial wave data would be beneficial:

- to fill in nearshore knowledge gaps: wave height and wave directions nearshore;
- using satellite wave height timeseries in addition to in-situ stations;
- quantifying the effect of offshore wind farms (OWFs).

For each use case potential satellite products have been indicated, but most have not been further studied. An exception is the use case ‘wave height and wave directions nearshore’, for which the use of optical imagery has been further explored.

3.2 Wave height and wave directions nearshore

3.2.1 Problem description

In complex coastal areas, like estuaries or near navigation channels there is a need for spatial wave data like the significant wave height and wave directions. Note that in this paragraph nearshore means a few kilometres distance from the coast where in Chapter 3 nearshore was indicated less than 100 kilometres distance from the coast.

Here, three cases are described, that would potentially benefit from satellite derived wave products nearshore:

Eastern Scheldt barrier

As part of the asset management and the design conditions of the Eastern Scheldt storm surge barrier, research has been carried out into the influence of wave loads on the barrier and the consequences for its required strength. In 2024, three wave buoys have been deployed for a longer period in front of the barrier.

The measuring buoys have been deployed in front of the three gates flowchannels to gain better insight into wave directions near the Eastern Scheldt barrier and the variation in wave heights and directions per flowchannel-gate. The data from the measuring buoys is very valuable, but there is a need for more spatial insight. Information from satellite images could potentially be valuable to learn more about the development of incoming wave fields from deep water towards the barrier, both in wave height and wave direction.

Insight in the wave field in front of the Eastern Scheldt barrier would be valuable during both operational open conditions and closed barrier conditions in storm situations. Benefits are to increase system knowledge of wave loads along the Eastern Scheldt barrier to ensure robust and more cost-effective maintenance works and to have measurements to validate and/or calibrate wave models.

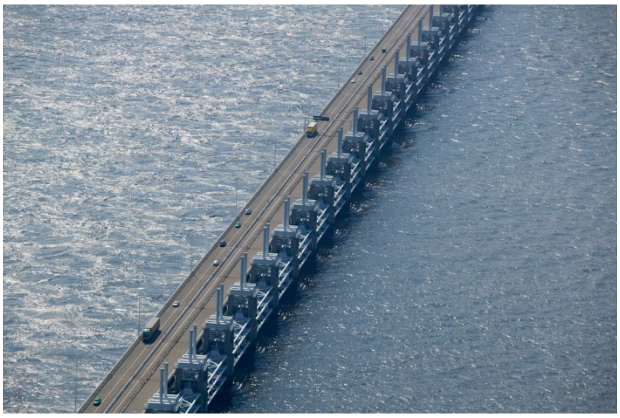


Figure 3.1 Aerial view of the Storm surge barrier in the Eastern Scheldt

Western Scheldt ebb-tidal delta

Navigation along the ebb-tidal delta of the Western Scheldt can be challenging, since the channels and tidal flats influence the waves significantly, in particular the wave direction. There are various locations along the ebb-tidal delta, where wave measurements are carried out, but this does not provide a complete picture of the wave propagation. Information from satellite images could be potentially valuable, to provide spatial wave data, especially in areas where it is not possible to deploy wave buoys.

Navigation would benefit from wave data during operational conditions. Preferably, data would be available real-time. Another option would be to validate and improve our wave models with the satellite information to ensure an accurate forecast. An essential wave parameter in this case is the *wave direction.* Wave height and other wave parameters would be nice to have.

Eems-Dollard wave propagation during storm conditions

For the assessment and design of our flood defences numerical wave models of the Wadden Sea are run to determine hydraulic boundary conditions. These wave models have been calibrated and thoroughly validated with existing wave measurements, however, in some areas doubts about the quality of the models still exist. One of the areas is the Eems-Dollard estuary.

During storms it is often observed that the modelled low-frequency wave height does not correspond well with the measured low-frequency wave height. As the low-frequency waves are not locally generated but propagate from the North Sea into the Eems-Dollard estuary, it is hard to conclude which processes are not properly modelled. Groeneweg et al. (2015) point at the non-linear processes that may affect the directional spreading of the waves, but other processes cannot be excluded.

In addition, the water board Noorderzijlvest has its doubts about the modelled amount of wave energy that reaches the eastward facing flood defences.

Here wave information from satellites would be welcome to provide a spatial picture of the waves, especially during north-westerly storms, when there is a large amount of wave energy penetrating into the Eems-Dollard. Most interest is in the *wave direction*, however, wave height, low-frequency wave height and wave periods would also be nice to have.

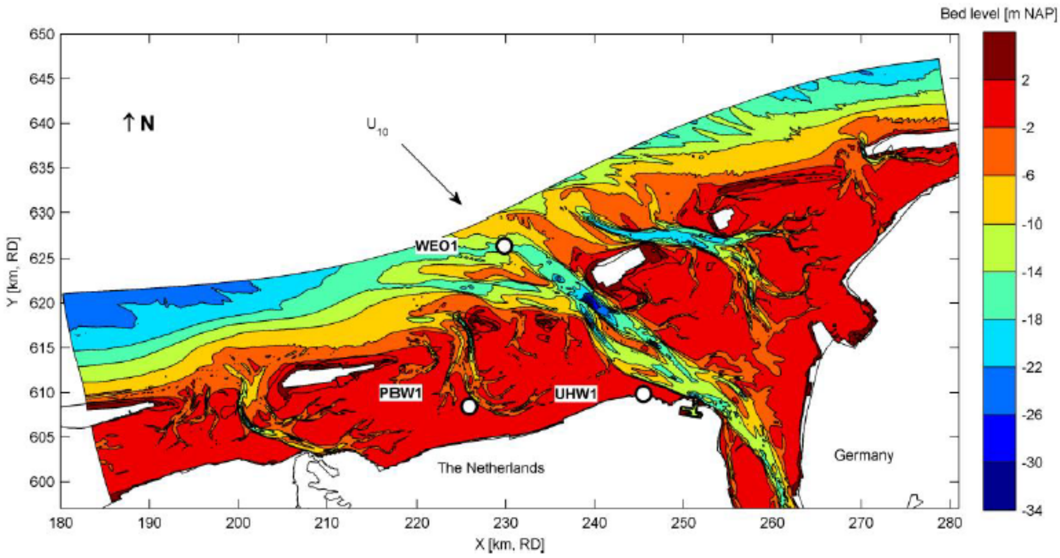


Figure 3.2 An overview of the Eems-Dollard estuary with its complex bathymetry and a selection of measurement locations. (source Groeneweg, 2015).

3.2.2 Added value of satellites

SAR-mode altimetry has a high resolution and therefore offers potential for achieving a high coastal accuracy. From the altimeter missions, Sentinel-3 with unfocussed processing promises better coastal accuracy compared to LRM altimetry. For example, Nencioli and Quartly (2019) confirmed this for the English coast. More recently, Sentinel-6 is available, designed for fully focused processing. Schlembach et al. (2023) compared this to high resolution wave model data for the Dutch Coast. Apart from these, SWOT is particularly interesting because of its wide swath (2 x 50km) and resolutions varying from 500 m to 2 km for LR raster ocean products . Note that some altimeters provide collocated surface wind speed measurement that might be valuable for cross-validating wave models. Finally, the methods like Pleskachevsky (2022, 2024) for SAR imagery from Sentinel-1 or TerraSAR-X could offer an option, although more focus of their algorithm nearshore would be necessary.

Optical satellite imagery is also an option near the coast, especially for deriving wave direction. Figure 3.3 shows three examples of wave directions that have been derived from optical Sentinel-2A-B images for this project with a depth-inversion method used in Gawehn (2022a, b). Downloaded via the STAC catalogue https://earth-search.aws.element84.com/v1. It can be seen that the wave direction can be derived in high resolution. This means that spatial wave processes like wave refraction on the tidal ebb-delta can be observed as well. In addition, when wave observations are present, the image spectrum could be scaled using the observation spectrum and this means that other wave parameters could also be derived. The downside of using optical images is that the method does not work when clouds are present, as can be seen in Figure 3.3. Therefore, optical satellite imagery may be a solution for some applications (e.g. SWAN model validation during operational conditions, wave knowledge and trends), but probably not for model validation during stormy conditions or direct operational use of the satellite imagery.

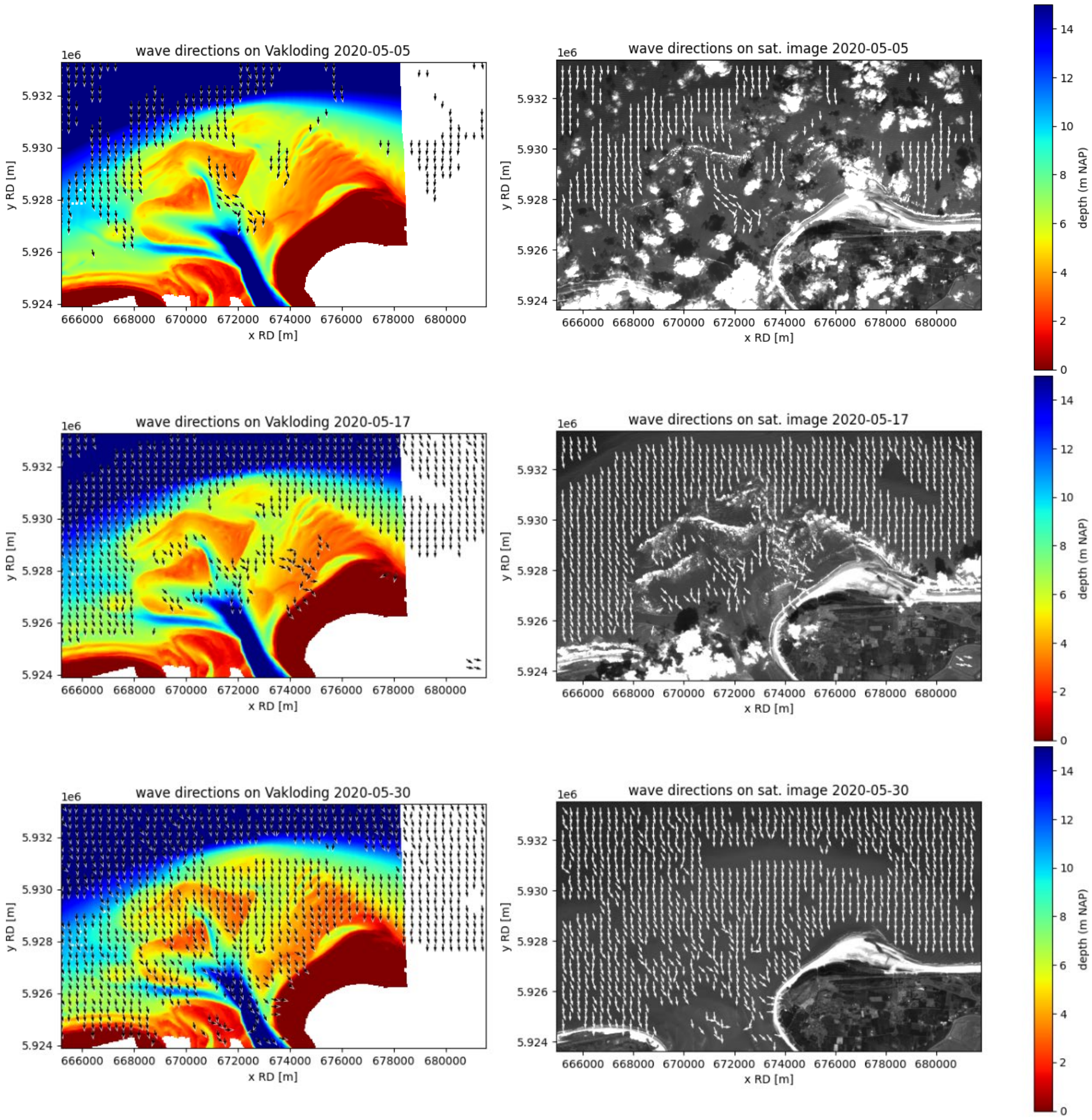


Figure 3.3 Wave directions from optical Sentinel-2A images for Amelander Zeegat on high-resolution bathymetry (left) and on satellite image (right).

3.2.3 Recommendations

It is recommended to further look into the options that are available to derive waves from satellite data nearshore. Interesting products are SWOT data, Sentinel-1 or TerraSAR-X in combination with a wave-deriving method like Pleskachevsky et al., 2024 did. And finally, also the optical satellite imagery that was shown in Figure 3.3.

The selected nearshore cases in this section have been defined as most urgent for further study. In 2025, a follow-up project of CIP addresses how the cases ‘Eastern Scheldt barrier’, ‘Western Scheldt ebb-tidal delta’ and ‘Eems-Dollard wave propagation’ would potentially benefit from satellite derived wave products nearshore.

3.3 Satellite wave height timeseries in addition to in-situ stations

3.3.1 Problem description

Offshore wave measurement stations are often combined with oil/gas platforms. Those platforms are disappearing and therefore the question arises whether these stations could be replaced by wave information from satellite data. However, the requirements of the quality of the measurement data for Rijkswaterstaat are high in terms of accuracy and availability. In addition, some of these stations have measured waves for decades, which offers valuable information for statistics and climate change research.

3.3.2 Added value of satellites

Satellites do not offer long robust time series as in-situ data do. If such data is required for wave model validation, satellite data are less suitable.
Most convenient would be, to select a set of complementary satellite altimetry missions (multi-mission, such as the CMEMS product). Since in-situ data is required to calibrate the satellite observations, satellites cannot replace all in-situ observation stations.

It is highly uncertain whether the desired accuracy and availability (in time) can be achieved with the currently available satellite data. It depends on the application whether satellite data could provide a solution as partial replacement for measuring stations. An example is that the satellite data do not have a continuous time signal and therefore, it cannot be used directly for navigation purposes. On the other hand, when used for validation of wave models, wave statistics, or data assimilation/ machine learning, the satellite data could offer a valuable addition to the currently available in-situ wave measurements.

3.4 Effect of offshore wind farms

3.4.1 Problem description

Offshore wind farms (OWFs) affect wind and wave fields. Behind the OWF wakes with lower wind velocity and streaks with higher wind velocity develop. However, the effect of the OWF is not well known.

3.4.2 Added value of satellites

Satellites could provide a solution for this application as spatial information can be offered. There are already various studies that have been looking at the effect of wind parks on the wind fields with SAR image data, see for example Figure 3.4 from Wijnant & Stepek (2023). Since the wind velocity varies, the waves will too. However, this effect has only been shown with numerical wave models, but not with satellite measurements.

For this application SWOT data or (Sentinel-1) SAR imagery could be interesting. Further research is needed for this.

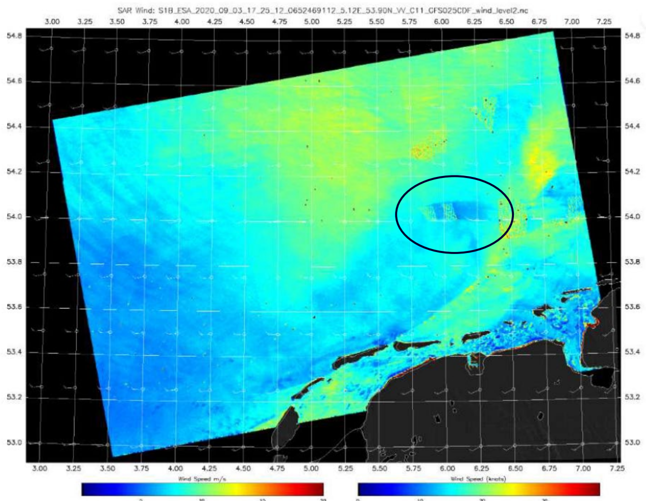


Figure 3.4 SAR-image 03-09-2020 17:25:12 UTC with clear wakes behind offshore wind parks. Colorbar shows the wind speed in m/s (left) and knots (right). From Wijnant & Stepek (2023)

4 Conclusions and recommendations

4.1 Conclusions

In this project a technology scan was performed on existing technologies to derive wave information from satellites. One of the objectives was to give an overview of these technologies and to identify which have the most potential for the improvement and validation of the SWAN North Sea wave models. Through this study, we aim to lower the threshold for applying satellite data for wave applications in Deltares and Rijkswaterstaat projects by building up knowledge and expertise.

The three relevant satellite technologies to derive wave fields are:

- Radar altimetry (RA); directly measuring the heigh of the Earth's (sea) surface. This can be done for example in low resolution mode (LRM) or unfocussed Synthetic Aperture Radar (SAR)-mode;
- SAR Imagery; acquiring 2- or 3-D images of the Earth's (sea) surface;
- and optical satellite imagery; acquiring information making use of the spectrum of visible light (colours) but also the near-infra red.

Several datasets/products that make use of one or more of these technologies were analysed in more detail. It was found that:

- In general, processed satellite data from radar altimetry can provide accurate wave field information in deeper parts of the North Sea.
- The CMEMS (Copernicus Marine Environmental Monitoring Service) significant wave height product provides accurate information at 100 km or more distance from the coastline. The product is derived from radar altimetry. The product can be used for model validation of SWAN-North Sea (SWAN-NS) , sensitivity studies, to improve the SWAN (RWsOS) forecasts using Machine Learning (ML) or data assimilation. The CMEMS data set is user friendly and can be relatively easy implemented depending on type of application. It is recommended to apply this product within the SITO-PS Model schematizations program.
- CFOSAT (RA; RAR) and Sentinel 1 (SAR Imagery) can be used for wave spectra validation within the model domain of SWAN-NS and at the model boundary of SWAN-NS.
- With some additional effort SWOT may be useful for insights nearshore and/or to capture wave fields in a large area.
- The fully focused FF-SAR technique has potential for nearshore applications, but needs more attention before it can be applied for real applications.
- The WAVERYS combined satellite and coarse wave model products (Level 4) do not give better results in comparison with the current SWAN wave models.

The use of satellite wave information has also been explored for other applications, such as filling in nearshore knowledge gaps (for instance for BOI and navigation), satellite in addition to in-situ measurements and quantifying the effect of offshore wind parks on wave propagation. For these applications the use case was described and requirements given. Potential satellite products were listed. Satellite data is likely interesting for the various applications. However, at this stage it is not yet possible to say how useful the satellite information is.

4.2 Recommendations

Recommendations for further research and application of wave information, derived from satellite data, are given for two questions: (1) Which satellite techniques and data products can be applied in the SWAN North Sea project and (2) which satellite missions and techniques are promising and worth further investigation for near shore applications. The expectation is that several applications can benefit from the use of satellite information.

1. Application of satellite data in SWAN North Sea models:
    - It is recommended to further study the wave spectra derived from CFOSAT and Sentinel-1 data to fully understand their benefits and limitations. As the use of wave spectra derived from CFOSAT and Sentinel-1 may be highly beneficial to understand the underestimation of the swell wave height in the SWAN-NS domain, it is recommended to use these data within the 2025 SITO-PS Model schematizations program.
    - The CMEMS L3 significant wave height product has a high potential to improve SWAN North Sea (SWAN-NS) results using Machine Learning (ML) and/or data assimilation (DA). It is recommended to use the processed satellite data in SWAN-NS validation studies and (once a ML/DA method is developed) to implement it in the operational forecasts. Once SWAN-NS is improved, SWAN-Kuststrook (SWAN-KS) using SWAN-NS boundary conditions probably also generates more accurate results. As a first step, it is highly recommended to further explore the CMEMS product and how to apply it (e.g. application close to shore) within the SITO-PS Model schematizations program.
    - It is recommended to develop and test methods to combine satellite and SWAN model results with ML or DA. Potential follow-up projects are:
        - To use the outcome of the PhD research of Elias de Korte for the operational SWAN-NS and SWAN-KS models.
        - To connect with the CIP project confidence intervals for wave forecasts. In this project a surrogate wave model of the North Sea is developed. By using data assimilation, the measurement and satellite data can be used to improve the surrogate model results.
        - Training a Machine Learning model with satellite data to use as hybrid model to correct the results of the numerical wave model, similar to the approach used in Bieman (2023). Satellite data could benefit the training as it offers spatial data for the training data instead of point measurements.

    ML or DA methods can significantly improve SWAN North Sea models. However, the research needed to use ML or DA methods for SWAN North Sea will take years to develop and requires sufficient investment. It is therefore important to get support at Rijkswaterstaat for these developments.

2. For application of satellite data nearshore, the following recommendations are made:
    - It is recommended to further explore SWOT and its potential to supply (nearshore) spatial wave information.
    - Further explore the options with Sentinel-6 data with fully focussed processing. Contact the authors of Schlembach et al. (2023) to see whether there are opportunities to bring this method one step further.
    - Further explore the options with Sentinel-2 optical imagery. It is recommended to apply the optical imagery processing for some of the locations of interest (Western Scheldt, Eastern Scheldt). In addition, further validation of the method could be provided by comparing the wave directions of the optical imagery with wave model results. Finally, it should be explored whether wave heights could be derived from this method by fitting the optical imagery spectra to the wave spectra of in-situ measurements.
    - Explore the use of SAR images nearshore. For example with a possible collaboration with the German Aerospace center DLR (Deutsches Zentrum für Luft- und Raumfahrt) to use their algorithm and our models to improve nearshore applications (Pleskachevsky et al., 2019, 2022, 2024).

Within the CIP follow-up project, a selection of these satellite data will be further studied for nearshore applications, depending on their relevance and potential.

Glossary & Acronyms

Acronym	Meaning
Azimuth	Along-track direction
CFOSAT	China France Oceanography Satellite
CMEMS	Copernicus Marine Services
CNES	Centre national d’études spatiales
DD	Delayed-Doppler
ESA	European Space Agency
EUMETSAT	European operational satellite agency for monitoring weather, climate and the environment from space
FF-SAR	Fully focussed SAR
InSAR	Interferometric SAR
L0	Level 0 - Unprocessed instrument data[3]
L1	Level 1 - Data processed to sensor unit
L2	Level 2 - Derived geophysical variables
L3	Level 3 - Georeferenced data
L4	Level 4 - Data have had the greatest amount of processing applied, possibly including modelled output and measurements from several satellites and several days.
LRM	Low Resolution Mode
Nadir	Point on Earth directly beneath a satellite
NASA	National Aeronautics and Space Administration
PLRM	Pseudo Low Resolution Mode
RA	Radar Altimetry
RAR	Real Aparture Radar
SAR	Synthetic Aperture Radar
SAR Imagery	Synthetic Aperture Radar in 2- or 3D mode
Scatterometer	Active remote sensing instrument for deriving for example wind direction and speed from the roughness of the sea
Sentinel-1	Sentinel-1 is operated by ESA and measures in the C-band with Synthetic Aparture Radar[4]
Sentinel-2	Sentinel-2 consists of two identical satellites in the same orbit. Both carry an innovative wide swath high-resolution multispectral imager.[5]
Sentinel-3	Consists of Sentinel-3A and -3B. It measures systematically Earth’s oceans, land, ice and atmosphere with cutting edge instruments.[6]
Sentinel-6	Copernicus Sentinel-6 is the next radar altimetry reference mission to extend the legacy of sea-surface height measurements until at least 2030. The satellite carries a Poseidon-4 radar altimeter and a microwave radiometer.[7]
SSH	Sea Surface Height

[3] https://help.marine.copernicus.eu/en/articles/5046705-which-levels-are-used-for-data-processing
[4] https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1
[5] https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-2
[6] https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-3
[7] https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-6

Acronym	Meaning
Swath	The area continuously imaged from the radar beam is called radar swath
SWH	Significant Wave Height
SWIM	Surface Wave Investigation and Monitoring
SWOT	Surface Water Ocean Topography Mission
WAVE TAC	Wave Thematic Assembly Center

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A Satellite technologies

A.1 Introduction

We see three relevant satellite technologies that are being used to derive wave fields are:

- Radar altimetry (RA); directly measuring the height of the Earth's (sea) surface. This can be done for example in low resolution mode (LRM) or unfocussed Synthetic Aperture Radar (SAR)-mode;
- SAR Imagery; acquiring 2- or 3-D images of the Earth's (sea) surface;
- and optical satellite imagery; acquiring information making use of the spectrum of visible light (colours) but also the near-infra red.

These technologies are discussed in the following sections.

A.2 Radar Altimetry (RA)

Low-resolution mode (LRM) altimetry is also known as conventional radar altimetry (RA). It requires an antenna pointing vertically towards the Earth's surface (nadir-looking) and measures the distance based on the returning echoes and corresponding time differences. Sea Surface Height (SSH) and ocean currents and circulation can be uniquely derived. Apart from this, the shape of the intensity signal can be used to derive Significant Wave Height (SWH) and wind speed (typically at 10m above the surface). The typical along-track resolution is ~7 km (Chelton et al., 2001). Figure A.1 shows a low-resolution mode altimeter wave form (referring to the shape of the signal) for a flat and a wave-dominated sea-state. The steepness of the signal is proportional to the wave height.

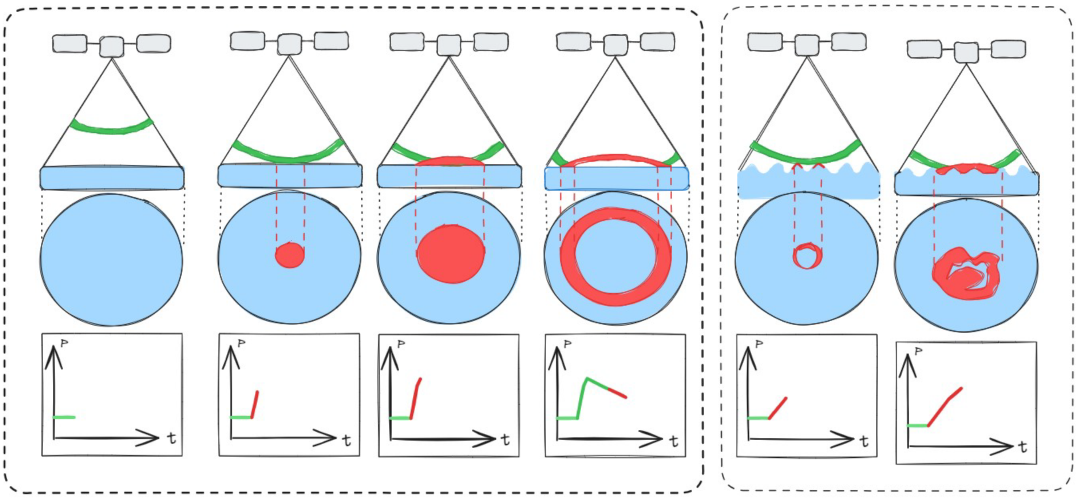

Figure A.1 Conventional low-resolution altimeter wave form (referring to the shape of the signal) for a flat sea-state (left) and wave-dominated sea-state (right). The steepness of the altimeter wave form decreases with more rough sea, as the signal hits a wave crest first and other concurrent wave crests later, resulting in a more gradual leading edge of the power signal. Figure adapted from Halimi (2013).

There is a range of conventional altimeters that are better validated compared to the newer but innovative missions. A combination of altimeters makes it possible to validate time series of several decades.

SAR-mode / Delay-Doppler Altimetry (Unfocussed) SAR-mode is a technique to process altimetry data. It uses a similar technique as SAR imagers (such as Sentinel-1) and exploits the Doppler effect that is caused by the movement of the satellite in along-track direction. This greatly improves the spatial resolution in along-track direction, while the resolution over the track remains the same as with conventional height measurements. Compared to LRM altimeters, pulses are emitted at higher rates, which allows to exploit the Doppler effect, see Figure A.2. Typically, 18000 microwave/laser pulses are emitted compared to 2000 for LRM. Unfocussed satellite altimeters are currently the standard method of processing SAR-mode altimetry. Pulses are generally processed in bursts or packs of 64, resulting in an along-track resolution of approximately 300 m per strip. The satellites concerned are currently (March 2019) Cryosat-2 and Sentinel-3 (A & B), and in the future Sentinel-3 (C & D) and Jason-CS/Sentinel-6.

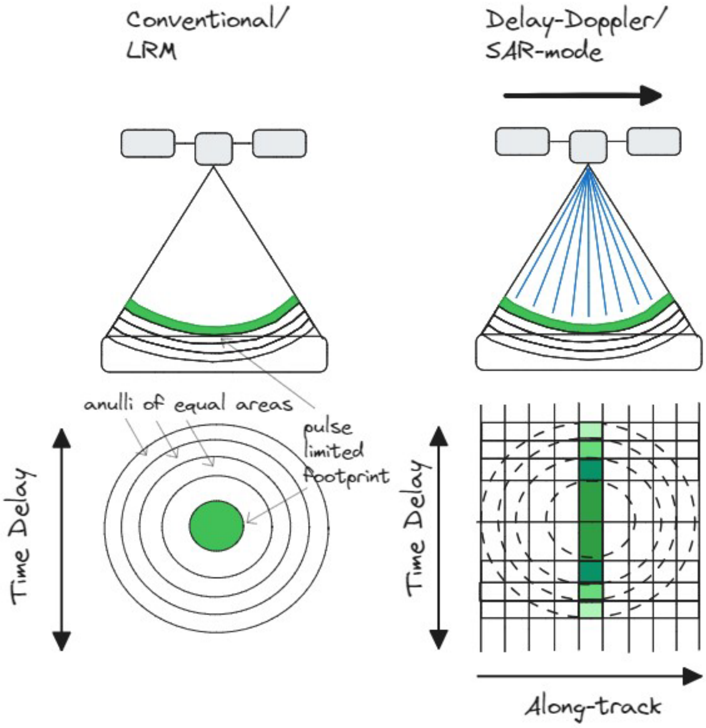

Figure A.2 Schematic overview of LRM (left) and Delay-Doppler Altimetry (right) principles. LRM has a spherical return signal, while the Doppler effect allows to identify strips by processing a burst of echos. Figure adapted from (Grgić & Bašić, 2021)

Fully Focussed SAR-mode altimetry Fully focussed SAR (FF-SAR) processing takes advantage of the increased SAR integration time; the processing of SAR is focused along track and pulse limited across track. The fully focussed processing is possible with Sentinel-6. Sentinel-3 and Cryosat do not operate under this interleaved mode, but also enable FF-SAR. The Sentinel-6 pulses are sent in interleaved mode, covering the entire illumination period of the surface. The technique can increase the resolution from 300 m (unfocussed SAR) to maximum 0.5 m along-track (FF-SAR). It is known that swell waves deteriorate the estimation of SWH in SAR-mode altimetry. Interestingly, for the first time Altiparmaki et al. (2022) have derived a swell wave spectrum from these data, thereby showing the potential of swell derived spectra from SAR-mode altimetry.

Interferometric SAR Wide-Swath (InSAR) and SWOT. SAR technology has been used to build 2-D or 3-D images of the measured backscatter intensity and phase. InSAR techniques use two images of the same ground surface taken from two different satellite positions or view angles (Morrow et al., 2018). Although Cryosat-2 has an InSAR acquisition mode, this was not optimal for ocean surfaces. This satellite used successive images from the same radar at two different times whereas SWOT has two radar antennas that acquire these two images simultaneously (Figure A.3). The Ocean L2 product provides two 50 km wide swath images with a resolution of 2 km for SWH after on-board processing (Morrow et al., 2018). In this ‘imaging’ way, SWOT is measuring the height of the planet's oceans and freshwater lakes and rivers, providing one of the most detailed, comprehensive views yet. SWOT also carries a regular (Jason-like) nadir altimeter, which measures in between the strips. SWOT was launched on 16 December 2022.

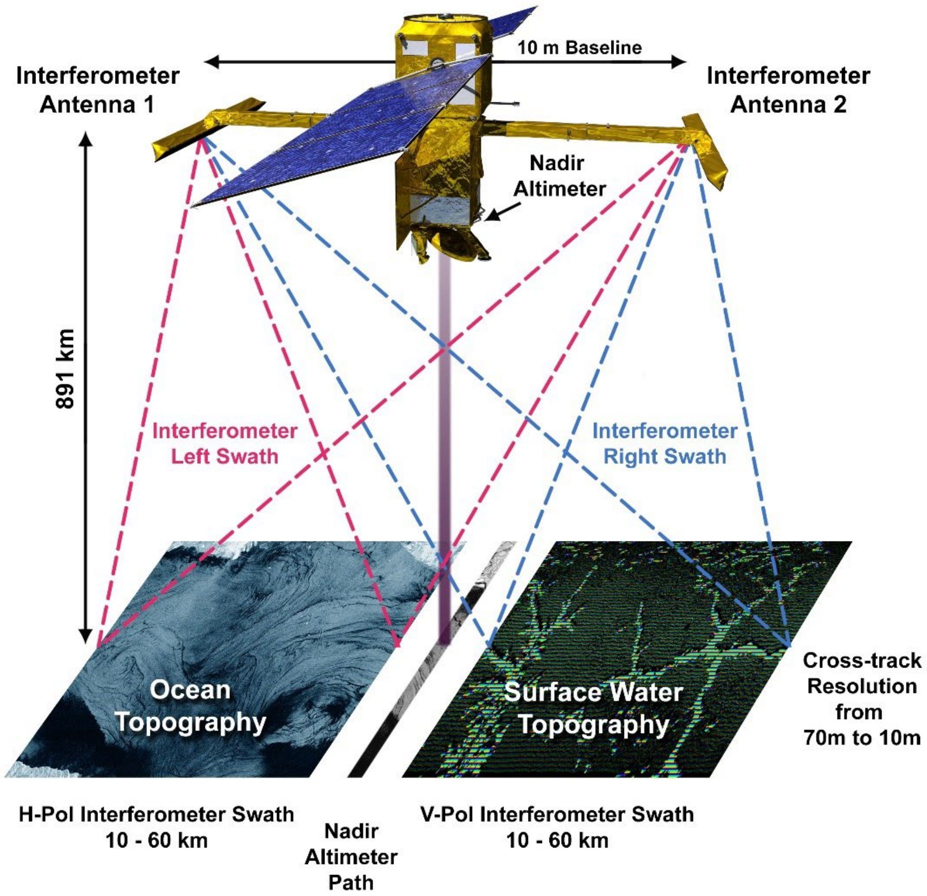

Figure A.3 Schematic of the SWOT measurement technique using the KaRIn instrument for SAR-interferometry over the two swaths, and a Jason-class nadir altimeter in the gap. (Source: NASA-JPL,2020).

Scanning-beam RAR: CFOSAT SWIM The SWIM sensor of CFOSAT is based on a scanning-beam real-aperture radar, Ku-band RAR (Hauser et al., 2020), see Figure A.4. This mission was specifically designed to extract spectral wave and surface wind information. These measurements allow to systematically extract wave spectra. The principle and sensor are explained in more detail by Hauser et al. (2017). An advantage of CFOSAT is that it has collocated wave spectrum and surface wind speeds from a scatterometer on board (Hauser et al., 2017, 2020). This could be interesting for cross-validation in wave models. Li et al. (2023) examined wave spectra for the South China Sea. There is a need for more regional studies of CFOSAT to assess the quality and flexibility of obtaining wave spectra in regional seas.

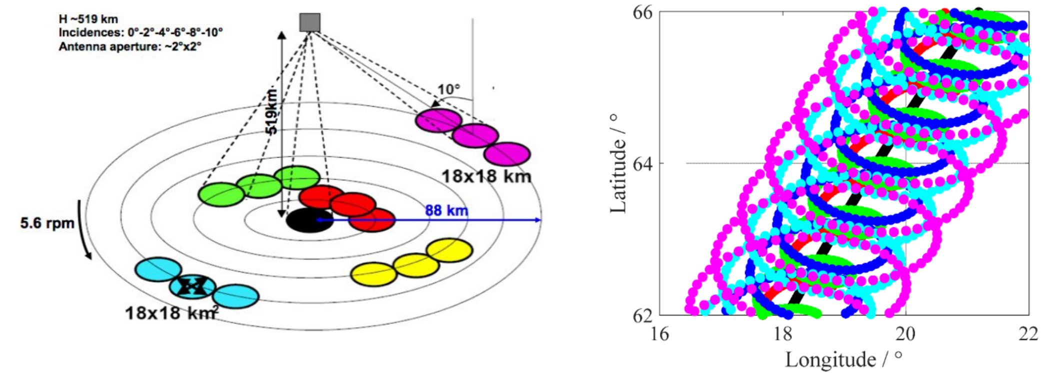

Figure A.4 SWIM beam rotation and angle incidences. Left: schematic of the illumination geometry formed by the six beams during three macrocycles. One macrocycle comprises the illumination patterns formed by the six successively transmitted beams; these are not continuous in azimuth. Right: schematic, using geographical coordinates, of a portion of the Earth's surface sampled during several macrocycles. Antenna aperture: 2° × 2°. Figure from (Hauser et al., 2020)

A.3 Synthetic Aperture Radar (SAR) Imagery

Classical **imaging SAR**, such as Sentinel-1 has a side-looking (off nadir) antenna and produces high-resolution 2- or 3-dimensional images of the Earth's surface. In the direction perpendicular to the satellite path (range direction), the backscatter of a signal that changes frequency, is sampled based on the frequency shift of the returning signal after it hit the ocean surface. In the other along-track direction, the range of echoes is separated by the Doppler shift. Wave information can be extracted either by 1) a transfer function that converts the image spectrum into a wave spectrum; or 2) estimating wave parameters directly from features in the images. SAR data have limitations in coastal areas, due to short waves and/or distortion of images due to artefacts. Despite this, it is possible to derive wave spectra by either inversion of the image spectrum or using empirical functions for feature detection. It was estimated that only 30% of the Sentinel-1 SAR images for the North Sea is suitable for inversion, but 99% for estimating integral wave parameters directly (Pleskachevsky et al., 2019, 2022, 2024). Some Satellites technologies, e.g. TerraSAR-X and RADARSAT-2 (commercial satellites) use a higher frequency and therefore have a lower wave length threshold. This way, the data of these satellites are more suitable to be used near the coast.

A.4 Optical satellite imagery

Traditionally many sensors also acquire information in the optical wavelengths, this covers the spectrum of visible light (colours) but also the near-infra red. Open datasets from the Sentinel-2 mission are being used to retrieve information on waves (e.g. wave length, wave celerity, wave period and wave direction), using glint (glitter), or a small time-lag in of collection of data for each image between the Sentinel-2 bands (Bergsma et al., 2019). Detection of water wave mechanics has also been used to derive coastal bathymetry, and waves are an interesting product from these processing lines aiming at bathymetry (Gawehn, 2022a, b). The wave height cannot be derived directly from optical satellite imagery. However, wave heights could possibly be derived using in-situ measured wave spectra for scaling/assimilation.

A.5 Complexity and Potential Information

Conventional products with more straight-forward methods like the LRM altimetry products are readily available, quality controlled and validated, but are usually bound to be less accurate for specific situations. Estimating geophysical variables in coastal areas continues to be challenging, for various reasons (Grgić & Bašić, 2021; Schlembach et al., 2023), such as: coarse resolution and land contamination. Various efforts have been made to improve this by developing retracking algorithms and neural network approaches. Relatively newer satellite missions can operate in SAR-mode with a higher resolution, increasing the potential to derive coastal SWH estimates. Figure A.5 displays a schematic overview of different satellite products in relation to complexity, potential coastal accuracy and information. Although SAR imagery and CFOSAT uniquely allow for the extraction of wave spectra and consequently possess more wave information, limitations can be expected in regional seas.

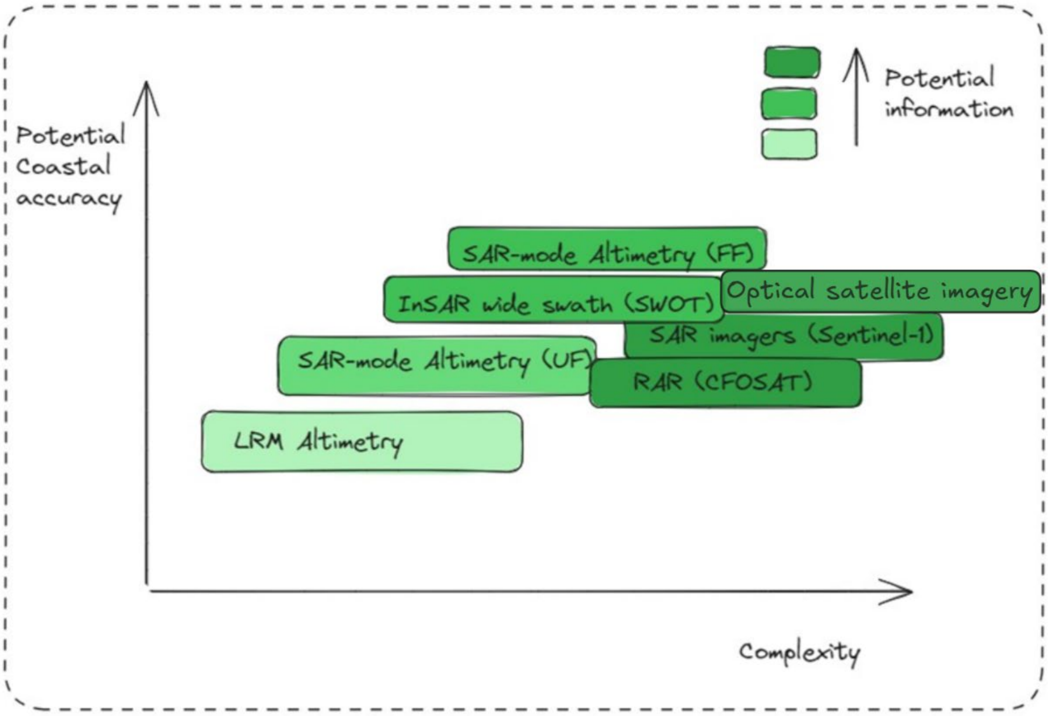

Figure A.5 Schematic overview of different satellite products from which wave information can be derived in relation to the complexity to derive information, the potential for coastal accuracy and the potential wave information

B Tools and code examples

Python notebooks with code examples on retrieving and exploring CMEMS altimetry can be found on Github here: https://github.com/cwedk/cmems_wave_sat and contain the following notebooks.

```
cmems_wave_sat/
└─ notebooks/
   ├─ 01-get_sat_data.ipynb
   └─ 02-explore_cmems_altimetry.ipynb
```

Python notebooks with code examples on exploring wave spectra from CFOSAT wave data can be found on Github here: https://github.com/cwedk/cfosat_wave and contain following code:

```
cfoasat_wave/
├─ src/
│  └─ plot_2D_spectre.py
└─ notebooks/
   ├─ CFO_SWIM_2D_wave_spectrum_visu.ipynb
   ├─ CFO_SWIM_wave_param_visu.ipynb
   ├─ CFO_SWIM_omini-dir_spectrum_visu.ipynb
   ├─ sigma0_visu.ipynb
   ├─ CFO_SWIM_visu_nadir.ipynb
   └─ visu_mini_prof_sigma0.ipynb
```

Wavy is a Python package for model validation with satellite altimetry, including optionally using CMEMS, collocation method and a storm tracking feature (https://wavyopen.readthedocs. 188 io/en/latest/tutorials_validate.html).

Python package for looking at swells in SWOT GitHub - ardhuin/swellSWOT

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