Ocean Surface Topography Meeting, 2025
Online forum

Nearshore wave processes detected using Sentinel-6 MF & SWOT satellite radar altimetry

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Nearshore wave breaking is involved in the exchange of heat and gases between water and air, dissipates energy that could erode the shore, and can pose a hazard to coastal users and boats. Wave set up can affect the water level at the coast and add to wave overtopping and flood risk. Currently, it is difficult to measure the spatial distribution of coastal wave breaking and set up, as it requires in situ sensors, such as cameras, water level gauges, marine radar and wave buoys. Satellite sensors offer the potential to map nearshore wave processes on a global scale. Using Penzance a high wave energy bay in SW England, with an array of available coastal monitoring, the added value satellite information can be explored.

Introduction

- SPLASH project: AI model for seawall overtopping prediction (McGlade et al., 2025)
- Where waves break should affect overtopping at seawalls (energy dissipated)
- Could wave breaking effect the model?
- Can we detect coastal wave breaking and set-up in radar altimeter data? (S6MF and SWOT)

The Wirewall overtopping system deployed at Crosby, NW England, UK

For the SPLASH project a wave overtopping prediction model for a seawall was developed (McGlade et al., 2025) using data from a wave buoy in Penzance Bay (CCO, 2025), the tide gauge at Newlyn (NTSLF, 2025) and the Wirewall overtopping system (Brown et al., 2020; Yelland et al., 2023). However, could wave processes between the wave buoy and shore affect the model? And can these be resolved in satellite data?

Wave breaking in Sentinel 6-MF data

- Reduction in wave height along track should indicate wave breaking
- As the backscattered radar signal is affected by sea surface roughness, breaking waves should affect the backscatter coefficient
- But how can this be verified? By wave buoy (red circle)

Sentinel 6 –MF radar altimeter

Launched: 21/11/2020

Along track resolution of ~260 m

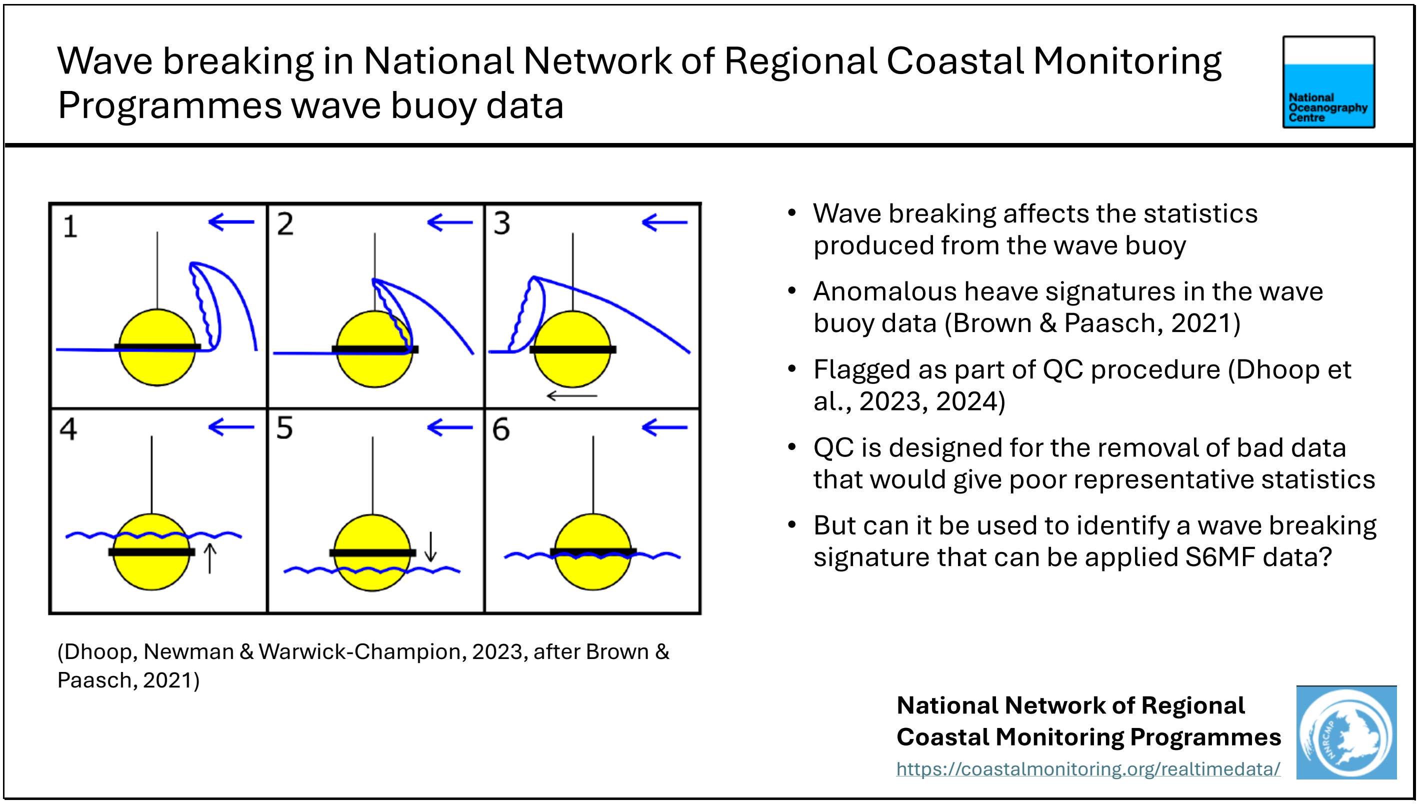
Repeats track every 10 days

Orbital track varies by about 1.3 km in the cross-track direction

Data used here from 7 May 2024 to 24 February 2025

Pulse limited radar altimeters can only measure reliably to ~3 km of the coastline. Improved Synthetic Aperture Radar (SAR) altimeter instruments, launched since 2010, can measure within a few km of the shoreline with a resolution of about 350 m. Sentinel-6A Michael Freilich (S6A-MF) follows on from Jason-3 as the current ocean surface topography reference mission. S6A-MF is a SAR altimeter, with a ten day repeat orbit and an along track resolution of ~262 m (ESA, 2025). It measures water level, significant wave height and wind speed (ESA, 2025). The orbital track varies by about 1.3 km in the cross-track direction (ESA, 2025). The track of the S6A-MF passes east of Penzance, nearly perpendicular with the beach, and the footprint of the altimeter covers a wave buoy. This allows the data from S6A-MF to be compared to an in-situ data set of wave heights, which have been flagged for wave breaking as part of the data quality control process (Dhoop et al, 2023, 2024).

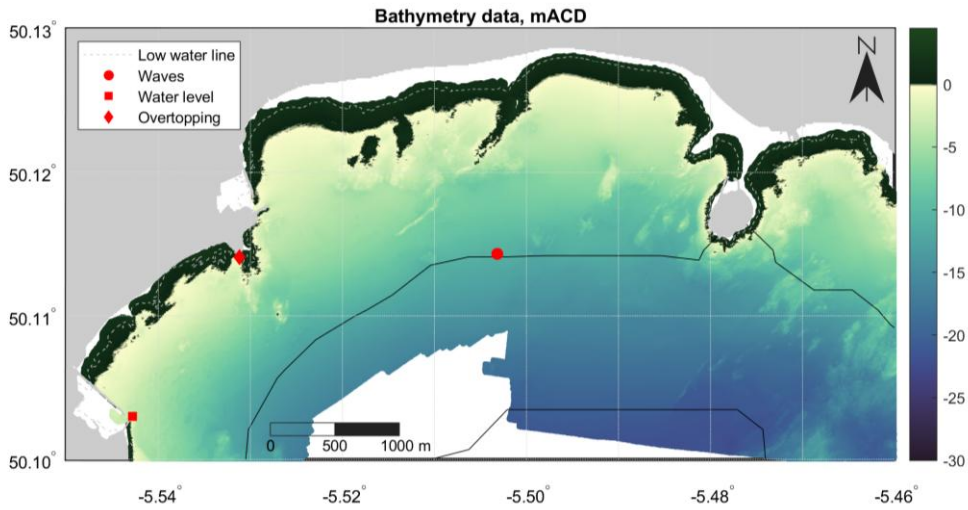
Figure: Penzance Bay showing the track of S6MF, the location of the wave buoy (red circle), overtopping measurement sites (including Wirewall. White markers) and Newlyn tide gauge (green dot).



As waves break over a wave buoy it causes anomalous heave signatures in the wave buoy data, by affecting the acceleration sensor, which can result in wave heights of 10's of metres and these are flagged as part of QC procedure (Brown & Paasch, 2021; Dhoop et al., 2023, 2024).

National Network of Regional Coastal Monitoring Programmes - https://coastalmonitoring.org/realtimedata/

Bathymetry and the depth wave breaking index



- The depth wave breaking index, γ, gives a limit to the size of unbroken waves
- Can be determined from wave buoy H_{max} (flagged) and the depth
- Wave buoy is at ~10 m above chart datum (ACD)
- Water level variation from Newlyn tide gauge

$$H_{max} = \gamma(d + \eta)$$

d – height above bed,
η - water level variation

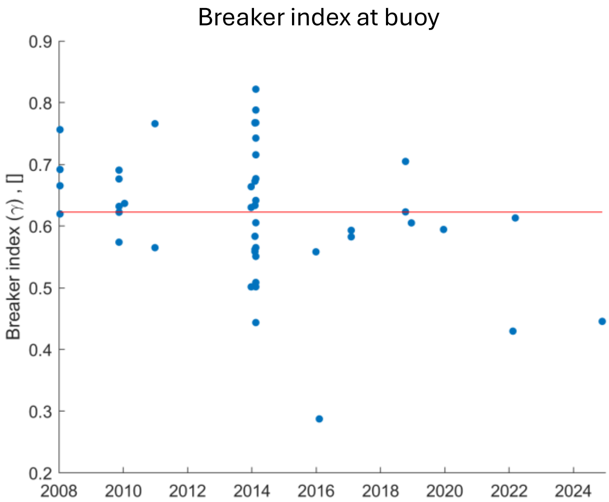
Applying the wave buoy data and water level values to the depth wave breaking equation, values for the depth wave breaking index can be calculated for when wave breaking is occurring (Holthuijsen, 2007; NNRCMP, 2025; NTSLF, 2025).

Figure: Bathymetry of the Penzance area. high resolution bathymetry (colour scale. UKCHP, 2023), GEBCO 2024 bathymetry shown for comparison (contour lines, 10 & 20 m), Coastline and low-water line: Office for National Statistics licensed under the Open Government Licence v.3.0 contains OS data © Crown copyright and database right 2025.

Wave breaking in Sentinel 6MF data (breaker index)

- Wave breaking index from the buoy data is 0.62 (mean of all points), compares well to the standard empirically derived value of 0.78
- H_{max} is estimated from S6MF SWH, assuming a Rayleigh distribution* and the number of waves (number of waves per footprint, n = 150)
- Assuming H_{max} represents the waves about to break, for $H_{max} > \gamma(d + \eta)$ breaking is occurring

*Cartwright & Longuet-Higgins, 1956 in Thornton & Guza, 1983

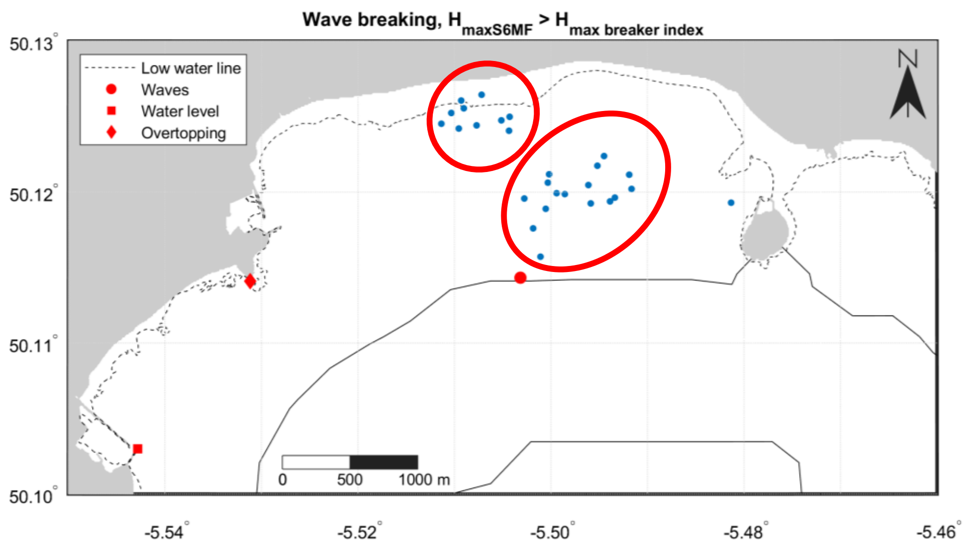


The flagging of wave breaking is a manual process and different people processed different years of data.

The number of waves used to determine H_max from the S6MF data is estimated using the footprint along track (~300m), so an average of 2 m wavelength would give 150 waves. This is a first attempt and could be improved with a better estimate of the wavelengths based on the wave buoy data.

Using the wave breaking index determined from the buoy data and the water level, the estimates of H_max from the S6MF significant wave height (SWH) can be assessed to determine if they are unstable (too big) and about to break.

Wave breaking in Sentinel 6MF data (breaker index)

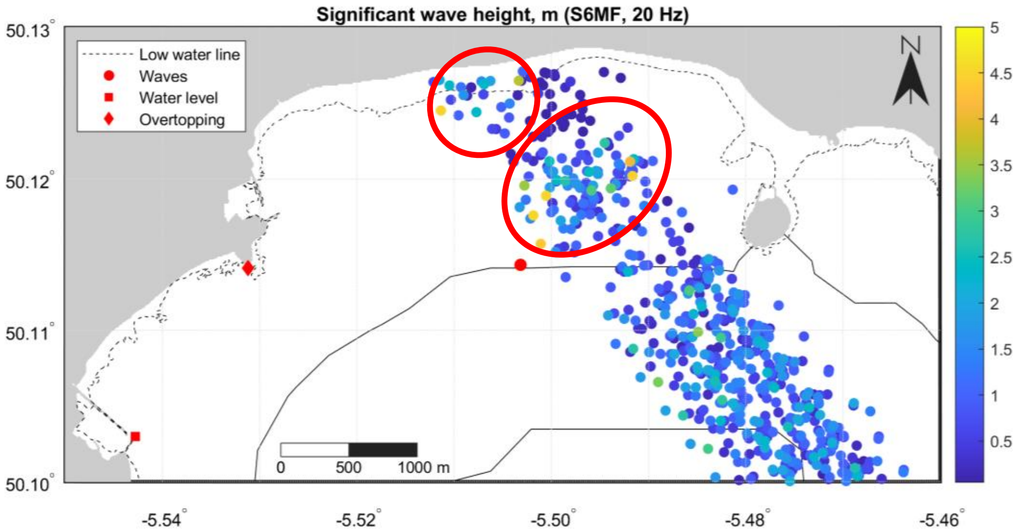


- Two clusters of points
- The nearshore cluster crosses the LW line and could be the beach
- Suggests wave breaking and reforming as waves travel to the shore
- Is this pattern consentient with the other methods?

The red ellipses, highlighting the two clusters are the same for the following four maps, to allow comparison.

[Flick through this slide and the next four to see the differences between the methods. In Acrobat Reader select Single page view and Zoom to page level, and uncheck Enable scrolling, which should keep the slides in the same position.]

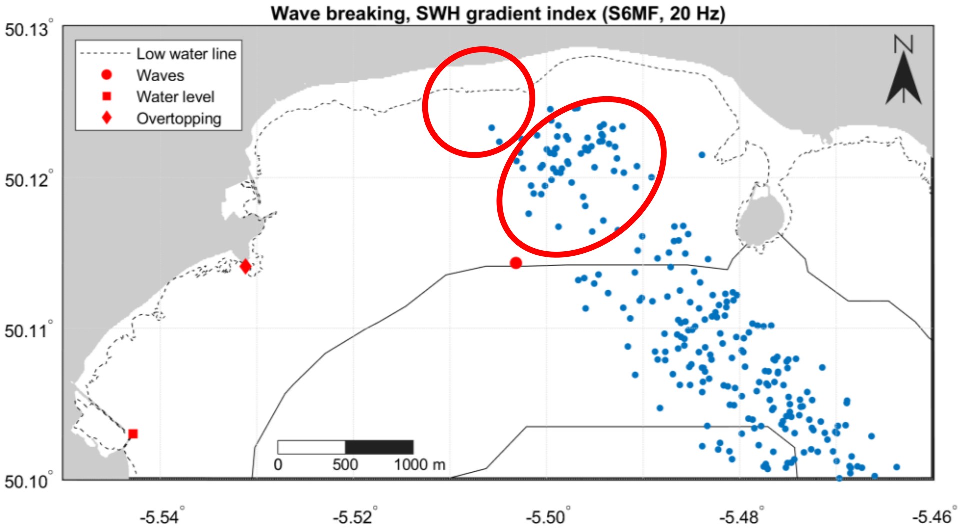
Wave breaking in Sentinel 6MF data (Significant Wave Height)



- Near-shore waves are deflected by the bathymetry to travel perpendicular to the shore
- Wave height increases, then decreases going towards the shore from the buoy, finally increasing at the LW line

Looking at the SWH areas of high waves stand out. A pattern of increasing SWH, decreasing then increasing at the shore is seen, suggesting that waves are growing and breaking as they travel to the shore.

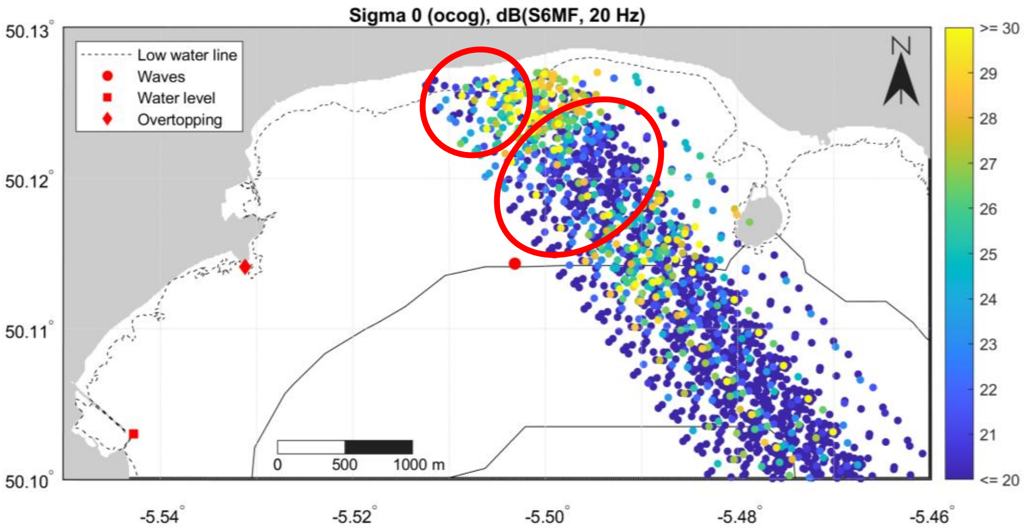
Wave breaking in Sentinel 6MF data (SWH change)



- S6MF track is roughly perpendicular to the shore, therefore we assume waves travelling along-track
- Decrease in SWH along track should be related to wave breaking (SWH grad > 0)

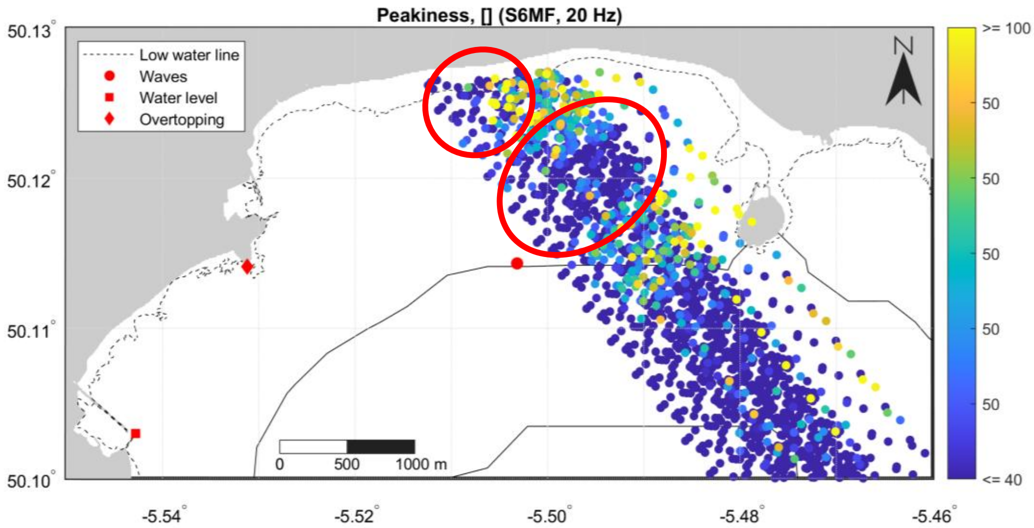
However, when the change in SWH is determined, the pattern is not as clear.

Wave breaking in Sentinel 6MF data (Backscatter)



- Backscatter is reduced where breaking is expected
- Offshore from the wave buoy also shows reduced backscatter
- Does it show developing/re-forming waves?

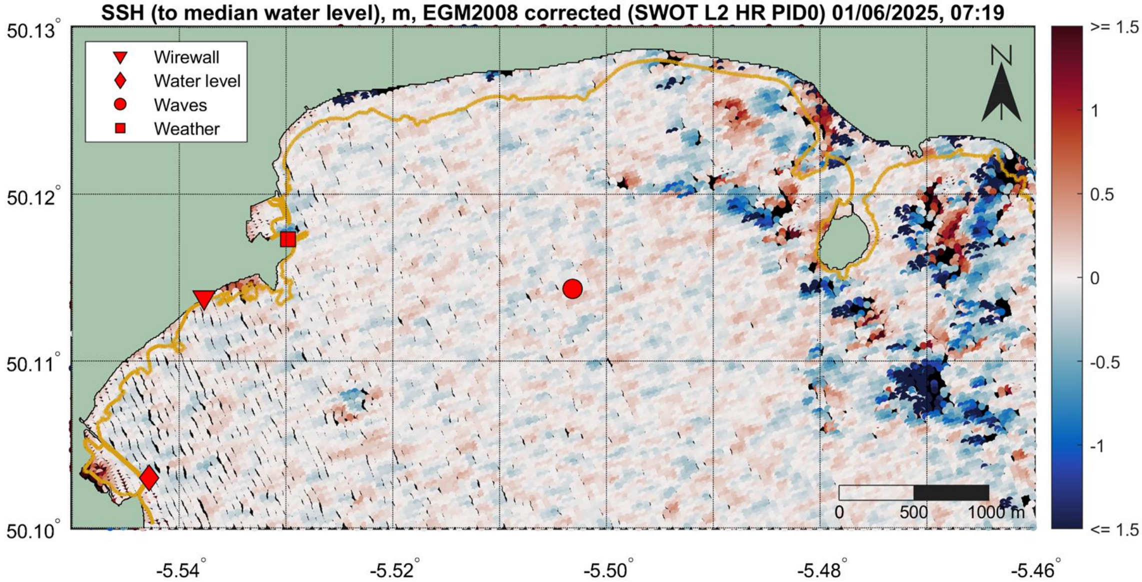
Wave breaking in Sentinel 6MF data (Peakiness)



- Similar pattern to the backscatter

Radar altimeters measure the peakiness of the returned radar waveforms, which should detect areas of breaking waves due to increased specular reflection.

SWOT HR SSH: high-water



The SWOT satellite mission provides 2D water surface elevation measurements, for the first time from space. The HR PIXC data product, though designed for rivers and inshore water bodies, can detect nearshore features in water level at about 30 m spatial resolution. Though care must be taken as SWOT will also detect intertidal and beach areas, mistaking them for water.

SWOT: launched – 16/12/2022, products have resolutions from 2 km to ~30-60 m, vertical accuracy better than 10 cm, 21-day repeat (https://www.aviso.altimetry.fr/en/missions/current-missions/swot.html).

[Flick through this slide and the next two to see the differences between high water, mid-water ebb and low water]

Figure: Sea surface height for the Penzance area at high-water, mid-water ebb & low-water, metres, corrected to geoid (EGM2008) and the median water level. SWOT L2 HR PIXC product (version PID0). The locations of Wirewall (overtopping), Newlyn tide gauge (water level), Penzance wave buoy and Penzance weather station are shown. Missing data and gaps between SWOT measurements are shown in black. The colour scale has been adjusted to ±1.5 m to highlight the wave affects. The low-water line is shown in light orange. Coastline and low-water line: Office for National Statistics licensed under the Open Government Licence v.3.0 Contains OS data © Crown copyright and database right 2025.

SWOT HR SSH: Mid-water ebb

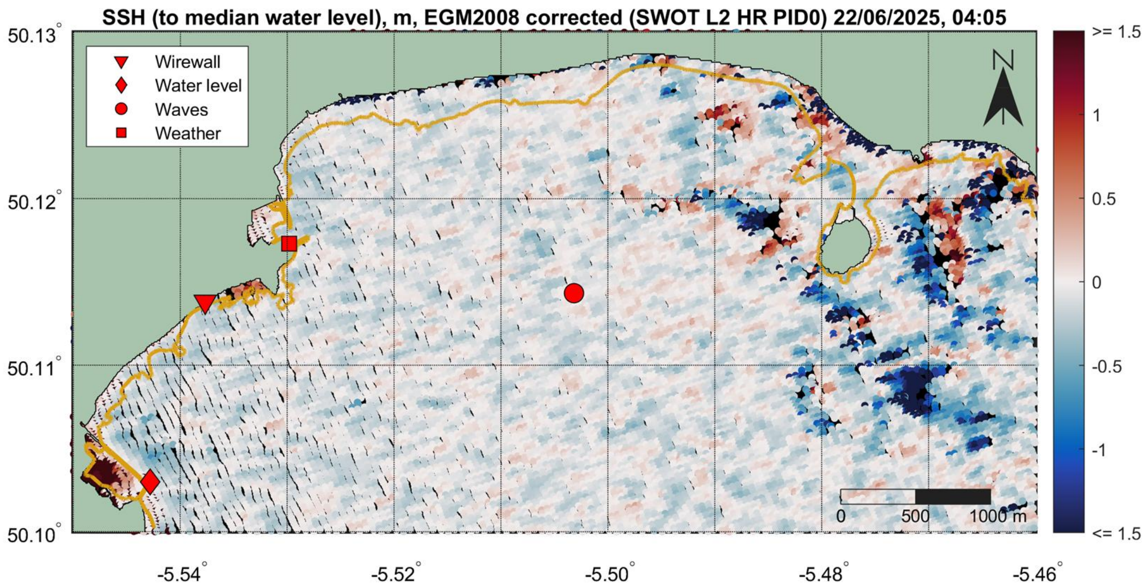
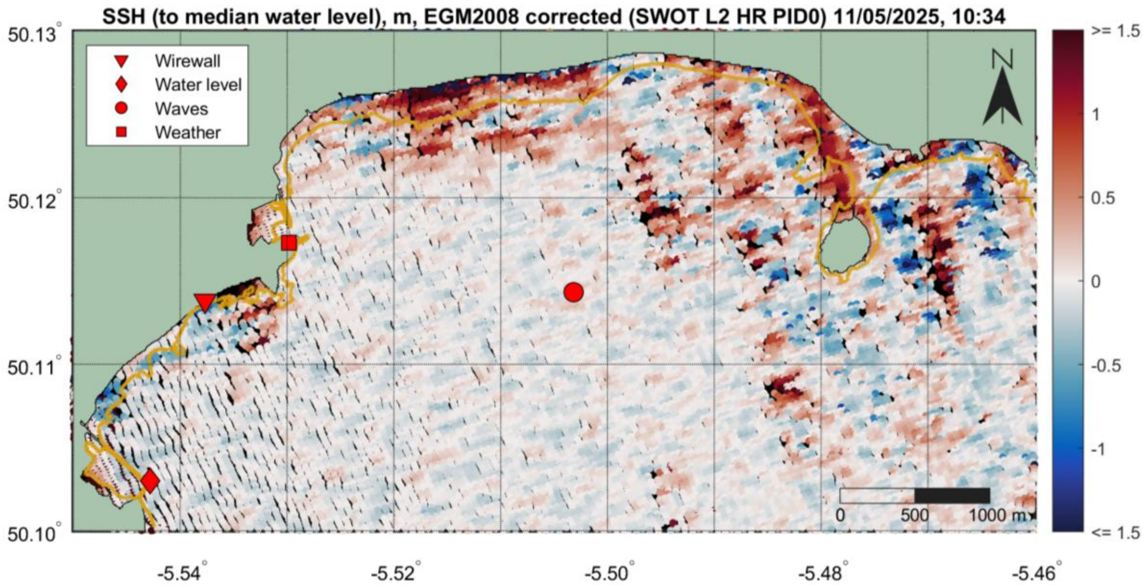


Figure: Sea surface height for the Penzance area at high-water, mid-water ebb & low-water, metres, corrected to geoid (EGM2008) and the median water level. SWOT L2 HR PIXC product (version PID0). The locations of Wirewall (overtopping), Newlyn tide gauge (water level), Penzance wave buoy and Penzance weather station are shown. Missing data and gaps between SWOT measurements are shown in black. The colour scale has been adjusted to ±1.5 m to highlight the wave affects. The low-water line is shown in light orange. Coastline and low-water line: Office for National Statistics licensed under the Open Government Licence v.3.0 Contains OS data © Crown copyright and database right 2025.

SWOT HR SSH: Low-water - wave set-up and depth limited wave breaking



Waves traveling to the shore have an effect of increasing the water level, known as set-up. This should be seen as increased water levels in the nearshore area compared to areas further from the shore. Due to variation in the wave field and bathymetry, varying patterns of set-up and down are expected along the shore.

The sea surface height map from 11 May, low-water, shows lines of higher water level near the shore to the north of the bay and by the Wirewall deployment at Penzance, which would be expected for wave set-up and depth limited wave breaking. Along the low-water line, areas of higher and lower water level can be seen. In the east of the bay persistent features (at high, mid and low water) suggest circulation patterns caused by the coastal morphology, but these would need to be verified by in situ measurements.

Figure: Sea surface height for the Penzance area at high-water, mid-water ebb & low-water, metres, corrected to geoid (EGM2008) and the median water level. SWOT L2 HR PIXC product (version PID0). The locations of Wirewall (overtopping), Newlyn tide gauge (water level), Penzance wave buoy and Penzance weather station are shown. Missing data and gaps between SWOT measurements are shown in black. The colour scale has been adjusted to ±1.5 m to highlight the wave affects. The low-water line is shown in light orange. Coastline and low-water line: Office for National Statistics licensed under the Open Government Licence v.3.0 Contains OS data © Crown copyright and database right 2025.

Conclusions

- Can we show coastal wave breaking in S6MF data? Yes, but better validation is needed for more confidence in the results (shore-based radar and cameras)
- The sea surface height map at low-water, shows higher water level in areas where wave set-up and breaking is expected.
- In the east of the bay persistent features suggest circulation patterns caused by the coastal morphology, but this would need to be verified.
- Satellite radar altimetry should be able to map nearshore breaking waves, in suitable areas, around the globe.

Thank you for reading

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Find SWOT-UK at https://noc.ac.uk/projects/swot-uk

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