Deutsches Geodätisches Forschungsinstitut
TUM School of Engineering and Design
Technical University of Munich

Coastal Significant Wave Height Gradients from SWOT and Sentinel-6

G. Tafuni[1], M. Passaro[1], O. Gassot[2], S. Causio[3], and I. Federico[3]

[1]Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Germany
[2]Collecte Localisation Satellites (CLS), France
[3]CMCC Foundation – Euro-Mediterranean Center on Climate Change, Italy

Motivation

As part of the ESA CoastDyn Project, this study investigates the dynamics of Significant Wave Height (SWH) in the North Sea–Wadden Sea transition zone. We evaluate the performance of the SWOT KaRIn instrument by performing a cross-validation with Sentinel-6 (S6) tracks that intersect the SWOT swath.
To optimize coastal data retrieval, we processed the Sentinel-6 data using both SAR and Fully-Focused SAR (FF-SAR) data. These results are compared with specialized coastal retrackers—WHALES [1] for low resolution mode altimetry, and CORAL [2] for SAR altimetry—which are designed to mitigate land contamination and improve precision near the shoreline.
Furthermore, we assess the potential of SWOT for long-term monitoring of coastal SWH gradients by leveraging historical data from the ESA Sea State CCI project (Jason-1, -2, and -3) alongside recent observations from Sentinel-6.

Data

- **Sea State Climate Change Initiative (CCI) v4:** Multi-mission cross-calibrated SWH observations from Jason-1, -2, and -3 [3].
- **SWOT KaRIn:** Level-2 Low Resolution Sea Surface Height (`L2_LR_SSH`) Expert Version D [4], recalibrated using a Beta-angle decorrelation correction [5].
- **Sentinel-6 Standard Level-2:** Low Resolution (`L2_LR`) ocean products [6].
- **FF-SAR Product:** Fully-Focused SAR (FF-SAR) reprocessing of Sentinel-6A data to optimize along-track precision when approaching the coast.

Methods

Temporal and spatial data matching

- **Spatio-Temporal Filtering:** 38 matching pairs of SWOT and Sentinel-6A passes within the Wadden Sea region (53–55°N, 2–10°E), utilizing a ±6-hour temporal window, were identified.
- **1:1 Point Matching:** A nearest-neighbor approach (within a 5 km radius) was applied to match SWOT observations with four distinct Sentinel-6A data reprocessing:
  - Standard SAR (`L2_LR`)
  - Fully-Focused SAR (FF-SAR)
  - S6 data retracked with WHALES
  - S6 data retracked with CORAL
- **Statistical Analysis:** The statistical median was calculated to evaluate systematic biases across three primary variables: latitude, distance from the coast, and cross-track distance within the SWOT swath.

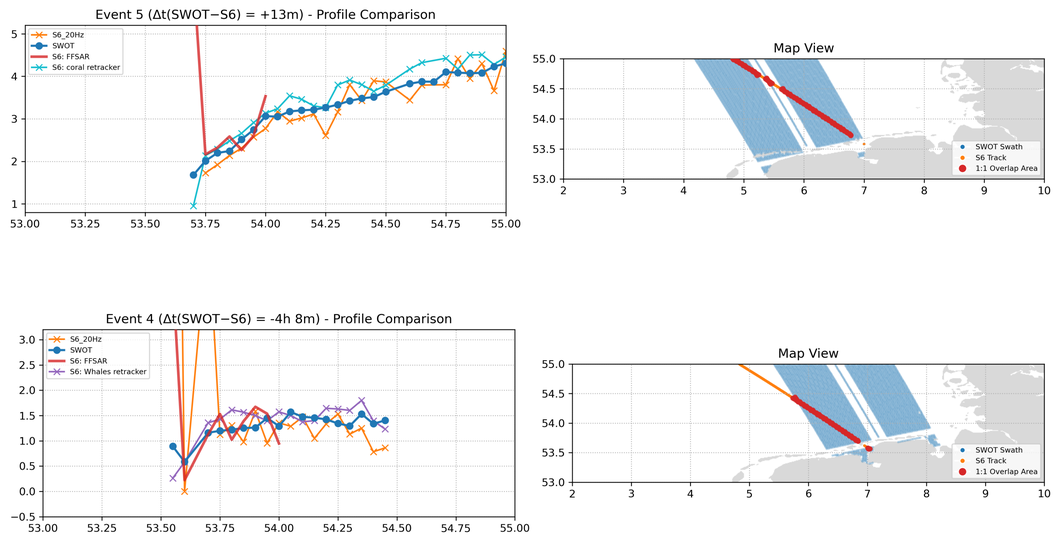

Figure 1 Spatio-Temporal Data Matching: Spatial configuration of intersecting SWOT swaths and Sentinel-6A tracks within the Wadden Sea region.

Coastal gradient

- **Gradient Computation:** Normalized attenuation ratios (from the coast to 30 km offshore) were computed to evaluate consistency between satellite observations: Sea State CCI (Jason-1, -2, -3), Sentinel-6A, SWOT, ERA 5 reanalysis

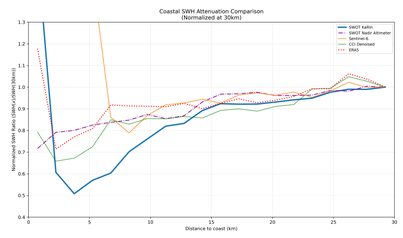

Figure 2 Cross-Mission Coastal SWH Gradients: Normalized attenuation ratios computed from the shoreline to 30 km offshore, comparing historical Sea State CCI (Jason-1, -2, -3), Sentinel-6A, and SWOT observations against ERA5 reanalysis data.

Evaluating Wave Models with SWOT 2D Altimetry

An additional application of SWOT 2D SWH measurements is their comparison with numerical wave models. These models typically rely on 1D nadir measurements from traditional altimetry for validation. This example instead shows how the **Adriatic Sea Forecasting System (AdriFS)** [7] is resampled onto the SWOT KaRIn pixels. AdriFS is a coastal wave modeling system based on WAVEWATCH III™ (WW3) [8], a state-of-the-art third-generation spectral wave model implemented on an unstructured grid with a resolution of approximately 250 m along the coast and 2.5 km offshore. The system uses the 2024 EMODnet bathymetry dataset and is forced by atmospheric fields from the ECMWF IFS010 analyses and forecasts.
The comparison offers mutual benefits:

- **Spatial Feature Agreement:** Two-dimensional features, such as coastal attenuation gradients, are clearly evident in both datasets.
- **Product Quality Improvement:** The comparison helps refine the data-flagging strategies of this experimental SWOT product, which still exhibits inconsistencies very close to the shoreline.

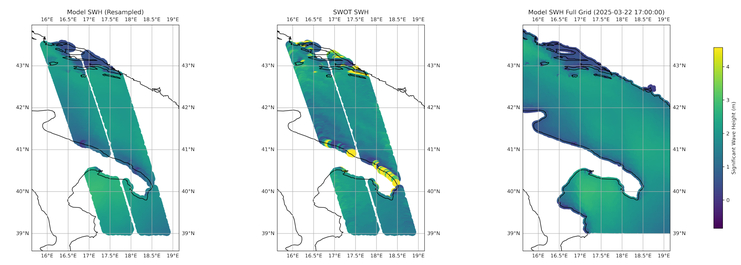

Figure 3 2D SWH Spatial Intercomparison in the Adriatic Sea: Resampled AdriFS model significant wave height (left) mapped directly onto the SWOT KaRIn swath geometry (center), contrasted against the continuous full-grid AdriFS wave model forecast (right).

Results

- **SWOT vs. Sentinel-6:** Multi-mission tracks show strong baseline agreement, with SWH discrepancies generally bounded within ±25 cm, and mostly due to non-coincident temporal sampling.
- **Coastal Attenuation Gradient:** Attenuation ratios (0–30 km) diverge within the final 10 km from the coast. Reasons are to be further investigated. True consistency should be re-evaluated using upcoming Sentinel-6 WHALES and CORAL reprocessed data, as the standard baseline SAR product exhibits inconsistencies within the last 10 km to the coast.
- **FF-SAR Performance:** Fully-Focused SAR processing significantly enhances geophysical consistency and signal stability close to the coast compared to unfocused SAR. However, in the complex land-water transition zone, signal land contamination is still visible.
- **Coastal retracking:** The WHALES and CORAL retrackers successfully remove the outliers observed in the standard Sentinel-6 products, underscoring the need for coastal retracking when comparing nadir altimeter measurements with SWOT observations in the coastal zone.

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Contact & Institution
Deutsches Geodätisches Forschungsinstitut
Technical University of Munich
Email: giulia.tafuni@tum.de