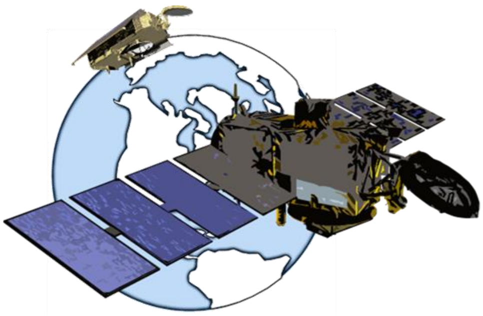
Sentinel-6 Michael Freilich and Jason-3 Tandem Flight Exploitation (S6-JTEX)

Scientific Roadmap



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ACRONYMS AND ABBREVIATIONS

CNES	Centre National d'Etudes Spatiales
ENL	Equivalent Number of Looks
ESA	European Space Agency
FFSAR	Fully Focused SAR
GDR	Geophysical Data Record product
HR	High Resolution
HFMR	High Frequency Microwave Radiometer
HRMR	High Resolution Microwave Radiometer
IR	Altimeter Impulse Response
ISW	Internal Solitary Waves
J3	Jason-3 mission
LRM	Low Resolution Mode
L1	Level 1
L2	Level 2
LIT	Lake Ice Thickness
LSE	Least-Square Estimator
MLE	Maximum Likelihood Estimator
MSL/GMSL	(Global) Mean Sea Level
MSS	Mean Sea Surface
MWR	Micro-Wave Radiometer
NR	Numerical Retracker
NTC	Non Time Critical delay
POS4	Poseidon-4 altimeter
PRF	Pulse Repetition Frequency
RMSE	Root Mean Square Error
S6-JTEX	Sentinel-6 Michael Freilich and Jason-3 Tandem Flight Exploitation
S6-MF	Sentinel-6 Michael Freilich
SAP	Science Activities Plan
SAR/SARM	Synthetic Aperture Radar (Mode)
SIC	Sea Ice Concentration
SLA	Sea Level Anomaly
SSB	Sea State Bias
SSH	Sea Surface Height
SWH	Significant Wave Height
USAR	Unfocused SAR
VS	Virtual Station
WL	Water Level
WSH	Water Surface Height
WTC	Wet Tropospheric Correction

1 Introduction

1.1 Scope of the document

This document is the Scientific Roadmap (SR) document which, following studies of the tandem phase of Sentinel-6MF (S6-MF) and Jason-3 (J3), suggests avenues for future research, with the aim in particular to exploit the second tandem phase of opportunity between the two satellites scheduled in early 2025.

2 Lessons learned from the S6MF - J3 tandem phase

The exploitation of the sixteen-month tandem flight configuration between Sentinel-6 Michael Freilich (Scharroo et al., 2016; Donlon et al., 2021) and Jason-3 has offered a unique opportunity to provide valuable insights into characterizing the differences between the two missions, and importantly, to demonstrate the high benefit of this new altimeter reference mission in extending the legacy of sea-surface height measurements. Furthermore, it allowed the implementation of a number of scientific studies aimed at fully exploiting the capabilities of the mission, including the use of innovative processing to enable new potential products and applications, as described in the Science Activity Plan, but also available on the project website https://www.s6-jtex.org/.

Below, we highlight the main findings of the S6-JTEX case studies, and the lessons that have been learned from them to improve the quality and scientific value of the S6-MF altimeter products. These results were also presented in conferences (e.g., Moreau et al., 2023).

2.1 CalVal Ocean and GMSL analyses

The Sentinel-6MF/Jason-3 tandem phase enabled us to validate the S6-MF measurements against Jason-3 over open ocean. Such tandem phases are crucial to investigate small discrepancies between missions in a configuration where natural variability mostly cancels out.

This study focused on the assessment of Low-Resolution (LR) data and the improvements brought by the numerical retracker (NR) with respect to the historical MLE4 (operated in both J3 and S6-MF processing chains) to provide high-quality records of sea-level observations. A first major result is that the agreement between Jason-3 and Sentinel-6MF was documented, down to the mm (range and SSH) or 0.01dB (backscatter) level. Some of these small discrepancies were attributed to different components of the system (orbits, or C-band processing). The improvement brought by the NR in terms of sea-state correlated bias with respect to MLE4 has been demonstrated.

Another important result is that we were unable to establish an obvious benefit of an NR retracker regarding long term stability, despite theoretical considerations suggesting that the NR, by design, should do a better job at mitigating instrumental changes. We were however able to identify some reasons why this theoretical benefit could not be empirically established:

1/ inconsistencies in the processing of radiometer data on both Sentinel-6MF and Jason-3 lead to inter-mission differences larger than the altimeter effects we are looking for,

2/ some S6-MF altimeter effects were empirically adjusted based on MLE4 data, these effects appear as inconsistencies now affecting NR measurements.

2.2 Uncertainties and GMSL analyses

Tandem flight phases have been crucial in verifying and ensuring the consistency of sea level measurements between successive altimetry reference missions (TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, and more recently Sentinel-6 Michael Freilich). However, detecting instrumental drift during a tandem phase is challenging due to its short duration (9 months to 1 year). The study described in Ablain et al. (2024) proposes a validation method using a second tandem phase to assess long-term stability of altimeter parameters. By reevaluating systematic instrumental errors during the second tandem phase and calculating trends between errors from both phases, this method aims to detect drift and estimate uncertainty globally and regionally. Results suggest the method can assess parameter stability with +/- 0.15 mm yr-1 uncertainty globally, increasing to +/- 0.4-0.6 mm yr-1 at regional scales. Regular double tandem phases between successive altimetry missions are recommended for accurate evaluation of altimeter parameter stability in the future.

2.3 Coastal study

Within this project, our analysis of the Sentinel-6MF/Jason-3 tandem phase showed that the SAR altimetry measurements perform better than the corresponding low-resolution mode, although these performances significantly improve if the waveforms are retracked with a dedicated coastal retracker (Passaro et al., 2023).

In parallel to this project, it has been demonstrated that nadir altimetry has the capability to assess the SWH attenuation typical of the transition from offshore to coastal zone due to several issues such as land sheltering and interaction with bathymetry (Passaro et al., 2021). Thanks to its improved performances, S6-MF may be able to quantify this decay at least up to 1 km from the coast, as first results show (Schlembach et al., 2023). This is of great interest for the operational exploitation of altimetry data, since it allows for example the quantification of wave energy resources to be exploited close to the coast and the verification of high-resolution models employed to plan coastal defenses taking in consideration near coastal wave transformations across a full distribution of shelf environments.

2.4 Validation of S6-MF sea state measurements

The continuity and stability of the long term altimetry record is of great importance to the sea state community and the research of long term variability from coastal to global scales (Timmermans et al. 2020a,b). This study therefore evaluated uncertainties in sea state data from the Sentinel-6MF / Jason-3 tandem phase and, for the study area in question (north east Pacific), generally established that significant wave height measurements on the two platforms are highly consistent.

Discrepancies between J3 and S6-MF LR collocated Hs measurements are small compared to differences with the in situ moored buoys. S6-MF HR data, affected by a sea state dependent bias, is corrected robustly through regression modelling, based on significant wave height. Subsequent triple collocation analysis appeared to show that S6-MF HR mode has the lowest error, by a small margin, but result robustness was limited by collocation sampling. This principally motivated evaluation against buoys closer to the coast—typically avoided in wave climate studies owing to the difficulties of applying an accurate and consistent collocation methodology.

Building on the work of Timmermans et al. (2020b), we therefore developed methodology to address this issue (within 50 km), avoiding data affected by local sea state gradients, thus increasing the number of possible collocations for aggregate analysis methods like TCA, and facilitating valuable coastal research. In fact, the methodology readily identifies buoy data that is statistically questionable w.r.t. altimeters, and shows how these are likely linked to both buoy-specific issues and local sea state gradients. In this study, we found that data from at least one widely used moored buoy appears as an extreme outlier, and identify others that are questionable. These results, described in Timmermans et al. (2024) have important consequences for validation of observations and the study of sea state variability. A full implementation, currently ongoing, will provide new insights into use of HR mode altimetry for these kinds of study.

2.5 Sea State study: ocean waves dynamics

The aim of CLS sea state study was to further evaluate the impact of ocean wave dynamics on the estimates of significant wave height and sea surface height from Sentinel-6MF delay/Doppler measurements. In addition to vertical velocities, we analyzed the impact of wind speed and direction, the impact of Stokes drifts and finally the impact of total surface currents. For this, we used a year of real Sentinel-6MF data and information on waves and currents from the ERA5 and MERCATOR models. A theoretical analysis was also carried out to explain the observed behavior.

The results of the real data analysis combined with the theoretical analysis enabled us to conclude that delay/Doppler measurements are influenced by the combination of three phenomena: waves orbital velocity, wind speed (inducing roughness asymmetry between upwaves and downwaves) and along-track Stokes drifts. More specifically, we found that estimates of significant wave height (SWH) are affected by an error linked to sea state, waves orbital velocity and wind speed (total amplitude), while estimates of range are affected by sea state, wind speed (total amplitude and not just the along-track component), orbital velocity and Stokes drifts in the satellite along-track direction.

Recommendations have been made for the development of two new corrections, one for SWH and the second one for the range or SSH. The SWH correction using SWH, orbital velocity and wind speed should provide improved results over the Egido et al. (2022) correction thanks to the addition of wind speed. The correction of the range can be considered as a generalized sea-state bias or pseudo sea-state bias correction, as it includes the classic SSB correction but also the surface effects that affect the Doppler signal. This latter requires the development of a new SSB correction method.

2.6 Statistical analysis of level-1 data

As with previous Cryosat-2 and Sentinel-3 missions (Egido and Smith, 2019; Clerc et al., 2020), pulse-to-pulse correlation effects were analyzed theoretically for the S6-MF mission (using ENL methodologies), then characterized with real LR data for different pulse-decimation configurations (PRF) and sea-state conditions. Impacts of using PRF at 9-kHz on range and SWH estimates were measured precisely, highlighting non-negligible biases due to the use of a non-optimal estimation method (least-squares estimator that does not account for the varying noise statistics across the waveform) and the need to use adapted LR LUTs to ensure data continuity of this mode with previous Jason time series (Recchia et al., submitted).

2.7 Fully-Focused SAR processing study

FFSAR has been subject of active research as part of this project, giving rise to a wealth of interesting results, also allowing us to assess the benefits of this processing on different surfaces, for many applications (Amraoui et al., 2024).

It has been demonstrated that this processing, when properly configured (Doppler bandwidth, integration time and the use of antenna whitening and a proper window), is capable of greatly enhancing the observation of specular and diffuse targets, opening up a multitude of possibilities for monitoring various types of surfaces, from the traditional open ocean to hydrology and sea-ice.

One of those findings concerns the ability of FFSAR data to image long-wave modulations at the sea surface, and the confirmation that the left/right ambiguities are due to folding of the backscattered signal in nadir-looking altimetry, as demonstrated for the Madeira case study. In this example, as the S6-MF track passes along the coast of the island, the altimeter sees only one side of the flight track (very weak signals are backscattered by the island), enabling the unambiguous determination of the wave field direction (except for the uncertainty in the forward/backward direction inherent in imagery).

The benefits of FFSAR were also shown in sea-ice areas, particularly with regard to its ability to detect thinner leads than those observed on Sentinel-1 imagery, which is of great interest for observing polar sea surfaces during glacial transition. The study enabled us to go even further by analyzing S6-MF FFSAR radargrams as images to map floe and lead structures and their extent using satellite imagery techniques. This way, valuable new information about the surface could be provided, which is not accessible from conventional LR and SAR data.

Another major result is the removal replicas strategy proposed for the S6-MF mission where replicas (due to the two missing Ku pulses) are particularly concerning for specular surfaces. If the method effectively cleans off these artefacts from the radargrams, it also removes incoherent targets. The applicability and benefits of this method have yet to be assessed on a larger data set.

This work further led to the recommendation of a set of configuration parameters (i.e. percentage of Doppler bandwidth, integration time, Doppler windows, replica mitigation and posting rate) to enable optimal processing of S6-MF FFSAR data from various surface types.

2.8 Inland Water analyses

The S6-MF/J3 tandem phase allowed for in-depth comparison of water level retrievals over inland waters (lakes and rivers) between S6-MF and J3, with a particular focus on SAR data of Sentinel-6MF (Taburet et al., 2024). The results first indicate that the SAR-LRM WSH bias strongly depends on the transect size, highlighting the need for users to account for this bias when constructing Jason-S6-MF water level timeseries from operational products (based on standard empirical retracking approach). The study also highlights the higher precision of the SAR mode compared with LRM, observed across a wide range of rivers from 10 m to 300 m wide.

However, the most complex river cases demonstrated that when slope information is unknown and/or contamination from surrounding water bodies arises, the precision of S6-MF with respect to J3 cannot be leveraged to improve precision with respect to in-situ ground truth. To address this, we introduced a novel approach involving virtual stations that exploit not only altimetry data over the rivers but also measurements acquired from off-nadir water bodies. This approach, specific to exploiting SAR altimetry data, improves precision in WSH timeseries and reduces the number of outliers with SAR mode, reinforced with the application of SAR-specific processing techniques (using along-track Hamming filtering or FF-SAR).

2.9 Lake Ice Thickness analyses

Within this project, we developed a novel and efficient analytically based retracking approach for estimating the Lake Ice Thickness (LIT) from high-resolution Ku-band SAR altimetry data processed in unfocused (USAR) and focused (FFSAR) beam forming (Mangilli et al. 2024). The retracker method is based on the analytical modeling of the SAR radar echoes over ice-covered lakes, which exhibit a characteristic double-peak feature attributed to the reflection of the Ku-band radar waves at the snow-ice and ice-water interfaces, as recently shown for LR in Mangilli et al., 2022. The method applied to S6-MF data demonstrates its ability to retrieve robust LIT measurements for different seasons and different type of lakes. These estimates are fully compatible with the ones obtained with LRM data, confirming the continuity of the LIT measurements and timeseries from conventional altimetry missions and current and future SAR altimetry missions. This study further demonstrates the advantages of using high-resolution S6-MF USAR data to obtain more precise measurements (a factor of 2 to 3 improvement). Additionally, high-posting rate data enhances performance with respect to 20 Hz, especially at the melting transition, due to the increased statistics.

The main limitation of LIT retrackers based on Ku-band waveform data is that they only work if certain conditions relating to the properties and thickness of the snowpack and the ice layer are met. In the case of melting snow on the ice surface or snow-free lake ice where the ice related signature is absent, it is not possible to generate consistent LIT estimations and timeseries for these targets. Overall, when the LIT signature is present in the radar waveforms, the method can precisely capture the seasonal LIT evolution and the inter-annual LIT variability, making it a powerful tool for robust LIT estimates for climatology and monitoring purposes.

2.9 Internal Waves Detection

Magalhaes et al. (2023) demonstrated that radar backscatter between Sentinel-6MF and Jason-3 is consistently correlated, either negatively or positively, in Internal Solitary Waves (ISW)-like signals, depending on whether the standard MLE4 or the alternative ALES/Adaptive retrackers in Jason-3 are used, respectively. This correlation arises from the inherently different acquisition geometries between SAR and conventional altimeters, where the sharper along-track resolutions in Sentinel-6MF (about 300 m) enable the sampling of ISW structures, while the larger footprints in conventional Jason-3 (typically a few kilometres wide) cannot.

This finding has broader implications for satellite altimetry, as it challenges the assumption of a uniform ocean surface at finer scales pursued by SAR altimetry, revealing the potential impact of small-scale ocean phenomena such as ISWs, fronts, and variable surface wind on altimetry measurements. The study suggests that alternative algorithms like ALES and Adaptive retrackers, which provide more focused views of conventional waveforms (namely in the leading edge), can achieve similar performance to SAR altimeters in capturing sharp transitions in ocean radar backscatter. The tandem phase between Sentinel-6MF and Jason-3 is deemed crucial for reconciling SAR altimeters with conventional altimetry records. Additionally, the study recommends that Jason-class level-2 products should provide SSHAs at 20 Hz (similarly e.g., to $\sigma 0$ or SWH).

3 Roadmap for future studies

The following sections present avenues for further investigations and research, as well as recommendations for the forthcoming second S6-MF/J3 tandem phase and future close-flight configurations between altimetry missions.

3.1 CalVal Ocean and GMSL (CLS /Magellium)

Based on the novel validation method proposed by Ablain et al. (in preparation) which relies on the realization of a second tandem phase between two successive reference missions, the following activities shall be encompassed:

- To apply the proposed validation method once the second tandem phase between Sentinel-6 Michael Freilich (S6-MF) and Jason-3 (J3), planned for early 2025, is performed, see the details below (*).
- To extrapolate this validation method to other satellite configurations, where tandem phases can be performed with 3 successive altimeter missions (A with B, B with C, and C with A), we could investigate how such satellite configurations will allow us to analyze the altimeter parameter stability. Such an approach would be useful for Sentinel-3 altimeter missions.

(*) The second phase tandem between S6-MF and J3 (planned early in 2025) is a unique opportunity to re-evaluate the relative errors made between the two altimeter missions a few years after the initial tandem phase. The second tandem phase will allow us to characterise the evolution of the instrumental errors and potentially detect any altimeter parameter drifts with a very low uncertainty (+/- 0.15 mm/yr).

Currently comparisons between S6-MF and J3 can be performed at crossovers, which imply larger sensing time differences than a tandem phase and hence larger contributions from natural ocean variability. The second tandem phase will allow to investigate to what extent the agreement between S6-MF and J3 has changed over time. This is possible for the altimeter itself and for the radiometer.

The second tandem phase also provides an opportunity to verify our current uncertainty budget on the long-term stability of the altimeter and radiometer parameters. An updated estimation of the S6-MF/J3 intermission offset can be translated to a relative drift between S6-MF and J3. If this relative drift happens to be significant, relative to the uncertainty budget, it should trigger 1/ an update of this budget and 2/ dedicated investigations to attribute this drift to one or several components of the system.

Note that this analysis should be performed on consistent (same processing baselines) and delayed mode (NTC) data.

3.2 Coastal study (TUM)

A recommended study for future research aims to assess the S6-MF mission capability to measure the SWH attenuation at the transition from offshore to coastal zone, focusing on the improvement of SAR altimetry compared to the low-resolution mode on both S6-MF and J3 in the tandem phase. The study shall encompass the following activities:

1) Dedicated outlier analysis in order to clean the SWH records from spurious measurements that would influence the derivation of an along-track SWH gradients
2) Derivation of the SWH gradient at a global scale using already available dataset (official J3 and S6-MF products), including coastal-reprocessed Jason-3 measurements (from the WHALES retracker available in the context of the ESA Sea State CCI project), during the tandem phase, and comparison between S6-MF and J3 results

3) Focus on attempt to assess the gradient using 20-Hz measurements up to 1 Km from the coast, as opposed to 1 Hz averages farther than 3 km from the coast as done in Passaro et al. (2021)
4) Focus on assessing whether present SAR altimetry data are able to accurately measure the SWH gradient when approaching the coast despite known issues of biases in SWH derivation compared to LRM altimetry
5) As a global coastal retracking (using either the SAMOSA+ retracking or its evolution CORAL) using a dedicated strategy for S6-MF is likely unfeasible with the resources of this project, a regional study can be planned for that. In case of SAMOSA+, the use of ESA resources (ESA Altimetry Virtual Lab) may be essential for this.
6) Depending on time and resources needed for the previous points, we also plan to conduct case studies in areas of particular interest, such as coral reefs to study their role as wave barriers.

3.3 Sea State (NOC/CLS)

3.3.1 NOC activities

Research Topic #1: Global ocean collocation study to evaluate sea state measurement uncertainty for tandem and model / reanalysis data.

Description: A direct extension of our triple collocation (TC) study, potentially quite “low-hanging fruit”, consisting of a modified collocation analysis based upon a large-scale global analysis of S6-JTEX data. Common analysis methods for sea state observations, such as TC, invoke strict statistical conditions (e.g. error independence), driving the need for data from independent sources like moored buoys. However, this presents a considerable limitation and burden on the analysis. This method proposes to obtain similar uncertainty measures as a TC analysis but by using only two datasets, thus alleviating the need for moored buoys, and specifically leveraging abundant tandem observations over global oceans to improve statistical robustness. A synthetic "proof of concept" case was examined (reported PM5 & 6) and appeared fruitful (possibly similar to Jiang, 2023). This approach would provide a better opportunity to examine the sea state dependence of altimeter observations, including SAR mode altimetry for sea state. Subject to available resource, an extension could involve the use of drifting buoys (e.g. Sofar Ocean “Spotter” buoys).

Key activities:

1 Perform further testing of methodological approach developed during previous study, using global model / reanalysis data (possibly ERA5);
2 Establish coherent geographic regions for analysis (by e.g. climatology, latitude, follow e.g. Lobeto et al. 2022);
3 Quantify uncertainties in tandem data using “double collocation” method (yields error variances similar to TCA). Probably start e.g. wind sea vs swell dominated regions;
4 Assess results w.r.t. sea state dependence (readily available from reanalysis, e.g. ERA5). Behavior of S6-MF HR mode will be of particular interest;
[5 Optional] Compare results against drifting buoys, e.g. Sofar Ocean Spotter Network (Houghton et al., 2021)?

Reseach Topic #2: Uncertainty in wave height measurements due to short timescale sea state variability.

Description: Short timescale sea state variability is a topic of recent interest, is poorly understood and contributes to uncertainty in sea state observations. Recently, De Carlo et al. (2023) have shown that “wave groups”, arising from certain sea state conditions, where spectral spreading occurs, can account for up to ~25% of observed sea state variability over spatial scales of 20 to 100 km. Due to their propagation, wave groups can manifest on timescales of ~30 seconds to ~few minutes. If signatures of wave groups can be identified in along-track Hs variability, then the 30 s lag in the tandem data may provide a sufficient time for those signatures to vary (or disappear). Therefore, analysis of along-track Hs variability in the concurrent tandem data, or any future tandem configuration, may detect this phenomenon. This investigation would naturally be applied to both S6 LR and HR observations (each providing a 30 s lag), and could also be conducted using both 1 Hz and 20 Hz data.

However, regardless of the underlying cause, any discrepancies between the tandem members detected through the 30 s lag, are worthy of investigation and clearly potentially contribute to uncertainty, whether spurious, or linked coherently to a specific physical process. This would represent an important step in estimating and reducing uncertainty in Hs measurements—relevant to many applications, such as the development of sea state Climate Data Records produced by the ESA Sea State CCI project.

Key activities:

5 Use reanalysis wind / wave data and spectral wave data to identify suitable regions (e.g. North Atlantic) and wave events of interest, during the tandem phase, that might give rise to small scale sea state variability (e.g. storms, currents);
6 Configure the datasets for analysis of along-track variability between J3 and S6-MF LR/HR data (1 Hz or 20 Hz), considering the detection of anomalous discrepancies;
7 Search for and identify variations and discrepancies, that may be linked to small scale variation. Methods may range from basic using statistical clustering or machine learning methods.
4a Assess contribution of detected Hs variance to overall uncertainty estimates previously established (e.g. though collocations).
4b Attempt to attribute Hs variance to specific physical phenomena (e.g. wave groups).

3.3.2 CLS activities

The current study relied on the analysis of one year of Sentinel-6MF real data and on theoretical analysis to characterize the impact of ocean waves dynamics on the delay/Doppler measurements. It concluded that delay/Doppler measurements are influenced by the combination of three phenomena: waves orbital velocity, wind speed and along-track Stokes drifts, in addition to the conventional Sea State Bias. Hence, it is important for delay/Doppler altimeters to develop new SSH corrections moving from the classical SSB to Pseudo-SSB correction using more than 3 parameters. For instance, we should develop a new SSB correction using SWH, wind speed and mean wave period as already done in the current SSB 3D model developed for conventional altimetry but adding along-track Stoke drifts (and orbital velocity with lower priority).

However, this requires extending the current SSB method (the non-parametric empirical method developed by Gaspar and Florens, 1998) to consider more than 3 parameters for the estimation. A work plan has been established between CLS, CNES and Mathematics Experts from Toulouse School of Economics and Paul Sabatier University to assess the feasibility, on a mathematical point of view, of developing such a method in 2024. The work started beginning of 2024 and is on-going. We expect the availably of the new tools by September 2024.

We propose as a future study, to use this mathematical new tool to develop a new SSB or pseudo-SSB correction for delay/Doppler altimetry and more specifically on Sentinel-6MF.

3.4 Unfocused and Fully-Focused SAR processing and data analysis (CLS)

A recent study using Sentinel-3 data has shown that long ocean waves are responsible for artifacts in the small-scale Sea Level Anomaly (SLA) spectra (Rieu et al., 2020) that could potentially cause spurious trends in the SAR altimeter climate record if left uncorrected. These artifacts result from the traditional 20-Hz posting rate that does not sample fast enough to capture long ocean waves. High-frequency signals induced by swells are therefore aliased down to lower frequency and are mistaken for another signals, degrading the observability of the ocean dynamics at meso-scales.

This work has also led to the development of a new SAR altimeter processing configuration to optimally mitigate this spectral aliasing, involving the application of a higher posting rate in the USAR altimeter processing at 80-Hz (Dinardo et al., 2014; Egido et al., 2021) followed by a low-pass filter before down sampling the data back to 20-Hz. These analyses however did not allow us to draw any definitive conclusions about the improvement brought by this processing for observing ocean features on shorter scales. Larger amount of data is needed to assess its capability globally and regionally. In view of that, the question now is to determine whether long ocean waves have similar impact on Sentinel-6MF SLA spectra, given the existing differences between the two missions (differences in range resolution, SAR operating mode and azimuth cutoff) and whether this technique is recommended for the new reference mission. This is also of high importance for the future missions that tend toward more use of SAR-mode altimeters, contributing thus increasingly to the time series of ocean topography measurements.

The study by Rieu et al. (2020) has provided other interesting information, highlighting in particular the value of exploiting a two-satellite close formation constellation for detecting evolving phenomenon at the sea surface. This was demonstrated by a cross-spectral analysis of the Sentinel3-A and Sentinel3-B acquisitions, which revealed phase shifts corresponding to waves travelling according to the wave dispersion relation. This analysis could only be carried out with USAR data, with therefore limited resolution, as Sentinel-3 FFSAR data (in closed-burst operating mode) are severely altered by the grating lobes (which cause an energy drop in the wavenumber spectra like a pass-band filter) preventing long-waves observation in azimuth. Future activities based on S6-MF and S6B altimeter data could further explore this technique in order to improve the characterization of these moving processes, but in greater detail taking full advantage of the FFSAR processing capabilities. These analyses could be supplemented by analyses carried out using SAR spectral imaging techniques (Altiparmaki et al., 2022) which have already shown promising results for extracting long ocean wave parameters by exploiting swell-induced backscatter modulations in FFSAR altimeter data.

As regards the sea ice region, FFSAR has shown high capability to image floe and lead structures with unprecedented accuracy, from which valuable surface information could be extracted. To this end, altimetry can draw upon image processing techniques and methods used in SAR and optical imaging. Although these techniques are only just beginning to be used in altimetry, they are already yielding very promising results, opening up the possibility of accessing new valuable and meaningful information on sea-ice leads, complementing waveform retracking outputs (Amraoui et al., 2024; Hernández-Burgos et al., 2024). However, further studies are needed to accurately assess the consistency of FFSAR in mapping sea-ice leads and their extent. A preliminary study could, for instance, focus on analyzing the floe/lead coverage estimates from Sentinel-6MF FFSAR data by comparing them with Sentinel-2 and sea-ice index (OSI-SAF) data in a selected region at different times of the year. Further analyses would result from this first evaluation.

3.5 Inland Water (CLS)

As emphasized in our work (also confirmed by other projects e.g. St3Tart), to fully exploit S6-MF improved performances with respect to J3 at the nadir of rivers to reconstruct water level timeseries, river slope must be accounted for. With SWOT first results providing estimates of river slopes (and also recent exploitation of IceSat2 data e.g. Scherer et al 2023), we are now provided with more and more complete bases of river slopes allowing us to further extent the precise assessment of S6-MF performances over a larger set of rivers. The question of improving Water Level timeseries reconstruction from S6-MF data exploiting SWOT derived slopes should be addressed. In combination with the second S6-MF / J3 tandem phase this method should allow to emphasize that S6-MF improved performances can now be exploited over rivers with significant slope (>30cm/km) to reconstruct WL timeseries better than J3 ones.

Exploiting the potential of the newly introduced 'off nadir' virtual stations presented in the first part of the study should be pushed further. In particular to address VS at distances larger than 1 or 2 km our first study was limited to. With larger slant ranges corrections to be applied, the sensitivity of the reconstructed Water Level estimates to the correct identification of the backscattering surface increases. Combined analysis of the Sentinel-6MF SAR radargrams with SWOT maps of the backscatter coefficient should be performed to better understand and exploit the off nadir S6-MF radargrams.

3.6 Lake Ice Thickness (CLS)

An interesting follow-up of the Lake Ice Thickness study would be to further investigate the radar waves propagation at difference frequencies through snow and ice over ice covered lakes. Indeed, the propagation of the waves at different frequencies depends on the properties of the surface and media encountered and is not fully understood so far. A goal of this study would be to assess the possibility of measuring snow-on-ice depth over iced covered lakes with altimetry data from different sensors at different frequencies, namely Ku-band data (Sentinel-6MF), Ka-band data (Altika) and laser data (IceSat2). In fact, laser waves do not penetrate through snow or ice and would allow to define the backscatter surface at the air/snow interface. On the other hand, Ka-band radar waves are in principle also reflected at the air/snow interface, but their propagation and reflection can depend on the snow and ice properties. Ku-band radar waves, in the case of fresh water (dry) snow and ice, back scatters at the snow/ice and ice/water interfaces. Comparing the laser and Ka-band data with Ku-band data on well-known target lakes, as for instance the Great Bear or the Great Slave lake in Canada, would allow to measure the snow-on ice depth and also better understand the Ka-band propagation through snow and ice.

These topics are particularly interesting in view of the future Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission that will carry both Ka and Ku bands altimeters. The analysis of Ka and Ku bands radar waveform on known ice-covered lakes, when the ice is well established, could indeed offer a robust way to characterise the Ku and Ka signals, providing with a sort of calibration sites that could be included to regularly monitor and assess the performances of the dual band CRISTAL measurements.

3.7 Internal Waves Detection (University of Porto)

The detection of large-scale Internal Solitary Waves (ISWs) with radar altimeters was first reported in Jason-2/3 conventional pulse-limited altimeters (Magalhaes and da Silva, 2016). Since then, developments in SAR altimetry revealed a rich variety of ISW signatures in three main geophysical parameters: sigma0, SWH and SLA. This finding (Santos-Ferreira et al., 2018) led to the development of semi-automatic algorithms for detecting ISWs in SAR altimeters (Santos-Ferreira et al., 2019) and further exploration of ISW signatures with various processing schemes, including FF-SAR and new retrackers that use a truncation of the dynamic range around a local epoch to effectively enhance the altimeter spatial resolution (i.e. shorten the footprint both along and across-track). Furthermore, synergy capabilities with visible imagery (Sentinel-3/2) allowed the identification of wave-breaking bands associated to deep ocean ISWs, which were captured in SWH signals in scales of the order of 20 km (Santos-Ferreira et al., 2022).

Thus far, the geophysical parameter that has been less explored in ISW applications with SAR altimetry has been the Sea Level Anomaly (SLA). Yet, SLAs convey perhaps the most important information that can be retrieved from satellites: internal wave amplitudes, and hence the ISWs' energies (Pinkel, 2000). While, in the beginning of our studies, it was not obvious if the SLA signatures of ISWs were truly physical features, or rather some artifacts of the retracking schemes currently utilized in unfocused SAR processing, we have now consistently observed SLAs of the order of 10-30 cm in practically all SAR products (including FF-SAR) and different processing schemes. It should also be pointed out that the SWOT KaRIn mission is providing a myriad of coherent SLAs consistent with ISWs, simultaneously with the traditional and expected sigma0 signatures of ISWs. It seems therefore a natural step forward, concerning ISW altimetry applications, to analyze and unveil the applications of SLA signatures of ISWs.

In this Task we intend to establish a technique to convert SLAs detected by altimetry (Sentinel-6 and Jason-3) into ISWs amplitudes, within reasonable bounds of error. The technique should follow a sequence that includes:

- Compare sigma0 and SLA signatures for all "qualified observations" of ISWs in Sentinel-6 SAR; sigma0 should provide an independent estimate of ISW amplitude by the "peak-to-peak distance" method (Zheng et al., 2001), and SLA can be converted in ISW amplitude under some assumptions about local unperturbed stratification (Santos-Ferreira & da Silva, 2020).
- Dubreil-Jacotin-Long (DJL) fully nonlinear theory (Long, 1953) shall be used to estimate ISW morphologies based on stratification profiles (obtained from ARGO system buoys) close enough in space-time of the altimetry observations; note that DJL provides solitary wave solutions which may be tuned (to a reasonable extent) to match independent estimates of either wavelength or amplitude (see Xu et al., 2023).
- We intend to determine reasonable bounds for SLA variability due to typical along-track roughness changes (produced by ISWs observed in the SAR altimeter) and compare those with SLA amplitudes that are expected owing to ISWs; for this task, a retracker in full range and over a reduced range of bins (truncation carried out dynamically ten gates away from the estimated epoch position) needs to be used.

This new method to estimate ISW amplitudes could be converted in the ISW surface velocity field under reasonable assumptions, and verified for consistency with the "peak-to-peak distance" method (Xu et al., 2023). We note that ISW current velocities are a major concern for the offshore industry, and currently there are no reliable methods to estimate such currents from satellite remote sensing.

3.8 Sea ice parameters estimation using S6MF HRMR brightness temperatures (CLS)

Sea ice concentration (SIC) or sea ice fraction describes the relative area covered by ice compared to a reference area. A good knowledge of SIC is essential for determining the sea ice extent in a region as well as for estimating sea ice freeboard and thickness from altimeter measurements. Snow depth is also an important parameter allowing an enhanced estimation of sea ice thickness.

Recently, we carried out a study assessing the feasibility of estimating Sea Ice Concentration using S3A/B MWR brightness temperatures. This study was under an ESA contract (F. Borde) and in collaboration with CNES. From the state of the art (ESA Sea Ice Climate Change Initiative report, 2013, Ivanova et al. 2015), two algorithms have been identified as being applicable to S3A/B MWR channels, characterized by two microwave frequencies (23.8 GHz and 36.5 GHz) and a near-nadir incidence angle. These algorithms are the One-channel algorithm (Pedersen, 1991) and the Bootstrap algorithm (two-channel) in frequency mode (Comiso, 1986 and 1995). We adapted and implemented these two algorithms using one year (2017) of S3A MWR brightness temperatures at the North and South Poles. The OSI SAF Sea Ice Concentration product was used as a reference to validate, evaluate performance, and compare algorithms.

The resulting average root mean square error between the retrieved S3A MWR SIC and OSI SAF SIC for both algorithms, was in the range of 5 % in Winter and 6-8 % in Summer with a really low average bias, most of the times less than 1%. These results are very promising as they show similar performance to other state-of-the-art algorithms applied to radiometer missions as AMSR-E, SSM/I or SMMR (ESA Sea Ice Climate Change Initiative report, 2013). There is still room for further improvements: altimeter Sigma0 in C and Ku bands could bring useful information in addition to brightness temperatures. Corrections such as weather filters to remove spurious ice concentration over open ocean, land-to-ocean spillover correction or atmospheric correction could further improve these performances.

Sentinel-6 MF embarks a low frequency radiometer, AMR (3 frequency channels as for Jason-3 radiometer) and a high-frequency radiometer HRMR with 3 new high frequency channels: 90, 130 and 168 GHz. From the literature on the sea ice concentration algorithms using radiometer brightness temperatures (for eg. ESA Sea Ice Climate Change Initiative report, 2013) we can find two different algorithms using high frequency channels (89 or 85 GHz) to enhance the ground resolution.

Based on our recent experience using S3 MWR data, we propose to carry out a new analysis using Sentinel-6MF HRMR data to assess the sensitivity of the 90 GHz channel to sea ice parameters and feasibility of estimating sea ice concentration using this frequency in addition to the low frequency ones.

In the previous ESA study using Sentinel-3 MWR data, we also assessed the feasibility of estimating snow depth on sea ice using algorithms from the literature. Estimating snow depth is much more complex than sea ice concentration even for radiometers dedicated to sea ice. We propose to use Sentinel-6MF HRMR 90 GHz channel to caracterize its sensitivity to snow depth and assess the feasibility of estimating snow depth by combining the 90 GHz channel to the 18 or 23 GHz channel.

3.9 Performance of the wet tropospheric correction using high-frequency channels (CLS)

Sentinel-6 MF is the first altimetry mission embarking a high frequency radiometer HFMR with 90, 130 and 168 GHz channels in addition to the usual frequency channels as already exist in the Jason Series and SWOT 18, 23 and 36 GHz channels. The HRMR objectives are to enhance the Wet Tropospheric Correction below 1 cm uncertainty up to 10 km from the coast.

In the frame of Sentinel-3 NGT phase AB1 study, CLS was responsible of the performance of the radiometer (among other activities on Poseidon-5 and SAOOH altimeters). It is foreseen that S3NGT radiometer also embarks high frequencies. CLS assessed the performance of the Wet Tropospheric Correction of such a radiometer over ocean and coastal for what concerns the Wet Tropospheric Correction. This analysis has been achieved thanks to end-to-end simulation.

Our analysis confirmed the good behavior of the WTC uncertainty up to 10 km from the coast but also showed better performances over ocean if we compare to the performance of WTC using only low frequency channels. We propose to assess the impact of high frequency channels of S6 HRMR on the Wet Tropospheric Correction performance over ocean.