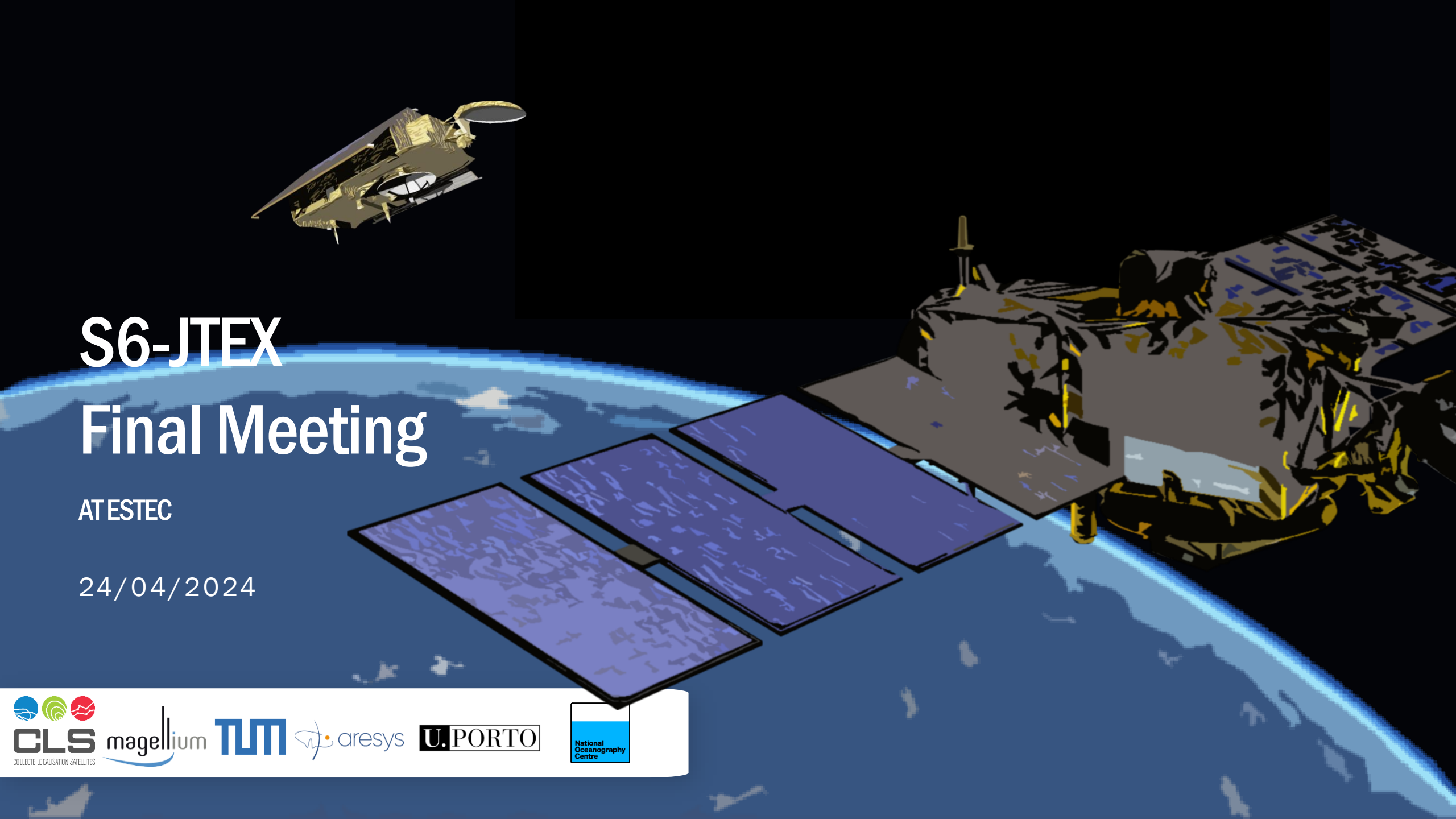


S6-JTEX
Final Meeting

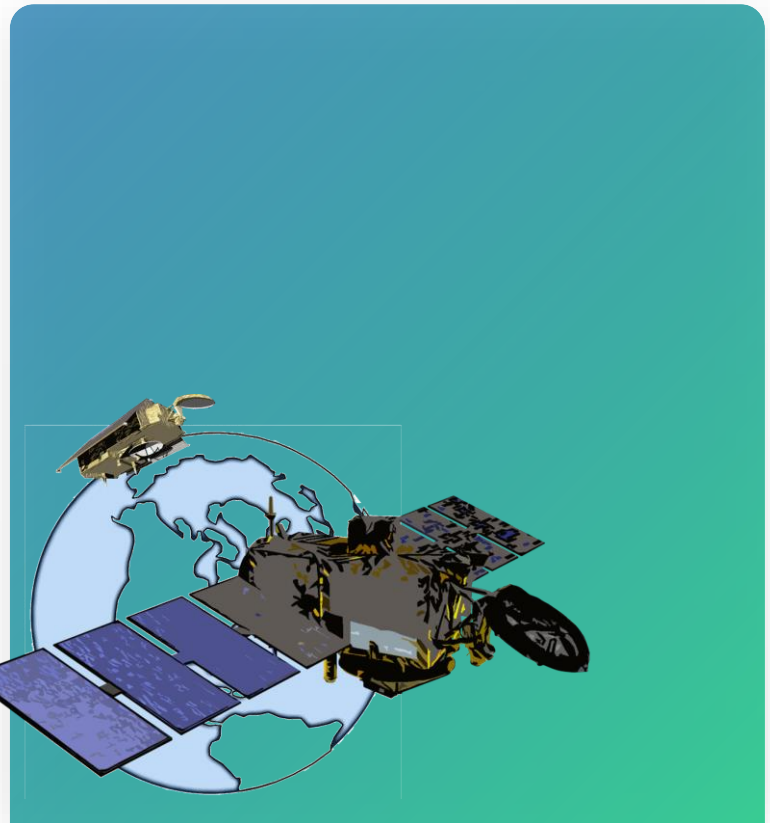
AT ESTEC

24/04/2024

AGENDA

[08:45] Introduction (ESA)
[09:00] Project objectives and way forward (CLS/All)
- Project objectives
- Perspectives

[09:30] CalVal Ocean/GMSL (CLS)
[10:00] Benefit of a second S6-MF/J3 Tandem Phase (Magellium)
[10:40] Internal waves detection study (Univ. Porto)
[11:20] Coastal study (TUM)
[13:30] Validation of S6-MF sea state measurements (NOC)
[14:15] Sea-state study (CLS)
[15:00] Lake Ice Thickness (CLS)
[15:30] Statistical analysis of L1 data (Aresys)
[16:00] FF-SAR processing (CLS/Aresys)
[16:30] Inland Water analysis (CLS)
[17:15] Project status (CLS)
- Documentation delivered
- Review of actions
- AOB



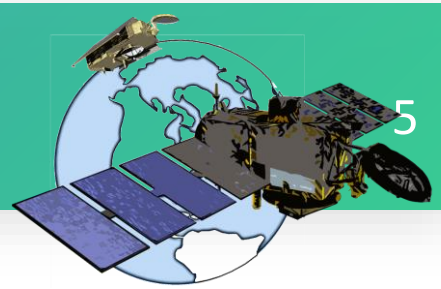
Overview of S6-JTEX and way forward

Sentinel-6MF Mission

Copernicus Sentinel-6 Michael Freilich (S6-MF)

- New reference mission to ensure enhanced continuity of the long-term data record for climate studies
- New sensors: Highly precise radiometer (AMR-C) and new radar altimeter (POS4) with a new architecture and new capabilities currently commissioned to assess:
  - Continuity of LR mode with previous Jason series
  - Consistency between LR and SAR mode data
  - Consistency between SAR RAW and SAR RMC
  - Also analysis of new LR and SAR configurations and processings to better exploit the altimeter performance
    - mitigating any possible GMSL error, sea state effects and mesoscale error
    - benefit of using higher resolution processing over inland waters, cryosphere surfaces but also over ocean

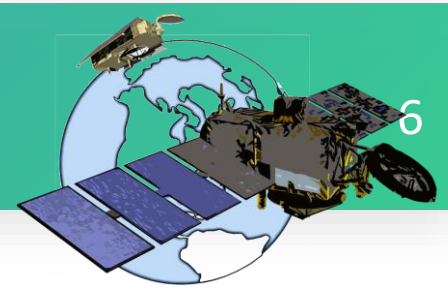
S6-JTEX Science Objectives



Tandem from a Climate perspective

- To perform very accurate calibration of the S6-MF altimeter (for the two chains) and radiometer against the reference mission
- To identify discrepancies between missions and different operating modes, but also drifts or periodic signals and establish strategies to correct for these errors
- To produce homogeneous and unbiased time-series observations and allow a precise estimate of uncertainties (with an error on the trend of less than 1mm/year) for long term climate data records and applications
- To also ensure the continuity of the long-term radiometric correction time series

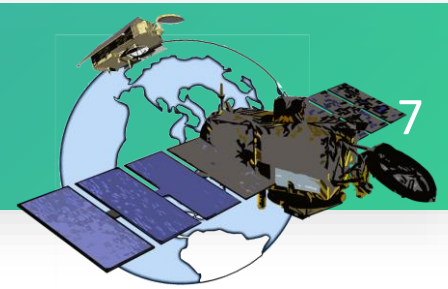
S6-JTEX Science Objectives



Expected impact of the Tandem for sea state

- To provide accurate SWH quantities for marine weather and sea state forecasting but also growing interests in long-term multi-mission altimeter records of sea state
- To gain understanding of the different sea state effects contributing to the sea surface height retrievals uncertainty
  - Increase of measurement noise on SSH with SWH
  - Sensitivity to long ocean waves (T02, energy, orientation):
    - High-frequency noise on altimeter estimates
    - Increase of SSH variance at long wavelengths (spectrum aliasing)
  - SWH bias induced by orbital wave velocities which can in turn impact SSH through SSB correction
  - Other phenomena affecting SAR altimetry signals (surface currents, wind speed)

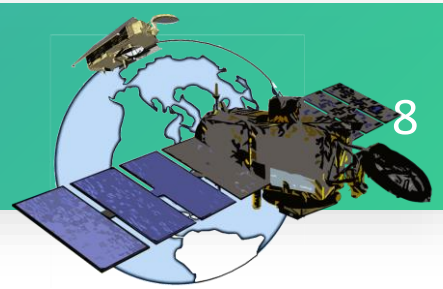
S6-JTEX Science Objectives



Expected benefit from innovative processing and applications

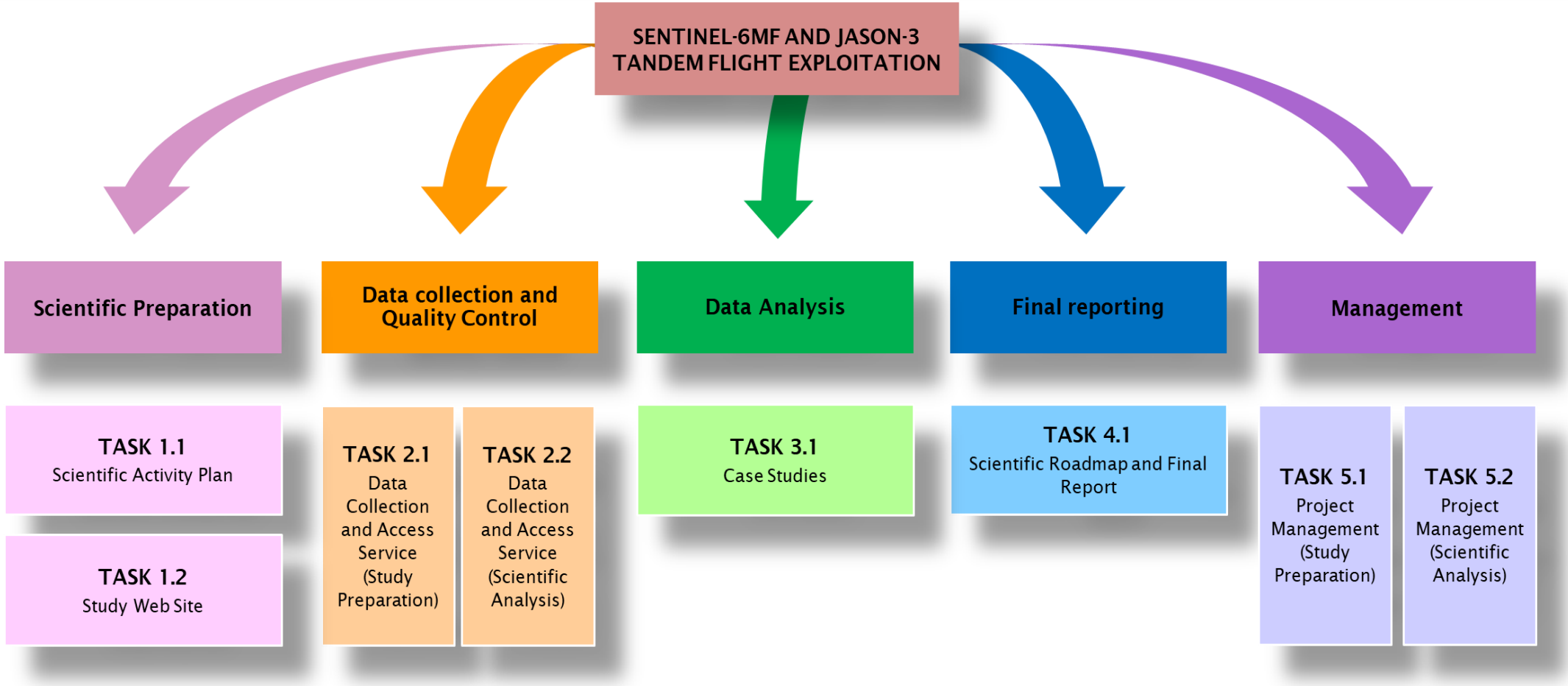
- To make use of innovative algorithms to improve the altimeter performances:
  - SAR processing at higher sampling to better sample water targets (leads, river/lakes, frozen lakes), but also to mitigate swell-induced aliasing artifacts
  - Use of customized solutions for more challenging applications as coastal zone, inland water and sea-ice
  - Benefit of new delay-Doppler processing at mesoscale, ..
- To assess the enhanced fully focused SAR (FF-SAR) capabilities to better map inland waters (and sea ice leads) but also provide more details of the ocean surface structure

S6-JTEX Science Objectives

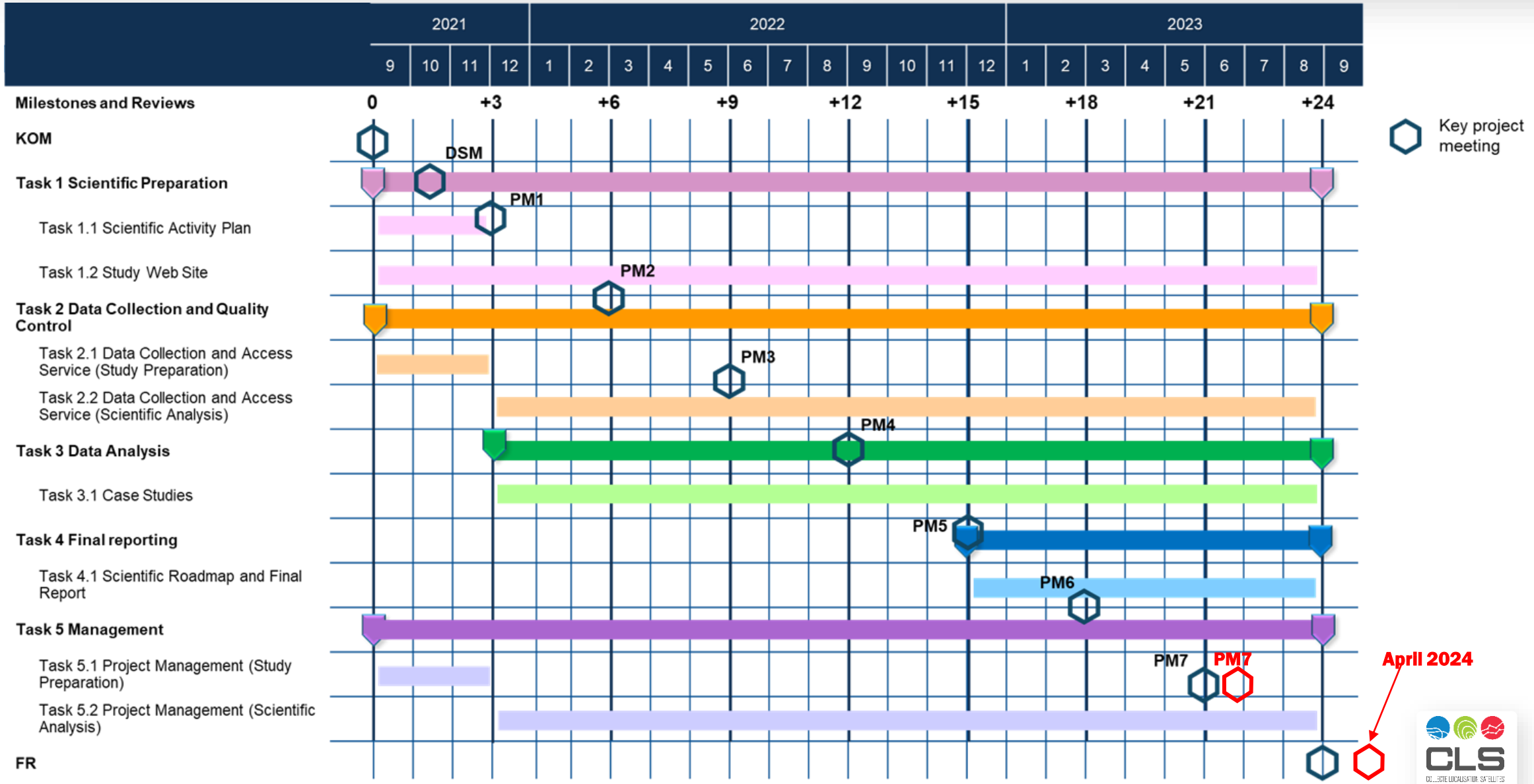


- To exploit the tandem phase between S6-MF and Jason-3 to demonstrate the high benefit of this new altimeter reference mission to extend the legacy of sea-surface height measurements
- To gain understanding of the different sea state effects contributing to the sea surface height retrievals uncertainty, but also impacting the quality of SWH quantities
- To develop a number of scientific studies that fully exploit the S6-MF capabilities and make use of innovative processing (higher posting-rate UFSAR, FF-SAR) to allow for new potential products and applications
- To report these results to the science community in peer-reviewed journal articles and present them in conferences, also available on the project website (https://www.s6-jtex.org/)

S6-JTEX WBS


SENTINEL-6MF AND JASON-3 TANDEM FLIGHT EXPLOITATION
Scientific Preparation
Data collection and Quality Control
Data Analysis
Final reporting
Management
TASK 1.1
Scientific Activity Plan
TASK 1.2
Study Web Site
TASK 2.1
Data Collection and Access Service (Study Preparation)
TASK 2.2
Data Collection and Access Service (Scientific Analysis)
TASK 3.1
Case Studies
TASK 4.1
Scientific Roadmap and Final Report
TASK 5.1
Project Management (Study Preparation)
TASK 5.2
Project Management (Scientific Analysis)

S6-JTEX Study Planning and Milestones



S6-JTEX Case Studies

Id	Title	Activity Theme	Status	Article	Leader
1.1	Validation of the S6-MF measurements over open ocean and characterization of potential differences/discrepancies with respect to Jason-3	CalVal ocean	Submitted	D-70	CLS
1.2	Evaluation of the performance of S6-MF measurements in coastal areas	CalVal ocean	Published	D-80	TUM
2.1	Study of second calibration phase between S6-MF and Jason-3	uncertainties and GMSL	Submit in May	D-160	magellium
3.1	Validation of S6-MF sea state measurements using triple collocation analysis	sea state	Submitted	D-100	National Oceanography Centre
3.2	Exploiting differences and processing techniques to study ocean swell waves and high sea states and mitigate their impact on S6-MF SSH measurements	sea state	Submit in May	D-110	CLS
4.1	Exploiting the S6-MF effective number of looks (ENL) for sea state applications	statistical analysis of L1 data	Submitted	D-120	aresys
5.1	Exploitation of Fully focused SAR (FFSAR) processing using S6-MF over ocean and sea ice surfaces	FF-SAR processing	Published	D-130	CLS
6.1	Characterization and exploitation of S6-MF and J3 in support of improved hydrology products	inland water analysis	Submitted	D-140	CLS
7.1	Study of the S6-MF capability for estimating the Lake Ice Thickness	cryosphere surfaces	Submitted	D-230	CLS
8.1	Study of new S6-MF capability in tandem with J3 and together with other satellite data sets to measure internal wave surface signatures over the ocean	internal waves detection study	Published	D-150	U.PORTO

S6-JTEX Papers

D-70 "Assessment of Sentinel-6MF low resolution numerical retracker over ocean: continuity on reference orbit and improvements" (CLS)

D-80 "Coastal Assessment of Sentinel-6 Altimetry Data during the Tandem Phase with Jason-3" (TUM)

D-160 "Benefits of a second tandem flight phase between two successive satellite altimetry missions for assessing the instrumental stability " (Magellium)

D-100 "Uncertainties in sea state observations from buoys and satellite altimeters during the Jason-3/Sentinel-6 MF Tandem Experiment " (NOC)

D-110 "Analysis of the sea state impact on Sentinel-6MF Delay/Doppler measurements" (CLS)

D-120 “Exploiting the Sentinel-6 Michael Freilich Equivalent Number of Looks for Sea State Applications" (Aresys)

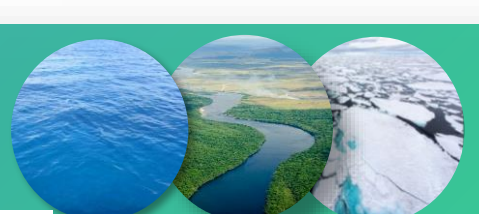
D-130 "Optimal configuration of Omega-Kappa FF-SAR processing for specular and non-specular targets in altimetric data: the Sentinel-6 Michael Freilich study case" (CLS/Aresys)

D-140 "Characterization and exploitation of S6-MF products over inland waters exploiting the tandem phase with Jason3, towards centimetric accuracy hydrology products" (CLS)

D-230 "Improving the Estimation of Lake Ice Thickness with high resolution altimetry data" (CLS)

D-150 "Using a Tandem Flight Configuration between Sentinel-6 and Jason-3 to Compare SAR and Conventional Altimeters in Sea Surface Signatures of Internal Solitary Waves" (Univ. Porto)

S6-JTEX Papers



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Article

Improving the Estimation of Lake Ice Thickness with High Resolution Radar Altimetry Data

Anna Mangilli [1]*, Claude Duguay [2,3], Justin Murfitt [3], Jaya Sree Muguntham [3], Thomas Moreau [1], Samira Amraoui [1,4], Pierre Thibaut [1] and Craig Donlon [5]

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[3] H2O Geomatics, ON N2L 1S7, Canada; claude.duguay@h2ogeomatics.com
[4] Bioceanor, Nice, France; samira.amraoui@bioceanor.com
[5] ESA / ESTEC, Noordwijk, Netherlands; craig.donlon@esa.int
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Abstract: Lake ice thickness (LIT) is a sensitive indicator of climate change identified as a thematic variable under Lakes as an Essential Climate Variable by the Global Climate Observing System. Here, we present a novel and efficient analytically based retracking approach for estimating LIT from high-resolution Ku-band (13.6 GHz) Synthetic Aperture Radar (SAR) altimetry data. The retracker method is based on the analytical modeling of the SAR radar echoes over ice-covered lakes that show a characteristic double-peak feature attributed to the reflection of the Ku-band radar waves at the snow–ice and ice–water interfaces. The method is applied to Sentinel-6 Unfocused SAR (UFSAR) and Fully Focused SAR (FFSAR) data, with their corresponding tailored waveform model, referred to as the SAR_LIT and FFSAR_LIT retracker, respectively. LIT retrievals from Sentinel-6 SAR data at different posting rates are evaluated against those obtained from thermodynamic lake ice model simulations and Low Resolution Mode (LRM) Sentinel-6 and Jason-3 data over two ice seasons during the tandem phase of the two satellites, allowing precise assessment of the continuity between LRM and SAR LIT retrievals. Consistency checks of the Sentinel-6 SAR LIT estimates are also performed using optical/radar images that provide information on the snow/ice conditions on the same dates. The analysis is performed over Great Slave Lake and Baker Lake (Canada), which differ in terms of lake size, bathymetry, snow/ice properties, and seasonal evolution of LIT. The accuracy of the LIT estimates with the SAR LIT retrackers is on the order of 5 cm once the ice is well established on the

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Article

Characterization and exploitation of S6-MF products ov land waters exploiting the tandem phase with Jason3, t centimetric accuracy hydrology products.

Taburet Nicolas [1], Moreau Thomas [1], Amraoui Samira [1] and Boy François [2]

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[2] CNES; François.boy@cnes.fr
* Correspondence: ntaburet@groupcls.com

Abstract:

The Sentinel-6 Michael Freilich altimeter was launched on November 21st, 2020 Topex-Jason orbit. During the first phase of the satellite operations and immediately ment , it was in tandem flight with Jason-3 until April 2022 when this latter was interleaved orbit. This article exploits this long tandem flight to emphasize the mances for continental water level estimates brought by SAR mode (S6) with res lution mode (∫3). The SAR-LRM bias is shown to depend on target sizes: from lakes and rivers to +10 cm over the largest lakes with OCOG retracking algorithm in-situ data show that WSH measurements over French rivers with S6 SAR acquisi a lower absolute bias than WSH derived from ∫3. The precision with S6 SAR is als ∫3 with respectively 9.7 and 29 cm u-RMSE over a set of 12 virtual stations (VS) pr able geometrical configuration covering rivers from 10 m to 300 m width. It is s mance improvements brought by S6 at nadir are limited over more complex VS d as river slope, than cannot be perfectly accounted for, and mainly contamination water bodies. A new definition of VS exploiting not only altimetry data over t measurements acquired from off-nadir water surface targets is proposed to avoi and is shown to provide improved precision in WSH timeseries with SAR mod the application of SAR specific processing technics better focusing the signal abo tion of Hamming filtering leads to a precision of 8.7 cm and more importantly us mates when combined with a sinc2-based model retracking algorithm. Hamming shown to reduce the percentage of outliers by 10%. Another 10% precision gain v increasing the posting rate to 140 Hz. Eventually, SAR altimetry also allows Full cessing that yields another 10% precision gain on WSH retrievals, reaching 6.2cm the set of stations and reducing the percentage of outliers.

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. *Remote Sens.* 2022, 14, x. https://doi.org/10.3390/xxxxx

Academic Editor: Firstname Lastname

Received: date
Accepted: date
Published: date

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Keywords: altimetry; hydrology; water level; Sentinel-6MF; Jason-3; SAR altim SAR

1. Introduction

Inland water is a more and more pressured resource for the populati as a societal risk for local populations. It is also a fundamental element f agriculture, therefore becoming an economic and political stake. The mon water level, proxy to freshwater stocks, conditions of navigability on inl

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Article

Exploiting the Sentinel-6 Michael Freilich Equivalent Number of Looks for Sea State Applications

Lisa Recchia [1,†], Pietro Guccione [1,2], Thomas Moreau [2,‡] and Craig Donlon [3]

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‡ These authors contributed equally to this work.

Version April 3, 2024 submitted to Journal Not Specified

Abstract Sentinel-6 Michael Freilich (S6-MF) is the first altimeter operating in a continuous high-rate pulse mode, i.e. interleaved mode. This ensures the generation of Low-Resolution (LR) mode measurements with a Pulse Repetition Frequency (PRF) of ∼ 9 kHz (variable along the orbit) for Ku-band as well as the processing of High Resolution (HR) echoes on ground. This operating mode provides an elevated number of highly correlated single looks with respect to the fewer number, weakly correlated echoes of Jason-3 altimeter. A theoretical model has been exploited to envisage the correlation properties of S6-MF pulse limited waveform echoes for different sea-state conditions; after that, the model has been validated by comparison with the Equivalent Number of Looks (ENL) empirically estimated from real data. The existence of a significant dependence of the statistical properties in range has been verified, and its impact on the precision and on the accuracy in the estimation of the geophysical parameters has been assessed in case of the 9 kHz PRF of S6-MF. Finally, by applying pulse deximation before the multilook processing, an investigation on new processing techniques has been performed, aimed at exploiting the higher ENL in S6-MF low-resolution mode waveforms.

Keywords: Sentinel-6; Jason-3; Delay-Doppler altimeter; Sea-state; geophysical parameters.

Introduction

The radar altimetry measures the two-way travel time of a radar pu ferina and the Earth's surface at the nadir of the spacecraft. This measurem

Benefits of a second tandem flight phase between two satellite altimetry missions for assessing the instrume

Michaël Ablain[1,*], Noémie Lalau[1,*], Robin Fraudeau[1,*], Anne Barnoud[1], Benoit M Gérald Dibarboure[3], Alejandro Egido[4], and Craig Donlon[4]

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*These authors contributed equally to this work.
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Abstract.

The five successive reference missions, TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, and more Freilich, have ensured the continuity and long-term stability of the altimetry data record. Tandem key role in verifying and ensuring the consistency of sea level measurements between successive a They enable us to measure the relative errors between the two altimeter missions. By averaging th errors (< 10 days) over several months, the systematic instrumental errors can be assessed, allowin altimeter parameters. Thanks to a tandem phase, the global mean sea level offset between two succ estimated with an uncertainty of approximately ± 0.5 mm ([16-84]% confidence level). However, t drift poses a challenge because of the short duration of the tandem phase. Therefore, this stud validation method with a better ability to assess the stability of altimeter parameters in sea level c implementation of a second tandem flight phase between two successive satellites a few years after sea level differences during the second tandem phase provides a new accurate evaluation of relat successive altimeter missions . With a second tandem phase long enough, the short-term time corre be averaged, allowing us to reevaluate systematic instrumental errors. The trend between the systen two tandem phases can be calculated to assess the stability of the altimeter parameters over the en tandem phases. In this paper, we present the approach developed to analyse the ability of this novel the altimeter parameter stability. On the global scale, we show that the 2-tandem-phase validation the stability of the altimeter parameters with an uncertainty of approximately ± 0.15 mm yr^{-1} ([The uncertainty increases to ±0.4-0.6 mm yr^{-1} at regional scales of 2000-4000 km ([16-84]% con the results with regard to the scenario foreseen for the second phase between Jason-3 and Sentinel for early 2025, 2 years and 9 months after the end of the first tandem phase. We conclude that condu phases between successive altimetry missions would be a valuable approach to accurately evaluat stability in the future, both at global and regional spatial scales.

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Article

Coastal Assessment of Sentinel-6 Altimetry Data during the Tandem Phase with Jason-3

Marcello Passaro *, Florian Schlembach, Julius Oelsmann, Denise Dettmering and Florian Seitz

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM), Arcisstr 80333 Munich, Germany; florian.schlembach@tum.de (F.S.); julius.oelsmann@tum.de (J.O.); denise.dettmering@tum.de (D.D.); florian.seitz@tum.de (F.S.)
* Correspondence: marcello.passaro@tum.de

Abstract This study presents a comparative analysis of the coastal performances of Se and Jason-3 altimeters during their tandem phase, considering their different processing We examine the measurements available in the standard geophysical data records (GDR) a perform dedicated reprocessing using coastal retracking algorithms applied to the original wa The performances are evaluated, taking into account the quality of retrievals (outlier ar their precision (along-track noise analysis), potential systematic biases, and accuracy (corre against tide gauges). The official SAR altimetry product of Sentinel-6 demonstrates improved monitoring capabilities compared to Jason-3, except for the remaining issues related to sig wave height, which have already been identified. These findings highlight the signific dedicated coastal retracking algorithms for enhancing the capabilities of both traditional limited altimeters and more recent developments utilizing SAR altimetry.

Keywords: coastal oceanography; satellite altimetry; Sentinel-6; validation; Jason-3

check for updates

Citation: Passaro, M.; Schlembach, F.; Oelsmann, J.; Dettmering, D.; Seitz, F. Coastal Assessment of Sentinel-6 Altimetry Data during the Tandem Phase with Jason-3. *Remote Sens.* 2023, *15*, 4161. https://doi.org/

1. Introduction

The monitoring of coastal sea level from space is increasingly possible through s altimetry, which is based on the measurement of the two-way travel time that pulses employ from transmission towards the ocean surface to reception [1]. Indee improvement of coastal altimetry performance is one of the expected results of the generation of altimeters: the SAR altimeters based on the delay-Doppler principle

Analysis of the sea state impact on Sentinel-6MF Delay/Doppler measurements

L. Amarouche[1], N. Tran[1], M. Mrad[1], T. Pirotte, H. Etienne[1], T. Moreau[1], F. Boy[2], C. Maraldi[2], C. Donlon[3], A. Egido[3]

[1]CLS, [2]CNES, [3]ESA

Abstract

We evaluated the impact of ocean wave dynamics on the estimates of significant wave height and sea surface height from Sentinel-6MF delay/Doppler measurements. To this end, we used one 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 qualitatively how surface dynamics impact delay/Doppler signals and hence the corresponding estimates. We concluded 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. We also found that, except for Stokes drifts, the other surface currents have no impact on delay/Doppler estimates. We finally recommended to develop two new corrections, one for SWH and the second one for the range or SSH. The SWH correction should use SWH, orbital velocity and wind speed as input variables. This correction should provide improved results over the Egido et al. (2022) correction thanks to the addition of wind speed. The correction of the range could be considered as a generalized sea-state bias or pseudo sea-state bias correction, as it includes the classic SSB correction and additional surface characteristics that affect the delay/Doppler signal. This latter requires the development of a new SSB correction mathematical method.

Keywords: Satellite altimetry; Sentinel-6MF, Sea State, Ocean Waves, Sea State Bias, Delay/Doppler, Orbital Velocity, Stokes Drifts, Currents

1 - Introduction

The S6-MF mission continues to serve the innovative record of altimetric Delay/Doppler more lower measurements noise than what has already been achieved by S3-A/B from the interleaved operating mode; (2) simultaneous generation of both conventional Low Resolution R) data

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Article

Optimal Configuration of Omega-Kappa FF-SAR Processing for Specular and Non-Specular Targets in Altimetric Data: The Sentinel-6 Michael Freilich Study Case

Samira Amraoui [1,†], Pietro Guccione [2], Thomas Moreau [1,*], Marta Alves [3], Ourania Altiparmaki [2], Charles Peureux [1], Lisa Recchia [2], Claire Maraldi [4], François Boy [4] and Craig Donlon [5]

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* Correspondence: tmoreau@groupcls.com
† Current address: Bioceanor, 06560 Valbonne, France.

Abstract: In this study, the full-focusing (FF) algorithm is reviewed with the objective of optimizing it for processing data from different types of surfaces probed in altimetry. In particular, this work aims to provide a set of optimal FF processing parameters for the Sentinel-6 Michael Freilich (S6-MF) mission. The S6-MF satellite carries an advanced radar altimeter offering a wide range of potential FF-based applications which are just beginning to be explored and require prior optimization of this processing. In S6-MF, the Synthetic Aperture Radar (SAR) altimeter acquisitions are known to be aliased in the along-track direction. Depending on the target, aliasing can be tolerated or may be a severe impairment to provide the level of performance expected from FF processing. Another key aspect to consider in this optimization study is the unprecedented resolution of the FF processing, which results in a higher posting rate than the standard SAR processing. This work investigates the relationship between posting rate and noise levels and provides recommendations for optimal algorithm configurations in various scenarios, including transponder, open ocean, and specular targets like sea-ice and inland water scenes. The Omega–Kappa (WK) algorithm, which has demonstrated superior CPU efficiency compared to the back-projection (BP) algorithm, is considered for this study. But, unlike BP, it operates in the Doppler frequency domain, necessitating further precise spectral and time domain settings. Based on the results of this work, real case studies using S6-MF acquisitions are presented. We first compare S6-MF FF radargrams with Sentinel-1 (S1) images to showcase the potential of optimally configured FF processing. For highly specular surfaces such as sea-ice, distinct techniques are employed for lead signature identification. S1 relies on image-based limnic reconstruction, while S6-MF utilizes phase coherency of focalized pulses for lead detection. The study also delves into two-dimensional wave spectra derived from the amplitude modulation of image/radargrams, with a focus on a coastal example. This case is especially intriguing, as it vividly illustrates different sea states characterized by varying spectral peak positions over time.

Keywords: fully focused SAR; altimetry; processing; optimization; Sentinel-6 Michael Freilich

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Citation: Amraoui, S.; Guccione, P.; Moreau, T.; Alves, M.; Altiparmaki, O.; Peureux, C.; Recchia, L.; Maraldi, C.; Boy, F.; Donlon, C. Optimal Configuration of Omega-Kappa FF-SAR Processing for Specular and Non-Specular Targets in Altimetric Data: the Sentinel-6 Michael Freilich Study Case. *Remote Sens.* 2024, *16*, 1112. https://doi.org/10.3390/rs16061112

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Published: 21 March 2024

1. Introduction

The full-focusing (FF) algorithm, initially introduced in altimetry by [1], coherently processes a synthetic aperture of pulse echoes produced by pulse-limited nadir-looking radar altimeters within the whole target illumination time. This technique closely resembles

Article

Uncertainties in sea state observations from buoys and satel altimeters during the Jason-3/Sentinel-6 MF Tandem Experi

Ben W. Timmermans [1,*], Christine P. Gommenginger [1] and Craig J. Donlon [2]

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Abstract: The Copernicus Sentinel-6 Michael Freilich (S6-MF) and Jason-3 (J3) Tandem Exp (S6-JTEX) provided over 12 months of closely collocated altimeter sea state measurements, in "Low-Resolution" (LR) and synthetic aperture radar "High Resolution" (HR) modes onboa Consistency and uncertainties associated with these measurements of sea state are exami region of the north east Pacific. Discrepancies in mean significant wave height (Hs, 0.05 root-mean-square deviation (0.06 m) between ∫3 and S6-MF LR are found to be small com differences with buoy data. S6-MF HR data is found to be highly correlated with LR dat but affected by a nonlinear sea state dependent bias. However, the bias can be explained through regression modelling based on Hs. Subsequent triple collocation analysis (TCA very little difference in error variances (≈0.18 ± 0.03 m) for the three altimetry datasets, c with buoy data and ERA5 reanalysis, although statistical precision, limited by total coll (N=535), both obscures interpretation and motivates use of a larger dataset. However, we uncertainties in the collocation methodology, with important consequences for methods such Firstly, data from some commonly used buoys are found to be statistically questionable, linked to erroneous buoy operation. Secondly, we develop methodology based on altimet show how statistically outlying data also arises due to sampling over local sea state gradie methodology paves the way for accurate collocation closer to the coast, bringing larger co sample sizes and greater statistical robustness.

Keywords: Sea state; satellite altimetry; uncertainty; moored buoys; Sentinel-6 Michael S6-JTEX; tandem experiment; significant wave height; triple collocation

Citation: Timmermans, B.W., C. P. Gommenginger and C. J. Donlon Uncertainties in sea state observations from buoys and satellite altimeters during the Jason-3/Sentinel-6 MF Tandem Experiment. *Remote Sens.* 2022, *1*, 0. https://doi.org/

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1. Introduction

Sea state observations from satellites are increasing in duration, abundance, and applications. The long term continuous altimetry record is particularly signi this context, having begun in 1992 and affording us the capability to investigate lo variability on a global scale from remote observations [1,2]. The continuity and sta this record is, therefore, of great importance, and to that end, since the TOPEX/P mission [3] launched in August 1992, the Jason series of satellites [4] have mai the same reference orbit and ensured a consistency of measurement to the pres A growing abundance of sea state observations from other missions, spanning a of platforms and instruments with heterogeneity in spatiotemporal coverage, motivates the continuation and maintenance of a consistent long term record. For e the European Space Agency (ESA) Sea State Climate Change Initiative (CCI) empl reference record extensively when intercalibrating missions as part of the producti multimission sea state Climate Data Records [5].

With the approaching retirement of Jason-3 (J3), ESA's Sentinel-6 Michael (S6-MF) mission [6] launched in 2020 and formally succeeded J3 as the long term a reference mission in April 2022. To ensure smooth operational continuity, S6-MF sioning involved a unique 12 month S6-MF / J3 Tandem Experiment (S6-JTEX) s

Version April 11, 2024 submitted to *Remote Sens.*

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Article

Using a Tandem Flight Configuration between Sentinel-6 and Jason-3 to Compare SAR and Conventional Altimeters in Sea Surface Signatures of Internal Solitary Waves

Jorge M. Magalhaes [1,2], Ian G. Lapa [2], Adriana M. Santos-Ferreira [1,2], José C. B. da Silva [2,3,*], Fanny Piras [4], Thomas Moreau [4], Samira Amraoui [4], Marcello Passaro [5], Christian Schwatke [5], Michael Hart-Davis [5], Claire Maraldi [6] and Craig Donlon [7]

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Abstract Satellite altimetry has been providing a continuous record of ocean measurements with numerous applications across the entire range of ocean sciences. A reference orbit has been used since 1992 with TOPEX/Poseidon, which was repeated in the Jason missions, and in the newly launched Sentinel-6 Michael Freilich (in November 2020) to continually monitor the trends of sea level rise and other properties of the sea surface. These multisecadal missions have evolved alongside major technological advances, whose measurements are unified into a single data record owing to continuous intercalibration and validation efforts. However, the new Sentinel-6 provides synthetic aperture radar (SAR) processing, which improves the along-track resolution of conventional altimetry from a few kilometres (e.g., for Jason-3) to about 300 m. This means a major leap in sampling towards higher frequencies of the ocean spectrum, which inevitably means reconciling the assumption of a uniform Brown surface between the footprints of the larger kilometre-scale conventional altimetry

check for updates

Citation: Magalhaes, J.M.; Lapa, I.G.; Santos-Ferreira, A.M.; da Silva, J.C.B.; Piras, F.; Moreau, T.; Amraoui, S.; Passaro, M.; Schwatke, C.; Hart-Davis, M.; et al. Using a Tandem Flight Configuration between Sentinel-6 and Jason-3 to Compare SAR and Conventional Altimeters in Sea Surface Signatures of Internal Solitary Waves. *Remote Sens.* 2023, *15*, 392.

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Assessment of Sentinel-6MF low resolution numerical retracker over ocean: continuity on reference orbit and improvements

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Received 1 May 2013; Received in final form 10 May 2013; Accepted 13 May 2013; Available online 15 May 2013

Abstract

On April 7th, 2022, after 16 months of tandem flight with its predecessor, Jason-3, the Copernicus Sentinel-6 Michael Freilich (MF) satellite became the regional reference mission in the sea level climate record. Its on-board altimeter, POSeidon-4, is the first radar altimeter allowing a simultaneous and continuous acquisition in Low Resolution (LR) as well as in High Resolution (HR) mode. In march 2023, a new version of Sentinel-6MF ground segment (processing baseline F08) brought major improvements for the LR mode, with the implementation of a numerical retracker in addition to the historical Maximum Likelihood Estimator-4 (MLE4) retracker. The present work covers the full assessment of this new LR numerical retracker over open ocean, spanning from the retracker's outputs to their contribution to the Global Mean Sea Level. Improvements with respect to MLE4 appeared mainly in terms of sea-state related effects, leading to a 60 % reduction of the Sentinel-6MF/Jason-3 Sea Surface Height Anomaly bias correlated to Significant Wave Height. Such result improves an already very good continuity between the two missions. The agreement between Jason-3 and Sentinel-6MF over the tandem phase is also precisely assessed. The small remaining discrepancies are attributed to different components of the system, such as the orbit, the radiometer wet troposphere correction, C-band processing or an MLE4-based empirical adjustment. Another important feature of the Sentinel-6MF numerical retracker is the use of the in-flight Point Target Response to mitigate instrumental changes and thus improve long term stability. The Global Mean Sea Level analysis presented in this paper shows no significant trend difference with respect to Jason-3, once the radiometer wet troposphere correction impact is removed.

Keywords: Sentinel-6 Michael Freilich ; Radar altimetry ; Low Resolution Mode ; Numerical Retracker

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Other project-related documents

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

Science Activity Plan

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CLS-ENV-NT-24-0138

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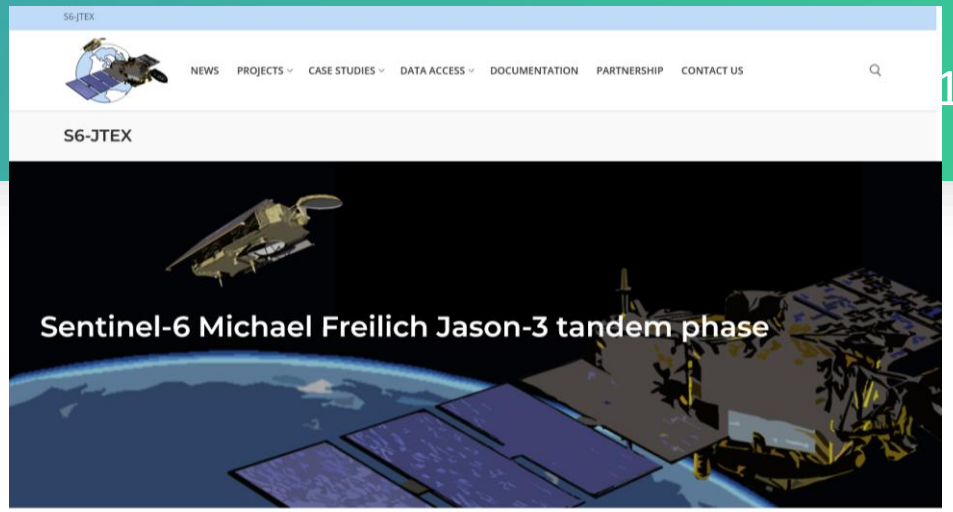
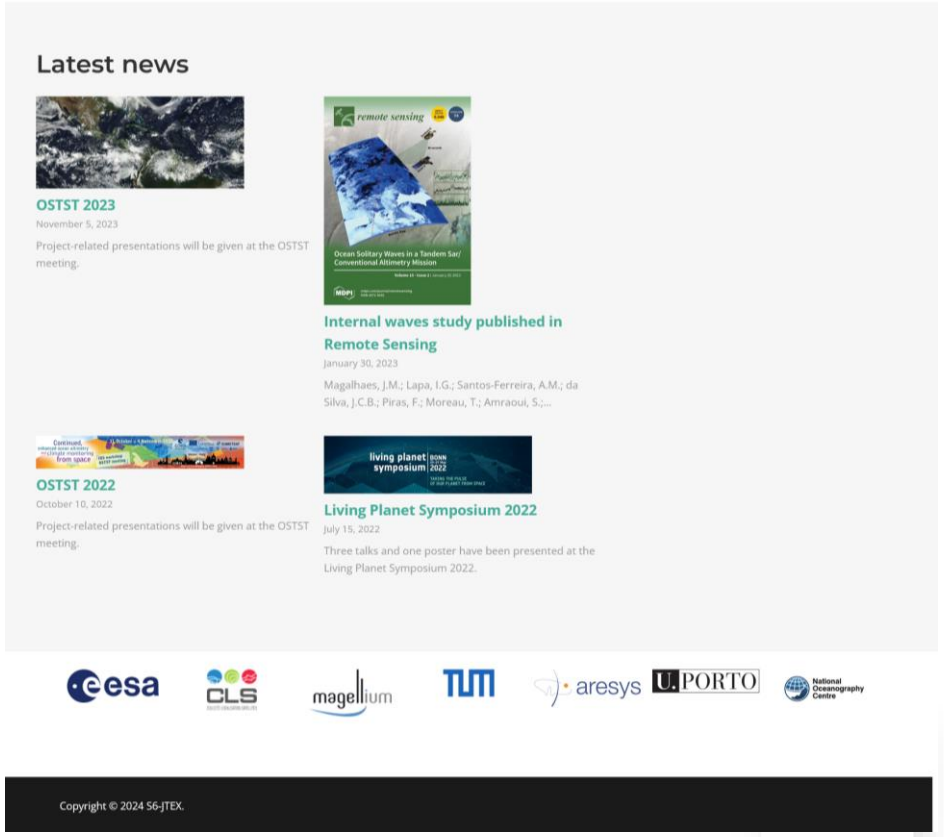
Website

Communication

- Project website (https://www.s6-jtex.org/) opened on a public server
- Containers:
  - ❑ News
  - ❑ Projects
    - ❑ About S6-JTEX
    - ❑ Calendar/Meetings
  - ❑ Case studies
    - ❑ …
  - ❑ Data Access
    - ❑ Satellite Activity TimeLine (SATL)
    - ❑ ..
  - ❑ Documentation (project reports, article/presentation references)
  - ❑ Partnership
  - ❑ Contact us





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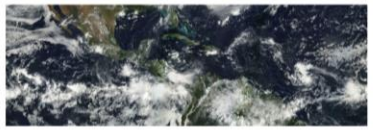

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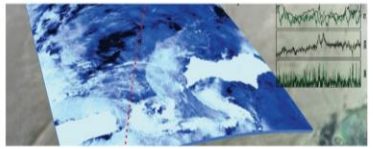

Internal waves st

JANUARY 30, 2023 DOCUME

Magalhaes, J.M.; Lapa, I.G.; Amraoui, S.; Passaro, M.; S

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JULY 15, 2022 MEETINGS

Three talks and one poster have been presented at the Living Planet Symposium 2022.

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Sentinel-6 Michael Freilich launch

OCTOBER 12, 2021 UNCATEGORIZED

Sentinel-6 Michael Freilich has been successfully launched on 21 November 2020.

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Internal Waves Detection Study

HOME › S6-JTEX › CASE STUDIES › INTERNAL WAVES DETECTION STUDY

Study of new S6-MF capability in tandem with J3 and together with other satellite data sets to measure internal wave surface signatures over the ocean

Internal waves are characterized by large-amplitude vertical displacements (typically 50-150 meters) near the largest density gradient in the water column. Their energy propagates for hundreds of kilometers perpendicularly to their crests, from generation sites near steep underwater topography to eventually breaking nearshore or dissipating offshore. They are also characterized by significant vertical velocities, mixing and associated vertical fluxes. These have implications in biological productivity and biomass observable from satellites, and can crucially affect the ocean up to the climate scale.

Recent work (Magalhaes and da Silva, 2017; Santos-Ferreria et al, 2018; 2019; Magalhaes et al., 2021) demonstrates that internal waves can be observed by satellite altimetry. This study focus on an analysis of the signature of internal waves by inter-comparing S6-MF and J3 in tandem together with other satellite data sets (e.g. Sentinel-3 OLCI/SLSTR, Sentinel-2 MSI and Sentinel-1 SAR images). Subsurface internal waves alter the ocean surface roughness that is imprinted in sigma0 signatures as well as SWH impacts at small-scale (1-3 kms) to medium-scale (10s of kms). The signature of SAR and LRM on the same internal waves, collocated with other

basis of this work. An analysis of the SWH signatures in the same fa

This activity aims to perform:

- ISW signature comparison in L2 HR Sentinel-6 MF and Jason-3
- Multi-Scale analysis of SWH in L2 HR Sentinel-6 MF and Jason-
- FFSAR S6-MF L1b radargram analysis over ISWs

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S6-JTEX

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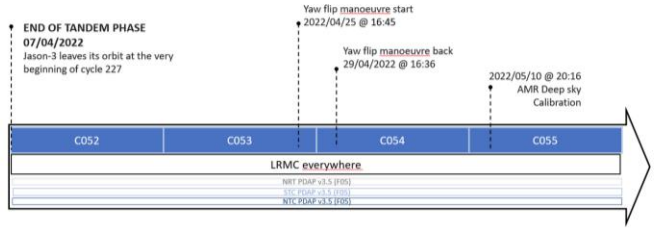
Satellite Activity TimeLine (SATL)

HOME › S6-JTEX › DATA ACCESS › SATELLITE ACTIVITY TIMELINE (SATL)

The Satellite Activity TimeLine (SATL) records a number of noteworthy events with particular relevance for the S6-MF data analysis, that is:

- S6-MF commissioning timeline: phases (S6-MF drift, tandem, J3 drift) and reviews
- S6-MF (and J3) operations: manoeuvres, calibrations, special acquisitions, instrument modes, mode mask, restart
- S6-MF (and J3) on-board anomalies (satellite and instrument)
- S6-MF (and J3) on-ground activities: processing baselines and ADF for each instrument and processing levels
- S6-MF (and J3) on-ground processing anomalies

The timeline is displayed as synthetic graphs to easily see where and which operations/changes have been occured. The synoptic view of the latest S6-MF cycles is shown below:



New MOE on 19/04/2022.
J3 restarted on the 25/04/2022

PDAP v3.6 in OPE planned on 31/05/2022 (delayed?).

The full S6-MF timeline can be found here.

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Documentation

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S6-JTEX reports

- The **Science Activity Plan (SAP)** providing an exhaustive list of S6-JTEX case studies of interest based on the exploitation of the Sentinel-6MF (S6-MF) and Jason-3 (J3) data acquired in tandem phase. The document can be found here.

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Partnership

Partners

The consortium partners involved in this project have a strong expertise in altimetry data science, namely:

- a great understanding of the physical processes that impact the measurements over various surfaces (open ocean, coastal ocean, sea ice and hydrological regions),
- a solid knowledge of the instrumental characteristics and processing algorithms that are applied on measurements, and
- a large expertise in the methods and metrics used to analyse altimetry signals.

CLS (Collecte Localisation Satellites) is the prime contractor for this project. CLS, created in 1986, is a subsidiary of the French Space Agency (CNES) and CNP, an investment firm. Its mission is to create innovative space-based solutions to understand and protect our planet and to manage its resources sustainably. CLS employs 900 people in the world. The company works in five strategic markets:

- environmental monitoring,
- maritime surveillance,
- fleet management, and
- energy & mining.

CLS processes data from 150,000 transponders per month (such as drifting buoys, animal tags, VMS transponders, & GNSS tracking) and observes the oceans and inland waters more than 26 instruments onboard satellites daily deliver information to CLS on the world's seas and oceans. In addition, CLS monitor's land and sea activities by satellite (nearly 10,000 radar images and several hundred drone flights are processed each year). The CLS Group had revenue of nearly 135 million Euros in 2020. Committed to a sustainable planet, the company works every day for the Earth, from Space.

CLS holds more than 25-year experience in environmental monitoring by remote sensing techniques. CLS has been acting continuously to Earth Observation (EO) projects providing services to French and European space agencies, CNES, ESA, EUMETSAT and European stakeholders like the European Union, through research programmes, FP5, 6, 7, H2020 and through the operational Copernicus programme.

magellium

Founded in 2003 by personnel with considerable experience in the space sector, in particular sensor geometry and image processing, the company is headquartered near Toulouse, France, in the heart of the French space sector. It has grown rapidly and steadily over the past 10 years to its present size of 161. Magellium has a subsidiary in the Paris area (Courtaboeuf) as a result of the acquisition of the defence branch of Géomédia d'Infographie in 2009. In 2019, Magellium acquired a digital cartography specialist company, Geolinest, thus consolidating its offer in this market.

Magellium benefits from recognized skills in the fields of Earth observation, geographic information systems, geo-intelligence and vision-based embedded systems. These are the four departments of the company. Our offer includes scientific studies, software & IT system development, supply of turnkey products and services, as well as consulting services.

- Earth observation: Our know-how is highly relevant for satellite imagery; we have expert knowledge of sensors & image processing, atmospheric corrections and calibrators, algorithms and geophysical parameters retrieval, instrument and algorithm ground segment processing and geophysical applications of Space and Earth Observation data.
- GIS and Mapping: We integrate third-party GIS solutions for various applications and handle challenging security, mobility and data fusion issues. We can deliver generic tools for large-scale map production and dissemination.
- Geointelligence: Our expertise covers the whole 3DI (Spatial Data Infrastructure) life cycle from open source intelligence (OSINT) to emergency mapping production.
- Computer vision and robotics: Our expertise in geometry and image processing is valuable in many robotics and opto-electronics applications ranging from 2D/3D pattern recognition to vision-based localization.

aresys

ARESYS S.r.l., Advanced Remote Sensing Systems, is an Italian SME spin-off of "Politecnico di Milano", providing solutions since 2003 to the aero-space & defense, oil & gas and industrial markets. ARESYS designs and develops ad-hoc innovative monitoring solutions, at HW & SW level, exploiting cutting-edge sensing technologies like microwave Radar/SAR and optical imaging, seismic surveys and vibroacoustic sensors. Based in Milan, ARESYS is divided in four business units, each of them covering specific technologies and markets.

Nowadays (2020) ARESYS can count on a group of about 60 high skilled professionals (nearly half of them hold a PH.D. degree), composed by top-level engineers, physicists and computing science experts for an annual turnover of about 6M€. The following figures show respectively ARESYS historical revenues, current revenues distribution among business units and personnel qualification level. The Kenya! Earth Observation business unit will be the one involved in the proposed activity. Aresys is well known for its expertise in altimetry and in particular on CryoSat and Sentinel-6 missions, thanks to the involvement of the company in different European altimetry and SAR Missions.

TUM

The Technische Universität München (TUM; Technical University of Munich) is a public funded research university with campuses in Munich, Garching, and Weihenstephan. Since its charter in 1868 TUM has established the sound reputation as a leading academic institution. It is one of the largest and most notable German institutes of technology. TUM comprises 14 Academic Faculties and 8 Corporate Research Centers. Around 40,000 students, 500 professors, and roughly 10,000 academic and non-academic staff are forming a strong university community. The Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM), Chair: Prof. F. Seitz) is a unit within the Faculty of Civil, Geo and Environmental Engineering of the TUM.

Since many decades, DGFI-TUM has been involved in the processing, analysis and combination of observations from various space-geodetic observation systems (among them SLR, SLR, GRSS, DORIS, satellite altimetry) for the determination and provision of highly accurate and consistent geometrical and physical parameters related to the Earth's geometry, rotation, gravity field, ocean and inland waters. Furthermore DGFI-TUM is strongly engaged in the determination of precise satellite orbits, in particular from SLR observations.

Satellite altimetry is one of the key research areas of DGFI-TUM. Since many years the Institute has been engaged in the determination, monitoring and investigation of global and regional variations of the water level of the ocean (open ocean, sea-ice regions and coastal areas) and of globally distributed inland water bodies on different spatial and temporal scales. This research is based on our carefully harmonized and cross-calibrated multi-mission data set from the complete record of all radar and laser altimeter missions since 1992. In many projects, DGFI-TUM uses the multi-mission data for various ocean applications (e.g., the estimation of the global mean sea level trend and regional sea level trends, the determination of the dynamic ocean topography and ocean surface currents, and the computation of empirical ocean tide models like EOT11a), and for the determination of water levels of lakes, reservoirs, rivers and wetlands.

The National Oceanography Centre (NOC) is the United Kingdom's centre of excellence for oceanographic research. As a charitable company limited by guarantee, it is an independent self-governing organisation. The NOC employs around 650 staff across two sites in Southampton and in Liverpool. It is co-located at both sites with University of Southampton and University of Liverpool, giving NOC a unique position in UK marine research. NOC works with a number of leading UK universities to support education and training in marine science.

As the NOC is part-funded by UK Research and Innovation (UKRI) to deliver marine science in National Capability programmes. NOC manages on UKRI's behalf, the National Marine Equipment Pool - Europe's largest fleet of autonomous and robotic vehicles, and two state-of-the-art research ships RRS Discovery and RRS James Cook. The acquisition, curation and analysis of geospatial data are at the core of many of the activities we carry out, across our five main areas of research: Marine Geoscience; Ocean Biogeochemistry and Ecosystems; Marine Systems Modelling; Marine Physics and Ocean Climate; and Ocean Technology and Engineering. We are also home to the nation's marine data assets: the British Oceanographic Data Centre (BODC), the British Ocean Sediment Core Research Facility (BOSCORF) and the Discovery Collections.

The NOC Satellite Oceanography team delivers research, consultancy and training in remote sensing techniques relevant to monitoring ocean, shelf-seas and coastal regions globally. The team has an international reputation for the development and validation of new sensors and missions, and for the development of new data-processing techniques, tools and products to enable novel research and applications. The NOC team has particular strengths in satellite altimetry (sea level, waves and winds), scatterometry and GNSS-Reflectometry (ocean winds, waves, sea ice), SAR and SAR-along-track interferometry (high-resolution ocean surface current vectors), L-band radiometry (sea surface salinity) and high-resolution hyperspectral and multi-spectral imaging of ocean and coastal waters.

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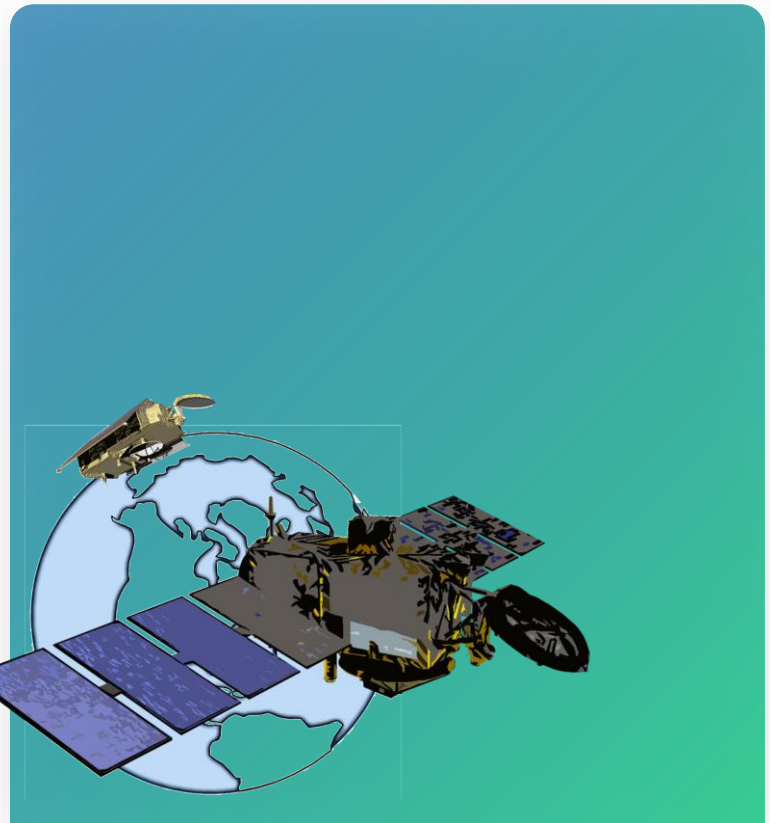
The Faculty of Sciences of the University of Porto (FCUP) is one of the oldest and largest schools of the University of Porto. It was established in 1911 and has been providing high-quality training in the field of exact and natural sciences and mathematics. Over the years it has been incorporating other fields of studies, such as Geographical Engineering, Astronomy, Computer Science and Information Technology, Biochemistry, Landscape Architecture, Environmental and Agricultural Sciences.

FCUP currently hosts six academic departments and six high-performing Research and Development Units: the centres of theoretical physics (CFP), geology (CGUP) and mathematics (CMUP), along with CICEE (Geo-Space Sciences Research Centre), CIQUP (Chemical Research Centre) and IFIMUP (Applied Physics Centre). FCUP is also partnered with twelve other R&D Units, including the Interdisciplinary Centre of Marine and Environmental Research (CIIMAR). Offering more than 70 teaching programmes, FCUP has a highly-qualified teaching and research staff responsible for providing a high-quality education, at both undergraduate and postgraduate levels. Besides its core infrastructures, FCUP also incorporates other buildings, such as a Marine Zoology Station, a Geophysical Institute, Botanical Gardens, a Science Museum, an Astronomical Observatory, a Museum of Natural History and a museum with an old collection of documents. FCUP also provides external services related to documents and handwriting examination, statistics and physics.

FCUP has been involved in several ITT projects with ESA, particularly in the field of satellite altimetry.



CCN#1 TASKS

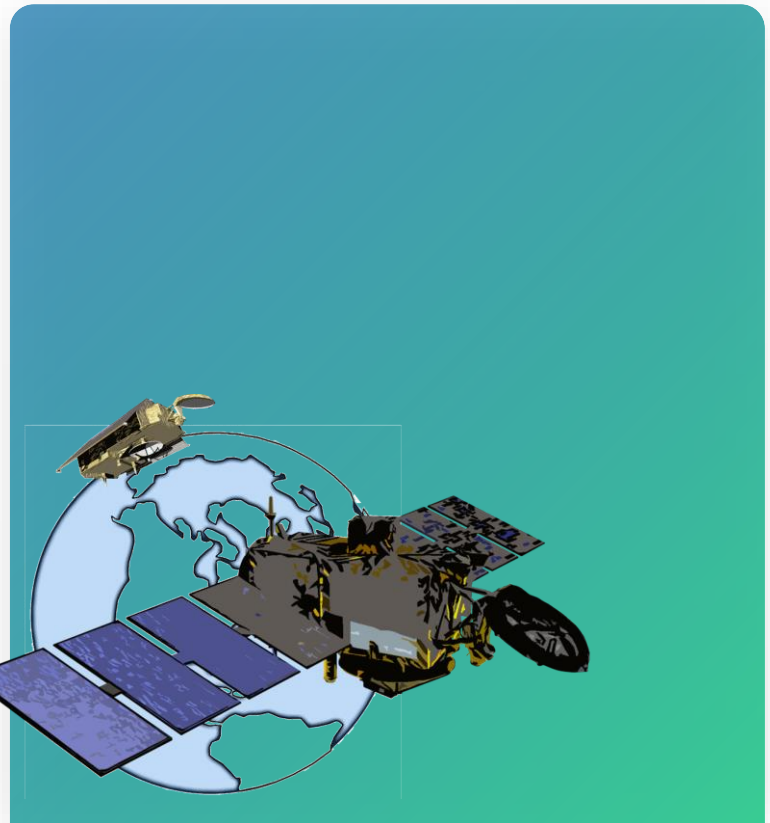
Perspectives

- List of activities for possible CCN#1

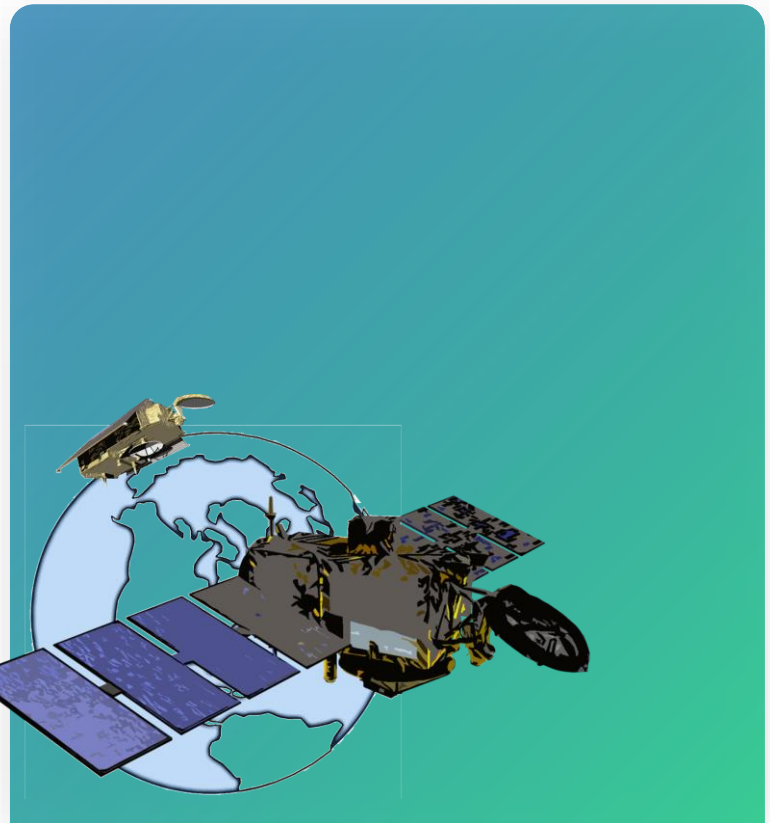
  https://groupcls.sharepoint.com/:x:/r/sites/S6-JTEX/CCN%231_S6JTEX_studies.xlsx

Follow-on S6-JTEX activities

Id	Title	Activity Theme	Leader
1	Lake Ice Thickness follow up: multi-sensor analysis	cryosphere surfaces	CLS
2	Floe/lead coverage estimation from Sentinel-6 altimetry data	cryosphere surfaces	CLS
3	Very short temporal scale sea state variability	sea state	National Oceanography Centre
4	Global oceans collocation study to evaluate sea state uncertainty for tandem and model / reanalysis data	sea state	National Oceanography Centre
5	Development of a new Sea State Bias or pseudo-SSB correction dedicated to delay/Doppler measurements	sea state	CLS
6	Coastal evaluation of S6: how does it compare to SWOT?	coastal study	TUM
7	Capability of S6 to observe SWH gradient in the coastal zone	coastal study	TUM
8	Characterization of Internal Solitary Waves based on Sea Leval Anomalies for S6/J3 tandem mission	internal waves detection study	U.PORTO
9	Leveraging the second S6/J3 tandem phase to quantify relative inter-mission drifts	CalVal ocean	CLS
10	Application and generalization of the two-tandem-phase validation method	uncertainties and GMSL	magellium
11	Assessment of Sea Ice Concentration and Snow Depth estimation algorithms using S6 AMR-C and HRMR radiometer brightness temperatures	radiometer / cryosphere surfaces	CLS
12	What is the impact of high frequency channels of S6 HRMR on the Wet Tropospheric Correction performance over ocean and coastal areas	radiometer / ocean study	CLS



Scientific Activities



Project Status

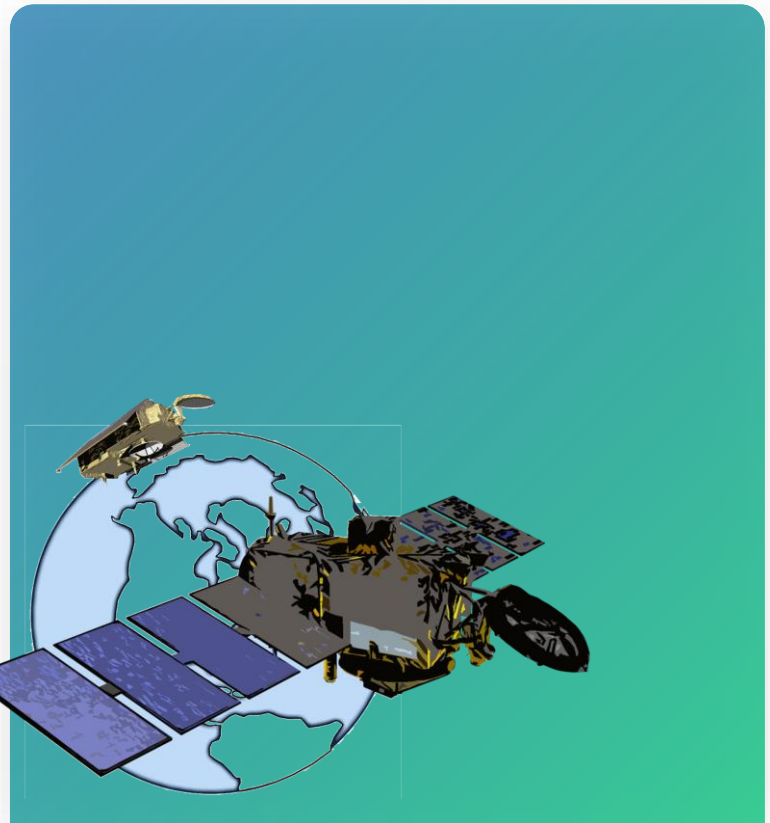
S6-JTEX Deliverable Item List

Item	Title	Title	Responsible	Deliveries	Completion	Status	issue	Associated Milestone
D-10	SAP	Science Activity Plan	CLS	KO+1.5, KO+3	100%	available on website	1.0	DSM (T0+1.5m)
D-20	WWW	Study web site	CLS	KO+3, each PM, FR	100%	site publicly accessible	1.0	-
D-30	PPT	PowerPoint for each case study	ALL	KO+3, each PM, KO+21	100%	available on sharepoint	1.0	-
D-40	S6-JTEX-DATA	Master data set	CLS	KO+3, FR	-		1.0	
D-50	S6-JTEX-DB	Master data set searchable database	CLS	KO+3, FR	-		1.0	
D-60	S6-JTEX-SATL	satellite activity timeline	CLS	KO+3, FR	100%	available on website	1.0	-
D-70	Paper-1	CalVal open ocean and GMSL	CLS	KO+12, each PM, FR	100%	submitted	1.0	FR
D-80	Paper-2	Coastal study	TUM	KO+12, each PM, FR	100%	published	1.0	PM6
~~**D-90**~~	~~Paper-3~~	~~Uncertainties and GMSL~~	~~CLS~~	~~KO+12, each PM, FR~~				
D-100	Paper-4	Sea state	NOC	KO+12, each PM, FR	100%	submitted	1.0	FR
D-110	Paper-5	Sea state	CLS	KO+12, each PM, FR	-%	in prep	1.0	-
D-120	Paper-6	Statistical analysis of L1 data	ARESYS	KO+12, each PM, FR	100%	submitted	1.0	FR
D-130	Paper-7	FF-SAR processing	CLS	KO+12, each PM, FR	100%	published	1.0	FR
D-140	Paper-8	Inland water analysis	CLS	KO+12, each PM, FR	100%	submitted	1.0	FR
D-150	Paper-9	Internal waves detection study	UNIV PORTO	KO+12, each PM, FR	100%	published	1.0	PM4
D-160	Paper-10	Uncertainties and GMSL	MAGELLIUM	KO+12, each PM, FR	-%	in prep	1.0	-
D-230	Paper-11	LIT	CLS	KO+12, each PM, FR	100%	submitted	1.0	FR
D-170	SR	Scientific Roadmap	CLS	FR-1	100%	available on sharepoint	1.0	FR
D-180	FR	Final Report	CLS	FR-1	100%	available on sharepoint	1.0	FR
D-190	TDP	Technical Data Package	CLS	FR				
D-200	CCD	Contract Closure Documentation	CLS	FR				
D-210	FP	Final Presentation	ALL	FR	100%	available on sharepoint		FR
D-220	MR	Executive progress report and Actions	CLS	FR	100%	available on sharepoint		-

Deliverables

Available on the S6-JTEX sharepoint

- Deliverables
  https://groupcls.sharepoint.com/:f:/r/sites/S6-JTEX/03-Deliverables
- Meeting presentation/MoM
  https://groupcls.sharepoint.com/:f:/r/sites/S6-JTEX/04-Meeting



Actions, AOB and Conclusions

Review of Actions

- XX

AOB & Conclusions

- XX