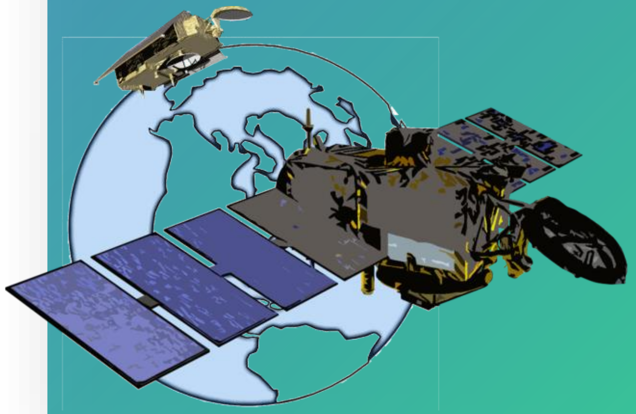
Final review 24/04/2024



Scientific Activities: S6-MF FFSAR Processing

S. Amraoui, P. Guccione, T. Moreau, M. Alves, O. Altiparmaki, C. Peureux, L. Recchia, C. Maraldi, F. Boy, C. Donlon

OBJECTIVES

- To make use of the **high-resolution FF-SAR technique** (Egido and Smith, 2017) **to fully exploit the S6-MF capabilities** with a view to implement this solution in ground segment of current and future altimeter missions
- **To recommend optimal processing configurations** for the Omega-Kappa (WK) algorithm (Guccione et al., 2018) in various scenarios (transponder, rough and specular surfaces)
- **To develop new applications and potentially define new products** for different targets (long ocean waves, open-water leads, coastal regions, and inland waters) **using new altimeter imagery capability**
- Using tools and methodologies developed in CNES/ESA R&D studies

OBJECTIVES

We used the **Omega-Kappa (WK) SAR focusing algorithm** (Guccione et al., 2018) which has proved to be computationally efficient and, if properly tuned, just as valid as the Back-Projection (BP) algorithm. **But WK algorithm operates in the Doppler frequency domain, necessitating further precise spectral and time domain settings** to provide an optimal processing of the altimeter data

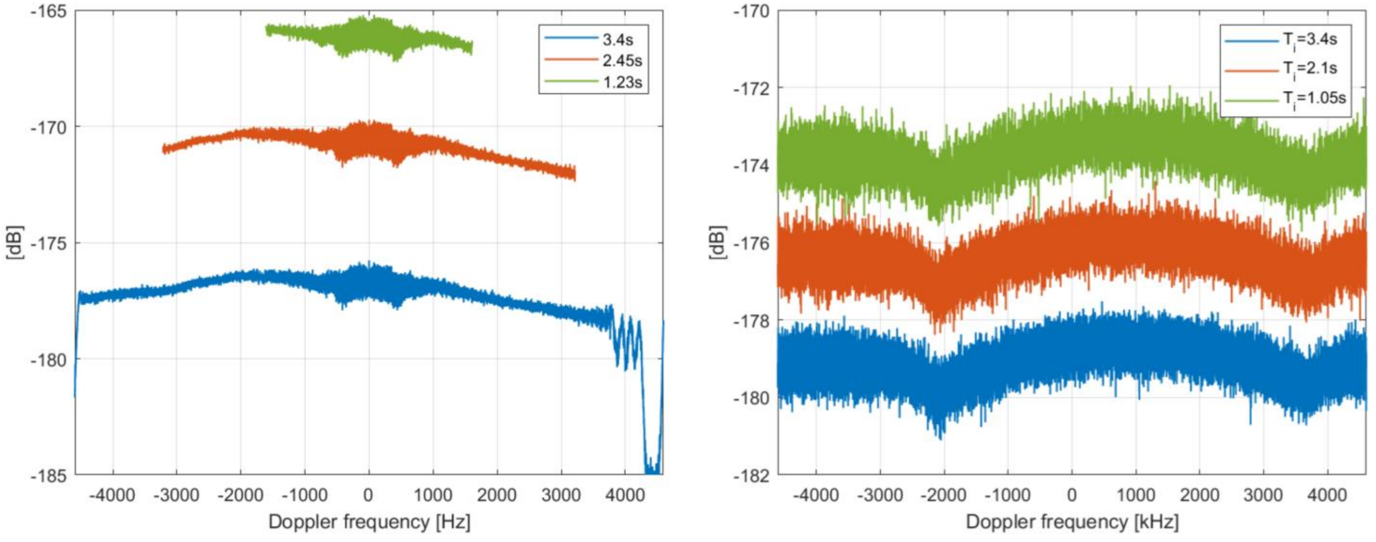
- **Task 1: Find the optimal WK processing parameters**
  - Percentage of doppler bandwidth
  - Integration time
  - Doppler windowing
  - Replica mitigation
  - Multilooking

To be tuned to provide aliasing and replica reduction, as well as high posting rate and low noise measurements for the different target types

- **Task 2: Show case studies using S6-MF acquisitions (in synergy with S1)**
  - On specular targets: lead detection
  - On non-specular surfaces: 2D modulation FFSAR spectra

FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: **Percentage of Doppler bandwidth**, integration time, Doppler windowing, replica mitigation, multilooking



(**a**) Transponder (**b**) Open ocean

For a single scatterer (**transponder**), it exists a one-to-one correspondence between the Doppler spectrum and the acquisition time

For multiple scatterers (**open ocean**), the spectrum is completely folded regardless the portion of data cut. Given that ~30% of S6-MF spectrum is aliased, the spectrum must be truncated during WK processing to preserve 60% to 70% of the band

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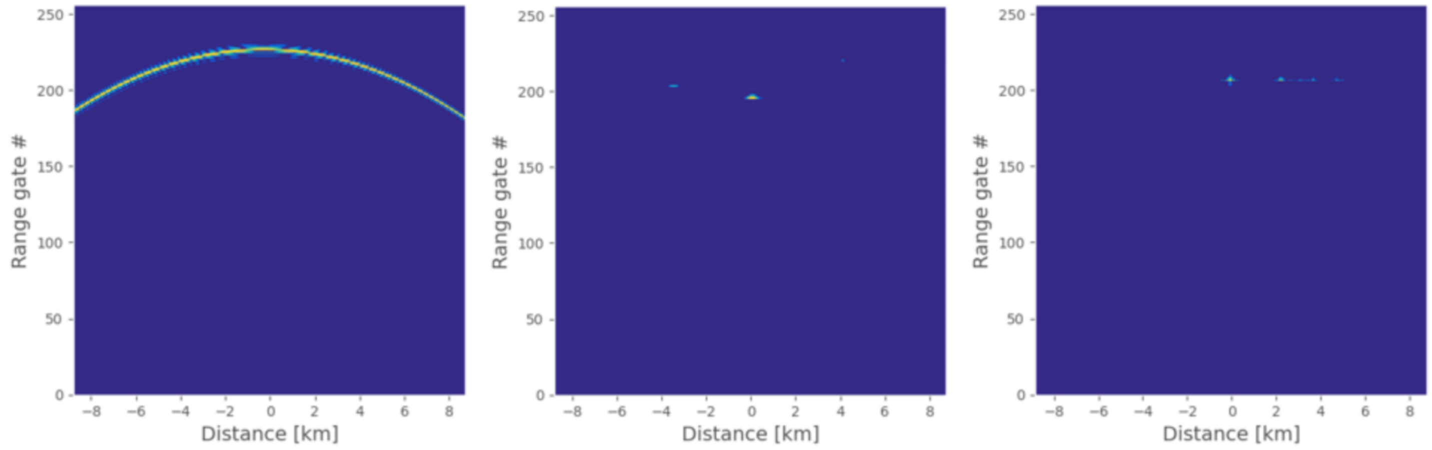
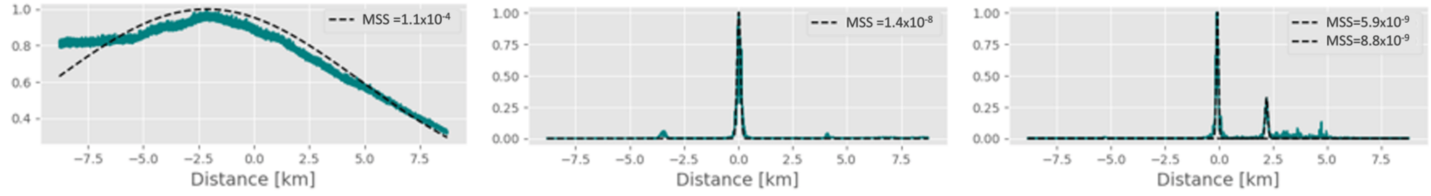
FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: Percentage of Doppler bandwidth, integration time, Doppler windowing, replica mitigation, multilooking



(**a**) Stack over transponder (**b**) Stack over Guadalquivir river (**c**) Stack over sea-ice lead



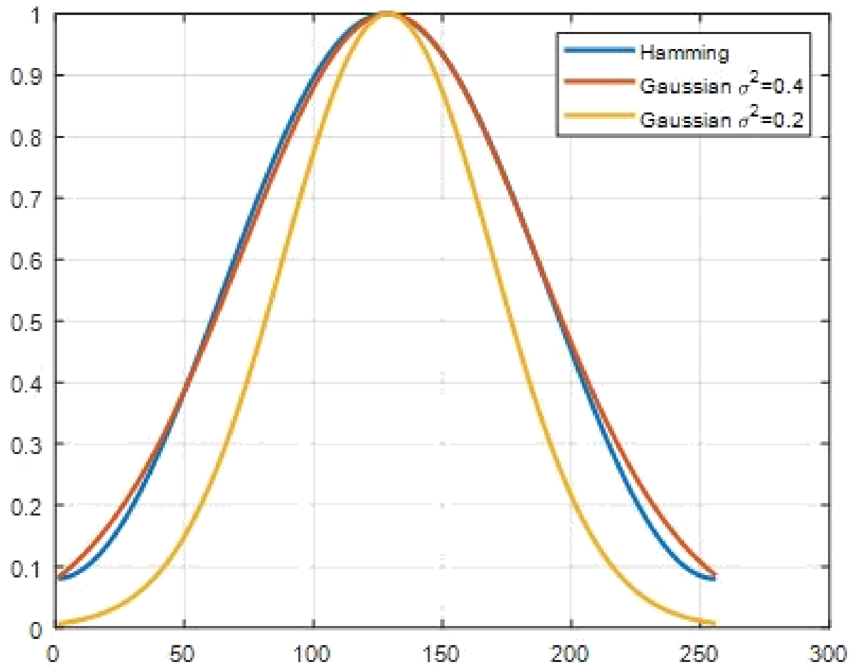
(**d**) MSS over transponder (**e**) MSS over Guadalquivir river (**f**) MSS over sea-ice lead

For isotropic targets (**antenna pattern is dominant**), the FF resolution is inversely proportional to the integration time (for T_i=3.4s the resolution is 55cm)

For anisotropic targets (**highly reflective surface where *mss* is dominant**), the FF resolution is driven by the *mss*, which acts as a natural along-track Doppler windowing. **Along-track signal is naturally devoid of side lobes**

FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: Percentage of Doppler bandwidth, integration time, Doppler windowing, replica mitigation, multilooking



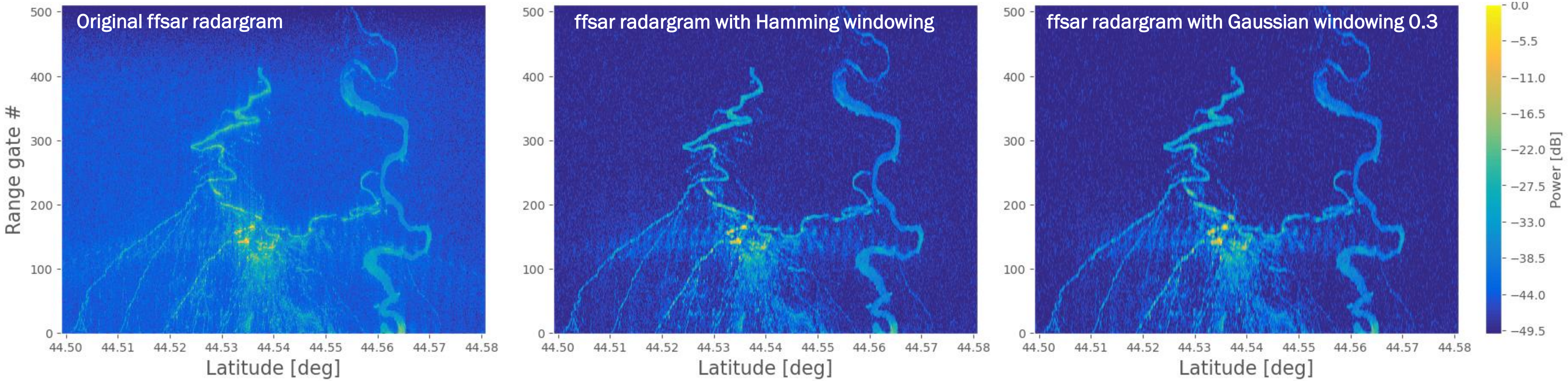
Parameter	No antenna	Antenna only	Hamming	Gaussian 0.4	Gaussian 0.2
Resolution [m]	0.643	0.614	0.858	0.837	1.083
PSLR [dB]	-15.42	-14.11	-32.69	-35.26	-41.70
ISLR [dB]	-13.45	-11.86	-31.56	-32.85	-41.81
Replica [dB]	-30.7	-30.8	-34.8	-35.0	-37.0

Doppler windowing reduces the side lobes and replicas level at the expense of the resolution, this effect is amplified when the windowing is sharp

FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: Percentage of Doppler bandwidth, integration time, Doppler windowing, replica mitigation, multilooking

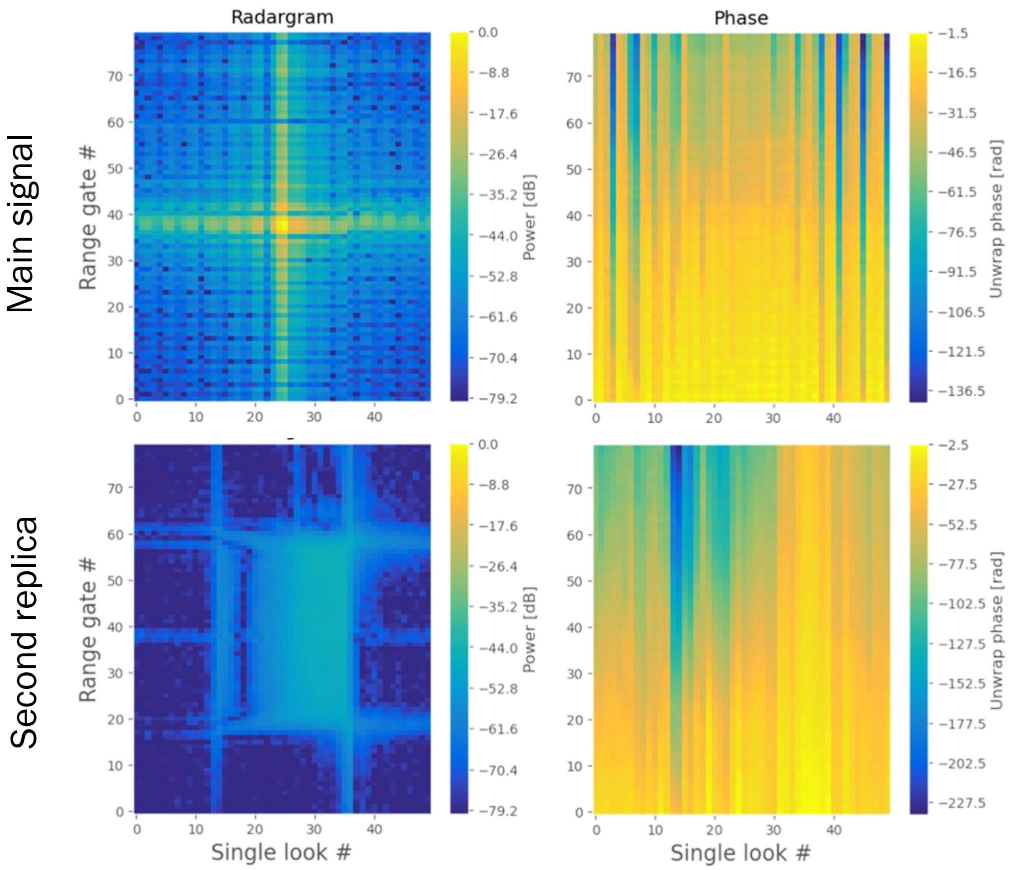
Lot River, France



More details in Amraoui et al., 2024

FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: Percentage of Doppler bandwidth, integration time, Doppler windowing, replica mitigation, multilooking

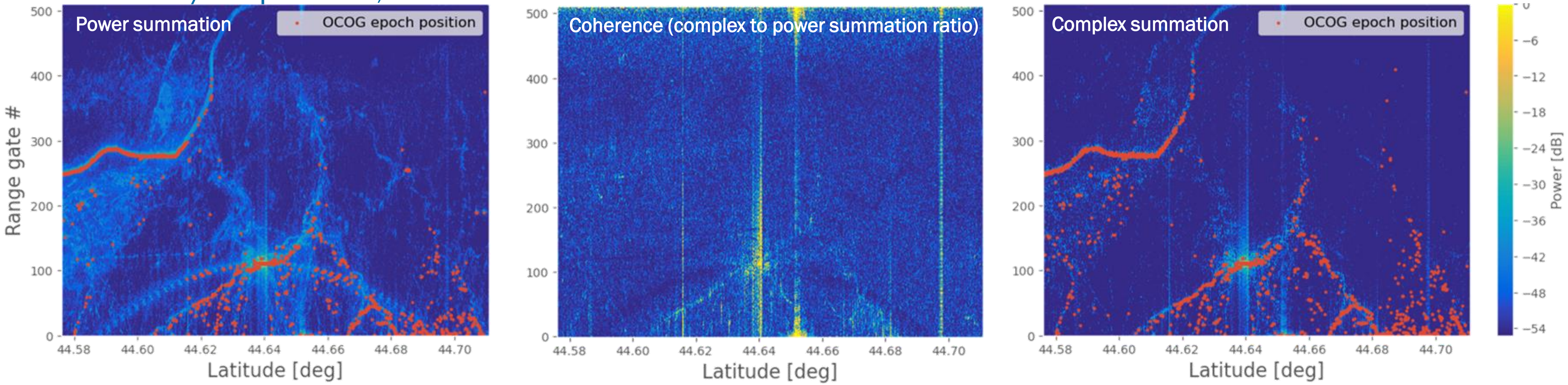


- **Range-smearing effect** (Ehlers et al., 2022) due to imperfect RCMC correction blurs the FFSAR grating lobes in range and azimuth (but stable in amplitude)
- **Phase variation effect** also due to RCMC mis-correction at replica positions. By making a **complex summation** instead of a power summation **while multilooking, SL interfere destructively** removing the replicas but also the incoherent signal

FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: Percentage of Doppler bandwidth, integration time, Doppler windowing, replica mitigation, multilooking

Garonna/Dropt River, France

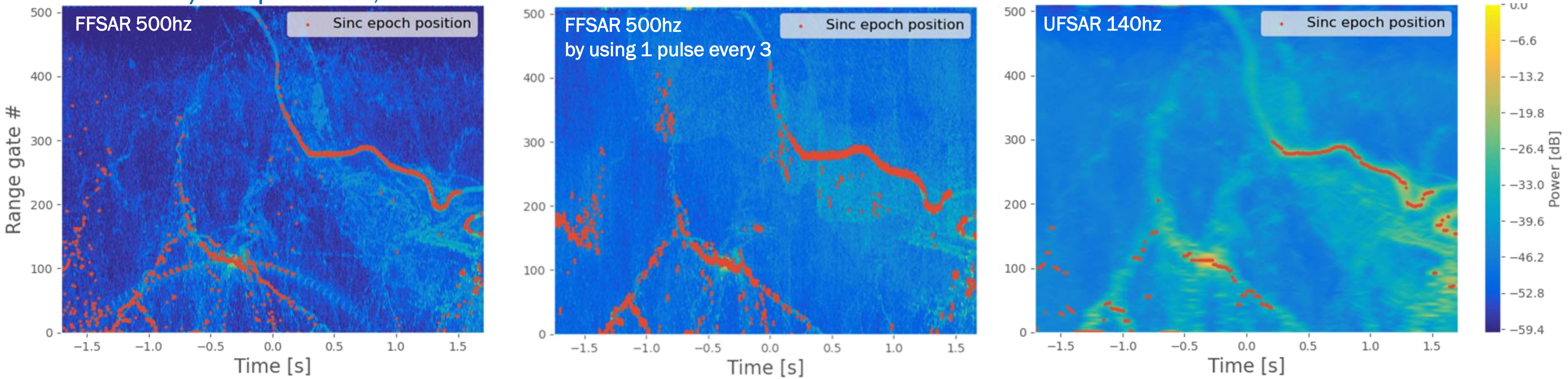


More details in Amraoui et al., 2024

FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: Percentage of Doppler bandwidth, integration time, Doppler windowing, replica mitigation, multilooking

Garonna/Dropt River, France



(From CNES R&D) Removing 1 pulse every 3 creates a perfect interleaved chronogram (i.e., removing replicas) but reduces the PRF by 3 (i.e., increasing aliasing effect and the noise level from 5 to 10dB). Improved SNR in FFSAR than in UFSAR even in the aliasing case. FFSAR follows the river better in across-track direction

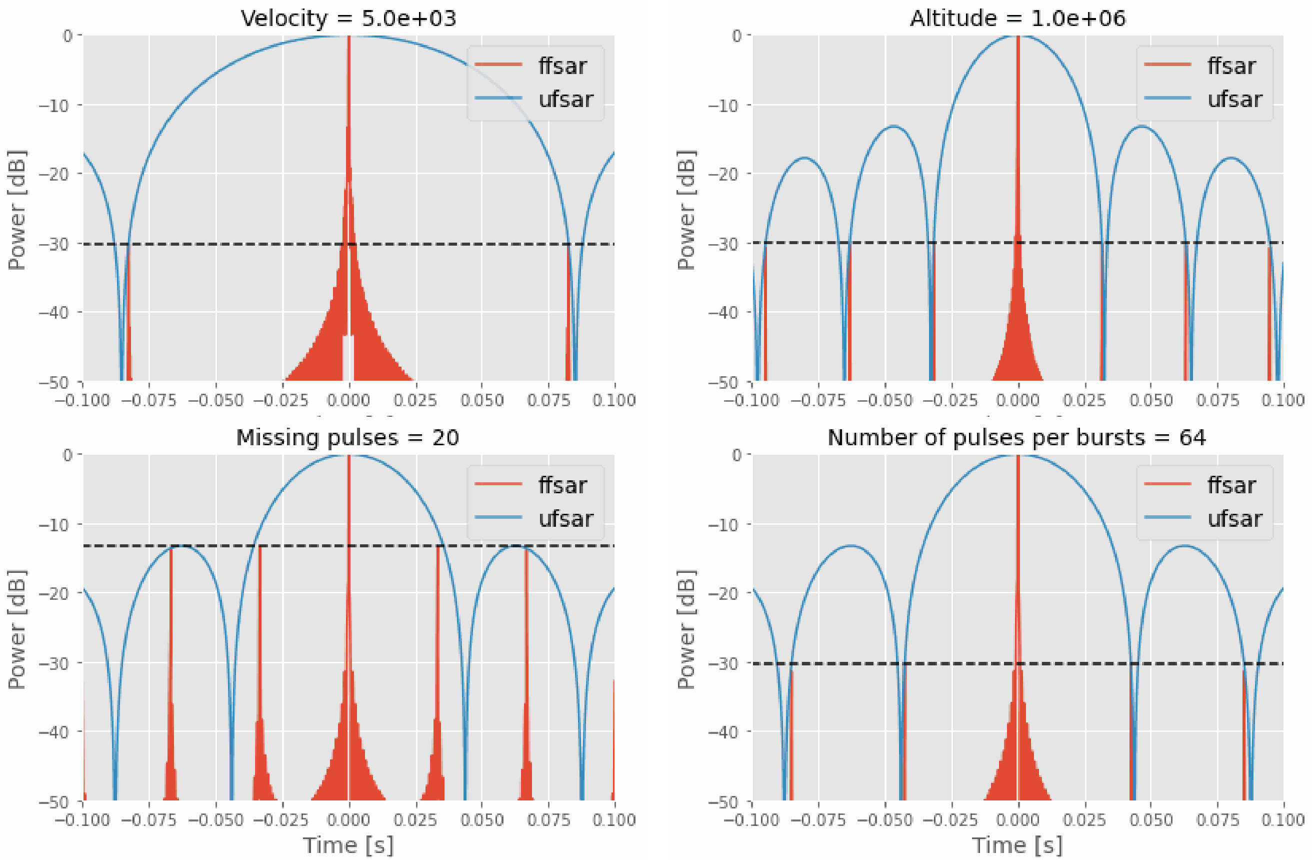
FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: Percentage of Doppler bandwidth, integration time, Doppler windowing, replica mitigation, multilooking

Altitude and **velocity** has no impact on the replicas level in dB

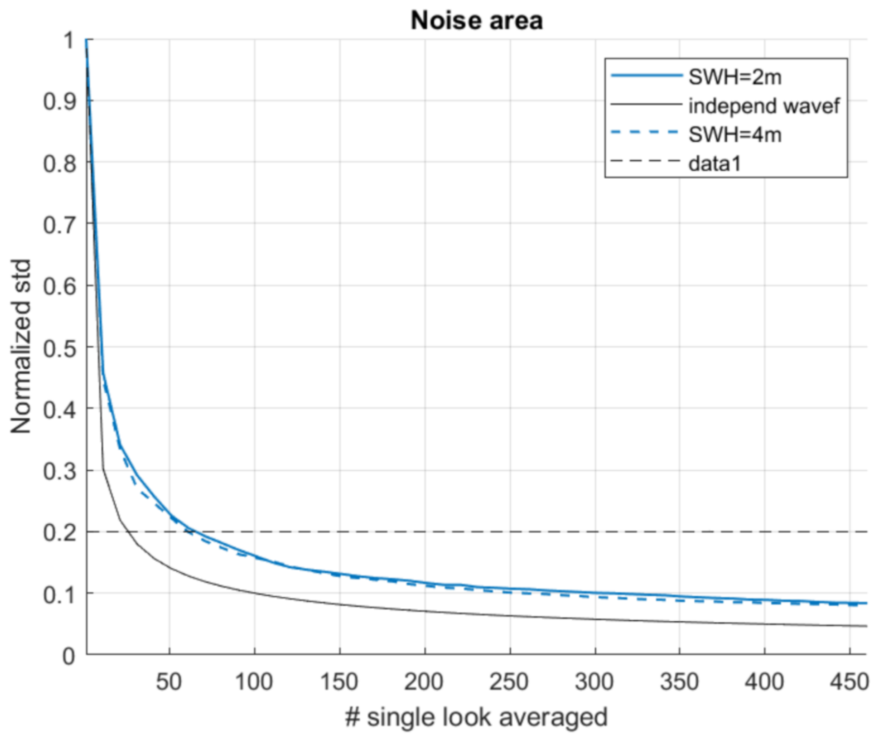
Number of missing pulses and the **number of pulses per burst** are the only parameters that can reduce the replicas level in dB

(from CNES R&D)



FF-SAR Optimal Processing Configuration

Optimal configuration for FF-SAR WK processing for diffusive (open ocean) and specular surfaces (inland waters, open-water leads) by tuning the parameters: Percentage of Doppler bandwidth, integration time, Doppler windowing, replica mitigation, multilooking



To determine the optimal posting rate, it is necessary to trade-off between two contrasting requirements:

1. High posting rate means higher resolution, but lesser single waveforms averaged together (i.e., higher noise level)
2. Low posting rate means more single waveforms averaged together (i.e., lower noise level) but less resolution

To achieve a 7dB noise reduction (80%), 60-65 waveforms must be averaged together, corresponding to 140-150Hz posting rate

Greater noise reduction requires averaging much larger number of single looks, resulting in a significant loss of resolution

FF-SAR Optimal Processing Configuration

Final recommendation of the best configuration for S6-MF FF-SAR processing.
The targets are separated into two categories, specular and non-specular, with their own recommendations

Surface Type	% of DB	Int. Time	Ant. Comp.	Windo-Wing	Replica Mit.	Multi-Looking
Specular	75%	2.55	yes	yes	yes	300–500 Hz
Non-specular	60%	2.05	yes	no	no	150–200 Hz

see Amraoui et al., 2024

FF-SAR Optimal Processing Configuration

Final recommendation of the best configuration for S6-MF FF-SAR processing.
The targets are separated into two categories, specular and non-specular, with their own recommendations

Enhances the along-track resolution of point targets

Surface Type	% of DB	Int. Time	Ant. Comp.	Windo-Wing	Replica Mit.	Multi-Looking
Specular	75%	2.55	yes	yes	yes	300–500 Hz
Non-specular	60%	2.05	yes	no	no	150–200 Hz

see Amraoui et al., 2024

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Non-specular	60%	2.05	yes	no	no	150–200 Hz

see Amraoui et al., 2024

Reduces the level of sidelobes at the expense of resolution

FF-SAR Optimal Processing Configuration

Final recommendation of the best configuration for S6-MF FF-SAR processing.
The targets are separated into two categories, specular and non-specular, with their own recommendations

Surface Type	% of DB	Int. Time	Ant. Comp.	Windo-Wing	Replica Mit.	Multi-Looking
Specular	75%	2.55	yes	yes	yes	300–500 Hz
Non-specular	60%	2.05	yes	no	no	150–200 Hz

see Amraoui et al., 2024

High resolution is crucial for **specular areas** to discriminate small structures effectively

FF-SAR Optimal Processing Configuration

Final recommendation of the best configuration for S6-MF FF-SAR processing.
The targets are separated into two categories, specular and non-specular, with their own recommendations

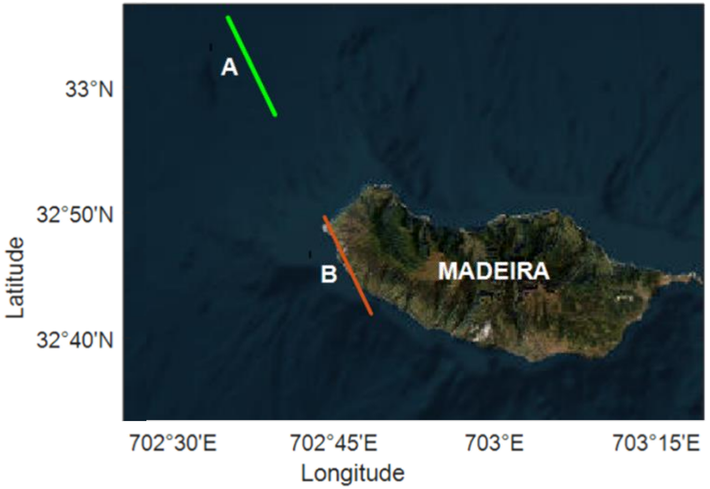
Surface Type	% of DB	Int. Time	Ant. Comp.	Windo-Wing	Replica Mit.	Multi-Looking
Specular	75%	2.55	yes	yes	yes	300–500 Hz
Non-specular	60%	2.05	yes	no	no	150–200 Hz

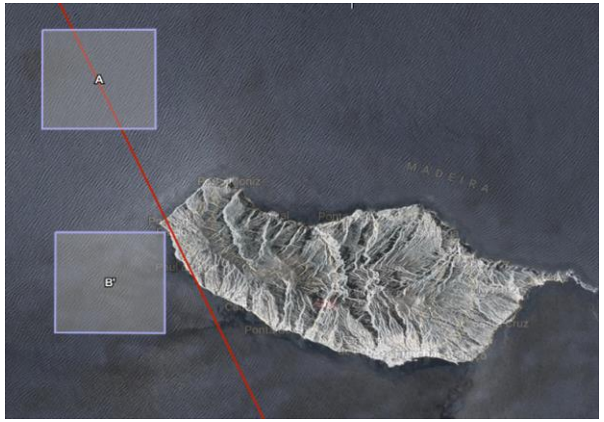
see Amraoui et al., 2024

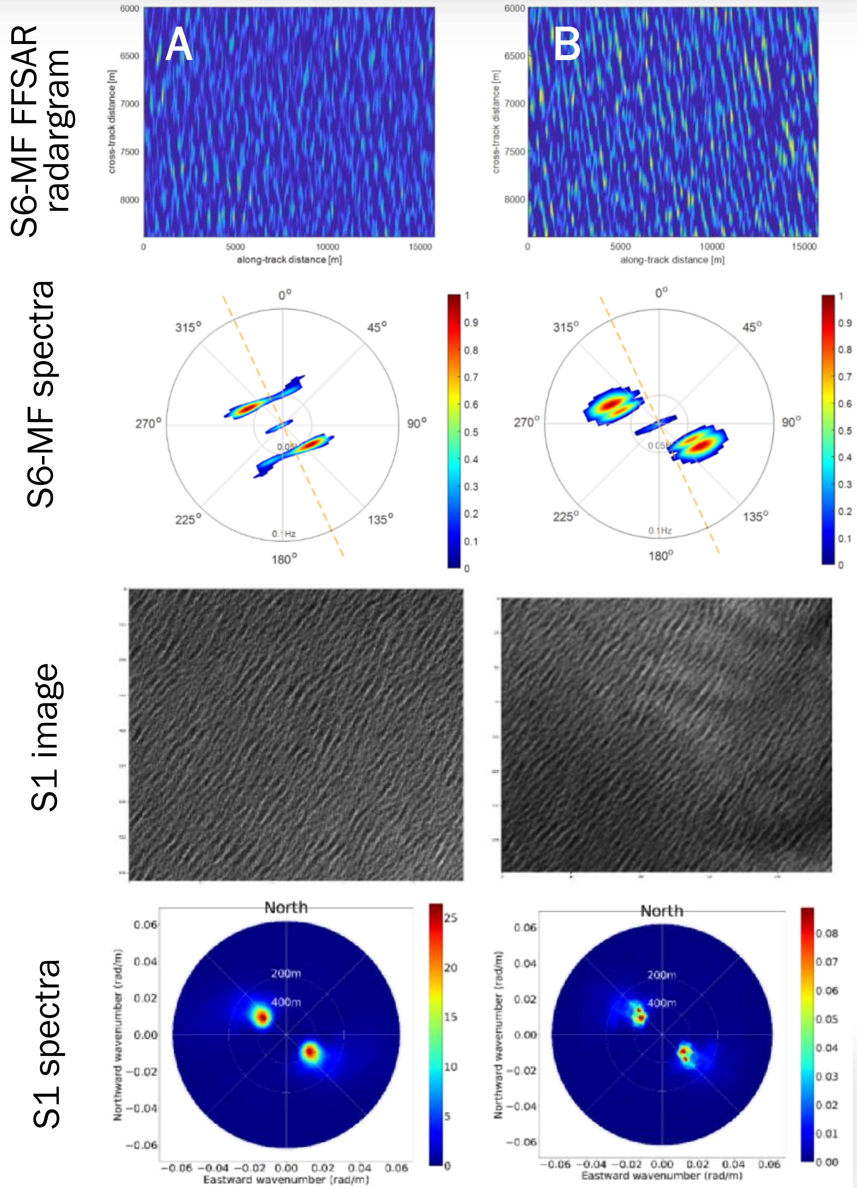
Lower posting rate enhances noise reduction but at the expense of resolution. Better suited for **open ocean** (larger and more homogeneous surface)

FF-SAR imagery for swell parameters retrieval

- **2D modulation spectra from S6-MF FFSAR data** allows swell parameter estimates: direction, amplitude and period (Altiparmaki et al., 2022) leading to new potential products and applications (e.g. assimilation in ocean wave models)



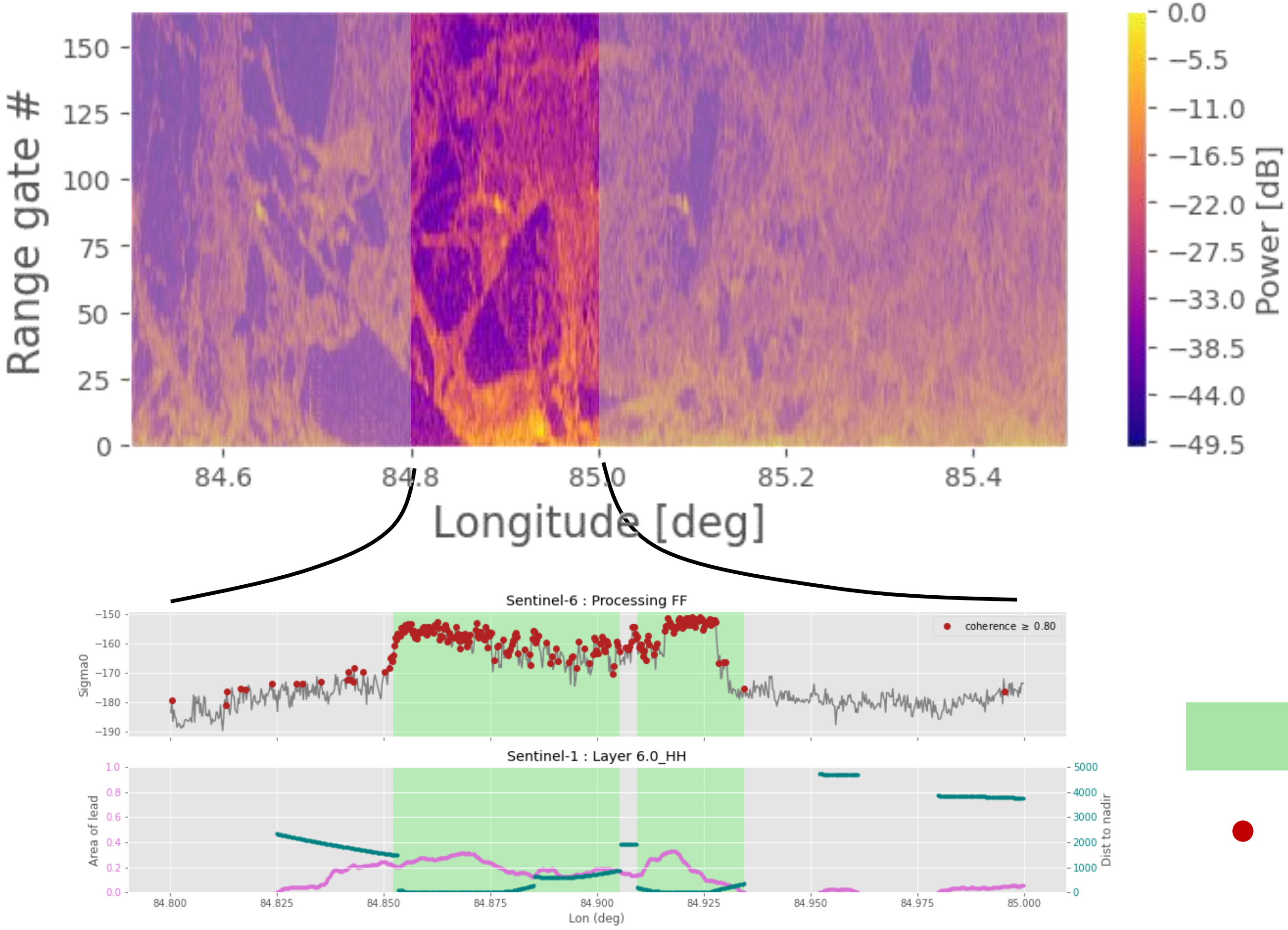


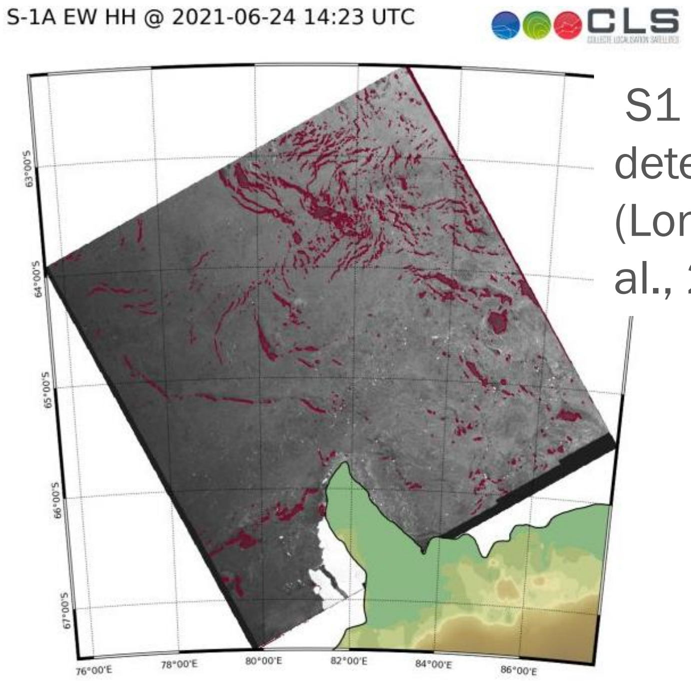


- Two additional peaks due to left/right ambiguity (on top of 180°ambiguity) can be eliminated in coastal region to ease comparison with S1 spectra

FF-SAR imagery for sea-ice leads detection

Good consistency between S6-MF FFSAR data and S1 data to detect sea-ice leads





S1 leads detection (Longépé et al., 2019)

Sentinel-1 lead : area of lead <40% and distance to nadir <1500m

Sentinel-6 lead : coherence>0.8

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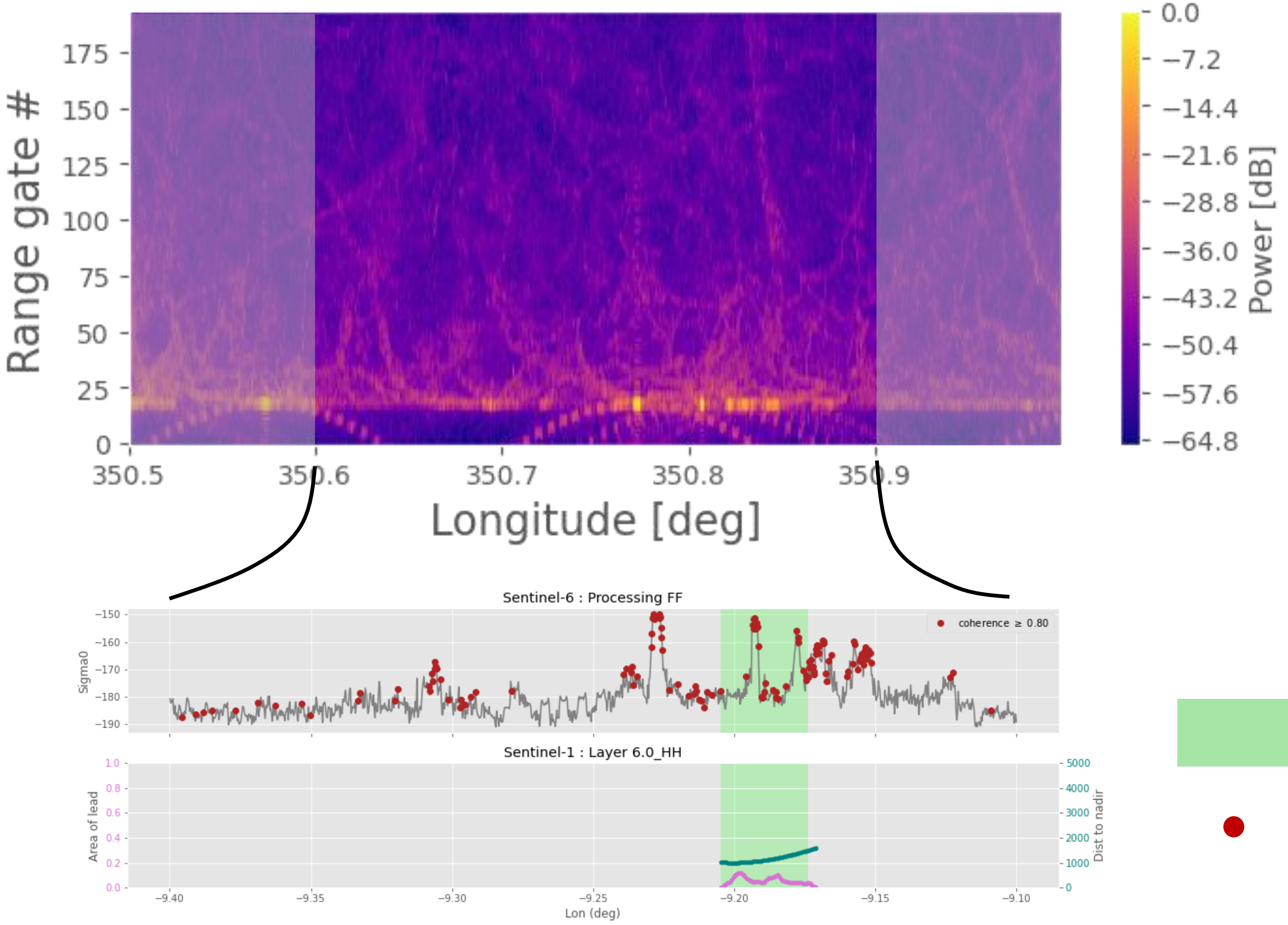
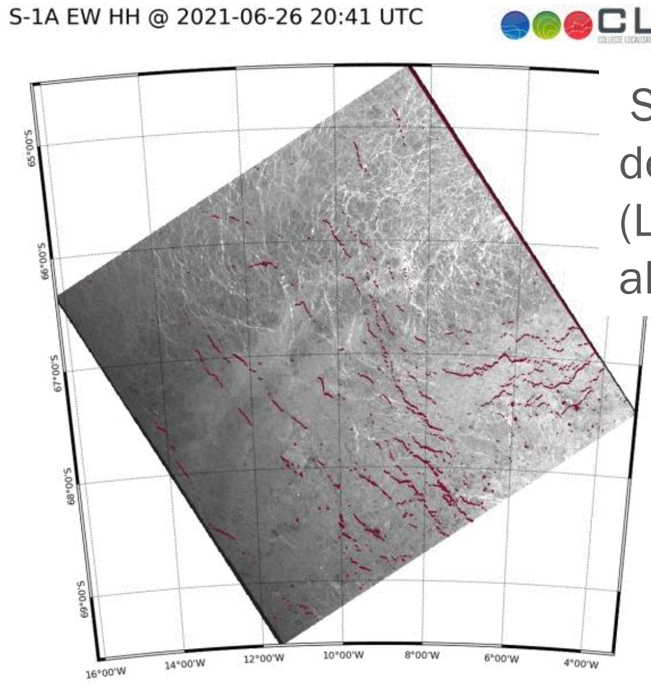
FF-SAR imagery for sea-ice leads detection

Presence of small sea-ice leads detected by S6 and not seen by S1





S1 leads detection (Longépé et al., 2019)

Sentinel-1 lead : area of lead <40% and distance to nadir <1500m

Sentinel-6 lead : coherence>0.8

CONCLUSIONS

- This work further led to the recommendation of a set of configuration parameters to enable optimal processing of S6-MF FFSAR data from various surface types https://doi.org/10.3390/rs16061112
- **This processing**, when properly configured, **is capable of greatly enhancing the observation of specular and diffuse targets**, opening up a multitude of possibilities for monitoring various types of surfaces (open ocean, hydrology and sea-ice)
- **FFSAR is able to image long-wave modulations.** We confirmed that the **left/right ambiguities are due to folding of the backscattered signal** in nadir-looking altimetry
- **FFSAR is able to detect thinner leads than those observed on Sentinel-1 imagery,** which is of great interest for observing polar sea surfaces during glacial transition
- A removal replicas strategy has been developed for the S6-MF mission, for specular surfaces. Its applicability and benefits have yet to be assessed on a larger data set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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

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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 lineic 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

check for updates

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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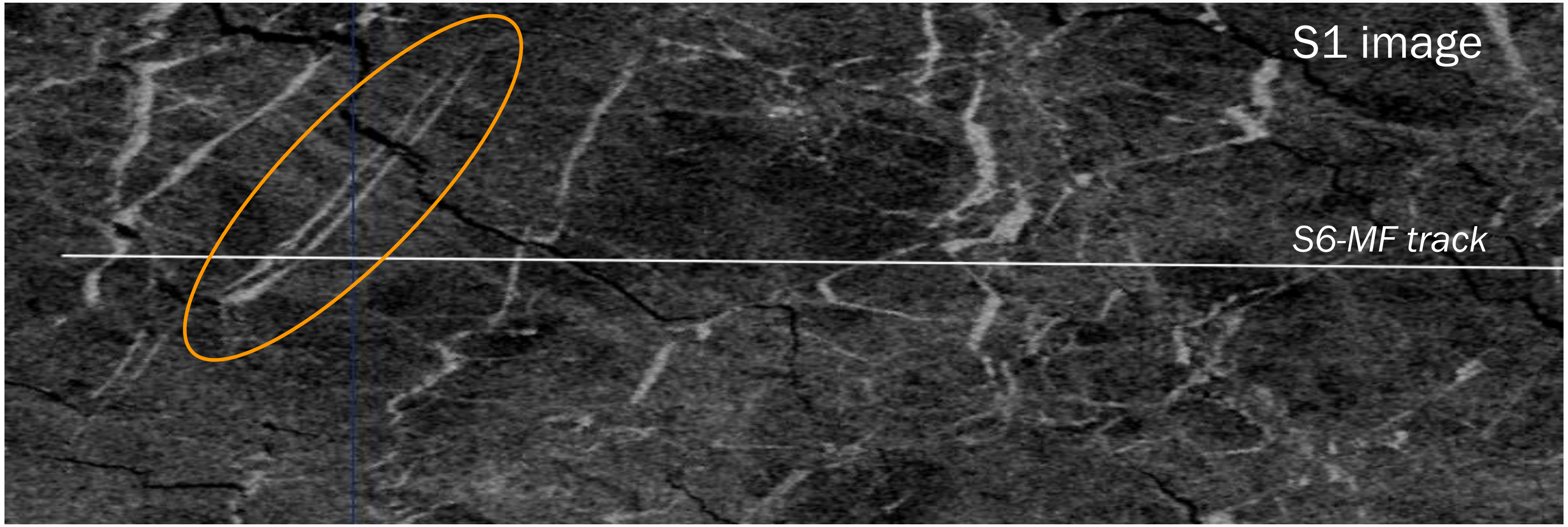
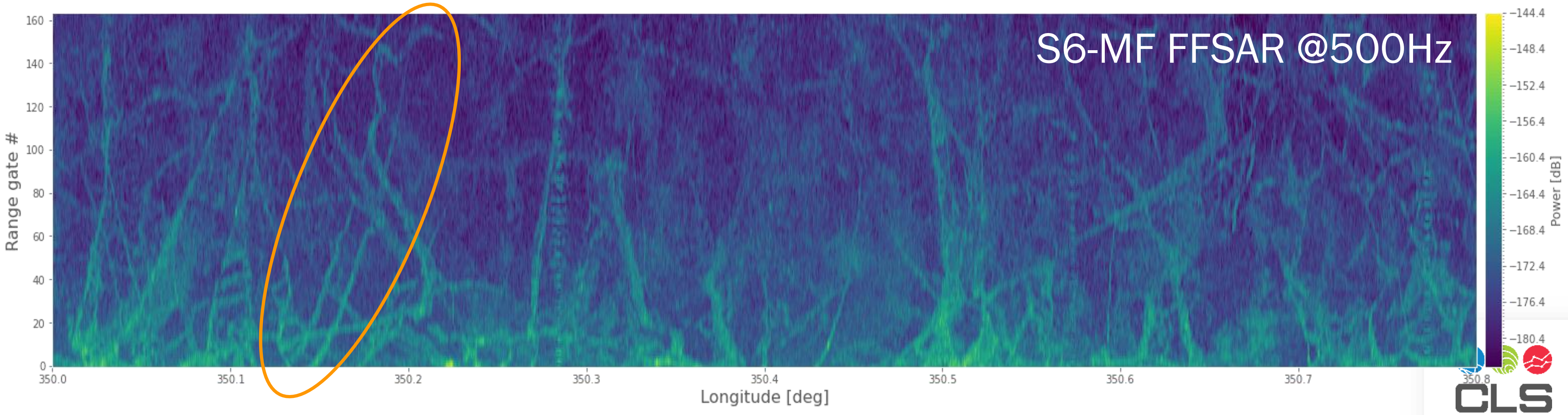
1. Introduction

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

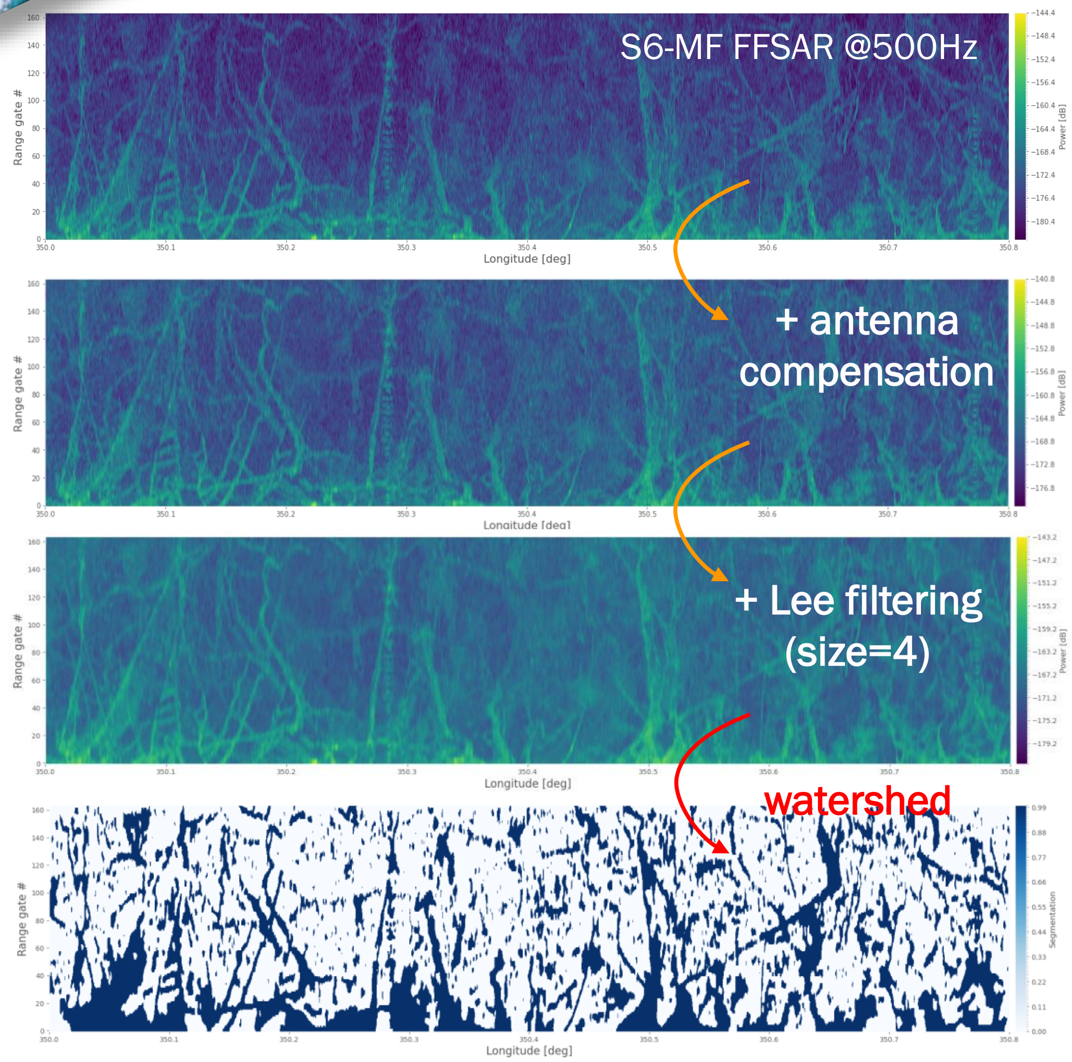
Remote Sens. 2024, 16, 1112. https://doi.org/10.3390/rs16061112 https://www.mdpi.com/journal/remotesensing

FF-SAR imagery for sea-ice leads detection





FF-SAR imagery for sea-ice leads detection

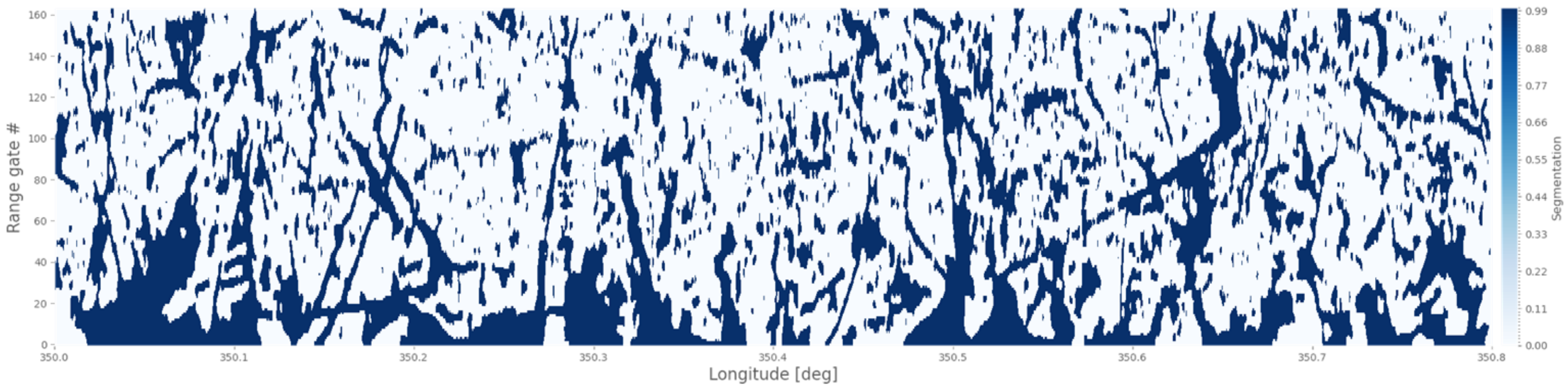


S1 lead detector can be adapted to S6-MF using the following methodology :

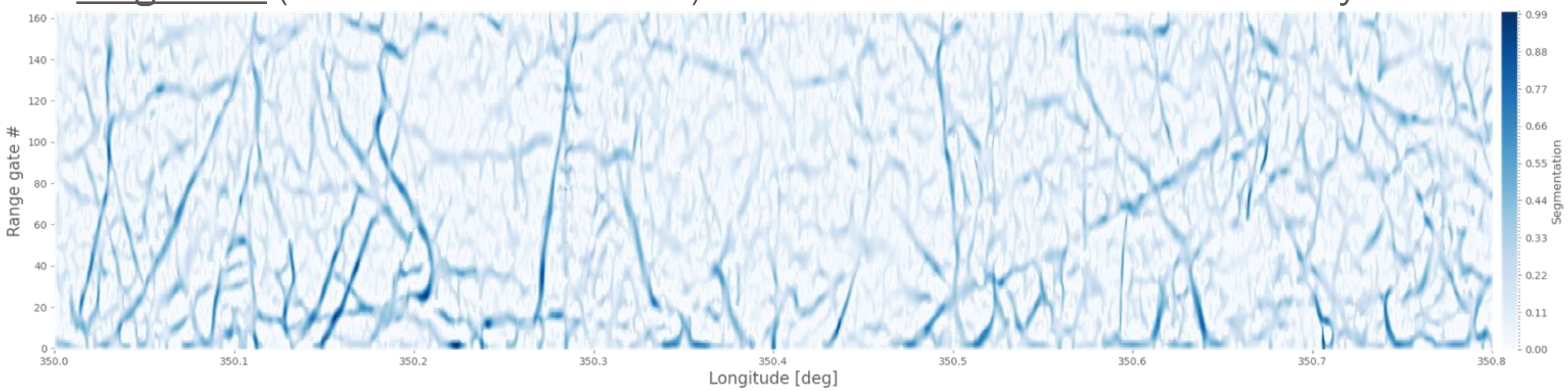
- To compensate the antenna gain to align the power in across-track direction
- To reduce the speckle noise by applying a Lee denoising filter to σ_0 values
- **Final watershed** lines are the segmentation of the filtered image into **leads and floes**

FF-SAR imagery for sea-ice leads detection

Watershed method (32% leads - 68% floes)



Ridge filter (12% leads - 88% floes) efficient for small lineic retrieval only



- 2D-view is an important source of information to know whether a sea-surface height is coming from a lead or a flow
- S6-MF imagery processing can also provide valuable information on **lead/floe coverage**

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CCN#1: Floe/lead coverage estimation from Sentinel-6 altimetry data

- Analysis of the floe/lead coverage estimates using imagery technic applied to Sentinel-6 FFSAR waveforms, and
- Comparison with Sentinel-2 (and possibly Sentinel-1) and sea-ice index (OSI-SAF) over a selected region at different times of the year to assess the consistency of the FFSAR capability to provide valuable information on floe/lead coverage

Further perspectives

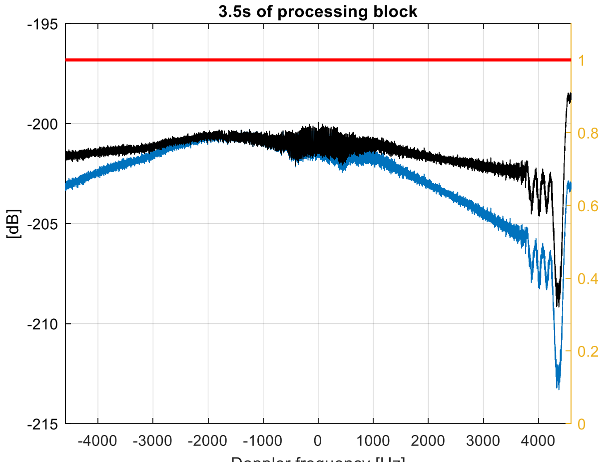
- To explore the Rieu et al. (2020) technique using altimeter data from S6-MF and S6B in tandem phase to characterize moving processes (e.g., swells) on sea surface, in greater detail taking full advantage of the FFSAR processing capabilities
- These analyses could be supplemented by analyses carried 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

Back slides

Relationship between doppler band and integration time: summary

In the table, the differences between the two cases are summarized

Case / Domain	Single / Dominant scatterer	Distributed target
Integration time	For a point target, spectrum resembles the antenna pattern shape. There is convenience to acquire at least for a integr. time equal to the synthetic aperture. If less integr. time is acquired, spectrum appears cut.	For a perfect distributed target, spectrum resembles the antenna pattern shape regardless of the integration time (see slide 5). For a not-distributed target (example high reflective surface) the relation between intergation time and Doppler must be evaluated case by case (see next slide).
Doppler bandwidth	Doppler bandwidth is proportional to the integration time. For a transponder, the maximum bandwidth is required. Final resolution is a function of such width	Doppler bandwidth is reduced to avoid alias. 60% of PRF has been found as a good compromise between accuracy of single waveforms and alias reduction, at least for ocean products.



$$\rho_{az} \approx 0.886 \cdot \frac{v_{gr}}{B_d} \Rightarrow B_d = 0.886 \cdot \frac{v_{gr}}{\rho_{az}} = 0.886 \cdot \frac{5755m/s}{0.555} = PRF$$

$$B_d = 1.0 \cdot PRF$$

$$T_{\text{int},transp} = B_d / |f_R| \geq 3.4s$$

$$T_{block} = T_{\text{int},transp}$$

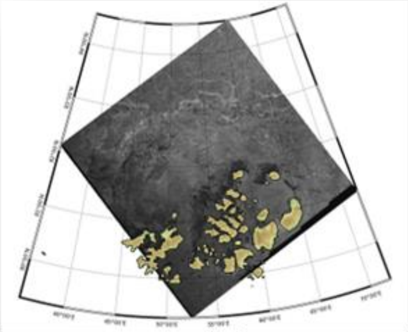
$$T_{\text{int},sea-ice} = 1s$$

$$T_{\text{int},specular} = 2.1s$$

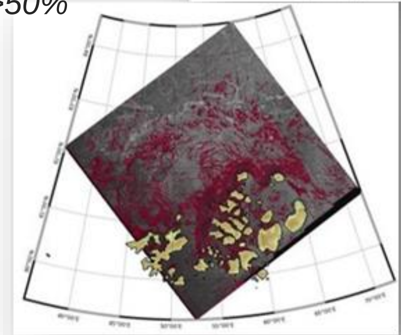
$$B_d = 0.6 \cdot PRF$$

Can we apply the same technique used on S1 to S6 ?

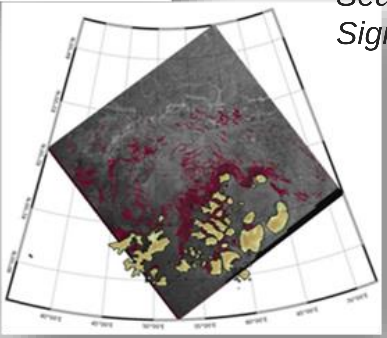
Original Image



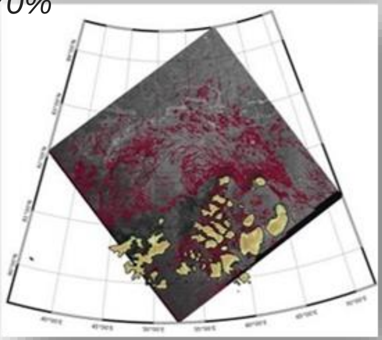
Sea ice conc.>50%
Sigma0>6dB



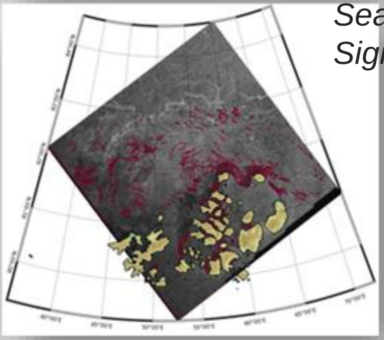
Sea ice conc.>50%
Sigma0>9dB



Sea ice conc.>70%
Sigma0>6dB



Sea ice conc.>70%
Sigma0>9dB



The detector has been designed by [Longépé, 2019] and adapted for Sentinel-1 SAR images

Lead signature :

- ❖ dark areas
- ❖ relatively high backscatter background (sigma0)

Methodology :

- start from EW GRDM S1-a and b data as input
- reduce the speckle noise by applying a Lee denoising filter to the sigma0
- detect dark regions (minima points) by using a gray-scale reconstruction algorithm
- each local minima is considered a single lead and is “filled-in” up to a certain threshold (of sigma0 and sea-ice concentration) to recreate the lineic

Synergy with S1 for lead detection

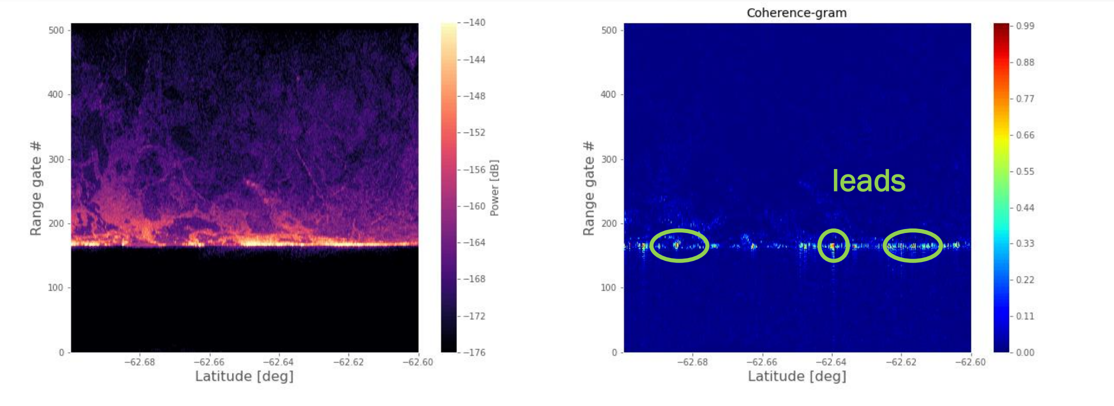
Lead signature on S6 :

❖ Bright areas (sigma0)

❖ Highly correlated in time

Methodology :

- at l1b: Evaluated the correlation factor in the radargram
- at l2: Extract this value to the retracked epoch position



Lead signature on S1 : (N. Longépé, et al, 2019)

❖ Dark areas

❖ Relatively high backscatter background (sigma0)

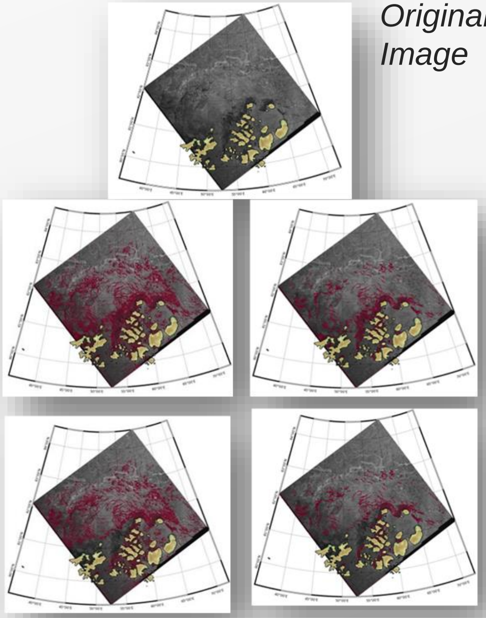
Methodology :

- reduce the speckle and detect dark (using a gray-scale reconstruction algorithm)
- each single lead is "filled-in" up to a certain threshold (of sigma0 and sea-ice concentration) to recreate the lineic

Original Image

Sea ice conc.>50% Sigma0>6dB

Sea ice conc.>50% Sigma0>9dB



Sea ice conc.>70% Sigma0>6dB

Sea ice conc.>70% Sigma0>9dB

CLS
COLLECTE LOCALISATION SATELLITES