A facet-based numerical model to retrieve ice sheet topography from Sentinel-3 altimetry

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Introduction – Sentinel-3 mission

- **Sentinel-3A** (launched in February 2016) and **Sentinel-3B** (launched in April 2018) are monitoring the polar ice sheets up to ± 81.5°. **The constellation is planned to operate until 2035, at least.**

- The status of the two missions is “nominal”. **Excellent stability.** The Global Mean Sea Level (GMSL) is in close agreement with Sentinel-6 / Jason-3 (S3VT#8 – Dec 2023).

- Except early mission life, **Sentinel-3 A/B are continuously operating in SAR altimetry mode.**

- While first promising results of Sentinel-3 SAR altimetry over ice sheets were shown in previous studies (McMillan et al., 2019**), there are still strong improvements that can be made in the ground segment processing**, in particular at level-2 (i.e. echo relocation).

Sentinel-3 artist view (credits: ESA)

Plan

01 **Context: Sentinel-3 ground segment processing over ice sheets**

- Quick overview of new ESA Sentinel-3 Land Ice Thematic Products

02 Presentation of an alternative level-2 processing: **the so-called AMPLI software**

- Improved relocation, based on numerical modelling

03 **Evaluation of Sentinel-3 AMPLI over Antarctica, by comparison to ICESat-2**

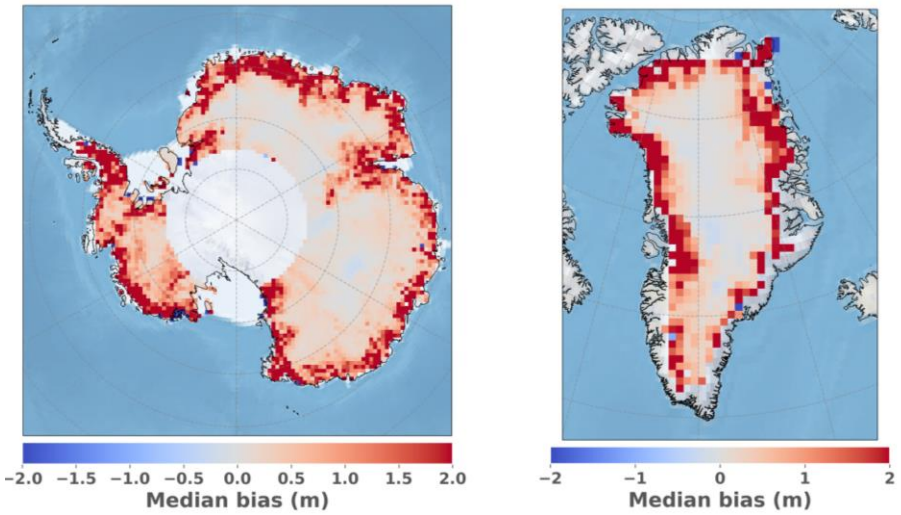
- **In the surface elevation** estimated along the satellite track (~330 m posting rate)
- **In the Surface Elevation Change** (SEC) of the Antarctic ice sheet

Context: The new Sentinel-3 Hydro-Cryo Thematic Products

Since September 2023, ESA is operationally generating the "**Sentinel-3 Hydro-Cryo Thematic Products**", to address the needs of **Land Ice**, **Sea Ice** and **Hydrology** users.

- **A mission reprocessing** was achieved with the Thematic Processors, providing a complete harmonised dataset of Sentinel-3 data over the 3 Thematic surfaces.
- In the new **Land Ice processing** the delay-Doppler is improved with the so-called "extended window processing" (Aublanc et al., 2018) … **but large errors remain in the estimated ice elevation, in particular over the ice sheet margins** (right figures).
- The poor performance over the ice sheet margins are mainly explained by "relocation errors" (i.e. estimation of the location of the radar impact point on-ground).

Median bias between Sentinel-3 Land Ice Thematic Product and ICESat-2 ATL06 *(from S3 MPC project, computed as S3-IS2)*



<u>To improve the Sentinel-3 performance over ice sheets:</u>

A new relocation algorithm was recently developed at CLS using **facet-based modelling**

=> the Sentinel-3 AMPLI software

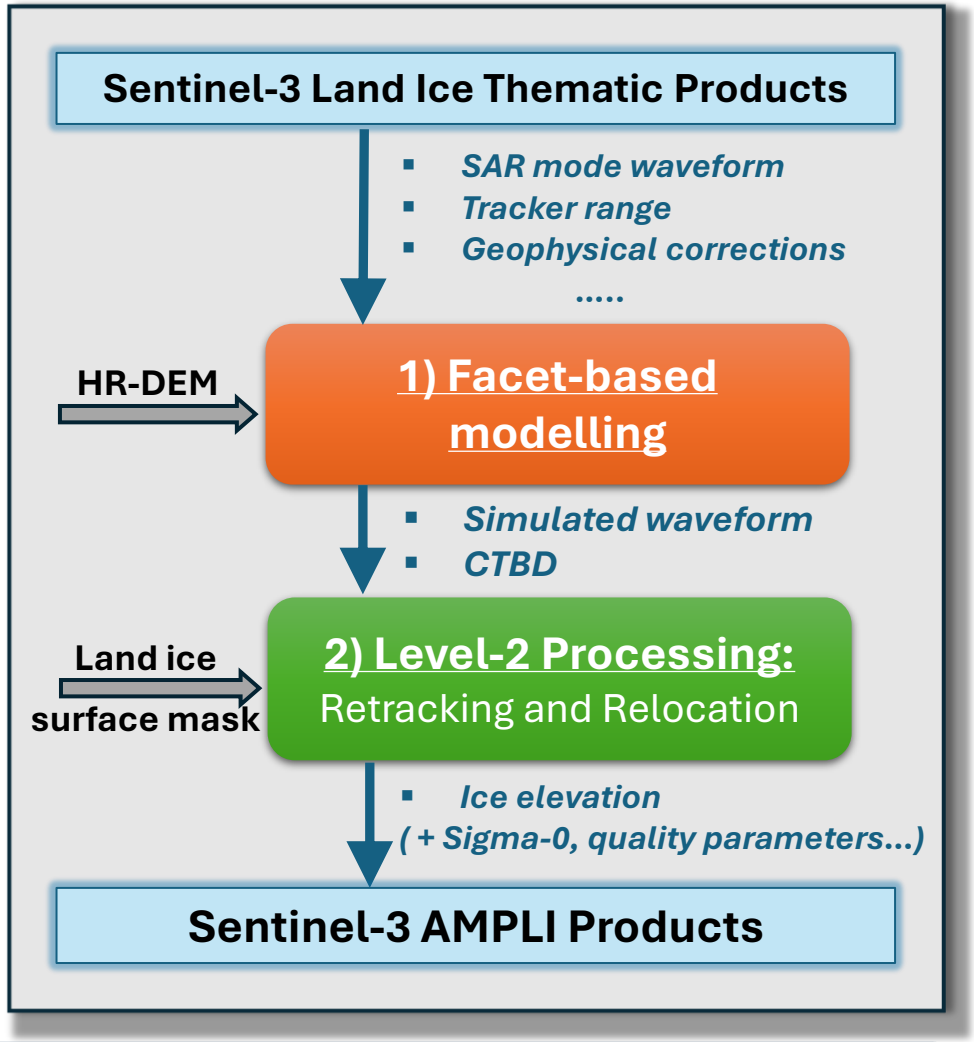
Sentinel-3 AMPLI: overview

The AMPLI software includes two main modules:

1) Facet-based modelling
Through numerical simulation, the model emulates (a) Sentinel-3 UF-SAR waveforms and (b) outputs the histogram of the energy backscattered in the delay-Doppler footprint (the "Cross Track Backscatter Distribution" - **CTBD**).

2) Level-2 Processing
- **Relocation**: To determine the coordinates of the **impact point on-ground,** using outputs from based-based modelling
- **Retracking**: To estimate the altimeter range (i.e. round trip time delay)

AMPLI provides ice topography estimations along the satellite track
(posting rate: ~ 20 Hz / 330 m)



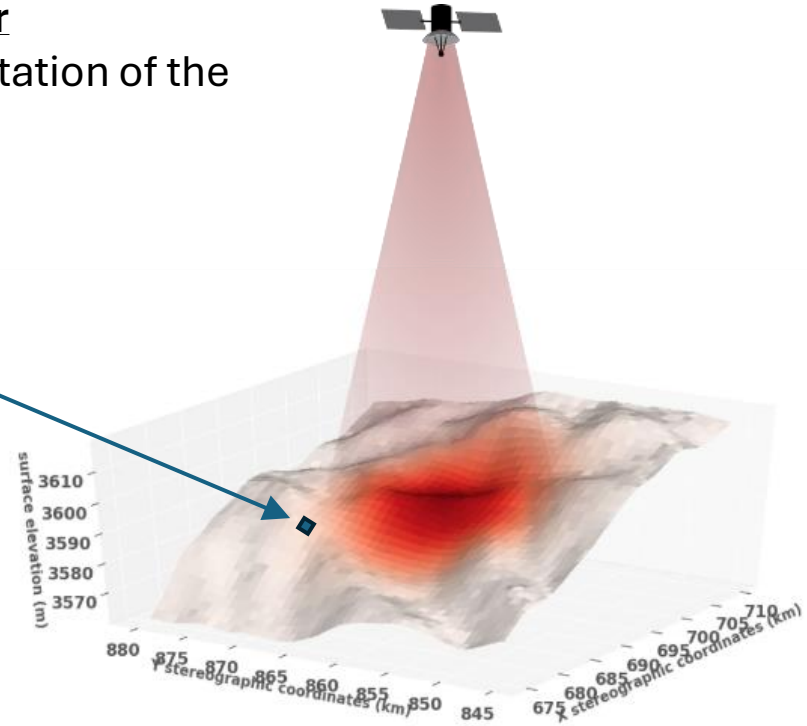
Detailed description available in a preprint in "The Cryosphere": 10.5194/egusphere-2024-1323

AMPLI: Overview of facet-based simulation

➢ **<u>For each 20 Hz location, a 35 km x 35 km DEM* area is extracted around nadir</u>** (~12 millions of DEM facets for a 10 m resolution DEM). For each DEM facet, computation of the energy backscattered by solving the radar equation:

Pe : Emitted power of the antenna (W)
λ_0 : Wavelength (m)
R : Satellite – facet distance (m)
G : Antenna gain (dB)
θ_0: Backscatter coefficient (dB)

$$Pr\,(facet) = Pe\,\frac{\lambda_0^2\,G^2\sigma_0}{(4\pi)^3\,R^4}$$



➢ **Delay-Doppler Maps (DDMs)** are constructed by integrating the energy calculated for millions of DEM's facets, given the facet-satellite distance in **slant range** (range domain), and in **along-track** (Doppler frequency domain).

➢ **The UF-SAR processing is performed,** following as closely as possible ground segment processing (+ some adaptations to speed-up CPU time). **SAR waveforms are finally simulated along the track, at ~330m posting rate.**

At the moment, **the input DEMs are:*

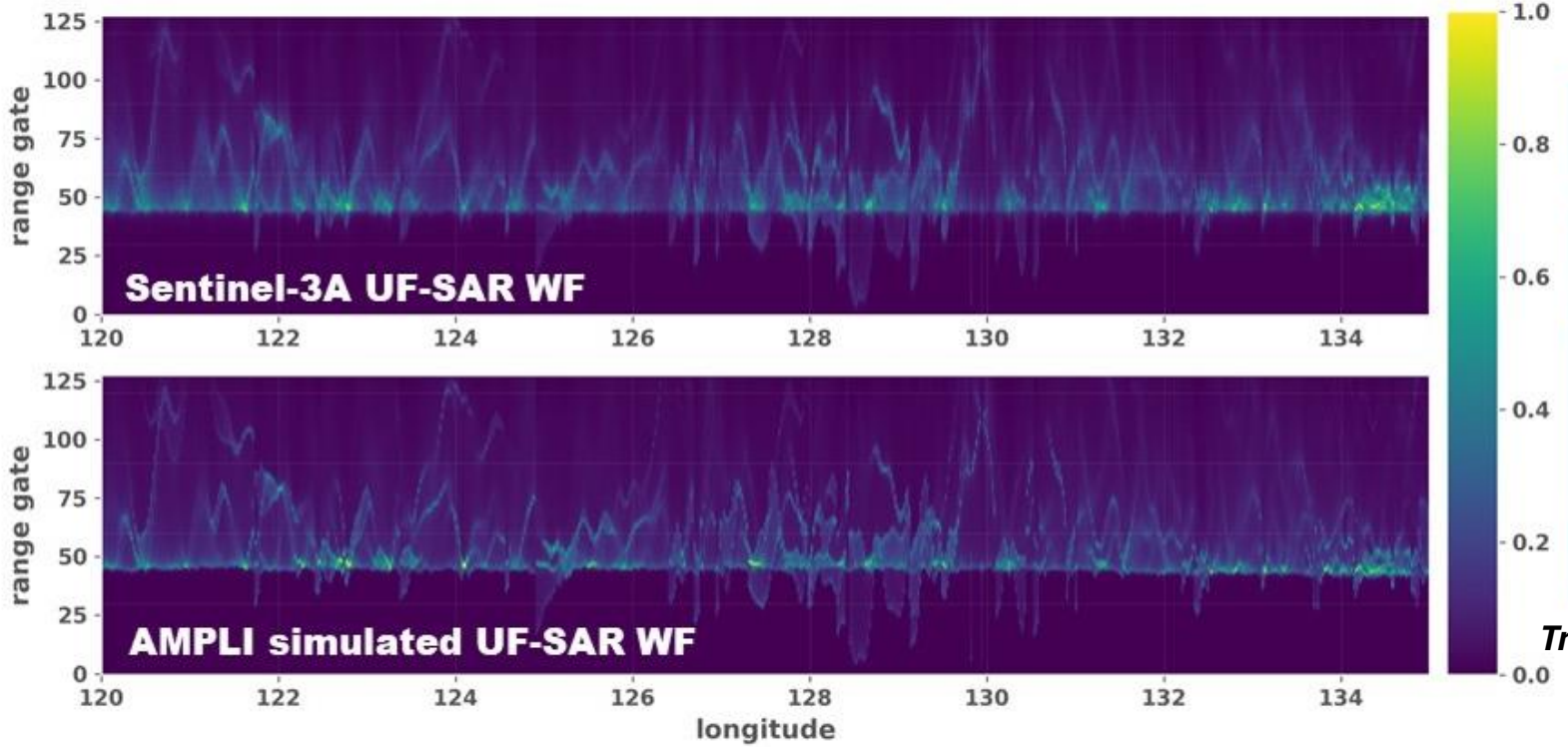
- ❑ *Antarctica: **REMA v2.0** (Howat et al., 2022)*
- ❑ *Greenland : **ArcticDEM v4.1** (Porter et al., 2022)*

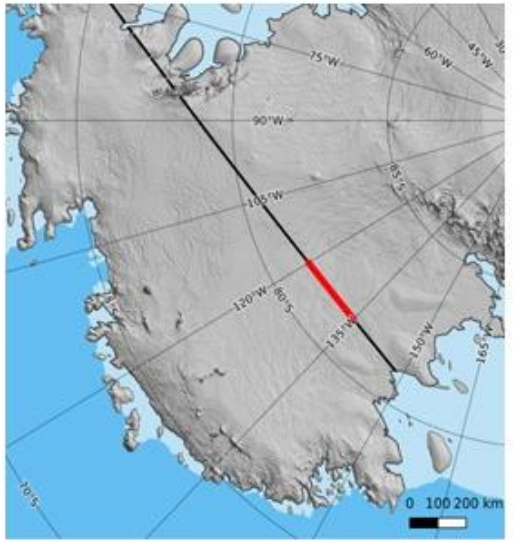
Facet-based simulation: Illustrations

Sentinel-3A UF-SAR waveforms produced by the ESA ground segment processing (top), and simulated with the AMPLI software (bottom)

Ground segment processing

AMPLI facet-based modelling





Track portion of ~ 250 km length located in West Antarctica

Quantitative assessments have been performed over the entire Antarctic ice sheet, showing the overall validity of the modelling

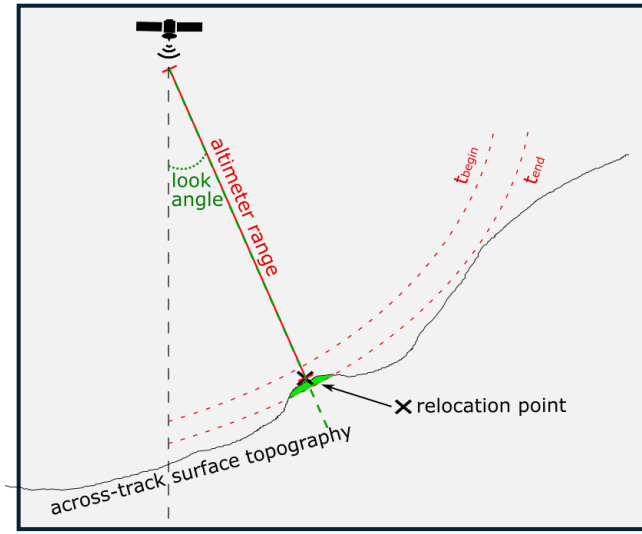
Level-2 relocation processing in a nutshell

1) ***Cross-correlation between real and simulated waveforms.***

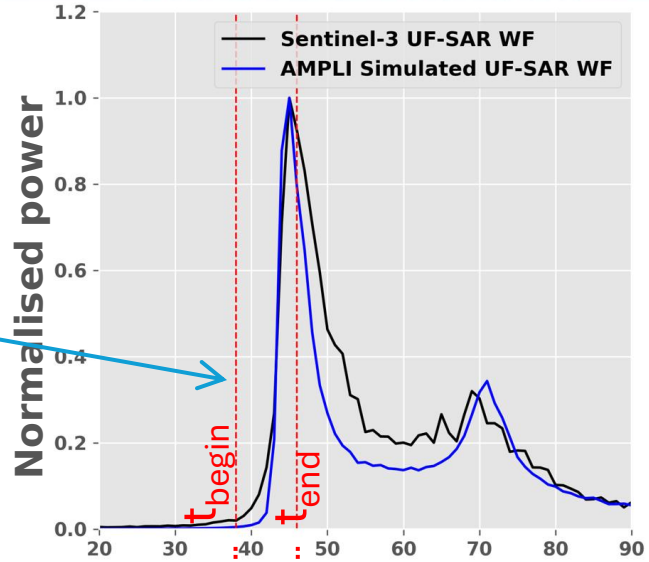
2) ***Identification of waveform (WF) energy peak*** *("t_{begin} / t_{end}")*

3) ***Determination of the cross-track area(s) illuminated*** *by the waveform energy peak ("u_{begin} / u_{end}"), using the outputs from facet-based modelling*

4) ***Estimation of point of first radar return****, a) surface ambiguity resolution by clustering segmentation b) COG computation in the selected cluster to determine the location of impact point on-ground* ***=> look angle estimation***



With both the **look angle** and the **altimeter range**, estimated from a retracking developed for CryoSat-2 SARIn (Aublanc et al., 2021), the topography can be estimated in the cross-track plan



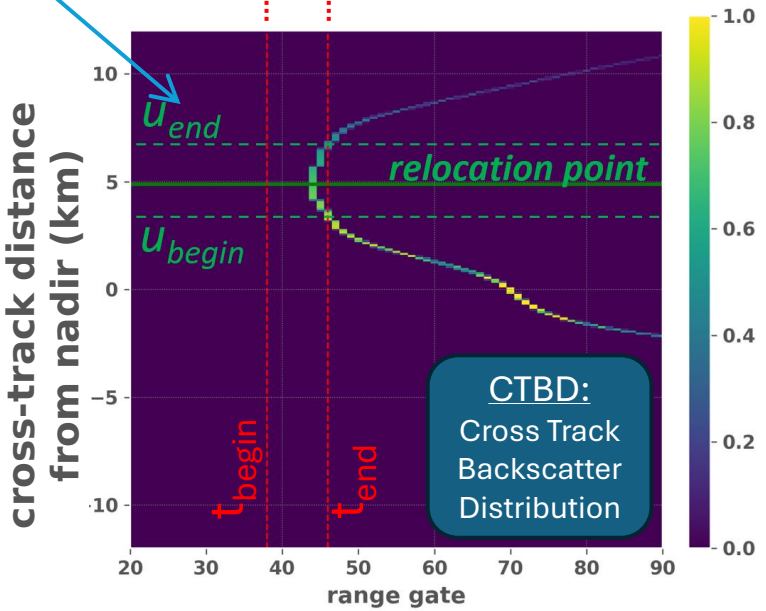
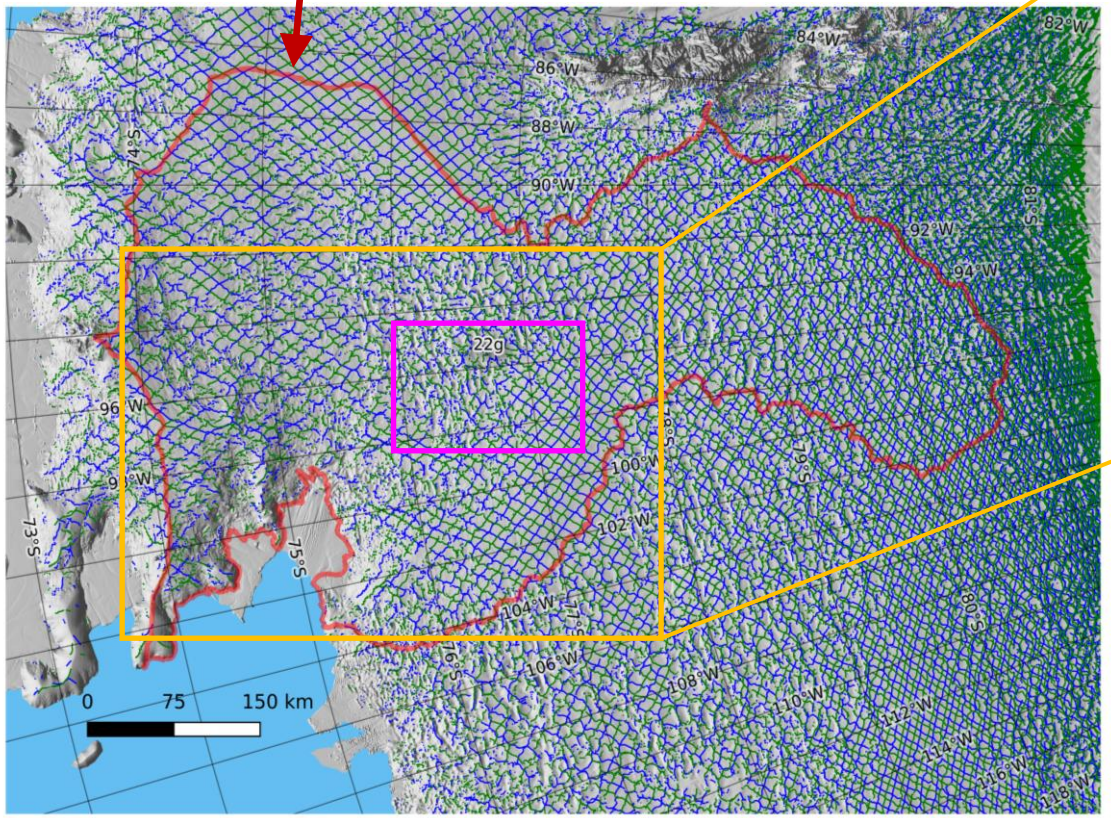
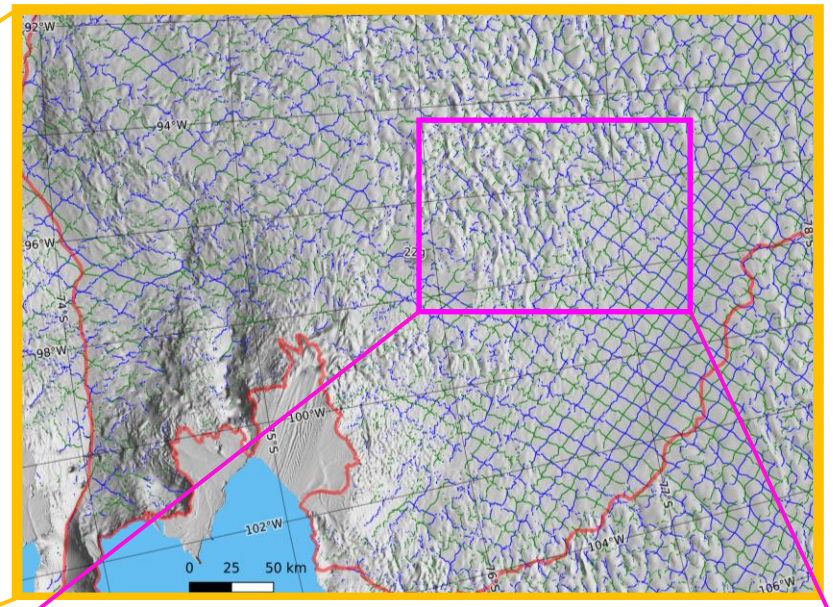
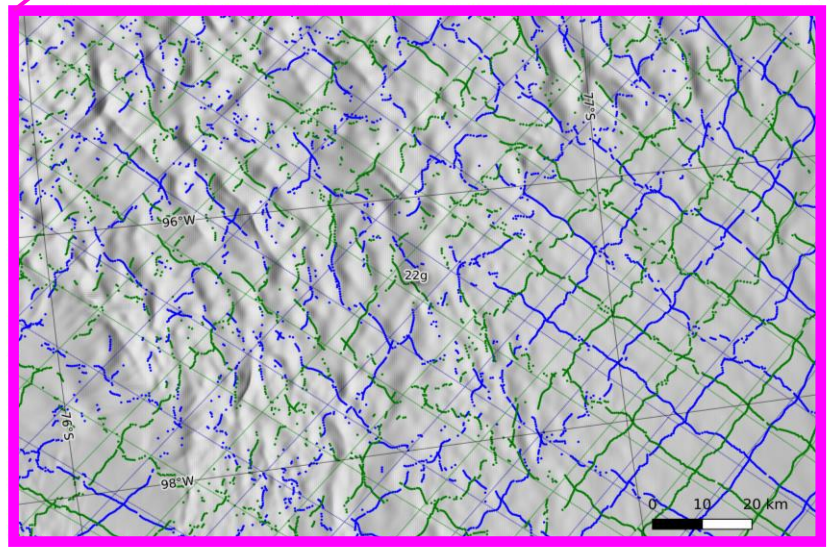


Illustration of data sampling with AMPLI, in West Antarctica

Pine Island drainage basin, *outlined in red*







***Sentinel-3A (green)* and *Sentinel-3B (blue)* relocated coordinates**

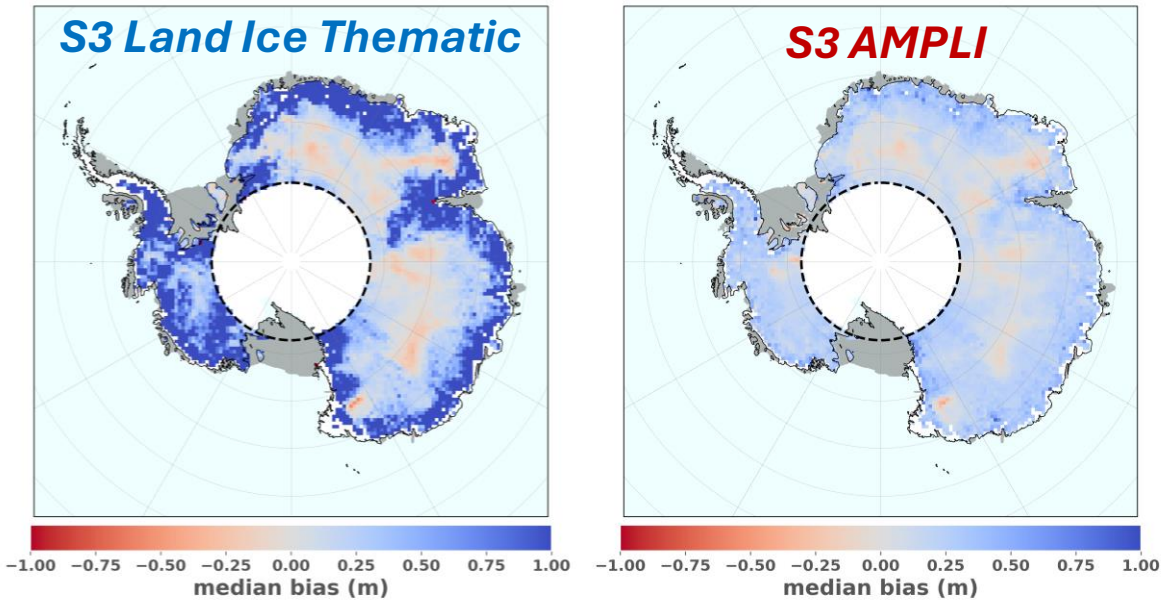
1 orbit cycle of 27 days displayed for both missions (sampling over ice shelves not shown)

AMPLI Performance Evaluation

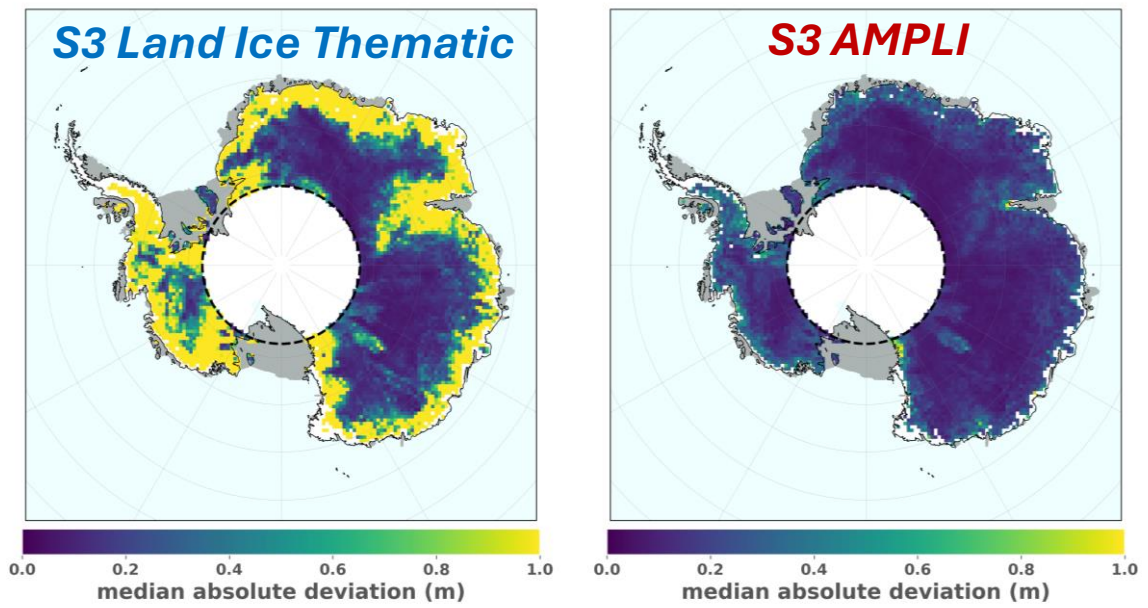
Comparison between **Sentinel-3 A/B** and **ICESat-2 ATL06** elevations at nearly co-located points

(25 m search radius; 46 days maximum between acquisitions; 1,750 millions of co-located points found in May-August 2019)

Median elevation bias between Sentinel-3 (S3) and IS2



Median Absolute Deviation (MAD) between S3 and IS2



With AMPLI, substantial improvements compared to ESA Land Ice Thematic Products

- ❖ *Especially over the ice margins (precision improved by a factor of ~10)*
- ❖ *Spatial patterns in the ice sheet interiors discussed in the perspectives*

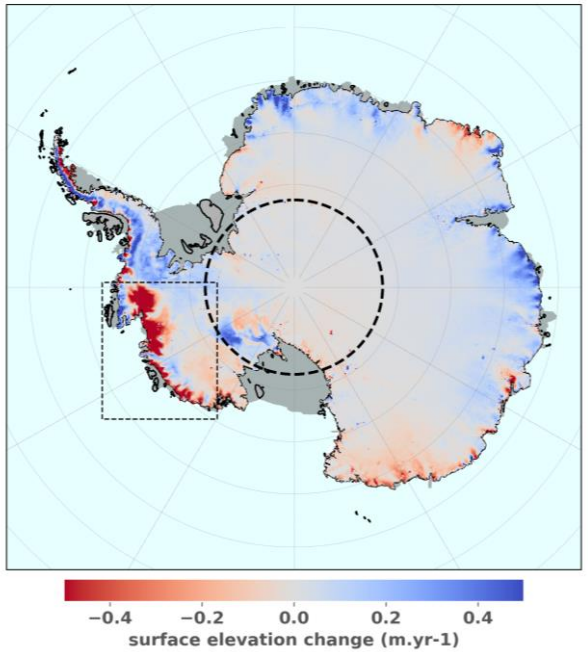
AMPLI Performance Evaluation

Surface Elevation Change (SEC) of the Antarctic ice sheet, in the 2019-2022 period (10 km grid)

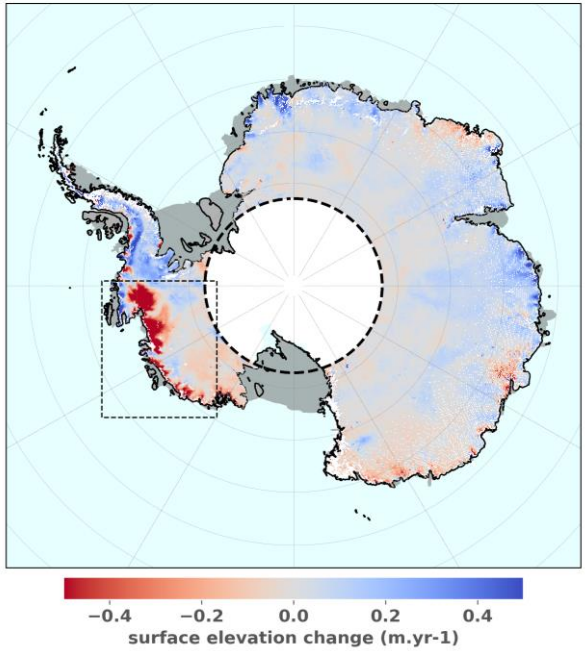
Read from the **ICESat-2 ATL15** product

Estimated in the frame of this study with **Sentinel-3A** and **Sentinel-3B** *(4 orbit cycles in Summer 2019 and Summer 2022)*

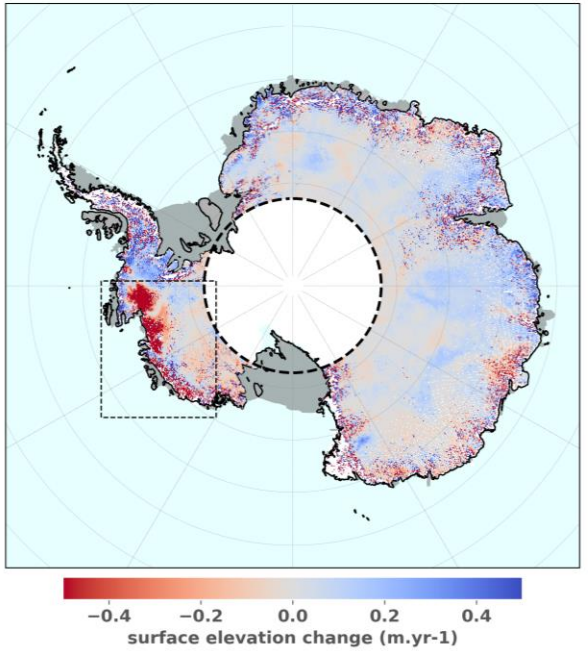
ICESAt-2 ATL15 v003



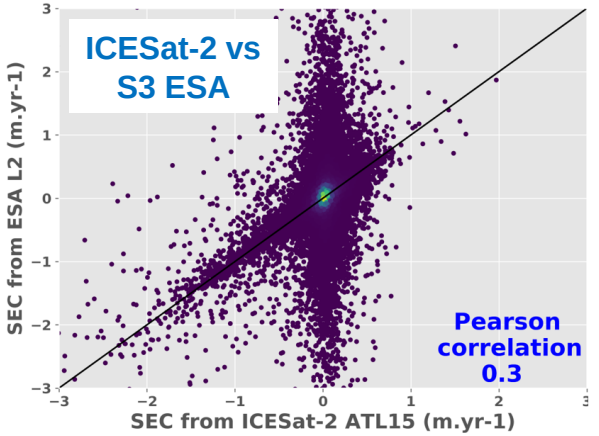
Sentinel-3 AMPLI

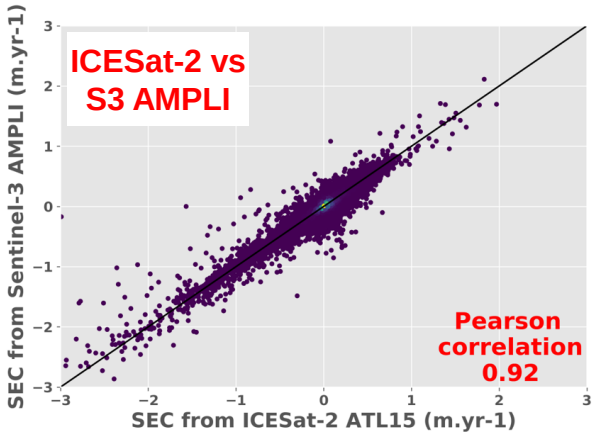


Sentinel-3 ESA Land Ice Thematic



Scatter plots of the map grid point differences (IS2 vs S3)

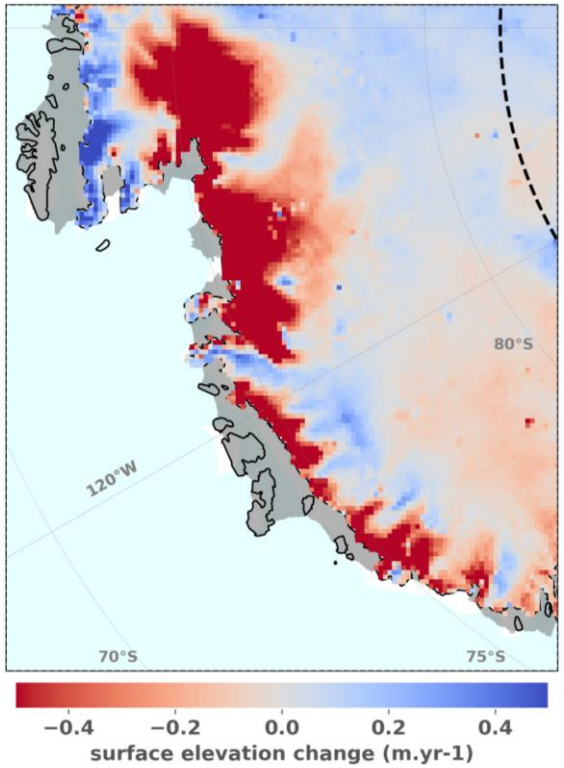




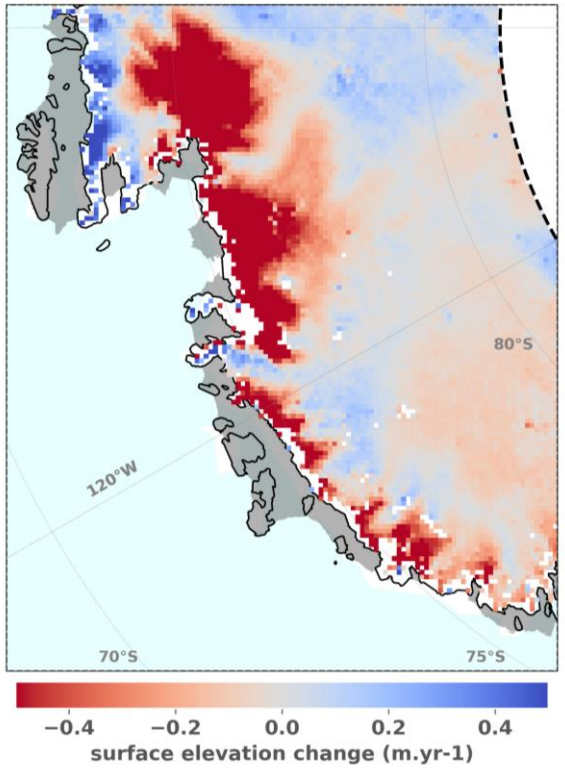
Surface Elevation Change (SEC) of the Antarctic ice sheet, in the 2019-2022 period (10 km grid)

Zoom over West Antarctica

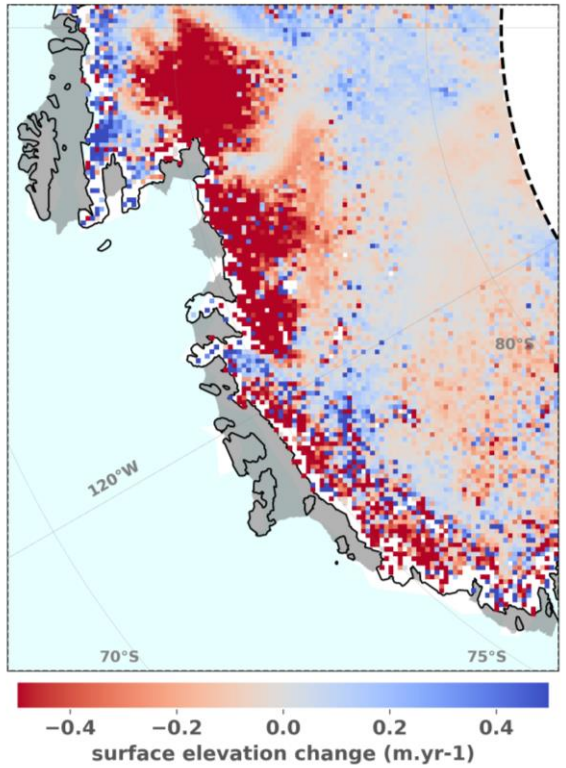
ICESAt-2 ATL15 v003



Sentinel-3 AMPLI



Sentinel-3 ESA Land Ice Thematic Products



Conclusions

Key messages

- **AMPLI is a processing chain dedicated (for the moment) to Sentinel-3 land ice altimetry that:**
  - Starting from ESA Thematic Products data, simulates SAR mode waveforms using facet-based simulation over HR-DEM
  - Use the numerical simulation to relocate the measurement at the impact point on-ground

- **In the along-track "surface elevation"**, AMPLI outperforms the ground segment processing. The improvement is substantial over the ice sheet margins *(precision improved by a factor of ~10 where slope is > 0.5°)*.

- **In the gridded "Surface Elevation Change" (SEC)**, first promising results showing that Sentinel-3 has the capability to monitor the changes over Antarctica in close agreement with ICESat-2. Where Sentinel-3 data are available, there is a **0.92 Pearson Correlation** between S3 AMPLI and IS2 ATLA5 SEC map grid points.

- **The developed method has several advantages**. In particular:
  - the measurement is relocated in the actual surface sampled (connection between retracking and relocation)
  - it can handle surface ambiguities (when distinct on-ground areas are sampled by the radar waveform).
  - it is theoretically weakly affected by vertical offset/error in the input HR-DEM

Sentinel-3 AMPLI Demonstration Products

Full Reprocessing of Sentinel-3 A/B missions with AMPLI

Sentinel-3 "AMPLI Demonstration Products" … **coming soon => Q4 2024 !**

- **The complete Sentinel-3A and Sentinel-3B time series are being reprocessed with AMPLI**
  2016-2024 data set: *Antarctica + Greenland*
- **Relatively "light" user-friendly Products,** inspired from ESA CryoTempo project
- **Greenland reprocessing is already finished !** First promising results in Surface Elevation Change.

Data will be available in the ESA CDSE

https://browser.dataspace.copernicus.eu

contact: jaublanc@groupcls.com

Acknowledgements to CNES*, for making available their computational cluster (mandatory for solving CPU time constraints)*

Priorities for future improvements

This is only the start for Sentinel-3 AMPLI:
the algorithms can (and will) evolve and improve !

- **On-going study funded by ESTEC, to characterise (and correct?) for snow volume scattering** (i.e. Ku-band radar wave penetration into the snowpack). This effect likely explains the spatial variation of the bias between S3 AMPLI and ICESat-2 ATL06, visible in the ice sheet interior (~decimetre level variations)

- **Improvement of detection of (rare) modelling errors, using deep or machine learning**
  - To better flag cases for which there were heterogeneous temporal variations of surface elevation between static DEM and altimetry data acquisition.
  - For successfully monitoring regions undergoing rapid elevation changes (> ~2 m/yr) over a long period.

- **Improvement of facet-based modelling, by integrating the snow volume scattering effect**. This can be done by continuing the work done made by IGE with SMRT, supported by CLS (Larue et al., 2021)

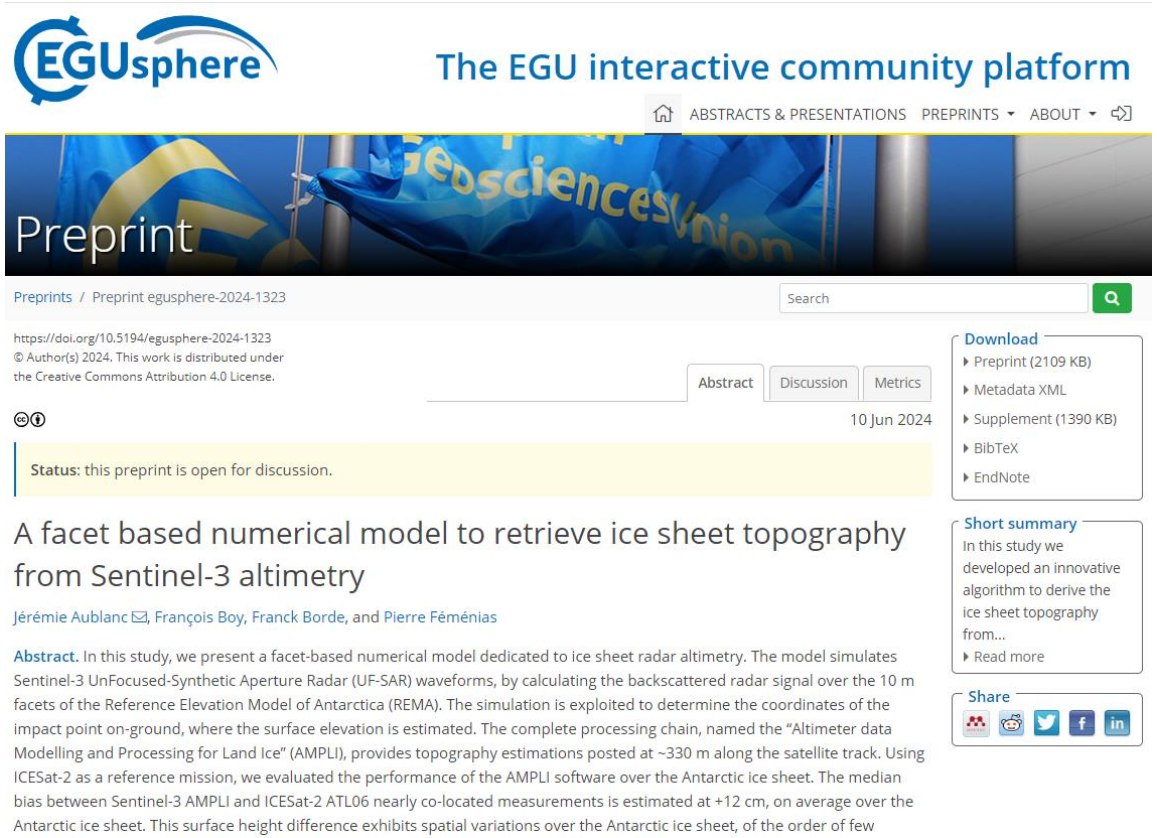
- **Data processing and evaluation over ice caps and glaciers.** Promising results were recently obtained over Svalbard, as shown by the Norwegian Polar Institute (NPI)

- **Adaptations to LRM altimetry** => *On-going in the frame of ESA FDR4ALT project*

- ....

Thank you !
Any questions ?

More information in “The Cryosphere” (preprint)
10.5194/egusphere-2024-1323



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Abstract Discussion Metrics

10 Jun 2024

Status: this preprint is open for discussion.

A facet based numerical model to retrieve ice sheet topography from Sentinel-3 altimetry

Jérémie Aublanc, François Boy, Franck Borde, and Pierre Féménias

Abstract. In this study, we present a facet-based numerical model dedicated to ice sheet radar altimetry. The model simulates Sentinel-3 UnFocused-Synthetic Aperture Radar (UF-SAR) waveforms, by calculating the backscattered radar signal over the 10 m facets of the Reference Elevation Model of Antarctica (REMA). The simulation is exploited to determine the coordinates of the impact point on-ground, where the surface elevation is estimated. The complete processing chain, named the “Altimeter data Modelling and Processing for Land Ice” (AMPLI), provides topography estimations posted at ~330 m along the satellite track. Using ICESat-2 as a reference mission, we evaluated the performance of the AMPLI software over the Antarctic ice sheet. The median bias between Sentinel-3 AMPLI and ICESat-2 ATL06 nearly co-located measurements is estimated at +12 cm, on average over the Antarctic ice sheet. This surface height difference exhibits spatial variations over the Antarctic ice sheet, of the order of few

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Short summary
In this study we developed an innovative algorithm to derive the ice sheet topography from...
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BACK-UP

Illustration of relocation made with AMPLI

AMPLI Relocation processing illustrated

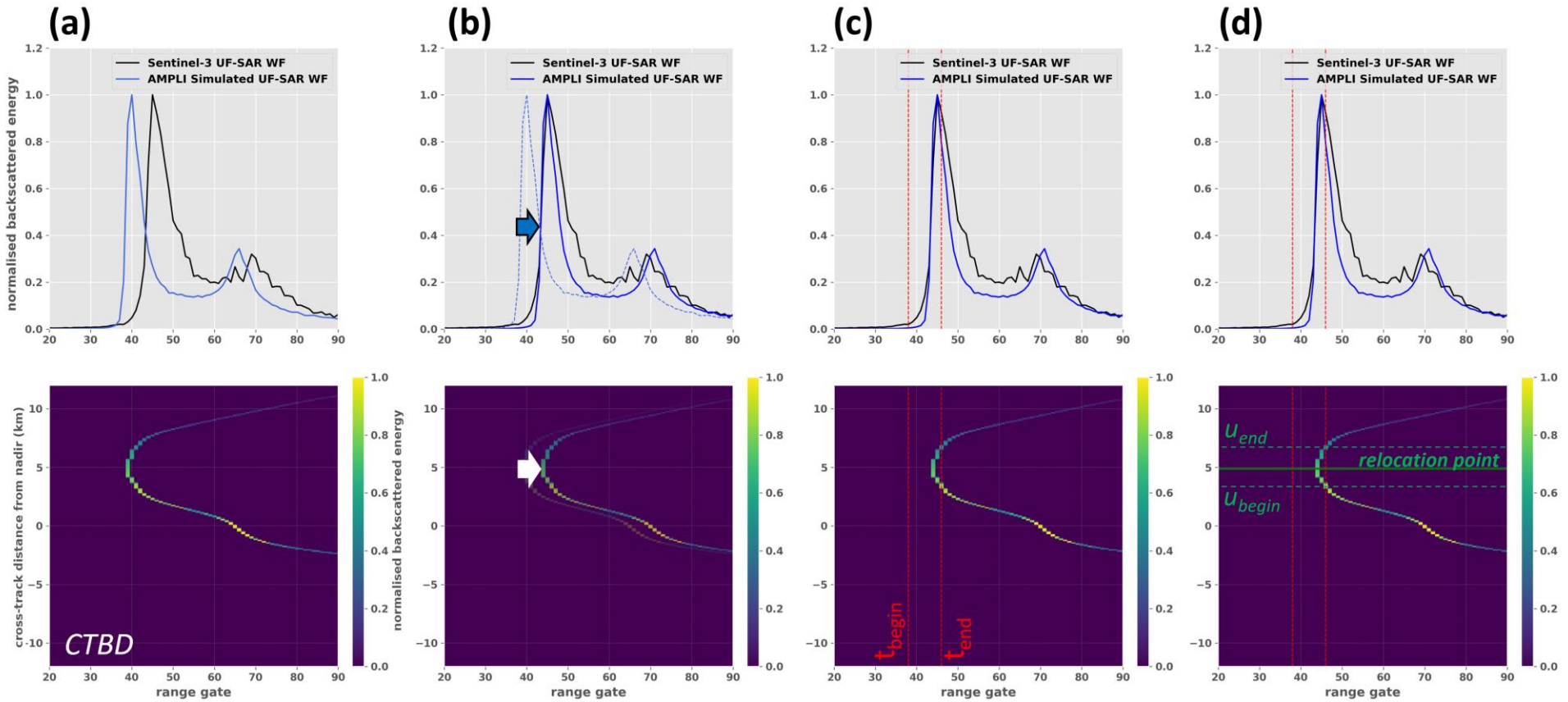

Illustration of relocation made with AMPLI

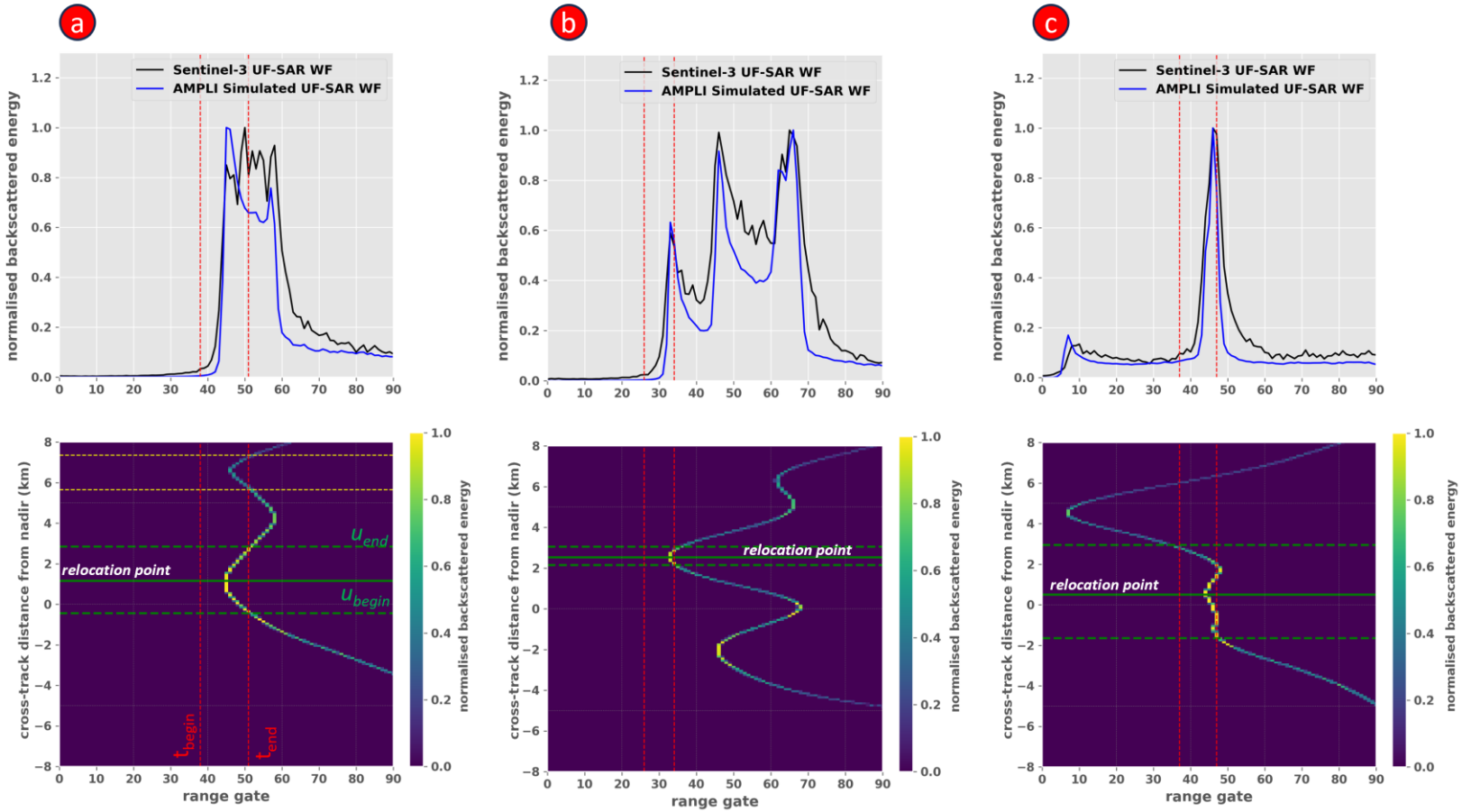

Illustration of the relocation method implemented in the AMPLI software, for three case studies (a, b, c). Sentinel-3A UF-SAR waveforms (black) and AMPLI simulated waveforms (blue) are displayed in the top panels. The corresponding AMPLI Cross Track Backscatter Distributions (CTBD) are displayed in the bottom panels. Red dotted lines indicate the start and stop indexes of the waveform leading edge, as identified by the retracker. Solid dotted lines indicate the centre of gravity of the cluster, where the measurement is relocated. In the cases of (a) and (b), yellow dotted lines indicate the location of an ambiguous cluster.

Key links and other projects

Sentinel-3 related

- **Results presented in this talk were submitted in "The Cryosphere"** (under review)
https://egusphere.copernicus.org/preprints/2024/egusphere-2024-1323/
- **Sentinel-3 SRAL/MWR Land User Handbook** (documenting Sentinel-3 characteristics + ground segment processing)
https://sentiwiki.copernicus.eu/web/document-library#DocumentLibrary-TechnicalDocumentLibrary-S3-SRAL-TD
- Release of **Sentinel-3 AMPLI Demonstration Products** + a dedicated handbook
=> coming soon: Q3/Q4 2024....

Facet-based modelling used in other projects

- **ESA "FDR4ALT Follow-On"** => On-going adaptations to LRM altimetry. Goal is to reprocess Envisat / ERS / AltiKa missions (project presented by F.Piras, session 8.2).
- **ESA "CRISTAL OLTC"** => CLS leads an ESA project for generating the CRISTAL Open Loop Tracking Commands (OLTC). Over land ice, CLS is responsible for defining these tracking commands, with support of facet-based modelling for some areas.
- **ESA "CLEV2ER"** => Simulation of UF-SAR waveforms in Ku and Ka bands with CRISTAL configuration. Scope is to analyse differences in shape between Ku and Ka waveforms, due to terrain characteristics, to anticipate where the measurements will be co-located.
- **Perspectives for CryoSat-2 SARIn ?** (a) the Sentinel-3 study related to volume scattering correction will likely be useful for CS-2 SARIn data. (b) for reducing errors due to surface ambiguities ... *(there is no official contract or study engaged yet)*