On-going studies to improve the Sentinel-3 performances over land ice

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Introduction

- **Sentinel-3A (launched in Feb. 2016) and Sentinel-3B (launched in April 2018) are continuously monitoring the polar ice sheets for several years now**. The two missions were the first ones embarking an altimeter (SIRAL) operating exclusively in SAR mode.

- **Benefits of SAR altimetry against conventional Low Resolution Mode (LRM) over land ice were demonstrated in previous studies** *(for instance, in Aublanc et al., 2018; McMillan et al., 2018; McMillan et al., 2019).* Among the added-value of SAR altimetry, the slope-induced errors (or relocation errors) are lowered thanks to the reduced along-track footprint.

- **Nevertheless, the relocation errors still represent the largest source of uncertainties over the polar ice sheets margins**. In addition, the coverage of the polar ice sheets margins is not optimal because the Sentinel-3 closed-loop tracker is not capable to follow the rapid changes of surface topography.

- The availability of **new high resolution DEM (~10m)**, almost entirely covering the Antarctica and Greenland continents (REMA / ArcticDEM), opens new perspectives to address these issues.

Plan

1) Introduction: Sentinel-3 data quality over Antarctica
Current status and open issues

2) The CLS Ice Sheet Simulator (ISS)
A facet-based simulator coupled with high resolution DEM, to model Sentinel-3 waveforms over land ice

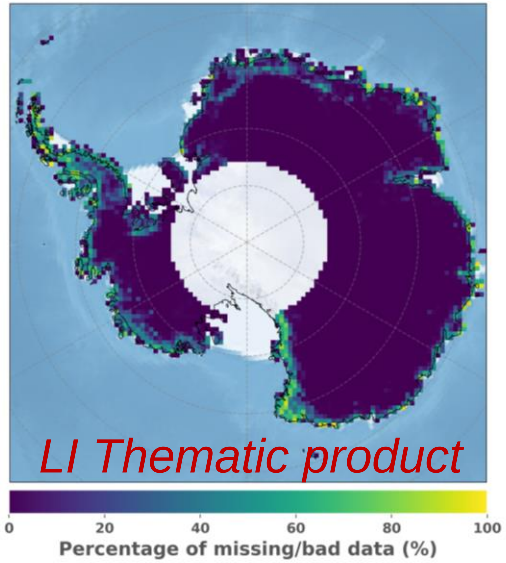
3) A new relocation method for land ice acquisitions, based on numerical simulations
Methodology and first results

4) Definition of new Open Loop Tracking Commands (OLTC)
Presentation of a first methodology to improve the data coverage over the ice margins

Antarctica Sentinel-3A measurements were assessed in terms of:

- **Missing data,** when the altimeter looses the useful signal, and shifts from measurement to acquisition mode
- **Low SNR**, using a backscatter coefficient derived from waveform maximum power
- **Invalid waveforms,** using the "waveform quality flag" available in the ESA L2 products

	1) Missing data	2) low SNR	3) Invalid waveforms	Total of lost/useless data
Current ESA LAND products	2.47%	3.22%	6.33%	= 9.09%
ESA Land ice thematic products		1.62%	2.05%	= 4.76%



With the current closed-configuration, and the current operational products, **~9% of the data are lost or useless over the Antarctic ice sheet** (mostly in the margins)

~4.5% of the data are recovered thanks to the delay-Doppler processing with extended window *(Aublanc et al., 2018)* implemented in the Land Ice Thematic IPF that will be deployed in Q2 2023

Sentinel-3 data quality over Antarctica

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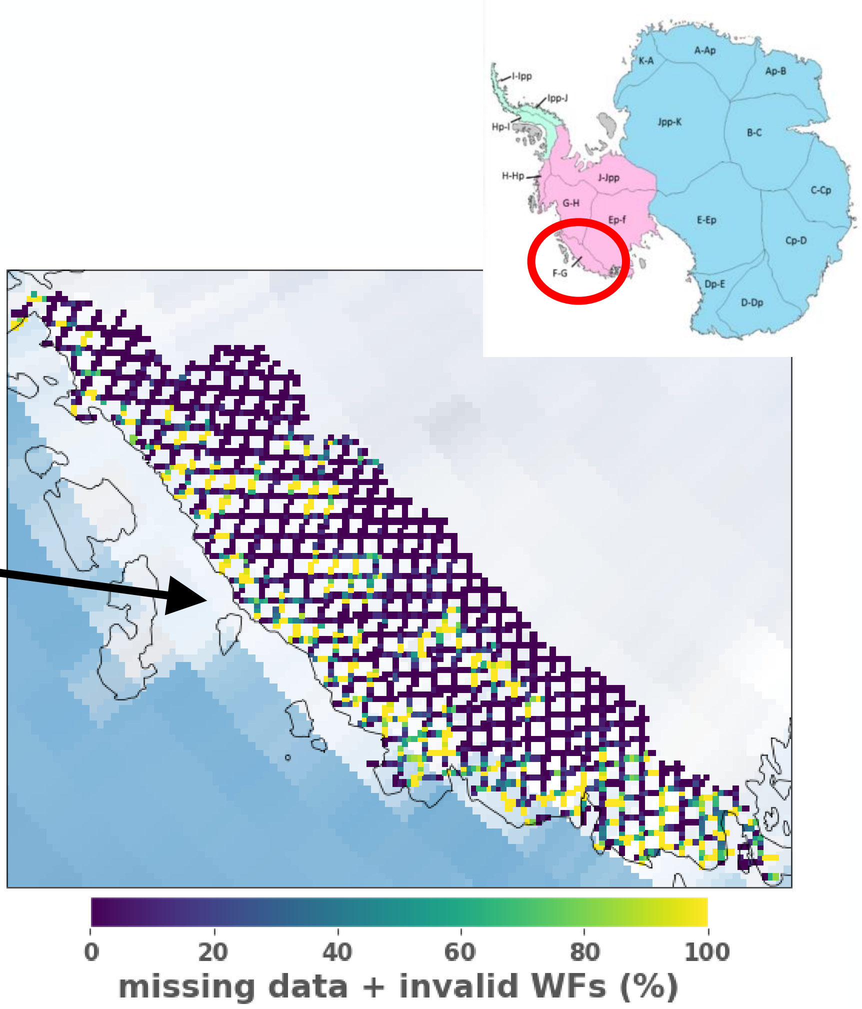
Main conclusions

- With the upcoming Land Ice Thematic products, **~95% of Sentinel-3 data acquired over the Antarctic ice sheet should be suitable/usable for a topography estimation => <u>clearly a positive result !</u>**

- Nevertheless, **a relatively large ratio of measurements are either missing or useless over the Antarctica margins**, where the most important topography changes are occurring. For instance, over Getz drainage basin, ~12 % of the measurements are missing and ~10% can be considered of bad quality.

- In addition, **the relocation method implemented in the ESA processor** (using slope models precomputed from DEMs) **is not adapted for the measurements acquired over irregular and complex surfaces**, as encountered over the ice margins.



To address the current issues observed with Sentinel-3 over the polar ice sheets margins, ESA is funding dedicated studies: **“the SRAL processing studies over land ice”**

3 main tasks in 2022:

1) Ice margins tracking challenge*: Analysis of technical feasibility and new methodology to define Open Loop Tracking Command (OLTC) over Antarctica ice margins areas*

2) Improvement of level-2 relocation processing*: Main source of errors over land ice are induced by the surface slope/topography. Objective was to defined new relocation method to reduce these errors*

3) Assessment of Sentinel-3 data over glaciers*: New OLTC were defined over different glacier areas, objective was to assess the data quality, in terms of 1) Radar waveforms quality 2) Surface elevation*

The talk is mainly dedicated to the new relocation processing (task 2), but promising results were also obtained in the two other tasks

2) The CLS Ice Sheet Simulator (ISS)

A facet-based simulator coupled with high resolution DEM, to model Sentinel-3 waveforms over land ice

The CLS Ice Sheet Simulator (ISS): presentation

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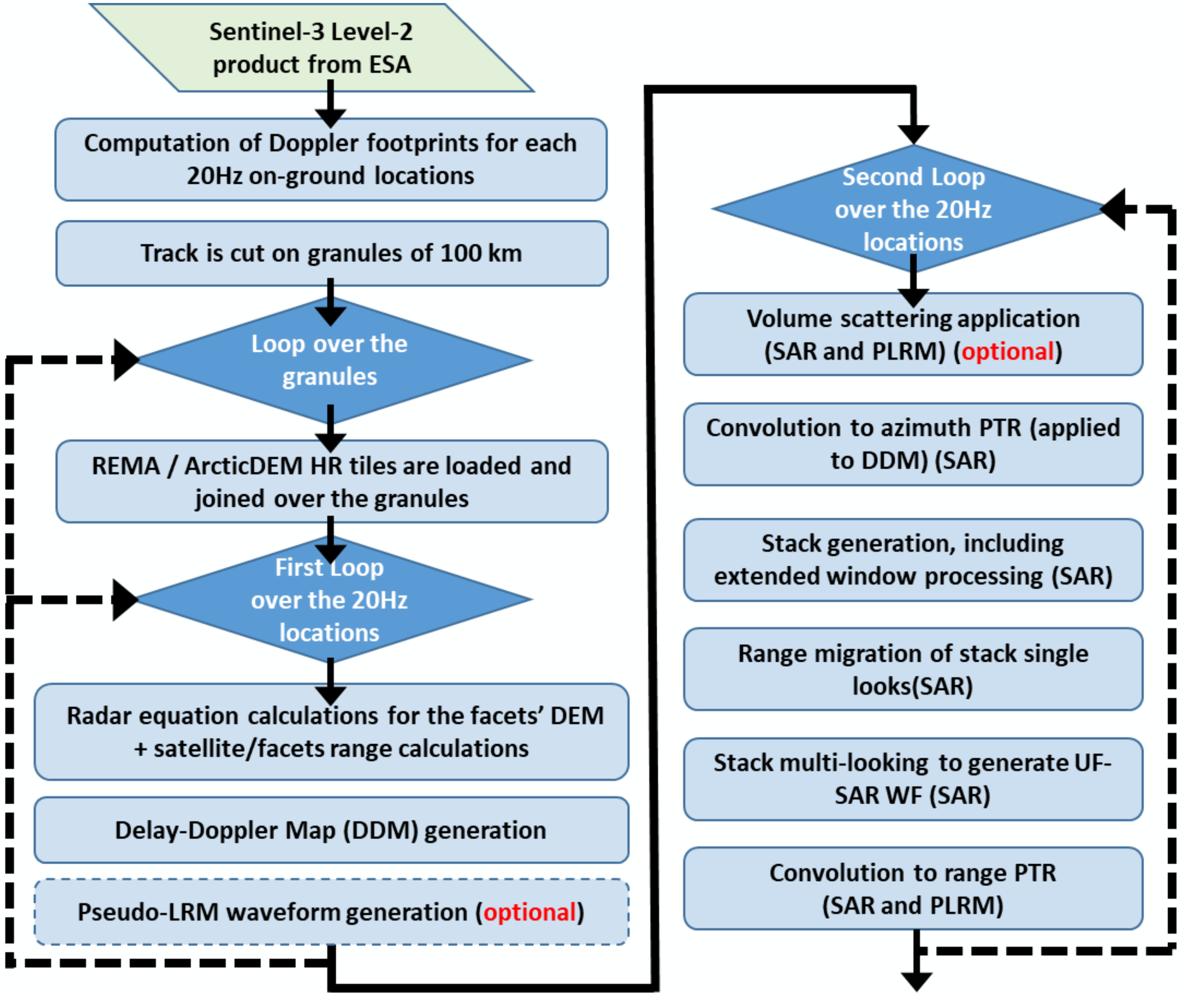
These studies were performed using the **Ice Sheet Simulator (ISS)** developed at CLS

=> a facet-based simulator, exploiting the High Resolution of new ice sheet DEM (REMA, 8 m resolution) to reproduce the altimetry waveforms in Ku/Ka and LRM/SAR

In the frame of the "2022 SRAL processing studies over land ice", the ISS was improved:

- *Simulation over very large window (for defining new OLTC)*
- *A new relocation method*
- *Integration into an end-to-end processing, from simulation to level-2 (see next slide)*
- *+ other improvements in the data modelling*

ISS general flow chart

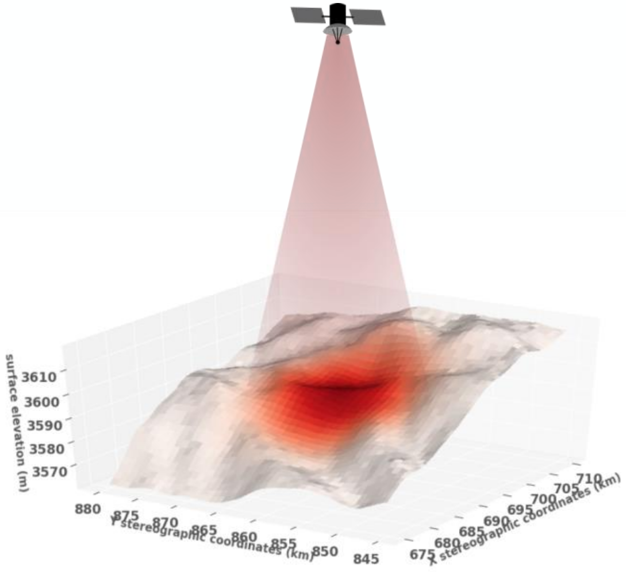


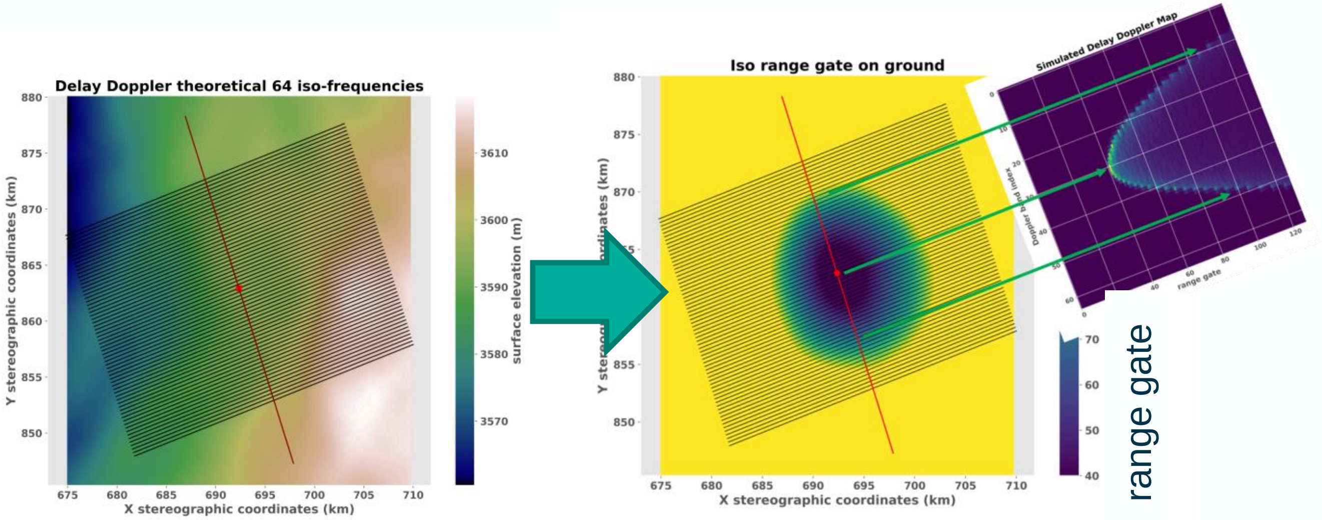
The CLS Ice Sheet Simulator (ISS): illustration

<u>For each 20 Hz measurements, a 35 km x 35 km DEM area is extracted around nadir</u> (~19 million of DEM facets at 8 m resolution). For each DEM facets, computation of the energy backscattered by solving the radar equation:

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

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)*



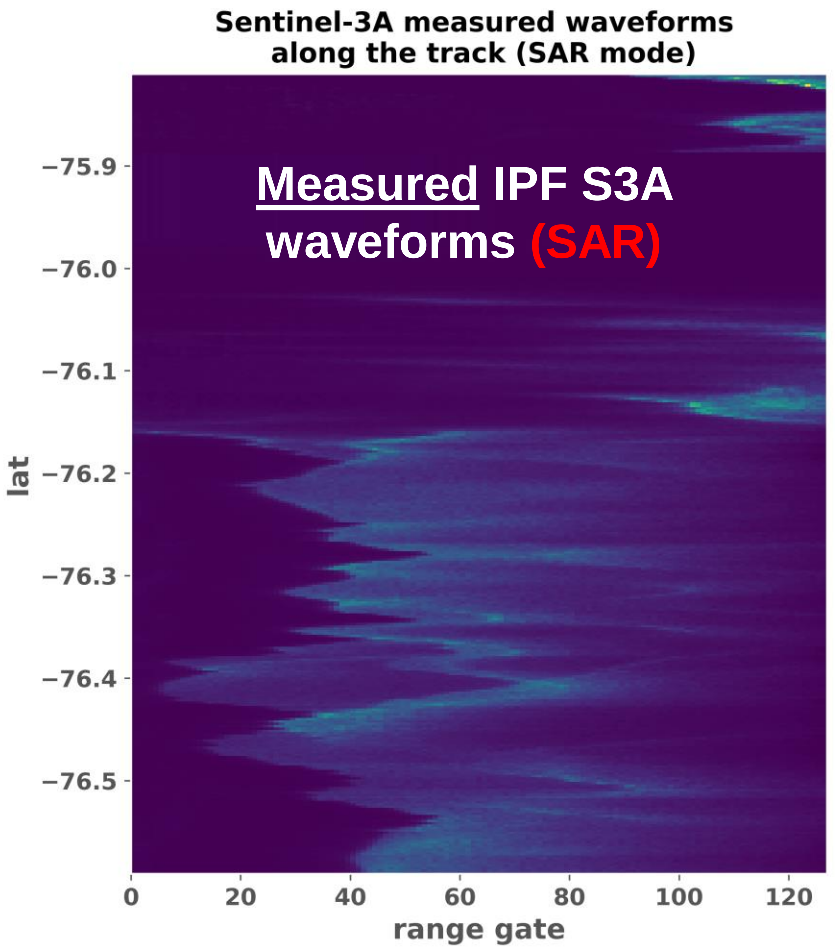


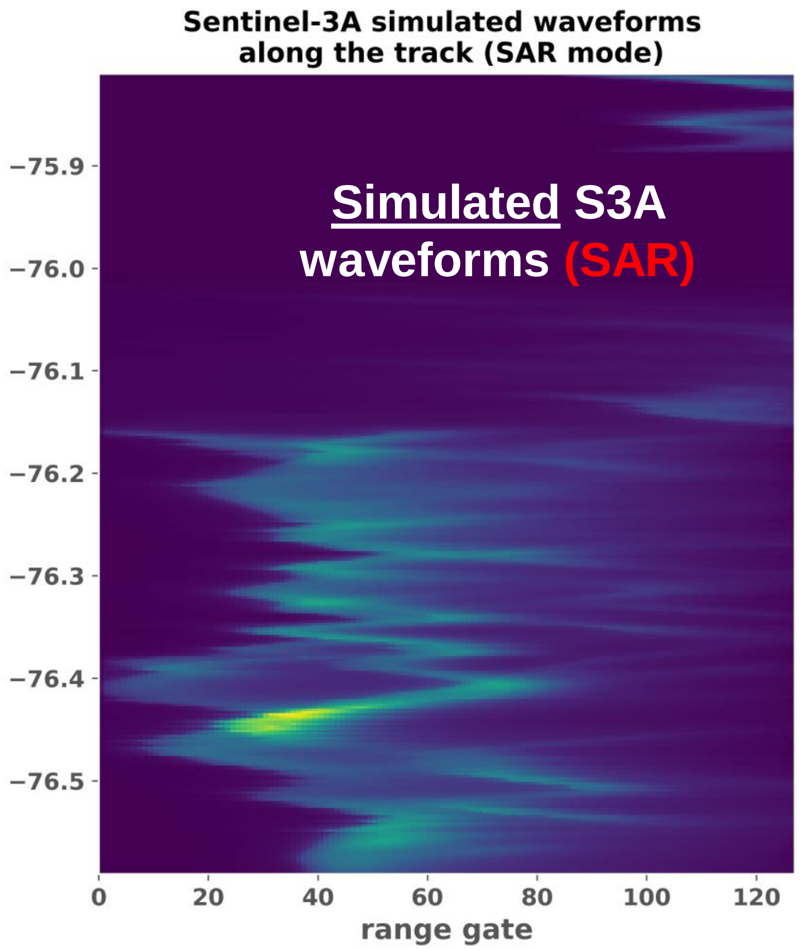
From HR DEM information, the corresponding iso range matrix is computed. Using this information with backscattered energy, the DDM are reproduced.

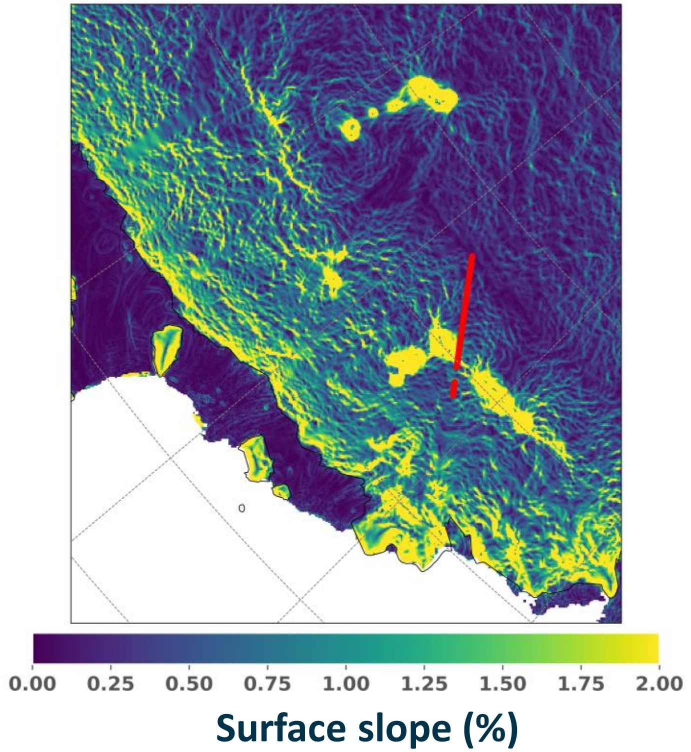
Using this backscattered energy, along with range and Doppler frequency of the facets, the **Delay-Doppler maps (DDM) are generated** (at 20 Hz rate)

From these DDM, simulated at different look angles, the delay-Doppler stack are generated (same "architecture" as S3 IPF). After range migrations and multi-looking (+ other operations, see flow chart) the simulated SAR waveforms are finally available.

Radargrams over Getz drainage basin (Sentinel-3A, track 7)







The CLS Ice Sheet Simulator (ISS): radargrams over the margins

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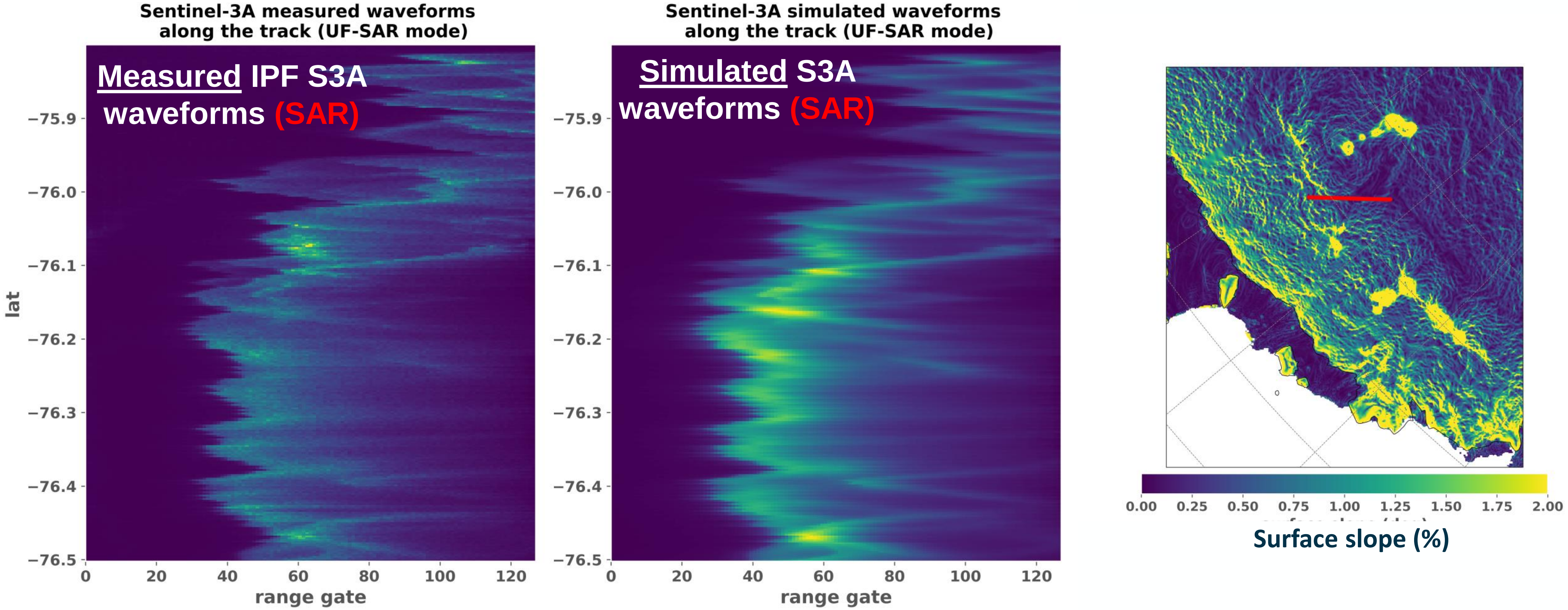
Radargrams over Getz drainage basin (Sentinel-3A, track 11)



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The CLS Ice Sheet Simulator (ISS): evaluation over Getz drainage basin

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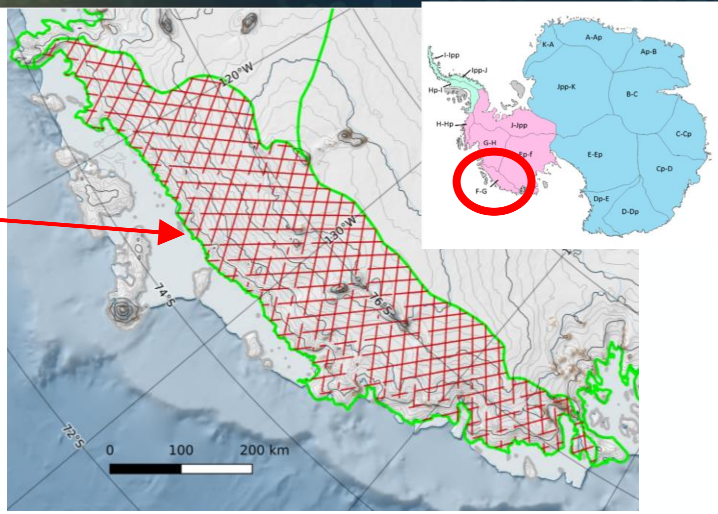
The simulator was evaluated over the Antarctica margins, in the Getz drainage basin

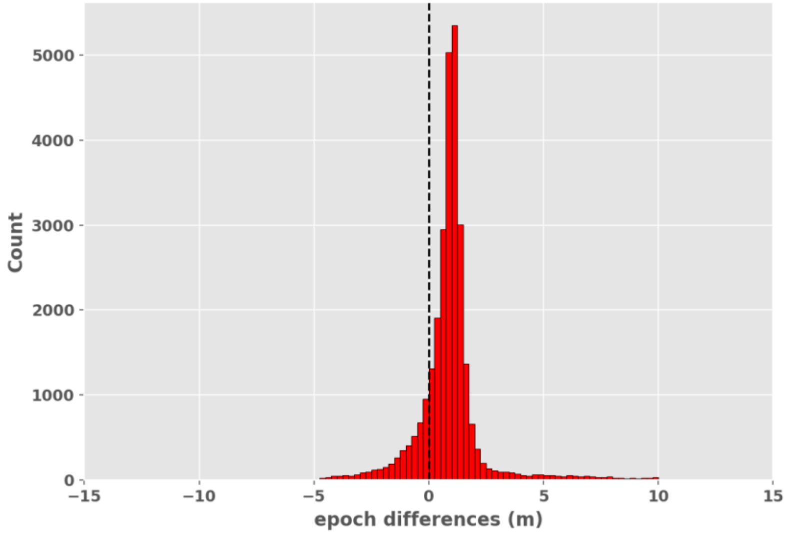
*over **33 572** Sentinel-3A 20 Hz measurements acquired in 1 cycle (in red color)*



Range comparison: **Using OCOG/ICE-1 retracker,** we compared the leading edge position of the simulated and “real” Sentinel-3 waveforms**:**

- **88.7%** of the measurements are in a **2 meters agreement**
- **96.2%** of the measurements are in a **5 meters agreement**
- **98.6%** of the measurements are in a **10 meters agreement**

Histogram of epoch differences between data/simulation from OCOG/ICE-1



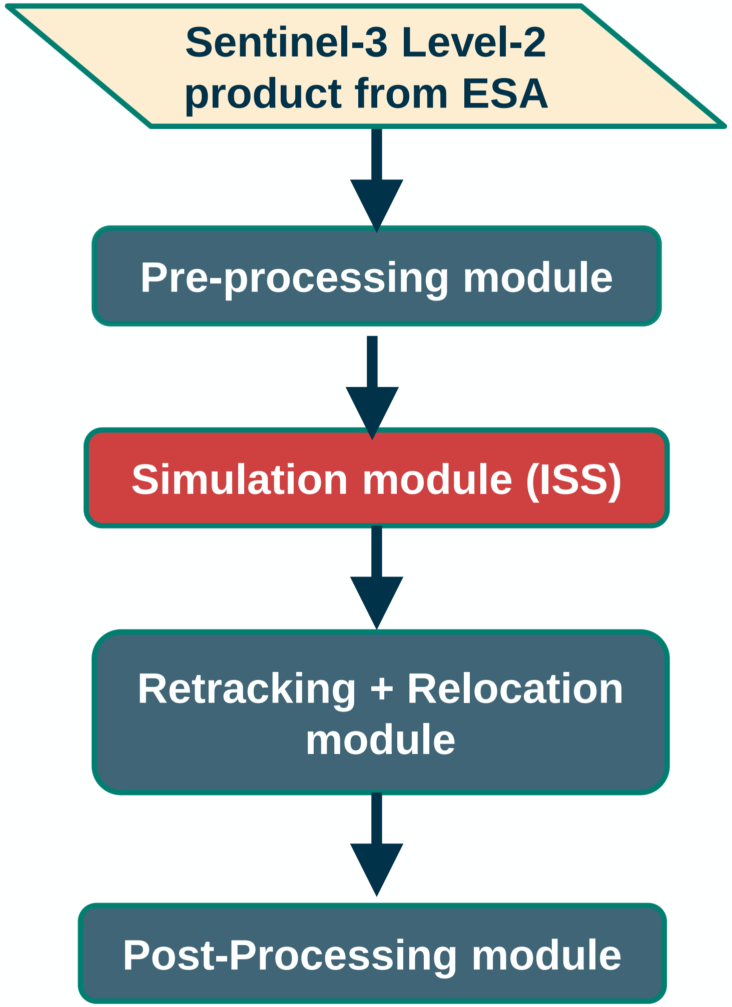
In addition to modelling approximations, biases can be explained by:

- *Surface elevation change between altimetry data (2020) and REMA (2015-2016)*
- *A bias/offset in REMA, as shown in Howat et al. (2019)*

Sigma-0 comparison: **Median Absolute Deviation (MAD) between Sigma-0 from data and simulation is around 2 dB => Good overall agreement**

(except over ice shelves, most likely du to different surface backscatter properties)

The CLS Ice Sheet Simulator (ISS): end-to-end simulation



The Ice Sheet Simulator is now integrated into a "end-to-end" processing *(from simulation to geophysical estimation):*

- **Pre-processing module:** to decompress geophysical corrections from 1Hz to 20Hz, to select data over specific drainage basins, estimate the locations of missing measurements…
- **Simulation module (ISS):** to simulate the radar waveforms in SAR and PLRM, as seen in previous slides
- **Retracking + Relocation module:** to estimate surface elevation by exploiting the simulated data ***(new innovative method, to address task 2 of the ESA studies => see next slides)***
- **Post-processing module:** to extract topography, slopes, and roughness from REMA, Perform the CLS "Leading Edge Detection" (LED), Perform the Roemer et al. relocation, ICE-1 retracker, Sigma-0 computations …

3) A new relocation method for land ice acquisitions, based on numerical simulations

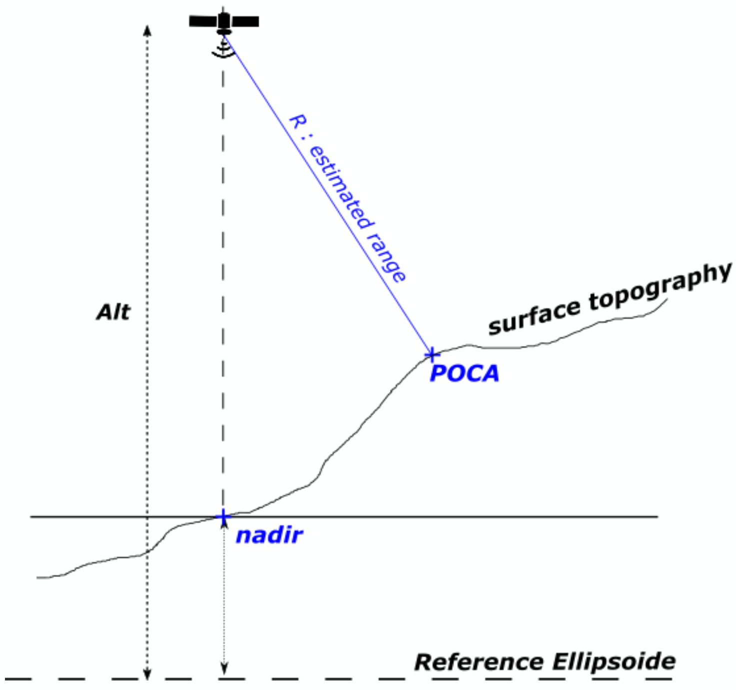
Methodology and first results

Over a non-flat surface, the first radar return does not originate from nadir, but from the closest point to the satellite, the so-called "Point Of Closest Approach" (POCA)

To account for this effect, the measurement is relocated at the POCA location (also called "slope correction). Among the existing methods:

- **The Sentinel-3 IPF (ESA ground segment)** relocates the data using a **surface slope model** precomputed from an auxiliary DEM
  - ⇒ *The method provides consistent results as long as the surface is linear (not the case over the margins). Advantage is the fast CPU time.*

- **State-of-the-art methods** directly determine the POCA by **searching for the shortest range within the auxiliary DEM** (Roemer et al., 2007)
  - ⇒ *The method provides better results over irregular surfaces, but remains basic and limited (does not take into account antenna pattern, does not consider the "actual" surface sampled…). Much more time consuming in terms of CPU time.*



2022 SRAL processing studies: new relocation method

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A new innovative method was developed to relocate the measurement, based on the ISS numerical simulations

Summary of the main operations

1) During waveform simulation, an "energy cross-track distribution" is computed *(i.e., indicating where the energy is backscattered within the Doppler band, for each waveform sample)*

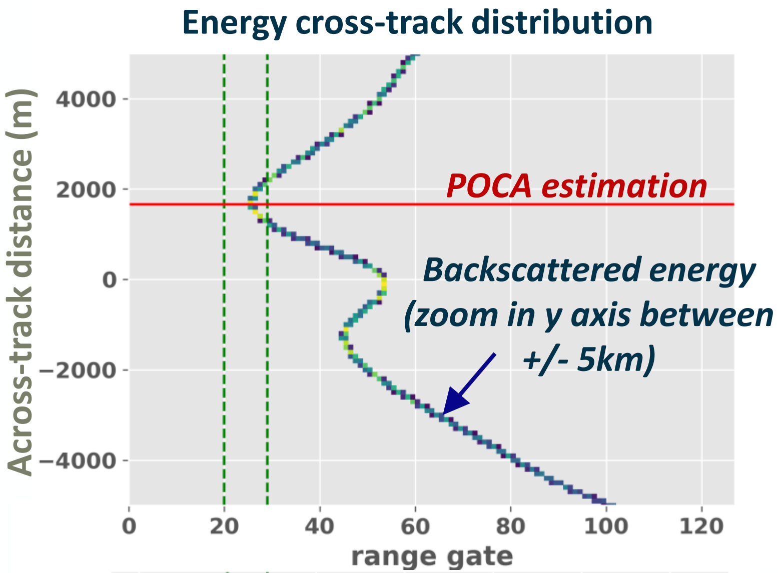
2) Real and simulated waveforms are aligned using cross-correlation (to correct for delays between data and simulation)

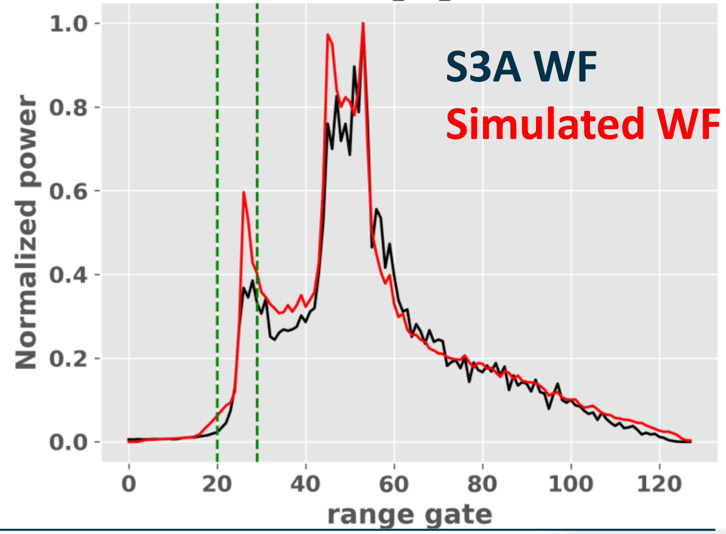
3) Using the portion of "**cross-track energy distribution**" sampled by the **first detected leading edge** (adapted Canny edge detection, Aublanc et al. 2021), **the measurement is geolocated at its "echoing point"** (POCA in general)

4) **From the coordinates of echoing point and satellite, determination of the "satellite look angle"** *(i.e., satellite angle between nadir and estimated echoing point)*

5) **The "altimeter range" is derived during a retracking operation** *(epoch is retrieved by taking the middle point in the first detected leading edge)*

6) **The relocated elevation** is finally estimated using the **satellite look angle**, and the **altimeter range** *(+ different geophysical corrections to account for tides and iono/tropo delays).*

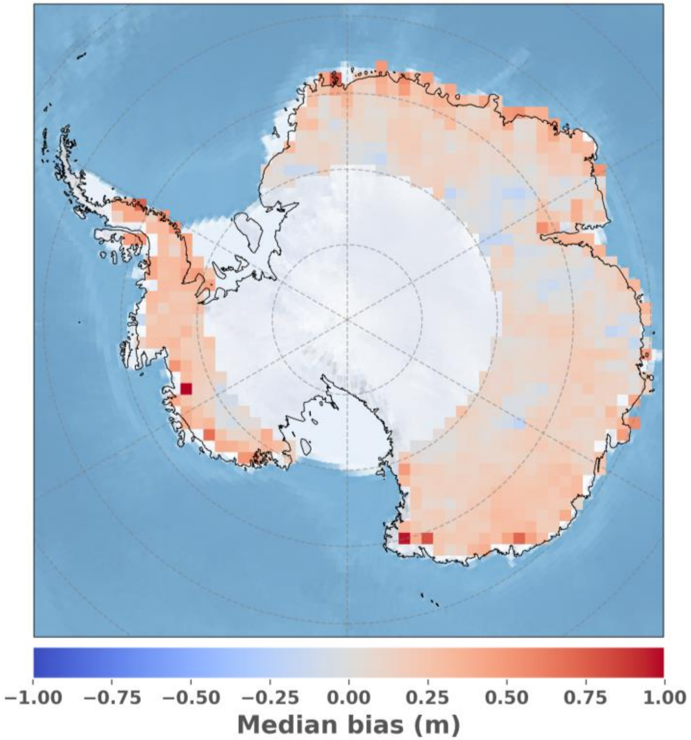




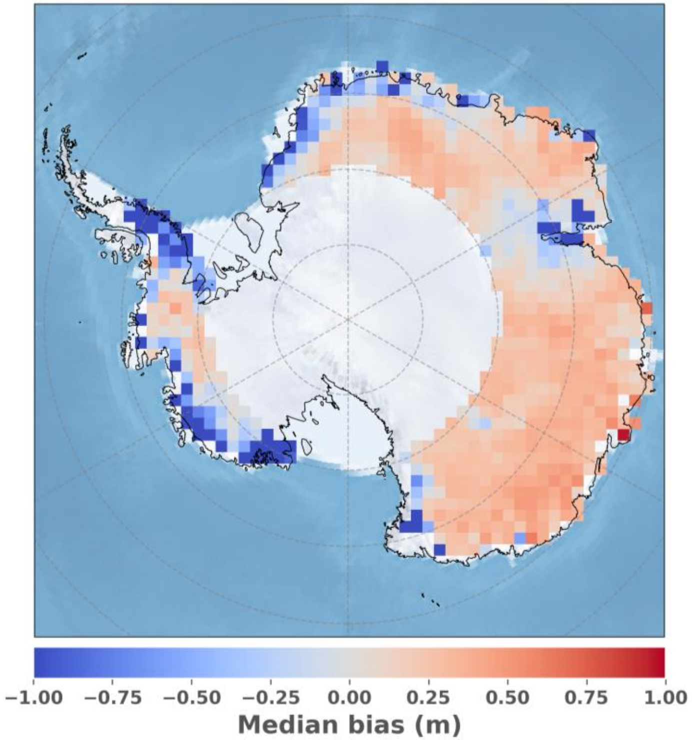
2022 SRAL processing studies: new relocation method

First results: Median bias between Sentinel-3A and ICESat-2 ATL06 co-located data

The new relocation method

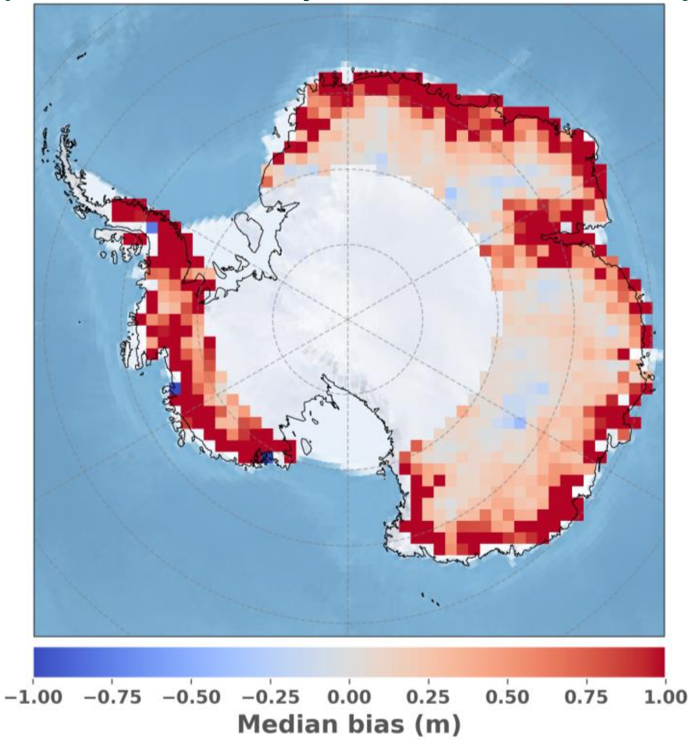


Roemer et al. relocation



relocation from slope model

(ESA LI Thematic products – OCOG RTK)



***Note**: the retrackers are not exactly the same between the 3 data set, but they remain "threshold" retrackers (no major impact). For ESA products (right figure), slope models are computed from Helm et al. DEMs. Performances of ESA products should be slightly improved with HR REMA, used here for the new and Roemer relocations (left and center).*

2022 SRAL processing studies: new relocation method

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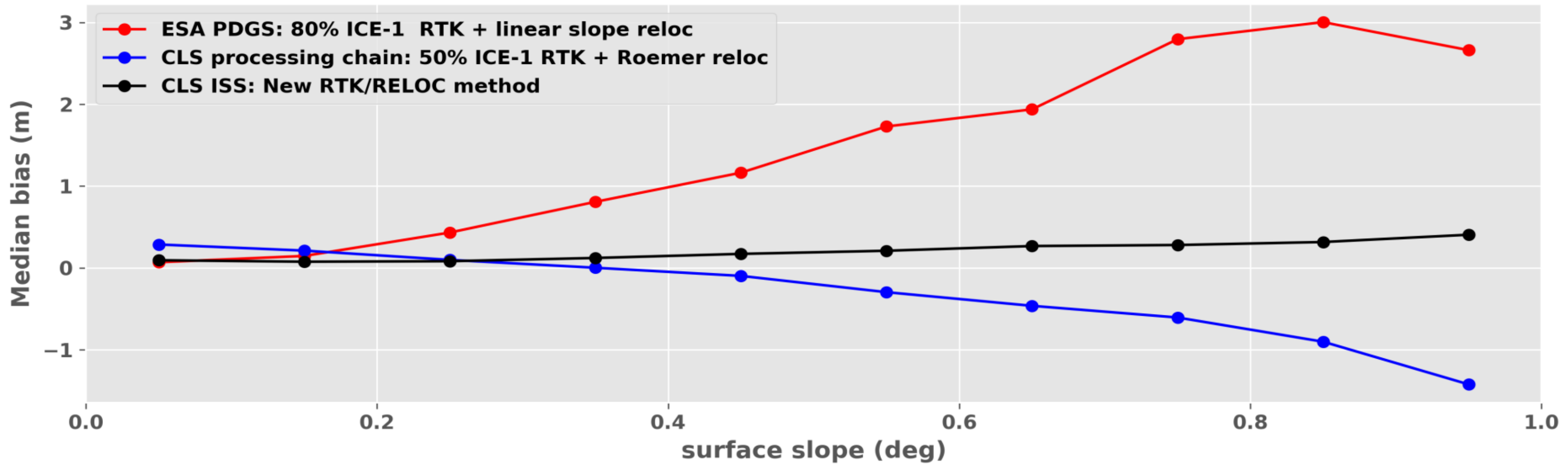
First results: Median bias between Sentinel-3A and ICESat-2 ATL06 co-located data, as a function of surface slope

-- The new relocation method

-- Roemer et al. relocation

-- relocation from slope model *(estimation from ESA LI Thematic products)*



With the new relocation method (black curve), the accuracy is much more homogeneous over the Antarctic continent

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2022 SRAL processing studies: new relocation method

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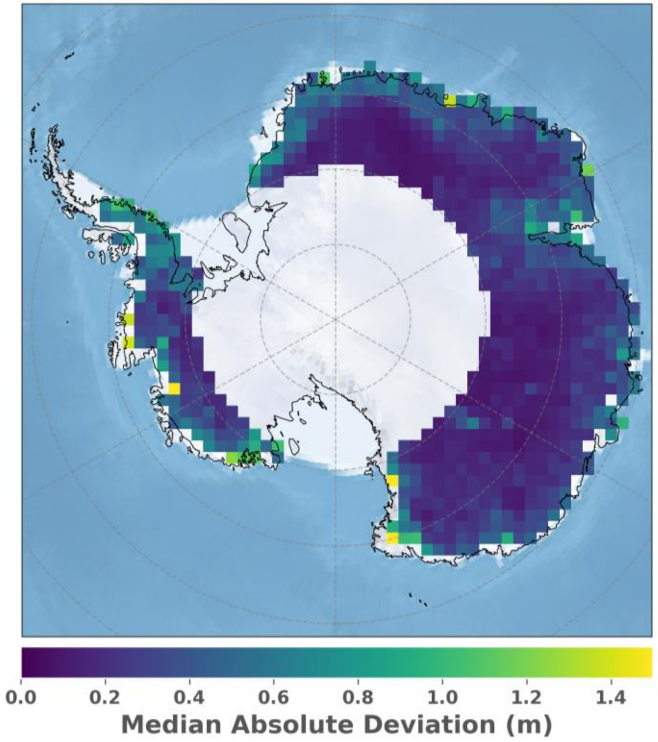
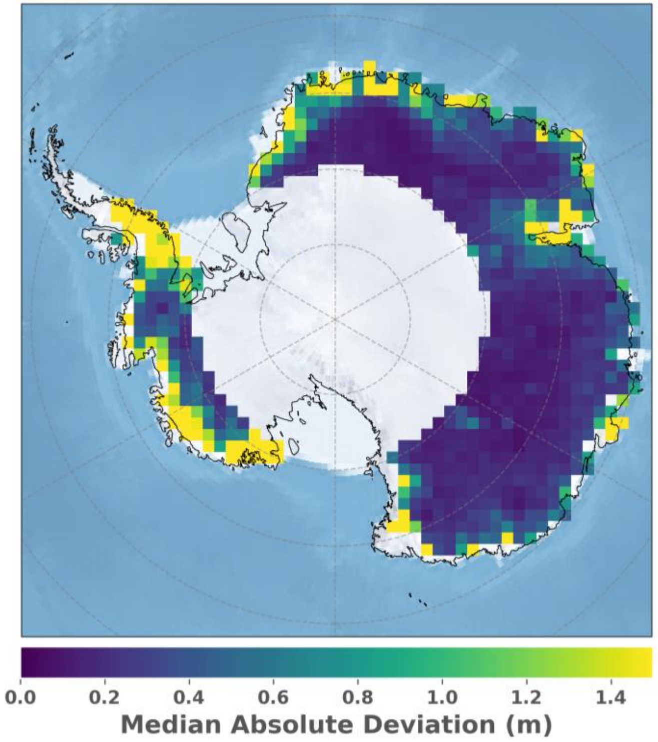
First results: Median Absolute Deviation (i.e., dispersion) between Sentinel-3A and ICESat-2 ATL06 co-located data

The new relocation method

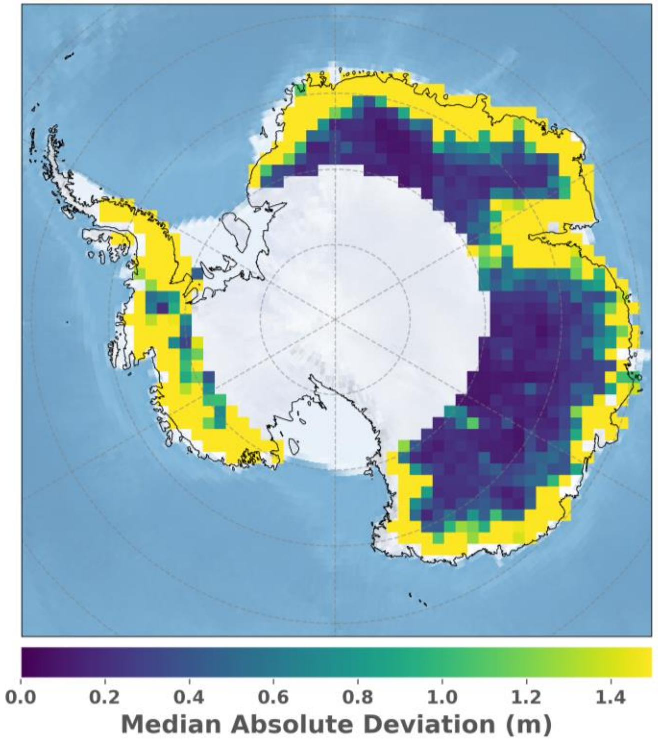


Roemer et al. relocation



relocation from slope model

(ESA LI Thematic products – OCOG RTK)



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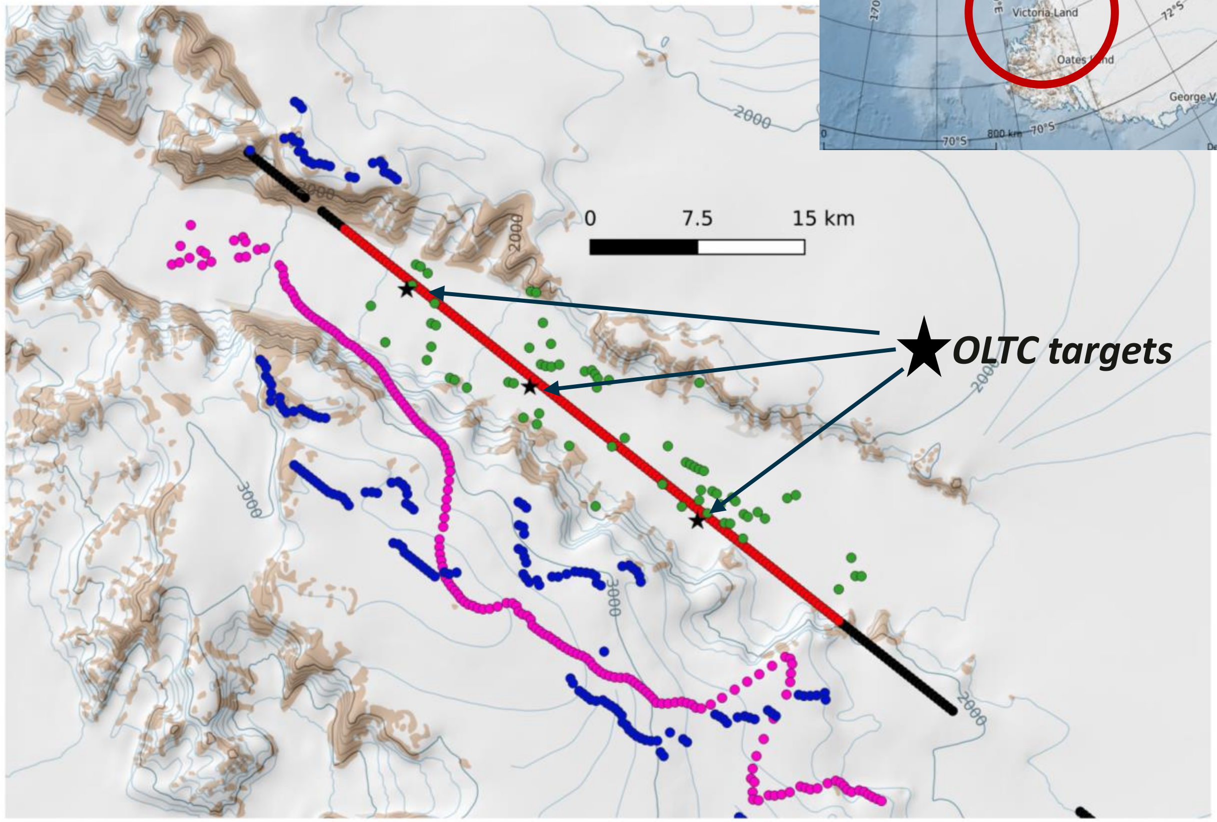
2022 SRAL processing studies: new relocation method

Case study: OLTC acquisitions over glaciers in Victoria Land

In end 2021, ten Antarctica glacier targets have been added in the Sentinel-3 on-board OLTC tables. These targets are in the Victoria Land area, a mountainous region with glaciers in Antarctica. **The open-loop tracker is tunned to measure the elevation inside the glacier** (elevation at nadir, not at POCA).

The right map shows the Sentinel-3A track for 1 of the 6 track impacted:

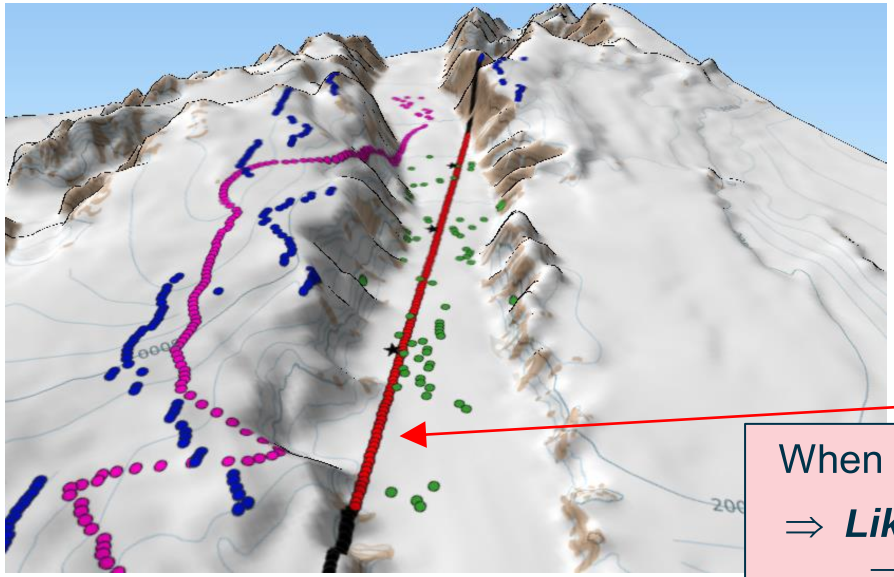
- **Nadir locations** *(in red those who are inside the glacier)*
- **Relocation from ESA Land Ice Thematic products**, pilot version, from slope model
- **Relocation from Roemer et al. (2007),** closest range in DEM
- **Relocation from the new method**, using the CLS Ice Sheet Simulator



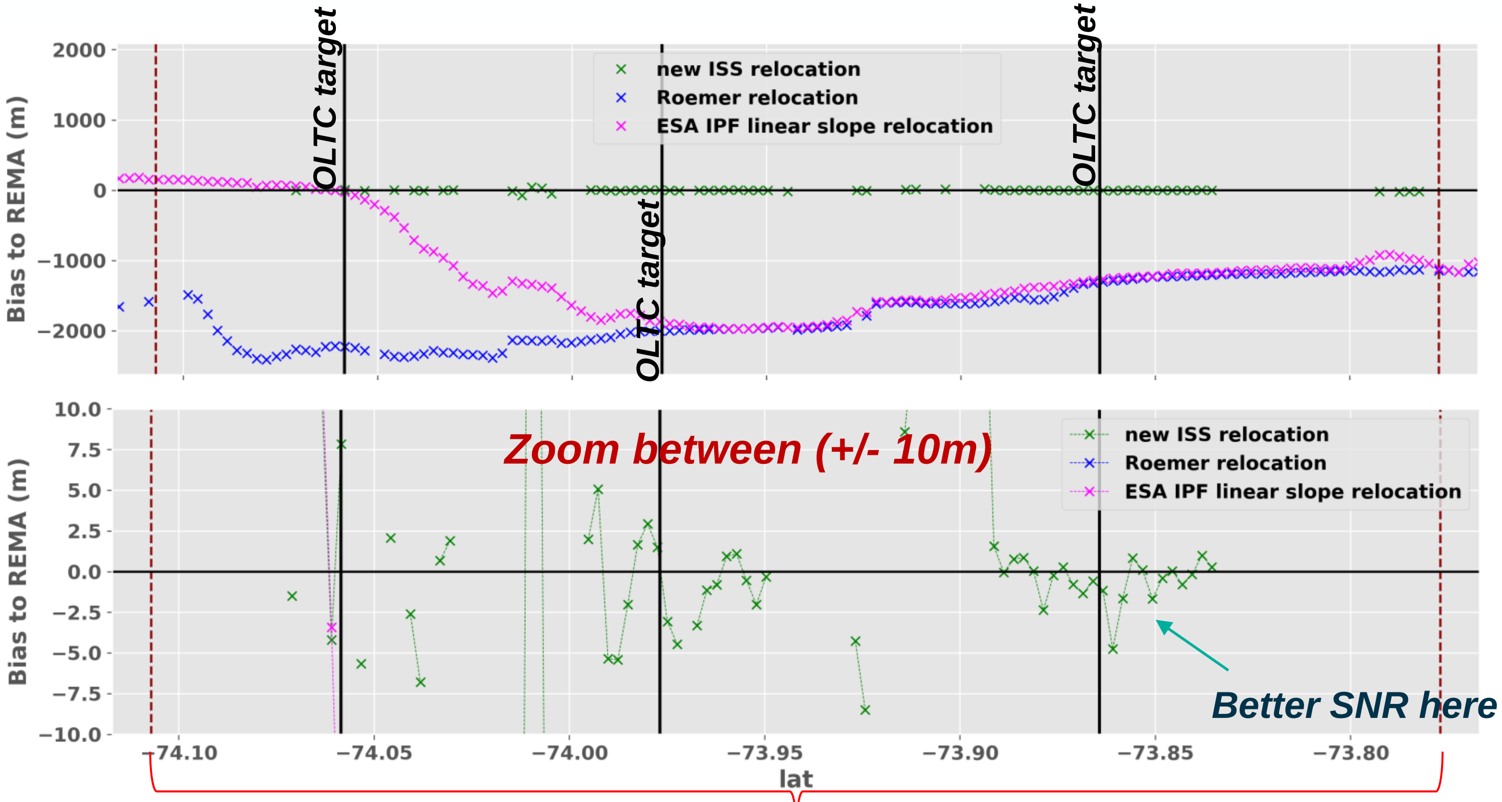
Sentinel-3A track 266, cycle 88 (July 2022)

2022 SRAL processing studies: new relocation method

- The new developed method (green) relocates the measurement in the **actual** surface sampled by the altimeter (*by using the tracker range information in the simulation)*
- While the two other methods (ESA IPF, magenta and Roemer, blue) attempt to relocate at a theorical POCA in any circumstances



Biases to the REMA DEM along the track



When SNR is "sufficient" (see back-up), the new relocation method provides relevant elevations

⇒ ***Likely there are rooms of improvement in the retracking of these complex waveforms***

⇒ ***<u>Challenge</u>: will it be possible to monitor the glacier variations over the time?***

The new relocation method, preliminary conclusions

Compared to ESA Land products, and state-of-the-art algorithms:

- **Accuracy much more homogeneous** over the whole Antarctic continent
- **Precision greatly improved**, in particular over the margins/steepest surfaces
- **The method remains "robust",** by providing as much as 20 Hz valid elevation estimates compared to the two other methods (even slightly more)
- **The method has the ability to estimate the surface elevation in the actual surface sampled by the altimeter,** not at a strict "POCA" location, which is not always "seen" by the altimeter
- **Additional information are provided for each measurement,** in particular a surface ambiguity flag
- **A remaining limitation is the REMA coverage** (*3.5% of measurements not relocated over Antarctica because HR REMA does not cover these areas => waiting for a "complete" REMA version)*

4) Definition of new Open Loop Tracking Commands (OLTC)

Presentation of a first methodology to improve the data coverage over the ice margins

2022 SRAL processing studies: OLTC over the ice margins

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Objective:

Based on waveform simulation performed with the Ice Sheet Simulator: **definition of a new methodology to generate Open Loop Tracking Commands (OLTC) over the ice margins**.

Tests performed were performed on 10 track portions close to the grounding line and where the ratio of missing/low SNR data is significant.

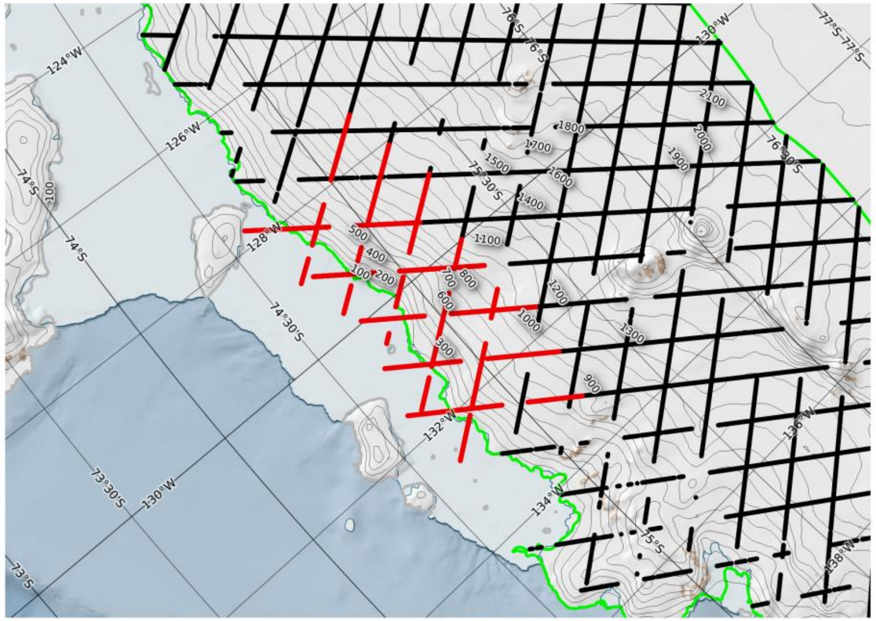
Methodology:

1 – Simulation of SAR mode waveforms with a large extended window (1536 samples, ~720 m).

2 – Detection of the tracking "epoch" along the track (using dedicated algorithms).

3 – Epoch positions are converted to OLTC, at a 0.01° latitude sampling.

4 – New simulation using the computed OLTC with a nominal window analysis (128 samples) => *to check if the useful signal is correctly acquired.*



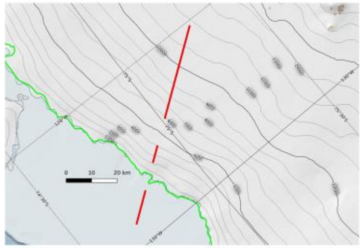
In red the10 track segments analysed to implement new OLTC, located over Getz drainage basin in Antarctica (-20 km to 60 km around grounding line).

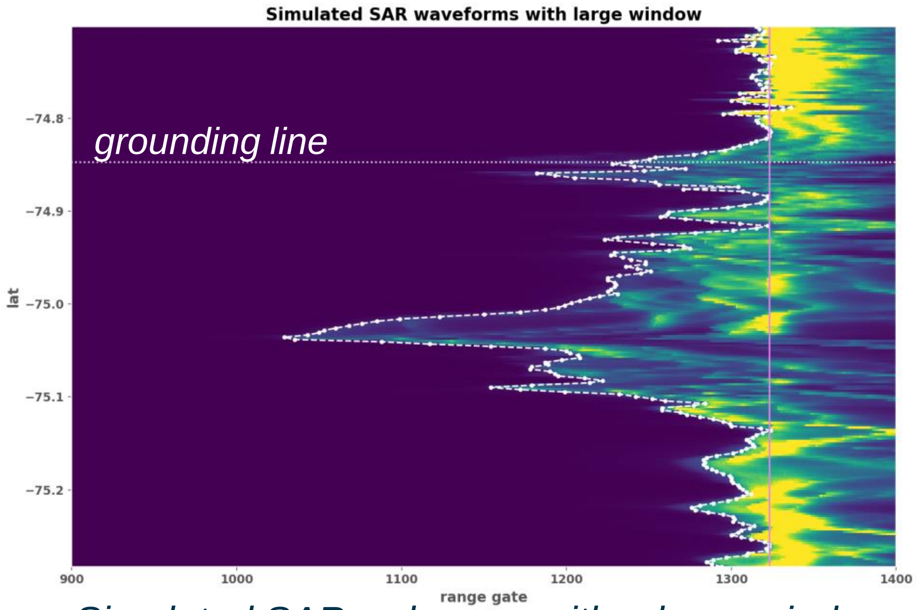
First conclusions:

- Using simulation with a large window analysis (~720 m !), it is possible to detect the useful signal that can be captured in an UF-SAR waveform.
- Thanks to these simulations, **a first methodology was developed to generate OLTC over the Antarctica margins.**
- **Over the 10 track portions studied, the closed-loop tracker always lost the signal at some point,** the ratio of missing data and low SNR measurements is between 25% and 50%. On the other hand, **OLTC shall provide a complete data coverage for most of the 10 tracks.**

Perspectives:

- CNES/Noveltis/CLS will assess the possibility to implement/upload these new OLTC in 2023 *(for about a dozen of tracks in Greenland and Antarctica, and potentially over few other large glaciers).*





Simulated SAR radagram with a large window analysis, over a track portion close to the Antarctica grounding line (Getz).
The white dotted line shows the signals intended to be tracked with OLTC

The studies continue in 2023 with NPI and Noveltis:

- **In 2023, the new relocation method will be assessed in details:**
  - Over Antarctica and Greenland by comparison to ICESat-2 and CryoSat-2 *(by CLS).*
  - Over different glaciers in Svalbard and/or Dronning Maud Land *(by the Norvegian Polar Institute).*
  - Preliminary assessments to prepare for a **potential** operational implementation in the ground segment.
- **Upload of new Open Loop Tracking Commands for S3A and/or S3B, over land ice test areas.** Technical feasibility is under investigations between CNES/Noveltis/CLS.

Other perspectives

- **Glaciers monitoring,** large and small ones (for instance where OLTC are already defined).
- **Swath processing,** based on the numerical simulation.
- **Adaption of the new relocation method to LRM data,** for reprocessing of past/current missions.
- **Retracking improvements,** using the simulated waveform as a “retracking model”.
- **Integration of snow modelling in the simulation,** preliminary studies made with SMRT from IGE are promising (Larue et al., 2021).

BACK-UP

The CLS Ice Sheet Simulator (ISS): presentation

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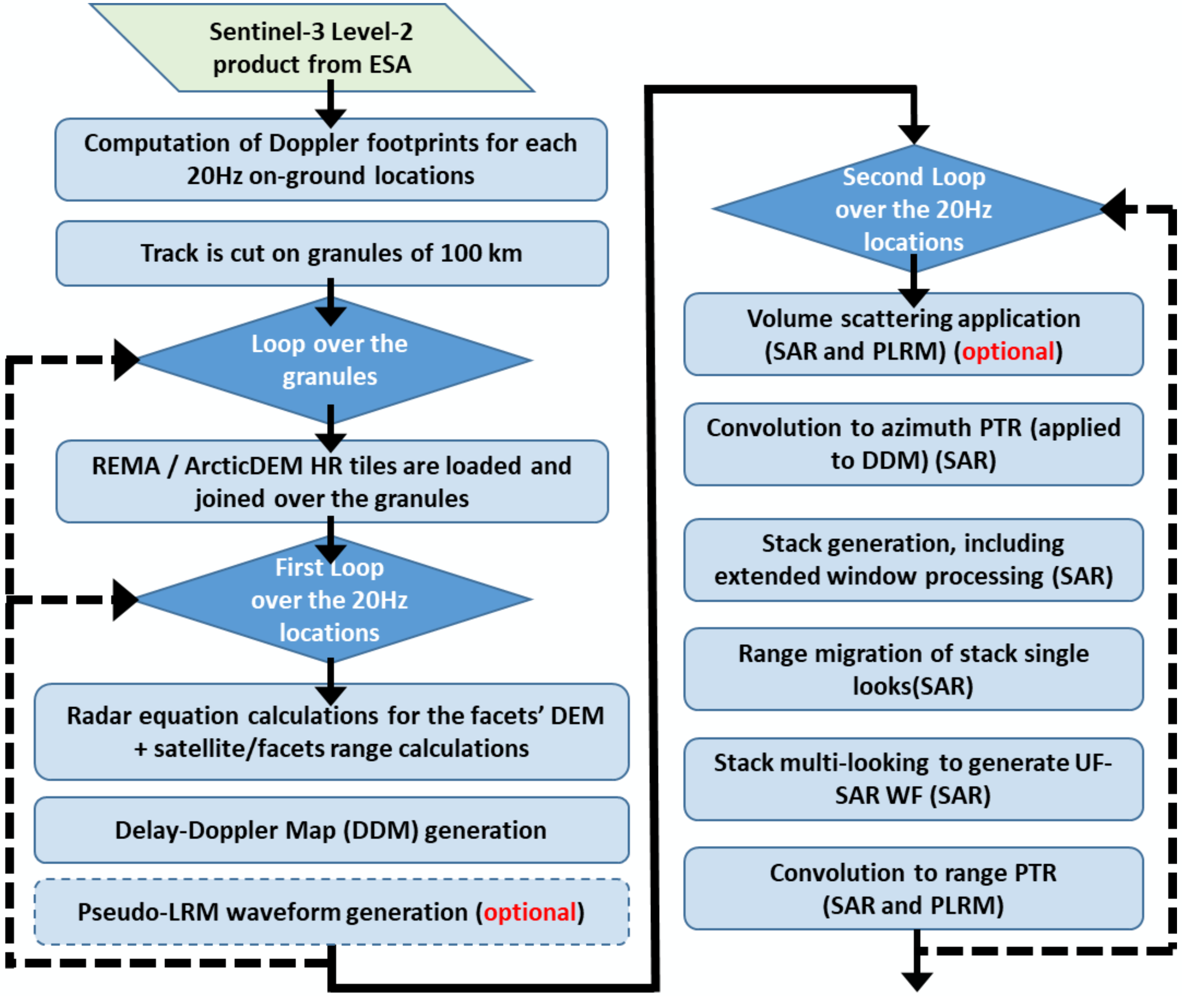
To perform these studies, CLS relies on a numerical tool developed internally: <u>the Ice Sheet Simulator (ISS)</u>

=> a facet-based simulator, exploiting the High Resolution of new ice sheet DEM (REMA, 8 m resolution) to reproduce the altimetry waveforms in Ku/Ka and LRM/SAR

In the frame of the "2022 SRAL processing studies over land ice", the ISS was improved to address the study objectives:

- Simulation over very large window (for defining new OLTC)
- A new relocation method
- Integration into an end-to-end processing, from simulation to level-2 (see next slide)
- + other improvements in the data modelling

ISS general flow chart



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Methodology:

The measurements acquired over the Antarctic ice sheets are classified in 3 categories:

1) Missing data

- The missing measurements, in case the on-board tracker lose the signal, and shift from acquisition to research mode
  => no measurement at all, they are quantified by interpolation made on the 20 Hz locations, when measurement gaps are detected along the tracks

2) Very low Signal Noise Ratio (SNR) measurement

- Measurements with a very low Sigma-0. Meaning that the tracker did not succeed to catch the any useful signal.
  =>To obtain a Sigma-0 estimation for all measurements, it was computed based on waveform maximum power

3) Invalid waveforms (from two different methods)

- SNR is considered high enough, but the waveforms are too noisy or too “distorted” to be useful for surface topography retrieval (no clear leading edge). Defining such category is relatively complex and arbitrary, two methods are employed:
  a) Using the ice waveform quality flag available in the L2 product
  b) Using CLS leading edge detection algorithm (initially developed for CS-2 SARIn data at CLS)

=> Analyses made with the CLS neural network classification are also presented

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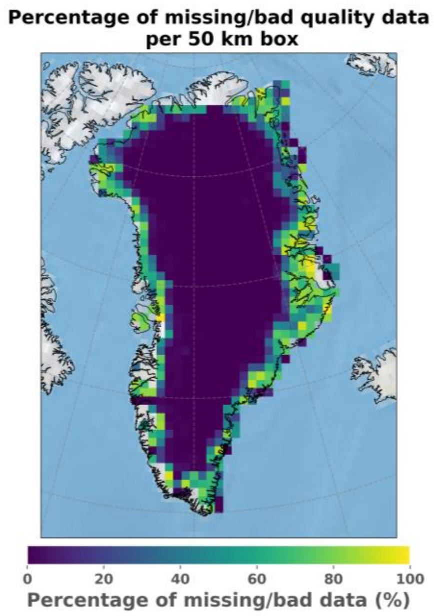
Greenland Sentinel-3A measurements were assessed in terms of:

- **Missing data,** when the altimeter looses the useful signal, and shift from measurement to acquisition mode
- **Very Low SNR**, using a backscatter coefficient derived from waveform maximum power
- **Invalid waveforms,** using the “waveform quality flag” available in the products

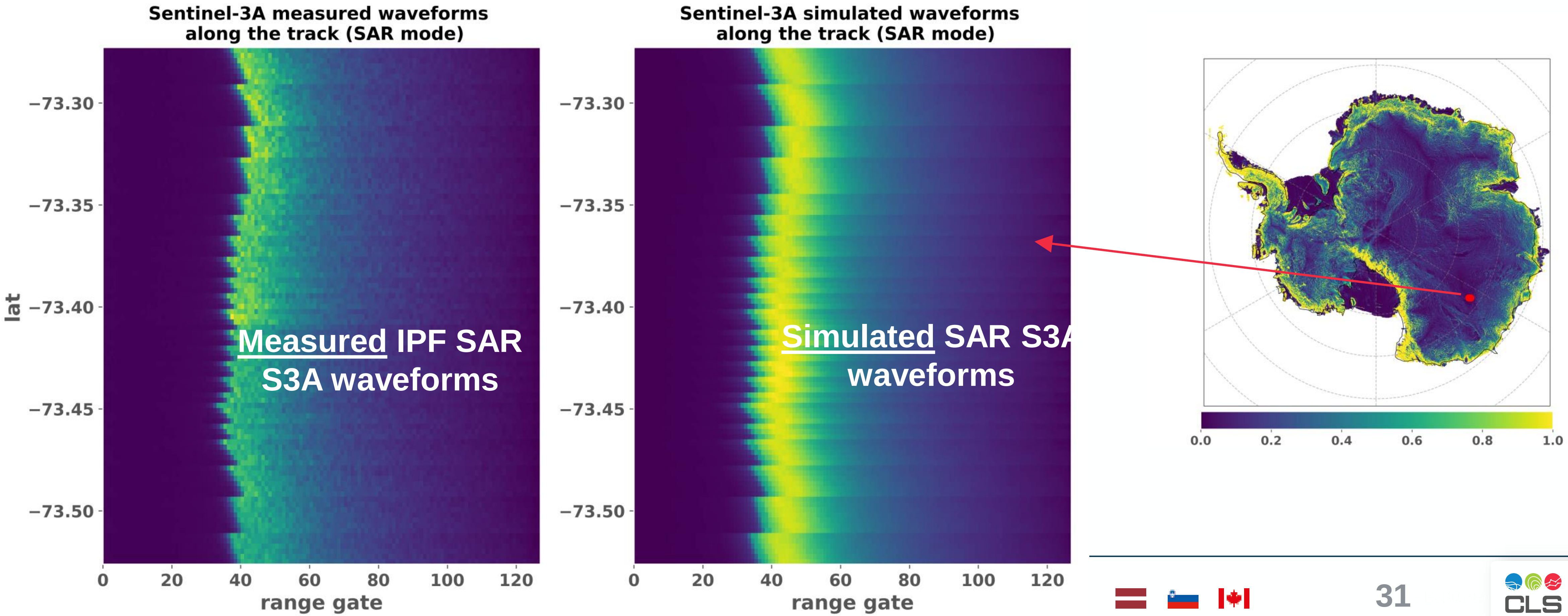
	1) Missing data	2) Very low SNR	3) Invalid waveforms	Total
Current ESA LAND products	7.31%	6.09%	9.12%	17.18%
ESA Land ice thematic products		3.82%	4.57%	12.54%



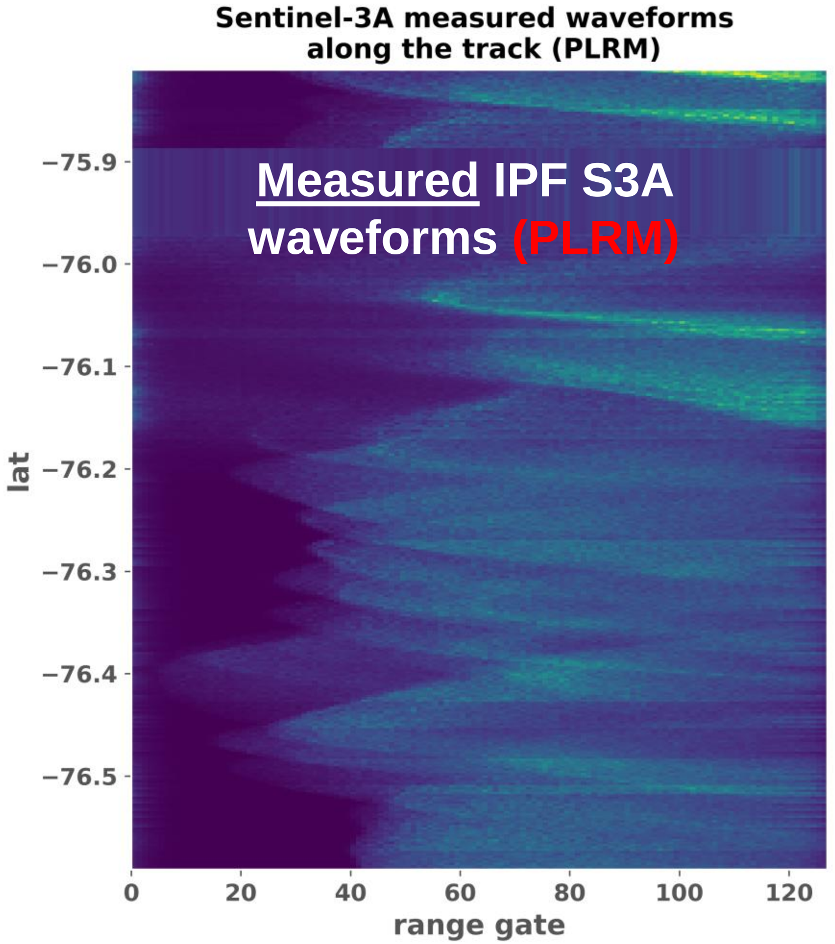
The CLS Ice Sheet Simulator (ISS): radargrams over the margins

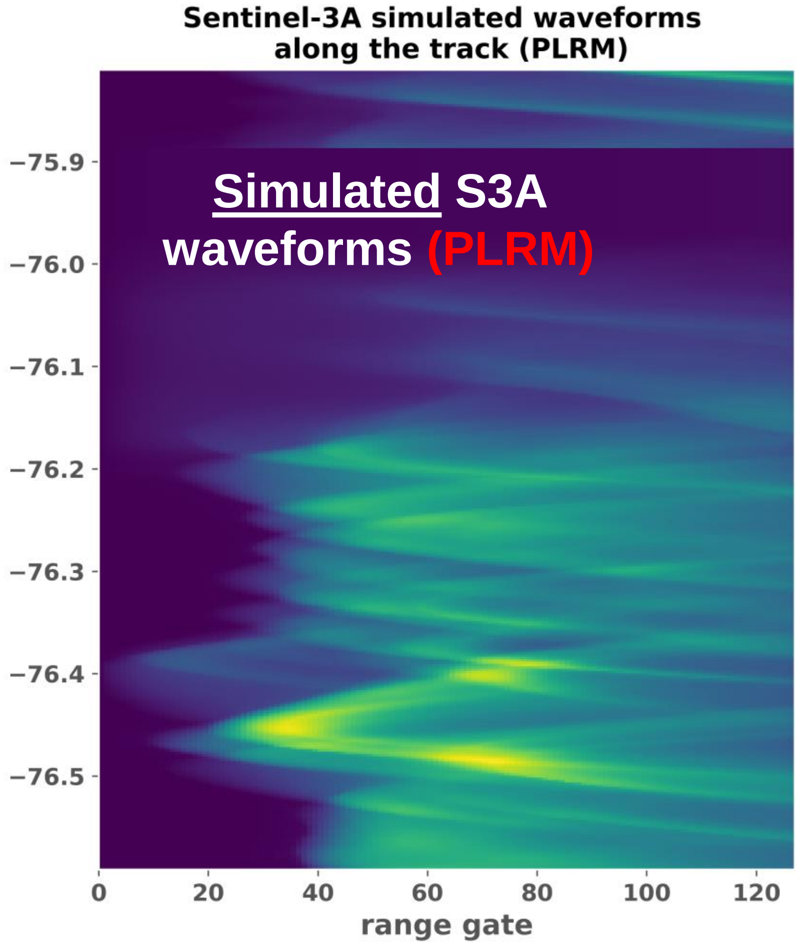
In this simulation, SAR altimetry waveforms are simulated over a relative flat area (measured WFs are from the "nominal" IPF, not the landice prototype)

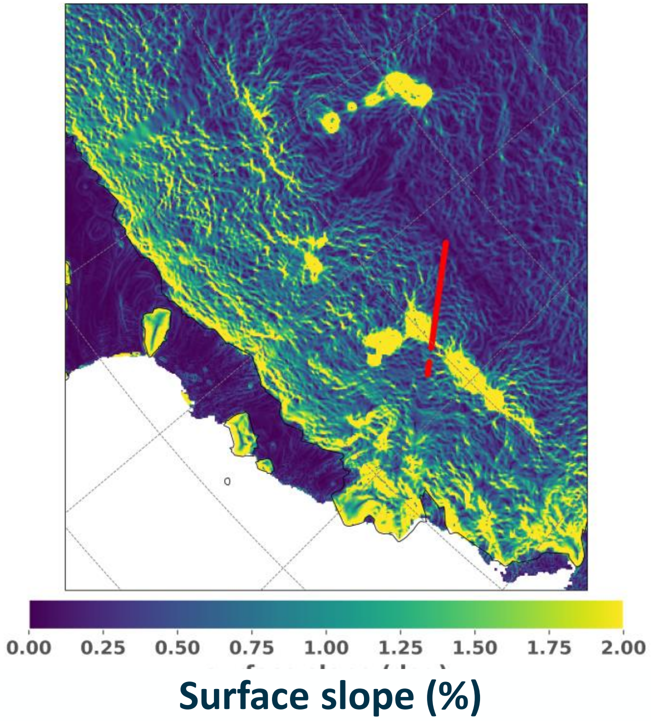
=> The simulation reproduces the "saw-tooth" effect



Pseudo-LRM Radargrams over Getz drainage basin (Sentinel-3A, track 7)

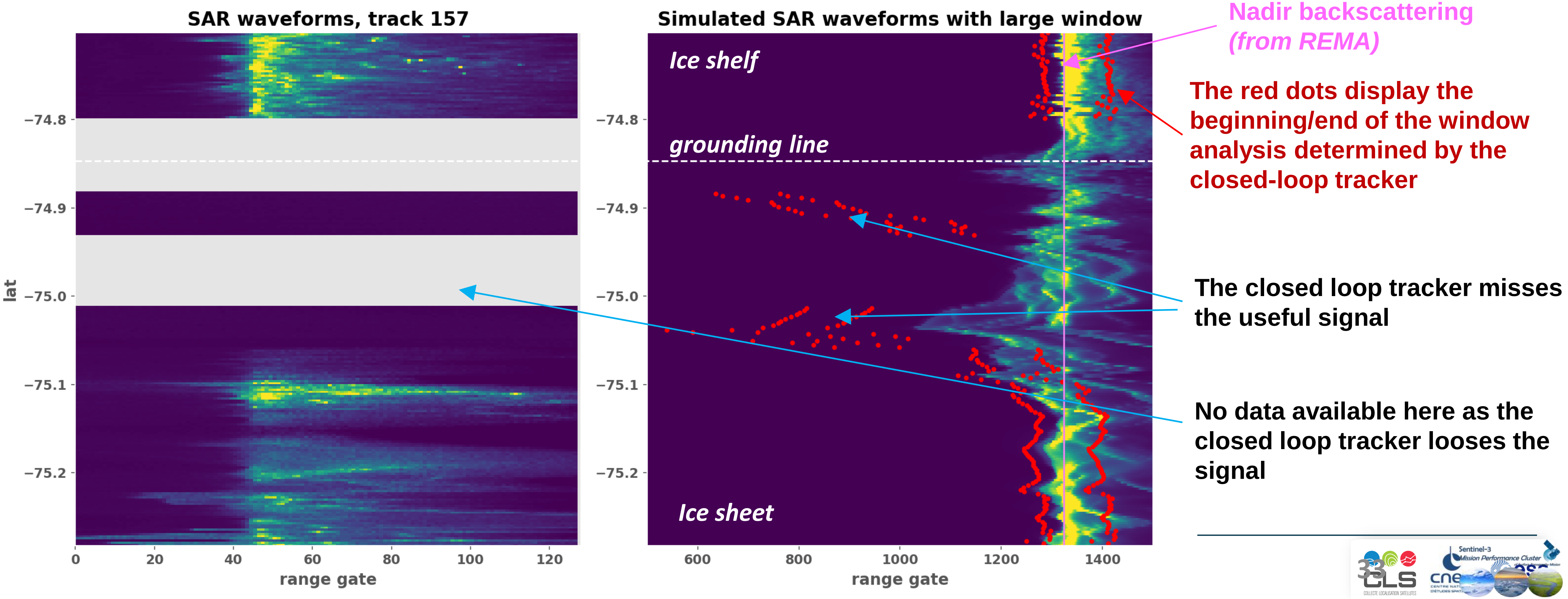






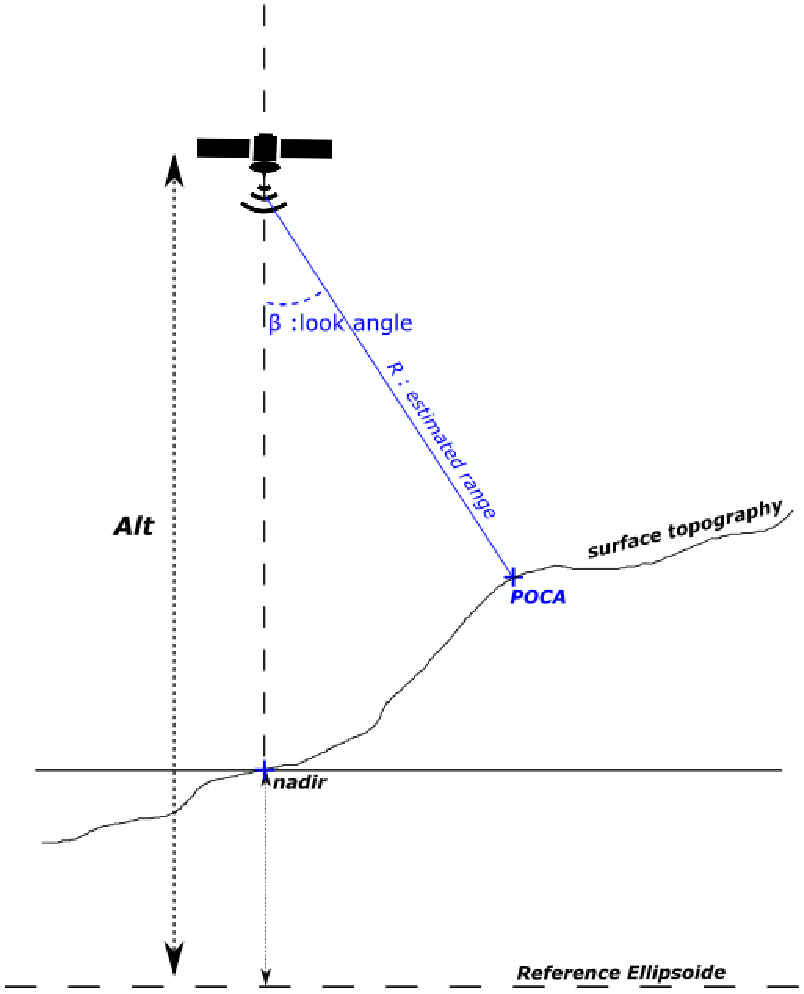
2022 SRAL processing studies: OLTC over the ice margins

- On the left, the SAR mode waveforms recorded in the Sentinel-3 LAND ICE Thematic products
- On the right the waveforms simulated with a long extended window analysis :1536 samples, **the tracker used for this simulation position the nadir elevation (from REMA) at gate n 1324**



The measurement is relocated using:

-> **The altimeter range** (from WF retracking)
-> **The satellite look angle** (derived using the X/Y POCA location)
-> **nadir and satellite coordinates** (from the MOE/POE)



Two main steps (equations not detailed here):

1) Satellite coordinates are shifted from lat/lon/altitude to Earth CEntered Frame (x_{sat},y_{sat},z_{sat}) coordinates. Determination of the along-track unit vector in the ECEF frame using the next measurement coordinates. From the along-track unit vector, the across-track unit vector can be derived.

2) Measurement geolocation (x_{poca},y_{poca},z_{poca}) in the across-track plan with geometrical computations in the ECEF frame involving the altimeter range and the satellite look angle. Estimated POCA is shifted back to lat/lon/altitude coordinates

⇒ *Same methods/equations as used in SARIn (Aublanc et al., 2021)*
⇒ *Only difference: In SARIn mode the look angle is determined with interferometry. In SAR mode the look angle is computed as explained the previous slides*

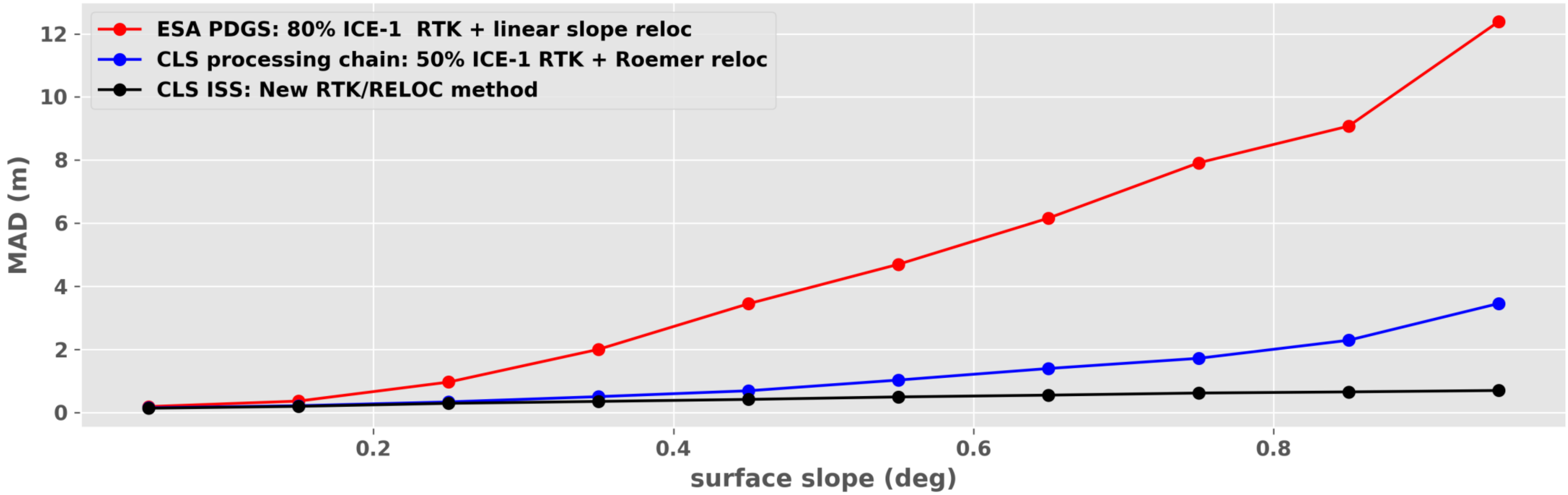
PROGRAMME OF THE EUROPEAN UNION

First results: Median Absolute Deviation between Sentinel-3A and ICESat-2 ATL06 co-located data, as a function of surface slope (with 1 cycle of S3A data)

-- The new relocation method

-- Roemer et al. relocation

-- relocation from slope model
(ESA LI Thematic products)



2022 SRAL processing studies: new relocation method

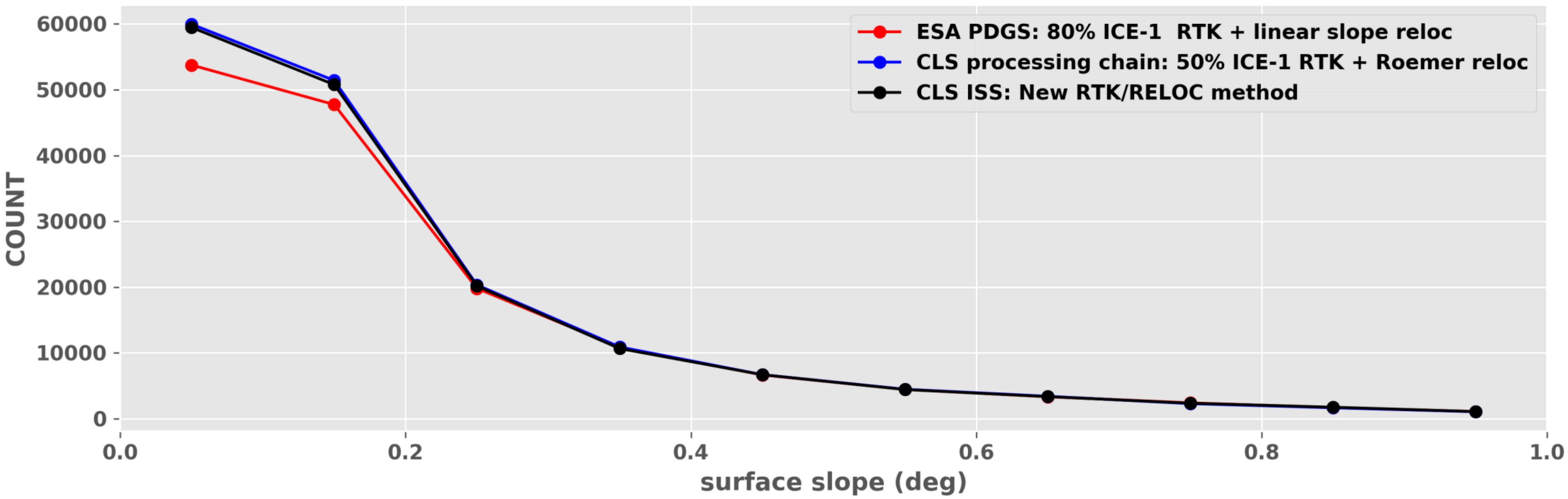
PROGRAMME OF THE EUROPEAN UNION

First results: Population of Sentinel-3A and ICESat-2 ATL06 co-located data, as a function of surface slope (with 1 cycle of S3A data)

-- The new relocation method

-- Roemer et al. relocation

-- relocation from slope model
(ESA LI Thematic products)



New Victoria LAND acquisitions in OLTC

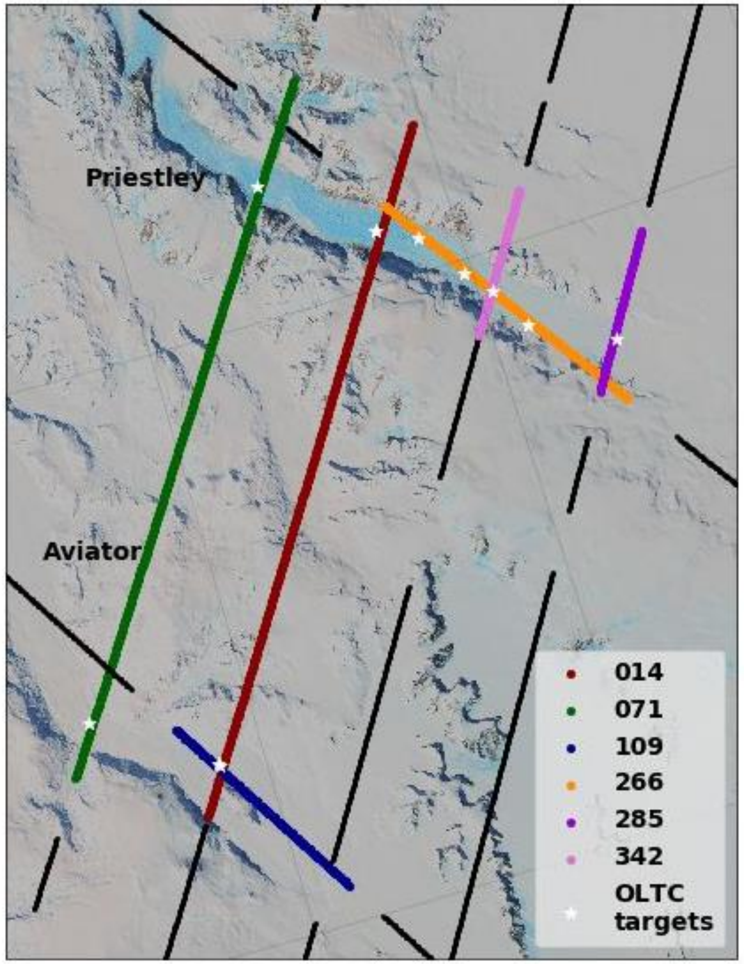
PROGRAMME OF THE EUROPEAN UNION

Date	Start UTC	End UTC	RON [1-385]	Start Lat[deg]	End Lat[deg]	Targets
2021-12-09	13:18:34	13:18:43	266	-74.14	-73.74	3
2021-12-10	21:09:38	21:09:43	285	-73.70	-73.90	1
2021-12-14	21:05:56	21:06:01	342	-73.85	-74.04	1
2021-12-18	21:01:59	21:02:20	14	-73.22	-74.20	2
2021-12-22	20:58:17	20:58:38	71	-73.34	-74.33	2
2021-12-25	13:03:51	13:03:58	109	-73.41	-73.11	1

Table 1. *First acquisition dates and approximate UTC times for each Sentinel-3A relative orbit number (RON, as seen in the Sentinel-3 product filename) over Antarctica glaciers. The same open-loop data acquisitions re-occur on the designated orbits and latitudes once every repeat cycle (27 days / 385 orbits).*

More information available here in Sentinel OnLine:

here



2022 SRAL processing studies: new relocation method

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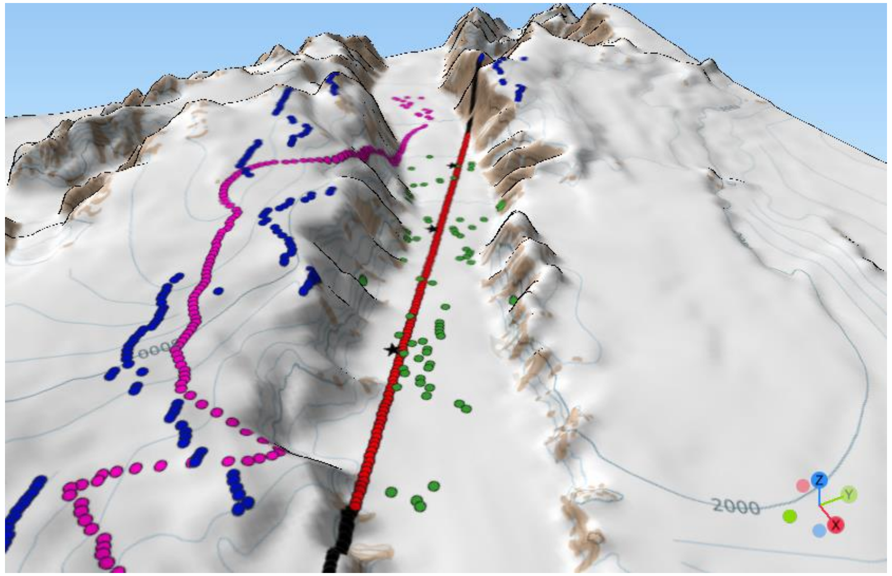
Case study: OLTC acquisitions over Victoria Land



Biases to the REMA DEM