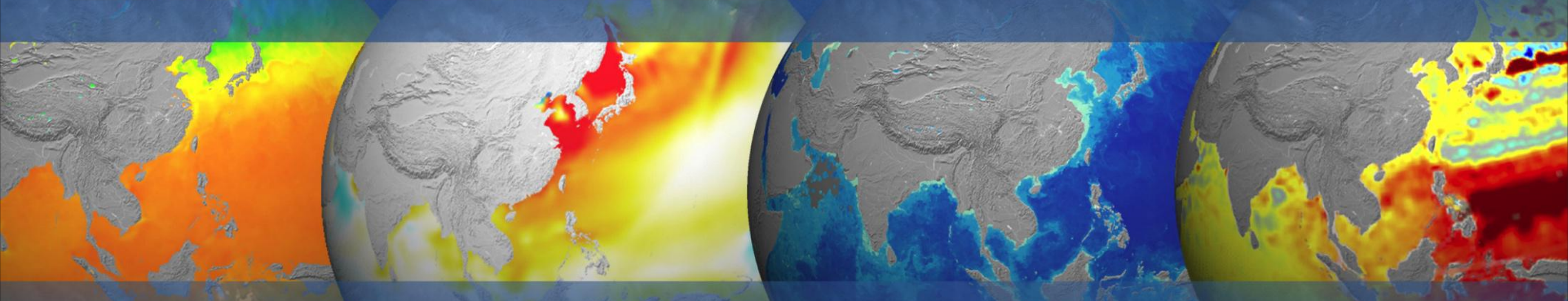
ESA–MOST China Dragon 4 Cooperation

→ ADVANCED TRAINING COURSE IN OCEAN AND COASTAL REMOTE SENSING



12 to 17 November 2018 | Shenzhen University | P.R. China

Altimetry for Polar Regions with BRAT & the ESA SPICE Project

Hosted by

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& **SPICE** and **BRAT** Teams

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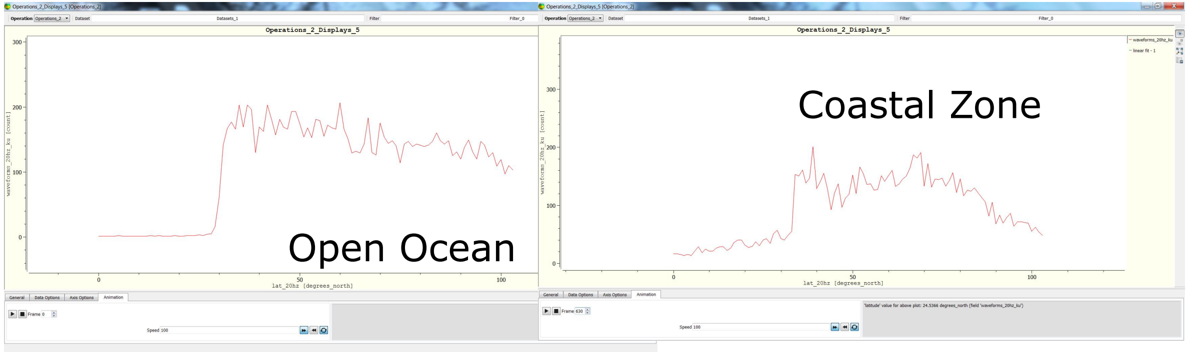
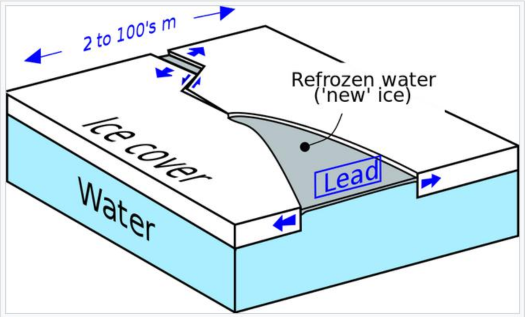
L1b Waveforms in Polar Regions

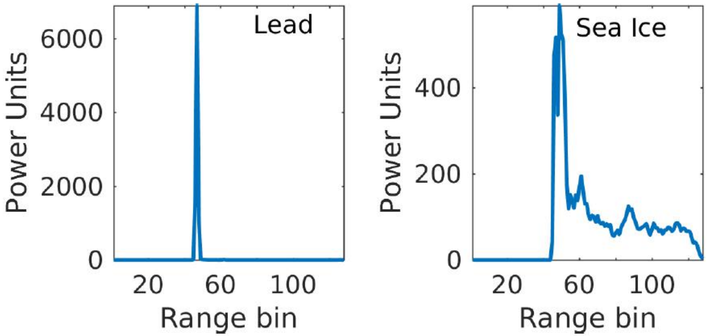
- In the BRAT practical, L1b waveforms acquired in **open ocean** and **coastal zone** have been investigated

- In **polar regions**: **leads**, **sea ice** and the **interaction with the snowpack** produce different L1b waveforms *requiring different retrackers*

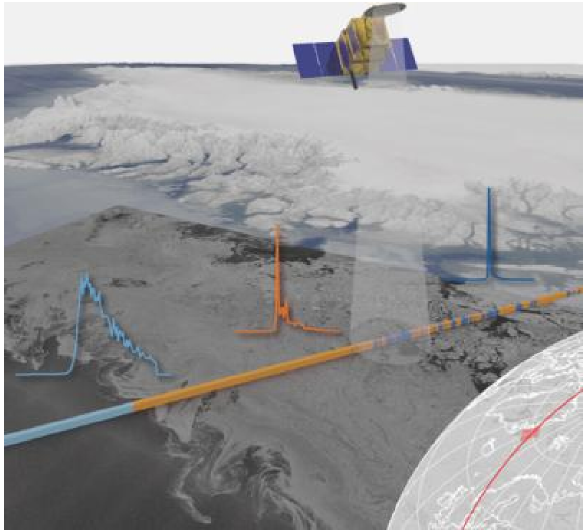




Schematic representation of a lead developing in a sea ice cover.



Müller, F.L.; Dettmering, D.; Bosch, W.; Seitz, F. Monitoring the Arctic Seas: How Satellite Altimetry Can Be Used to Detect Open Water in Sea-Ice Regions. *Remote Sens.* **2017**, *9*, 551. https://doi.org/10.3390/rs9060551



Sea Ice Classification

Sea Ice & Ice Freeboard

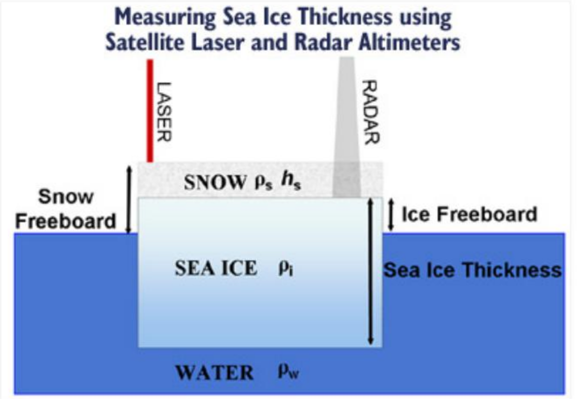
- **Sea ice** is frozen **ocean** water. It forms, grows, and melts in the **ocean.**

- **Sea ice thickness** can be obtained from the **Ice Freeboard, i.e.** the difference in height between **open water** and **snow/ice** surfaces obtainable by altimetry measurements.

- Laser altimeter work at 10^{14} Hz (S, Ku & Ka-Band altimeters between 2-40 GHz.

- **The higher the frequency the lower the penetration in the ice.**

- Moreover, by using both the **altimeter** and the **radiometer**, ocean **surfaces potentially covered** by **sea ice** can be classified in several sea ice **type and age**.



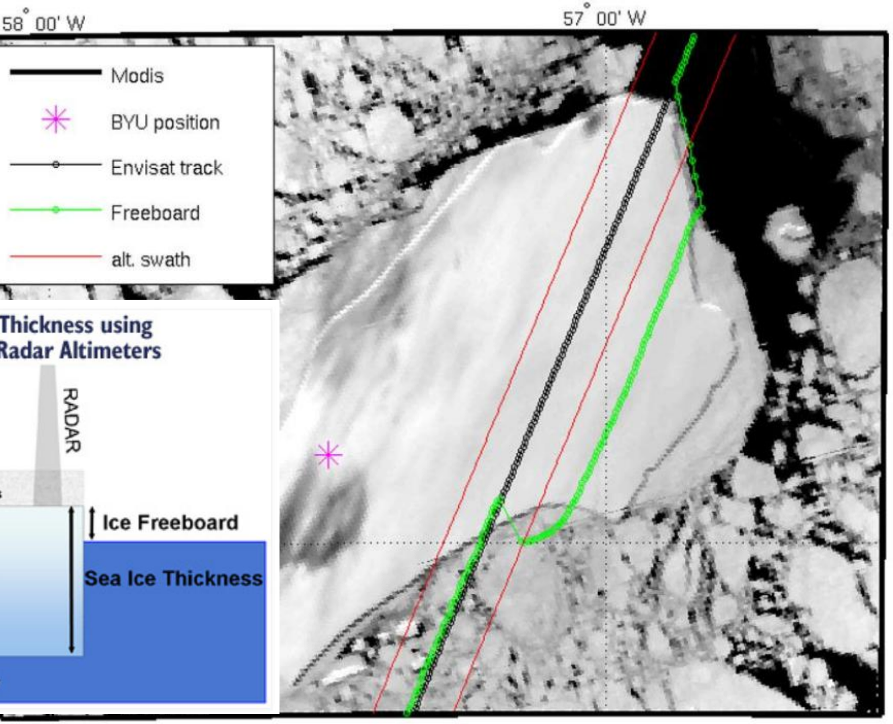


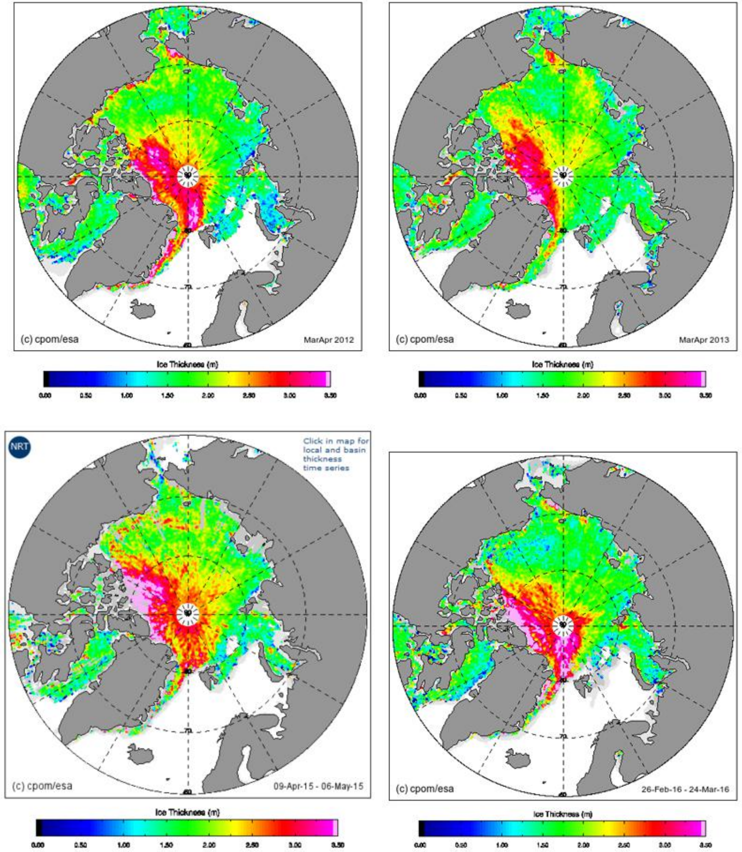
fig 2. MODIS image of iceberg A43A on 2 October 2003 13:20 UT and ENVISAT RA2 ground track (fine black line) and freeboard profile (green line) on 1 October 2003 12:35 UT. The two red lines indicate the width of the altimeter swath and the magenta star the location of the iceberg in the BYU database. (Credits J. Tournade)

From Freeboard to Sea Ice Thickness

- **Ice freeboard** data are **converted to sea ice thickness** using fixed ice, snow and water densities and regional monthly snow depth.

- Conversion is related to the Archimedes' principle.

- The mean thickness excludes thin ice (less than 0.5-1 m) and open water.



Average spring (March-April) Arctic sea ice thicknesses from 2012 to 2016 from CS-2 satellite altimeter measurements of ice freeboard (height by which the ice extends above the water's surface) ->

(Credit: University College London/Centre for Polar Observation and Modelling)

ating Polar Regions - Strategies

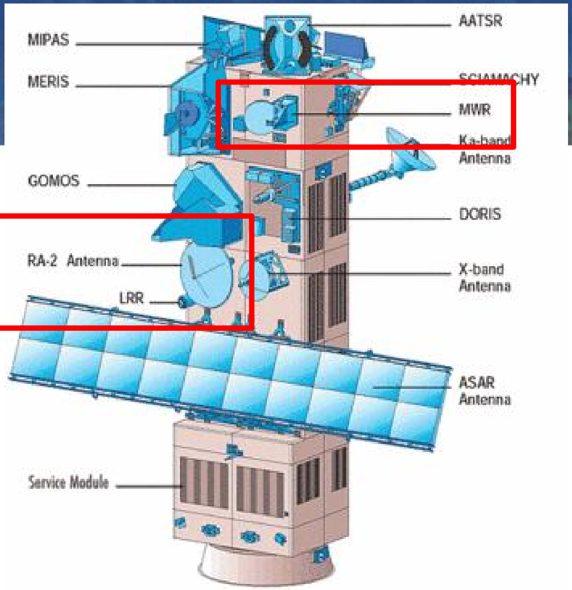
- If earliest altimetry missions were dedicated to studying the open ocean, the ability of radar altimetry to monitor ice surfaces has also been demonstrated.

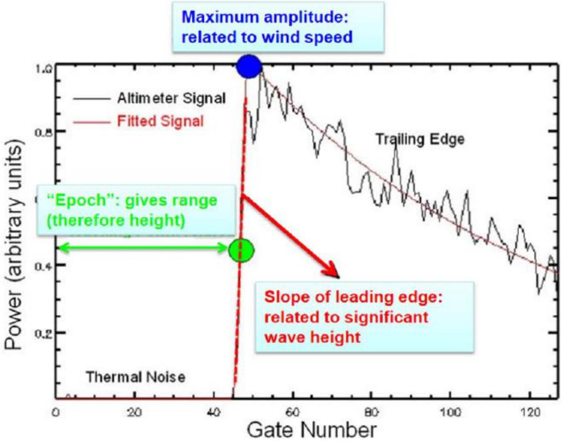
- By giving a good overview of **Polar Regions (-82.5°S / 82.5°N)**, the Envisat mission is well adapted. However, since the **period cycle is 35-days**, the sea ice distribution can vary due to processes of formation, motion or melting.

- The **Envisat GDR** data brings the opportunity to use **retracking algorithms** other than the classical ocean-oriented ones that are better suited for non-ocean surfaces. One of them is optimized for sea ice, the so-called **sea ice retracker**.

- The **brightness temperature** from the **MWR** (dual-channel microwave radiometer operating at **23.8 GHz** and **36.5 GHz** to measure the tropospheric water vapour path delay correction for RA-2 altimeter) can be contribute to the classification of sea ice (**type and age).**

- Microwave radiometers are very sensitive receivers (passive sensors) designed primarily to measure the thermal electromagnetic radiation (expressed in the form of brightness temperature) emitted by atmospheric gases. Equipped with **multiple receiving channels**, they allow to derive the characteristic emission spectrum of the atmosphere.





Sea Ice Classification

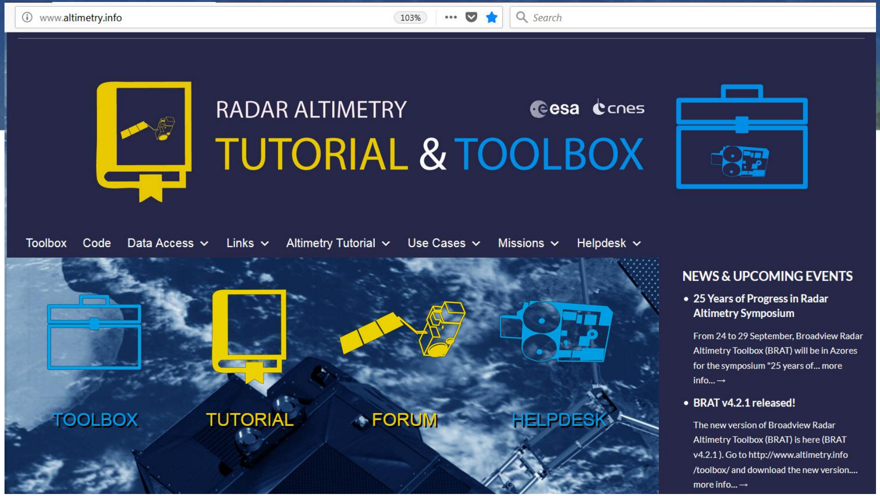
- The Broadview Radar Altimetry Toolbox (BRAT) can be used to **analyse sea ice changes**.

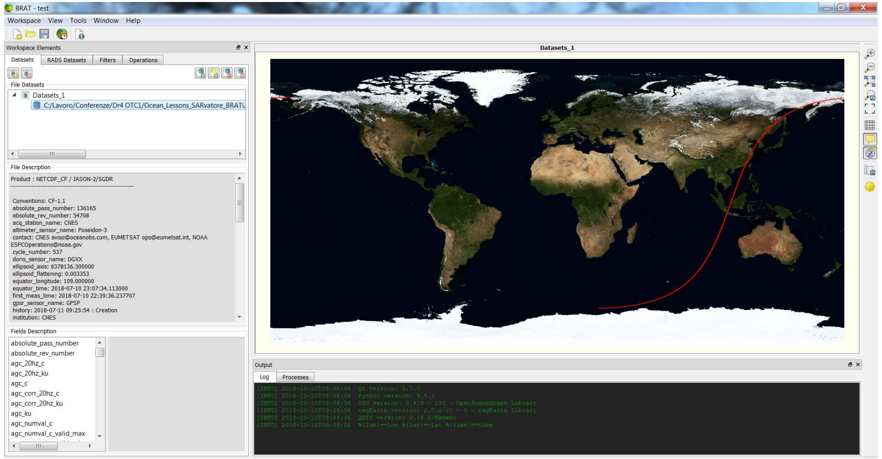
- We use data from **winter 2004** (**Envisat** cycle 025). Envisat altimeter (RA-2) and microwave radiometer (MWR) data can be downloaded from ESA.

- In order to compute the brightness temperatures only on Polar Regions, areas between 50°N and 82.5°N and between 50°S and 82.5°S are considered.

- A **land mask** to **exclude data acquired over continents** will be used.

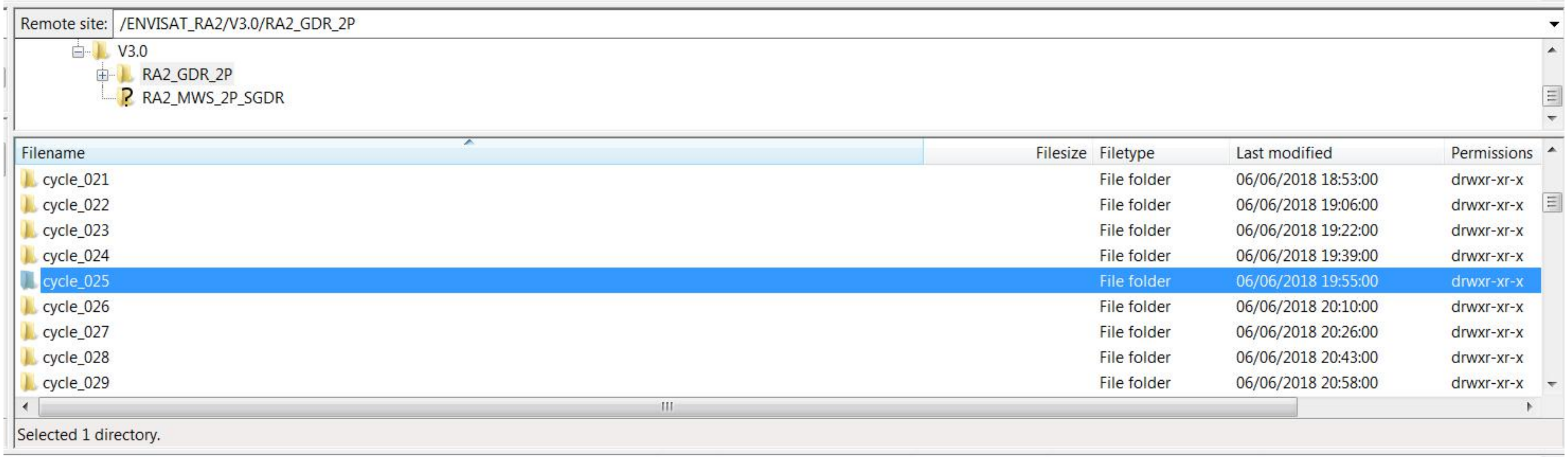
- Please consider the material presented during the BRAT practical as a starting point for the next exercises.





ENVISAT Data Access

- ENVISAT data can be found on the FTP: ra2-ftp-ds.eo.esa.int
- Credentials to access the FTP shall be requested at: https://earth.esa.int/web/guest/data-access/how-to-access-esa-data
- ENVISAT Data used in these exercise can be found in the path below (Each cycle: **35 days ->501 orbits**).



Filename	Filesize	Filetype	Last modified	Permissions
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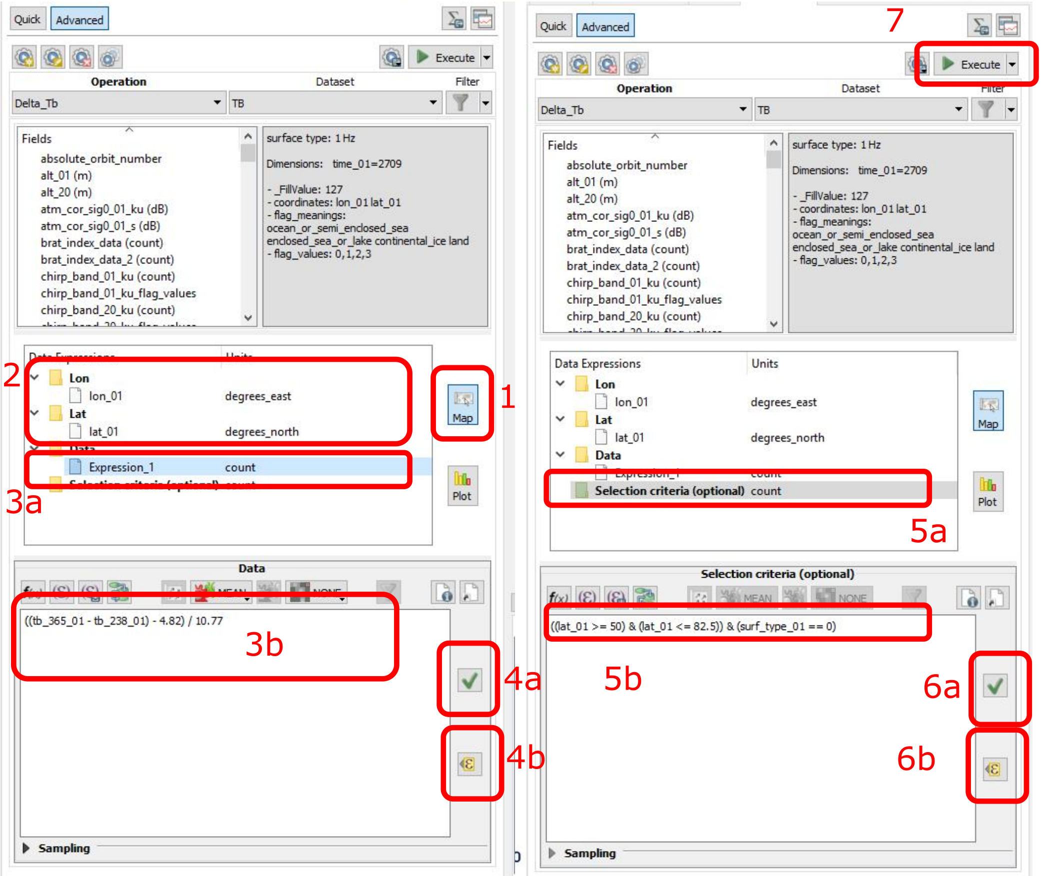
cycle_022		File folder	06/06/2018 19:06:00	drwxr-xr-x
cycle_023		File folder	06/06/2018 19:22:00	drwxr-xr-x
cycle_024		File folder	06/06/2018 19:39:00	drwxr-xr-x
cycle_025		File folder	06/06/2018 19:55:00	drwxr-xr-x
cycle_026		File folder	06/06/2018 20:10:00	drwxr-xr-x
cycle_027		File folder	06/06/2018 20:26:00	drwxr-xr-x
cycle_028		File folder	06/06/2018 20:43:00	drwxr-xr-x
cycle_029		File folder	06/06/2018 20:58:00	drwxr-xr-x

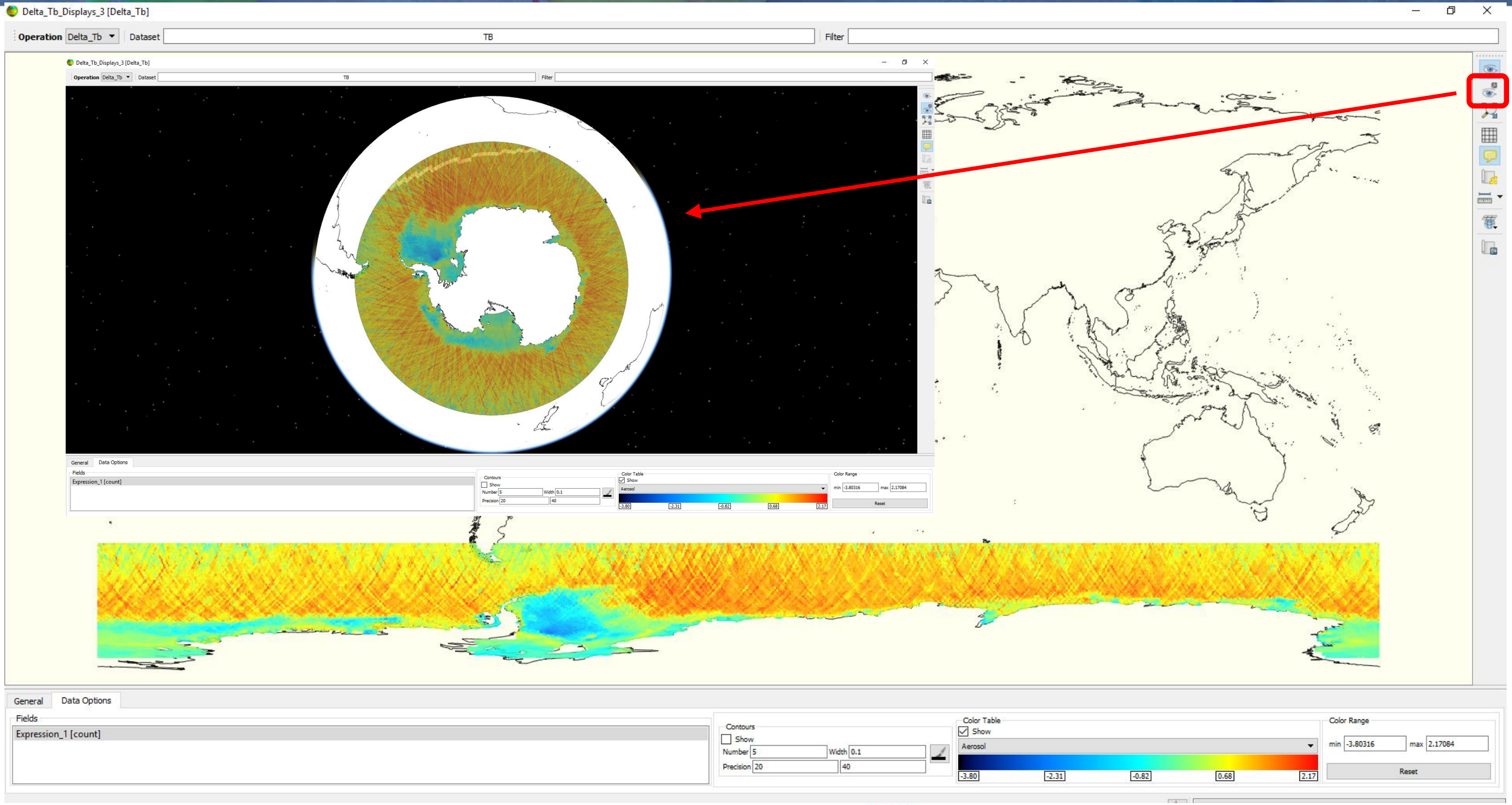
Selected 1 directory.

Sea Ice Classification in BRAT (1)

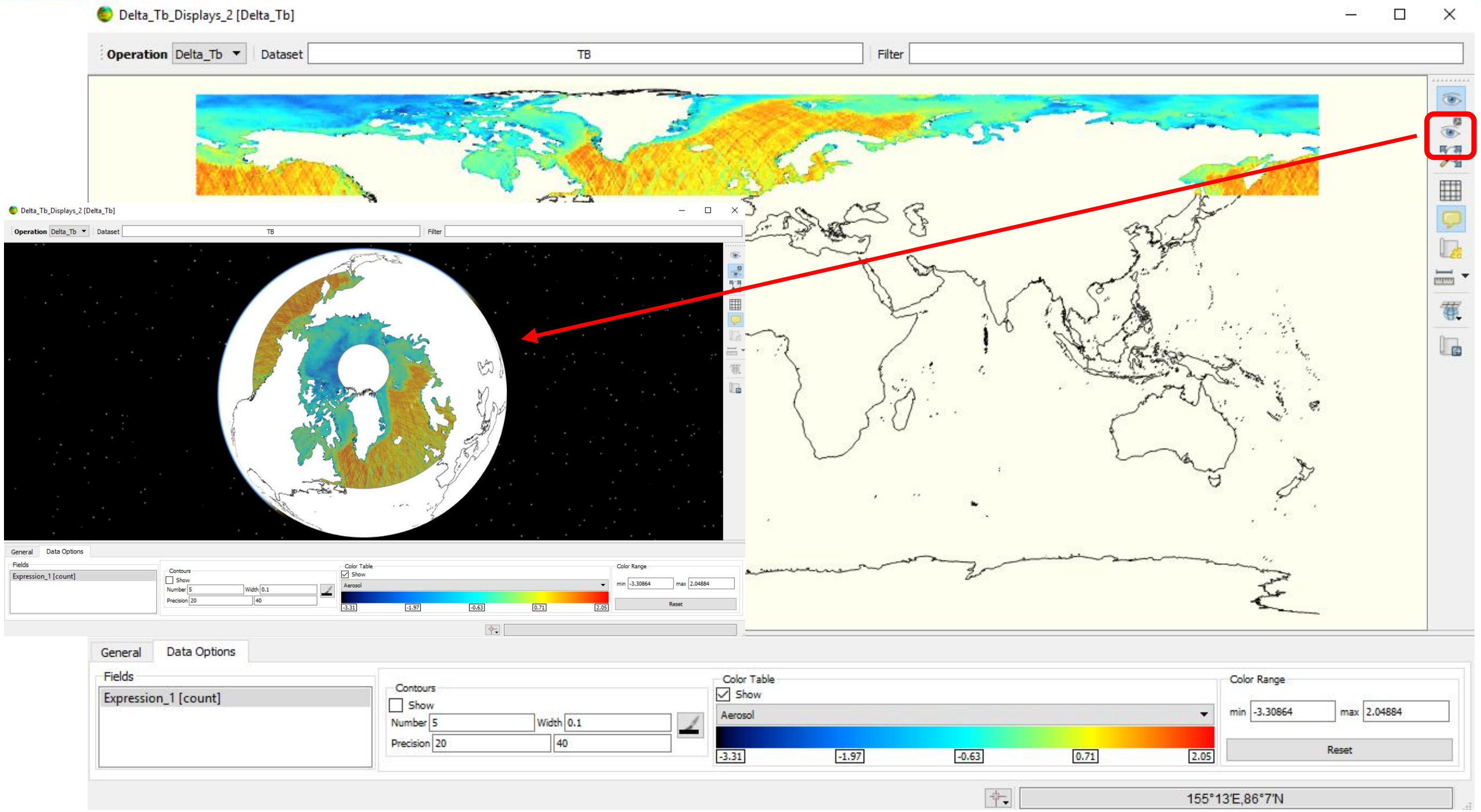
- 1. Select the **Map** mode
- 2. Fill the **Lon**, **Lat** and as showed.
- 3a & 3b. Create an **empty expression** (Data-> right click) for the Data field and make the normalized difference (**ΔTB**) between the two brightness temperatures **((tb__365_0.1 – tb_238_0.1) – 4.82) / 10.77**.
- 4a & 4b. **Check** & **save** the operation.
- 5a & 5b. Insert a "**selection criteria**" selecting the latitude band **(lat_01 >= 50) & (lat_01 <= 82.5)** to include **Greenland** and excluding the data on land by using the surface_type_flag (**surf_type_01==0**).
- 6a & 6b. **Check** & **save** the operation.
- 7. Run and Plot in 2D and 3D to see results.
- Repeat the operation for **Antarctica** editing the "selection criteria" (5b) to include the latitude band **(lat_01 <= -50) & (lat_01 >= -82.5).**



Sea Ice Classification in BRAT (2) – 3D Plots

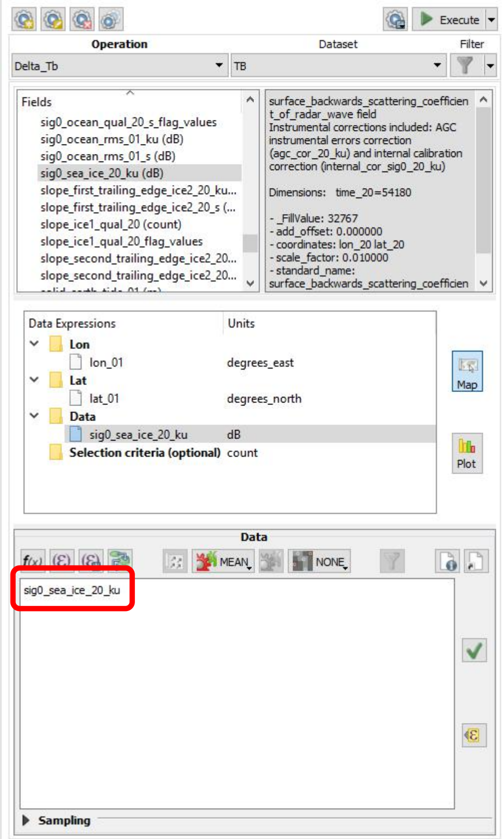


Sea Ice Classification in BRAT (3) – 3D Plots



First comments

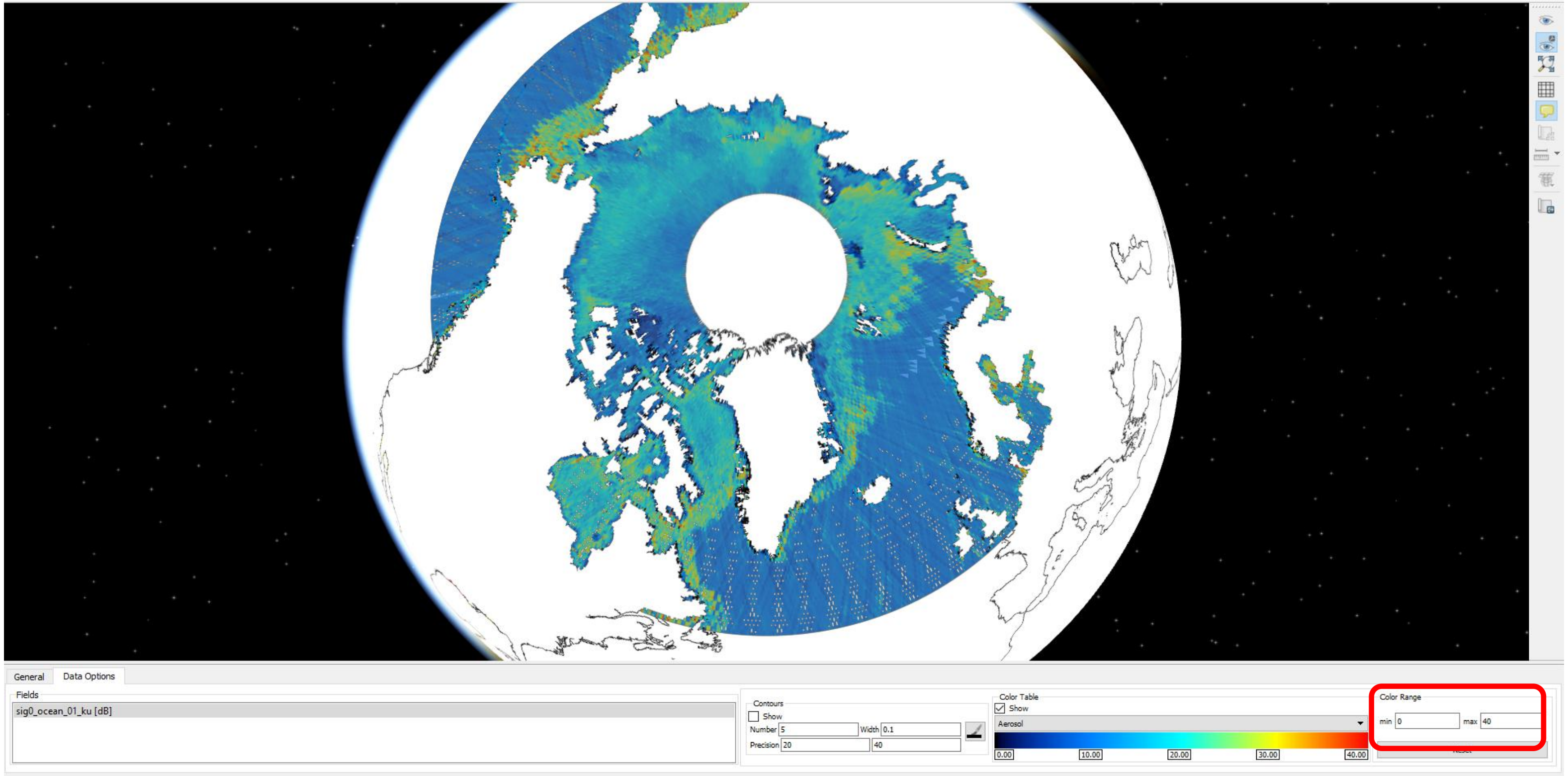
- The distribution of the ΔTBs normalized values displays several structures with negative values (in dark colours), with neutral values(in light-blue colours) and positive values (in red colours). These structures are in accordance with those shown in
    - Tran, N., Girard-Ardhuin, F., Ezraty, R., Fenf, H., Fèmènias, P., Defining a Sea Ice Flag for Envisat Altimetry Mission, in *IEEE Geoscience and Remote Sensing Letters*, Vol. 6, No. 1, January 2009.



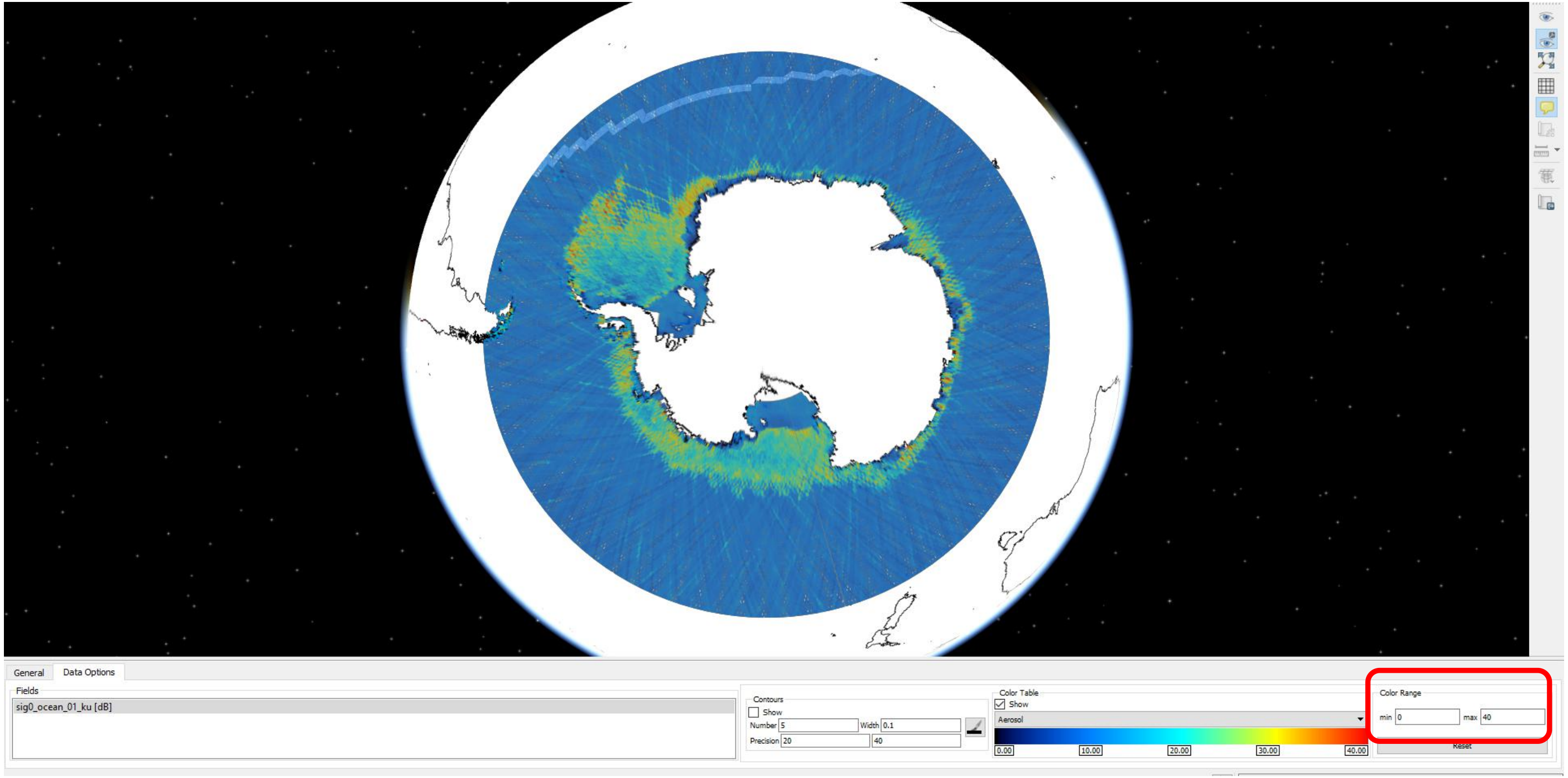
- *To **investigate ice classification** the **sigma0** shall be investigated as well.*

- *The Data expression field in the previous runs shall be modified as shown ->*

3D Plots [0, 40 dB]



3D Plots [0, 40 dB]



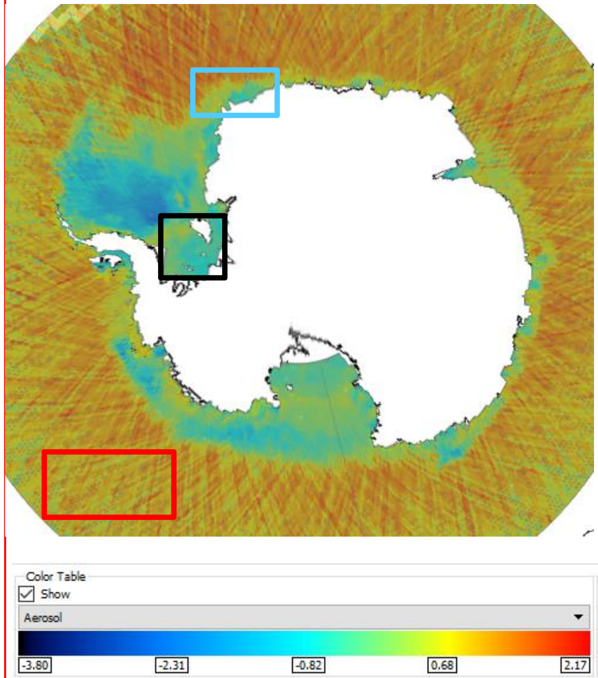
Conclusions

We can easily retrieve some of these sea ice category over our maps using the TB classification criteria selected in Tran et al. 2009 (left) and relate to altimetry (right):

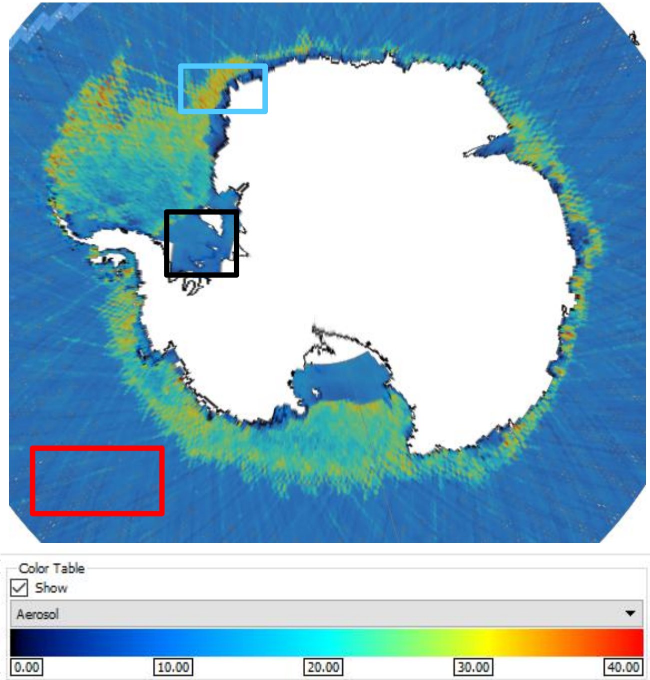
1: ice-free ocean for the highest positive ΔTB-norm values and the lowest sigma0 values (<10 dB -> the SWH is very high in this region, see the SWH global map in the next slide and comparison to the inland water case, SWH=0).

2: multi-year sea ice for the low ΔTB-norm values and low sigma0 values (0-15 dB). Old sea ice 3 m or more thick that has survived at least two summers' melt (rough structure reflecting less power) and is almost salt fre.

3: first year sea ice for neutral ΔTB-norm values and the highest sigma0 values (20-30 dB). Sea ice of not more than one winter's growth, developing from young ice, with a thickness of 30 cm to 2 m. It is almost flat if compared to multi-year sea ice and saltier (reflectivity is high).

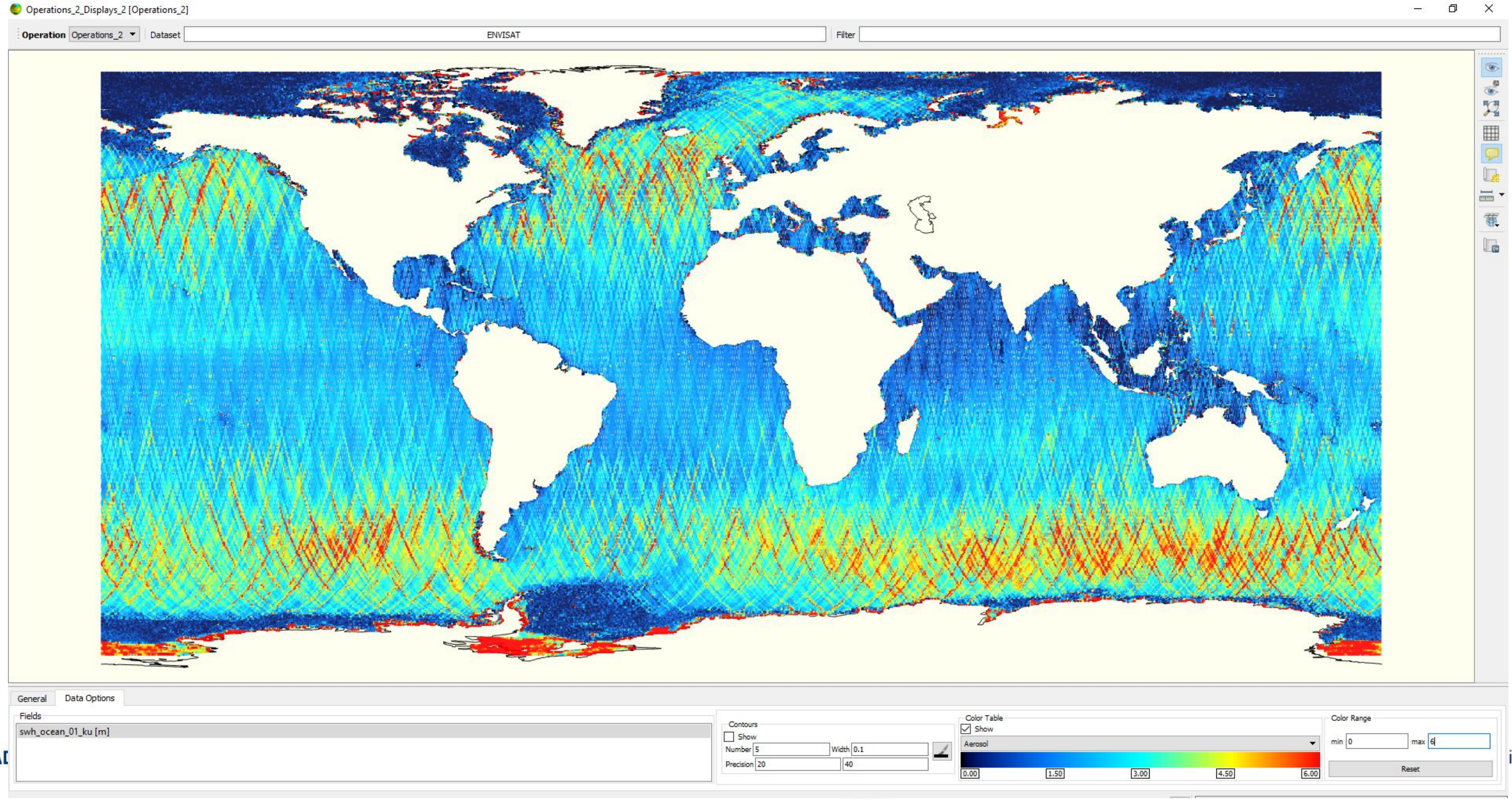


ΔTB-norm[Kelvin]



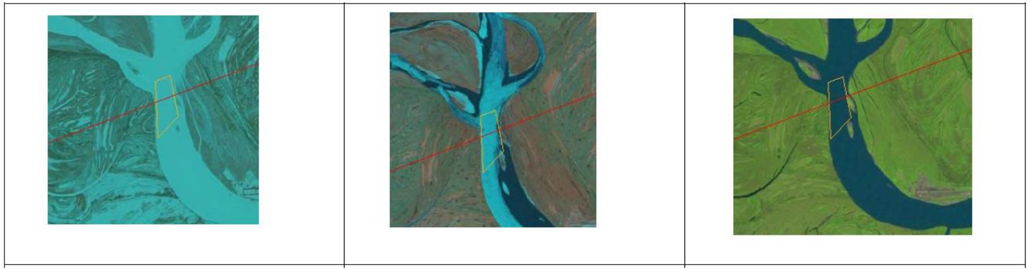
Sigma0 [dB]

SWH for ENVISAT Cycle 25 (BRAT Practical)



Sigma0 over Rivers (SWH=0, flat surface)

- Altimeter measurement of radar backscatter, σ 0, was extracted from the Jason-2 data set.
- Relative ice cover was determined visually from the Landsat image.
- Water typically returns a much higher reading than ice or land.
- Land Contamination spreads the occurrences in the **partial ice cover** and **no ice cover** cases->



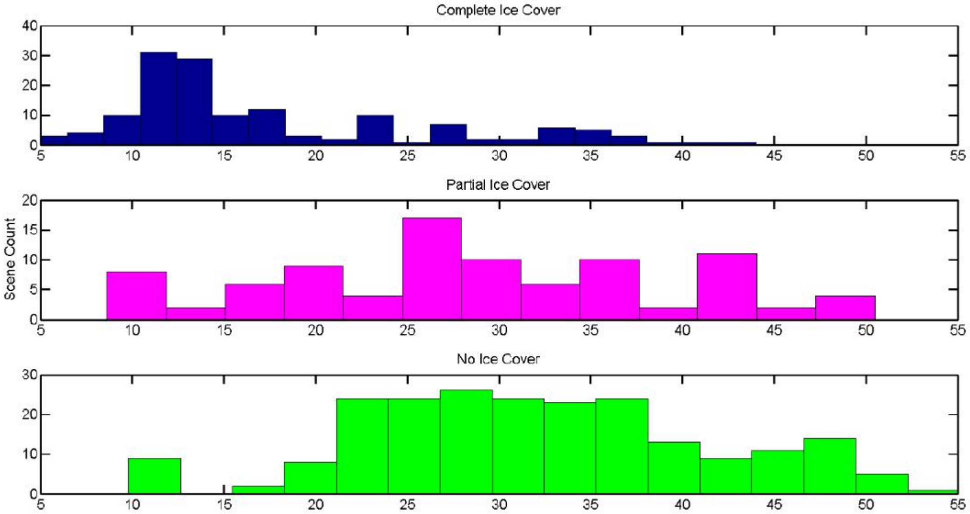


Figure 7 A histogram of σ_0 Values across all years and stations for all three classifications

Images taken from "Using radar altimeter backscatter to evaluate ice cover on the Yukon River", Stephen P. Coss, August 2015 (Research Thesis).

Wave penetration in the snowpack

The Snowpack

- The **Snowpack** forms from **layers of snow** that accumulate in geographic regions and **high altitudes** where the climate includes cold weather for extended periods during the year.

- Snowpacks are an important water resource that feed streams and rivers as they melt.

- **Stratified Layers** can include **impurities** (see the brown stratification in the box). Such layers have **different physical properties** (permittivity **ε**, conductivity **σ…**) if compared to pure ice.

- A radar wave is **reflected & transmitted at the interface** of two media having **different physical characteristics** (e.g. *air-water interface* or *pure_ice-impure-ice* interface).

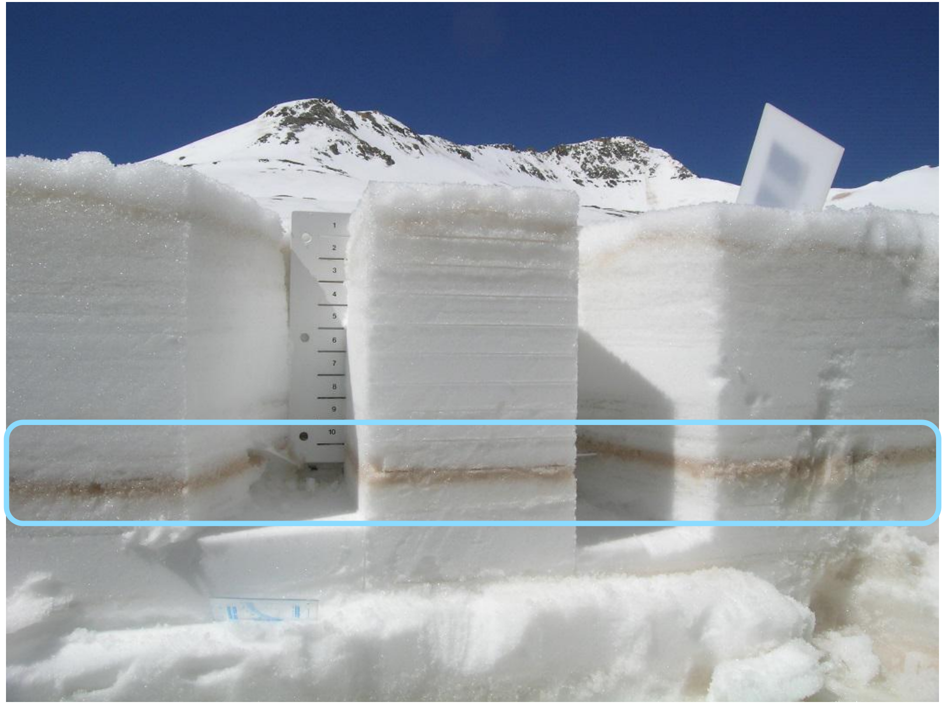


Image credit:
https://www.strafeouterwear.com/blog/spring-fever/

Ku-Band vs S-Band / Retracking Strategies

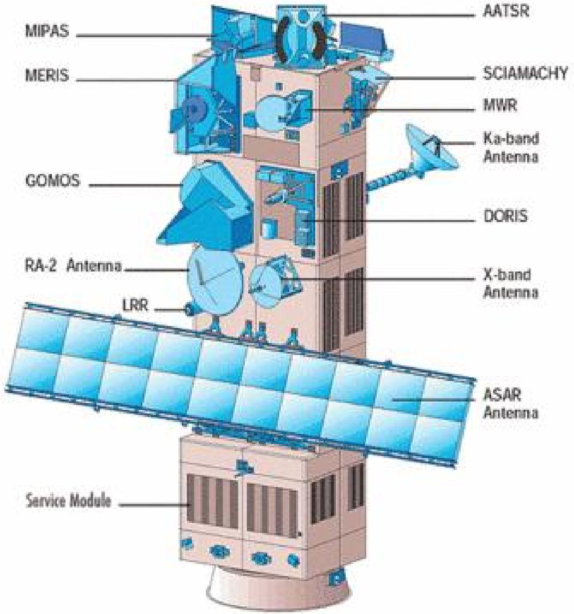
- The Envisat mission (**-82.5°S / 82.5°N**) is well adapted and able to accurately **map 80% of Antarctica** and almost all the Greenland.

- The RA-2 altimeter on Envisat platform is a **dual-frequency radar** operating at **Ku-band (13.575 GHz)** and at **S-band (3.2 GHz)**.

- This **dual-frequency** can be used for better **quantify wave penetration in the snowpack** and improve the knowledge of the ice sheets surface topography evolution.

- For RA-2 data alternative retracking algorithms, better suited for non-ocean surfaces, are available. One of them is optimized for **ice surfaces**, the so-called **ICE-2 retracker**.

- In the next exercise, estimates from the **Ocean** and **ICE-2 retrackers** will be discussed.

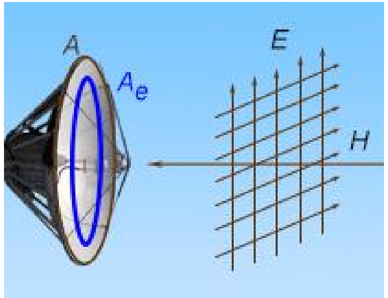


Radar Band	Frequency	Notes
HF	3 - 30 MHz	High Frequency
VHF	30 - 300 MHz	Very High Frequency
UHF	300 - 1000 MHz	Ultra High Frequency
L	1 - 2 GHz	
S	2 - 4 GHz	
C	4 - 8 GHz	
X	8 - 12 GHz	
Ku	12 - 18 GHz	
K	18 - 27 GHz	
Ka	27 - 40 GHz	

Antenna Aperture

- The RA-2 altimeter on Envisat platform is a **dual-frequency radar** operating at **Ku-band (13.575 GHz)** and at **S-band (3.2 GHz)**.

- The **effective antenna aperture (receiving cross section)** is the area over which the antenna collects the power of a plane wave and changes with the transmitted frequency:



$$A_e = \frac{\lambda^2}{4\pi} G$$

- For a gain **G** of 50 dB, $\mathbf{A_e}$ will be wider for the S-Band (80 m^2) than for the Ku-Band (3.17 m^2). **S-Band estimates will be related to a wider area**.

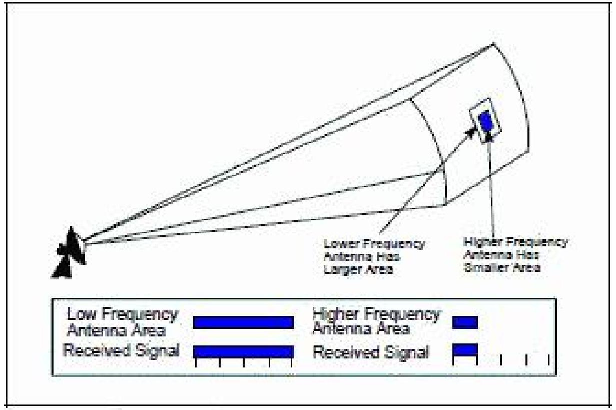


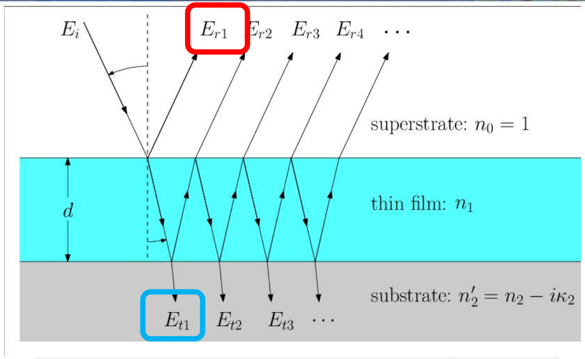
Figure 2. Capture Area vs Frequency

Radar Band	Frequency	Notes
HF	3 - 30 MHz	High Frequency
VHF	30 - 300 MHz	Very High Frequency
UHF	300 - 1000 MHz	Ultra High Frequency
L	1 - 2 GHz	
S	2 - 4 GHz	
C	4 - 8 GHz	
X	8 - 12 GHz	
Ku	12 - 18 GHz	
K	18 - 27 GHz	
Ka	27 - 40 GHz	

Propagation in the ice

- Once the transmitted wave reaches the interface (air/ice), the generation of the reflected ($\boldsymbol{E_{r1}}$) and transmitted ($\boldsymbol{E_{t1}}$) waves is governed by

- 1) The electric field impacting the interface $\boldsymbol{E_i}$ from the medium having impedance $\boldsymbol{\eta_1}$.
- 2) The **Reflection** Γ and **Transmission** $(1-\Gamma)$ coefficients related to the impendence of the media $(\boldsymbol{\eta_2}, \boldsymbol{\eta_1})$. These can be conductive, lossy or lossless (e.g. air).
- 3) The attenuation **α(z)** and propagation **β(z)** terms in the respective media along the direction of propagation z.



$$\boldsymbol{E_{r1}} = \Gamma\, \boldsymbol{E_i}\, e^{-a_1(z)\,-j\beta_1(z))} \qquad \boldsymbol{E_{t1}} = (1-\Gamma)\, \boldsymbol{E_i}\, e^{-a_2(z)\,-j\beta_2(z)}$$

$$\alpha(z) = \sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}}\frac{\sigma}{2}z = \alpha\cdot z$$

$$\Gamma = \frac{\eta_2-\eta_1}{\eta_2+\eta_1} \quad -> \quad \eta_{1(lossless)} = \sqrt{\mu/\varepsilon} \qquad \eta_{2(lossy)} = 1 + j\sqrt{\omega\mu/2\sigma}$$

$$\beta(z) = \frac{\omega}{c}\sqrt{\mu_r\varepsilon_r}\, z = \beta\cdot z$$

- Considering the ice having complex permittivity **ε = ε′ + jε′′**, the attenuation **α(z)** is governed by the conductivity **σ** (low-loss medium,*see figure), which increases with frequency **ω=2πf** and is temperature-dependent.

- As RA-2 on Envisat operates at **Ku-band (13.575 GHz)** and **S-band (3.2 GHz)**, **the Ku-band waves will be more attenuated**.

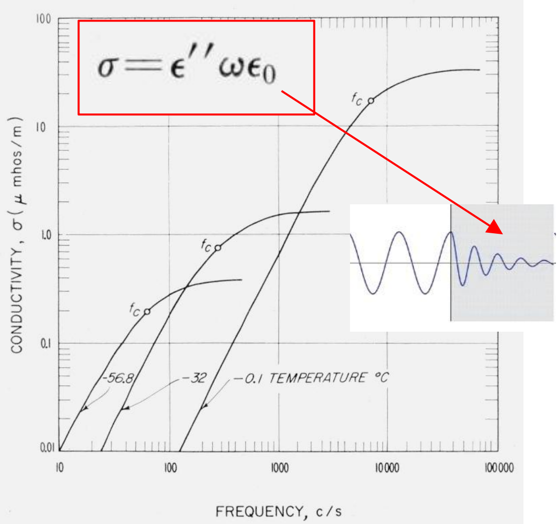
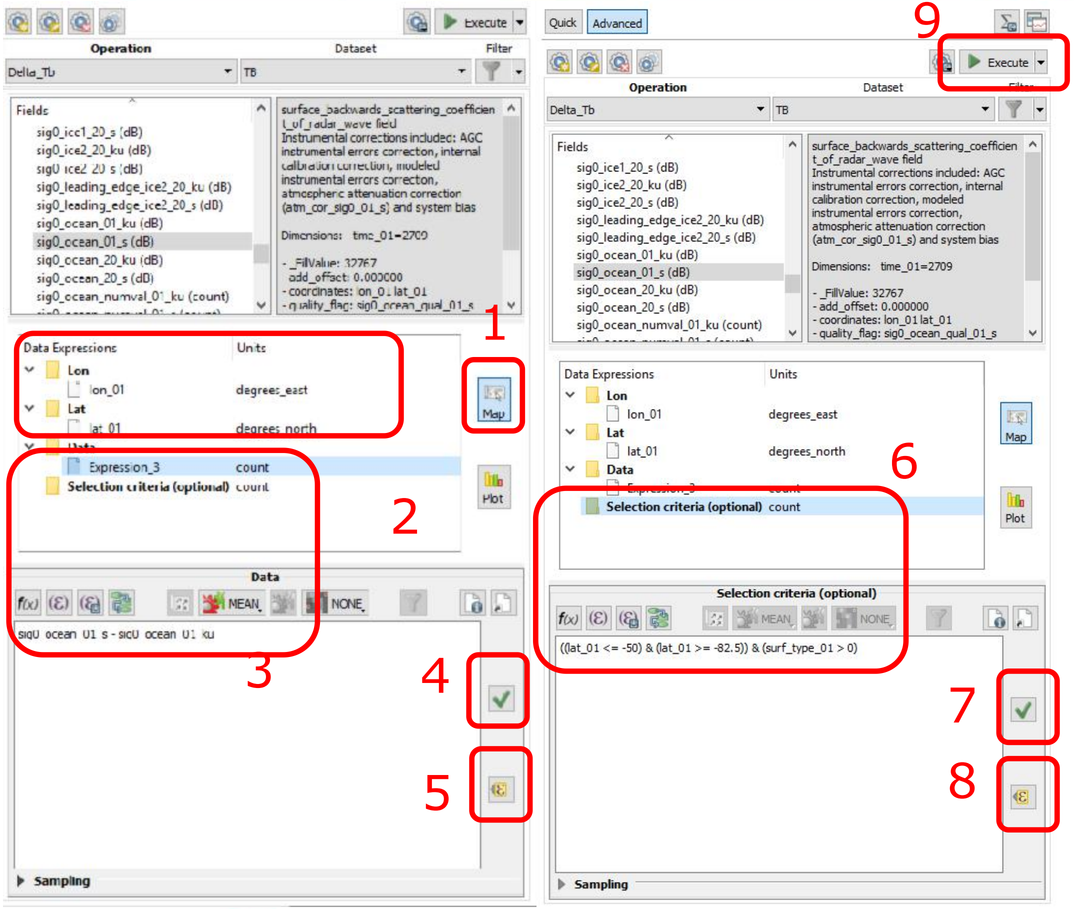


FIGURE 7. Conductivity of pure ice.

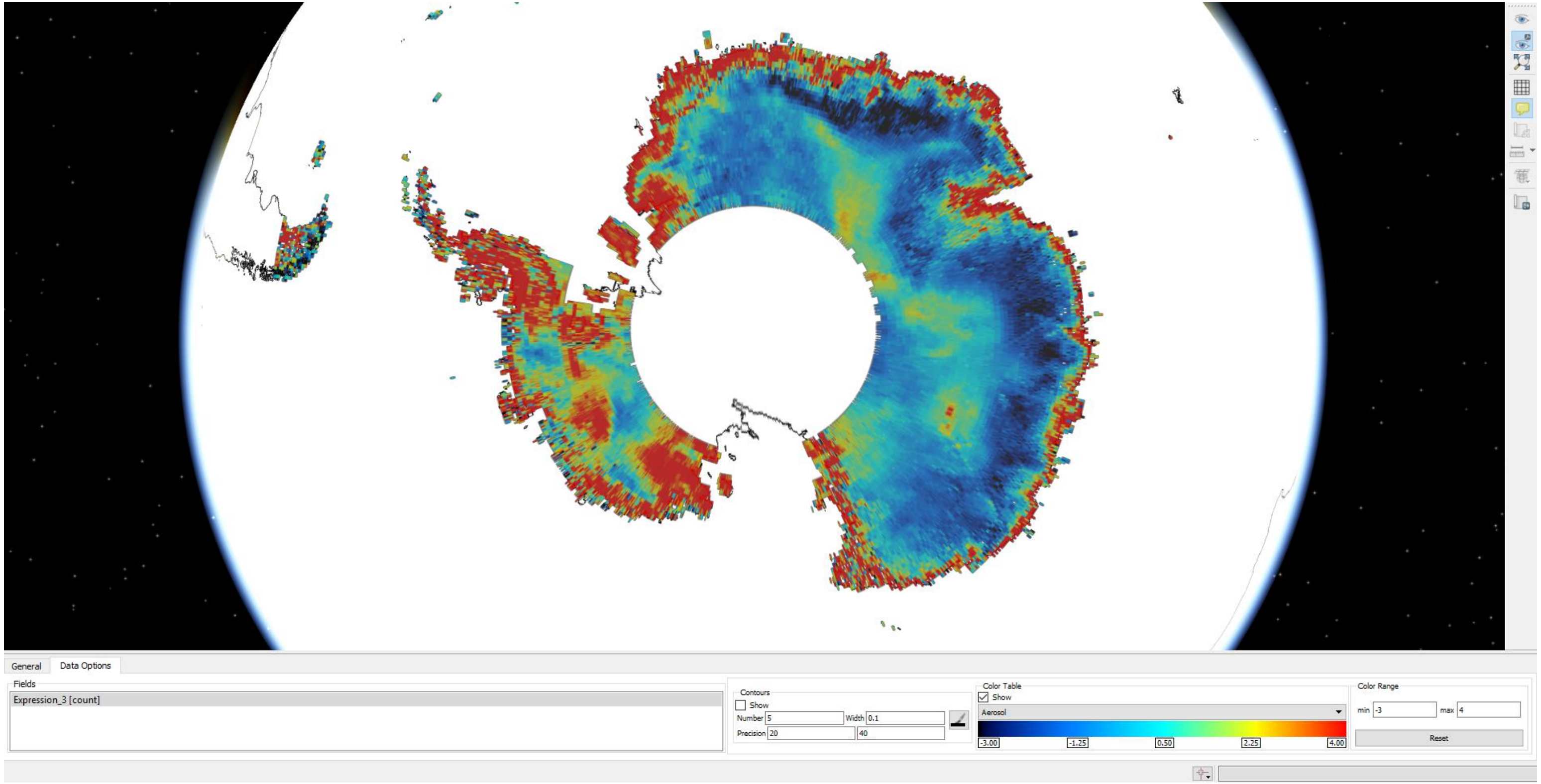
* Watt and Maxwell, Measured Electrical Properties of Snow and Glacial Ice, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation Vol. 64D, No. 4, July- August 1960

Wave penetration in the snowpack

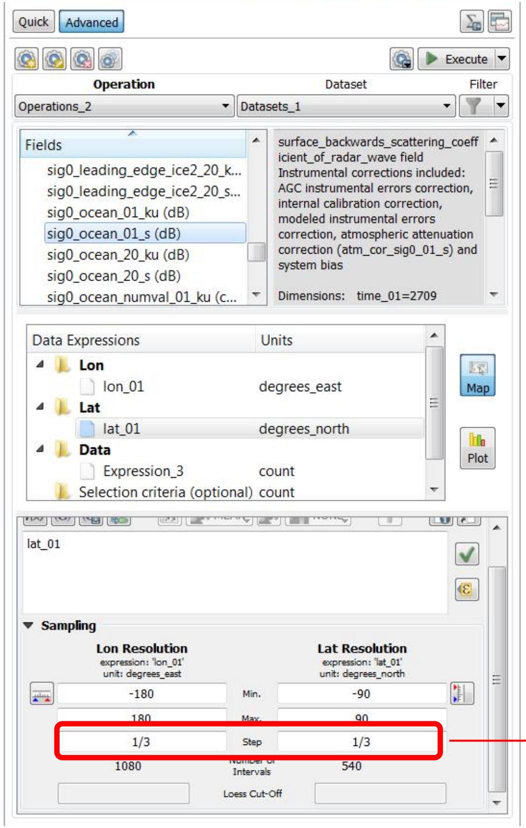
- 1: Select the **Map** mode
- 2: Fill the **Lon**, **Lat** and as showed.
- 3: Create an expression for the Data field and make the difference between the two sigma0 values: **sigma0_ocean_01_s - sigma0_ocean_01_ku**.
- 4-5: Check & save the operation.
- 6: Insert a "**selection criteria**" selecting the latitude band (**lat_01 <= -50**) & (**lat_01 >= -82.5**) to include Antarctica and excluding the data on the ocean by using the surface_type_flag (**surf_type_01>0**).
- 7-8: **Check** & **save** the operation.
- 9: Run and Plot in 2D and 3D to see results.

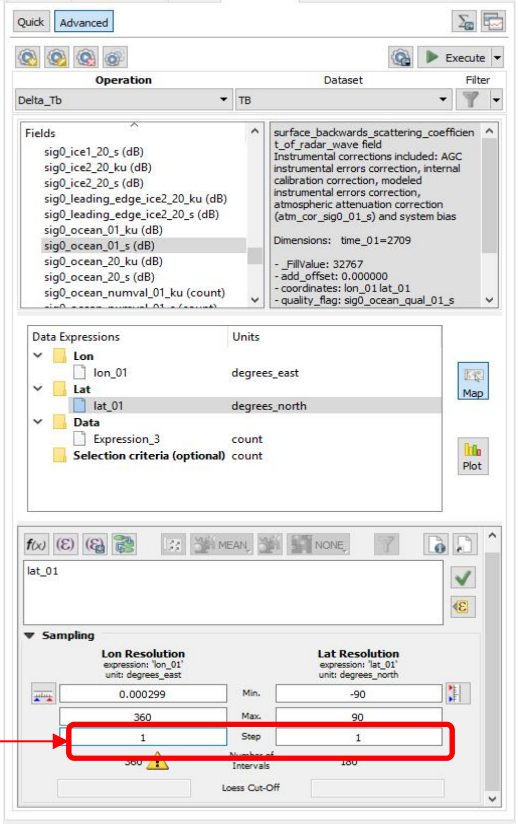


Wave penetration in the snowpack (2)

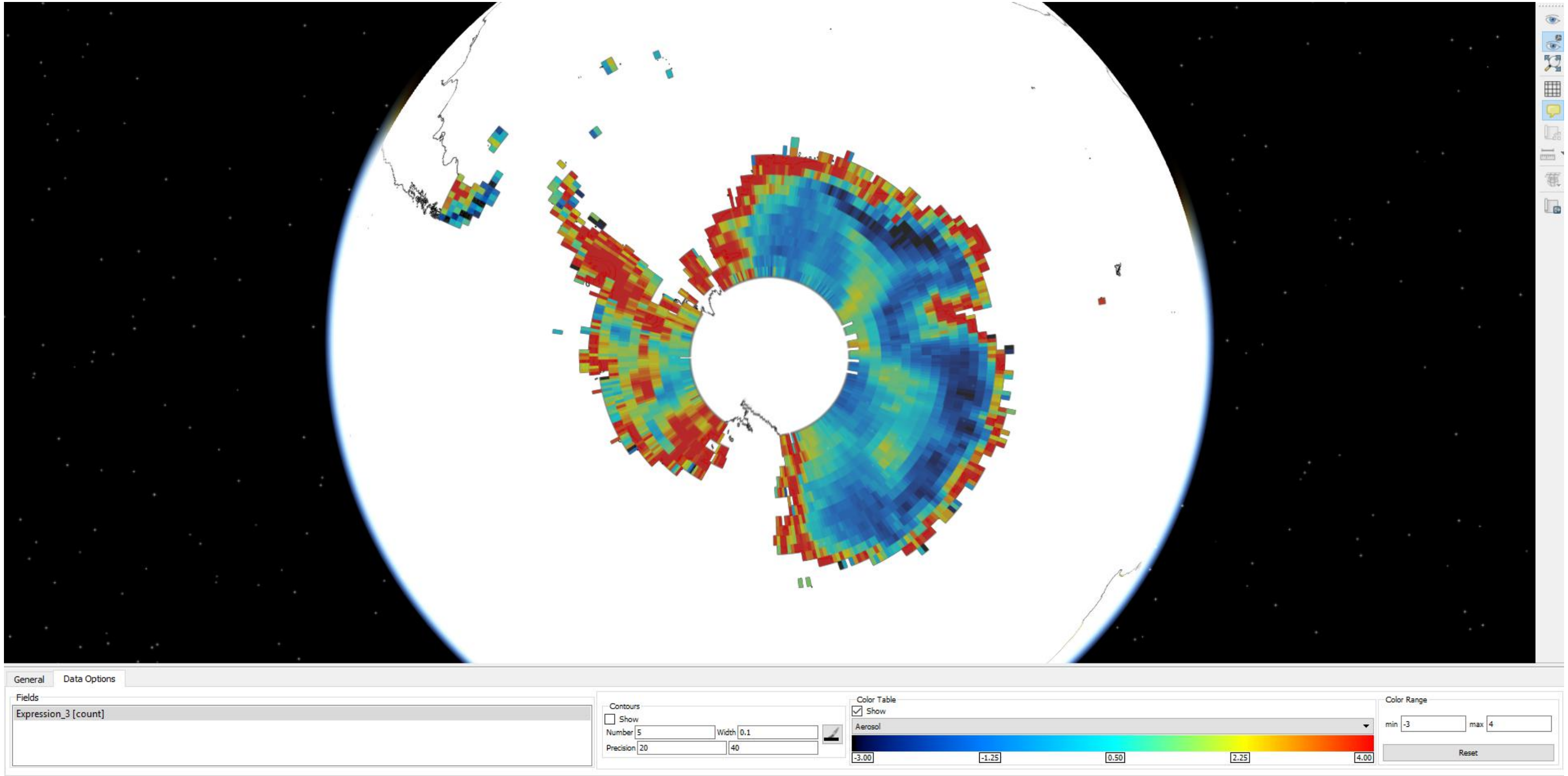


Modify the sampling

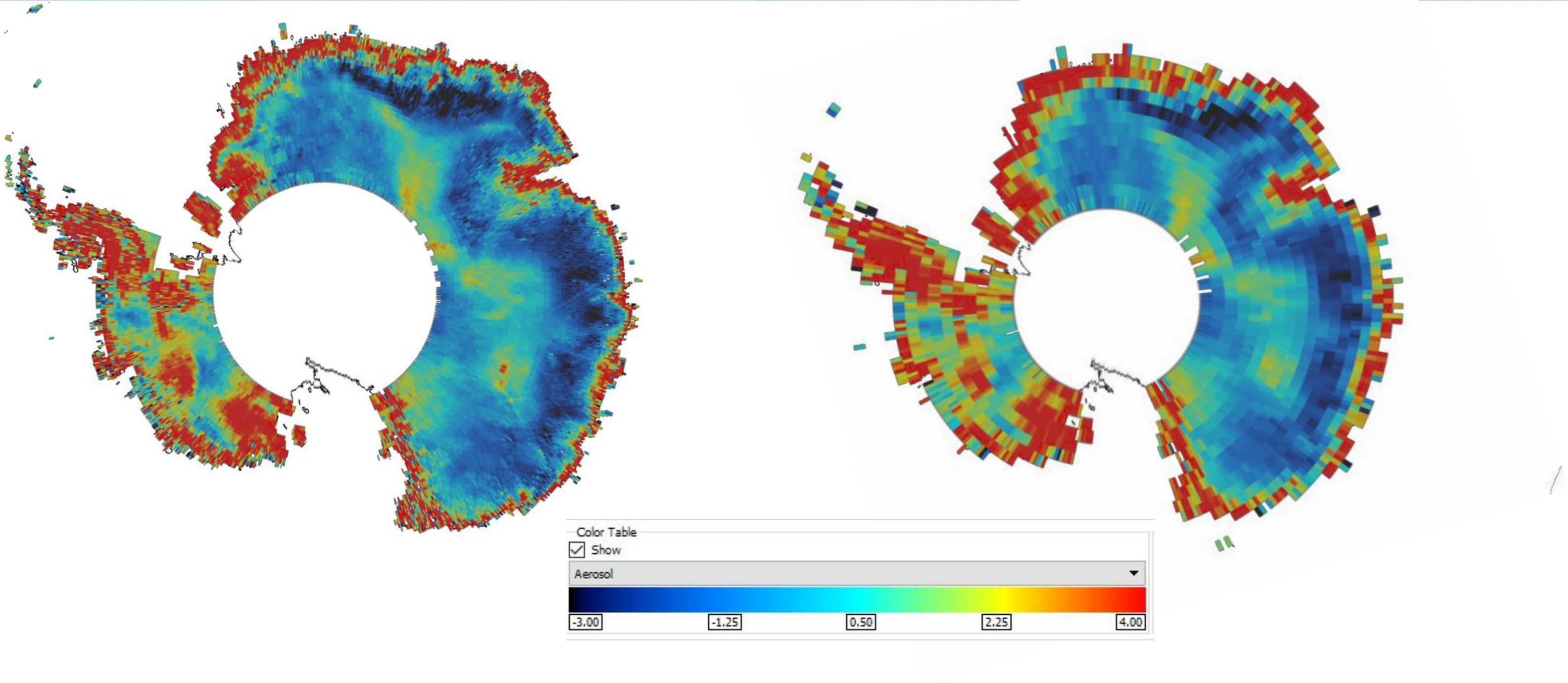




Modify the sampling (2)



Ocean Retracker - Results



Sigma0 difference (in dB) between the S- and the Ku-bands over Antarctica for cycle 25 (two different geographical resolutions: 1/3° on the left and 1° on the right).

Ocean Retracker – Results (2)

Coastal areas: lower altitude, higher roughness and surface slope.

Inland areas: higher altitudes, lower roughness and surface slope.

S-Band: Lower frequency -> deeper penetration, less affected by the surface slope thanks to the wider antenna aperture.

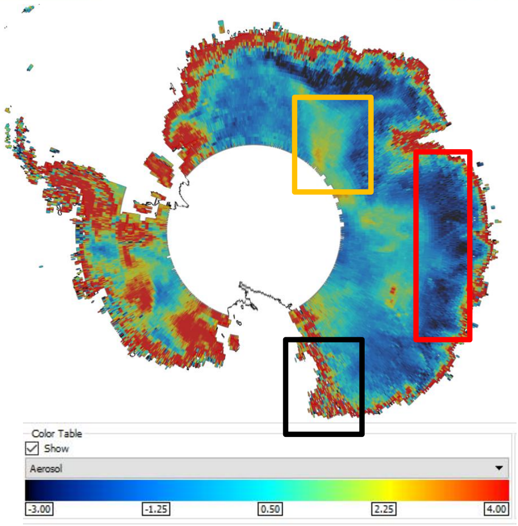
Ku-Band: Higher frequency -> lower penetration, more affected by the surface slope because of the narrower antenna aperture.

Δ = (S-Band - Ku-Band) -> to investigate the different echoing physics.

Δ>0 over high altitude where the surface is flat: waves are less attenuated in S-band and the flat stratification produces many coherent returns in the nadir direction increasing the power with respect to Ku-band (penetrating less and integrating less power as the antenna aperture is narrower).

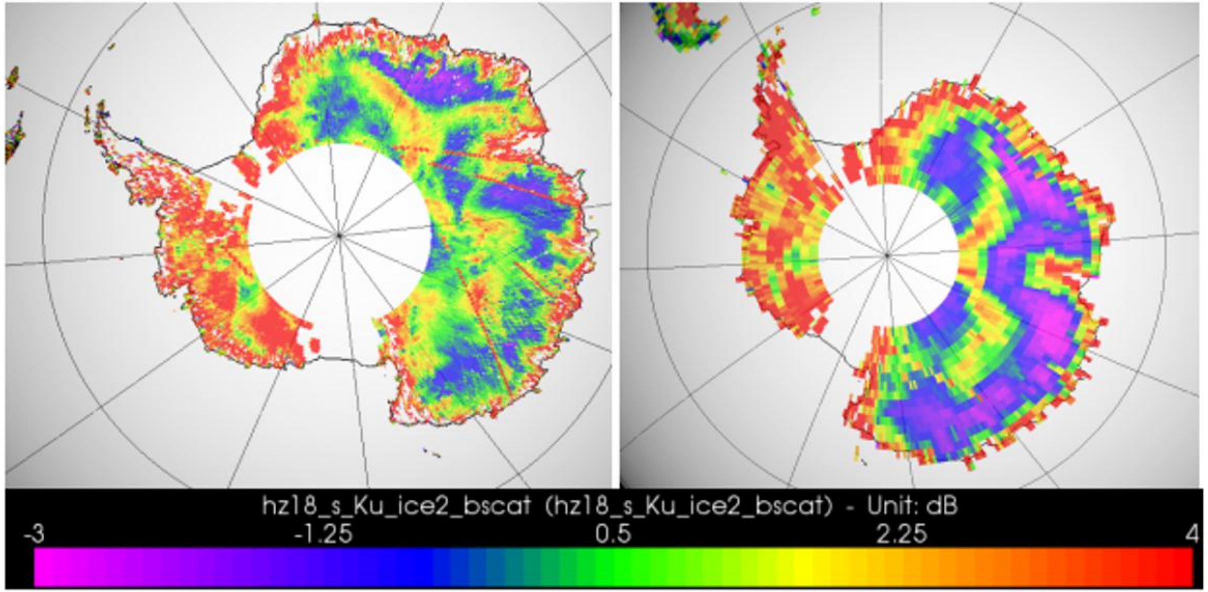
Δ<0 over windy and snow depositional areas: the S-band integrates less power because of the rough surface (incoherent scattering). The waveforms penetrates more but the energy is backscattered in other directions resulting in a reduced power in comparison to Ku-band (penetrating less).

Δ>0 at the coast: melting/refreezing produces a specular reflection on steep slopes. <u>When slopes are greater than the antenna aperture, the received energy is very low</u>. As the S-Band has a wider antenna aperture, it is less affected by the slope and collects more power than Ku-band.



Radar Band	Frequency	Notes
HF	3 - 30 MHz	High Frequency
VHF	30 - 300 MHz	Very High Frequency
UHF	300 - 1000 MHz	Ultra High Frequency
L	1 - 2 GHz	
S	2 - 4 GHz	
C	4 - 8 GHz	
X	8 - 12 GHz	
Ku	12 - 18 GHz	
K	18 - 27 GHz	
Ka	27 - 40 GHz	

Ice-2 Retracker - Results



Sigma0 difference (in dB) between the S- and the Ku-bands over Antarctica, from Envisat cycle 034 (left) and 040 (right). As before, two different geographical resolutions: 1/3° (on the left) and 1° (on the right) are reported. Conclusions are the same reported in the previous slide.

Impact on the Leading Edge
(Exercise from the Radar Altimetry Tutorial)

Ice-2 Retracker – Leading Edge Width (LEW)

- The **leading edge width (LEW)** is scenario-dependent. Comparing to ocean waveforms, land ice waveforms have a wider leading edge in LRM mode.

- ENVISAT products include the leading edge width, that can be investigated in BRAT.

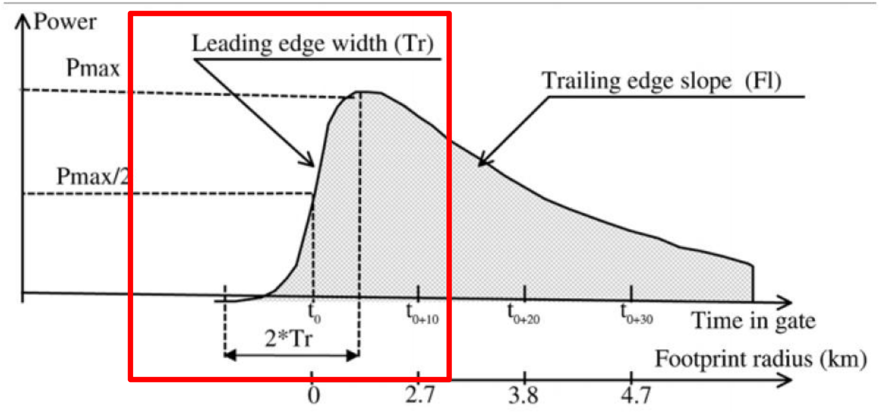
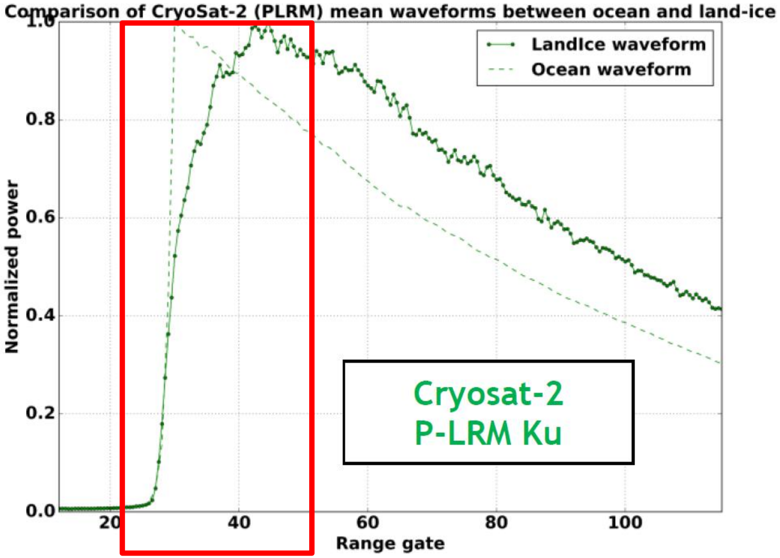


Figure 3. Waveform parameters description. From this waveform, the altimetric height, the backscattering coefficient related to the waveform integral (in dB), the half leading edge width, expressed in meters, and the trailing edge slope in a logarithmic scale are extracted. The corresponding kilometer scale of the temporal footprint evolution is also given.



Ice Sheet And Satellite Altimetry, Rémy, F., Legresy, B. & Testut, L.
Surveys in Geophysics (2001) 22: 1. https://doi.org/10.1023/A:1010765923021

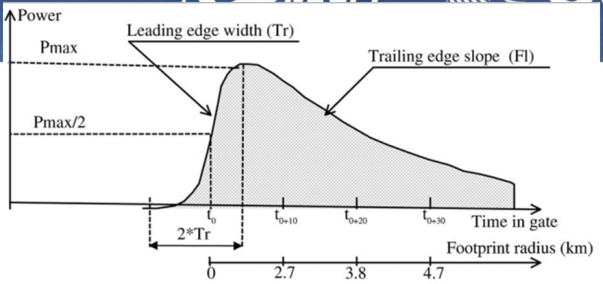
Ice-2 Retracker – Leading Edge Width (LEW)

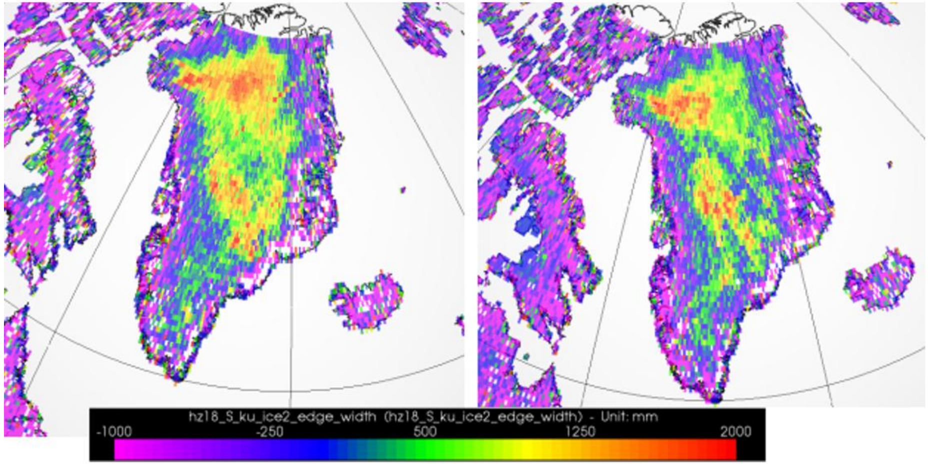
The **leading edge width (LEW),** available in ENVISAT products for both S and Ku Bands**,** is related to:

- 1) the **penetration into the medium** (S-band penetrates more)
- 2) the **surface roughness** (Ku band is more sensitive having higher frequencies).

Results in the figure:

- The leading edge width (Tr, top figure) in S-band tends to have smaller values than the Ku-band one toward the coastal areas over Greenland **(Ku band is more sensitive to roughness)**.
- On the contrary, the leading edge width (Tr, top figure) in S-band has higher values on the plateau and its distribution seems to be lightly larger during winter (Envisat cycle 034, left).
- The **SPICE Project** has investigated the interaction with the snowpack on LRM and SAR waveforms considering both **CryoSat-2** & **SARAL/AltiKa** data.

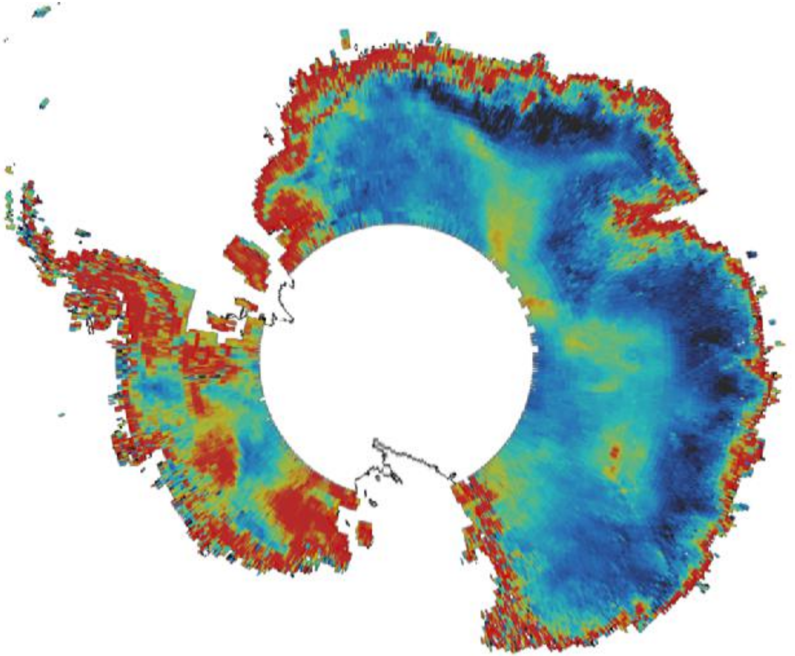




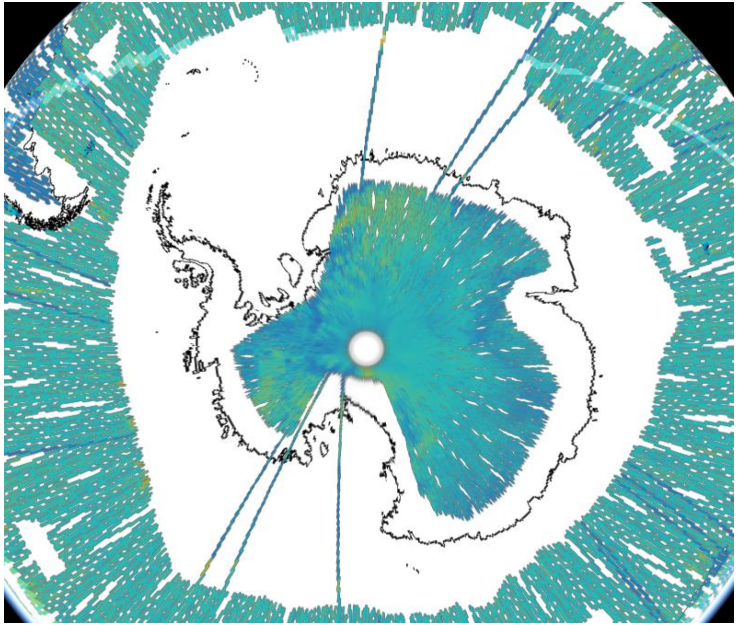
Plot in BRAT of Δ|LEW = (S_Band|LEW – Ku_Band|LEW) in southern winter (Envisat cycle 034 –left-, Jan.-Feb. 2005) and in southern summer (Envisat cycle 040 -right-, August-Sept. 2005). Roughness increase toward the coast.

CryoSat-2 Coverage & Mode Mask

CryoSat-2 vs. ENVISAT Coverage



ENVISAT [Lat:+/- 82.5°]



CryoSat-2 [Lat: +/- 88°]

CryoSat-2 Mode Mask

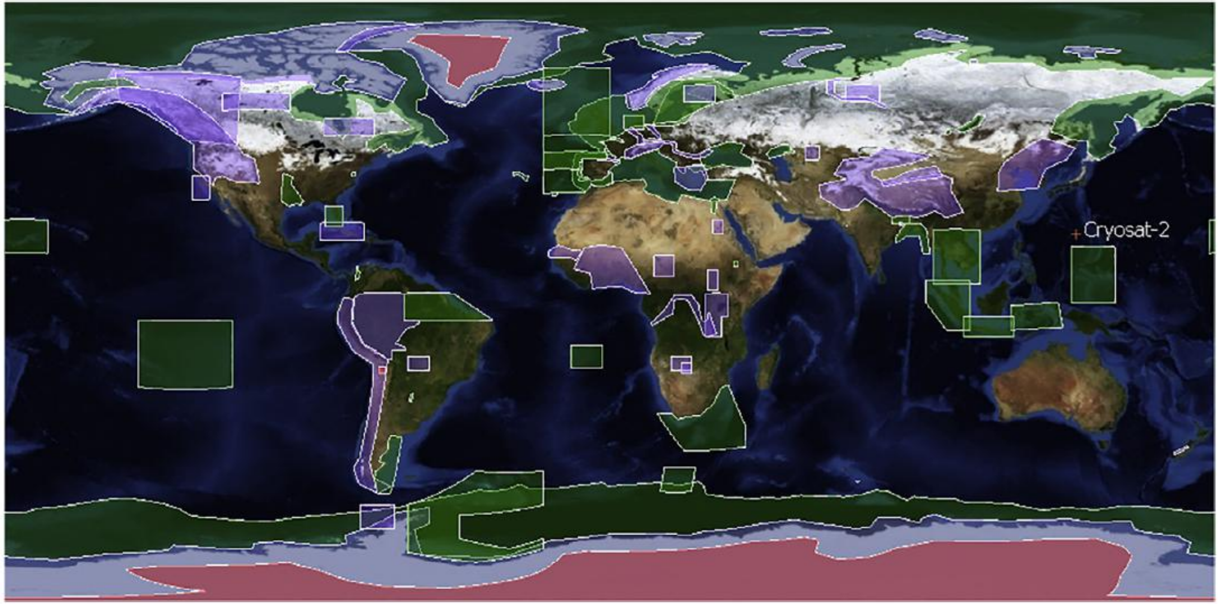


Fig. 4. Geographical mode mask 3.9. CryoSat is designed to acquire continuously while revolving around our planet, switching automatically to its three measurement modes according to a geographic mode mask. SAR (green) is operated over sea-ice areas and over some ocean basins and coastal zones. SARIn) (purple) mode is used over steeply sloping ice-sheet margins, over some geostrophic ocean currents and over small ice caps and areas of mountain glaciers. It is also used over some major hydrological river basins. LRM is operated over areas of the continental ice sheets (red), over oceans and over land not covered by other modes. Credits (ESA). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Image credit: Parrinello, T., et al. CryoSat: ESA's ice mission – Eight years in space. Adv. Space Res. (2018), https://doi.org/ 10.1016/j.asr.2018.04.014

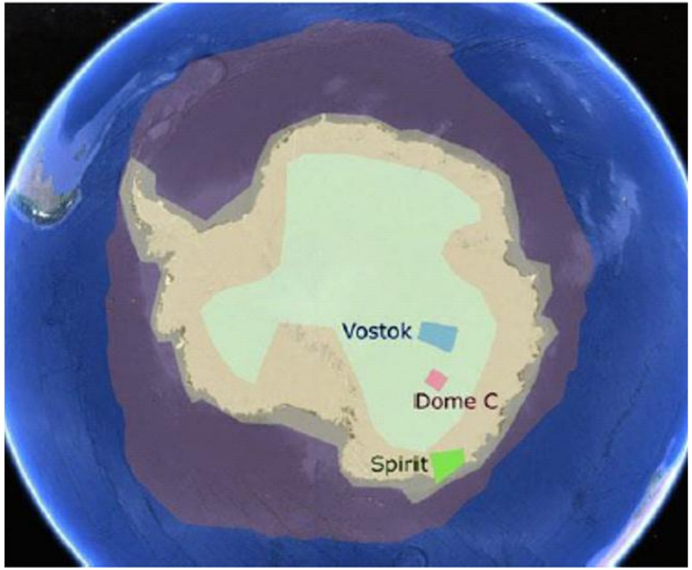
SPICE
Sentinel-3 Performance Improvement for Ice Sheets

Malcolm McMillan, Roger Escolà, Mònica Roca, Pierre Thibaut, Jeremie Aublanc, Andrew Shepherd, Frédérique Remy

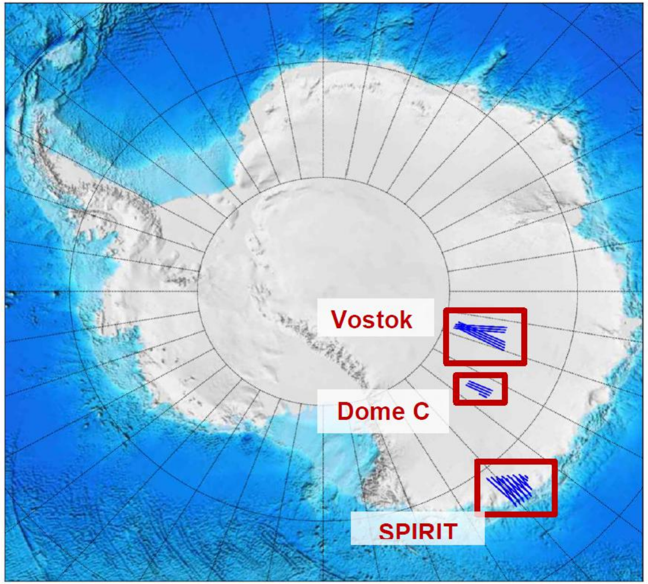
Jérôme Benveniste, Américo Ambrózio and Marco Restano

Objectives

To develop and evaluate **novel Synthetic Aperture Radar (SAR) altimetry processing methods over ice sheets**, to contribute to the future exploitation of Sentinel-3.



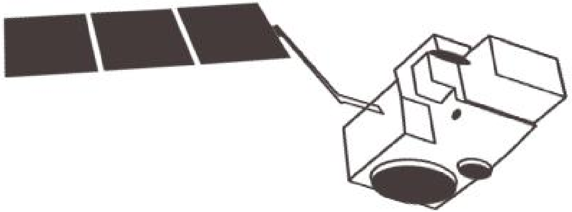
Dedicated SAR patches acquired by CryoSat-2 in 2014.



Objectives (2)

Assess and develop **SAR retracking** for ice sheets.

Assess and improve L1B **Delay-Doppler altimeter processing** for ice sheets



Assess the impact on SAR altimeter measurements of **radar wave interaction with the snowpack.**

Evaluate the performance of **SAR altimetry relative to conventional pulse limited altimetry.**

Innovative Processing Strategies

On Processing algorithms in SPICE

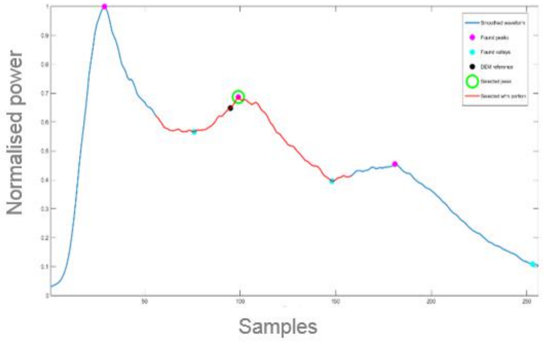
The **SPICE project** is divided in two main phases:

- **One first phase** during which Cryosat-2 SAR mode and P-LRM acquisitions are processed and evaluated using **conventional L1/L2 algorithms**.
- **One second phase** during which **innovative L1/L2 processing** are implemented and evaluated for both modes (WP3 & WP4 objectives).

Finally, based on a validation performed during WP4, the most performant processing baselines are selected to produce phase-2 dataset.

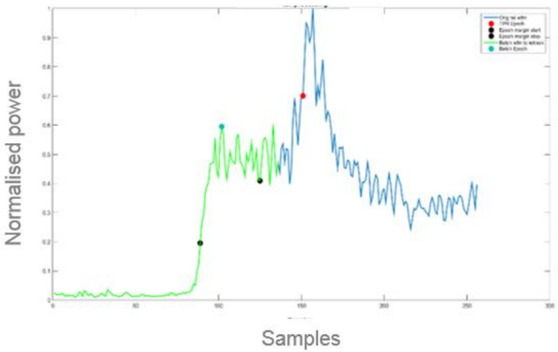
Pre-Retracking Innovation

DEM pre-retracking module



Auxiliary DEM (black dot) is used to identify the peak (red) that corresponds to the nadir reflection within a complex waveform.

Batch pre-retracking module



Batch processing uses the history of previous waveforms to maintain consistency in the peak selection, for complex multi-peaked waveforms.

- Digital elevation models (DEMs) are sets of data representing the estimated height of a surface above a certain level, i.e. a Geodetic datum.

On Processing algorithms in SPICE

		Phase-1	Phase-2
P-LRM	level-1	/	Zero-padding factor 2
	level-2	TCOG (ICE-1) retracker (30%)	TCOG (ICE-1) retracker (50%) Batch processing
SARM	level-1	/	Zero padding factor 4
	level-2	TPR retracker (75%)	TPR retracker (75%) DEM to identify WF peak

Table 1: level-1 and level-2 processing used for generating phase-1 and phase-2 products in P-LRM (top) and SARM (bottom)

Physical vs Empirical Retrackers

Retrackers can be **empirical** or **physical**

Physical retrackers (e.g. Brown and SAMOSA model): work by fitting a mathematical model of the backscattering process to the raw SAR waveform.

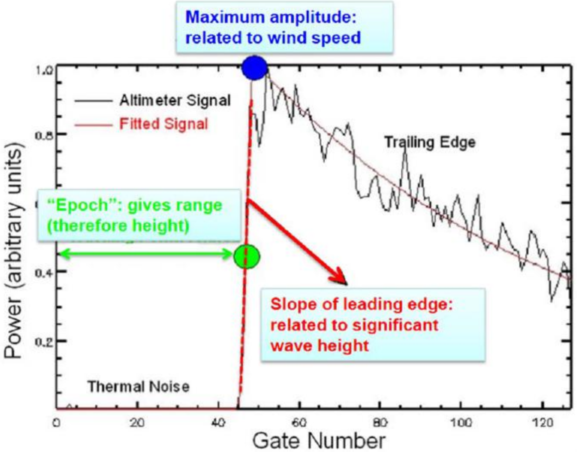
As several models will be tested and fitted to the altimeter signal (by varying SWH, range and amplitude), the best fit will minimize the error according to some criteria (e.g. the Normalised Residual Error (NRE)).

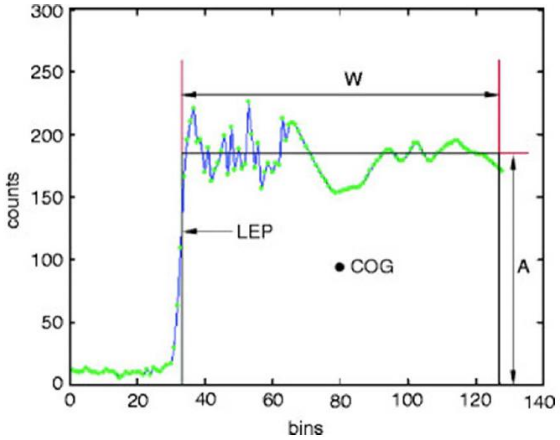
Empirical retrackers (e.g. OCOG, threshold, β retracker): work on the statistics of the waveform to extract only the leading edge position.

In OCOG retracking, the echo is replaced with a box that has the same center of area as the echo. The leading edge position (LEP) is taken as the point on the echo that first crosses the amplitude T1, where T1 is an empirically determined threshold.

No functional fitting applied. Fast and easy to implement but less accurate than physical retrackers (e.g., **<u>they do not account for the platform bad pointing</u>**).

<u>No single retracker can meet the diverse needs of all altimetry data user</u>.



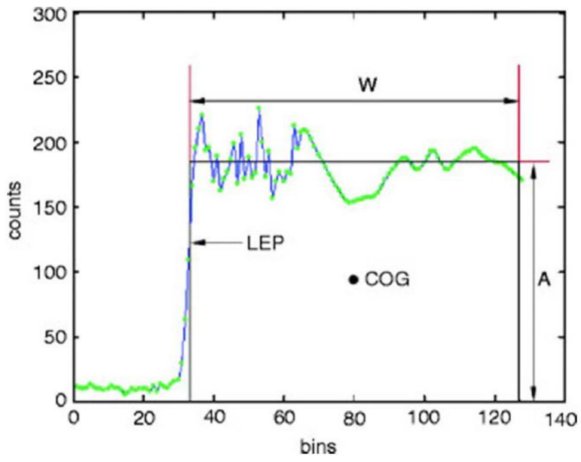


On Empirical Retrackers

OCOG (Offset Centre of Gravity) Retracker

Based on the definition of a rectangle about the effective centre of gravity of the waveform, the **amplitude (A)** and **width (W)** of the waveforms and the gate position of the waveform centre of gravity (**COG**) are estimated from the waveform data using:

$$A = \sqrt{\sum_{i=1+n_1}^{N-n_2} P_i^4(t) \Big/ \sum_{i=1+n_1}^{N-n_2} P_i^2(t)} \qquad W = \left(\sum_{i=1+n_1}^{N-n_2} P_i^2(t)\right)^2 \Big/ \sum_{i=1+n_1}^{N-n_2} P_i^4(t) \qquad LEP = COG - \frac{W}{2}$$



OCOG is an easy-to-implement, robust waveform retracker, which depends solely on the statistics of the waveform samples. It is the algorithm behind the **Ice-1** retracker for the Envisat RA-2 altimeter.

Threshold Retracker

This method is based on the dimensions of the rectangle computed using the OCOG method. The threshold value is referenced with respect to the OCOG amplitude or the maximum waveform amplitude as 25%, 50% and 75% of the amplitude. The retrieved range gate is determined by linearly interpolating between adjacent samples of the threshold crossing the steep part of the leading edge slope of waveform.

Radar Interaction with the Snowpack

SARAL AltiKa

- **SARAL (Satellite with ARgos and ALtiKa)** is a satellite mission resulting from a French and Indian collaboration (CNES and ISRO). It was launched on **February 2013**.

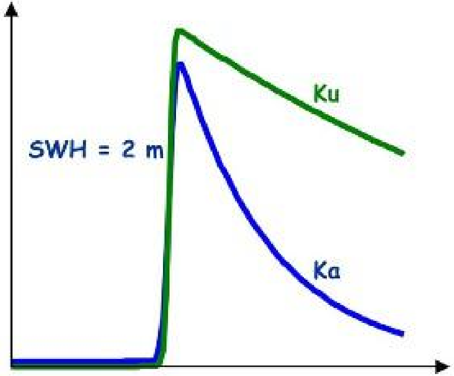
- The **antenna footprint is reduced** in Ka-band, which is enhanced by a lower altitude: at 800 km altitude, the 3-dB footprint radius is about 4 km versus 15 km for Poseidon on Jason missions.

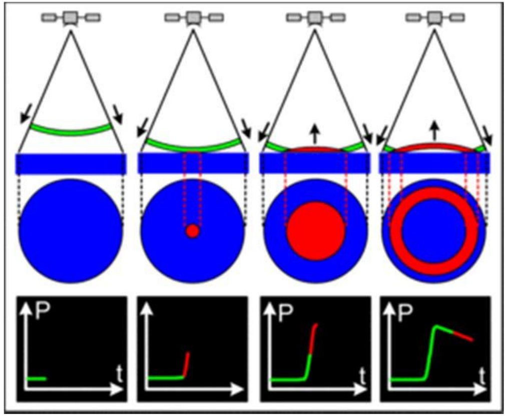
- In other words, **the altimeter is close to beam limited one**. Indeed, as **the antenna aperture is smaller** than for Poseidon, gain decreases more rapidly with incidence: there is thus **nearly no trailing edge in the echo.**

- SARAL is the first satellite carrying on-board a **Ka-band** altimeter: AltiKa (**35.75GHz**).

- Over **land-ice the Ka-band** brings the advantage of **being much less sensitive to volume scattering** compared to conventional Ku-band.

Parameter	Value
Altimeter band	35.75 GHz ± 250 MHz
Pulse bandwidth	500 MHz
Pulse duration	110 µs
Altimeter Pulse repetition frequency	4 kHz
Echo averaging (altimeter)	25 ms
Spectrum analyser (altimeter)	128 points
Altimeter Link budget	11 dB (sigma naught = 6.5 dB)
Antenna diameter	1000 mm
Focal length	700 mm
Offset	100 mm
Radiometer band	23.8 GHz ± 200 MHz 36.8 GHz ± 200 MHz
Radiometric resolution	<0.5 K
Radiometric accuracy	<3 K
Radiometer averaging	200 ms
Mass (altimeter+radiometer)	<33 kg
Power consumption (altimeter+radiometer)	<76 W





Waveform shapes in Ka- and Ku-bands for a 2 m significant wave height (SWH). (Horizontal axis: Time; Vertical axis: Return Power)

SARAL AltiKa (2)

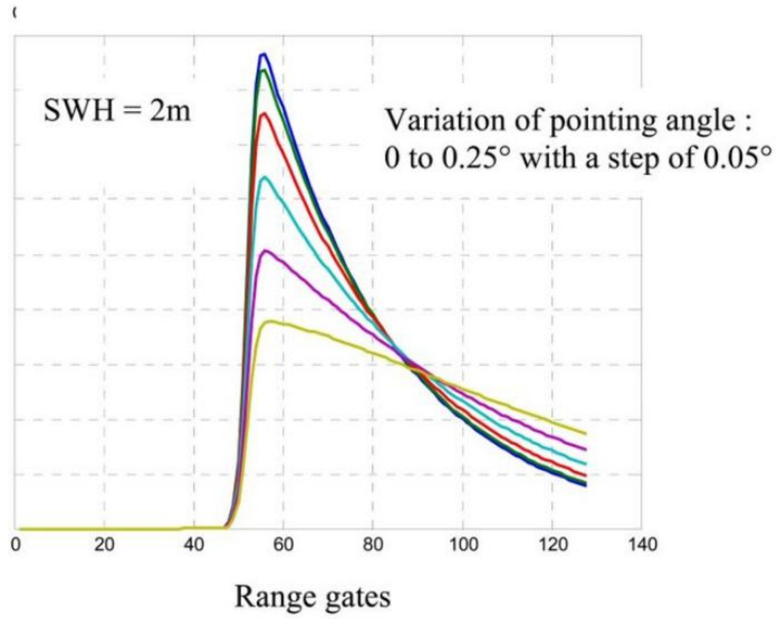
- The large AltiKa bandwidth (480 MHz) provides a better range resolution (**31cm** in Ka-band, versus **47cm** in Ku-band). Consequently, the footprint is reduced: **4 km diameter**.

- Finally, the AltiKa PRF provides twice more elementary data than usual altimeters (40Hz rate in Ka-band versus 20Hz rate in Ku-band).

- In case of **strong platform mispointing**, the measured **waveform can be dramatically distorted ->**

- This could lead to large retracking errors, in particular when using **empirical retrackers** such as TFMRA, ICE-1… as they **do not account for the platform bad pointing**.

- AltiKa operates exclusively in LRM. It is positioned on the **same orbit as Envisat: 35-day repeat orbit**, inclination of 98.54° and a mean altitude of 790km.



Pointing errors effect on Ka-band waveforms. (Horizontal axis: Range gate number; Vertical axis: Return Power)

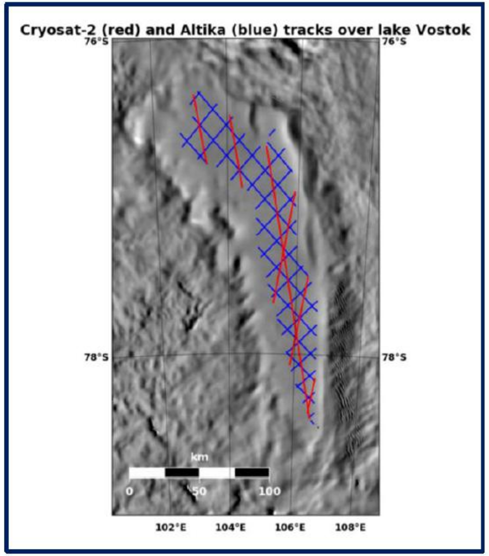
Point Of Closest Approach

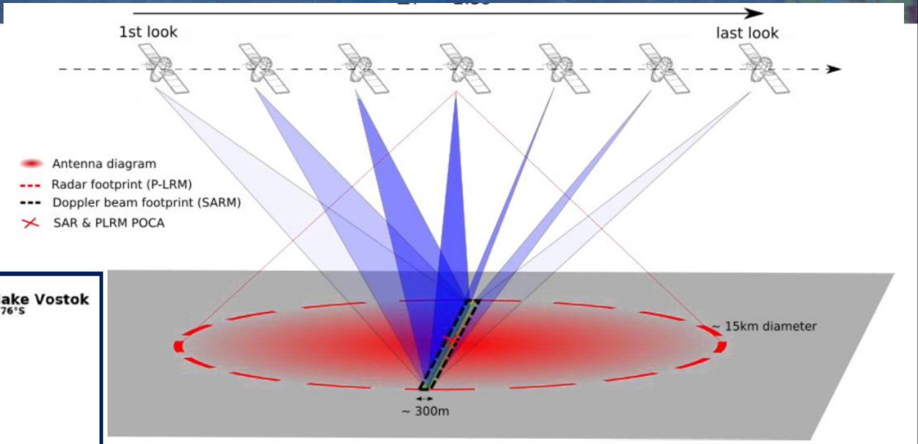
- In case of along-track slope (**discussed before in BRAT**), the POCA (Point Of Closest Approach) does not originate from the same location on-ground for a co-dated SAR and P-LRM measurement.

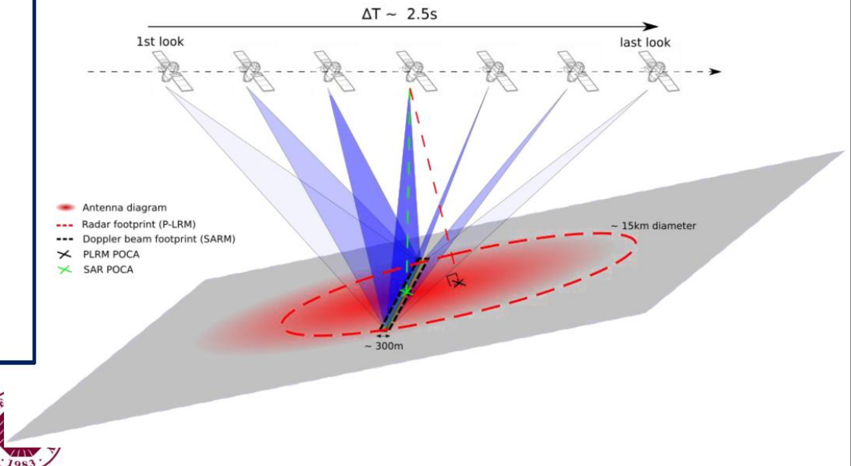
- This **complicates comparisons** at **crossovers** between SAR mode and P-LRM measures.

- The slope induces errors on the altimeter range. **Errors quickly increased with the surface slope intensity**.

- In case of along-track slope, POCA location remains in the Doppler band in SAR mode, while it is shifted upslope within the radar footprint in LRM.







Slope induced errors

Radar Band	Frequency	Notes
HF	3 - 30 MHz	High Frequency
VHF	30 - 300 MHz	Very High Frequency
UHF	300 - 1000 MHz	Ultra High Frequency
L	1 - 2 GHz	
S	2 - 4 GHz	
C	4 - 8 GHz	
X	8 - 12 GHz	
Ku	12 - 18 GHz	
K	18 - 27 GHz	
Ka	27 - 40 GHz	

- To be **correctly interpreted**, crossover (Ku & Ka) analysis must be **performed at POCA locations**, where surface elevation is estimated, not at the satellite nadir.

- With the knowledge of the surface topography over the radar footprint, it is theoretically possible to estimate the POCA location in LRM and SAR, and therefore possible to find exact crossover points.

- Nevertheless, Antarctica topography is not perfectly well known and large uncertainties remain.

- As anticipated in the BRAT exercise, the **Ka-Band (27-40GHz)** is more impacted by the slope than **Ku-Band (12-18GHz).**

Cryosat-2

Slope (%)	0.01	0.025	0.1	0.25	0.5	1	1.5	2
Slope (°)	0.006	0.014	0.057	0.143	0.286	0.573	0.859	1.146
Error on the altimeter range (m)	0.003	0.02	0.33	2.03	8.14	32.55	73.23	130.17
POCA displacement on-ground (m)	65	163	651	1 627	3 255	6 510	9 764	13 018

AltiKa

Slope (%)	0.01	0.025	0.1	0.25	0.5	1	1.5	2
Slope (°)	0.006	0.014	0.057	0.143	0.286	0.573	0.859	1.146
Error on the altimeter range (m)	0.004	0.02	0.35	2.22	8.88	35.53	79.96	142.12
POCA displacement on-ground (m)	71	178	710	1 777	3 554	7 108	10 661	14 215

Figure 10: Based on equations given in 3.1.2, LRM slope-induced errors considering Cryosat-2 nominal altitude, 730km, (top) and AltiKa nominal altitude, 800km (bottom). Same errors in SARM for the across-track slope only.

Analysis of Ka waveforms

- Snow surface properties can change with meteorological conditions (temperature, wind, humidity…) and in case of snowfall events, bringing fresh snow at the surface.

- With a very dry atmosphere giving extremely rare rainfall events, Antarctica is considered as a desert. At a month time scale, surface snow properties are not expected to drastically change.

Radar wave interaction with the snowpack (Ku vs Ka)

- **Surface topography** has a strong impact on the **altimetry measure**. It complexifies crossovers interpretation in two main ways:

➢ First, in LRM, the **waveform shape** is modified by the **surface slope**. The **waveform trailing edge** is specifically impacted, with an **increase of its energy**.

This effect is linked to the antenna pattern, and a same surface slope will act differently on AltiKa and Cryosat-2 waveform shape. In SAR mode this problem is currently not well quantified.

Selected regions

- To discriminate volume scattering effect from topography effect, two sites are selected for this study, presenting relative flat and smooth topography:

- **Lake Vostok:** The “ideal” site, reported very smooth, with an average slope of 0.025%. Measurements are geographically selected over the lake thanks to a dedicated shapefile generated for the study.

- **DOME-C:** Probably not as smooth as lake Vostok, but relatively flat with an average slope of 0.07% (from Bamber DEM)

Selected regions (2)

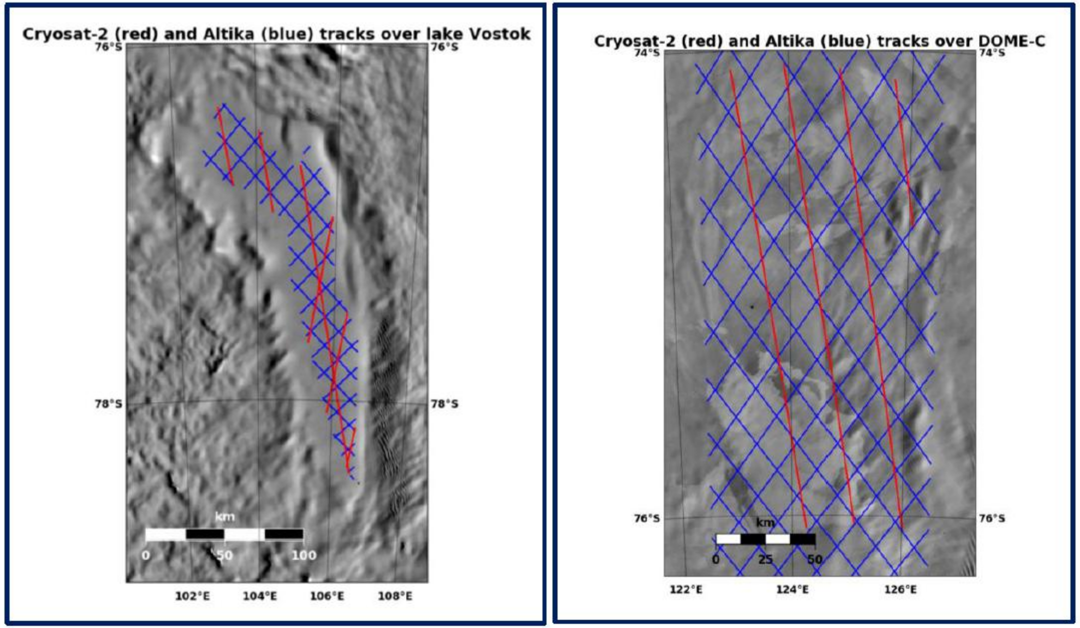


Figure 11: Location of the Cryosat-2 SAR mode (red) and AltiKa (blue) tracks over the two selected sites for the WP5 study: lake Vostok (left) & DOME-C (right)

Finally, considering that surface is flat, <u>no surface slope corrections are applied</u>. Crossover analyses are performed at nadir location of measurements

Methodology

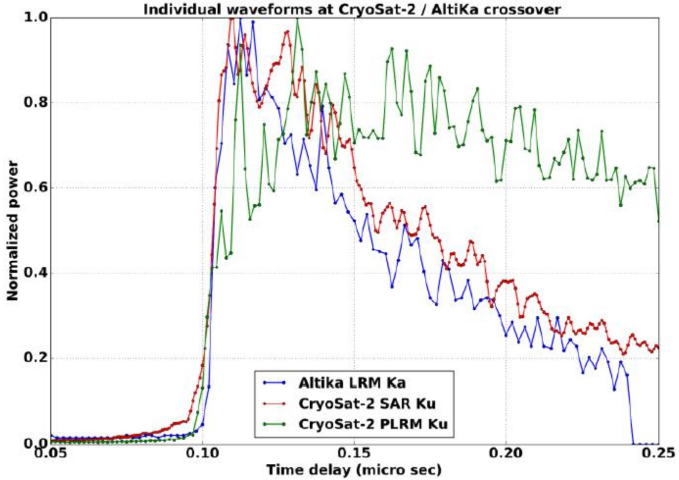
The waveform **analysis at crossovers** (distant by **less than 7 days**) is performed following these processing steps:

➢ Find the two closest measurements at each Altika/Cryosat-2 crossovers located on the selected sites.

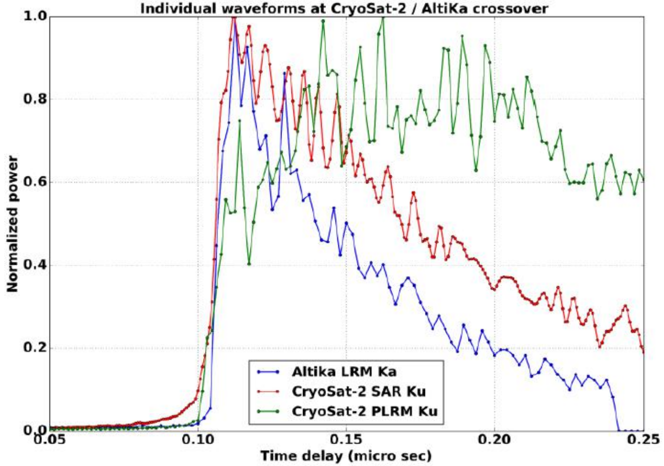
➢ To precisely analyze waveform shape, the **waveform speckle noise is reduced** by **averaging individual measurements**. Mean waveforms are generated by averaging 2 seconds of acquisition for both missions, around the crossover point (+/- 1s).

➢ Shift the leading edges for both missions to superimpose them with the aim to make the comparison more comprehensible. As range gate resolution differs between missions (31cm Altika vs 47cm Cryosat-2), range gates are converted to time delays beforehand to enable a consistent comparison.

Individual waveforms at Lake Vostok

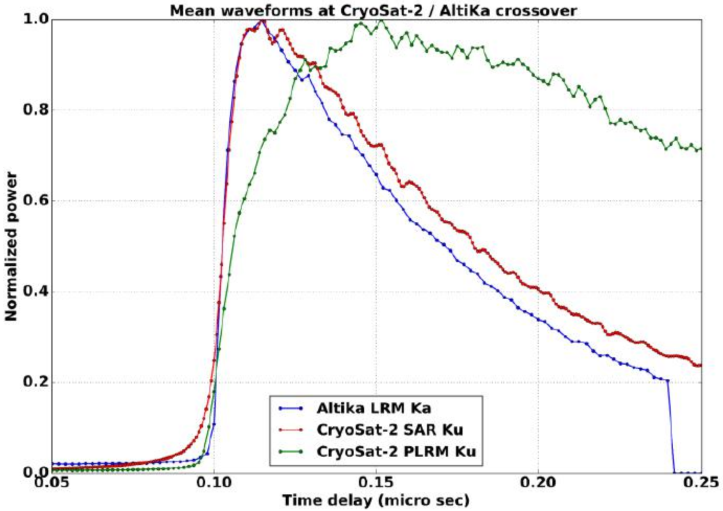


Individual waveforms at the first crossover studied over lake Vostok: AltiKa LRM (blue), Cryosat-2 P-LRM (green) & Cryosat-2 SAR (red)

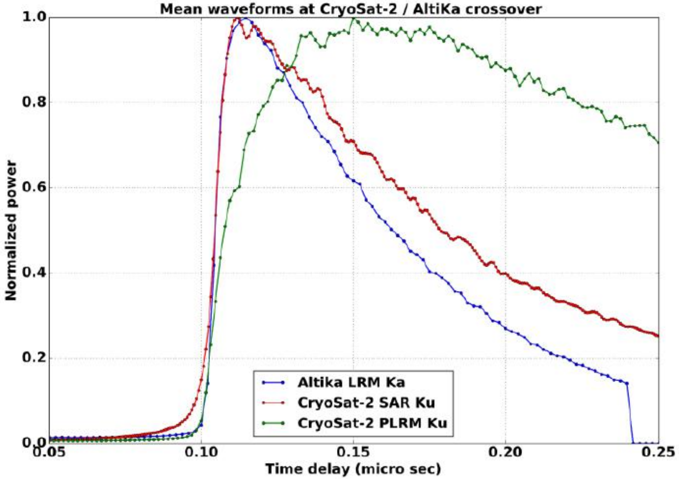


Individual waveforms at the second crossover studied over lake Vostok: AltiKa LRM (blue), Cryosat-2 P-LRM (green) & Cryosat-2 SAR (red)

Averaged waveforms at Lake Vostok

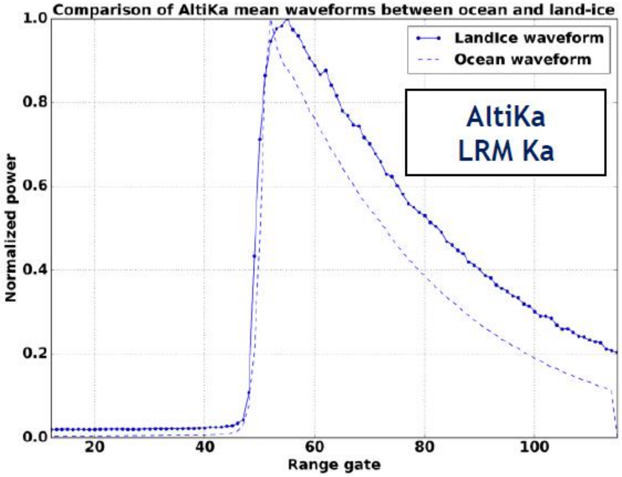


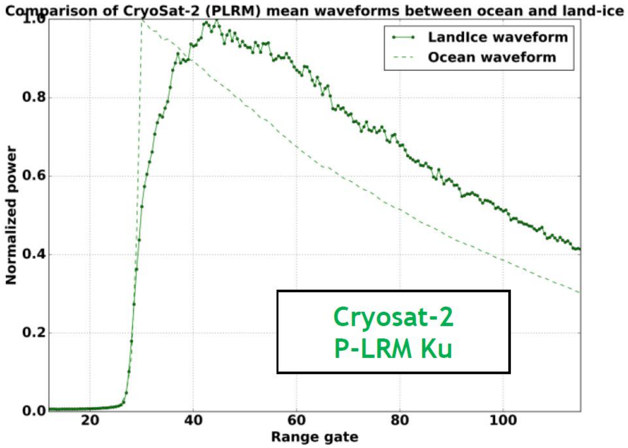
Mean waveforms at the first crossover studied over lake Vostok: AltiKa LRM (blue), Cryosat-2 P-LRM (green) & Cryosat-2 SAR (red)

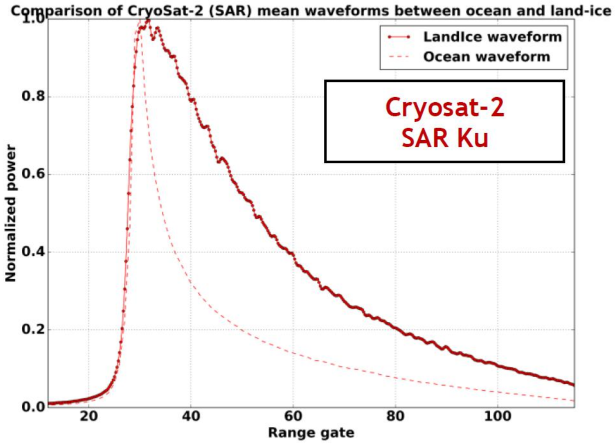


Mean waveforms at the second crossover studied over lake Vostok: AltiKa LRM (blue), Cryosat-2 P-LRM (green) & Cryosat-2 SAR (red)

Land ice vs. Oceanic Waveforms





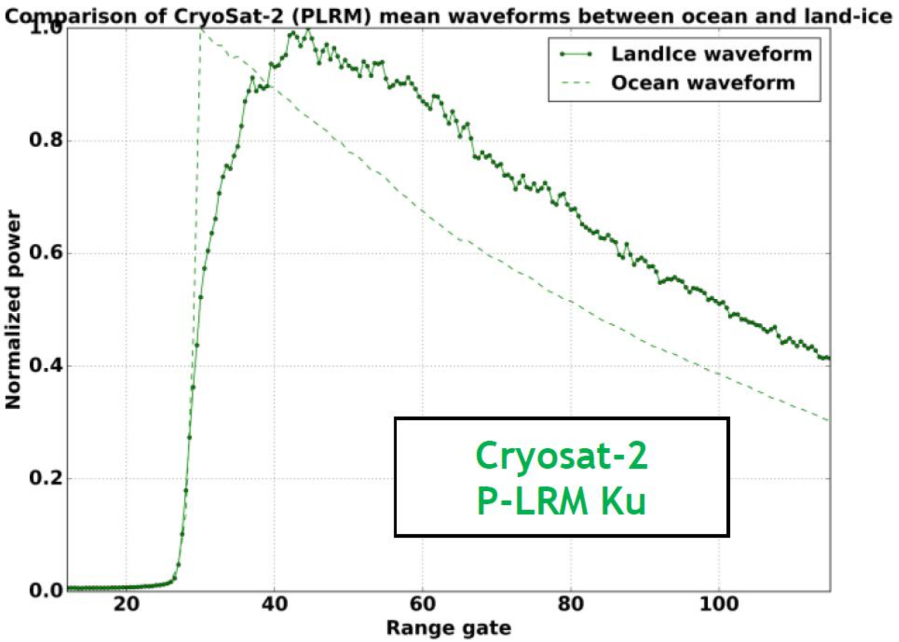


Conclusions about the interaction with the snowpack

Cryosat-2 P-LRM Ku band

- For acquisitions over ice sheet in LRM/P-LRM **in Ku band**, the waveform leading edge (green) is distorted by the volume scattering effect, particularly from mid-power.

- The waveform reaches its maximum power approximately 10 to 15 range gates later compared to an oceanic measurement.

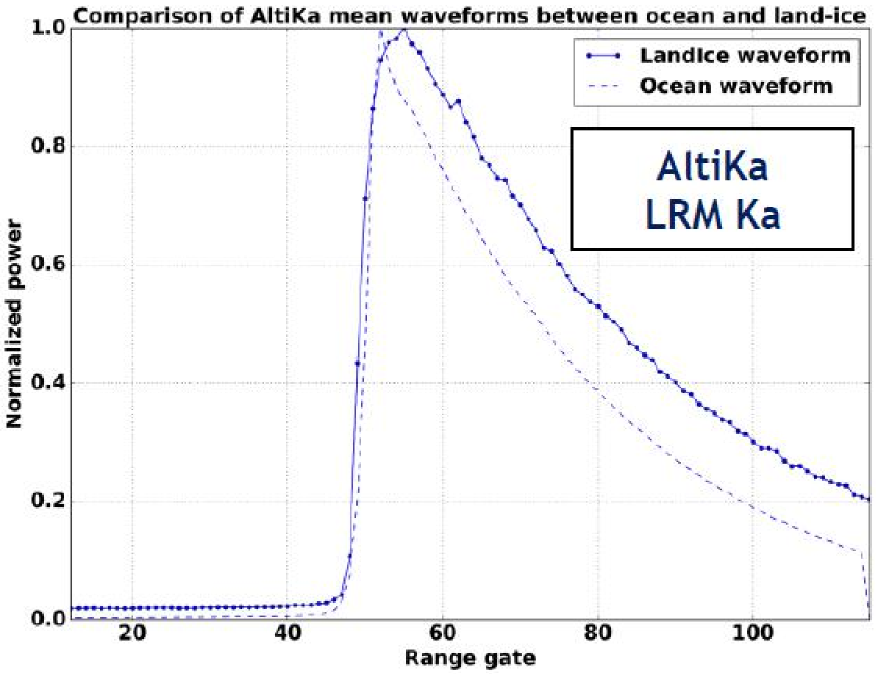


AltiKa LRM Ka band

In contrast, the AltiKa leading edge waveform measured over ice sheet remains visually steep. At least as steep as over ocean. **<u>This would indicate that the leading edge is generated by backscattered energy coming from the top layer of the snowpack</u>**, corresponding most probably to the snow/air interface (Ka penetrates less than Ku due to its higher frequency) and the antenna aperture is lower in Ka-Band.

This is consistent with the theory, stating that the snow scattering coefficient increases from Ku to Ka band. The volume scattering effect is clearly visible when comparing oceanic and ice-sheet waveforms.

Over ice sheet, the upper part of the leading edge is slightly bended, and the waveform is more "volumic". This proves that a part of the Ka-band signal penetrates the snowpack and is backscattered by internal layers and/or snow grains.

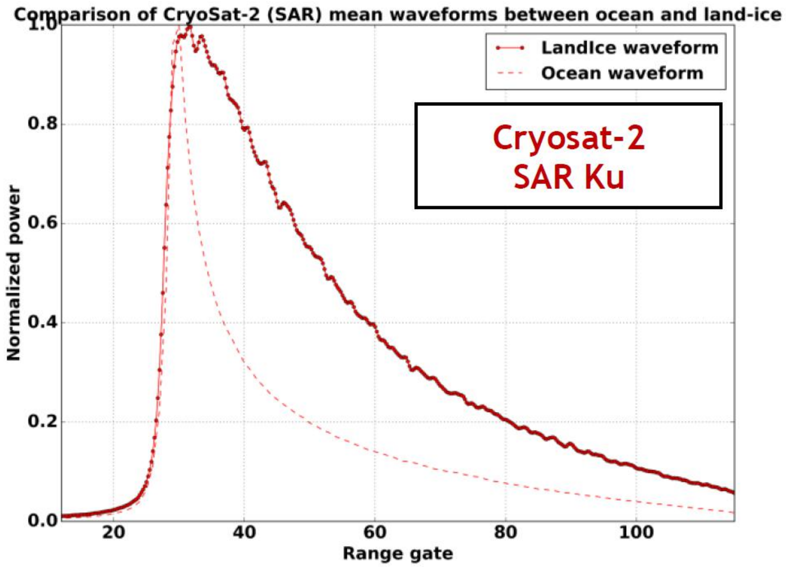


SAR Ku band

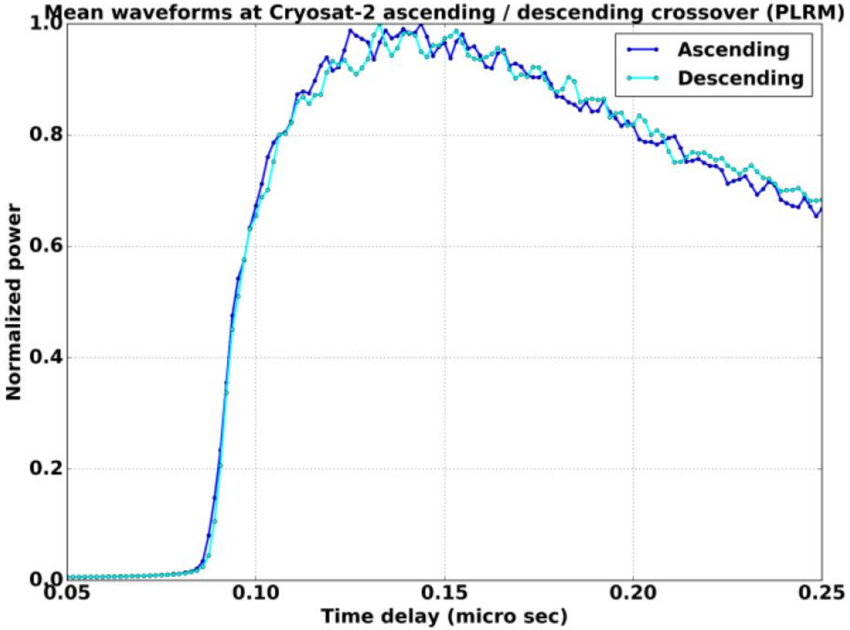
As observed with AltiKa, the waveform leading edge of the ice sheet acquisitions remains visually steep, at least until 80% of maximum power. This was not expected in a first approach, as the LRM/P-LRM Ku band waveform leading edge is strongly distorted.

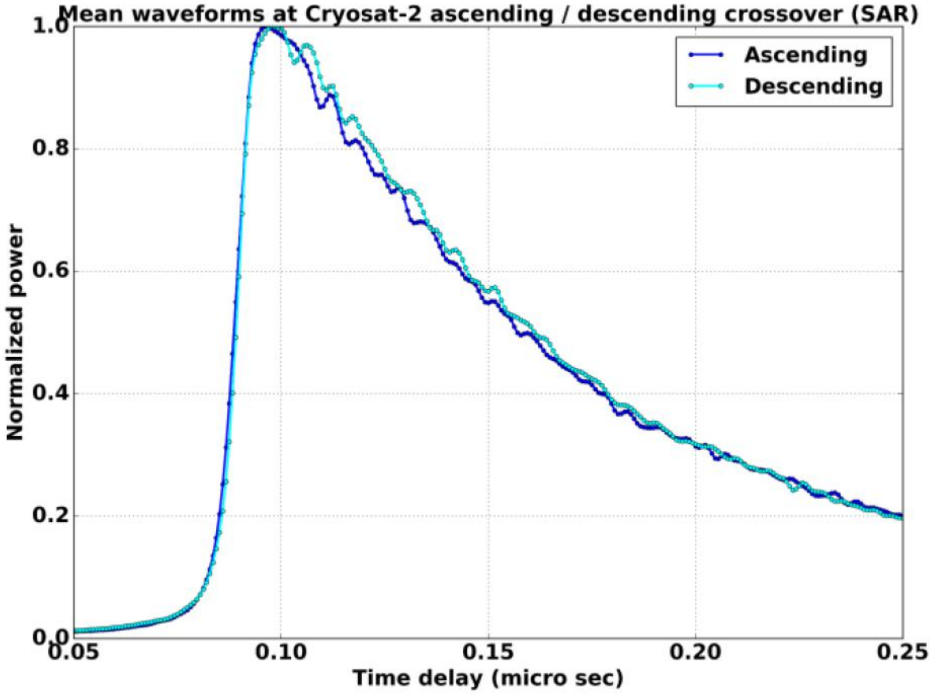
The difference is explained by the specific sampling of the SAR altimetry measure. On the contrary to P-LRM, there is an exponential decrease of the surface area covered on ground by each range gate. Hence, oppositely to LRM / P-LRM, the delayed energy coming from the snowpack interior does not bring enough power to distort the waveform leading edge.

However, the volume scattering effect clearly impacts the trailing edge, much more volumic compared to ocean. In Ku band, the leading edge stability observed in SAR mode looks clearly as a strong advantage compared to LRM / P-LRM. We expect that the estimations retrieved from the SAR waveforms will be less sensitive to volume scattering and its temporal/spatial variations.



Ascending & Descending Tracks





Validation against Airbone data

Improved Performance

Elevation biases relative to airborne validation sets* at each site, and for the different processing scenarios. **->**

Phase 2 reflects the optimal SPICE configuration, including zero padding factor of 4 in the L1 processing and a DEM pre-retracking module in the L2 processing.

This new configuration shows significant reductions in the bias at all sites.

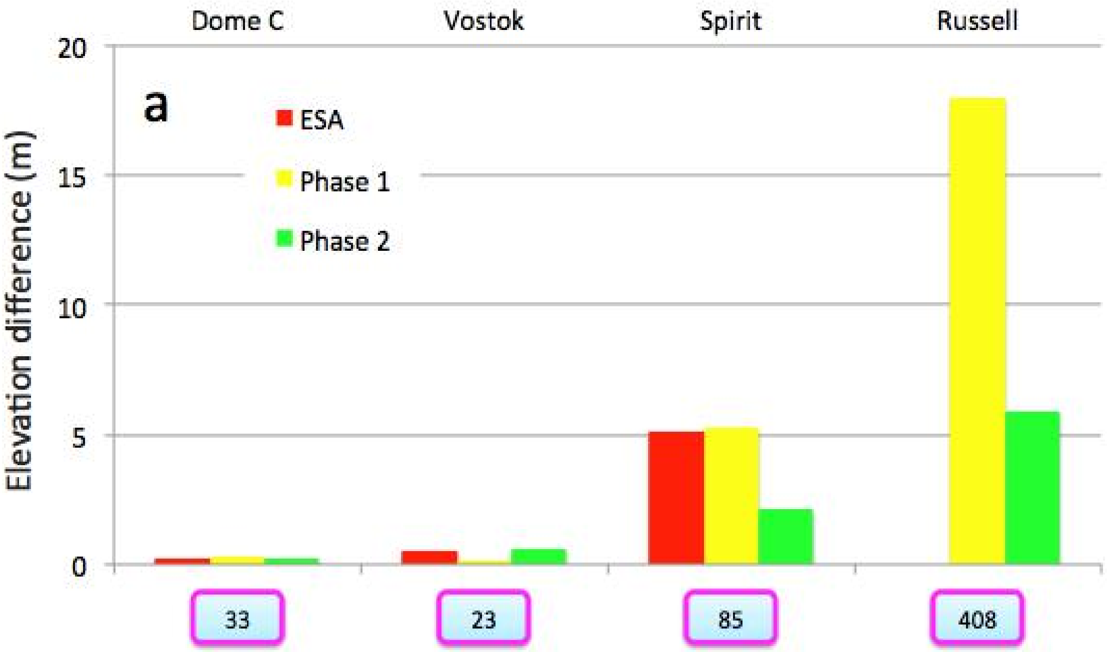
*Laser Altimetry, Airborne Topographic Mapper (ATM) instrument flown onboard ICEBridge campaigns.

Improved Performance

Dispersion of elevation differences relative to airborne validation sets* at each site, and for the different processing scenarios **->**

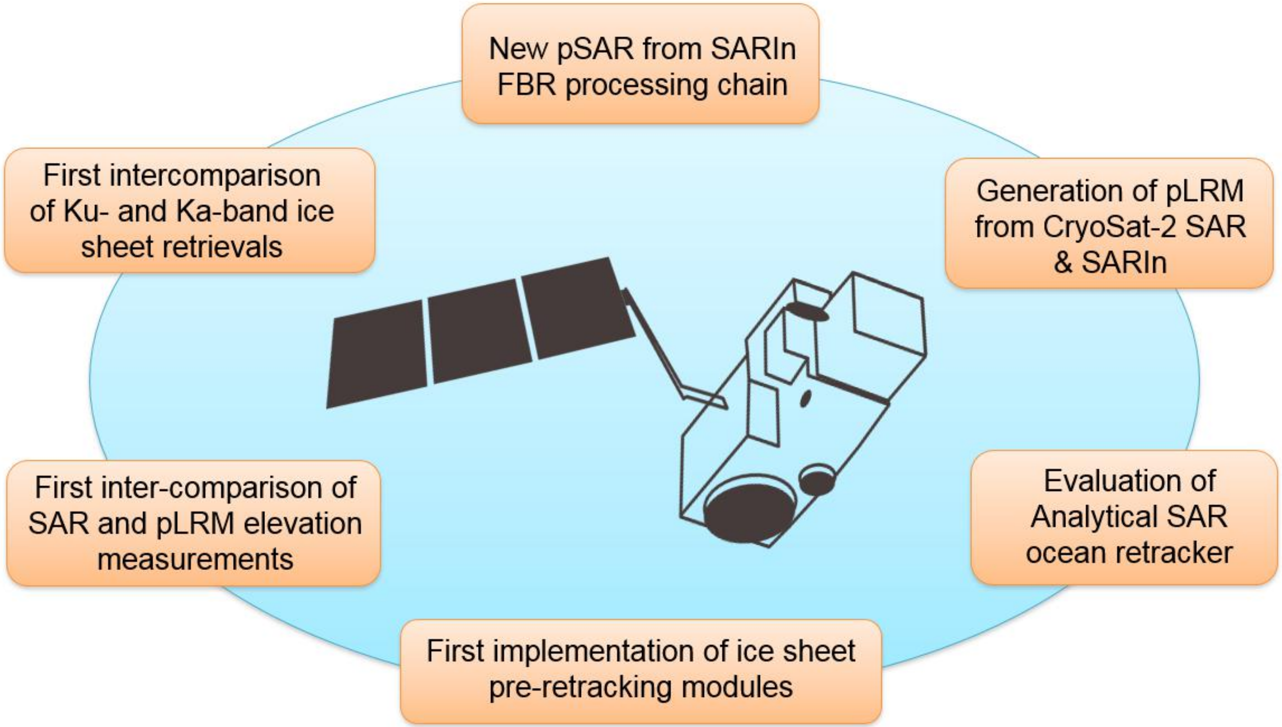
Phase 2 reflects the optimal SPICE configuration, including zero padding factor of 4 in the L1 processing and a DEM pre-retracking module in the L2 processing.

Large improvements are seen at the coastal sites of Spirit and Russell where the topography is more complex.



*Laser Altimetry, Airborne Topographic Mapper (ATM) instrument flown onboard ICEBridge campaigns

Achievements



https://www.seom-spice.org/