PolarMonitoring study:
WP3 : CRISTAL performance analysis over snow surfaces

Results from simulations: AltiDop/SMRT

WP3 objectives

WP31: Snow / firn models (IGE)

Objectives: *To build a snow model to be integrated in the CLS altimeter simulation tool => SMRT from IGE*

WP32: Integration of the snow model code into the CLS simulation tool ("AltiDop") (IGE / CLS)

Objectives: *To merge the CLS altimeter simulator, valid for oceanic surface, with the snow model (SMRT) from IGE*

WP33: Performance analysis (CLS)

Objectives: *To evaluate the simulated waveforms, provide analysis of sensitivity to snow parameters, assess the dual Ku / Ka performances over snow surfaces*

WP32

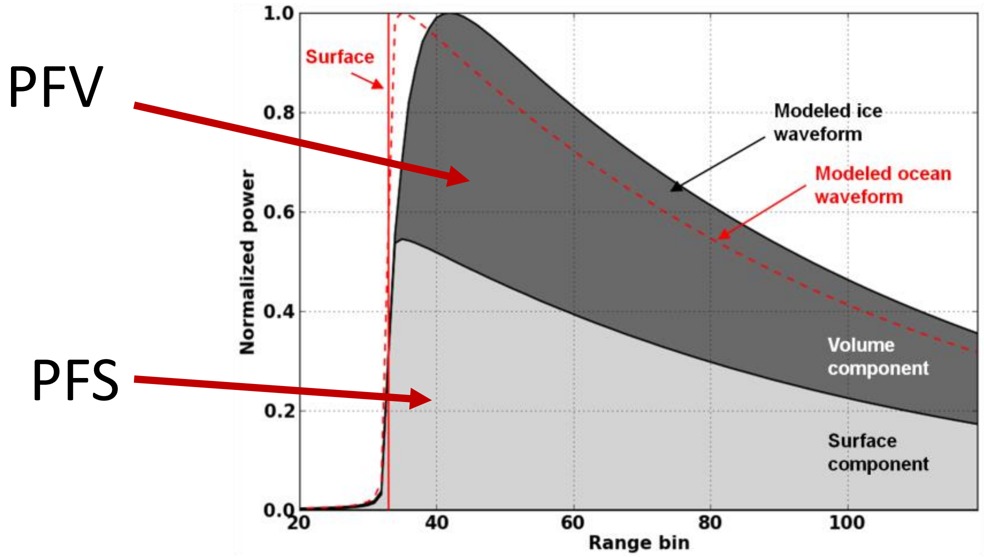
Combination of SMRT & AltiDop

The AltiDop/SMRT simulator

The theory in a nutshell:

Altimetry waveform acquired over snow surface can be discriminated in two signals:

- **PFS** (**Power From Surface**): the signal backscattered at snow/air interface
- **PFV** (**Power From Volume**): the signal backscattered by the snowpack, with two different origins:
  - The scattering from snow grains within the snowpack (P_{grain})
  - The backscattering from snowpack internal interfaces (P_{layers})



Simulation in LRM, using CryoSat-2 configuration and over an ice sheet snowpack

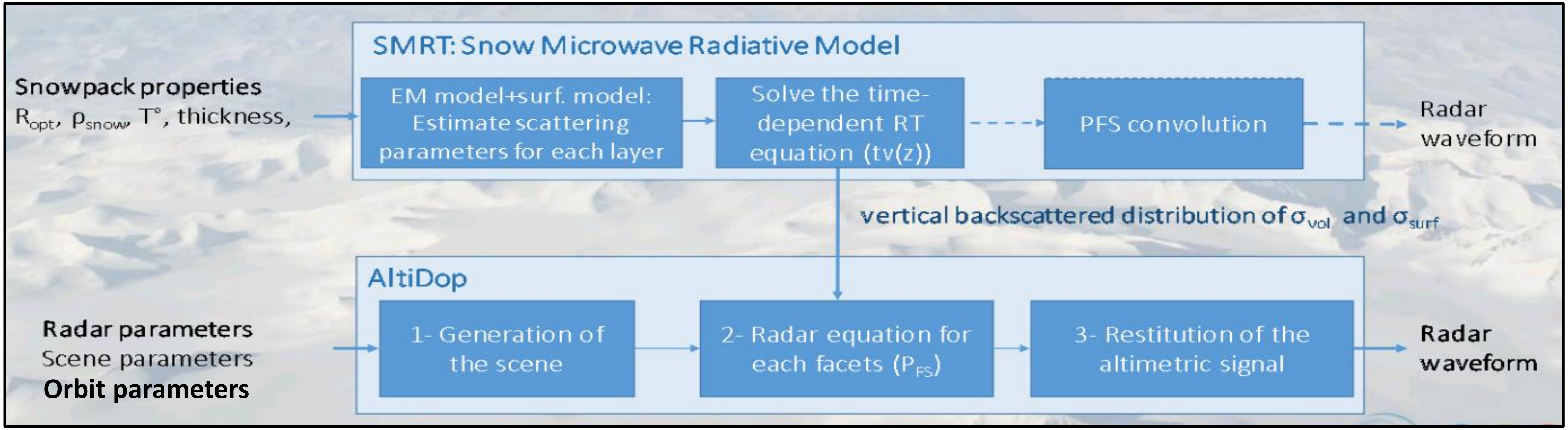
Aublanc et al. [2018]

General operating diagram of the AltiDop/SMRT simulator

Simulations can be performed in two ways

1 - SMRT alone. PFV signal is numerically convolved with PFS from Brown model. Simulation only possible in LRM, over a flat surface.

2 – Combination of AltiDop & SMRT. The PFS signal is computed by AltiDop, over a numerical pixelized scene. The PFV signal is simulated by SMRT, and is added to the facet's PFS signal (detailed explanations further).

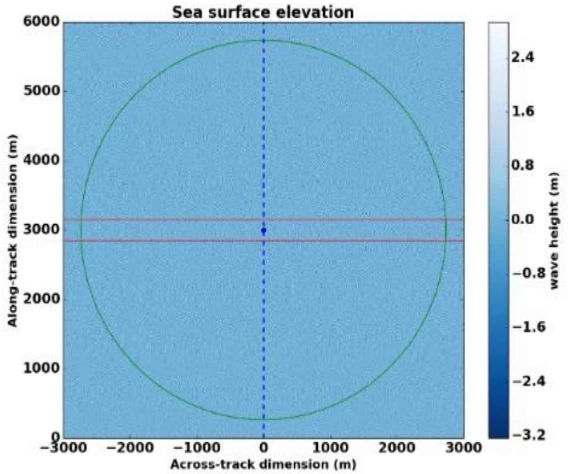


AltiDop presentation

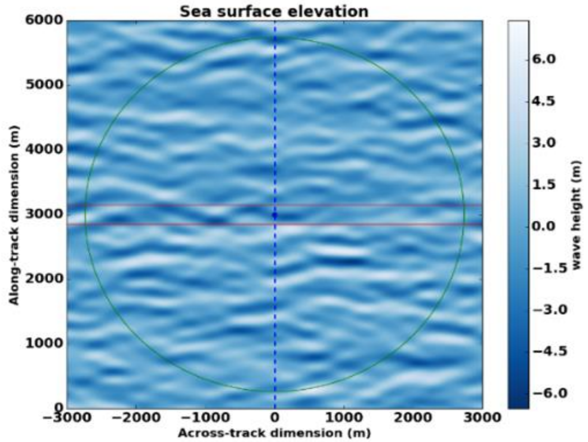
Step 1 : scene generation

- The oceanic surface is numerically modeled as a 2D matrix, composed of multiple pixels/scatterers. Each pixel of the matrix represents the facet elevation (DEM).
- Over ocean, usual scene resolution is 10 meters, which is a good trade-off between results consistency and CPU time.
- Depending on user choice, possibility to simulate the facet elevation based on realistic sea surface spectra: wind driven sea (Pierson & Moskovitz), swell conditions (Durden & Vesecky). Or to perform simple simulations with gaussian distribution of facets elevation. Addition of a topographic surface slope is also possible.

Wind driven sea [Pierson & Moskovitz]



Swell [Durden & Vesecky]



Step 2 : radar equation computation

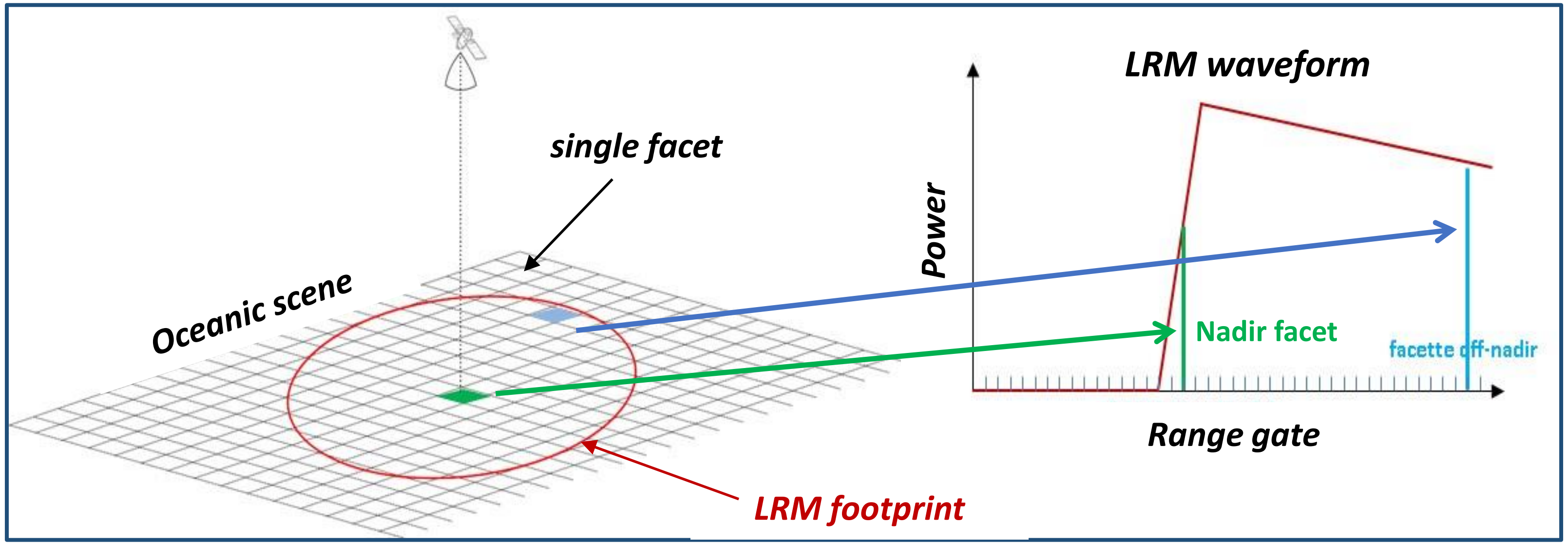
The energy backscattered by the scene (integration of all facets) is computed by solving the radar equation :

$$\mathrm{Pr} = Pe \, \frac{\lambda_0^2}{(4\pi)^3} \int_{sea\ facets} \frac{G^2 \sigma_0}{R^4} \, dS$$

Pe : *Emitted power*
λ_0 : *Wavelength = c / Fc (with c the light speed and Fc the signal frequency)*
R : *The satellite – facet distance*
G : *The antenna gain pattern*
σ_0: *Backscattering coefficient*
dS : *Surface of a sea facet*

Step 3 : altimetry signal generation

- Depending on the satellite/facet distance, all facet contributions are accumulated in the adequate range gates of the altimetry pulse/waveform
- For complex simulations (I&Q), a dedicated level-1 processing chain generates the LRM & SAR waveforms



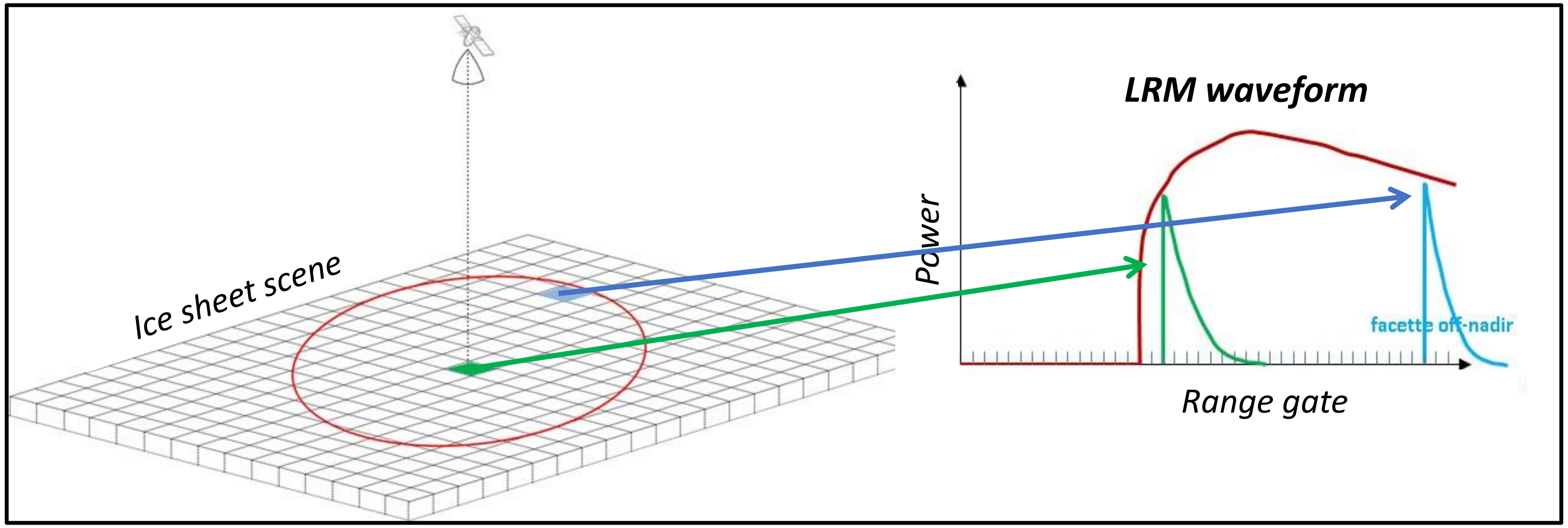
AltiDop has been fully validated with bias less than 1cm in range/SWH by comparison to Brown model (in LRM) & CNES numerical model (SAR)

AltiDop/SMRT combination

Simulation with SMRT

- The signal backscattered by each facet includes the PFS signal (from radar equation) + the PFV signal (from SMRT). Power simulations for now [I2 + Q2].

- Therefore, the facet's signal is no more a Dirac function, but can be modelled as an decreasing exponential function (first approach), as the energy backscattered rapidly decreases in intensity along the snow penetration depth



The AltiDop/SMRT coupling was validated by comparing the simulations with SMRT alone (with convolution to the Brown model). Agreement is almost perfect

WP33

CRISTAL performance analysis over snow surfaces

Definition of the reference snowpack

- First, sensitivity studies conducted by IGE show that the three main parameters acting on the altimetry waveform shape are: **density, snow grain size and mean square slope.**

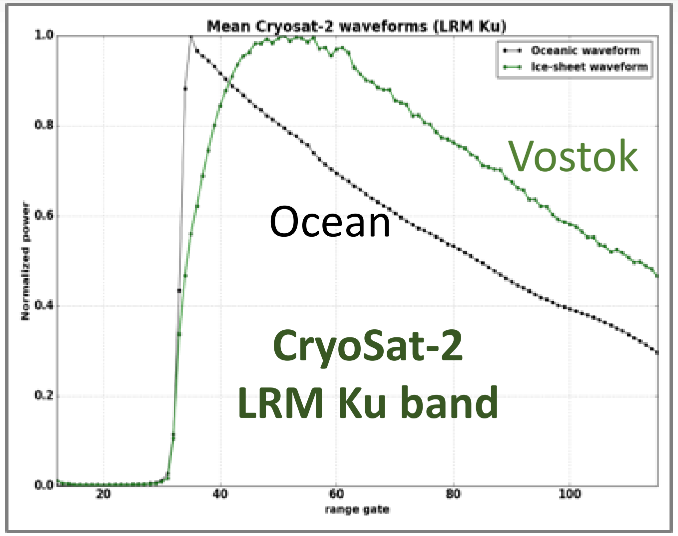
- The following methodology was taken to build a single-layered reference snowpack
  - **Density is set at 320 kg.m^{-3}** (mean value over DOME-C [Picard et al., 2014])
  - We search, within realistic ranges, the couple [snow grain radius – MSS] values for which simulated waveforms reproduce well the measured signal over lake Vostok:
    - **Snow grain radius is set at 225µm** (within the range [100µm - 500µm])
    - **MSS is set at 0.03** (within the range [0.001 – 0.05])

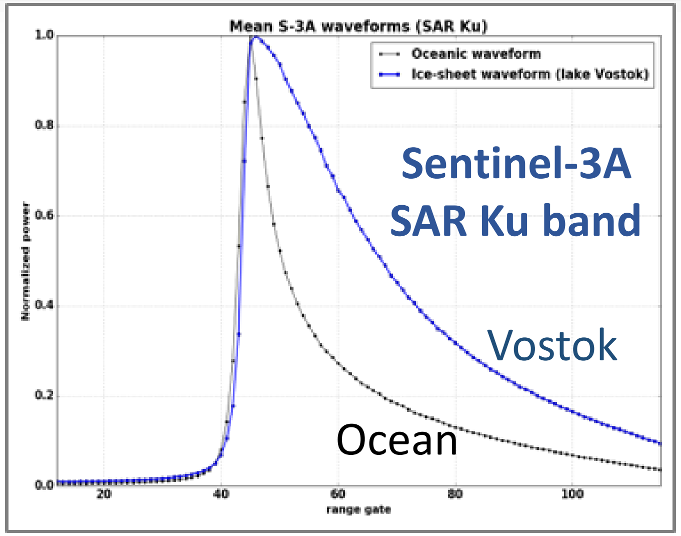
- **The objective is to simulate consistent waveforms**, not the "perfect" ones, to get a reference snowpack around which it is possible to study the sensitivity of CRISTAL measurements to snow parameters and surface slope. Without in-situ snow measurements, and considering the time available for the study, this strategy has been taken.

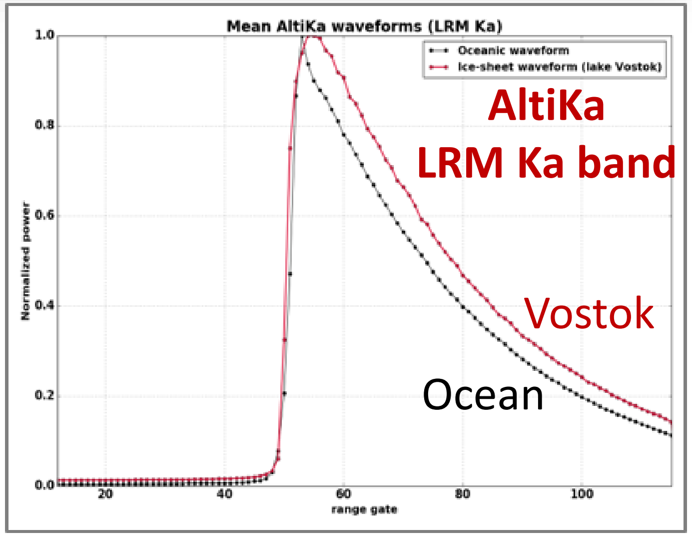
Definition of the reference snowpack

Mean waveforms measured over lake Vostok (color) & over ocean, calm sea state (black)

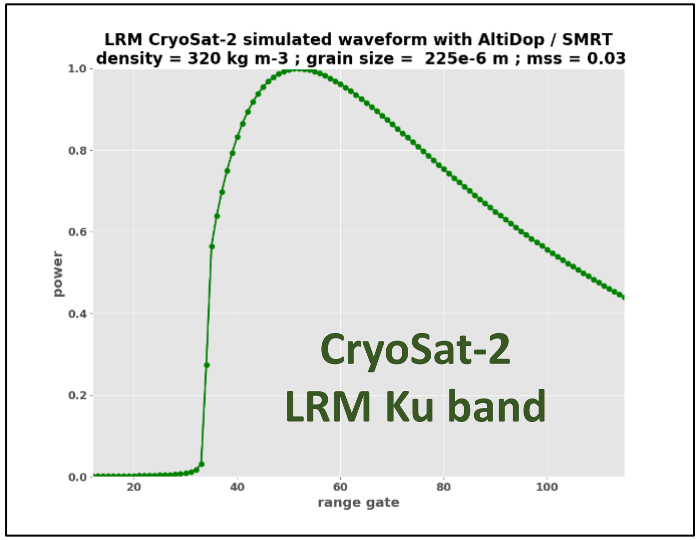
[CLS study, Aublanc &al, OSTST 2017]

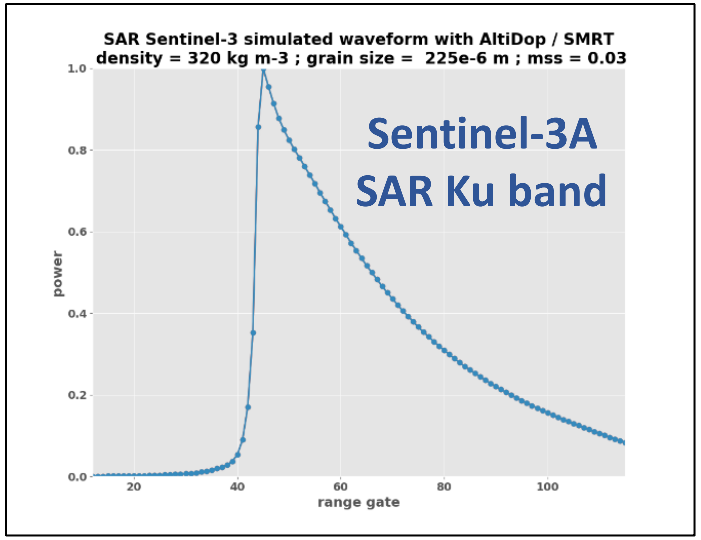


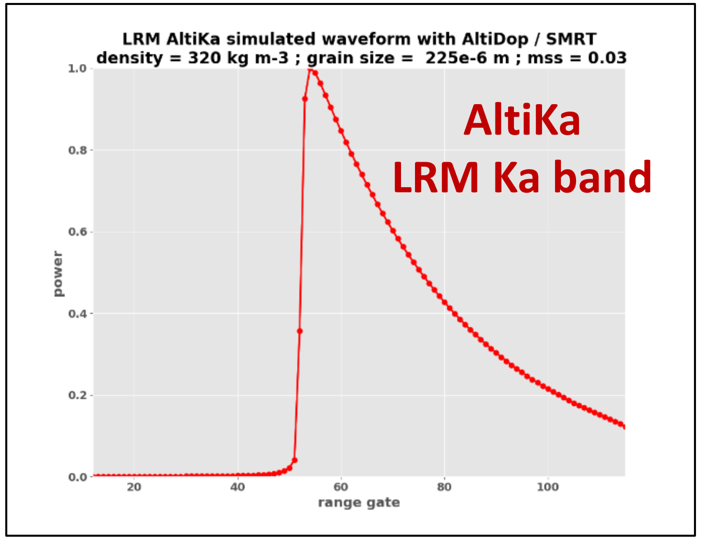




Simulated waveforms from AltiDop/SMRT







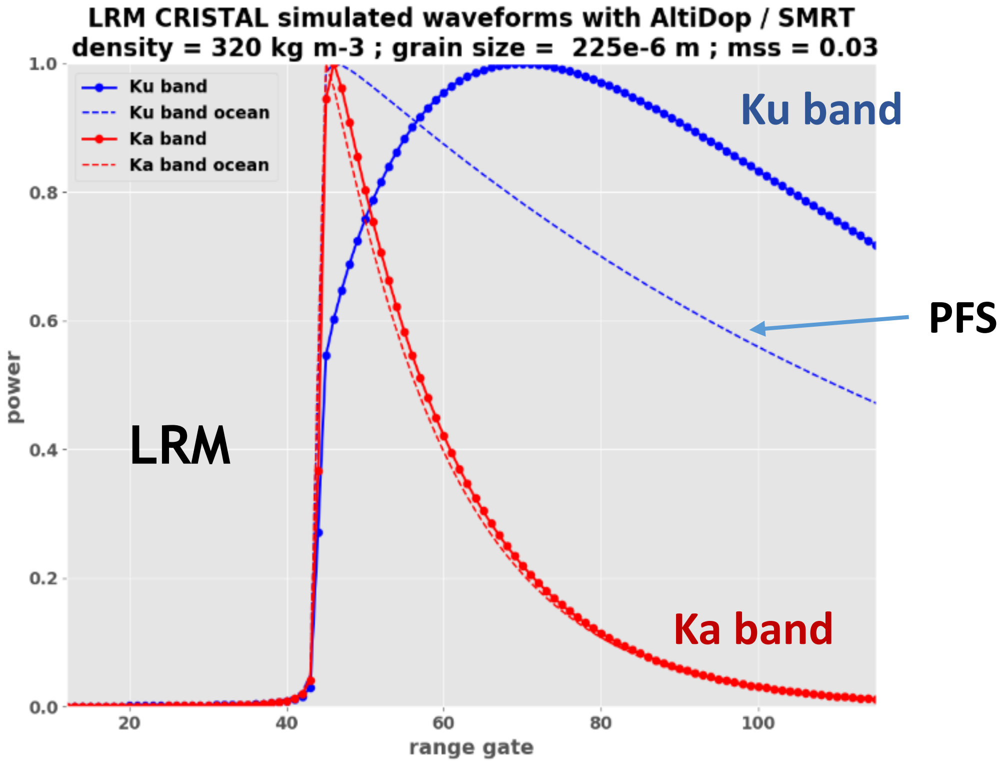
CRISTAL simulations over the reference snowpack

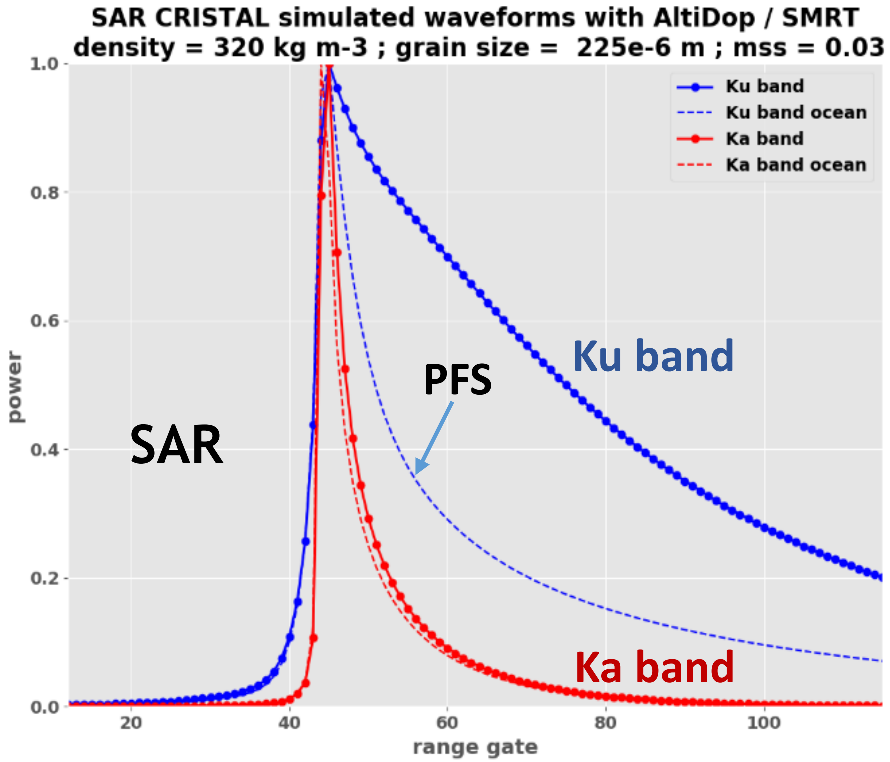
Using CRISTAL altimeter configuration, waveforms are simulated in LRM/SAR modes and in Ku/Ka bands

- Frequency = 35.75GHz in Ka band / 13.5GHz in Ku band
- Bandwidth and sampling = 500 MHz
- Pulse length = 49µs
- Antenna aperture = 0.43° in Ka band / 1.04° in Ku band
- Antenna gain = 50.1dB in Ka band / 42.1 dB in Ku band
- Pulse Rate Frequency = 18kHz
- Burst Rate Frequency = 80Hz
- Pulses per burst = 64
- Burst per 20Hz radar cycle = 4
- Satellite altitude = 800km (arbitrary choice, same as Sentinel-3A)
- Reference gate = gate 44 (arbitrary choice, same as Sentinel-3A)

CRISTAL simulations over the reference snowpack

Using CRISTAL altimeter configuration, waveforms are simulated in LRM/SAR modes and in Ku/Ka bands (waveforms without volume scattering are displayed in dotted lines for comparison)



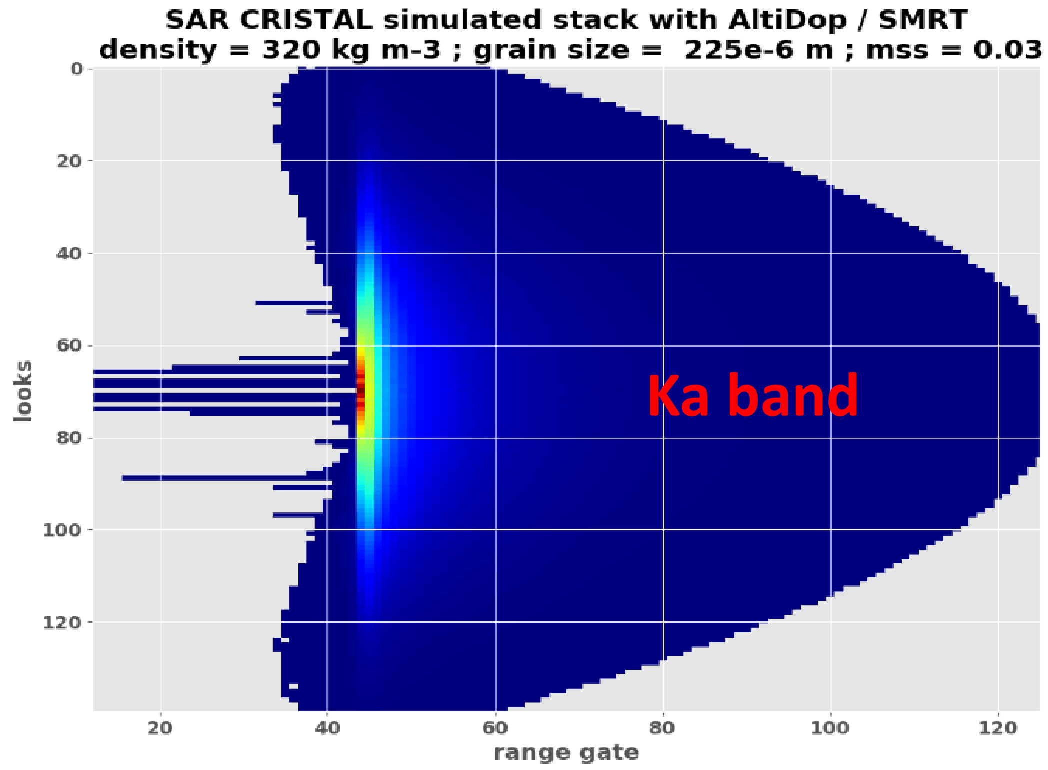


A perfect flat surface is simulated in this case study

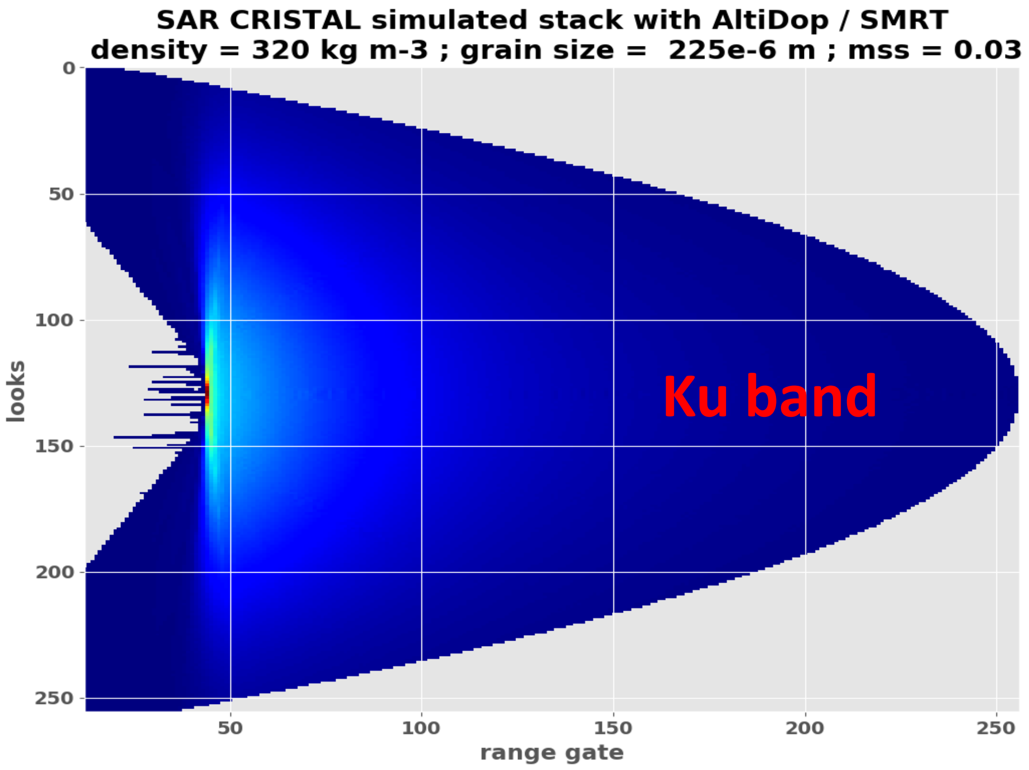
CRISTAL simulations over the reference snowpack

Simulated CRISTAL SAR stack in Ka & Ku bands

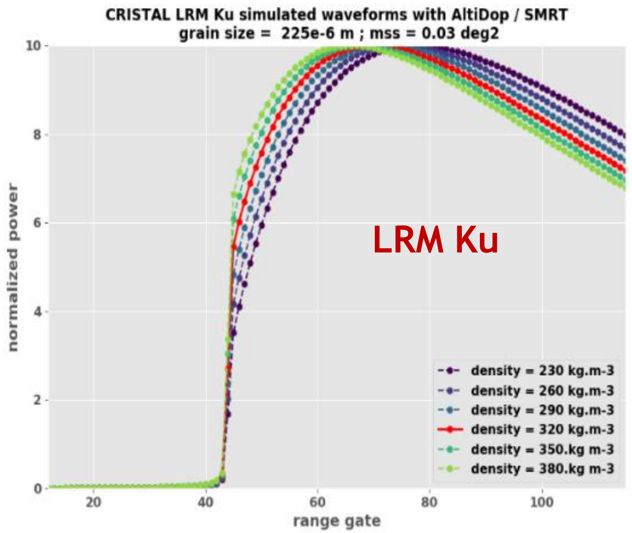
~75 useful looks

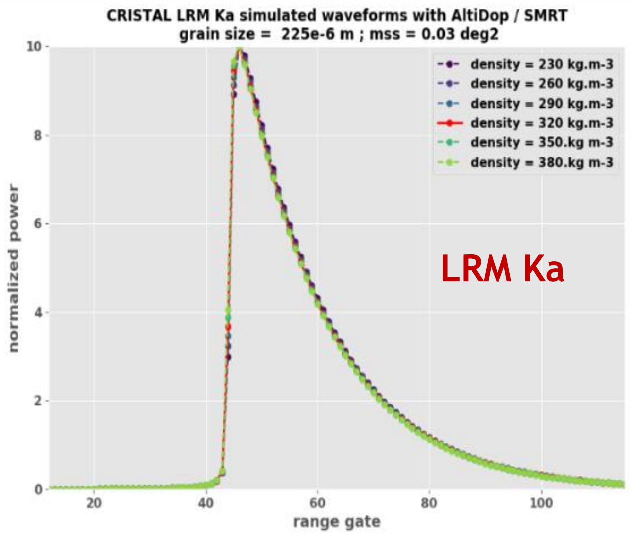


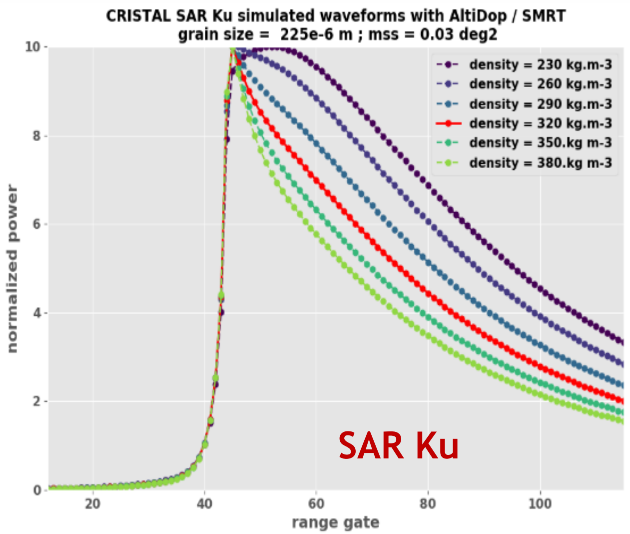
~160 useful looks

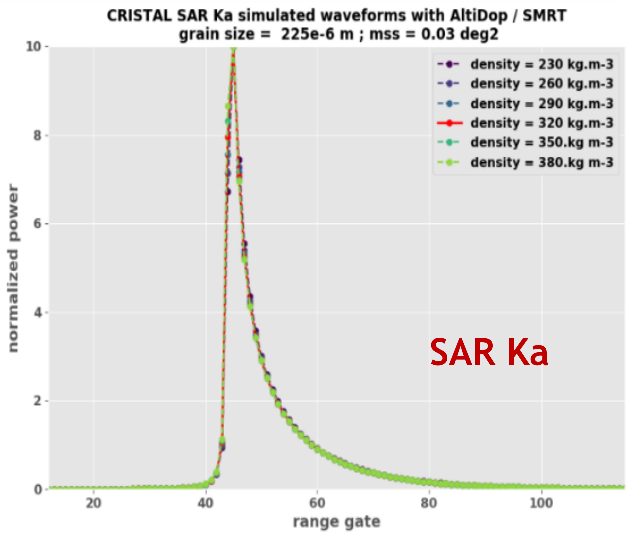


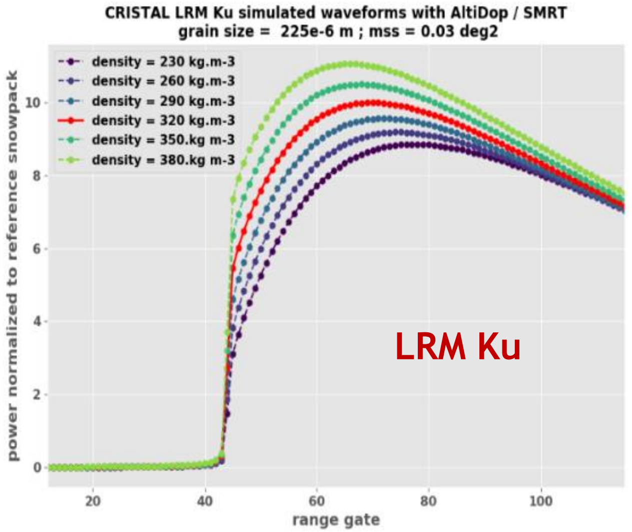
Sensitivity to snow density

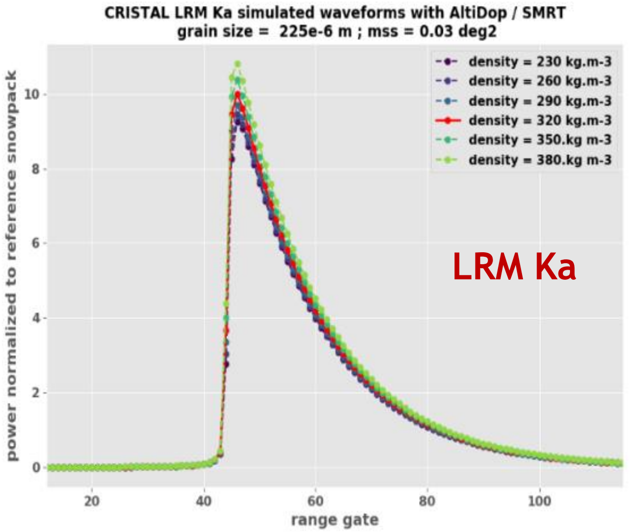


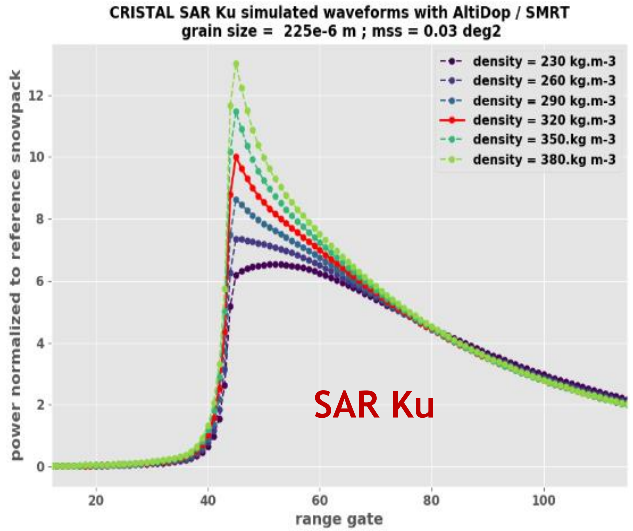


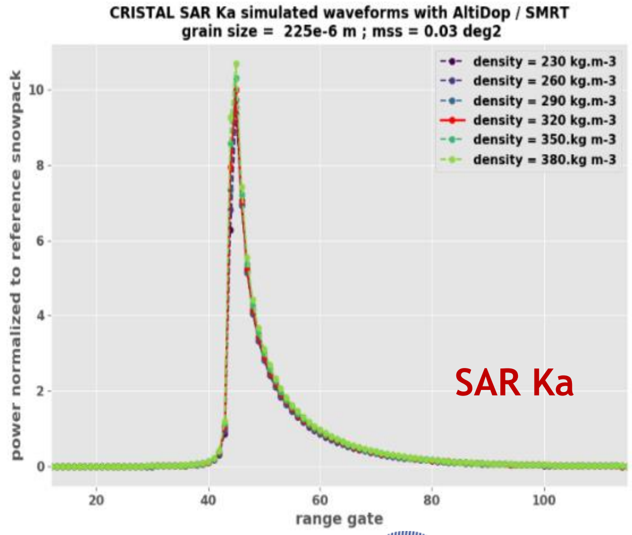




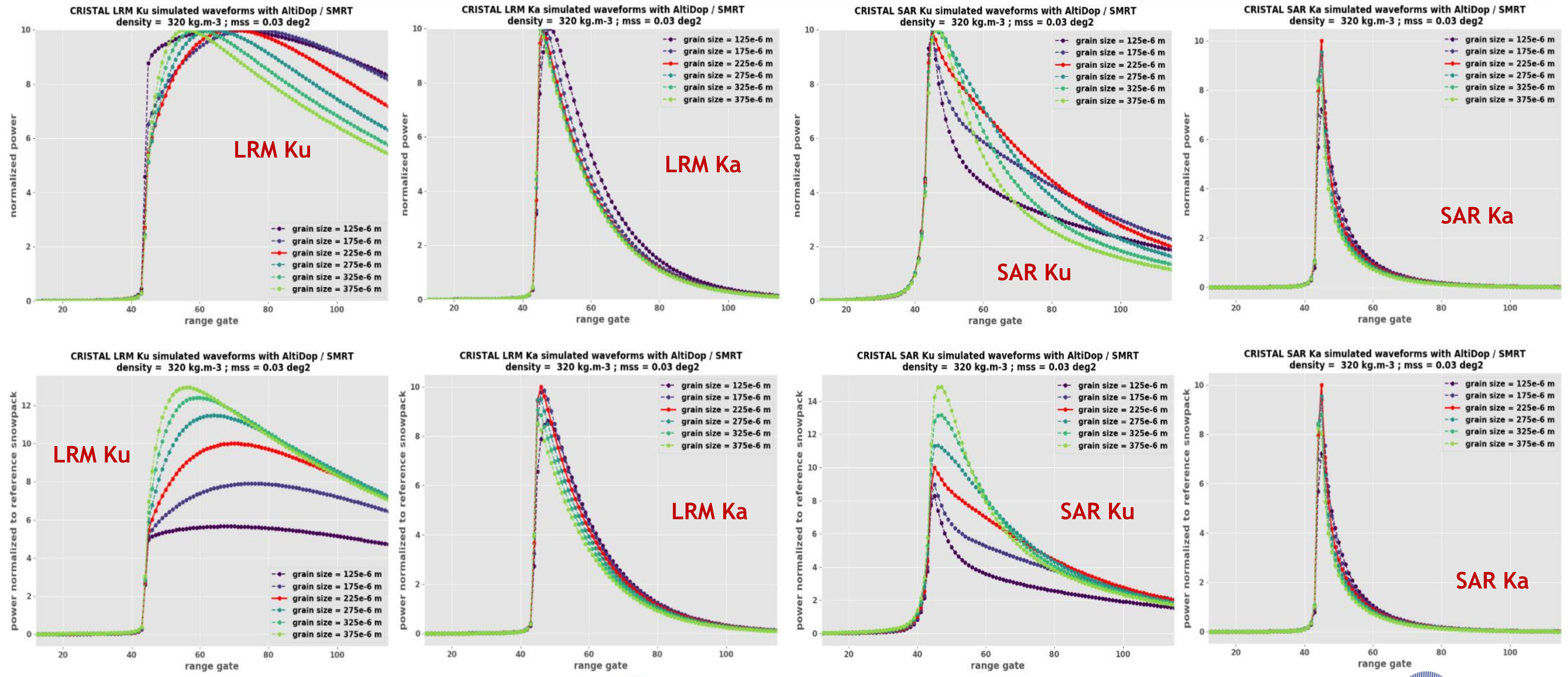




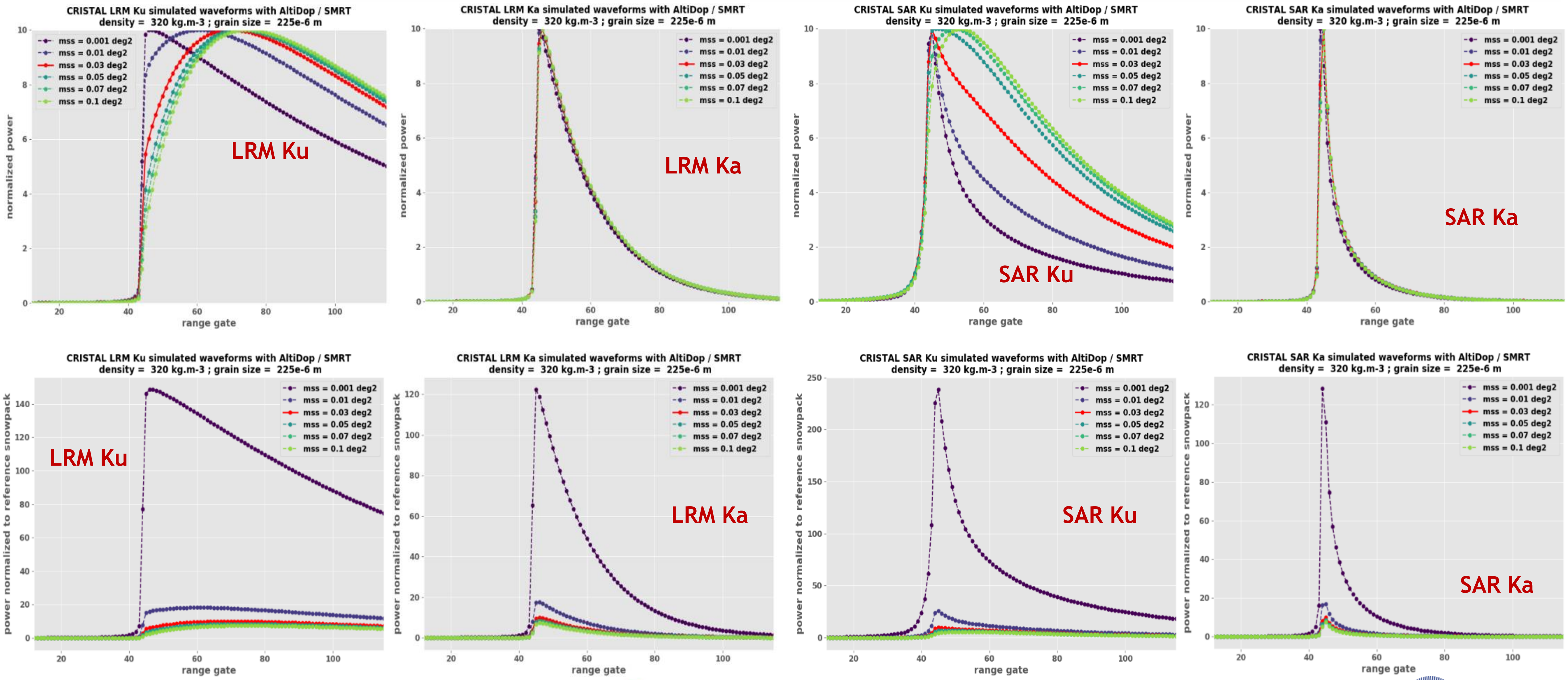




Sensitivity to snow grain size (values given for grain radius)



Sensitivity to mean square slope



Level-2 parameters estimated on simulated waveforms

- The **surface elevation** using a threshold relative to the waveform maximum energy (method used in TFMRA retracking for instance)
- The **air/snow threshold** to derive the exact surface elevation, at snow/air interface.
- The **leading edge width**, a parameter introduced with the ICE-2 algorithm [Legresy et al., 2005]. Here it is computed between [10% – 100%] of waveform maximum power.
- The **pulse peakiness parameter**, a classical waveform shape parameter, defined as the ratio between the waveform maximum energy and waveform mean energy (here computed over [12-115] waveform samples). **Only computed in SAR mode for this study, as it is less relevant in LRM.**
- The **backscattered energy, relative to the waveform reference snowpack (in dB)**. In this study, this value is computed as follows:

$$\theta r\ (dB) = 10 * \log \frac{Px}{Pref}$$

with Px maximum power of the analyzed waveform
with Pref maximum power of the reference waveform

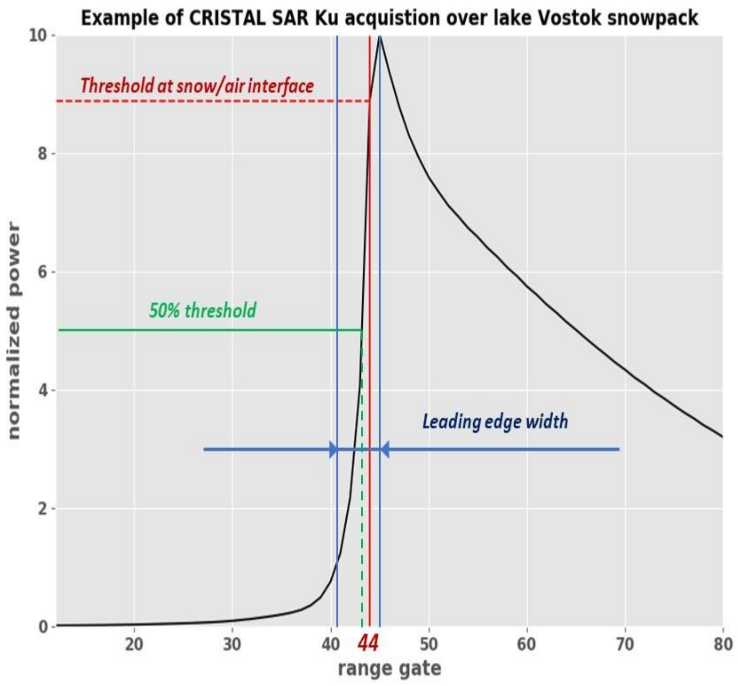
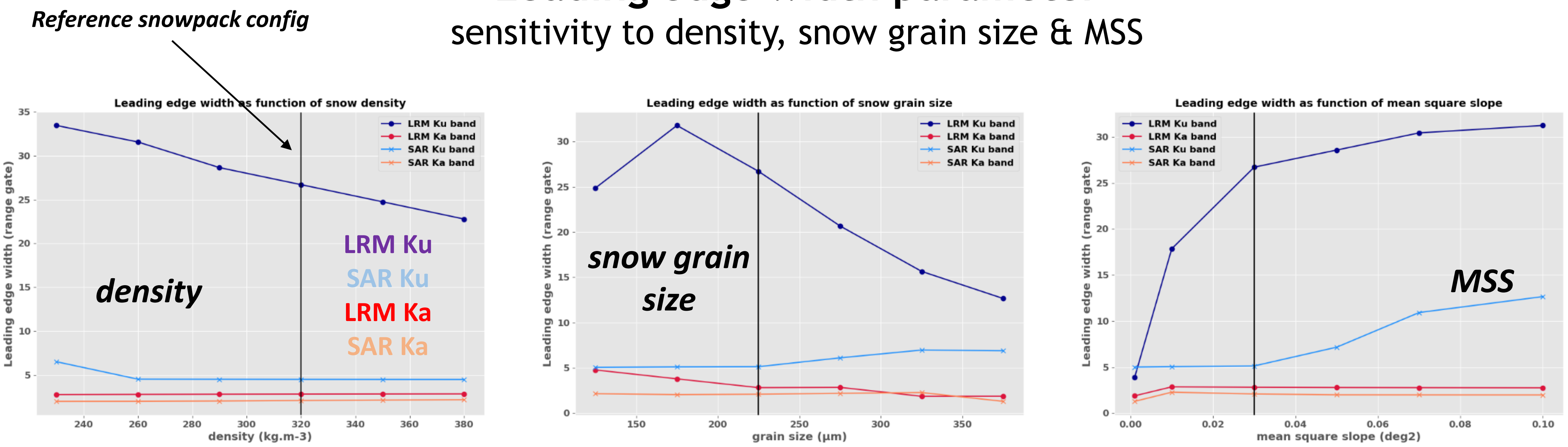


Illustration of some level-2 parameters analyzed in this study.

Performance analysis results

Leading edge width parameter

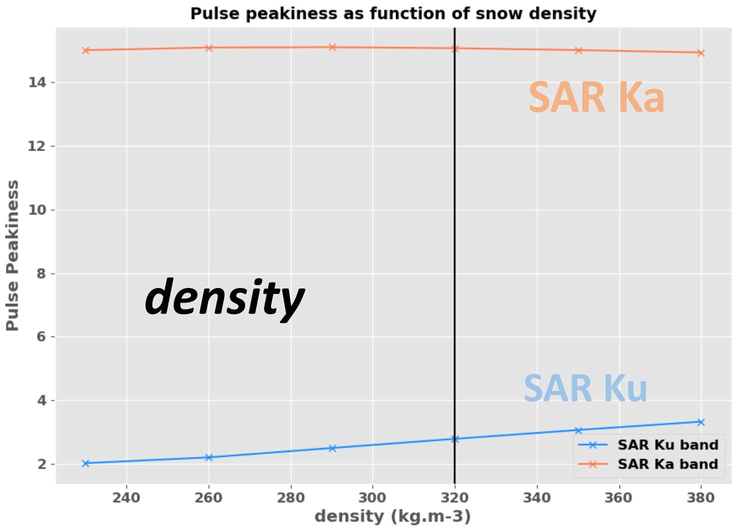
sensitivity to density, snow grain size & MSS

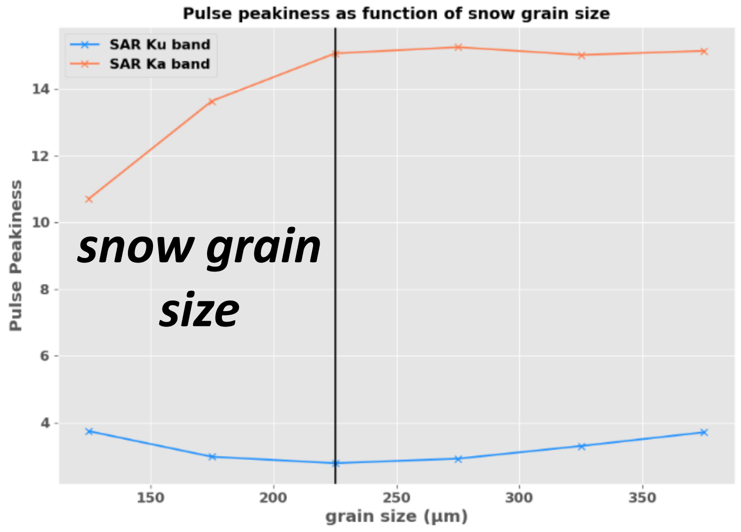


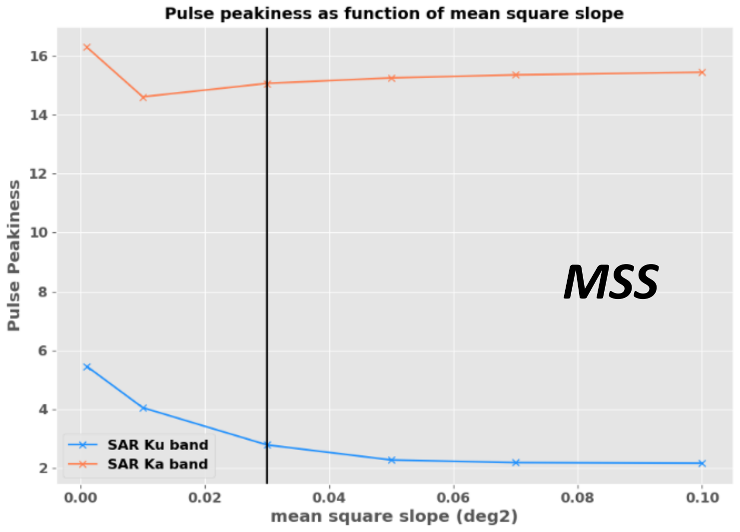
- In LRM Ku band, the leading edge width is sensitive to the three parameters studied.
- In SAR Ku band, the leading edge width is mainly sensitive to mean square slope
- In Ka band, the leading edge width remains stable, except for grain size variations

Pulse peakiness parameter

sensitivity to density, snow grain size & MSS







- In SAR Ku band, the pulse peakiness is sensitive to the three parameters studied.
- In SAR Ka band, the pulse peakiness is relatively unsensitive to snow parameters & MSS. Except for snow grain with radius < 225µm

Performance analysis results

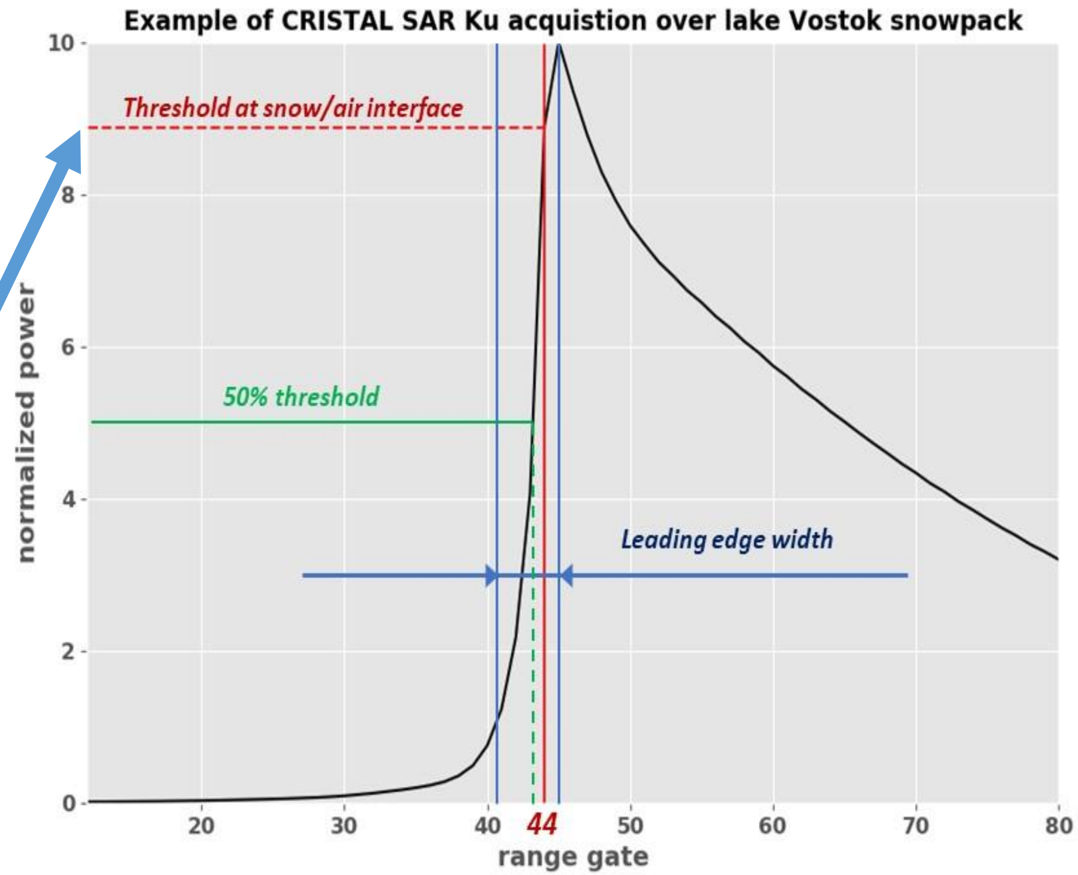
Retracking threshold to estimate elevation at snow/air interface

sensitivity to density, snow grain size & MSS

Simulations are performed such as the range corresponding to snow/air interface coincides to gate 44

In this analysis, we study the variation of the threshold to estimate surface elevation at snow/air interface

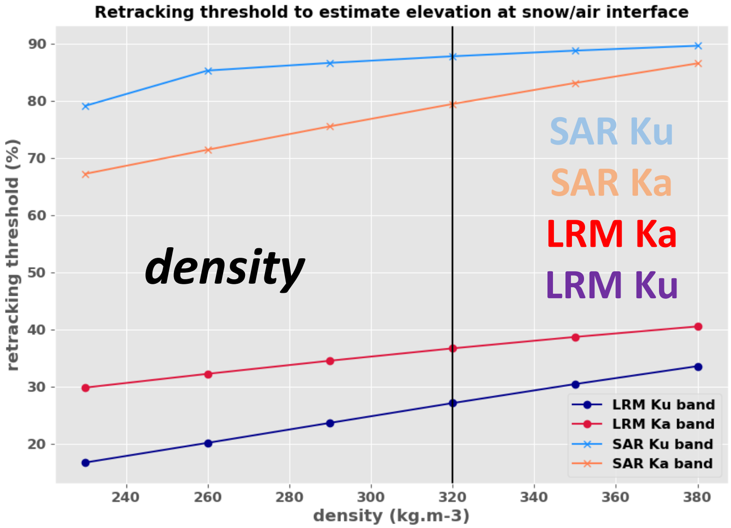
The threshold being a ratio of the waveform maximum energy, in this example ~90%

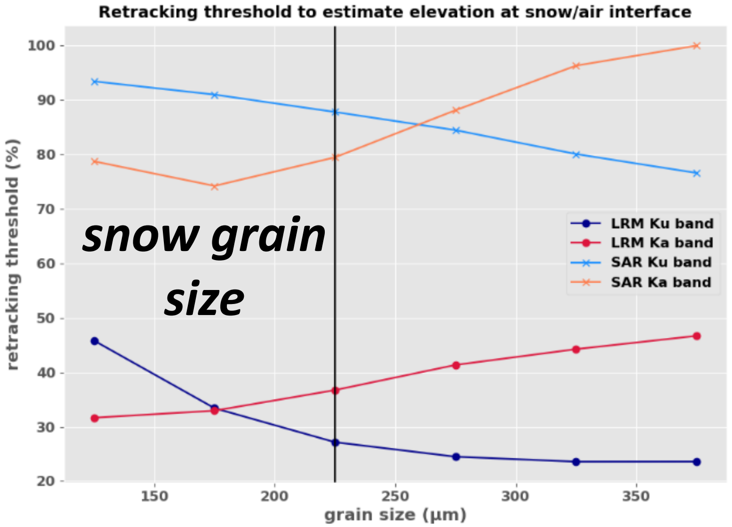


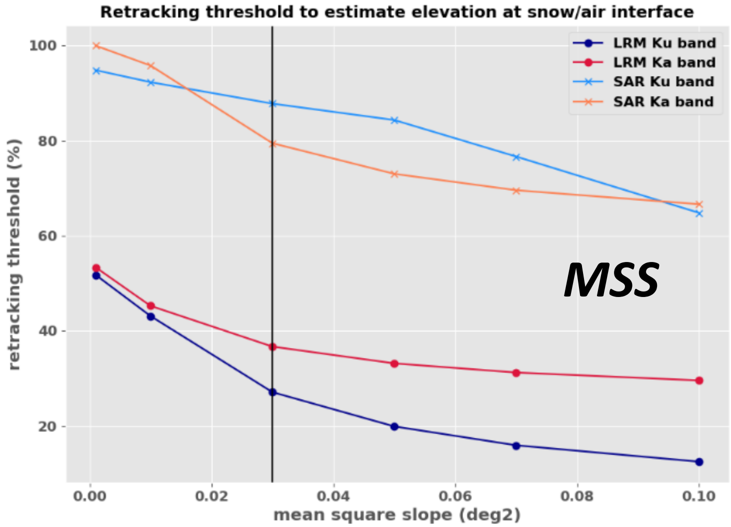
Performance analysis results

Retracking threshold to estimate elevation at snow/air interface

sensitivity to density, snow grain size & MSS







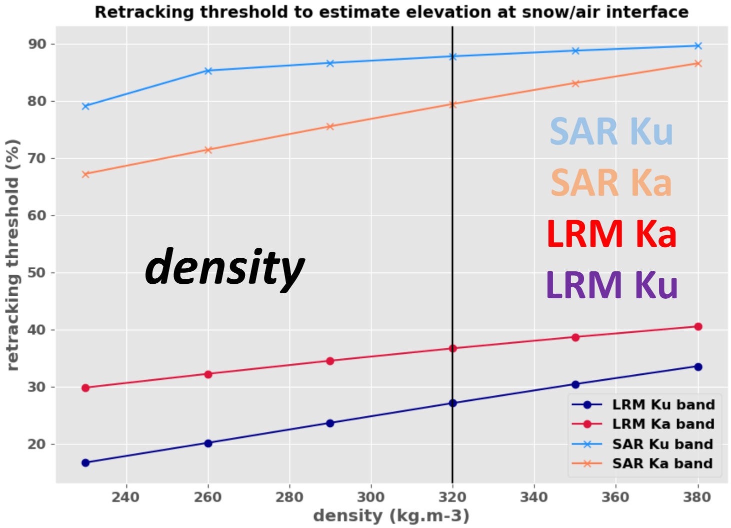
- The retracking threshold that provides the estimation of surface elevation at snow/air interface is sensitive to the three parameters studied.
- In LRM, Ka band is slightly less sensitive compared to Ku band
- In SAR, both bands appear to be equally sensitive

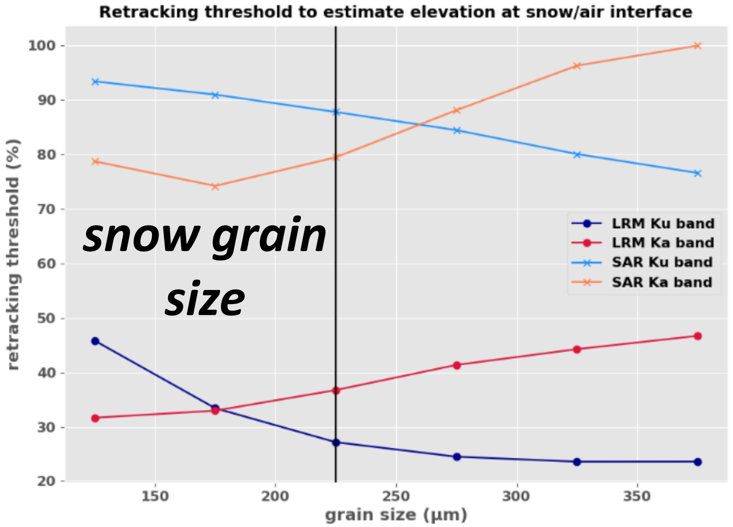
=> But this analyse must be conducted with a layered snowpack, that reproduces better the snowpack upper part, which drives the leading edge shape, and subsequently the surface elevation derived

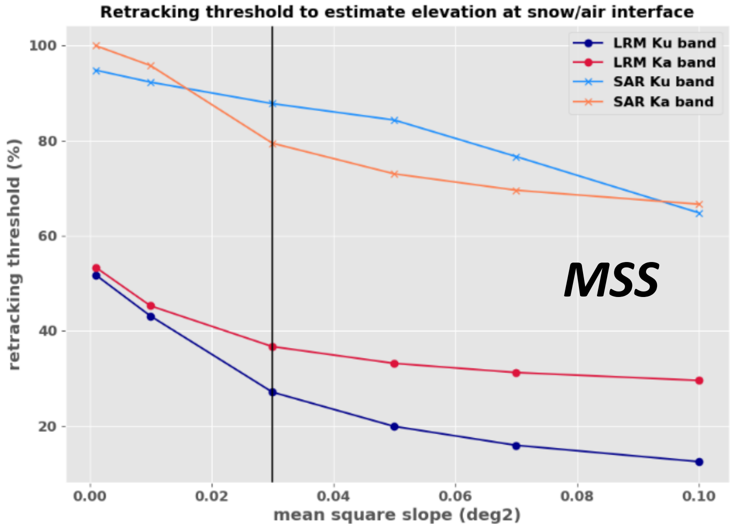
Performance analysis results

Retracking threshold to estimate elevation at snow/air interface

sensitivity to density, snow grain size & MSS







⇒ The variations observed also illustrate the limitations of empirical retrackers, generally using a constant threshold to estimate surface elevation.

<u>Snow parameters variations therefore create surface elevation biases with such retrackers.</u>

Performance analysis results

First conclusions

- The three parameters (density, snow grain size and MSS) have a significant influence on the waveform shape.

- We can anticipate that the CRISTAL dual band altimeter will be valuable to discriminate snowpack variations. For instance, in these simulations:
  - SAR Ka band pulse peakiness parameter is only sensitive to small snow grain size
  - SAR Ku band leading edge width is mainly sensitive to mean square slope
  - For all configurations, the backscattered energy is strong for low mean square slopes values

- Nevertheless, it will be necessary to refine this study with more realistic variations of the parameters. This is particularly true for the mean square slope.

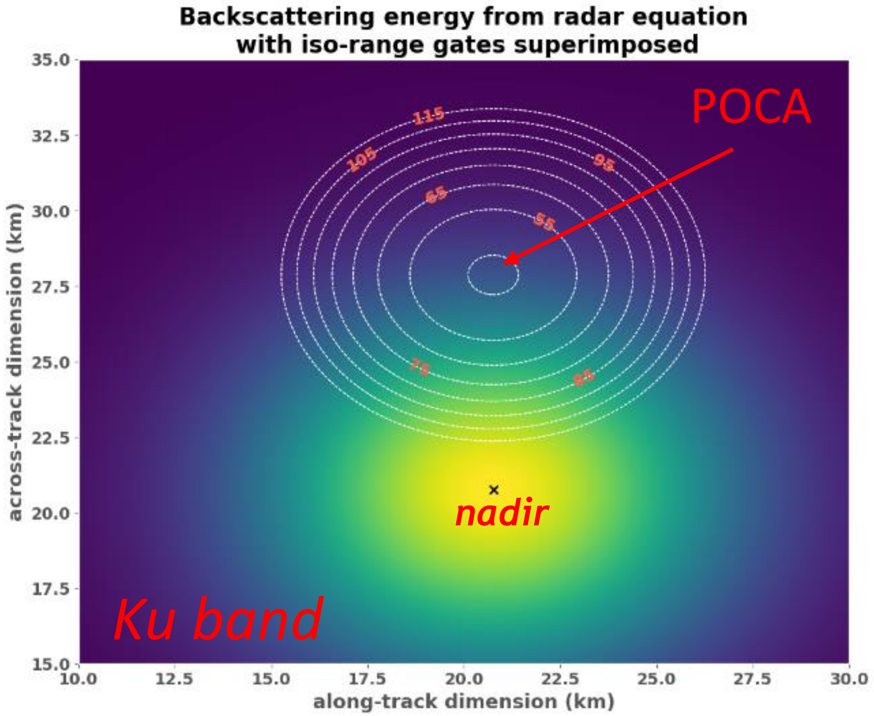
- Finally, it will also be necessary to assess snow parameters variations on layered snowpack, as the leading edge is sensitive to vertical variations at the snowpack upper part. The vertical stratification will be another parameter to account for.

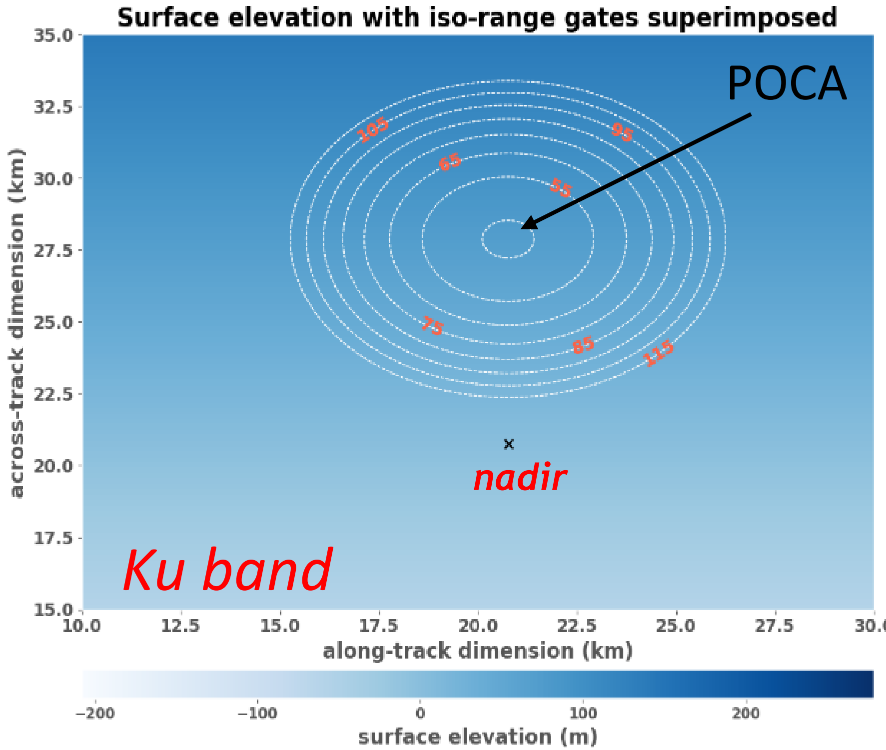
Performance analysis results

Sensitivity to surface slope

A surface slope of 1% magnitude is applied to the scene

A surface slope of 1% shifts the Point Of Closest Approach (POCA) about 7km upslope.
In Ku band, the POCA remains illuminated by the antenna aperture





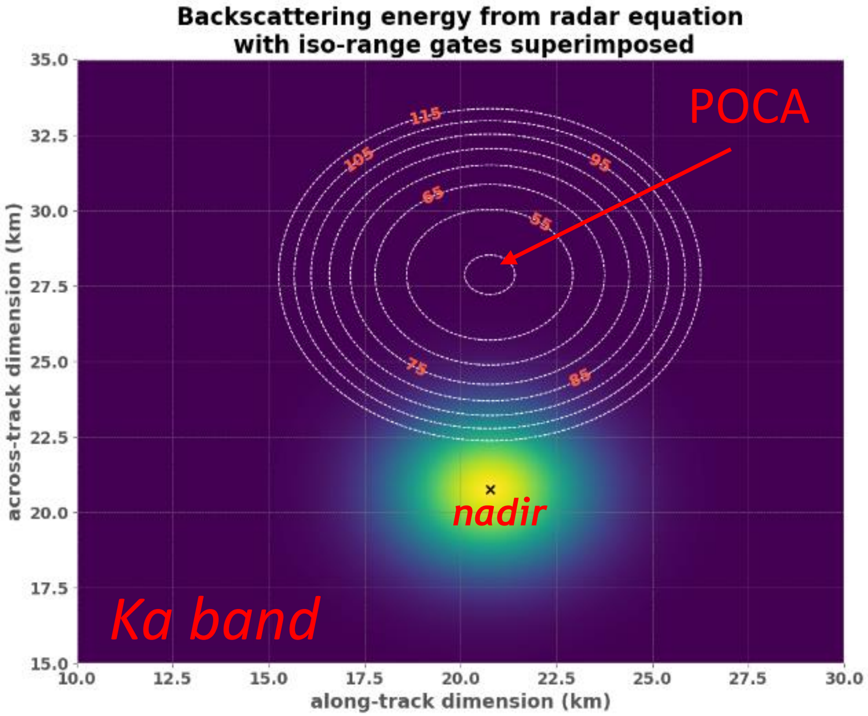
Performance analysis results

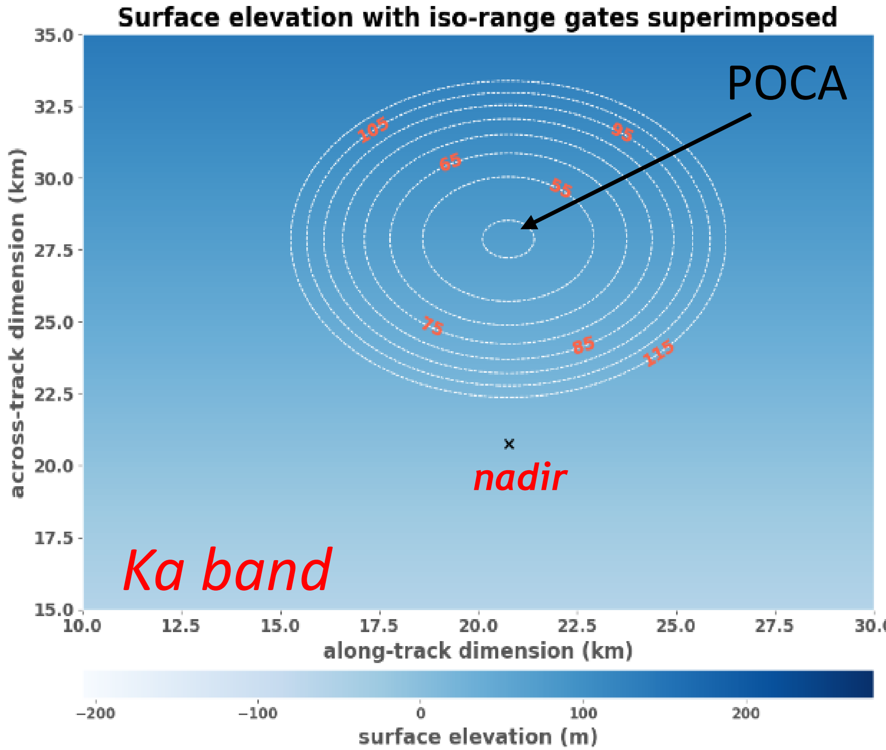
Sensitivity to surface slope

A surface slope of 1% magnitude is applied to the scene

In Ka band, due to the narrower antenna pattern (0.43° at -3dB), signal seen at POCA is strongly reduced

Note that most of the Antarctica topography is relatively smooth, with surface slope < 1%

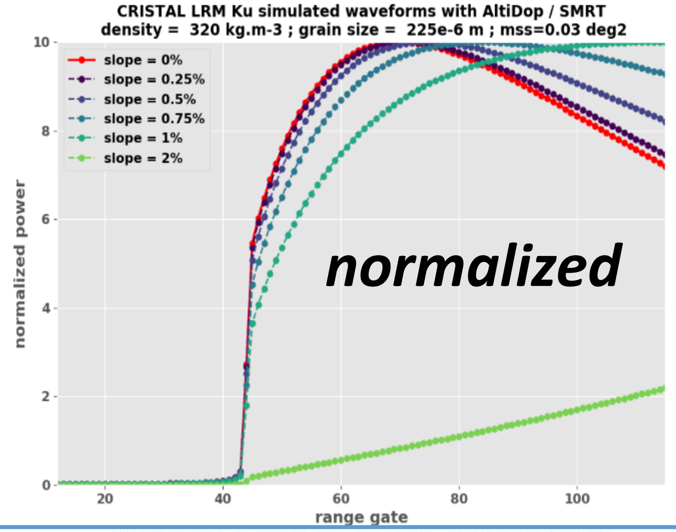


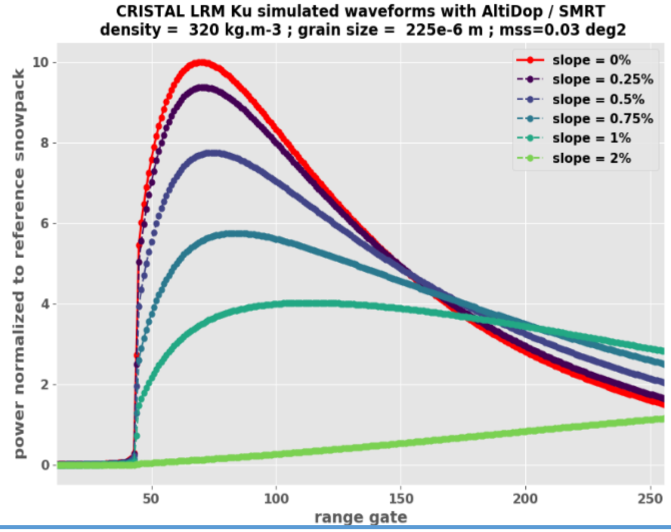


Sensitivity to surface slope – CRISTAL LRM

CRISTAL LRM waveforms as a function of surface slope

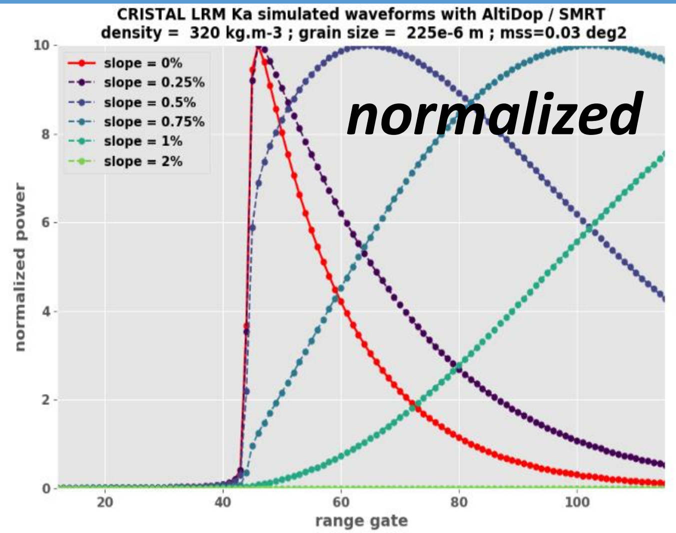
LRM Ku

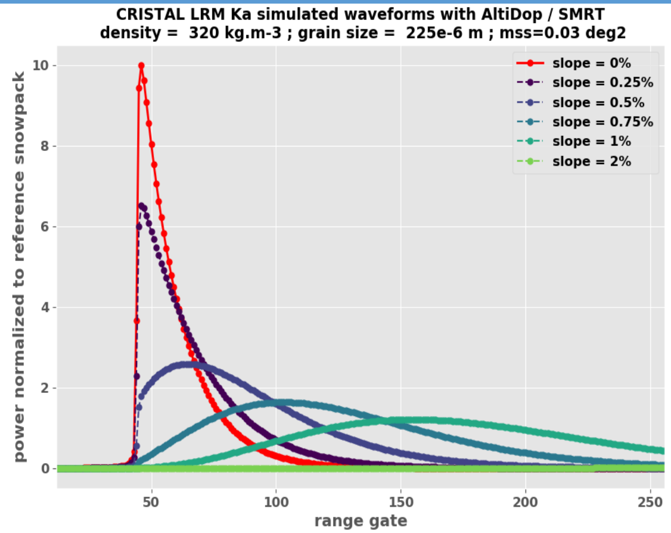




In **Ku band,** LRM waveforms shape are relatively preserved up to **1% of surface slope**

LRM Ka



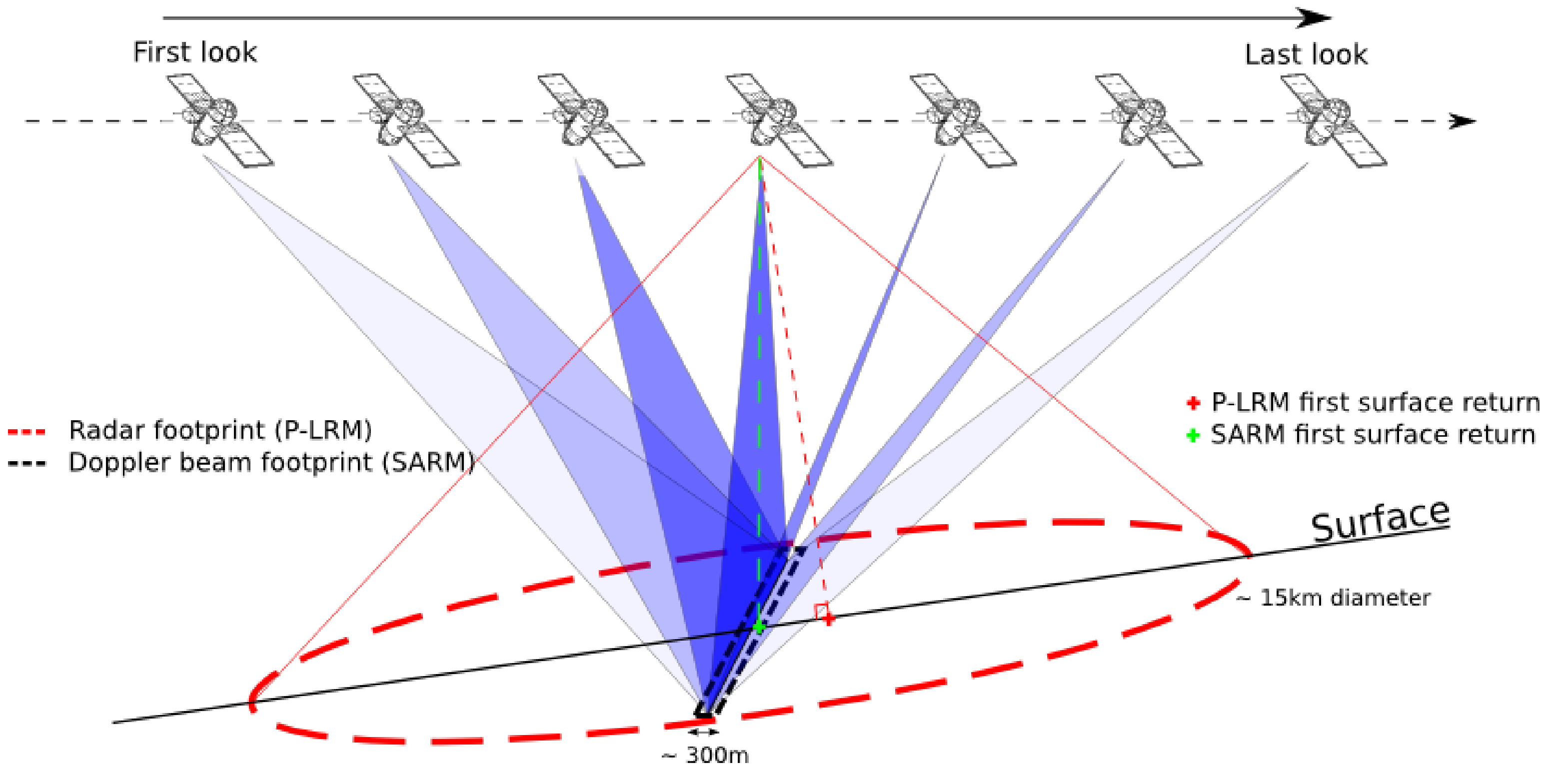


In **Ka band,** LRM waveforms shape are more sensitive to surface slope, as expected, with a leading edge distorted **from 0.5% of surface slope**

Sensitivity to surface slope – CRISTAL SAR mode

In SAR mode, the problematic changes, as the measurement is not, or weakly, impacted by the <u>along-track slope</u>.

Nevertheless, the across-track slope sensitivity remains.



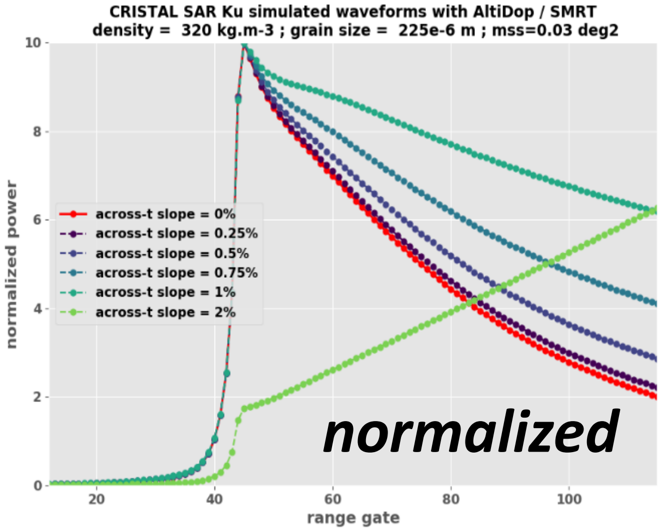
LRM* : *the closest point of the surface is shifted upslope (red mark)

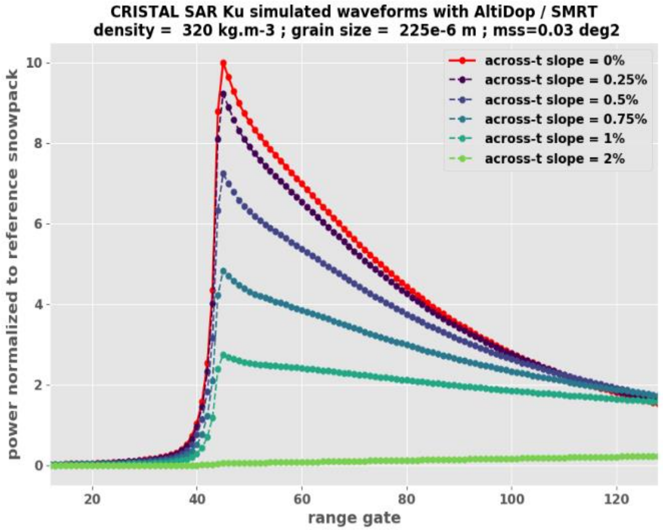
SARM* : *the footprint limits the shift within the Doppler strip (green mark)

Sensitivity to surface slope – CRISTAL SAR – across-track slope

CRISTAL SAR waveforms as a fct of across-track surface slope

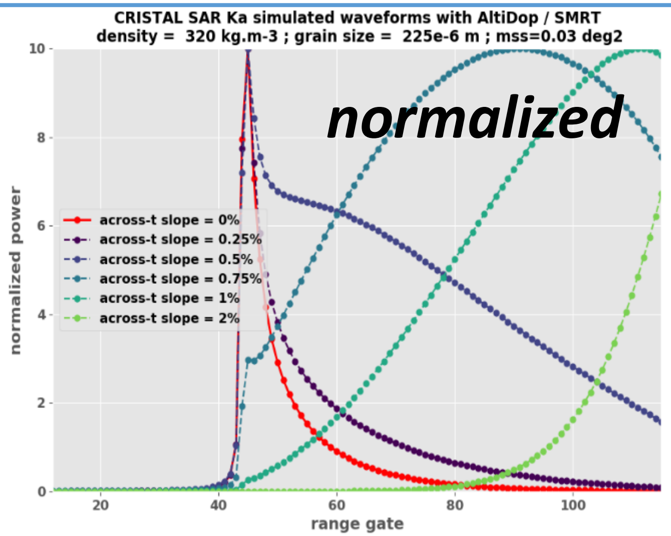
SAR Ku

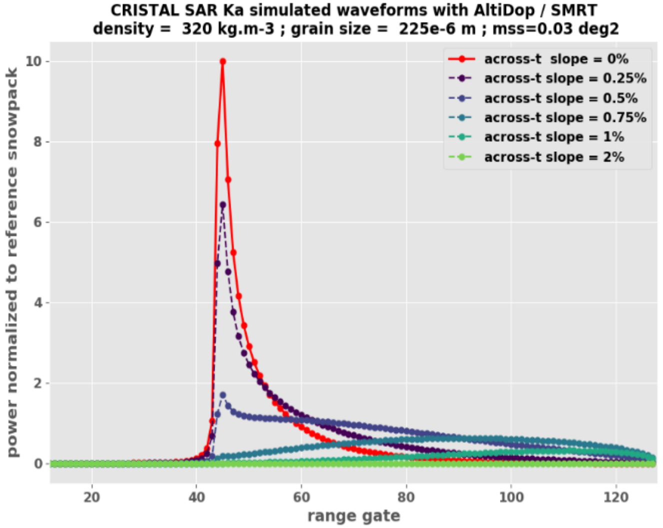




In **Ku band,** SAR waveforms shape are relatively preserved up to **1% of surface slope**

SAR Ka



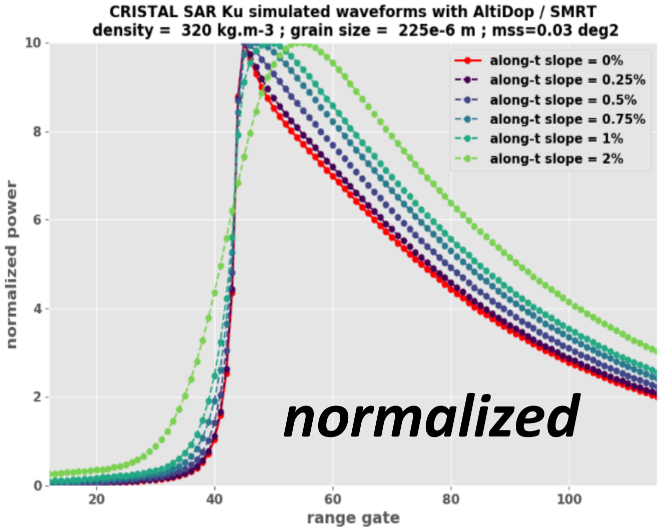


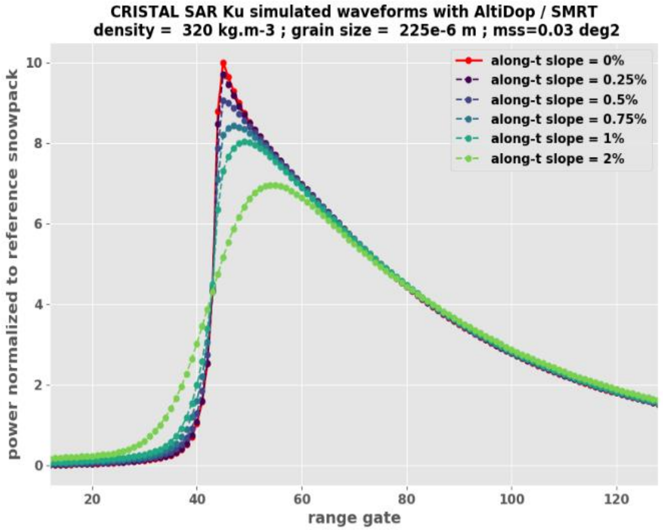
In **Ka band,** SAR waveforms shape are more sensitive to surface slope, as expected, with a leading edge distorted, **from 0.5% of surface slope**

Sensitivity to surface slope – CRISTAL SAR - along-track slope

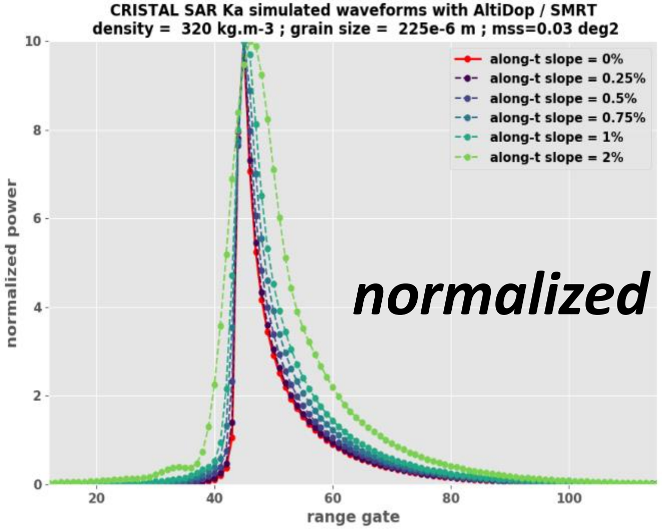
CRISTAL SAR waveforms as fct of along-track surface slope

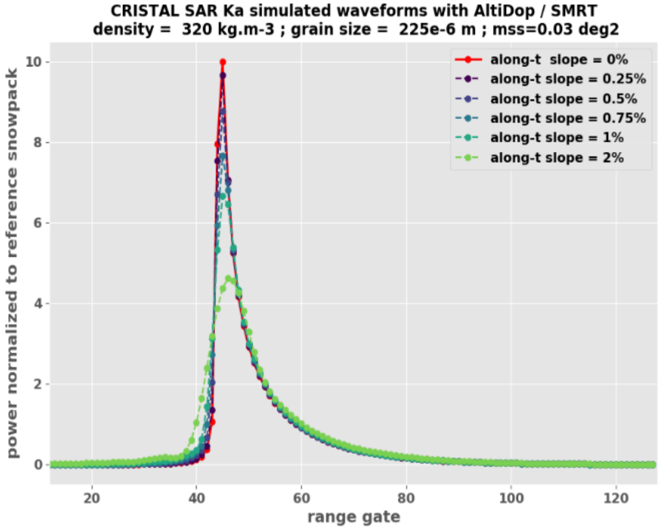
SAR Ku





SAR Ka





As the POCA remains located at nadir, the altimeter samples a surface area where antenna gain is maximal.

=> Leading edge remains clear up to 2% of along-track slope

But:

- *The waveform leading edge distortion has to be understood*
- *The energy reduction has also to be understood*

Sensitivity to surface topography - perspectives

Simulation with the new REMA DEM (Antarctica topography at 8m resolution)

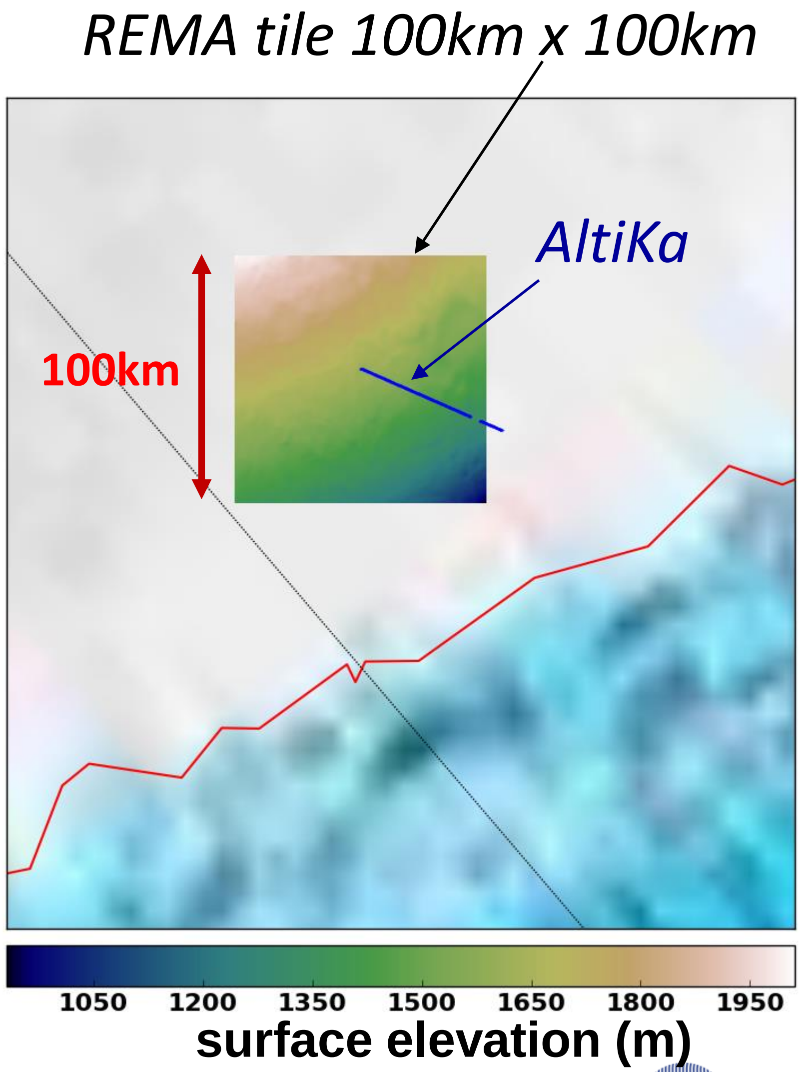
Short demonstrator over one track

- A REMA tile was downloaded, covering a part of Adelie land
- Selection of the first AltiKa track found overflying the DEM
- From the AltiKa orbital informations (lat/lon/altitude) + the tracker: waveforms were simulated with the REMA DEM as input of the simulator

The surface slope ranges from 0.2% to 1.2% along the track portion, with important variations

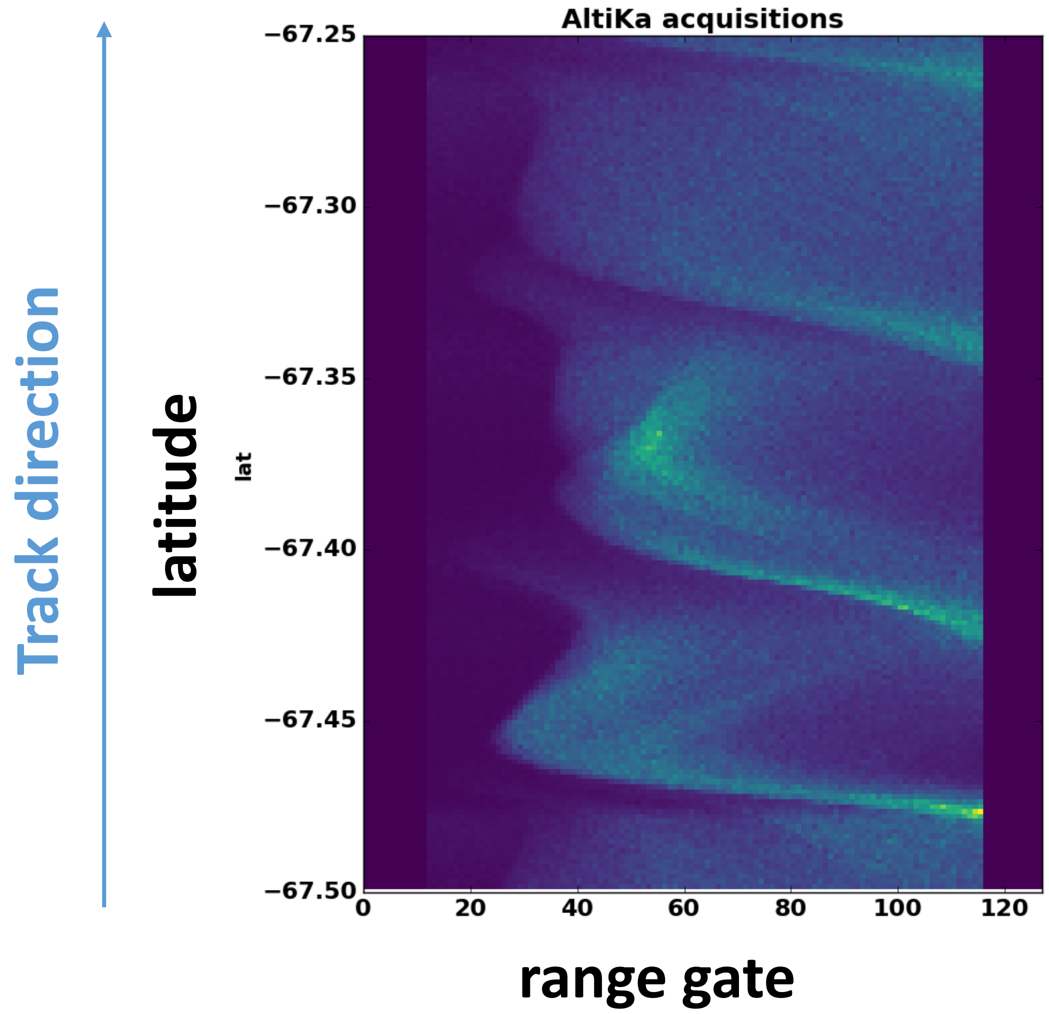
SMRT volume scattering was not introduced for these simulations

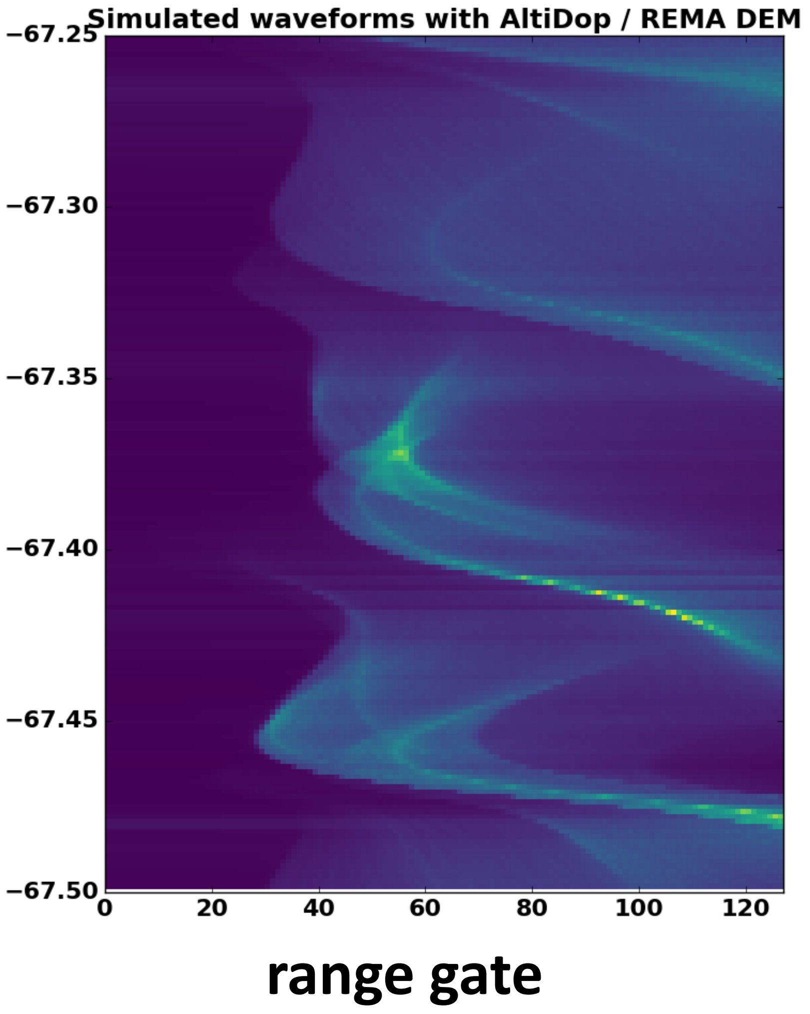
Analyses not performed in the frame of the PolarMonitoring study



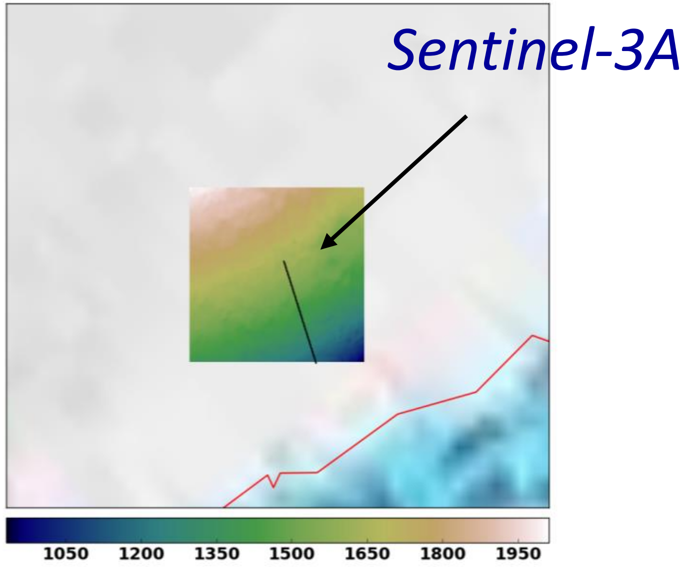
Simulation using REMA DEM: demonstration with AltiKa

Measured AltiKa waveforms **Simulated AltiKa waveforms**



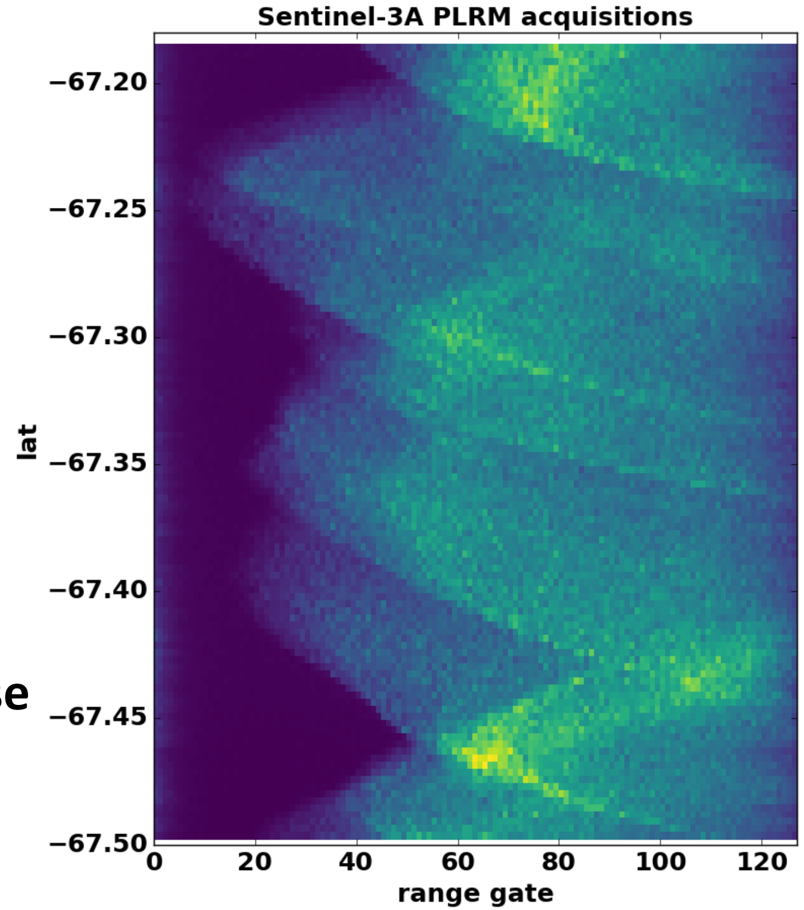


Simulation using REMA DEM: demonstration with Sentinel-3A

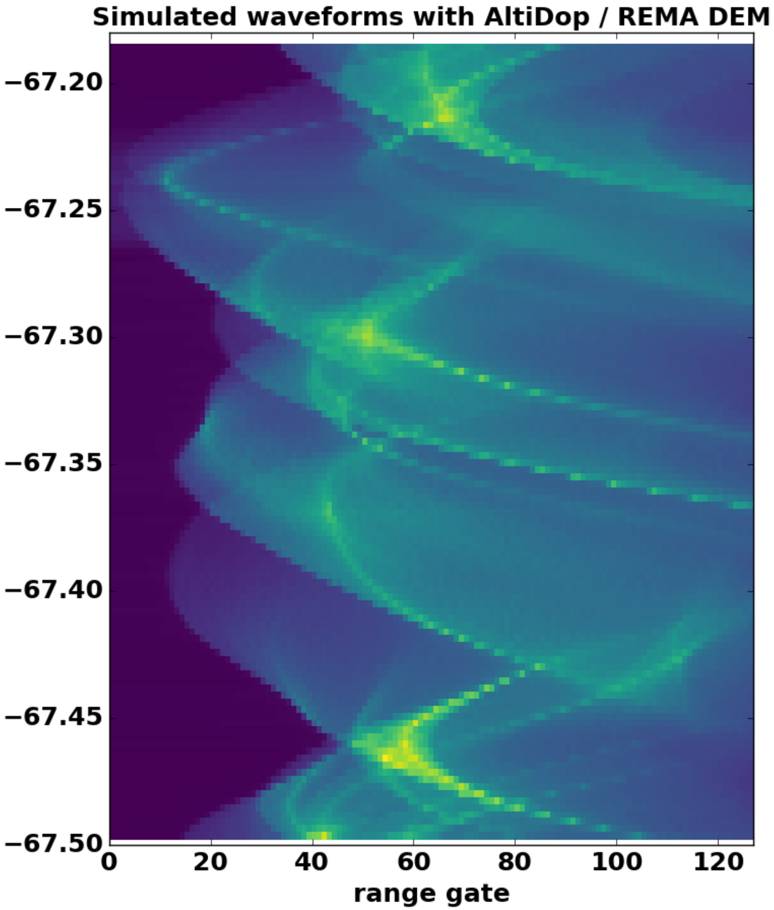


→ **Excellent agreement for these first case studies !**

Measured Sentinel-3A waveforms (PLRM)



Simulated Sentinel-3A waveforms (PLRM)



Simulation using REMA DEM: perspectives

- **To assess influence of radar topography on the waveform shape. Quantify the ice sheet area that can be successfully sampled by the CRISTAL altimeter**. And conversely the area where topography is too steep/rough to be adequately measured.

- **To precisely assess the differences between Ku and Ka measurements**, in term of relocation, and in particular regarding potential colocation differences over complex topographies.

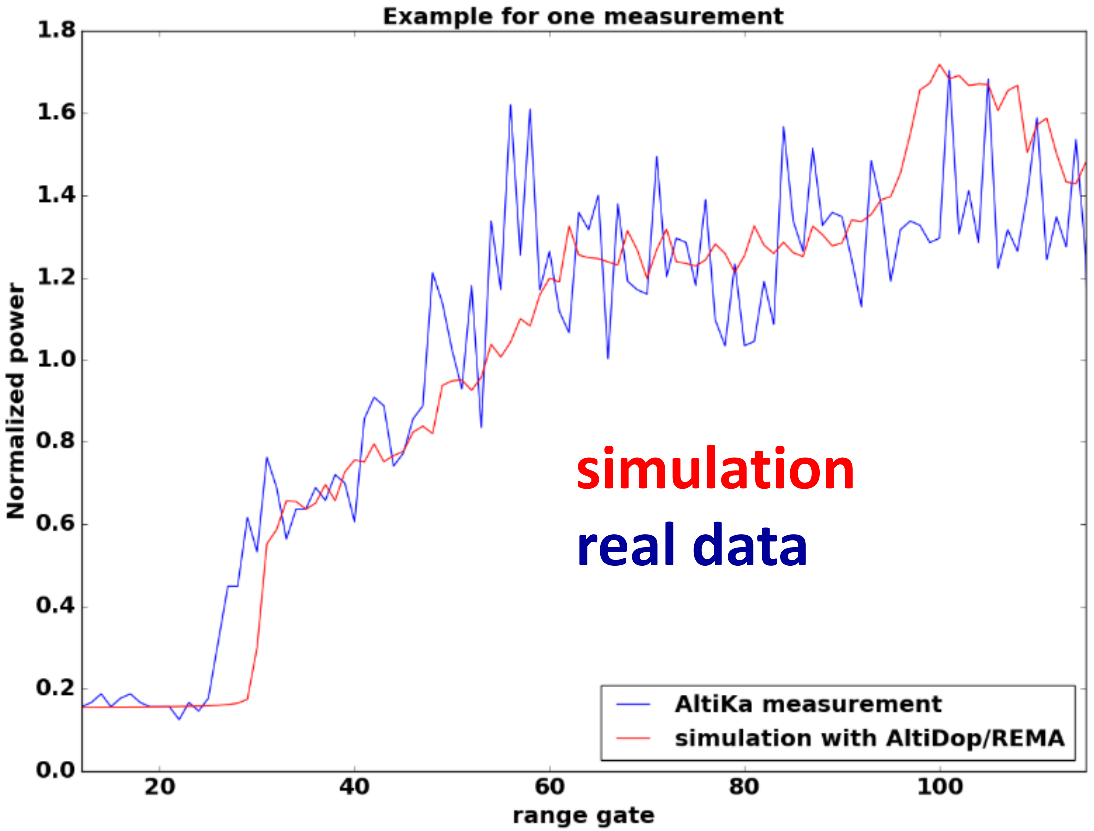
- **To improve the level-2 algorithms** that perform retracking & measurement relocation

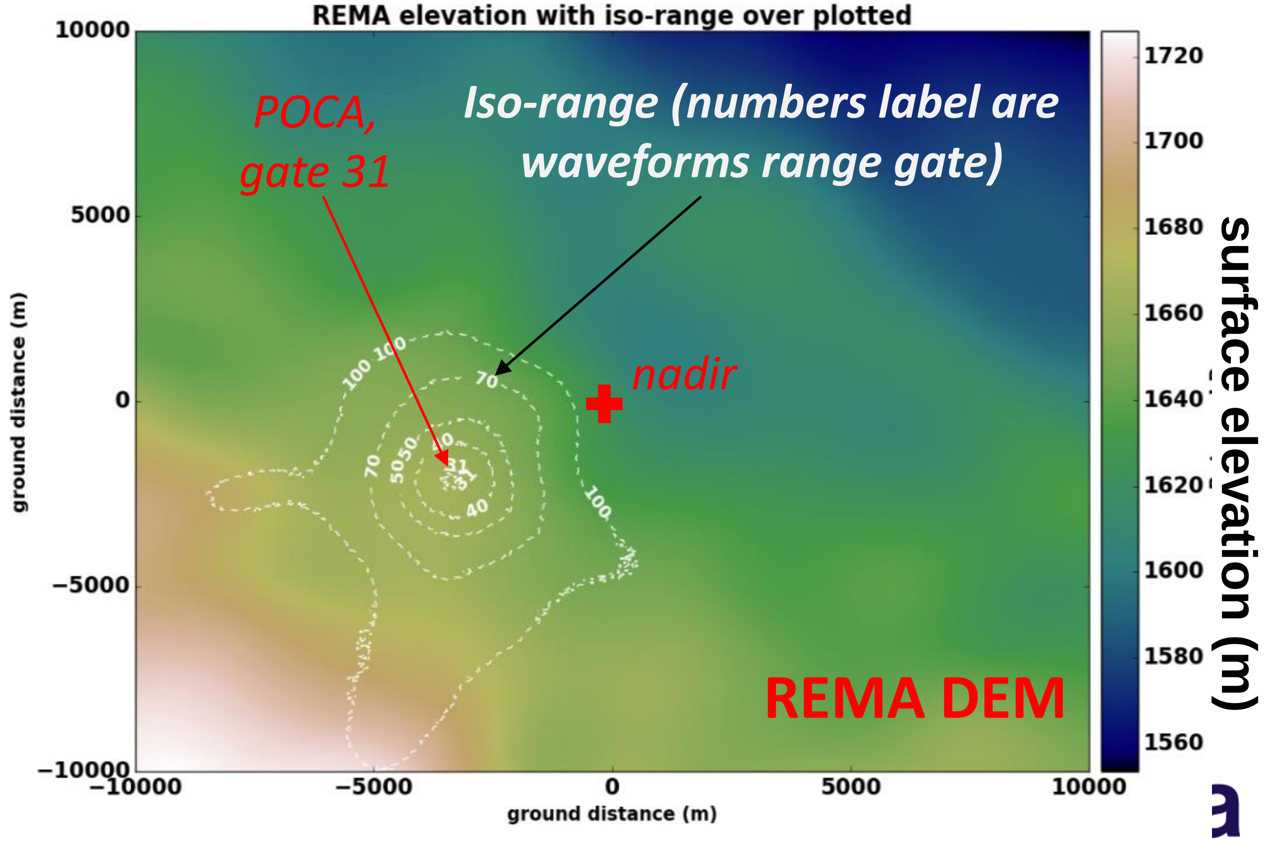
- It should help to **define the OLTC (Open-Loop Tracking Command)** that will be used by the altimeter.
  => *Studies will begin soon at CLS for Sentinel-3A in the frame of a CNES study.*

Back-up slides

Simulation with REMA over Antarctica

- Slight shift still unexplained at the beginning of waveforms (REMA accuracy, surface elevation variation, simulation to be improved ?)
- But, the most important is the shape consistency between simulation/acquisition
- From the simulation we can make the correspondence between every pixel DEM & each waveforms range gate (map on the lower right)





What consequences in case of surface elevation change ?

- **A shift of 10 meters is applied to the DEM**. It represents a worst case of 20 years difference between DEM & altimetry measurement, over the most instable areas of the continent
- In theory, if elevation variation is homogenous in the footprint, it creates an horizontal shift on the POCA of **20cm only** (depending on surface slope, 1% on this example)
- In the simulation, it creates a 32 gates shift, but waveform shape remains the same