Multistatic Radar Workshop 2025

SnowCAT: an Innovative MIMO SAR Mission for Snow Characterization by SAR Tomography

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Motivation

- Seasonal snow cover affects the global climate system and freshwater availability to billions of people
  - recognized as an Essential Climate Variable by WMO
  - included as one of ESA's Living Planet Challenges

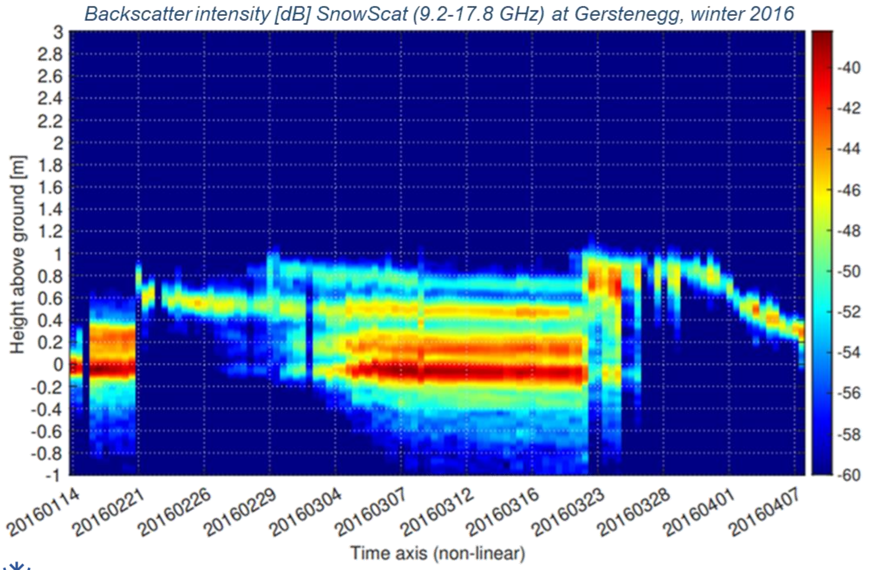
- Accurate assessment of ***Snow Depth*** (SD) and ***Snow Water Equivalent*** (SWE) is ***still challenging at operational level***, especially in mountain regions with complex topography
  - high-res optical stereo imagery
    - SD retrieval by DEM differencing, accuracy about 50/70 cm over few meters, clouds hinder systematic coverage
  - altimeters are limited by spatial sampling (LiDAR) and coarse resolution (RADAR)
  - SWE retrieval from SAR radiometry & polarimetry assumes specific snowpack models
    - accuracy about few cm/1 m in controlled conditions, problematic estimation in heterogeneous areas
  - DInSAR-based retrieval allows direct measurement of SWE variations across two dates (for dry snow conditions with highly transparent snowpack)
    - accuracy reported to be up to few cm, strongly depends on local coherence and compensation of topographic and atmospheric delays
- *There is currently no EO mission specifically dedicated to monitor snow mass in mountain regions*

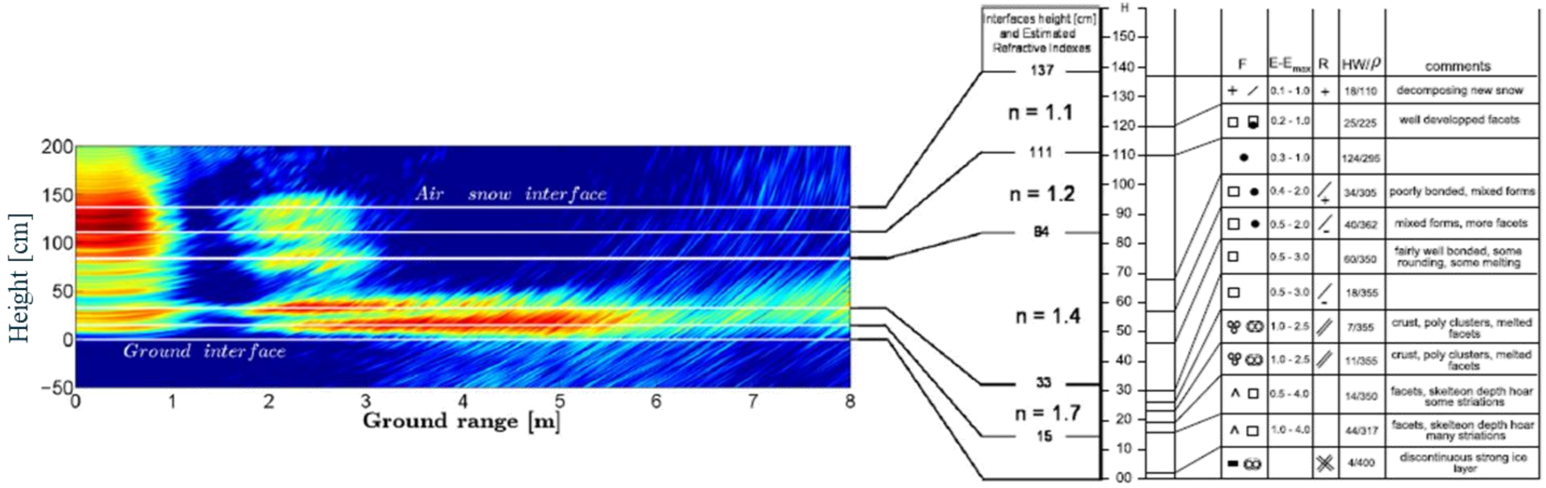
Retrieval of physical snow parameters using TomoSAR

TomoSAR acquires SAR data along ***multiple trajectories*** and provides a **3D representation** of RADAR backscatter. It is a consolidated technology for remote sensing of forested areas using P- and L-Band SAR data.

<u>TomoSAR at X- and Ku-Band allows for direct measurement of physical parameters of the dry snow pack:</u>

- Total Snow depth
- Refractive index
- SWE
- Internal layering





Data from AlpSAR 2013 (Rennes 1, ESA)

Rekioua et al., Comptes Rendus Physique , 2017

<u>Demonstrated in various ground campaigns</u>:

- ESA AlpSAR (2013)
- ESA SnowLab & ESA SnowLab NG (2016-2020)
- NASA SnowEx (2018)
- Altay UAV-SAR Ku-Band experiment (2023)

SnowCAT Mission concept

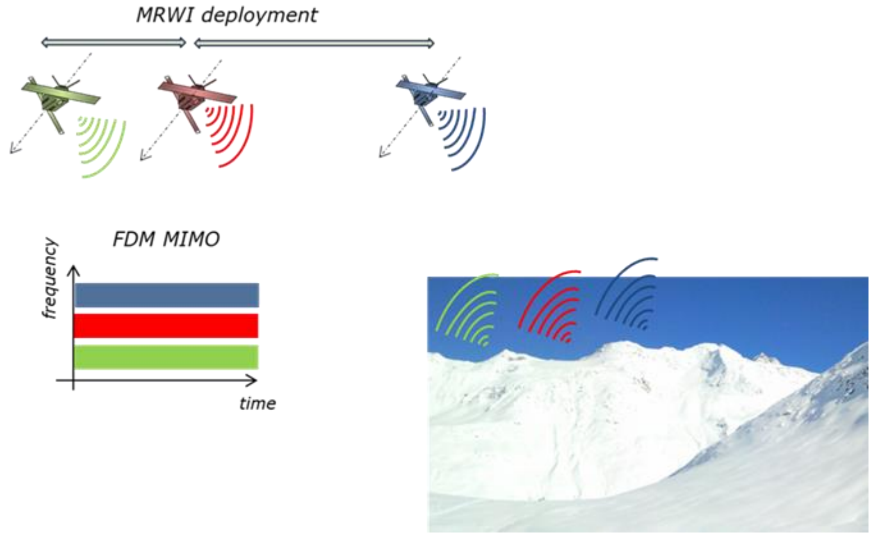
- TomoSAR formation of 3 **small satellites**, all Tx/Rx (**MIMO**)
  - reduced costs wrt classic concepts
  - mitigation of temporal decorrelation & atmosphere

- *X-Band* Radar: large bandwidth (ITU), good compromise between penetration/sensitivity to snow layers
- *Dual*-Pol
- Horizontal resolution of few meters

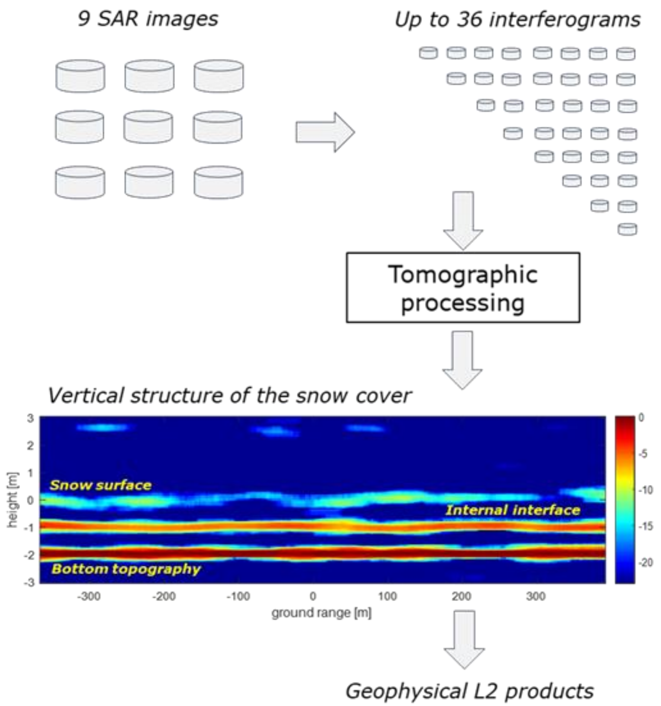
- Channel access via Frequency Division Multiplexing (**FDM**): Rainbow system
- Sub-meter vertical resolution by **MRWI** formation flying

- *Incidence angle diversity*
  - layered snow→ simultaneous retrieval of layer depth and density allowing derivation of SWE
  - transparent snow (snow/terrain or snow/ice interface detectable only) → SWE retrieval by differencing apparent snow depths at two incidence angles

SnowCAT Mission concept



SnowCAT Processing concept



MIMO Correlation TomoSAR

- Issue: design ***optimal formation from few real elements*** (i.e., maximize uniformly spaced virtual elements)
  - *optimizing virtual monostatic formation equivalent to MIMO brings limited gain*
- Alternative approach: ***correlation tomography***
  - tomographic imaging depends on the set of available **baselines**, i.e. differences in sensor positions
  - optimization brings more gain!

Minimum Redundancy Virtual Array (MRVA)

N real MIMO satellites → **Up to $N_v = \frac{N(N+1)}{2}$ virtual satellites** → **Up to $N_d = \frac{N_v(N_v-1)}{2}$ baselines**

The number of available baselines ideally goes with up to the 4-th power of the number of physical satellites

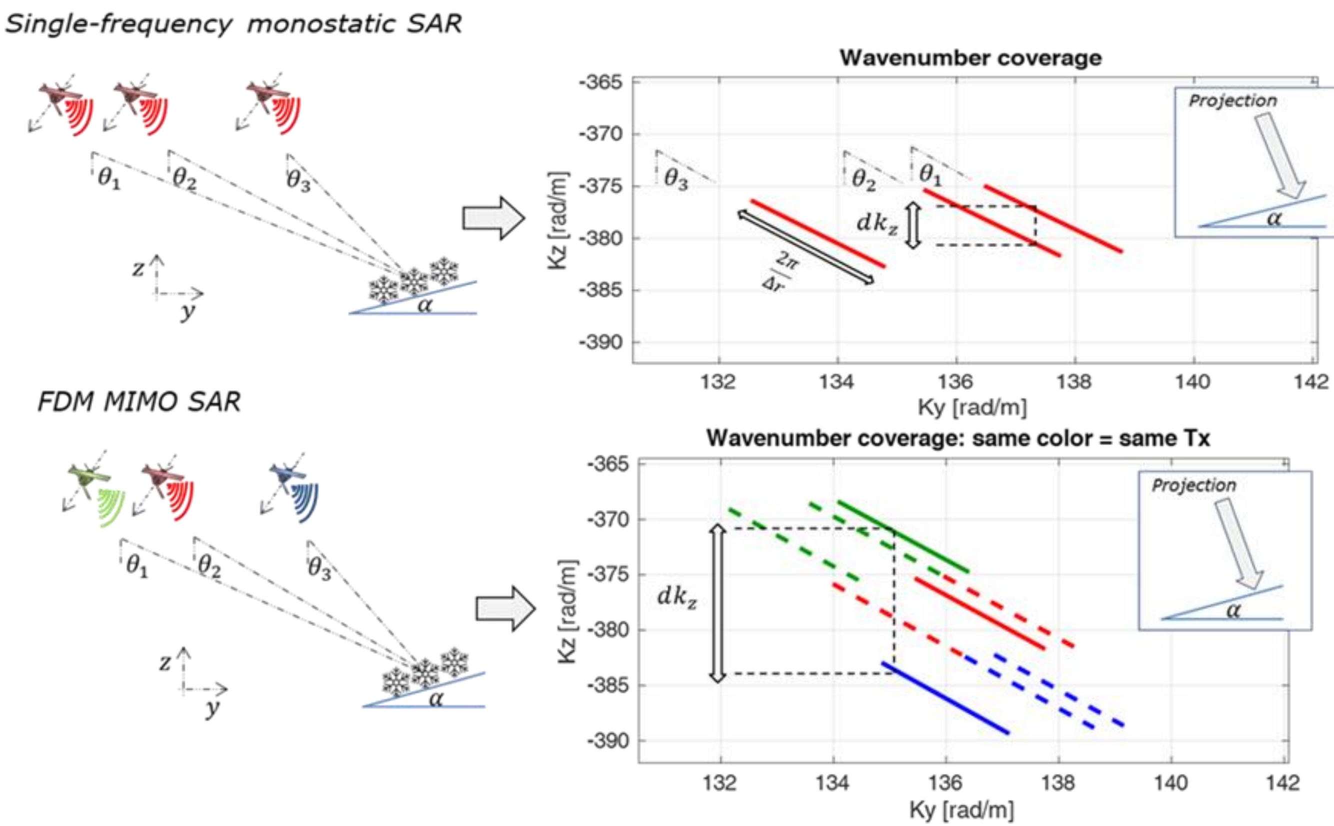
See for details in TGRS (2024)

Spaceborne MIMO TomoSAR

Problem: *MRVA assumes isotropic point scatterers, not accounting for spatial decorrelation as a function of baseline*

- ➢ *not directly applicable to the case of TomoSAR*

Solution: *design the formation to achieve sub-meter resolution while* ***accounting for decorrelation due to spatial wavenumber shift***



Using different frequency bands results in InSAR pairs with:

- large common bandwidth (**high coherence**)
- large InSAR wavenumber (**fine vertical resolution**)
- *impossible to achieve with traditional architectures*

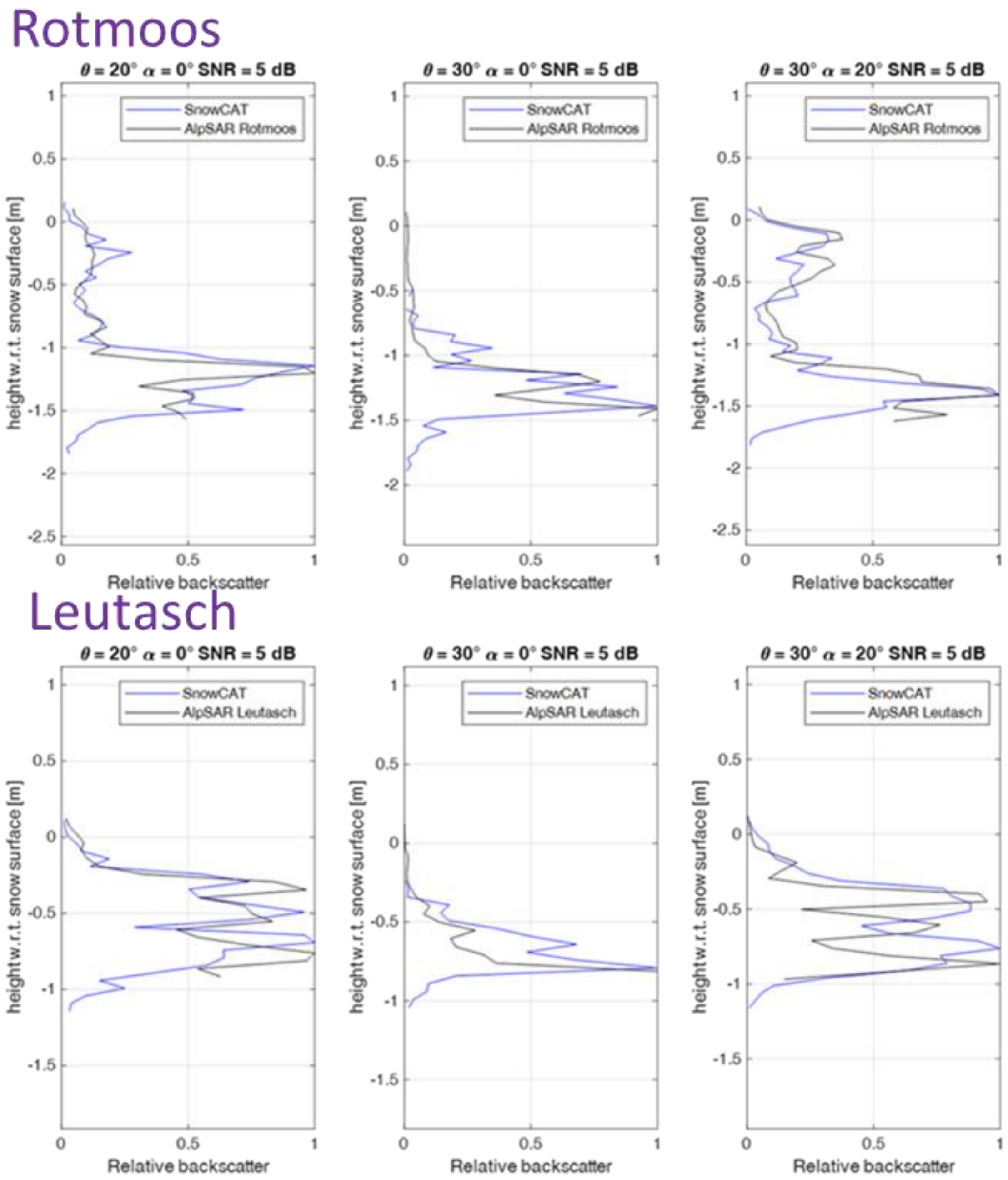
High number of FDM MIMO acquisitions gives also small InSAR wavenumbers:

- large height of ambiguity (TomoSAR **sidelobe mitigation**)

Expected TomoSAR imaging

- Data generated with diffractive simulator:
  - AlpSAR TomoSAR giving scatterers distribution
  - Projection to SnowCAT with bistatic delays
  - 5 dB SNR
  - SnowCAT formation optimized for:
    - 1.2 m vertical resolution
    - 8.4 m HoA
    - 20° incidence angle on flat terrain
  - TomoSAR focusing through COMET approach (super-res)

- Most critical case: LoS=30°, α=0° (flat terrain)
  - ➢ no detection of near surface scattering (lower backscatter)
- LoS between 20°/30°
  - ➢ increasing near surface scattering
- LoS=30°, α=20° (foreslope towards Radar)
  - ➢ incidence angle wrt snow surface β=10°
  - ➢ further increment of near surface backscatter



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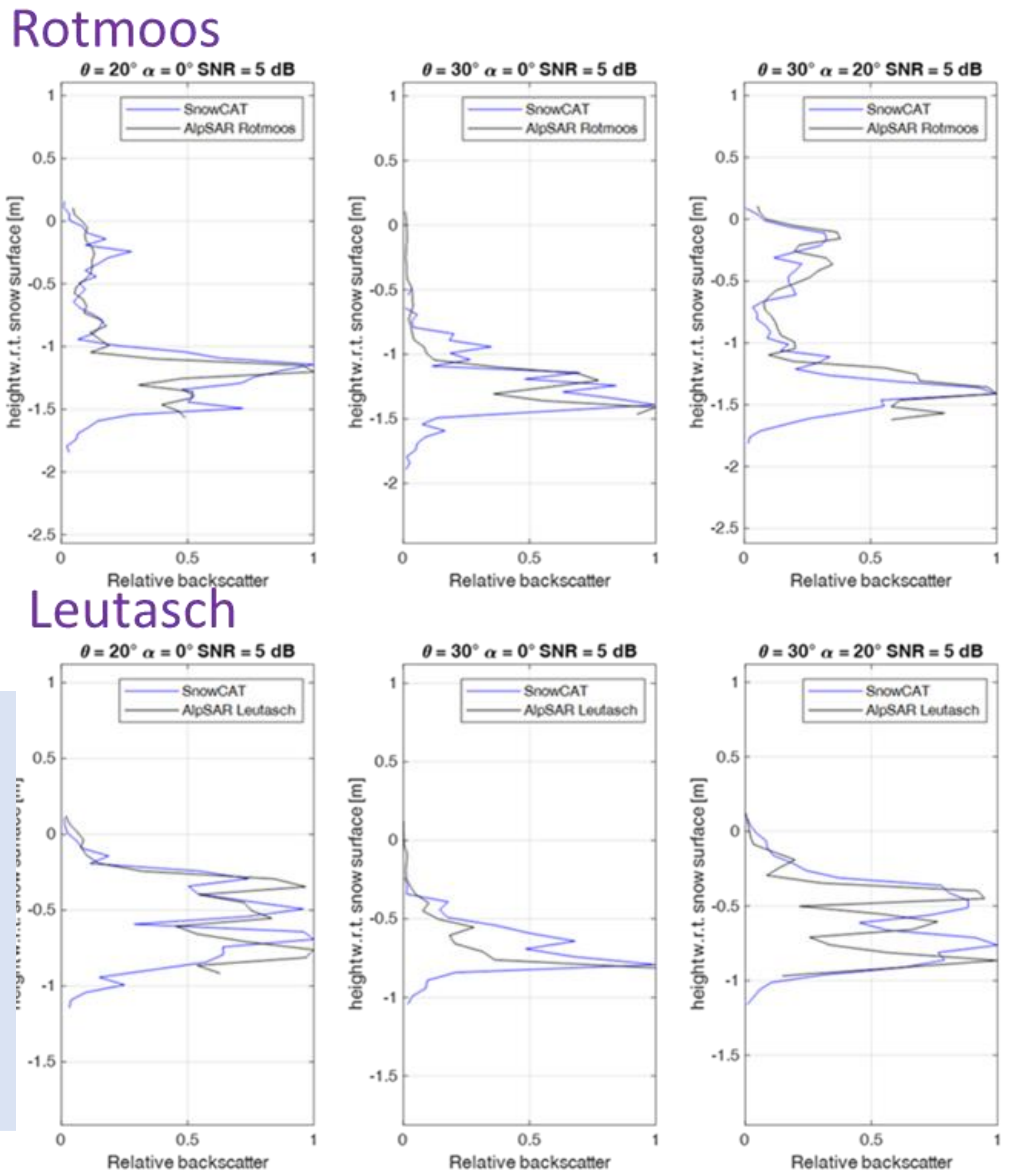
> ➢ **SnowCAT expected to meaningfully map dry snow vertical structure when LoS wrt snow surface is strictly less than 30°**
> ➢ **Ascending/descending passes & different LoS help in mountain areas (complex topography)**
> ➢ **Sea ice (no background terrain slope) provides a favourable target for SnowCAT, observed at shallow incidence angle (<30°)**

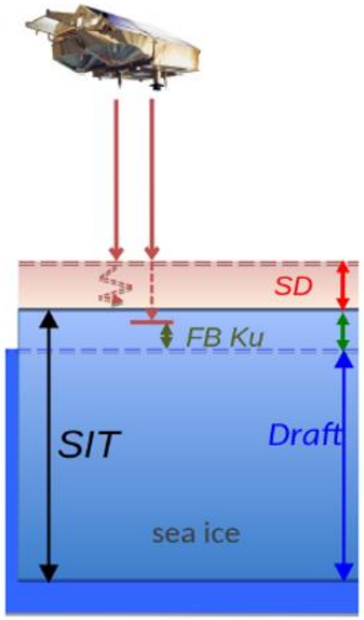


Objectives

- Characterization of snow cover in mountain regions at fine spatial resolution:
  - Snow Depth and Snow Water Equivalent (SWE) can be mapped in mountainous regions, and across hydrological basins.
  - Quantify winter snow accumulation on glaciers and ice caps
  - Identify snow pack conditions including areas with wet snow

- Evolution of snow stratigraphy by assimilation into land surface models:
  - Understand assimilation of high-resolution snow stratigraphy into weather prediction models
  - Assess the role of EO snow stratigraphy for avalanche forecasting, to simulate evolution of the soil temperature, assess thermal insulation, ecosystem evolution, predict crust thickness

- Better understanding of the influence of the snow cover on sea ice:
  - High-resolution (few meters) and precise freeboard height and snow depth determination on smooth and rough ice, further declined as:
    - Separate rough and smooth ice by estimation of ice topography at fine resolution
    - Characterization of snow structure by identification of scattering horizons, for example caused by layers of superimposed ice or a layer of snow ice



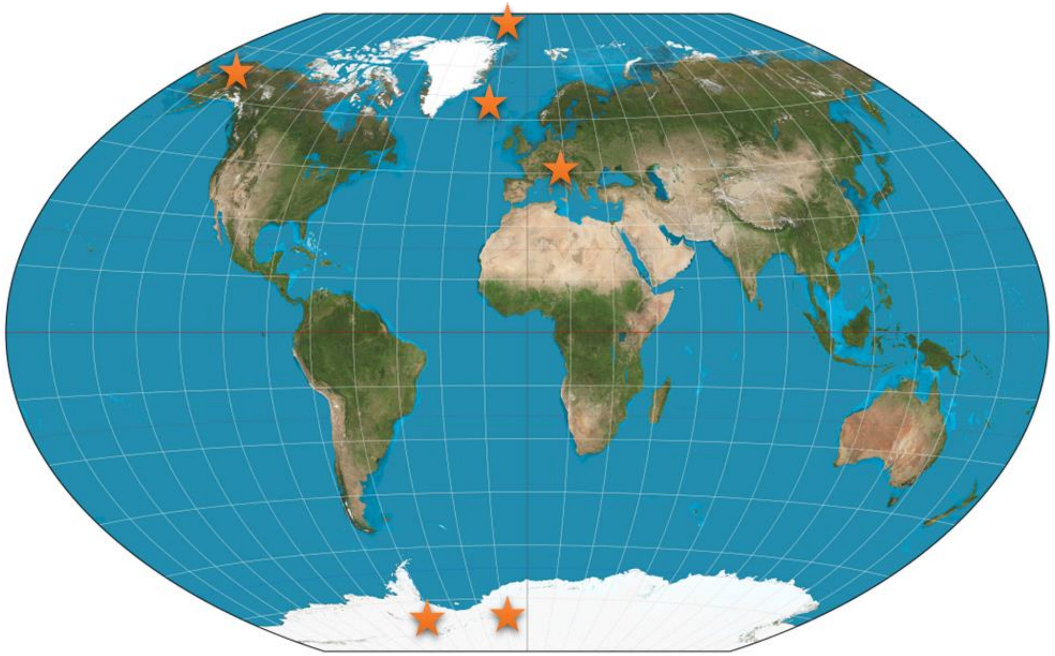
Mission scenarios & Radar payload

- SnowCAT is intended to provide systematic observations over Alpine and Arctic regions
  - ➢ total coverage about a million square kilometers
  - ➢ selected AoIs, based on availability of reference validation data & scientific relevance
  - ➢ optimization of retrieval performance wrt orbits and range of incidence angles

- The two phases will be characterized by different sets of InSAR baselines (shorter for land snow, larger for snow-covered sea ice)

- Target is to provide weekly or sub-weekly revisit & about 4/5 Stripmap images per orbit

Parameter	Value
Altitude	500 km
Revisit	<1 week
Acquisition mode	Stripmap
Antenna	Offset reflector
Incidence angle	20°/40°
Ground swath	about 10 km
Frequency	X-band
BW	100 MHz
PRF	6KHz
NESZ	< -17 dB (LoS<25°) <-14 dB (LoS> 25°)
Orbital deviation	<100m



Example Tomo & L2 products

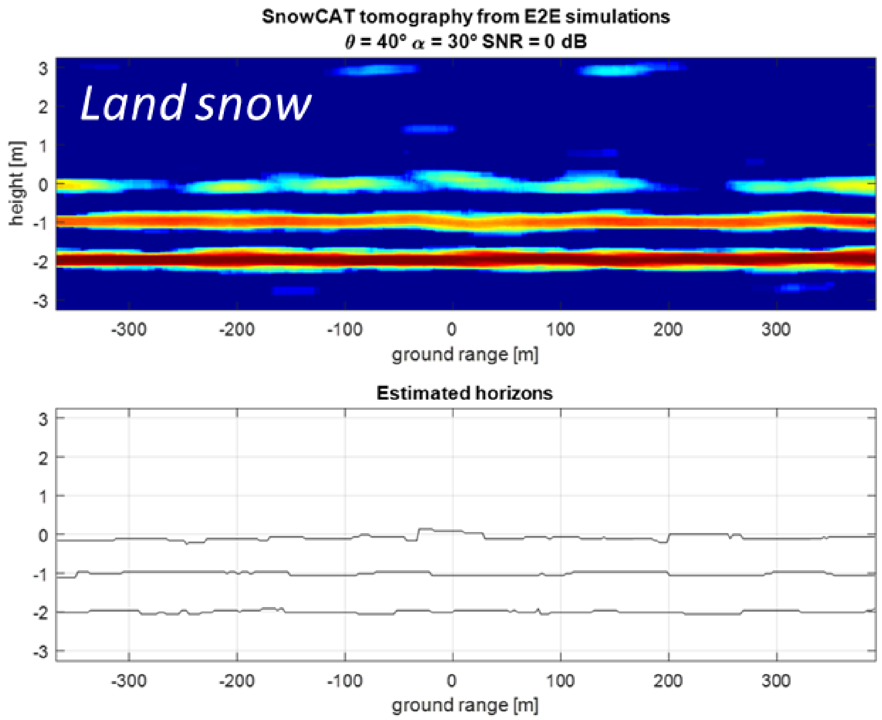
- Layered snow model & E2E simulation
- Layer identification through matching pursuit
- CRB accuracies are compared to L2 retrieval accuracy (standard deviation)
- L2 retrieval accuracy slightly higher than CRB (theoretically consistent)
- Values consistent with scientific targets for relevant applications

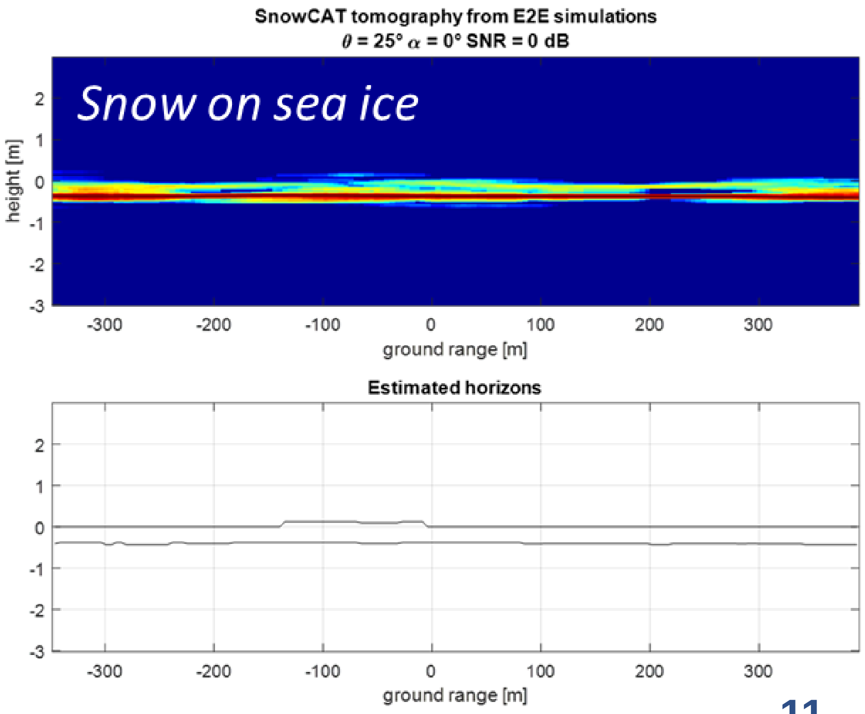
Land snow retrieval accuracy

Simulation parameters	SNR = 0 dB Estimation window = 50 x 50 m (goal requirement) Apparent snow density = 2 m. Snow cover intensity is 10 dB weaker than bottom topography		
Geometry	$\theta = 17° \ \alpha = 0°$	$\theta = 25° \ \alpha = 0°$	$\theta = 40° \ \alpha = 30°$
Bottom topography retrieval accuracy	CRB: 0.011 m E2E: 0.038 m	CRB: 0.023 m E2E: 0.040 m	CRB: 0.015 m E2E: 0.039 m
Snow depth retrieval accuracy	CRB: 0.087 m E2E: 0.110 m	CRB: 0.180 m E2E: 0.210 m	CRB: 0.113 m E2E: 0.122 m
Localization of an internal horizon	CRB: 0.028 m E2E: 0.040 m	CRB: 0.072 m E2E: 0.110 m	CRB: 0.036 m E2E: 0.043 m

Snow covered sea ice retrieval accuracy

Simulation parameters	SNR = 0 dB Estimation window = 90 x 90 m (goal requirement) Apparent snow density = 40 cm. Snow cover intensity is 10 dB weaker than bottom topography		
Geometry	$\theta = 17° \ \alpha = 0°$	$\theta = 21° \ \alpha = 0°$	$\theta = 25° \ \alpha = 0°$
Bottom topography retrieval accuracy	CRB: 0.005 m E2E: 0.009 m	CRB: 0.004 m E2E: 0.013 m	CRB: 0.006 m E2E: 0.019 m
Snow depth retrieval accuracy	CRB: 0.042 m E2E: 0.058 m	CRB: 0.030 m E2E: 0.045 m	CRB: 0.049 m E2E: 0.042 m





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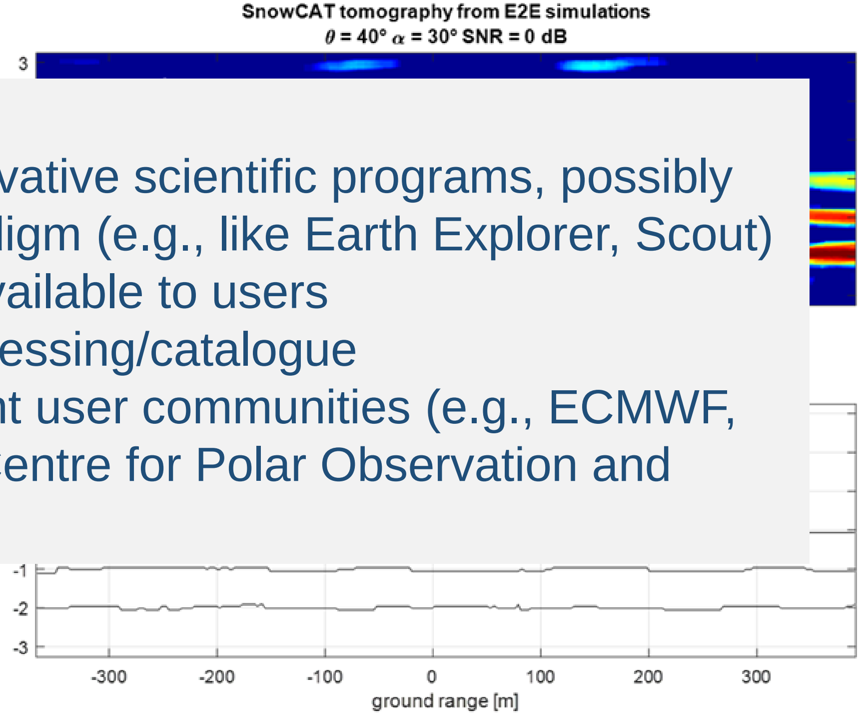
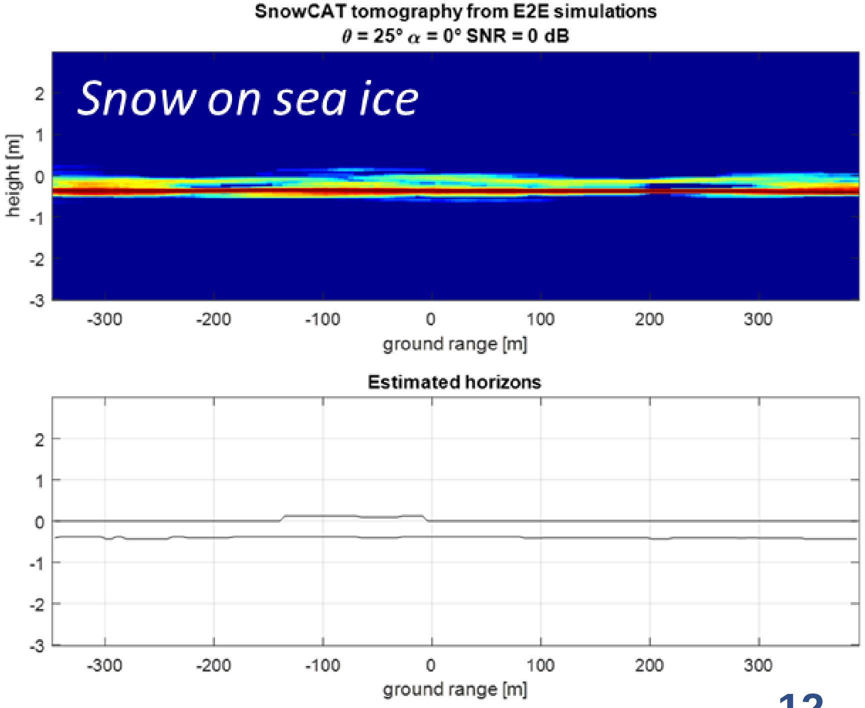




Dissemination strategy

- SnowCAT is intended to fit innovative scientific programs, possibly embracing Open Science paradigm (e.g., like Earth Explorer, Scout)
  - L1/L2/L3 products freely available to users
  - dedicated platform for processing/catalogue
  - specific attention to relevant user communities (e.g., ECMWF, Méteo France, NPI, AWI, Centre for Polar Observation and Modelling)

SnowCAT

Possible synergies with upcoming EO missions

- Feasibility of InSAR with small satellites is recently demonstrated by Hongtu-1
- SnowCAT to be the first space mission for high resolution 3D snow imaging
- SnowCAT would open to synergistic use with other ESA/Copernicus programs

  - it complements with ***CRISTAL*** in solving interpretation problems in complex ice topography
  - retrieval of snow density by integrating the apparent snow depth observed by SnowCAT & CRISTAL

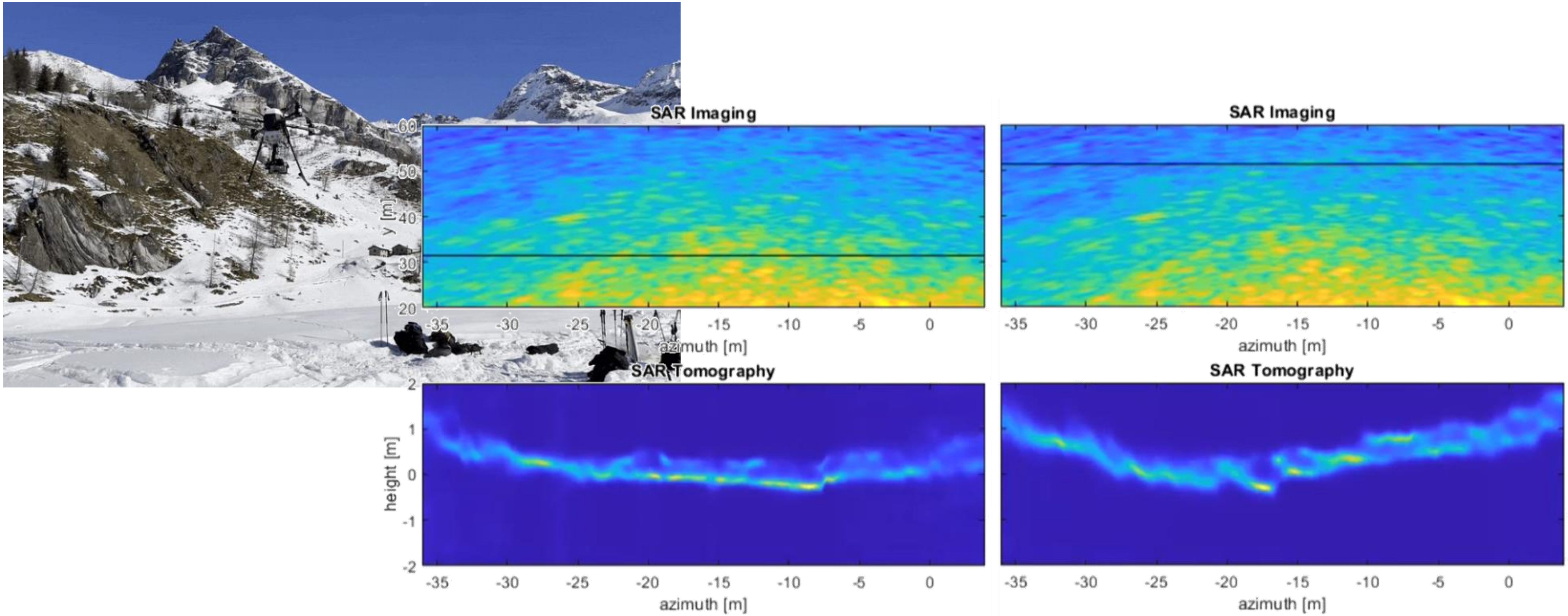
  - SnowCAT snow depth & SWE can serve as a reference for ***ROSE-L*** time series, sensitive to snow changing conditions, imperfect phase calibration and unwrapping
  - ROSE-L & SnowCAT can be jointly analysed to derive snow density at local scales

  - SnowCAT stratigraphy can enhance multifrequency capabilities of ***CIMR*** (& MetOp-SG) to capture snow structure and ultimately atmospheric information

  - SnowCAT information on snow layering provides insights into radar signal penetration into polar ice, thereby supporting the development of methods to correct ***Harmony*** penetration bias

A lot of work in progress

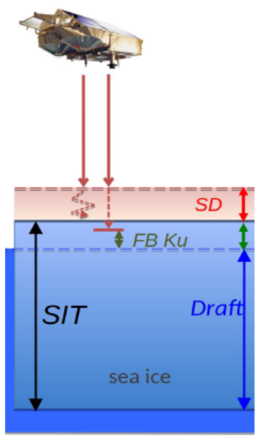
X-band snow TomoSAR at Cheneil (Aosta, 2100 m a.s.l.), 40 flights at about 50 m altitude



Thanks for your attention!

Altimeters

- Nadir-looking geometry determines sensitivity to specular scattering
- Horizons are detected by ranging
- Horizontal resolution on the order of hundreds of meters across-track
- Coverage along transects



TomoSAR

- Side-looking geometry determines sensitivity to back-scattering
- Horizons are detected by SAR tomography
- Horizontal resolution on final products the order of few meters in both directions
- Continuous coverage over the imaged swath