AN INVESTIGATION OF SNOW WATER EQUIVALENT RETRIEVAL BY ACROSS-TRACK SAR FORMATIONS

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Introduction

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

Yet, accurate assessment of Snow Depth (SD) and Snow Water Equivalent (SWE) is still challenging when considered at an operational level, especially in mountain regions characterized by complex topography

- High-res stereo imagery from Pléiades allows for SD retrieval by DEM differencing. Accuracy is reported to be on the order of ≈ 50 – 70 cm at the scale of few meters.
- Measurements of SD from altimeters are limited by spatial sampling (Lidar) and coarse XT resolution (Radar).
- SWE retrieval based on SAR radiometry and polarimetry is inherently linked to the assumption of specific models of the snowpack. Accuracy is reported to range from over 1 m up to a few cm in controlled conditions, but inversion can be problematic in heterogeneous areas where the link between Radar observables and snow parameters is modulated by local conditions.
- DInSAR-based retrieval allows for a direct measurement of SWE variations across two dates, under the fundamental assumption of a transparent snowpack. Accuracy reported to be up to few cm, but critically dependent on local coherence and compensation of topographic and tropospheric delays at local scale.

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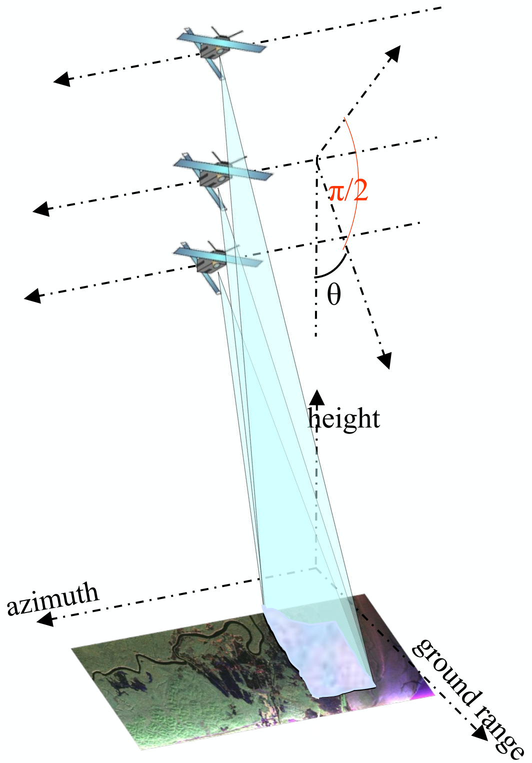
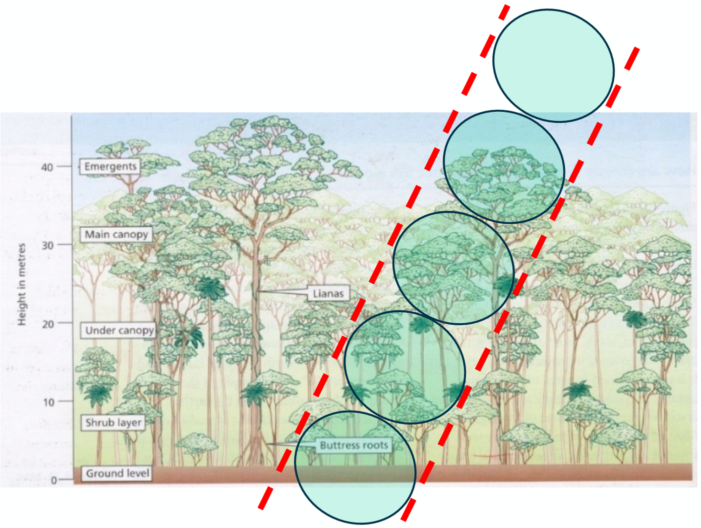
The idea explored within this work is to use SAR tomography for retrieving SD and SWE

TomoSAR systems employ a RADAR sensor flown along multiple trajectories to provide a 3D representation of Radar scattering at a given wavelength

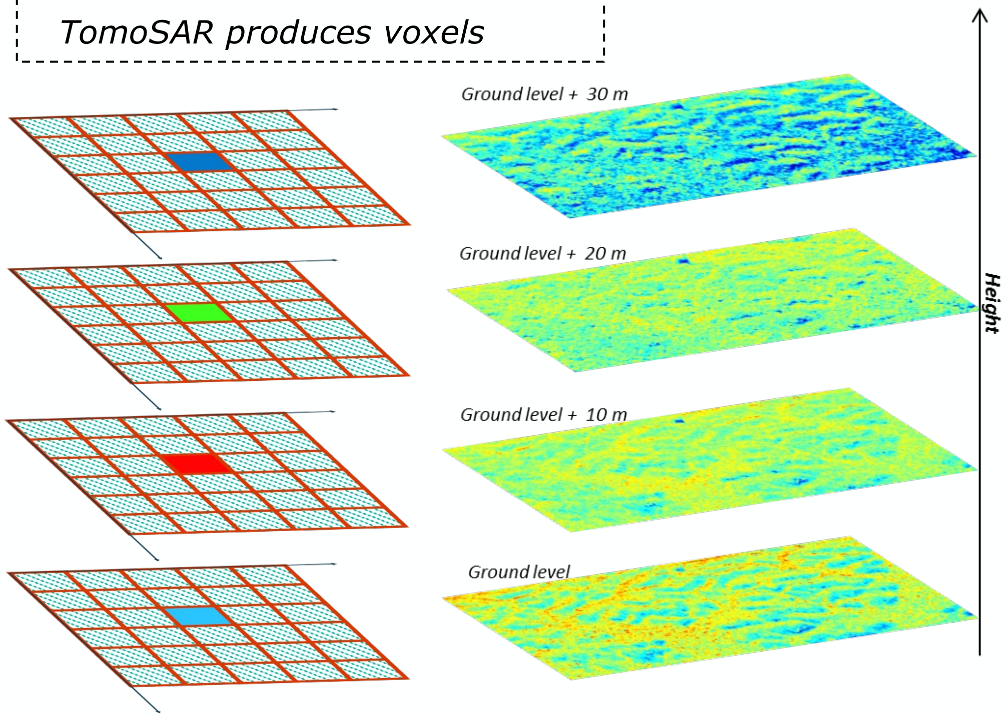
- Consolidated technology the remote sensing of forested areas at P- and L-Band





SAR produces pixels

TomoSAR produces voxels



SD and SWE by SAR Tomography

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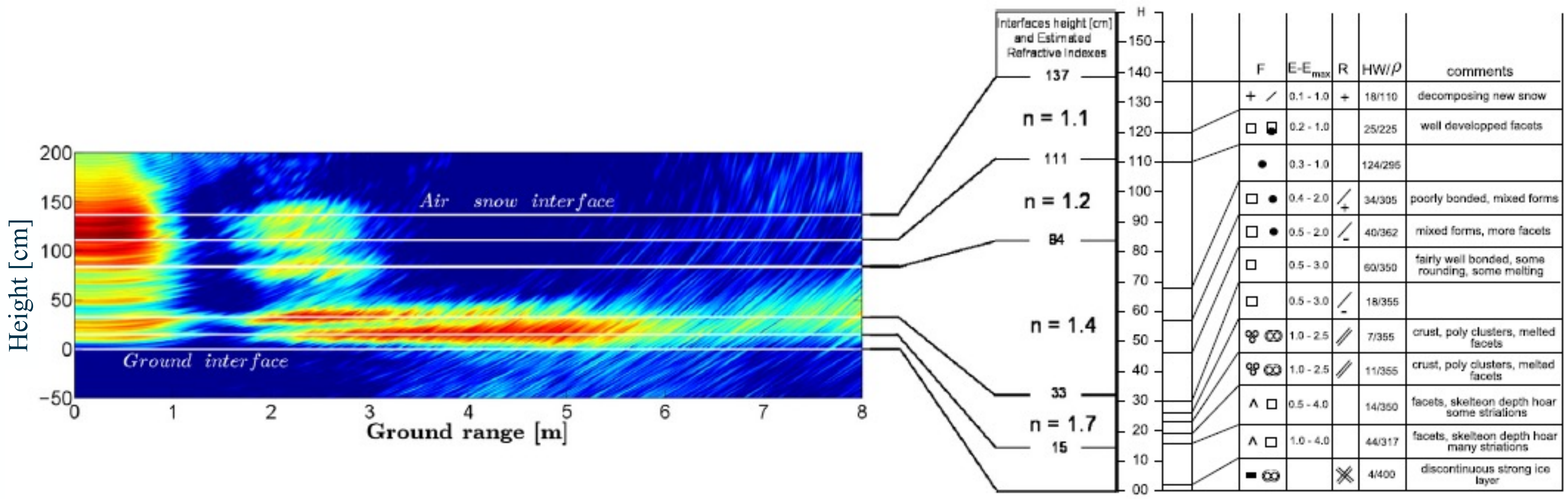
TomoSAR systems employ a RADAR sensor flown along multiple trajectories to provide a 3D representation of Radar scattering at a given wavelength

- Consolidated technology the remote sensing of forested areas at P- and L-Band
- X- and Ku-Band TomoSAR allows for imagining the fine structure of the snowpack
  - ⇒ *Total Snow depth*
  - ⇒ *Refractive index*
  - ⇒ *SWE*
  - ⇒ *Internal layering*



Data from AlpSAR 2013 (Rennes 1, ESA)

Rekioua et al., Comptes Rendus Physique , 2017

Background: the AlpSAR experiment

The AlpSAR TomoSAR experiment

- Carried out in February 2013 in the Austrian Alps, in the frame of the ESA campaign AlpSAR, led by ENVEO
- Snowpit data, GPR, Airborne SAR, GBSAR
- TomoSAR data acquired using the Ground based SAR by the SAPHIR team at the University of Rennes 1
- SAR imaging enabled by sensor motion along a 3 m rail

Rotmoos valley
- *Italian border*
- *≈ 2300 m a.s.l.*
- *140 cm snowpack*

Main Radar parameters
- ✓ X-Band: 4 GHz @ 10 GHz
- ✓ Ku-Band: 4 GHz @ 14 GHz
- ✓ VV Polarization
- ✓ Vertical resolution ≈ 10 cm (Ku-band), 15 cm (X-Band)
- ✓ Range resolution ≈ 4 cm
- ✓ Azimuth resolution ≈ 4 cm

Leutasch
- *North of Innsbruck*
- *≈ 1150 m a.s.l.*
- *70 cm snowpack*

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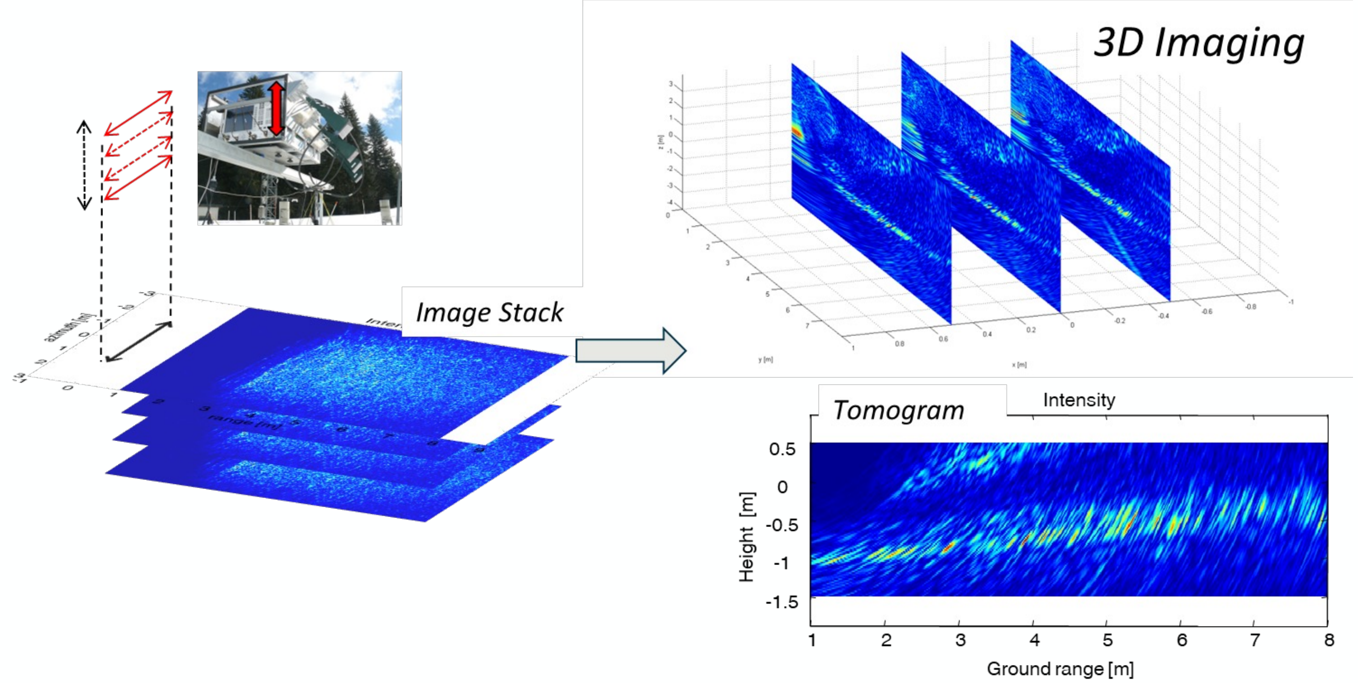
- SAR imaging enabled by sensor motion along a 3 m rail
- Collection of tomographic data by varying antenna and rail height



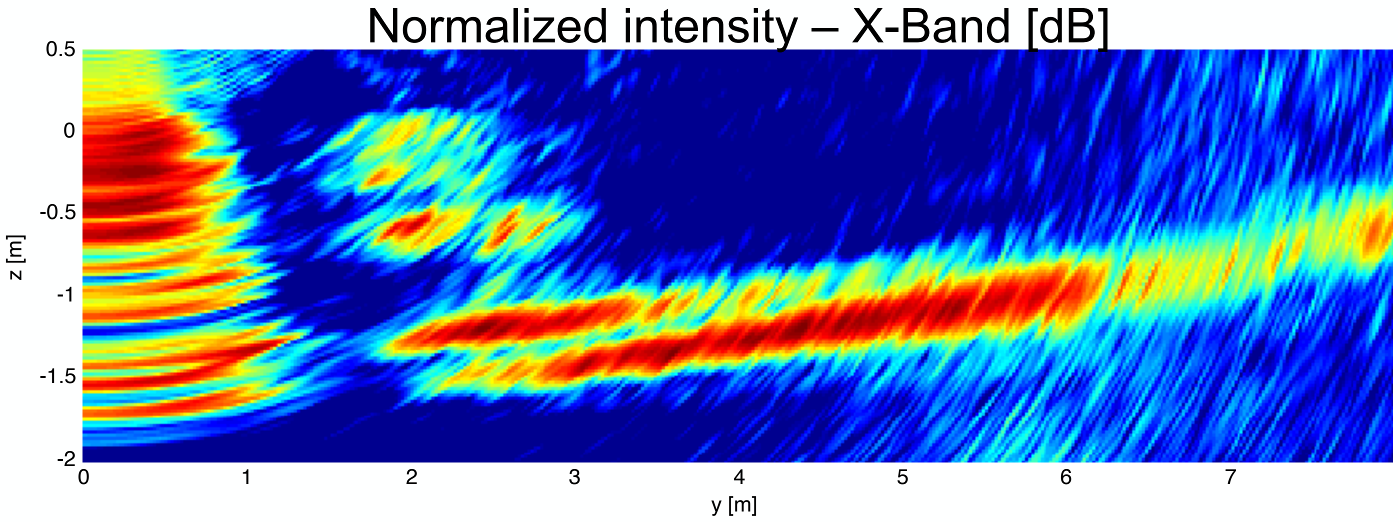
Background: the AlpSAR experiment

Tomographic processing under assumption of free-space propagation

Normalized intensity is presented to highlight contrasts

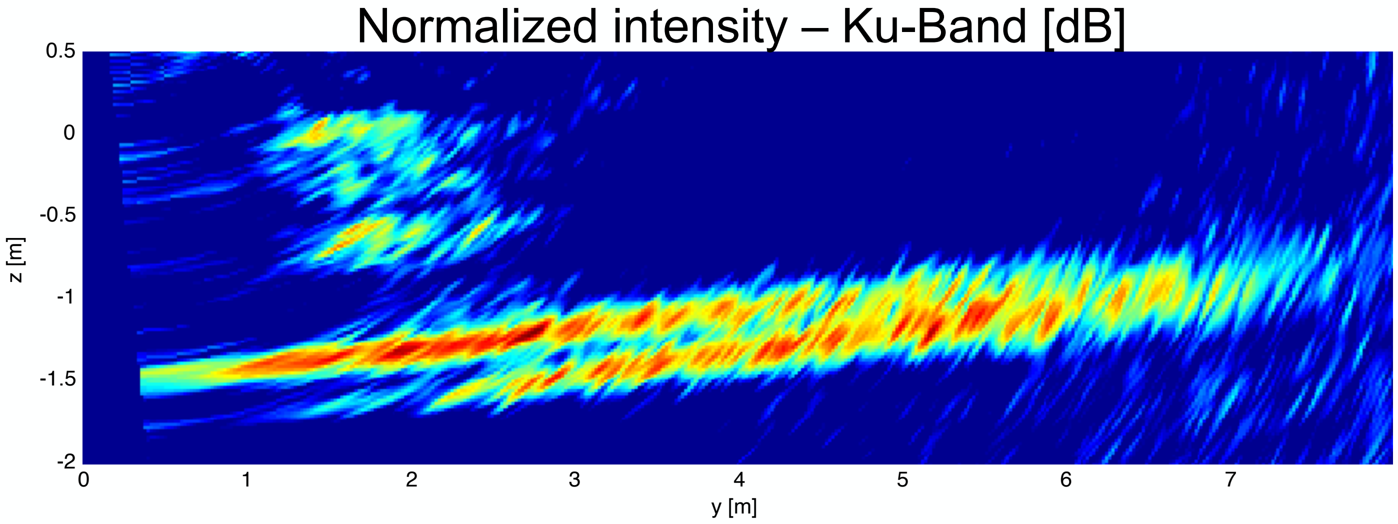
True snowpack thickness = 140 cm

Flat terrain



Remarks

- Neat imaging
- 5 scattering horizons
- Interfaces are tilted towards the Radar
- Bottom interface is deeper than true snow depth



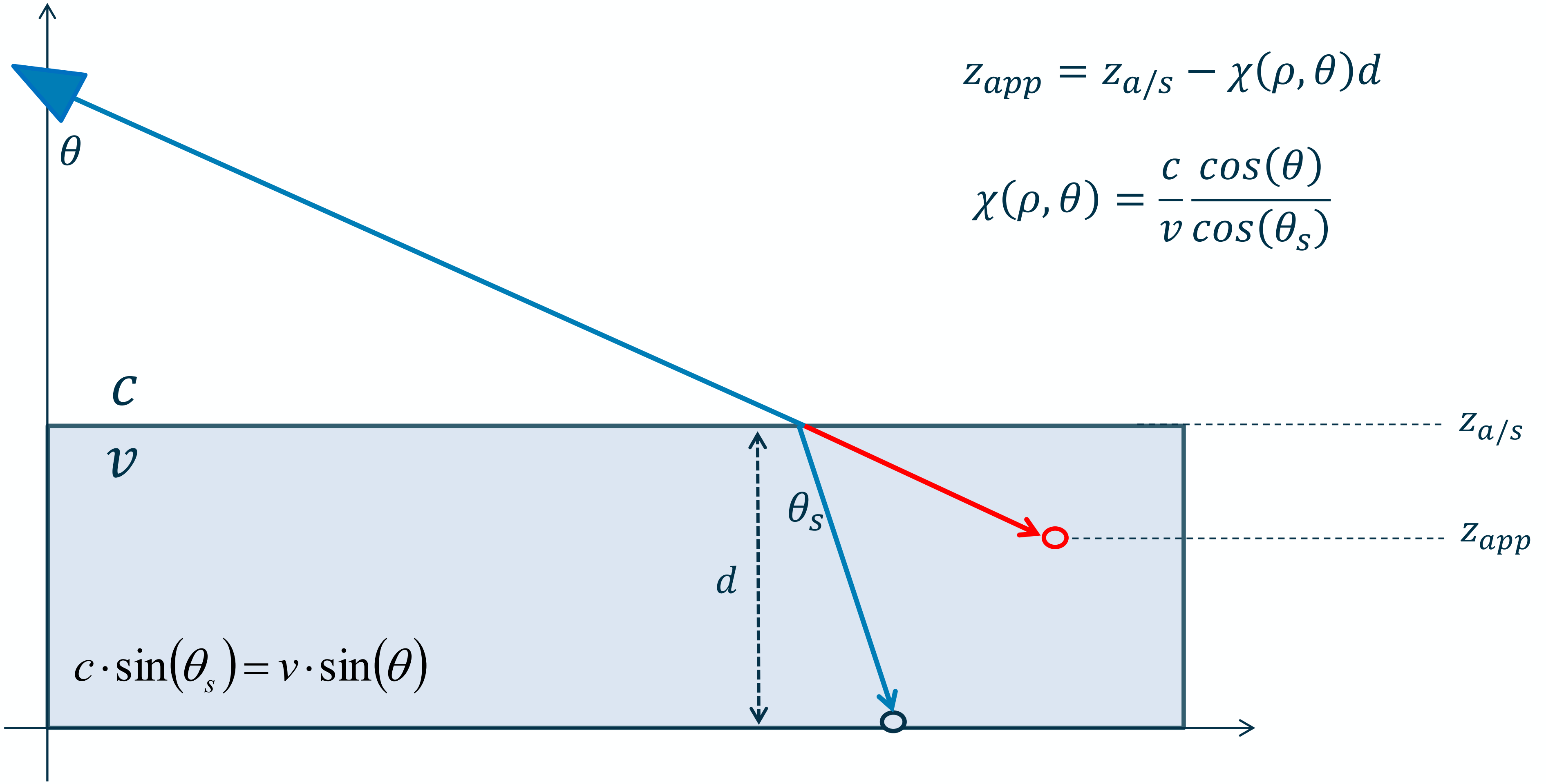
Background: the AlpSAR experiment

Free-space processing in a refractive medium results in targets to be displaced w.r.t. their true geometrical position

- Same direction of arrival as the ray emerging from the air/snow interface
- Same total delay
- Propagation velocity within the snowpack is determined by snow density ρ

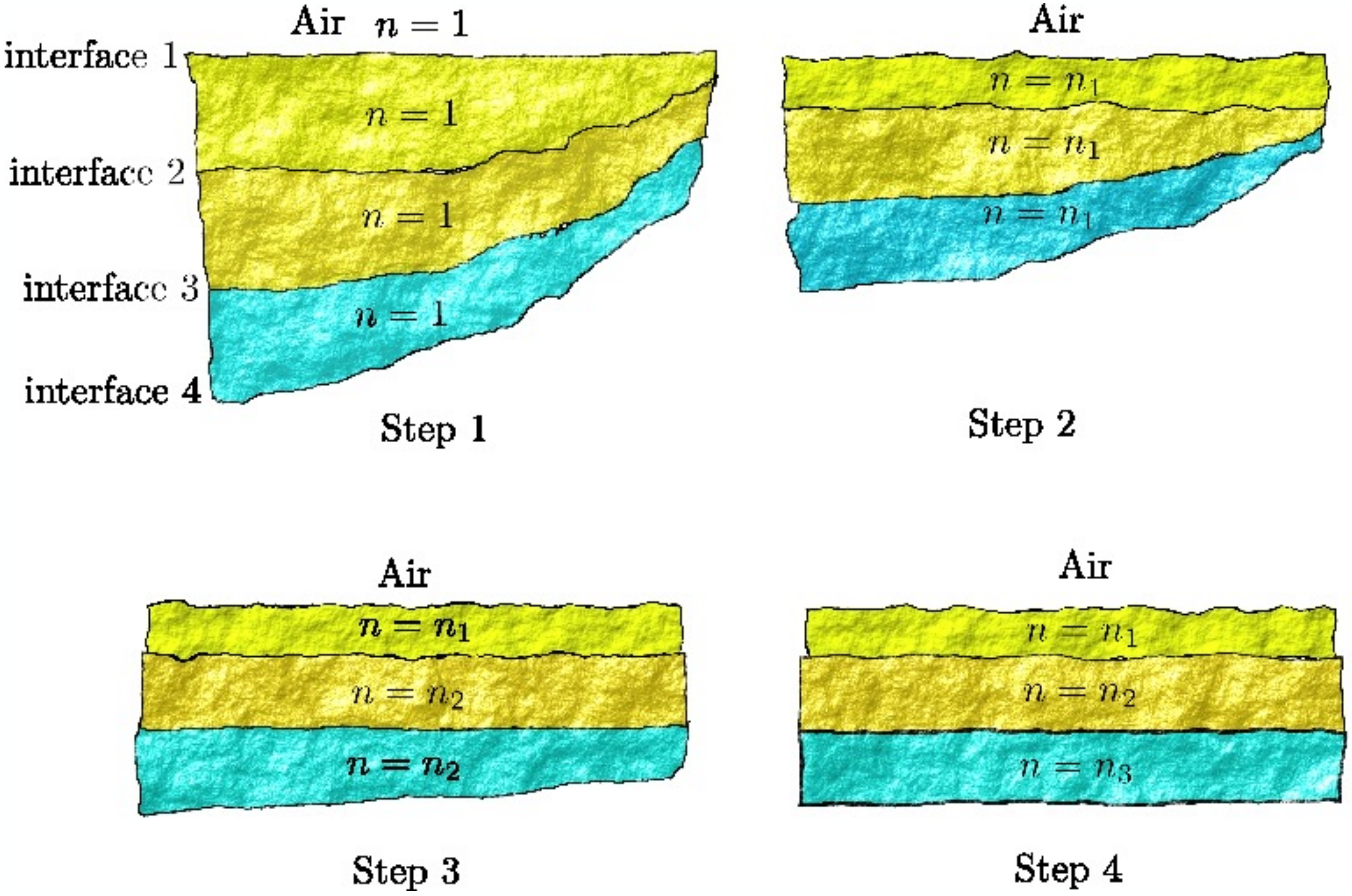
$$z_{app} = z_{a/s} - \chi(\rho, \theta) d$$

$$\chi(\rho, \theta) = \frac{c}{v} \frac{\cos(\theta)}{\cos(\theta_s)}$$



Iterative procedure for estimation of refractive indices:

- Assumption : horizontal snow layers with horizontal snow slabs;
- Criterion: determine refractive indices for the identified layers to make detected interfaces appear as horizontal



Result and comparison against snow-pit data

- Refractive index is observed to increase with snow wetness and density
- The detected horizons correspond to changes in the physical parameters of layers reported on the snow stratigraphy.

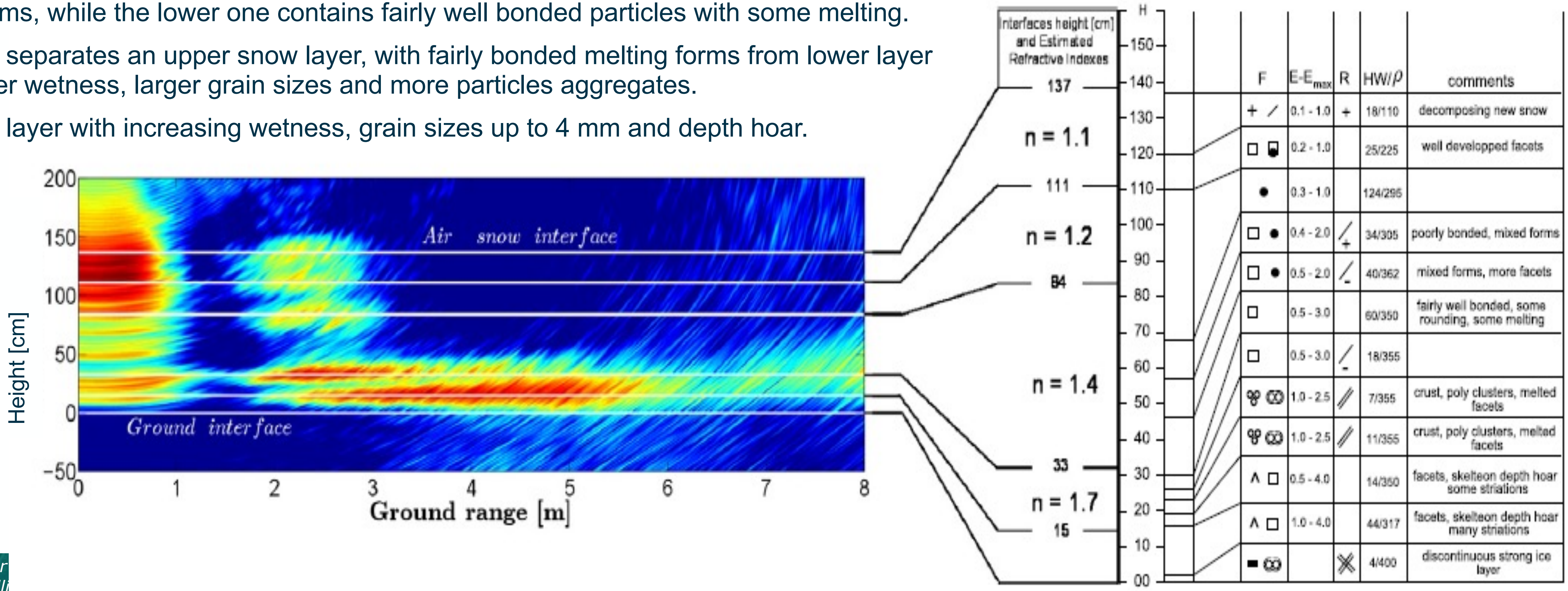
Interface 1: air/snow

Interface 2: transition from low density and decomposing new-fallen snow into a denser layer with spherical particles.

Interface 3: separation between two layers with different particle shapes. The upper one contains mixed forms, while the lower one contains fairly well bonded particles with some melting.

Interface 4: separates an upper snow layer, with fairly bonded melting forms from lower layer with higher wetness, larger grain sizes and more particles aggregates.

Interface 5: layer with increasing wetness, grain sizes up to 4 mm and depth hoar.



Background: literature

Other examples from the recent literature:

- *ESA SnowLab campaign (see for example Frey et al. Tomographic profiling with SnowScat within the ESA SnowLab Campaign: Time Series of Snow Profiles Over Three Snow Seasons, 2018)*

⇒ Multi-temporal tomography of the snowpack to investigate tomographic response to varying snow conditions

- *Xu et al, Multi-Frequency Tomography Radar Observations of Snow Stratigraphy at Fraser During SnowEx, 2018*

⇒ Snow stratigraphy by TomoSAR in changing conditions

- *Qiao et al., Snow profile reconstruction from tomographic UAV SAR, 2023*

⇒ SD retrieval based on UAV SAR tomography. Reported accuracy of few cm

- *Lei et al., Dry Snow Parameter Retrieval With Ground-Based Single-Pass Synthetic Aperture Radar Interferometry, 2022*

⇒ Single-pass single-baseline SWE retrieval from snow-on/snow-off phase difference

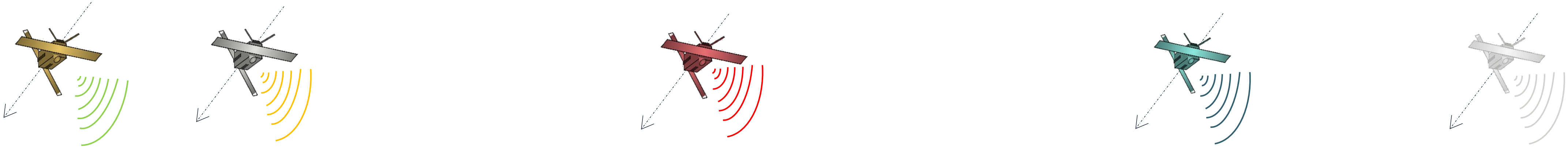
- *Patil et al., Snow depth and snow water equivalent retrieval using X-band PolInSAR data, 2020*

⇒ Inversion based on empirical relationship between hv coherence and SD

A concept for a snow TomoSAR mission

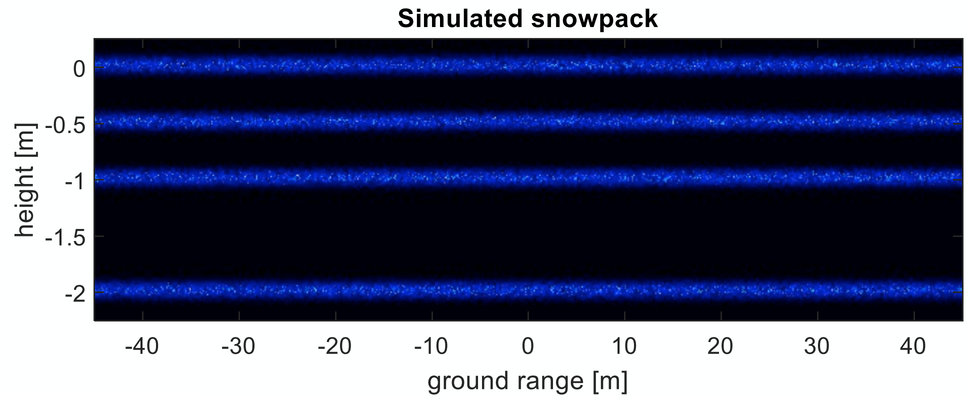
Mission concept: a formation of 4 to 5 small satellites, any of them operated as Tx and Rx

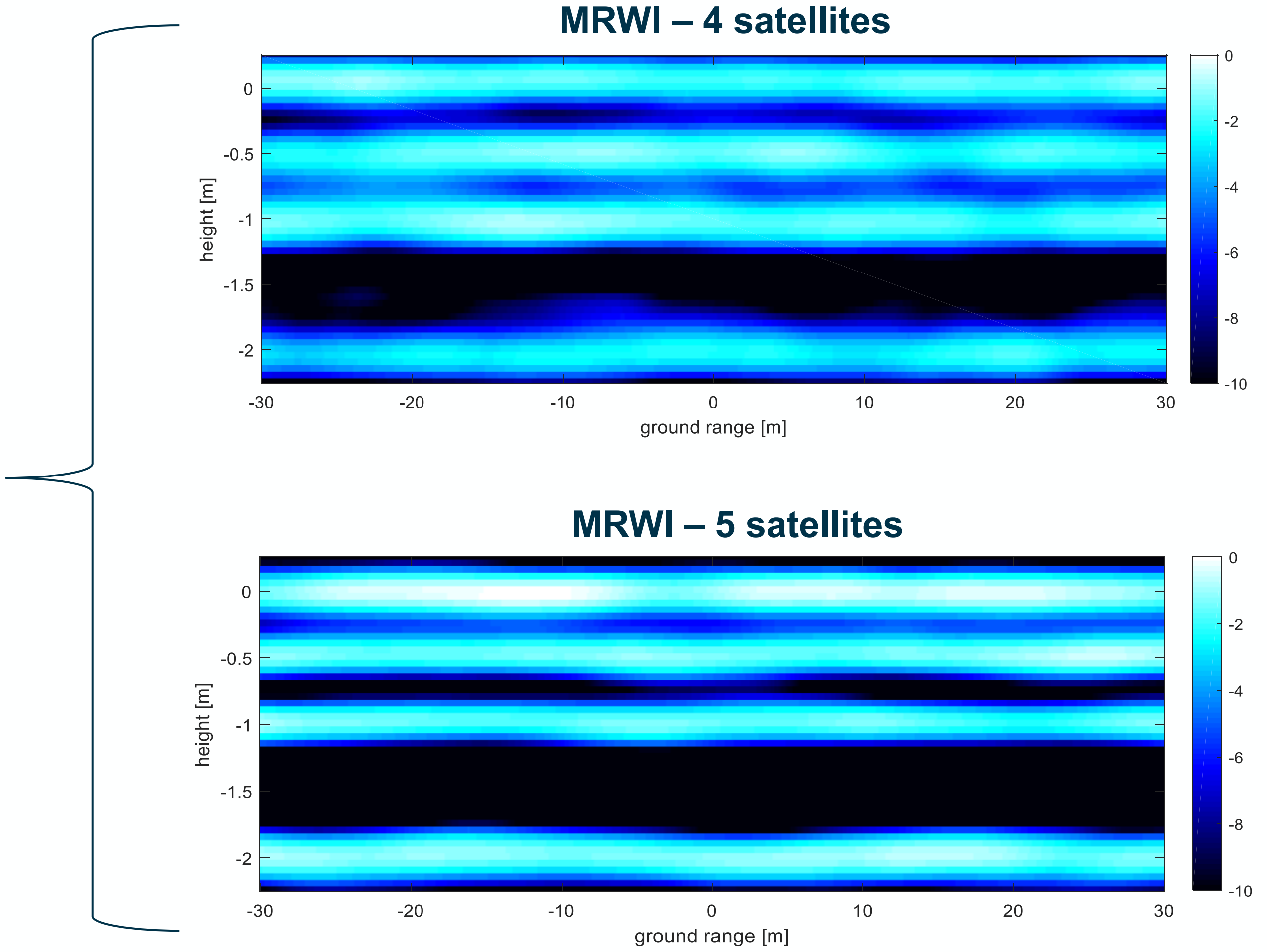
- X-Band Radar payload ⇔ large bandwidth allowed by ITU, good compromise between penetration and sensitivity to snow layers
- Full Multiple Input Multiple Output (MIMO) capabilities
- Access via Frequency Division Multiplexing (FDM) ⇔ Rainbow system
- Across-track displacement according to the MRWI principle (see talk *Spaceborne FDM MIMO SAR Tomography*)



Number of satellites	Height of ambiguity (m)	Free-space Vertical resolution (m)	Equivalent number of monostatic passes
4	8.4	0.51	16
5	10.5	0.41	25

Expected tomographic imaging performance (from numerical simulations)





Retrieval algorithm – layered snowpack

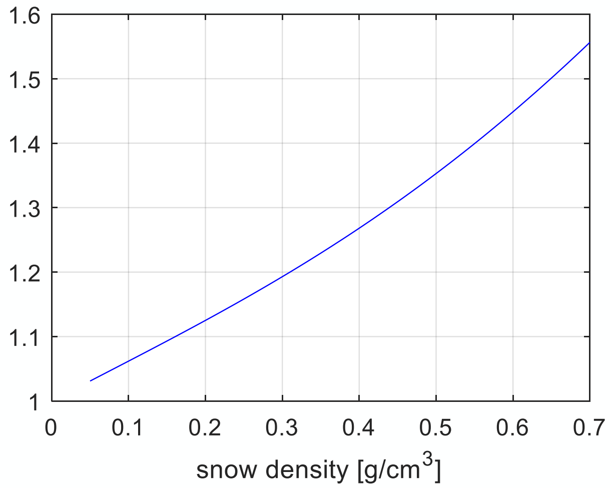
Retrieval of SD and SWE leverages TomoSAR capability to detect scattering horizons and measure their apparent height within the snowpack

Apparent layer depth is obtained as the difference between the height of two nearby scattering horizons, and is related to true depth (unknown) via:

$$d_{app} = \chi(\rho, \theta) \cdot d \qquad (1)$$

Where $\chi(\rho,\theta) = \frac{c}{v}\frac{cos(\theta)}{cos(\theta_s)}$ depends on the local incidence angle (known) and snow density (unknown)

$\chi(\rho,\theta)$



Equation (1) does not allow inversion for layer depth since density is not known

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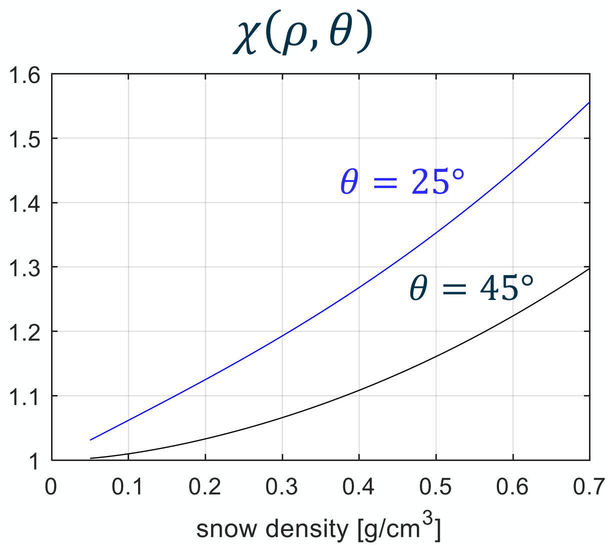
Equation (1) does not allow inversion for layer depth since density is not known

Unless we add another measurement of apparent depth at a difference incidence angle

- (1) and (2) form a system of two equations in two unknowns (d,ρ)

⇒ Simultaneous retrieval of layer depth and density, hence SWE



Retrieval algorithm – transparent snowpack

By transparent snow we refer to the case where the only detectable horizon corresponds to the snow/terrain (or snow/ice) interface

- Typically valid at L-Band, yet assumed in part of the literature in case of shallow and dry snowpack at X-Band
- Impact on Radar imagery is limited to an increase of the optical path, resulting in the bottom interface to appear at position:

$$z_{app} = z_{a/s} - \chi(\rho,\theta)d \quad (1)$$

$z_{a/s} =$ height of air/snow interface

$d =$ total snow depth

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$z_{a/s}$ = height of air/snow interface

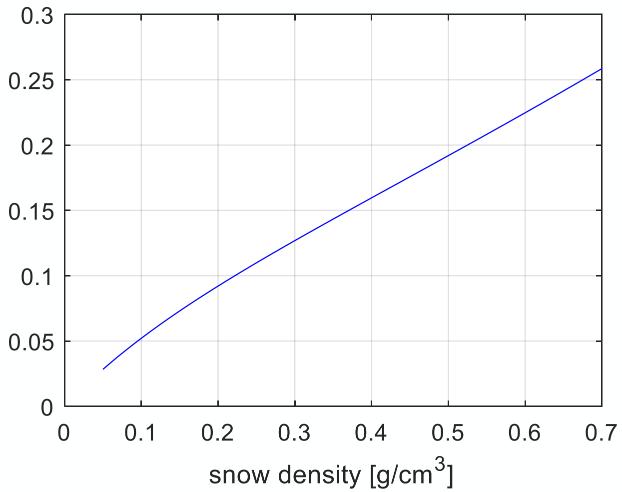
d = total snow depth

No direct measurement of snow depth is possible

Yet, it is possible to solve for SWE by differencing apparent snow depths at two incidence angles

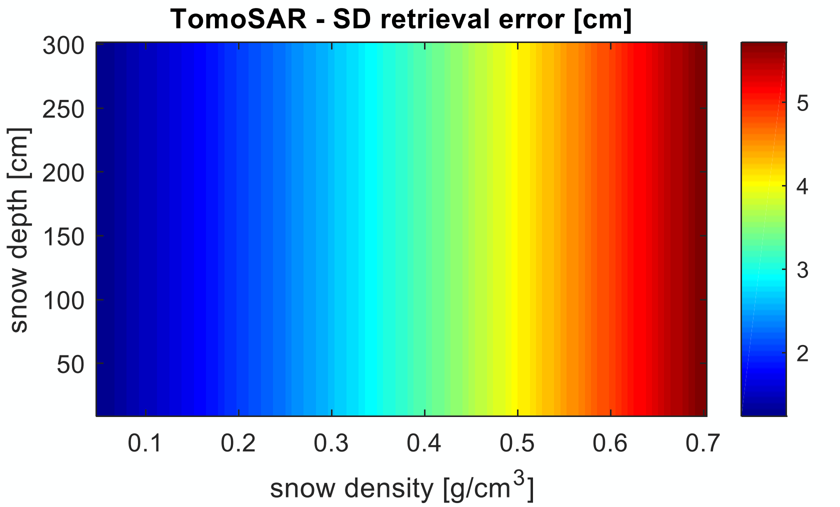
$$z_{app\_1} - z_{app_2} = \{\chi(\rho, \theta_1) - \chi(\rho, \theta_2)\} d \approx M \cdot \rho d = M \cdot SWE$$

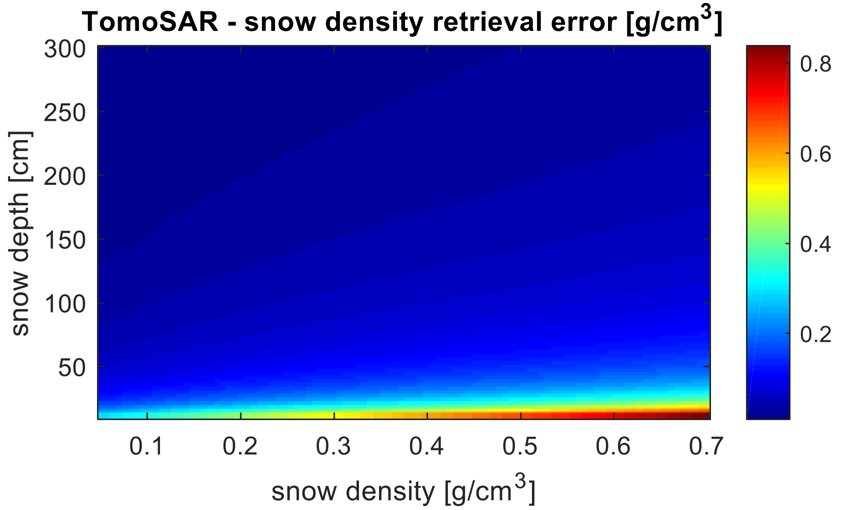
$\chi(\rho, \theta_1) - \chi(\rho, \theta_2)$

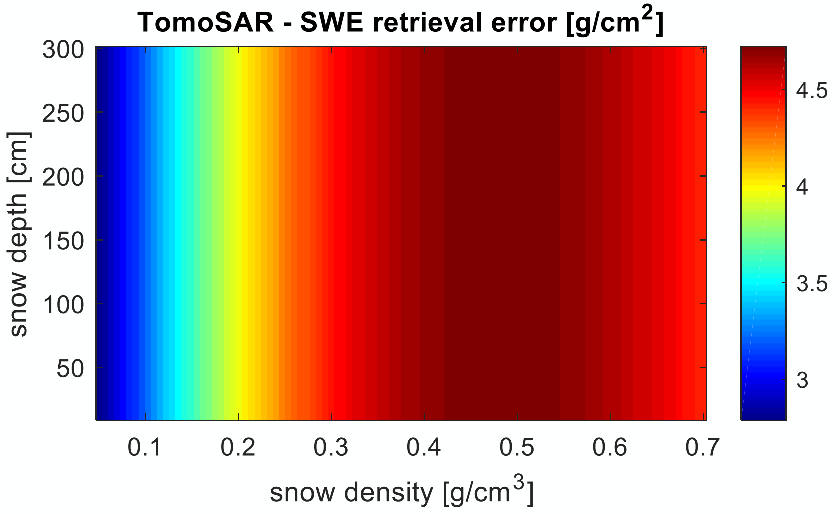


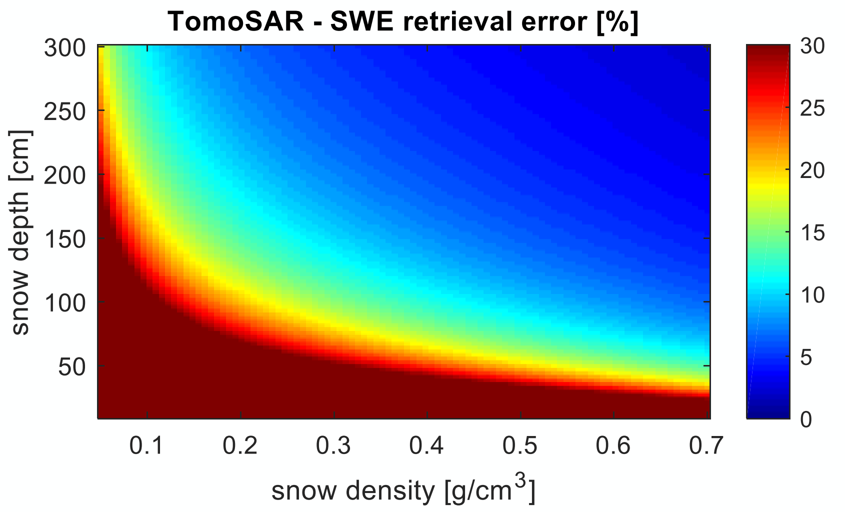
Sensitivity analysis

Layered snowpack – errors for a 1 cm dispersion about apparent height. Incidence angles: $\theta_1 = 25°$, $\theta_2 = 45°$









Sensitivity analysis

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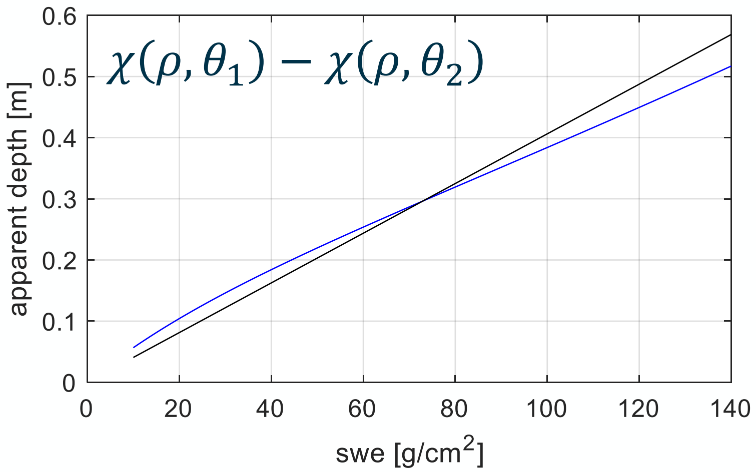
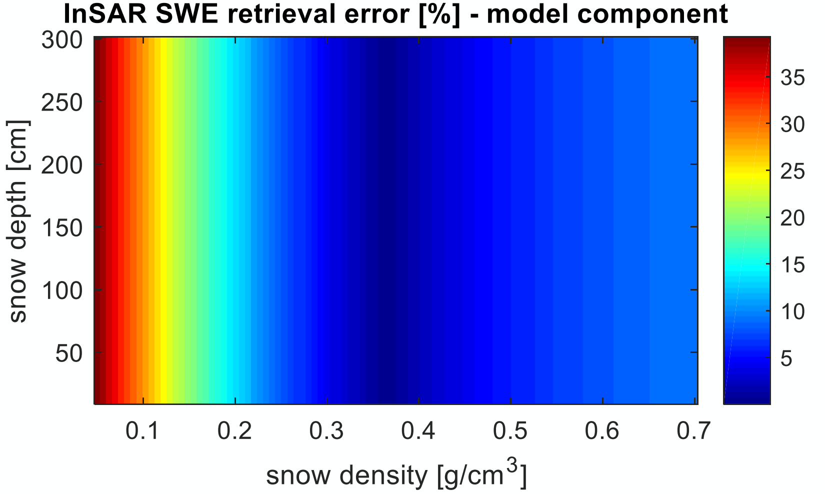
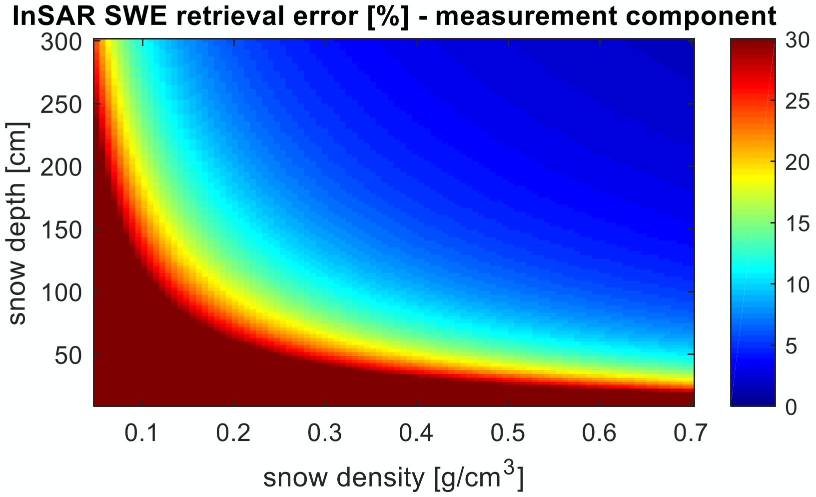
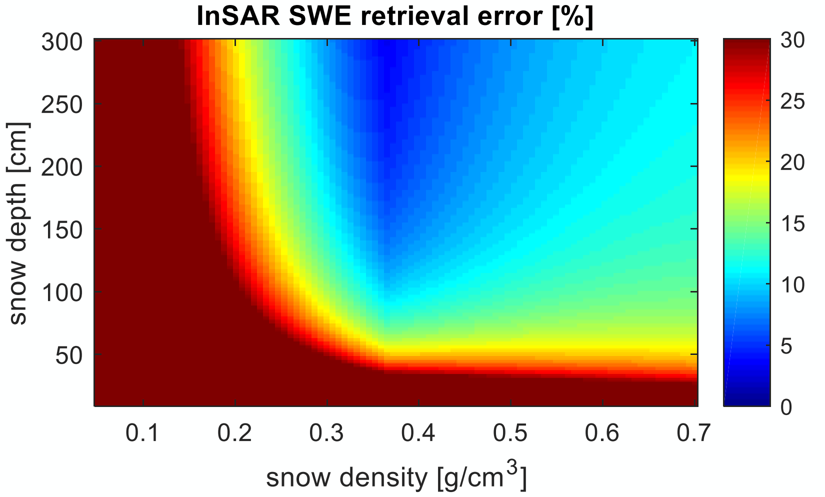
Transparent snowpack – errors for a 1 cm dispersion about apparent height. Incidence angles: $\theta_1 = 25°$, $\theta_2 = 45°$





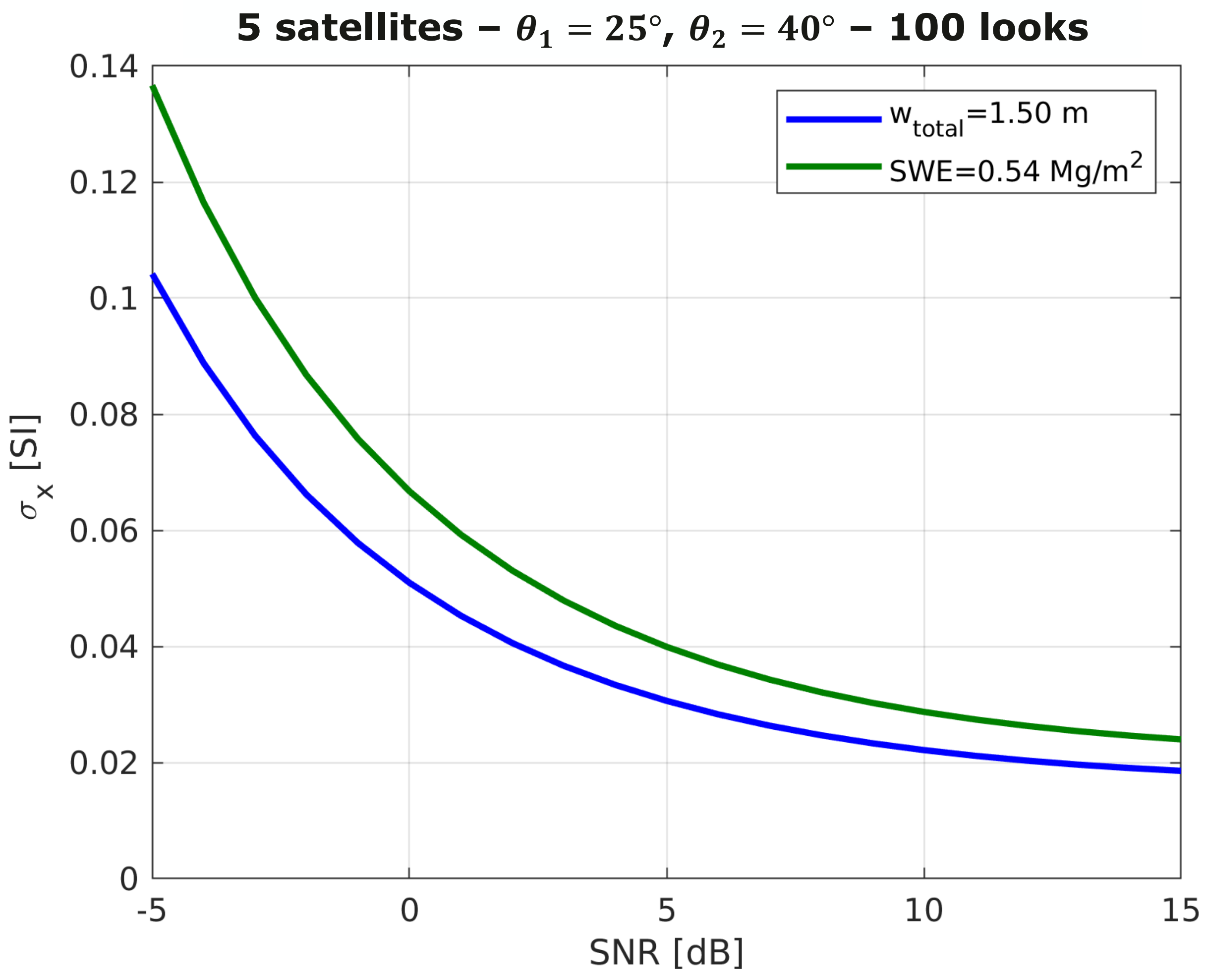


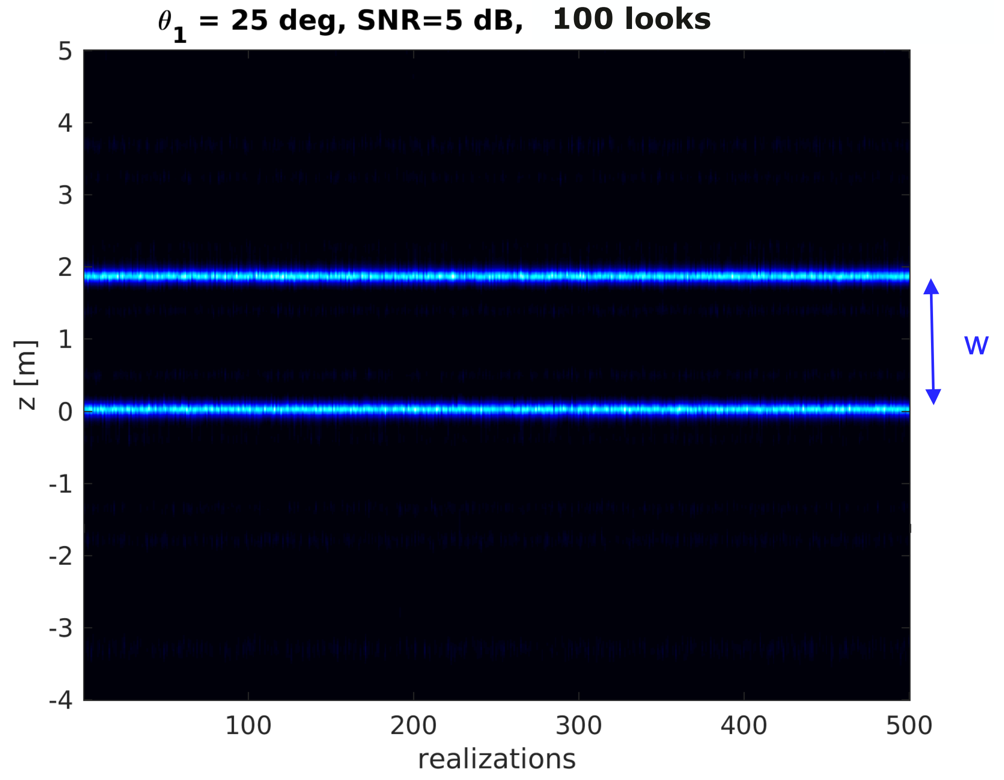


Performance analysis

Performance analysis has been preliminary carried out by computing the CRB about snow parameters

- Scenario 1: single-layer snowpack





Performance analysis

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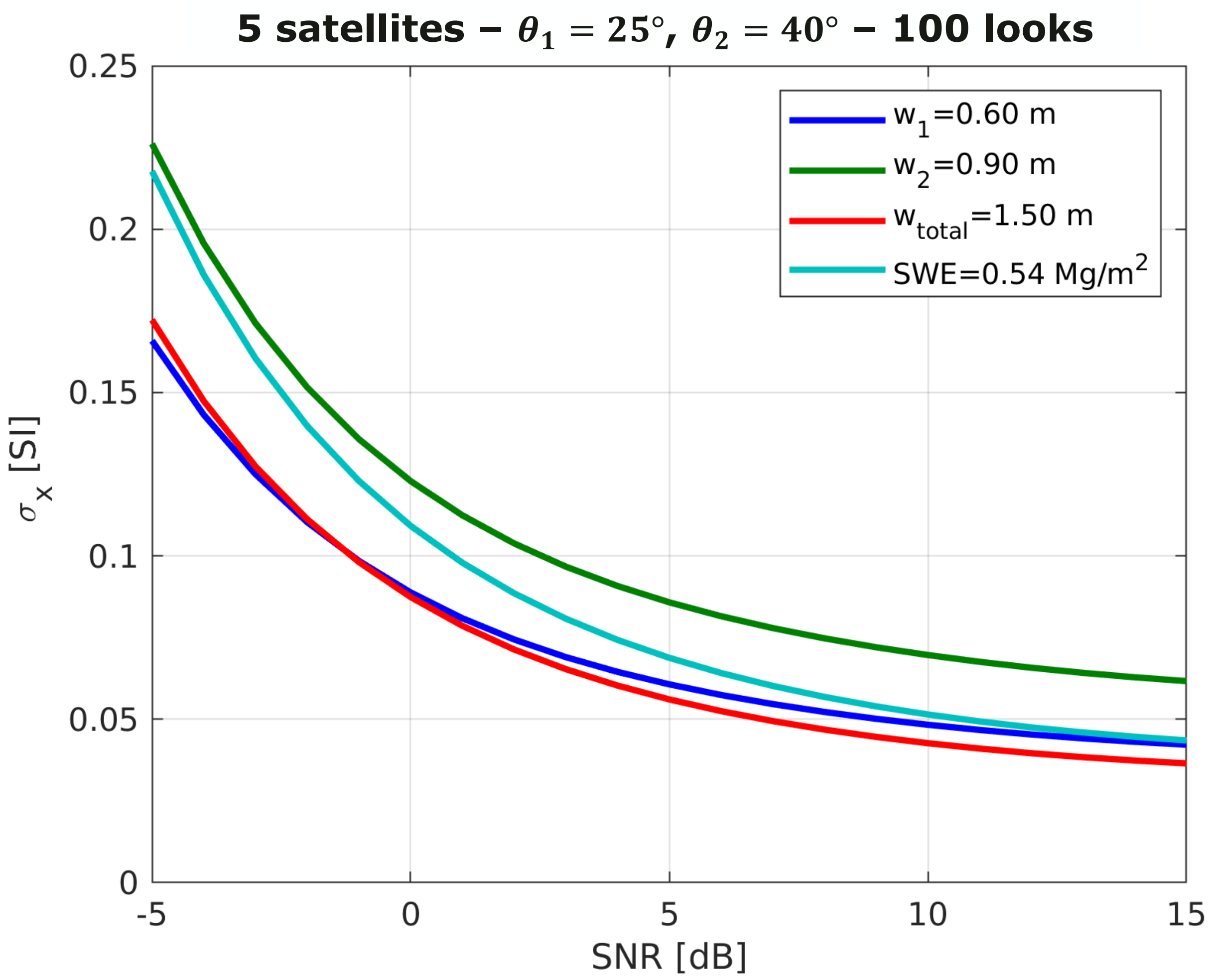
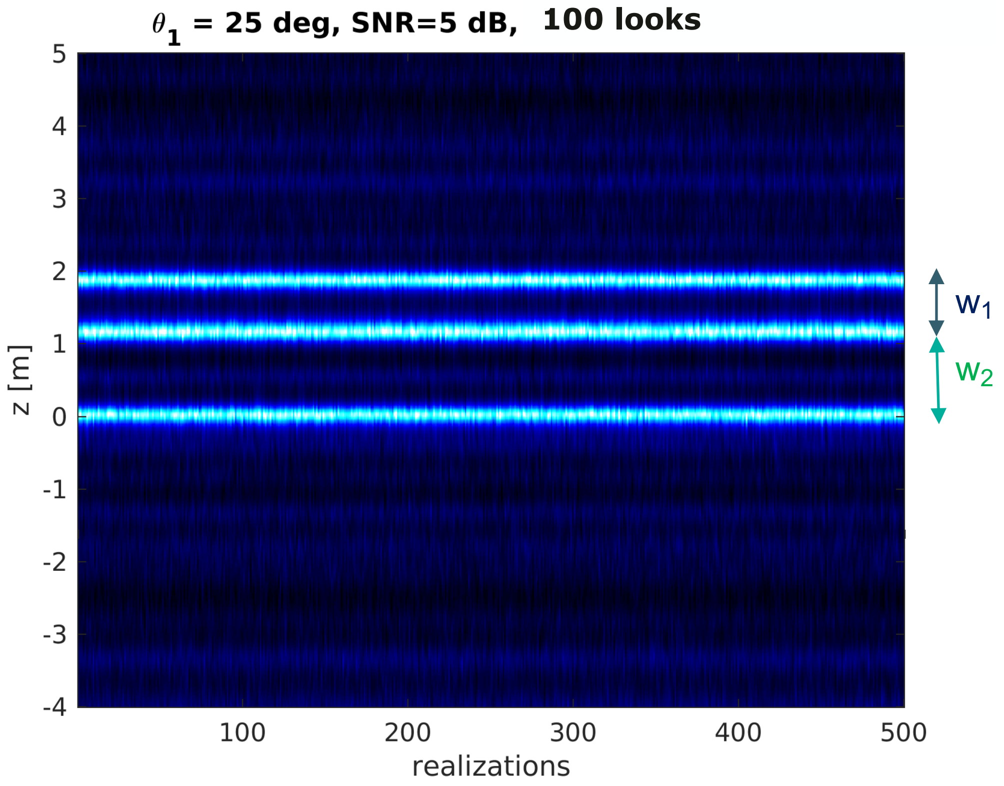
- Scenario 2: two-layer snowpack





Discussion

This work has investigated a Tomographic SAR concept to retrieve snow depth and SWE

- Direct measurement of snow parameters – no regression or empirical model needed
- New mission concept employing a formation of small satellites capable of sub-meter vertical resolution
- Preliminary analyses indicate promising results

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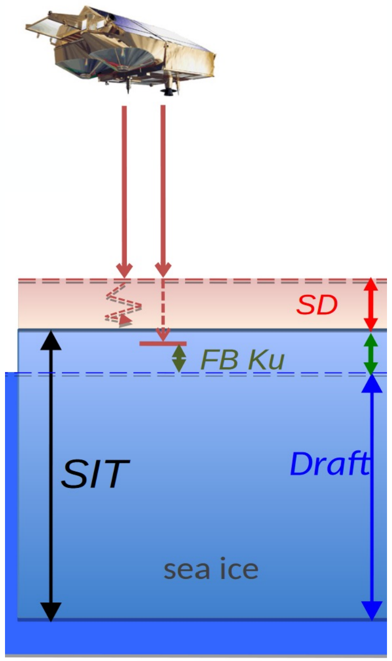
- Preliminary analyses indicate promising results
- Mission concept is complementary to Radar altimeters like Cristal

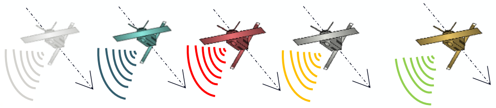
Altimeters

- 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



Challenges

SWE retrieval performance is ruled by the accuracy to within which apparent heights are estimated

- Fine vertical resolution is provided by MRWI formation flying
- Yet, granting adequate SNR has to be regarded as the first challenge to face in view of a spaceborne implementation based on small satellite technology

Another important aspect is the need for incidence angle diversity to retrieve snow density. Different approaches are being considered:

- Soft: exploit topographic variations (in mountain regions)
- Brute-force: observe under two different incidence angles in ascending and descending passes
- Practical: exploit synergy with Radar altimeters to measure snow density by comparison of apparent depths in nadir- and side-looking geometry (most likely viable for snow-covered sea ice)