SAR Tomographic Profiling of Seasonal Alpine Snow at L/S/C-, X/Ku-, and Ka-Band Throughout Entire Snow Seasons Retrieved During the ESA SnowLab Campaigns 2016-2020

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Background / Motivation

- High-level scientific objectives of large-scale / global radar-remote-sensing-based retrieval of snow mass include (Tsang et al. 2022) :
  - quantification of the spatiotemporal variability of the amount of water stored as snow,
  - retrieval of snow structure,
  - ➔ transfer of this information into numerical weather forecasting, hydrological forecasting, and climate models.
- Several spaceborne radar/SAR missions are being planned / realized in this context
  - at a wide range of microwave frequencies – CRISTAL (Ku/Ka), TSMM (dual Ku-band), ROSE-L & NISAR (L) and prev. CoReH20 (X-/Ku), Hydroterra (C-band), …
  - with mission objectives around assessing snow parameters
    ➔ primarily snow mass / snow water equivalent and extent of snow cover.
- Detailed knowledge is required on
  - temporal evolution of radar-related parameters during a snow season, including: penetration depths, backscattering contributions at different layers & frequencies.
  - These parameters play an essential role to retrieve temporal changes of snow characteristics (snow mass / SWE (change), structural anisotropy, stratification).
- For **seasonal snow** these relations are poorly / only partially understood.

➔ **Knowledge gaps addressed with SAR tomographic profiling** as part of ESA SnowLab:

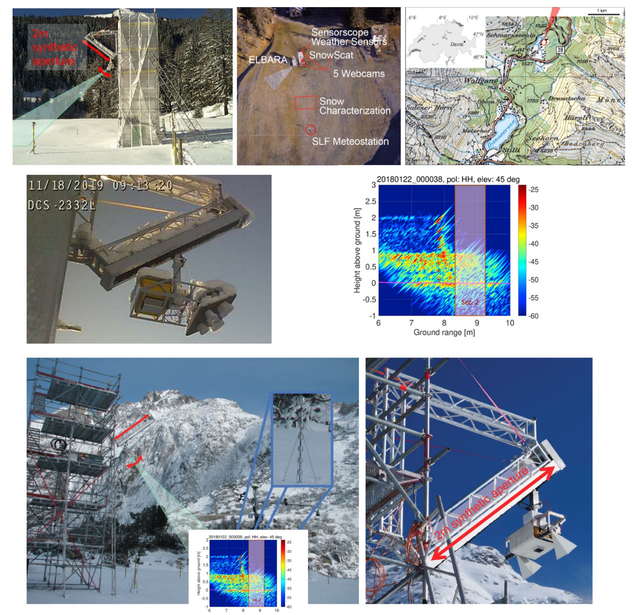
- Provide time series of high-resolution depth-resolved SAR imagery of seasonal snow:

  (1) backscatter ➔objective: identify (vertical) distribution of backscatter contributions depending on snow-pack depth and condition/properties.

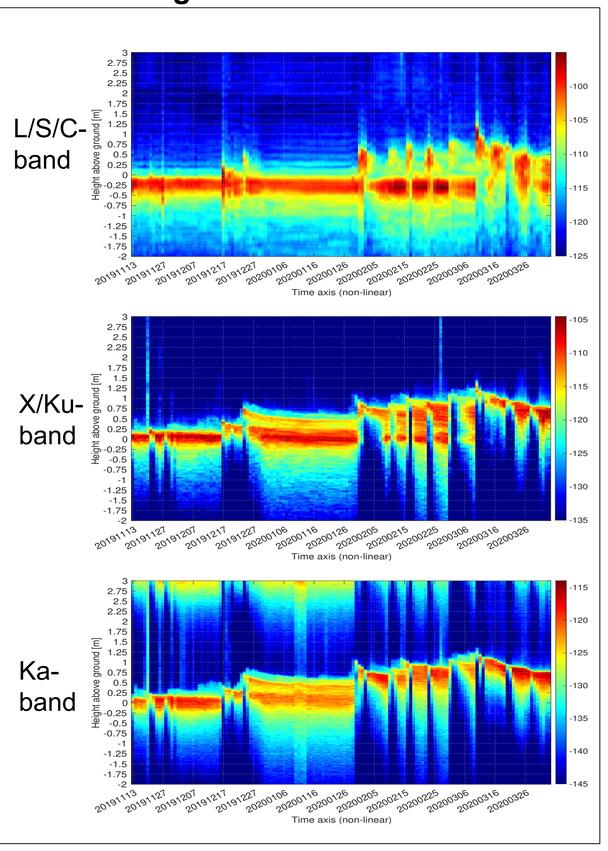
  (2) temporal interferometric phase/coherence for selected periods ➔objective: identify layer-wise phase difference ←➔ Delta-SWE (for cold & dry-snow periods).

  (3) copolar phase diff. ➔objective: identify layer-wise anisotropy of snow microstructure.

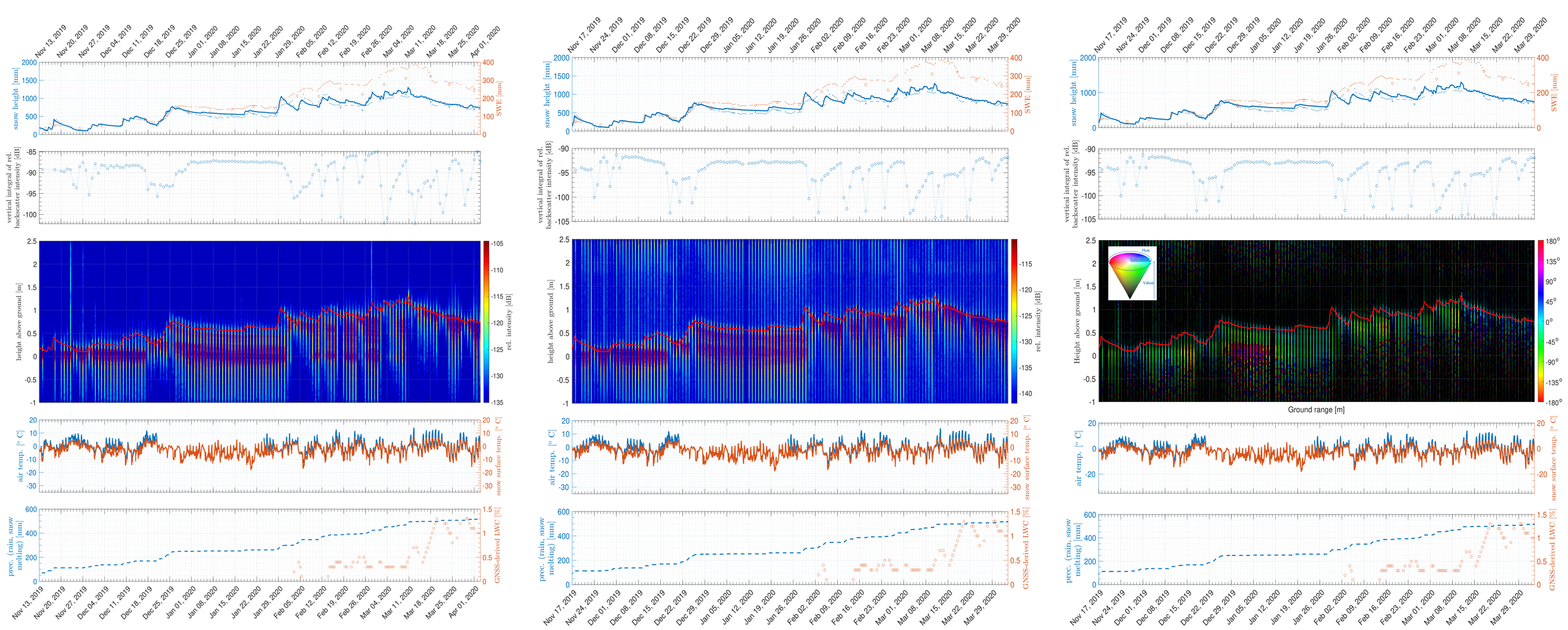
Experiment: SnowScat/WBScat tomography in Davos during ESA SnowLab 2016-2020



Campaign season	Instrument	polarization channels	freq. band
2015/2016	SnowScat	HH, HV, VH, VV	9.2 - 17.8 GHz
2016/2017	SnowScat	HH, VV	9.2 - 17.8 GHz
2017/2018	SnowScat	HH, VV	9.2 - 17.8 GHz
2018/2019	SnowScat / WBScat	test phase	
2019/2020	WBScat	HH, HV, VV	1-6 GHz
		HH, HV, VV	12-18 GHz
		HH, HV, VV	28-40 GHz



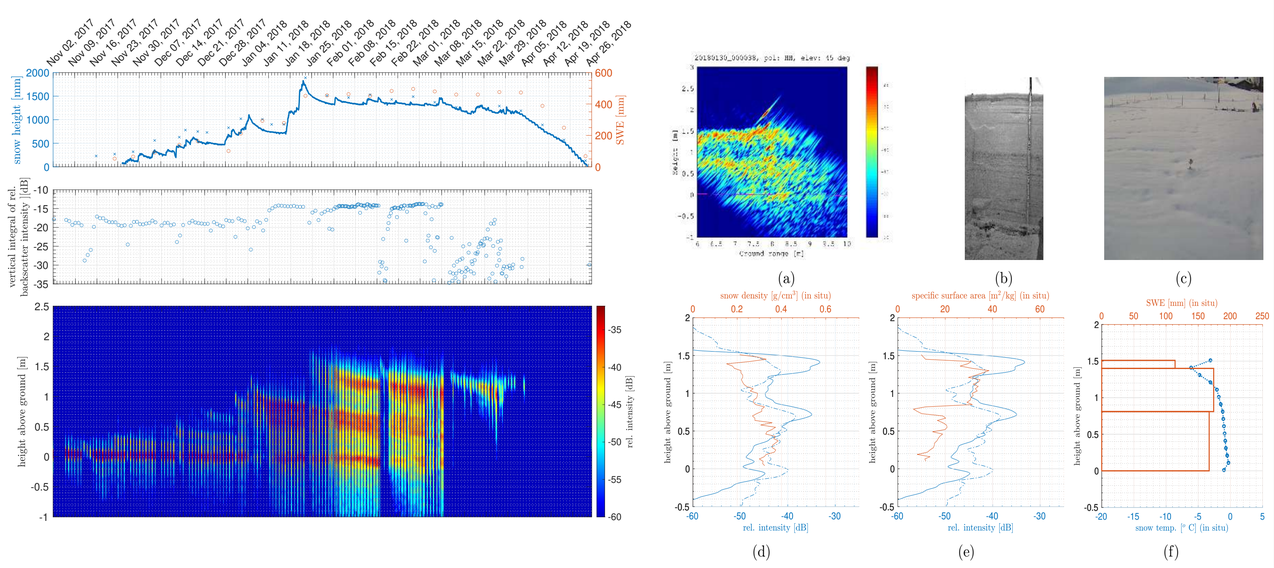
Results: Excerpts of ESA WBScat times series of SAR tomographic profiles



Time series of tomographic profiles in HH polarization mode at **15-18 GHz (left)** and **34-40 GHz (middle)** as obtained from WBScat tomographic mode at the ESA Snowlab site in Davos Laret, in winter 2019/2020 aligned with time series of in-situ measurements of snow and meteorological parameters. Top row: snow height as measured at the SLF meteo station Davos Laret (—), snow height from snowpits (x), and GNSS-derived snow height (··), plus SWE from snowpits (o) and GNSS-derived SWE (··). Second row: vertical integral of relative backscatter intensity. Third row: vertical profiles of relative backscatter intensity as extracted from WBScat tomographic profiling measurements with bandwidth 15-18 GHz at Davos Laret, winter 2019/2020. The snow height (red line) as measured at the SLF meteo station Davos Laret is also given is again reproduced as reference. Fourth row: air temperature and snow surface temperature measured at SLF meteo station. Last row: precipitation (rain and melted snow, only) measured at SLF meteo station and GNSS-derived LWC.

Time series of vertical profiles of copolar phase difference (CPD) as extracted from WBScat tomographic profiling measurements with bandwidth 34-40 GHz at Davos Laret, winter 2019/2020. The snow height (red line) as measured at the SLF meteo station Davos Laret is also given is again reproduced as reference. The auxiliary data plotted in the other rows are as on the plots on the left.

Results: Excerpts of ESA SnowScat times series of SAR tomographic profiles



(a) SnowScat tomographic profile acquired on 20180130 during the ESA SnowLab 2017/2018 campaign at the test site Davos Laret, Switzerland. (b) Photograph of the snowpit profile and (c) photograph of the situation (view from SnowScat on the tower to the scene). The horizontally averaged tomographic profiles of the sections in front of (—) and behind (- -) the reference targets (spheres) are plotted against vertical profiles of snow density (d) and specific surface areas (e) that were obtained from an adjacent snowpit. (f) Vertical distribution of SWE and snow temperature obtained from the snowpit in-situ measurements.

Discussion & Outlook

- ESA SnowLab: Time series of SAR tomographic profiling data (partic. WBScat data 2019/2020) with:
  - frequency diversity (L/S-C-band , Ku-band, Ka-band)
  - polarization diversity
  - at very high spatial and vertical resolution and daily temporal sampling

  provides a **new level of depth- & time-resolved radar data** about **vertical stratification** of
  - backscattering intensity
  - co-polar phase difference
  - interferometric phase and coherence between consecutive profiles.

➔New input for verification of refined layer-wise modelling of the snowpack.

➔Relevant for a number of planned radar missions including CRISTAL (dual-freq.: Ku-/Ka-band), TSMM (dual-freq Ku-band), ROSE-L, and NISAR (L/S), and potentially others.

- Further consolidation and distillation of mission-specific aspects needed.
- Outlook/next points to address based on the **tomographic** data:
  - Co-polar phase difference and anisotropy: Verify the layer-wise co-polar phase difference (CPD) as measured from SAR tomographic profiling with layer-wise model-based CPD based on the inputs layer thickness, snow density, anisotropy and incidence angle.

This work was performed at Gamma Remote Sensing in collaboration with the WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland as part of the ESA-funded project:
"Scientific Campaign Data Analysis Study for an Alpine Snow Regime" SCANSAS (ESA SCANSAS), Contract No. 4000131140/20/NL/FF/ab.
ESA SnowLab campaign and data processing: ESA/ESTEC Contract No. 4000117123/16/NL/FF/MG. Hardware extension (rail) to enable SAR tomographic profiling: ESA/ESTEC Contract No. 20716/06/NL/EL CCN3.
ESA Wide-Band Scatterometer (WBScat) development: ESA/ESTEC Contract No. 4000117123/16/NL/FF/mg.