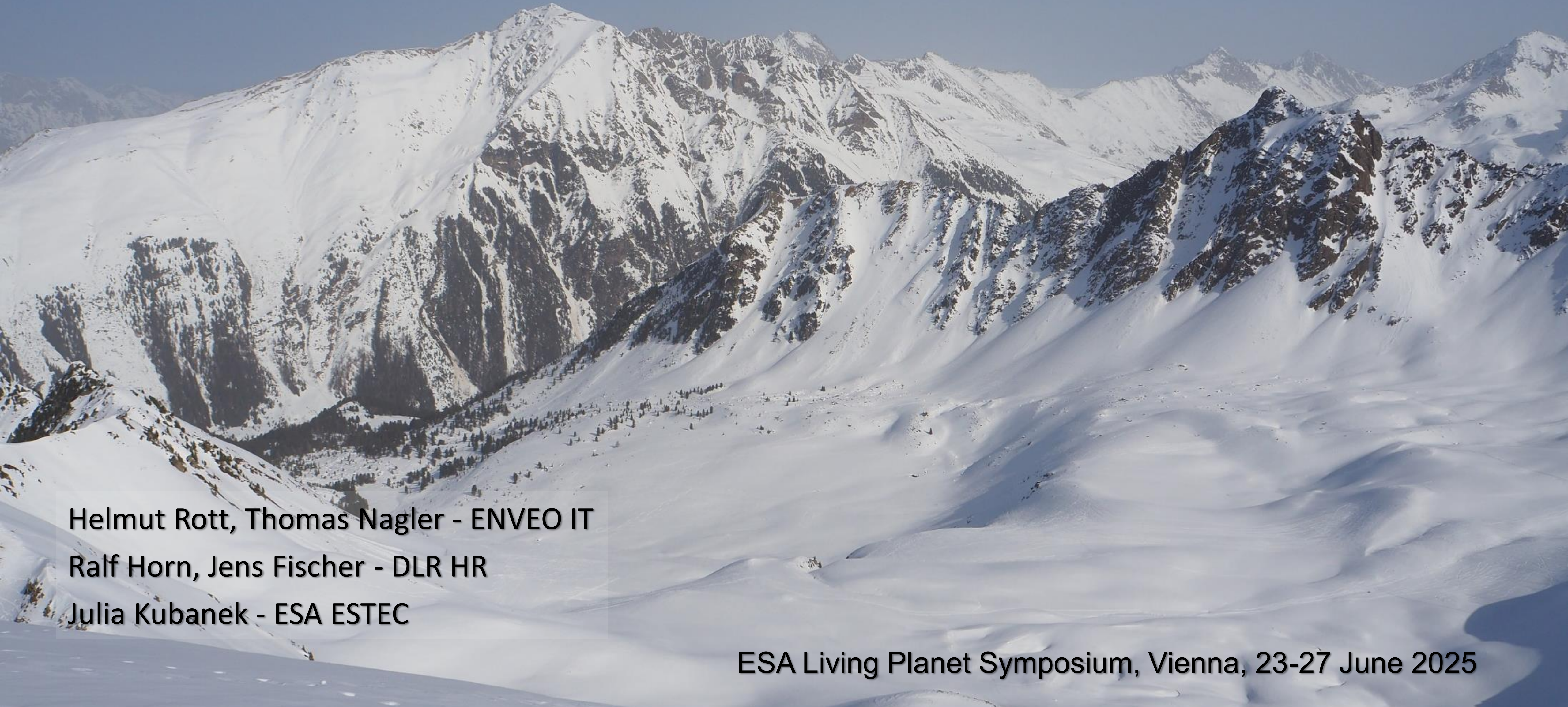
Dual-Frequency Airborne SAR Campaign on Snow Mass Retrieval for High-Alpine Terrain



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Project Objectives and Contents of Presentation

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Main Objectives of the Field Campaign

- Testing and evaluating methods for snow mass (SWE) retrievals in Alpine environment with focus on the repeat-pass interferometric SAR (RP-InSAR) approach within preparations for upcoming satellite missions.
- Evaluating the performance of SWE retrievals, in support of preparations for ROSE-L (Radar Observation System for Europe at L-band) and Sentinel-1 NG (Next Generation).
- Proof of concept for applying geosynchronous SAR for InSAR SWE retrieval, addressing the feasibility of the proposed HydroTerra (HT) mission (C-band SAR).

Airborne Sensor: DLR F-SAR, C- & L-band **Test site:** Wörgetal - Kühtai (Stubai Alps)

Contents of Presentation

- Overview on test site and in-situ meteo data & snow measurements
- Temporal evolution of backscatter intensity and co-polarized phase difference
- Coherence, phase & InSAR SWE retrievals by means of RP-InSAR, Delta-K InSAR & simulated HT data
- Conclusion: Implications for future operational use of C- and L-band InSAR for SWE retrieval

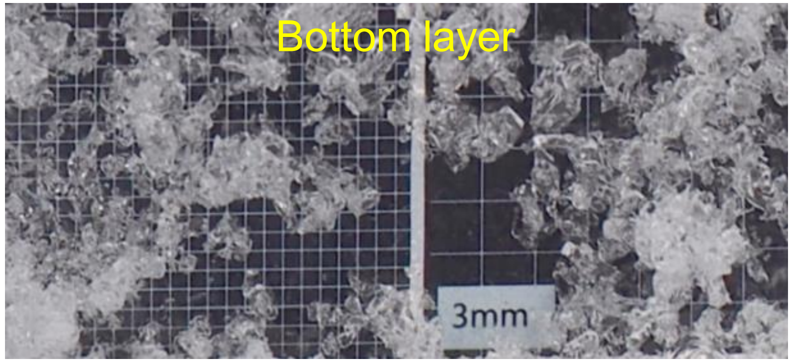
The airborne campaign & data analysis were supported by *ESA Contract 4000134680/21/NL/FF/an* SARSimHT

SARSimHT Campaign Airborne and In-situ Measurements

DLR F-SAR

Sensor and processing parameters

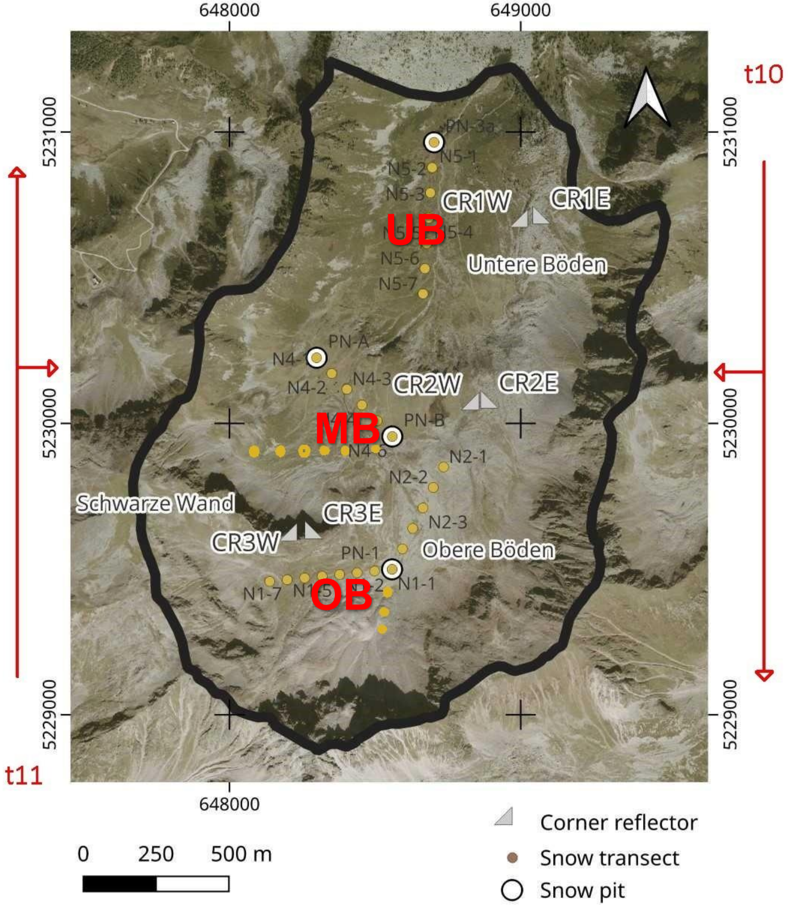
DLR F-SAR C+L	C-band	L-band
Center frequency	5300 MHz	1325 MHz
Signal bandwidth	384 MHz	150 MHz
Azimuth resolution	0.50 m	0.60 m
Range resolution	0.50 m	1.30 m
Pixel size	0.2 m x 0.3 m	0.4 m x 0.6 m



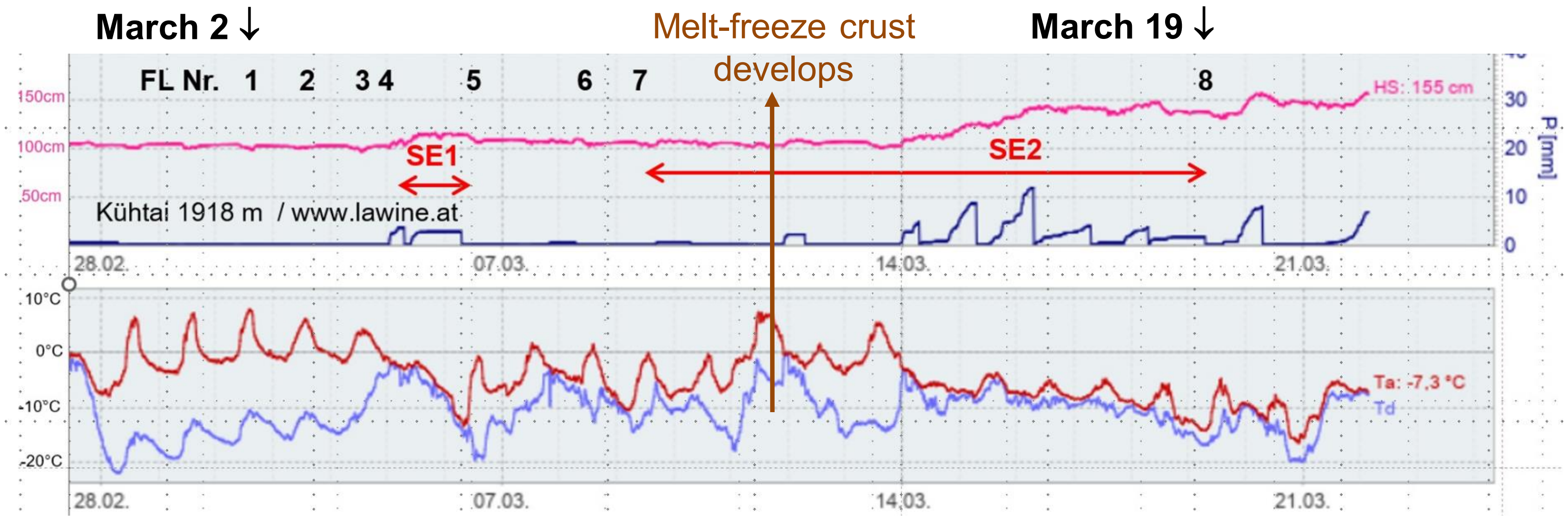
Location of snow transects, pits & corner reflectors

t10, t11 F-SAR Flight tracks

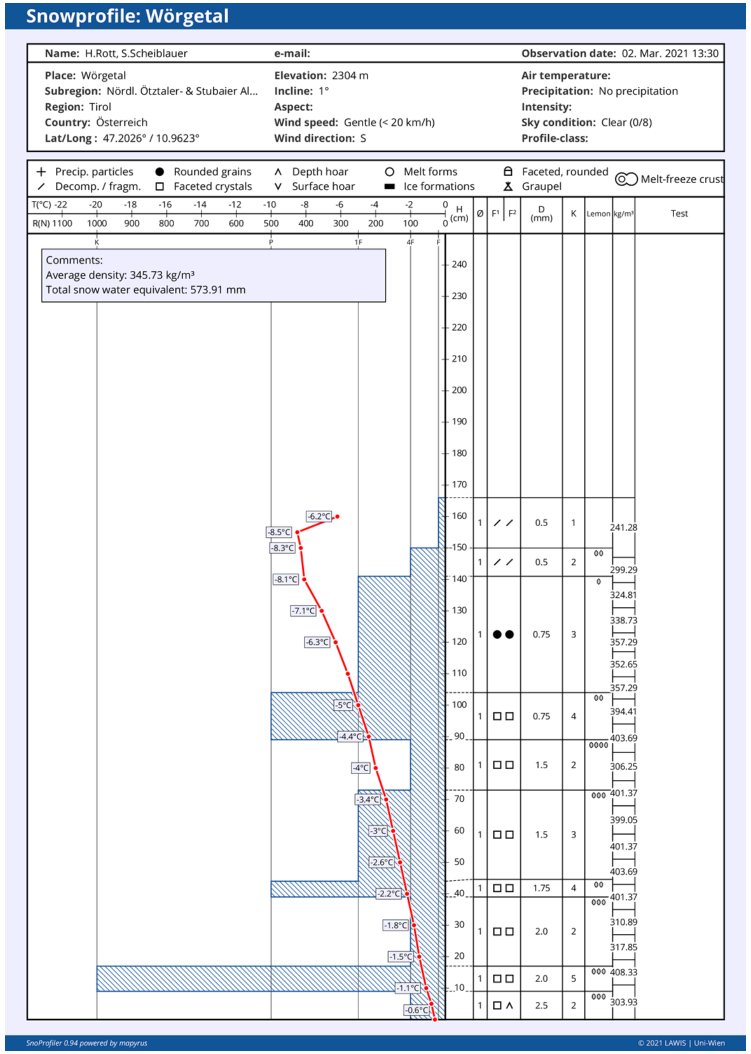
OB, MB, UB – RoI for retrieval validation



Meteorological Parameters and Snow Properties



Snow pit Oberer Boden (OB) 2304 m
2 March 2021



SE1, SE2 snowfall events spanned by RP-InSAR flights ↔; FL – Flight Nr.

Snowfall events: SE1: 5 March, **ΔSWE 13 mm** SE2: 14-18 March **ΔSWE 63 mm**

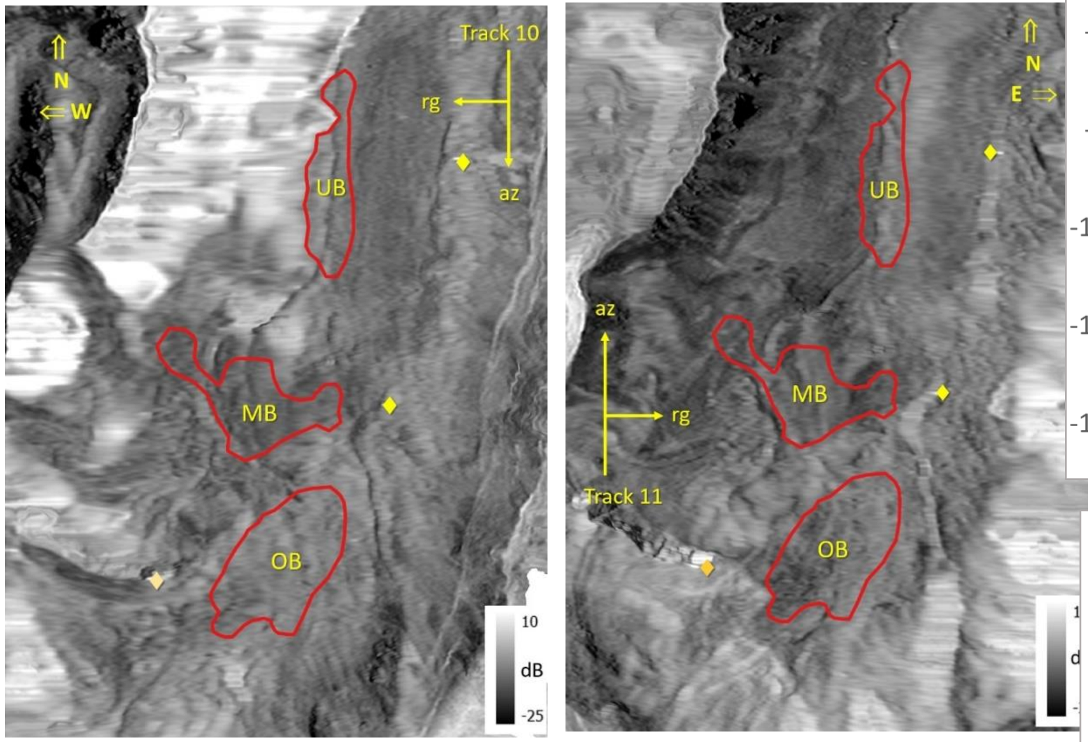
RoI Snow Depth (SD) and SWE SE1: [ρ] = 0.95 g cm^{-3} SE2: [ρ] = 0.145 g cm^{-3}

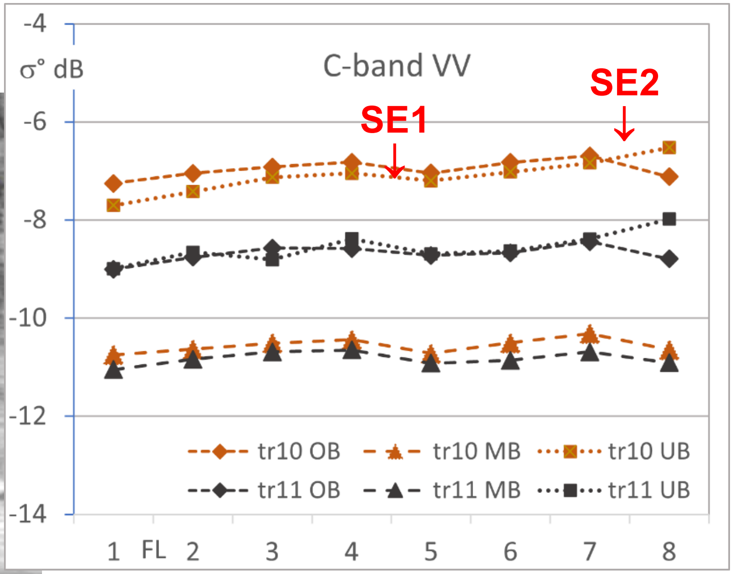
RoI	SD [cm] 2&3 March	Total SWE [mm]	ΔSD SE1 [cm]	SE1 SD std. dev.	SE1 ΔSWE [mm]	ΔSD SE2 [cm]	SE2 SD std. dev.	SE2 ΔSWE [mm]
OB	140.8	480.1	15.6	2.1	14.8	43.2	2.3	62.6
MB	127.6	435.1	13.3	2.4	12.6	47.2	6.2	68.4
UB	116.2	396.2	12.3	1.1	11.7	42.1	6.2	61.0

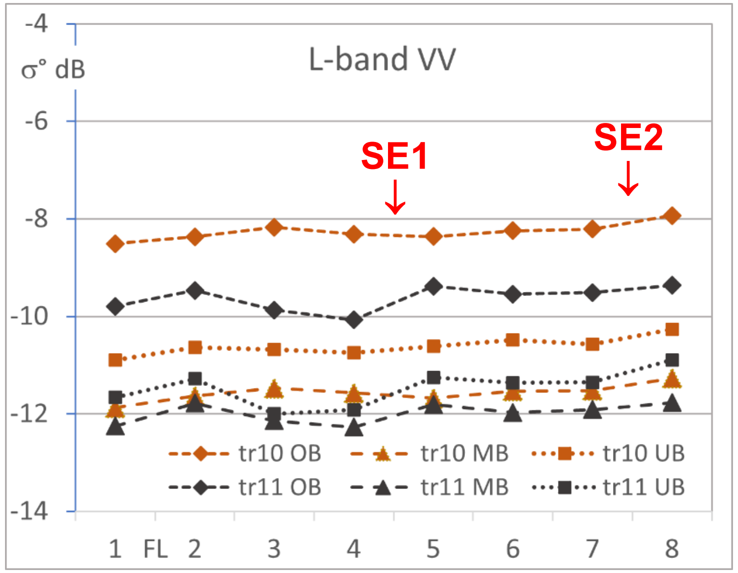
Backscatter Intensity at the RoIs during the F-SAR Flights

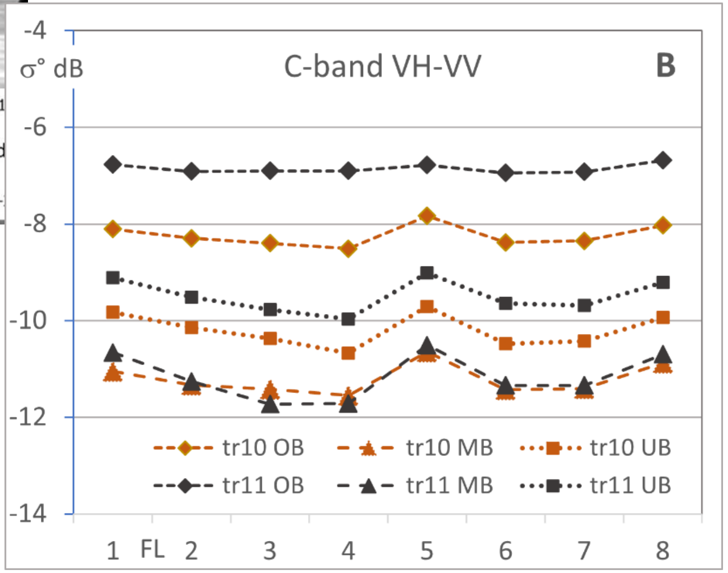
F-SAR σ°_{VV}, geocoded

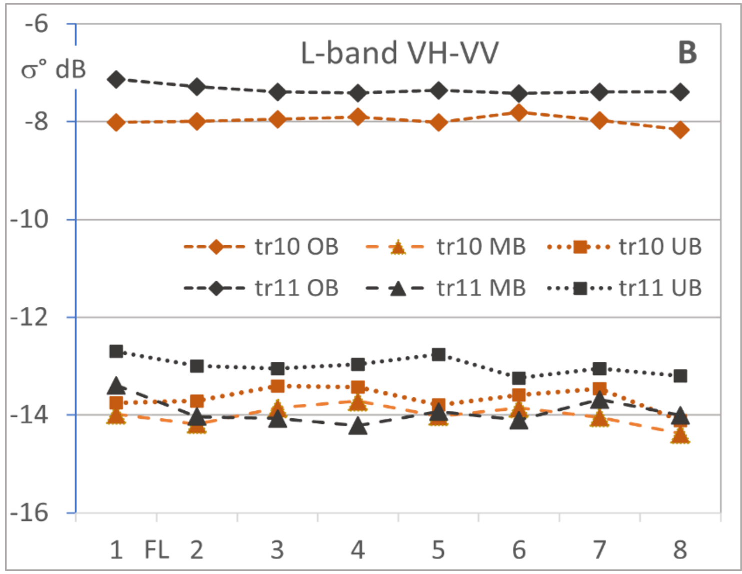
track 10 track 11











- Low variability of σ° in the RoIs - dry snow during the F-SAR acquisitions
- Occasional transient melt on steep sunny slopes (non-RoI); melt all over on 11.3. & 12.3. (no flights)
- Magnitude of σ° related to roughness of the snow/ground interface (max.OB → MB → min.UB)

VV-HH Co-Polarized Phase Difference

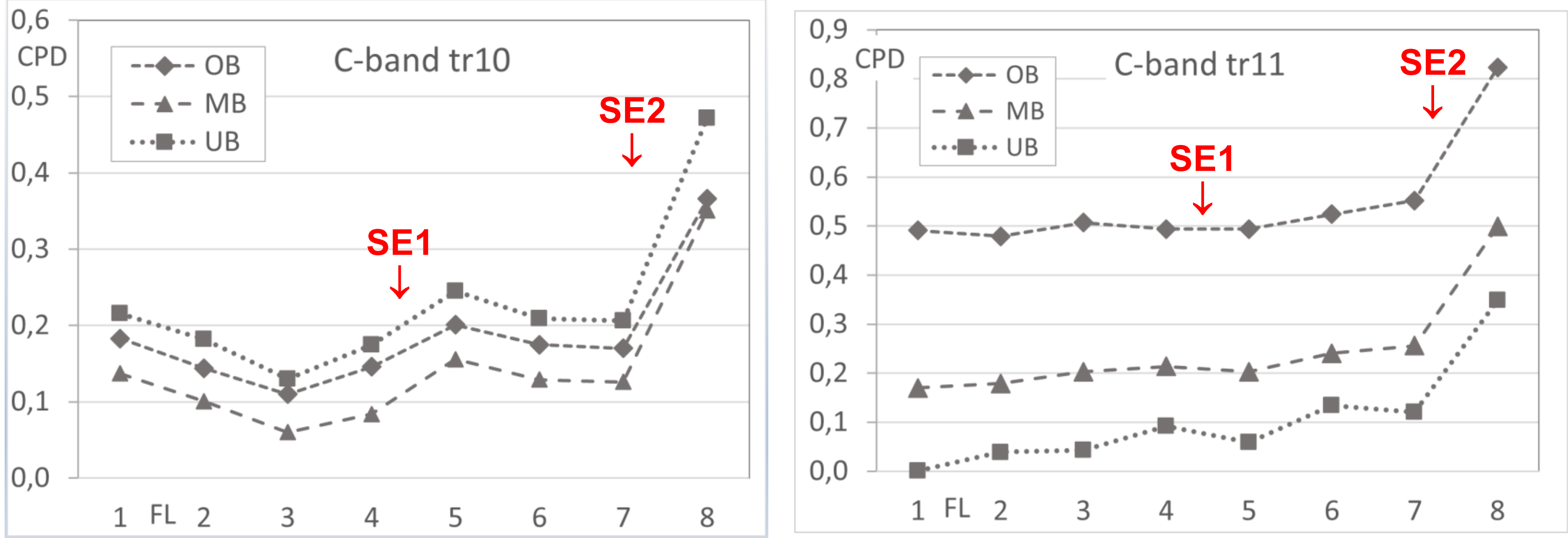
The co-polarized phase difference (CPD) is related to structural anisotropy of snow.

$$\phi_{CPD} = \phi_{vv} - \phi_{hh} = arg(\gamma_{vvhh})$$

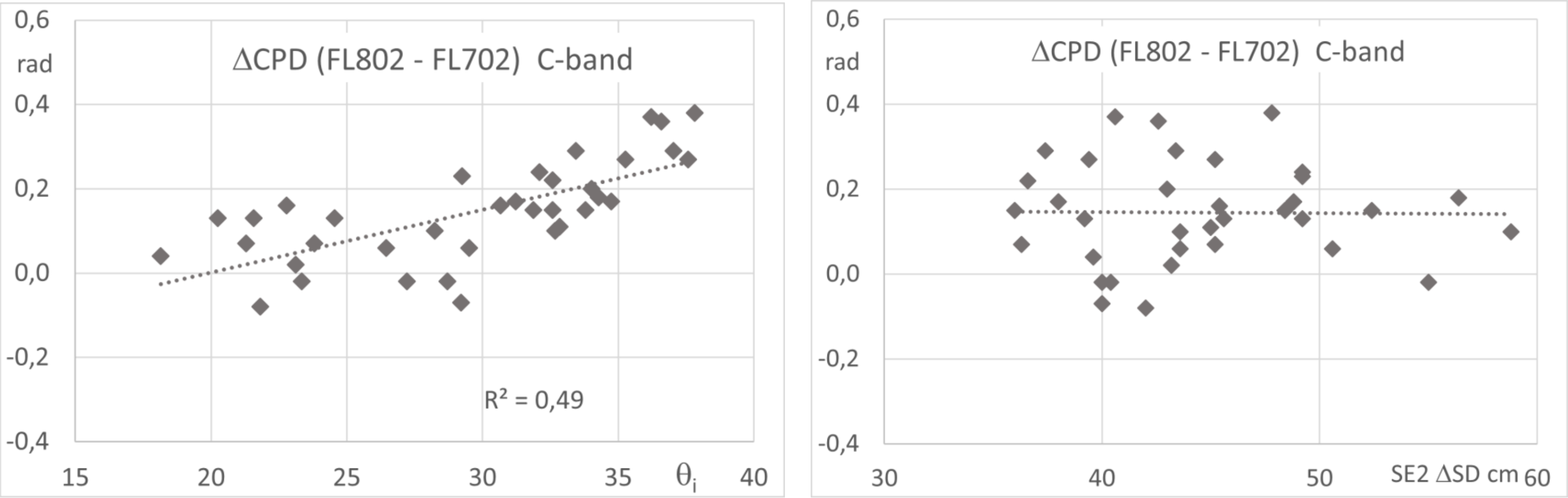
X-band CPD has been used as indicator for the depth of fresh snow.

- CPD shows a major increase between FL702 (09.03) & FL802 (19.03) spanning the main snowfall event.
- The change in CPD does not show a relation with the depth of fresh snow, but with the local incidence angle.
- This response is probably caused by the polarization dependent scattering phase within the melt-freeze crust that formed 2 days before the snowfall.

CPD of RoIs, track 10 & track 11



SE2: ΔCPD at in-situ SD measurement points, track 10



SWE Retrieval by means of Repeat-pass SAR Interferometry

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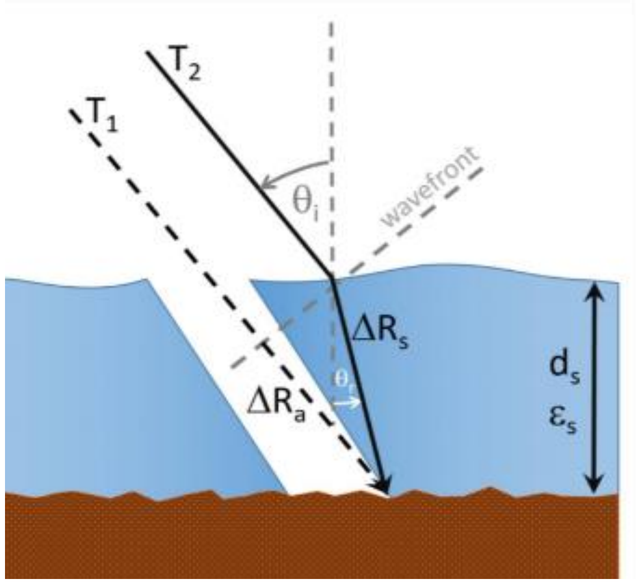
- Differential processing of repeat-pass InSAR data to obtain $\Delta\phi_{snow}$ (t_2-t_1) accounting for other phase contributions: $\phi = \phi_{flat} + \phi_{topo} + \phi_{atm} + \phi_{snow}$
- The change of InSAR phase delay in **dry snow** is related to snow depth and density

$$\Delta\phi_{snow} = -\frac{4\pi}{\lambda}\Delta d_s\left(cos\theta_i - \sqrt{\varepsilon - sin\theta_i^2}\right); \ \varepsilon' = 1 + 1.60\,\rho_s + 1.86\,\rho_s^3\ [\mathrm{g\ cm^{-3}}]$$

$$\Delta SWE(t_1,t_2) = \rho\,\Delta d_s = -\Delta\phi_s\,(t_1,t_2)\,\frac{\lambda_0}{4\pi}\rho\frac{1}{\cos\alpha}\frac{1}{cos\theta_i - \sqrt{\varepsilon - sin\theta_1^2}}\ ;\ \alpha \text{ -slope angle}$$



For obtaining $\Delta\phi_{snow}$ from observed $\Delta\phi_t$ a reference phase (at sites with zero or known ΔSWE) is needed: $\Delta\phi_{snow} = \Delta\,\Delta\phi_t - \Delta\phi_{ref}$

Error estimate: $\sigma_{\phi,ran} = \frac{1}{\sqrt{2N_L}}\frac{\sqrt{1-|\gamma|^2}}{|\gamma|}\ [rad]$

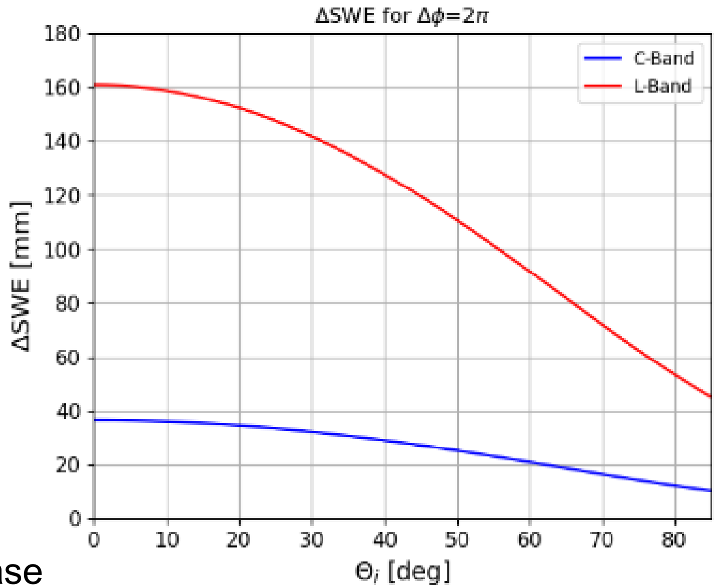
$$\sigma_{\Delta\phi,snow} = \sqrt{\sigma^2_{\phi,ran} + \sigma^2_{\phi,ref}(x,y)}$$

Critical issues:

- Temporal decorrelation (related to snowfall, snow drift, …)
- Reference phase at sites with zero or known ΔSWE *
- 2π phase ambiguity ⇒ affects short wavelengths
- Correction for change in atmospheric propagation (ϕ_{atm}) *

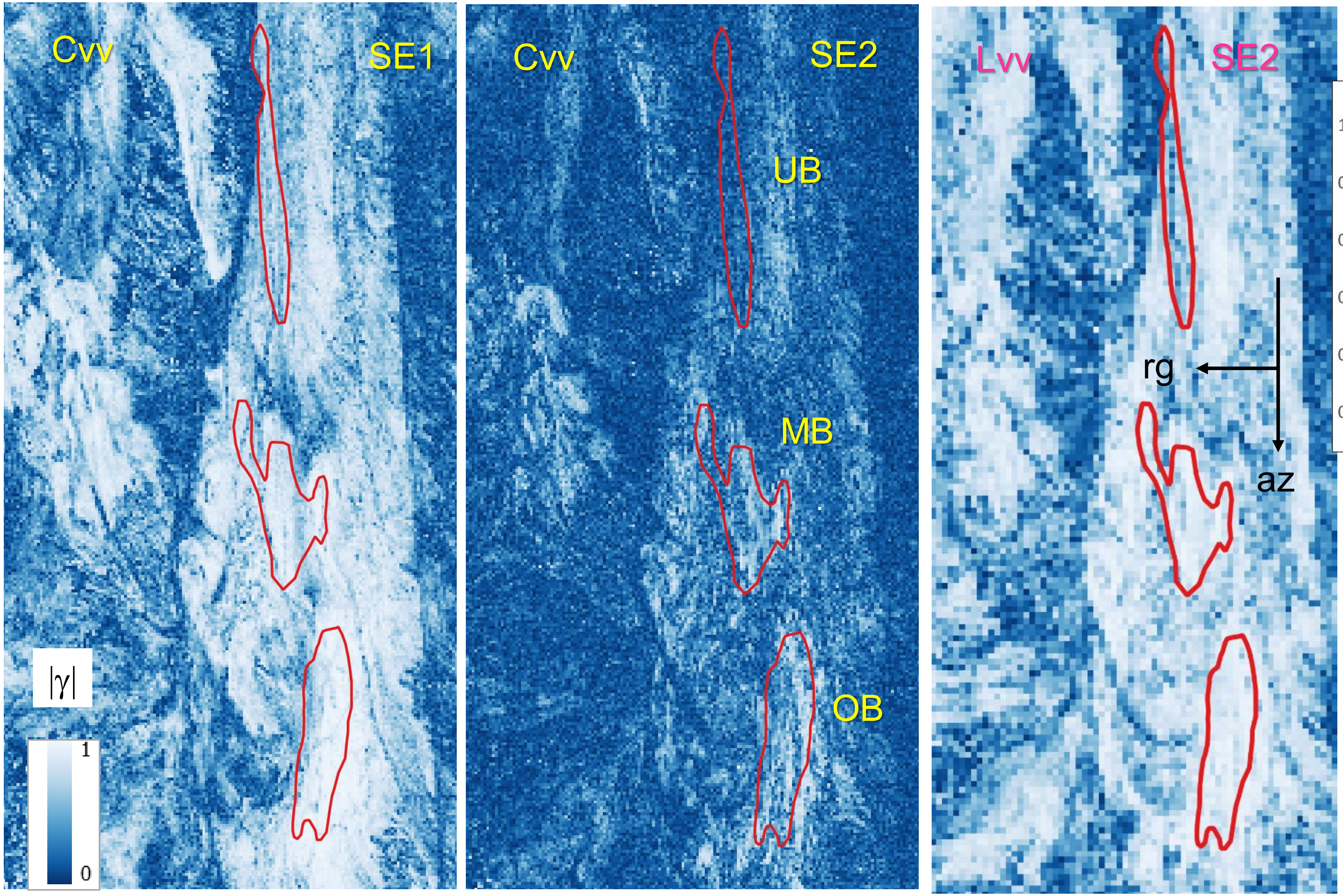
Data window: 25 x 25 pixels

Error	C- band	L-band
N_L	150	192
$\sigma_{\phi,ran}$ (SE1)	0.045 rad	0.018 rad
$\delta_{\phi,CR}$ (SE1)	0.31 rad	0.12 rad
σ(ΔSWE)	1.58 mm	2.44 mm
$\sigma_{\phi,ran}$ (SE2)		0.044 rad
$\delta_{\phi,CR}$ (SE1)		0.33 rad
σ(ΔSWE)		6.73 mm

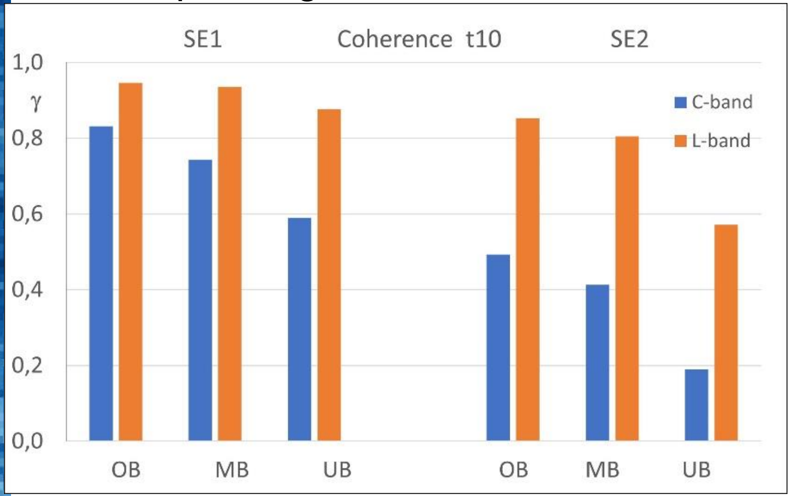


* Wörgetal-campaign: $\phi_{CornerReflector}$ used as reference phase → $\delta_{\phi,CR}$ max. abs. deviation of CR phase

Coherence of InSAR Data Spanning the two Snowfall Events



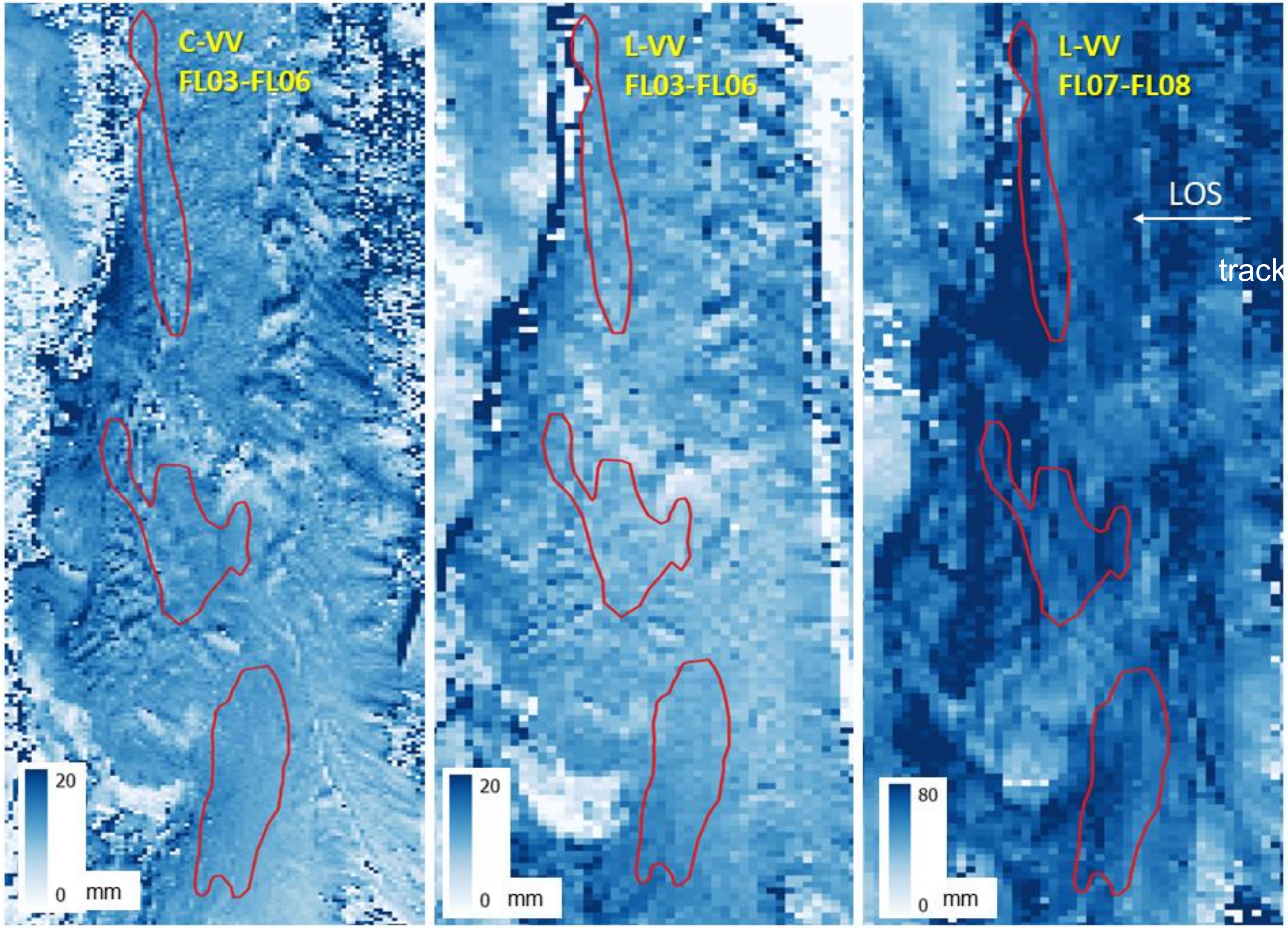
C- and L-band coherence at RoIs for data spanning the snowfall events.

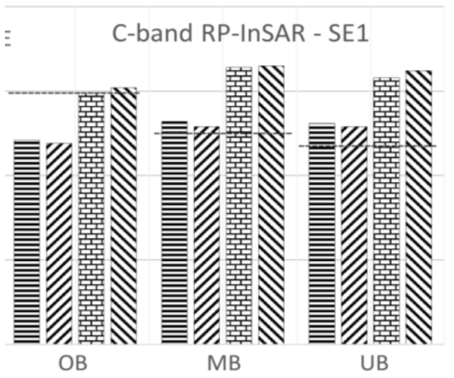


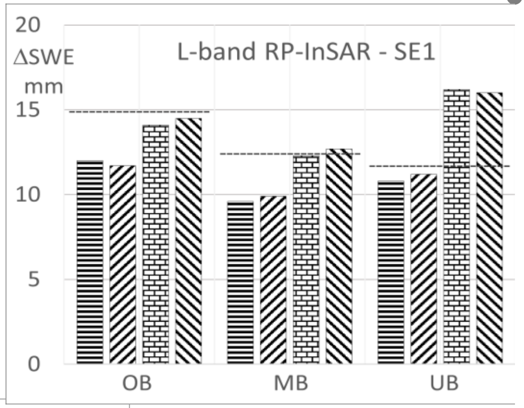
UB is affected by high terrain roughness, resulting in low coherence.

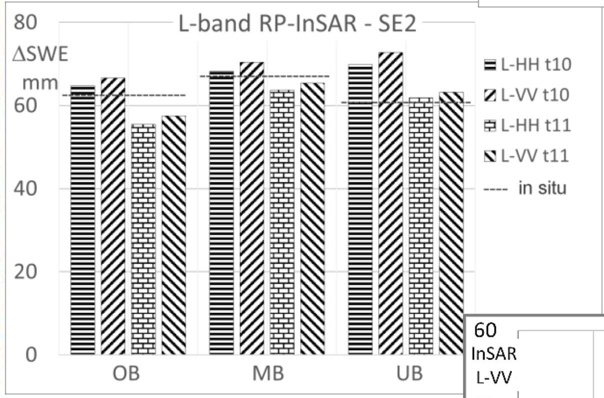
- Clear preference for L-band in terms of coherence
- Low coherence and 2π ambiguity impair the application of C-band RP-InSAR SWE retrievals for SE2

RP-InSAR ΔSWE of the two Snowfall Events









Mean SWE difference for RoIs InSAR-in situ

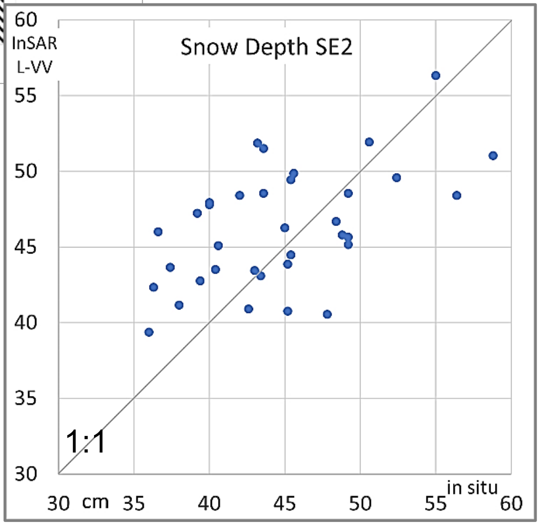
SE2 L-band: 1.6 mm

SE1 L-band: 1.2 mm

SE1 C-band: 0.3 mm

RMSD 2.7 mm (SE1)

5.4 mm (SE2)



SE2

SD at in-situ points by L-band VV

RMSD = 5.0 cm

SE2 : Low coherence and 2π ambiguity prohibit the application of C-band

SWE Retrieval by Delta-k Interferometric Processing

Split-Bandwidth Processing *Ref: Bamler & Eineder, IEEE GRSL, 2005*

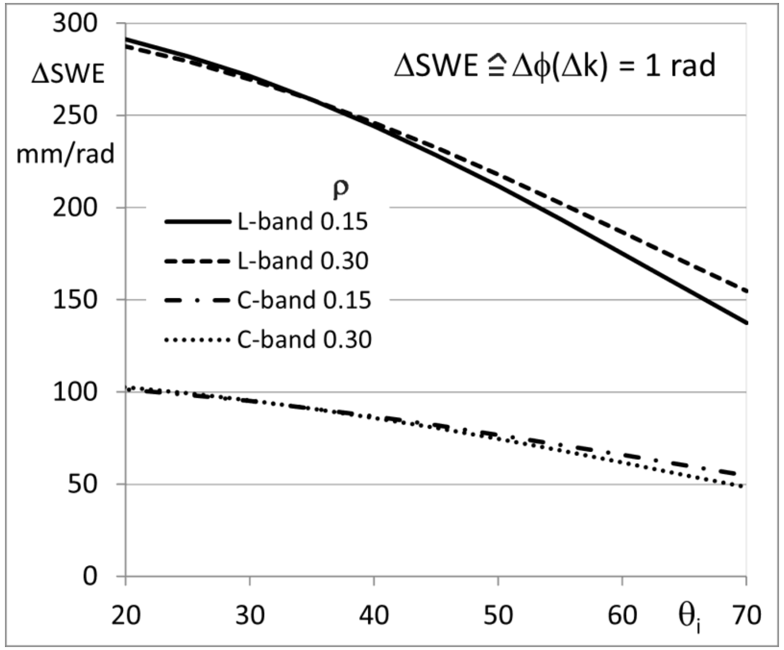
- Range bandpass filtering of images t_1 & t_2 , generating low and high frequency sub-band images: $s_{1,l}$ $s_{1,h}$; $s_{2,l}$ $s_{2,h}$
- Generating sub-band phase images: $\phi_l = \angle\left(s_{1,l}s_{2,l}^*\right)$ $\phi_h = \angle\left(s_{1,h}s_{2,h}^*\right)$
- Generating the Delta-k phase image: $\phi_{\Delta k} = \phi_l - \phi_h = \angle\left[\left(s_{1,l}s_{2,l}^*\right)\left(s_{1,h}s_{2,h}^*\right)^*\right]$

Uncertainty estimate for $\Phi_{\Delta k}$ $\sigma_{\Delta\varphi,\Delta k} = \frac{\sqrt{2}\,\sigma_{\varphi,b}}{2\pi}\frac{B}{b-B} = \frac{1}{2}\frac{B}{b-B}\sqrt{\frac{B}{b}}\frac{1}{\sqrt{N}}\frac{\sqrt{1-\gamma^2}}{\pi\,\gamma}$

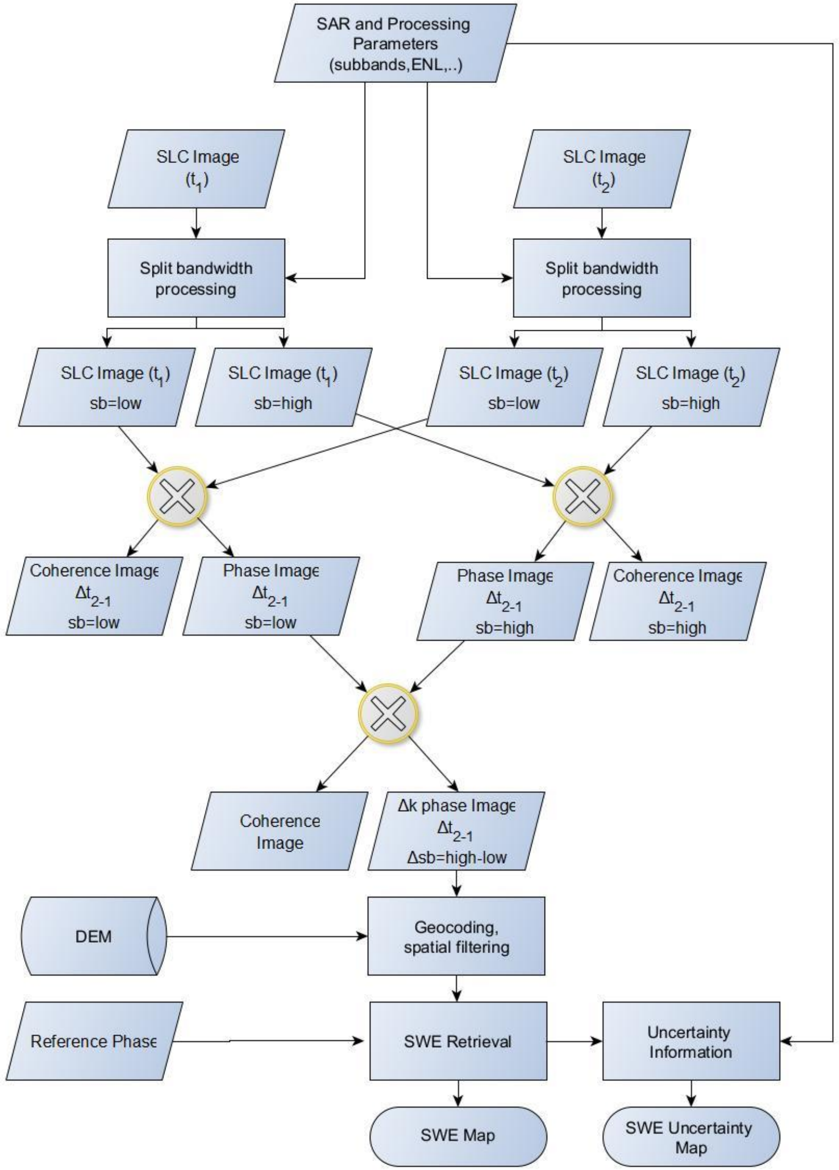
F-SAR Delta-k analysis:

C-band B = 384 MHz, b = 100 MHz

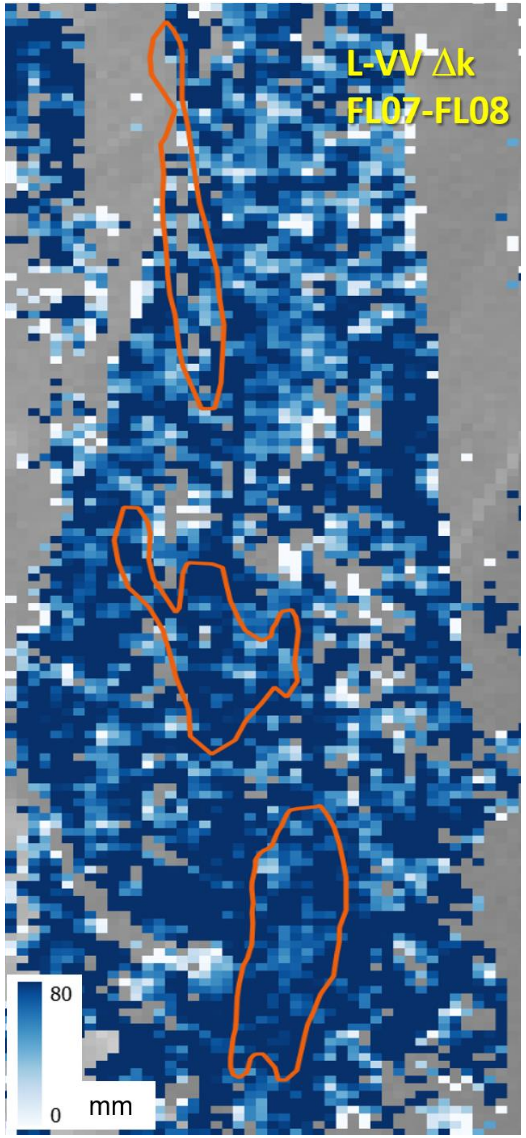
L-band B = 150 MHz, b = 50 MHz



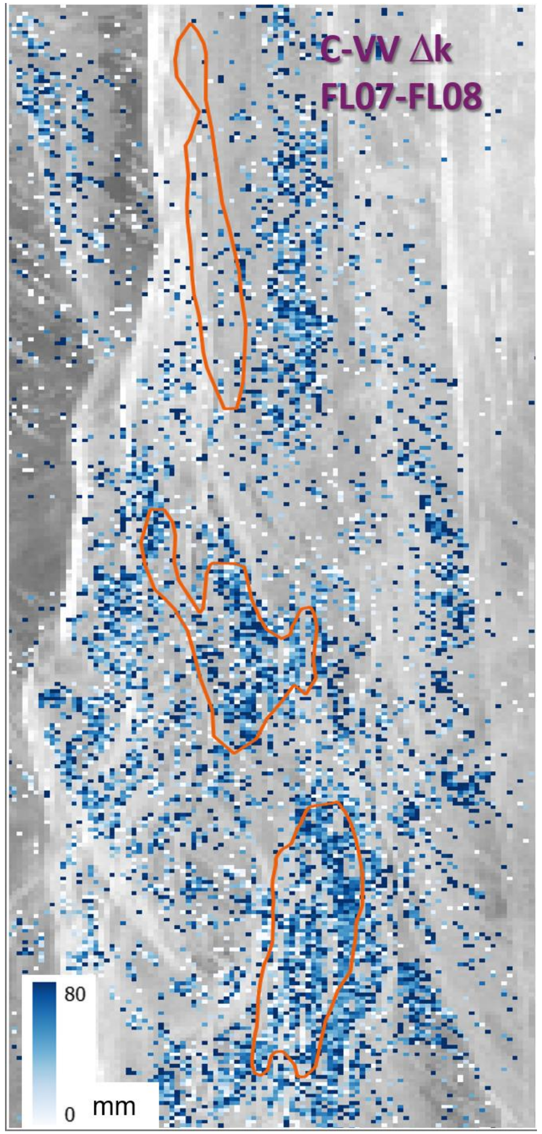
Reduced sensitivity of phase in respect to ΔSWE →



Delta-k SWE Retrieval Results



Clipped at |γ| <0.4

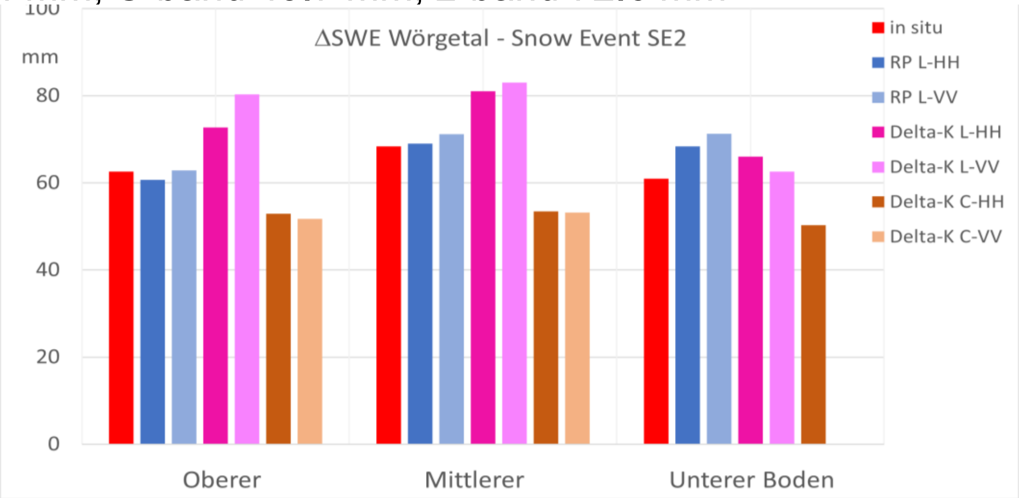


at |γ| <0.3

Δk SWE retrievals, **mean values of RoIs**

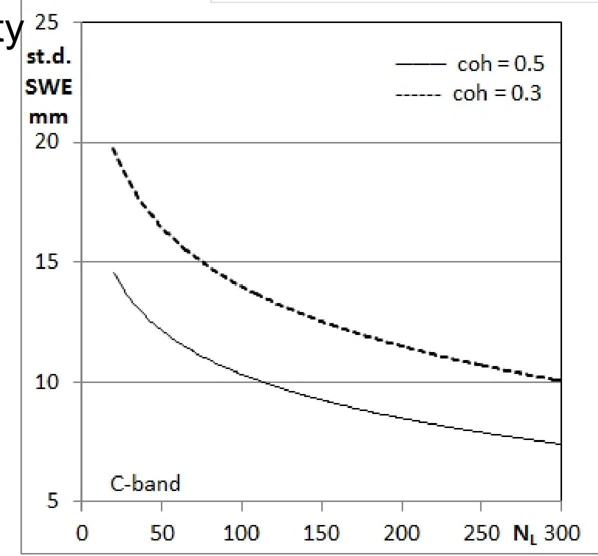
Processing window 25 x 25 pix, N_L= 150 C-band; N_L= 190 L-band

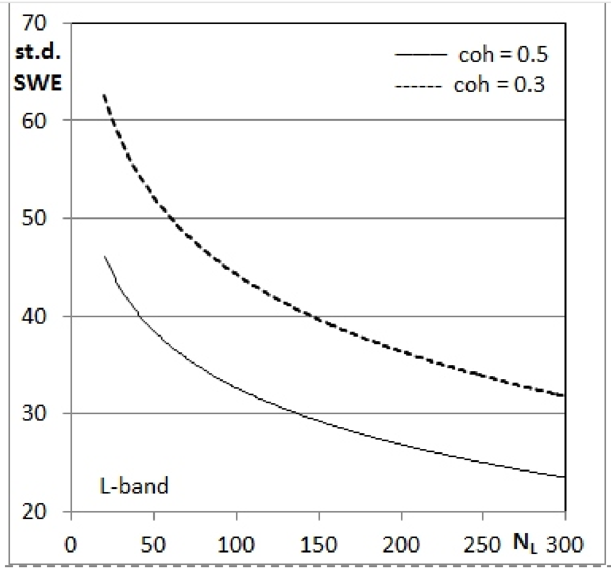
SE2: in situ 63.4 mm, C-band 49.7 mm, L-band 72.6 mm



Low coherence of C-band, similar to conventional RP-InSAR

Phase-related uncertainty





Properties of Simulated HydroTerra Products

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Specifications of HT products used for SWE retrieval:

Parameter	Value
Frequency	5.3 GHz
HT01x01 Single look, resolution az x range	5 m x 22. 2 m
Range bandwidth	6 MHz
Multi-look product 10 x 1 pixels	10 looks
NESZ	-21.1 dB

Error estimate, multi-look product, ENL = 10, θ_i= 50°

Random Phase error:

$|\gamma|$ = 0.3: $\sigma_{\varphi,ran}$ = 0.71 rad, $\sigma_{SWE,ran}$ = 2.27mm

$|\gamma|$ = 0.6: $\sigma_{\varphi,ran}$ = 0.30 rad, $\sigma_{SWE,ran}$ = 0.96 mm

The additional error of the reference phase (corner reflectors) is of the same order of magnitude.

The CR phase is taken from the full resolution simulated geosynchronous SAR products (F-SAR pixel size)

Simulated HT products **spanning** snowfall events were processed for the following F-SAR flight combinations:

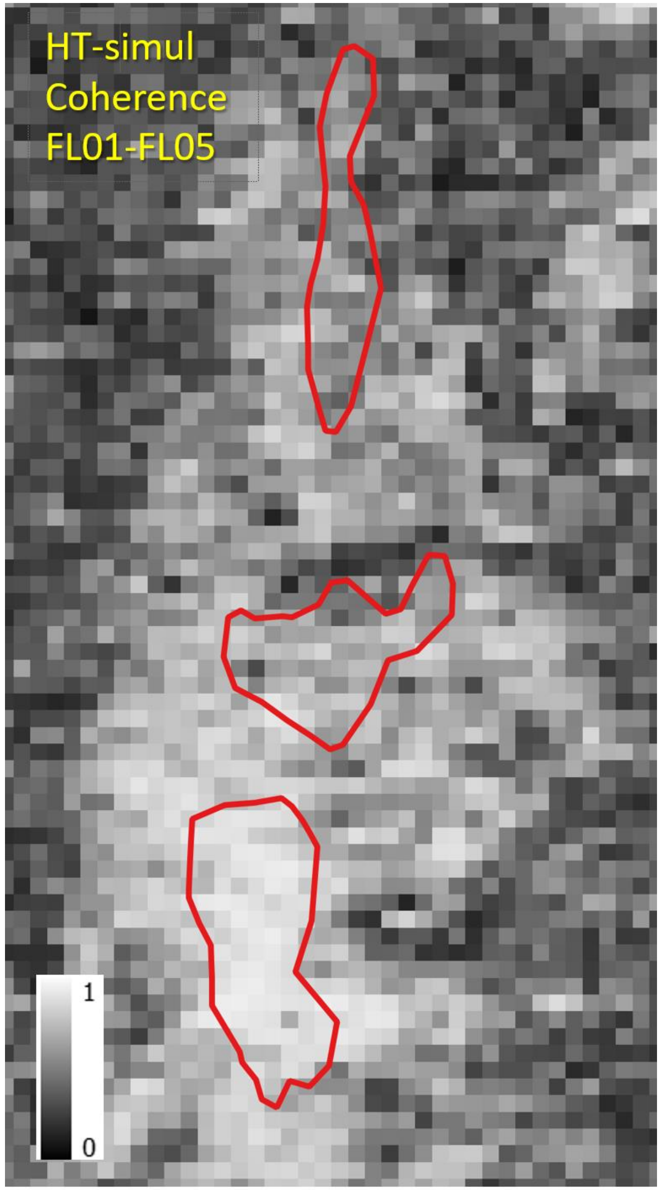
- FL01 – FL05, 2.3. – 6.3., SE1, mean ΔSWE 13 mm
- FL02 – FL08, 3.3. – 19.3., SE1 & SE2, mean ΔSWE 77 mm

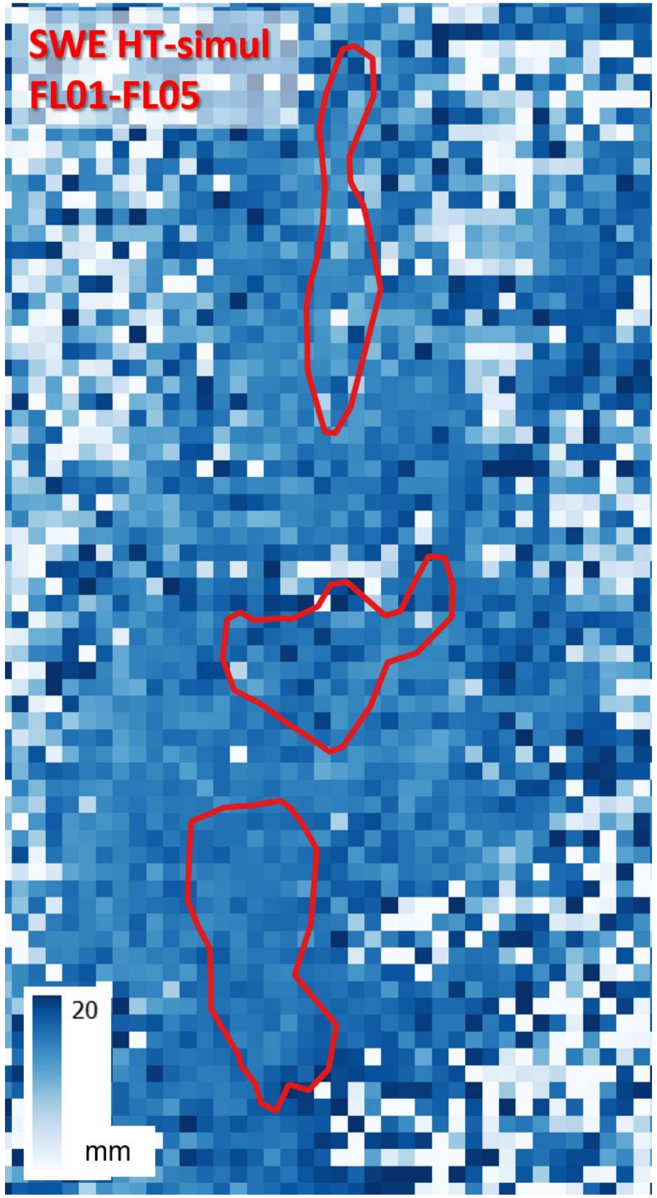
Integration time FL01: 107 min, FL05: 110 min; FL02: 24 min, FL08: 23 min

The FL02-FL08 case is not applicable for SWE retrievals because of low coherence, large phase noise and 2π phase ambiguity

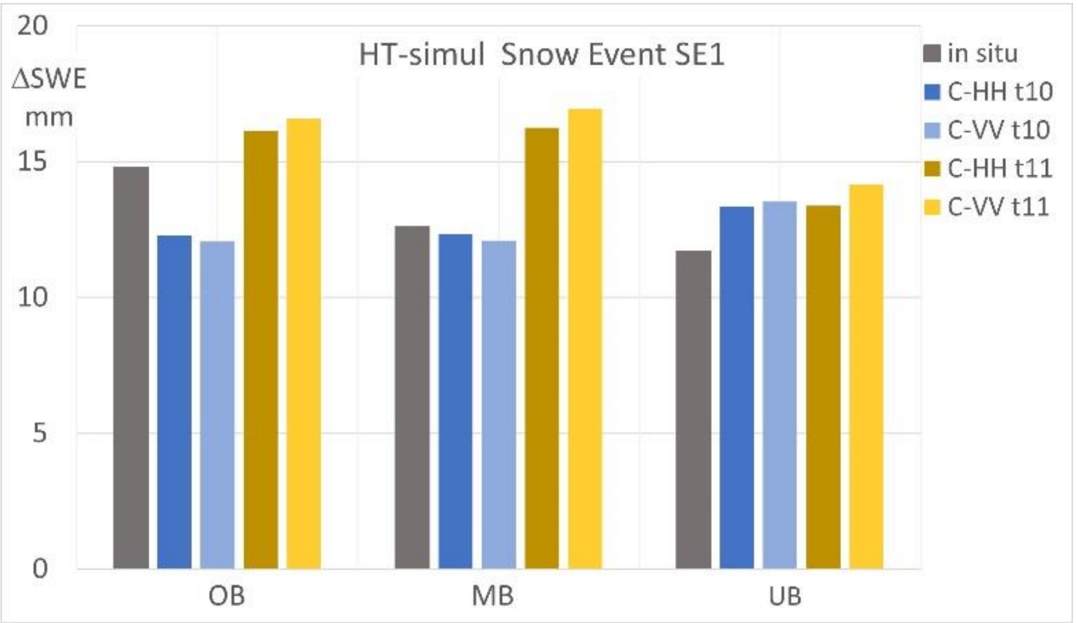
Δ SWE of FL02-FL08 exceeds up to 3 times the 2π phase ambiguity.

Simulated Hydroterra Products – Coherence and ΔSWE





In situ and computed ΔSWE, SE1



- Bias of HT-simul for average ΔSWE of RoIs:
  t10 -0.4 mm, t11 +2.6 mm
- Maximum biases of individual RoI & track:
  -2.6 mm / + 3.9 mm
- The SWE retrievals on steep slopes are noisy (low coherence). Improvements to be expected by shorter repeat intervals of geosynchronous SAR and larger window size (N_L)

Conclusions

- The Wörgetal campaign, based on L- and C-band SAR data, confirms the high potential of the Repeat Pass InSAR approach for observing snow accumulation at high spatial resolution. The L-band InSAR data show high coherence and good performance for SWE retrieval also for high snow accumulation events.
- C-band InSAR data show good results for retrieving snow accumulation of moderate intensity but are not well suitable for intense snowfall due to low coherence and 2π phase ambiguity.
- VV-polarized RP-InSAR data show slightly higher coherence than HH-polarized data, but the differences in retrieved SWE are not significant.
- Delta-k interferometric processing is able to capture intense snowfall events and to cover extended time spans, an option for closing gaps in conventional RP-InSAR SWE retrievals.
- Geostationary SAR offers short repeat observation intervals, of interest for obtaining continuous time series of snow accumulation. Further studies are needed to assess the impact of snowfall on SAR image formation and decorrelation.
- Critical issues for InSAR SWE retrieval are: - limited to dry snow, - selection of reliable reference points for phase / SWE calibration, - reduced sensitivity in forests, - topography related gaps (to be filled by data from crossing orbits), - correction for atmospheric phase delay.