ASSESSING THE POTENTIAL OF INTERFEROMETRIC AND POLARIMETRIC SAR FOR THE RETRIEVAL OF SNOW WATER EQUIVALENT

Kristina Belinska[1,2], Georg Fischer[1], Julia Boike[3], Irena Hajnsek[1,2]

[1]Microwaves and Radar Institute, German Aerospace Center

[2]Institute of Environmental Engineering, ETH Zurich

[3]Alfred-Wegener-Institute, AWI

Motivation

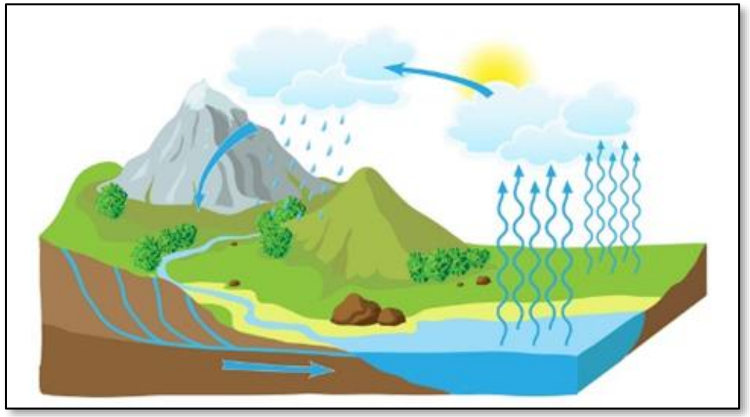
Snow Water Equivalent

- Amount of liquid water contained within a snow pack
  → depth of water, if whole snow pack melted instantaneously

$$SWE = \frac{1}{\rho_w} \int_0^{Z_s} \rho_s(z)\, dz \approx Z_s \rho_s / \rho_w$$

Important Parameter for

Hydrological and climate models



https://www.sieker.de/en/fachinformationen/flood/hydrological-modelling.html

Water resource planning

https://www.drax.com/about-us/our-sites-and-businesses/cruachan-power-station/

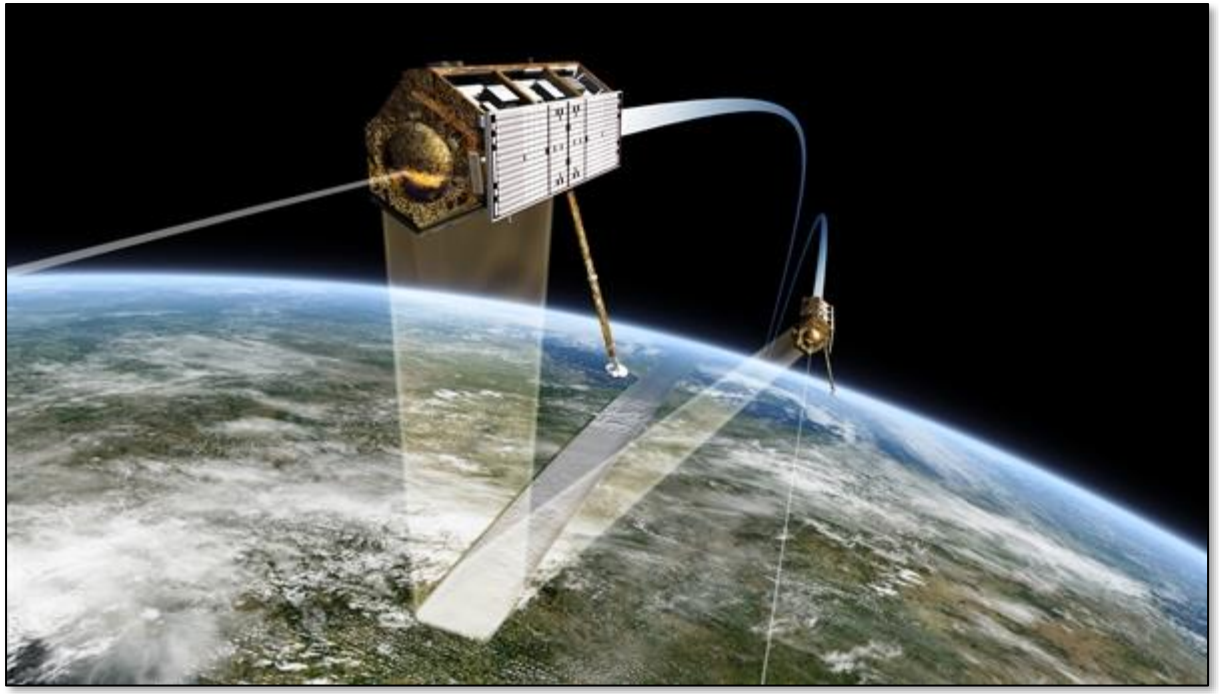
Flood predictions

https://www.wkbw.com/news/local-news/rain-snow-melt-floods-basements-of-orchard-park-homeowners

Motivation

Advantage of SAR

- Monitor snow covered areas with high spatial resolution
- Independent from weather and illumination conditions
- Microwaves penetrate into dry snow → sensitive to structural parameters



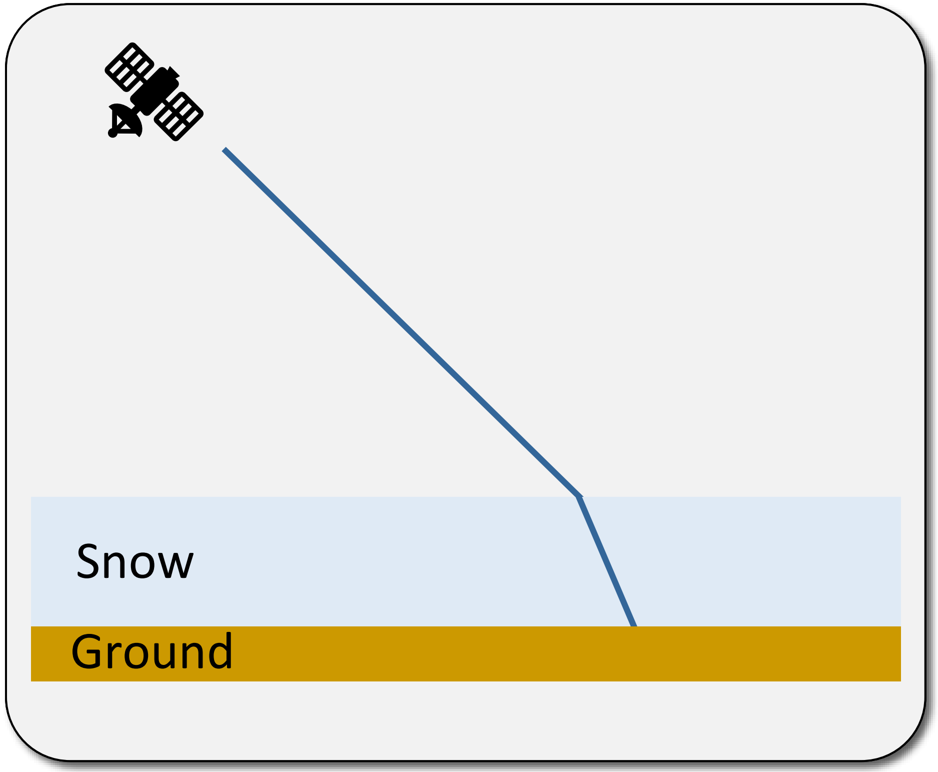
https://tandemx-science.dlr.de/cgi-bin/wcm.pl?page=TDM-Mission

Differential SAR Interferometry Model for SWE Estimation

- Repeat pass SAR acquisitions with zero baseline
- Different dielectric properties in snow compared to air

  → Refraction of radar waves in the snow pack

  → Different optical path length for snow compared to no snow conditions
- Only dry snow



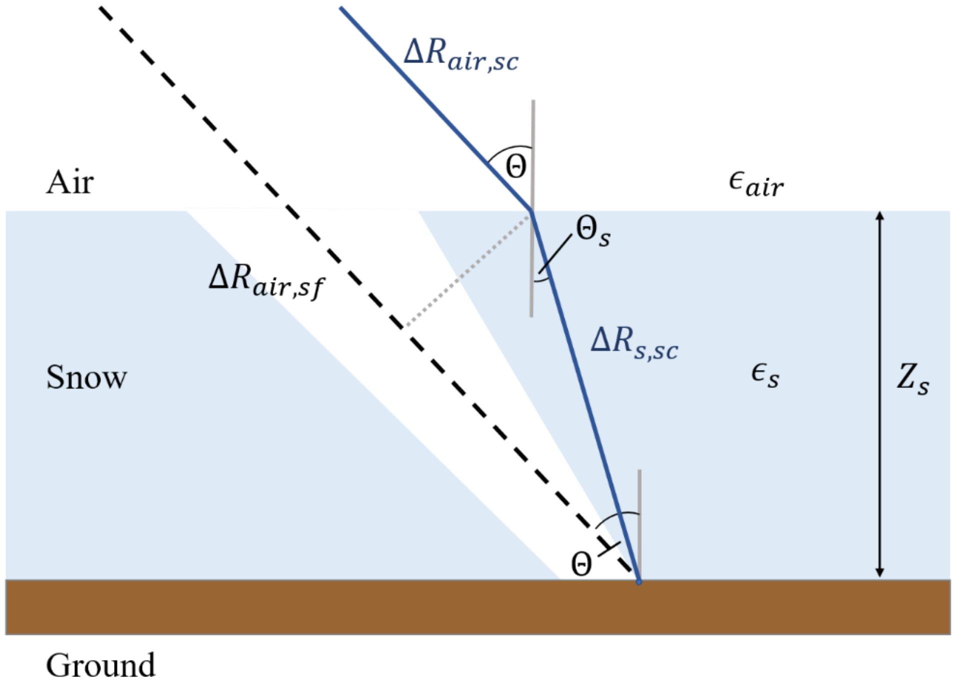
DInSAR Model for SWE Estimation

- Path delay ΔR can be translated into an interferometric phase difference

$$\Delta\Phi_s = 2\,\frac{2\pi}{\lambda}\,\Delta R$$

$$\Delta\Phi_s = -2\,k_i\,\Delta Z_s \underbrace{\left(\cos\Theta - \sqrt{\epsilon - \sin^2\Theta}\right)}_{=:\ \xi(\Theta,\rho_s)}$$

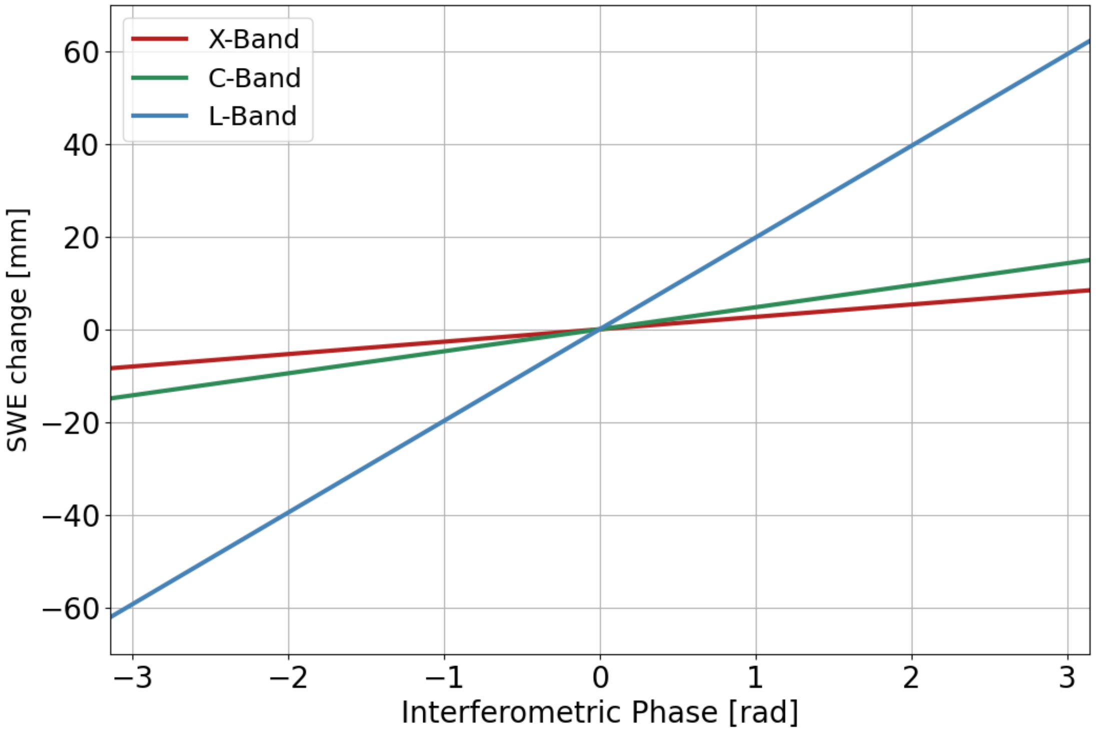
$$\boxed{\Delta\Phi_s = 2\,k_i\,\frac{\alpha}{2}\left(1.59 + \Theta^{\frac{5}{2}}\right) * \Delta SWE}$$

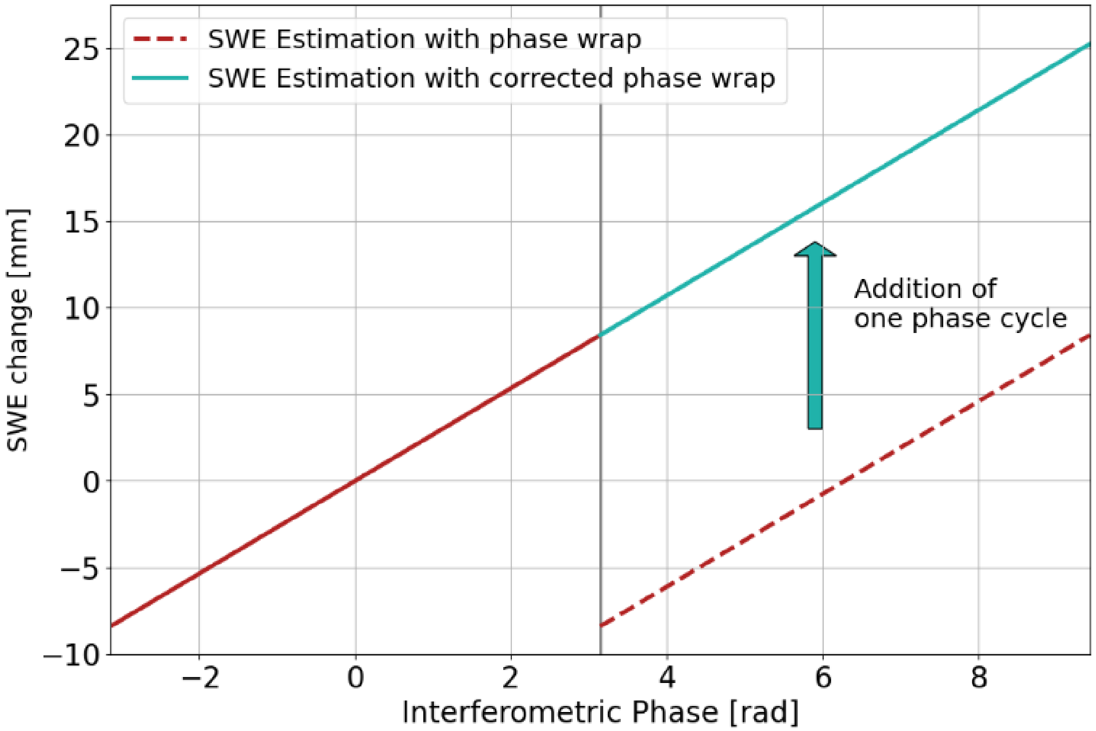


DInSAR Model for SWE Estimation

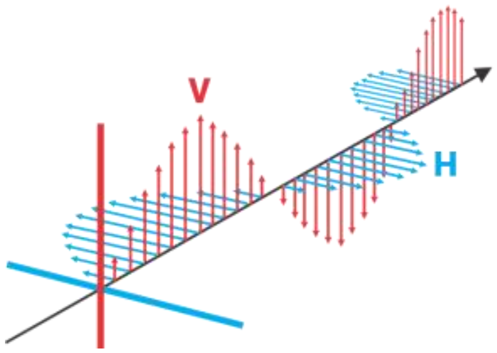
$$\Delta SWE = \frac{\Delta\Phi_s}{\alpha * k_i(1.59 + \Theta^{\frac{5}{2}})}$$

- $\Delta\Phi_s$ between [-π, π] → outside this interval phase wrapping errors
- SWE changes exceeding the threshold, will be underestimated (red dotted line)





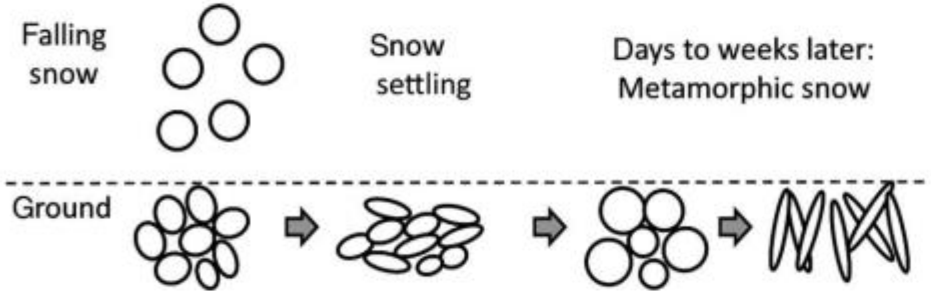
Copolar Phase Difference (CPD): Snow Depth Estimation



- Additional information about snow accumulation contained in co-polar-phase difference

$$\boxed{\Phi_c = \Phi_{VV} - \Phi_{HH}}$$

- Different polarizations show different propagation speeds in anisotropic snow
- Fresh snow
  → more horizontally aligned ice grains
  → slower propagation speed for H-polarized microwaves
  → increasing CPD values
- Decreasing CPD values due to recrystallisation under temperature gradients



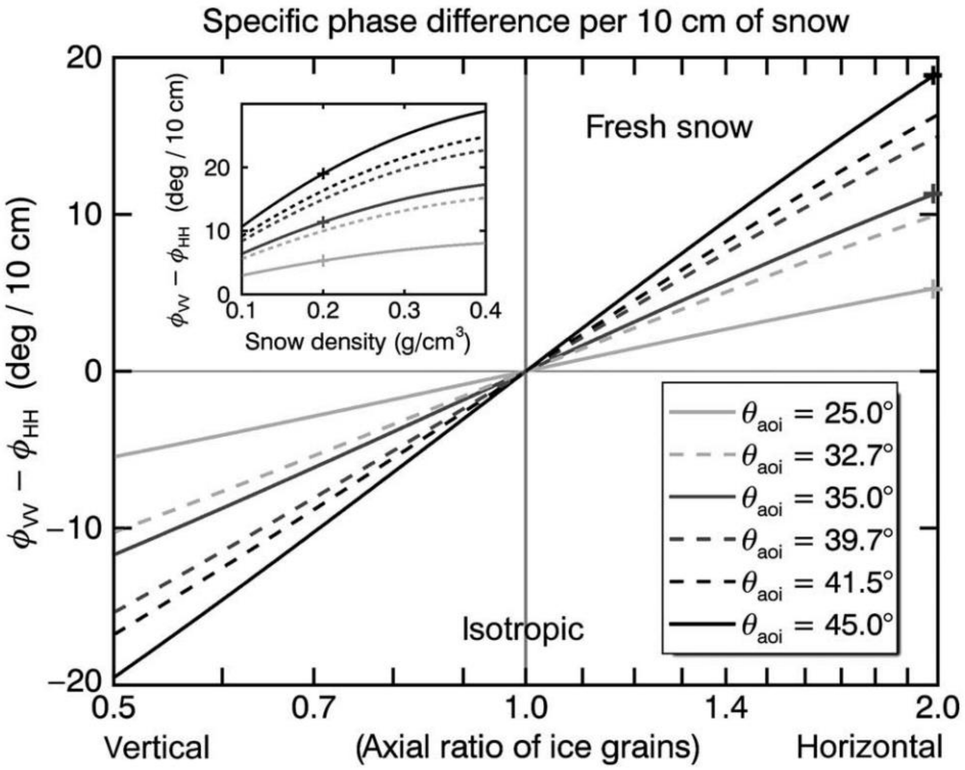
→ CPD can detect snow fall events
→ help to correct phase wrapping

PolSAR CPD Model for Snow Depth Estimation

- Snow model: ellipsoidal ice inclusions in air

- Assumption of snow anisotropy
  → Depolarization factors along main axes
  → Effective permittivity
  → refractive indices for HH and VV

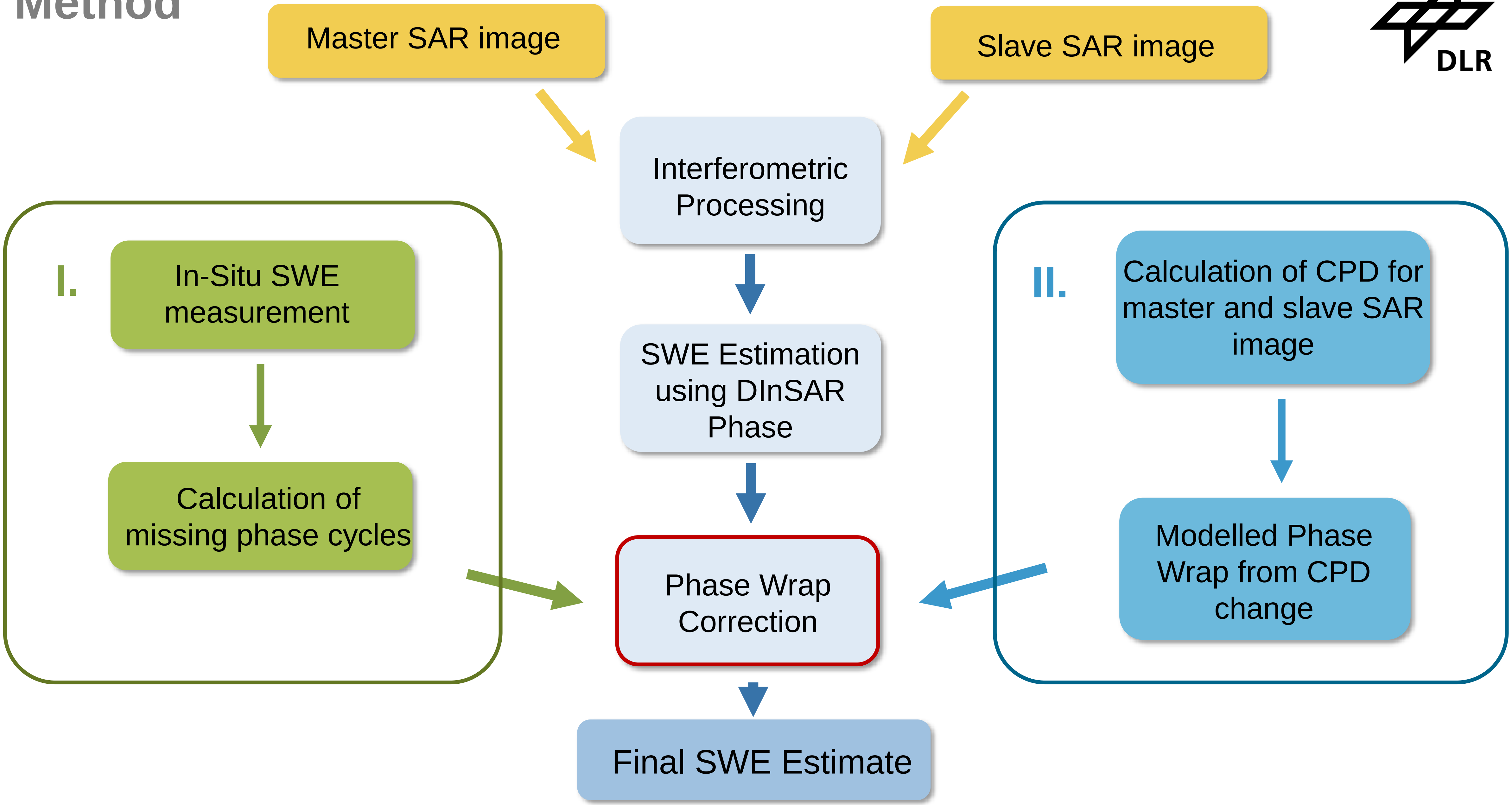
- CPD:



$$\Phi_{CPD} = (-1)\frac{4\pi}{\lambda}\Sigma\,\Delta Z_s \underbrace{\left(\sqrt{n_V^2 - \sin^2(\Theta)} - \sqrt{n_H^2 - \sin^2(\Theta)}\right)}_{\Delta\zeta(\rho, A, \Theta)}$$

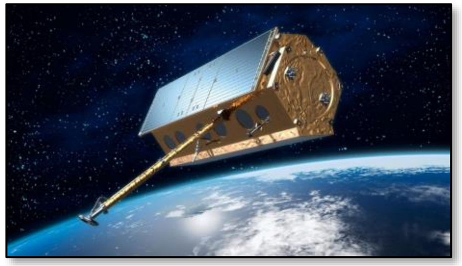
Leinss et al., Snow Height Determination by Polarimetric Phase Differences in X-Band SAR Data, 2014
Leinss et al., Anisotropy of seasonal snow measured by polarimetric phase differences in radar time series, 2016

Method


Master SAR image
Slave SAR image
Interferometric Processing
SWE Estimation using DInSAR Phase
Phase Wrap Correction
Final SWE Estimate
I.
In-Situ SWE measurement
Calculation of missing phase cycles
II.
Calculation of CPD for master and slave SAR image
Modelled Phase Wrap from CPD change

SAR Data

- TerraSAR-X (TSX) and TanDEM-X (TDX)
- X-Band measurements
- Svalbard

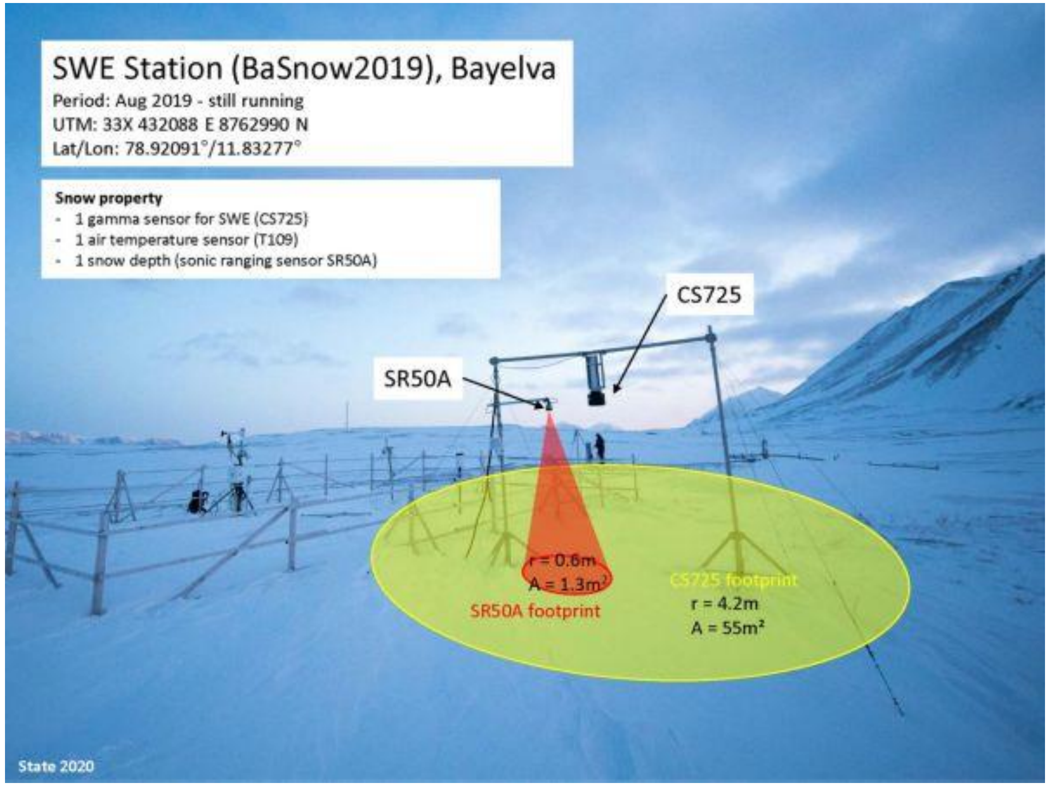


- Short time series for the winter 2020/21 and 2021/22
- Dual polarized data: HH and VV polarization
- Incidence angles of around 39°
- Temporal baseline 11 days

https://www.dlr.de/content/de/artikel/missionen-projekte/terrasar-x/terrasar-x-erdbeobachtungssatellit.html

AWI Test Site

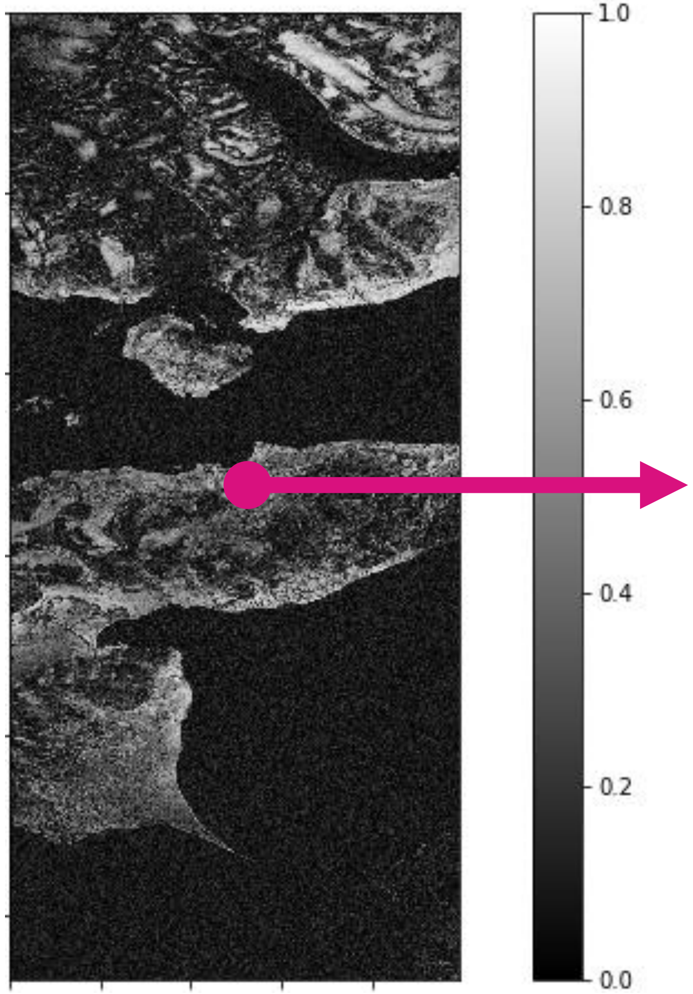
- Bayelva test site located on Svalbard
- Evaluation of automated monitoring techniques for SWE measurements
- Since August 2019: sensor installed by Alfred-Wegener-Institute (AWI)
  - Measures SWE with a passive gamma ray sensor
  - Temporal resolution: 6 hours



Jentzsch, K. , Bornemann, N. , Cable, W. , Gallet, J. C. , Lange, S. , Westermann, S. and Boike, J. (2020): Near real-time observations of snow water equivalent for SIOS on Svalbard – (SWESOS) , doi: 10.5281/zenodo.4146835

InSAR Coherence

- Coherences below 0.3 are masked out (9x9 Window)



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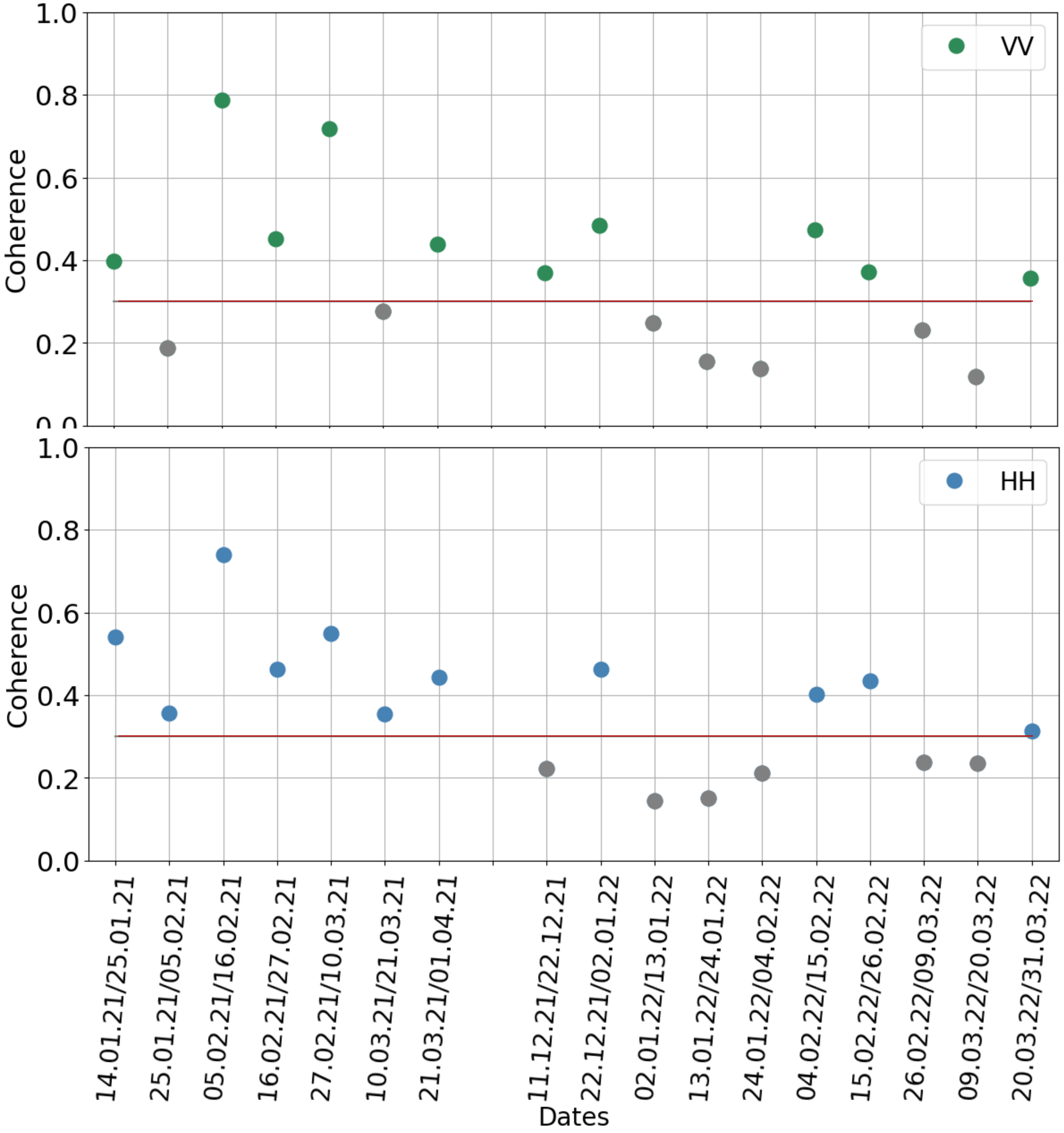
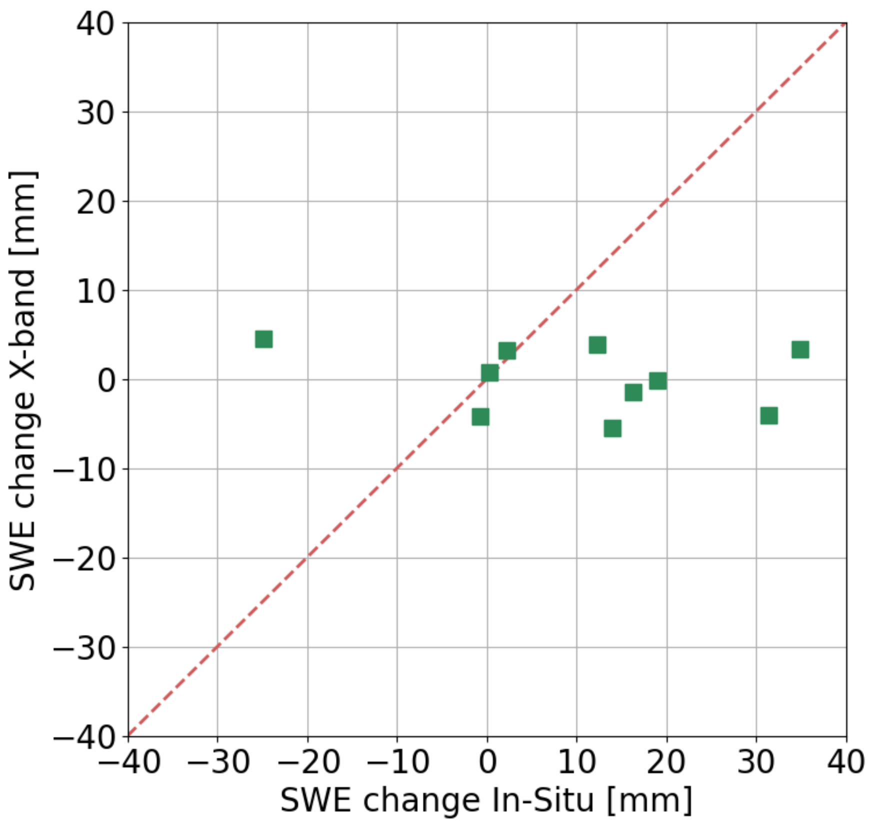


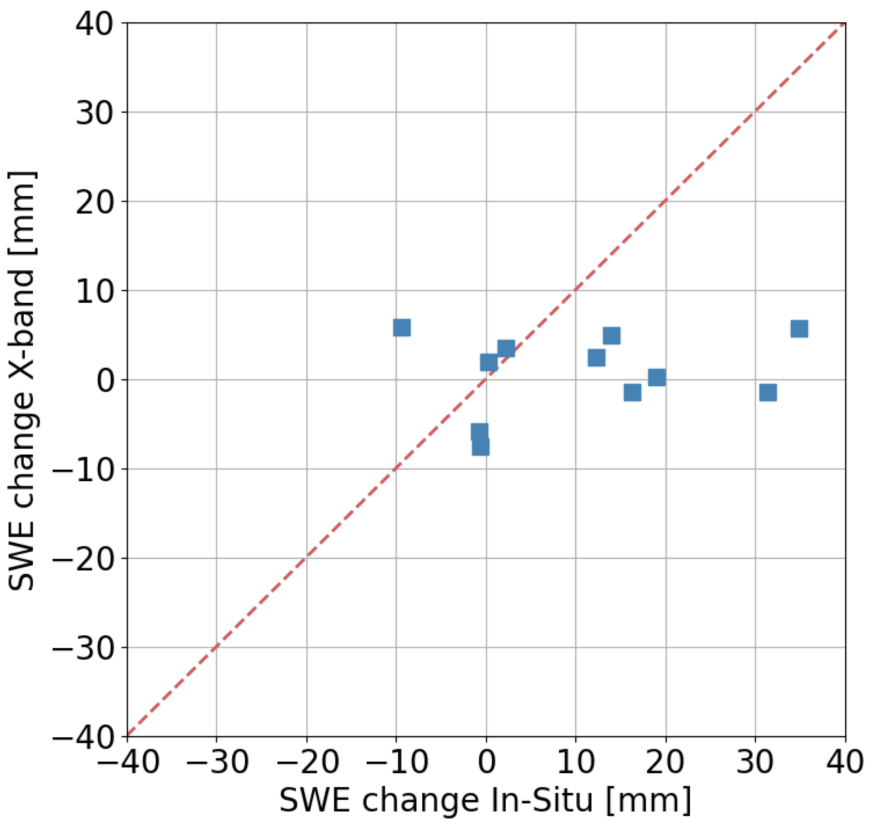
DLR

SWE Estimation using DInSAR Phase Without Phase Wrap Correction

VV



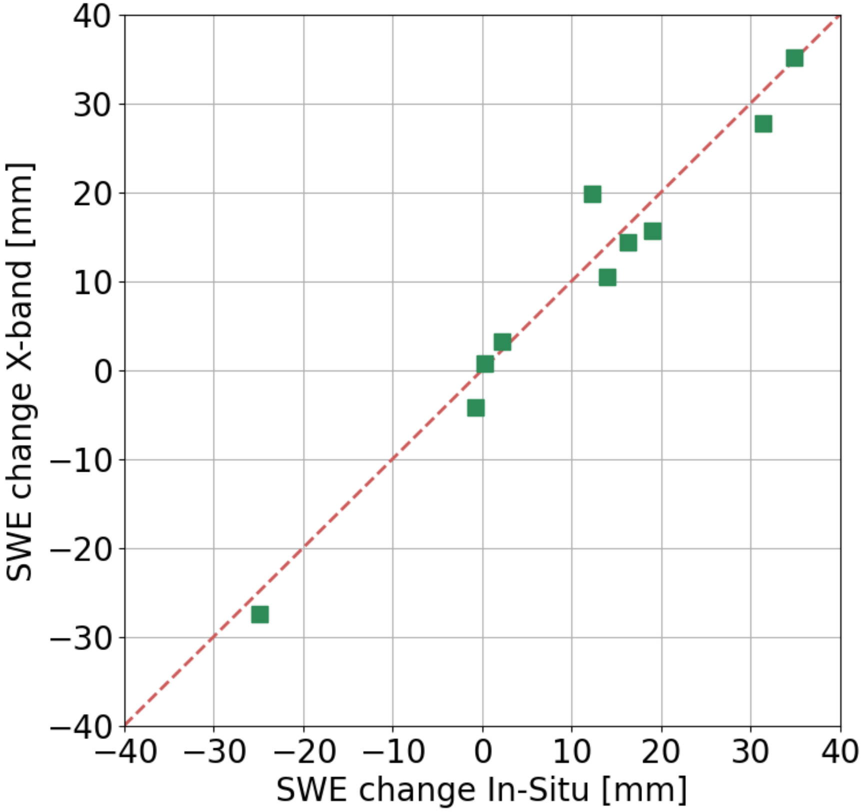
HH



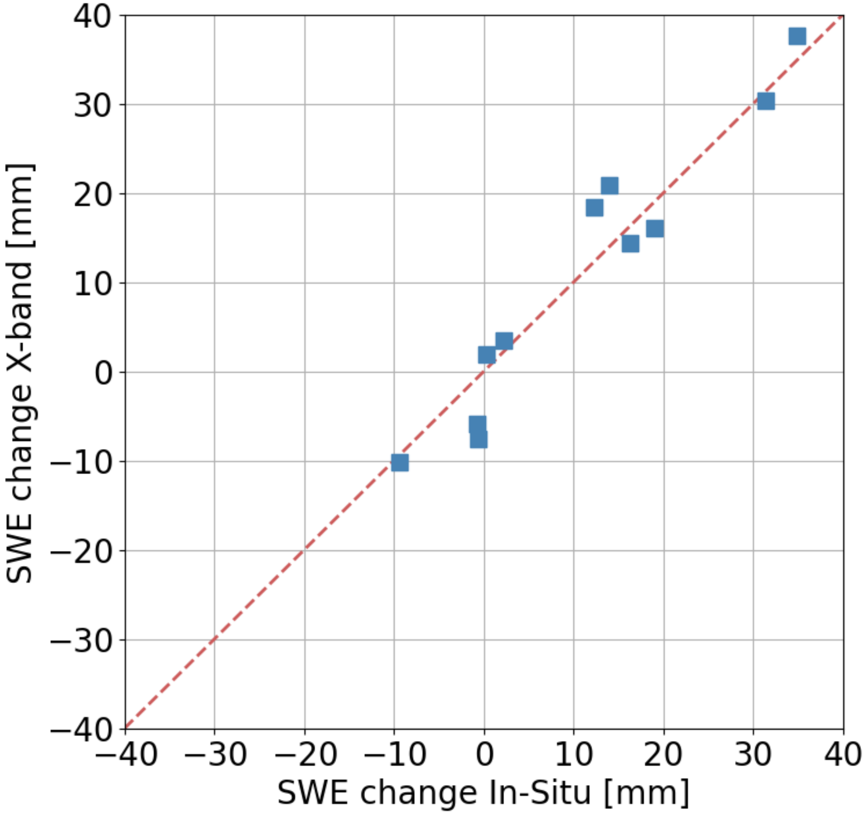
- $\Delta\Phi_s$ between [-π, π] → only limited range of SWE change can be retrieved using the X-band measurements
  - ~ [-8 mm, +8 mm]
- Underestimation of SWE changes above this threshold

SWE Estimation using DInSAR Phase – I. Correction In-Situ

VV

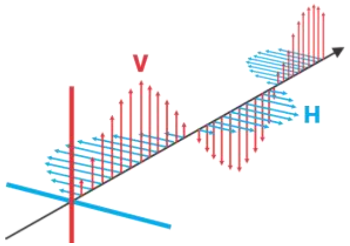


HH

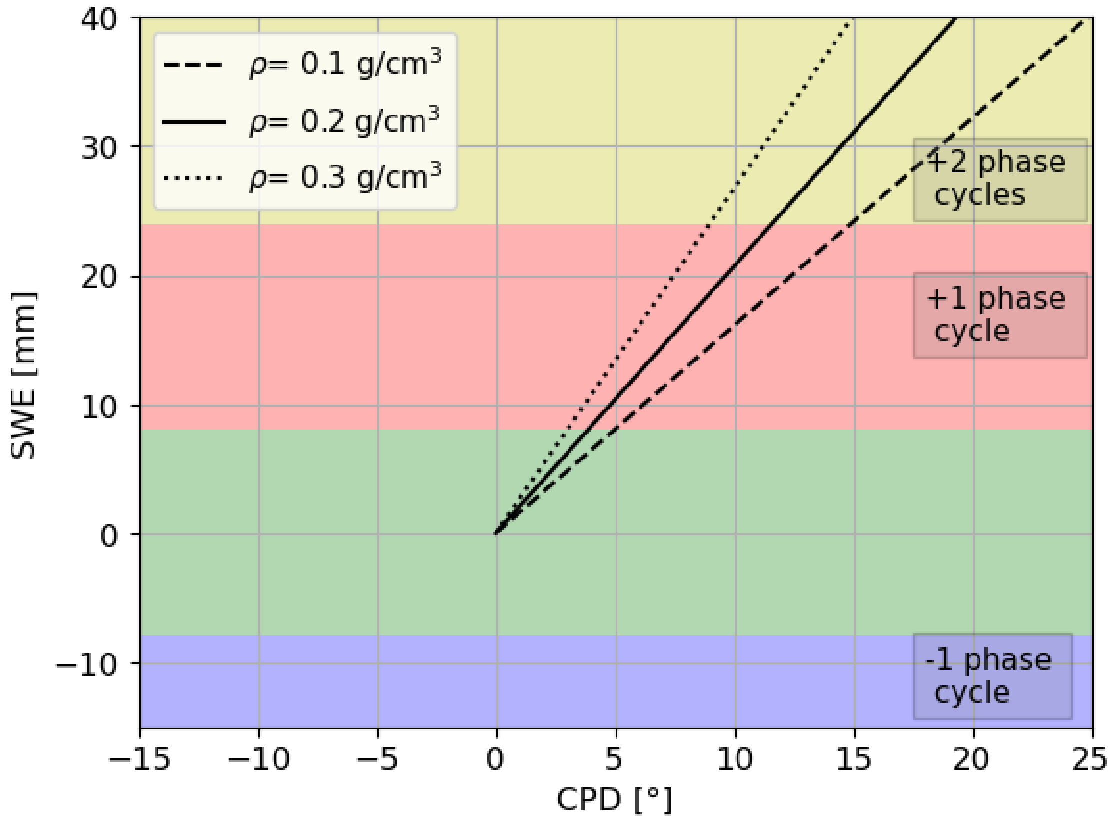


- In-Situ measurements used to check if SWE change lies above phase wrap threshold → if yes, phase cycle is added
- High agreement
- Phase wraps are one of the main limitations

SWE Estimation using DInSAR Phase – II. Correction Copol-Phase-Difference (CPD)



- CPD model to relate the CPD change between two measurements to the amount of fresh snow

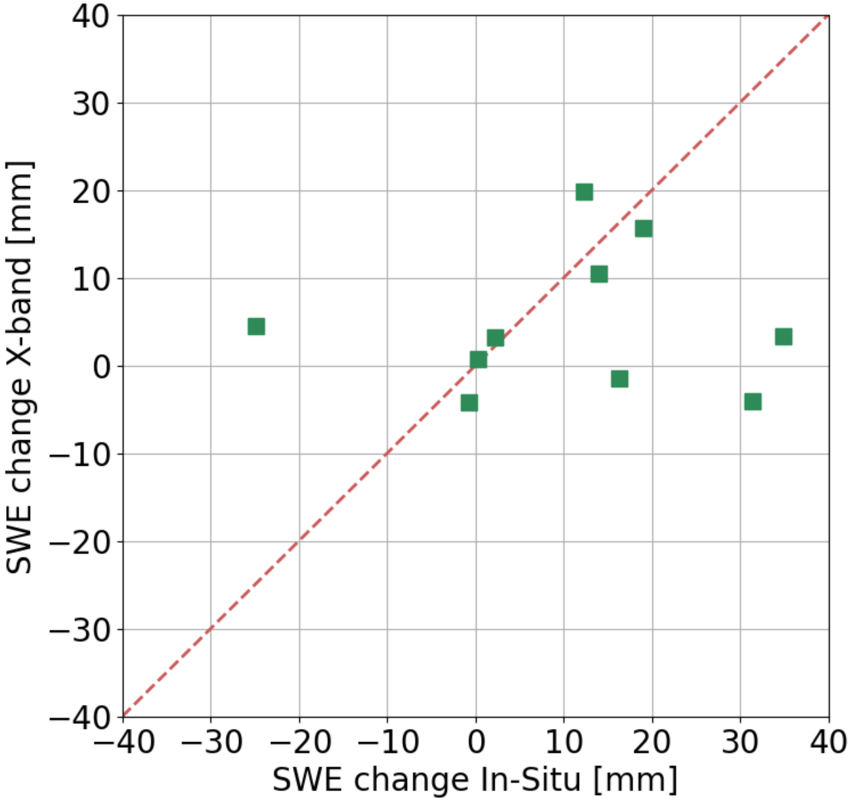


- Assuming A = 0.2 (fresh snow)

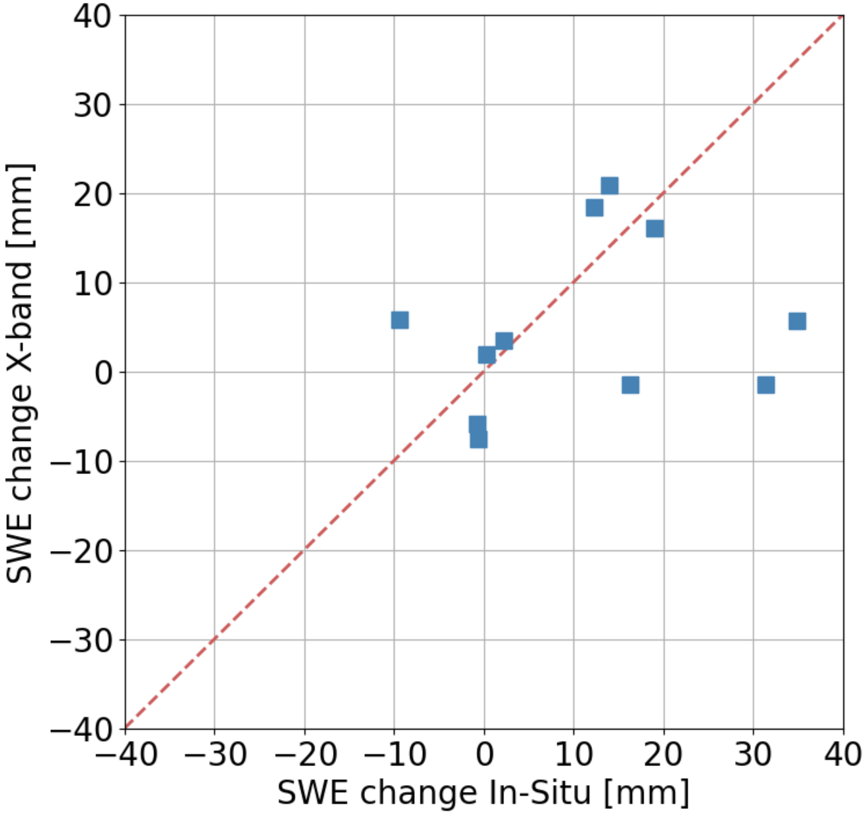
- Example CPD = 10°
  - For snow density of 0.1 and 0.2 g/cm3
    → 1 phase cycle needs to be added
  - For snow density of 0.3 g/cm3
    → 2 phase cycles need to be added

SWE Estimation using DInSAR Phase – II. Correction Copol-Phase-Difference (CPD)

VV



HH

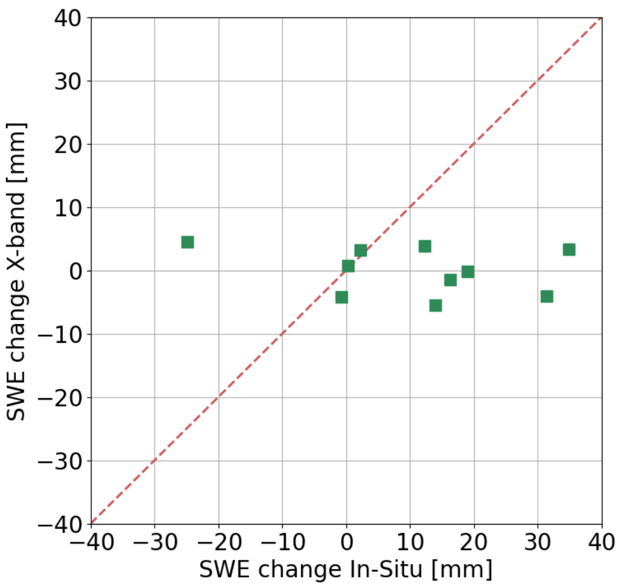


- CPD change used to check if SWE change lies above phase wrap threshold
  → if yes, phase cycle is added
- Higher agreement compared to no correction
- Not all measurements are corrected → snow metamorphism between measurements

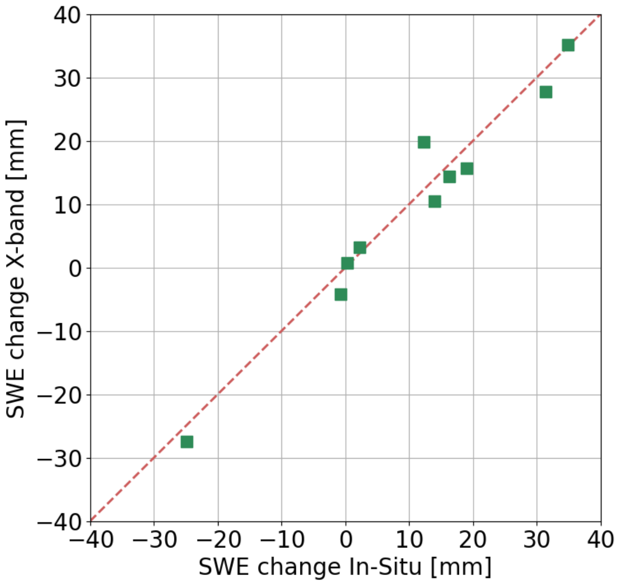
Summary

- **SWE retrieval results show a good** agreement with the ground measurements **after correcting the phase wraps**
- Phase wraps of the interferometric phase are one of the main limitations when using X-band measurements with 11 days temporal baseline
- **CPD model** can help to **predict some phase wraps**, but the performance is limited due to snow structure change between the measurements

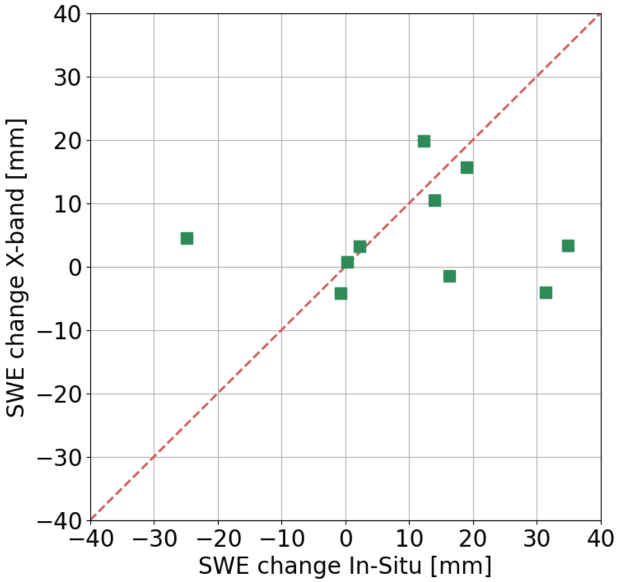
No correction



In-Situ



Copol-phase Difference (CPD)



Outlook

- So far: DInSAR and CPD were used separately
  → DInSAR Phase to estimate SWE
  → CPD to estimate snow depth

- CPD change has also an influence of the DInSAR phase in the VV and HH channel
  → Influence on DInSAR SWE estimation if snow microstructure changes between the acquisitions
  → Needs to be investigated

- Combination of different frequencies