Repeat Pass Interferometric and Polarimetric SAR Data for Snow Water Equivalent Retrieval

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FRINGE 2023, 12.09.2023

DLR

Motivation

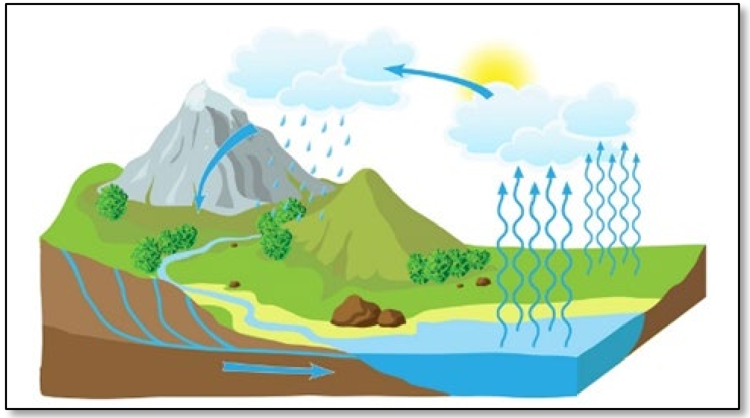
Snow Water Equivalent

- 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

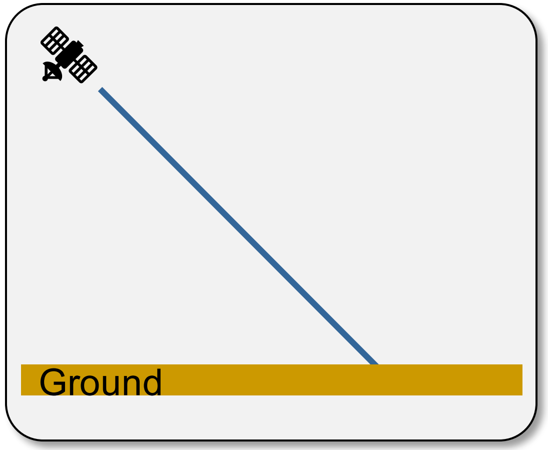
https://www.drax.com/about-us/our-sites-and-businesses/cruachan-power-station/

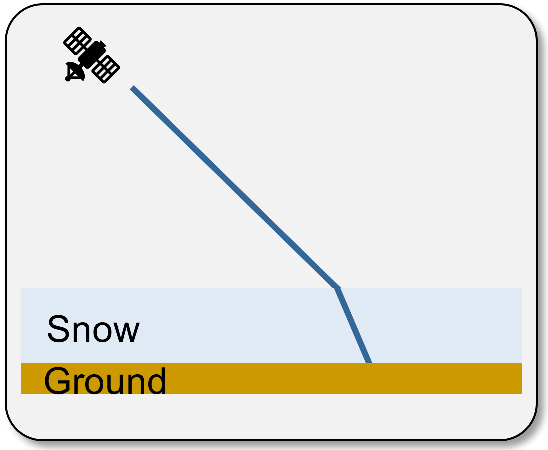
Flood predictions

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

DInSAR model for SWE Estimation

- Repeat pass SAR acquisitions

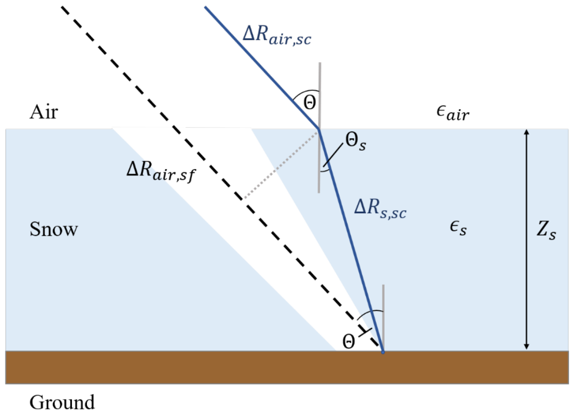




- Different dielectric properties in snow compared to air
  → Refraction of radar waves in the snow pack
  → Different optical path length for snow compared to no snow conditions

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

$$\Delta\Phi_s = -2\, k_i\, \Delta Z_s(\cos\Theta - \sqrt{\epsilon - \sin^2\Theta})$$

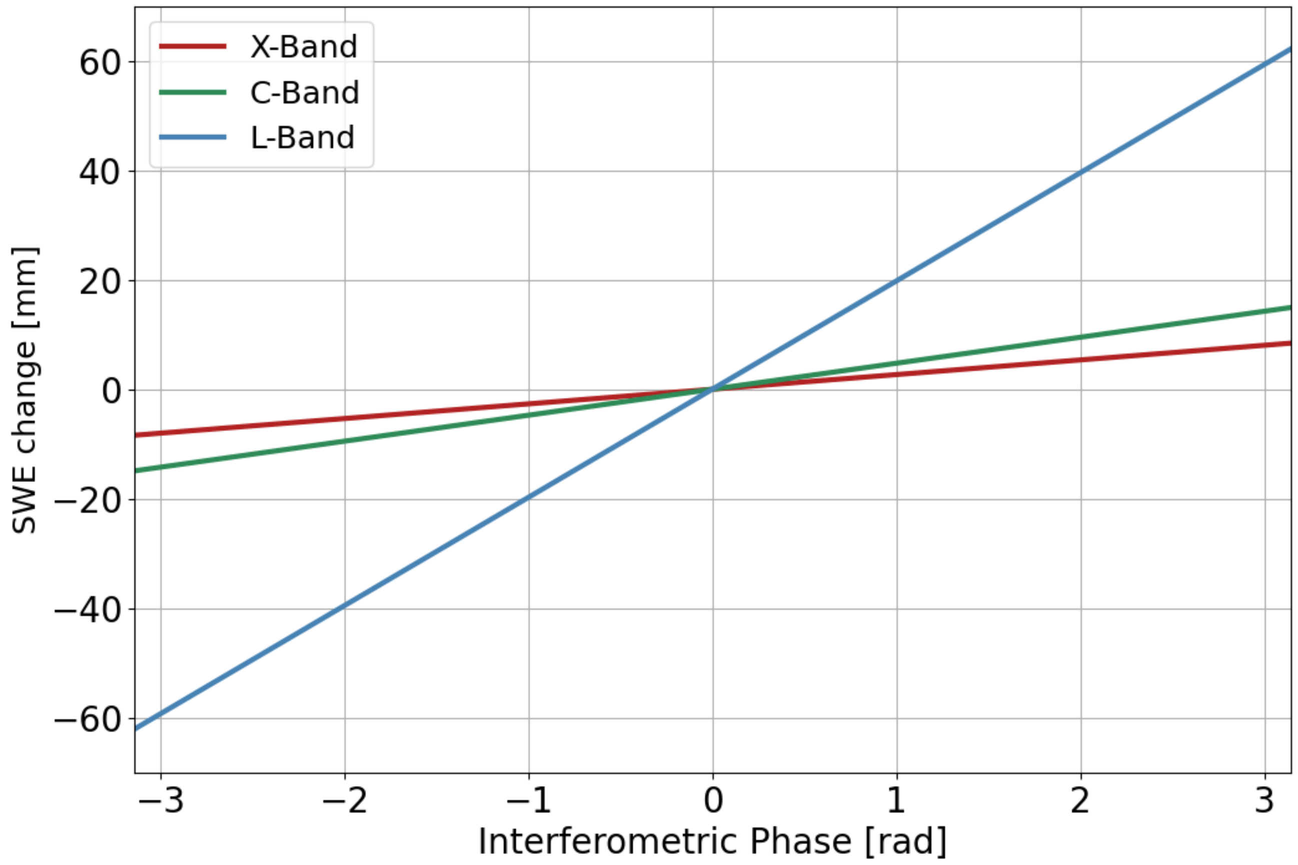


- Guneriussen et al.: InSAR for estimation of changes in snow water equivalent of dry snow, 2001
- Leinss et al.: Snow Water Equivalent of Dry Snow Measured by Differential Interferometry, 2015

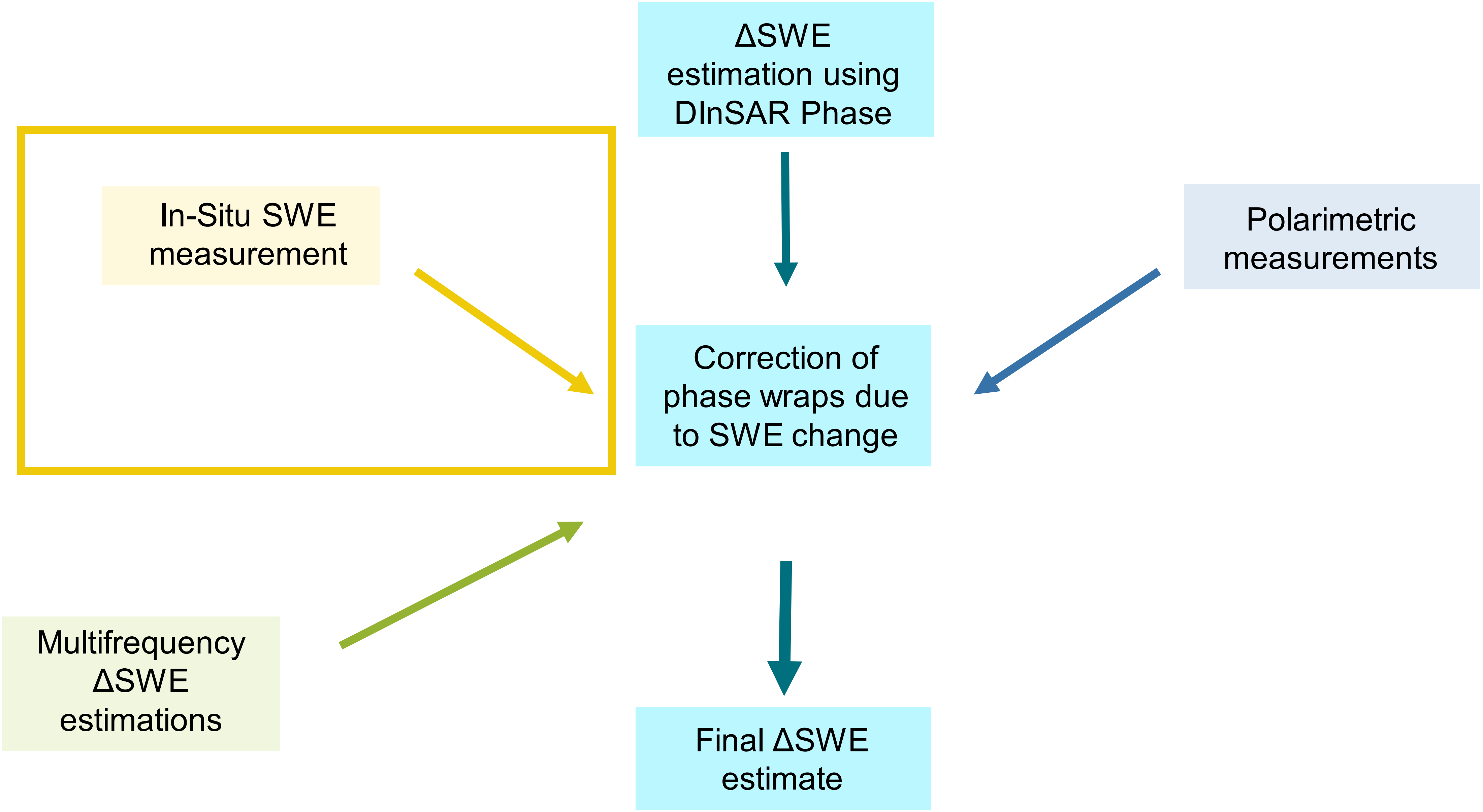
DInSAR model for SWE Estimation

Limitations

- Temporal decorrelation
- Phase calibration
- Different phase delay for different polarizations
- $\Delta\Phi_s$ between [-π, π] → outside this interval phase wrapping errors

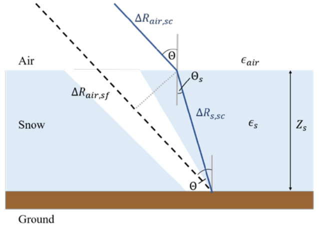


Methods



ΔSWE estimation using DInSAR Phase
In-Situ SWE measurement
Polarimetric measurements
Correction of phase wraps due to SWE change
Multifrequency ΔSWE estimations
Final ΔSWE estimate

SWE Estimation using DInSAR Phase

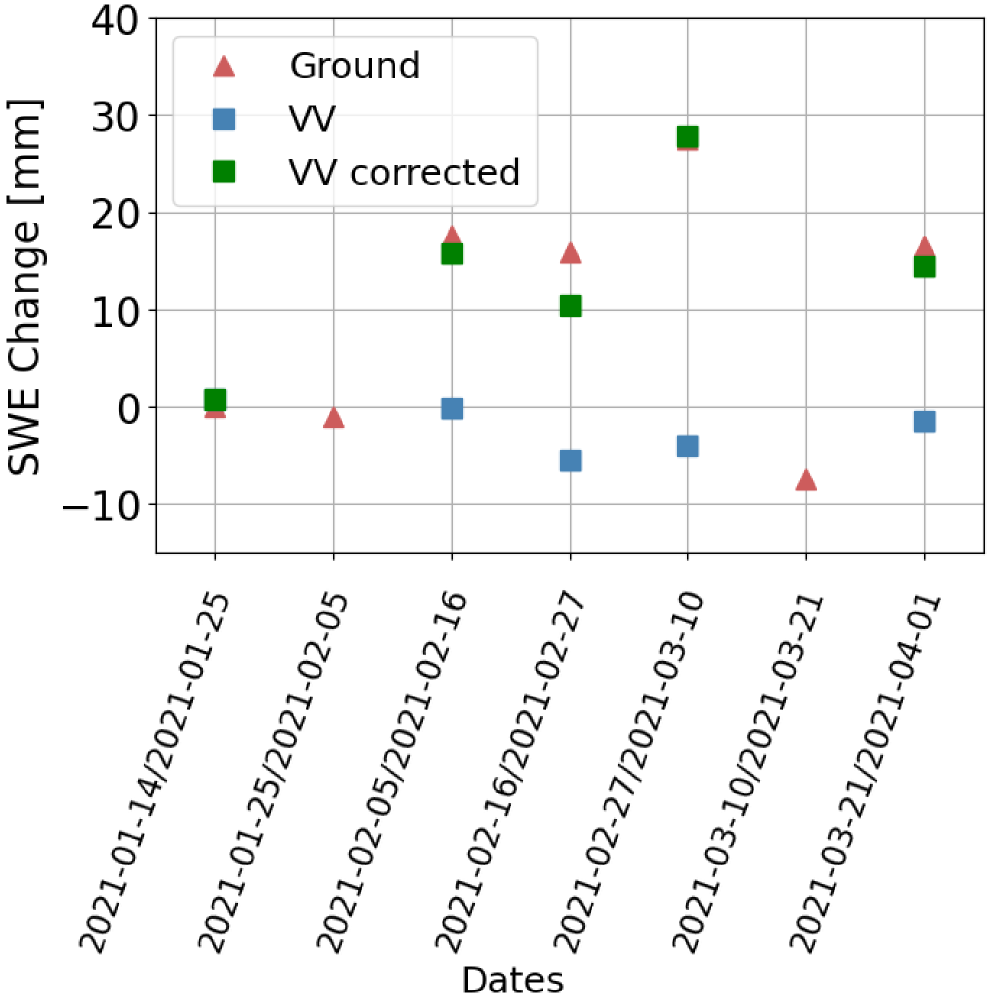


- Only limited range of SWE change can be retrieved using the X-band measurements → [-8 mm, +8 mm]

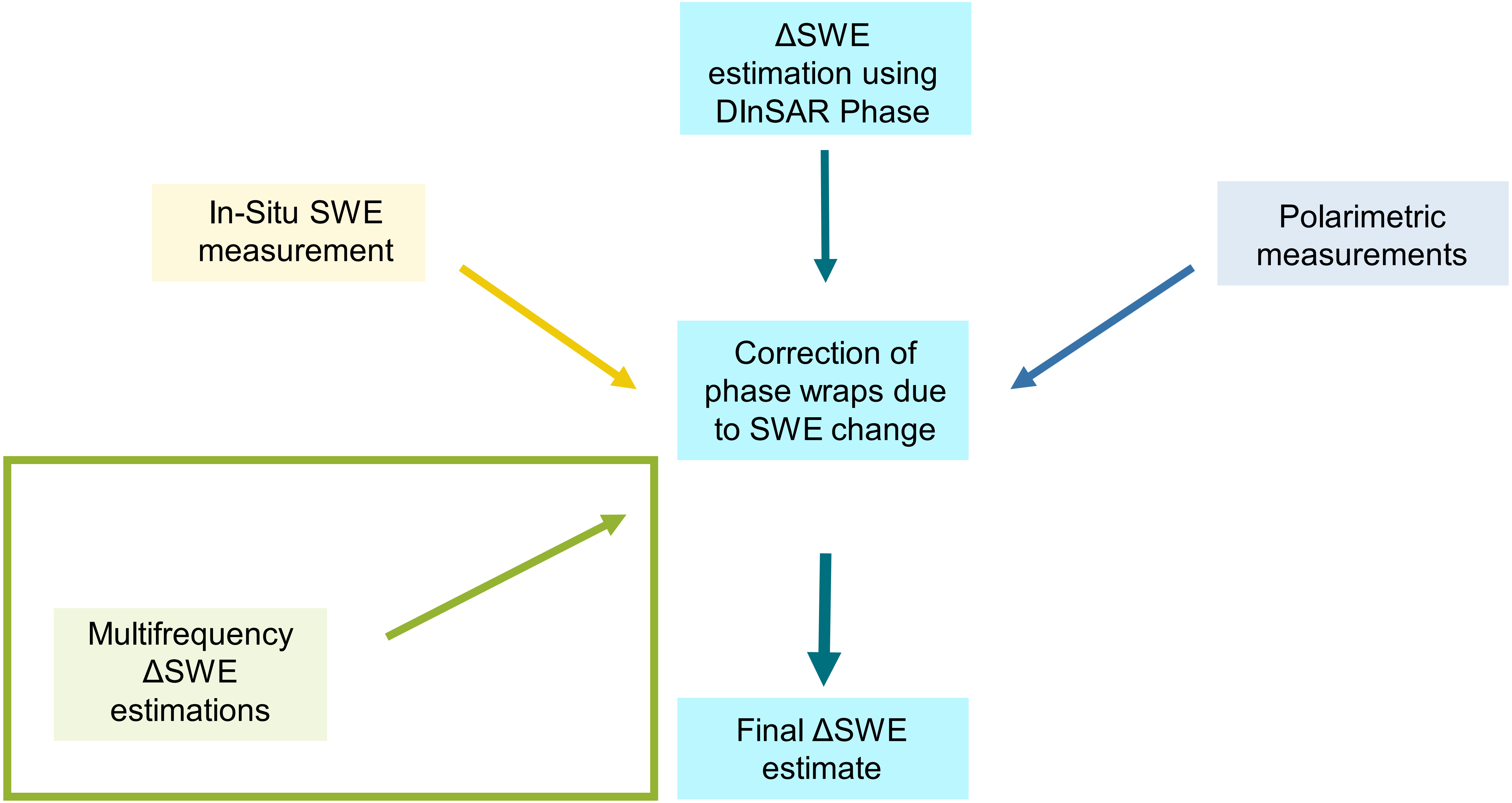
- Underestimation of SWE changes above this threshold

- In-Situ measurements used to check if SWE change lies above phase wrap threshold
  → if yes, phase cycle is added

- Phase wraps are one of the main limitations



Methods


ΔSWE estimation using DInSAR Phase
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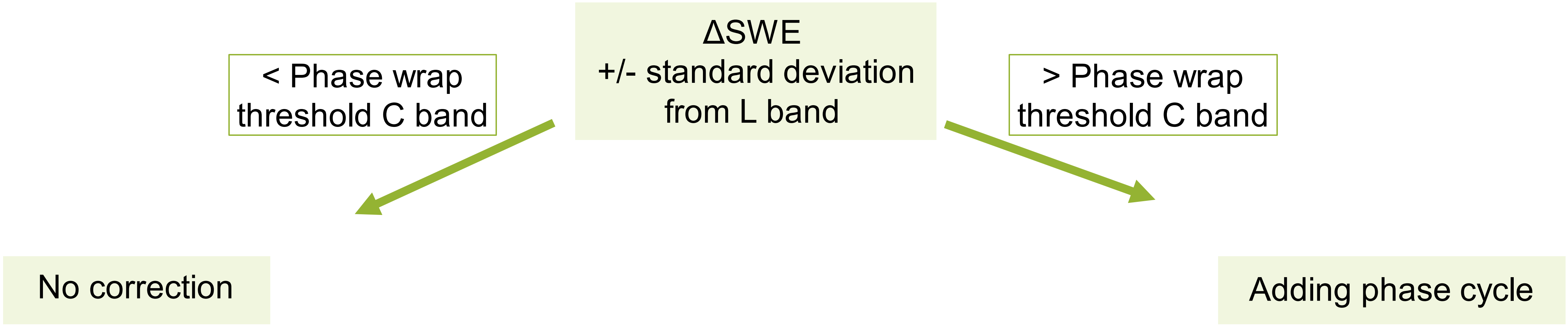
Multifrequency ΔSWE estimations
Final ΔSWE estimate

Multifrequency Approach for Phase Wrap Correction

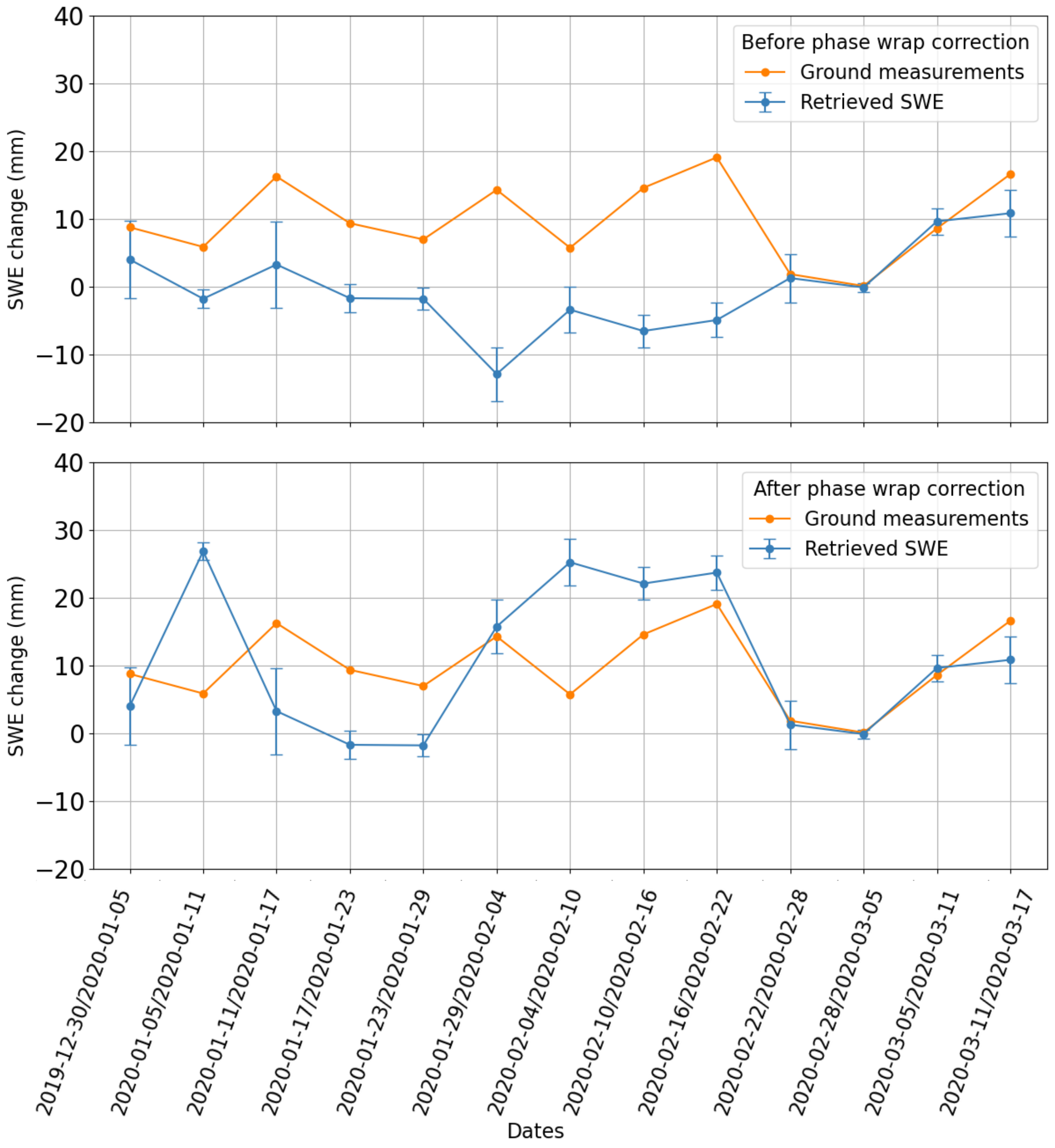
- ΔSWE estimates from longer wavelength (e.g. L band) are used to correct the ΔSWE estimates from shorter wavelength (e.g. C band)

Correction:



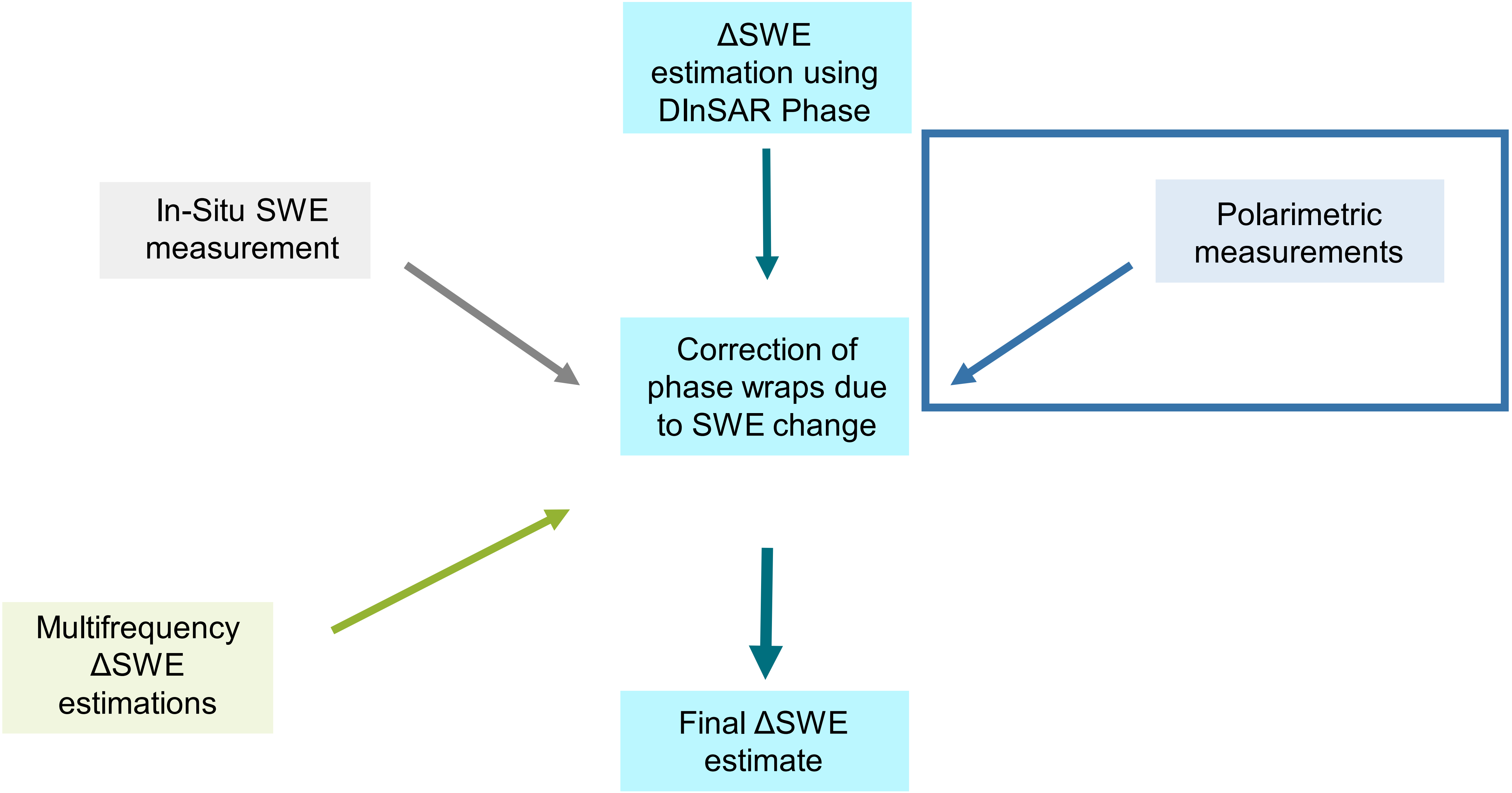
Multifrequency Approach for Phase Wrap Correction

- Sentinel 1 data is used to retrieve the SWE change
  → Multifrequency correction using ALOS 2 data



	RMSE (mm)
No correction	13.38
Multifrequency correction	10.09
In-Situ correction	9.66

Methods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PolSAR CPD model for Snow Depth Estimation

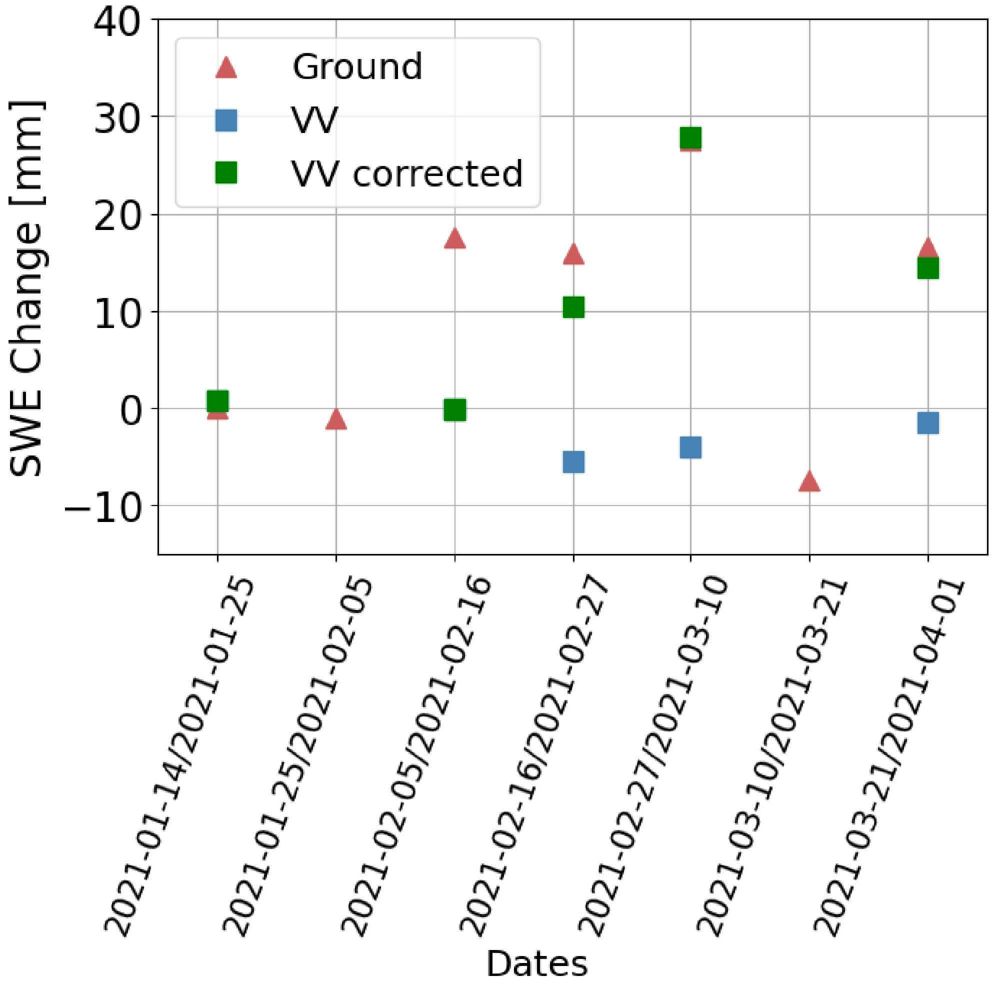
- Additional information about snow accumulation contained in co-polar-phase difference

$$\Phi_{CPD} = \Phi_{VV} - \Phi_{HH}$$

- Different polarizations show different propagation speeds in anisotropic snow

- Snow model: ellipsoidal ice inclusions in air
- Assumption of snow anisotropy and density → refractive indices for HH and VV

- Example TDX



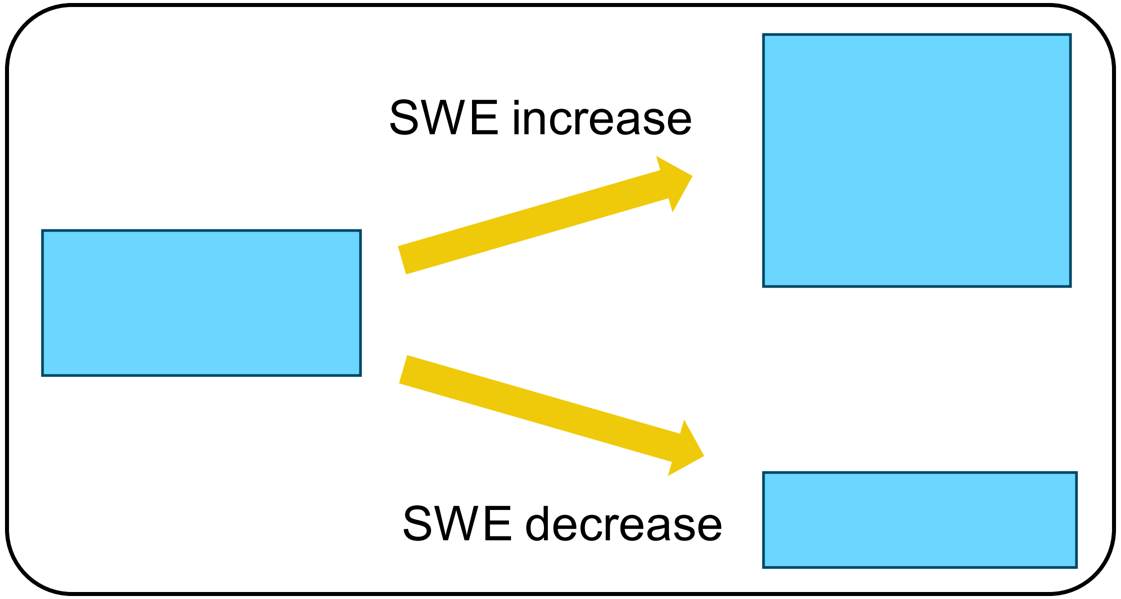
- Leinss et al., Snow Height Determination by Polarimetric Phase Differences in X-Band SAR Data, 2014
- Leinss et al., Anisotropy of seasonal snow measured by polarimetric phase differences in radar time series, 2016

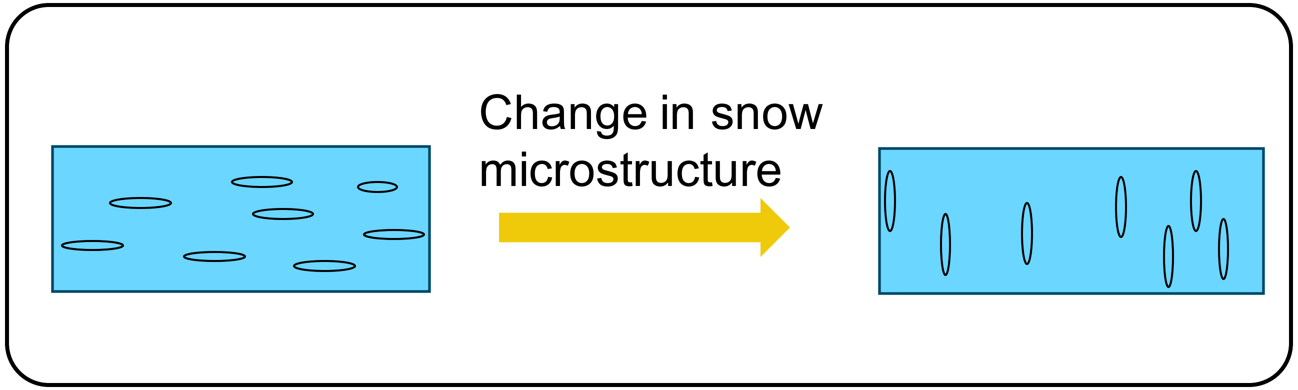
PolSAR CPD model for Snow Depth Estimation

Advantages

- Less sensitive to phase wraps
- No absolute phase calibration necessary

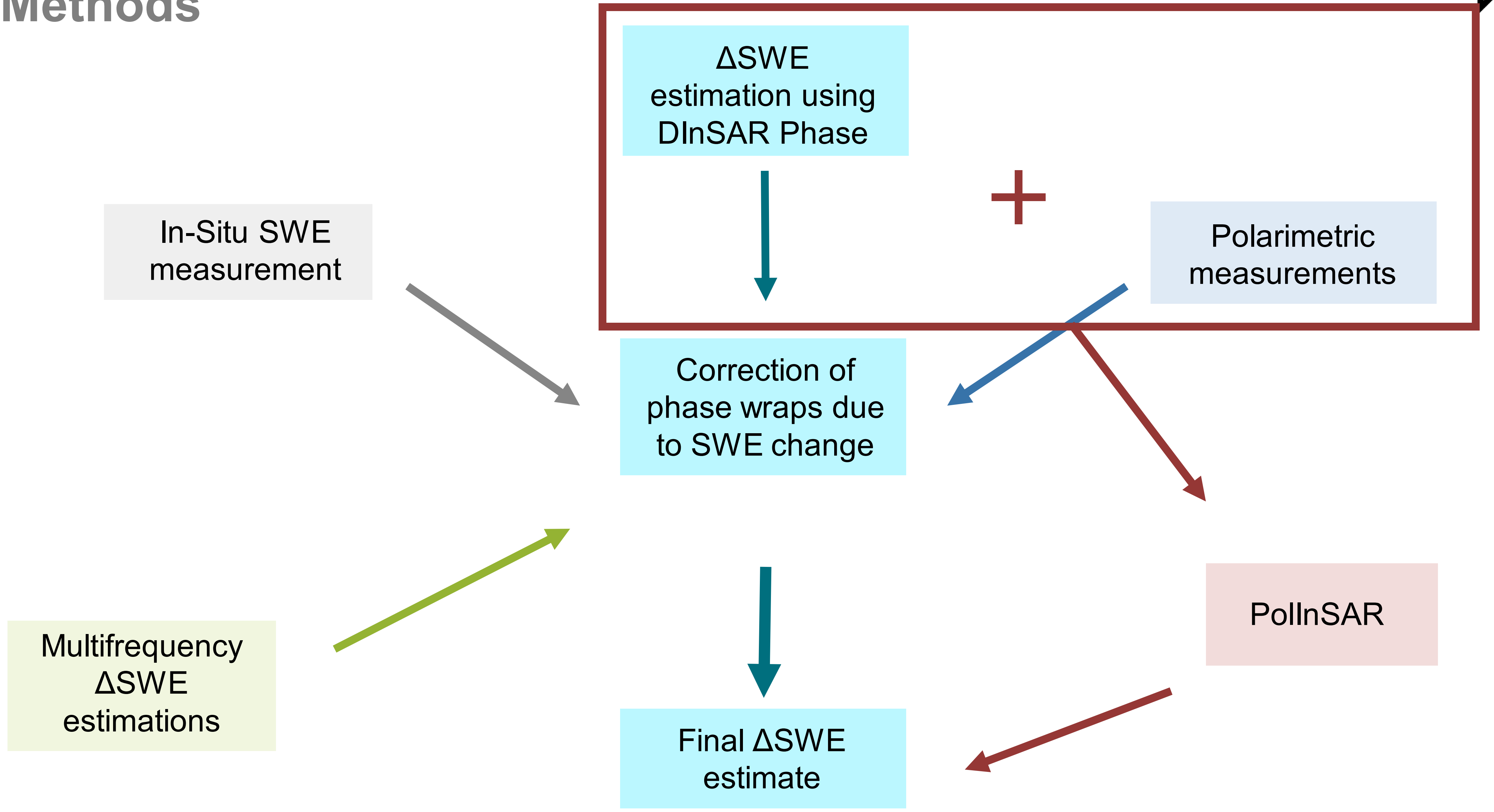
Limitation for InSAR and PolSAR





- Phase change obtained for SWE change and for anisotropy change → possible to separate these effects?

Methods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+
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PolInSAR
Final ΔSWE estimate

Combination of Interferometric and Polarimetric Measurements –Temporal Coherence Region

- Two PolSAR acquisitions

  → coherency matrices $\boldsymbol{T}_{11}$ and $\boldsymbol{T}_{22}$

  → temporal PolInSAR matrix $\boldsymbol{\Omega}_{12}$

- Temporal polarimetric coherence ρ

$$\rho(\omega_1, \omega_2) = \frac{\omega_1^H \boldsymbol{\Omega}_{12} \omega_2}{\sqrt{(\omega_1^H \boldsymbol{T}_{11} \omega_1)(\omega_2^H \boldsymbol{T}_{22} \omega_2)}}$$

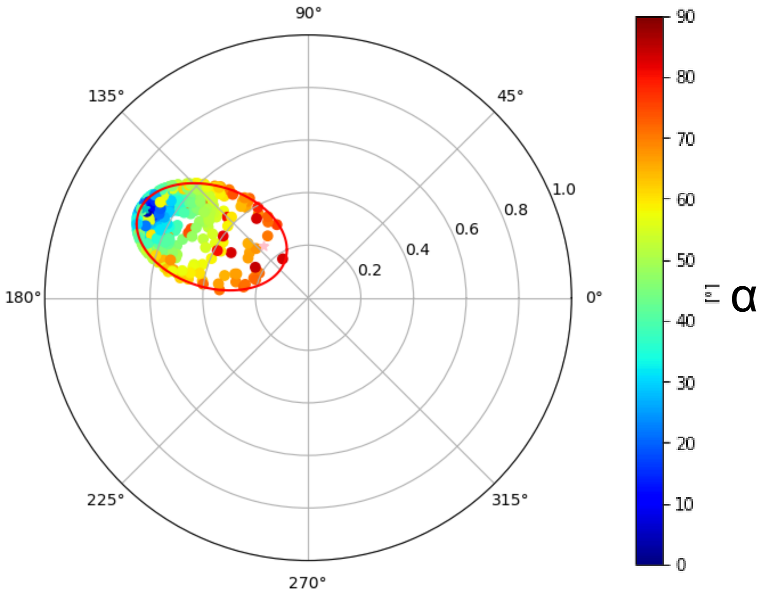
ω → unitary vectors of polarization states

TDX

27.02./10.03.

ΔSnow Depth = 17.4 cm

ΔSWE = 27.5 mm



Model Scattering Matrix

$[S_P] = [P_2][S][P_2]^T$

S: Scattering Matrix

P_2: Propagation Matrix

DInSAR model

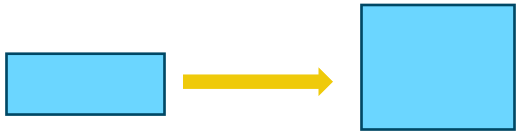
CPD model

Jun Ni et al., Multitemporal SAR and Polarimetric SAR Optimization and Classification: Reinterpreting Temporal Coherence, 2022

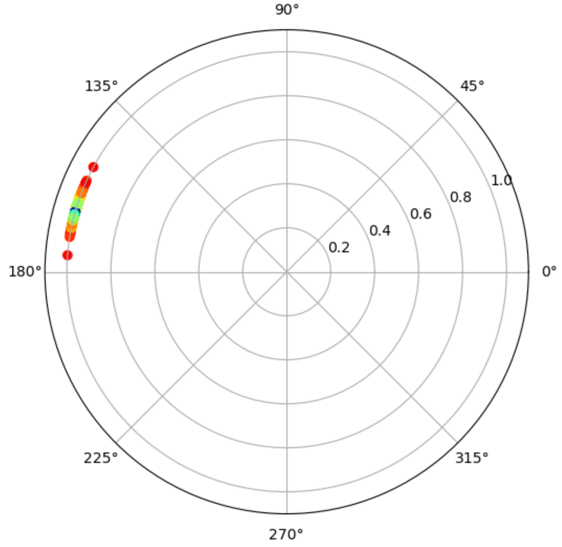
Temporal Coherence Region

X band

SWE Increase

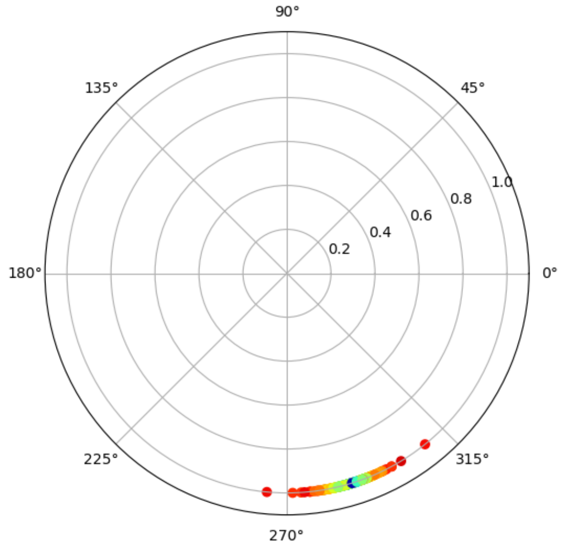


Δr = 4cm



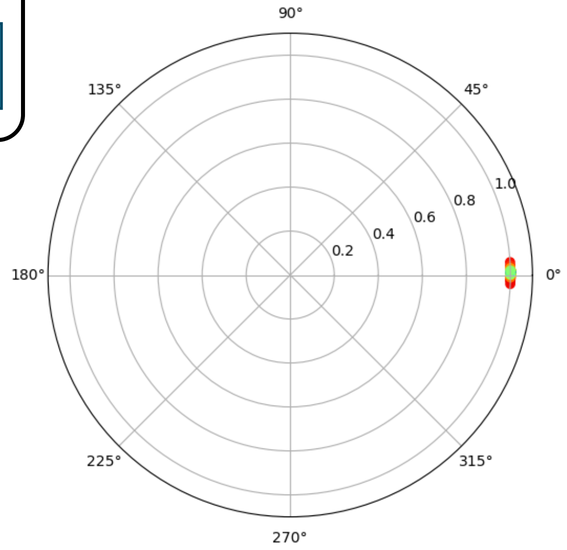
- A = 0.2
- $\rho = 0.2\,\frac{g}{cm^3}$
- R1 = 1 cm

Δr = 7cm



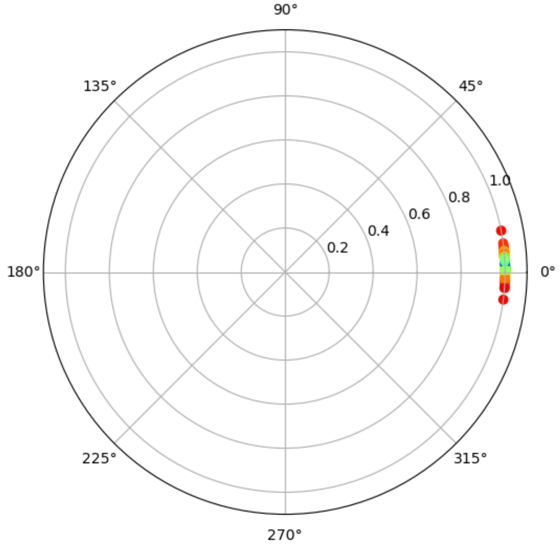
Anisotropy change

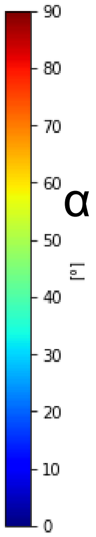
ΔA = 0.1



- r = 2 cm
- $\rho = 0.2\,\frac{g}{cm^3}$
- A1 = 0.1

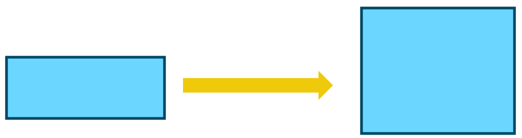
ΔA = 0.3





DInSAR phase and polarimetric phase change

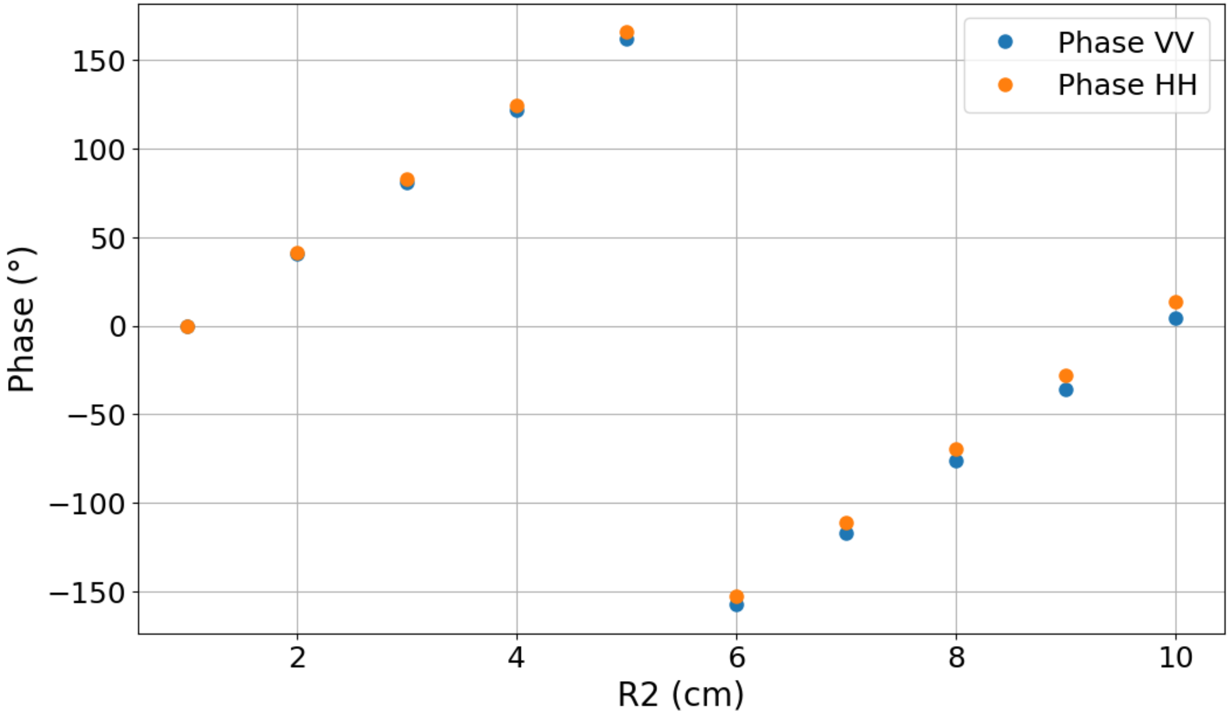
SWE Increase



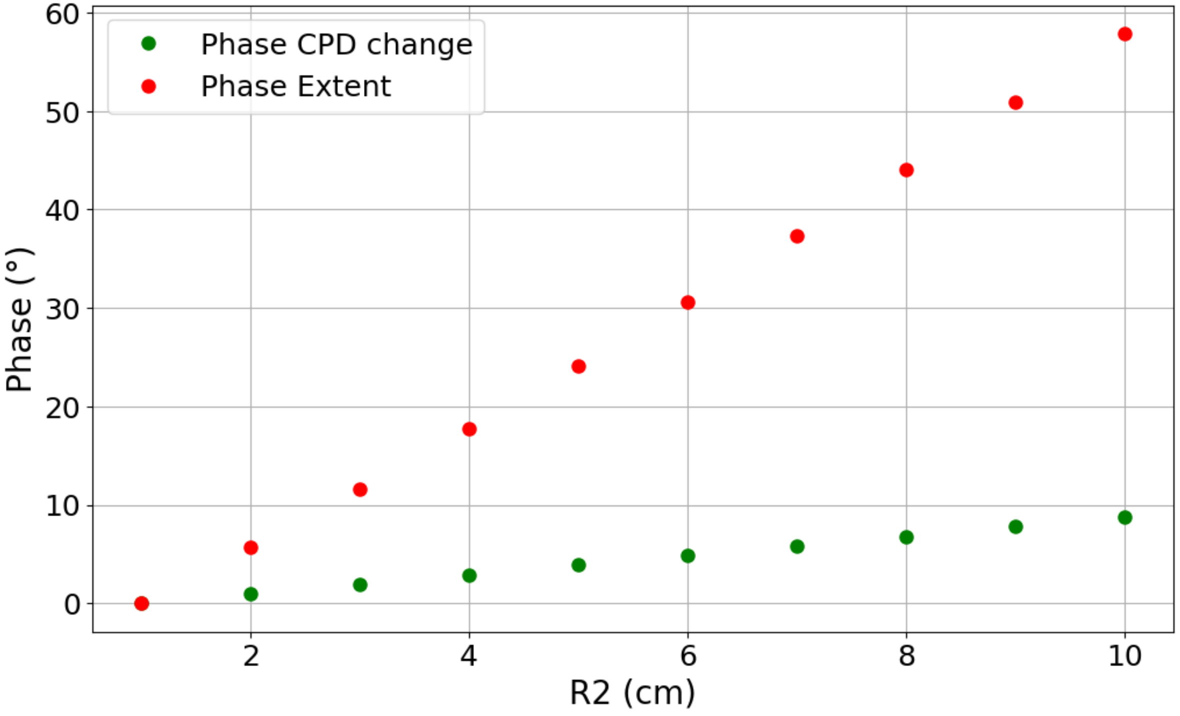
X band

- R1 = 1 cm
- R2: snow depth at 2. acquisition

Interferometric Phase



Polarimetric Phase



- Phase wrap can be observed
- Increasing difference between VV and HH

- Phase extent yields higher values than CPD change

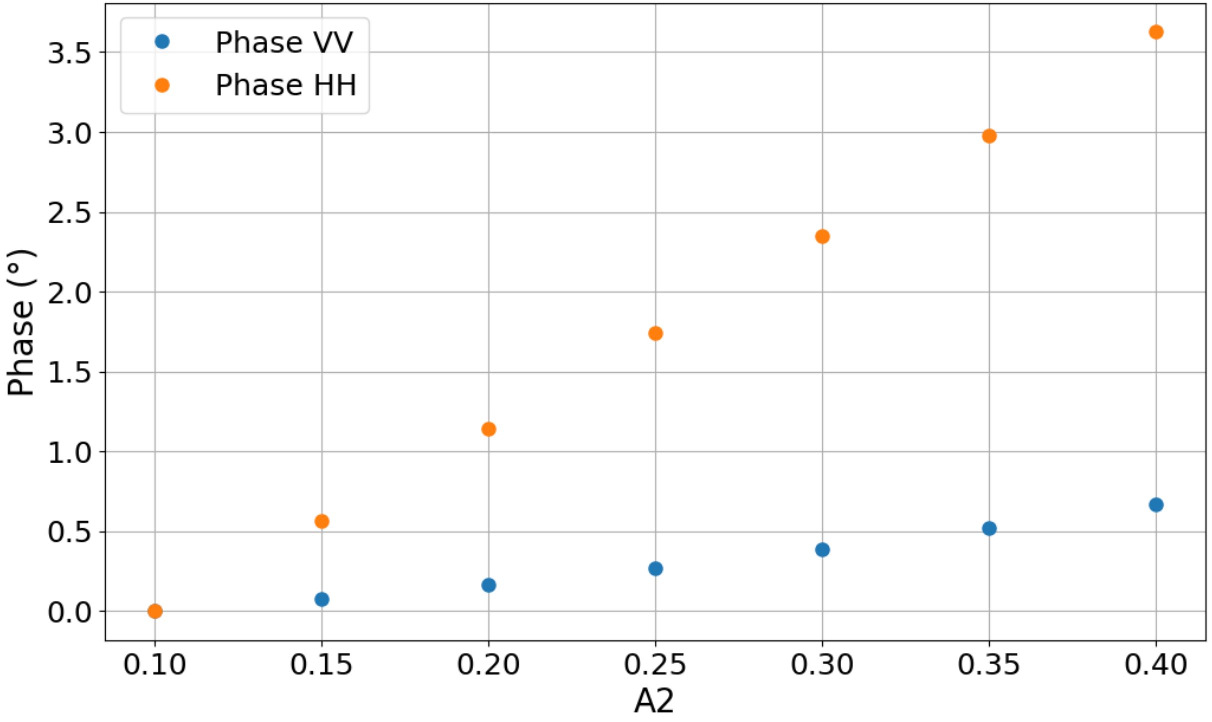
DInSAR phase and polarimetric phase change

Anisotropy change

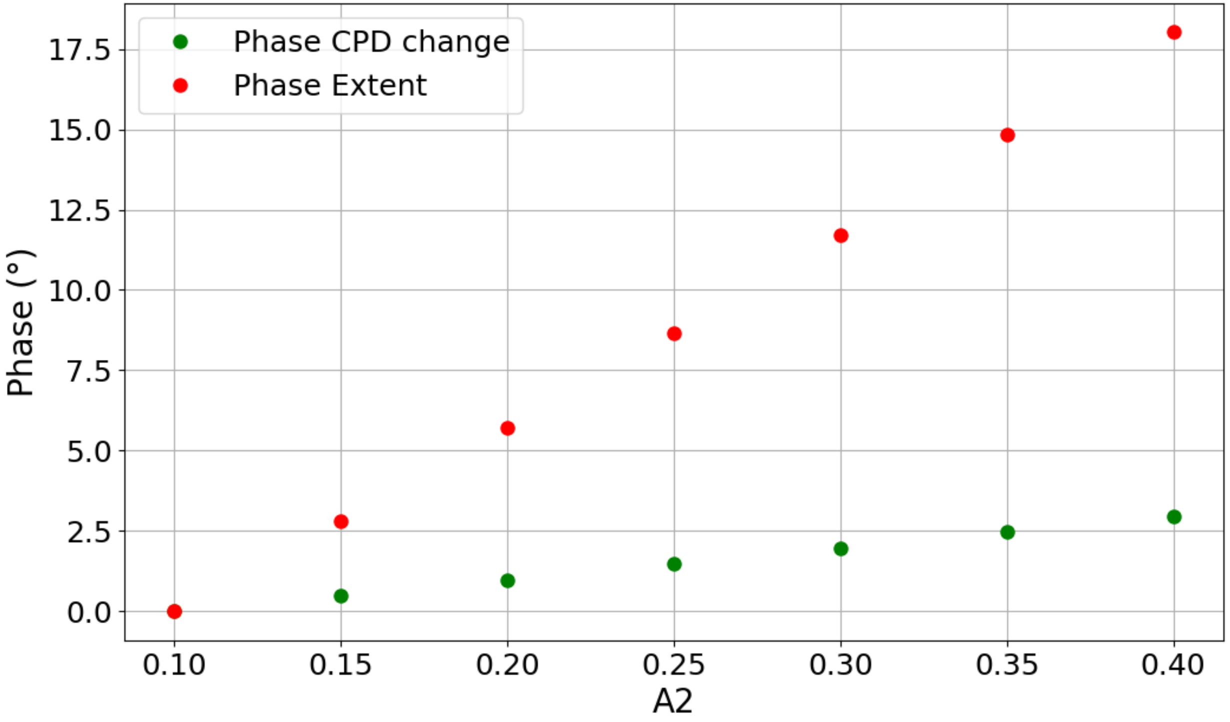
X band

- A1 = 0.1
- A2: anisotropy at 2. acquisition

Interferometric Phase



Polarimetric Phase



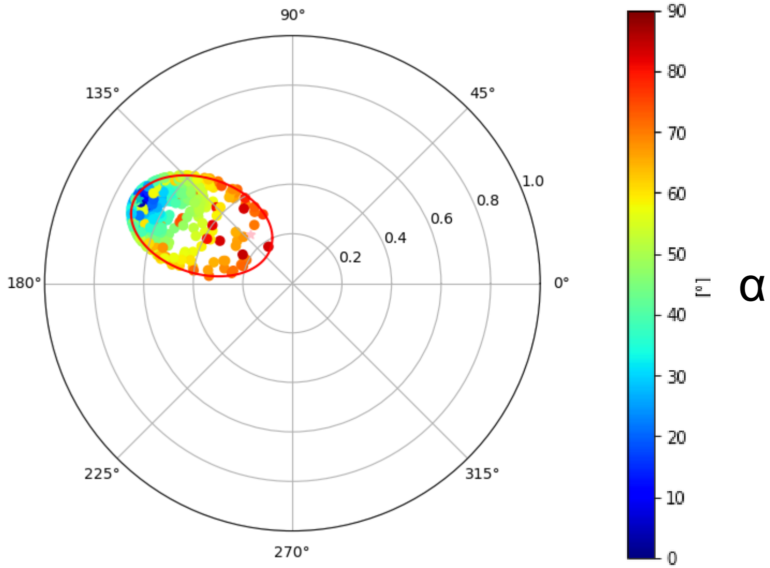
- Increasing difference between VV and HH
- Similar behavior as for snow depth change

Temporal Coherence region

TDX

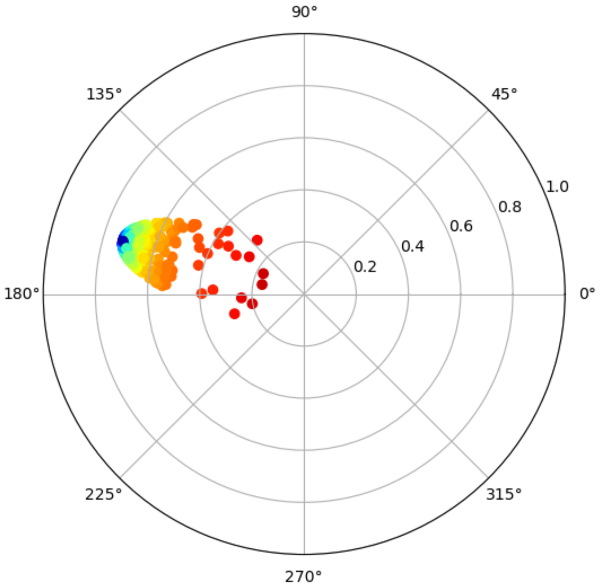
27.02./10.03.

ΔSnow Depth = 17.4 cm
ΔSWE = 27.5 mm



Model

- A = 0.1



- Include decorrelation effects
  - Temporal decorrelation [1]
  - $|\gamma_{temp}| \approx 0.75$
  - SNR decorrelation
  - Noise: -10dB

[1] Helmut Rott et al., Snow Mass Retrieval by Means of SAR Interferometry, 2003

Summary and Outlook

Summary

- Multifrequency and polarimetric approach promising for phase wrap correction
- Phase extent of D-PolInSAR higher sensitivity than CPD
- Modeling of coherence regions for snow depth and anisotropy changes shows similar behavior as real data

Next Steps

- Not yet possible to separate anisotropy and snow depth change

  → Further investigation of the influence of snow changes on different polarization states
- Establishment of a retrieval based on coherence region parameters