TOWARDS SNOW WATER EQUIVALENT RETRIEVAL USING INTERFEROMETRIC AND POLARIMETRIC SAR DATA

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[1]Microwaves and Radar Institute, German Aerospace Center

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DLR

Motivation

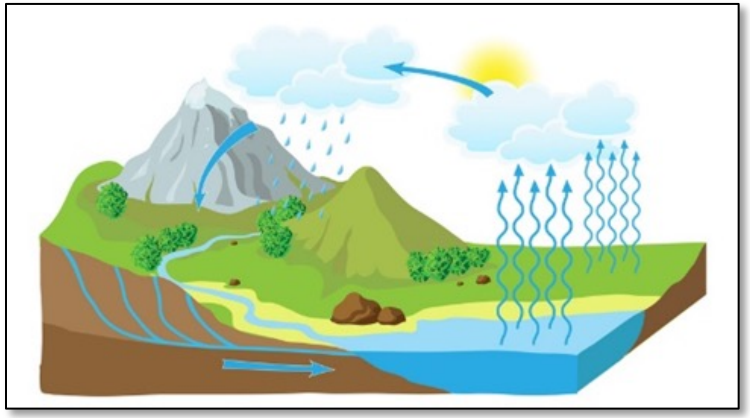
Snow Water Equivalent

- 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

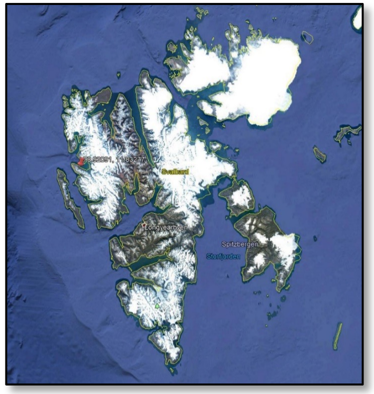
Water resource planning

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

SAR data and test site

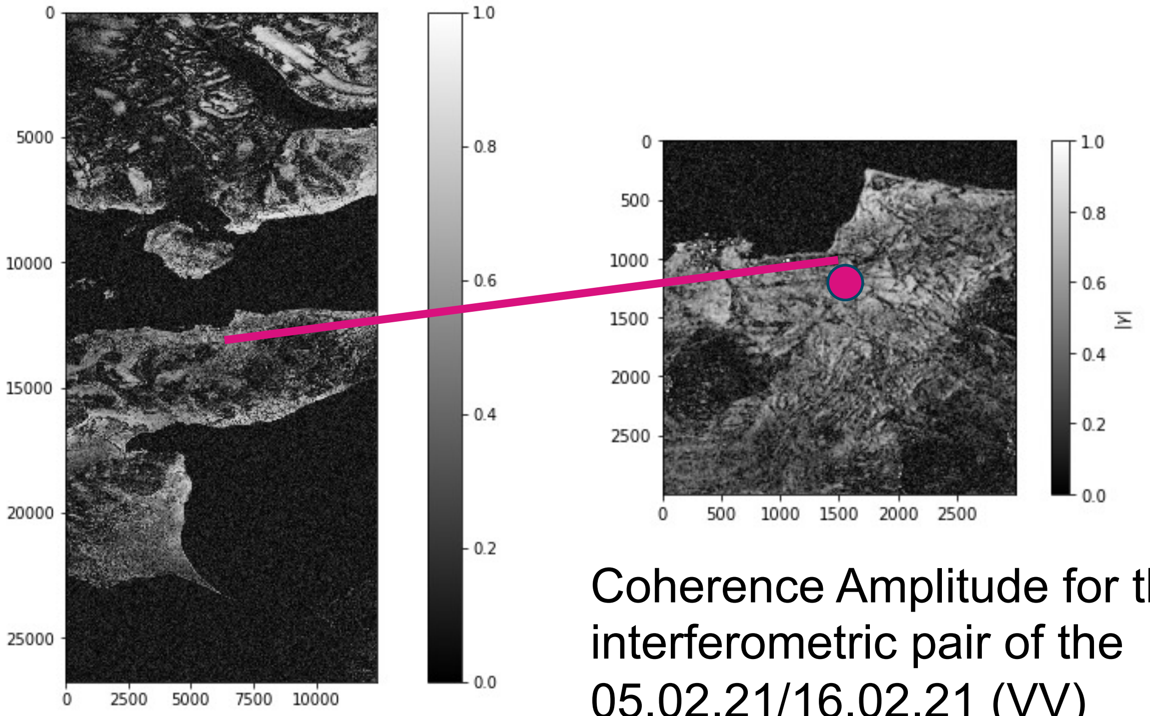


SAR

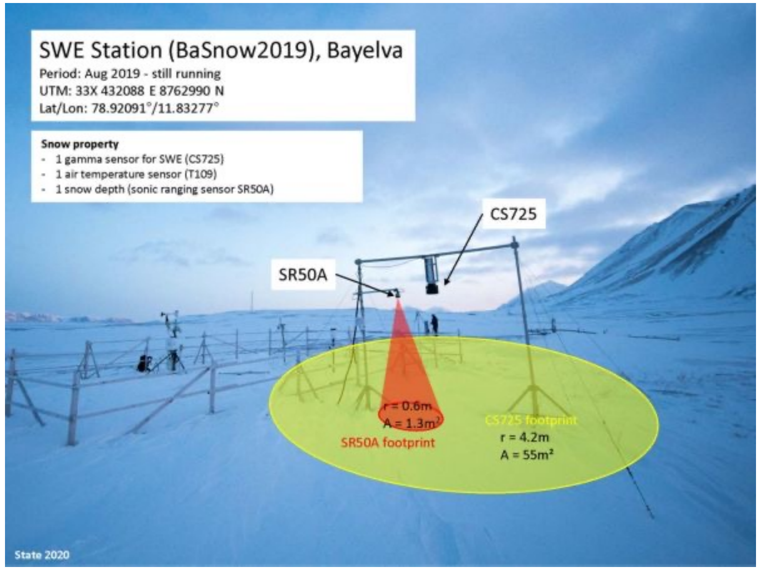
- TanDEM-X (TDX), X band
- Dual polarized data: HH and VV polarization
- Temporal baseline 11 days

In-situ measurements

- SWE measurements with a passive gamma ray sensor since 2019
- Temporal resolution: 6 hours



Coherence Amplitude for the interferometric pair of the 05.02.21/16.02.21 (VV)



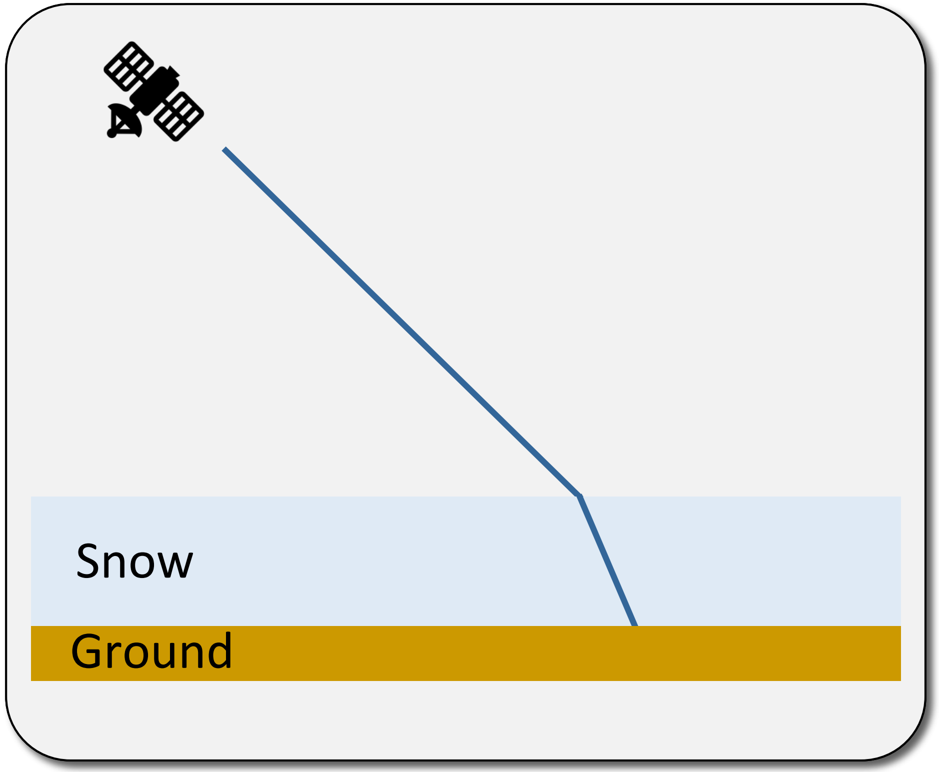
Jentzsch, K. , Bornemann, N. , Cable, W. , Gallet, J. C. , Lange, S. , Westermann, S. and Boike, J. (2020): Near real-time observations of snow water equivalent for SIOS on Svalbard – (SWESOS) , doi: 10.5281/zenodo.4146835

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

- Only dry snow

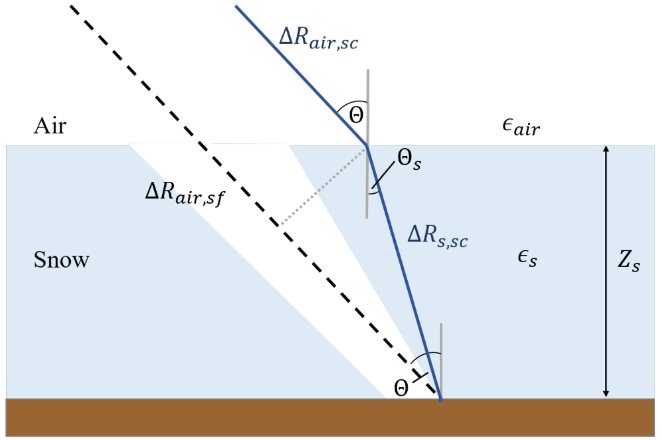


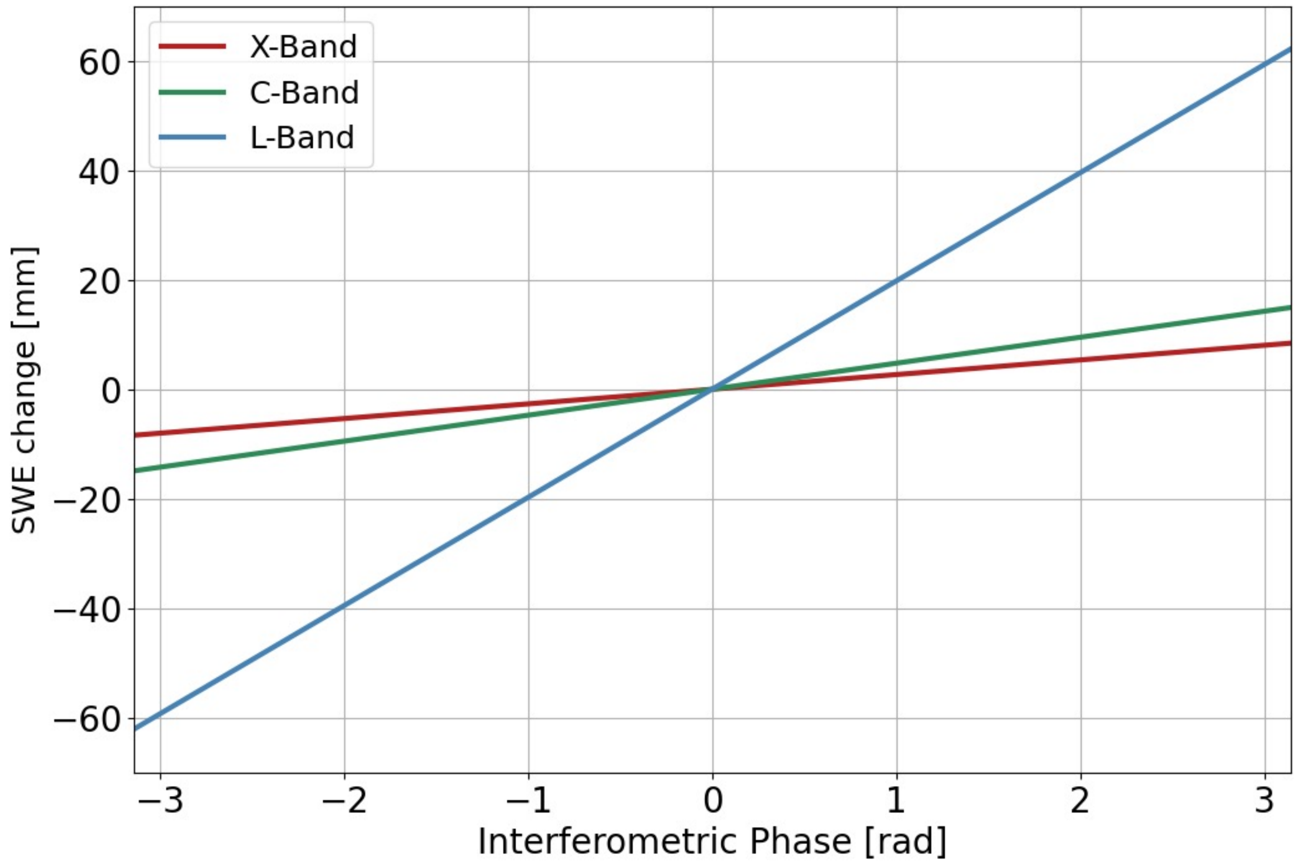
DInSAR model for SWE Estimation

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

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

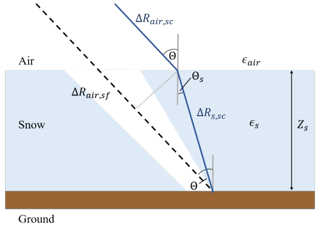
$$\Delta\Phi_s = -2\,k_i\,\Delta Z_s(\cos\Theta - \sqrt{\epsilon - \sin^2\Theta})$$





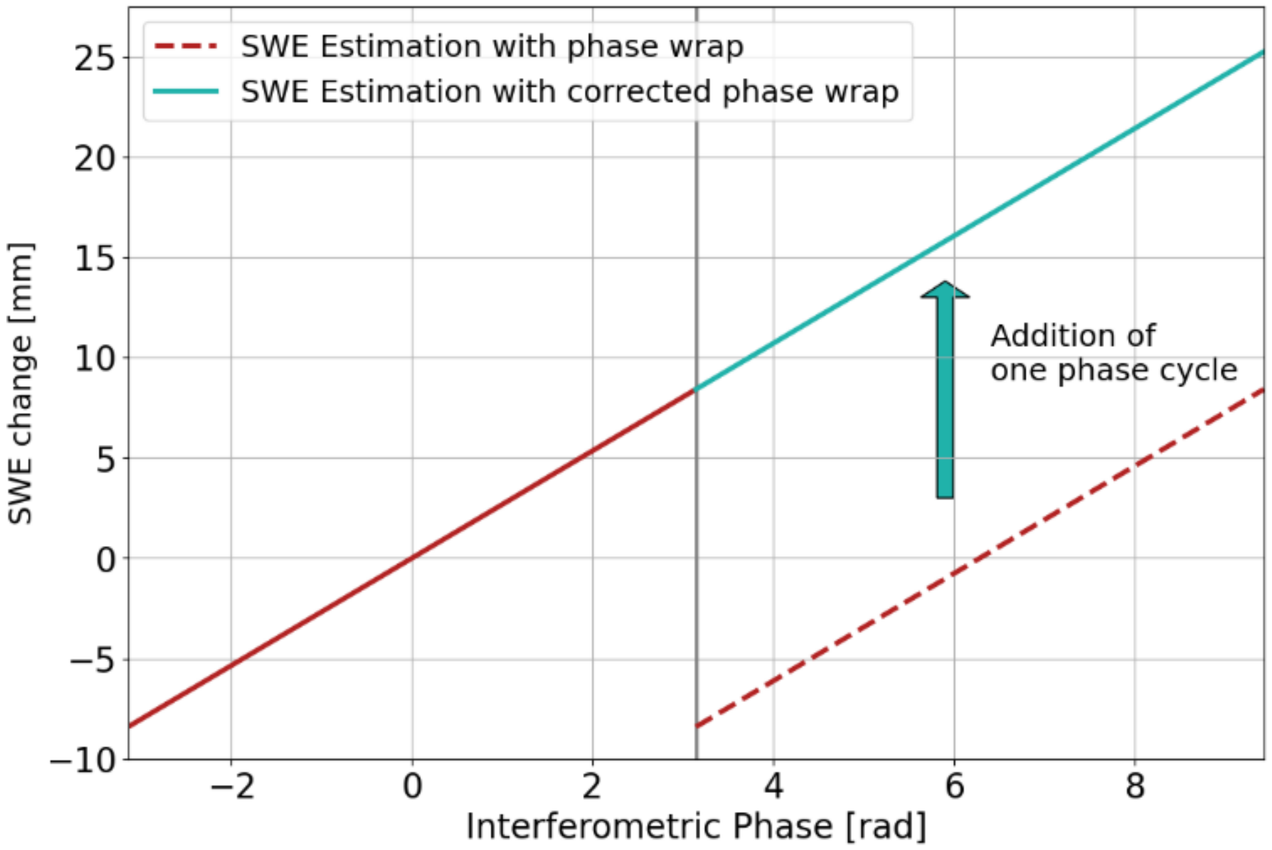
S. Leinss et al.: Snow Water Equivalent of Dry Snow Measured by Differential Interferometry , 2015

DInSAR model for SWE Estimation

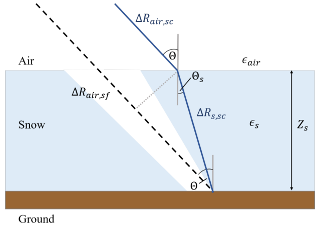


Limitations

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



SWE Estimation using DInSAR Phase



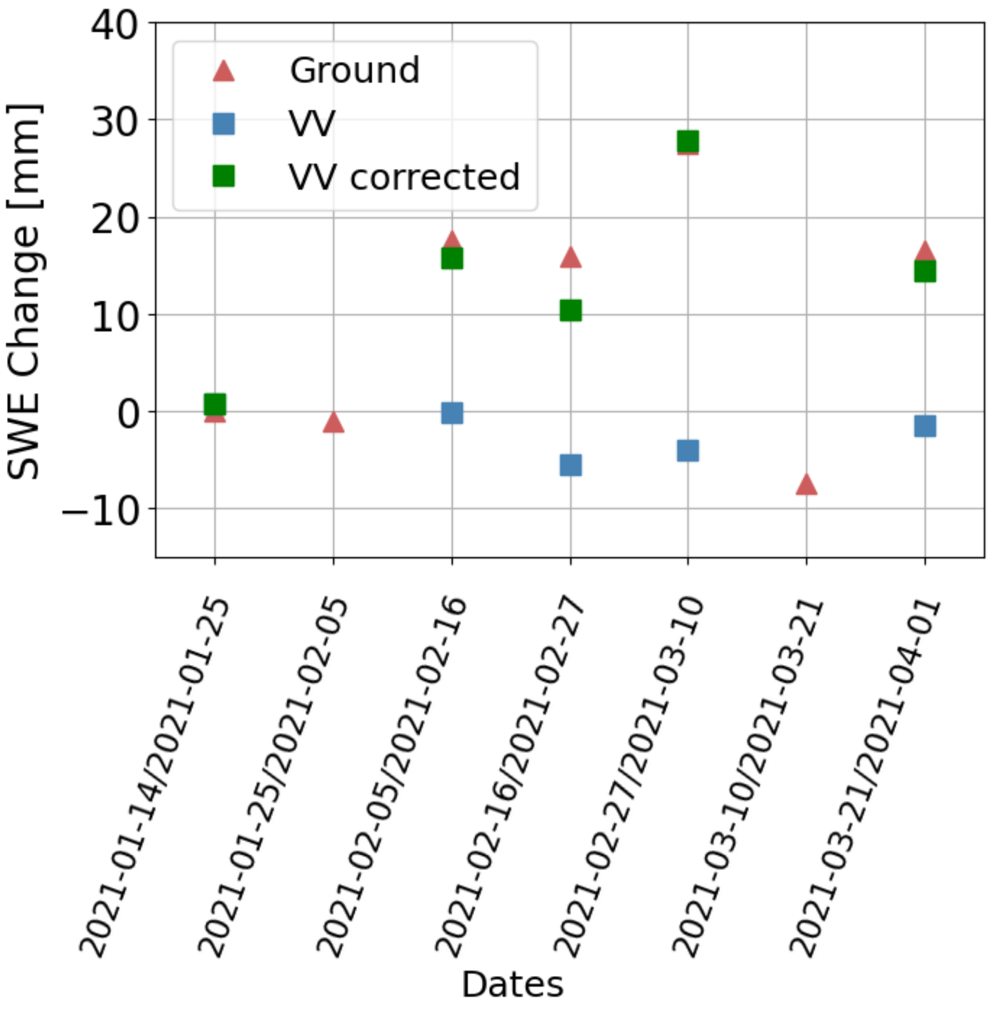
- Only limited range of SWE change can be retrieved using the X-band measurements → [-8 mm, +8 mm]

- 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

Idea Inclusion of polarimetric measurements for phase wrap corrections

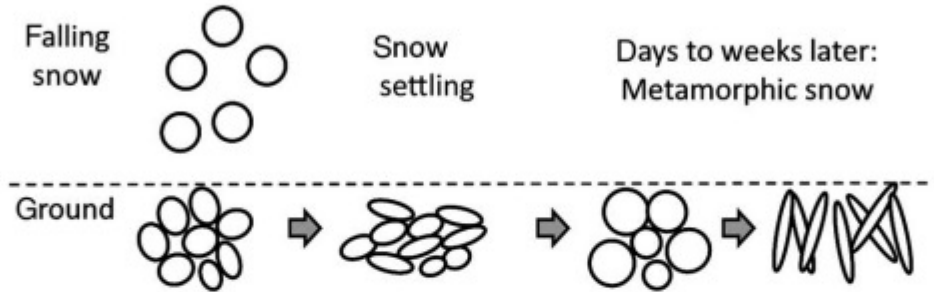


PolSAR CPD model for Snow Depth Estimation

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

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

- Different polarizations show different propagation speeds in anisotropic snow



- Fresh snow → more horizontally aligned ice grains → increasing CPD values

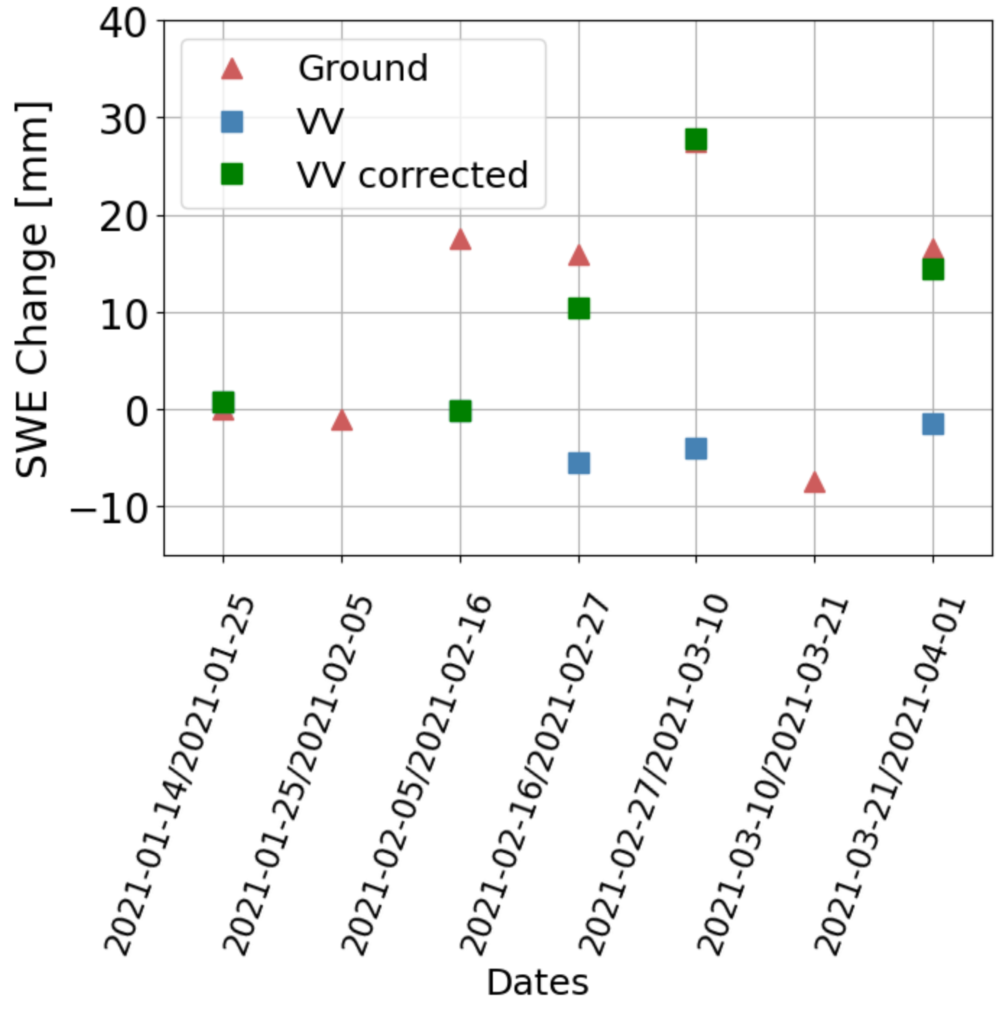
- Decreasing CPD values due to recrystallisation under temperature gradients

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

PolSAR CPD model for Snow Depth Estimation

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

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



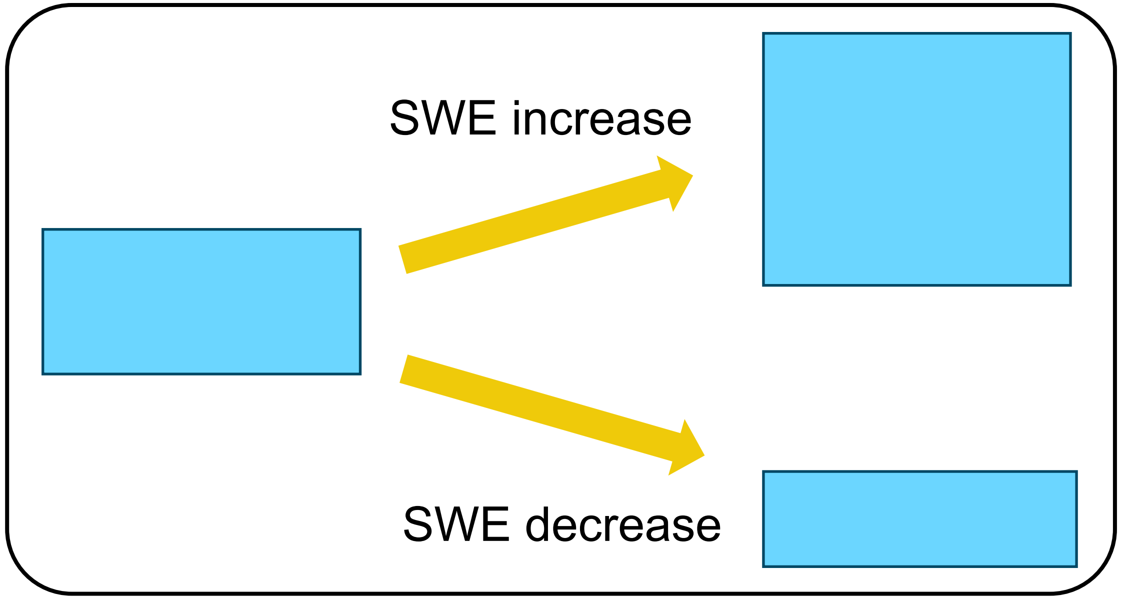
Leinss et al., Snow Height Determination by Polarimetric Phase Differences in X-Band SAR Data, 2014
Leinss et al., Anisotropy of seasonal snow measured by polarimetric phase differences in radar time series, 2016

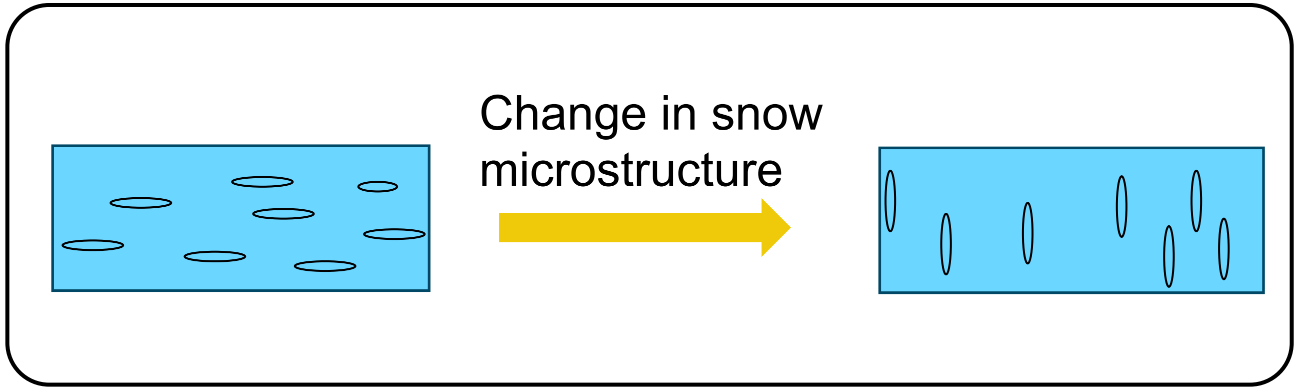
PolSAR CPD model for Snow Depth Estimation

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 using PolInSAR?

Combination of Interferometric and Polarimetric Measurements –Temporal Coherence region

DLR

- Two PolSAR acquisitions

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

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

- Temporal polarimetric coherence ρ

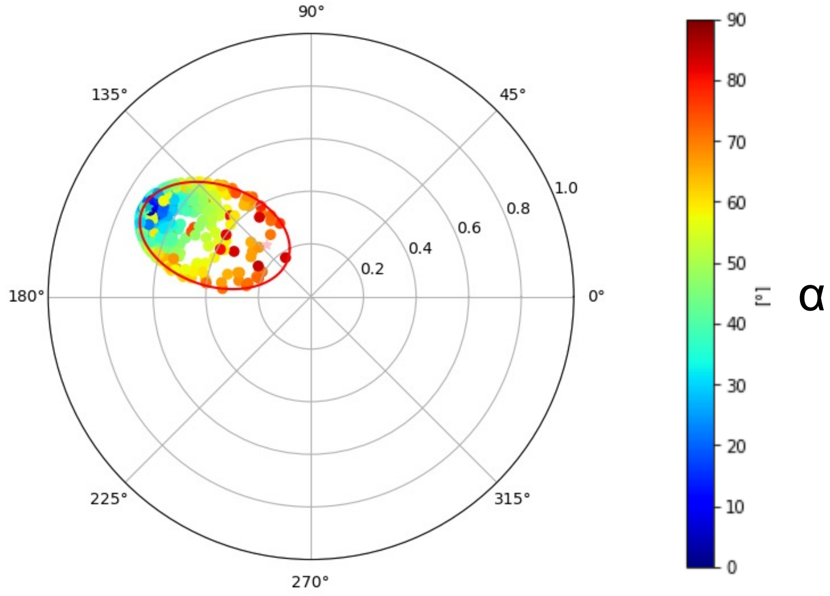
$$\rho(\omega_1, \omega_2) = \frac{\omega_1^H \boldsymbol{\Omega}_{12} \omega_2}{\sqrt{(\omega_1^H \boldsymbol{T}_{11} \omega_1)(\omega_2^H \boldsymbol{T}_{22} \omega_2)}}$$

ω → unitary vectors of polarization states

TDX

27.02./10.03.

ΔSnow Depth = 17.4 cm
ΔSWE = 27.5 mm



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

Combination of Interferometric and Polarimetric Measurements – Model Scattering Matrix

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

S → Scattering Matrix

- Scattering Matrix of Corner Reflector $S = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

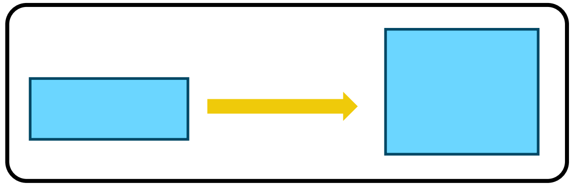
P_2 → Propagation Matrix

$$P_2 = \begin{bmatrix} \exp(i\kappa_H r) & 0 \\ 0 & \exp(i\kappa_V r) \end{bmatrix}$$

$$\kappa = \frac{2\pi}{\lambda}\left(\cos\theta - \sqrt{\epsilon - \sin^2\theta}\right)$$

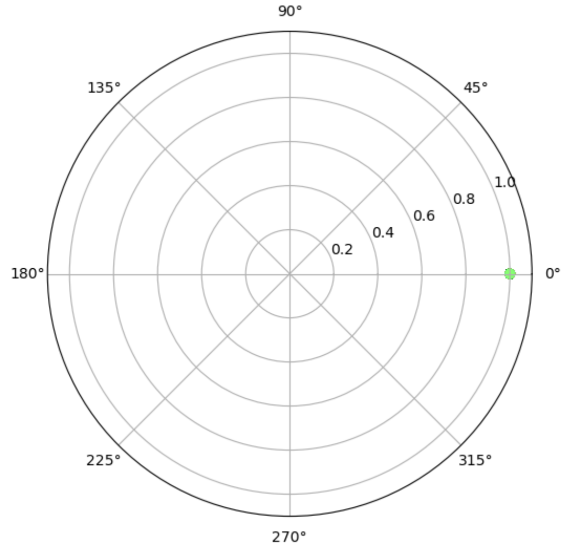
ϵ_{HH} and ϵ_{VV} from snow anisotropy model

Temporal Coherence Region

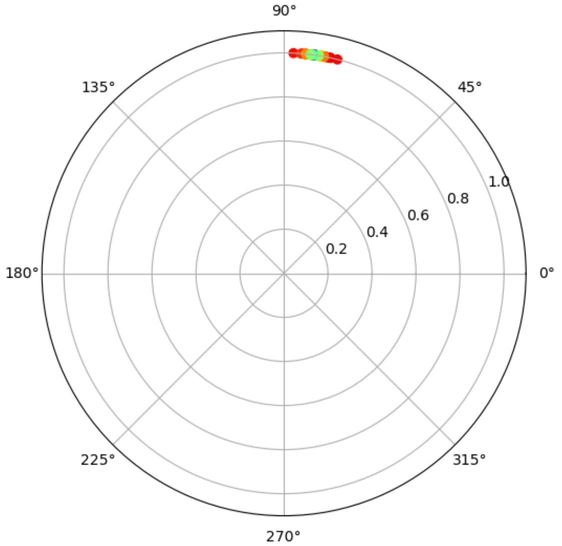


- A = 0.2
- $\rho = 0.2\,\frac{g}{cm^3}$
- R1 = 1 cm

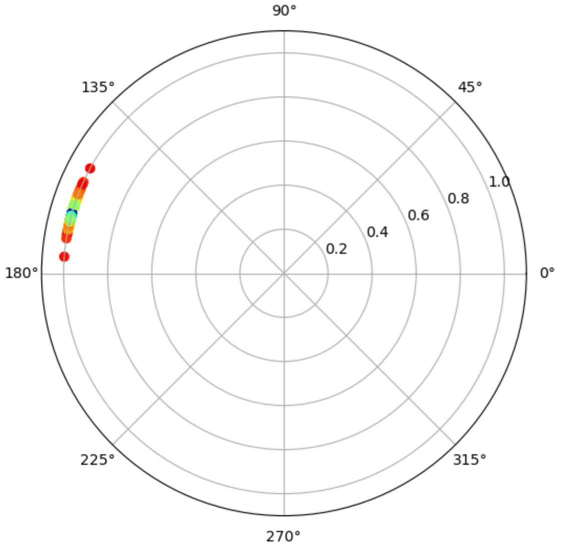
Δr = 0cm



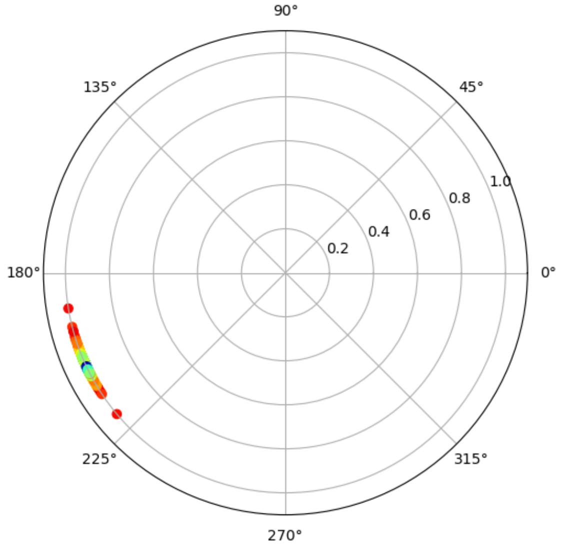
Δr = 2cm



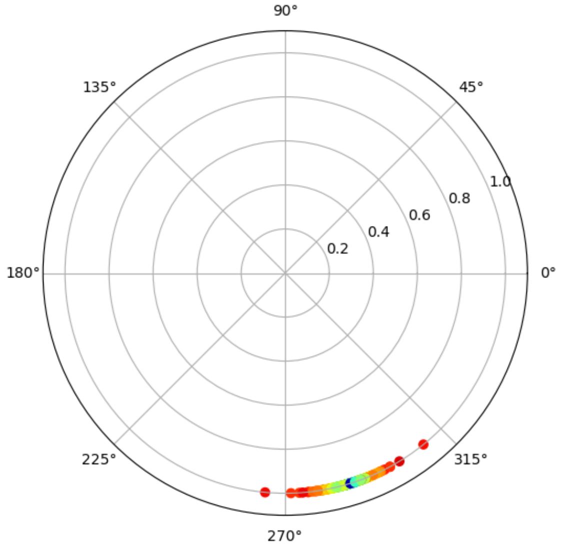
Δr = 4cm



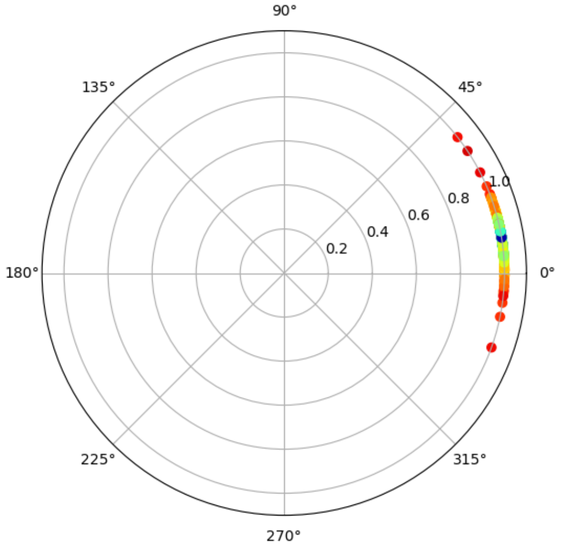
Δr = 5cm



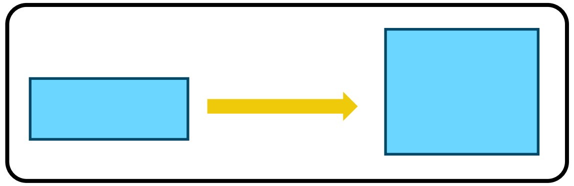
Δr = 7cm

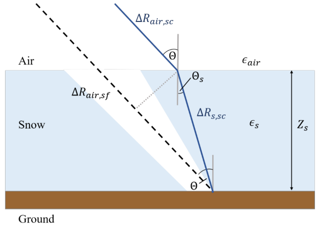


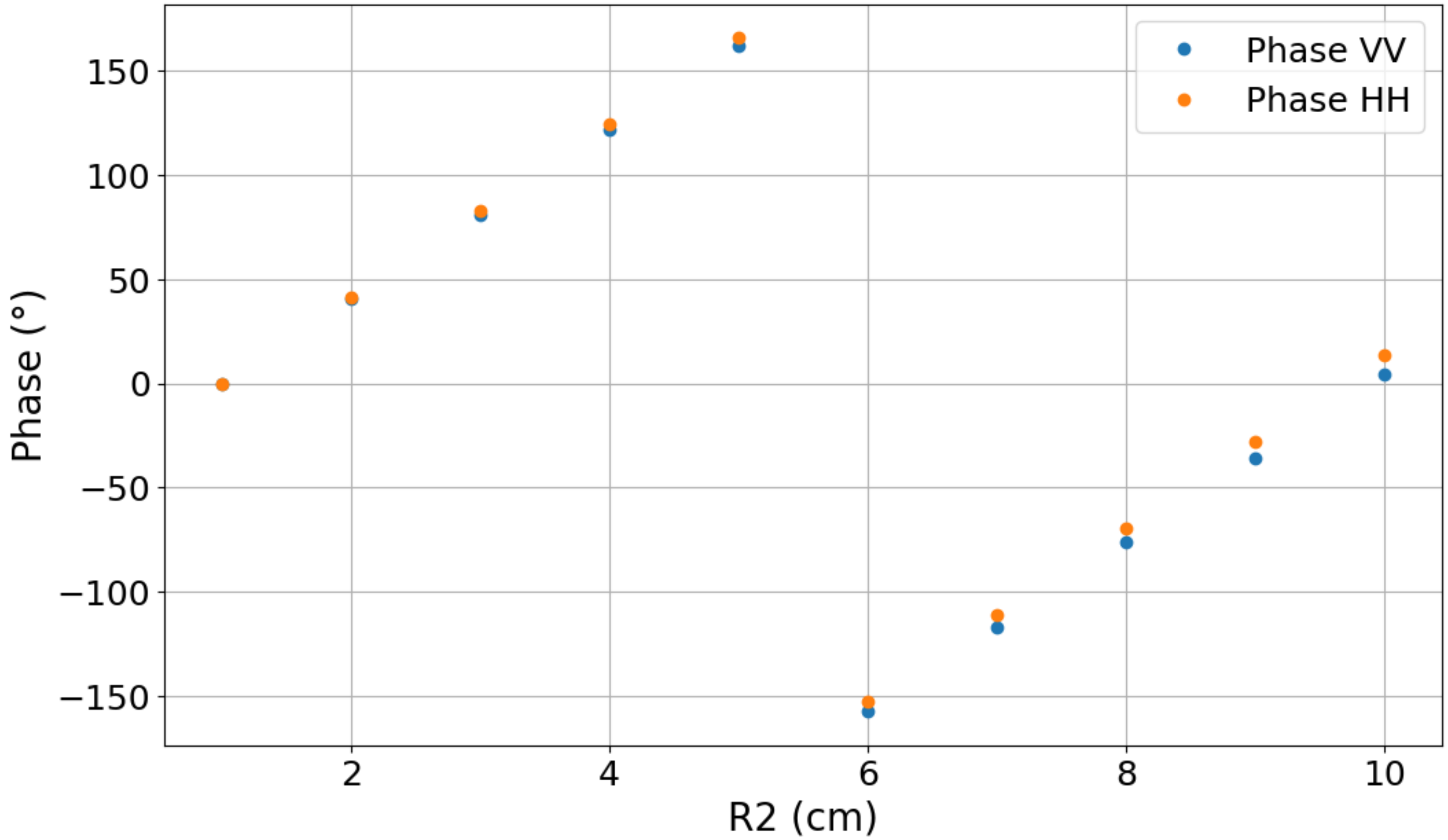
Δr = 9cm



DInSAR phase



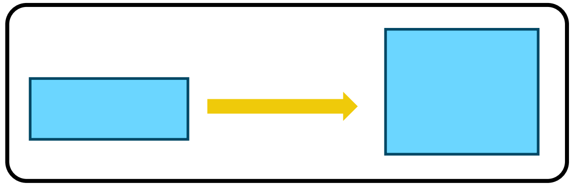


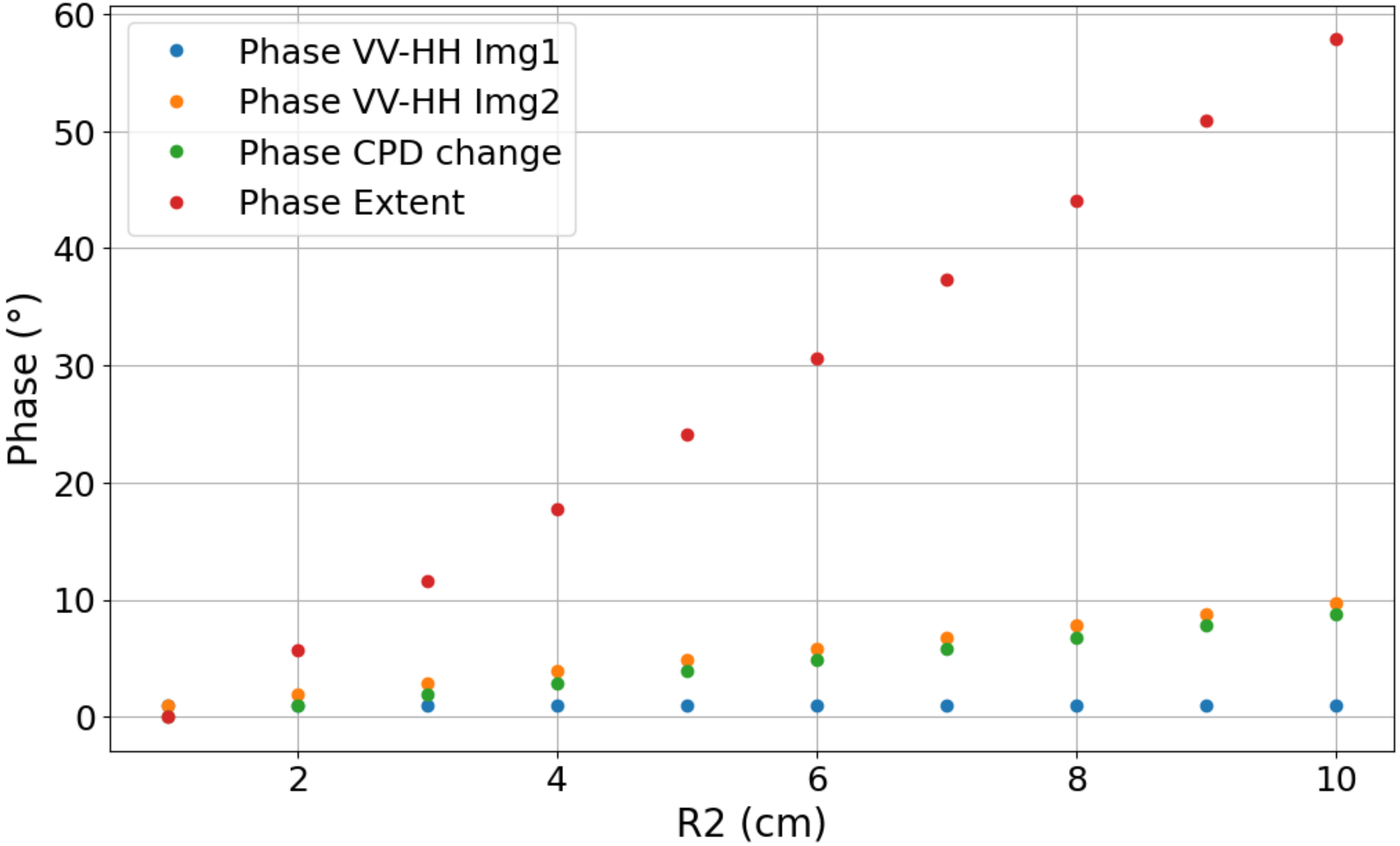


- Phase wrap can be observed
- Increasing difference between VV and HH

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

Polarimetric Phase change

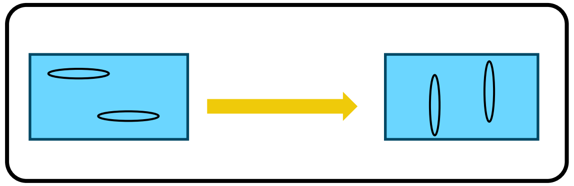




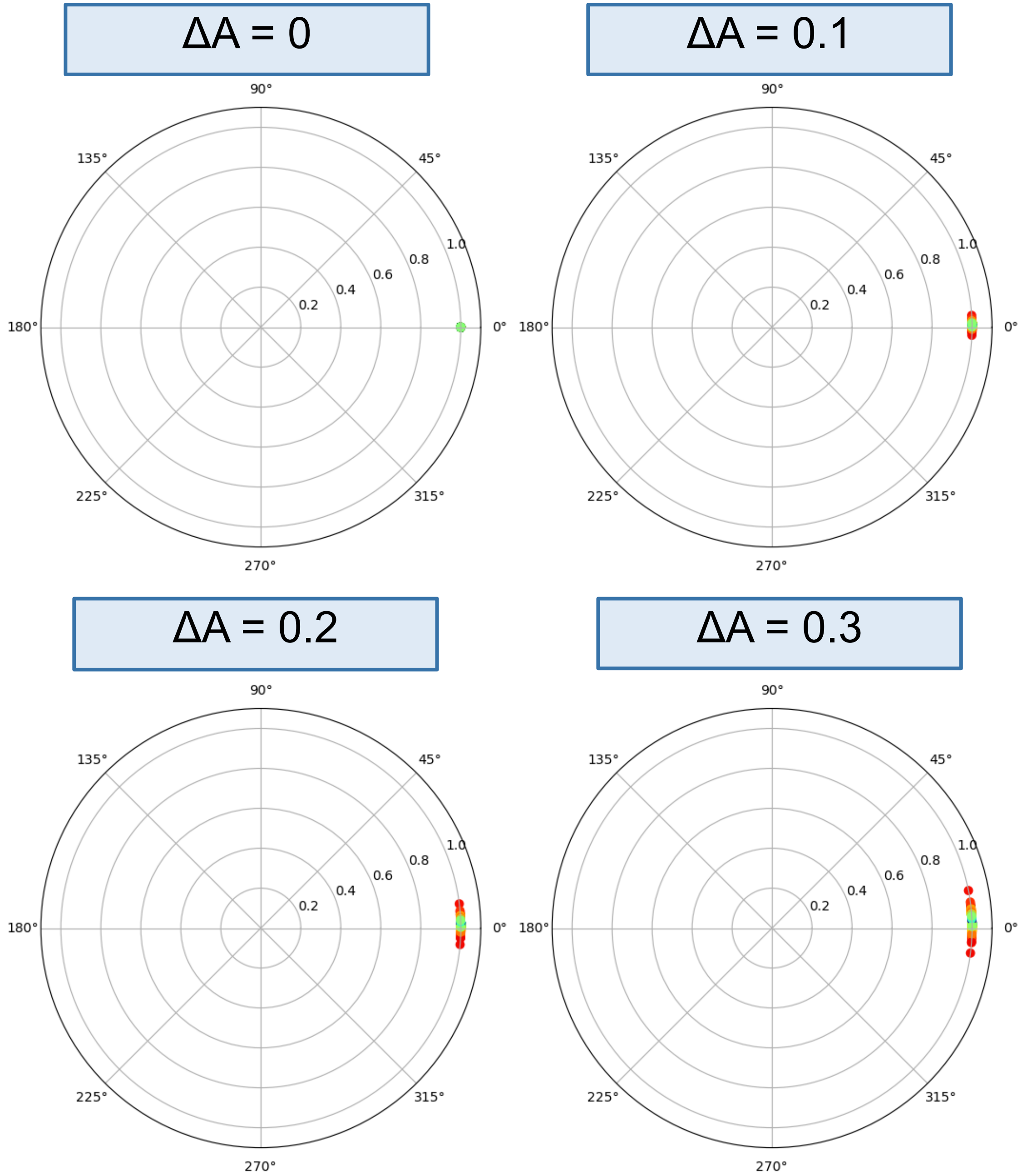
- Phase extent yields higher values than CPD change

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

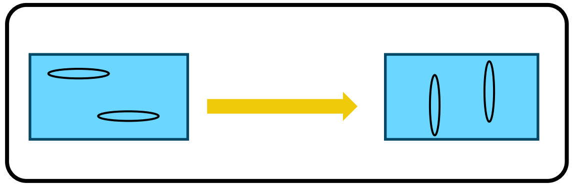
Temporal Coherence Region

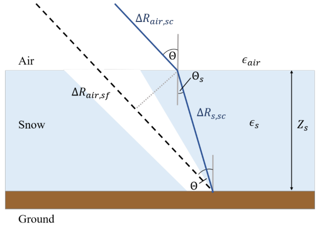


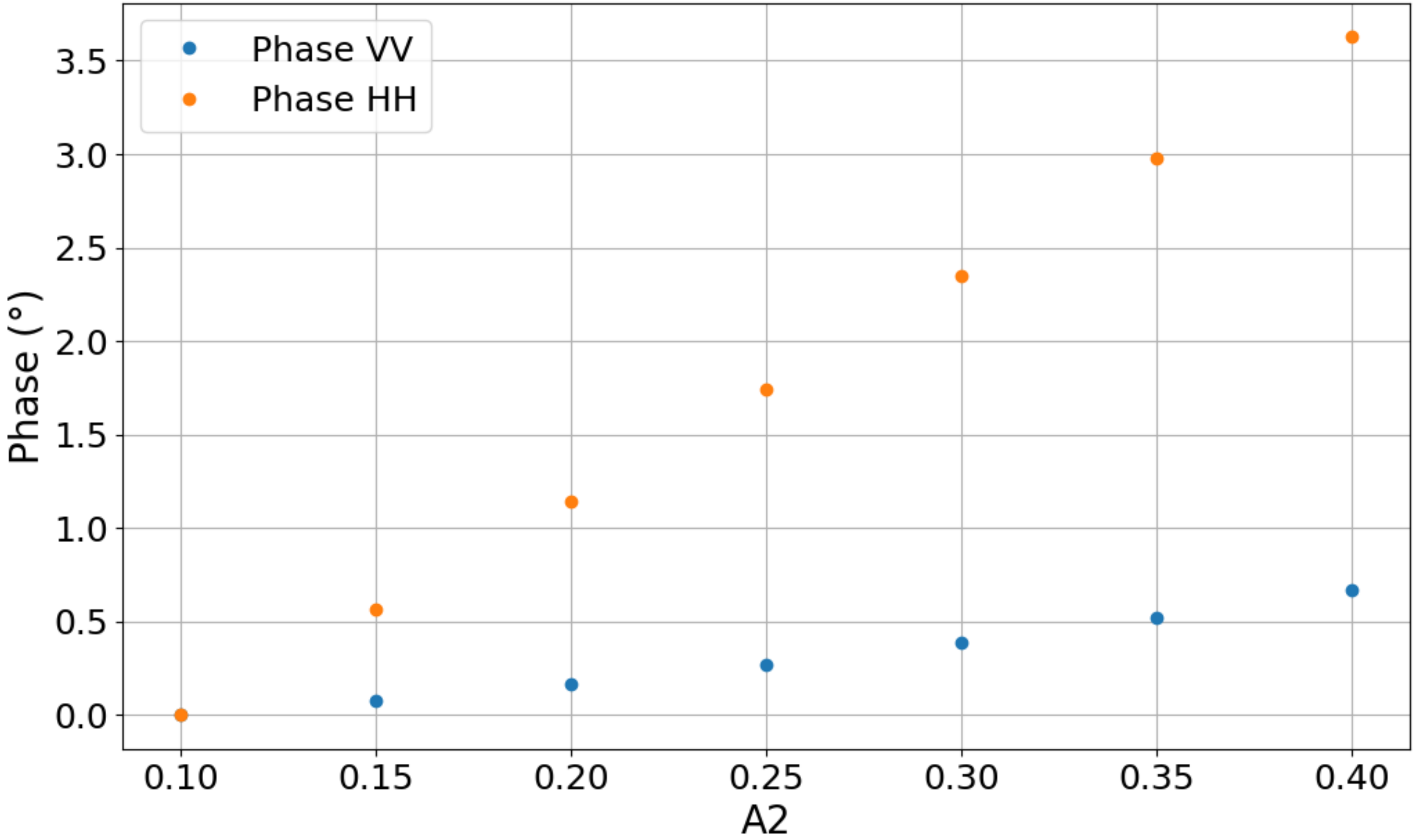
- r = 2 cm
- $\rho = 0.2 \frac{g}{cm^3}$
- A1 = 0.1



DInSAR phase



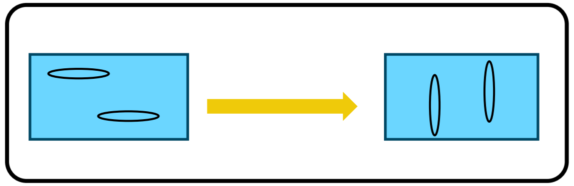


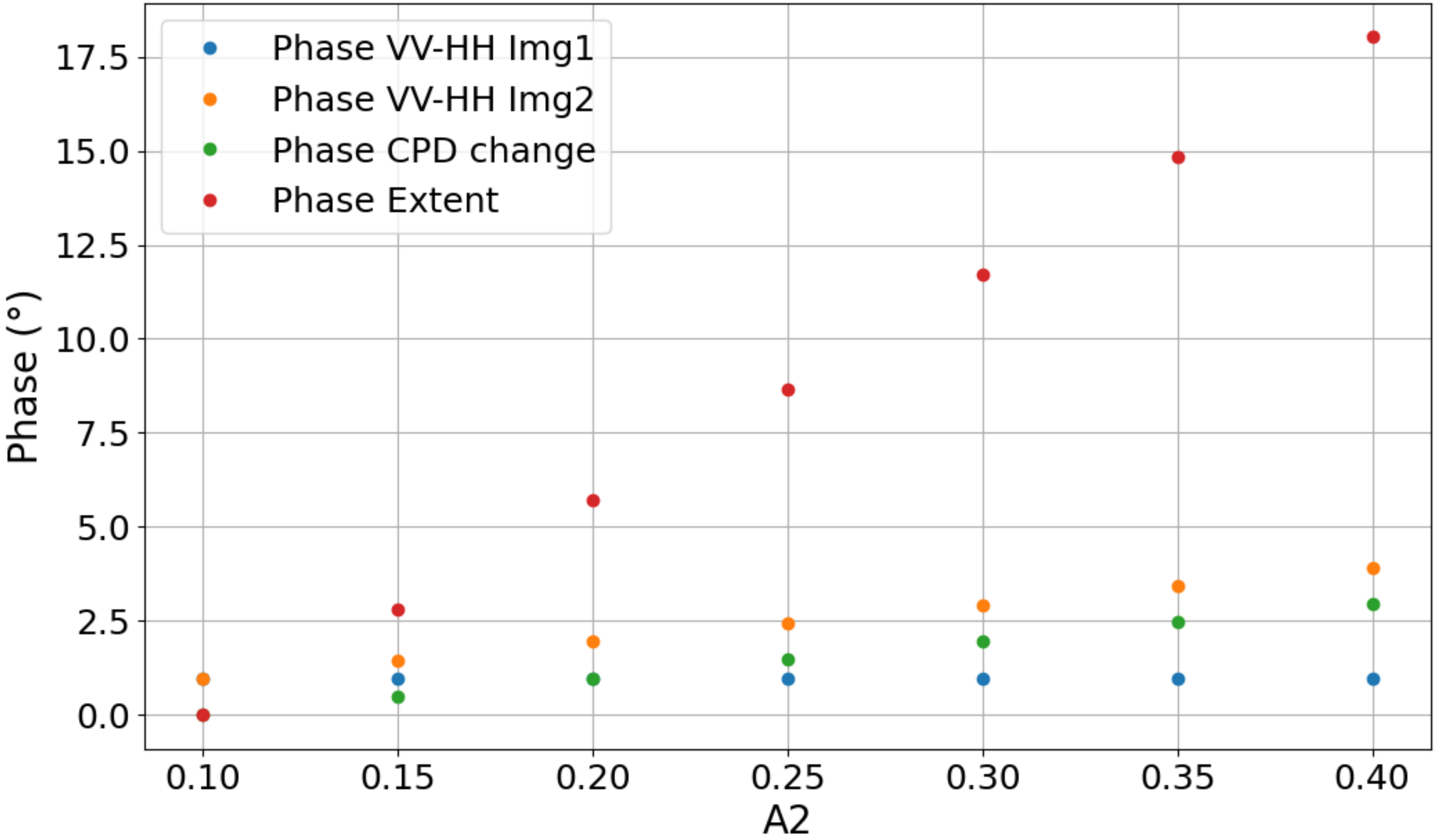


- Increasing difference between VV and HH

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

Polarimetric Phase change





- Similar behavior as for snow depth change

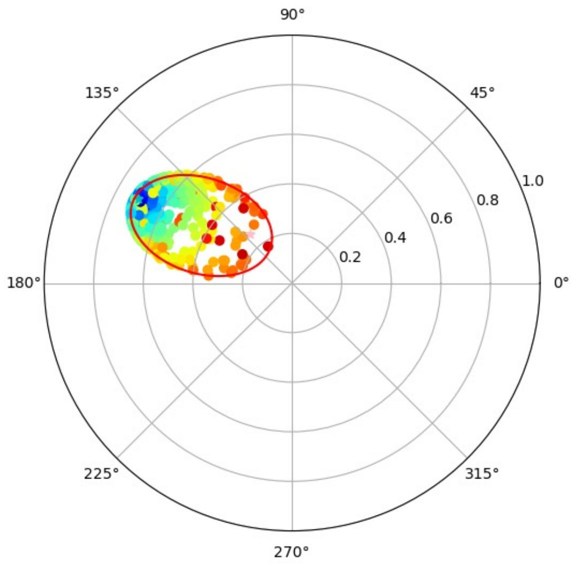
- A1 = 0.1
- A2: anisotropy at 2. acquisition

Temporal Coherence region

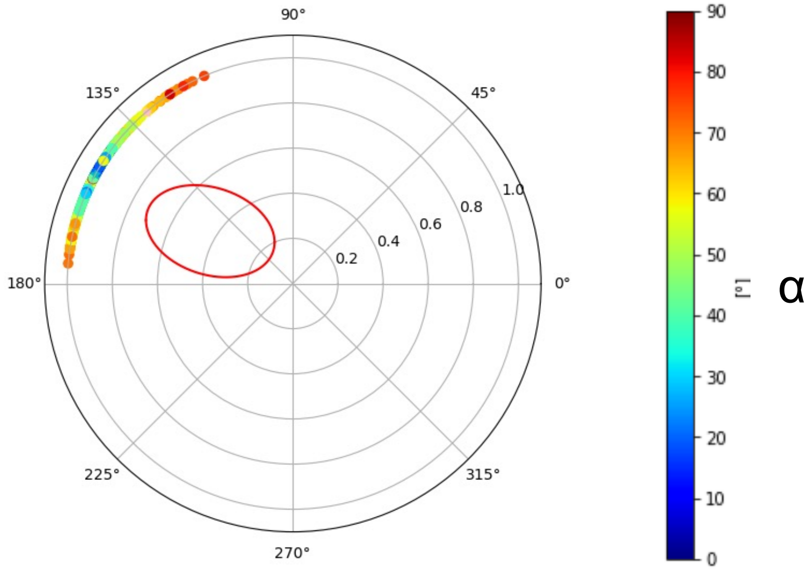
TDX

27.02./10.03.

ΔSnow Depth = 17.4 cm
ΔSWE = 27.5 mm

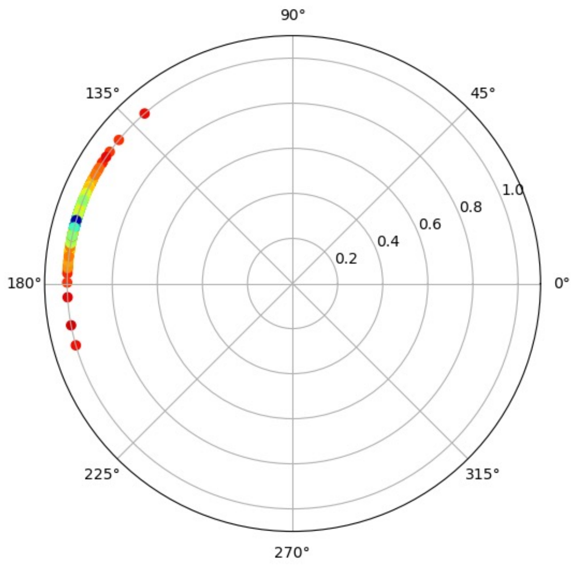


Projection to unit circle



Model

- A = 0.1

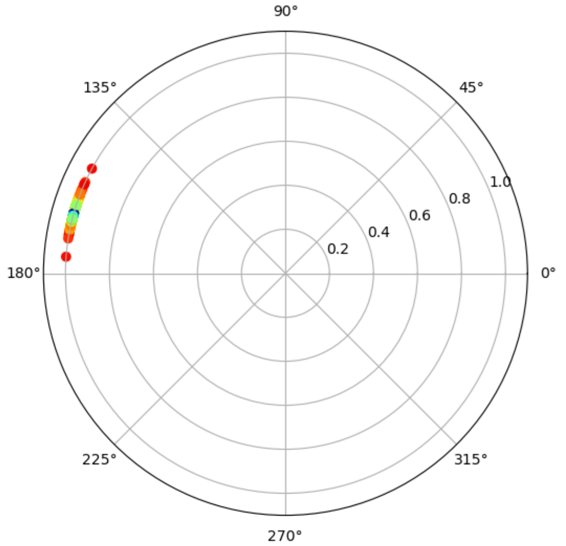


Summary and Outlook

Summary

- Modeling of coherence regions for snow depth and anisotropy changes
- Behavior of simulated coherence regions similar to real data
- Phase extent higher sensitivity than CPD

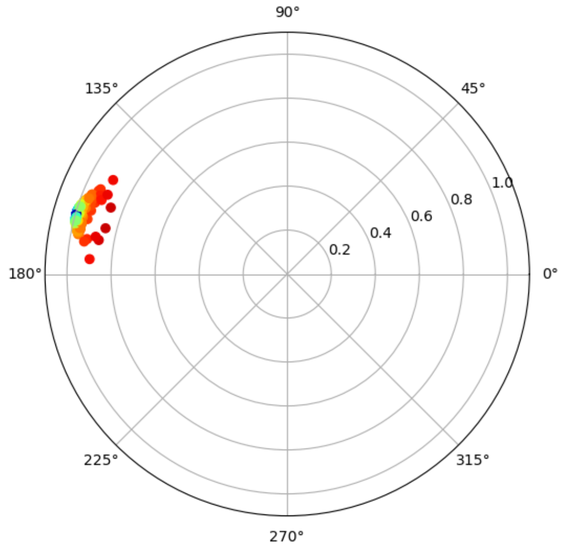
Δr = 4cm



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



Including SNR

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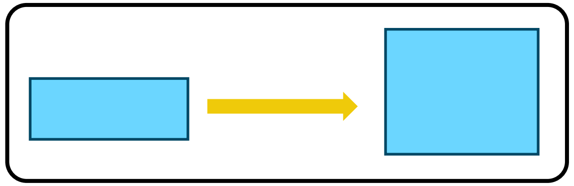
DLR

Temporal Coherence Region



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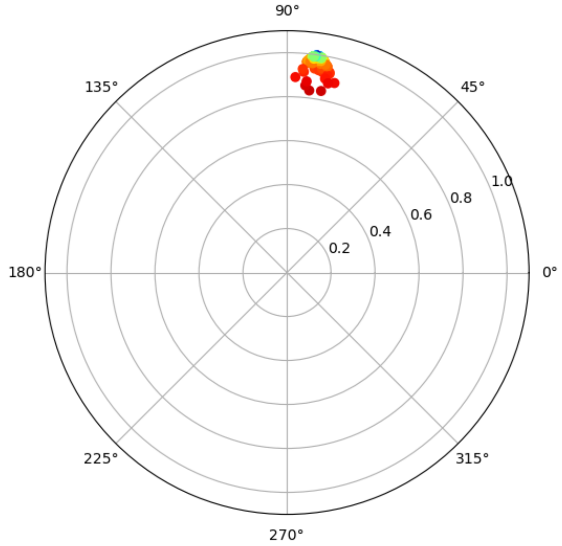

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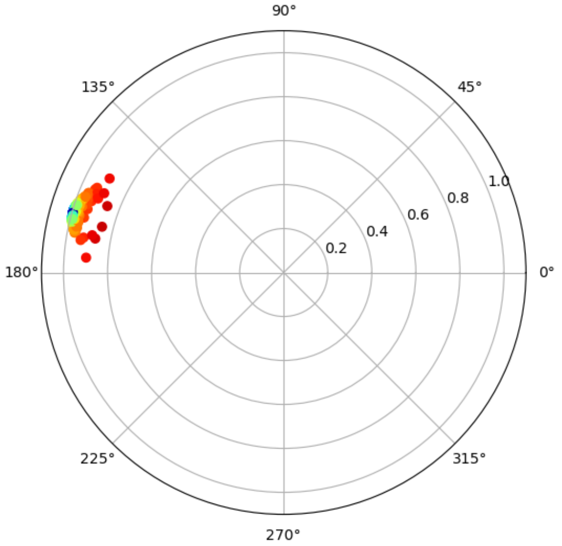

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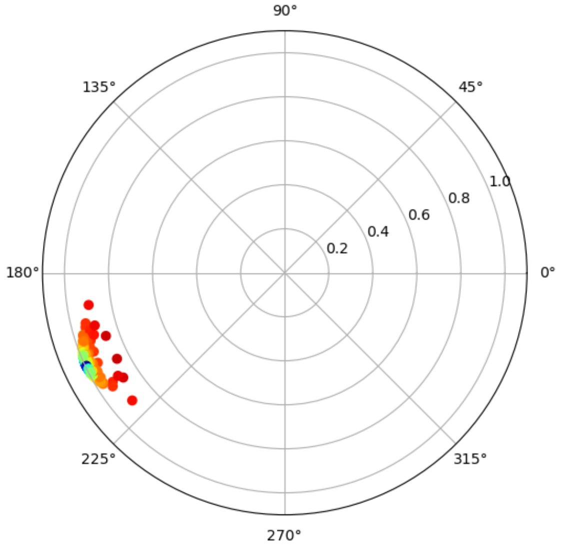

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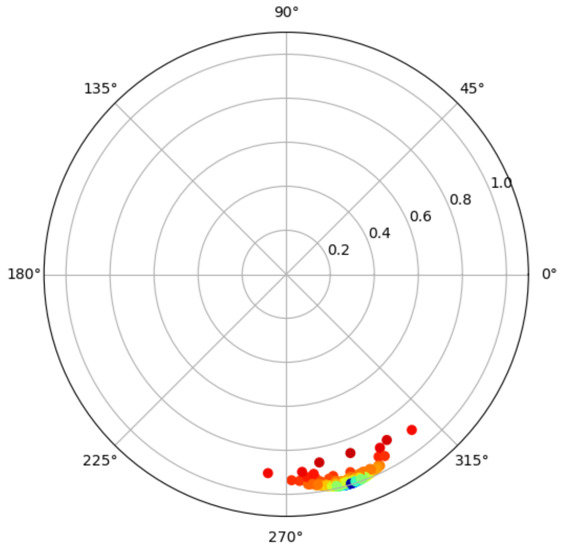

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