Differential SAR Interferometry and Co-polar Phase Differences for Snow Water Equivalent Estimation

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Abstract

The Snow Water Equivalent (SWE) is an important parameter for hydrological and climate models. It has been shown previously that the interferometric phase between two repeat-pass SAR measurements can be related to the SWE change between those acquisitions, but this method is limited due to phase wrapping. Furthermore, it is possible to relate the Co-polar Phase Difference (CPD) between two polarimetric channels to the depth of newly accumulated snow. This study presents an approach to include the information obtained from the CPD in the Differential Interferometric Synthetic Aperture Radar (DInSAR) SWE retrieval algorithm to overcome the problem of phase wraps and improve its performance. Preliminary results show that the link between CPD and snow depth change can be used to estimate phase wraps of the interferometric phase.

1 Introduction

Snow properties like the Snow Water Equivalent (SWE), which describes the amount of water stored in the snow pack, are essential parameters for hydrological and climate models. To obtain SWE measurements on a global scale, remote sensing measurements are needed [1].

Especially Differential Interferometric Synthetic Aperture Radar (DInSAR) has a great potential to measure snow properties. A promising approach to estimate SWE using repeat pass DInSAR has been proposed first in [2] and was later refined in [3] exploiting the interferometric phase between two SAR acquisitions. Due to the fact that microwaves are refracted in the snow pack, an effect on the interferometric phase can be observed. It can be physically shown that the interferometric phase between two SAR acquisitions can be linked to the SWE change between both measurements.

However, this approach has limitations due to the 2π ambiguity of the interferometric phase causing phase wraps, which occur when the SWE change between two acquisitions exceeds a certain threshold.

On the other side, studies have shown that the Co-polar Phase Difference (CPD) between the VV and HH polarimetric channels contains information on the retrieval of meteorological parameters, like in [4] , where the CPD is included in an algorithm for rainfall estimation. The CPD has also a dependency on the fresh snow depth [5]. The physical model established in [6] expresses the CPD as a function of anisotropy, density and depth of the snow pack. Hence, the inclusion of the CPD measurements, which can be linked to the accumulation of fresh snow, into the DInSAR SWE retrieval algorithm can help to improve the estimation results by detecting the phase wrapping errors.

Therefore, the aim of this study is to jointly exploit the complementary information delivered by DInSAR and polarimetric SAR (PolSAR) observables for SWE estimation by combining the methods proposed in [3] and [5]. This is investigated at a test site located on Svalbard using TerraSAR-X data.

2 Methods

2.1 SWE Estimation using DInSAR

The model proposed in [2] and in [3] exploits differential interferometry between two SAR acquisitions, which are temporally separated, to estimate the SWE change of dry snow. It can be shown, that there is a nearly linear relation between the differential phase and the SWE change between the two measurements.

Radar waves are refracted in the snow pack, since snow has a different dielectric constant than air, as show in Figure 1.

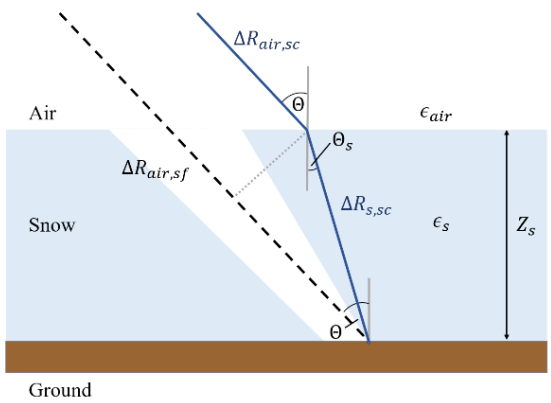

Figure 1 Refraction of the radar wave for snow (blue line) compared to no snow conditions (dotted line).

When comparing snow-free and snow-covered conditions, a path delay of the wave can be observed, which is proportional to the snow depth change ΔZ_S between both measurements. This path delay can be translated in the phase difference $\Delta\Phi_S$ by considering the geometry in Figure 1:

$$\Delta\Phi_s = -2\, k_i \Delta Z_s \left(\cos\Theta - \sqrt{\epsilon - \sin\Theta^2}\right) \quad (1)$$

where $k_i = 2\pi/\lambda$ is the wavenumber of the wavelength λ and Θ is the incidence angle of the radar wave. The permittivity ϵ of the snow depends on the density. In [3] a refinement was presented for the density and incidence angle dependent part of the equation, to make it valid for a wider range of snow densities. The relation between the interferometric phase and SWE change ΔSWE is then given by:

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

α is a parameter close to 1, that can be adapted to reduce the Root Mean Square Error (RMSE) between the numerical approximation and the exact solution for different incidence angles and snow densities. However, it has to be considered, that the interferometric phase lies in an interval between -π and π. Therefore, only a limited range of ΔSWE can be retrieved unambiguously. This range is proportional to the radar wavelength. ΔSWE values exceeding this interval result in phase wraps, which need to be detected and corrected for a correct ΔSWE estimation.

2.2 Snow Depth Estimation using CPD

The model in [6] relates the Co-polar Phase Difference (CPD) Φ_{CPD} between the phase Φ_{VV} of the VV and the phase Φ_{HH} of the HH polarized channel to the fresh snow depth. The CPD can be defined as:

$$\Phi_{CPD} = \Phi_{VV} - \Phi_{HH}. \quad (3)$$

When snow has an anisotropic structure, the signal delay in the snow pack depends on the polarization. Accumulating snow forms horizontal structures due to its own weight. This causes a slower propagation speed for the horizontal polarized radar waves. Later, due to recrystallization under temperature gradients, the snow forms vertical structures. That decreases the propagation speed of the vertical polarization [5].

The snow is modelled as ellipsoidal ice inclusions in air. An empirical extension of the Maxwell-Garnett mixing formulas is used to calculate the depolarization factors along the three main axes of the inclusions for different assumptions of the anisotropy. These factors are used to obtain the effective anisotropic permittivity. The permittivity gives then the refractive indices n_H of the H-polarized wave and n_V of the V-polarized wave and are used to calculate the CPD [6]:

$$\Phi_{CPD} = (-1)\frac{4\pi}{\lambda}\Delta Z_s \left(\sqrt{n_V^2 - \sin^2(\Theta)} - \sqrt{n_H^2 - \sin^2(\Theta)}\right) \quad (4)$$

The CPD yields positive values for fresh snow and becomes negative when the snow forms vertical structures. Therefore, this equation can be used, to estimate the thickness of the fresh snow layer.

In [7] the authors have already presented that there is a positive correlation between the CPD and dry fresh snow height at the same test site on Svalbard. In this study, the relation between the CPD and the fresh snow depth will be analysed with the purpose to estimate if phase wrapping in the DInSAR phase has occurred.

3 Test site and SAR data

The Bayelva test site is located on Svalbard. Since August 2019, a sensor installed by the Alfred-Wegener-Institute (AWI) performs automated SWE measurements. A Potassium source located below the sensor is emitting gamma rays, that are attenuated by the snow pack. This is used to calculate the SWE with a temporal resolution of 6 hours [8]. These ground-based measurements are used as reference data.

The previously described method for SWE estimation has been tested using TerraSAR-X (TSX) data available in HH and VV polarisation. A time series for spring 2021 is available with incidence angles of around 39° and a temporal baseline of 11 days between two consecutive acquisitions.

4 Preliminary Results

4.1 SWE Estimation using DInSAR

Preliminary results for the SWE change retrieval using the interferometric phase and an estimation window of 11x11 are shown in **Figure 2** (top) before applying the phase wrapping correction.

A high discrepancy between the in situ measured values and the DInSAR-retrieved SWE changes is observable in many cases. To investigate where phase wrapping errors have occurred, ground-based measurements can be utilized to check if the SWE change was larger than the phase wrapping threshold. Then, the estimated phase values are corrected by adding or removing phase cycles if the threshold was exceeded. The results for the corrected SWE changes are presented in **Figure 2** (bottom).

A high agreement between the in situ and retrieved SWE values can be observed. Therefore, the correction of the phase wrapping errors is essential for SWE estimations using the interferometric phase from space-borne X-Band measurements.

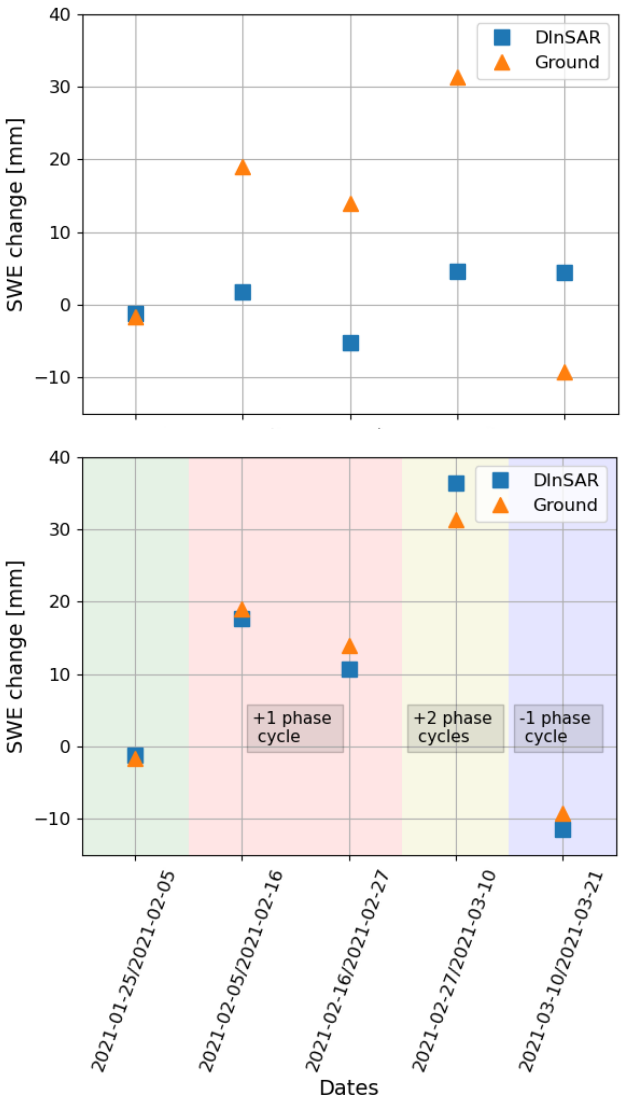

Figure 2 Comparison between DInSAR-retrieved and in situ-measured SWE change. TOP: Uncorrected DInSAR retrieval with missing phase cycles. BOTTOM: Phase wraps corrected in the DInSAR retrieval. Background colours indicate the amount of added/removed phase cycles.

4.2 CPD and Snow Depth

In the next step, the aim is to correct these phase wrapping errors without the need of ground measurements. For this purpose, the CPD between the HH and VV channel is calculated, which is displayed in **Figure 3**.

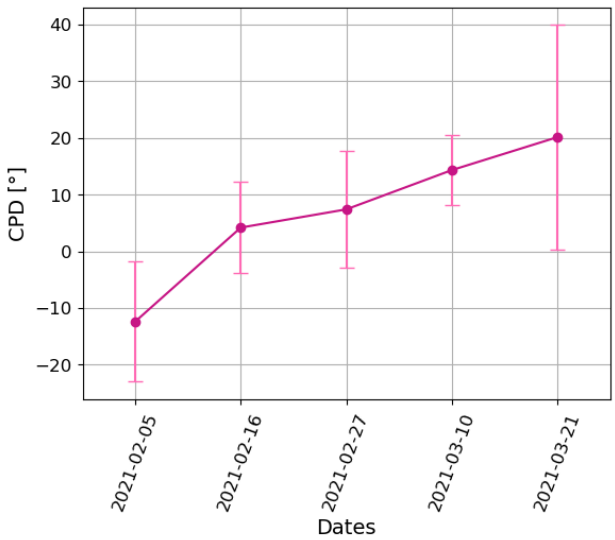

Figure 3 CPD of the SAR acquisitions.

Additionally, the CPD is plotted to together with the measured snow depth change between the acquisitions, excluding the last time stamp due to snow melt, in **Figure 4**, to explore if a correlation can be found between the snow accumulation and the co-polar phase.

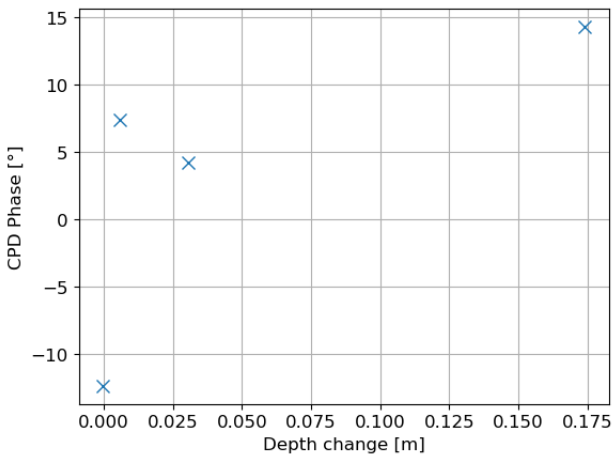

Figure 4 Measured CPD values compared to snow depth changes.

According to the CPD model, negative values correspond to already vertically aligned snow crystals, which leads to the assumption, that no snow fall occurred. This can also be observed in the ground measurements. Positive CPD values indicate that snow fall occurred between the two measurements. In general, higher CPD values should then correspond to a higher fresh snow depth.
It has also to be considered that positive CPDs are only sensitive to fresh snow, and here the snow depth change was calculated for the 11-day acquisition interval, to ensure consistency with the 11-day temporal baseline of the DInSAR measurements. However, the anisotropic structure of snow can disappear in shorter time spans.

4.3 CPD Model

The model in [6] can be used to relate the CPD to the fresh snow depth. With an anisotropy of 0.2 corresponding to horizontally aligned grains and snow densities between 0.1 and 0.3 g/cm^3, the estimated fresh snow depth can be translated into a SWE change. In **Figure 5**, these CPD model simulations are plotted together with the corrected DInSAR SWE estimates from **Figure 2**, to investigate the ability of the CPD model to predict the DInSAR phase wraps.

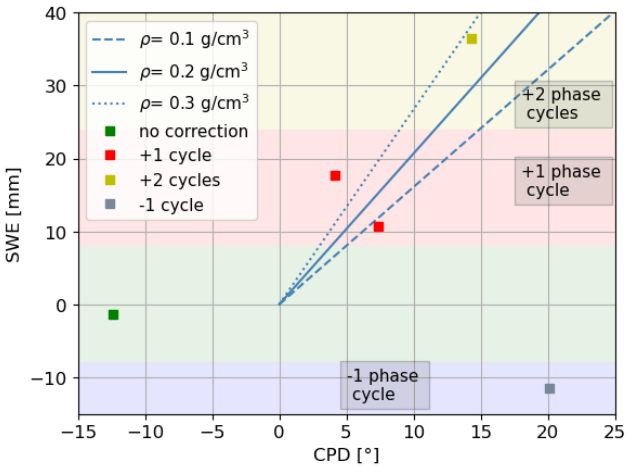

Figure 5 SWE change in dependence of the CPD using the model in [6] assuming a density of 0.1 – 0.3g/cm^3 and an anisotropy of 0.2.

The colours of the measurement points represent the number of phase cycle corrections. For the data where one (in red) or two (in yellow) phase cycles had to be added, the CPD model would have predicted the same correction for snow densities of 0.2 and 0.3 g/cm^3. This can be seen when comparing the measurements to the solid and dotted lines, since the SWE values of the CPD model correspond to the correct amount of phase wrap corrections. Negative CPD values indicate that there was no accumulation of new snow and that the snow started to form more vertically aligned structures, which does not have to be connected to a decrease in snow depth or SWE. Therefore, negative CPD values are treated as no correction. This is the case for the green data point. The outlier in grey has the highest CPD values, but corresponds to a negative SWE change. However, SWE decreases are not accounted for in the CPD model. Furthermore, this point is also affected by melting, which is also not part of the CPD model. Therefore, this point measurement cannot be predicted correctly by the model. However, excluding melt events, and associating negative CPDs with no SWE change, the CPD to snow accumulation relationship is promising to correct the missing phase cycles in DInSAR SWE estimates.

5 Conclusion and Outlook

This study indicates the potential of combining DInSAR and PolSAR for an improved SWE estimation.

Preliminary results indicate that the CPD can detect SWE changes that result in phase wraps in the DInSAR method and can therefore be utilized to detect these errors. However, assumptions on the snow density and anisotropy are required for the CPD model. Further, the temporal baseline of 11 days can be too long to detect only fresh snow. This will be analysed in more detail in the upcoming research, which also will include the analysis of a longer time series. Eventually, the goal is to derive DInSAR SWE change estimates with a phase cycle correction based on CPD measurements.

6 Acknowledgement

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7 Literature

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