Multi-Baseline Pol-InSAR Inversion of the Subsurface Scattering Structure of Ice Sheets

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Abstract

The influence of the subsurface properties of ice sheets on polarimetric synthetic aperture radar interferometry (Pol-InSAR) measurements is well known. In order to invert this relationship for the extraction of geophysical parameters from Pol-InSAR data, models of the subsurface scattering structure are required. One potential application is the estimation of the penetration bias in interferometric surface elevation measurements of ice sheets, which was demonstrated based on single-baseline data. However, the model complexity and performance are constrained by the limited observation space. This study, therefore, investigates the inversion of subsurface scattering structures with multi-baseline fully polarimetric Pol-InSAR data, which allows accounting for more realistic scattering scenarios. Preliminary results indicate a more robust inversion of the penetration bias compared to the single-baseline case.

1 Introduction

The potential to derive information about the subsurface structure of ice sheets with polarimetric synthetic aperture radar interferometry (Pol-InSAR) is well known [1], [2]. The geophysical properties of the subsurface, in particular the characteristics of the scatterers and their distribution, influence the vertical backscattering distribution, which determines the volume decorrelation measured by InSAR configurations. Adding the polarimetric observation space to interferometry, by means of Pol-InSAR, the vertical distribution of different scattering mechanisms can be assessed. However, the inversion of the potentially complex subsurface scattering structure from the limited observation space of Pol-InSAR measurements requires scattering models. The tradeoff between the model complexity and the available observation space imposes constraints on how realistic such models can be, respectively how strong the subsurface scattering structure needs to be approximated. A widely used model, which is simple enough to be inverted with single-polarization single-baseline InSAR data, is the Uniform Volume (UV) model [3]. There, a constant scattering extinction is assumed in the subsurface, which leads to an exponential vertical backscattering profile. The inversion of this model was used to derive extinction coefficients, which have a vague relationship to the subsurface properties. Furthermore, this model can be also used to estimate the depth of the interferometric phase center below the surface of ice sheets. This is a simple, yet effective way to estimate the penetration bias in digital elevation models (DEMs) derived with InSAR over ice sheets [4], [5], [6]. However, the UV model was shown to both overestimate [6] and underestimate the penetration bias [5], [7], depending on the subsurface characteristics. Even though these studies indicated the benefit of a UV inversion to improve topographic information derived from (Pol-)InSAR measurements, there is potential to further improve the inversion accuracy by overcoming the relatively simple model setup characterized by a single parameter. However, more flexible parameterizations of the subsurface scattering structure can be only exploited by means of a larger observation space.

The UV model was extended to fully polarimetric (full-pol) InSAR data in the sense of an oriented volume model, to account for polarization dependent penetration depths in [5]. This was shown to reduce the variance in the penetration bias estimates, but does not improve the average results compared to the single-polarization inversion. Another approach for the inversion of the penetration bias was based on a Weibull function. The improved flexibility of this function to describe the scattering structure was demonstrated in tomographic modeling investigations [8], but only a constrained inversion is possible with single-baseline Pol-InSAR data, and its performance is similar to the full-pol UV model inversion [5]. In addition, focusing on the modeling of coherence magnitudes, the study in [9] demonstrated that the scattering from distinct layers, formed by refrozen melt water, has to be taken into account and can be simulated by Dirac deltas. Even though pure volume models can approximate the phase center behavior also in the presence of layers, accounting for the layer effects is expected to improve the inversion performance.

In this study, we exploit an increased observation space by using three instead of two Pol-InSAR acquisitions providing a triple-baseline configuration. This allows the use of more complex models, which are investigated with respect to their performance to estimate the penetration bias. A model setup consisting of a UV model for the volume scattering component and a Dirac delta to account for the effect of distinct subsurface layers is investigated. The inversion approach is introduced, preliminary results are discussed, and the performance is investigated with respect to the estimation and compensation of the penetration bias, based on airborne L-band SAR data from the Greenland ice sheet.

2 Test Site and SAR Data

An unique airborne SAR dataset was acquired with DLR's F-SAR system in Greenland during April and May 2015. Fully polarimetric and multi-baseline interferometric datasets were acquired in five different microwave frequency bands (i.e. X-, C-, S-, L-, P-band) over various glacier zones of Greenland. Preliminary results are shown on two test sites (South Dome, EGIG T05) in the percolation zone that have different subsurface structures. South Dome is the highest elevated area in southern Greenland, with a clear subsurface layering in a firn column of several tens of meters depth and affected by rather limited seasonal melting. Ground penetrating radar (GPR) profiles confirmed the aforementioned stratigraphy [9]. The second test site, EGIG T05, is characterized by an abundance of ice inclusions within the firn, due to more refrozen melt water because of its lower elevation. This leads to a more homogeneous vertical backscattering structure, which is also confirmed by GPR data. More information about the campaign can be found in [9] and [8].

Prior to the analysis, the multi-baseline phase calibration of the SAR data was validated and refined at corner reflectors. The temporal decorrelation is considered negligible for the ARCTIC15 dataset with only about 15 min between consecutive acquisitions at stable negative temperatures. Noise decorrelation is always above 0.96.

3 Methods

In a generic way, the interferometric coherence γ in polarization $\vec{w}$ can be modelled as

$$\gamma(\vec{w}) = \frac{\gamma_{Vol}(f_V, \vec{w}) + \sum_{j=1}^{N} m_j(\vec{w}) e^{ik_{zVol} z_j}}{1 + \sum_{j=1}^{N} m_j(\vec{w})}. \qquad (1)$$

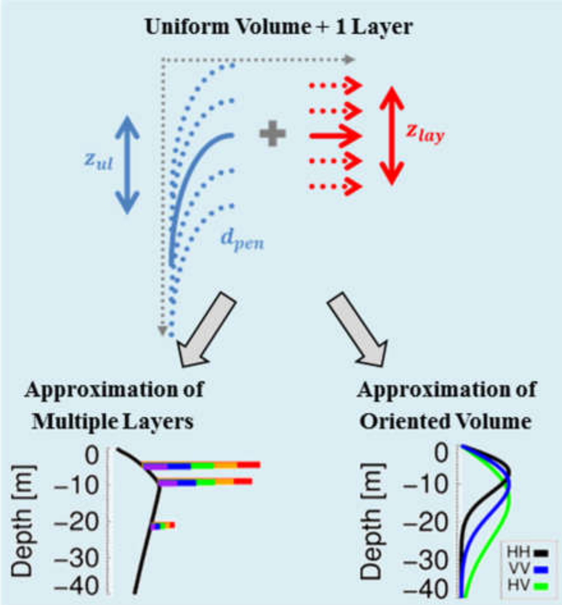

Figure 1 The idea behind the Random Uniform Volume plus 1 Layer approximation. As a first case, this model setup can approximate the effects of several layers combined with a random volume. As a second case, the polarization dependence of the volume in an oriented volume scenario can be also accounted for by a single virtual layer in the model

Here, $\gamma_{Vol}(f_V, \vec{w})$ is the volume coherence, which depends on the vertical scattering structure f_V, as described by volume models. For instance, f_V is an exponential function in the UV model, which can be polarization dependent. Distinct scattering layers, as they are present at the South Dome test site, are modelled as Dirac deltas at depth z_j with layer-to-volume scattering ratio m_j. The interferometric phase-to-height variation is described by the vertical wavenumber in the volume

$$k_{zVol} = \frac{4\pi\sqrt{\epsilon}}{\lambda} \frac{\Delta\theta_r}{sin\theta_r}, \qquad (2)$$

considering the refracted incidence angle θ_r and propagation in the subsurface. The permittivity ϵ can be derived from the density of firn cores and is set to 2.0 for this analysis. The model setup in (1) can have an arbitrary number of parameters, depending on the complexity of the volume model and the assumed number N of layers. Therefore, it is necessary to adapt the model complexity to the available observation space. For single-polarization single-baseline InSAR data, a UV model, which has only one parameter can be inverted if layers are not considered [3], [4], [5], [6]. With full-pol single-baseline data, a polarization dependent UV model, in the sense of an oriented volume scenario can be inverted, which can reduce the variance of penetration bias estimates [5]. Inversion techniques for more flexible volume models, using a two-parameter Weibull function, were also described based on such an observation space. However, in order to account for layer effects or to improve the representation of the polarization dependence of the volume scattering structure, larger observation spaces are required. The exploitation of PolInSAR data from 3 tracks, providing 3 baselines, allows taking layer effects into account. Still, the model setup in (1) needs to be carefully constrained.

One way of achieving a model setup that is invertible with triple-baseline full-pol Pol-InSAR data is by assuming a polarization independent volume and one (virtual) layer. This allows to approximate two cases: First, the virtual layer can account for the combined effect of several layers. The resulting Dirac delta can be seen as a vector superposition of different Dirac deltas at different depths with amplitude m_j and phase $e^{ik_{zVol}z_j}$ in the complex plane. Second, if no layers are present, the virtual Dirac delta is a way to approximate the polarization differences in the volume structure. This concept is sketched in **Figure 1**. In the following, the volume structure is parameterized as a polarization independent UV model, with penetration depth d_{pen} and a vertical shift parameter z_{ul} that defines its upper boundary

$$\gamma_{Vol} = e^{ik_z z_0} \frac{1}{1 + \frac{i d_{pen} k_{zVol}}{2}} e^{ik_{zVol} z_{ul}}. \qquad (3)$$

z_{ul} allows to shift the volume structure downwards to account for snow or young firn, which can be transparent at longer wavelengths. This uniform volume plus 1 layer setup corresponds to considering γ_{Vol} from (3) in (1) and setting N = 1.

For the inversion, we follow the algorithm proposed in [10], which minimizes the Frobenius norm between the matrices of the multi-baseline full-pol coherences of the data and their modeled counterparts. The advantage of this approach is that the minimization is based only on the structure parameters (layer depth z, UV penetration depth d_{pen}, UV upperlimit z_{ul}) and then, given a certain structure solution, the resulting polarimetry (layer-to-volume ratio m) is extracted from the multi-baseline full-pol coherence matrix. This reduces the dimensionality of the parameter search space in the minimization. The solution of the minimization is given then by the model parameters that provide the best fit to the data. The upper limit parameter z_{ul} of the UV model is then considered an estimate of the surface, which can be used to compensate for the penetration bias.

4 First Results

Preliminary results are derived for both the EGIG T05 (**Figure 2**) and the South Dome (**Figure 3**) data. The figures show Capon tomograms derived from 6 (South Dome) respectively 9 (EGIG T05) parallel tracks [8]. The tomogram in **Figure 2** shows the rather homogeneous subsurface scattering structure at the EGIG T05 test site with a gradual decrease of the intensity with depth. At the South Dome test site (**Figure 3**), the tomogram shows two distinct subsurface layers, at about -5 m and -10 m, which originate from refrozen melt water. The tomograms are referenced to GNSS measurements at the surface, which were acquired during the campaign. The triple-baseline inversion is conducted with average k_{zVol} values of 0.25, 0.38, and 0.63 at South Dome and with average k_{zVol} values of 0.32, 0.45 and 0.76 at EGIG T05. The result is shown as a red line by means of the z_{ul} parameter, which provides an estimate of the surface location. In both examples, the surface estimates accurately follow the upper boundary of the tomograms. The first few meters below the real surface are widely transparent and are thus not accounted for by the inversion. The estimation of the position of the first significant scattering contributions at the upper boundary of the tomogram can be seen as a reliable topographic information from a radar perspective. Even if it is still few meters below the surface, it is a clearly more accurate "surface" information than the pure interferometric phase center, which is located deeper, as indicated in **Figure 4**, and can strongly depend on the baseline [11], [5]. A comparison of the triple-baseline surface estimates to the surface estimates of a single-polarization single-baseline UV model inversion is shown in **Figure 5**. The single-channel results are shown for the same baselines used in the triple-baseline inversion. They strongly vary across polarizations and across baselines. Even some overestimation of the surface location are visible. The result of the triple-baseline inversion, indicated by the red line, provides clearly more robust estimates. It is important to note that while these preliminary results are promising, the inversion performance strongly relies on the selected baselines and the applied minimization strategy. First tests on other frequencies and employing a Weibull function for the volume were conducted, but further research is necessary to achieve robust results also in these cases.

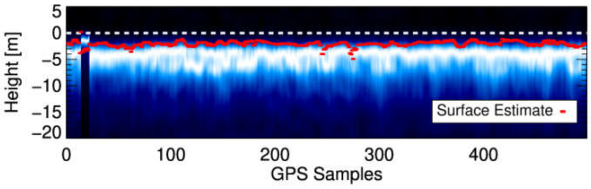

Figure 2 Capon tomogram from the lower percolation zone (EGIG T05) at L-band in HH polarization. The red line shows the surface estimation by means of the UV upperlimit parameter z_{ul} from the triple-baseline full-pol inversion.

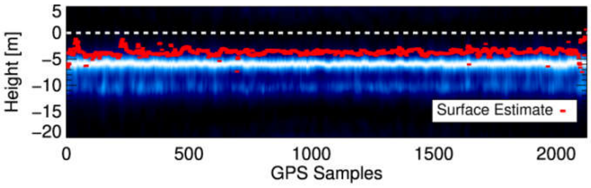

Figure 3 Capon tomogram from the upper percolation zone (South Dome) at L-band in HH polarization. The red line shows the surface estimation by means of the UV upperlimit parameter z_{ul} from the three-baseline full-pol inversion.

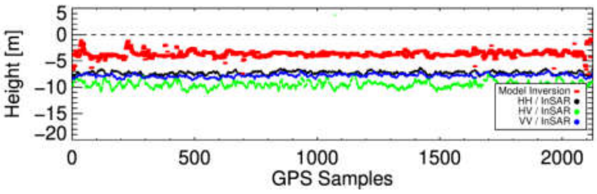

Figure 4 InSAR phase centers in three polarizations derived from one baseline ($k_{zVol} \approx 0.38$) compared to the surface estimate.

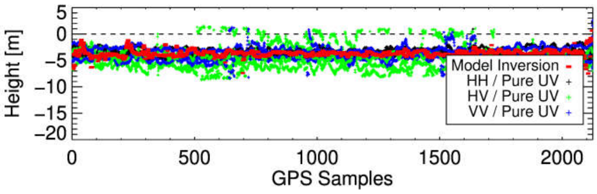

Figure 5 The surface estimate of the triple-baseline Pol-InSAR inversion (red line) compared to the surface estimates of a single-polarization single-baseline UV model inversion from the same baselines.

5 Conclusions and Outlook

The inversion of the subsurface scattering structure of ice sheets from Pol-InSAR data provides more reliable topographic information than the interferometric phase centers, which are conventionally used to derive digital elevation models from InSAR data. However, the tradeoff between model complexity and the available observation space has to be considered in the inversion. In this study, the use of triple-baseline full-pol Pol-InSAR data allows to increase the model complexity compared to existing approaches. A model setup of a polarization independent volume structure and a Dirac delta is investigated. This allows approximating polarization dependent volume structures or the effect of several distinct layers in the subsurface of ice sheets. The inversion performance is investigated with respect to the estimation of the surface location, which can be used to compensate the penetration bias of InSAR DEMs. The proposed approach was shown to provide robust estimates of the location of the first significant scattering contribution below the surface. Even though this obviously ignores the first few transparent meters below the surface, these estimates provide more reliable topographic information than interferometric phase centers. In comparison to the proposed triple-baseline approach, the results from a single-baseline single-polarization estimation of the penetration bias show a stronger variance across polarizations and baselines. There is still the need for further investigations regarding the minimization procedure, the baseline selection, the applicability to other frequencies and test sites as well as different model setups. However, the first results indicate that the triple-baseline full-pol inversion of Pol-InSAR data can provide more reliable estimates of the subsurface scattering structure and of the penetration bias than single-baseline approaches.

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