Assessment of the capabilities and limitations of polarimetric SAR for glaciological applications for wet, crevassed and dry surfaces of the Greenland ice sheet

iCUPE - Technical Report

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Assessment of the capabilities and limitations of polarimetric SAR for glaciological applications for wet, crevassed and dry surfaces of the Greenland ice sheet

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Polarimetric data enable glaciologists to extend the current portfolio of products, in particular those, that are beneficial for the assessment of the hydrology and structure of the upper layers of ice sheets undergoing melt and precursors of rapid changes as instabilities of glacier systems. This assessment is based on iCUPE polarimetric studies for Greenland demonstrating winter liquid water storage, classification of wet snow and crevasses, as well as an innovative approach for shear zone detection.

Glaciological needs

The structure of the upper tenths of metres of ice sheets is of large interest for glaciologists in both cold and wet conditions. Firn densification is an important factor for understanding the climate signal in ice cores for the reconstruction of the climate of the past. To understand present day changes, it becomes an urgent need to understand the melt water retention in the porous firn matrix and how this affects the melt of this firn itself. These processes have an important impact on the energy budget of the upper parts of ice sheets. Furthermore, they also control if water is buffered at the surface or reaches the glacier base. Once at the base, this water can lubricate the ice flow and trigger dynamic ice flow with large potential impacts of future changes.

With an increasing availability of melt water at the ice sheet surface in Greenland, supraglacial lakes are forming in vast areas. Detection of the evolution of these lakes, their drainage dynamics and their capability of storing water over longer time periods (and thus extending their effect on ice sheet dynamics over the melt season period) is important to assess their effect on ice sheets. Even under a limited climate warming as settled in the Paris Agreement, these effects will intensify and become more crucial due to the polar amplification of the climate signal. Optical satellite data allow to study supraglacial lake formation during summer periods. However, this technique is limited by cloud coverage and polar night. Hence, weather and sunlight independent satellite radar imagery is a key technique to monitor these changes.

Vast crevasse fields exist in the vicinity of the grounding lines, along tidewater glacier margins and at the onset of fast flowing ice streams. The formation, orientation and density of crevasses is a consequence of stresses in glaciers, thus observation of these quantities enables glaciologists to infer stresses states. This field is yet not explored intensively, but is strengthening our capabilities to access fast change, like in instabilities of ice shelves, floating tongues or ice sheets, as the West Antarctic Ice Sheet. Progression of crevasse zones further inland is a clear signal of changing stresses and an advance warning. This propagation can only be detected by radar satellites in high resolution.

The West Antarctic Ice Sheet is potentially approaching a tipping point. The current observed changes are in the area of Pine Island and Thwaites glaciers, that contain a sea level equivalent of 1.2 m (Bamber et al., 2009; Joughin and Alley, 2011; Ritz et al., 2015; Scambos et al., 2017). As instabilities of such vast ice masses have never been observed by mankind, the time scale is yet unclear - it thus may range from days to centuries. An early warning system about critical states of these regions can feed into an early warning system for coastal planners. One such system could be the detection of changes in crevasse fields, based on polarimetric SAR.

General principles of polarimetry

A radar signal can be transmitted in any specific polarization. As displayed in Fig. 1 the orientation can be vertical, horizontal or it can even change over time and result e. g. in a circular polarization. When this signal is reflected from the ground, the interaction with the scattering medium influences the polarization. Hence, the polarization of a SAR signal contains additional information about the observed objects.

Dual polarimetric

In dual polarimetric mode, a satellite transmits a signal in one specific polarization but records both polarization components of the return signal. Over some specific orbits over Greenland, Sentinel-1 transmits a horizontally polarized signal but records the horizontal (HH or co-pol) and in vertical component (HV or cross-pol) of the return. As shown in the lower part of Fig. 1, a return signal from an ice sheet surface consists of a co-pol and a cross-pol part, as parts of the signal are modified due to volume scattering within the uppermost layers. In contrast, the interface between a supraglacial water body and air or ice above such a lake has a very strong dielectric contrast and, hence, acts as a surface scatterer for the radar signal. This results in a characteristic signature of an ice covered supraglacial lake, allowing to monitor these important features during the whole year, which would not be possible from optical satellite images (due to snow cover and polar night) or even single polarimetric HH SAR data.

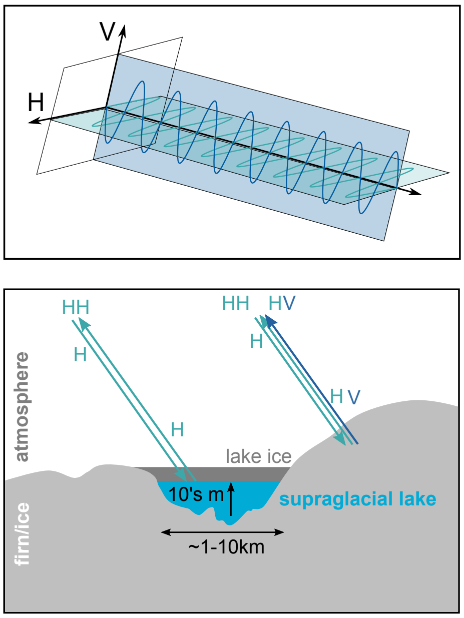

Figure 1: Top: Schematic representation of horizontal and vertical polarization. Bottom: Characteristic reflection mechanisms on an ice sheet with a supraglacial lake.

Furthermore, the backscattered radar power from an ice sheet is also sensitive to the dielectric properties of the snow, firn or ice at the surface. The total return power is influenced e.g. by wetness or changes in conductivity, but also depends on variations in geometric properties such as surface roughness, grain size distribution and the internal structure (Fahnestock et al., 1993). All these are important parameters for understanding ice sheet processes. However, in the backscattered signal power all these effects are cumulated and a separation of single parameters is not trivial. In order to obtain specific parameters from the backscattered power, the scattering behavior of the surface needs to be modelled adequately and several assumptions are necessary in the model setup (Sharma et al., 2011; Parrella et al., 2016). Dual polarimetric SAR provides two observations, which can be interpreted as surface and volume scattering. Hence, with the help of prior knowledge about the other factors, these observations can be used for a range of further applications as described below.

Full polarimetric

In addition to the dual polarimetric mode, also the polarization of the transmitted signal can be switched frequently between horizontal and vertical orientation. The four resulting channels HH, HV, VH and VV contain additional information and would help to reduce the need of assumptions on the scattering material. According to Freeman and Durden (1998), measurements of a full polarized SAR system can be decomposed into the simple scattering mechanisms of single bounce, double bounce and volume scattering. In the absence of a vertical transmit channel (dual polarimetry), the surface scattering components single bounce and double bounce scattering cannot be separated. For some applications, as the detection of supraglacial lakes, this is acceptable. However, for a deeper understanding of the ice sheets, additional observations are necessary. This could, for instance be important for a more reliable detection of crevasses or for a better understanding of the refreezing processes of meltwater in ice lenses and ice pipes.

Beyond the backscattered power of the different channels, a full polarized system is of main importance for the analysis of the phase information of the return signal (see Sect. below). The phase difference between HH and VV can be interpreted as small scale range differences to the effective scatterer for each polarization within a single scene. This range difference contains important information about the internal structure of the reflecting material. Analyzing several successive scenes allows to study their changes over time. This could help to improve glaciological and meteorological models and could also help to better interpret the effect of an observed elevation change to sea level. In contrast, the phase difference between the co-pol and the cross-pol channel (e.g. for HH and HV of a S1 scene) is ambiguous due to the random scattering of the volume component of the signal.

PolInSAR

Interferometric processing of two SAR scenes (InSAR) from slightly different orbit locations allows to derive the topography of the observed surface by analyzing the phase difference of the return signals. Due to the signal penetration into the uppermost layers of an ice sheet, the decorrelation between two scenes can be used to study the subsurface characteristics (Hoen and Zebker, 2000). Extending InSAR to different polarizations (PolInSAR, Cloude and Papathanassiou, 1998) allows investigating the vertical distribution of different scattering processes and is currently mainly applied for forest applications. With the help of experimental results during an airborne campaign in Greenland, Fischer et al. (2018, 2019) demonstrated the potential of PolInSAR also in the application to ice sheets. The combination of several interferometric baselines with different polarizations and different signal frequencies allowed to derive a model for the vertical structure of the firn layer. This is key for many glaciological applications. However,

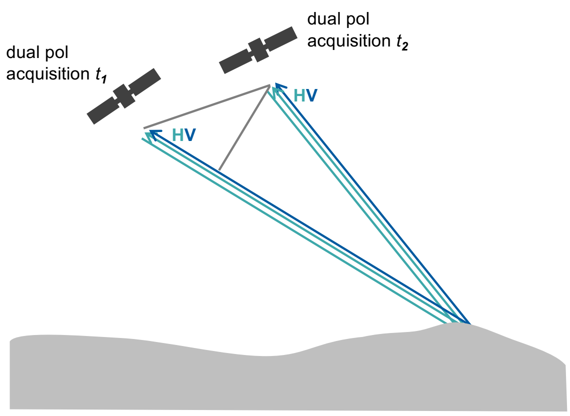

Figure 2: Schematic of the principle of PolInSAR with two different acquisitions at time t_1 and t_2, recording two polarizations of the return signal each.

the parametrization of these models requires several assumption and further research is needed to justify these assumptions and to make the models more robust. Furthermore, these studies were limited to a very small test site. Only a satellite mission can obtain such observations on larger scales and, hence, provide firn parameters on an ice sheet scale.

Beyond enhancing the glaciological understanding of firn composition and processes, these firn parameters can also provide important information for the interpretation of the measurements of other satellite missions. Radar based elevation measurements as InSAR or Altimetry suffer from biases due to weakly constrained signal penetration into the top layers (Dall et al., 2001; Helm et al., 2014). More detailed information about the subsurface structure and their temporal variations could provide key information for a correct interpretation of these data.

Applications using Sentinel-1 over Greenland

First glance into application of Pauli images

A first level of analysing full polarimetric data is using the Pauli vector, that assings [HH-VV], [HV] and [HH+VV] to RGB, that is often used to understand the dominant scattering mechanism. Although Pauli images are difficult to interpret, this simple example in Figure 3 shows, that this type of analysis might be well suited for analysing structures arising from water percolation/retention. Figure 3 suggests, that drainage channels of supraglacial lakes are detectable. These drainage channels are crack systems that do not heal entirely after drainage. However, ground truthing data and also extensive time series of classical SAR data are required for establishing reliable interpretation.

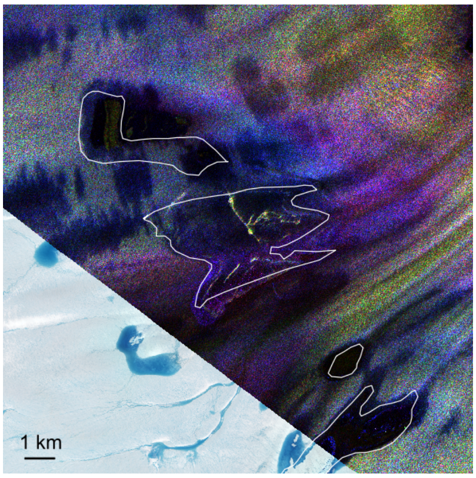

Figure 3: Pauli representation of an ALOS PALSAR image (2007-04-03) of several supraglacial lakes (white lines) at 79NG, showing [HH-VV], [HV] and [HH+VV] as RGB.

Lake classification - winter liquid water storage

Based on the detection of different scattering mechanics in polarimetric SAR we developed and tested an algorithm for supraglacial lake detection. We see a strong contrast between the surface-dominated reflection from the top of the lakes and the volume-dominated reflection of the ice next to the lakes (see Fig. 1). Existing lake classification algorithms are based on optical data, which work well for open water surfaces. However, under bad weather conditions, during polar night or when the lake is covered by ice and snow, supraglacial lakes cannot be identified from optical images. In contrast, as an active sensor, SAR does not depend on daylight and the signal can penetrate clouds and even a layer of snow and ice (depending on the frequency). We found that most supraglacial lakes do not drain or freeze through at the end of the summer. They get covered by a lid of ice and fresh snow but can persist for many years. The accompanying flight campaign of this project confirmed these

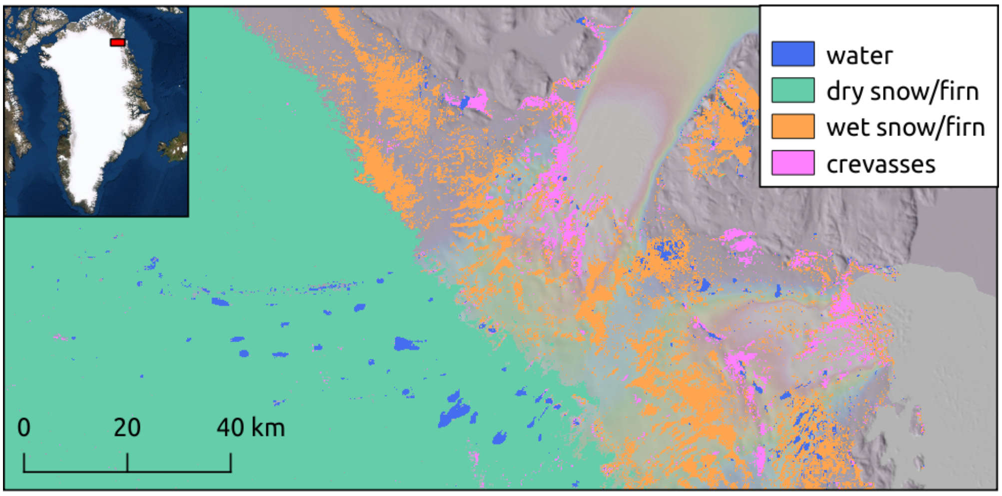

Figure 4: Example of surface types classification from a dual polarimetric Sentinel-1 scene from 2018-08-20.

findings and detected an ice lid covering the lake with a step-like structure. During each winter the thickness of the lake ice increases and due to the ongoing ice flow, the downstream part of the ice lid reached a thickness of up to 10 m.

Large parts of the supraglacial lakes, detected by our algorithm, remained ice-covered, even during the summer. This means that the total volume of supraglacial water is significantly larger as previously thought. However, it also means that most of the water remains liquid at the ice sheet surface, which is an important finding for modelling the surface heat budget. The existence of such lakes over long time periods requires sufficient heat to prevent freezing through. An independent detection of lake ice coverage over time, combined with the polarimetric based time series would improve the heat budget estimates of these lakes and, hence, improve the understanding of the whole system.

The application of lake classification has been our focus within the iCUPE project. However, this technique is also promising for ice marginal lake detection. Similar to supraglacial lakes, ice marginal lakes also store water longer than the duration of the melt season. As their detection is currently mainly based on optical imagery, their monitoring is also limited to the summer season and hindered by cloud cover. Ice marginal lakes are a source for hydropower but at the same time, they are also a risk for several settlements. Hence, monitoring these ice marginal lakes can be of high importance for the Greenlandic authorities.

Dry and wet snow/firn classification

The penetration depth and, hence, the backscattered power of the radar signal is very sensitive to the snow wetness. Existing approaches already analyze the co-pol backscatter (HH or VV) in order to distinguish between dry and wet snow/firn conditions. However, the variation of the co-pol backscatter can be influenced by many different factors as grain size, internal structure, dirt or crevasses. Hence, classifying these regions within a single scene using a single threshold for all pixels cannot provide reliable results. Therefore, existing approaches analyze the yearly cycle of backscattered power within a certain location separately to derive the start of the melt season (Nagler and Rott, 2000). In contrast, our polarimetric classification approach is able to distinguish between wet and dry within one scene directly. The cross-pol channel gives additional information towards the ratio between surface and volume scattering. Hence, using these two dimensions together with their spatial structure allows us to classify wet and dry snow within one scene.

In order to obtain further insights into the wetness of snow or firn, an experimental analysis of PolInSAR by Leinss et al. (2015) has shown promising results to obtain Snow Water Equivalent (SWE) on a test site in Finland. However, for a similar application on the surface of an ice sheet, a more complex parametrization would be necessary and further research is needed.

Crevasse classification

Crevasse detection using the polarimetric approach matches in our test area very well with the observed crevasses zones from optical imagery, onboard camera of Polar 5/6 and TerraSAR-X imagery. The results are promising and the technique can next be applied to study changes in crevasse zone extent in fast changing glaciers as of the West Antarctic Ice Sheet or tidewater glaciers in Greenland that are undergoing fast changes. Here, we suggest to conduct studies that are focussing on the potential to detect crevasse density, a quantity that would allow to obtain a measure for absolute damage, and to get further into classifying if the reflection of old crevasses with eroded crack faces can be distinguished from sharp, fresh crack faces. This would be of interest not only for change detection like for changing glaciers as response to climate change, but also be beneficial for classification of surfaces at the termini of tidewater glaciers, where mechanical calving laws might be able to parameterise the effect of surface melt water on calving rates based on this technique.

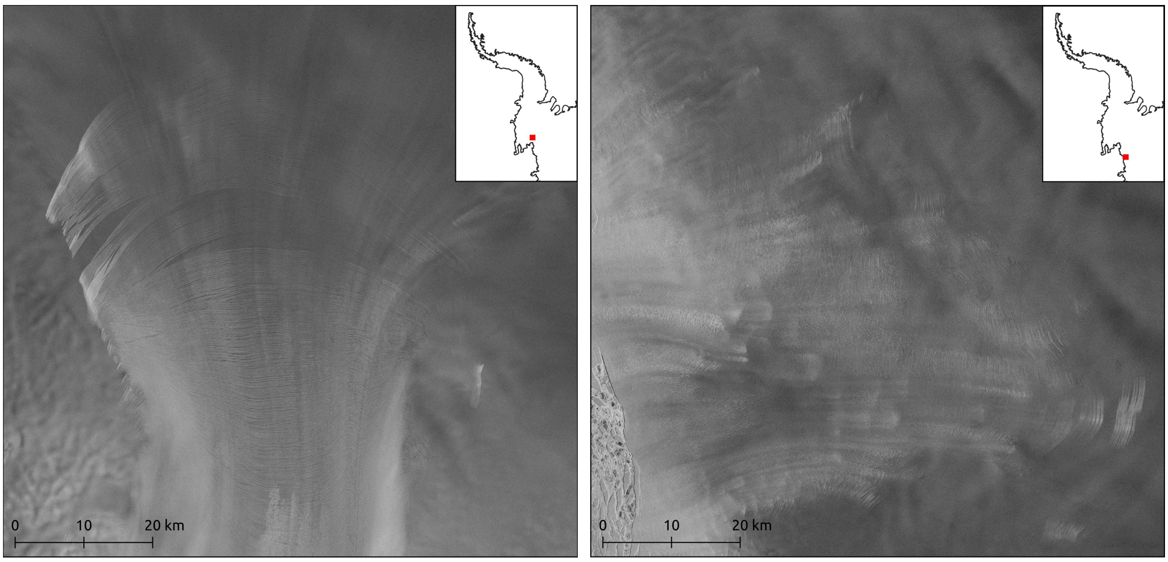

Figure 5: Crevasses upstream the grounding line of Pine Island Glacier (left) and Thwaites Glacier (right) as seen by Sentinel-1 in HH polarisation. This area of the West Antarctic Ice Sheet is projected to become instable and contains a sea level equivalent of 1.2 m, highlighting the importance of detecting change using remote sensing techniques.

PolInSAR example - shear zone

A simple application of the principle of PolInSAR in the area of the North-East Greenland Ice Stream is presented in Fig. 6. The phase difference between two acquisition times (InSAR) allows to determine a topography or the ice flow under some specific assumptions. Calculating the difference between these interferograms of both polarizations HH and HV as $\Delta\phi = (\phi_1^{HH} - \phi_2^{HH}) - (\phi_1^{HV} - \phi_2^{HV})$ removes the contribution of topography and the motion of the glacier. Hence, this difference $\Delta\phi$ represents the phase difference of the effective scattering center between the two acquisitions. This pattern shows a good agreement with the shear margins from strain-rate results derived from InSAR based velocity fields. However, we also find patterns that are not in connection with shear deformation.

This bears large potential in enhancing classical strain-rate results, which often suffer from noise or systematic errors in the flow velocity data, but also opens possibilities for further applications, which are by now not fully understood. Given that shear margins and also change in shear margin positions is of large interest for glaciologists, an ice sheet wide applications of this technique should be compared with airborne ice penetrating radar that can resolve also old, buried, shear margins over the depth of the glacier. This could provide additional data to constrain and, hence, to improve ice sheet models.

This is just one relatively simple example where PolInSAR is opening new opportunities for classifying glaciological quantities. However, a full exploitation of the potential of PolInSAR would require full polarized observations in a repeat orbit that allows a range of different baselines. Even more insights could be obtained if such observations would be performed at different frequencies. The different penetration depths of different frequencies would e.g. allow to combine the observations and to obtain firn parameters that reach significantly further into the snow pack and provide a much higher resolution.

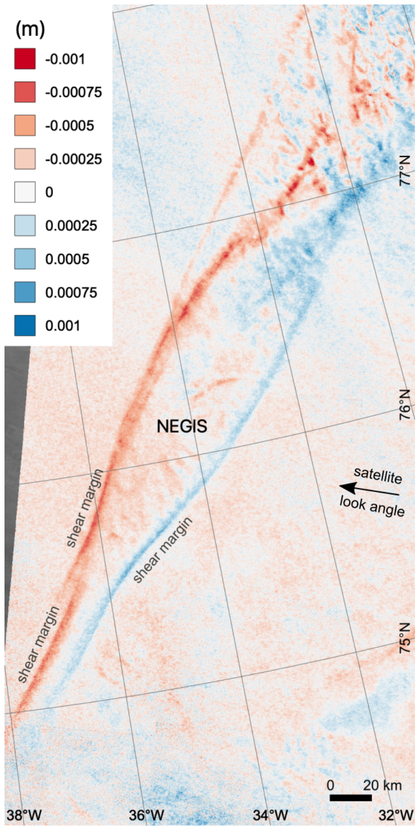

Figure 6: PolInSAR example of the NEGIS, Greenland.

Polarimetric ice penetrating radio echo sounding

The principle of polarimetry can also be applied in ground or airborne-based ice penetrating radar. The difference to satellite-borne application is that the depth of the reflection is recorded and that the technique is currently applied in nadir geometry. The reflected signal contains two types of informations: birefringence and crystal anisotropy. To distinguish between these contributions the angle dependence of the reflections need to be recorded. Ground-based applications are changing orientation of the antenna typically in steps of 22.5°steps.

First studies of polarimetric measurements using a phase sensitive radio echo sounder (pRES) demonstrate, that crystal anisotropy of the ice can be inferred. Crystal anisotropy is created by the deformation of polycrystalline ice in glaciers over long time periods. Figure 7 shows measurements conducted at the deep drill position EGRIP. The anisotropy of the ice is measured from samples of the ice core, which allows to compare in-situ measured crystal anisotropy and anisotropic radar reflections. The capability of polarimetry to detect anisotropy would allow to assess ice sheet deformation patterns over larger horizontal extent, as it is current only available at few positions of deep drills. Crystal anisotropy sets in typically a few hundred meters below the ice sheet surface, thus even in L-band would not allow us to access this quantity from space.

In our studies, we found anisotropic surface reflections in the upper layers of the ice sheet. It is yet unclear, what exactly causes this type reflection. We consider former surface roughness, like arising from sastrugis or dunes, to play a role. This roughness is on a spatial scale that can be sounded with airborne laser scanners. This shall be further investigated in future studies.

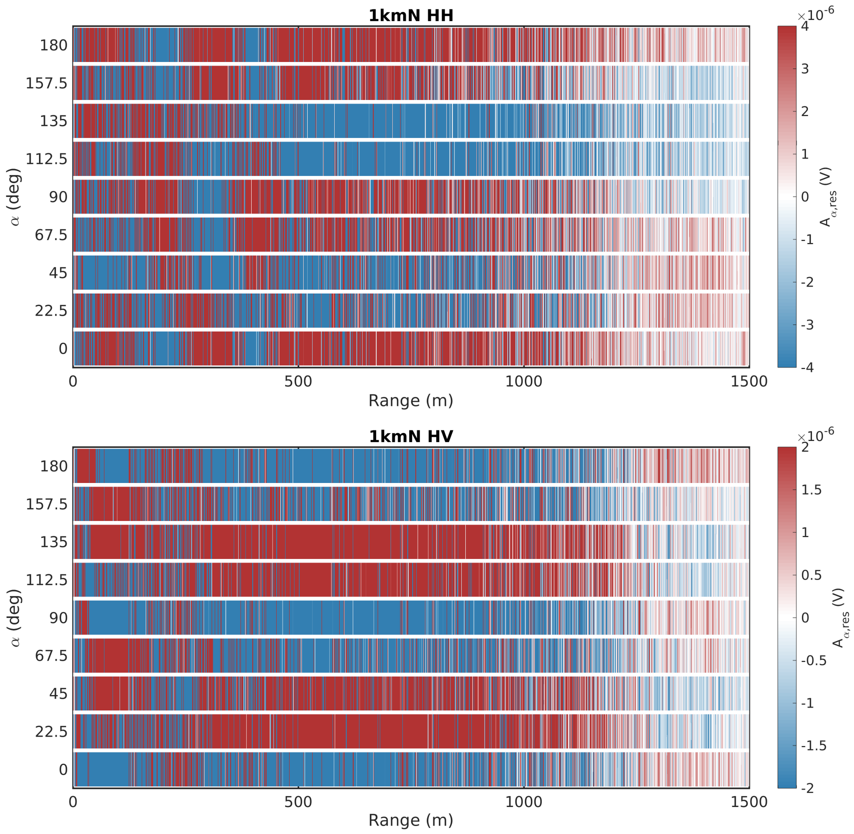

Figure 7: Polarimetric pRES measurement in HH and HV 1 km next to EastGRIP ice core.

In future AWI's airborne ultrawideband (UWB) radar system will also be used to acquire polarimetric ice penetrating data. This field is yet unexplored, but given the ground polarimetric applications, this may open completely new opportunities. This system will also allow to retrieve ground truthing data for missions like Tandem-L in particular as the retrieved signal has a high depth resolution. In the long term perspective, satellite-borne, air-borne and ground based ice penetrating radar combined with shallow, medium and deep drills, is an observational system that enables the development of reliable retrieval algorithms enlarging the portfolio of satellite data products of glaciological relevance.

Recommendations for future satellite missions

Glaciological interest in future satellite data lies mainly in classifying surface types, resolving internal structure of the upper layers of ice sheets and detecting changes over time. For this purpose a combination of polarimetric capabilities in X-, C-, and L-band are expected to boost knowledge beyond current limits. Important are repeat visit times of 6 to 11 days, given that margins of ice sheets are moving fast and are the zones of largest changes. The orbits of X-, C- and L-band missions should be coordinated such, that a subset of cycles over the Greenland ice sheet allows to acquire all bands in similar look angles and nearly synchronous. Given that the melt season will alter the penetration depth on time scales of hours to days, a synchronous operation of polarimetric X- and C-band missions would be highly beneficial when monitoring the hydrological system of firn over Greenland. As water retention in firn is limiting mass loss estimates using altimetry and melt in Greenland will be increasing in future, this is becoming more important over time.

Ultimatively, layering of the upper hundred meters, as it would be available from full polarimetric SAR tomography in L-band, would be a break-through in knowledge of the structure of ice sheets over large horizontal scales and high vertical resolution.

Our capacity to assess the benefit of quad pol versus dual polarimetric data is currently limited by both, the available satellite datasets and comparison to synchronously acquired airborne or ground ice penetrating radar over ice sheets.

We found that the comparison to nearly synchronous acquired airborne ice penetrating radar data was necessary to validate the polarimetric supraglacial lake detection. Similarly lack of such data limits the understanding of patterns found using PolInSAR, in particular if not dealing with larger features, but e.g. roughness of internal layers, alteration of the firn by melt water pipes or refrozen aquifers. In summary: polarimetric missions are enabling glaciologists to extend the current portfolio of products, in particular those that are beneficial for the assessment of the hydrology and structure of the upper layers of ice sheets undergoing melt and precursors of rapid changes as instabilities of glacier systems.

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