Multi-Frequency Analysis of Snow-Covered Areas using SAR-Polarimetry

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Ziel dieser multi-Frequenz Analyse von C-Band (quad-pol), X-Band (dual-pol) und Ku-Band (dual-pol) SAR-Daten von Schneegebieten in Sodankylä, Finnland, ist die Invertierung des Schneewasseräquivalents (SWE) für den Winter 2011/2012. Dabei wird das Vorwärtsmodell und der Invertierungsalgorithmus der ESA CoReH$_2$O Mission verwendet. Es wird untersucht, inwiefern jede der drei Frequenzen unabhängig voneinander dafür geeignet ist. Außerdem wird analysiert, ob ein Vorteil darin besteht, nach einer Dekomposition der quad-polarisierten C-Band Daten nur den Volumenanteil der Rückstreuung für die Invertierung zu nutzen. Die Ergebnisse zeigen, dass im X-Band der gemessene Trend des SWE teilweise reproduziert werden konnte. Im C-Band jedoch sind die Invertierungsergebnisse nicht zufriedenstellend. Eine zusätzliche Eigen-Analyse der C-Band Daten zeigt allerdings einen signifikanten Zusammenhang mit dem Tau- und Gefrierzyklus des vom Schnee bedeckten Bodens.

1 Introduction

Monitoring of Earth‘s snow reservoirs and their dynamic over time is increasingly important in the context of climate change. The large scale retrieval of snow parameters, such as snow water equivalent (SWE), with Synthetic Aperture Radar data can provide essential information about fresh water resources. In this multi-frequency analysis of C-band (quad-polarized), X-band (dual-polarized) and Ku-band (dual-polarized) radar data of snow cover in Sodankylä, Finland, SWE was retrieved for a time series within the winter season 2011/2012. For that purpose, the forward model and inversion techniques of ESA's CoReH$_2$O mission were used. The inversion algorithm has been originally developed for a dual-frequency dual-polarization approach at Ku-band (17.2 GHz) and X-band (9.6 GHz) combined (NAGLER et al., 2008). For this study however, it was analyzed, how the different frequencies perform in a single-frequency approach using VV and VH polarization, and in particular, what C-band can contribute to a SWE inversion. By comparing dual-polarized with quad-polarized data, it was also examined, whether there is an advantage of decomposing the total backscatter into volume and ground surface components and, subsequently, of using only the volume backscattering in the inversion process for SWE. Thus, bypassing a parameter-expensive soil surface scattering model in the inversion process is possible. A polarimetric eigen-analysis of the quad-polarized C-band data was also performed, in order to analyze an assumed connection to freezing and thawing processes under the snow cover.

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2 Multi-Frequency Analysis

2.1 Data Description

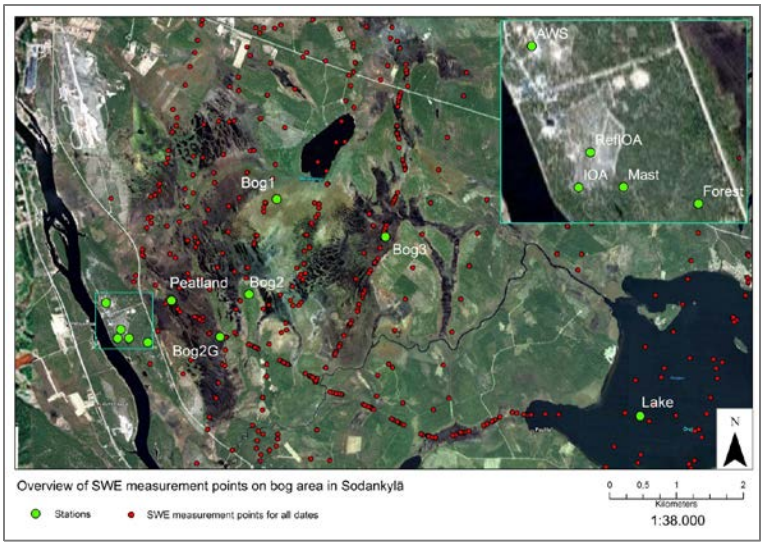


Figure 1 Map of the Sodankylä area with location of different stations, where SWE was retrieved (green dots). Apart from boreal forest, the land cover is mostly characterized by open bog, which was used for SWE inversion.

A test site in Sodankylä, northern Finland, at the location of the Finnish Meteorological Institute – Arctic Research Centre was chosen for research (see Figure 1). Time series of quad-polarimetric (HH, HV, VH, VV) Radarsat 2 C-band data (10 dates), as well as dual-polarimetric (VV, VH) TerraSAR-X X-band data (23 dates) and SnowSAR Ku-band data (2 dates) were available for analysis from October 2011 to May 2012. The coverage of the entire winter season 2011/2012 gave the opportunity to investigate the complete period from snow accumulation to snow melt and from soil freezing to thawing. The radar data were complemented by ground measurements of SWE, snow depth, soil moisture and various meteorological and hydrological parameters for analysis and validation.

2.2 Methodology

2.2.1 Forward Model for Backscatter from a Snow-Covered Ground

A SWE inversion technique, including a dual-polarization scattering model from the CoReH$_2$O mission was tested at X-, C- and Ku-band. The forward model is based on a semi-empirical radiative transfer method developed by ULABY et al. (1984), which relates the measured snow backscattering signal to the target parameter SWE. The assumed scattering scenario from a snow-covered ground is illustrated in Figure 3. Here, only volume and ground scattering components (after transmission through the snow pack) are taken into account.

The forward scattering model requires the six input parameters of SWE, snow grain size, snow density, snow temperature, permittivity of frozen soil and the standard deviation of ground surface height. The two free parameters of the forward model, SWE and snow grain size, are retrieved in the inversion procedure. For driving the forward model in the inversion process the remaining parameters were fixed using *in situ* measurements and the available SAR data, adapting the procedure as well as possible to the local environmental conditions on the test site.

2.2.2 Inversion Procedure for SWE

For the SWE retrieval, an optimized statistical inversion procedure, based on the approach by ROTT et al. (2010), was implemented. Figure 2 shows an overview of the inversion process. It iteratively minimizes a cost function, i.e. the error between the simulated backscatter from the forward model and the measured backscatter, as well as between guesses of SWE and grain size and a set of regularization values. The Nelder-Mead Algorithm is implemented for optimization of SWE and grain size guesses. As input observables for the SWE retrieval the total backscatter coefficients for each frequency were taken (VV, VH). Additionally, at C-band the scattering mechanisms were decomposed and an inversion was done separately with only volume scattering powers to investigate the potential of quad-polarimetric data and the possibility to neglect the ground scattering component of the model. Thus, four different inversion scenarios were implemented and compared, indicated by the four yellow circles on the input side in Figure 2.

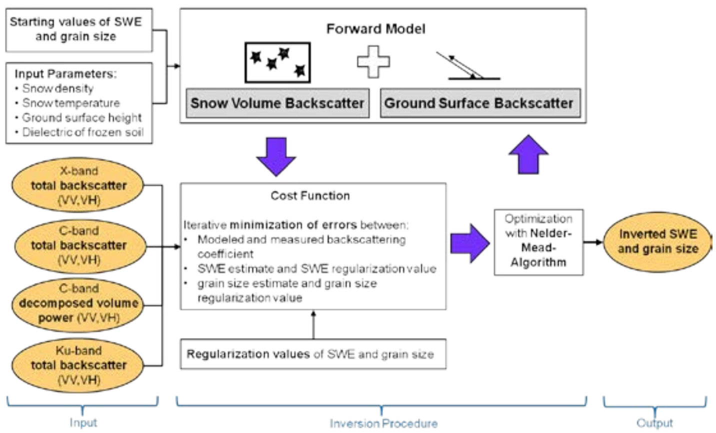


Figure 2 Inversion procedure for retrieving the snow water equivalent.

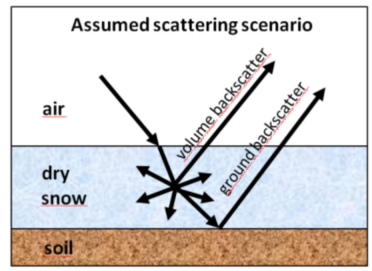


Figure 3 Simplified scattering contributions from a dry snow pack on ground (after ROTT et al., 2010).

2.3 Results and Discussion

2.3.1 Inversion of Snow Water Equivalent

Figure 4 illustrates the SWE inversion results for X-, C- and Ku-band for all four inversion scenarios compared to SWE values from *in situ* measurements. The inversion was done at the four test sites RefIOA, Bog2G, Bog3 and Peatland, due to the absence of a strong vegetation influence at these locations.

Ku-band: The retrieved SWE in Ku-band (purple diamonds) is always underestimated for each date and test site, but the restriction to only two acquisition dates limits a thorough interpretation.

X-band: The results of SWE retrieval from total backscatter are represented by the dark blue line. Only the period, where the snow cover is expected to be dry (white area), can be considered for interpretation. Outside of this period (grey areas) the snow might be wet due to positive air temperatures. The inverted SWE values between mid December 2011 and end of April 2012 in the dry snow cover period show an upward trend, as can be seen from the measured SWE values. The inversion outcomes reveal a fluctuation around the measurements, a variability caused by the sensitivity to model input parameters (RMS surface height and snow density). At RefIOA the inversion performs worst, which results in an inverted SWE curve dropping too early in March 2012. The disadvantage of using only dual-polarized data in this case is the restriction to include the ground surface component of the backscatter signal. A previous study by PISCIOTTANO (2012) using quad-polarimetric X-band data and only the decomposed volume scattering component has already shown better applicability.

C-band: The inversion results in C-band do not show a sensitivity for snow parameter retrieval with this algorithm. The inversion from C-band total backscatter (green solid line), as well as the decomposed volume component (green dashed line), cannot reproduce the trend of the measured SWE values. Thus, for SWE retrieval there is no improvement from a decomposition with quad-polarized C-band data and the use of only the snow volume component for SWE inversion. The results from both C-band inversion scenarios are a significant indication that this frequency exhibits no distinct direct interaction with snow properties. Hence, there seems to be no use of inverting with C-band data within the present implementation of the CoReH$_2$O forward model and inversion technique.

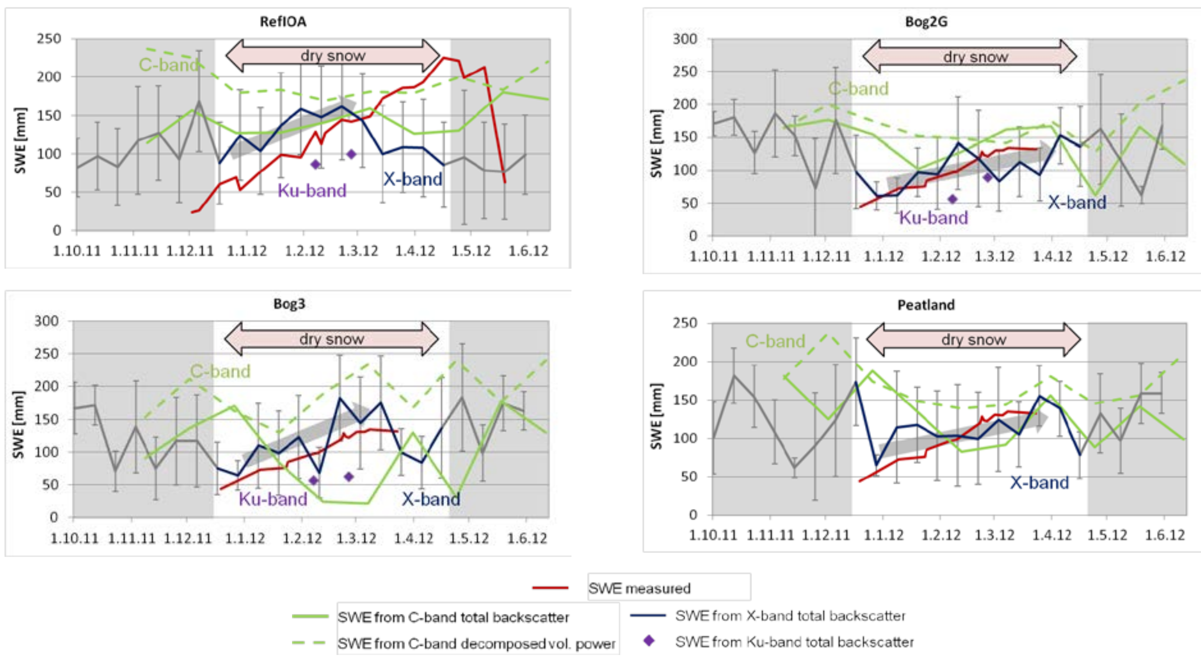
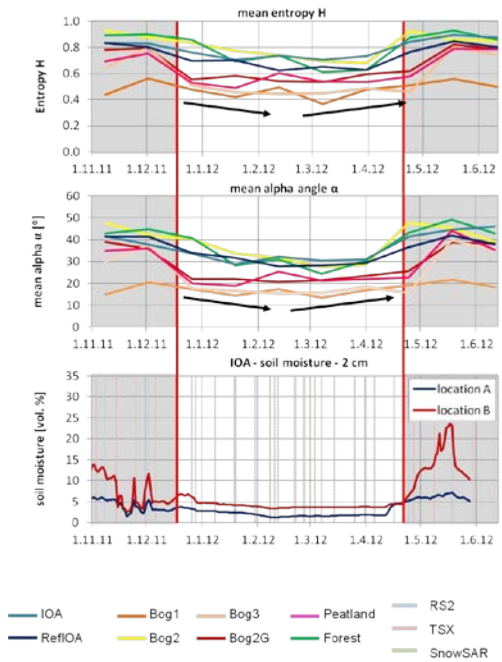


Figure 4 SWE inversion results for C-, X- and Ku-band from all four inversion scenarios compared to measured SWE values (red). Grey bars to both sides indicate the invalid areas for SWE inversion due to mainly wet snow conditions or lack of snow at the end of the winter period.

2.3.2 Polarimetric Analysis over Snow-Covered Areas in C-Band

Despite the poor performance of C-band for snow water equivalent retrieval, this data indicated potential to provide information about the underlying soil. A polarimetric eigen-analysis of the quad-polarized C-band data shows a significant connection to the soil freezing and thawing states. The entropy H and mean scattering alpha angle values exhibit a noticeable drop during the time of soil freezing in the dry snow cover period and an increase when the soil thaws, as indicated in Figure 6 in comparison to the soil moisture content. The polarimetric H-α-planes in Figure 7 reflect the described behaviour in entropy and mean alpha angle and demonstrate a change in the scattering behaviour along the winter period. The H-α-planes indicate a change from high entropy volume scattering to medium entropy surface scattering and back afterwards. This means that the dielectric contrast is reduced during the winter as less water is contained in both, the soil and the vegetation (if present). Rough surface scattering has also been identified as the dominant scattering mechanism over frozen soils by ROUSSEAU et al. (2009).

The assumed connection of the eigen-based parameters to changing scattering mechanisms in the soil due to soil freezing and thawing cycles and a change in the soil dielectric constant can be further examined. When modelling the dielectric constant of the soil after ZHANG et al. (2003), it exhibits a major drop as soon as the temperature assumes negative values and the soil freezes (see Figure 5). At 5 GHz (C-band region) - that means for lower frequencies - the difference is especially pronounced with a jump of permittivity values from less than 2 to more than 11. This discrepancy can be used to distinguish frozen and unfrozen soil with microwave remote sensing. Applying the X-Bragg scattering model (after HAJNSEK et al., 2003) to simulate the entropy and alpha values for this range of dielectric constants for frozen and unfrozen soil, demonstrates a shift of the eigen-parameters between both permittivities depending on the frozen or thawed state of the soil. The modelled H-α-values decrease for freezing and increase for thawing processes. This fits the measured dynamics within the C-band data very well (see Figure 7).



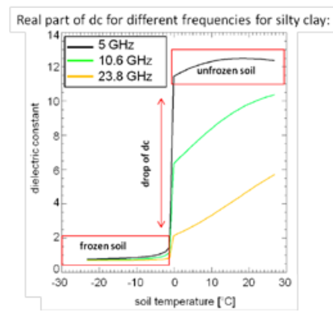


Figure 5 Modelled behaviour of the real part of the soil dielectric constant in dependence of soil temperature after ZHANG et al. (2003) for three different frequencies. For the C-band region the black 5GHz curve is applicable.

Figure 6 Entropy H and mean scattering alpha α time series from C-band data over the whole winter period 2011/2012 for different test site locations in comparison to measured soil moisture content in 2cm depth. Grey areas and red bars confine the dry snow cover period.

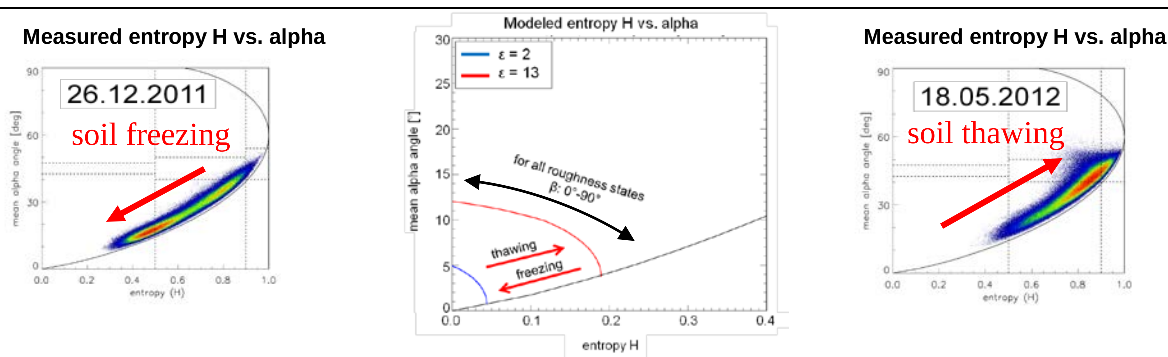


Figure 7 Modelled entropy H and mean alpha α values (graph in middle) with X-Bragg scattering model (HAJNSEK et al., 2003) for the two soil permittivities of $\varepsilon = 2$ and $\varepsilon = 13$ for all roughness states $\beta: 0° - 90°$. A clear shift in H-α-values between frozen and unfrozen state of the soil can be seen, a trend, which is also found in the measured H-α-values in the early and late winter period (left and right).

3 Conclusion

In this study the performance of a CoReH_2O inversion algorithm for SWE was tested for the first time for three different microwave frequencies in a single-frequency approach. It was also analyzed, whether having quad-polarimetric data available might prove beneficial. In conclusion, the retrieval of SWE from dual-polarimetric X-band data showed first promising results. The measured upward trend of SWE is partly reproduced; however, using quad-polarimetric data, which allows concentrating only on the volume scattering, might be more suitable. It was also found that C-band in dual-polarization as well as quad-polarization configuration performs unsatisfactorily in comparison to X-band for SWE retrieval. Separating the different mechanisms by SAR polarimetry is not of benefit in this frequency. A polarimetric eigen-analysis of the quad-polarimetric C-band data, however, revealed a significant correlation to the underlying soil and its freezing and thawing processes and not to snow cover. Hence, it is easily possible to establish a robust correlation between the polarimetric entropy and mean scattering alpha values and the dielectric constant of the (snow covered) soil during the entire winter period.

4 References

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