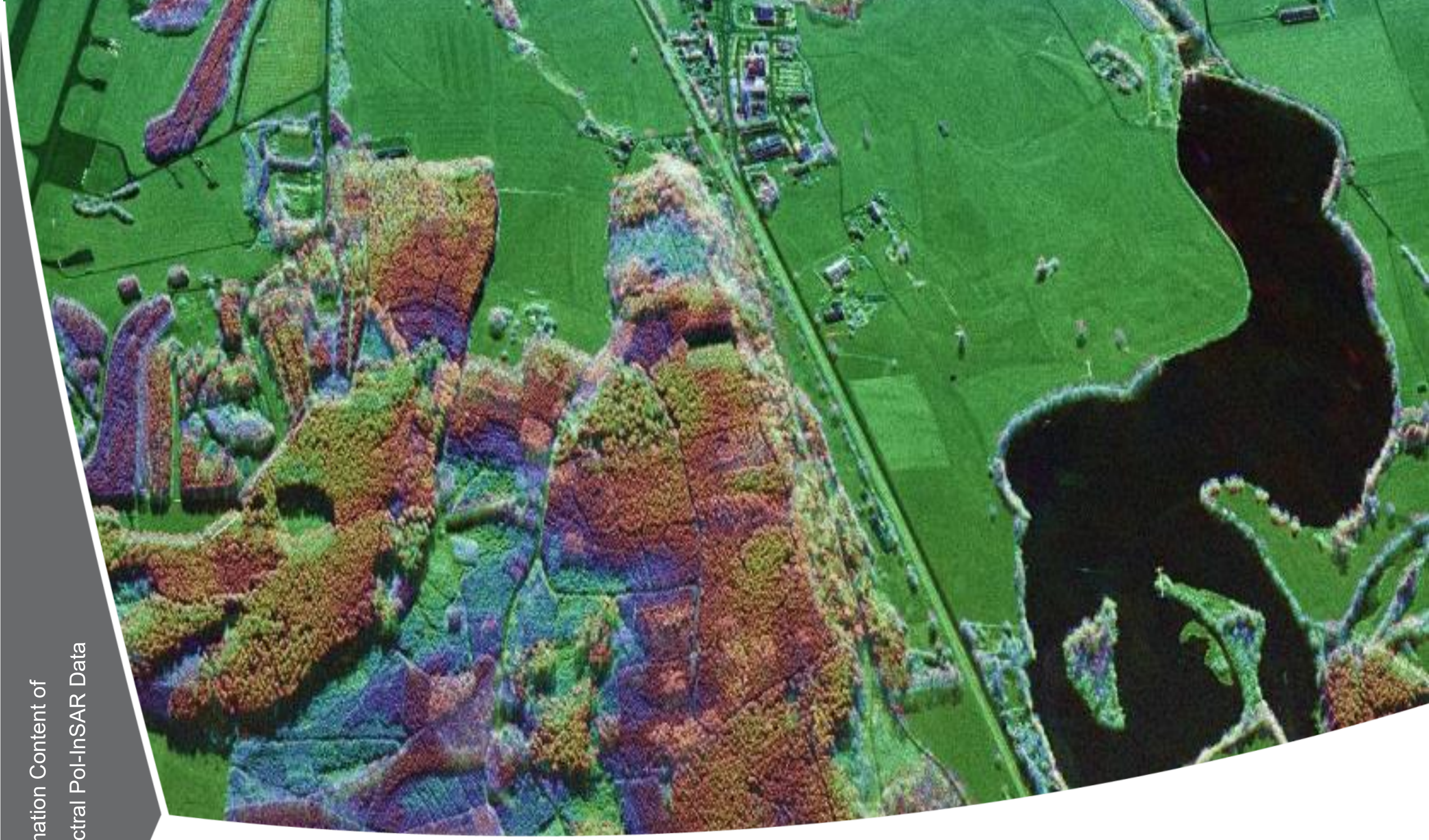

Information Content of
Multi-Spectral Pol-InSAR Data

ESA Contract no. 4000133590/20/NL/AS/hh
Information Content of Multi-Spectral Pol-InSAR Data

EXECUTIVE SUMMARY REPORT

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DLR Universitat d'Alacant Universidad de Alicante enveo ETH

Authors

Organization	Name	Document sections
DLR-HR	Matteo Pardini	All

Custodian of this document is Matteo Pardini, DLR-HR
Email matteo.pardini@dlr.de
Phone +49 8153 28 1168
Fax +49 8153 28 1135

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DOCUMENTS

Applicable Documents

[A1] ESA Statement of Work "Information Content of Multi-Spectral Pol-InSAR Data", ESA-TECEFW-SOW-0188, Issue1, 22.09.2020, A0/1-10331/20/NL/AS/hh.

[A2] DLR, University of Alicante, ENVEO, ETH, "Information Content of Multi-Spectral Pol-InSAR Data" Technical Proposal in response to ESA A0/1-10331/20/NL/AS/hh", 11 December 2023.

[A3] DLR, University of Alicante, ENVEO, ETH, "Deliverable D1 – ATBD on Multi-Spectral and Multi-Temporal Pol-InSAR Forward Models – Version 1", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A4] DLR, University of Alicante, ENVEO, ETH, "Deliverable D2 – ATBD on Multi-Spectral and Multi-Temporal Pol-InSAR Inversion Models – Version 1", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A5] DLR, University of Alicante, ENVEO, ETH, "Deliverable D3 – Uncertainty estimation analysis – Version 1", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A6] DLR, University of Alicante, ENVEO, ETH, "Deliverable D4 – Technical Note on Generalised Pol-InSAR architecture – Version1", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A7] DLR, University of Alicante, ENVEO, ETH, "Deliverable D5 – Multi-Spectral and Multi-Temporal Pol-InSAR Data Set Description", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A8] DLR, University of Alicante, ENVEO, ETH, "Deliverable D6 – Sensitivity Analysis of the Multi-Spectral Pol-InSAR signatures", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

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[A11] DLR, University of Alicante, ENVEO, ETH, "Deliverable D2 – ATBD on Multi-Spectral and Multi-Temporal Pol-InSAR Inversion Models – Version 2", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A12] DLR, University of Alicante, ENVEO, ETH, "Deliverable D3 – Uncertainty Analysis – Version 2", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A13] DLR, University of Alicante, ENVEO, ETH, "Deliverable D4 – Technical Note on Generalised Pol-InSAR architecture – Version 2", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A14] DLR, University of Alicante, ENVEO, ETH, "Deliverable D8 – Performance Analysis", ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

[A15] DLR, University of Alicante, ENVEO, ETH, "Deliverable D9 – Lessons Learned and Recommendations, ESA contract no. 4000133590/20/NL/AS/hh, 11 December 2023.

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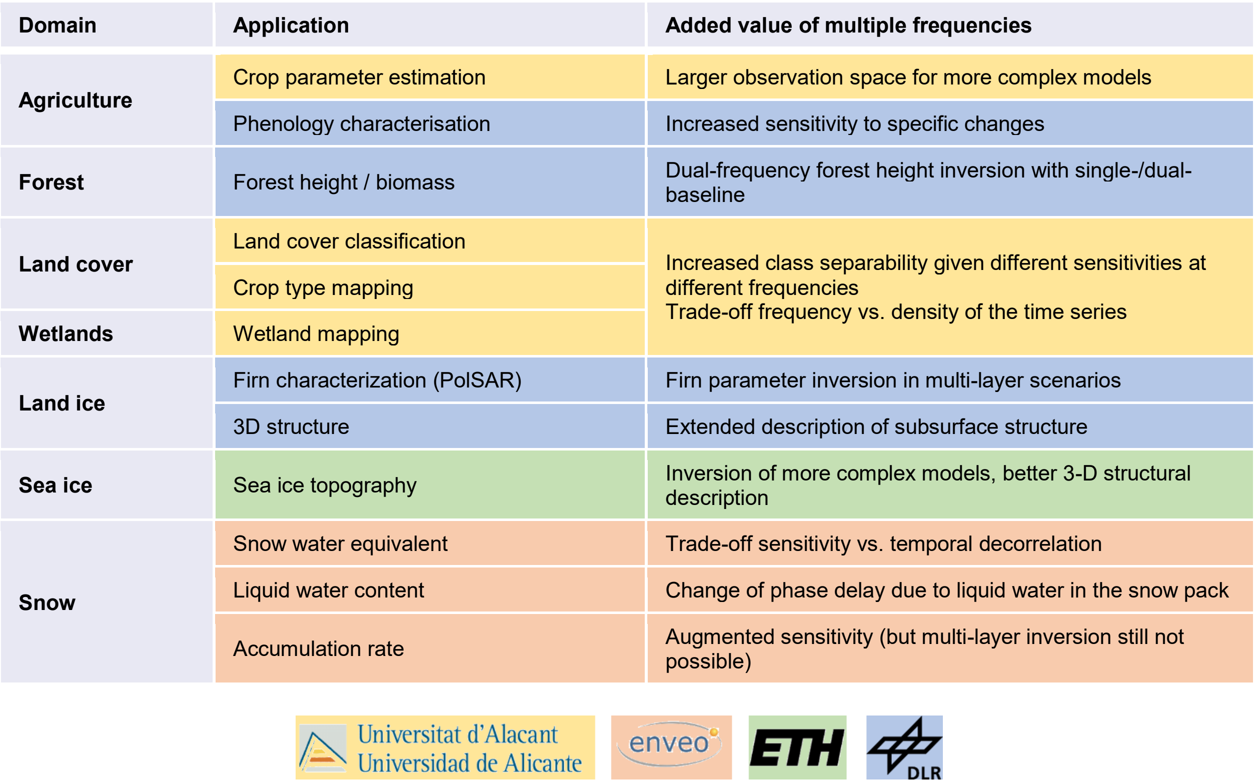
1 INTRODUCTION

The inherent sensitivity of the interferometric (InSAR) coherence to the vertical reflectivity of volume scatterers combined with the potential of SAR polarimetry (PolSAR) to characterise individual scattering processes allowed the development of unique applications. In the last years polarimetric interferometry (Pol-InSAR) had a dynamic development and advanced to an umbrella term for a range of processing techniques and inversion algorithms for quantitative and qualitative remote sensing applications. At the same time Pol-InSAR evolved from single- to multi-baseline and tomographic configurations raising its potential to a new level. The fact that the vertical reflectivity of natural and man-made volume scatterers depends on the frequency of the SAR configuration employed to perform the Pol-InSAR measurements opens the way to address multi-spectral synergies.

The objective of the present study was to investigate and assess the complementarity and synergy of multi-frequency Pol-InSAR measurements for 1) **agriculture**, 2) **forest**, 3) **wetlands**, 4) **land cover classification**, 5) **land ice**, 6) **sea ice**, and 7) **snow** in terms of

- absolute coherence and interferometric phase
- the feasibility / potential of multi-spectral Pol-InSAR combinations to improve model inversion performance for established and new applications enabled by multi-spectral measurements
- the role of scattering models and their ability to handle multi-spectral data
- their projection to actual / planned realistic space borne SAR missions assessing the implications on the performance arising from different interferometric implementations (e.g., single- vs. repeat- pass, zero- vs. non-zero spatial baseline), spatial resolutions, timing of the acquisitions (near-simultaneous vs. interleaving vs. significantly separated), imaging geometry (e.g. incidence angle), polarimetric implementations

These points were addressed in a series of 6 consecutive tasks for one or more application in each domain summarized in the Table 1.1, and individuated and reviewed in the first part of the project.



Domain	Application	Added value of multiple frequencies
Agriculture	Crop parameter estimation	Larger observation space for more complex models
	Phenology characterisation	Increased sensitivity to specific changes
Forest	Forest height / biomass	Dual-frequency forest height inversion with single-/dual-baseline
Land cover	Land cover classification	Increased class separability given different sensitivities at different frequencies Trade-off frequency vs. density of the time series
	Crop type mapping	
Wetlands	Wetland mapping	
Land ice	Firn characterization (PolSAR)	Firn parameter inversion in multi-layer scenarios
	3D structure	Extended description of subsurface structure
Sea ice	Sea ice topography	Inversion of more complex models, better 3-D structural description
Snow	Snow water equivalent	Trade-off sensitivity vs. temporal decorrelation
	Liquid water content	Change of phase delay due to liquid water in the snow pack
	Accumulation rate	Augmented sensitivity (but multi-layer inversion still not possible)

Table 1.1 – List of the considered applications in the review phase and relative added value of multifrequency implementations.

A critical point is was the availability of the appropriate experimental data sets required for the evaluation and validation of individual multispectral retrieval algorithms or applications. Especially the availability of reference validation data is often difficult. The selected data sets and test sites are summarized in Table 1.2.

Domain	**Application**	**Data sets**
Agriculture	Crop parameter estimation	F-SAR CROPEX L, C, X (Wallerfing) – TanDEM-X (Sevilla)
	Phenology characterisation	F-SAR CROPEX L, C, X (Wallerfing)
Forest	Forest height / biomass	F-SAR AfriSAR P, L (Lope, Mondah, Mabounie)
Land cover	Land cover classification	ALOS-2, Sentinel-1, TanDEM-X (Sevilla) F-SAR CROPEX L, C, X (Wallerfing)
	Crop type mapping	
Wetlands	Wetland mapping	ALOS-2, Sentinel-1, TanDEM-X (Doñana)
Land ice	Firn characterization (PolSAR)	F-SAR ARCTIC15 P, L, S, C X (South Dome, EGIG05, DYE3, K-transect)
	3D structure	
Sea ice	Sea ice topography	TanDEM-X (Weddel sea)
Snow	Snow water equivalent	F-SAR L, C (Woergetal)
	Liquid water content	E-SAR L (Kuetai) / SIR-C, X-SAR L, C, X (Rofental)
	Accumulation rate	TanDEM-X (Union Glacier) / Sentinel-1, TanDEM-X (Kottas mount.)

Table 1.2 – List of available multi-frequency data sets and test sites for each application.

However, there are applications areas where the availability of multi-spectral Pol-InSAR data and appropriate reference data is inherently difficult as for example in the case of sea ice, wetlands and snow. For this reason, some or all the related applicatons were not considered after the initial review phase. For the remaining application domains, multi-frequency developments were carried out on the specific focus areas outlined in Table 1.3. Criteria for the selection were the significance of the multi-frequency contribution, and the maturity of the application. The Section 2 reports on the findings related to the multi-frequency development, while Section 3 concludes on the projection of these findings onto present and future spaceborne missions.

Domain	**Application**	**Proposed application focus**
Agriculture	Crop parameter estimation	Dual-frequency inversion of crop height
	Phenology characterisation	Multi-frequency change detection + InSAR ground/volume separation
Forest	Forest height / biomass	Dual-frequency inversion of forest height
Land cover	Land cover classification	Inclusion of features at multiple frequencies
	Crop type mapping	
Wetlands	Wetland mapping	No appropriate multi-frequency InSAR and reference data
Land ice	Firn characterization (PolSAR)	Early stage of development, additional tests needed
	3D structure	Multi-frequency Pol-InSAR localization of refrozen melt layers
Sea ice	Sea ice topography	No appropriate multi-frequency InSAR and reference data
Snow	Snow water equivalent	Delta-k at multiple frequencies
	Liquid water content	No appropriate multi-frequency InSAR and reference data
	Accumulation rate	AR vs. InSAR coherence at multiple frequencies

Table 1.3 – Multi-frequency application focus, or limitation for multifrrquency development (in red).

2 RELEVANT RESULTS FOR EACH APPLICATION

2.1 Agricultural crop parameter estimation

Models Pol-InSAR two-layer (ground and volume) models are well developed to describe volumetric scattering from agricultural crops. Here the case of a uniform volume of randomly distributed scatterers above a ground is considered. The volume scattering is parameterized by one scattering extinction across polarizations.

Consolidation / development of algorithms Two cases have been considered in dual-frequency cases: (1) the two frequencies share the same volume extinction in addition to ground and volume height, and (2) the lowest frequency is used to estimate the ground topography to initialize the parameter inversion in the highest frequency.

Performance With special focus on crop height estimation, assuming a common extinction in the two frequency brings no performance improvement with respect to the single-frequency case. The obtained performance remains unsatisfactory in general, likely due to unaccounted temporal decorrelation factors and / or the limited sensitivity of the model to extinction. On the other hand, the practical application of the common topography method is severely limited by the required phase calibration accuracy.

Recommendations New and extended studies are needed to understand the sensitivity of Pol-InSAR data to scene properties using additional data sets from dedicated airborne (bistatic) campaigns. When collecting time series, acquiring data with no vegetation is important to estimate the ground topography.

2.2 Characterization of phenological changes in agriculture

Models Polarimetric diversity can be used to follow and determine crop phenological changes. Multiplicative changes of the polarimetric covariance matrices at two acquisition times can represent changes with smaller intensity.

Consolidation / development of algorithms The conventional single-frequency multiplicative polarimetric change analysis, which provides Pauli representations of the changing scattering mechanisms, has been extended in a multi-frequency context.

Performance Real data analyses have shown that the multi-frequency extension of the change analysis provides (1) sensitivity to additional phenological changes, and / or (2) increased contrast of the detected changes. Separating the ground and volume polarimetric covariance matrices brings a higher sensitivity to weak changes in the coherence matrix before separation.

Recommendations The availability of more data with a larger temporal coverage and / or in different sites with an appropriate ground truth is critical for the evaluation of current multi-frequency algorithms and the development of new ones.

2.3 Forest height estimation

Models Pol-InSAR two-layer (ground and volume) models are well accepted to describe volumetric scattering from forest. Forest height is obtained by inverting a parameterization of the Pol-InSAR volumetric coherences.

Consolidation / development of algorithms The parameterization of the Pol-InSAR volumetric coherence at one frequency is performed by using tomographic SAR vertical reflectivity profiles and ground topography at a second frequency at which forest height is estimated.

Performance The estimation of forest height with single-baseline single-polarization Pol-InSAR acquisitions at L-band with a model initialized by the P-band tomographically reconstructed profiles has a better performance than using a single-baseline quad-pol L-band acquisition alone and the conventional exponential volume profile.

Recommendations (1) Allow phases of (preferable variable) non-zero spatial baselines in future spaceborne interferometric SAR missions. (2) Operate in a quad-pol mode (when this is possible) at all latitudes where full coverage (for the same temporal revisit time) is achieved. (3) Investigate the role functional structure bases can play in combining multi-frequency interferometric/tomographic measurements, as well as to relate the parameterisation of the 3D scattering structure at different frequencies.

2.4 Land cover classification

Consolidation / development of models The use of multi-frequency SAR features for land cover classification has been implemented as a stacking of the sets of features obtained independently at every available frequency band, which in turn can be provided by polarimetry, interferometry, and/or forming time series. There is no explicit formulation for the combination of data at different frequencies to form more elaborated features (e.g., correlations, ratios, matrices, etc.) because they are regarded as independent information sources. An algorithm based on fusion at decision level is the classification approach that is employed in this project for multi-frequency SAR data. After deciding the inputs, training, executio, and evaluation phases proceed as in any classification problem.

Performance The fusion of L-, C-, and X-band data outperforms the use of only one or two bands. Further, the exploitation of repeat-pass interferometric coherence at multiple frequency has also demonstrated a performance improvement. Finally, a trade-off between the length of the time series and the number of frequency bands has been found. In the special case of crop-type mapping, multi-frequency acquisitions, lead to performance improvements of more than 10% in the overall accuracy for any set of input features (i.e. polarimetric, interferometric and/or multi-temporal). All the experiments confirm the complementarity of the different frequency bands. The same accuracy of multi-temporal single-frequency polarimetric data using a multi-frequency Pol-InSAR dataset at a single date could be achieved only in specific dates.

Recommendations For general land cover classification, a dedicated campaign with airborne SAR acquisitions covering all data dimensions is not existing yet, and would close a fundamental gap. On the other hand, it would constitute a necessary step to understand whether the multi-spectral dimension contributes in better ways by using neural networks than by random forest in a dedicated study. For crop type mapping, data availability could be improved especially regarding total temporal coverage and regular and dense sampling.

2.5 Ice scattering structure retrieval in land ice

Models Pol-InSAR models can parameterize vertical reflectivity functions in land ice and in turn volumetric coherences, but their link to actual geophysical structure parameters is not yet established. In addition to the volume scattering structure models, height-compact (Dirac-delta-shaped) contributions have been recently included to account for distinct scattering layers e.g. from refrozen melt layers within firn.

Consolidation / development of algorithms In a Pol-InSAR / TomoSAR framework, the positions (depths) of the refrozen melt layers has been estimated at each frequency independently and their use for a unified firn representation was attempted. Given the particular modelling of these layers, high-performing model-based TomoSAR algorithms can be used. They are robust to the presence of the underground volume of ice inclusion and can handle even with dual-baseline acquisitions.

Performance The positions of the refrozen melt layer estimated with dual-baseline configurations at P- / L- / C- / X-band were confirmed by GNSS, accumulation probes and GPR measurements on site. The sensitivity to the baseline configuration has been confirmed by the real data analyses. The combination of multiple frequencies essentially allows locating three instead of only two layers in this particular test case.

Recommendations Inversion algorithms should be further studied. More explicit and physical Pol-InSAR modelling and interpretations should be included. BIOMASS will be the most promising mission in the near future for a subsurface structure application: dedicated BIOMASS acquisitions over ice sheets coordinated with ground campaigns are recommended. Single-baseline approaches or zero-baseline repeat-pass (Pol-)InSAR, which will be the most common acquisition mode of future missions, should be further investigated for 3D ice structure change retrieval.

2.6 Snow water equivalent

Models In InSAR contexts, Delta-k techniques have been proposed to derive SWE from the phase difference between repeat-pass acquisitions. The retrieval is less sensitive to small SWE changes than conventional repeat-pass interferometry, but can handle lower decorrelations (larger snowfalls). This phase difference is then modelled in terms of (change of) the snow dielectric constant, which is a function of SWE.

Algorithms Each one of the two complex SAR images is split into a lower and an upper range band-pass filtered version and two interferograms are formed, one from the lower and one of the upper band. Then a differential interferogram (lower vs. upper) is generated.

Performance Experimental results with airborne C- and L-band data demonstrate the feasibility of the Delta-k method for SWE retrievals. The InSAR performance in the estimation of SWE difference depends critically on the quality of the phase. Due to the lower sensitivity of the phase, the uncertainty of Delta-k SWE is higher than for conventional repeat-pass InSAR, but due to phase ambiguities Delta-k becomes preferable especially at C-band. If continuous dense time series of L- and C-band frequencies are available, C-band would focus on moderate snowfall amounts by the conventional repeat-pass InSAR method. L-band conventional repeat-pass InSAR can be applied for observing snowfall amounts up to about 100 mm. For larger amounts Delta-k can be applied, using C-band (if the coherence is OK) and/or L-band data.

Recommendations Further studies are needed for a detailed assessment of the Delta-k performance, constrains and complementarity to conventional SWE retrievals in different environments. it is also necessary to check options for obtaining reliable phase reference values. Another interesting issue is also the impact of interim melt/freeze events during the winter season.

2.7 Snow accumulation rate

Models Currently there is no model that can describe completely InSAR data and handle the inversion of multi-layer models. Because of this, radar-based methods for estimating accumulation rates (AR) use correlations with in-situ data..

Algorithms Assuming an uniform volume, the penetration depth can be estimated from the phase of the scattering center of mass referred to the phase of the volume top. From here, the extinction coefficient can be derived, and from it the penetration length. If the complex permittivity of the volume is known, then the scattering coefficient can be derived, and from the scattering coefficient the accumulation rate.

Performance There is an incidence angle dependency of the empirical model coefficients relating propagation constant and AR denoting deviations from the uniform volume. It was found that the application of single-pass X-band is limited to AR < ca. 0.25 m/yr due to signal saturation. Only a small sample of C-band data (Sentinel-1, 12-day repeat) was available, affected by temporal decorrelation. The C-band data indicate reasonable sensitivity of coherence to AR up to ca. 0.5 m/yr, but this value might have been affected by temporal decorrelation.

Recommendations The integration of single-pass interferometric and backscatter intensity and of polarimetric parameters, using C-band and X-band frequencies is an interesting option. A dedicated airborne interferometric C-band SAR campaign would be beneficial to enhance understanding and modelling, not least as a contribution to Harmony scientific mission preparation. A dual frequency airborne system (C- and X-band) would be the first choice, but X-band SP-InSAR data of satellite missions may as well be appropriate if dedicated acquisitions can be provided.

3 PROJECTION ON PRESENT / FUTURE SPACEBORNE SAR CONFIGURATIONS AND MISSIONS

The application summaries in Section 2 made more or less explicitly clear that the development of multi-frequency Pol-InSAR approaches critically depends on the ability to combine volume decorrelation measurements at different frequencies or to relate the parameterisation of the vertical reflectivity profile at different frequencies to each other. In general, the necessary understanding continues to be not established today. Nevertheless, the availability of critically relevant real multi-frequency data set in the project allowed to develop a number of data-driven multi-frequency approaches that can be projected all or in part onto present and future SAR configurations and missions. Exploiting multi-frequency common parameter dependencies leads to the possibility to invert these parameters in smaller observation spaces. Multi-frequencies complementarities provides a better sensitivity to and representation of scattering mechnisms,

The studied agriculture applications pose strict requirements in terms of the closeness in time (and revisit) of the acquisitions at multiple frequencies for the same growth stage due to the dynamic and fast evolution of crops in time. Interferometric estimations of crop volume parameters further require large baselines for achieving interferometric sensitivity to such short vegetation. In the future, ESA's Harmony and ROSE-L may provide some possibility. But the need for large baselines complicates this possibility as they are not easily achievable in general at L-band, and even less for ROSE-L. On the other hand, the characterization of the growth stage relies on polarimetry and can relax these requirements, but not the temporal one. Different incidence angles, resolutions, polarimetric spaces or even ascending/descending passes for each frequency or sensor can be accommodated, theoretically allowing the use of e.g. Sentinel-1 NISAR, BIOMASS and/or ROSE-L, provided that the same viewing geometry is used for all sensors. Certainly, such flexibility requires a deeper ability to understand the results. A similar flexibility subject to the same temporal constraints characterizes also crop type mapping. The short revisit time and consistent acquisition schemes of future sensors, like the L-band missions (e.g., NISAR, ROSE-L), are expected to enhance the current performance in crop classification provided nowadays by Sentinel-1 data especially at lower resolutions for smaller fields.

The next launch of L-band missions (e.g., NISAR, ROSE-L) is expected to contribute also for the general land cover classification with an additional sensitivity source to existing C- and X-band sensors. There is no strict requirement for future sets or constellations of multi-spectral SAR sensors about collocation of orbits and acquisition plans. If InSAR is to be used, at larger frequencies repeat-pass data with short revisit (e.g. Sentinel-1 6 days) are preferable. But single-pass / bistatic mode would maximise the performance.

The P-band BIOMASS mission finds interesting perspectives in forest and land ice applications, especially exploiting its combination with L-band ROSE-L data. A quite immediate application is found for forest height estimation. Indeed, vertical reflectivity profiles tomographically reconstructed at P-band (in the context of BIOMASS) could be used to invert a limited number of volume decorrelation measurements at L-band (in the context of ROSE-L or of a ROSE-L bistatic extension) even with moderate temporal decorrelation. In presence of scalar temporal decorrelation in repeat-pass acquisitions, a dual-baseline implementation would provide a solvable inversion problem. But non-zero baseline data are need for a meaningful inversion. Concerning land ice, the only limitation on using BIOMASS data for separating layers is the achievable vertical resolutions, especially towards the poles where the orbits converge. The timing among multi-frequency acquisitions becomes a strong requirement for fast-flowing glaciers. The combination with higher frequencies would provide a larger information content, but requires single-pass implementations.

C-band acquisitions could be considered for snow applications. In order to estimate snow water equivalent, If continuous dense time series at L- and C-band are available, C-band would focus on snowfall amounts of moderate intensity by the conventional repeat-pass InSAR method. L-band conventional repeat-pass InSAR can be applied for observing snowfall amounts up to about 100 mm. For larger amounts Delta-k can be applied, using C-band and / or L-band data. But for C-band the temporal decorrelation is very likely a limiting factor in case of large snowfall amounts and large time spans. A promising future sensor for SWE monitoring is ROSE-L, allowing the combination of the conventional RP-InSAR and the Delta-k method for sensing large snowfall amounts and bridging long time spans during the snow-cover season. Because of the possibility to acquire single-pass InSAR data, The Harmony SP-InSAR data, in synergy with bistatic backscatter measurements and X-band data will open-up excellent opportunities for consolidating and applying advanced methods for retrieving accumulation rates and other physical properties of snow and firn.