Field experiments for InSAR retrieval of snow mass in preparation for Copernicus ROSE-L

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Abstract

Repeat-pass differential SAR interferometry (RP-InSAR) offers a well-defined, physically based approach for mapping snow mass (SWE) at high spatial resolution by measuring the path delay of the radar signal propagating through a dry snowpack. We present the results of two field experiments on SWE retrieval using InSAR carried out in the Eastern Alps in the winter periods 2019/20 and 2020/21 using airborne and satellite-based C-band and L-band SAR data. The experiments confirmed the suitability of the relation between changes in SWE and the interferometric phase for monitoring snow mass in mountain areas but revealed also critical issues for the operational generation of snow mass products calling for further developments. The experiments are aiming to prepare for the utilization of SAR data of the upcoming Copernicus ROSE-L mission for SWE monitoring.

1 Introduction

Repeat-pass differential SAR interferometry (RP-InSAR) offers a well-defined approach for mapping snow water equivalent (SWE) at high spatial resolution by measuring the path delay of the radar signal propagating through a dry snowpack [1] [2]. In C-band and lower radar frequencies the absorption and scattering losses in dry seasonal snow are small so that the change in the InSAR phase delay of the signal reflected from the snow/ground interface is directly related to the snow mass that accumulated during the repeat-pass time span. A critical issue for routine application of RP-InSAR is the temporal decorrelation caused by changes in the complex backscatter signal. In C-band comparatively moderate snowfall amounts may already cause major decorrelation whereas this effect is of less concern in L-band.

In preparation for the Copernicus Radar Observing System for Europe L-band SAR (ROSE-L) [3], field campaigns have been conducted in two Alpine test sites in order to consolidate the techniques for monitoring the evolution of snow mass in mountain regions using RP-InSAR and to evaluate the product performance. ROSE-L is one of six Copernicus Expansion Missions which were selected to fill gaps in monitoring the environment and climate from space [3]. The baseline concept for the operations of the ROSE-L mission foresees two L-band SAR satellites, each having a 12-day repeat orbit cycle with a 180 degree phasing in a common orbital plane, resulting in 6-day repeat pass acquisitions. One of the primary mission goals is to observe snow mass changes (ΔSWE) with high resolution suitable also for complex terrain.

In March 2021 an airborne campaign was carried out in the high Alpine test site Wörgetal / Kühtai, Austrian Alps. C- and L- band SAR data were acquired on seven days with DLR's airborne radar system F-SAR installed on a DO-228 research aircraft. Comprehensive in-situ snow measurements were performed. The second experiment was carried out in Engadin, Swiss Alps in winter 2019/2020, using repeat pass L-band ALOS-2 PALSAR data with 14 and 28 days repeat acquisitions, complemented by Sentinel-1 SAR acquisitions with 6 day repeat. In-situ snow observations and data from automatic stations are used for the interpretation of interferometric signatures and for quality assessment of the retrieved snow mass product.

2 SWE Retrieval Method

The change in the mass of dry snow (the snow water equivalent, SWE) during time interval Δt is computed by the following equation based on the approach proposed by Guneriussen et al. [1]:

$$\Delta SWE(\Delta t) = -\frac{\lambda}{4\pi} \cdot \Delta\varphi_s(\Delta t) \cdot \rho \cdot \frac{1}{\cos\alpha} \cdot \frac{1}{\sqrt{\varepsilon' - \sin\theta^2} - cos\theta} \quad [1]$$

where ρ is the density of the accumulated snow, ε' is the real part of the dielectric permittivity, θ is the local incidence angle, $\Delta\varphi_s$ is the change of the interferometric phase due to snow accumulation. As reference phase for deducing $\Delta\varphi s$ from the observed total phase, sites with known changes in SWE (e.g. snow station data) or sites with $\Delta SWE = 0$ are required as reference. In accordance with the guidelines for field measurements [5] snow depth and SWE are measured vertically. Therefore, the slope angle, α, needs to be considered for deriving SWE from the observed phase, particularly in mountainous areas. For dry snow, the real part of the permittivity, ε', depends on snow density. An estimate for ρ is needed for computing ε' by means of Eq. [1]. In Alpine regions typical ρ-values of fresh snow are ranging from 100 to 150 kg m^{-3}.

Major constraints for deriving ΔSWE from $\Delta\varphi s$ are brought about by the 2π phase ambiguity, by temporal decorrelation, caused by changes in the complex backscatter signal due to snowfall, and by the reliability of the reference phase. At C-band for snow with a density of 100 kg m^{-1}, a 2π phase difference corresponds to ΔSWE = 32 mm for θ = 30° on a horizontal surface, and to ΔSWE = 20 mm for θ = 60°. The corresponding values for L-band are ΔSWE = 127 mm and ΔSWE = 80 mm.

3 Wörgetal Airborne Campaign

The test site Wörgetal (Fig. 1), a short south to north oriented high-Alpine valley, is located in the Austrian Alps about 35 km southeast of Innsbruck. It extends from 2000 m to 2700 m in elevation. Alpine grassland, locally intersected by dwarf shrubs, is the main land cover type in the central section of the valley. The in-situ snow measurements were performed along transects in moderately inclined sections of the valley at elevations between 2050 m and 2400 m, showing a slight increase of snow depth with elevation.

Stratigraphy and vertical profiles of snow properties (grain size and type, density, temperature, hardness) and the state of the ground were measured in snow pits at different elevations. Snow depth and the accumulation of fresh snow were measured along transects. During the flight campaign, extending from 2 to 19 March 2021, there were two major snowfall events spanned by RP-InSAR acquisitions. The 1st event on 5 March yielded snow accumulation (ΔSWE) of 10 mm to 15 mm water equivalent, and the 2nd event from 14 to 18 March snow accumulation of 50 mm to 70 mm. During the campaign the snowpack was largely dry, except on steep east and south facing slopes where on some days around noon the snow surface was affected by transient melt caused by solar illumination.

SAR data were acquired on seven days (2, 3, 4, 6, 8, 9, 19 March 2021) with DLR's airborne radar system F-SAR installed on a DO-228 research aircraft [4]. During each sortie multiple repeat acquisitions were obtained from 5700 m altitude (about 3000 m above terrain) along two flight tracks aligned in exactly southward, respectively northward, direction. F-SAR was operated in dual-frequency, C- and L-band, polarimetric mode (Table 1).

Table 1
F-SAR sensor and processing parameters for the Wörgetal campaign data.

	C-band	*L-band*
Center frequency	5300 MHz	1325 MHz
Signal bandwidth	384 MHz	150 MHz
Azimuth resolution	0.50 m	0.60 m
Range resolution	0.50 m	1.30 m
Pixel size	0.2 m x 0.3 m	0.4 m x 0.6 m

Examples of SWE maps derived from C-band and L-band F-SAR data for the two snowfall events are shown in Figs. 1 and 2. The coordinates refer to the WGS84/UTM zone 32N. As reference phase we used the average value of the phase of the corner reflectors that were cleaned of snow before each flight. Whereas the increase in snow mass of the event on 5 March is well within the 2π phase constraint both in L-band and C-band, for the 2nd event (14 to 18 March) this is only the case in L-band, whereas in C-band the magnitude of snow accumulation (ΔSWE) is in the order of 2 phase cycles or above. In both cases the coherence is in L-band higher than in C-band, as to be expected for snowfall events [6][7]. In the moderately inclined sections of the valley the mean coherence magnitude in the interferogram of 4 to 8 March (1st event) is in C-band 0.72, in L-band 0.91. The coherence of the 9 to 19 March data is in C-band 0.36, in L-band 0.77. During the 2nd event in C-band complete decorrelation is observed on steep slopes. For the coherence estimates windows of 25 x 25 pixel (azimuth x range) are used.

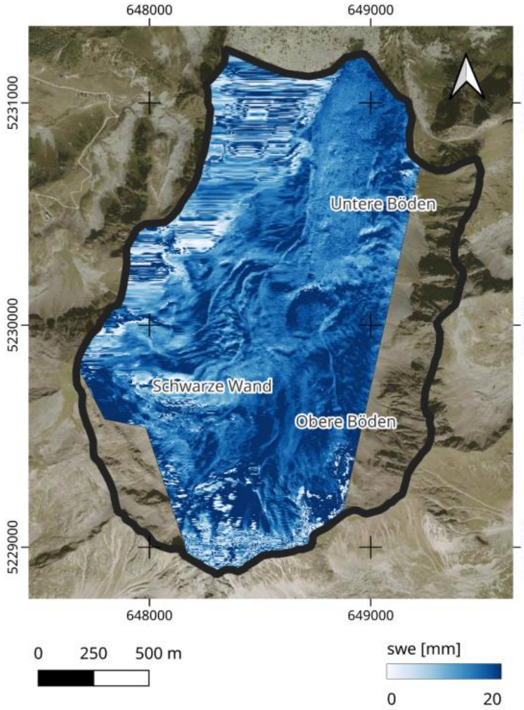

Fig. 1. Map of snow accumulated on 5 March 2021, derived from airborne C-band VV InSAR data of 4 and 8 March 2021. Color scale: $0 \leq \Delta\text{SWE} \leq 20$ mm.

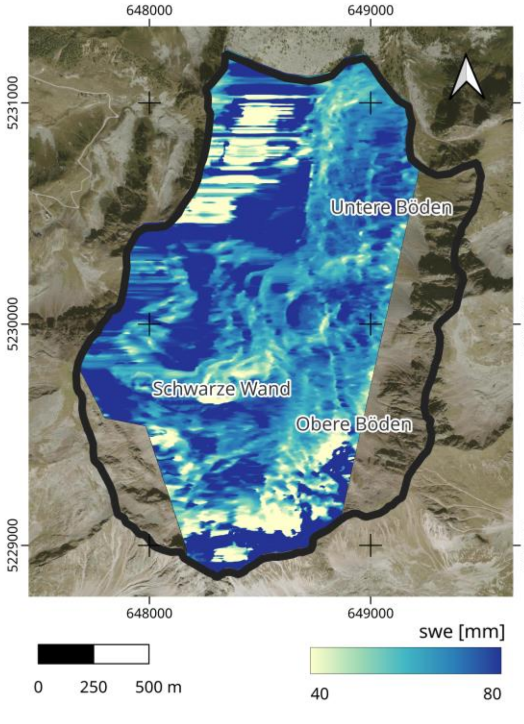

Fig. 2. Map of snow accumulated during the period 14 to 18 March 2021, derived from L-band VV InSAR data of 9 and 19 March 2021. Color scale: $40 \leq \Delta\text{SWE} \leq 80$ mm.

For 3 homogeneous horizontal areas at about 2050, 2200 and 2400 m in elevation with detailed in-situ snow observations the ΔSWE values derived from InSAR data and ΔSWE from in-situ measurements show high agreement. For the 1st period with low snow accumulation (4-8 March) the mean difference ($\Delta SWE_{INSAR} - \Delta SWE_{insitu}$) is 1.2 and 0.2 mm in L- and C-Band, respectively. For the 2nd event (9-19 March) ($\Delta SWE_{INSAR} - \Delta SWE_{insitu}$) the mean difference in L-band is 1.6 mm. For this event the retrieval using C-band data was not successful due to low coherence and 2π ambiguity.

4 Engadin field experiment

In the winter seasons 2019/2020 and 2020/2021 we studied the feasibility and performance of SWE retrievals derived from L- band RP-InSAR data of ALOS-2 PALSAR and C-band RP-InSAR data of Sentinel-1 in the Upper Engadin, Swiss Alps. ALOS-2 PALSAR strip map mode data of different tracks were acquired in 14 and 28 day repeat intervals, starting from snow free conditions in October 2019 until the beginning of the main melting period in March 2020. Sentinel-1 IW TOPS dual-pol mode data were acquired at 6-day repeat intervals.
Continuous time series on the temporal evolution of snow accumulation, melt events and meteorological parameters are available from automatic weather stations. In the season 2019-2020 these measurements were complemented by snow and soil measurements on days of satellite overpasses.
In case of dry snow, the coherence of the PALSAR data is preserved also for snowfall events, although intensive snow accumulation causes a substantial decrease in coherence. Fig. 3 shows a 14-day repat pass PALSAR coherence image (30.1.2020 to 13.2.2020) across the Swiss Alps. The coherence magnitude in the main Engadin valley, with ΔSWE between 10 mm and 30 mm water equivalent, is in the order of 0.4 to 0.5. To the north of this region the snow accumulation was 2 to 3 times higher, reflected in lower coherence.

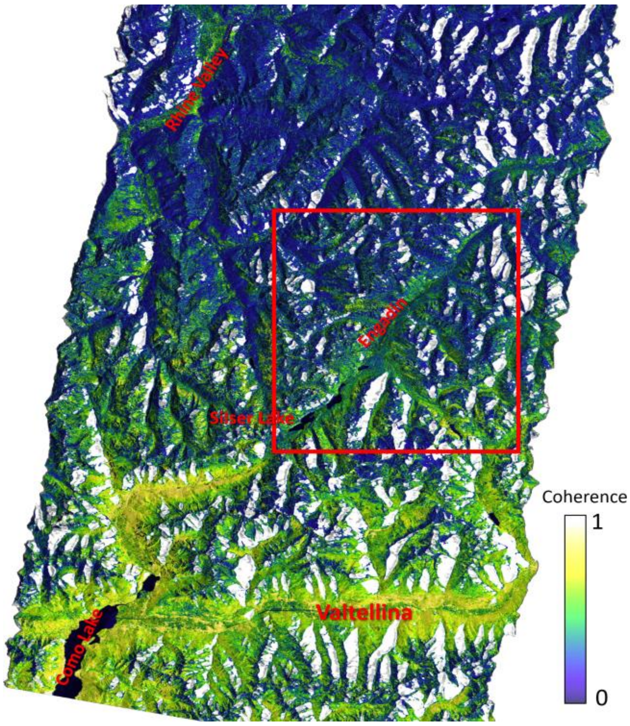

Fig. 3. Map of coherence from ALOS-2 PALSAR HH polarized data of 30.1/13.2.2020. Red Square - area of InSAR SWE analysis shown in in Fig 4 and Fig 5.

A stack of 6-day Sentinel-1 InSAR image pairs, processed for the same period, shows that in the case of moderate and heavy snow fall events the coherence is in general very low, inhibiting useful SWE retrievals. In the case of no snow fall, the coherence is widely preserved also in C-band data, except for areas with wet snow.

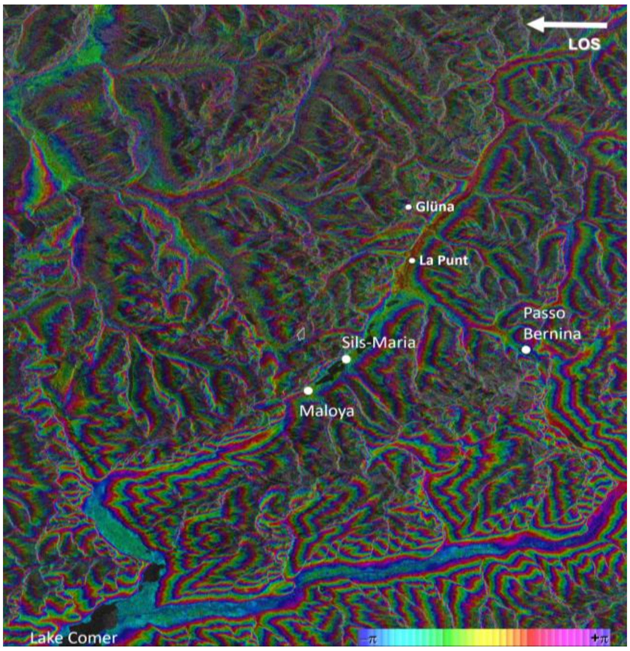

Fig. 4. Interferometric phase image in SAR slant range geometry of ALOS-2 PALSAR HH data, of 30.1/13.2.2020. LOS – Line of sight direction.

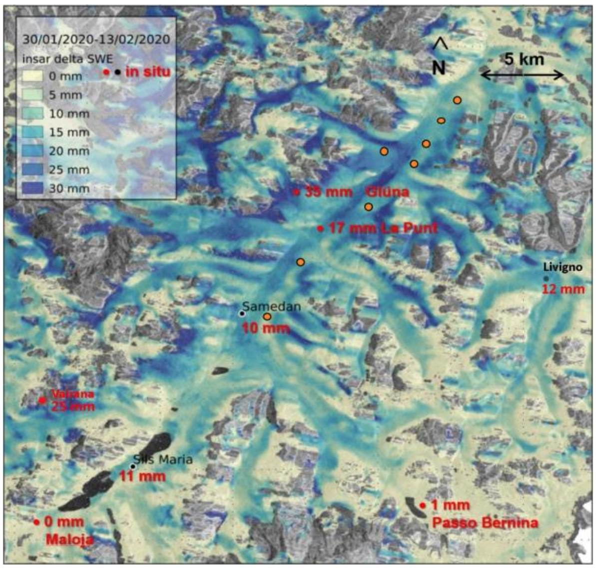

Fig. 5. Map of snow accumulated during the period 30.1 to 13.2.2020 derived from ALOS PALSAR L-band HH InSAR data. Color scale: 0 ≤ ΔSWE ≤ 30 mm. Orange dots indicate the location of forests along slopes of the main valley. The red numbers are in situ ΔSWE data.

SWE retrievals based on 14-day PALSAR data show for dry snow cases good agreement with in-situ snow measurements (Fig. 5). In forested areas the coherence is suitable to obtain reliable phase retrievals. However, due to scattering contributions and signal attenuation in the forest canopy the retrieved ΔSWE is underestimated if the same scaling factor is used as in open terrain, as the case in the SWE map of Fig. 5.

A continuous time series throughout winter periods could not be obtained because of the lack of continuity of repeat pass PALSAR acquisition over the study area and because on some dates the coherence was affected by transient melt. Limitations in the spatial coverage are imposed by the steep topography causing large gaps due to layover and foreshortening, calling for the acquisition of data from ascending and descending passes.

5 Conclusions

The two field experiments, caried out in the Eastern Alps in winter seasons 2019/2020 and 2020/2021, provide a valuable basis for consolidating and evaluating the InSAR based approach for snow mass retrieval and for performance assessment of the products. The airborne dual-frequency C- and L-Band SAR data cover multiple repeat pass time spans ranging from 0.2 hours to 17 days and are spanning two snowfall events of quite different intensity. The analysis of image pairs covering time spans with different amounts of fresh snow accumulation shows good performance for the L-band InSAR based snow maps. C-band RP-InSAR retrievals show good performance for the low intensity snowfall event, but the interferometric signal of the intense snowfall event is affected by low coherence, not suitable for reliable SWE retrievals.

The second experiment refers to SWE retrieval performance of ALOS PALSAR-2 and Sentinel-1 RP-InSAR data, acquired over the Engadin region in the Alps. It shows that coherence is widely preserved at L-band even in case of 14-day time spans. Continuous repeat pass acquisitions during the full winter period are needed for measuring the total amount of SWE which in this case was not provided by the PALSAR acquisition plan.

Furthermore, the study reveals critical issues for InSAR SWE retrieval in mountains, including the selection of reliable reference points for phase calibration to obtain the snow-related phase, the reduced sensitivity in forests, and the need for topography-related correction for changes in atmospheric propagation. For 6-day Sentinel-1 C-Band InSAR the coherence is largely lost in the case of significant snow fall events.

Both experiments confirm the high capability of L-Band InSAR to monitor changes of snow mass in mountain regions and point out the need for further studies to achieve operational RP-InSAR based SWE monitoring systems. The 6 days repeat pass acquisitions of the ROSE-L mission with two satellites, combined with a systematic and continuous acquisition plan, will provide the required data for routinely monitoring the accumulation of snow during winter over extended areas.

6 Acknowledgements

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7 Literature

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