Terrestrial radar interferometry for snow glide activity monitoring and its potential as precursor of wet snow avalanches.

Rafael Caduff[1]; Andreas Wiesmann[2]; Yves Bühler[3]; Claudia Bieler[3]; Philippe Limpach[4]

ABSTRACT

Snowpack displacement and resulting full depth gliding snow avalanches are a widespread problem in alpine regions during springtime after snow-rich winters. This is a major threat for infrastructures nearby. Today field observers detect gliding snow visually. However, they can only detect suspicious snowpack displacement after gliding cracks opened. Many wet snow avalanches release without formation of visible tension cracks in an early stage so that they appear to happen spontaneously. Terrestrial radar interferometry has recently proven to be an effective method for the detection and monitoring of snow glide activity on a slope scale. Movements of the snowpack less than 0.5 mm/h can be detected as validated with a total station. Detection of snow glide activity is therefore achievable at a very early stage. Continuous measurements with rates of up to one scene per minute allow the immediate assessment of snow glide activity on the monitored slope. Therefore this method might be applied in future to detect precursors for full depth gliding snow avalanches.

KEYWORDS

snow glide monitoring; terrestrial radar interferometry; wet snow avalanche; data validation

INTRODUCTION

Different gravitational deformation processes such as settlement, creep and full depth snow glide are acting on snow slopes. Once full depth gliding is present, it can have a twofold impact on infrastructures within the snow slope. The impact is either direct, i.e. through immediate contact of the gliding snow column with the infrastructure, or the impact is indirect, i.e. the infrastructure gets impacted by a full depth snow glide avalanche from above. In both cases infrastructure such as buildings, roads, railways and power lines can be damaged severely (Bartelt et al., 2012). Gliding snow avalanches are hard to predict because they depend on surface roughness (Feistl et al., 2014) as well as on the moisture penetration into the snow pack which can change within very short time (Höller, 2013; Mitterer et al., 2011). Full depth snow glide is not limited to extraordinary snow glide winters with high snow columns but is common as well during wet snow conditions with low snow height. Full depth snow glide is usually identified on a slope by the presence of clearly visible morphologi-

1 GAMMA Remote Sensing AG, Gümligen, SWITZERLAND, caduff@gamma-rs.ch
2 Gamma Remote Sensing, Switzerland
3 WSL Institute for Snow and Avalanche Research SLF, Switzerland
4 ETH Zürich, Institute of Geodesy and Photogrammetry, Switzerland

cal features such as extensional cracks or compression structures at the toe of a snow glide area (stauchwall) that can be detected e.g. by time lapse photography (Van Herwijen et al., 2013). Besides these morphological signs, detection and quantification of very small snow glide movements was possible only point-wise. All measurements leading to information on the movement of the snow column had to be instrumented on site (Höller, 2014). Terrestrial radar interferometry was recently introduced as an innovative method that allows very high spatio-temporal sampling on a slope-wide scale during day and night, foggy conditions and independent from the existence of visible deformation related features in the snowpack (Caduff et al. 2015a; Wiesmann et al. 2015).

Here we shortly summarize the technical preconditions necessary to monitor the snow pack displacements on a slope wide scale. We then discuss the potential and the limitations of interferometric measurements of snow to determine the rate of glide movement with a sensitivity of less than 0.5 mm/h. It was possible for the first time to validate measurements from the terrestrial radar interferometer with survey data obtained from a total station. Finally, we compare the snow glide activity with the avalanche activity on the Dorfberg test site in Davos, Switzerland during the winter 2014/2015.

METHODS

The GAMMA Portable Radar Interferometer (GPRI), operating at 17.2 GHz (Ku-band) was used for the campaign (Werner et al. 2012). The GPRI was deployed for continuous monitoring of the Dorfberg area at the valley bottom of Davos Dorf and was protected with a radome of 2.4 m diameter (Figure 1). From this position, the instrument illuminates the target area with an azimuthal scan (mechanical rotation of the antennas with 10°/sec). The received backscatter signal (amplitude and phase) forms a 2-dimensional image of the area with a pixel resolution of 0.75 m in range and a nominal azimuth resolution of 8m in 1 km distance. The final georeferenced maps were resampled to a pixel resolution of 1×1 m. The distance to the scatterer influences the relative phase value, therefore movement towards or away from the sensor induces phase changes. This effect is used to detect displacement in the target area in the order of a fraction of the instrument wavelength (1.74 cm). A recent review of the method with examples in the geoscientific field is given by Caduff et al. (2015b).

It is necessary for the conversion of phase changes to 1-dimensional displacement in line-of-sight (LOS) that patches show high interferometric coherence. Coherence is a value that expresses similarity of surrounding raster cells (0: no similarity, 1 high similarity). The temporal behavior of the scatterers determines the amount of coherence of the interferogram (Figure 2). There are mechanical changes on the target surface, vegetation movement due to wind, snow drift or avalanches that lead to almost immediate decorrelation. In our study, avalanches were detected and mapped using coherence maps as shown in Figure 2. Avalanche outlines were drawn and verified manually. An operator decision led to a qualitative classification of the degree of decorrelation as seen in Figure 2 that allows a rough separation

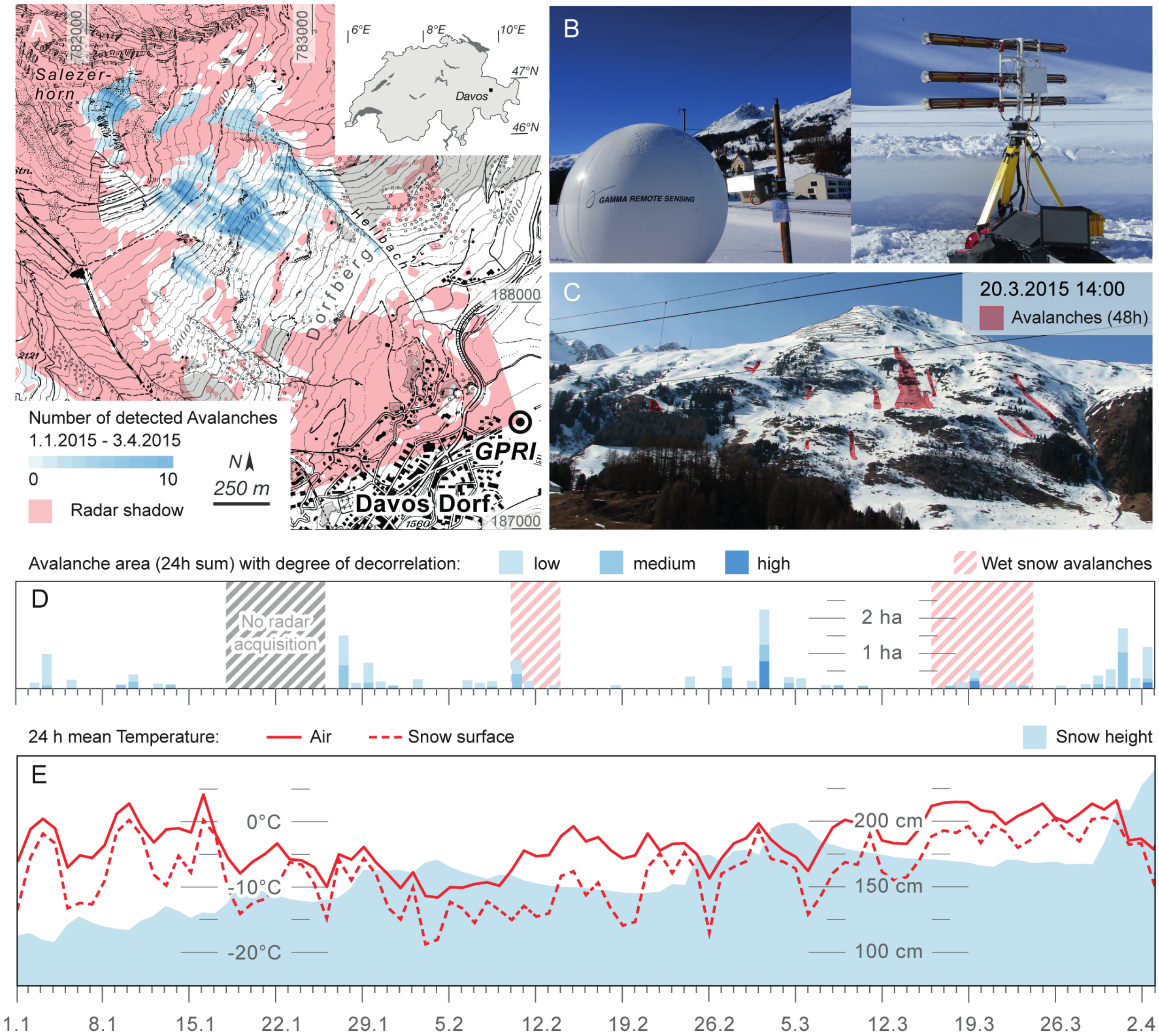

Figure 1: Overview of the monitored slope of the Dorfberg located in Davos Dorf, Switzerland. All detected avalanches during the observation period are shown in map (A). The radome (B left), containing the GAMMA Portable Radar Interferometer GPRI (B right) is located at the spot indicated with "GPRI". The wet snow avalanches of a 48 h period are drawn on the image (C) The total daily sum of the area of the detected avalanches is shown in D. The corresponding daily mean temperature and snow height measurements from the weather station located 100 m apart from the GPRI are shown in plot E.

of full depth avalanches (high degree of decorrelation) and superficial impacts on the snow (low degree of decorrelation).

Changes in the physical state of the snow (dry/wet) lead to changes in the dielectric properties of the surface and have an influence as well on interferometric coherence especially during transition times (e.g. immediately after sunrise). In Figure 2 this effect is expressed in the maps showing the distribution of the coherence after 2 min and after 21 min during wet snow conditions. Comparisons to dry snow conditions show that the decorrelation time ranges from several hours during dry snow conditions to less than ten minutes in wet snow conditions without visible mechanical impact. In conclusion, the sampling interval must be below the decorrelation time to be able to convert the interferometric phase to displacement information.

The campaign was performed using acquisitions with 2 or 3 minute intervals to retain high coherence. After each acquisition an automated processing calculated interferograms, coherence maps and stacks of temporal averages (30 min) of the displacement to reduce atmospheric phase noise. A mobile data connection allowed remote access to the instrument and the data through a web-interface.

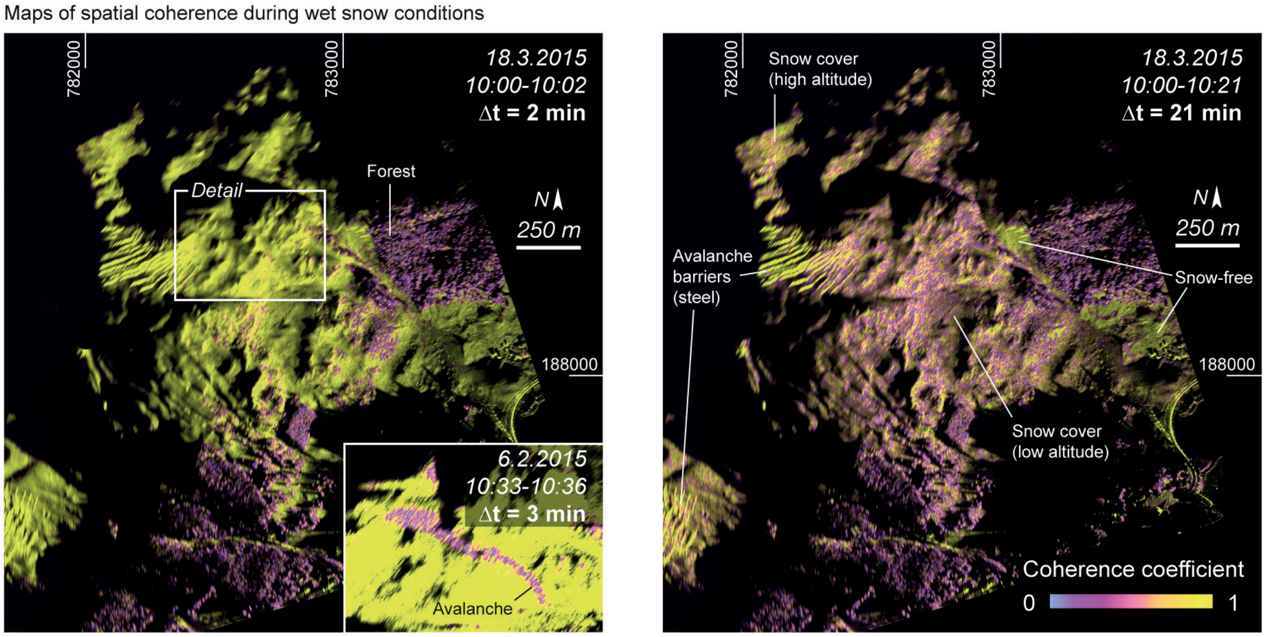

Figure 2: Coherence maps with 3 min and 21 min temporal baselines show different effects reducing the coherence on the slope. Snow surface is completely decorrelated after 21 min during wet snow conditions.

RESULTS

Evaluation of optimal temporal sampling rates

Even though the interferometric coherence can be kept high during wet snow conditions, transition effects may still be visible in the final displacement diagrams. Figure 3 shows such effects and the attempt to reduce their impact in order to separate them from the actual snow displacement. The matrix shows the averaged displacement of stacks with different counts of observations prior to an avalanche release from point d1. However, since for early warning purposes, the time for the detection should be as short as possible, different temporal sampling intervals were tested.

Although the deformation hot-spot d1 is visible already in the 2 min interferograms of 14:02 and 14:14, those scenes suffer from atmospheric effects that impact the entire scene. Small changes in the physical parameters of the air (temperature, pressure, humidity) can induce phase delays in the interferogram. The patches, if not detected and filtered properly could lead to a misinterpretation of atmospheric disturbances as deformation signals. Patches of atmospheric effects with similar size and shape as snow glide deformation signals show randomness in time and therefore get reduced significantly with increasing number of observations (stacking).

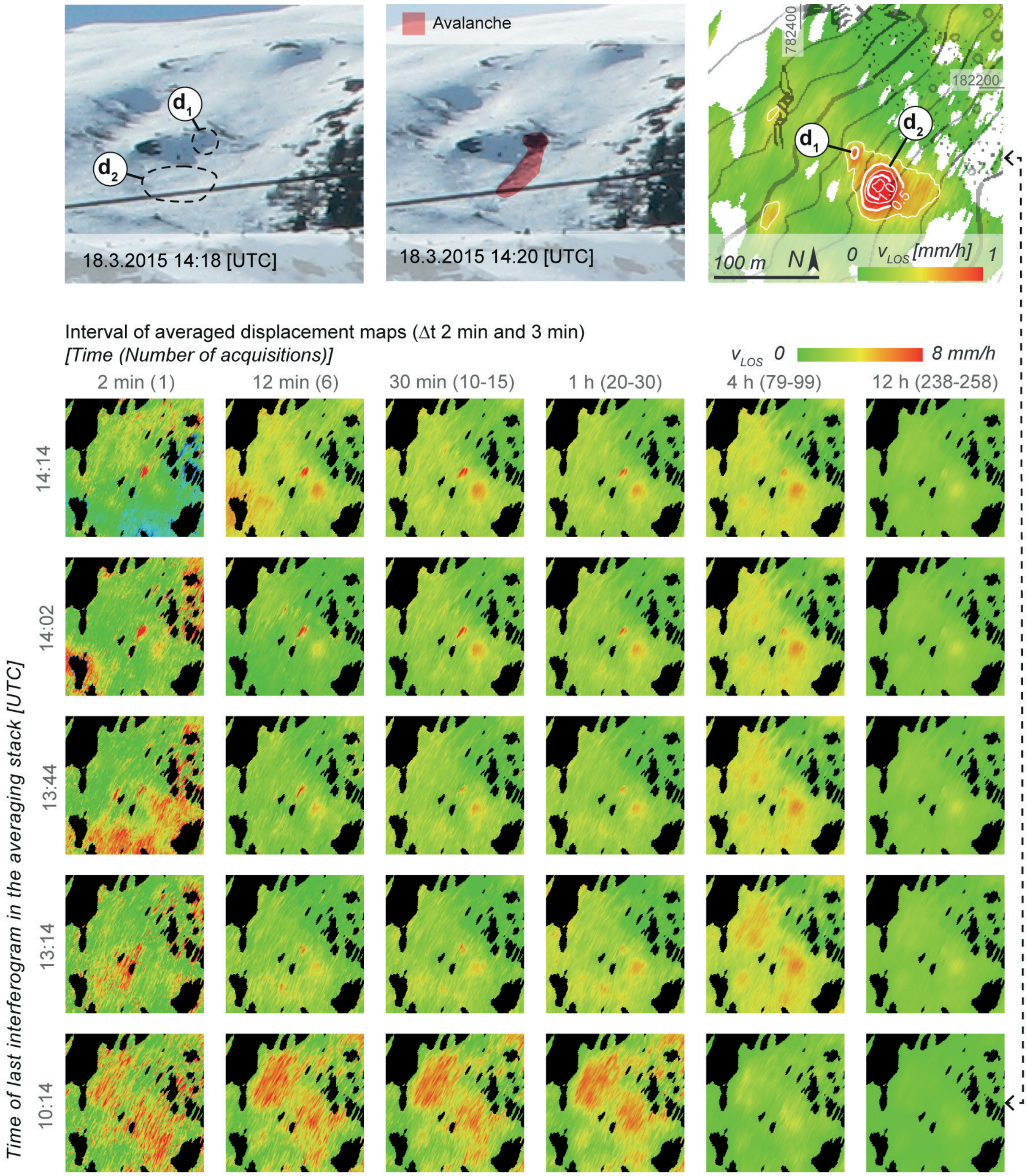

Figure 3: Effects of different averaging intervals on the displacement maps in a small subset. The used dataset shows the preceding situation of an avalanche triggered by the release of the snow glide area d1. A second snow glide area is marked as d2. For this area the validation with the total station was performed (see Figure 5).

For comparison, the single interferogram scenes in Figure 3 were normalized to a stable point (rock) close to the area since patches of atmospheric influences are present over the entire scene. In the 12 h stack, the velocity is less visible since both areas d1 and d2 were slower the days before and during the night. The temporal evolution of d1 and d2 is shown in Figure 4. The enlarged map in Figure 3 shows that the sensitivity of the measurements can reach less than 1 mm. Areas with LOS velocities of 0.25 mm/h can clearly be separated. However, such a precision is achieved only if the snow surface is not disturbed by snowfall or snowdrift. Another effect that may hinder the detection of snow glide hot-spots is the settlement of freshly fallen snow. The deformation in the vertical is partly seen as deformation in LOS. Since the deformation values are in the same order or even exceed deformation induced by snow gliding, a clear distinction between both processes is not possible.

The LOS displacement during the transition of dry to wet snow (10:14) is strongly disturbed by effects described in the method section. During this short time period, a high precision measurement of snow glide motion is difficult.

Snow glide activity maps

Snow glide activity on the slope was assessed by creating daily average LOS velocity (vLOS) maps. The maps were spatially filtered (5x5 pixel average) to calculate isotachs. The isotachs were grouped in 3 classes (1, 2 and 3 mm) for which the total area and number of isolated snow glide hot-spots were calculated. The results are plotted in Figure 4. Information about the number of avalanches and the total area affected by the avalanches are plotted for the same period. The period between the 15th and 29th of March is considered as a wet snow avalanche period. Here the avalanches are often preceded by snow glide movement. The displacement diagram of different selected points shows the temporal evolution of the snow glide displacement. Snow-melt and other snow related effects were corrected for each point with the subtraction of those signatures using a local non-gliding reference. Point d1 shows movement on a cm-scale only before the avalanche release, while the release area of d2 showed long term continuous and constant snow glide activity beginning more than 8 days before the release. A strong acceleration was recorded a few hours before the avalanche release. Other points (d3, d4, d5) show clear acceleration cycles during day/night.

VALIDATION

A validation of the displacement measurements with the GPRI was performed with a combined approach of total station and experimental single frequency GPS sensors. The GPS phase data is processed differentially with respect to a nearby reference station. The field setup is shown in Figure 5. Reflective foil targets were put on lightweight styrofoam plates equipped with plastic anchors for fixation on the snow surface. The targets were installed early in the morning, when a firm snow surface was present on a target area previously detected with the GPRI.

The survey was started at 10:30. A second measurement was acquired at 14:00. Shortly after this measurement, a small avalanche was released above the test field and went through the middle of the field, destroying some targets and sweeping away both GPS boxes. The avalanche released from point d1 (Figure 3 and Figure 4). It is a very small area with a local slope angle of 40-45°. It is to mention, that the avalanche from d1 was not able to trigger the release of the entire area of d2. However, the total station measurements were continued on the remaining targets. After the campaign, the total deformation of each point was calculated (small image in Figure 5). To compare the measurements with the GPRI LOS velocity map, it

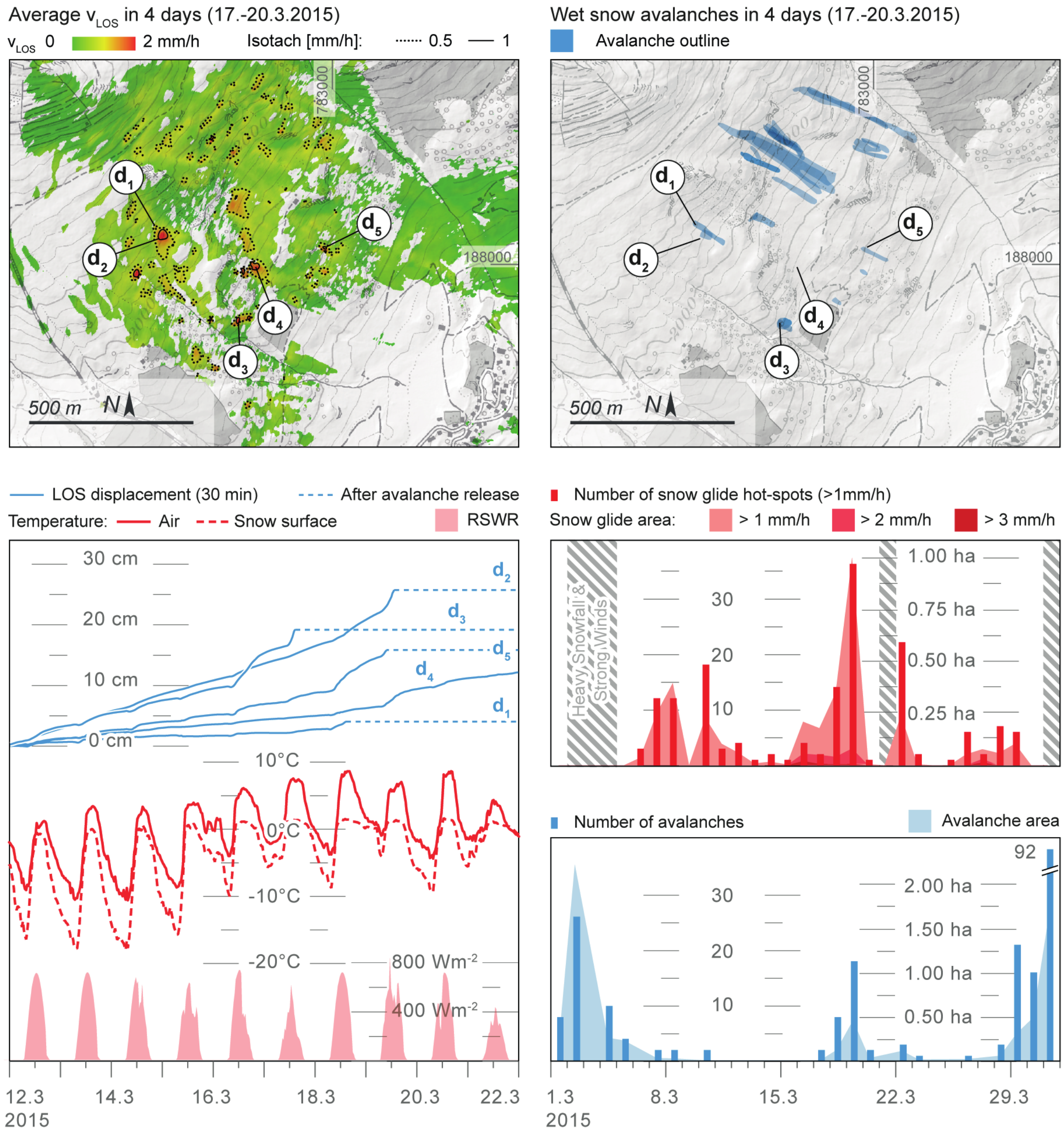

Figure 4: Synthesis of the results of the wet snow avalanche period in March 2015. Top left: Snow glide activity map. Top right: avalanche activity map. Bottom left: Line of side snow glide displacement for selected points together with temperature (air and snow surface 30 min) and reflected short wave radiation (RSWR). Bottom left: Comparison of snow glide activity (number and area) with avalanche activity (number of avalanches and affected area).

was necessary to convert the total station results to LOS. The LOS fraction was determined by calculating the angle between the displacement vector and the look vector of the GPRI for each point. The total displacement was then scaled with the LOS fraction and plotted on top of the GPRI LOS velocity map using the same color scale. The results of the LOS-corrected values of both, the GPRI and the total station measurements are in very good agreement (within 0.5 mm/hour) for the relatively short observation period.

After their installation at around 09:30, the GPS boxes were slowly gliding along the slope and deforming the snow surface due to their weight, mainly coming from the battery included in the boxes. Unfortunately, the GPS boxes were swept away by the avalanche before they reached an equilibrium that would allow detecting the movement of the snow pack.

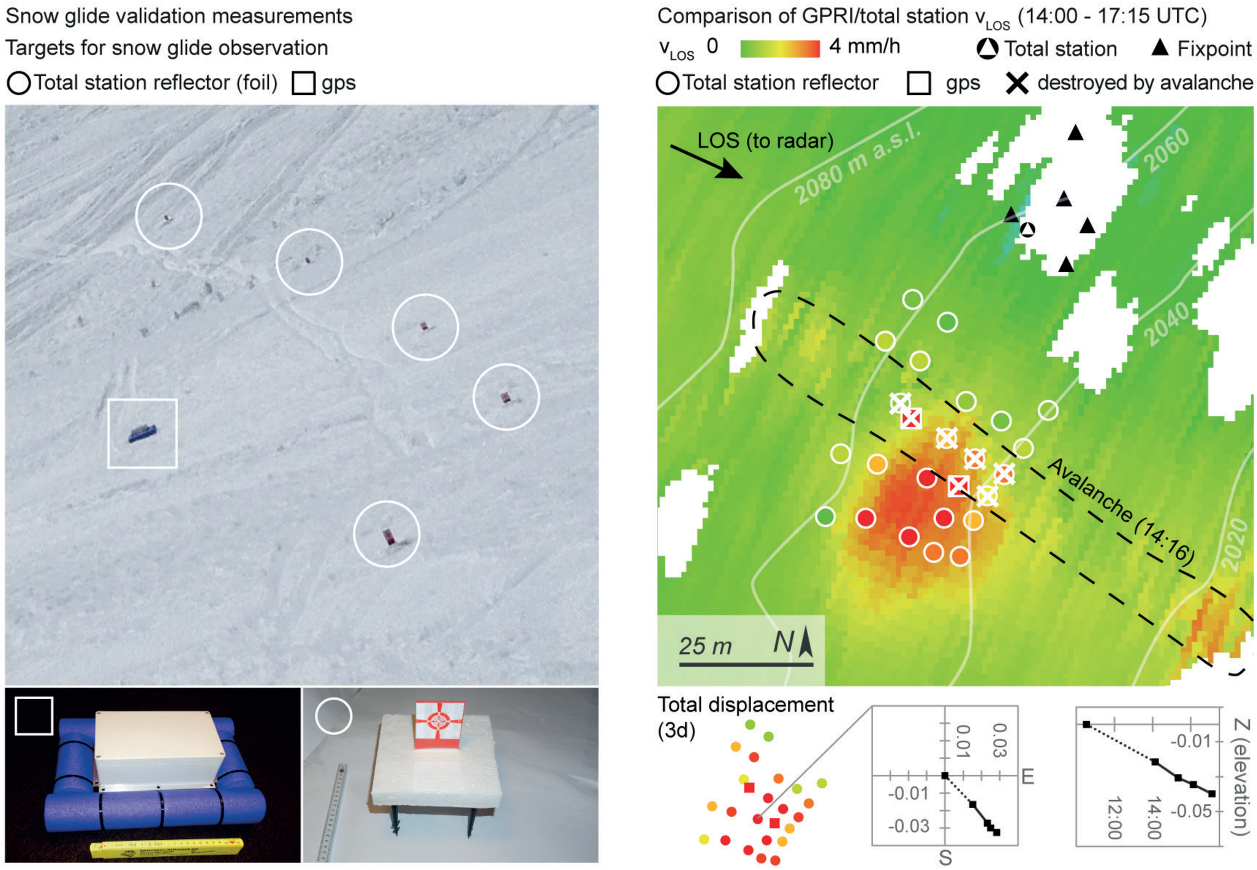

Figure 5: Field setup of the validation with total station and GPS boxes. The total station is located at (782494/188159). The results of the total station measurements were calculated for the observation period after the avalanche and were converted to LOS velocity. The results are plotted as color coded points on top of the GPRI LOS velocity map of the same observation period (14:16-17:00 UTC) with the same color coding. Below the map, the uncorrected total station displacement values and an example of the displacement vector are given.

CONCLUSIONS

The presented results confirm the feasibility of snow glide displacement measurements using terrestrial radar interferometry. With proper stacking, determination of the slope wide snow glide activity with relative sensitivity down to 0.25 mm/h and an absolute accuracy of 0.5 mm is reached during weather conditions without precipitation and with absent strong winds. This is the case for parts of the observed slope that are free of shrub vegetation that emerges from the snowpack. The results and the tests performed during the campaign clearly show that the atmospheric influence is negligible when the data is averaged in periods of 12 min to 4 h. This simplifies the in-situ data processing and allows faster acquisitions. However, due to the high sensitivity of the instrument, small changes in the snow column as induced by snow-fall or wind drift can lead to phase changes and exceed the displacement signatures. During these conditions, signatures seen by the radar could not be clearly identified as either snow glide or some other processes acting on the snow pack. A careful

interpretation of the interferometric data is as well necessary during times of transition from dry to wet snow (e.g. after sunrise). The transition of the liquid water content in the snowpack may shift the phase center from within the snowpack to the surface (Caduff et al. 2015a) and therefore induce phase changes. Once snow glide hot-spots are located, tracking of the point displacement is possible in shorter intervals using simple normalization to suppress atmospheric or snow property induced phase effects. Interpretation of the temporal evolution of snow glide hot-spots led to the conclusion that most release zones of wet snow avalanches show signature of movement hours to days before the release and in most of the cases, strong acceleration of the movement hours before the avalanche release was recorded. Since many of the released wet snow avalanches show acceleration hours to minutes before the event, acceleration might be valuable indicator for the timing of the release. However, as the deformation signature of d1 in Figure 4 shows, additional investigations of the influence of the local topography are needed since the trigger-acceleration of d1 was apparently lower due to its steep release zone.
For the first time, an absolute validation of the snow pack displacement measured using terrestrial radar interferometry was performed using total station measurements. The resulting LOS velocities show very good agreement within less than 0.5 mm/h. However, since the validation campaign lasted only a few hours and the temperature conditions did not allow coverage of a full freeze/thaw cycle of the snow-surface, the quantification of the phase effects during the transition are not yet fully understood.
The campaign helped to solve major open question regarding the use of terrestrial radar interferometry rapid detection and quantification on snow glide on a slope. The technique opens new possibilities in the research on snow gliding and wet-snow avalanches. We also expect it to prove valuable in the management of high-risk situations during elevated snow glide and wet-snow avalanche activity.

ACKNOWLEDGEMENTS
Part of the funding for this research has been provided through the Interreg project STRADA 2.

REFERENCES
- Bartelt, P., Pielmeier, C., Margreth, S., Harvey, S., Stucki, T. (2012). The underestimated role of the Stauchwall in full-depth avalanche release. Proceedings of the International Snow Science Workshop, September 16-21, 2012, Anchorage, AK, USA. 127-133.
- Caduff R., Wiesmann A., Bühler Y., Pielmeier C. (2015a). Continuous monitoring of snowpack displacement at high spatial and temporal resolution with terrestrial radar interferometry. Snowpack displacement monitoring. Geophysical Research Letters 42(3), 813-820.
- Caduff R., Schlunegger F., Kos A., Wiesmann A. (2015b). A review of terrestrial radar interferometry for measuring surface change in the geosciences. Earth Surface Processes and Landforms 40(2), 208-228.

- Feistl T., Bebi P., Dreier L., Hanewinkel M., Bartelt P. (2014). Quantification of basal friction for technical and silvicultural glide-snow avalanche mitigation measures. Natural Hazards and Earth System Science 14, 2921-2931.
- Höller P. (2013). Snow gliding and glide avalanches: a review. Natural Hazards 71, 1259-1288.
- Mitterer C., Hirashima H., and Schweizer J. (2011). Wet-snow instabilities: Comparison of measured and modelled liquid water content and snow stratigraphy. Annals of Glaciology 52, 201-208.
- Van Herwijen A., Berthod N., Simenhois R., Mitterer C. (2013). Using time-lapse photography in avalanche research, Proceedings of the International Snow Science Workshop, October 7-11, 2013, Grenoble, F, 950-954.
- Wiesmann A., Caduff R., Mätzler C. (2015). Terrestrial Radar Observations of Dynamic Changes in Alpine Snow. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 8(7), 3665-3671.
- Werner C., Wiesmann A., Strozzi T., Kos A., Caduff R., Wegmüller U. (2012). The GPRI multi-mode differential interferometric radar for ground-based observations. Proceedings of the 9th European Conference on Synthetic Aperture Radar, April, 23-26, 2012, Nuremberg, D, 304-307.