Integration of space-borne DInSAR data in a multi-method monitoring concept for alpine mass movements

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Abstract

This study presents the results of an experimental application of a multi-method measurement concept for the monitoring of alpine mass movements. Satellite-borne differential interferometric synthetic aperture radar (DInSAR) was applied as the key technology. To improve the information contents of the DInSAR displacement data for an individual mass movement, a complementary measurement was carried out with a three dimensional measurement system. The information on the 3D movement characteristics obtained by this complementary measurement was used to extrapolate subsequent DInSAR measurements to 3D. Terrestrial laser scanning (TLS) and Global Navigation Satellite System (GNSS) data were tested as complementary 3D measurement systems. The deviations between the single measurement systems were mainly controlled by the error budgets of the different methods. An exception were short term GNSS single point time series which included small scale surface movements that were not captured by the other methods. TLS proved to be the most suitable complementary method. A single TLS repeat measurement was sufficient to create a mask, which enables the projection of DInSAR displacement data to 3D. The application of satellite-borne DInSAR in alpine terrain is challenging; signal decorrelation is a problem due to fast terrain movements and snow coverage and can cause failure of the measurement system.

Keywords: Monitoring; Remote sensing; Alpine mass movements; Terrestrial laser scanning; DInSAR; GNSS

1. Introduction

The densification of infrastructure and settlement areas in the European Alps requires careful consideration of natural hazards and the activity of geomorphological processes, in particular in the light of climate change. Alpine mass movements like landslides, permafrost creep or rock slope failures are the source of potentially hazardous processes.are the source of potentially hazardous processes. They can show a low activity for decades or even centuries without being seriously hazardous – before unexpectedly accelerating. Some of these accelerations can be forecasted or at least detected in real time if the mass wasting zone is monitored on a long term basis. These include for example rock glacier creep surges (Delaloye et al., 2013; Kenner et al., 2014), accelerations of landslides and deep seated gravitational slope deformations (Angeli et al., 2000) or rock fall events (Abellán et al., 2010; Kenner et al., 2011).

However, decision makers in natural hazard prevention are confronted with a considerable number of critical mass movement processes in alpine environments, which are often insufficiently documented. Long term monitoring tasks using classical monitoring methods are in many cases associated with high costs. This may force the natural hazard managers into a mode of reactionary operation. In many cases potentially dangerous mass movements are only focused on after the occurrence of larger events, which is suboptimal in terms of hazard prevention (Tobler et al., 2012). A cost-efficient long term monitoring system, mostly working in a self-operating mode over regions of hundreds of square kilometers, with cm accuracy and capturing changes in existing mass movement processes or even detecting new ones, would clearly help decision makers. This is the point on which the current study was based on. Our aim was to develop a measurement concept that enable a supra-regional, long term monitoring of as many individual mass movements as possible.

Numerous measurement technologies are currently used for monitoring tasks in alpine terrain (table 1). They can be classified into in-situ and remote sensing methods but also into single point tracking systems or those enabling data acquisition over wide areas. The information content of the data obtained varies substantially according to the measurement system. Mass movement processes were traditionally monitored using total stations (Veulliet et al., 2009). Air-borne photogrammetry has been used for several decades for long term monitoring tasks (Fabris et al., 2005; Kääb, 1999; Kaufmann and Ladstädter, 2003). In recent years, this method has been applied more frequently and facilitated by the development of air-borne digital sensors (ADS), the availability of drone-borne photogrammetry (Bühler et al., 2012; Eisenbeiß, 2009) and software improvements. Meanwhile GNSS measurements have become a widely used additional method to the classical surveying techniques (Lambiel and Delaloye, 2004; Wirz et al., 2015). Since the beginning of the 2000s, laser scanning technology has developed rapidly and allowed the terrestrial and air-borne acquisition of widespread 3D terrain data (Bauer et al., 2003; Kenner et al., 2014; Sailer et al., 2012). This was a notable development, especially for monitoring inaccessible and steep terrain areas. Simultaneously, radar technology proved to be a very powerful method for high accuracy applications in mass movement monitoring (Colesanti and Wasowski, 2006; Gischig et al., 2009; Kos et al., 2013; Strozzi et al., 2005), allowing to monitor millimeter scale deformations of the ground surface over areas of up to hundreds of square kilometers. Table 1 gives an overview of the characteristics of these technologies. Several of the methods have been applied by Strozzi et al. (2010) for the monitoring of a rock slide in high alpine terrain. This study provides additional information about the characteristics of the methods and differences between them.

Based on this evaluation of measurement systems, our study focuses on satellite-borne differential interferometric synthetic aperture radar (DInSAR) as a key technology to realize the aim of a self-operating large scale monitoring concept providing centimeter accuracy. Space-borne DInSAR is an established method to detect and monitor large scale surface displacements. Similarly it can be used to monitor numerous small scale displacements distributed over areas of several hundred square kilometres (Pritchard and Simons, 2002). In the last decade, a large number of case studies successfully applied DInSAR methods for detecting and monitoring ground deformations in alpine environments, and in particular in permafrost-affected areas (Barboux et al., 2012; Barboux et al., 2015; Echelard et al., 2013; Strozzi et al., 2004). A comprehensive overview of differential InSAR and the application of the method to alpine environments and the detection of ground deformations is provided by Barboux et al. (2015).

However all these studies also underline several limitations of DInSAR, making it difficult to rely exclusively on DInSAR data when analyzing and monitoring a mass movement; the one-dimensionality of movement measurements has to be mentioned here in particular. We tried to overcome this weakness by embedding DInSAR measurements into a monitoring concept that can implement the results of a complementary measurement system if necessary. A locally and temporally limited application of such complementary data provides 3D movement information on individual mass movements to understand their general movement characteristics. The complementary data should enable the operator to draw clear conclusions from further DInSAR measurements and also monitor complex movement processes using DInSAR only.

2. Study site

The study was carried out at a test site located above Pontresina in the Upper Engadin valley, Grisons (Switzerland). The monitoring area includes three individual active rock glaciers in a West oriented mountain cirque called Foura da l'amd Ursina. The rock glacier complex henceforth referred to as Ursina (Figure 1) ranges between 2700 and 2900 m asl. The steep surrounding ridges and rock walls reach elevations over 3000 m and are subject to intermittent rock fall. The lowest rock glacier has a steep front in the top of the Val Giandains gully, which is the source area of potential debris flows. A protection dam was built at the base of the gully above Pontresina in 2003.

3. Methods

3.1. Monitoring concept

Satellite-borne differential interferometric synthetic aperture radar (DInSAR) (Bamler and Hartl, 1998; Skolnik, 1980) provides data on surface changes over areas of several hundred square kilometers with up to mm accuracy and a minimum of effort for the recipient of the data.

However, there are also considerable problems using DInSAR. The InSAR-specific effects regarding overlay, foreshortening and shadowing (Speck et al., 2007) prevent the complete surface coverage. Fast surface movements can lead to a decorrelation of multi-temporal InSAR images (Bingyuan et al., 2008). Closed snow- and dense vegetation cover entirely prevent the capture of surface movements using DInSAR. However, the major disadvantage of DInSAR is that surface changes are only displayed one dimensionally along the line of sight (LOS) of the satellite, making it difficult to infer the type of movement and its exact kinematic characteristics. Additional information is therefore necessary to correctly interpret DInSAR data. This information can be obtained via a spatially and temporally limited reconnaissance campaign using a different measurement system that provides information on the 3D surface kinematics. The three dimensional interpretability of the DInSAR signal can thus be established for individual sites by referencing it to the reconnaissance campaign. Ideally DInSAR measurements, supported by process information obtained from such local reconnaissance campaigns can then be used to perform an autarkical long term monitoring and provide estimations of the 3D kinematics. The complementary measurement system applied for the reconnaissance campaign must be embedded in the measurement geometry of DInSAR and be suitable to acquire information on the unknown detailed process kinematics. We therefore defined requirements for the complementary measurement system:

- The reconnaissance campaign is temporally limited, so a high accuracy is required to capture even slow movements

- Measurement results should be provided in direct 3D

- If not already available, a digital elevation model (DEM) should be derivable from the measurement data to determine slope and to project the DInSAR data onto

- In some cases the moving terrain is not accessible and must be monitored remotely

Terrestrial laser scanning (TLS) offers adequate solutions for all these issues but depends on an unchanging surface structure for creep detection (see 3.4.) and its accuracy is limited to a few cm.

These limitations can be narrowed, if necessary, using single point measurements such as GNSS or terrestrial surveying with a total station. Both provide a higher accuracy - up to mm (table 1) and capture movements based on the tracking of individual points. Their disadvantages include the need for accessible terrain and the spatially sporadic data records in contrast to the area-covering TLS method. In our pilot study we tested both TLS and GNSS as complementary methods to DInSAR.

3.2. Reference framework

Each of the measurement systems used has its own reference system. GNSS and DInSAR operate within the World Geodetic System 1984 (WGS84) but their registration can differ due to satellite orbit uncertainties. The TLS data are referenced in a local frame of control points. To create coherence between the measurements these reference frames must be linked. We therefore installed two local terrestrial control points. Theoretically a third linking point would be necessary to join the reference frames exactly; however, due to the limited spatial extent of the study site and the high temporal stability of the reference frames we could neglect the remaining deviations between the reference frames. The linking reference points were set on stable bedrock and were equipped with an artificial InSAR reflector, a GNSS antenna base and a TLS reflector (Figure 2). The linking points acted as stable reference points for the TLS and DInSAR measurements and the GNSS base stations were located on them. The InSAR corner reflectors consist of an orthogonal open aluminium trihedral with a short edge length of 57 cm (Mair et al., 2016 in Press). This size results in a theoretical radar cross section of approximately 20 dB for the COSMO-SkyMed© X-band data used. To reduce the weight of the reflector and to facilitate snow melt, a regular grid of circular holes was drilled in the 3 mm aluminium plates. The hole diameter of 6 mm does not interfere with the wavelength used by the satellite system. The TLS reflectors consist of metal plates laminated with retro-reflecting foil. In addition to the linking points four other reflectors were used to define the TLS reference frame. They were mounted on stable bedrock at various distances from the scan position, i.e. shorter distances for the positioning and longer ones for the orientation of the scanner.

3.3. GNSS

Relative GNSS measurements were carried out using two base stations in stable terrain and one rover for the data acquisition in the mass wasting zone. The double frequency sensors Leica Viva GS10 and Leica GS530 were used. A network of GNSS measurement platforms was installed, taking into account the expected surface kinematics and the geometrical GNSS requirements (i.e. satellite visibility, baseline length). The platforms consisted of measurement poles mounted on large boulders; 14 measurement points were defined in addition to the base stations (Figure 1). One GNSS campaign was carried out in summer 2012 and three during the summers 2013 and 2014 (table 2). To obtain highly accurate results, each point was measured in static mode for at least 30 minutes with a 5 second sampling rate.

The post-processing of the collected GNNS data was performed using the ʼLeica Geo Officeʻ software, by Leica Geosystems. Baselines of all rover points to both base stations were calculated and the relative coordinates of these points were defined. The comparison of the baselines from two different base stations allowed the identification of large errors. Random errors of single points were minimized by calculating a least squares adjustment of the GPS network baselines. In order to refer the local net to the global reference system the base stations were connected to permanent reference stations belonging to the Swiss geodetic network (SWIPOS). The results of two measurement campaigns A and B were referred against each other by correcting the point coordinates of the repeat measurement B by the deviation A-B of the barycenter between the local reference stations. The degree of precision between two measurement campaigns is equivalent to the accuracy of the displacement values. This precision was equivalent to the remaining deviation of the reference station coordinates between two measurement campaigns, after they have been corrected by Barycenter bias (accuracy specifications are given in the Results section).

For calculating displacement velocities from the GNSS data we carried out a pre-selection of rover points. A few of these rover points showed movements below the level of significance (Figure 7), a few others could not be measured during each campaign due to logistic reasons and thus show data gaps. Both types of rover points were therefore excluded from the calculation. For the remaining points a mean velocity per measurement interval was defined.

3.4. TLS

Annual TLS measurements have been carried out for the entire site since 2009. Shorter measurement intervals showed no significant movement results. The instruments used were a Riegl LPM321, and from 2013 onwards a Riegl VZ6000. Both scanner systems are specified for long range applications (for technical details see: www.riegl.com). Measurements were carried out from a single fixed scan platform on the mountain ridge Mout da Barba Peider (Figure 1). The scans were performed with a resolution of < 10 cm (range dependent). Referenced images of the scan areas were taken using the camera integrated in the scanners. To reference the data, six retro-reflecting reference points including the reference frame linking points were scanned at a very high resolution. The absolute coordinates (WGS84) of the reference points were defined in advance, using a Leica TPS1200 total station.

The point clouds acquired were filtered to remove outliers and to homogenize the spatial resolution. To achieve an optimal relative referencing of the multi-temporal scans, the iterative closest point (ICP) algorithm was applied to match unchanged terrain parts in the scan (Chen and Medioni, 1991). Subsequently the set of relative registered point clouds was transformed into global coordinates using the least squares adjustment of all observations on reference points carried out for the single scans. The point clouds were then transformed into grid based digital elevation models (DEM) with 20 cm resolution. Small data gaps were filled using a 3x3 cell mean interpolation.

Horizontal 2D displacements (i.e. rock glacier creep) were derived from the multi-temporal DEM using the surface structure of the blocky terrain. The DEM grids were filtered using a high pass filter which removed information about the raw topography from the grid and only conserved the high frequency surface structure (blocks and boulders). These surface models were grey value scaled to visualize the surface pattern and saved as images. Subsequently image patches of 10x10 m were matched using the particle imaging velocimetry correlating method introduced by Roesgen and Totaro (1995). This algorithm produced a 2D displacement vector for each patch. The resulting vector field was filtered to eliminate faulty correlations (Kenner et al., 2014).

Regarding the vertical component of the displacement, a simple difference DTM would show the surface change on a specified location in the reference system. The GNSS and DInSAR methods track the movement of a single surface point or surface patch instead. This methodical difference would not allow a direct comparison of the vertical displacement components between the different measurement systems. An additional processing step was therefore applied to the TLS data. Initially, the DEMs of the first measurement t_1 and a repeat measurement t_2 and the horizontal 2D displacement vector field between both measurements were used. For the initial position of each horizontal 2D displacement vector, the elevation value was defined by calculating a weighted average between the four closest cell centres of DEM t_1 surrounding the point. Subsequently the displacement value was added to the initial positions of the displacement vectors and the elevation calculation was applied to this second set of points using the DEM t_2. Both elevations were subtracted to define the change in elevation for each point pair. This elevation difference represents the dZ component of the final 3D displacement vector field. Figure 3 summarizes this procedure.

An accuracy analysis of the TLS measurements at this site was previously carried out by Kenner et al. (2014), detailing a methodical approach to define accuracy specifications for TLS displacement measurements in position and elevation (accuracy specifications are given in the Results section blow).

3.5. DInSAR

The spatial and temporal resolution of space-borne SAR imagery were important characteristics on which the selection of a satellite system was based on. Additional analyses were carried out including a topographical analysis, applying distortion masks to simulate the layover, shadowing and foreshortening effects. Based on this, the satellite platform COSMO-SkyMed, operated by the Italian Space Agency and the Italian Ministry of Defense was selected. It consists of four satellites with a revisit time of 8-16 days. To capture the West oriented mountain cirque, descending orbits were used with a resulting off-nadir angle of 30.620 degrees. The SAR acquisition was carried out in stripmap mode with a nominal spatial resolution of 3 m.

Multi-temporal DInSAR uses stacks of SAR images acquired with the same geometry and exploits the redundant information of phase difference to measure ground displacements. The available techniques can be grouped in two main classes: Persistent Scatterers (PS; Ferretti et al., 2001) and Small BAseline Subsets (SBAS; Berardino et al., 2002). Both methods can deliver displacements along the line of sight (LOS) direction with accuracy in the order of a few millimetres per year (Pasquali et al., 2014). In a recent paper, Barboux et al. (2015) applied PS and SBAS interferometry based on TerraSAR-X for the monitoring of Swiss rock glaciers. One central finding of the aforementioned study was that SBAS interferometry was able to detect maximum displacements ten times larger than PS interferometry (3.5 cm/a versus 35 cm/a for SBAS) but inaccurate measurements due to phase unwrapping errors were already observed for velocity rates larger than 20 cm/a. Referring to the creep velocities of up to 25 cm/a we chose the SBAS technique developed by CNR IREA of Naples (Lanari et al., 2004) for our data analysis. This technique uses the surface structure as natural scatter and allows an analysis of the study area with a high spatial resolution. The study site, showing a complete absence of vegetation and widespread rocks and boulders, was particularly suited for the application of this algorithm.

The influence of atmospheric distortions such as refraction in SAR images declines with an increasing number of images. To achieve a high accuracy, multi-interferometry of SAR data requires a minimum of 20 images to effectively remove the distortions by applying spatial and temporal filtering operations (Colesanti et al., 2003). The implementation of our concept showed that due to the short snow free period at this elevation, only 5 images could be captured in 2012, 8 in 2013 and 9 in 2014. This not only affected the accuracy of the results, but also the resolution of spatially differential movements. The spatial resolution of the generated surface velocity maps was thus adapted to the significance of the data and lowered to 15 m x 21 m.

Geometrical or electrical changes in the properties of the Earth's surface between data acquired at different times are potential sources of temporal decorrelation. If the temporal decorrelation between two consecutive images is high (usually a threshold of 0.7 is used), no reliable interferogram or deformation map can be created. Moreover, if the deformation along the LOS is greater than half the wavelength (i.e. 1.55 cm in the COSMO-SkyMed data) aliasing problems can occur. Similar problems arise for parts of a scene covered by snow. In our study area, the snow-free period only lasted for 3-4 months each year and thus hindered the determination of interannual displacements.

3.6. Integration of multi methodical measurement results

To compare the results acquired with GNSS and TLS, each GNSS displacement vector was linked to the mean of all TLS displacement records in its 15 m x 15 m surroundings. The deviation between both solutions was calculated for each data pair in all three spatial components. Subsequently the mean absolute error deviation was specified for each directional component.

To allow a comparison of the DInSAR monitoring results and the results obtained from TLS and GNSS, the 3D movement information of the latter had to be projected on the line of sight (LOS) of the SAR satellite. In a Cartesian coordinate system both the displacement and the LOS of the radar sensor are represented by a 3D vector. The scalar product of the displacement vector $\vec{\boldsymbol{a}} = (a_x, a_y, a_z)$ and the unit vector $\widehat{\boldsymbol{b}} = (b_x, b_y, b_z)$ of the radar LOS results in the projection of $\vec{\boldsymbol{a}}$ on $\widehat{\boldsymbol{b}}$. The TLS and GNSS displacement vectors were projected on the SAR LOS to achieve comparability between the different datasets.

The GNSS measurements were carried out with a similar temporal resolution as the DInSAR measurements and were used as comparative data. All DInSAR displacement values in a 15 m radius around each GNSS point were averaged and linked to the GNSS displacement result. These values were normalized by time and then directly compared to define the absolute accuracy of DInSAR monitoring results.

So far, data from different measurement systems were only compared with each other. In the next step the three dimensional information of a TLS reference measurement is linked to DInSAR results of another measurement period, to extrapolate these DInSAR results into 3D. The information content of the DInSAR is thus clearly improved. To do this, TLS displacement data was transformed into an extrapolation mask for DInSAR in the following way: TLS displacement vectors $\vec{a}$ for the monitoring period 2013-14 were projected onto the LOS of the SAR sensor. This projection is called $\vec{c}$. Subsequently all three spatial displacement components of $\vec{a}$ were expressed as a fraction of the length of the vector $\vec{c}$ (equations 1-3).

$$(1)\ \ a_x = u \cdot \lceil \vec{\boldsymbol{c}} \rceil$$

$$(2)\ \ a_y = v \cdot \lceil \vec{\boldsymbol{c}} \rceil$$

$$(3)\ \ a_z = w \cdot \lceil \vec{\boldsymbol{c}} \rceil$$

Using the vector specific fraction parameters u, v and w a 1D DInSAR displacement value can be extrapolated to 3D under the assumption that the creep directions remain constant. We extrapolated the DInSAR displacements in summer 2013 to 3D by splitting each DInSAR displacement value into the components *dx, dy* and *dz* by multiplication with the mean fraction parameters of all TLS vectors in their 15x15 m vicinity.

In a following step, the reliability of the DInSAR derived 3D dataset was tested. Although TLS and DInSAR datasets were now both available in 3D, they could not be compared directly due to their different temporal resolution. TLS measurements were taken with an annual resolution, whereas no interannual DInSAR processing was possible. However, the relative spatial distribution of the creep velocity was assumed to be similar between the different but temporally close observation periods of both datasets. This implies that the ratio in velocity between a fast moving zone and a slow moving zone should be approximately the same for both methods. Although the relative velocity pattern remained constant, the absolute displacement values differed between different observation periods due to: a) temporal creep velocity differences and b) different durations of the monitoring intervals.

To eliminate this scale difference between both datasets, the TLS displacement vectors were scaled on the DInSAR vectors. The scaling factor was defined using the ratio of the mean norm of all DInSAR displacement vectors and the mean norm of all TLS displacement vectors. Subsequently root mean square error and mean absolute deviation between the datasets were calculated.

4. Results

4.1. Results and comparability of GNSS and TLS

The individual results of GNSS and TLS measurements were plausible and coherent. TLS captured highly differential surface movements with a high area covering resolution (Figure 4). GNSS single point measurements confirmed the vector field obtained by TLS and provided a higher temporal resolution during the summer months (Figure 5).

The 3D mean absolute error (MAE) between displacement records of GNSS and TLS was found to be 3.7 cm and the root mean square error (RMSE) 3.4 cm. There is no significant difference in the deviation for the single directional components. The deviations are slightly higher than the TLS precision of 3.3 cm for the position, and 3 cm for the elevation and clearly greater than the GNSS precision of 2 mm on the East-, 0.8 mm on the North- and 6 mm on the elevation component.

4.2. Results, validation and integration of DInSAR measurements

The rock glacier movement at Foura da l’amd Ursina could also be verified with the satellite-borne DInSAR measurements. As mentioned in the method section the DInSAR displacement solutions only exist for individual summer seasons and not on a full annual basis. A first comparison shows that the zones of mass movements detected by DInSAR are almost the same as the zones detected by terrestrial laser scanning. These zones correspond to the geomorphologically defined spatial extent of the rock glaciers (Figure 6). DInSAR captured the mass movement area with a similar reliability as TLS at this site, yet with a lower spatial resolution. Unfortunately, movement rates could not be quantified in some of the fast moving zones of the rock glacier complex by DInSAR. No correlation between the limited number of SAR images could be established here by the DInSAR processing. As a couple of GNSS basements are located in these fast moving zones the comparison of GNSS and DInSAR displacement results is based on a small statistical baseline. This comparison was intended to give an estimation of accuracy and reliability on the DInSAR results. However, we obtained differences between both methods that cannot be explained by the error budgets alone. Figure 7 shows the differences of GNSS and DInSAR displacement records projected on the LOS of the radar sensor. The values are given in mm per day and are based on the monitoring period 2013 (61 days for GNSS and 76 days for DInSAR) (table 2). Although the 3D GNSS displacements include larger error influences compared to the 2D solutions, they are probably more relevant in this figure, as the elevation component of the movement is disproportionately strong represented in the LOS projection. Parts of the differences between GNSS and DInSAR are related to measurement errors. The error bars for the GNSS measurements are included in the figure. Certainly also the DInSAR results show sub-optimal accuracy. This is likely due to the relatively low number of available acquisitions; as a rule of thumb, an accurate SBAS analysis requires 20-25 images – however, for our analyses, a lower number of images was available. Another problematic issue is the uneven distribution of the images over time. Moreover, the analysed deformation phenomena are characterised by fast ground displacements (i.e. in relation to the X-band wavelength) and high spatial (Figure 4) and temporal (Figure 5) heterogeneity. These conditions are not ideal for DInSAR applications and lead to errors in the phase unwrapping, particularly in fast moving areas. Another error source contributing to the deviations between GNSS and DInSAR in Figure 7, is the spatial averaging of the DInSAR displacements over a 15m radius around each GNSS monitoring point. While the GPS value represents the displacement of one point, DInSAR represents the displacement of a large area surrounding this point. However, also GNSS points that are surrounded by homogeneous DInSAR displacement values (Figure 6, e.g. point 18 and 27) show high deviations (Figure 7). Another explanation for the deviations is therefore, that the GNSS single point measurements include small scale surface movements that superimpose the large scale rock glacier creep and disturb the creep signal, especially for short measurement periods (Wirz et al., 2014). These small scale effects e.g. the toppling or subsiding of single rocks are not included in the DInSAR signal that is achieved by the correlation of larger surface patches. An accuracy assessment using single point measurements is therefore only reasonable for a longer monitoring period.

The 3D vector field extrapolated from DInSAR displacement values with the help of the TLS extrapolation mask showed visually plausible results (Figure 8). Unfortunately, large parts of the moving area are not included in the dataset: on the one hand the areas of DInSAR decorrelation and on the other the areas in the TLS shadow. The comparison with the scaled TLS 3D vectors resulted in an MAE of 1.1 cm and a RMSE of 1.5 cm. The highest displacement values within the reference period, i.e. the DInSAR monitoring period of 2013, were around 6cm. We can therefore consider the relative velocity pattern of TLS and DInSAR as significantly coherent.

5. Discussion

Space-borne DInSAR is an established method to detect and monitor large scale surface displacements or numerous small scale displacements that are distributed over large areas. One aim of this pilot study was to identify an appropriate complementary method for large scale DInSAR data at local scales and for a limited time period to provide 3D movement information of individual mass movements. TLS and GNSS were tested as complementary methods. When comparing TLS and GNSS directly, we found consistent results; the deviations between both were mainly controlled by the measurement precision of the TLS system. Static GNSS showed the higher precision, thus providing the possibility of a higher temporal measurement resolution or rather shorter significant monitoring intervals. This advantage turned out to be of limited value when comparing both complementary methods to DInSAR. GNSS did indeed offer more accurate displacement values, however referring to time scales of weeks to a couple of months, the GNSS measurements included deviations to DInSAR that are probably not explainable by error budgets of both measurement systems alone. Possibly the GNSS data include short term surface movements, which are not captured by DInSAR or TLS. Small scale surface movements of the blocky surface (toppling, subsidence or acceleration of single boulders) induced by the creep process may have distorted the signal of the large scale creep process in the GNSS single point measurements (Wirz et al., 2014). In the short term, the deviations between both measurement systems occasionally reached magnitudes higher than the creep process itself and caused a total misalignment with the DInSAR results. An accuracy analysis of the DInSAR results using GNSS data was difficult due to the unknown origin of these deviations. However these deviations are random and become less significant with increasingly long measurement periods. Therefore the phenomenon was not observed in the comparison of GNSS and TLS, as these results were compared over a much longer time span. The GNSS advantage of high accuracy associated with higher temporal resolution was nevertheless almost invalid. Instead, the weakness of GNSS in relation to TLS became more relevant: this is mainly the very low spatial resolution of the data. It is highly improbable that meaningful conclusions can be drawn from the GNSS displacements mapped in the upper section of Figure 5 regarding the rest of the rock glacier complex. Nevertheless, it is still possible to derive an overview of the seasonal creep velocity signal for the entire site out of the GNSS data by using the spatial redundancy of multiple GNSS monitoring points to filter out the small-scale distortions (lower section of Figure 5).

TLS was the more convincing complementary method to DInSAR in this study. It allowed the creation of an area-wide 3D extrapolation mask for the DInSAR displacements and showed a high degree of relative conformity with them. This is due to the similar procedure of displacement tracking of these methods. Both correlate surface patterns of several square meters to detect movements. In contrast to GNSS measurements, small-scale surface movements were therefore not captured; the movement signal rather represents the movement of the entire rock glacier body instead. Moreover, TLS has the great advantage of being a remote sensing method avoiding time consuming and potentially dangerous work directly on the difficult terrain of the monitored object. However, in contrast to GNSS, TLS fails due to visibility disruptions by cloudage, fog, snow coverage or terrain shadows.

For this study site, space-borne DInSAR measurements did not meet all the expectations of our study. This was mainly due to the loss of SAR image correlation caused by a) the long period of snow coverage and b) the too low frequency of SAR image acquisitions in relation to the rock glacier movement. As both issues are valid for many high alpine mass movement zones, this must be considered as being a characteristic limitation of the method. The long snow period not only prevents the capture of inter-annual deformation time series, it also lowers the spatial resolution and accuracy of intra-seasonal results. The decorrelation in fast moving terrain parts can theoretically be limited with shorter measurement intervals. However, the planning of data acquisition is subject to restrictions by the provider and this study used the highest temporal resolution available. Our study area is small and not representative for all alpine mass movements. It is therefore likely, that other problems and restrictions may occur when applying this concept to other alpine sites. In particular, shadow effects inherent to the remote techniques TLS and DInSAR might play a much more important role at other sites.

Apart from these limitations, DInSAR delivered reliable and plausible results and was in general suitable for our measurement concept. The common reference frame proved to be stable for all three methods and allowed data comparability. The DInSAR extrapolation mask created using the 3D TLS information allowed a simple 3D projection of the radar data. In contrast to the original DInSAR deformations, these 3D vector fields can be interpreted intuitively and allow a rapid recognition of potentially hazardous accelerations: Depending on the SAR geometry, the raw DInSAR displacements results show sometimes just a small fraction of the actual movement; the movement velocity and so the absolute magnitude of a possible acceleration are strongly underestimated. This can lead to misinterpretations regarding the risk assessment. The 3D extrapolation allows the estimation of the real velocity and acceleration values. Moreover, the comparison with the TLS monitoring results showed that the DInSAR method captured spatial velocity differences with a similar reliability as TLS.

6. Conclusions

Summarising, the applied measurement concept is a sufficient way of rationalising the monitoring efforts for selected mass movements. This selection is mainly based on the applicability of spaceborne DInSAR measurements regarding overlay, foreshortening and shadowing as well as the duration of Snow coverage and the continuous availability of SAR images in a sufficient frequency. Furthermore the movement directions of the mass movement have to stay constant and the application of TLS or other terrestrial measurement systems must be feasible. Apart from this limitations the initially defined requirements cost-efficiency, long term monitoring, self-operating mode and large scale application with cm accuracy are fulfilled.

Additionally we can draw the following conclusions:

- Referring to the initially defined requirements, TLS was shown to be the more suitable complementary measurement method for DInSAR. The reasons are the similar tracking method for surface displacements, the high spatial resolution and the efficient remote sensing. It should be noted that there may be different results for other sites.
- On short time scales up to months, GNSS and DInSAR displacement values show large deviations. They are probably the result of small scale surface movements included in the GNSS signal or originate from error sources which could not be identified within this study.

- Space-borne DInSAR showed considerable limitations in alpine terrain due to a short measurement season (long snow coverage), spatially differential creep velocities and complex terrain. This led to spatial and temporal data gaps and a reduced accuracy and spatial resolution.
- Nevertheless, reliable and valid 3D results could be extrapolated from the DInSAR records with the help of a single TLS repeat measurement. These results are easy to interpret and include considerably more information.
- Considering its limitations, a suitable practical application for space-borne DInSAR in combination with a complementary reconnaissance method is the monitoring of extensive, slightly active, long term mass movements that require observation. Furthermore, the area wide acquisition and analysis of DInSAR data allows to detect hitherto unknown mass movements which can then be investigated using the presented monitoring concept to facilitate the early recognition of hazardous areas.

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Table 1: Most frequently applied monitoring technologies for mass movments in alpine terrain

	GNSS	**Total Station**	**Terrestrial laser scanning**	**Air-borne laser scanning**	**Air-borne photogrammetry**	**Terrestrial Radar**	**Space-borne SAR**
Platform	Terrestrial: On site	Terrestrial: On site	Terrestrial: Ground base close to site	Remote: Aeroplane/ Helicopter	Remote: Aeroplane/Drone	Terrestrial: Ground base close to site	Remote: Satellite
Highest possible Spatial resolution	Single Point measurement	Single Point measurement	few cm	> 50cm	> 25cm	> 1 m @ 1 km	> 1m
Spatial coverage	Local	Local	Local	Regional	Supra-regional	Local	Supra-regional
Dimensionality	Direct 3D point coordinates	Direct 3D point coordinates	Direct 3D surface coordinates	Direct 3D surface coordinates	Indirect 3D surface coordinates	Direct 1D coordinate differences	Direct 1D coordinate differences
Highest accuracy	>mm	mm	>cm	dm	sub-dm	mm	mm
Image information	Not available	Not available	Referenced images	Not available	Multiband image information	Not available	Not available
Natural radiation	Independent	Independent	Independent	Independent	Dependent	Independent	Independent
Topographical effects	Satellite shadowing	Surface shadowing	Surface shadowing	No influence	In steep terrain	Surface shadowing and layover	Surface shadowing and layover
Vegetation	No Influence	No influence	Influence	Influence	Influence	Influence	Influence
Effort (time for data acquisition, logistics, costs)	High, Manual measurement on every single point	High, Manual measurement on every single point	Medium, remote sensing over long ranges, Close to site access required	High, Long flight time, expensive	Medium, Efficient area coverage, expensive	Medium, Automatic operation, heavy equipment,	Low, Automatic operation, efficient, reasonable prices

Table 2: Dates of the measurement campaigns.

	TLS	GNSS	DInSAR
2009	Sep, 11	-	-
2010	Aug, 04	-	-
2011	Aug, 18	-	-
2012	Sep, 18	Sep, 18	Jul, 21 Aug, 06 Aug, 22 Sep, 07 Sep, 23
2013	Aug, 29	Jul, 24-25 Aug, 29 Sep, 23.	Jul, 24 Aug, 09 Aug, 22 Aug, 25 Sep, 07 Sep, 10 Sep, 14 Sep, 09
2014	Aug, 15	Jul, 09 Aug, 18-19 Sep, 30	Jul, 15 Jul, 23 Aug, 16 Aug, 25 Aug, 28 Sep, 13 Sep, 29 Oct, 03 Oct, 12

Figure Captions

Figure 1: Study site Ursina with measurement configurations. The area covered by DInSAR includes only these regions in which displacement rates or a proof of stability could be deduced from DInSAR data.

Figure 2: Example of a multi-functional control point. The TLS reflector target (bottom right), the InSAR Corner and on it the basement for the GNSS reference station with attached GNSS antenna.

Figure 3: Sketch showing the mode of extracting the z component of a movement from two TLS DTMs.

Figure 4: Results of the TLS measurements between 2009 and 2014. Horizontal 2D creep rates are shown for visualization. The vertical differences represent the differences between the DTMs.

Figure 5: Velocities of the GPS point displacements during the monitoring period 2012-2014, in spatial resolution (top) and temporal resolution (bottom).

Figure 6: sdkdjakdsjh

Figure 7: Differences between GNSS displacements projected in the line of sight of the radar and the surrounding DInSAR displacement values; the values are based on the summer monitoring period 2013 (61 days for GNSS and 76 days for DInSAR). Systematic deviations are evident.

Figure 8: 3D Vector field extrapolated from DInSAR measurements using a TLS extrapolation mask.