

Surveying the activity of permafrost landforms in the Valais Alps with InSAR

Chloé Barboux¹, Reynald Delaloye¹, Christophe Lambiel², Tazio Strozzi³, Claude Collet¹ and Hugo Raetzo⁴

¹ Department of Geosciences, Geography, University of Fribourg, Ch. Du Musée 4, CH-1700 Fribourg, bardoux.chloe@unifr.ch

² Institute of Geography, University of Lausanne, christophe.lambiel@unil.ch

³ Gamma Remote Sensing, Worbstrasse 225, CH-3073 Gümligen, Switzerland, strozzi@gamma-rs.ch

⁴ Federal Office for the Environment, Worblentalstrasse 68, CH-3063 Ittigen, Switzerland, hugo.raetzo@bafu.admin.ch

Abstract

InSAR (space-borne Synthetic Aperture Radar Interferometry) data has revealed to be useful for surveying landslides and permafrost creeping features (e.g. rock glaciers) as it permits a time-lapse quantification of topography changes at mm to cm resolution over alpine areas where dense vegetation is no longer present. The capability of InSAR for detecting both the location of moving zones and the magnitude of their displacement rate has been successfully tested in various regions of the Swiss Alps. Research challenges are mainly focusing on the possibilities of using InSAR for monitoring tasks. The present contribution presents first basic principles, potentials and limitations of InSAR and its use in a mountain area. Then, it overviews some past, present and future InSAR projects dealing with the detection and the monitoring of moving zones in the Alpine periglacial belt.

Keywords: InSAR, permafrost landforms, detection, monitoring

1 Introduction

InSAR (space-borne Synthetic Aperture Radar Interferometry) is a remote sensing technique that has been developed after the launch of the first SAR satellite in 1991 (ERS-1). Time-lapse changes of the Earth topography can thus be provided at mm to cm resolution where dense vegetation is no longer present. Several studies have shown the potential of InSAR for the interpretation and quantification of different kinds of alpine mass movements like landslides and rock glaciers (e.g. DELACOURT *et al.* 2004; KENYI and KAUFMANN 2000, 2001, 2003; NAGLER *et al.* 2001, 2002; RIGNOT *et al.* 2002; ROTT and SIEGEL 1999; STROZZI *et al.* 2003, 2005, 2007, 2008, 2009a, 2009b, 2010). The capability of InSAR for detecting and inventorying both location and displacement rate magnitude of moving zones on mountain periglacial slopes has also been successfully tested (e.g. DELALOYE *et al.* 2007a; LAMBIEL *et al.* 2008). The analysis of InSAR data can moreover help to understand geomorphologic processes by giving indications on the temporal development of a landform over the last two decade or so (e.g. DELALOYE *et al.* 2007a, 2007b, 2010; LAMBIEL *et al.* 2008; ROTT and SIEGEL 1999; SJOGREN *et al.* 2003; STROZZI *et al.* 2007, 2010). Such results contribute indirectly to a better assessment of the ongoing sediment transfer in the catchments of many alpine torrents or valley slopes and can be seen also as a useful tool for natural hazard management and process understanding of slope movement in non-vegetated areas, particularly in permafrost areas (e.g. DELALOYE *et al.* 2007a, 2007b, 2010; LAMBIEL *et al.* 2008).

In the context of climate change and in view of natural hazard management there is a great need to investigate automated methods to detect and monitor slope instabilities at both

local and regional scales. InSAR appears to be an appropriate method for this kind of large-scale survey. In this perspective the present contribution firstly provides basic principles of the InSAR technique in order to understand potentials and limitations of its use for slope motion detection and monitoring in an alpine topography. An overview of past and on-going research activities related the use of InSAR for detecting and monitoring slope instabilities in the Valais Alps and conducted by the Universities of Fribourg and Lausanne in collaboration with the Swiss Federal Office for the Environment (FOEN) and Gamma Remote Sensing is then presented.

2 SAR Interferometry

2.1 Synthetic Aperture Radar (SAR)

SAR data is obtained by continuously scanning the Earth surface with a sensor carried by a spacecraft pointing on its right, nearly the perpendicular of the flight direction. The transmitted pulse (sinusoidal signal) propagated from the radar is reflected from targets located at increasing distances from the radar along the ground. The received echoes from a single transmitted pulse are function of the time delay to the targets. The wavelength λ of the pulse determines the penetration depth of the transmitted signal into the vegetation layer. The longer is the wavelength, the deeper is the penetration in the vegetation layer. A complex data is achieved for each cell containing both phase and amplitude of the received signal. The phase is related to the propagation time of the wave, while the amplitude depends on the backscattering coefficient of the targeted object. The direction along the Line of Sight (LOS) is called slant-range direction. In a resulting SAR image, the direction of the satellite's movement is called azimuth direction, and the imaging direction is the range direction (Fig.1).

The inclination of the antenna with respect to the curvature of the earth is called incidence angle θ (between 20° and 45° in the Valais Alps depending on the technology). The orbital direction of the SAR data is determined by the satellite position at the start of the imaging

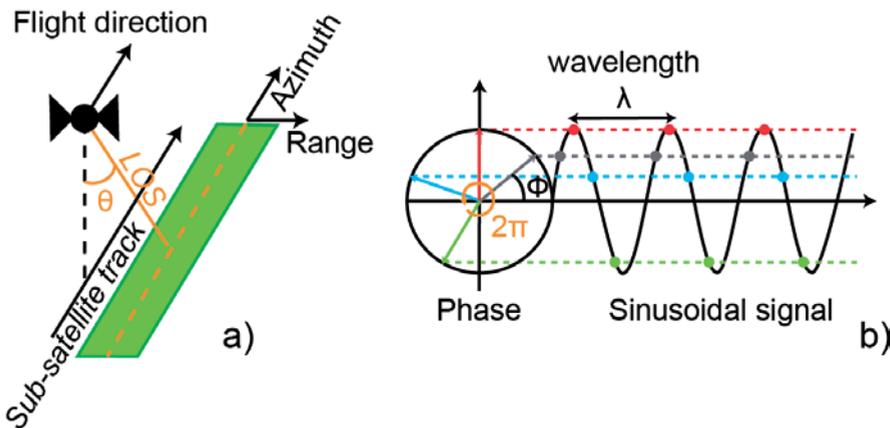


Fig. 1. a) SAR geometry and acquisition and b) the transmitted pulse (adapted from FERRETTI *et al.* 2007)

activity. The ascending mode refers to the portion of the orbit during which the satellite is heading northward (the satellite advances from South to North), and descending mode refers to the opposite (FERRETTI *et al.* 2007).

Radar sensors are designed into 3 main categories defined by the wavelength range of λ . The L-band is designed in 15–30 cm and illustrated by the Japanese Earth Resources Satellite (JERS-1: 1992–1998) and Japanese Advanced Land Observation Satellite (ALOS Palsar: from 2006). These sensors have the advantage to be less affected by atmospheric artifacts and noise due to vegetation. However, their repeat cycle, which is the minimum time that gets the satellite to come back imaging the same surface area, is large (44 and 46 days respectively). The C-band is designed in 4–8 cm and characterized by the European Remote Sensing satellites (ERS-1: 1991–2000 and ERS-2: 1995–2011), the European Environmental Satellite (Envisat: 2002–2012) and the Canadian Radar Satellites (RADARSAT-1: 1995–2011 and RADARSAT-2: from 2007). The 3 days repeat cycle of ERS-1 and the 1 day ERS1/2 tandem mission have offered a unique opportunity to observe changes over a very short space of time. Finally, the newest technology of X-band is designed in 2.5–4 cm. The German satellite TerraSAR-X (TSX: from 2007) and Italian constellation COSMO-SkyMed (CSK: from 2007) both have the advantage to currently deliver the best deformation information for displacement rate due to their high temporal sampling and resolution. Since the repeat cycle of TSX is 11 days, the CSK constellation of (currently) four satellites permits to acquire X-band interferograms with 4 days time interval.

2.2 SAR Interferometry (InSAR)

SAR interferometry (InSAR) is a technique involving phase measurements from a pair of satellite SAR images taken from the same sensor at different times (Fig. 2). The satellite should be at almost the same position for both acquisition times. The time lapse is the duration between the two radar acquisitions used to compute an interferogram. The repeat cycle is the minimal available time lapse (from 3 to 46 days depending on the technology).

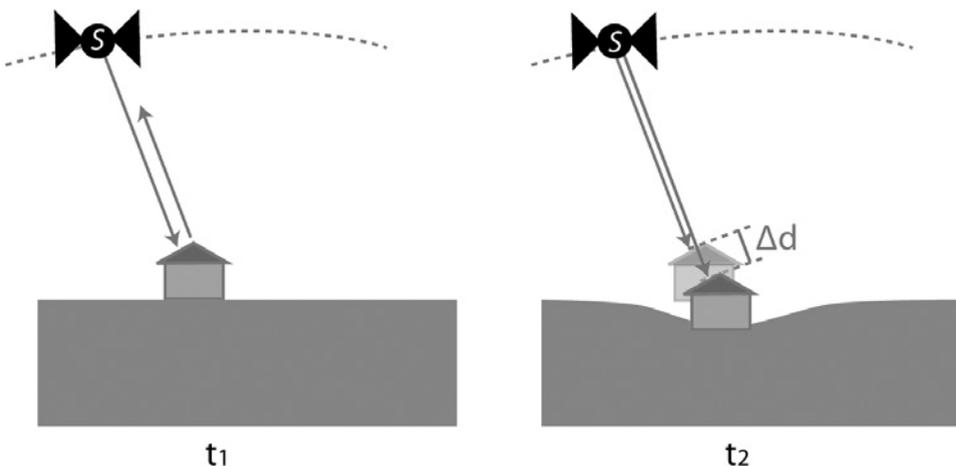


Fig. 2. Detection of topography change (Δd) by InSAR (simplified).

To produce the interferogram, the backscattered signals received at each acquisition time are mixed or interfered. Firstly, the two SAR images are matched each other to identify pixels corresponding to the same area of ground. Then, for each pixel, the interferogram is defined as the product of the complex SAR values of the first image by the complex conjugate of the second image. Thus the difference of phase values is calculated for each position.

The two main interferometric products are the phase and the coherence. The interferometric phase is ambiguous and takes values in $[-\pi, \pi]$. A phase cycle is represented by a full color cycle and is equivalent to a change of the target of half a wavelength in the LOS direction between the first and the second acquisition (MASSONNET and FEIGL 1998). The phase unwrapping is the integration of the phase between neighboring pixels to solve the ambiguity. The coherence estimates the phase noise by cross-correlation of the SAR image pair estimated over a small window. The values of coherence range from 0, where there is no useful information in the interferogram, to 1, where there is no noise in the interferogram.

An example of interferometric phase is given in Figure 3. There is a high coherence in most of the illuminated area, well visible and quantifiable movement of some parts of the glaciers and no movement elsewhere (yellowish areas). The noise (low coherence, neighboring cells with contrasted colors) is here due to either not well illuminated areas (usually steep slopes, rock walls), or to large displacement rate (on some parts of the glaciers), often associated with rough terrain surface (here crevassed areas), or possibly also wet snow on south-oriented slopes. Layover and shadow occur in areas where there is no data (white).

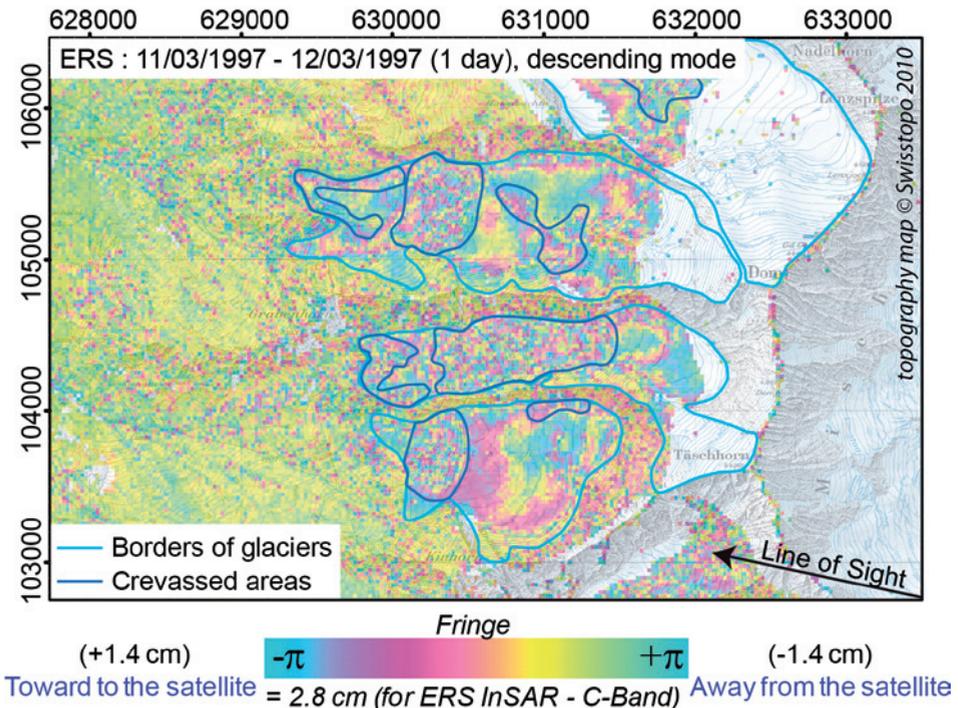


Fig. 3. 1-day interferometric phase on the Festi and Kin glaciers in winter 1997.

In a mountainous area, a significant phase effect is introduced due to the slight difference in satellite position altering the distortion caused by topography. As the aim is to identify the displacement component, this topographic phase component has to be removed. The process, called 2-pass differential interferometry (DInSAR), uses a Digital Elevation Model (DEM) in conjunction with parameters of the satellite orbits, to estimate and compensate for topography in the final interferogram (WEGMÜLLER and STROZZI 1998). By misuse of language InSAR is often used instead of DInSAR in the literature and that will be the case in this contribution. Restrictions to the use of InSAR for detecting and monitoring landforms are related to the velocity rate, the terrain (slope, aspect, roughness, etc.), the time lapse between the two acquisitions, and a number of additional phase effects degrading the coherence (DELALOYE *et al.* 2007a; ROTT and SIEGEL 1999; SJOGREN *et al.* 2003; STROZZI *et al.* 2010).

2.3 Specifications of applying InSAR in an alpine area

Acquisition geometry

The terrain area imaged in each SAR resolution cell depends on the local topography (Fig. 4). The foreshortening (c–d) is the effect of imaged terrain surfaces sloping towards the radar appearing shortened relative to those sloping away from the radar. The layover (a–b) is an extreme case of foreshortening and occurs when the terrain slope angle exceeds the incidence angle. In these conditions the targets are imaged in reverse order and superimposed on the contribution coming from other areas). The second irreversible phenomenon concerns shadow (d–e) and appears when a point is not illuminated by the radar beam.

Spatial decorrelation

Acquisition geometry slightly differs between two SAR images involving difficulties to match the two SAR images during interferogram computation. In order to reduce this spatial decorrelation, the baseline (separation between two repeated antenna positions) of selected pairs has to be as shortest as possible.

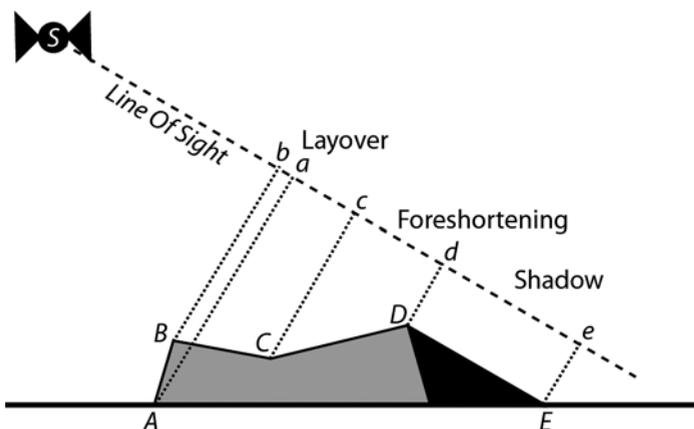


Fig. 4. Acquisition geometry.

Temporal decorrelation

The movement rate of terrain depends among others on the time lapse and the surface preservation between repeated acquisitions. The interferometric SAR signal decorrelates over the parts having a per pixel deformation rate in the LOS direction larger than $\lambda/2$ (MASSONNET and FEIGL 1998) – this is why linear sediment transfer along rivers for instance cannot be surveyed. Temporal decorrelation can also be caused by the rough surface of the moving terrain (e.g. crevassed area on Fig. 3). Thus, the experience shows that on a rock glacier decorrelation often occurs when the deformation rate of the landform in the LOS direction is larger than about $\lambda/2$.

Natural constraints

Atmospheric effects may cause pixel misregistration and artifacts in the phase difference (TARAYRE and MASSONNET 1994). Moreover, the coherence could be lost when the terrain is destructed or the surface humidity changes significantly. In high mountains the presence of snow and its temporal changes have significant influence on the electromagnetic response in the microwave spectrum making that InSAR analysis is only feasible in wintertime over short time lapse (e.g. Fig. 3) (DELALOYE *et al.* 2007a). Finally, vegetation disturbs the reflection of the radar wave and water (as well as wet snow and melting ice) prevents any coherent signal to be measured.

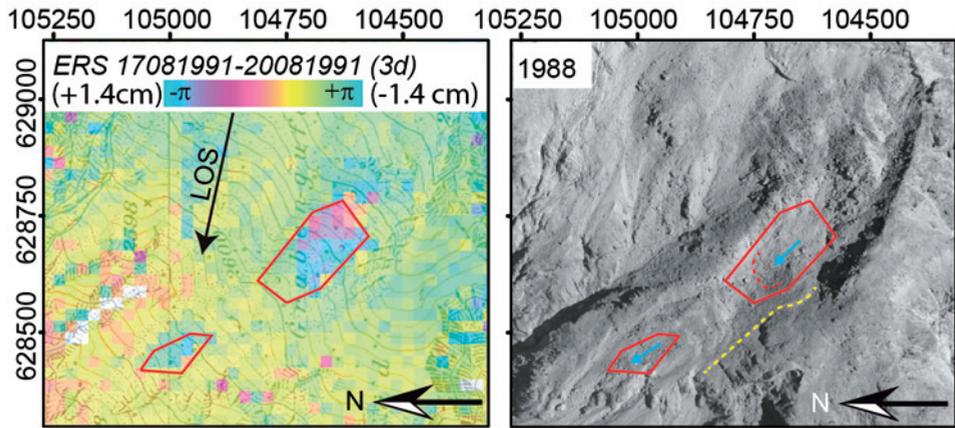
3 Detection of moving zones on mountain slopes

InSAR can be used at both local (landform) and regional scale. Requirements to select, to analyze and to interpret InSAR data in an alpine environment is discussed in many studies (DELALOYE *et al.* 2007a, 2007b; LAMBIEL *et al.* 2008; NAGLER *et al.* 2001, 2002; STROZZI *et al.* 2004). In Valais, the topography – mainly consisting of north-south oriented valleys – is optimal for an application of the InSAR technique especially during the snow free period between early summer and mid fall making that various projects are taking (or have taken) place in this region.

3.1 Analyze of a slope movement

InSAR scenes build up a significant archive of data since 1991 at earliest. In addition to the survey of current phenomena, analyzing InSAR data may also help for reconstructing the development and evolution of a landform. An example is given in the Matternal Valley by the surging Graben Gufer rock glacier whose maximal velocity culminated in 2009/10 close to 100 m/year. The crisis of this rock glacier was first detected by InSAR (DELALOYE *et al.* 2008). A combined analysis of repeated SAR interferometry, terrestrial and airborne optical data was carried out for reconstructing the development of the crisis (BARBOUX and DELALOYE 2010). It has appeared that it started in the upper rooting zone of the rock glacier during the 1980's, and then accelerated and propagated progressively by compression to the median part of the rock glacier during the 1990's and the early 2000's, before to reach finally and to destabilize the frontal part of the landform. Figure 5 illustrates the situation in the early 1990's as it can be observed using the InSAR archive. On a 3-day interferogram in summer 1991 a rapidly moving mass wasting (permafrost creep or landslide?) was obviously visible in the rooting zone of the rock glacier. The displacement rate could be estimated about 1 cm in 3 days in the LOS (1.2 m/year). In 1995 the displacement rate in this upper zone accelerated to about 1 cm per day in the LOS (3.5 m/year).

Phase 1: Landslide in the rooting zone



Phase 2: Landslide propagation throughout the rooting zone

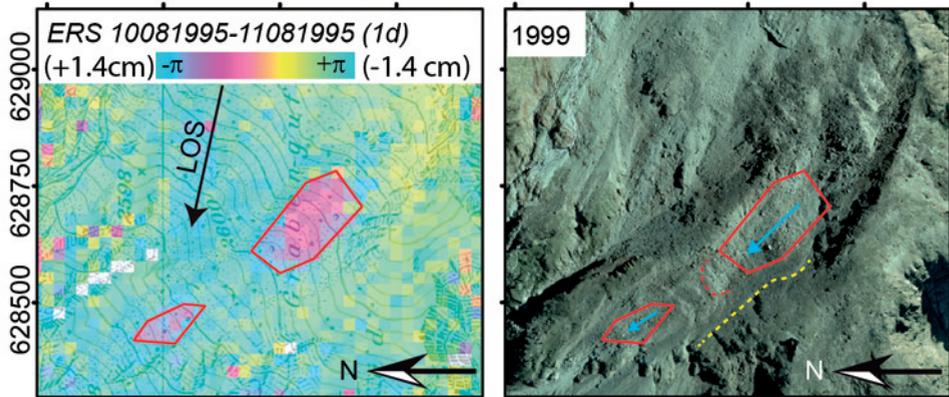


Fig. 5. The onset of the destabilization of the Grabengufer rock glacier described by aerial images and InSAR data in the early 1990's.

3.2 InSAR-based inventories of moving zones

Using a large set of data (mainly ERS-1/2 and ENVISAT (C-Band), JERS and ALOS PALSAR (L-Band) data archive), large inventories of InSAR-detected moving zones have been compiled at a regional scale in Swiss Alps since 2005 (DELALOYE *et al.* 2007a, 2007b, 2008, 2010; LAMBIEL *et al.* 2008). With different levels of confidence, it has been possible to detect thousands of zones (sometimes several zones on the same landform) moving at a velocity ranging from a few centimetres to several meters per year. Inventories contain the outline of the zones, the magnitude order of their LOS displacement rate and the geomorphological interpretation of the movement defined with the help of topographic map and orthophotos (Fig. 6). They are generated manually and zone outlines are sometimes uncertain and inaccurate. Inventories are subjective and highly depend on the experience of their authors. To build them, no automatized procedure exists so far. Before making them available, the FOEN is currently upgrading and adapting the inventories, in particular by integrating into the analysis the more recent TerraSAR-X (X-Band) data.

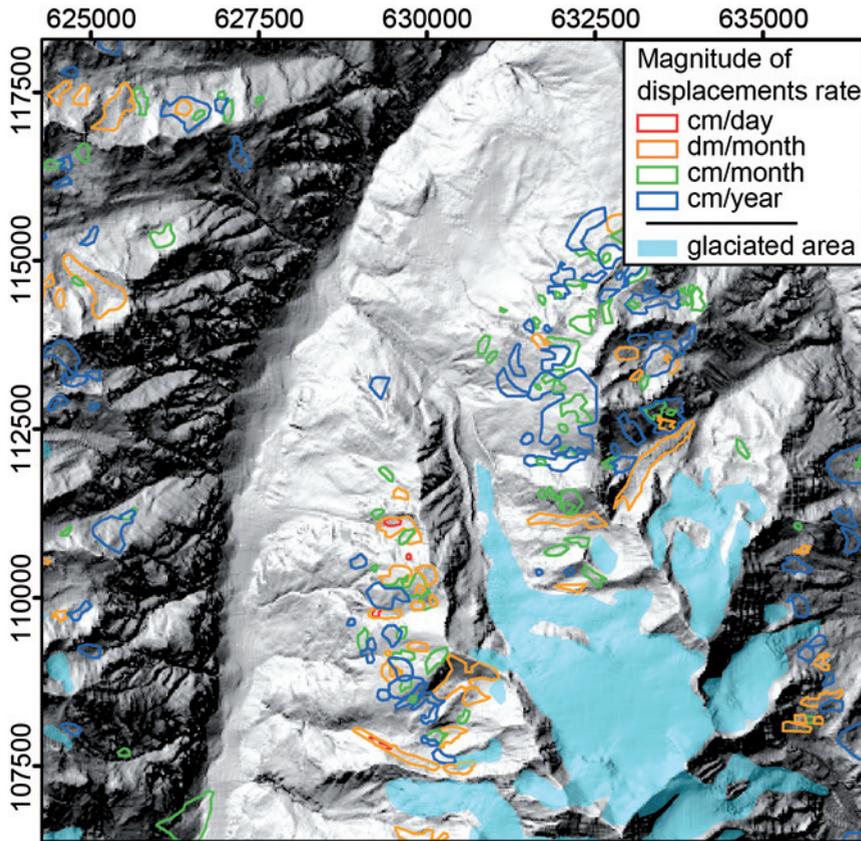


Fig. 6. Typical example of detected moving zones. DHM25 © Swisstopo 2003.

Worth is to note that a precise detection of zones moving faster than about 1 to 2 m/year highly depends on the availability of SAR acquisition with short repeat cycles. It was the case between 1991 and 1999 with the 1-day and 3-day repeat cycle of the satellites ERS-1 and ERS-2, but such data do not exist for the following decade. Available 1991–1999 ERS-1/2 scenes with short repeat cycles has allowed the identification of 11 rock glaciers in the Swiss Alps moving at an unusual rate of 1 cm/day or more, at least during the summer season. They were all located in the Valais Alps and 5 of them along the orographic right side of the Mattertal valley (DELALOYE *et al.* 2008).

4 Toward new potential of InSAR for the detection and monitoring of mass movements

The main objective is to investigate new sensors to detect and monitor creeping landforms. This analysis starts by the assessment of which level InSAR can be used independently of field surveying as a monitoring tool of mass wasting kinematics in rough alpine terrain topography. Then, it proposes a method to monitor active landforms which are often badly explored by using conventional processes. Finally, the objective is to automatically update (detect the changes in activity rate) and upgrade (identify more accurately the active landforms and the quantification of displacement rate) the creeping landform inventory and especially active rock glaciers in the region of interest using new sensors.

4.1 Terrasar-X assessment for slope movement monitoring

The study focuses on the new high temporal sampling and resolution of TerraSAR-X (TSX) sensor and aims to assess the potential of this new technology for slope movement detection and monitoring. The X-Band TSX sensor offers the opportunity for updating the inventories and also for upgrading them in term of identification of the landform outline and quantification of the displacement rate (BARBOUX *et al.* 2011). Moreover, the potential of using facing mode (ascending, resp. descending mode for West-, resp. East- oriented slopes) to monitor fast moving landforms was investigated. For instance, considering a west-oriented landform and the movement slope directing toward the slope direction, the viewing geometry in ascending mode implies a larger compression of the signal than in descending mode (see part 2.3 Potentials and Limits – Acquisition geometry). Thus, in this case the ascending mode is more suitable to monitor large velocities whereas low velocities can be well monitored using descending mode (Fig. 7).

By analyzing 30 sites located in the Valais, with a distribution that seems to be representative of the region according to their location, aspect, elevation as well as velocity, results confirm the possibility to theoretically monitor some very active rock glaciers with velocities up to 3.5m/year (if West or East oriented) when layover and/or distortions does not hide them using InSAR TSX with the shortest repeat pass of 11 days. Thanks to the compression factor, it is therefore possible to determine the maximal velocity of each landform which can be well monitored with TSX.

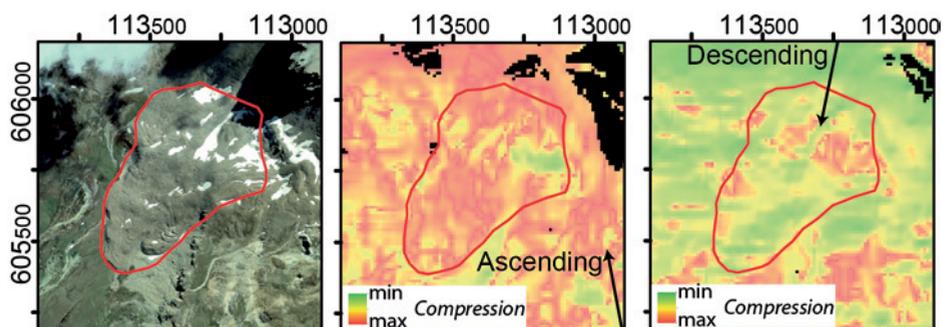


Fig. 7. ORTHOIMAGE (2005) of the North-West oriented Rechy rock glacier (left). Compression factor for ascending mode (center) and in descending mode (right). Adapted from BARBOUX *et al.* 2011.

4.2 Monitoring of active rock glaciers using profiles

The consequence is to use TSX for a precise slope motion monitoring at local scale that is the scale of a single landform. In Valais, active rock glaciers are relatively small and show sometimes rapid and complex movements (DELALOYE *et al.* 2008, 2010). These particularities are not suitable for deriving a complete spatial distribution of the surface deformation using conventional unwrapping algorithm of InSAR data. Thus, a method is currently developed consisting on the quantification of movement on a profile defined through the rock glacier (BARBOUX *et al.* 2012). In order to analyze fast moving landform, the shortest time lapse of 11 days is chosen. Firstly, the interferometric coherence trend along the profile is analyzed and key points are localized (root and front of the landform, acceleration, break slope, etc.). This profile is then used to roughly evaluate the possible change in the activity rate of landform between two pairs by manually analysing the variation of the coherence. Finally, when the quality of the pair is efficient, the deformation rate in the radar LOS direction is estimated on the profile using phase signal (Fig. 8).

Results show the potential to accurately monitor movements when the signal is not decorrelated. Moreover, when the quality of the phase is not good enough to estimate the deformation rate, the study suggests that it is possible to estimate annual and seasonal variations through the analysis of only the coherence parameter. This specific examination and automation will be carried out in future projects.

4.3 Toward upgrading and automated updating of inventories

The higher temporal sampling and resolution of TSX offers the opportunity of upgrading the inventories by outlining moving zones and quantifying their displacement rate in many cases with higher precision. In this context, a future objective is to automatically update inventories of slope movements when new InSAR data are made available in order to detect possible changes in the activity rate of landforms without checking them manually. The compatibility between different sensors – according to their respective wavelength and repeat cycle implying InSAR signal decorrelation at different deformation rates – has to be considered to allow accurate upgrading and updating processes.

Efforts are currently being made to develop updating procedure by concentrating the analysis either on a core area, which has to be defined for a landform or inside a moving zone, or on a profile along the landform. The analysis consists of evaluating the coherence trend and detecting the variation around this trend in order to evaluate possible activity change as explained in part 4.2.

5 Conclusion and outlook

InSAR has revealed to be a useful tool for a large-scale survey of permafrost creep as it contributes to provide a regional overview of surface displacement at mm to cm resolution. At local scale the analysis of InSAR provides the quantification of landform motion and the understanding of geomorphologic processes. Past studies were successfully conducted in the region of interest to inventory moving slopes possibly related to permafrost creep with a velocity ranging from a few centimetres to several meters per year. Current investigations focus on the capability of new sensors (especially X-Band TSX) to detect and monitor creeping landforms. This analysis assesses the potential of InSAR which can be used independently of field surveying as a monitoring tool of mass wasting dynamics in rough alpine topography, but also contributes to understand the dynamics involved in some specific rock glaciers. Future

examinations will continue to explore capabilities of InSAR to monitor landforms in alpine environment as well as focus on the possibility to automate some processes for updating and upgrading inventories with the most recent InSAR data.

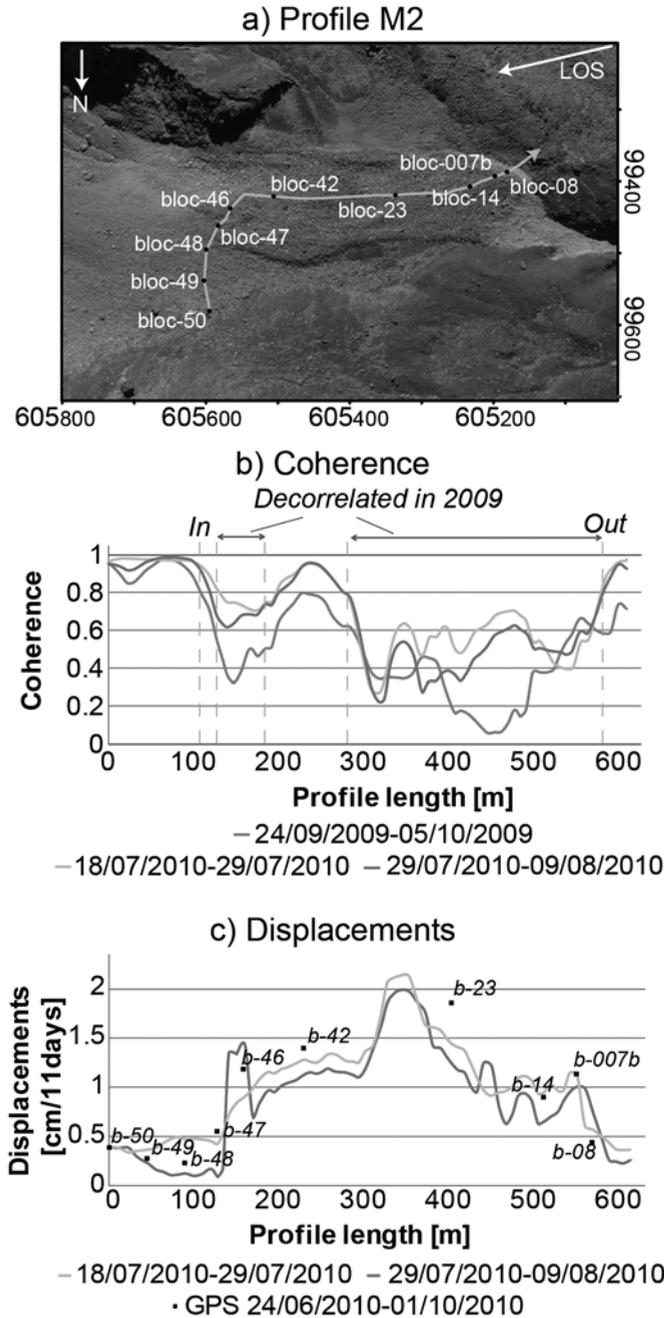


Fig. 8. Profile analysis on Tsarmine rock glacier: a) Orthoimage (2007), profile and DGPS points, b) Coherence analysis for 3 InSAR selected pairs c) Displacements estimation for the 2 high quality pairs of 2010. Adapted from BARBOUX *et al.* 2012.

Acknowledgements

ERS SAR data courtesy of CPI.2338, © ESA; ENVISAT SAR data courtesy of CPI.3069, © ESA; TERRASAR-X data courtesy LAN0242, LAN0411, LAN1145, © DLR; ALOS PALSAR data courtesy AOALO.3550, © JAXA; DHM25 ©2003 Swisstopo; Swissimages © 2010 Swisstopo

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