EVOLUTION OF A DEEP-SEATED ROCK MASS MOVEMENT OBSERVED WITH SATELLITE SAR INTERFEROMETRY

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ABSTRACT

The displacement of an unstable slope in the Aletschwald region (Canton of Valais, Switzerland) has been observed between 1992 and 2007 with satellite SAR interferometry. Analysis of ERS-1, JERS, ERS-2, ENVISAT and ALOS differential SAR interferograms revealed an acceleration of the movement. The ERS-1 / ENVISAT-IS2 line-of-sight displacement rate increased from about 3 cm/year at the beginning of the observation period to more than 15 cm/year in the summer of 2007 in the centre of the unstable slope. These values correspond to about 5 cm/year and 30 cm/year, respectively, when projected on the direction of maximum slope derived from a digital elevation model, and are consistent with the rates detected with JERS and ALOS differential SAR interferograms.

1 INTRODUCTION

Landslides are a natural hazard of special relevance to mountainous areas with severe human and economic consequences. In particular in the alpine zones, i.e. for regions above the tree line, global warming causes a decline of permafrost and valley glaciers, which results in a number of situations in increased slope instability such as landslides[1]. Therefore, an efficient survey of unstable slopes in these regions is required and will be of even increasing importance in the future.

In Switzerland the decline of alpine glaciers has been observed since the end of the Little Ice Age (LIA, ca. 1850) with an acceleration phase since the 1980s [2]. The retreat of valley glaciers changes the stress regime of the adjacent slopes [3]. At first, the glacial retreat causes a decompression and elastic rebound, leaving the landslide mass in plastic state [4]. Slope failure initiates then at the toe of the slope and move uphill until completion of the rupture surface. At that moment the landslide enters a kinematic phase of potentially unstable equilibrium, moving slowly downhill.

Repeat-pass differential SAR interferometry (InSAR) is a powerful technique for mapping land surface deformation from space at fine spatial resolution over large areas [5,6]. Potential and limitations of InSAR for the periodical survey of alpine displacements were investigated in [7,8,9]. For the alpine territory, which is characterized by low or even absent vegetation, differential SAR interferometry shows a relatively high coherence during the snow-free season permitting the detection and monitoring of unstable slopes on a regular basis. Limitations to the spatial coverage arise from decorrelation over forested and snow covered areas and from layover and shadowing caused by the very rugged topography.

After a short review of data and methods considered in this study, the evolution of a deep-seated rock mass movement in the Swiss Alps observed with ERS-1, JERS, ERS-2, ENVISAT and ALOS differential SAR interferometry is presented and discussed. An outlook to future analyses with complementary methods to InSAR is summarized in the conclusions.

2 DATA AND METHODS

In this study, a series of SAR images from the European Remote Sensing satellites ERS-1, ERS-2 and ENVISAT and the Japanese Earth-Observation satellites JERS-1 and ALOS from 1992 to 2007 have been analyzed. A total of 17 interferograms with short baselines and acquisition time intervals between 35 and 1144 days were considered (see Table 1). For topographic reference and orthorectification an external Digital Elevation Model (DEM) with a pixel spacing of 25 m (DHM25 © 2003 swisstopo) was used. For the quantitative measurement of the identified displacement phase unwrapping was performed with a region-growing algorithm [10]. Phase unwrapping of interferograms in rugged terrain and for complicated displacement fields is a critical task that was successful only for small areas depending also on the time period and wavelength of the interferogram. The line-of-sight displacement was finally transformed to displacement along the slope gradient using the DEM.

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From the different error sources of InSAR (atmospheric phase distortions, signal noise, inaccuracy in the orbit determination, phase unwrapping mistakes, assumption of displacement along the slope direction), we consider signal noise and assumption of displacement along the slope direction as the main limiting factors for the proposed application. The analyzed rock mass movement has a relatively small dimension, whereas atmospheric artifacts and inaccuracy in the orbit determination mainly cause relatively large-scale distortions. Phase unwrapping was carefully performed with a region-growing algorithm and only areas with reliable information were retained. To prevent errors caused by the transformation of the line-of-sight displacement to the displacement along the slope direction, only measurements of slope with an orientation within 80° of the line-of-sight are presented. Assuming an error in phase noise of one quarter of wavelength leads to an error in line-of-sight displacement of 0.7 cm for ERS and of 2.9 cm for JERS.

Table 1. Acquisition time differences and perpendicular baselines of the selected SAR interferograms.

SAR Sensor	Acquisition Dates	Time Interval	Perp. Baseline
ERS	19921006_19930921	350 days	-44 m
ERS	19930608_19950706	758 days	39 m
JERS	19930617_19960804	1144 days	45 m
ERS	19950811_19960726	350 days	121 m
ERS	19950811_19970815	735 days	35 m
ERS	19960726_19970815	385 days	-86 m
ERS	19970815_19980904	385 days	-53 m
ERS	19981009_19990716	280 days	-126 m
ERS	19990716_19991029	105 days	7 m
ERS	19991029_20001013	350 days	-15 m
ERS	20020913_20030829	350 days	64 m
ERS	20030829_20040709	315 days	-69 m
ENVISAT	20041022_20050624	245 days	21 m
ENVISAT	20050902_20060714	315 days	87 m
ENVISAT	20060609_20061027	140 days	-27 m
ALOS	20060613_20061029	138 days	-496 m
ENVISAT	20070629_20070803	35 days	1 m

3. RESULTS

Eight out of the 18 displacement maps of an unstable slope in the Aletschwald region (Canton of Valais, Switzerland) are shown in Figure 1 to 8. Displacement maps for different time periods and acquisition time intervals are presented. The displacement is in the line-of-sight direction and the negative sign indicates the direction away from the satellite. From 1992 to 1998 the highest annual displacement rate in ERS SAR interferograms was about 3 cm in the center of the landslide (see Figures 1 and 2). In the summer of 1999 an increase of the displacement to about 2 cm in 105 days has been observed (Figure 3), possibly triggered by exceptionally strong snowfall during January and February, corresponding large amount of melt water in the following spring, and additional heavy spring rainfall. Indeed, in the spring of 1999 as many as 350 landslides in Switzerland have been triggered with a total damage of about 60 to 75 Mio CHF [11]. From 2002 to 2004 the highest annual displacement rate in ERS / ENVISAT-IS2 SAR interferograms in the center of the landslide remained larger than about 4 cm/year (Figure 4). In the summer of 2006 an ENVISAT interferogram with 140 days time interval (Figure 5) revealed a further increase of the line-of-sight displacement rate to about 8 cm/year. Finally, in the summer of 2007 the signal related to the displacement of the landslide was visible even in a 35 days time interval interferogram, which indicates a displacement rate in the order of 3 cm/month.

A similar increase of the displacement rate has been also observed on L-band SAR interferograms [12]. In the three years between 1993 and 1996 a JERS SAR interferogram shows about 12 cm of displacement. In 139 days during the summer of 2006 an ALOS PALSAR interferogram revealed a displacement of about 5 cm.

In order to compare all the different interferograms with different acquisition time intervals, the displacement at the end of a cableway (i.e. at the point with an elevation of 2335 m a.s.l.) and around the center of the landslide (i.e. where the path way makes a curve) have been extracted and transformed to annual displacement rates. The two plots are presented in Figures 9 and 10 for the displacement in the line-of-sight direction. In both figures the vertical error bars indicates an error of one quarter of wavelength and the horizontal bars indicate the acquisition time intervals. Three periods of different activity - from 1992 to 1998, from 1999 to 2005, and in the last years - can be observed in particular in Figure 10, where the displacement rates are higher and therefore the relative errors smaller.

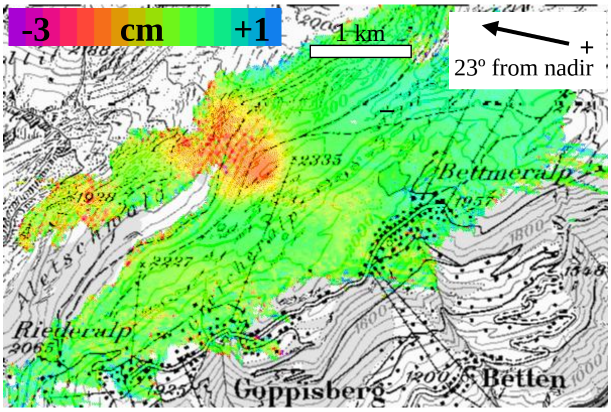

Figure 1. ERS SAR 19921006_19930921.

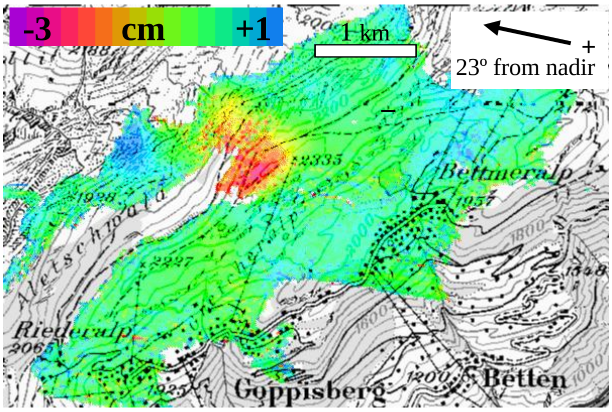

Figure 2. ERS SAR 19970815_19980904.

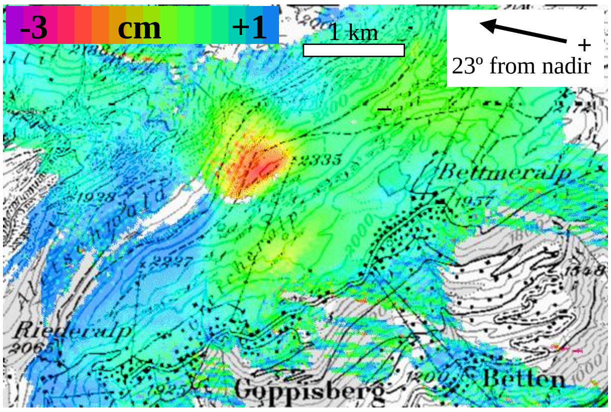

Figure 3. ERS SAR 19990716_19991029.

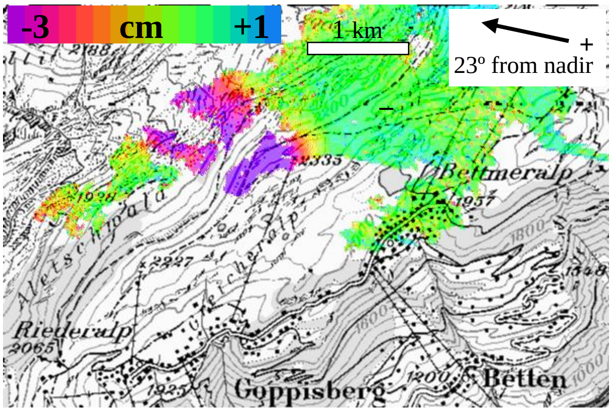

Figure 4. ERS SAR 20020913_20030829.

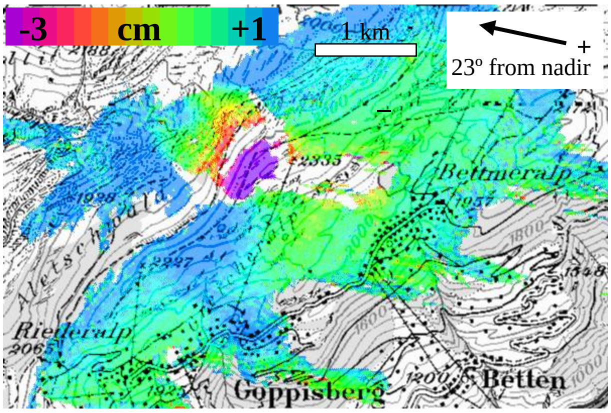

Figure 5. ENVISAT ASAR 20060609_20061027.

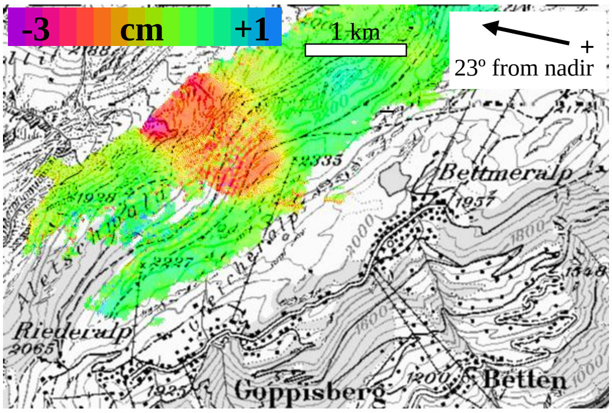

Figure 6. ENVISAT ASAR 20070629_20070803.

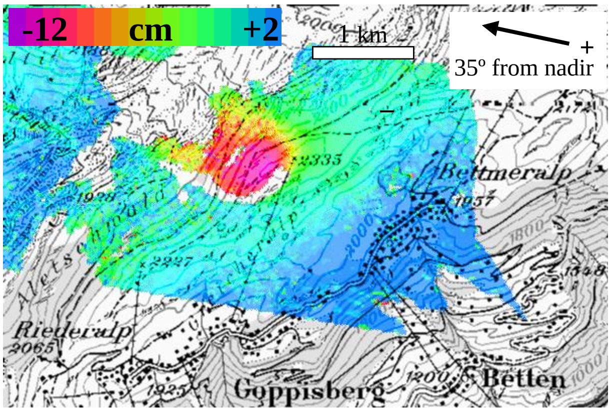

Figure 7. JERS SAR 19930617_19960804.

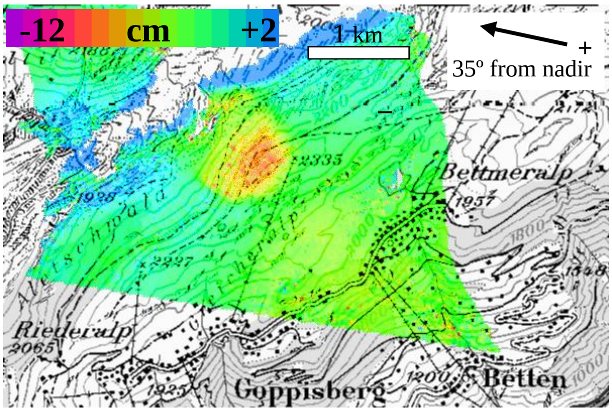

Figure 8. ALOS PALSAR. 20060613_20061029.

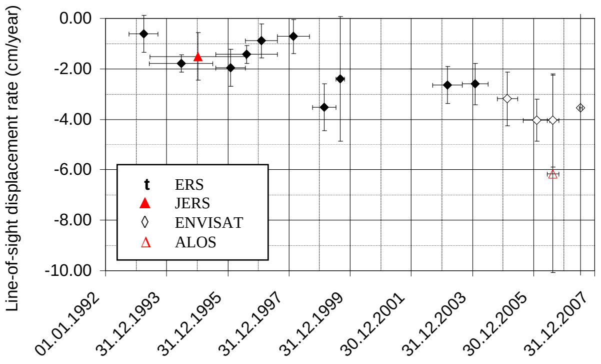

Figure 9. Line-of-sight displacement rates at the end of the cableway.

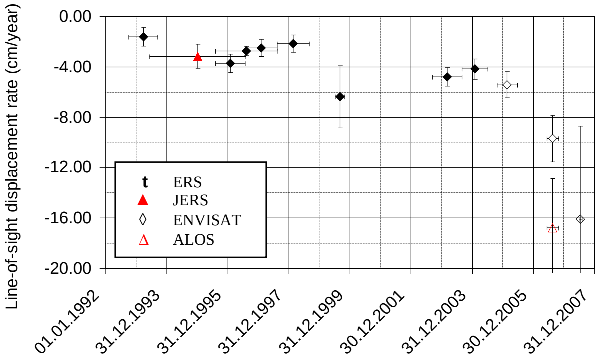

Figure 10. Line-of-sight displacement rates around the center of the landslide.

4. DISCUSSION

For further discussion, the line-of-sight displacement rates were transformed to displacement rates along the slope gradient using the DEM. The result is presented in Figure 11 for the end of the cableway and in Figure 12 for the area around the center of the landslide. For the end of the cableway the projection along the slope is uncertain because that area is rather flat. Also, the error bars of some of the measurements are quite large compared to the observed displacement. On the other hand, in Figure 12 we can observe that in the center of the landslide the ERS / ENVISAT-IS2 displacement rates increased from about 5 cm/year at the beginning of the observation period to more than 30 cm/year in the summer of 2007. These values are consistent with the rates detected with JERS and ALOS differential SAR interferograms. In particular in the summer of 2006 the ENVISAT and ALOS rates compare very well. The apparent discrepancy in Figure 10 is related to the different incidence angles of the two sensors.

The observed mass movement can be explained by debutressing of the slope from the retreating Grosser Aletsch glacier, that has lost in the region of interest 200 m and more of ice thickness since the LIA. The deep-seated movement of the rock mass can be well delimited from the differential SAR interferograms as a fairly consistent unit affecting an area of more than 1 km^2. However, aerial photography and field observations so far do not disclose the landslide through related surface features, possibly because the displacement is recent, morphological evidences associated to the displacement are masked by moraines, and sparse forest is largely covering the area.

Differential GPS measurements, matching of repeat air photos, further airphoto interpretation, numerical modeling of the slope deformation, and analysis of meteorological data are ongoing to complement the differential SAR interferometric analysis. Initial velocity measurements between 6 September 1976 and 2 October 1995 as determined from orthoimage matching [3] did not disclose any significant movement. The total displacement between 1976 and 1995 was thus smaller than 50 cm, i.e. about 3 cm/year. It appears therefore well possible that the movement only started to be pronounced at the beginning of the 1990's.

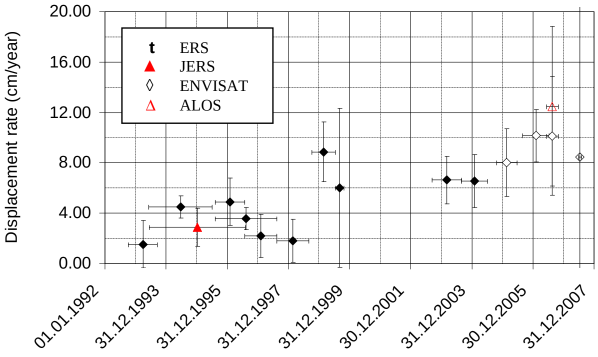

Figure 11. Displacement rates at the end of the cableway along the slope gradient using the DEM.

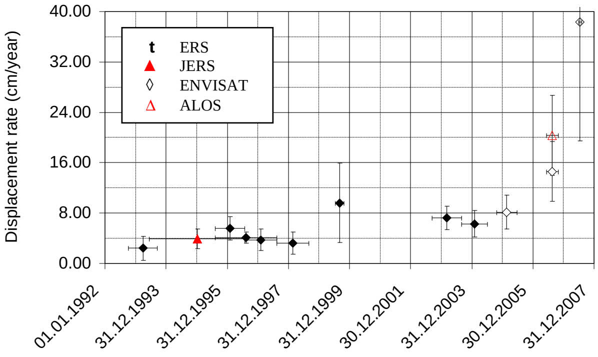

Figure 12. Displacement rates around the center of the landslide along the slope gradient using the DEM.

5. CONCLUSIONS

The displacement of an unstable slope in the Aletschwald region has been observed between 1992 and 2007 with SAR interferometry from the ERS-1, JERS, ERS-2, ENVISAT and ALOS satellites. Differential GPS measurements, matching of repeat air photos, further aerial photography interpretation, numerical modeling of the slope deformation, and analysis of precipitation are ongoing to complement the differential SAR interferometric analysis.

6. ACKNOWLEDGMENTS

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