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Survey and monitoring of landslide displacements by means of L-band satellite SAR interferometry

Abstract This paper illustrates the capabilities of L-band satellite SAR interferometry for the investigation of landslide displacements. SAR data acquired by the L-band JERS satellite over the Italian and Swiss Alps have been analyzed together with C-band ERS-1/2 SAR data and in situ information. The use of L-band SAR data with a wavelength larger than the usual C-band, generally considered for ground motion measurements, reduces some of the limitations of differential SAR interferometry, in particular, signal decorrelation induced by vegetation cover and rapid displacements. The sites of the Alta Val Badia region in South Tyrol (Italy), Ruinon in Lombardia (Italy), Saas Grund in Valais (Switzerland) and Campo Vallemaggia in Ticino (Switzerland), representing a comprehensive set of different mass wasting phenomena in various environments, are considered. The landslides in the Alta Val Badia region are good examples for presenting the improved performance of L-band in comparison to C-band for vegetated areas, in particular concerning open forest. The landslides of Ruinon, Saas Grund, and Campo Vallemaggia demonstrate the strength of L-band in observing moderately fast displacements in comparison to C-band. This work, performed with historical SAR data from a satellite which operated until 1998, demonstrates the capabilities of future planned L-band SAR missions, like ALOS and TerraSAR-L, for landslide studies.

Keywords Landslide displacement investigation · SAR interferometry · L-band · Swiss and Italian Alps

Introduction

Differential Synthetic Aperture Radar (SAR) interferometry is an emerging technique for large-scale detection and monitoring of ground displacements due to geophysical phenomena at cm to mm accuracy and high spatial resolution (Bamler and Hartl 1998; Rosen et al. 2000). Surface deformations include land subsidence, tectonic and volcanic activities, ice sheet and glacier movement, and landslides. In recent years differential SAR interferometry has been widely applied for the monitoring of mass movements (Fruneau et al. 1996; Rott et al. 1999; Kimura and Yamaguchi 2000; Kenyi and Kaufmann 2001; Nagler et al. 2002; Rott et al. 2003; Delacourt et al. 2003; Berardino et al. 2003; Singhroy and Molch 2004; Strozzi et al. 2004; Hilley et al. 2004; Catani et al. 2005; Farina et al. in review). However, the current applications are restricted within the research framework and significant difficulties are found when using this technique as an effective and operational tool for landslide monitoring (Farina et al. 2003; Casagli et al. 2004). This situation is partly related to the large variability of slope instabilities in terms of mechanisms of movement, failure geometries, materials involved, vegetation cover, size of the unstable areas and deformation rates, which range over more than 10 orders of magnitude from imperceptible creeping to very fast failures. But, severe limitations are also connected to the acquisition parameters of the current satellite SAR platforms. Incidence angle, spatial resolution, wavelength, and acquisition time interval of these operational sensors are not optimal compared to the particular spatial and temporal pattern of movements that are being dealt with. So far, the best results in the investigation of landslide displacement through satellite SAR interferometry have been reached in the case of extremely slow movements (velocity less than a few centimeters per year, just the slowest class of mass movements with reference to the velocity scale proposed by IUGS/WGL in 1995) affecting areas on gently sloping terrains characterized by sparse vegetation. In many cases, therefore, the detection and measurement of surface displacements with differential SAR interferometry is not feasible because of signal decorrelation induced by vegetation cover and moderately rapid displacements. In addition, the particular SAR imaging geometry causes incomplete coverage in very rugged topography ("layover" and "shadow") and the sensitivity to the displacement is restricted to the satellite line-of-sight direction.

To date, most of the applications of differential interferometry have been demonstrated with SAR data at C-band (5.3 GHz, 5.7 cm wavelength), because the current satellite SAR missions (ERS-2, ENVISAT, Radarsat-1) operate within this band. However, new imaging radar missions at L-band (1.3 GHz, 23.5 cm wavelength) are intended or under study, like ALOS (Shimada et al. 2002) or TerraSAR-L (Zink 2003). Despite the Japanese Earth Resource Satellite (JERS) program (Nemoto et al. 1991) and the NASA Shuttle Imaging Radar (SIR) missions (Evans et al. 1997), the experience with L-band applications especially in Europe is not as well developed as for C-band. As already demonstrated for land subsidence monitoring (Strozzi et al. 2003), L-band interferometry has the capability of complementing the existing applications based on C-band, because of its capacity to penetrate the vegetation canopy, and thus, achieve high coherence interferograms over vegetated areas. Furthermore, the larger wavelength is more appropriate for mapping rapid displacements. As demonstrated for active rock glaciers (Strozzi et al. 2004), decorrelation due to rapid displacements is typically higher at C-band than at L-band and the use of a larger wavelength avoids to some extent problems related to the intrinsic ambiguity of the phase measurements.

The scope of this work is to illustrate with SAR data of the JERS satellite the capabilities of an interferometric L-Band SAR mission for landslide deformation monitoring. The JERS SAR mission (Nemoto et al. 1991) was developed jointly by the Japanese Ministry of International Trade and Office and the Japan Aerospace Exploration Agency (JAXA). JERS was operated between 1992 and 1998 collecting a huge amount of SAR data at L-Band during the six and a half years mission period. JERS SAR data are archived both at JAXA and at the European Space Research Institute (ESRIN), where there are more than 100000 JERS SAR frames over Europe acquired at the Tromsø and Fucino ground stations (De Groote and Greco 2003). This study concentrates on the joint exploitation of JERS SAR data archived at ESRIN and JAXA. Considering the special format of JERS SAR raw data archived at ESRIN, some adaptations of the GAMMA SAR processing software (Werner et al. 2000) to support this data format were necessary. In total, 47 JERS SAR frames (23 from the JAXA archive and 24 from the ESRIN archive) were processed for landslide displacement monitoring in the Italian and Swiss Alps.

After a review of differential SAR interferometry and JERS SAR data processing, results of landslide survey and displacement monitoring are presented for four sites in Italy and Switzerland. The JERS SAR data analysis is supported by a validation with ground truth information, and the impact of the coherence at L-band in comparison to C-band is discussed. Finally, some concluding remarks are given.

JERS differential SAR interferometry

Differential SAR interferometry makes use of two SAR images acquired from slightly different orbit configurations and at different times to exploit the phase difference of the signals (Bamler and Hartl 1998; Rosen et al. 2000; Catani et al. 2005). The phase signal derived from an image pair relates both to topography and line-of-sight surface movement which has occurred between the acquisitions, with atmospheric phase distortions, signal noise, and inaccuracy in the orbit determination as main error sources. The basic idea of differential SAR interferometry is to subtract the topography related phase from the interferogram to derive a displacement map.

One of the major limitations of SAR interferometry is decorrelation (Zebker and Villasenor 1992). Temporal decorrelation occurs from changes in time of the scatterer characteristics within the resolution cell. Vegetation, for example, causes significant decorrelation that often completely prevents interpretation of interferometric phases of C-band SAR pairs with acquisition time differences of more than 1 month. Spatial decorrelation precludes interpretation of interferometric phases for extended targets in pairs with long baselines. Often, in SAR interferometry only interferograms with short baseline (e.g., less than 1000 m for the JERS satellite) are considered.

The JERS SAR raw data of this study were processed to full resolution Single-Look Complex (SLC) images. Interferometric processing was done to 6 azimuth and 2 range looks with common-band filtering after co-registration of the SLC images. The topography related phase was estimated from available external Digital Elevation Models (DEM). The baseline was first estimated from the orbit data and subsequently refined based on the fringe rate in range and azimuth directions. For presentation and interpretation, the differential interferograms were terrain corrected geocoded according to the projections and cell resolutions of the employed DEMs (Werner et al. 2002a).

The differential interferograms were used for a large-scale landslide survey. Landslide survey is defined as the process of determining location, size, boundaries, and approximate velocity of an unstable slope. In particular, for this application we rely on complex interferograms without phase unwrapping. For a regional detection of unstable slopes short baselines are preferred. Acquisition time intervals from one cycle (44 days for the JERS satellite) up to a few years are useful depending on the displacement velocities, landcover, and season. Multiple interferograms are preferred for a cross-validation of the results, avoiding misinterpretation of topography, atmosphere, and noise as displacement.

For landslides identified in the survey, monitoring of displacement was then completed. Displacement monitoring is defined as the process to quantitatively measure the displacement field of a landslide, assessing the temporal evolution of the unstable area. For this purpose, phase unwrapping—i.e. the process to resolve the module 2π (11.75 cm for the JERS SAR sensor) ambiguity of the interferometric phase—is required. Phase unwrapping of interferograms in rugged terrain and for complicated displacement fields is a difficult task that needs a cautious validation. Usually, only small, well-defined areas are considered. Phase unwrapping was performed after adaptive filtering (Goldstein and Werner 1997) with various strategies (Werner et al. 2002b), usually applying a region-growing algorithm. Finally, the unwrapped interferograms were converted to displacements expressed in cm along the line-of-sight direction of the satellite and geocoded.

Experience from a previous study on land subsidence (Strozzi et al. 2003) was considered to process only selected JERS interferograms. In this previous study complete decorrelation was found for perpendicular baselines larger than around 2000 m independently of land use and acquisition time interval, also by applying the spectral-shift filtering. For acquisition time intervals of more than 2 years the coherence was high only over urban areas, where the phase signal was considered interpretable but noisy for baselines between around 1000 and 2000 m and high coherence was observed for short baselines of less than 1000 m. Short-baseline L-Band interferograms with an acquisition time interval of 44–264 days produced subsidence values also for vegetated areas and short-baseline L-Band interferograms of 44–88 days gave subsidence values also for forest.

The differential SAR interferometry records of landslide displacement are only valuable if errors can be shown to be small in comparison to the signal. From the different error sources of differential SAR interferometry (atmospheric phase distortions, signal noise, inaccuracy in the orbit determination, phase unwrapping mistakes), the major difficulties faced in the processing of JERS SAR data were concerned with the estimation of the baseline and the low signal-to-noise ratio. Assuming an error in phase noise of one quarter of a wavelength leads to an error in line-of-sight displacement of 2.9 cm. Inaccuracy in the orbit determination mainly causes relatively large-scale distortions (several kilometers) whereas the analyzed landslides have a smaller dimension. Obvious atmospheric artefacts have not been found on the JERS interferograms analyzed so far and phase unwrapping was carefully performed by retaining only areas with reliable information. With respect to the millimetric accuracy claimed by ERS differential SAR interferometry when atmospheric artefacts are compensated, the typical errors of JERS differential SAR interferometry are, therefore, in the order of centimeters.

Alta Val Badia (South Tyrol, Italy)

The Alta Val Badia region features a large number of landslides that result from the Late-Glacial and Holocene geomorphological evolution of the slopes (Soldati et al. 2004). Landslide types are differentiated with respect to the affected bedrock. Large phenomena showing a complex style of movement, in most cases rock slides evolving into earth flows, are predominant below 2000 m a.s.l. in the intermediate and lower part of slopes where bedrock is made up of flysch rock masses. Many other types of phenomena, such as rock slides, rock falls, debris flows and creep of permafrost in rock glaciers, are predominant above approximately 2000 m a.s.l., where fractured dolimitic rocks are found together with a large amount of coarse debris. At intermediate and low altitudes the slopes are covered by forests and meadows and not densely inhabited, but widely used for tourist activities such as skiing and mountain trekking. Near the village of Corvara in Badia, one large complex earth slide—earth flow phenomenon—has been active for over 9000 years, as proved by numerous radiocarbon dates from buried wood remains (Corsini et al. 2000; Soldati et al. 2004), causing, at present, a risk to infrastructure and socio-economic activity. The Corvara landslide, involving an estimated 300 million m^3

of clay rich debris, has been continuously monitored since 2000 with ground-based instrumentation and a geodetic differential GPS network (Corsini et al. 2005). Average displacement rates have ranged between some millimeters to some decimeters per month, with higher rates in the spring and early summer period.

During the snow-free period and for acquisition time intervals of 44–132 days with baselines of less than 1 km the signals related to displacement in the Alta Val Badia region are usually well preserved in JERS interferograms (see Fig. 1a and 1b). The coherence varies between pairs depending on vegetation, snow cover, displacement, acquisition time interval, and baseline. More in detail, the signal related to the Corvara landslide is always evident (see areas bordered by yellow ellipses) and a number of other signals related to ground displacements can also be appreciated (see areas bordered by white ellipses). While the signal of the Corvara landslide is confirmation of known data based on other monitoring instruments (Corsini et al. 2005), the signals obtained for the other locations in the Alta Badia represent new relevant information about the state of activity of some of the landslides mapped by Corsini (2000).

A series of ERS differential SAR interferograms was also computed in the Alta Val Badia area. In Fig. 1c and 1d the two interferograms with the best quality, resulting from a time interval of 35 days in late summer and a short baseline, are presented. The stronger layover effect in ERS SAR data than in JERS SAR data, caused by the different incidence angles of observation, is obviously evident along the steeper slopes. The signals identified with the JERS interferograms of Fig. 1a and 1b are highlighted in Fig. 1c and 1d. In most cases, the signals related to the displacements observed with JERS interferometry are also visible with ERS data. However, the noise with ERS is larger than with JERS, preventing the correct unwrapping of the phase on a regional scale. Only for limited areas and after cautious phase filtering and masking of all residual signals may displacement maps be computed with ERS interferometry (Belitz et al. 2003). In addition, it is very likely that some of the signals related to the displacements in the ERS interferograms are confused with atmospheric artifacts of similar spatial distribution and intensity.

For the interferogram from 2 July to 28 September 1998 a displacement map was derived along the line-of-sight direction after phase unwrapping. The signal related to the landslide of Corvara is presented in Fig. 2a. The maximum displacement observed in the 88 days time interval is in the order of 7 cm. In Fig. 2b it can be observed that the signal in the JERS interferogram is well preserved in the accumulation area, covered by meadows and with a deformation rate measured by GPS receivers in the order of a few mm to some cm per month (Corsini et al. 2005). Over the track area, strong decorrelation occurs in relation to larger movement rates (cm-dm/month measured by GPS). Displacement in the source area is mainly found in the JERS interferogram towards the south–east, where deformation rates are still relatively high (cm/month measured by GPS) but a quite uniform meadows coverage is present. A comparison between the measurement rates of selected GPS benchmarks, transformed in the JERS line-of-sight (LOS) direction, and the corresponding pixels in the JERS displacement map of the time period from 2 July to 28 September 1998 (see Fig. 2c) indicates a typical centimetric accuracy of JERS differential SAR interferometry. GPS benchmarks for the comparison were selected among those with information from JERS differential SAR interferometry after phase unwrapping and excluding the area between benchmarks 16 and 23 which was affected by strong temporal changes of the displacement rate between 1998 and 2003. In general, however, displacement rates computed with JERS SAR interferometry confirm that the landslide velocity during the last decade is consistent with the data acquired by inclinometers and the geodetic network in the last 4 years.

Ruinon (Lombardia, Italy)

The Ruinon rock slide (literally "huge ruin") is located in Valtellina, in the Italian Alps along the Frodolfo River (Agliardi et al. 2001). The phenomenon, which affects the lower part of the southwest facing slope of the valley with an average inclination of 36°, reaches a total length of 770 m and a width of 410 m. From a geomorphological point of view it is characterized by two main scarps oriented northwest–southeast, parallel to the main fracture system. The upper scarp is located at an elevation of about 2100 m a.s.l., the lower scarp at about 1900 m a.s.l.. The movement involves both the superficial Late Pleistocene and Holocene deposits and the bedrock, which consists of fracturated phyllites. The phenomenon has been interpreted as the most active sector of a larger deep-seated gravitational deformation, with a spatial extension of about 6 km^2, affecting the whole slope of the valley. The landslide represents a compound movement (combined translational and rotational sliding), which affects an estimated volume of about 30 million m^3, with average velocities ranging from 0.5 up to 2 m/year. A potential risk from this landslide, which is suspended above the valley, is the possibility of a fast moving rock avalanche affecting the important tourist road from Bormio to Santa Caterina in Valfurva. For this reason a permanent monitoring network, consisting of topographic instrumentations (total station and GPS receivers) and conventional in situ systems, such as inclinometer tubes and extensometers, has been installed since 1997 (Laffi et al. 1998). Due to difficulties in acquiring data in the most active sectors of the unstable area, in summer 2000 a ground-based SAR interferometric measurement campaign has been also carried out (Tarchi et al. 2003; Antonello et al. 2004).

In this study, seven JERS interferograms with baselines shorter than 1 km and acquisition time intervals of 44 or 88 days in late summer have been computed. For differential interferometry an external DEM covering an area of about 3 km × 2 km with a posting of 5 m built by digitizing topographic contour lines on a 1:2000 map produced by the Regione Lombardia was used. The differential interferograms acquired during the snow-free season with acquisition time intervals of 44 days are clearly indicating a signal related to ground displacement (see Fig. 3). For acquisition time intervals of 88 days the signal related to the displacement is still visible but noisy.

Phase unwrapping of the differential interferograms was performed in order to retrieve displacement maps along the line-of-sight direction (see Fig. 4). The activity of the landslide was different in July to September 1993 and in October to November 1994. The approximate extension of the landslide, as mapped by the Geological Survey of the Lombardia Region, and the position of the in situ equipments were superimposed to produce the displacement map over the time period 10 October to 23 November 1994 in Fig. 5a. In general, there is good agreement regarding the position of the landslide, with the maximum displacement measured between the upper and lower scarps. At the top of the upper scarp (see Fig. 5b) decorrelation is observed because of the strong displacement gradient. There, geocoding problems are visible, probably related to the phase filtering before unwrapping. The displacement map obtained with JERS SAR interferometry over the whole unstable area with a spatial resolution of about 20 m can support the retrieval of the seasonal creep which affects the slope, neglecting chaotic patterns of movement induced by single blocks characteristic of point-wise traditional measurements.

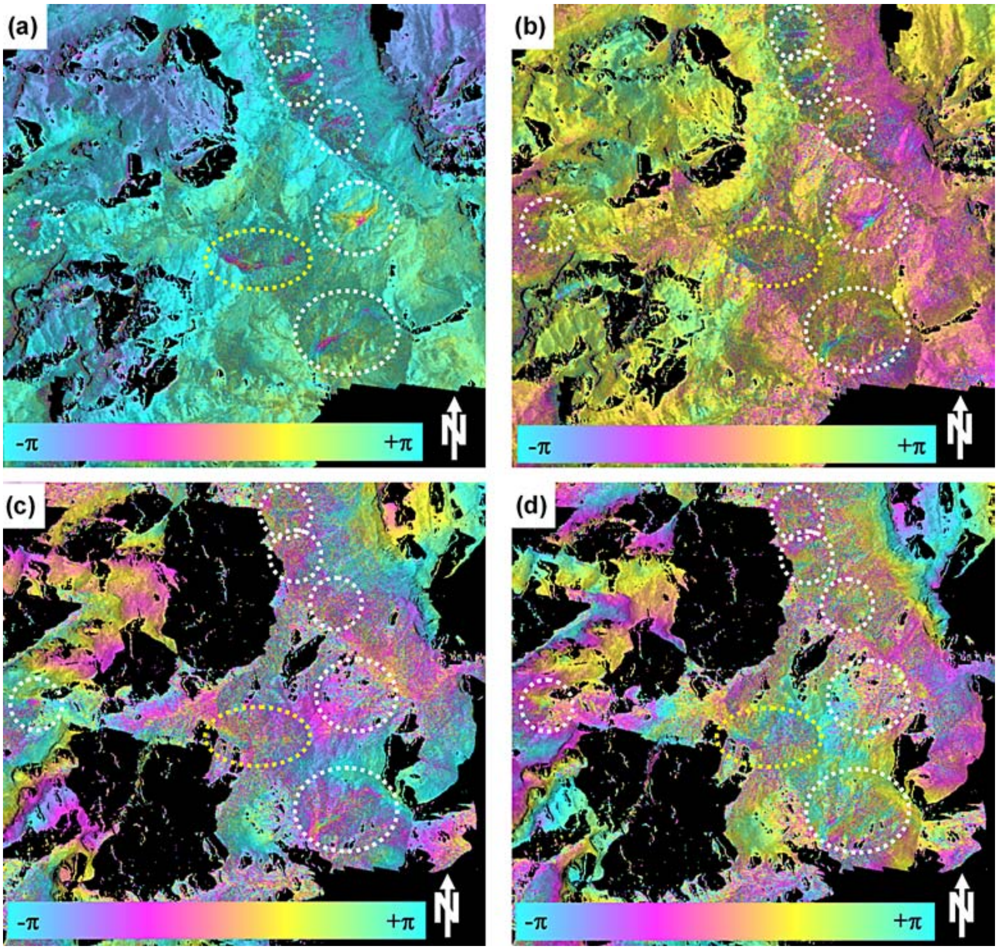

Fig. 1 Alta Val Badia: differential, filtered, geocoded SAR interferograms. The signal related to the landslide of Corvara is highlighted in yellow. Black is layover. Image size is 16 km × 15.4 km. **a** JERS interferogram for the time period 2 July to 28 September 1998 (88 days, 217 m), **b** JERS interferogram for the time period 11 August to 7 November 1995 (88 days, 254 m), **c** ERS interferogram for the time period 9 August to 13 September 1997 (35 days, 76 m), **d** ERS interferogram for the time period 13 September to 18 October 1997 (35 days, −85 m)

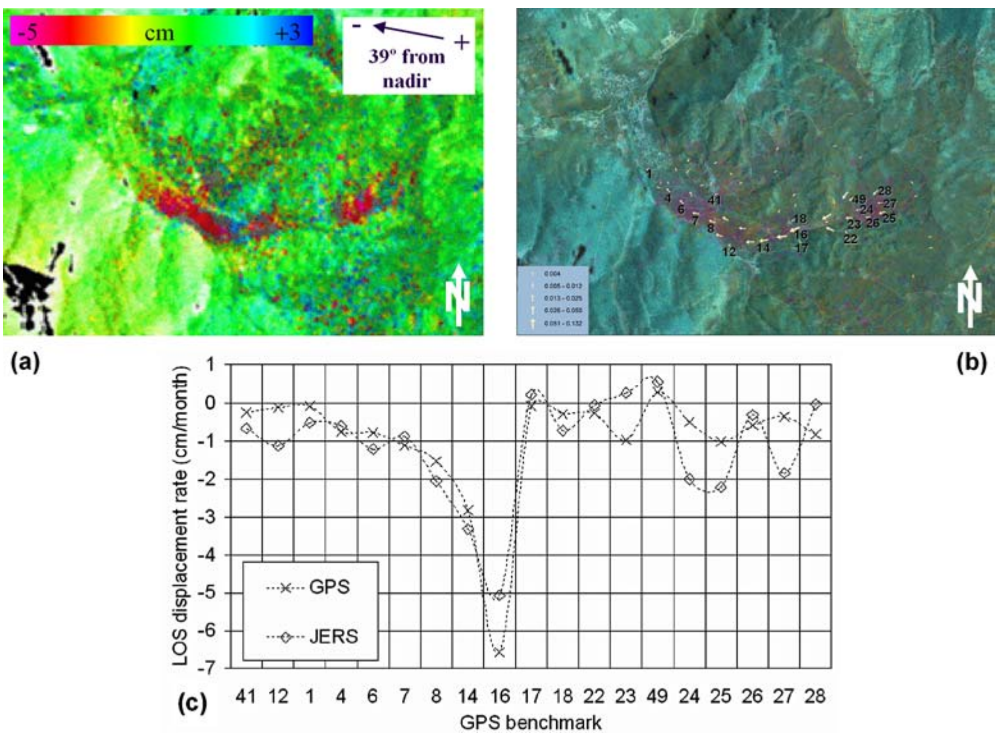

Fig. 2 Corvara in Alta Val Badia. **a** Geocoded JERS displacement map in the line-of-sight direction for the time period 2 July to 28 September 1998 (88 days, 217 m), **b** GPS measurement rates (in meter/month from September 2001 to September 2003) superimposed on the interferogram of Fig. 1a, orthophotograph in the background, **c** Comparison between measurement rates in the JERS line-of-sight (LOS) direction of selected GPS benchmarks and the corresponding pixels in the JERS displacement map of Fig. 2a. See Fig. 2b for the location of the GPS benchmarks

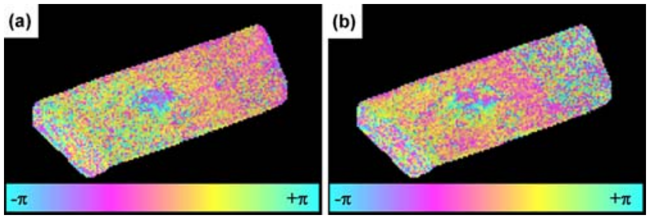

Fig. 3 Ruinon: differential JERS interferograms in SAR geometry. **a** Time period 27 July to 9 September 1993 (44 days, 483 m), **b** Time period 10 October to 23 November 1994 (44 days, 780 m)

Most of the in situ measurements over the Ruinon rock slide have only been regularly acquired since 1997 following an acceleration phase. For this reason a quantitative comparison between different datasets can not be carried out. Ground-based interferometric SAR measurements performed between July and August 2000 (Tarchi et al. 2003) show the largest displacements in the south–eastern sector of the upper scarp and in the lower scarp with deformation rates up to 1.2 mm/h (i.e., around 3 cm/day). The velocity rates observed with JERS interferometry in 1994 are lower, with a maximum of 15 cm in 44 days along the line-of-sight direction. Also GPS measurements acquired in 2002 and 2003 show higher displacement rates, with a maximum of 2 m/year in the JERS line-of-sight direction (see Fig. 5c). Such differences are consistent with the "power law trend" in the time interval 1998–2001, showing increased cumulative displacement and displacement rate on a multi-yearly scale, as inferred from the in situ measurements (Crosta and Agliardi, 2003). Spatial distribution of the rock slide activity, on the other hand, is similar in JERS and GPS measurements, with the highest deformation rates located in the western portion of the upper scarp and a decreasing trend in the eastern part of the landslide from higher to lower altitudes.

In conclusion, the analysis at Ruinon is a good example of the strength of L-band in observing comparatively fast landslides. Various interferometric attempts of motion analysis were carried out at C-band without success in the area where JERS SAR interferometry functions (Rott et al. 2002). On the other hand, the C-band analysis performed through permanent scatterers has allowed the

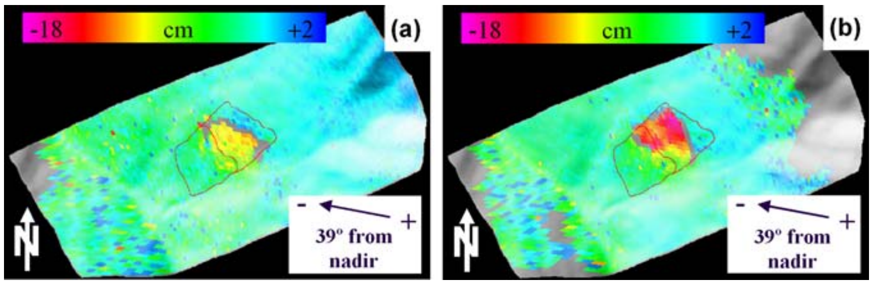

Fig. 4 Ruinon: geocoded displacement maps in the line-of-sight direction with approximate extension of the landslide. Image size is about 3 km × 2 km. **a** Time period 27 July to 9 September 1993 (44 days, 483 m). **b** Time period 10 October to 23 November 1994 (44 days, 780 m)

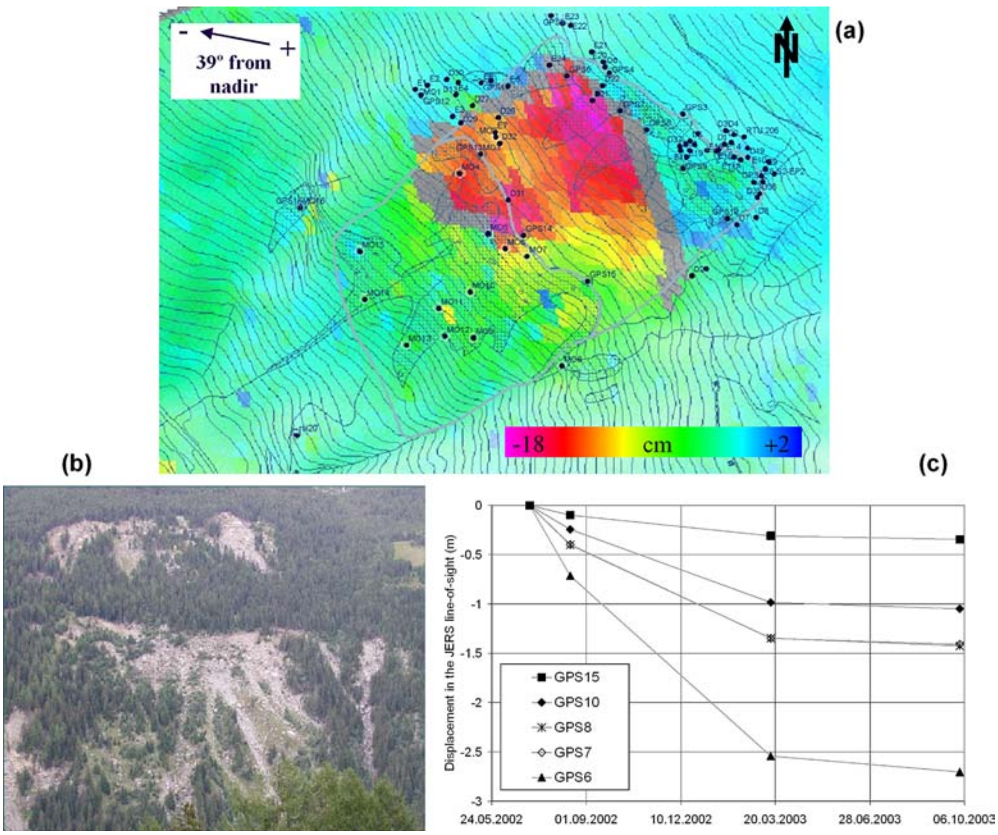

Fig. 5 Ruinon. **a** Approximate extension of the landslide and position of the automatic extensometers (E), manual extensometers (D), optical levelling benchmarks (MO), and GPS benchmarks (GPS) superimposed on the line-of-sight JERS displacement map for the time period 10 October to 23 November 1994. **b** Photograph from the opposite site of the valley showing the two main scarps of the landslide. **c** GPS measurements in 2002 and 2003 projected in the JERS line-of-sight direction

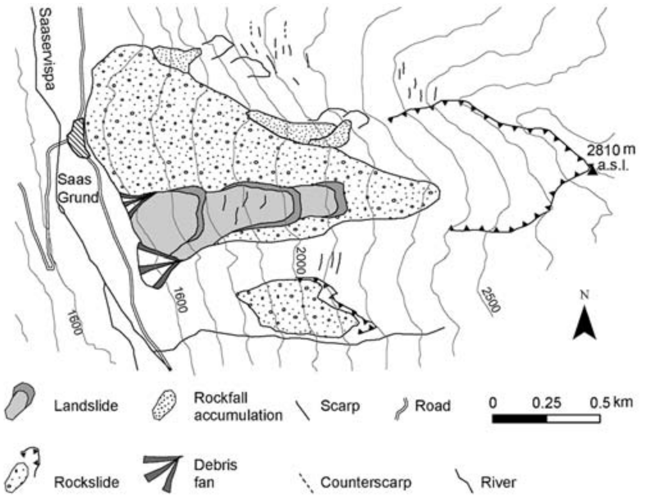

Fig. 6 Saas Grund: geomorphological features of the landslide from the interpretation of aerial photographs

detection of the slow deep-seated gravitational movements affecting the whole slope around the Ruinon slide (Crosta and Agliardi, 2003). The displacements affecting the entire slope ranges between 7 and 25 mm/year, but no information was obtained in the lower part of the slope due to the high deformation rates.

Saas Grund (Valais, Switzerland)

The western valley flank above Saas Grund presents a very large blocky accumulation derived from a paleo-rockslide (Fig. 6). The landside debris covers an area of about 1 km², ranging from the toe of the slope up to 2330 m a.s.l.. The failure occurred in massive gneisses, Mesozoic sediments (Bündnerschiefer) and mica-rich paragneisses belonging to the Pennidic Mt. Rosa and Grand St-Bernhard nappes. The schistosity dips mainly 40° to the east and northeast. A large continuous head scarp, up to 400 m high and 660 m long, delimits the rockslide accumulation in the upper part of the slope from 2400 to 2810 m a.s.l.. A series of north–northeast trending foliation-parallel counterscarps are visible in the middle and upper part of the slope indicating a block slumping deformation mechanism of the rock mass. A large talus slope supplied by rock falls cover the northeast flank of the landslide. The southern part of the paleo-rockslide, below 2150 m a.s.l., has a strongly hummocky profile resulting from three orders of landslides that overlap one another at different levels and that collectively cover an area of 0.2 km². These landslides represent compound movements (combined translational and rotational sliding) which affect an estimated volume of about 10 mm³. The lower landslide scarps trending north northwest are located at an elevation of around 1780 m a.s.l., the middle section is about 2030 m a.s.l. and the upper scarps are around 2150 m a.s.l. Indications of ongoing activity of this part of the landslide include an extremely irregular profile, numerous large north-northeast trending scarps between 1750 and 1850 m a.s.l. and debris flow activity along this southern slope.

The displacement in the western valley flank above Saas Grund is particularly evident in the JERS interferogram from 9 November 1992 to 17 June 1993 (Fig. 7b), but is also visible in the interferogram from 21 June to 17 September 1996 (Fig. 7a). The coherence in the interferogram of Fig. 7b is preserved at low altitudes, in sparsely forested areas, probably because of the absence of snow cover in November. For time intervals of more than 3 years and acquisitions in summer, coherence is preserved only over a portion of the landslide (see Fig. 7c).

The unstable slope is covered by open forest in its low and middle part and has very sparse vegetation in its upper part (see Fig. 8a, where green is generally forest and red-orange alpine meadows and rocks). With 35–105 days ERS interferograms (see e.g., Fig. 8b) the low and middle part of the landslide is generally decorrelated. For time intervals of about 1 year ERS SAR interferograms acquired during the snow-free period are able to highlight displacements on high alpine areas (Kenyi and Kaufmann 2001; Nagler et al. 2002; Strozzi et al. 2004). For a quantification of surface displacement in the line-of-sight direction, targets that exhibit a point-like scattering behavior and remain phase-coherent over time for a large number of summer SAR acquisitions were considered. Through the use of many summer images, even if separated by large baselines, Interferometric Point Target Analysis (IPTA, Werner et al. 2003) permitted the retrieval of displacement information at high altitudes, but incomplete coverage

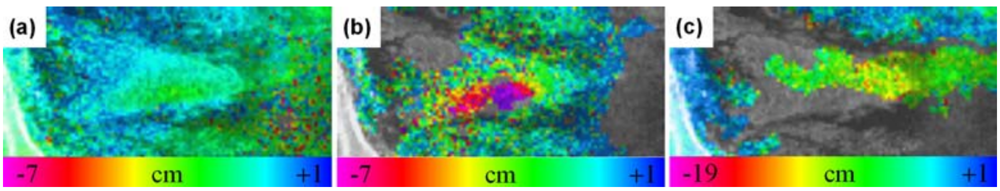

Fig. 7 Saas Grund: JERS displacement maps in the line-of-sight direction in SAR geometry (from right to left, incidence angle is 39°). Image width is ∼1 km. **a** Time period 21 June to 17 September 1996 (88 days, 69 m). **b** Time period 9 November 1992 to 17 June 1993 (220 days, 1228 m). **c** Time period 17 June 1993 to 4 August 1996 (1144 days, 85 m)

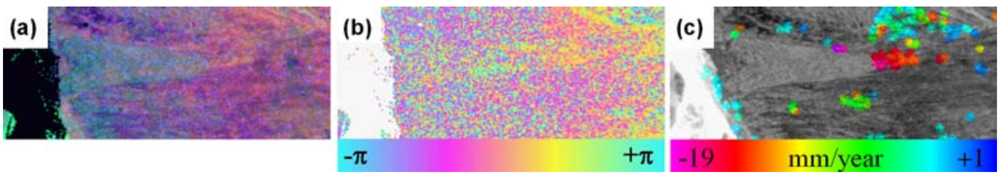

Fig. 8 Saas Grund: ERS differential interferometry in SAR geometry. **a** Color composite of Tandem coherence (*red*), backscatter intensity (*green*) and backscatter intensity change (*blue*). **b** differential SAR interferogram for the time period 16 July to 29 October 1999 (105 days, 5 m). **c** IPTA displacement rates in the line-of-sight direction (from right to left, incidence angle is 23°). Image width is ∼1 km

was achieved for the middle and low part of the landslide (see Fig. 8c). The maximum annual displacement rate of the landslide is estimated with JERS interferometry in the order of 15 cm. This would explain the absence of points for the area of maximum displacement in the ERS IPTA displacement map of Fig. 8c. For time intervals of more than 3 years and acquisitions only in summer, coherence is preserved at L-band over part of the landslide, where ERS SAR data are also noisy. For this area, the absence of points in the ERS IPTA displacement map and decorrelation on ERS SAR interferograms of around 1 year time interval are explained by the presence of open forest.

Campo Vallemaggia (Ticino, Switzerland)

The landslide of Campo Vallemaggia (Fig. 9a) is located in the Rovana valley, a lateral valley of the Maggia valley in Ticino. The mass movement has a spatial extension of about 6 km^2, it is about 2 km long and up to 170 m wide, and it involves a volume of several hundreds of millions of m^3. The landslide was activated about 200 years ago and is assumed to have been induced by man made changes in the hydrological system and deforestation. Studies and monitoring started more than a hundred years ago, providing a pretty good understanding of the landslide dynamics. The church of Campo Vallemaggia has been affected over the last 100 years by a horizontal displacement of about 30 m and a vertical settlement of about 6.5 m. The landslide has caused damage to various infrastructures and represents a threat as a potential obstruction of the river.

Studies demonstrated a strong correlation between precipitation and landslide displacement, and excessive water pressure inside the landslide was identified as the main cause for the landslide movement. Several mitigation works were therefore realized to stabilize the landslide mass. In particular, in order to reduce the high water pressure inside the landslide body, a 1800 m long drainage tunnel was constructed underneath the landslide mass between 1994 and 1995. From this tunnel about 30 drainage boreholes were then drilled into the landslide mass in 1995 and 1996 to extract the water and reduce the abnormally high pressures. During, and in the first year after the execution of the

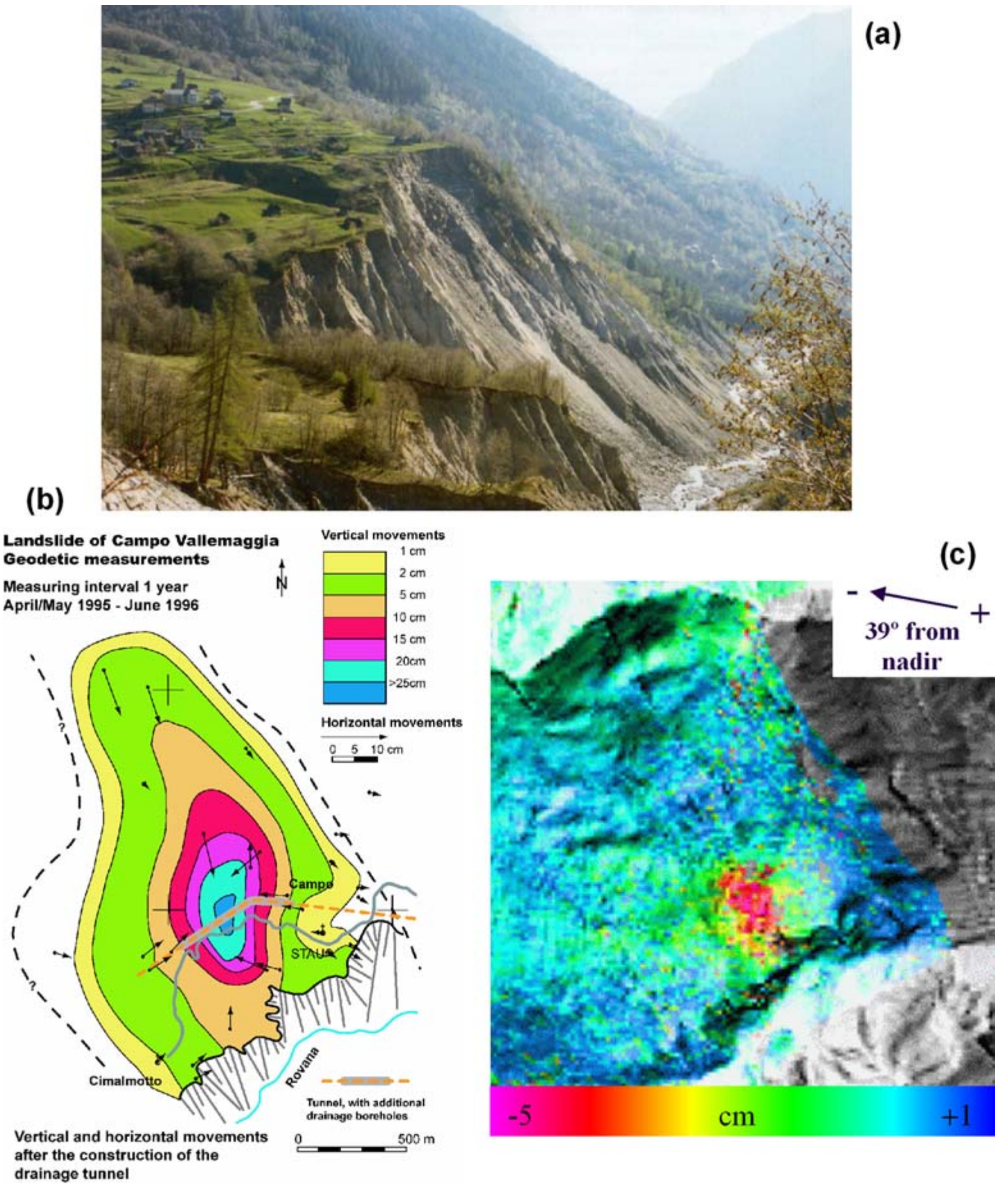

Fig. 9 **a** The village of Campo Vallemaggia on top of the landslide mass, with the landslide direction of movement from left to right and the height of the front at about 150 m. **b** Movement of the landslide in the first year after the execution of the drainage tunnel from April/May 1995 to June 1996. **c** JERS displacement map over 88 days as an average of the results from two interferograms for the time periods 20 June to 16 September 1996 and 21 June to 17 September 1996. Image width is about 3.3 km

drainage tunnel the pattern of the landslide movement changed drastically from a slide movement along the basal detachment horizon to a settlement movement with maximum velocities around the center of the drainage tunnel, as demonstrated by geodetic measurements (Fig. 9b).

Two JERS interferograms for the time periods 20 June to 16 September 1996 and 21 June to 17 September 1996 clearly indicate a signal related to displacement. The displacement maps derived via phase unwrapping of the differential interferograms were averaged in order to obtain a single observation of the displacement in the line-of-sight direction in 88 days (see Fig. 9c). The direction of the satellite observation is nearly perpendicular to the slope direction, so that the JERS measurements are more sensitive to the vertical component of the displacement. The approximate spatial extension of the displacement and its magnitude, with a maximum of 5 cm in 3 months, are in good agreement with the in situ observations represented in Fig. 9b. Leveling surveys carried out along the main road were also considered for a more specific validation. The maximum vertical settlement observed with two leveling measurements performed on 4 June and 24 October 1996 (142 days) was 12.5 cm. Projected along the JERS line of sight and scaled to 88 days, the maximum displacement from leveling survey corresponds to 4.9 cm for the JERS observation geometry.

The coherence in the 88 days JERS interferograms is generally well preserved for this site characterized by sparse urbanization, meadows and forests. On the other hand, the coherence of 35 days ERS interferograms is very low and in particular for the ERS SAR data acquired along the descending orbits the effect of layover is very strong. Also Interferometric Point Target Analyses (IPTA) were carried out without success with ERS SAR data for ascending and descending orbits in the area where JERS SAR interferometry already functions, because of high displacement rates and unsuitable imaging geometries.

Conclusions

This paper has demonstrated the capabilities of L-band SAR interferometry for the investigation of landslides displacements. Results obtained at regional scale for motion survey and at local scale for landslide monitoring using JERS SAR data were described, the validation with the available in situ data was illustrated, and the impact of the coherence at L-band in comparison to C-band was discussed. The sites of the Alta Val Badia region, Ruinon, Saas Grund, and Campo Vallemaggia were considered in the analysis, representing a comprehensive set of different mass wasting phenomena in terms of mechanism of movement, deformation rates, and geological environments. The presented results are considered a significant contribution towards an assessment of the L-band capabilities for landslide investigations.

The analysis of the JERS SAR data in the Alta Val Badia area demonstrates the performance of L-band SAR interferometry for vegetated areas. A regional survey of displacements using JERS interferograms of 44–132 days acquisition time intervals was found to be straightforward and reliable on the basis of existing landslide maps of the area. ERS SAR interferograms with a 35 days acquisition time interval in late summer showed more decorrelation and atmospheric artefacts. The quantitative results from JERS interferometry of the Corvara landslide, a slow moving complex earth slide—earth flow—could be successfully validated with ground-truth information, in particular GPS data.

The analyses at Ruinon, Saas Grund, and Campo Vallemaggia are good examples of the strength of L-band in observing comparatively fast landslides, confirming the results of a previous study focused on active rock glaciers in the Grubengletscher region in Valais, Switzerland (Strozzi et al. 2004). All these studies demonstrate that decorrelation by reason of rapid displacement is typically higher at C-band than at L-band.

Even if the results presented in this paper have been obtained using SAR data acquired by the JERS satellite, which operated until 1998, future new L-band missions are planned, ensuring the availability of SAR data in this frequency band. A prerequisite for a successful interferometric application of these missions is a continuous operation in a single interferometric mode. Problems related to the JERS SAR data, like the estimation of the baseline and the low signal-to-noise ratio, will be resolved by the intended Japanese ALOS mission or the planned European TerraSAR-L mission. In particular for TerraSAR-L, the short repeat cycle of 14 days, the high quality orbits resulting in constant short baselines, the high resolution, and the low noise equivalent sigma zero would represent a very high potential for operational landslide displacement recognition and monitoring, complementary to conventional in situ instrumentations.

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