

InSAR techniques and applications for monitoring landslides and subsidence

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ABSTRACT: Interferometric synthetic aperture radar (InSAR) methods and applications for mapping and monitoring displacements on mountain slopes and subsidence in urban areas were investigated in the EC project MUSCL (Monitoring Urban Subsidence, Cavities and Landslides by means of remote sensing) using various techniques. The area-extended differential InSAR technique was applied for mapping slow slope movements in Alpine areas, based on interferograms over annual time spans derived from ERS repeat pass SAR data. The Permanent Scatterer technique, using long time series of SAR data, was applied to map ground deformation at millimetric accuracy. The PS technique is based on dense grids of stable radar targets, enabling the correction of atmospheric noise and the measurement of motion at the scale of individual pixels. An example is shown for motion analysis of a landslide in the Italian Alps. The application of ground-based InSAR was investigated at a rockfall area in the Austrian Alps, revealing a complex deformation pattern. This technique offers flexibility in terms of observation geometry and enables continuous monitoring, making it an excellent tool for emergency cases. The investigations demonstrate the power and complementarity of various InSAR methods for detecting and monitoring hazardous mass wastes.

1 INTRODUCTION

Unfavourable stability conditions on mountain slopes and buried cavities in built-up areas pose serious threats to life and property in many regions worldwide. In order to reduce the risks from these phenomena, it is necessary to detect and monitor precursors to failure such as surface motion and deformation. Synthetic aperture radar interferometry (InSAR) offers the possibility to map movements at the Earth's surface with high precision over extended areas at reasonable costs. In order to advance InSAR methods and explore possibilities and limits of this technique, the project MUSCL (Monitoring Urban Subsidence, Cavities and Landslides by remote sensing) started in March 2000 as a Shared Cost Action project within the 5th framework programme for Research and Development of the European Commission.

The project MUSCL is concerned with methods and applications of InSAR for monitoring and studying mass movements on mountain slopes and subsidence in urban areas related to cavities or changes of ground water level. Test sites include several landslide areas in mountain regions of Austria, Switzerland and Italy, as well as urban areas in northern Italy. Synergistic approaches are applied to optimise the use of InSAR for monitoring various mass wasting phenomena. Area-extended differential InSAR, based on few interferometric image pairs, is applied to map slope motion in sparsely vegetated Alpine terrain. The Permanent Scatterer (PS) technique, based on time series of repeat pass SAR images, is used to detect objects with stable backscattering phase in built-up areas and to monitor their displacement over multi-year periods. Ground-based SAR interferometry is applied for monitoring local hazardous mass movements on slopes where satellite-borne SAR cannot be applied due to the lack of stable targets or unsuitable viewing geometry.

2 THE DATA BASE

As basis for satellite InSAR analysis SAR images acquired by the European Remote-Sensing satellites ERS-1 and ERS-2 were used. ERS SAR operates at the wavelength $\lambda = 5.66$ cm, with a nominal incidence angle $\theta = 23^\circ$ from the vertical in the centre of the swath which is 100 km wide. The standard orbital repeat period is 35 days. For topographic corrections interferograms from the tandem operation of ERS-1 and ERS-2, acquired within 24 hours time span, were used. Ground-based InSAR measurements were carried out at L-, C- and Ku-band with the mobile SAR system LISA which was developed at JRC-IPSC and can measure surface topography and motion with great spatial detail up to distances of a few kilometres.

The remote sensing measurements were complemented by in situ observations in order to validate the InSAR products and to study the synergistic use of the various information sources. In some of the test sites InSAR motion maps were combined with aerial photography and very high resolution optical satellite imagery to assist in the interpretation of the InSAR products.

3 SLOPE MOTION MAPPING IN ALPINE AREAS

Methods and possibilities of area-extended InSAR analysis were studied in several regions of the Austrian Alps (Ötztal Alps, Tuxer Alps, Hohe Tauern) and Swiss Alps (Wallis, Lichtenstein). The work focused on slopes with very slow movements, of the order of centimetres per year. Movements of this order of magnitude are not uncommon in Alpine regions, but these mass wastes are often not surveyed or not even known.

3.1 Method

The area-extended InSAR analysis requires only a small number of interferometric pairs. In principle two interferograms (made from 3 or 4 images) are sufficient to map a velocity field by differential processing, though better quality is achieved if a greater number of images is available. One of the reasons is the greater probability to obtain image pairs with good coherence, because this cannot be predicted accurately without having produced an interferogram. Another reason is the reduction of atmospheric propagation effects. Moreover, slope motion is often variable in time, and interferograms spanning different periods help to detect temporal variability.

In repeat-pass interferometry the phase difference $\Delta\phi$ of a pixel between two SAR images, acquired from similar antenna positions, consists of the fol-

lowing contributions:

$$\Delta\phi = \Delta\phi_{\text{flat}} + \Delta\phi_{\text{topo}} + \Delta\phi_{\text{dis}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{noise}}$$

where $\Delta\phi_{\text{flat}}$ and $\Delta\phi_{\text{topo}}$ are the phase differences due to changes of the relative distance satellite-target for flat earth and for topography, respectively, $\Delta\phi_{\text{atm}}$ is the phase difference due to changes in atmospheric propagation, and $\Delta\phi_{\text{noise}}$ represents phase noise, related mainly to changes of the target phase due to temporal variations of backscattering properties, but also to processor noise. $\Delta\phi_{\text{dis}}$ represents the phase difference due to displacement of the target in line-of-sight of the radar beam (slant range).

In order to determine terrain motion from interferograms, it is necessary to correct for the other phase terms. Below procedures are summarized which were found to be very suitable for producing accurate slope motion maps in Alpine terrain.

$\Delta\phi_{\text{flat}}$ was calculated accurately using the precise ERS orbit data from the Orbit Data Records of the Technical University of Delft, NL. For calculating the topographic phase images ($\Delta\phi_{\text{topo}}$) ERS-1/-2 tandem pairs with 1-day time span were used, because the motion-related phase of the slowly sliding slopes can be neglected and the coherence is higher than for longer time spans. In order to reduce phase distortions due to atmospheric effects and avoid phase unwrapping ambiguities, the topographic phase was derived from multiple interferograms by means of multi-baseline processing (Ferretti et al., 1999).

The predominant part of atmospheric phase variations is related to water vapour (Hanssen, 2001). There is no possibility to correct for atmospheric effects in a single interferogram without external information. However, because the spatial extent of landslides is small compared to the typical scale of tropospheric signals, disturbing effects of $\Delta\phi_{\text{atm}}$ can be effectively reduced for mapping landside motion by use of tie points on non-moving surfaces close to the sliding area. Temporal changes of the phase at pixel scale can be considered as random phase noise. This is the main factor determining the coherence and therefore is important for the quality of the interferograms, but does not produce any bias.

3.2 Application example

Many landslides have been identified and mapped in the Austrian and Swiss Alps using ERS SAR images. Because of the slow movements, typically of the order of a few centimetres per year, the analysis was mainly based on interferograms over annual or bi-annual time spans. The majority of the investigated slides is located above the treeline where the surfaces are sparsely vegetated and the coherence is preserved over long time intervals (Rott et al., 2000). The area-extended InSAR method was also applied

successfully for slope motion mapping in built-up areas at low elevations. Interannual variations of surface motion were studied using multi-year time series of ERS SAR data (Rott et al., 1999).

As an example for InSAR slope motion mapping we present a case study from the Saas valley in the Walliser Alpen, Switzerland. In this region several slides were detected, using interferograms of annual time spans. Fig. 1 shows the motion map of one of the slides, located on the west-facing slope below Jegihorn, above the village Saas-Grund. The mass waste extends over an altitude range of almost 1000 m; in the lower part it is about 1 km wide. The highest velocities, about 4 cm/year, are found just below the peak Jegihorn. The data gap south of the peak represents a steep foreslope where the image is strongly distorted.

The motion map was derived from an interferogram calculated from ERS SAR data of 14 August 1996 and 25 June 1997. The profile of surface motion shows velocities obtained from this interferogram, as well as from an interferogram of 18 September 1996 to 29 July 1997. The topographic phase of the slope was derived by means of multi-baseline processing, using 4 tandem pairs with perpendicular baselines between 36 m and 247 m. The topographic phase image was used for differential interferometric processing, as well as for geocoding.

3.3 Possibilities and limits

The application potential and limits of the area-extended InSAR method for slope motion mapping were analysed with a large data set of ERS SAR images (overall from 10 different frames), covering large parts of the Austrian Alps and parts of the Swiss Alps. The investigations revealed good applicability of the method for monitoring slow slope movements in high Alpine areas. Statistical investigations of coherence and viewing geometry showed that InSAR motion analysis over annual time spans is feasible on about 60% to 70% of the area above the treeline if ERS SAR data both from ascending and descending orbits are used. In vegetated zones below the tree line the application of InSAR is limited almost exclusively to sites where man-made, stable targets are available.

The main limitations for the application of InSAR over long time spans are caused by decorrelation due to temporal changes of physical target properties or due to motion at sub-pixel scale. Also changes of snow pack properties result in uncontrolled phase shifts and decorrelation, but this problem can be avoided by using SAR images from the snow-free period. The main problem is dense vegetation, where the signal decorrelates usually within a few days. In

these areas man-made targets are required to obtain stable phase signals.

SAR imaging geometry may also cause restrictions for interferometric motion analysis, particularly in steep mountain areas. Two factors play a role: (i) The geometric distortion of the image which affects the local spatial resolution. Layover, resulting in superposition of signals from three adjoining sections of the surface (fore-slope, back-slope, opposite slope) provides particular problems. These effects can be avoided by selecting a SAR swath under which the area of interest is on a backslope (if possible). (ii) The property of InSAR to measure only the component of the motion vector in direction of radar illumination (line-of-sight), respectively its insensitivity to the motion component along track. This needs to be taken into account for selecting a useful illumination geometry and for interpretation of interferometric motion.

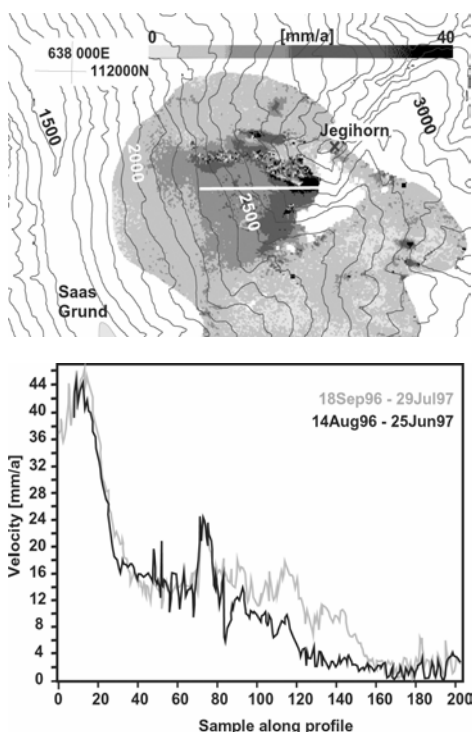


Figure 1. Motion map of the mass movement below Jegihorn, Walliser Alps, derived from an ERS SAR image pair over the time span Aug 1996 – June 1997. The velocity is coded in six grey-steps from 0 to 40 mm/year, assuming surface-parallel motion. The white line shows the location of the velocity profile, presented in the lower part of the figure.

4 DISPLACEMENT MONITORING USING THE PERMANENT SCATTERER TECHNIQUE

The Permanent Scatterers technique is a recently developed tool for millimetric accuracy ground deformation mapping on a high spatial density grid of phase stable radar targets, the so-called Permanent Scatterers, PS (Ferretti et al., 2000; 2001). Provided that long time series of SAR data and suitable targets are available, the PS approach allows to overcome the two most significant drawbacks of conventional Differential SAR Interferometry (DInSAR), namely decorrelation noise and atmospheric artefacts.

Since Permanent Scatterers are point-wise radar targets, they are only slightly affected by geometrical decorrelation even for large baseline values. On the sparse grid of Permanent Scatterers the various contributions to the differential interferometric phase, namely residual topography due to inaccuracies in the reference DEM, ground deformation, atmospheric signature and noise, can be discriminated. In particular, the atmospheric term (atmospheric phase screen, APS) can be estimated and subtracted from the original differential interferogram, provided that the PS spatial density is high enough (5-10 PS/km²).

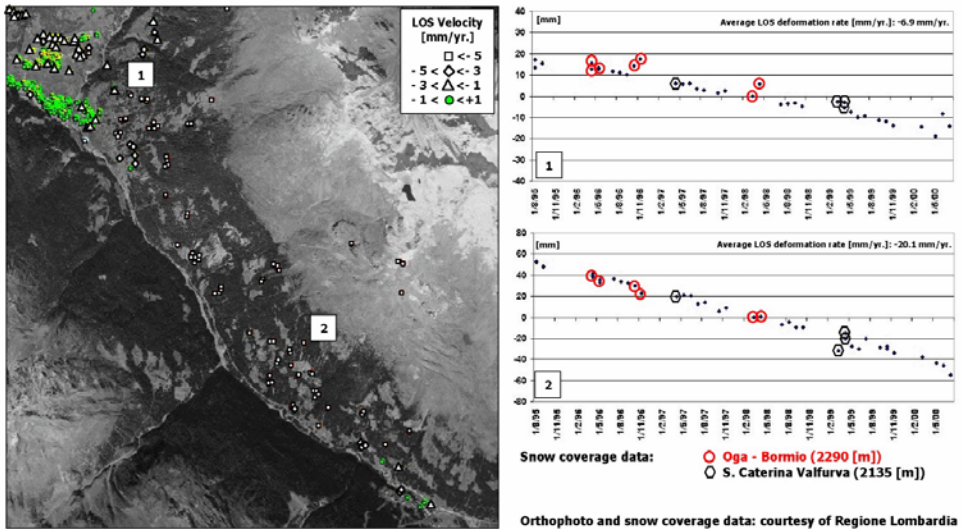
4.1 Method

The PS approach is based on the exploitation of long time series of interferometric SAR data (at least 25-30 images). Detailed descriptions of the processing technique can be found in Ferretti et al. (2000) and Ferretti et al. (2001). Here the basic ideas are briefly summarized.

All available images (N+1) are registered on the sampling grid of a unique master image. N differential interferograms are generated with respect to the common master, regardless of the normal (and temporal) baseline. In fact, due to their point-wise character, PS are only slightly affected by geometric decorrelation.

On the basis of a “pixel by pixel” analysis of the amplitude returns relative to each SAR image in the data set, points that are likely going to behave as PS are identified (Permanent Scatterer Candidates, PSC). The first step of the technique allows to isolate the APS term on the sparse grid of PSC. APS is then re-sampled (and filtered at once) on the regular grid of the master image by means of Kriging interpolation (Wackernagel 1998) taking account of the strong spatial correlation of atmospheric phenomena described by the Kolmogorov turbulence model (Hanssen 2001). This is feasible as long as the PSC spatial density is high enough (5-10 PSC/km²).

The second step of the PS approach is aimed at discriminating phase contributions due to residual topography from ground deformation terms. Since



large normal baseline interferograms are involved in the processing, inaccuracies in the reference DEM cannot be neglected. In a 1200 m baseline ERS interferogram the height of ambiguity, corresponding to a full phase cycle, is around 7.5 m. In order to separate the two phase terms, their different behaviour is exploited: the topography phase contribution is proportional to the normal baseline, whereas deformation is correlated in time. This last step is carried out (on the available set of differential interferograms compensated for APS) on a “pixel by pixel” basis identifying all Permanent Scatterers.

The sparse PS grid can be assimilated to a high spatial density (up to 400-500 PS/km², in urban areas) geodetic network allowing ground deformation measurements along the sensor-target Line of Sight (LOS) direction with millimetric accuracy (0.1±1 mm/yr. on the average LOS deformation rate and 1±3.5 mm on single measures).

4.2 Case Study: The Ruinon Sackung and Rockslide

We wish to illustrate briefly a significant example of landslide deformation that the PS approach allowed to map. To this end we shall have a look at the PS displacement data recorded in the area affected by the Ruinon Sackung and Rockslide on the south-west facing slope of Valfurva in the neighbourhood of Santa Caterina, located in a lateral valley of Valtellina, Lombardia, Italy. The PS analysis has been carried out by Tele-Rilevamento Europa -T.R.E. S.r.l. (a Politecnico di Milano commercial spin-off aimed at exploiting the PS technology) in the framework of a project with Regione Lombardia. A total of 51 descending mode ERS-1/2 images covering the time span August 1995 – July 2000 were used for processing.

Though many of the PS pixels in Fig. 2 are related to man-made structures, there are several tens of PS which represent natural targets. These pixels show phase stability during a large part of the year, even on some dates when snow-gauge stations in the region report snow cover. PS pixels are point-wise radar targets dominating the coherent combination of all scattering contributions of a resolution cell. Therefore it can be concluded that either the PS signal originates from a target protruding through the snow pack and the signal contribution of the background is insignificant, or that the snow gauge data are not representative for the snow extent of the whole area, which is often the case in Alpine areas due to small scale effects of wind drift and solar irradiation.

5 GROUND-BASED INSAR MEASUREMENTS

At the Institute for the Protection and Security of the Citizen (IPSC) of the Joint Research Centre of the EC ground-based mobile SAR instruments were developed which extend the application of the interferometric technique to cases and tasks for which satellite-borne InSAR is not applicable or does not show sufficient spatial detail. The system LISA (Linear SAR) consists of transmitting and receiving antennas moving on a linear rail of 1 to 5 m length, depending on the version of the instrument, a stepped-frequency CW radar unit, and a signal processor (Fig. 3). SAR images can be generated for areas up to a few kilometres distant at frequencies ranging from 500 MHz to 18 GHz (Tarchi et al., in press).



Figure 3. The mobile SAR system LISA of JRC-IPSC below Eiblschrofen.

In the project MUSCL the application of LISA for monitoring landslides was investigated based on a case study at the rockfall area Eiblschrofen near Schwaz, Austria. Four measurement campaigns of one week duration each were carried out between July 2001 and January 2002. SAR data were acquired at L-, C-, and Ku-band and processed to derive a digital elevation model and maps of surface displacement. The grid size of the DEM and of the motion map depends on the SAR frequency and the distance of the observed surface. At Eiblschrofen, observed under a slant range distance of about 1500 m, the spatial resolution at Ku-band is 2 m x 7 m.

The short term analysis of motion measured at Ku-band revealed displacements of 7 to 8 millimetres in one week in two small sections of the slope (Fig. 4). The displacement is shown on those parts of the slope where the coherence is good. The other areas of the slope, which are covered by forest, are masked out. The temporal evolution of the motion

could clearly be documented by means of differential InSAR analysis carried for the time sequence of SAR images throughout the week. The long-term differential analysis for a time span of several months showed a complex pattern of surface motion.

The measurement campaigns, carried out within the MUSCL project, provided further validation of the capabilities of the ground-based InSAR technique as an effective tool for landslide monitoring. The motion measurements can be carried out continuously and with very high precision, confirming that the system is an excellent tool for an early warning system. Due to the flexibility regarding frequency and geometry of observations, the high spatial resolution and the continuous temporal coverage, ground based InSAR is complementary to satellite-based measurements. It is of particular interest for observations of mass movements with high deformation rates and small spatial extent, for emergency cases and for local topographies which are not suitable for satellite-borne SAR observations.

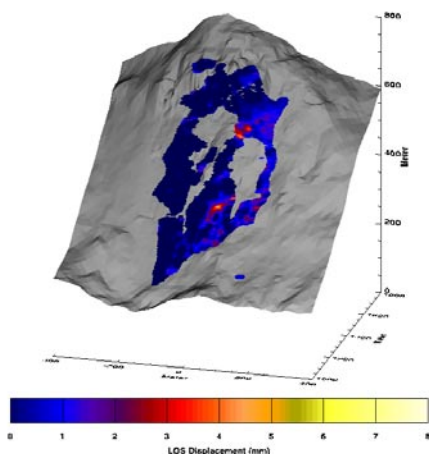


Figure 4. One-week surface displacement, superimposed to the DEM, at the rockfall area Eiblschrofen, measured with the mobile SAR LISA. The Line-of-Sight (LOS) displacement is colour coded from 0 to 8 mm.

6 ON THE OPERATIONAL POTENTIAL OF INSAR

The methodological developments and cases studies, carried out in the project MUSCL, confirm the great potential of InSAR for mapping landslide motion and subsidence. The various methods investigated in the project are complementary and jointly provide a powerful basis for detecting and monitoring hazardous mass wastes.

- Satellite based InSAR enables global access and provides very accurate data of surface displacement from local scales up to synoptic surveys of large regions. With available C-band SAR systems and minimum repeat imaging intervals of several weeks it is possible to map motions on the order of millimetres to a few metres per year.
- ERS SAR time series since 1991 are a valuable basis for retrospective studies of mass wasting phenomena.
- Present (ERS, ENVISAT-ASAR, RadarSat) and future systems guarantee the continuation of InSAR applications, though changes of certain technical system parameters (e.g. ASAR sensor frequency) necessitate new initialisation of InSAR time series.
- Area-extended differential InSAR, based on few SAR image pairs, is an economic means for mapping landslide motion on sparsely vegetated surfaces (e.g. in high Alpine areas) and in extended built-up areas, based on few SAR images.
- The permanent scatterer technique, using stable point targets, allows to overcome the two most significant drawbacks of conventional differential SAR interferometry, namely decorrelation noise and atmospheric artefacts, if suitable targets are available. It allows an analysis of the ground deformation on a pixel by pixel basis with millimetric accuracy, but requires extensive time series of SAR images.
- Ground-based InSAR enables continuous monitoring of individual slopes and thus is an excellent tool for online warning systems. In addition, it can map the motion of fast slides which cannot be observed by spaceborne InSAR because of the long repeat interval.

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