Advances in interferometric synthetic aperture radar (InSAR) in earth system science

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Abstract: During recent years, synthetic aperture radar (SAR) interferometry (InSAR) has become an important tool for precise measurements of the earth’s surface topography and deformation. This paper presents an overview on recent developments in InSAR applications, with emphasis on the use of satellite-borne sensors for applications in geoscience, topographic mapping, natural hazard monitoring and environmental research. InSAR measurement principles are briefly introduced. Recent results on the use of repeat-pass interferometry for mapping seismic and volcanic deformation, monitoring landslides and subsidence, and mapping glacier motion are described. Other InSAR applications introduced in the paper are: topographic mapping, retrieval of biogeophysical parameters on land surfaces, and measurements of water currents. Examples of interferometric products are shown for satellite-borne SAR systems operating at X-band, C-band and L-band radar frequencies. An outlook is provided on upcoming SAR systems which will spur further advances in InSAR techniques and applications.

Key words: ice motion, interferometry, radar, satellite, surface deformation, topography.

I Introduction

In the last two decades, synthetic aperture radar (SAR) interferometry (InSAR) has emerged as an essential tool for many applications in geoscience, environmental research, hazard monitoring and topographic mapping. SAR delivers two-dimensional images of the radar reflectivity of the illuminated scene, comprising intensity and phase of the backscattered signal. Conventional SAR images display the intensity (or amplitude). Radar interferometry utilizes the phase information. This enables very precise measurements of the distance between the radar antenna and the illuminated target. For the advance of InSAR in its early days, airborne interferometric SAR systems played an important role. Airborne InSAR is still an essential research tool (eg, Hajnsek et al., 2009; Nannini et al., 2009), and has also found its way into routine operations, with several specialized companies offering services in...
topographic mapping and monitoring of surface deformation. However, the boom in InSAR applications was triggered by the launch of a suite of radar satellite missions starting in the early 1990s.

In this paper, the basic principles of InSAR methods are summarized, followed by a review of applications in geoscience and environmental monitoring with the focus on recent activities. The examples presented are mainly drawn from satellite-borne SAR, but the same techniques apply to airborne interferometric SAR. Over the last few years, interferometric techniques have expanded into ground-based remote monitoring (Noferini et al., 2008; Werner et al., 2008). Ground-based interferometric SAR (GB-SAR) is particularly useful for continuous monitoring of unstable mountain slopes and surveillance of buildings that are imperilled by terrain movement (Tarchi et al., 2003; Pieraccini et al., 2006).

II Principles of cross-track radar interferometry

In order to explain the interferometric measurement principle, it is useful to recall the principle of image formation by a side-looking radar system. An imaging radar measures the position of a target in a two-dimensional coordinate system, with one axis along the flight track (‘along-track’) and the other axis across the flight track in line of sight of the radar beam (‘LOS’ or ‘slant-range’; Elachi, 1988; Raney, 1998). Because the position of a target in slant-range is determined by the distance (measured in terms of time delay) between the transmitted and received signal, the target locations are shifted in comparison to a planimetric projection. This results in major distortions of mountainous terrain in radar images. Targets at higher elevation are closer to the radar. Therefore, slopes facing towards the radar appear shortened (‘foreshortening’), and steep slopes are inverted and superimposed to adjoining sections of the scene (‘layover’; Leberl, 1998).

Even after transforming a radar image to a cartographic projection (‘geocoding’) the data in layover zones are ambiguous and cannot be used for quantitative analysis. This is also relevant for InSAR applications, noting also that the look direction of the radar beam is important. Level terrain and slopes facing away from the radar (‘backslopes’) are displayed in correct sequence, whereas image sections along steep foreslopes are often spoiled due to layover.

An interferogram is formed by very precise co-registration of two complex SAR images, acquired from nearby antenna positions in space, and multiplying one image with the complex conjugate of the other (Rosen et al., 2000; Hanssen, 2001). The resulting product can be displayed in two channels: a radar brightness image (power or amplitude) and an image of the phase difference between the two channels, the interferogram. A difficulty for the interpretation of interferograms (the ‘wrapped’ phase image) is the ambiguity of the phase in terms of $2\pi$. Because of the periodicity of the radar wave, distances along the radar beam that differ by an integer multiple of the wavelength display the same phase in the interferogram (Figure 1, inset B). Phase-unwrapping techniques are applied to solve the modulo-$2\pi$ phase ambiguity, transforming the wrapped phase image into an image of ‘absolute’ phase by adding the correct integer multiple of $2\pi$ to the phase of a given pixel (Bamler and Hartl, 1998; Rosen et al., 2000). Phase-unwrapping is an essential and critical step for transforming interferograms into geophysical products, such as maps of surface topography, surface motion, etc (Gens, 2003).
Because the path difference is measured in terms of phase of the radar wave, it can be determined at the precision of fractions of a wavelength, $\lambda$ (Figure 1, inset B). Satellite-borne SAR systems operate at wavelengths of 3.1 cm (X-band), 5.6 cm (C-band) or 24 cm (L-band). The slant-range resolution in SAR amplitude images, on the other hand, is typically of the order of metres, depending on the length of the radar pulse, $\tau$ (Figure 1, inset A).

A repeat-pass interferogram is computed from two SAR images taken at two different times.
epochs. In this case the interferometric phase is made up by the following contributions:

$$\Delta \phi = \Delta \phi_{\text{flat}} + \Delta \phi_{\text{topo}} + \Delta \phi_{\text{dis}} + \Delta \phi_{\text{atm}}$$  \hspace{1cm} (2)

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 topography. $\Delta \phi_{\text{atm}}$ is the phase difference due to changes in atmospheric propagation conditions, and $\Delta \phi_{\text{dis}}$ is the phase difference due to displacement of the observed surface element in LOS. The atmospheric phase contribution, $\Delta \phi_{\text{atm}}$, results mainly from changes in the water vapour content of the atmosphere (Hanssen, 2001). The flat earth phase can be computed accurately if precise data on the satellite orbits are available. Computing and subtracting the flat earth phase is one of the first steps in interferometric processing.

In equation (2) it is assumed that the phase of the observed target itself stays the same in both SAR images. Temporal phase changes of natural targets are usually random and therefore do not introduce a bias in the interferometric analysis. However, phase noise degrades the quality of the interferograms or may even inhibit the InSAR analysis. The stability of the target phase (coherence) is essential for forming an interferogram. There are various sources of phase noise, on the one hand related to geometric effects and sensor noise, and on the other hand to changes of target properties (Zebker and Villasenor, 1992; Bamler and Hartl, 1998). Regarding observation geometry, a major factor for phase noise is baseline decorrelation. With increasing baseline, the phase difference in the two SAR images increases until it approaches the critical baseline where the signal becomes completely incoherent. The critical baseline depends on the wavelength and slant range resolution of the sensor. This problem can be avoided by selecting baselines well below this threshold.

A major limiting factor for repeat-pass SAR interferometry is temporal decorrelation, caused by changes in the phase of the reflected signal. Distributed targets contain multiple scatterers, interfering coherently to induce a single phase value for any observed radar pixel. If the scattering properties of a target change in time or the individual scattering centres within a pixel move relative to each other, the image pair becomes incoherent. One cause of temporal decorrelation is, for example, the motion of a vegetation canopy due to wind (Koskinen et al., 2001), or the change of a scattering snow surface by melting (Rott and Siegel, 1997; Weydahl, 2001). On the other hand, coherence may provide useful information in support of land-cover classification (Strozzi et al., 2002a). If stable targets reside within vegetated areas, the problem of temporal decorrelation can be alleviated by applying the permanent scatterer technique (Ferretti et al., 2001).

Table 1 lists several current satellite-borne SAR systems, as well as a sample of precursors that played an important role in the development of InSAR techniques and applications. The active antenna array technology of the new sensors allows the operation in many different modes varying in swath width, look angle, polarization and spatial resolution. The SAR sensors on ERS, Radarsat and Envisat operate at C-band, the PALSAR on JERS-1 and ALOS at L-band, and COSMO-Skymed and TerraSAR-X at X-band. The longer wavelength (L-band) is less prone to decorrelation. On the other hand, the repeat interval also matters for coherence. In order to use SAR data for interferometric processing, the repeat orbits have to match closely. The Shuttle Radar Topography Mission (SRTM) so far has been the only spaceborne mission for single-pass SAR interferometry, carrying active (transmit/receive) C-band and X-band SARs in the shuttle bay and passive antennas on a 60 m mast (Farr et al., 2007). The ‘tandem mission’ of ERS-1 and ERS-2 acquired a unique InSAR data set at short repeat interval. Both satellites orbited in a 35-day repeat cycle, with an orbital timelag adjusted...
for imaging the same swath on the Earth surface exactly at one-day time difference (Dow et al., 1996).

III Topographic mapping

Topographic mapping by means of cross-track interferometry exploits the relative phase differences of the radar beam received by two antennas resulting from changes in surface elevation. For a dual-pass system the phase difference due to an elevation change, $\Delta z$, is given by:

$$\Delta \phi_{\text{topo}} = \frac{4\pi}{\lambda} \frac{Bn}{R \sin \theta}$$

(3)

where $B_n$ is the perpendicular baseline and $\theta$ is the radar look angle referring to a reference surface (e.g., an ellipsoid). For a single-pass system, i.e., with a single transmit antenna and two receive antennas, the term $4\pi$ is to be replaced by $2\pi$. A common measure for describing the height sensitivity of an interferometric configuration is the height of ambiguity:

$$H_a = \frac{\lambda}{2} \frac{R \sin \theta}{Bn}$$

(4)

$H_a$ is the height difference corresponding to a phase shift of $2\pi$ (one ‘fringe’). As $H_a$ is inversely proportional to the perpendicular baseline, long baselines are more sensitive to topography, but there are theoretical and practical limits. Above the critical baseline the wavenumber shift between the two SAR images exceeds the system bandwidth, and the individual fringes cannot be separated (Bamler and Hartl, 1998; Hanssen, 2001). For ERS SAR, the critical baseline is about 1100 m at a horizontal surface. With the baseline approaching the critical value, the coherence decreases and phase-unwrapping becomes difficult, in particular if the interferograms are noisy (Gens, 2003). If available, the use of multiple interferograms with different baselines offers a good solution to avoid phase-unwrapping ambiguities and increase the accuracy of digital elevation products (Ferretti et al., 1999).

Table I Overview of satellite-borne SAR systems used for InSAR applications

<table>
<thead>
<tr>
<th>Satellite, sensor</th>
<th>Swath width (km)</th>
<th>Spatial resolution (m)</th>
<th>InSAR revisit (days)</th>
<th>In operation, launch date</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS-1, SAR</td>
<td>100</td>
<td>25</td>
<td>35</td>
<td>1991–2000</td>
</tr>
<tr>
<td>ERS-2, SAR</td>
<td>100</td>
<td>25</td>
<td>35</td>
<td>1995</td>
</tr>
<tr>
<td>ERS-1/2 Tandem</td>
<td>100</td>
<td>25</td>
<td>1</td>
<td>1995–January 2000</td>
</tr>
<tr>
<td>JERS-I</td>
<td>75</td>
<td>18</td>
<td>44</td>
<td>1992–1994</td>
</tr>
<tr>
<td>SRTM, C-band SAR</td>
<td>225</td>
<td>30, 90 (DEM)</td>
<td>single pass</td>
<td>11–22 February 2000</td>
</tr>
<tr>
<td>STRM, X-SAR</td>
<td>50</td>
<td>25 (DEM)</td>
<td>single pass</td>
<td>11–22 February 2000</td>
</tr>
<tr>
<td>Radarsat-1, SAR</td>
<td>50–500</td>
<td>10–100</td>
<td>24</td>
<td>1995</td>
</tr>
<tr>
<td>Radarsat-2, SAR</td>
<td>10–500</td>
<td>3–100</td>
<td>24</td>
<td>2007</td>
</tr>
<tr>
<td>Envisat, ASAR</td>
<td>70–400</td>
<td>25–150</td>
<td>35</td>
<td>2002</td>
</tr>
<tr>
<td>ALOS, PALSAR</td>
<td>70–350</td>
<td>10–100</td>
<td>46</td>
<td>2006</td>
</tr>
<tr>
<td>Cosmo-Skymed, SAR</td>
<td>10–200</td>
<td>1–30</td>
<td>16 (1 satellite)</td>
<td>2007; in 2009 three satellites in orbit</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>10–100</td>
<td>1–16</td>
<td>11</td>
<td>2007</td>
</tr>
<tr>
<td>TanDEM-X</td>
<td>10–100</td>
<td>1–16</td>
<td>11</td>
<td>October 2009; formation with TerraSAR-X</td>
</tr>
</tbody>
</table>

*Different numbers refer to different operation modes
For topographic mapping, single-pass systems are preferable because they avoid phase deterioration caused by temporal decorrelation. Whereas dual antenna systems are rather common for airborne interferometric systems, the Shuttle Radar Topography Mission (SRTM) so far was the only dedicated single-pass interferometric mission in earth orbit (Rodriguez et al., 2005; Farr et al., 2007). SRTM was equipped with a C-band SAR of NASA-JPL and a X-band SAR of the German Aerospace Center (DLR) and the Italian Space Agency (ASI). Interferometric data were acquired over the land surfaces from 60°N to 56°S during an 11-day mission in February 2000. The C-band SAR, with a swath width of 225 km, provided a near complete digital elevation model (DEM) for these latitude zones. A global elevation data set at 3 arc-sec (∼90 m) grid, based on the C-band SAR, is distributed to the public through the USGS EROS Data Center. The absolute height errors (90% linear error) are specified at ±5.6 m to ±9.0 m, for different continents, and the relative height errors at ±4.7 m to ±9.8 m (Rodriguez et al., 2005). The comparison with ERS-1 altimeter elevation data over five continents shows slightly greater differences (Berry et al., 2007). This results partly from the fact that different surfaces are being observed by the two instruments, in particular in the case of vegetation. This is confirmed by comparisons with ICESat laser altimetry data that show differences between the two data sets increasing with the steepness of the terrain and density of tree cover (Carabajal and Harding, 2006).

The coverage by the SRTM X-band SAR is incomplete due to the narrow swath (50 km). The X-band radar had a slightly higher resolution and better signal-to-noise ratio (SNR) than the C-band system. In addition, the shorter wavelength with the fixed baseline defined by the mast results in higher sensitivity to elevation compared to C-band (equation 4). The X-band data provide an independent data set for quality control. Combining the C-band and X-band data sets results in significant improvement for the joint DEM compared to either input DEM (Hoffmann and Walter, 2006).

Nevertheless, there are major voids in the SRTM DEM, mainly in regions with steep mountain slopes, but also in some low geographic latitude regions. Various interpolation techniques are applied to fill these gaps, including kriging, spline interpolation, and the use of other topographic data sources (Reuter et al., 2007). Of interest is the combination of the SRTM DEM with topographic data of optical stereo satellite sensors (Bubenzer and Bolten, 2008; Fujita et al., 2008). Exploiting the strengths of the two different topographic mapping techniques is feasible for a large part of the global land surfaces since the recent release of the global ASTER DEM at 30 m grid (http://asterweb.jpl.nasa.gov/gdem.asp).

Repeat-pass interferometry played, and still plays, a role in topographic mapping, although it suffers from temporal decorrelation, in particular over vegetation and snow- and ice-covered areas. Before SRTM, the ERS tandem mission was an important source for elevation data because it was less affected by decorrelation due to the short repeat interval (Rufino et al., 1998). However, the data did not provide systematic coverage of large areas. Also, changes of atmospheric propagation conditions introduce errors. Atmospheric distortion can be largely eliminated and the precision of the DEM can be improved by using multiple interferograms with different baselines (Ferretti et al., 1999; Ferraiuolo et al., 2009).

In a study on micro- and meso-relief features of karst, Siart et al. (2009) apply ASTER and SRTM DEMs together with very high-resolution optical images. They emphasize the need for higher accuracy topographic data for geomorphological investigations. The new X-band SAR systems offer significant improvements for topographic mapping. The spotlight mode of TerraSAR-X, for example, has a slant range x azimuth
resolution of $1.2 \times 1.7$ m (standard spotlight mode) and $0.6 \times 1.1$ m (experimental high-resolution spotlight mode), though at limited spatial coverage. The feasibility for mapping the height and deformation of individual buildings in urban areas with spotlight mode data was demonstrated by Eineder et al. (2009).

Figure 2 shows an example of a high-resolution DEM for a badlands area near Las Vegas, covering 8 km x 10 km (Adam et al., 2007). TerraSAR-X operated in standard spotlight mode, the interferometric baseline was 309 m, and the incidence angle 59°. This configuration results in high sensitivity to topography, with an altitude of ambiguity $H_a = 22$ m. The DEM has a spacing of $5 \times 5$ m; the vertical accuracy is better than 5 m. Systematic acquisition of a global DEM with similar resolution is planned for the formation flight of the TerraSAR-X and TanDEM-X missions (Krieger et al., 2007).

Whereas TerraSAR-X and TanDEM-X is a formation of two active radar sensors, the formation of passive sensors (interferometric cartwheel systems) utilizing the signal of one active sensor has been promoted for several years (Massonet, 2001), but so far has not materialized. Massonet and Elachi (2006) provide a survey on satellite techniques for land topography mapping, stressing the potential of the cartwheel configuration for very precise mapping of surface elevation.

**IV Mapping and monitoring surface displacement**

Surface displacement during the time interval between two repeat-pass SAR image acquisitions introduces a phase shift ($\Delta \phi_{\text{dis}}$ in equation 2). In order to stay coherent, the structure of the surface resolution element (pixel) itself needs to be maintained in the two SAR images. Movements at subpixel scale, and also rotation of the whole pixel, result in

![Figure 2](https://example.com/figure2.png)

**Figure 2** Interferometric DEM of an area near Las Vegas (8 km x 10 km) with 5 m spacing generated from TerraSAR-X spotlight mode data. Top left: interferogram. Bottom left: radar amplitude image. Right: 3-D visualization

*Source: Adam et al. (2007).*
decorrelation (Zebker and Villasenor, 1992). The time interval of the interferometric measurement needs to match the magnitude of the motion, on the one hand to obtain an appreciable signal, and on the other hand to avoid decorrelation in the shear zones. The interferometric phase shift induced by surface displacement is given by:

$$\Delta \phi_{\text{dis}} = \frac{4\pi}{\lambda} \Delta R$$  \hspace{1cm} (5)

where $\Delta R$ is the component of the three-dimensional displacement vector that is projected onto LOS of the radar beam. Because fractions of a $2\pi$ phase cycle (corresponding to $\lambda/2$) can be detected, InSAR enables measurements of displacements at the precision of millimetres. The displacement is measured only relatively. In order to obtain an absolute value of motion, the measured phase has to be related to a spot of zero or known velocity in the image.

This restriction on the LOS component imposes constraints on the feasibility to observe motion phenomena and affects the interpretation of the data. InSAR is not able to measure displacement along the flight track of the sensor. Information on the orientation of the motion vector in space can be obtained by combining interferometric data from ascending and descending orbits (Joughin et al., 1998). However, this still requires additional assumptions to obtain the full 3D solution. Depending on the application, various model assumptions can be applied to infer the 3D motion, such as surface parallel flow (Mohr et al., 1998), geophysical models of inflation and deformation (Björnsson et al., 2001; Hooper et al., 2007), or applying the principle of mass conservation (Reeh et al., 2003).

For interferometric retrieval of surface displacement it is necessary to separate the motion-related phase contributions from the other terms quoted in equation 2. The flat Earth phase can be computed if accurate orbit parameters are available. For separating the topographic and motion-related phase, differential processing techniques are applied (differential SAR interferometry, DInSAR; Hanssen, 2001). For this task, two or more interferograms with different baselines are needed. In order to obtain a correct solution by DInSAR processing, the motion must remain constant over the observation period. If an accurate DEM and precise orbit parameters are available, the interferometric motion analysis can be performed with a single interferogram. A synthetic topographic phase image is computed and subtracted from the original interferogram to isolate the motion-related phase. In this case, temporal changes in motion are not a problem. Because the interferometric sensitivity to motion is independent of the baseline, whereas the sensitivity to topography increases with the baseline, short (or zero) baselines are preferable for motion mapping by InSAR.

A new technique, delivering the along-track component of surface deformation, is the Multiple Aperture InSAR (MAI) technique (Jung et al., 2009). The SAR scenes are split into forward-looking and backward-looking complex images. Separate interferograms are produced from those two components of the repeat-pass images. The phase difference between the two interferograms is related to surface displacement in along-track direction. MAI has lower sensitivity to motion than across-track interferometry, but may become a useful add-on for observing comparatively fast movements.

A problem that cannot be solved by use of a single interferogram is the atmospheric ambiguity. The atmosphere may introduce phase shifts equivalent to surface displacement of several centimetres (Hanssen, 2001). The magnitude of the atmospheric disturbances increases with distance across a SAR image. At the local scale, the use of nearby stable targets as reference points can help to reduce atmospheric effects. A more general solution is offered by stacking multiple interferograms, assuming the atmospheric disturbances are random. The concept of removing atmospheric phase contributions is
optimized in the Permanent (or Persistent) Scatterer (PS) technique which uses the signal of isolated stable objects in stacks of repeat-pass SAR images to separate the phase contributions due to topography, displacement and atmosphere (Ferretti et al., 2001; Ketelaar, 2009). Furthermore, the PS technique has the advantage of avoiding corruption of the signal by incoherent pixels, as only pixels with high coherence are selected for the analysis.

1 Crustal dynamics and volcanism

Studies on deformation of the earth’s crust due to seismic events and volcanic activities were among the first promising applications of satellite-borne radar interferometry (Massonet and Feigl, 1998). InSAR has become a basic tool for studies of pre-, co- and postseismic deformation due to the capability of observing deformation fields over large areas in great spatial detail. A few recent examples are cited below.

Wang et al. (2007) studied the coseismic deformation and slip distribution of the 1997 Manyi earthquake in Tibet (Mw = 7.5) using ERS-2 InSAR data of three adjacent tracks to cover the fault of 170 km over its full length. Whereas the main part of the area shows high coherence, the fault trace with a maximum slip of 5.5 m can be constrained by the combination of interferometric coherence images and azimuth offset analysis. For the 2003 Bam earthquake in Iran (Mw = 6.5) pre-, co- and postseismic deformation were measured using ERS-1, ERS-2 and Envisat ASAR data (Fialko et al., 2005). The surface displacement pattern from InSAR ascending and descending tracks revealed that slip occurred along a previously unknown fault (Stramondo et al., 2005). For these two cases, spatially continuous analysis of the deformation is possible because interferograms in dry regions are barely affected by decorrelation. For the L’Aquila earthquake in Italy of 6 April 2009 (Mw = 6.3) the coseismic surface displacement was mapped with the ASAR C-band data in built-up areas and on sparsely vegetated or bare surfaces, but the signal decorrelates in vegetated areas. The L-band interferogram of ALOS PALSAR shows coherent signals also over the vegetated areas (Wegmüller et al., 2009) (Figure 3). This geocoded coseismic differential interferogram is based on PALSAR images of 20 July 2008 and 22 April 2009, corresponding to a timespan of 276 days. One fringe corresponds to 12 cm motion in LOS; the maximum motion is about 20 cm LOS.

The combination of InSAR and GPS stations is a powerful approach to study deformation fields of seismic events (eg, Salvi et al., 2000; Donnellan et al., 2002; Simons et al., 2002). The two techniques are complementary. InSAR provides continuous deformation fields with one (in case of single track) or two (with ascending/descending track) components of the deformation vector, whereas GPS delivers the full 3D solution, although at low spatial density. GPS data are also able to support the corrections of InSAR data for atmospheric propagation effects. Feigl et al. (2002) combine InSAR analysis of ERS-1 and Radarsat-1 with optical satellite images of SPOT and GPS measurements to determine the distribution of slip and the fault geometry of the 1999 Izmit earthquake in Turkey (Mw = 7.5). Multiyear InSAR time series are applied to measure interseismic strain across fault systems, supporting the assessment of earthquake potential (Fialko, 2006; Elliott et al., 2008). Deformation measurements by means of InSAR are also relevant to studies of segmentation processes at continental rifts. Wright et al. (2006) use ASAR interferometry together with field observations and seismic data to document the deformation of a magmatic segment of the Afar rift during a rifting episode in 2005. The authors explain that, without satellite InSAR data, it would have been impossible to determine the full spatial extent of this event along the entire 60 km long rift segment that was associated with a massive injection of lava. Calais et al. (2008) study
Figure 3 Coseismic differential interferogram PALSAR 20080720–20090422, Abruzzi region, Italy. Superimposed to SAR amplitude image. Geocoded to Italian National coordinates, area 36 km × 40 km


InSAR has been applied to study volcanic sources and observe the time varying deformation of many volcanoes around the world. On an increasing number of volcanoes, the interpretation of the InSAR deformation...
fields is supported by 3D measurements of deformation at GPS stations (Poland et al., 2006; Sturkell et al., 2006; Palano et al., 2008). Particularly well documented are the spatial and temporal patterns of ground deformation during inflation and deflation for the Mount Etna volcano based on a few hundred SAR scenes acquired since the year 1993 (Lundgren et al., 2003; Palano et al., 2008). Interferometric deformation maps are used to model the shape of magma chambers (Yun et al., 2006; Lundgren and Lu, 2006). Masterlark et al. (2006) simulate thermoelastic contraction after an eruption matching the subsidence of a pyroclastic flow deposit observed by InSAR over several years. InSAR is also an important tool to study the uplift and magma intrusion of large calderas, such as the Yellowstone caldera in Wyoming (Wicks et al., 2006), the Long Valley caldera in California (Tizzani et al., 2007), and the Lazufre volcanic area in Chile/Argentina (Ruch et al., 2008).

Lu et al. (2005) use 88 ERS-1, ERS-2, Radarsat-1 and JERS-1 SAR images for InSAR measurement of surface deformation at Okmok Volcano, Alaska, before, during and after the 1997 eruption. They are able to discriminate different deformation processes, namely volcano-wide inflation due to replenishment of the shallow magma reservoir, subsidence of the 1997 lava flows, and deformation and compaction of lava flows from an eruption in 1958. In the L-band data of JERS-1, the coherence is better and persists longer than in the C-band data of ERS and Radarsat, especially in densely vegetated areas. A comparison of deformation maps on Kileuea (Hawaii) derived from ALOS PALSAR L-band data and ERS C-band data confirms the improved coherence of L-band at similar accuracy for the retrieved surface motion (Sandwell et al., 2008). The decorrelation problem can be mitigated by identifying pixels with point-like scattering characteristics (Persistent Scatterers), and performing the interferometric processing only for these coherent pixels. Initially, the

PS method relied primarily on manmade targets (Ferretti et al., 2001). Hooper et al. (2004) developed a method for identifying and processing Persistent Scatterers among low-amplitude natural targets. They tested the method successfully in a non-urban volcanic area.

2 Landslides and subsidence

Interferometric observations of slope movement are used for the assessment of landside hazard. However, there are limits to this application imposed by the observation geometry in steep terrain, temporal decorrelation in vegetated areas, and the restriction to slow movements. Landslides include a wide variety of processes causing the movement of slope-forming materials such as rock, soil and/or excavation material. The materials may move by falling, toppling, sliding, spreading or flowing. Satellite-borne InSAR is only applicable to observing rather slow sliding movements. Successful InSAR applications have been reported primarily for block-type movements (rotational or translational slides). The magnitude of motion observed by InSAR ranges from millimetres to centimetres per year (Rott et al., 1999), using interferograms over annual timespans, up to a few centimetres per day (Squarzoni et al., 2003), using one-day and three-day ERS repeat-pass data. For monitoring faster movement, ground-based SAR systems are applied (Pieraccini et al., 2006). The observation geometry plays a role for the feasibility of observing slope movements. The geometry is favourable for mountain slopes facing away from the radar (backslopes), whereas the strong distortion on foreslopes may prevent the application. Decorrelation by vegetation is a major limiting factor. With C-band data, slope deformation can be mapped over bare surfaces, sparse vegetation and urban areas using single interferograms (Rott et al., 1999; Rott and Nagler, 2006). If long time series are available, the application of the PS technique offers improvements, although in densely vegetated areas the
problem persists due to the lack of stable targets, at least in C-band (Colesanti et al., 2003a; Colesanti and Wasowski, 2006). In such areas L-band offers better coherence (Strozzi et al., 2005), as reported also for studies of volcanic deformation.

A notable part of the land surfaces is affected by subsidence and uplift, triggered by human activity and/or natural processes. Because of the spatial dimension of the areas that are potentially affected, and because of the complex pattern of surface deformation, conventional geodetic techniques do not allow for comprehensive survey and monitoring of these phenomena. A potentially hazardous phenomenon is the formation of sinkholes due to hydration and dissolution of evaporites in sedimentary deposits. Such a case was observed in Camaiore (Italy), leading to the collapse of buildings. The InSAR PS analysis of Ferretti et al. (2000) showed gradual subsidence preceding the collapse of buildings, pointing out the feasibility to detect precursors of such destructive events. Subsidence rates up to 2 cm/year, and locally up to 6 cm/year, were observed in the Dead Sea area which is increasingly facing subsidence and sinkhole hazards probably caused by the drop of the water level in conjunction with the particular tectonic setting (Baer et al., 2002; Closson et al., 2005).

Land subsidence caused by groundwater withdrawal affects many regions. InSAR has become an established tool for monitoring the subsidence, in particular in built-up areas (Raucoules et al., 2007). A striking example is the subsidence of Mexico City, where ground compaction due to overexploitation of the aquifer reaches up to 40 cm/year, as observed by means of JERS-1 data of 1994 to 1996 (Strozzi et al., 2003) and ASAR InSAR time series of 2002 to 2007 (López-Quiroz et al., 2009). Strozzi et al. (2003) also demonstrate applications of subsidence mapping for the wider Bologna area (related to groundwater pumping) and the Ruhr area (related to coal mining), comparing L-band (JERS-1) and C-band (ERS-1) data. The L-band data permit the retrieval of subsidence also over vegetated areas where C-band data decorrelate. Cycles of subsidence and uplift, in response to seasonal fluctuation of the groundwater level have been analysed by means of ERS InSAR in the San José area, California (Colesanti et al., 2003b). Fruneau et al. (2005) mapped subsidence and subsequent uplift in Paris in connection with subway construction activities. Other application examples include coseismic and postseismic subsidence caused by past underground nuclear tests (Vincent et al., 2003), and subsidence due to convergence of cavities of a salt mine in Poland (Perski et al., 2009). Ketelaar (2009) performed a comprehensive study on the techniques and application of PS interferometry (ERS 1992–2005, ASAR 2003–2007) to monitor the subsidence caused by exploitation of hydrocarbon reservoirs in the Netherlands, demonstrating the operational capability of this technique.

The maturity of the technique and the improved availability of SAR data spur the interest of public authorities in regional interferometric surveys of land subsidence and deformation. Vilardo et al. (2009) performed an ERS InSAR survey of the Campania Region (southern Italy) for 1992–2002, detecting ground deformation due to tectonic, hydrothermal, gravity, hydrogeological and anthropogenic processes. Bürgmann et al. (2006) studied vertical motions due to tectonic and non-tectonic processes in the San Francisco Bay Area combing InSAR and GPS analysis. They found the highest displacement rates for non-tectonic processes, such as active landslides, settling of unconsolidated sediments, and subsidence and rebound over aquifers. They were as well able to isolate vertical tectonic rates.

3 Glacier flow
Radar interferometry has become a well-established tool for glacier monitoring and
research. Surface velocity and deformation of glaciers and ice sheets are mapped in support of studies on ice dynamics and mass balance. Another product of differential processing is surface topography, requiring at least two interferograms and constant motion during the observation period (Joughin et al., 1996). Temporal decorrelation of the radar signal due to snowfall, snow drift and melting is the main obstacle for InSAR applications over snow and ice (Rott and Siegel, 1997). Therefore, one-day repeat-pass data for the ERS-1/-2 tandem mission have, to date, been the main data source for InSAR applications in glaciology, in particular for studies of mountain glaciers and ice streams. On slowly moving, cold ice masses with low accumulation rates the signal may stay coherent over longer repeat intervals, as for example shown with 70-day temporal baseline ERS data over the Lake Vostok area, Antarctica, with maximum velocities of 6 m/year (Kwok et al., 2000).

There are options to mitigate or bypass the problem of poor coherence by applying cross-correlation techniques for retrieving ice motion. Strengths and weaknesses of the different techniques for ice motion retrieval are summarized in Table 2. DInSAR provides the highest accuracy, but temporal decorrelation often inhibits the application, in particular in the case of multiday time-spans. Decorrelation in zones of strong ice deformation (e.g., along glacier margins) is also a problem, impairing phase-unwrapping and thus prohibiting a solution for ice velocity even in the coherent parts. The image cross-correlation techniques deliver two components of the velocity vector (slant range and azimuth) and can measure shifts at fractions of a pixel (Strozzi et al., 2002b; de Lange et al., 2007). The accuracy of velocity measurement can be improved by using SAR data of longer timespans if the features are stable. In case of cross-correlation of complex data (’speckle tracking’ or ’coherence tracking’) a certain degree of coherence is required. However, phase-unwrapping is not necessary so that decorrelation gaps can be bridged. Complex signal-based cross-correlation can also be applied in areas without obvious amplitude features which is often the case in accumulation areas. Amplitude cross-correlation (’feature tracking’) requires stable features, and therefore often fails in the upper reaches of glaciers. On the other hand, it can be applied also in case of complete absence of coherence. Luckman et al. (2007) studied the potential of InSAR and feature tracking for Himalayan glaciers using ERS SAR data and found the two methods to be highly complementary, depending on flow rate and surface type. The new high-resolution X-band SAR sensors are very attractive tools for ice motion mapping by means of image correlation techniques. The feasibility of resolving complex ice flow patterns by means of TerraSAR-X image

<table>
<thead>
<tr>
<th>Method</th>
<th>Signal requirements</th>
<th>Displacement accuracy</th>
<th>Special features</th>
</tr>
</thead>
<tbody>
<tr>
<td>DInSAR</td>
<td>Coherence</td>
<td>High (fractions of one wavelength, mm to cm)</td>
<td>Limitations due to decorrelation and shear</td>
</tr>
<tr>
<td>Cross-correlation of complex data or coherence images</td>
<td>Coherence, but less sensitive than DInSAR</td>
<td>Fractions of one pixel (submetre to ~1 m)</td>
<td>Provides two components of the velocity vector; works also in firn areas</td>
</tr>
<tr>
<td>Cross-correlation of amplitude or intensity images</td>
<td>Non-coherent, but stable amplitude features</td>
<td>Fractions of one pixel (submetre to ~1 m)</td>
<td>Provides two components of the velocity vector; limited application in firn areas</td>
</tr>
</tbody>
</table>
correlation was demonstrated for glaciers in Patagonia and the Antarctic Peninsula (Floriciou et al., 2008; Rott et al., 2008).

Radar interferometric studies supply essential information for quantifying the response of glaciers and ice sheets to climate change. InSAR analysis and image correlation of ERS, ASAR and Radarsat data revealed strong acceleration of most of Greenland’s major outlet glaciers south of 70°N causing a significant mass deficit for the Greenland ice sheet during the last few years (Rignot and Kanagaratnam, 2006; Joughin et al., 2008). The catchment of the Thwaites and Pine Island glaciers in West Antarctica is also subject to major mass imbalance. Basic information for estimating the mass fluxes was obtained by ERS InSAR (Rignot et al., 2002; Lang et al., 2004), and recently also from ALOS PALSAR (Rignot, 2008). ERS tandem interferometry provided the first evidence on the rapid acceleration of glaciers after the disintegration of the Larsen-A Ice Shelf on the Antarctic Peninsula, also demonstrating the significance of buttressing ice shelves for the stability of grounded ice (Rott et al., 2002).

InSAR data has also yielded new insights into glacier hydraulics. Uplift and subsidence features, detected by InSAR and satellite altimetry, provide evidence of water transport between subglacial lakes in Antarctica (Gray et al., 2005; Wingham et al., 2006). Ice deformation related to subglacial volcanism was studied on the Vatnjökull ice cap, Iceland, using ERS tandem data (Björnsson et al., 2001). For outlet glaciers of Vatnjökull, ice flow acceleration was detected preceding water outbreaks of subglacial lakes (jökullhlaups) (Magnússon et al., 2007) and in connection with dynamic instabilities (surges; Fischer et al., 2003). Figure 4 shows the interferometric analysis of surface motion at the Skeidararjökull outlet of Vatnajökull, during the early phase of a water outbreak from the subglacial lake Grimsvötn. The interferogram, acquired nine days before the flood reached its maximum, reveals up to a threefold increase in velocity relative to observations several weeks before. The three-dimensional flow field on the glacier was derived by combining interferometric (LOS) velocities from ascending, and descending, orbits and the mass continuity equation, following the approach of Reeh et al. (2003).

V Observations of water currents
The along-track SAR interferometry (ATI) technique can be applied to measure water currents at high precision (Budillon et al., 2008). ATI exploits the phase differences between two SAR images that are acquired with a short timelag (of the order of milliseconds) along the flight track. Technically, this can be achieved by accommodating two antennas along-track on a platform. The two X-band antennas of SRTM had an along-track antenna separation of 7 m, corresponding to an effective InSAR timelag of 0.45 msec (Romeiser et al., 2005). Another option for achieving along-track antenna separation is to use different sections of a programmable phase array antenna so that they act as two individual receiving antennas. This has been applied for TerraSAR-X which has a total antenna length of 4.8 m. Splitting the antenna results in a separation of 2.4 m on receipt (Romeiser and Runge, 2007). ATI measures the velocity component in LOS. The moving target is displaced in azimuth direction. For the interpretation of ATI data in terms of surface currents, it is necessary to account for phase contributions due to wave motion and wind effects (Romeiser et al., 2007). So far, ATI has been applied mainly for research studies. Current fields in the ocean were measured with SRTM X-band ATI data (Romeiser et al., 2005), and also in rivers (Romeiser et al., 2007). The accuracy of the retrieved flow velocity is estimated for these cases at about \pm 0.2 m/sec. The TanDEM-X mission in formation with TerraSAR-X will open up new opportunities for along-track SAR interferometry (Krieger et al., 2007). The orbit
will allow for along-track baselines between zero and several kilometres. Over water, the baseline needs to stay below about 100–200 m to avoid decorrelation (Romeiser and Runge, 2007). These baselines offer much higher sensitivity to motion than the split antenna concept of a single satellite but make phase-unwrapping more difficult because of the $2\pi$ phase ambiguity.

VI Monitoring biogeophysical parameters
Radar interferometric data are also used for estimating biophysical and geophysical parameters of land surfaces. Retrieval methods are often based on the combination of interferometric parameters with radar backscatter intensity. Various components of the interferometric signal are used: (1) changes in the length of the propagation path; (2) temporal changes in coherence; (3) changes in the phase and/or coherence related to signal propagation in a scattering and absorbing medium.

Differences in the propagation path measured in terms of phase shifts in repeat-pass data may be caused by changes in the geometric distance between the reflecting surface and the radar antenna, as well as by changes in the propagation conditions. The first process corresponds to the signal detected by differential interferometry as

Figure 4 Interferometric analysis of ice flow on Skeidararjökull outlet glacier of Vatnajökull, Iceland, based on ERS InSAR data of 27–28 March 1996. Left: interferogram, on the glacier topographically corrected. Right: map of surface velocity. The light blue line shows the estimated flood path of the water outbreaks of the subglacial lake Grimsvötn
Source: Magnússon et al. (2007).
applied for measuring surface deformation. In hydrology, it is used for measuring temporal changes in the water level of wetlands. Because the decorrelation time of water surfaces affected by wind or currents is <1 sec, another, stable, object is needed to obtain a coherent signal. In the case of water level measurement, these are trunks of vegetation, protruding from the water. The double bounce reflection (trunks-water, water-trunks) of the radar signal is utilized. Long wavelengths (L-band) yield best results because the signal of the trunks dominates the vegetation backscatter, whereas the coherence of shorter wavelengths suffers from diffuse scattering in the canopy. One-day changes in the water level of the Amazon flood plain were measured at centimetre accuracy with L-band data in the Shuttle Radar Mission (Alsdorf et al., 2000). Wdowinski et al. (2004) measured water level in the Everglades wetland, Florida, at the beginning, middle and end of the local wet season to derive sheet-flow characteristics. Lu and Kwoun (2008) applied C-band data of ERS and Radarsat-1 to map water-level changes beneath swamp forest in Louisiana, achieving best results for one-day repeat-pass ERS-1/ERS-2 tandem data. The comparison between Radarsat-1 and PALSAR data of the same region shows wider spatial applicability and better temporal coherence for the L-band (Kim et al., 2009).

Whereas phase shifts, caused by changes of the dielectric properties of the atmosphere, are noise for the retrieval of topography and surface deformation, this signal can be used to measure atmospheric constituents. If accurate surface topographic data are available, and the surface deformation is insignificant, the atmospheric phase signal can be isolated. This signal can be used to produce spatially detailed maps of columnar water vapour (Hanssen, 2001; Hanssen et al., 2001).

The interferometric phase and coherence are very sensitive to vegetation density and structural properties of the scatterers within a vegetation canopy. The decorrelation due to the different positions of the scatterers within the volume ('volume decorrelation') is sensitive to the vertical extension of the canopy and to the electromagnetic density of the scatterers. In repeat-pass data, these effects are often superimposed by temporal decorrelation, mainly due to canopy movement in the wind (Drezet and Quegan, 2006). The type and orientation of the scatterers may cause additional phase shifts, so that the signal is also sensitive to the structure of a canopy (Alberga, 2004). InSAR coherence data are applied for land-cover classification, based on differences in temporal and volume decorrelation of the various surface classes. This was shown with ERS tandem one-day coherence data for land-cover mapping in various parts of Europe (Strozzi et al., 2002a; Engdahl and Hyppä, 2003).

Because of the important role of forests in ecology and the global carbon cycle, InSAR has been considered as a tool for mapping and monitoring forest type, canopy height and biomass since the early days of this technique (Balzter, 2001). The interferometric phase and coherence are sensitive to the three-dimensional structure of the forest canopy, thus providing information complementary to the intensity of the backscattered signal (Cloude and Papathanassiou, 1998). Multitemporal ERS tandem coherence data over a one-day timespan were used to estimate the stem volume of boreal forest with good accuracy (Askne et al., 2003; Askne and Santoro, 2005). A combination of ERS tandem coherence and JERS-1 backscatter images was applied to produce a baseline forest map with four classes of growing stock volume over Siberia (Wagner et al., 2003). Tansey et al. (2004) showed the feasibility to use the same sensor combination for estimating growing stock volume in different forest ecosystems of the globe, merging stock volume >80 m³ha⁻¹ into one class because of signal saturation.

PALSAR, launched on board ALOS in January 2006, applies a well-defined global
observation strategy in order to support efforts in resolving uncertainties in the global carbon cycle (Rosenqvist et al., 2007). Thiel et al. (2009) demonstrate the capabilities of ALOS PALSAR for accurate mapping of forested areas and other surface classes in the boreal zone, using HH and VV polarized backscatter together with coherence images from winter. Because of signal saturation in dense forest, SAR at longer wavelength (P-band) is proposed for estimating the biomass over a wide range of forest types and densities (Le Toan et al., 2004). A promising technique for measuring forest height and biomass is polarimetric radar interferometry (Pol-InSAR), allowing the estimation of forest parameters such as tree height, average extinction and underlying topography (Papathanassiou and Cloude, 2001). The feasibility to accurately estimate forest height up to high biomass values was demonstrated by Garestier et al. (2008) using airborne P-band PolInSAR measurements.

VII Outlook
Over the last decade, radar interferometry has gained a prominent position as a remote sensing tool in geoscience and environmental monitoring. Although the development of techniques for interferometric analysis and processing will still go on for years, in tandem with the improvement of sensors, there are already some well-established techniques available for operational use. Geospatial services, based on the InSAR techniques, are offered by private companies and remote sensing institutions in many countries, addressing applications in natural hazard monitoring, topographic mapping, monitoring of surface deformation, ecology, and the exploration of natural resources. Nevertheless, the applications in science clearly exceed the operational use of InSAR products. The Sentinel-1 satellite series, to be deployed in 2011 by ESA in cooperation with the European Union, is dedicated to operational applications of SAR with interferometry being a main driver (Attema et al., 2007). In full deployment, the Sentinel-1 program will consist of a constellation of two C-band SAR satellites, jointly providing six-day repeat observations over a swath of 250 km.

The SAR missions launched in 2007 yield a large augmentation in interferometric data. They cover three different frequency bands and offer polarimetric capabilities: TerraSAR-X and COSMO/Skymed in the X-band, Radarsat-2 in the C-band, ALOS PALSAR in the L-band. Reports and publications on interferometric applications of these sensors are increasing. The high-resolution polarimetric and interferometric capabilities will foster major advances in InSAR applications. One of the new features is spotlight SAR interferometry, offering excellent precision for measurement of topography and surface deformation (Eineder et al., 2009).

There are several new SAR missions which are dedicated to InSAR applications. The TanDEM-X mission of DLR, scheduled for launch in October 2009, will operate in a close-controlled formation with TerraSAR-X employing a helix orbit concept at typical intersatellite distance of 250–500 m (Krieger et al., 2007). This will be the first bistatic SAR mission. The primary mission objective is the generation of a global digital elevation model at high accuracy. In addition, the bistatic configuration will enable the demonstration of several new InSAR techniques and applications. NASA has plans for the ‘Deformation, Ecosystem and Dynamics of Ice’ (DESDynI) mission, which will employ an L-band InSAR system with multiple polarization, and a multiple beam lidar operating in the infrared (Donnellan et al., 2008). Principal drivers for the mission are the measurement of forest height, observation of seismic deformation and volcanism, and studies of ice sheet dynamics. A second L-band SAR, Tandem-L, to fly in close formation with DESDynI for single-pass interferometry, is under consideration (Moreira et al., 2009). This will provide improved global data on forest height and
biomass, enable tomographic survey of vegetation and other volume scattering media, and monitor ocean surface currents. Another innovative interferometric concept is proposed for the Surface Water and Ocean Topography (SWOT) mission employing a Ka-band (35 GHz) radar interferometer with two antennas separated by 10 m on one platform (Fu et al., 2009). This is designed to measure the height of surface water and ocean topography over a 120 km swath at very high precision.

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