SAR Interferometry Technology

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1. Introduction

The technical challenges and the application of Synthetic Aperture Radar (SAR) interferometry (InSAR) for topographic mapping and deformation measurements from space have developed dramatically since the beginning of the 1990s. Whereas in the beginning of the 1990s only a few groups world-wide focussed on this new technique for remotely monitoring the Earth's surface, there are dozens of research teams currently active world-wide. Their background is completely different: among them are electrical engineers, geophysicists, geologists, space engineers, and geodesists. Correspondingly, the number of scientific publications related to InSAR technology and applications has exploded in the same period. In the meanwhile there are special symposia devoted to InSAR with hundreds of participants, e.g., the ESA FRINGE meetings and the yearly IGARSS symposia. In the same period there are special sessions on InSAR and its applications in geosciences at all large geoscientific meetings such as the General Assembly of the EGS and the yearly meetings of the AGU. For years, InSAR, was rather unknown to geodesists also geodesists have a long tradition in techniques and methods for mapping the topography and surface deformations from space. In 1995 at the XXI General Assembly of the IUGG in Boulder, Colorado, the IAG gave credit to this new technique and established the Special Study Group (SSG) 2.160 on InSAR Technology within the IAG Section II Advanced Space Technology.

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2. Research objectives

The major objective of the SSG was to develop techniques that allow extracting unambiguously the topographic and deformation signal from spaceborne repeat-pass across-track SAR interferometry, to develop data processing strategies and algorithms that allow to process radar interferometry data accurately and efficiently, to identify and examine the main limitations to SAR interferometry, to develop strategies to overcome these limitations, and to perform a thorough validation of topographic and deformation maps for various applications and under various environmental conditions. All thematic applications of SAR and InSAR and related problems such as land cover classification, bio-mass measurements, snow and soil moisture measurements, monitoring of sea ice thickness, and characterisation of oil slicks, were out of the scope of the SSG. A secondary objective was to promote InSAR in the geo-scientific community by publishing a number of review articles in scientific journals and by organising special InSAR related sessions at (geo-) scientific symposia and workshops of the IAG, EGS, and AGU. As far as the second objective concerns three larger review papers have been published by members of the SSG, cf. (Massonnet and Feigl 1998), (Bamler and Hartl 1998), (Klees and Massonnet 1999). Moreover, several InSAR devoted sessions have been organised at scientific meetings, workshops and General Assemblies of the EGS and the AGU, and members of the SSG usually act as convenor or chairman.

The scientific objective has led to the following research items:

1. Data processing strategies and algorithms
   Filtering, phase unwrapping, coherence estimation
2. Error sources and quality description
   Limitations to interferometric measurements, atmospheric disturbances, temporal decorrelation, nature of noise, and error propagation
3. Specific applications in geo-sciences
   Earthquakes, volcanoes, anthropogenic processes, glaciers and ice sheets

In the following I will summarise the major findings of the SSG. Section 7 contains the scientific output of the SSG.

3. Results

3.1 Data processing strategies and algorithms

The main focus of the SSG within this research item was on the problem of two-dimensional phase unwrapping. The reason is that phase unwrapping is the core technique that enables InSAR. SAR interferometry exploits the phase of two or more coherent signals. Since the phase influences the signal only through phase principal values between $\pm\pi$ radians we can actually measure only these principal values, the so-called wrapped phases. In other words, the phase measurements in SAR interferograms are ambiguous by integer multiples of 2π. This ambiguity must be resolved in order to obtain unambiguous information about the topography or the surface deformation. However, the relation between the discretely measured wrapped phase values and the geometric information is highly non-linear, and the problem of phase unwrapping is from the mathematical point of view a non-linear inverse problem. In addition, imaging geometry, noise, and aliasing can destroy our ability to unwrap the phase correctly. A variety of ideas and algorithms have been proposed so far, but to a large extent it is not clear which methods are good and which are not. A first step in order to answer this question was the definition of different test data sets by ESA's FRINGE group, which allow comparing and analysing the various algorithms under different conditions. Although the best method (if it exists at all) has not been found yet, the SSG could make some important contributions to the problem of phase unwrapping.

Phase unwrapping in SAR interferometry consists of two steps: (1) the estimation of phase gradients from the interferogram, and (2) the integration of the estimated phase gradients in order to obtain an unwrapped phase surface. The various phase unwrapping algorithms differ in the way these two steps are done. Bamler and Davidson (1996) and Bamler et al. (1996) showed that the commonly used estimator for phase gradients underestimates the slopes in the presence of noise. Hence, all linear estimators operating on these phase gradients like least squares methods tend to globally distort the reconstructed terrain or deformation field. This motivates the research on unbiased estimators for phase gradients. In a number of papers (Davidson and Bamler, 1996a, 1996b, Bamler and Davidson 1997, Bamler et al. 1998, Davidson and Bamler 1999) an estimator for phase gradients is proposed that is asymptotically unbiased. Whereas the usual approach uses small estimation windows of 2∗2 samples, leading to a high probability of aliasing, they propose to estimate local fringe frequencies over larger windows at the cost of lower spatial resolution. This estimate is then used to reduce the phase variation of the next higher resolution, i.e., of the next smaller estimation window. This is repeated until the highest resolution is obtained. The final frequency estimation at the highest resolution is obtained by summing up the frequency differences as long as aliasing errors in the frequency estimates do not occur as detected by the curl of the measured phase gradient. Although aliasing errors due to noise still occur, the error has asymptotically zero mean because of the smaller frequencies being estimated at each level, and a smooth reconstruction of the unwrapped phase is obtained. Thus, a trade-off between bias and resolution has to be made taking the coherence as indicator of the local quality of the phase values into account. Multiresolution frequency analysis, using a modification of a spectral centroid estimator as local frequency estimator given by the phase of the autocorrelation function at the lag of 1 sample, allows for such an adaptive adjustment of window sizes. Moreover, it makes the estimation computationally more efficient. The estimator is proved to provide asymptotically unbiased gradient estimates. In Davidson and Bamler (1999) the approach to 2D phase unwrapping is further improved. The idea is that phase unwrapping can be improved if a coarse resolution phase surface is available. Instead of using a DEM they estimate a coarse phase surface from the data itself using a weighted least-squares method based on coherence weighting. Then, the coarse phase is used in their slope-adaptive spectral shift filtering approach in order to improve the coherence and to reduce the phase variation in the interferogram. The resulting “flattened” interferogram can be performed more accurately with any algorithm, and the effect of phase slope on the aliasing error in phase gradient estimation is reduced.

Just et al. (1995) compared different approaches to phase unwrapping, namely the cut-and-branch approach, the classical representative of path-following methods, and two minimum-norm methods, the weighted and unweighted least-squares methods. Main emphasis has been put on how these methods behave in the presence of noise and undersampling. They concluded that the cut-and-branch approach is likely to introduce global errors in the unwrapped image. Later on Ghiglia and Pritt (1998) argued that this may be due to their special implementation of the original algorithm.

Massonnet et al. (1996) proposed a method, which sometimes avoids phase unwrapping in topographic mapping. The method requires a (rough) digital elevation model (DEM) to be available. The unwrapping procedure is replaced by forming a number of integer linear combinations of interferograms with an artificially high height of ambiguity such that unwrapping is not necessary. The method is a variant of the so-called multi-baseline technique, which uses at least three SAR images with one baseline large and the others small. The small baseline interferogram (large height of ambiguity) is used to provide a coarse estimate of the topography. Then, a more precise estimate is derived from the large baseline interferogram. Although this procedure is not general enough, it may sometimes reduce the need for phase unwrapping.

Coherence is a very important indicator of the quality of the phase values in interferograms, and is thus needed in many interferometric processing steps, e.g., in weighted least-squares techniques to phase unwrapping. Touzi et al. (1996a-b, 1998) derived the statistics of classical coherence estimators for Gaussian scenes. They showed that the classical coherence estimator is biased towards higher values for partially coherent areas. They proposed a multilook complex coherence estimator, which has been shown to be “less” biased than the classical multilook magnitude estimator. The statistics of the former is then used to remove the coherence bias. They also discussed coherence estimation for non-stationary targets and showed that the averaged sample coherence permits the calculation of an unbiased coherence estimate provided that the original signals can be assumed to be locally stationary over a sufficiently coarse resolution cell. Vachon et al. (1995) corrected for the estimation bias for low coherence levels based on a theoretical probability density function. They found that the temporal decorrelation is strongly dependent on local weather conditions and vegetation type. Zebker et al. (1996) confirmed an empirical result of Wegmueller and Werner (1995) that the number of pixels used to compute the ensemble mean biases the correlation coefficient in low coherence areas, and that a larger window size is required for those areas.

3.2 Error sources and quality description

There are numerous processes that affect the quality of the phase values and may introduce bias in the estimated topography or deformation field. Among them are satellite clock errors, residual topographic signals in differential interferograms, satellite orbit errors, atmospheric disturbances, and various types of decorrelation. In a number of studies the SSG could prove that the most serious limitations to SAR interferometry are changes of the refractive index in the time between the image acquisitions (atmospheric disturbances), and changes of the backscatter characteristics within a pixel (temporal decorrelation). Whereas atmospheric disturbances may be interpreted as topography or deformation signal, temporal decorrelation causes loss of coherence, thus degrading the quality of the phase values or even make SAR interferometry impossible.

The main focus of the SSG was on a detailed examination of phase distortions in SAR interferograms caused by atmosphere and on the problem of temporal decorrelation. As far as atmospheric disturbances concerns the objective was to detect atmospheric effects in SAR interferograms, to assess their impact on the performance of spaceborne InSAR for topographic mapping and deformation measurements, and to understand their relation to physical characteristics of the atmosphere. The followed strategy was to select test areas and SAR images that allow studying the atmospheric distortions, to perform the interferometric data processing, to detect artefacts using methods still to be developed, to estimate the delay, e.g. from weather radar observations, radio sondes, satellite imagery or ground meteo observations, and to correlate these estimates with estimated phase variations from InSAR. Massonnet and Feigl (1995) and Massonnet et al. (1995) published first speculations on the contamination of interferograms of atmospheric origin. They developed a pair-wise logic useful in order to discriminate signal from various types of artefacts, and correspondingly applied this approach to identify artefacts in interferograms and to speculate about the origin of these effects. They argued that both ionospheric and tropospheric effects are responsible for phase distortions in interferograms. The pair-wise approach (cf. Massonnet and Feigl 1995, Tarayre and Massonnet 1996) is based on the fact that single-epoch events contaminate every interferometric pair that uses the image acquired at this epoch. By comparing several interferograms, this single-epoch event can be distinguished from the topographic or deformation signal. Consequently, the corresponding SAR image is removed from the data processing. In that way it was possible to identify phase signatures in interferograms as caused by local neutralisation of the ionosphere and water vapour and turbulence in the troposphere. However, the pair-wise logic cannot remove atmospheric signatures from interferograms, which is still the most serious and unsolved problem.

Other studies of the SSG also described various types of atmospheric effects in SAR interferograms and showed that temporal and spatial variations of the refractive index of the propagation medium lead to phase variations in the interferograms (cf. Hanssen and Feijt 1996, Rosen et al. 1996, Hanssen and Usai 1997, Zebker et al. 1997, Fujiwara et al. 1998). Tarayre and Massonnet (1996) observed up to three phase cycles localized phase shift caused by cumulus clouds, while Hanssen and Usai (1997) reported wave effects with a wavelength of about 2 km and amplitudes of 0.25 cycles, and localised phase shifts up to 5 phase cycles. In a detailed study on atmospheric effects in InSAR surface deformation and topography maps Zebker et al. (1997) analysed shuttle imaging radar-C/X-SAR C- and L-band Hawaii data. They showed that time and space variations of atmospheric water vapour are by far the dominant error source in repeat-pass spaceborne SAR interferometry in wet regions. Spatial and temporal changes of 20% in relative humidity lead to 10-cm errors in deformation products, and perhaps 100 m of error in topographic maps for unfavourable baseline lengths. For topographic mapping the errors may be mitigated by choosing interferometric pairs with relatively long baselines (within the limits of baseline decorrelation), as the error is inversely proportional to the perpendicular component of the baseline. In the case of deformation measurements the error is almost independent on the baseline length, and the only solution is averaging of independent interferograms. This requires that many SAR images are available and that the deformation is a linear function of time. Then, accuracies of 10 m for digital elevation models and 1 cm for deformation maps are possible even in wet regions.

The currently most detailed assessment of the influence of the atmosphere on SAR interferograms has been done by Hanssen (1998). He analysed the influence of atmospheric heterogeneities on the interferometric phase observations from a series of 26 ERS tandem mission interferograms, and evaluated them using additional meteo data. Main emphasis has been put on a quantitative analysis of the observed atmospheric phase artefacts in terms of spatial scale and magnitude, on a classification of the effects, and a comparison with meteo data in order to assess the atmospheric phenomena causing the artefacts. Moreover, he investigated how and which meteo data can serve as a warning flag for atmospheric contamination in the automatic processing of SAR images. Atmospheric effects have been observed in each of the 26 interferograms. The observed spatial scales reached from hundreds of meters to 100-200 km. Observed rms values reached from 0.5-4 radians. Extreme ranges of 4 phase cycles are found during thunderstorms at the two SAR acquisitions. The effects have been classified into five categories: (1) *isolated anomalies*, i.e. anomalies with a spatial extent of 20 km or less and a phase disturbance of 2 radians or more, observed in 18 interferograms. (2) *striated anomalies*, i.e. linear features over a significant portion of the interferogram, often connected with transport of moisture, observed in 10 interferograms. (3) *wave effects* such as gravity waves or cloud/moisture streets, which have been often observed in only a part of the interferogram. (4) *frontal zones* with quite different characteristics from smooth phase gradients to very distinct wave crest with a wavelength of just some 5 kilometres. Finally, (5) *overall atmospheric variation* characterised by a limited phase magnitude and varying wavelengths mostly connected with turbulent behaviour of air and its constituents. As driving mechanisms of localised temporal and spatial variations in the refractive index not only pressure, temperature, and water vapour distribution have been identified but also rain fall and cold fronts. Mostly, the spatial variation of pressure and temperature is not large enough to cause strong localised phase gradients within a full scene but rather gradients over the whole interferogram, which are difficult to separate from orbit errors. The dominant driving mechanism is the spatial and temporal variation of humidity.

Two methods to handle atmospheric signals in interferograms have been developed and successfully applied by members of the SSG: the first one is a careful selection of the SAR images using the pair-wise logic in order to eliminate suspicious images from the data processing, the second one is statistical suppression based on stacking and averaging interferograms. The latter has been successfully applied if overall atmospheric variations occurred, whereas this procedure did not work if convective processes were responsible for the atmospheric distortions since many interferograms will be necessary in order to eliminate these type of effects.

The second error source, which has been studied intensively by members of the SSG, is temporal decorrelation, i.e. time variations of the radar-scattering characteristics within each pixel, specifically the rms position of the surface scatters within a pixel. The objective is to understand the relation between temporal decorrelation and the type of vegetation, to determine the role of the radar wavelength in this context, and to develop strategies for extracting the deformation signal even in highly decorrelated interferograms.

It is well-known that temporal decorrelation precludes or makes difficult the phase comparison of the SAR images. In a number of studies done by members of the SSG temporal decorrelation has been observed on time scales of a few hours in vegetated areas experiencing windy conditions. On the other hand, results obtained for the arid Landers area in California has shown to be sufficiently high over time scales of years. Similar results have been obtained for other arid regions. Murakami et al. (1995, 1996a, 1996b) and Rosen et al. (1996) could show operationally what has been noted many times theoretically, namely that the correlation at longer wavelengths (e.g., SIR-C/X-SAR and JERS 1 SAR L-band SAR) generally exceeds that at the shorter wavelengths (e.g. ERS 1 and ERS 2 C-band SAR) since L-band radar waves penetrate the vegetation more easily. Also, it has been demonstrated by Zebker et al. (1997) that the scattering behaviour and decorrelation causative mechanisms at C- and L-band may be quite different and is not simply related by scaling of the surface roughness. For instance, they found that for L-band correlation gets steadily weaker with time, with the rate dependent on surface terrain, whereas for C-band abrupt correlation changes have been noted several times related to freezing and thawing of the ground surface. Fujiware et al. (1998) examined temporal decorrelation over de Izu Peninsula, Japan, using SAR images acquired by the Japanese Earth Resources Satellite JERS 1, the only continuously operating spaceborne L-band SAR so far. Their analysis has shown that decorrelation in mixed conifer and deciduous forest is a weak function of the time between observations, imposing a roughly constant level of additional decorrelation relative to scatter-stable areas. They also demonstrated that wet snow cover may reduce correlation significantly although scatters such as buildings and tree branches seem to remain correlated. Finally they found that elevation-dependent weather effects such as snow cover are likely to cause decorrelation above a certain altitude in high altitude areas.

Another research line followed by the SSG is to investigate whether anthropogenic features contain valuable information in otherwise completely decorrelated SAR interferograms. This would be necessary when applying InSAR for monitoring slow deformation processes. Usai and Hanssen (1997) and Usai and Klees (1998, 1999) studied information derived from highly decorrelated interferograms. In order to understand whether the correlated anthropogenic features provide valid though point-wise information over long time spans they tested man-made features for their phase stability in space and time on a pixel-by-pixel basis. For a single feature such as a building or a road they showed that they are phase stable in space and time on a level of 0.4 radians. For a city, the homogeneity in space and time is reduced since it must be considered as a collection of objects instead of a single object only, and therefore, the chance is higher that the phase information of some of them is affected differently by local processes. The proven stability properties permit to use man-made features for monitoring slow deformation processes in otherwise decorrelated interferograms.

4. Specific applications in geo-sciences

Most activities of the SSG were devoted to the development of algorithms that convert interferometric observations to quantitative geophysical parameters. The main questions the SSG wanted to answer were (1) what is the potential of spaceborne InSAR in topographic mapping and ground deformation monitoring, (2) what are the specific problems related to the application and how to solve these problems, and (3) what is the benefit of InSAR derived deformation fields in geophysical modelling? In order to answer the latter, various new co-operations with other geoscientists have been established. Main emphasis was on the application of InSAR for ground deformation monitoring connected with natural hazards, in particular earthquakes and volcanic eruptions, but also for monitoring surface deformations caused by anthropogenic processes and ice sheet and glaciers motions.

In numerous studies of displacement fields the SSG could gain more insight into the potential and limitation of InSAR for surface deformation detection. In particular, the studies showed that the potential of InSAR to detect surface deformations depends on the magnitude and the spatial scale of the crustal movement. Interferometric limitations such as surface preservation, maximum phase gradient, ambiguity estimation, swath width, pixel size, roughness of the topography put constraints on the upper and lower bound of the acceptable magnitude and spatial scale of the deformation. The most important results are summarised in the overview paper (Massonnet and Feigl 1998).

Since the exciting demonstration of the potential of InSAR for monitoring of co-seismic surface deformation (Massonnet et al. 1993) a number of more detailed studies have been conducted by the SSG. Among them are the Eureka Valley, California, earthquake in 1993 (Peltzer and Rosen 1995, Massonnet and Feigl 1995), the Northridge California earthquake in 1994 (Murakami et al. 1996, Massonnet et al. 1996), the Grevena, Northern Greece earthquake in 1995 (Meyer et al. 1996), the Kobe earthquake in 1995 (Ozawa et al. 1997), the North Sakhalin earthquake in 1995 (Tobita et al. 1998), the Neftegorsk, Northern Sakhalin earthquake in 1995 (Murakami et al. 1996, Nakagawa et al. 1997), and the Kagoshima-ken Hokusei-bu earthquake in 1997 (Tobita et al. 1998). Both ERS 1, ERS 2 and JERS 1 data have been processed, and sometimes SAR images acquired by both ERS and JERS are used providing more insight into the role of InSAR in earthquake-related studies (e.g., Massonnet et al. 1996). The similarity of the interferometric results with fake interferograms build from surface rupture measurements assuming an elastic behaviour of the crust has led to a wide acceptance of InSAR in the geophysical community. The results are not only convincing due to the complete picture over large scales InSAR gives but in particular due to surprisingly accurate results on by-phenomena such as tiny fault shifts triggered by the main shock. Often, these shifts have not been detected by GPS and terrestrial geodetic networks. Similar holds for other features like surface deformation patterns associated with individual aftershocks and surface offsets, features that would be very difficult, if not impossible, to detect on the ground. For the first time it was also possible to investigate the influence on the derived fault models of high spatial resolutions as provided by InSAR compared to typically sparse pointwise information provided by GPS: Massonnet et al. (1996) showed that a fault model based on GPS measurements fails to account for significant parts of the fringe patterns observed by InSAR for the co-seismic deformation field of the Northridge California earthquake in 1994. This was attributed to the low number of fault parameters estimable from the GPS measurements due to the poor spatial sampling of the GPS network. For the same reason GPS measurements did not give evidence of the effects of several aftershocks and localised ground motion. The interferogram, however, allowed to estimate a more detailed fault model, thus providing a much better fit to the data than the GPS derived model. In a study of the North Sakhalin earthquake, Tobita et al. (1998) concluded that GPS and terrestrial geodetic techniques do not provide efficient information to estimate slip distribution with high resolution (due to the coarse spatial sampling and the rapid decay of ground displacements from a fault movement), whereas InSAR does due to the high spatial sampling. In other cases, InSAR confirmed fault shifts observed in the field.

The studies have been extended to post-seismic deformation fields following the Landers California earthquake (Massonnet et al. 1996, Peltzer et al. 1996) and the North Sakhalin earthquake (Tobita et al. 1998). The major result is that InSAR maps the complex near-fault patterns of post-seismic deformation, which cannot be provided by GPS and terrestrial geodetic techniques without setting up an (impossible) dense and costly observation network. Moreover, various unexpected deformations near faults have been detected in interferograms spanning up to 3 years and different mechanisms have been proposed, which may produce the observed deformations. While InSAR agrees with GPS measurements the latter cannot decide between various geophysical models because of the strong spatial undersampling of the deformation field.

Unfortunately the SSG did not succeed in detecting precursory displacements in SAR interferograms assuming that such precursors exist. In addition, the interferometric limitations mentioned before often prevent mapping deformations very near the fault trace due to loss of coherence. Finally, it has been shown that not every earthquake creates clear interferometric fringes. Only co-seismic deformation fields with sufficient magnitude and proper orientation can be mapped. Mostly, moderate (M>5) earthquakes at shallow depth (< 10 km) with predominantly vertical surface displacements generate fringes allowing for an unambiguous interpretation (Massonnet and Feigl 1998). In co-operation with geophysicists models of the centroid and focal mechanism have been developed from the deformation fields mapped by InSAR for different earthquakes. It has been shown that the high spatial sampling of InSAR allows developing much more detailed fault models with less a priori assumptions. Usually the earthquake fault is modelled by a number of vertical planar elements, and each element is parameterised by up to 10 parameters. The fault parameters are estimated by minimising the difference between the observed and evaluated values of the surface deformations. Usually iterative linear least-squares schemes are used for the non-linear inversion with a priori covariance matrices. The major problem still to be solved is the suitable choice of the stochastic model for the SAR-derived deformation fields. Usually no correlation between the measured ground deformations are assumed and often only errors due to various types of decorrelation and residual topography are taken into account (e.g., Murakami et al. 1996).

Nonetheless, the derived relatively detailed models are shown to be consistent with the results of seismic studies and field surveys.

Volcano monitoring offers a clear near term perspective in disaster prevention because many, perhaps most of the world's volcanoes that actually do erupt experience significant pre-eruption surface deformation. In addition, the location of a volcano is well-known, the deformation is usually continuous and runs over time scales of months rather than years, and, finally, many volcanoes remain sufficiently coherent although it was observed that atmospheric distortions, steep topographic gradients, vegetation, and snow coverage may cause serious problems. The SSG studied various volcanoes among them the Mount Etna in Italy (Massonnet et al. 1995, Briole et al. 1997), the Long Valley Caldera, Eastern California (Thatcher and Massonnet 1997), the Kilauea volcano on Hawaii (Rosen et al. 1996), Vatnajokull volcano on Iceland (Thiel et al. 1997), and the Krafla volcano on Island (Sigmundsson et al. 1997). See also the review papers (Massonnet and Feigl 1998, Klees and Massonnet 1999). Typical deformation rates of several centimetres per month have been observed, which are easy to measure with monthly passes. Then, temporal decorrelation is not a major concern. For instance, several ERS 1 and JERS 1 images of Merapi volcano (Indonesia) have shown to remain coherent over a month despite heavy vegetation in a humid tropical region. Coherence also lasts over 3 years at La Palma, another tropical volcano. On the other hand, Rosen et al. (1996) found significant atmospheric signatures in interferograms of Kilauea on Hawaii introducing spurious apparent deformation signatures at the level of 12 cm peak-to-peak in the radar line-of-sight direction. They conclude that the atmospheric distortions are large enough to limit the interpretation of the results. In particular when being faced with centimetre-scale deformations spatially distributed over tens of kilometres it is very difficult to characterise them without simultaneous, spatially distributed measurements of refractivity along the radar line-of-sight. Studies of the coherence of SAR images also show that L-band is far superior to C-band in the vegetated areas, even when the observations are separated by only 1 day as during the ERS tandem mission and the SIR-C/X-SAR experiment (cf. Section 3.2).

The SSG also focussed on the monitoring of surface deformations due to anthropogenic processes such as withdrawal of water, oil or gas and mining activities (Carnec et al. 1996, Massonnet et al. 1997). Unlike the other applications addressed before, man-made activities involves subtle economical, strategic or even legal issues. Moreover, the related deformation processes are small scale and may run very slowly with deformation rates on the order of 1 centimetre a year. Temporal decorrelation and/or atmospheric disturbances have been identified as the major limitations for this type of application. Bree et al. (1999) conducted a very detailed study on the monitoring of land subsidence due to the extraction of natural gas in the area of Groningen, The Netherlands. The conditions were very unfavourable: slow subsidence rates of below 1 cm/yr combined with a humid climate and severe temporal decorrelation caused by agriculture. 18 ERS-1/2 SAR images were processed covering about 3 years of data. A new database structure for the SAR data was designed and a theoretical error analysis was performed, which included interferometric processing errors, erroneous orbit parameters, atmospheric distortions, topographic effects, and various types of decorrelation. A priori information about the deformation pattern was used to parameterise the deformation in space and time by an algebraic polynomial. InSAR and levelling data have been used to estimate the model parameters in a standard least squares approach. Large atmospheric effects and severe temporal decorrelation prevent to detect statistically significant deformations over the 3-year period. They conclude that dedicated filters are indispensable, which can separate subtle deformations from disturbing effects caused by the atmosphere, residual orbit errors, and (residual) topography.

The results obtained so far are encouraging but not satisfactory. But even when InSAR fails monitoring these small deformations over long time scales under rather unfavourable conditions it can help in optimising the location of geodetic networks in areas that effectively show ground movement.

With regard to glacier and ice sheet monitoring the SSG demonstrated that InSAR can provide high-resolution high-accuracy topographic maps of glaciers and ice sheets, measure ice flow velocity without any ground control, detect and monitor surface changes, and identify the line separating floating from grounded ice, e.g. Vachon et al. (1996a,b), Cumming et al. (1996a,b), Thiel et al. (1996), Wu and Thiel (1996), Thiel and Wu (1996), Thiel et al. (1997). Among the major problems that have been reported are the usually quite rapid movement of flowing ice, which requires short orbital and temporal separations between successive satellite passes, the alteration of the reflective ice surface by freeze, thaw, or precipitation and snow fall, which may reduce coherence even in 1 day interferograms, the proper reconstruction of the 3D surface flow field from the measured fringes, which is not possible without additional assumptions because InSAR only measures the line-of-sight component of the deformation vector, and the removal of the topography signal from the interferogram, which requires either a DEM or a third SAR image to be available. Thiel et al. (1996) estimated topography, differential tidal variations (assuming a steady ice flow) and horizontal ice movements (assuming no vertical component) for the region around the Hemmen Ice Rise in Artarctica (using ascending and descending SAR images and assuming zero vertical component and slang range changes during the 3 hours between the ascending and descending data acquisitions). The SAR images have been acquired during the ERS

1 Ice Phase with a repeat period of 3 days. Vachon et al. (1996a,b) reconstructed the 3D surface flow field of the mid-latitude Athabasca glacier in the Columbia Icefield in the Canadian Rocky Mountains from the radar line-of-sight component extracted from ERS tandem phase SAR images assuming a plastic flow model and flow vectors pointing downslope, in the direction of the maximum basal slope. This assumption can only provide reasonable results near the centreline of the glacier but not near the glacier's margins. The downslope direction was determined from an airborne SAR DEM. A comparison with in situ measured point velocities derived from historical and more recent point displacement measurements showed an excellent agreement to within 10%. Moreover, they showed that the fine-scale structure of the glacier flow patterns are very repeatable. High scene coherence has proved to be associated with below freezing maximum temperatures, the absence of precipitation, and no blowing snow during the data collection interval. Therefore, InSAR appears to work best during winter when the potential of daytime melting is minimised. Another key problem is the removal of the topography phase from the interferogram. The usual double differencing approach of taking two interferograms with different baselines and/or different data take intervals requires the assumption that the glacier velocity is constant between the two pairs of data takes and that coherence remains sufficiently high. The latter however is often not guaranteed over glacier and ice sheet surfaces. The second approach uses a DEM (if it exists at all) and a satellite geometry model to compute the topography phase. Residual topographic errors may be minimised using short baseline SAR images for flow field mapping. Here, airborne InSAR DEM's are especially well-suited. The same strategy was applied by Cumming et al. (1996) for the neighboured Saskatchewan Glacier and quite similar results were obtained, see also (Vachon et al. 1996a,b). Although these studies showed that InSAR is a promising technique for monitoring glaciers and ice sheets, we are not in the position yet to fully exploit its potential. Too many problems have not been solved yet. For instance, present satellites carrying a SAR do not fully cover polar regions (ERS satellites leave a gap of about 8 degrees at the poles). In addition, Greenland and polar regions suffer from severe weather conditions, which may lead to complete decorrelation within a few days, e.g. due to snow storms, melting, and blowing snow. Atmospheric disturbances may corrupt the interferograms. Finally, the mapping geometry (angle between across-track direction and flow direction) and the line-of-sight component provided by InSAR can make the reconstruction of the 3D surface flow field very difficult and require additional assumptions such as a surface-parallel flow assumption, which ignore for instance submergence and emergence velocities.

5. Outlook

SAR interferometry will become increasingly important over the next decade with the development of airborne and space-borne sensor systems. Improved antenna design, RF electronics, digital electronics and data processors will allow exploiting optimally this technology. At the same time, the commercial application of SAR interferometry will increase, as well, offering new perspectives for geodesists. Currently four SAR satellites are in orbit (ERS 1 and 2, RADARSAT and JERS 1) and a few airborne InSAR systems are operated by national organisations and private companies (cf. Bamler and Hartl (1998) for an overview). The next European satellite-borne SAR will be the ASAR system on board ENVISAT, a C-band system like ERS but with considerably higher flexibility. At least two other systems are approved and planned for launch in the first years of the next millenium, among them NASA's LightSAR. They will be smaller, lighter, cheaper, with dual frequencies and shorter revisit cycles.

Phase unwrapping will continue to be an important issue. A good description of the quality of each pixel of the given phase data set seems to be a crucial point since the quality guides several of the path-following algorithms and is necessary for some of the weighted minimum norm algorithms. Up to now the correlation is widespread used to describe the quality of each pixel but there are also other candidates such as the variance of the phase value, the phase derivative variance, the second differences of the phase data, and the maximum phase gradient. In practise the quality measure may depend on the situation; a quality measure that works fine in one situation may fail in another one. Other areas where further work needs to be done are the development of techniques for the evaluation of phase unwrapping results and the proper choice of the norm in minimum norm solutions. The latter may be related to solution phase gradients that deviate from the measured phase gradients in as few places as possible, where the magnitude of the deviation is of no concern, sometimes called L^0-norm solution (cf. Ghiglia and Pritt 1998).

Research on atmospheric effects has to be intensified. As elimination of these effects concerns weather radar data should be further analysed and compared with observed phase delays in the interferograms and a functional relationship between both types of data should be established as a starting point towards the elimination of localised anomalies in SAR interferograms. The synergy of various sensors on board of future satellite missions carrying a SAR antenna should be investigated. For instance, for ENVISAT it would be important to study the use of MERIS in this context. Moreover, it is important to continue research towards the use of permanent GPS tracking networks for estimating tropospheric and ionospheric path delay with applications to SAR interferometry. Finally it has been demonstrated by Hanssen et al. (1999) that spaceborne SAR interferometry may also be used to infer high-resolution maps of integrated atmospheric water vapour, which can be readily related to meteorological phenomena. This opens new perspectives for local and regional operational meteorology. The proper use of airborne and spaceborne SAR systems with short repeat periods, which may become available in the future, could improve the meteorological understanding and forecasting.

The combination of GPS and InSAR observations and the development of methods for deformation analysis using different types of geodetic and geophysical data are important issues. Since INSAR-derived deformation maps provide only line-of-sight changes with (currently) poor temporal resolution GPS data from well-selected sites are needed to provide information about the three-dimensional deformation vector and to provide a continuous data record against which the SAR data can be compared.

Internal consistency and quality of the InSAR observations are currently derived from statistical variations of the phase estimates based on the S/N ratio, by empirically determined statistical variations over various test areas in the interferogram or by comparison with field measurements. Sometimes, simple atmospheric models and assumptions about residual topographic errors have been taken into account. What is still missing is a proper error propagation starting from raw or SLC data to geo-coded topography or deformation maps. A realistic quality description of InSAR-derived end products is also the basis for the optimal combination with deformation maps provided by other geodetic techniques such as GPS and terrestrial measurements. The stochastic model of the phase values should also include the atmospheric behaviour on different scales.

Applications in geo-sciences in particular for hazard monitoring still require a number of future studies. For instance, more experiences have to be gained about the degree to which temporal decorrelation limits the applicability of InSAR for various types of terrain, the expected decorrelation due to weathering, and the effects of vegetative ground cover on the topographic and deformation signature of the radar interferometer. Moreover, the studies on the phase stability of single scatters, which carry the information about the deformation in otherwise completely de-correlated interferograms should be extended to other types of man-made features and should also be extended to natural objects.

Moreover, more effort has to go into exploring the potentials of InSAR in the commercial and industrial sector, in particular the development of rapid and cost effective airborne and spaceborne mapping systems, near-real time interferometric processor development, automatic mosaicking, and mapping and feature extraction.

6. References

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