Complimentary Measurement of Geophysical Deformation using Repeat-Pass SAR

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1. ABSTRACT / INTRODUCTION

Differential radar interferometry has proven to be an excellent method to measure displacements associated with geophysical phenomena such as glacier flow, subsidence, tectonic plate motion, and earthquake displacement. Since the technique utilizes the interferometric phase, it is limited in cases where large displacements in the slant range direction result in complete decorrelation. Similarly, if the surface deformation causes rotation of the scene or other disturbance the interferometric signal will be lost.

The geophysical displacement field can also be measured via incoherent or coherent cross-correlation of small image chips. This method has the advantages that it does not require phase unwrapping In cases where there is some degree of interferometric coherence between data acquisitions, the single-look complex image speckles themselves become features that can be accurately tracked. This method is complimentary to the phase-based approach since it works well with the large displacements. Examples for the successful application of the two techniques are found in the mapping of the velocity fields of surging glaciers and displacement fields of major earthquakes. Furthermore, image cross-correlation measurements yield the two-dimensional displacement field while measurements of the phase yield deformation only along the line-of-sight. Accuracy of the cross-correlation method is dependent on the scene content, correlation, and image chip size.

2. DISPLACEMENT MEASUREMENT USING OFFSET-TRACKING PROCEDURES

Two different techniques for the estimation of the SAR image offsets are introduced in this section. Then, the conversion of the offsets to motion values is presented, followed by the error analysis. Advantages and disadvantages of the different techniques are then evaluated and also compared to differential SAR interferometry. Based on this discussion a strategy for the selection of the methodology for a specific case is developed.

Apart from general aspects, our discussion includes some implementation specific aspects that are of wider interest. Our specific implementation is part of the commercial GAMMA Software (see for example Werner et al., 2000, or http://www.gamma-rs.ch) and is therefore available to a wide user community.

2.1 Intensity tracking

The first method we describe to estimate the slant-range and azimuth registration offset fields of two SAR images is called intensity tracking, also known as feature tracking. The offset fields are generated by cross correlation of image patches of detected single-look complex (SLC) SAR images. The estimation of local image offsets depends on the presence of nearly identical features in both images, at the scale size of the patches. The location of the peak in the two-dimensional cross-correlation function yields the image offset. Apart from the precision in the determination of peak location, the estimation of a confidence level is very important. To optimize the accuracy of the peak location, over-sampling of the image patches prior to cross-correlation followed by a two-dimensional regression fit to correlation function are performed. The confidence level of each offset is estimated by comparing the height of the correlation peak relative to the average level of the correlation function to determine an effective correlation Signal-to-Noise Ratio (SNR). To optimize the efficiency and flexibility, coarse offset estimates are used to guide the search and the user can select the image patch sizes for each specific case. For the ERS SAR configuration, a nominal patch size of 64x64 SLC pixels is appropriate corresponding to 500 m in the slant-range and 250 m in azimuth.

2.2 Coherence tracking

The second method is called coherence tracking, also known as the fringe visibility algorithm. For small patches throughout the single-look complex SAR images, a series of small interferograms with changing range and azimuth offsets are calculated and by finding the peak average coherence the offset is determined. Sub-pixel accuracy is achieved by over-sampling of the SLCs and using a two-dimensional regression function to model the measured coherence function. The magnitude of the coherence maximum relative to the average level is used as a quality factor to help reject unsuitable patches. Coarse information on the slant-range and azimuth offsets is used to guide the search for the coherence maximum. Again, the image-patch size may be adapted to a specific case. Typically, patch sizes of 8x8 SLC pixels corresponding to about 60 m in the slant-range and of 30 m in azimuth direction are used with the ERS SAR data. Reliable offset estimates depend on having a minimum coherence level. For areas with very low coherence, such as observed for open water, dense vegetation, and many snow conditions, but also for other targets, especially in image pairs with long baselines or acquisition intervals, no reliable offsets can be determined by using coherence tracking.

2.3 Conversion of image offsets to displacement values

The image offsets in slant-range and azimuth directions are functions of both the satellite tracks and the displacement that occurred between SAR image acquisitions. Estimation of displacement values requires separating these two effects. Orbital offsets can be simply determined using stable reference points. Orbital offsets can be determined by fitting a regression function to the measured offsets between SLCs obtained for stable zones in the scene. After subtraction of the orbital offsets, the remaining pixel shifts in slant-range and azimuth directions are related only to the surface displacement. Given the range and azimuth pixel spacing, these offsets can be directly converted to displacements in meters.

Slant range and azimuth displacements are however insufficient to derive the full 3-dimensional displacement vector. In some cases additional assumptions can be used to further constrain the deformation such that the 3-dimensional deformation can be derived. For example, with glaciers one can assume flow parallel to the terrain surface [4]. Normally, a DEM is also required to determine the 3-dimensional deformation but in cases of low relief terrain, this requirement can also be relaxed. If such geometric restrictions are not applicable, then displacements measured from different look directions (ascending and descending passes) are required to retrieve the full 3-dimensional displacement vectors.

2.4 Error analysis

Offset estimation accuracy can be estimated from the offsets determined in stable zones of the image. The standard deviation from the regression of the offsets provides this information. Typical offset estimation errors in range and azimuth are .05 pixel. The resulting accuracy of the offset estimates in each of the directions: along the look vector, cross-track, and along-track, are summarized in Table 1. These are compared with the error in the interferometric estimates introduced by a relatively high atmospheric distortion of $\pi/2$. In the cross-track directions interferometry provides an order of magnitude improvement than what can be expected from offset-tracking procedures; but this is true only as long as decorrelation and fringe density permit reliable interpretation of the interferometric phase.

Table 1. Displacement estimation errors for ERS SAR offset-tracking (with range and azimuth offset estimation errors assumed to be 0.05 pixel) and ERS differential SAR interferometry (for an atmospheric phase distortion of $\pi/2$).

Displacement Direction	Displacement estimation error [m]	
	Offset tracking	Interferometry
slant-range	0.395	0.007
ground-range	1.011	0.018
azimuth	0.198	-

2.5 Application strategy

Intensity and coherence tracking are two complementary techniques for the estimation of the same parameters. Furthermore, the offset-tracking procedures are complementary to differential SAR interferometry. The definition of a strategy to map the surface deformation in a specific case depends on various factors, including the deformation values, the required spatial resolution and accuracy, local coherence, local image contrast, and computational issues.

By far the most accurate estimates of the displacement component in slant-range direction are obtained with differential SAR interferometry. Therefore, this method is used when applicable. The spatial resolution of the interferometric method is high. Apart from high enough local coherence, the feasibility of phase unwrapping is the most limiting constraint. Apart from low coherence areas, phase unwrapping may not be reliable for very high fringe rates as well as for disconnected patches of high coherence separated by areas of low coherence. Unlike the offset tracking methods, interferometry does not provide an estimate of the offsets in azimuth direction.

Coherence tracking is suitable for areas of high coherence. Unlike in SAR interferometry, absolute offset estimates are obtained, making it also suitable for disconnected areas of high coherence. Coherence tracking provides information on the displacements not only in slant-range direction, but also in azimuth direction. Main drawbacks are the lower accuracy, about an order of magnitude below differential SAR interferometry, and the reduced spatial resolution. Apart from the information on the offset in azimuth direction, the applicability of coherence tracking for large offsets, when interferometry fails due to problems in resolving the phase ambiguities with phase unwrapping, is a clear advantage. The computational efficiency is also a somewhat limiting factor. Long processing times are necessary to estimate the offsets for a large area at high spatial resolution.

The big advantage of intensity tracking is that it does not depend on coherence. In many cases the successful analysis of SAR image pairs with long acquisition time intervals is restricted to intensity tracking because coherence is not retained for more than a few days for large fractions of the image. This is particularly important since all the current and near future planned SAR missions (ERS-2, RADARSAT, ENVISAT and ALOS) have revisiting times of 24 days or more.

A highly recommended strategy is to use a combined technique and to determine a displacement vector based on a differential SAR interferometric estimate of the displacement component in the slant-range direction, with an offset tracking based estimate of the displacement component in the azimuth direction. This approach is less accurate than that based on differential SAR interferometry alone using dual sense acquisitions (ascending, descending), but it requires only one image pair. The accuracy of this approach is more than five times better than using offset tracking alone.

3. EXAMPLES

3.1 Surge-type glacier motion monitoring

Surge-type glaciers switch between long periods of slow flow and short periods of accelerated flow, 10-1000 times faster [1]. Sortebræ, a large tidewater-terminating glacier in East Greenland, underwent a major surge between 1992 and 1995 during which the glacier terminus advanced by nearly 10 km [2]. The surge had a rapid initiation that saw velocities increase by 60 to 1500 times and within 13 months the entire lower 50 km of the glacier was affected. Surge termination occurred very rapidly in summer and ice velocity dropped from around 20 m/day to around 2 m/day in only 3 months.

ERS-SAR data covering Sortebræ suitable for interferometry and offset tracking are only available in descending mode during the Tandem phase of ERS-1 and 2. Suitable image pairs were obtained from dates in May 1995 and January 1996 [3]. The extreme velocities during surges mean that SAR interferometry is unsuitable for mapping ice dynamics. An interferogram formed from images from 26 and 27 May 1995 (Fig. 1) showed no coherence over Sortebræ, despite good coherence on neighboring glaciers. However, tracking nearly identical intensity features at the scale of groups of pixels between two of the SAR images allowed assessment of surface displacements where relatively large displacements had occurred (see Fig. 2). The technique is considered to be accurate to within ±1.2 m/day for a 1-day repeat-delay and provides the possibility for mapping rapid ice displacement during the active phase of surging. The velocity in the main trunk was around 13 m/day and generally increased down stream showing overall extensional flow. There were large-scale variations in velocity related to the glacier's flow around bends.

By January 1996 most of Sortebræ was coherent, suggesting that the ice flow rate had fallen dramatically and that the surge had terminated. Intensity tracking showed high velocities in the range of 5 m/day only in the upper basin. In the main trunk the horizontal velocity was determined by combing SAR interferometry in slant-range direction with coherence tracking in azimuth. Fig. 3 shows velocities of around 1 m/day. Notice that dual-azimuth SAR interferometry for Sortebræ is not possible because in this area ERS SAR data were acquired in descending mode only.

3.2 Mapping of large co-seismic deformation

The Landers earthquake of 28 June 1992 (magnitude 7.3) has been extensively studied with SAR interferometry [e.g. 5]. In order to analyze this event with SAR interferometry combined with offset tracking we used the ERS-1 SAR acquisitions of 24 April 1992 and 7 August 1992. The interferogram formed with these two images very well pictured the displacement in the slant-range direction associated with this dramatic earthquake. However, the large displacement gradient and the rotation of small crustal blocks reduced the coherence near the fault and precise, quantitative information about the magnitude of the displacement could be retrieved via phase unwrapping only for the areas less affected by the earthquake (see Fig. 4). Intensity tracking permitted assessment of the displacement in the azimuth direction as well near the fault (see Fig. 5). To extend the visibility of the fault as far in the near-range as possible, SAR processing was repeated using the near-range extension recently implemented in the GAMMA software [6]. Intensity tracking in the azimuth direction is considered to be accurate to ±0.2 m, well within the range of the measured displacements. In the slant-range direction intensity tracking was not considered because the expected accuracy of ±0.4 m is of the same order as the displacement component observed in this direction with SAR interferometry.

4. CONCLUSIONS

Intensity and coherence tracking have been presented as complementary techniques for the measurement of land surface deformation with repeat-orbit satellite SAR data. The tracking methods were found to be about one order of magnitude less accurate in the measurement of the interferometrically determined displacement component in the radar look direction. Advantages of the tracking techniques are the higher robustness for large displacements and the ability to simultaneously measure the slant range and azimuth deformation components.

5. ACKNOWLEDGEMENTS

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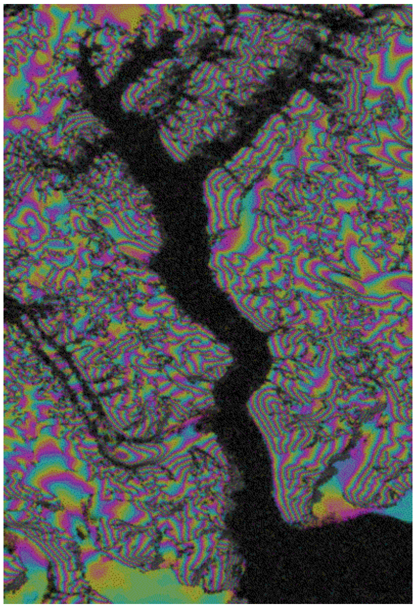

Fig. 1. ERS Tandem interferogram of Sortebræ for May 1995. Image is 40 km x 60 km. Perpendicular component of the baseline is -47 m. Look direction is from East-South-East.

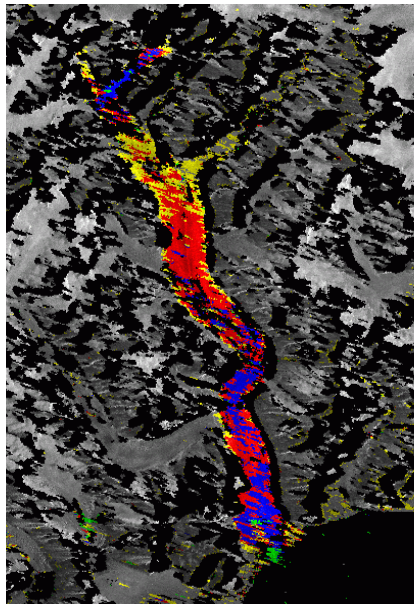

Fig. 2. Horizontal displacement from intensity tracking in May 1995. Green >20 m/day, blue 15-20 m/day, red 10-15 m/day, yellow 5-10 m/day, grey <5 m/day, black no data.

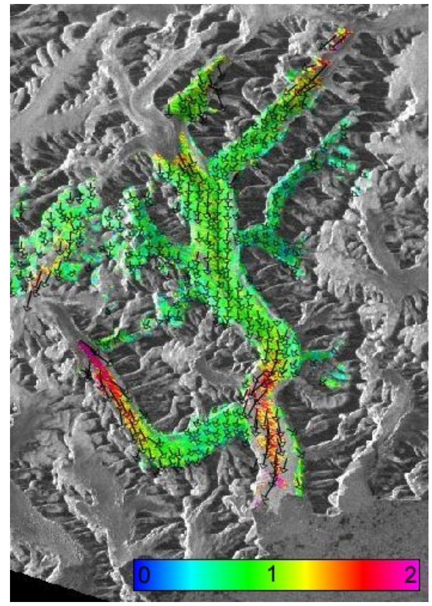

Fig. 3. Horizontal displacement (in m/day) from SAR interferometry in slant-range direction and coherence tracking in azimuth direction in January 1996.

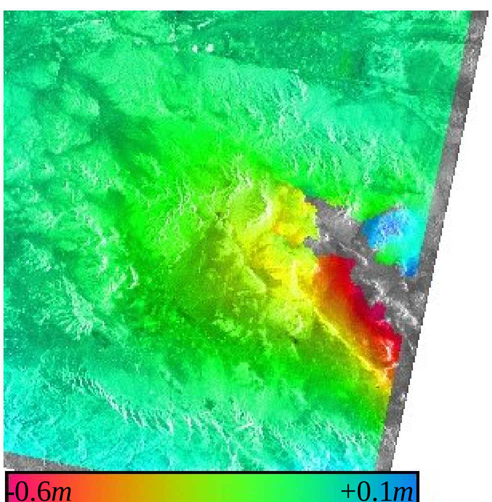

Fig. 4. Displacement map in the slant-range direction (elevation angle 67°) associated with the Landers earthquake of June 1992 from SAR interferometry.

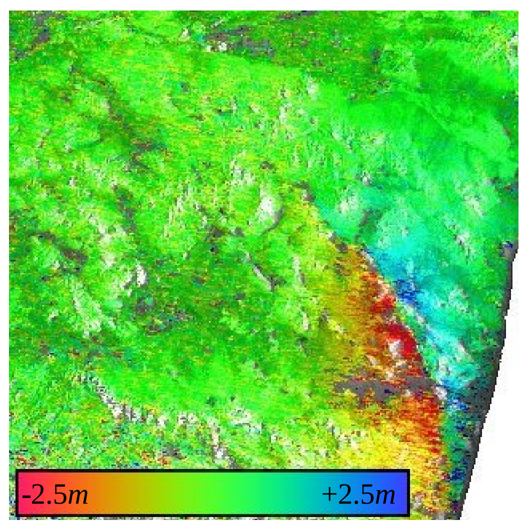

Fig. 5. Displacement map in the azimuth direction associated with the Landers earthquake of June 1992 from intensity tracking. Image is 80 km x 80 km.