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The Added-Value of TOPSAR Coherence Tracking for Sentinel-1 Interferometry Over Ice Shelves

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Abstract

Feature tracking has long been used as a technique to infer bidimensional displacement maps by locally maximizing the incoherent or coherent cross correlation of coregistered SAR images. Coherence tracking is based on the latter technique. Exploiting the phase information, the method tends to find local shifts that maximize the coherence information aiming at enhancing the interferometric signal while also bringing an estimation of bidimensional displacements. This is particularly important in fast-moving areas since it allows recovering an interferometric signal loss due to displacement-induced decorrelations. Here, we present the adaptation of the technique to TOPSAR acquisition mode and results in Antarctica.

1 Introduction

Differential SAR Interferometry (DInSAR) is a well-established technique that takes advantage of phase measurement difference between two SAR images acquired at two different dates to infer line of sight displacements [1]. SAR Earth observation satellites are using polar heliosynchronous orbits. Consequently, DInSAR allows getting primarily the East-West displacement component of horizontal displacements.

In Antarctica however, we observe that the main component of the ice flow goes Northward, following mainly the azimuth direction of SAR observations. Therefore, using DInSAR, displacements in this direction are poorly captured. Another problem concerns local misregistrations due to non-stationary scenarios in which local displacement may prevent global coregistration, leading to artificial local losses of coherence. This is particularly true in the case of ice streams or ice shelves where pixel-size misregistrations are common. To solve the first issue and estimate azimuth displacements one can use image matching techniques such as feature tracking. As an example, [2] used feature tracking to obtain velocity maps on the whole Antarctica.

Feature tracking comes in complement or in replacement to differential SAR interferometry to get an estimation of azimuth displacements and/or to get an estimate of range displacements when coherence losses do not allow to generate a usable interferometric signal. When feature tracking is performed using only the amplitude of SAR images, we talk about incoherent speckle tracking. In that case, we consider the feature to be tracked from one image to another. Feature tracking can be based on fringe visibility or maximization of local coherence, in which case it is called coherent speckle tracking [3].

We can go one step further when estimating and optimizing the local complex coherence, by directly exploiting the phase information, in order to also get the optimized tracked interferometric phase information at the given position [4, 5]. In this approach, using directly coherence estimation as the tracking criterion, we can retrieve bidimensional displacement maps, similar to coherent speckle tracking, but also recover the interferometric signal for precise estimations of slant-range displacements. Considering the high temporal decorrelation rate over fast-moving areas, tracking the ground scatterers are crucial for interferometric studies. In addition, range shifts can also help in assisting the phase unwrapping of the tracked interferometric signal for fine estimation of range displacements. The estimation of bidimensional displacements does not a require special care for the TOPSAR acquisition mode. However, the reconstructed interferometric signal requires a special attention to the azimuthal phase ramp inherent to this particular acquisition more.

In the following, we present coherence tracking technique adapted to the Sentinel-1 TOPSAR acquisition mode and show the results obtained in the context of ice-shelves displacement measurements in East Antarctica.

2 Method

2.1 TOPSAR Mode Specificity

If coherence tracking was demonstrated using Stripmap SAR acquisition mode such as ERS data [4, 5], Terrain Observation by Progressive Scans (TOPSAR) mode requires some preliminary steps to make coherence tracking applicable.

TOPSAR uses reverse beam steering to decrease aperture synthesis time for a given on-ground azimuth distance. The image formed on this distance is called a burst. Decreasing the required acquisition time, it allows to switch the beam to consecutive swaths and globally extend the observed cross track at the expense of azimuth resolution loss [6].

This reverse beam steering induces a variable Doppler centroid frequency along the azimuth dimension of the burst. Consequently, each burst contains an azimuth phase ramp that must be considered all along the interferometric processing [7].

Summarizing, slave image bursts must be moved to azimuth base-band (deramping) to allow interpolation of the data in the coregistration process. Following [8], this deramping process must be followed by a reramping process after burst interpolation in such a way that master and slave burst phase ramps coincide in order to cancel out in the interferometric process.

These deramping and reramping operations are applied as such in any TOPSAR interferometric processor. Consequently, after the coregistration process, one has coregistered master and slave images, still bearing this typical TOPSAR phase ramp.

If willing to fully exploit the interferometric signal, coherence tracking applied to a TOPSAR coregistered interferometric pair requires a full removal of this phase ramp from both the master and slave bursts [9]. While this step is not necessary for bidimensional displacement estimation [11], not removing this phase ramp produce a phase bias in the tracked interferogram. Indeed the additional azimuth shifts we are tracking lead to a misregistration of TOPSAR phase ramps that do not fully cancel out in the interferometric process, inducing an additional azimuthal phase difference between the master and slave images that depends on the additional azimuth shift amplitude.

2.2 Coherence Tracking

Coherence tracking is an original adaptation of the coherent speckle tracking method [5]. The basic idea is that large surface displacements will create an artificial coherence loss. Consequently, tracking coherence at pixel level allows recovering the interferometric phase information, while also determining an estimation of the bidimensional velocity field.

Similar to coherent speckle tracking, the goal of coherence tracking is to find where scatterers moved by locally performing fine coregistration using coherence maximization criteria. The local coherence is classically estimated using equation

$$\hat{\gamma}(s_1(x,y),s_2(x,y)) = \frac{\left|\sum_{(x,y)\in n} s_1(x,y)\cdot s_2^*(x,y)\right|}{\sqrt{\sum_{(x,y)\in n}|s_1(x,y)|^2\cdot\sum_{(x,y)\in n}|s_2(x,y)|^2}} \tag{1}$$

where n is a neighborhood around the (x,y) target location. We find the (i,j) pixel shift that maximizes local coherence by

$$(i,j) = \arg\max_{(i,j)}\{\hat{\gamma}(s_1(x,y),s_2(x+i,y+j))\} \tag{2}$$

Around this pixel shift position, we take the estimated coherence at the four-connected neighbors with which we perform a Gaussian fitting. Its maximum gives us a subpixel estimate of the local bidimensional displacement.

This simple technique enables us to find directly a bidimensional displacement (in terms of sub-pixels shifts) but also to retrieve the misregistered pixel for interferometry.

In fast-moving areas, we can use this shift to find in the slave image the *true* corresponding scatterers for interferometry. Such interferogram correction was originally applied to the Shirase glacier to infer the surface velocity field [4].

In addition, the estimation of range shifts from equation 2 helps in the unwrapping process, by giving a prior information of the integer phase cycle shift determination for each pixel in the interferometric phase, but also giving the global phase shift to match range displacement determined by range offset tracking.

3 Results

In the frame of the MIMO project (Monitoring melt where Ice Meets Ocean), we are re-developing and adapting the coherence tracking technique to the Sentinel-1 TOPSAR to perform surface velocity field measurements on the Roi Baudouin Ice Shelf, in Dronning Maud Land, Antarctica (figure 1).

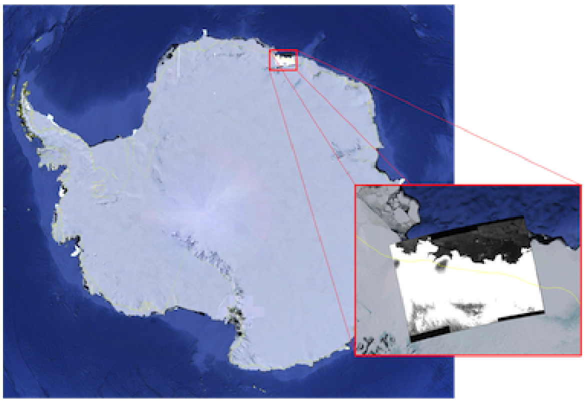

Figure 1 Roi Baudouin Ice Shelf, Dronning Maud land, Antarctica. The vignette represents a scaled-up illustration of the SAR amplitude image.

We present here preliminary coherence tracking results obtained using a Sentinel-1 TOPSAR pair in Interferometric Wide swath mode acquired on September 23 and October 5, 2017, along the relative orbit 59 over our area of interest. Both Sentinel-1 images were first coregistered using precise orbits and a DEM. At the end of the coregistration process, both the master and the slave images are deramped before debursting, leading finally to two stripmap-like images.

Coherence tracking was performed using 7×7 pixels windows on a 2×6 (azimuth × range) grid of anchor points for local coherence estimation. Tracking is performed from -3 to +3 pixels from the initial coregistration values in both

Figure 2 Coherence tracking results:
Background: Coherence image obtained after global images coregistration.
A & B: coherence before and after tracking on sub-zone delineating fast-flowing ice stream
H1 & H2 coherence histograms before and after tracking on a limited zone on fast-flowing ice stream. The coherence on this fast-moving ice stream is greatly improved, from 0.4 on average before tracking, to 0.8 after coherence tracking.

range and azimuth to map the local coherence.
Optimum coherence is found through a Gaussian fitting of the obtained coherence mapping.
Four main products are generated:

- the tracked coherence;
- the tracked interferogram;
- the range local displacements (with respect to initial coregistration);
- the azimuth local displacements (with respect to initial coregistration).

Figure 2 illustrates coherence improvements. The background image is the coherence obtained classically, coregistrating the Sentinel-1 pair based on precise orbits calculation. Red rectangles A and B show ice stream coherence before and after tracking. The histograms of sub-zones H1 and H2 are shown on the right. This shows clearly that coherence losses were due to local misregistration in this fast-moving area.
Improvement of fringes visibility on the fast-flowing ice stream is clearly shown on full resolution samples interferograms before and after tracking in figure 3. The signal was originally barely distinguishable whereas the tracked interferogram one enables us to infer precise displacement fields at the fastest parts of the shelf. This gain is visible through the coherence in figure 4.
The two last products derived from coherence tracking, i.e., range and azimuth local displacements with respect to global registration, may be represented as such in pixel unit (figure 5) or as vectorial representation (figure 6). Figure

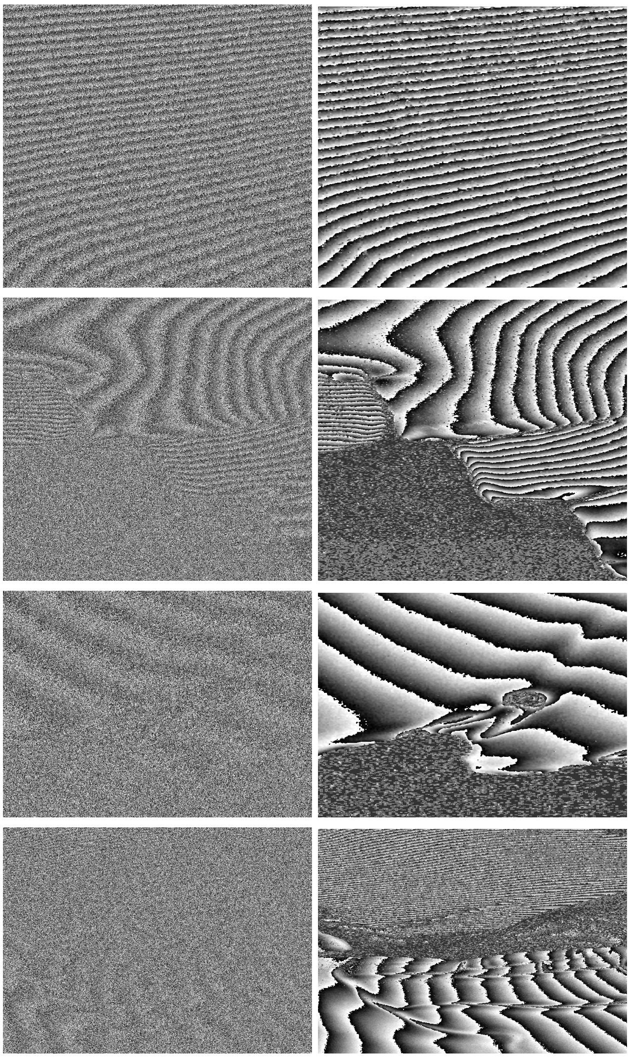

Figure 3 Full resolution, slant-range / azimuth geometry, sample interferograms before (left) and after tracking (right).

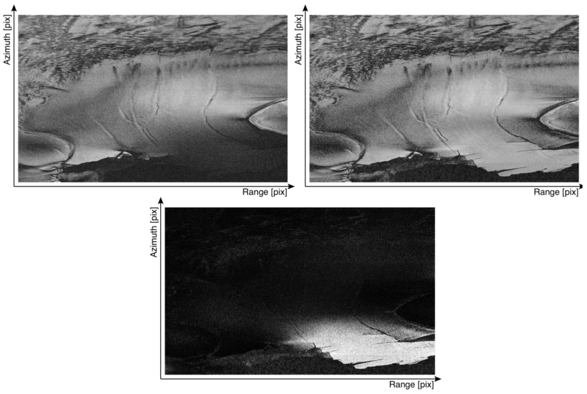

Figure 4 Full resolution, slant-range / azimuth geometry, coherence samples. Left = original coherence. Right = Coherence derived after tracking. Bottom = coherence gain/recovery (white represents a 0.5 gain).

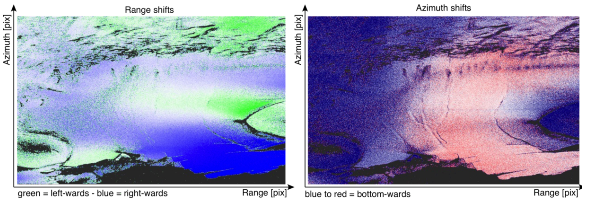

Figure 5 Full resolution, slant-range / azimuth geometry, range (left) and azimuth (right) shifts.

6 is an HSI-like representation of the tracked results with superimposed vectorial representation. The amplitude of the computed displacement, in meters, is used for the Hue channel, which is associated with the lookup table shown on the figure. The tracked coherence is used for the Saturation channel and the log of the amplitude of the master image is used for the Intensity channel. In this representation, the full surface velocity field is well delineated. We observe the Ragnhild ice stream deviates and passes on the left side of the Derwael Ice Rise. A smaller part of the ice stream is passing on the right side. The maximum displacement amplitude as measured by tracking is about 12 meters while the time lapse between acquisitions is 12 days.

4 Conclusion

Coherence tracking is shown to be applicable to Sentinel-1 TOPSAR acquisition mode. The results are impressive in terms of coherence gain, as well as in interferometric signal recovery. On the one hand, similar to coherent speckle tracking techniques, coherence tracking is able to retrieve the 2D-shifts at coarse level and, on the other hand, it also corrects the interferogram to get highly accurate range displacements.

Moreover, these products are computed where classical methods do not allow to use interferometry, because of the fast-moving nature of the surface. The 6-days revisit time of Sentinel-1 pairs is often considered too large for interferometry in the boundaries of the Antarctic Ice Sheet. Over these ice shelves, coherence tracking may offer a promising solution, pushing forward the boundary between the applicability of offset tracking techniques to SAR interferometry.

5 Acknowledgment

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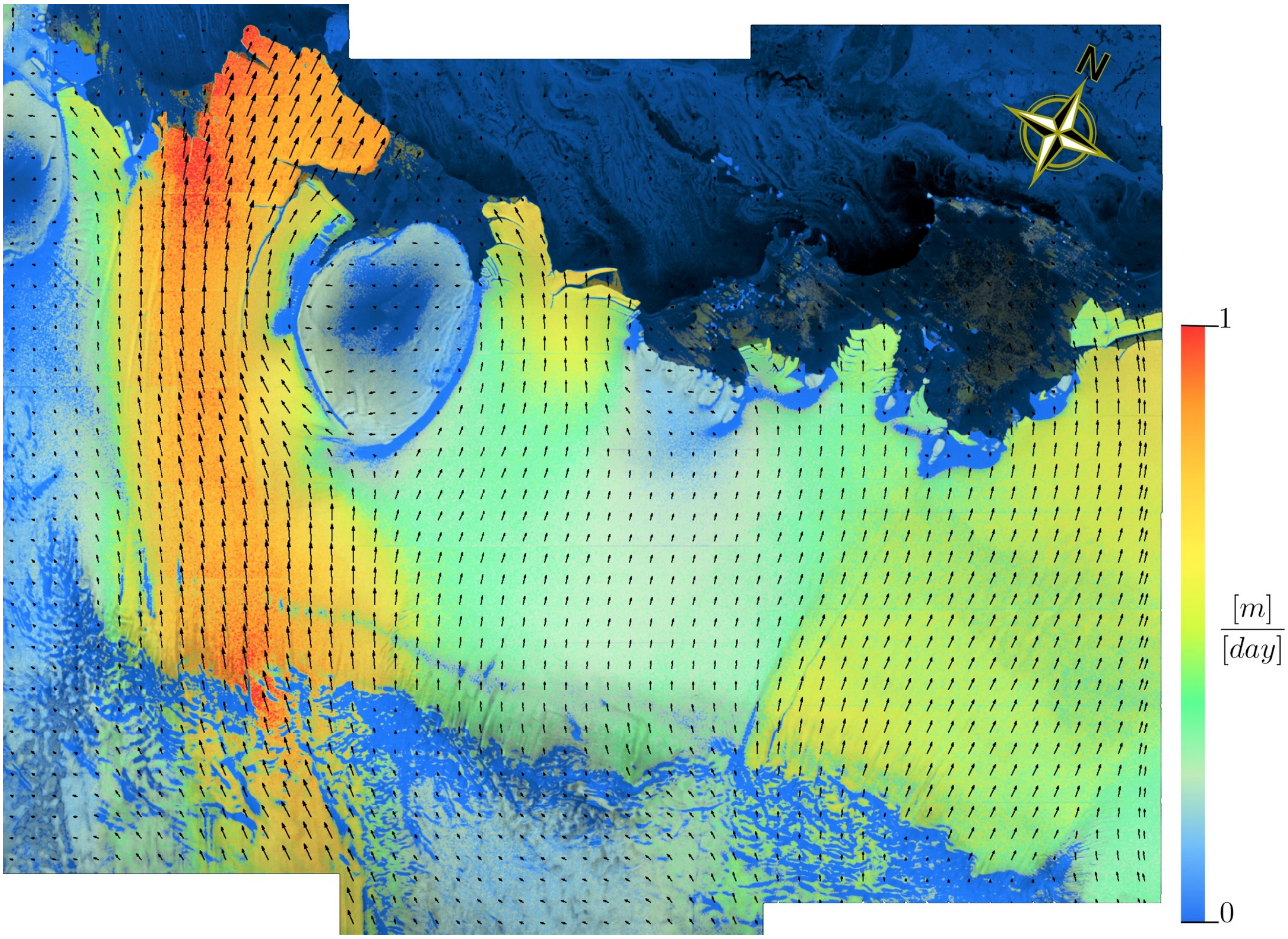

Figure 6 Combine representation of coherence tracking results. Hue = Displacement amplitude - Saturation = Tracked coherence - Intensity = log of master amplitude.