ScanSAR interferometric processing using existing standard InSAR software for measuring large scale land deformation

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ABSTRACT

Scanning synthetic aperture radar (ScanSAR) mode is an efficient way to map large scale geophysical phenomena at low cost. The work presented in this paper is dedicated to ScanSAR interferometric processing and its implementation by making full use of existing standard interferometric synthetic aperture radar (InSAR) software. We first discuss the properties of the ScanSAR signal and its phase-preserved focusing using the full aperture algorithm in terms of interferometry. Then a complete interferometric processing flow is proposed. The standard ScanSAR product is decoded subswath by subswath with burst gaps padded with zero-pulses, followed by a Doppler centroid frequency estimation for each subswath and a polynomial fit of all of the subswaths for the whole scene. The burst synchronization of the interferometric pair is then calculated, and only the synchronized pulses are kept for further interferometric processing. After the complex conjugate multiplication of the interferometric pair, the residual non-integer pulse repetition interval (PRI) part between adjacent bursts caused by zero padding is compensated by resampling using a sinc kernel. The subswath interferograms are then mosaicked, in which a method is proposed to remove the subswath discontinuities in the overlap area. Then the following interferometric processing goes back to the traditional stripmap processing flow. A processor written with C and Fortran languages and controlled by Perl scripts is developed to implement these algorithms and processing flow based on the JPL/Caltech Repeat Orbit Interferometry Package (ROI_PAC). Finally, we use the processor to process ScanSAR data from the Envisat and ALOS satellites and obtain large scale deformation maps in the radar line-of-sight (LOS) direction.

1. Introduction

InSAR has developed fast over the past several decades and gradually been adopted as one of the effective approaches to investigate geophysical and geomatic problems. Traditional stripmap mode synthetic aperture radar (SAR) data was the only data source utilized in InSAR in the past and remains the most commonly used data type. One of the inherent limitations of stripmap SAR is that its range swath is quite limited (~100 km), which has affected the use of InSAR for large scale geophysical studies. Since the full azimuth spectrum is not required in the signal processing to form a continuous image, it can be divided into several parts to image several subswaths at different incidence angles. This operation mode of SAR is usually referred to as ‘ScanSAR’ which has an overall swath width several times larger than that of stripmap mode from integrating several subswaths. ScanSAR data can also be focused with its phase preserved and therefore can be applied to SAR interferometry (Monti Guarnieri et al., 1994). The main advantages of ScanSAR interferometry are: (1) ScanSAR interferometry can obtain large scale geophysical information such as land deformation and topography using only one interferometric pair. For instance, typical Envisat ScanSAR mode has a swath width of 405 km, about 4 times of that of stripmap mode. (2) In order to obtain a deformation map over a large area, several tracks should be stitched together if stripmap data is used, which may cause discontinuities in the edges of tracks due to various internal and external factors affecting interferometric phase. On the other hand, ScanSAR interferometry can generate much more consistent deformation in the range direction. Of course, as a tradeoff, there is a significant variation in the LOS angle across a ScanSAR interferogram which would lead to interpretation difficulties. (3) Both the SAR operational facilities and users can benefit from the efficiency of ScanSAR. With ScanSAR, more areas can be imaged in the same amount of time, which can possibly meet the needs of more users. Otherwise, order conflicts may happen more frequently. Besides, ScanSAR uses less power to cover the same area than stripmap mode, which is of great importance for an active instrument. (4) Much more
computation and memory would be saved if ScanSAR interferometry, rather than stripmap interferometry, were adopted. Application of ScanSAR interferometry in the research of Wenchuan earthquake can be viewed as a good example to see the advantages of ScanSAR interferometry (Liang et al., 2009; Tong et al., 2010). However, most of the InSAR researches of this event were still based on stripmap acquisitions (Shen et al., 2009; Furuya et al., 2010), which is more expensive due to the use of large amount of datasets. ScanSAR interferometry, on the other hand, can map the deformation caused by this earthquake using a single interferometric pair from only one track.

Although ScanSAR has these advantages, few commercial or freely available InSAR software packages (only SARscape, Gamma and GMTSR (Sandwell et al., 2011), as far as the authors know) are capable of processing ScanSAR data for interferometric applications, implying that an easy implementation of ScanSAR interferometry is needed in order to promote the application of ScanSAR interferometry in the geophysical community. Furthermore, after the launch of the Canadian Radarsat-1 satellite that can operate in ScanSAR mode in November 1995, nearly all of the subsequent satellites carrying SAR instruments, such as Envisat, ALOS, Radarsat-2, TerraSAR-X and COSMO-SkyMed, have been able to provide ScanSAR products, accumulating a large amount of ScanSAR datasets available for interferometry. The exploitation of the potential of these datasets in terms of interferometry for geophysical purpose is the motivation of this study.

We have developed a way to implement ScanSAR interferometry, and we will discuss ScanSAR interferometry mainly in three aspects: (1) Analyze the raw burst data focusing using the full aperture algorithm (Bamler and Eineder, 1996) with emphasis on the use for interferometry. (2) Develop the full processing chain of ScanSAR interferometry for land surface deformation monitoring, which can be easily implemented based on the available stripmap InSAR software. Some techniques are also proposed to overcome problems such as Doppler centroid frequency estimation and subswath integration. (3) Write computer programs using C, Fortran and Perl to implement the processing flow based on the publicly available interferometric package ROI_PAC. Finally, the ScanSAR interferometric processor is used to process ScanSAR data from the Envisat and ALOS satellites to obtain large scale land deformation maps.

2. Focusing of ScanSAR signal for interferometry

In ScanSAR mode, the SAR antenna transmits and receives pulse sequences cyclically in each subswath. The pulse sequence is referred to as a ‘burst’ that typically consists of dozens to hundreds of pulses. The gap between adjacent bursts is usually much longer than the burst, consisting of hundreds of pulses. Since the general characteristics of each subswath are the same, only one subswath is considered in the following discussion that will apply to other subswhaths.

The way of data collecting in ScanSAR mode and the signal properties of ScanSAR can be represented in Fig. 1. Suppose that $T_b$, $T_p$ and $\eta_{\text{shift}}$ are the burst duration, burst repeat cycle and the time difference between burst center and zero Doppler time for a single point target, which is illustrated in Fig. 1(b). During the burst period $T_b$, the ScanSAR signal is the same as that of stripmap mode, whilst during the burst gap $T_p-T_b$, the SAR antenna does not transmit signal in this subswath. The alignment of bursts and burst gaps can be expressed as

$$w_b(t) = \text{rect} \left( \frac{t - \eta_{p}}{T_b} \right) \otimes \text{III} \left( \frac{t - \eta_{p} - \eta_{\text{shift}}}{T_p} \right)$$  \hspace{1cm} (1)$$

where $\otimes$ denotes convolution and $\text{III}(t)$ is an impulse sequence

$$\text{III}(t) = \sum_{n=-\infty}^{\infty} \delta(t-n).$$  \hspace{1cm} (2)$$

For a point target, the ScanSAR signal is then equivalent to the product of window (1) and stripmap signal that can be modeled as (Cumming and Wong, 2005)

$$s_0(t,\eta) = A_0 w_b(t) \left( \frac{2R(n)}{c} \right) w_d(\eta, -\eta_p) \exp \left\{ -\frac{4\pi R(n)}{\lambda} \right\} \times \exp \left\{ j\pi K_\eta \left( \frac{2R(n)}{c} \right)^2 \right\}$$  \hspace{1cm} (3)$$

where $A_0$ is an arbitrary complex constant, $c$ is the speed of light, $\lambda$ is the radar wavelength, $\tau$ is the fast time, $\eta$ is the slow time referenced to closest approach, $\eta_p$ is the beam center offset time, $w_b(t)$ is the range envelope (a rectangular function), $w_d(\eta)$ is the azimuth envelope (a sinc-squared function), $K_\eta$ is the range chirp FM-rate, and $R(n)$ is the instantaneous slant range. Considering (1) and (3), the received ScanSAR signal is

$$s_0(t,\eta) = A_0 w_b(t) \left( \frac{2R(n)}{c} \right) w_d(\eta, -\eta_p) w_\eta(\eta) \exp \left\{ -\frac{4\pi R(n)}{\lambda} \right\} \times \exp \left\{ j\pi K_\eta \left( \frac{2R(n)}{c} \right)^2 \right\}.$$  \hspace{1cm} (4)$$

The most efficient way to focus (4) is the SPECtral ANalysis (SPECAN) algorithm (Sack et al., 1985; Thompson et al., 1994) and its variants, such as the modified SPECAN algorithm (Lanari et al., 1998) and the extended chirp scaling (ECS) algorithm (Moreira et al., 1996). These algorithms will focus ScanSAR data burst by burst, but the interferometric processing based on these algorithms is not easy to be incorporated into the traditional stripmap InSAR software, because the geometrical and spectral properties of the image processed in this way are quite different from that of stripmap mode image. On the other hand, the full aperture algorithm (Bamler and Eineder, 1996) is inherently consistent with the traditional software in nearly all aspects. Existing robust programs in the traditional software can be applied to ScanSAR data without modifications. Therefore, the full aperture algorithm is adopted to focus the ScanSAR data.

In order to focus the ScanSAR data using the full aperture algorithm, the gaps between burst must be padded with zeroes. The focused image properties are similar to those of stripmap mode except for the low azimuth resolution, as well as the spikes in the sinc envelop. The spikes are caused by the inverse Fourier transform of (1), which is a sinc function multiplied by an impulse sequence representing the spikes. Although the interferogram will also be affected, subsequent azimuth averaging of adjacent interferogram samples will solve this problem (Holzner and Bamler, 2002). Due to the fact that each target on the ground will be illuminated by different parts of the antenna beam, the focused image will show an azimuth scalloping pattern. This effect can be removed by weighting the azimuth spectrum according to the azimuth antenna pattern. The phase at the peak of the focused point target is preserved, while at the other positions it is a superposition of phase from all of the bursts of this target. However, this phase preserving property can meet the needs of interferometry. In fact, nearly all of the existing focusing algorithms only preserve phase at the peak of the focused point target because of non-zero Doppler centroid frequencies or unequal length of the matched filter and target spectra. The phase at the peak of the focused target is usually matched to the slant range of the beam center, rather than the range of closest approach for interferometric processing. In the range cell migration correction (RCMC), the curved target loci are also interpolated to this range InSAR software packages that
implement all of their processing in a squinted geometry such as ROI_PAC (Rosen and Persaud, 2000, supplied with the ROI_PAC software and based largely on a chapter of the Buckley (2000) thesis). In addition, some InSAR software also processes the interferometric pair to the same Doppler in order to simplify the processing and improve accuracy. Nevertheless, most of these considerations will not lead to any additional development work, as the full aperture algorithm combined with any InSAR software will inherently accommodate these aspects, which is one of the main advantages of the full aperture algorithm.

3. Implementation of ScanSAR interferometry

The processing steps are summarized in Fig. 2. We first process each subswath individually until the generation of subswath interferograms and other interferometric products such as coherence maps, and then all of the subswaths are integrated to form the whole scene, after which the interferometric processing can proceed like the traditional stripmap mode. Some key steps in the processing are explained in the following subsections.

3.1. Raw data conditioning and Doppler centroid frequency estimation

This is the first step of the processing. Normally, raw echoes of all the subswaths are stored in a single formatted file arranged by receiving time. Therefore, raw data of each subswath should be extracted from this file in order to form subswath images and stored in an individual file. To meet the need of full aperture focusing, burst gaps of each subswath should be padded with zeros, and the number of zero-lines to be padded between burst \( i \) and \( i + 1 \) can be calculated as follows

\[
N_i = \text{round} \left( \frac{e_i - e_{i-1}}{\text{PRI}} \right)
\]

where \( e_i \) is the start time of burst \( i \) and \( e_{i-1} \) is the end time of burst \( i - 1 \). Note that, although the time span of burst gap is invariant, it is not integer multiples of PRI in most of the cases, implying that burst \( i \) will be shifted within 1/2 PRI after the zero padding, which will introduce phase errors. However, this error is negligible since the azimuth sampling grid of the image is very small, compared with the azimuth resolution (Bamler and Eineder, 1996). Here, we adopt a constant number of zero-lines, so the accumulating shifting effect will cause misalignment between subswaths. This problem is discussed in Section 3.4. On the other hand, padding zeros with a dithering method may avoid the problem. For example, if the time span is 201.5 times the PRI, we can alternate adding 201 and 202 pulses between bursts. However, this method will easily cause significant local misregistrations between the master and slave images, and therefore it is not adopted.

After the separation of subswaths, auxiliary data such as ephemeris, should also be extracted or interpolated for the scene. Then the Doppler centroid frequency of each subswath is estimated. Madsen (1989) has developed a time-domain algorithm that is still appropriate to the burst data for Doppler centroid frequency estimation. Madsen’s algorithm is first applied to each subswath to get the Doppler centroid frequency, and then the estimated values of all the subswaths, rather than a single subswath, are fitted to a quadratic or linear polynomial. This is very important to the subsequent differential processing for the whole scene, because the Doppler centroid frequency is geometrically related to the squint of the radar and therefore will be fundamental in the determination of the ground location of image samples. Furthermore, the unification of subswath Doppler centroid frequency also removes the regional geometrical inconsistency between adjacent subswaths, and therefore the
subswath mosaicking can be completed with pure resampling. An example of the estimated values and the fitted quadratic polynomial for all the subswaths of an Envisat advanced synthetic aperture radar (ASAR) wide swath (WS) mode scene is shown in Fig. 3.

3.2. Burst synchronization calculation and unsynchronized signal removal

In ScanSAR mode, the spectrum of a point target in a burst only holds a quite limited part of the full Doppler spectrum, and the location of the spectrum is not fixed. Interferometry requires that the spectrum of the pair must share as much common bandwidth as possible, meaning that the spectra of the master and slave bursts must overlap, which is referred to as ‘burst synchronization’. The unsynchronized signal representing non-overlapping parts of the spectra should always be removed because they will contribute to the noise, rather than the resolution of the interferogram.

Holzner and Bamler (2002) proposed a method which calculates the azimuth mutual offset of the interferometric pair and eliminates the unsynchronized raw data after aligning the pair according to the offset. This method is less efficient because we have to focus a small part of the bursts and coregister them in order to get the azimuth mutual offset. Since the orbit data of recently launched instruments is relatively precise, e.g., the Envisat ASAR orbit data can reach an accuracy that is on the order of several centimeters (ESA, 2011), the TerraSAR-X instrument also provides state vectors with errors less than 10 cm (Yoon et al., 2009); we calculate the burst synchronization using these satellite state vectors which are shown to be reliable.

After burst synchronization is calculated, the raw master and slave bursts are aligned in the azimuth direction, and the non-overlapping pulses containing unsynchronized signal are discarded. If there is no synchronization between the bursts, we are forced to give up on forming an interferogram at this stage.

3.3. Subswath mosaicking and smoothing

In Section 3.1, the Doppler centroid frequencies of all the subswaths are fitted with a polynomial, and the azimuth geometry of the focused subswath images will be consistent with this geometry. In addition, radar is a ranging system, and therefore the slant range geometry is already determined when the data are acquired. Therefore, both the azimuth and range geometrical relations are known, which can be used for subswath mosaicking directly. In particular, all of the current ScanSAR systems have certain overlaps between subswaths. These overlap samples, together with the geometrical relations between subswaths, can serve as the foundation of subswath mosaicking and smoothing.

To our experience, nearly no phase bias exists between the adjacent subswath interferograms after the aforementioned processing with the Envisat ASAR and ALOS Phased Array Type L-band Synthetic Aperture Radar (PALSAR) data, so there is no need to adjust the bias as done by Holzner and Bamler (2002). This can be clearly seen in Fig. 4 that shows the differential phase in the overlap area of subswath 4 and 5 of an ALOS PALSAR WB1 interferometric pair.
(ScanSAR mode, Burst mode 1) mode pair. However, in order to carefully process the data and remove the tiny phase differences, we propose an overlap area smoothing method that can effectively remove the differences in time domain using pixels of both of the adjacent subswaths in the overlap area.

Suppose that the overlap width is \(n\) samples, as illustrated in Fig. 5, and the corresponding lines of subswath 1 and subswath 2 are S1 and S2, respectively. Here, we assume that the sample value represents the center of the sample, and the smoothed value of sample \(i\) in the overlap line is given by:

\[
\begin{align*}
\text{re}_i &= \frac{(n-i+0.5) \cdot \text{re}_{S1}^i + (i-0.5) \cdot \text{re}_{S2}^i}{n} \\
\text{im}_i &= \frac{(n-i+0.5) \cdot \text{im}_{S1}^i + (i-0.5) \cdot \text{im}_{S2}^i}{n}
\end{align*}
\]

(6)

where \(\text{re}_{S1}^i\) and \(\text{im}_{S1}^i\) are the real and imaginary part of the \(i\)th sample in the overlap region of subswath 1, respectively, and \(\text{re}_{S2}^i\) and \(\text{im}_{S2}^i\) are the real and imaginary part of the \(i\)th sample in the overlap region of subswath 2, respectively.

In practice, however, because of the difference of the amplitude between two subswaths, (6) cannot be used directly. So the ratio of their amplitudes is computed

\[
\frac{\text{amp}_{S1}^i}{\text{amp}_{S2}^i} = \sqrt{\frac{(\text{re}_{S1}^i)^2 + (\text{im}_{S1}^i)^2}{(\text{re}_{S2}^i)^2 + (\text{im}_{S2}^i)^2}}
\]

(7)

This ratio is then used to remove the impact of amplitude difference. Considering this, the value of sample \(i\) is

\[
\begin{align*}
\text{re}_i &= \frac{(n-i+0.5) \cdot \text{re}_{S1}^i + r_i \cdot (i-0.5) \cdot \text{re}_{S2}^i}{n} \\
\text{im}_i &= \frac{(n-i+0.5) \cdot \text{im}_{S1}^i + r_i \cdot (i-0.5) \cdot \text{im}_{S2}^i}{n}
\end{align*}
\]

(8)

The width of the overlap area has been proved to be enough to effectively perform overlap area smoothing in our experience.

As samples of both of the adjacent subswaths are used to determine the final sample, the precision of the interferogram is much improved in the overlap area. If the sample is closer to subswath 1, then the sample of subswath 1 is given greater weight in the calculation, and vice versa. A comparison between interferograms before and after smoothing using ALOS PALSAR WB1 mode flattened interferograms is shown in Fig. 6.

In our implementation, the overlap area smoothing method is incorporated into the interferogram mosaicking program in order to save computation, rather than implemented seperately.

3.4. Compensation for non-integer PRI part of burst gap

As we have mentioned in Section 3.1, normally the time span of the burst gap is not integer multiples of the PRI. Although it will not severely affect the quality of the image, this difference should be properly dealt with because the accumulation of this effect will not only stretch the image with the increasing number of burst gaps, but also lead to misregistrations between subswaths. For example, there are about 320 burst gaps (or bursts) in subswath 1 of an Envisat ASAR WS scene, and the burst gaps are stretched by 0.48 or 0.50 times the PRI after zero padding. In this case, there will be about 155 additional lines after zero padding, which will cause a significant shift in the image.

To compensate for this effect, we use a sinc kernel weighted by a Kaiser window to resample the subswaths. This operation will distribute the jump between burst and burst gap over all of the burst cycle equally, and the error caused by the jump can then be neglected.

\[
\pi
\]

Fig. 5. Overlap area smoothing for one line in the range direction. The grids in the middle line represent the smoothed samples in the overlap area.

Fig. 6. (a) is the mosaicked interferogram after overlap area smoothing. (c) and (d) are interferograms before and after smoothing, respectively. (b) and (e) are the corresponding profiles of the corresponding horizontal lines in (c) and (d). To better illustrate the trend of the profiles, the interferograms are filtered by the power spectrum filter (Goldstein and Werner, 1998) before the profiles are depicted. Note that the differences between subswaths are exaggerated by means of applying slightly different flattening parameters in order to show the effect of this method.
3.5. Differential SAR interferometry

Nowadays, the most important application of SAR interferometry is measuring the deformation of the Earth’s surface after removing the topographic phase from the interferogram. After mosaicking all of the subswaths, topographic phase simulated from a digital elevation model (DEM), together with orbital fringe, is subtracted from the interferogram. The InSAR observation geometry must be modeled precisely in order to accommodate the large scale ScanSAR case. The SCH coordinate system has been proved to be an advantageous coordinate system for interferometric processing of stripmap SAR (Madsen et al., 1997). Here, it is also applied to ScanSAR, and it shows excellent performance.

4. Integration of ScanSAR processor and ROI_PAC

ROI_PAC, developed at Jet Propulsion Laboratory, California Institute of Technology, has been freely available to scientific community since 2000 (Rosen and Fielding, 2011). The current version of ROI_PAC (3.0.1) supports ERS-1, ERS-2, JERS, Envisat and ALOS data, and is configurable to work with stripmap mode data from all existing satellite radar instruments. ROI_PAC implements its fundamental algorithms in C and Fortran 90 and drives each executable module with a Perl control script, running on SGI, Sun, Mac OS X, and Linux platforms. ROI_PAC is a freely available package and widely used by the researchers in the field of geophysics, which is the main reason why we choose it.

The style of our ScanSAR processor is in accordance with ROI_PAC. That is, fundamental algorithms are implemented as C or Fortran programs, while the configurations and driving of the modules are the tasks of Perl scripts. Each Perl script may be driven by a higher level script, and the highest level script processes all the subswaths. The interferometric processing is composed of the following four main stages: (1) data conditioning; (2) subswath processing until the generation of subswath interferograms; (3) subswath mosaicking; (4) differential processing. All of the file structures are the same as those defined in ROI_PAC. The directory structure of the processing is shown in Fig. 7.

Since Jan. 3, 2010, our ScanSAR processor has been released on the ROI_PAC Wiki: http://www.roipac.org/EnvisatScanSar All the processing strategies described in this paper are associated with an updated version of the processor. This version will still be released at the same site and freely available to the scientific community.

5. Experiments with Envisat ASAR and ALOS PALSAR data

In this section, we apply the ScanSAR interferometric processor combined with ROI_PAC to two case studies: (1) experiment with Envisat ASAR WS mode data on Tibetan plateau; (2) experiment with ALOS PALSAR WB1 mode data in Northern Africa area.

5.1. Experiment with Envisat ASAR data

The C-band Envisat ASAR instrument was launched in 2002 by European Space Agency (ESA) with 5 operating modes: image mode (IM), alternating polarization mode (AP), wide swath mode

Table 1
Parameters of the Envisat ASAR WS mode interferometric pair used. RSF stands for range sampling frequency.

<table>
<thead>
<tr>
<th>Date</th>
<th>Track</th>
<th>Baseline [m]</th>
<th>Synchronization %</th>
<th>Wavelength [m]</th>
<th>RSF [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>070116–070327</td>
<td>405/D</td>
<td>~89</td>
<td>~98%</td>
<td>0.0562356424</td>
<td>19 207 680</td>
</tr>
</tbody>
</table>

Subswath

<table>
<thead>
<tr>
<th>Burst length [line]</th>
<th>PRF [Hz]</th>
<th>Chirp slope [Hz/s]</th>
<th>Pulse length [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 684.88421</td>
<td>697 584 051 000</td>
<td>2.11373784E-05</td>
</tr>
<tr>
<td></td>
<td>2 102.41681</td>
<td>767 277 925 000</td>
<td>1.67641277E-05</td>
</tr>
<tr>
<td></td>
<td>1 692.60486</td>
<td>500 662 579 000</td>
<td>2.09291283E-05</td>
</tr>
<tr>
<td></td>
<td>2 080.55459</td>
<td>563 396 729 000</td>
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</tr>
<tr>
<td></td>
<td>1 707.04586</td>
<td>423 935 395 000</td>
<td>2.07208783E-05</td>
</tr>
</tbody>
</table>

Fig. 7. The directory structure of ScanSAR interferometric processing. SS stands for subswath.
(WS), global monitoring mode (GM) and wave mode (WV). The AP, WS and GM modes use burst technique to acquire data, but only the first two modes are suitable for interferometry. The WS mode, consisting of 5 subswaths, can provide images with 405 km coverage and 150 m resolution. Here, we use WS mode data to test our processing chain. The test area is located on Tibetan plateau. We choose an interferometric pair covering this area, the important parameters of which are listed in Table 1.

First, the data is decoded, and subswaths are separated from the integrated file. At the same time, the high precision satellite state vectors produced by Delft University of Technology (Scharroo and Visser, 1998) are extracted and stored in a file. After Doppler centroid frequency estimation for each subswath, we use a quadratic polynomial to fit the estimated values. Synchronization calculation results shows that the synchronization of the pair is as high as 98%. Then master and slave of each subswath are focused, coregistered and interferometrically combined. In order to suppress azimuth scalloping, the azimuth spectrum of the data is weighted according to the predicted antenna pattern before the inverse fast Fourier transform (IFFT) of azimuth focusing (Bamler and Eineder, 1996). The above steps are implemented without multi-looking in both directions. Compensation for the non-integer PRI part of burst gaps is performed on the single look interferometric products. Multi-looking, aiming at...
reducing noise and data volume considering the low resolution of ScanSAR, is then applied as a final step of individual subswath processing.

Subswaths are then mosaicked and smoothed to get the full interferogram whose topographic and orbital phase is removed using a Shuttle Radar Topography Mission (SRTM) DEM (Farr and Kobrick, 2000). The SCH coordinate system shows good performance. The differential interferogram and coherence map are shown in Fig. 8. The geocoded and unwrapped differential interferogram converted to deformation is shown in Fig. 9.

There was no strong crustal movement during the time span of the two acquisitions. Therefore, the deformation should be zero. From Fig. 9, however, spatially correlated signals without systematic features are observed in the lower left mountainous areas. We deduce that these may be caused by atmospheric water vapor, a major limitation for high precision InSAR applications due to its significant impact on microwave signals (Li et al., 2006a). We should also note that these signals are highly correlated with topography (mountainous areas), which is further indication that they are probably due to topography-dependent water vapor effects (Li et al., 2006b). Despite these errors, there are still as many as 98.7% points with values within 1.5 cm. After rejecting points with errors greater than 1.5 cm, statistical analysis shows that the mean value and the standard deviation are 0.044 cm and 0.400 cm, respectively.

5.2. Experiment with ALOS PALSAR data

ALOS was launched by Japan Aerospace Exploration Agency (JAXA) in January 2006 carrying 3 sensors, one of which is PALSAR that provides data in 5 categories: FBS (Fine mode, Single polarization), FBD (Fine mode, Dual polarization), DSN (Direct Downlink mode), PLR (Polarimetry mode), WB1 (ScanSAR mode, Burst mode 1) and WB2 (ScanSAR mode, Burst mode 2). The last two modes are the so-called ScanSAR modes. Since PALSAR seldom operates in WB2 mode, a better choice for ScanSAR interferometry is WB1 mode which consists of 5 subswaths with an overall coverage of 350 km and an azimuth resolution of 100 m.

The full aperture algorithm has already been implemented in the GMTSAR software (Sandwell et al., 2011) to process the ALOS PALSAR WB1 data for ScanSAR interferometry (Tong et al., 2010), but less attention is paid to the consistency of the subswaths, so phase offsets may be observed in the overlap area. On the other hand, consistency is always considered in our processing when necessary. It should also be noted that PALSAR frequently changed its PRF. If the PRFs of the interferometric pair are different and do not change within a subswath, with enough synchronization, they can also be processed in the same way, but the burst synchronization will vary along the swath, as well as the interferogram quality. However, our processor cannot handle the case that PRF changes within a subswath at present.

In the research, we also use a WB1 pair to implement ScanSAR interferometry, and the important parameters of the pair are listed in Table 2.

Table 2
Parameters of the ALOS PALSAR WB1 mode interferometric pair used. RSF stands for range sampling frequency.

<table>
<thead>
<tr>
<th>date</th>
<th>Track</th>
<th>Baseline [m]</th>
<th>Synchronization</th>
<th>Wavelength [m]</th>
<th>RSF [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>080302–080417</td>
<td>325/D</td>
<td>~290</td>
<td>~71%</td>
<td>0.236057</td>
<td>16 000 000</td>
</tr>
</tbody>
</table>

| Subswath        | 1     | 2            | 3               | 4             | 5        |

| Burst length [line] | 247   | 356          | 274             | 355           | 327      |
| PRF [Hz]           | 1 692.047 | 2 369.668 | 1 715.266       | 2 159.827     | 1 919.386 |
| Chirp slope [Hz/s] | ~5.18519E+11 | ~5.18519E+11 | ~5.18519E+11 | ~5.18519E+11 | ~5.18519E+11 |
| Pulse length [s]   | 2.7E–05 | 2.7E–05       | 2.7E–05         | 2.7E–05       | 2.7E–05  |

Fig. 10. Large scale differential interferometric processing results of the ALOS PALSAR WB1 mode data covering northern Africa. (a) is the differential interferogram. (b) is the coherence map. The numbers of looks taken in the azimuth and range directions are 40 and 8, respectively. No filtering is performed. Although the coherences are different between the adjacent subswaths in some areas, the subswath differential phase is in good agreement.
exceeding 6 cm are rejected, leaving 99.8% pixels to be used in the analysis. The mean value and the standard deviation are 0.340 cm and 1.658 cm, respectively, which are much greater than those of Envisat ASAR WS mode data. The main causes of lower precision can be summarized as follows: (1) The much longer wavelength of ALOS PALSAR, about 4 times that of Envisat ASAR, makes it less sensitive to the surface changes as the sensitivity to LOS surface change is proportional to wavelength. (2) The precision of the state vectors of ALOS PALSAR released with its products is much lower than that of Envisat ASAR. In fact, before baseline re-estimation, many orbital fringes were observed over the interferogram.

6. Conclusions

The full aperture algorithm is a good option for ScanSAR interferometry, because the image focused by this algorithm has nearly the same geometric and spectral properties as stripmap data. This advantage allows the algorithm to be easily combined with the traditional InSAR software for ScanSAR interferometry. Based on this algorithm, the processing strategy we have proposed can make use of most of the robust algorithms realized in traditional InSAR software. In our processing flow, we focus the subswath images to a consistent geometry, which is predetermined in the Doppler frequency fitting of all the subswaths and important for mosaicking and the interferometric processing after mosaicking. The overlap area smoothing technique proposed works well. Although the non-integer PRI part of the burst gap will not lead to significant focusing errors, its accumulating shifting effect on a long subswath should be compensated, particularly for instruments with short burst durations, such as Envisat ASAR.

The proposed processing strategy is integrated with ROI_PAC to implement ScanSAR interferometry. The ScanSAR processor is then used to process Envisat ASAR WS and ALOS PALSAR WB1 mode data. The Envisat ASAR experiment reveals that despite the low resolution in azimuth, good precision can be achieved with our interferometric pair. However, like stripmap interferometry, the effect of atmosphere still represents one of the main limitations. The resultant precision of the ALOS PALSAR pair is lower than that of Envisat ASAR pair due to its coarse orbital precision and much longer wavelength.

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References


