Improving Segmented INSAR Processing Using Presumming

by: Clint Slatton

Literature Survey

Submitted to Professor Brian Evans

EE381K Multidimensional Digital Signal Processing

October 19, 1998

Abstract

Synthetic aperture radar (SAR) data constitute a shift-variant 2D process, but due to the large disparity between the time scales in the two coordinate bases (range and azimuth), the signal can be well approximated as two 1D processes. The range-Doppler (RD) method correlates the rapidly-varying pulse echo in the range dimension, and then correlates the result in the slowly-varying azimuth dimension. New SAR processing methods have been developed in recent years. However, these new algorithms have not addressed the phase errors associated with processing long, continuous strips of interferometric SAR (INSAR) data. When processing long strips of INSAR data, the strip must be divided into segments, each with its own set of Doppler parameters. The usual rectifying operations are not adequate for removing observed phase offsets between these segments. A procedure known as presumming may reduce these errors by rejecting aliased frequencies in the azimuth spectrum. The objective of this study is to implement presumming in the existing NASA/JPL TOPSAR processor and determine whether it reduces the observed segment discontinuities in the INSAR data.

Section 1: Introduction

Imaging radars comprise an important class of sensors for remote sensing and reconnaissance applications because they access the microwave portion of the spectrum and are capable of day/night, and nearly all-weather operation. In the general case, these data form a non-separable, shift-variant, 2D process [1, 2], but the time scales for the two coordinate bases of range and azimuth are sufficiently different that the signal can be well approximated as two quasi-independent 1D processes.

In the early days of SAR during the 1950s - 1970s, the only processing algorithm widely used was the range-Doppler (RD) method. This method autocorrelates the high-frequency, modulated pulse echo in the range dimension, corrects for a range cell migration effect, and then autocorrelates the Doppler-modulated result in the azimuth dimension. Processing was typically carried out using optical filtering until the 1980s, when digital processing became practical [3]. In recent years, the SAR processing problem has been revisited and some new methods have been developed. Even with the advent of these new algorithms, the RD method is still the most common processing technique.

Within the last decade, interferometric SAR (INSAR) has emerged as an important extension of SAR. The RD algorithm and the new processing techniques are all capable of preserving the relative phase of the received echoes, which is critical for INSAR. Current SAR literature discusses these processing techniques in terms of their ability to minimize phase errors within a single synthetic aperture. However, the literature does not address phase errors associated with processing long, continuous strips of INSAR data because most INSAR data are presented as images of nearly square dimensions. For such dimensions, it is adequate to process the entire scene to one set of Doppler and motion parameters. When processing long strips of INSAR data, as with the NASA/JPL TOPSAR product, Doppler and motion parameters vary too much to simply use one set of values. Processing the strip in segments, each with its own set of parameters is therefore necessary. Motion compensation and deskew operations are typically used to rectify (re-index the pixels in) the segments so that the final strip image appears continuous [4]. These techniques are sufficient to rectify SAR magnitude images, but systematic errors are still visible in the INSAR data because of its increased sensitivity to phase measurement. These segment discontinuities occur at regular intervals of roughly 1 km and consist of ± 2m jumps in topographic heights derived from the INSAR data. These errors are within the TOPSAR design specifications and are only visible when INSAR data are collected over low-relief regions. Errors of this size are often referred to as being at the "artifact level" in the literature and are therefore rarely addressed. However, low-relief areas usually correspond to flood-prone regions, where the need for precise knowledge of the topography for accurate flood forecasting is the greatest. If INSAR is to be successfully applied to low-relief regions, these errors must be addressed. A procedure known as presumming may reduce these errors by rejecting potentially aliased frequencies in the azimuth spectrum that are used to determine the pixel indexing in the deskew operation.

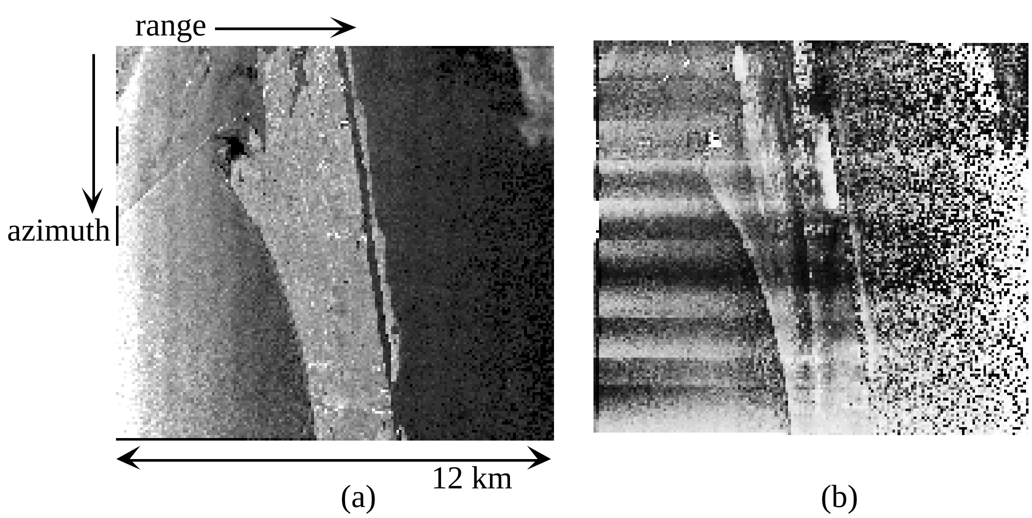

Figure 1. TOPSAR data: (a) magnitude image after deskew. (b) INSAR image after deskew showing residual segment discontinuities.

Section 2: Prior Work

SAR PROCESSING

Several focusing algorithms have been developed for processing SAR data into high resolution imagery. In general these algorithms can be divided into two classes: (i) time domain methods and (ii) frequency domain methods. The frequency domain methods can be further divided into two subclasses (ii.a) the RD method, which uses 1D Fast Fourier Transforms (FFTs) and (ii.b) the wave equation (WE) method, which uses 2D FFTs [6]. The time domain method can exactly account for the 2D space-variant SAR signal, but it is rarely used because the direct convolutions are quite inefficient [2] [7].

To date, the RD method has been by far the most common algorithm, and the TOPSAR processor is of this type. In principle, it can solve the problems of azimuth focusing (the basic SAR operation) and the range dependent range cell migration correction (RDRCMC) via secondary range compression (SRC) [6]. The primary disadvantages are (i) the SRC cannot easily incorporate the azimuth frequency dependence and (ii) the RDRCMC requires an interpolation. To be accurate, the interpolation kernel must have range-varying coefficients and should span many samples. In practice a trade off with efficiency is necessitated leading to kernels of 8 or fewer taps. This truncation degrades (spreads) the resulting impulse response [8]
.

The 2D frequency domain methods emerged in the late 80s, sparking the development of many different algorithms, but recently it has been shown that these algorithms are actually variations on the same idea. The first of the 2D frequency domain methods to receive serious attention for SAR processing was the WE method, also known as the wave number domain method [6]. The advantages of the WE method are that it deals directly with the natural polar coordinates arising in wave propagation and most of the signal processing operations are carried out in the 2D frequency domain using simple phase multiplies [8]. The primary disadvantage is that an interpolation is still needed to match the RDRCM parameter variations. The interpolation is either carried out as a Stolt change of variables in the 2D frequency domain or as a residual RDRCMC in the RD domain. It was initially reported that the WE approach did not require interpolation in the 2D frequency domain [6]. It was later realized that the Stolt change of variables (also called a grid deformation or Stolt mapping) was equivalent to a complex interpolator, and so the issue of interpolator length remained [2].

A novel way to stay with the 2D frequency domain, but avoid any interpolation was presented by Raney, *et al*. [8]. It was based on a chirp scaling algorithm, and required that the transmitted waveform be a chirp. Chirp waveforms are commonly used in SAR, but a more general algorithm was needed, prompting Lanari [2] to develop an algorithm based on a chirp z-transform. This was accomplished with a scaling of the inverse FT. Lanari and Fornaro [9] subsequently showed that the chirp z-transform was actually a particular implementation of the chirp scaling algorithm. Both are equivalent to a scaled inverse FT, and so these algorithms are sometimes called SCaled Inverse Fourier Transform (SCFT^{-1}) methods [10].

The spectrum of the 2D SAR return signal can generally be represented by

$$H(\xi,\eta) = G_0(\xi,\eta)\cdot\Gamma\left[\xi,\Omega(\xi)\eta+\mu(\xi)\right]$$

where (ξ,η) are the azimuth and range frequencies respectively, $\Omega(\xi)$ represents an azimuth-frequency dependent scaling of the range data, and $\mu(\xi)$ is an azimuth-frequency dependent offset. $\Gamma[\cdot]$ is the reflectivity spectrum and $G_0(\cdot)$ is the component of the transfer function independent of the range spatial coordinate. One solution to correctly focus the SAR data is to take a standard 2D FT followed by a non-standard inverse FT, called the SCFT^{-1}, that compensates for the scaling factor $\Omega(\xi)$. A SAR processing algorithm based on this concept is shown in Figure 2(a). With slight modifications, this same basic algorithm can be implemented using a chirp z-transform. The chirp z-transform effectively computes a SCFT^{-1} using one convolution and two phase multiplications by linear FM (chirp) functions, as shown in Figure 2(b). The chirp scaling algorithm replaces the SCFT^{-1} with a cascade of forward and inverse FTs in range interleaved with multiplications by chirp functions (see Figure 2 (c)).

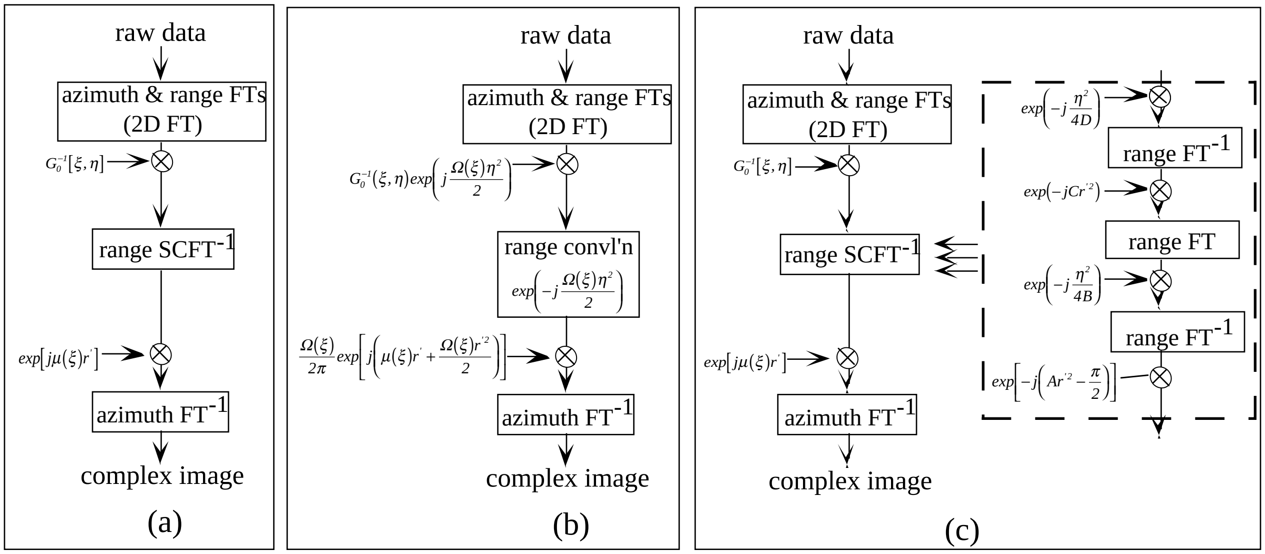

Figure 2. Block diagrams for (a) SCFT^{-1}, (b) chirp z-transform, (c) chirp scaling processing algorithms [9]

In the SAR processing literature, the emphasis has been on accurate phase preservation that leads to a well-focused impulse response of a point target. This is not to say INSAR data are never processed in segments. Data from spaceborne SARs (e.g. ERS-1, -2) are typically processed in blocks to limit array sizes in memory and because one scene usually contains many apertures; however, the entire scene is still processed to one set of Doppler and motion parameters. These algorithms do not address the issue of updating the Doppler and motion information within a continuous image strip.

PRESUMMING

As mentioned in the introduction, RD is the most common approach and is the algorithm used in TOPSAR processor. In this algorithm, the start-stop approximation (separability) is made, and so it is appropriate to talk about the range spectrum and azimuth spectrum individually. Desired range resolutions are typically such that no degradation is allowed in that dimension, but since azimuth resolution is controlled by the choice of synthetic aperture length, it is often the case that the pulse repetition frequency (PRF) oversamples the target relative to the desired azimuth resolution. The logical place for data reduction is therefore in the azimuth dimension. This is often done by processing only a portion of the bandwidth of the azimuth spectrum. This practice involves low pass filtering the azimuth spectrum and then downsampling (expanding) the remaining low frequencies. This practice is referred to as presumming in the SAR literature [11, 5].

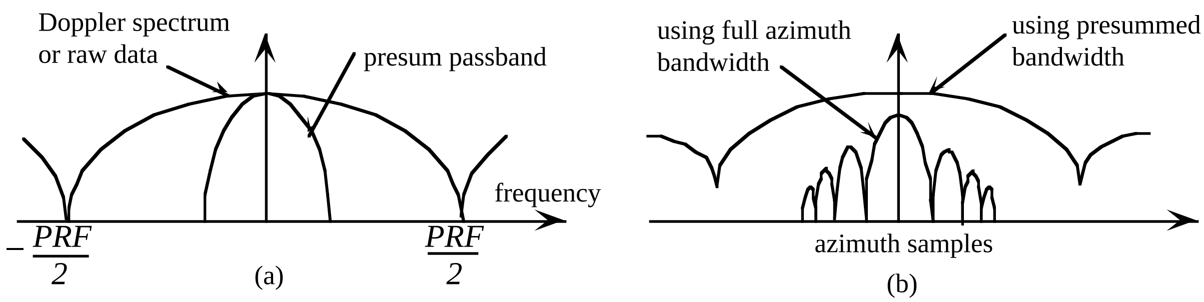

Figure 3. (a) Azimuth spectrum and the low-pass frequencies retained after presumming [5] (b) azimuth compressed results [12].

Massonnet, *et al* . [11] developed a versatile RD SAR processor that incorporated presumming. They pointed out that particularly in airborne SARs, a wide beam is required to overcome beam alignment variations caused by changes in attitude. The wide beam means targets are in view longer, leading to a greater range of Doppler frequencies, which in turn requires higher PRFs. Sampling the full bandwidth of the resulting azimuth spectrum can then require a compression factor N on the order of 35,000 to realize the finest azimuth resolution. It can be shown that reducing the number of azimuth samples k by a presumming factor α, reduces N by a factor of α^2, thus the FFT lengths can be as short as 128 or 512. The result is faster computation and a reduction in the amount of data.

Breit and Bamler [12] have proposed a near-realtime, medium-resolution INSAR processor for checking data quality during the upcoming NASA Shuttle Radar Topography Mapping (SRTM) mission. The RD processor employs phase weighting and presumming instead of true azimuth correlation. The full azimuth bandwidth is 1180 Hz, but only a 96 Hz low-pass portion is retained. In this particular implementation, the azimuth resolution degrades from 6 m to 76 m, which is adequate for data quality assessment. Although addressed in the literature for data reduction, presumming should reduce the segment discontinuities observed in the TOPSAR data.

Section 3: Conclusions and Proposed Implementation

By retaining only the lower frequencies of the azimuth spectrum, presumming reduces the likelihood of aliased frequencies impacting the azimuth compression. The interferometric phase computed for the pixels in a given aperture should be more accurate as a result. It is this phase information that is used to determine the re-indexing during the deskew operation in the TOPSAR processor. Thus adjacent segments in the TOPSAR strip product should exhibit reduced phase offsets from those currently observed if presumming were introduced into the TOPSAR processor. The pre-deskew result would have slightly lower azimuth resolution, but it would also have more accurate phase information from which to realign the segments.

To test this conjecture, a simple MATLAB presumming simulation will be developed in accordance with TOPSAR parameters. Once the algorithm is well understood, a FORTRAN-77 subroutine will be written and inserted into the azimuth compression routine in the TOPSAR processor. The subroutine will low-pass filter and downsample the azimuth spectrum. A nested loop structure will be used to accommodate the range-dependent azimuth response. Care will have to be taken to ensure the subroutine is compatible with the data formatting in the TOPSAR processor. Datasets will then be processed with the nominal TOPSAR processor and with the presumming version. Comparisons between the outputs will reveal the impact of the presumming. It is expected that presumming will reduce the segment discontinuities observed in the TOPSAR data, but not completely eliminate them. Other issues such as accurate Doppler frequency estimation and motion compensation must also be addressed before the segment discontinuities can be reduced below observable levels.

References

[1] R. Bamler, "A Comparison of Range-Doppler and Wavenumber Domain SAR Focusing Algorithms," *Trans. on Geosci. and Remote Sensing*, vol. 30, no. 4, pp. 706-713, July 1992.

[2] R. Lanari, "A New Method for the Compensation of the SAR Range Cell Migration Based on the Chirp Z-Transform," *Trans. on Geosci. and Remote Sensing*, vol. 33, no. 5, pp. 1296-1299, Sept. 1995.

[3] F. Ulaby, R. Moore, and A. Fung, *Microwave Remote Sensing: Active and Passive*, Artech House, ISBN 0-89006-191-2 1986.

[4] A. Chu, Y. Kim, J. van Zyl, W. Tung, E. O'Leary, and Y. Lou, "The NASA/JPL AIRSAR Integrated Processor," *Proc. Int. Geosci. and Remote Sensing Symp.*, June 1998, pp. 1908-1910.

[5] G. Morris and L. Harkness (ed.), *Airborne Pulsed Doppler Radar*, Artech House, ISBN 0-89006-867-4, 1996.

[6] C. Y. Chang, M. Y. Jin, and J. C. Curlander, "SAR Processing Based on the Exact Two-Dimensional Transfer Function," *Proc. Int. Geosci. and Remote Sensing Symp.*, June 1992, pp. 355-359.

[7] J. Curlander and R. McDonough, *Synthetic Aperture Radar: Systems and Signal Processing*, John Wiley & Sons, ISBN 0-471-85770-X, 1991.

[8] R. Raney, H. Runge, R. Bamler, I. Cumming, and F. Wong, "Precision SAR Processing Using Chirp Scaling," *Trans. on Geosci. and Remote Sensing*, vol. 32, no. 4, pp. 786-799, July 1994.

[9] R. Lanari and G. Fornaro, "A Short Discussion on the Exact Compensation of the SAR Range-Dependent Range Cell Migration Effect," *Trans. on Geosci. and Remote Sensing*, vol. 35, no. 6, pp. 1446-1452, Nov. 1997.

[10] O. Loffeld, A. Hein, and F. Schneider, "SAR Focusing: Scaled Inverse Fourier Transformation and Chirp Scaling," *Proc. Int. Geosci. and Remote Sensing Symp.*, June 1998, pp. 630-632.

[11] D. Massonnet, F. Adragna, and M. Rossi, "CNES General-Purpose SAR Correlator," *Trans. on Geosci. and Remote Sensing*, vol. 32, no. 3, pp. 636-643, May 1994.

[12] H. Breit and R. Bamler, "An INSAR Processor for On-Board Performance Monitoring of the SRTM/X-SAR Interferometer," *Proc. Int. Geosci. and Remote Sensing Symp.*, June 1998, pp. 1904-1907.