A SAR PROCESSING ALGORITHM WITH NO INTERPOLATION

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ABSTRACT

Current SAR processing algorithms incorporate interpolators to perform key functions. It turns out that the interpolators are difficult to implement, and are one of the largest sources of error in the processing. In this paper, we introduce a new algorithm which eliminates the use of the interpolation operation, yet achieves accurate range migration correction over the full range swath. The algorithm can handle large apertures and large squints, and has noticeably better phase and geometry accuracy than current algorithms, even when the apertures and squints are high.

The new algorithm is called the Differential Range Deramp – Frequency Domain (DRD-FD) Algorithm, because its key operation is to use the linear-FM property of the range chirp to differentially shift the range energy as a function of azimuth frequency, and then to do the remaining range cell migration correction in the two-dimensional frequency domain.

In this paper, the new algorithm is described, and simulation results are given to demonstrate its focussing, phase and geometric performance with squinted SAR data. In addition, an image is shown made from SEASAT data.

Keywords: SAR processing, phase accuracy, range migration corr'n.

1 Introduction

The Range/Doppler (R/D) algorithm for processing raw SAR signal data into complex images was first invented by Wu at the Jet Propulsion Lab in 1976 [1], and was refined by engineers at MacDonald Dettwiler and the Canada Centre for Remote Sensing [2]. It tackled the problem of range cell migration for satellite SAR geometries, and developed an efficient way of correcting the RCM using an interpolator in the range-time, Doppler-frequency domain — hence the name Range/Doppler.

Since that time, the R/D algorithm has become the world standard for production satellite SAR processors, and has been installed in at least 15 countries. Improvements continue to be made to the algorithm, the most significant of which is the addition of secondary range compression to allow the algorithm to handle satellite SAR geometries with a moderate amount of squint [3]. More recently, there has been a requirement for phase accuracy in SAR images, and the R/D algorithm has been refined in production processors to give good phase accuracy for moderate squints.

The R/D algorithm has only one significant disadvantage: that its focussing, phase and registration accuracy deteriorates when squints larger than a certain value are experienced. The threshold of allowable squint depends on the radar wavelength, the length of the processed aperture and the error tolerance.

Recently, several researchers have examined new SAR processing algorithms based on the seismic wave equation formulations [4,5]. These have the advantage of dealing directly with the spherical wave propagation, and in principle are tolerant of squint and variation of the azimuth phase modulation with respect to range.

Although the wave equation approach has structural improvements in its formulation, two problems remain: its inability to handle all parameter variations in range that arise in satellites with complete accuracy, and the fact that an interpolator is needed in the 2-dimensional frequency domain in its implementation.

The question of interpolation is one of efficiency and accuracy. Interpolators are harder to implement than normal linear convolutions, as their coefficients vary with each sample processed. This complicates the coefficient and address generator operations. In addition, the kernel of the interpolator has to be quite long to achieve accurate results, which leads to a less than ideal accuracy/efficiency tradeoff. Most processors use 4 – 8 point kernels, which favours to the efficiency side of the tradeoff.

With this background, we sought to develop a new SAR processing algorithm which took advantage of the best features of the R/D and wave equation algorithms, and removed their main deficiencies. The main disadvantage we sought to eliminate was the reliance on the interpolator in the implementation.

2 The New Algorithm

The new algorithm was derived by introducing the following new features to the range/Doppler and wave equation algorithms:

1. a *range perturbation* method of equalizing the range equation of all reflectors to allow more accurate RCMC,
2. a *memory utilization* scheme for handling large Doppler centroid changes,
3. *all parameter variations* are kept in the range equation,
4. *compensation* to keep the *phase* of the compressed image correct.

The structure of the new algorithm is shown in Figure 1, and a first-order analytic description may be found in [6]. Starting with range expanded data (*i.e.* the linear FM modulation is still present), the *distinctive steps* in the algorithm are as follows:

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Range perturbation (RP): –

This step is a multiplication by a near-linear-FM phase function to differentially shift the target energy in range by making a small range-time dependent frequency adjustment to each target. The range frequency adjustment is chosen to make the target trajectory congruent (after range compression) with a reference target at a selected range cell.

For simple SAR geometries, the RP phase function is linear FM. For more complicated geometries, a small nonlinear FM component is added to the phase function, using a polynomial structure.

Note:– Because the shift is a function of absolute rather than aliased Doppler frequency, this operation, and the next three operations in Figure 1, must be done on the full Doppler frequency span of the azimuth matched filters in the current range subswath. This means that the main range processing in the next three steps may have to be done on more than one azimuth ambiguity. This affects efficiency and is a factor in choosing the range subswath size.

RC & RCMC: –

Because of the RP operation, there is no longer any range-time dependence in the range curvature or the range phase encoding, so high-accuracy range processing is now possible in the 2-dimensional frequency domain.

The two operations of range compression and range cell migration correction are implemented together by a single phase multiply in the 2-dimensional frequency domain, where the phase value depends upon range frequency and azimuth frequency.

AC & Phase Compensation: –

After the range IFFT is applied, only the illuminated parts of the absolute Doppler spectrum are retained for the final compression steps. The retained frequencies can be adjusted every range cell if necessary.

The azimuth compression (AC) operation consists of multiplying each azimuth line by a phase function. At the same time, a phase compensation term is applied to correct for the phase distortion arising in the range perturbation stage.

Note:– If weighting is to be applied or multiple looks are to be extracted, they are done between the AC phase multiply and the azimuth IFFT, in the same way as in the R/D algorithm. In the case of multiple looks, the IFFTs are shorter than the forward FFTs, and pre-detection interpolation, detection and look summation follow the IFFT operation.

Geometry & Phase Compensation: –

If the Doppler FM rate varies with azimuth time, then a time-domain post-compression phase and registration correction is needed in addition to the compensation discussed above. This step consists of a phase multiply and an interpolation operation to make the image phase and registration continuous over the boundary between azimuth processing blocks.

Note that no interpolation operation is included up to the formation of the complex image. An interpolator is only needed if post-compression geometric correction is needed, as commonly done for slant-range to ground-range conversion, or for registration to a map grid. These post-compression interpolations are easier to apply, and do not affect image quality to the same extent as the interpolators which are used by the R/D and WE algorithms in the middle of the compression operations.

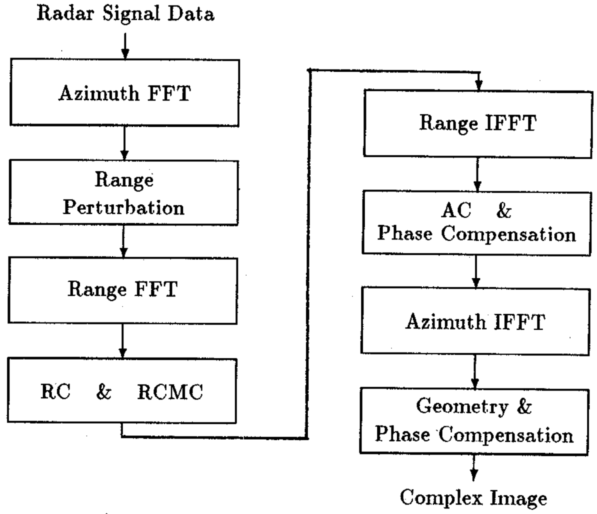

Figure 1: Steps in the new processing algorithm.

3 Simulation Experiments

Simulation experiments were performed with MATLAB to verify the performance of the new algorithm. The simulation parameters were chosen so that the bulk RCMC and change in range curvature matched those of RADARSAT, in units of resolution cells.

The target independent parameters used were:

Radar parameter	Value	Units
Carrier frequency	$6.0\ 10^{9}$	*Hz*
Range sampling rate	$20.0\ 10^{6}$	*Hz*
Chirp FM rate	$2.3\ 10^{12}$	*Hz/s*
Radar PRF	$1.0\ 10^{3}$	*Hz*
Pulse length	$8.0\ 10^{-6}$	*s*

A reference target and test target were chosen to have the following parameters:

Parameter	Ref. Tar.	Test Tar.	Units
Doppler centroid	$0.0\ 10^{0}$	$-22.0\ 10^{0}$	*s*
Azimuth *B* par.	$50.0\ 10^{6}$	$49.9\ 10^{6}$	m^2/s^2
Slant range	$1.00\ 10^{6}$	$1.02\ 10^{6}$	*m*

The antenna weighting was assumed to be rectangular. The reference target had no squint and was placed at mid-range. The test target was placed at the far swath edge, assuming a swath width of 40 *Km* slant range, so that the most severe RCMC curvature and change in this curvature were simulated. Also the value of *B* was allowed to change by 0.4% from near to far range. With these set of parameters, the RCMC (bulk) curvature was about 73 range cells and the change in RCMC curvature between the two targets was about 2 range cells. The beam centre offset of the test target was selected to be -22 *s* which corresponds to about 8° of squint (5° of antenna squint plus 3° due to earth rotation). With the chosen PRF, the azimuth exposure time was about 0.5 sec for 512 lines of signal data.

The simulated targets were processed by the new algorithm, and the results are shown in Figure 2. Figure 2(a) is a contour plot of the compressed test target in the image domain. Figure 2(b) shows the range profile through the peak, and Figure 2(c) shows the corresponding phase angle. The azimuth profile through the peak and azimuth phase angle are similar to those in the range direction.

The image quality parameters of the compressed reference and test targets were measured, using range and azimuth profiles taken through the peak of the target:

Range/Azimuth	Reference Target		Test Target		*Units*
Resolution	1.012	1.003	0.998	0.929	*sam.*
Registration	129.00	257.00	129.00	257.00	*sam.*
Phase angle	-90.4	-90.4	-86.4	-86.4	*deg.*
Peak SLR	-13.1	-13.1	-13.8	-13.8	*dB.*
Integ. SLR	-10.4	-9.8	-12.4	-11.9	*dB.*

The oversampling ratio can be shown to be 1.1 in either direction, hence giving a theoretical resolution of 0.975 cells for a rectangular pulse. In the experiments results to within 4.5% of this value were obtained. The theoretical phase angle was arbitrarily chosen to be 90° at the peak, and results to within 3.6° were obtained. A portion of the resolution and phase errors can be attributed to measurement inaccuracies. Both targets were compressed correctly to the midpoint of the simulation frame, thus achieving precise geometric registration despite the large Doppler offset.

The maximum and integrated SLR (one-dimensional) changed slightly in comparing these parameters of the test target to the reference target. This differences are due to the fact that the axes of the cross pattern of the test target's contour plot shown in Figure 1(a) are not parallel to the range and azimuth axes, but are parallel for the reference target. When range and azimuth profile plots are taken through the peak parallel to these two axes for the test target, they do not traverse through the actual peaks of the sidelobes.

The above results show that the image quality parameters do not suffer any significant degradations, despite the 8° of squint simulated. At this squint angle, the R/D and wave equation algorithms yield errors larger than those presented here.

The test target was then placed at the near range and similar results, to those when the target was place at the far range, were obtained. This shows that the results are insensitive to the location of the reference range; in other words, a large swath width does not impose problems on the new algorithm.

4 SEASAT Image

To further prove the effectiveness of the algorithm, an image has been made with SEASAT data. This data has a moderately wide aperture is terms of current satellite SAR practice, but does not have a large amount of squint. The squint is 1.1°, which is typical of SEASAT data.

The image is in the area of Niagara Falls, on the US/Canadian border. A region of 1024 x 833 pixels is shown, covering 25.6 *Km* ground range by 20.8 *Km* in azimuth. The processing was done with 4 looks, then the image was lowpass filtered and resampled to a 25 *m* grid. The image was printed on a Postscript laser printer, resulting in some loss of image quality.

To illustrate the range invariance properties of the algorithm, the reference range was set off the image by 500 range cells, in the near-range direction.

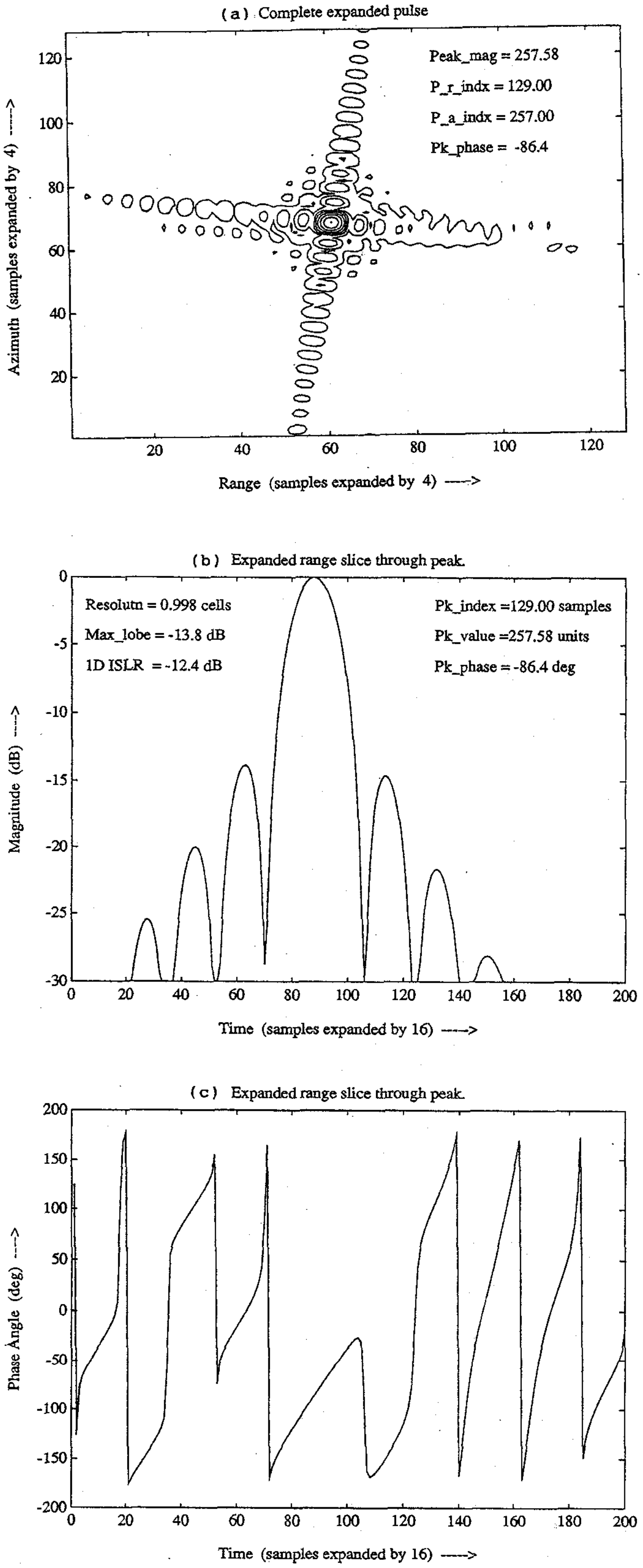

Figure 2: Simulation results on point targets

The image appears to be well focussed, and there are no visually apparent differences between it and an image produced by a precision R/D processor. A more-detailed quantitative comparison of the image qualities of this image and the R/D image is underway.

5 Conclusions

We have presented a new SAR processing algorithm which has better overall image quality than existing algorithms.

Image quality is more sensitive for SARs with large apertures and significant amounts of squint, and the image quality parameters which are most sensitive are firstly phase, secondly registration and thirdly focussing. We have shown that the new algorithm maintains good phase, registration and focus in the face of moderately large squints and apertures. We have also shown that an image produced from real data has good visual image quality.

The new algorithm has been called the Differential Range Deramp – Frequency Domain algorithm, as its central feature is to differentially shift the target energies at different ranges to be equal to that at a reference range using a deramping operator, and then to do range compression and range cell migration correction in the 2-dimensional frequency domain. We achieve accuracy and implementation improvements in this way, since range cell migration correction is done without the use of an interpolator In addition, parameter variations are kept in the 2-dimensional phase function, which maintains accuracy with large apertures and squints.

Note:– A patent application has been filed for the DRD–FD algorithm.

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It has recently come to the authors' attention that the new algorithm described here has also been the subject of work by scientists at DLR, as reported in another paper in this session.

References

[1] C. Wu. A digital system to produce imagery from SAR data. In *Proceedings of the AIAA Systems Design Driven by Sensors Conference*, October 1976.

[2] I. G. Cumming and J. R. Bennett. Digital Processing of SEASAT SAR Data. In *International Conference on Acoustics, Speech and Signal Processing*, IEEE, Washington, D.C., April 1979.

[3] M.Y. Jin and C. Wu. A SAR correlation algorithm which accommodates large range migration. *Geoscience and Remote Sensing, Vol. GE-22, No. 6*, November 1984.

[4] C. Cafforio, C. Prati, and F. Rocca. SAR Data Focussing using Seismic Migration Techniques. *IEEE Transactions on Aerospace and Electronic Systems*, 27(2):pages 194 – 207, March 1991.

[5] R. K. Raney and P. W. Vachon. A Phase Preserving SAR Processor. In *Quantitative Remote Sensing: An Economic Tool for the Nineties*, pages 2588 – 2591, Proceedings of the IEEE IGARSS'89 Symposium, Vancouver, B.C., Canada, August 1989.

[6] R. K. Raney. An Exact Wide Field Digital Imaging Algorithm. *Int. J. of Remote Sensing*, 1992. (In Press).