Model-Based Doppler Estimation for Frame-Based SAR Processing

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ABSTRACT[1] – **This paper presents a new method of Doppler centroid estimation whereby estimates are made over small blocks of data covering a whole frame of data, and examined for strong SNR and lack of bias. Poor estimates are rejected, and the remaining estimates are used to fit a surface model of the Doppler centroid *vs.* range and azimuth.**

The method is applied to both the fractional and integer PRF part of the centroid. A geometric model is used to constrain the model to allowable roll, pitch and yaw values of satellite attitude. The method is tested with RADARSAT-1 and SRTM/X-SAR data.

I. INTRODUCTION

Despite many advances in SAR processing and data handling in general, most production SAR processing systems suffer from unreliable Doppler centroid estimates. This raises the noise and ambiguity level in the processed image, sometimes to the point of seriously affecting its interpretability. The ScanSAR product is most affected because the centroid is harder to estimate, yet its accuracy requirements are more demanding than regular beams. The estimation difficulties arise from two main sources: the satellite does not have accurate enough attitude measurements or beam pointing knowledge, and the received data has local anomalies which upset the estimation process.

We have taken three approaches to improve the estimation accuracy. First, we have developed measurement procedures to identify and reject those parts of the received data that create the worst estimation anomalies. Second, we have developed a "global" model-based fitting procedure which fits a Doppler centroid "surface" over a whole frame of data at once. Third, we have used a model that predicts a Doppler surface given the satellite attitude. The model can be used if attitude measurements are available, but even if they are not available, the model can be used to constrain the estimates to be physically plausible.

We use SRTM/X-SAR and RADARSAT data to illustrate the operation of the new estimation algorithm, and to predict its accuracy. Results to date indicate the Doppler centroid estimation accuracy may be in the range of 5–10 Hz, good enough to ensure high image quality in the processed SAR images.

II. SPATIAL DIVERSITY

The concept of spatial diversity is based on the premise that there are parts of a radar scene which provide good Doppler estimates, and other parts that provide noisy or biased estimates. Poor estimates come from areas with very weak signals (low SNR) that adds noise to the estimates, and from areas where the radiometry is quite non-uniform that bias the estimates.

To avoid the bad areas, we have taken the "spatial diversity" approach where the scene is divided up into blocks or sub-scenes, and the primary estimators are applied to each block separately. The blocks can be sparse, contiguous or overlapping, depending upon the computing resources available. For our experiments, we used 256×1024 (range×azimuth) contiguous blocks of data, which represent about 5×5 km of ground coverage for typical C-band satellite SARs. This size represents approximately the size of the beam footprint.

III. BLOCK ESTIMATES

There are many estimators available for use on the blocks. Different methods are used to estimate the fraction PRF (baseband) part of the Doppler centroid and to estimate the Doppler ambiguity (the integer PRF part). We found that any method could be used for the fractional part, as reliability is usually not an issue. But for the ambiguity, it is very important to choose a robust algorithm. In fact, sometimes several algorithms have to be used, as their performance is content specific.

For RADARSAT data, we found that a sine wave on a pedestal is a good model for the averaged azimuth magnitude spectrum. A DFT is taken of the magnitude spectrum, and the modeled spectrum is:

$$G(f) \;=\; S_0 \,+\, 2\,Re\{S_1\} \,+\, 2\,Im\{S_1\} \qquad (1)$$

where S_0 and S_1 are the first two DFT coefficients. Then, the estimate of the fractional PRF part of the

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Doppler centroid is simply:

$$F_{\text{frac}} = \text{angle}\{S_1\}/(2\pi) \quad (2)$$

One has to be much more careful in estimating the Doppler ambiguity. We found that the phase increment or wavelength diversity method introduced by DLR [1], and the multi-look MLCC and MLBF methods developed by MacDonald Dettwiler to be the best choices [2]. These methods do not work well on all blocks, but as the DLR/MLCC methods worked best on low-contrast blocks, and the MLBF method works best on high-contrast blocks, it was found best to use both algorithms and select the most reliable answer.

IV. QUALITY MEASURES

After finding the estimates of each block, quality measures are used to estimate their accuracy. Some quality measures could be computed from the radar data itself, and some from parameters produced by the estimators.

In the case of the radar data, it was found useful to examine the contrast and radiometric gradients in each block of the scene. The contrast is measured by $C = E\{|P^2|\}/E\{|P|\}^2$, where P is the pixel amplitude of the range-compressed data. The gradients in range and in azimuth are measured by the changes in radiometry averaged over 1 km sub-blocks of the range-compressed data. High gradients were used to reject blocks, and contrast was used to select between the DLR/MLCC and MLBF ambiguity estimators.

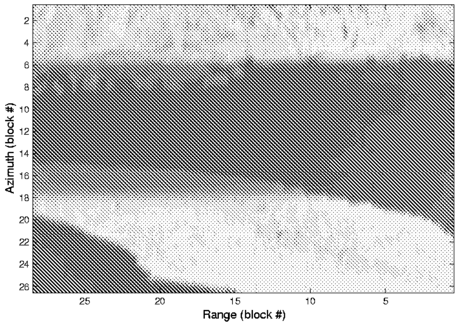

Figure 1: RADARSAT S7 Anticosti scene

In the case of the fractional PRF estimator, the SNR is estimated as the magnitude ratio between the S_1 and S_0 terms in (1). Poor SNR is indicated by low values of this ratio. The radiometric distortion is estimated by the rms deviation between the averaged spectra and the fitted curve (1). We divide by the average height of the spectrum and multiply by 100 to get a percent deviation.

In the case of the DLR/MLCC Doppler ambiguity estimators, the best quality measure was the standard deviation of the average phase increments. For the MLBF estimator, the best quality measure was the ratio between the peak beat frequency energy and the surrounding spectral energy.

After experimenting with different thresholds manually, an automatic method was developed to iteratively reject more and more blocks until the surface estimate settled down to a stable answer.

V. SURFACE FITTING

After obtaining the fractional PRF and ambiguity estimates for each block in the scene, and rejecting the bad estimates, a 3-dimensional surface of Doppler centroid *vs.* range and azimuth was fitted. The model of the surface is:

$$F = c_0 + c_{a1}\, a_i + c_{r1}\, r_i + c_{a2}\, a_i^2 + c_{r2}\, r_i^2 + c_{ar}\, a_i\, r_i \quad (3)$$

where r_i and a_i are the range and azimuth block numbers. Separate estimates are applied to the fractional PRF and ambiguity estimates. The coefficient c_{r1} accounts for most of the sizable variation with range, and c_{r2} allows a small quadratic component in the range variation. Normally a linear term c_{a1} is sufficient to model a slowly-varying azimuth drift in the Doppler centroid, but a quadratic c_{a2} component was found useful in the SRTM case to follow the faster Doppler changes caused by the firing of the attitude thrusters. Finally, a cross-coupling term c_{ar} was introduced to model a range slope which changes with azimuth, as happens as the satellite latitude changes or the antenna yaw angle drifts.

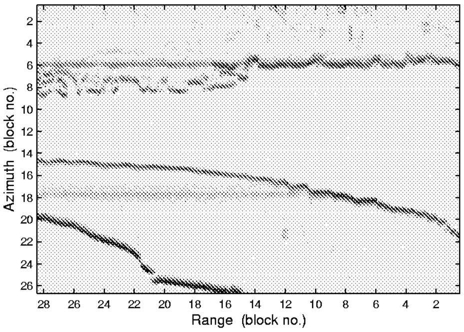

Figure 2: Azimuth radiometric gradient

A Nelder-Mead simplex direct search method was used in MATLAB to estimate the coefficients in (3). Because of the sensitivity of this method to initial conditions, it was found best to fit F first using one coefficient, then 3, then 5 and finally 6 coefficients, in the order given in (3). The coefficient values for each fit are used as the initial conditions for the subsequent fit.

VI. GEOMETRY CONSTRAINTS

The Doppler centroid can be computed for a given satellite orbit and antenna attitude angle. We did this by transforming the satellite state vector into the fixed Earth frame of reference, and solving for the coordinates of points on the earth's surface lying along the beam centerline. The Doppler centroid is given by the dot product of the satellite velocity vector and the target's velocity vector, scaled by $\lambda/2$.

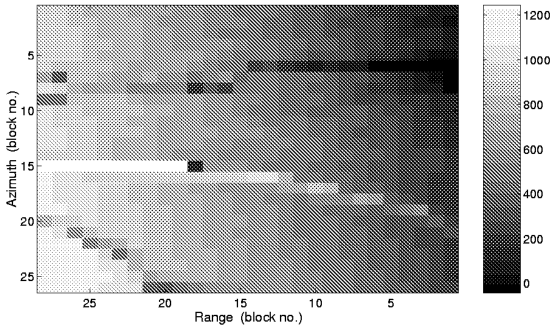

Figure 3: Ffrac block estimates in Hz

Then the attitude constraints are applied, which for the case of RADARSAT-1 are ±0.1° in attitude and $\pm 0.001^\circ/s$ in attitude rate. From these limits, extreme values of the coefficients are deduced, and used to limit the simplex search procedure. A logical extension of this constraining procedure is to express the centroid directly in satellite attitude parameters, and fit the Doppler surface using the attitude parameters.

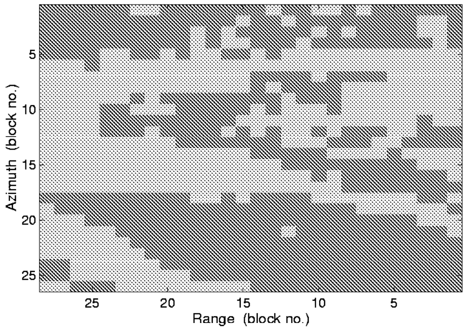

Figure 4: Fitting mask

VII. RADARSAT RESULTS

Because of space limitations, we will only give a few results from the fractional Doppler estimates of a RADARSAT-1 regular beam S7. The scene is shown in Figure 1. It consists of Anticosti Island in the St. Lawrence River, plus part of the north shore of the river. The image is not well focused, because the data has not been RCMCed nor azimuth compressed, as this is the stage in the processing where the Doppler estimation is usually done. The land/sea boundary creates a difficult Doppler estimation environment, and production processors have given incorrect estimates for this scene.

Figure 2 gives the azimuth radiometric gradient of the scene. The land/sea boundaries are clearly seen in the gradient, and this is the quality measure that has the best "good/bad" block discrimination in the current results. Also, an azimuth AGC effect is seen in the image and in the gradient, which caused further difficulty to the Doppler estimation algorithms.

Figure 3 shows the results of the fractional PRF estimator operating on each data block. The estimates form a consistent pattern, except those on the land/sea boundary. The surface fit algorithm was run in "automatic" mode, and 44% of the blocks were removed from the fit. The resulting mask is shown in Figure 4 where only the dark blocks are used in the fit.

Figure 5 gives the fitted surface (3), using only those blocks in the mask. The average deviation between the block estimates used in the fit and the fit itself is 7 Hz, which suggests that the accuracy of the overall fit is likely better than 5 Hz.

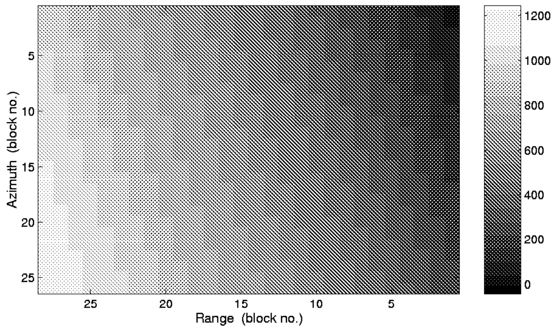

Figure 5: Fitted Doppler surface

VIII. CONCLUSIONS

We have presented a new Doppler centroid estimation scheme that embeds the normal estimators in a spatially diverse "global" fitting scheme. Parts of the image that lead to bad estimates are removed, so that good Doppler estimates are obtained even over areas with large radiometric changes such as land/sea boundaries.

Acknowledgments

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References

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