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MODIFIED MULTILOOK CROSS CORRELATION (MLCC) ALGORITHM FOR DOPPLER CENTROID ESTIMATION IN SYNTHETIC APERTURE RADAR SIGNAL PROCESSING

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Abstract—The Multilook Cross Correlation (MLCC) is one of the most reliable algorithms used for Doppler ambiguity number estimation of the Doppler centroid parameter. However, the existing MLCC algorithm is only suitable for low contrast scenes. In high contrast scenes, the estimated result is not reliable, and the error is unacceptable. Besides, the Doppler centroid estimation processing time is long and can only be used in offline processing. In this paper, we introduce a modified MLCC algorithm that has better sensitivity which is suitable not only for low contrast scenes, but also for high contrast scenes. In addition, the modified MLCC algorithm can be implemented on parallel signal processing units for better time efficiency. Experiments with RADARSAT-1 data show that the modified algorithm works well in both high and low contrast scenes.

1. INTRODUCTION

Synthetic Aperture Radar (SAR) is one of the most useful remote sensing radars that is capable to produce fine resolution 2D images which represent wealth of information. SAR system operates in the microwave frequencies (0.3 GHz to 300 GHz), which gives the advantage to penetrate the surface of many media. Signals will be able to travel freely without being affected by the atmosphere whether in the day or night time, good or bad weather. Thus, it has been widely utilized in many applications such as monitoring the motion

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of the ocean, land surface mapping, vegetation, reconnaissance and military [1]. By analyzing the phase change and measuring the time difference of the return echoes from the mapped area, SAR signal processing manages to retrieve information and generate a good quality image. The antenna, which is mounted on the moving platform, acquires the return echoes from different locations along the flight direction, and the combination of the data is performed in the complex signal processing part [2].

Doppler centroid, f_{dc}, is one of the key parameters in the azimuth SAR processing. Doppler centroid is required in the SAR image formation to focus the signal energy, correct the target intensity and improve the signal-to-ambiguity ratio [3]. The Doppler effect is due to the relative motion between the pointing angle of the antenna and the spotted target [4], where the frequency of the received echoes changes compared to the transmitted chirp signals. The Doppler centroid, f_{dc}, can be expressed as

$$f_{dc} = -\frac{2\nu}{\lambda}\sin\theta \tag{1}$$

where θ = the angle between the antenna main beam and zero Doppler plane, ν = velocity of the moving platform and λ = wavelength of the chirp signal.

Theoretically, f_{dc} can be estimated from the geometry model of the SAR system configuration through Equation (1). However, there are many uncertainties in the atmosphere that can cause estimation error in the calculation such as the velocity of the moving platform, satellite orbit and its altitude, and the pointing direction of the antenna beam. Due to all these errors, ambiguity signals will cause unfocused images. Therefore, to be more accurate and reliable, the best is to perform the Doppler centroid estimation based on the received data [5, 6].

The azimuth data are sampled with the pulse repetition frequency (PRF). Absolute Doppler centroid frequency is divided into two parts: the baseband Doppler centroid (fractional part of PRF, f_{rac}) and the integer multiple of PRF (ambiguity number, M_{amb}). Its equation can be written as

$$f_{dc} = f_{rac} + (M_{amb} \ast PRF) \tag{2}$$

There are several ways to determine f_{rac}. The Spectral Fit method and the Average Cross Correlation (ACCC) method are widely used in f_{rac} estimation [7–9]. They can achieve a few ten hertz of good accuracy [8, 10]. The f_{rac} could be extracted from the pre-process data spectrum by determining the peak of the baseband signal [11]. Although this method is very convenient, calibration is required for high contrast scenes [10]. The ACCC method was first introduced by Madsen [4], where the history of the phase variation of the range compressed data is analyzed and fully utilized to estimate f_{rac}. Due to the aliasing of the received data, is not so easy to extract the M_{amb} number. More complicated computation is required in order to determine accurate f_{dc}. Multilook Cross Correlation (MLCC), Multilook Beat Frequency (MLBF), Wavelength Diversity, and Multiple PRF are some of the famous ambiguity number estimation methods. In this paper, the fundamentals of the MLCC algorithm will be first introduced. A modified method based on MLCC is proposed to improve the estimation result and the time consumption of the required signal processing. Finally, experimental results will be presented to verify the performance of the proposed method.

2. PRINCIPLE OF THE EXISTING MLCC ALGORITHM

In the phase-based method, the absolute Doppler centroid, f_{dc}, could be obtained by investigating the variation in the received frequency compared to the transmitted frequency [6]. To operate the MLCC algorithm, range compressed signal has to be separated into two range looks, S_1 and S_2, by the frequency difference, Δf.

$$S_1(\eta) = w_a(\eta-\eta_c)\exp\left\{\frac{-j4\pi\left(f_c-\frac{\Delta f}{2}\right)R(\eta)}{c}\right\} \tag{3}$$

$$S_2(\eta) = w_a(\eta-\eta_c)\exp\left\{\frac{-j4\pi\left(f_c+\frac{\Delta f}{2}\right)R(\eta)}{c}\right\} \tag{4}$$

where $w_a(\eta-\eta_c)$ is the azimuth envelope; η is the azimuth time; η_c is the time when the target is at the center of the antenna beam; c is the speed of light; f_c is the center frequency; Δf is the frequency separation between two range looks; and $R(\eta)$ is the instantaneous slant range between radar and the target.

From each look, the history of the average phase is computed incrementally by summing up the sample, $S(\eta)$, to the next sample, $S(\eta+1)$, in the azimuth direction.

$$\overline{Look_1(\eta)} = \sum S_1(\eta)\,{S_1}^*(\eta+1) \tag{5}$$

$$\overline{Look_2(\eta)} = \sum S_2(\eta)\,{S_2}^*(\eta+1) \tag{6}$$

where ${S_1}^*$ and ${S_2}^*$ denote the complex conjugate of S_1 and S_2.

By converting the phase histories into the angle of radian, the

ACCC angle of $Look_1$ and $Look_2$ can be expressed as,

$$\emptyset_1 = \arg\left[\overline{Look_1(\eta)}\right] \tag{7}$$

$$\emptyset_2 = \arg\left[\overline{Look_2(\eta)}\right] \tag{8}$$

The difference between the two ACCC angles can be determined by,

$$\Delta\emptyset = \emptyset_1 - \emptyset_2 \tag{9}$$

or

$$\Delta\emptyset = \arg\left\{\overline{Look_1(\eta)}\left[\overline{Look_2(\eta)}\right]^*\right\} \tag{10}$$

By measuring the slope of the range compressed signal, $\triangle\emptyset/\triangle f$, in rad per Hertz, the absolute Doppler centroid could be estimated to resolve the ambiguity number, M_{amb} [6]

$$f'_{dc} = -\left(\frac{PRF f_0 \Delta\emptyset}{2\pi\Delta f}\right) \tag{11}$$

and the fractional PRF can be written as

$$f_{rac} = -\left[\frac{PRF}{2\pi}\left(\frac{\emptyset_1 + \emptyset_2}{2}\right)\right] \tag{12}$$

Using the results determined from (11) and (12), the M_{amb} can then be calculated by

$$M_{amb} = round\left(\frac{f'_{dc} - f_{rac}}{PRF}\right) \tag{13}$$

Since the angle difference is very small and yet divided by the $\triangle f$, phase wrapping issue can be neglected.

Finally, the estimated absolute Doppler centroid frequency is

$$f_{dc} = f_{rac} + (M_{amb} * PRF) \tag{14}$$

with the

$$Remainder = M_{amb}PRF - \left(f'_{dc} - f_{rac}\right) \tag{15}$$

According to [5], the accuracy of the MLCC method is around a few hundreds of Hertz. Thus, the error of the result should be limited to within PRF/2.

The technique employed to separate the signal into two looks is very important. The sensitivity of the MLCC method is highly dependent on the bandwidth of each look, BW, and the looks separation, Δf. The accuracy is proportional to the FM rate of the radar pulse, K_r, and the chirp duration, T_r. In order to secure the reliability of the estimation result, the maximum of the looks separation has to be limited to $\Delta f_{\max} = 2/3\,|Kr|\,Tr$ and the maximum of the look bandwidth to $BW_{\max} = |Kr|\,Tr/3$. The maximum looks separation could be achieved by setting the looks at the edge of the signal.

The MLCC method is an offset dependent Doppler Ambiguity Estimator. This means that the Doppler frequency slightly depends on the transmitted chirp frequency. The effect could be seen by plotting a graph of Doppler frequency versus transmission frequency. The intercept in the graph is the offset frequency for MLCC equation, f_{os}. Thus, to be more accurate in the MLCC estimation, the absolute Doppler centroid parameter should be as (16):

$$f_{dc} = f_{rac} + (M_{amb}\ * PRF) + f_{os} \tag{16}$$

3. PROPOSED METHOD

The conventional MLCC method only works best for low contrast scene [6], and its sensitivity to the evaluated area is not as high as the MLBF method. With the complexity of the signal processing procedure, the absolute Doppler centroid estimation is definitely time consuming which is not suitable for real time processing. Consequently, the modified MLCC method is introduced to improve the performance of the existing method.

Instead of dividing the range compressed signal into two looks in the conventional method, now the modified MLCC algorithm divides the bandwidth into four looks equally.

$$S_x(\eta) = w_a(\eta - \eta_c)\exp\left[\frac{-j\ 4\pi\left(f_0 - \frac{x\triangle f}{4}\right)R(\eta)}{c}\right] \tag{17}$$

where $x = 1, 2$.

$$S_y(\eta) = w_a(\eta - \eta_c)\exp\left[\frac{-j\ 4\pi\left(f_0 + \frac{y\triangle f}{4}\right)R(\eta)}{c}\right] \tag{18}$$

where $y = 1, 2$.

For the modified MLCC method, the fractional part of the PRF is extracted by averaging the four ACCC angles for the average phase increment of four.

$$f_{rac} = -\ \left[\frac{PRF}{2\pi}\left(\frac{\emptyset_1 + \emptyset_2 + \emptyset_3 + \emptyset_4}{4}\right)\right] \tag{19}$$

Since the signal has been divided into four looks, the frequency difference, $\Delta f'$, and the total phase difference of four looks, $\triangle\emptyset'$, are restructured as (21) and (24)

$$\Delta f_{ij} = f_i - f_j \tag{20}$$

$$\Delta f' = \sum \Delta f_{ij} \tag{21}$$

$$\Delta\emptyset_{ij} = \emptyset_i - \emptyset_j \tag{22}$$

or

$$\Delta\emptyset_{ij} = \arg\left\{ \overline{Look_i(\eta)} \left[\overline{Look_j(\eta)}\right]^* \right\} \tag{23}$$

$$\triangle\emptyset' = \sum \Delta\emptyset_{ij} \tag{24}$$

where $i = 1$, 2, 3 and $j = 2$, 3, 4.

Finally, the absolute Doppler centroid parameter can be rewritten as

$$f'_{dc} = -\frac{PRF f_0 \Delta\emptyset'}{2\pi\Delta f'} \tag{25}$$

The flow chart of the complete modified MLCC method is shown in Figure 1.

4. IMPLEMENTATION

The proposed modified MLCC method is tested by using the Vancouver scene of the RADARSAT-1 SAR data. For each block, 2048 range cells × 2048 range lines are extracted.

Firstly, range compression is performed on the raw SAR data. Then, range compressed signal in range time domain is equally separated into four looks, each look with the same amount of bandwidth, BW. Next, we compute the ACCC of each look and the frequency difference between looks, and the results are applied into (24) and (21). The M_{amb} is obtained by subtracting f'_{dc} from f_{rac}, and the result is divided by the PRF value. The acquired M_{amb} number is rounded up to the closest integer value. Lastly, all the acquired values are applied into the (25) to estimate the absolute f'_{dc}.

5. RESULTS

The experimental results are summarized in Table 1. Total of 6 blocks from the RADARSAT-1 real data, from the Vancouver scene have been extracted and evaluated by both the original MLCC method (two looks) and the modified MLCC method (four looks). Different types of

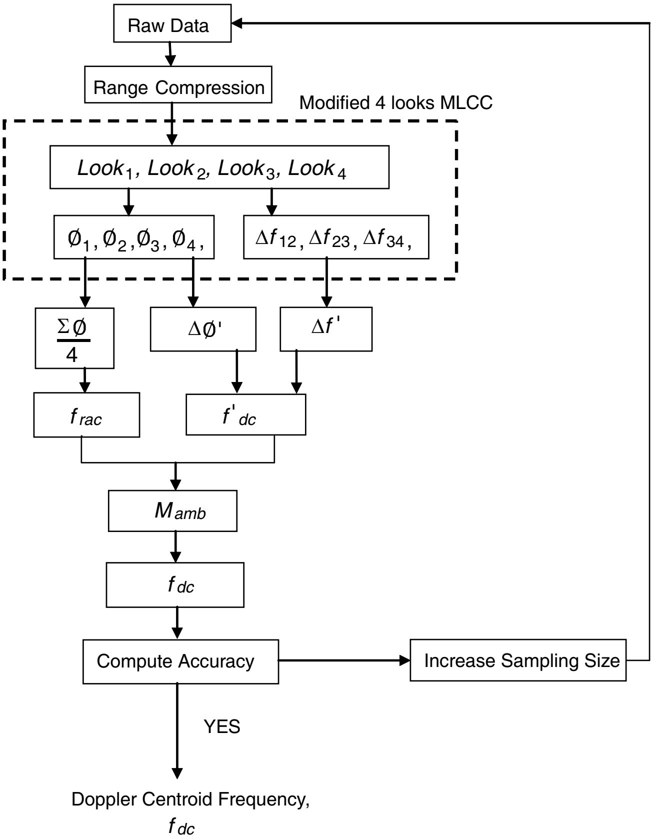


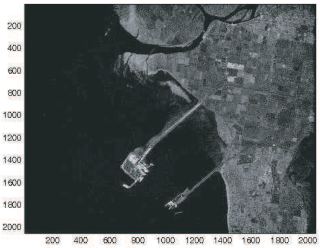
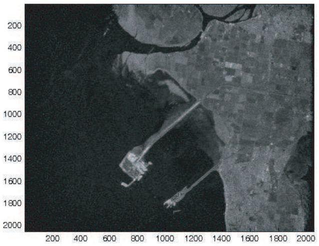
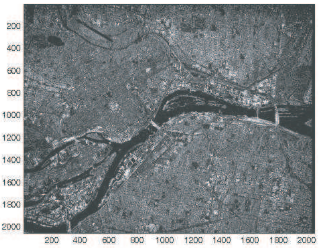
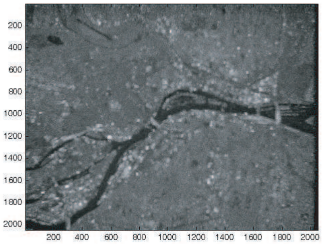
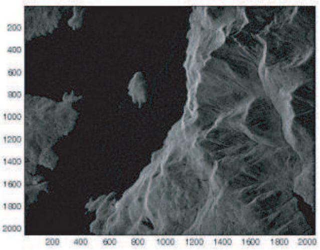
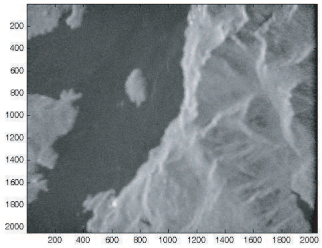
Figure 1. Flow chart of modified MLCC method.

Table 1. Comparison of the Doppler centroid estimation results.

	Modified MLCC (4 Looks)		Original MLCC (2 Looks)	
Block	f_{dc} (Hz)	Accuracy	f_{dc} (Hz)	Accuracy
1	6,876.10	0.019	9,342.70	1.943
2	6,678.50	0.176	14,260.00	5.855
3	6,866.40	0.027	18,170.00	8.966
4	6,833.30	0.053	27,667.00	16.521
5	6,688.10	0.169	19,274.00	9.844
6	6,632.50	0.213	19,250.00	9.825

landscape have been covered, including high and low contrast scenes. From the result shown, 90% of the total evaluated raw data managed to estimate the correct ambiguity number and give the precise Doppler centroid parameter.

The least difference between the estimated Doppler centroid value and the reference value ($-6900\,\mathrm{Hz}$) was only $23.9\,\mathrm{Hz}$, and the largest difference was $267.50\,\mathrm{Hz}$. The result shows that the modified MLCC method has higher accuracy than the original MLCC method. Besides, it also kept the accuracy to the remainder of below 0.2 PRF.

Block	Image from 4 Looks MLCC	Image from 2 looks MLCC
1		
2		
3		

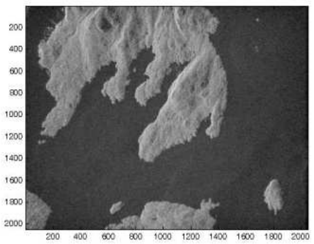
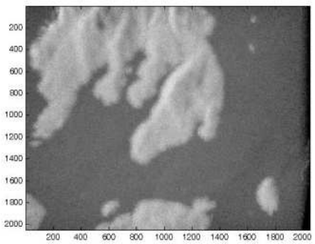
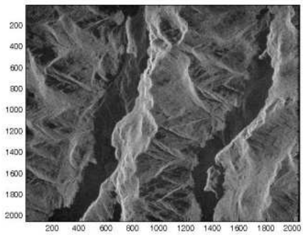
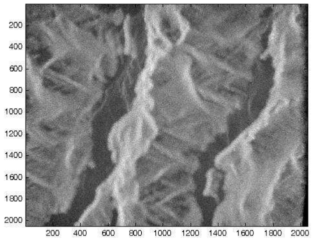
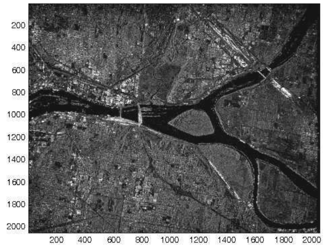
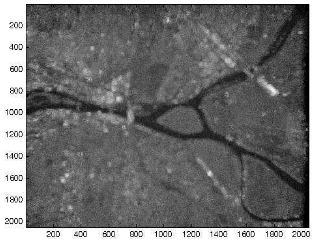
4		
5		
6		

Figure 2. Images generated from estimated doppler centroid.

The SAR images shown in Figure 2 are generated by using the estimated Doppler centroid stated in Table 1. Note that better quality images are generated with the Doppler centroid estimated from the modified MLCC method. The images are in higher resolution, sharper, and clearer to be viewed.

By applying parallel signal processing, the processing speed for the four looks MLCC algorithm is faster than that of the two looks'. The results of the time consumption for both the original and modified MLCC methods over the 6 generated blocks are summarized in Table 2. Averaging the original MLCC method took approximately 1.2345

Table 2. Comparison of the time consumption of Doppler centroid estimation.

	Time Consumption (seconds)	
Block	Modified MLCC	Original MLCC
1	0.7132	1.2388
2	0.7088	1.2395
3	0.7098	1.2297
4	0.7143	1.2356
5	0.7112	1.2293
6	0.7011	1.2342

seconds to complete the estimation job, but for the modified MLCC methods, it took only 0.7097 seconds, which is roughly 42.51% less. The time consumption is better because of the data size for each of the four looks is smaller, hence it could be processed faster, and the signal processing is less time consuming. The experimental results prove that the improvement of the time consumption does not degrade the reliability of the estimation result.

6. CONCLUSION

Based on the experimental results, the modified MLCC algorithm works well in all types of data, both high and low contrast scenes. The ambiguity number and the absolute Doppler centroid could be correctly estimated. The sharpness and quality of the image generated using the proposed method is better than that of the existing method. This modified MLCC method is very suitable for parallel signal processing and could be implemented into real-time SAR system as well because it has better time efficiency.

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