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MODIFIED ALGORITHM FOR REAL TIME SAR SIGNAL PROCESSING

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Abstract—The generation of the picture out of the SAR raw data is a computational intensive task. Both range compression and azimuth compression utilized Fast Fourier Transform (FFT) algorithms and Inverse Fast Fourier Transform (IFFT) in order to perform convolution with respective reference signal. Thus FFT and IFFT occupied about 70% of the total computation operation in SAR image formation. In this paper a modified algorithm based on conventional FFT is proposed to optimize the computation performance. It is shown that the proposed algorithm can essentially achieve better performance with minimum computational burden compare to conventional FFT.

1. INTRODUCTION

Radar has long been used for military and non-military purposes in a wide variety of applications such as imaging, guidance, remote sensing and global positioning Modern SAR system uses digital signal processing to improve the imaging resolution beyond the limitation of physical antenna aperture. With the radar system mounted on a flying platform, the forward motion of actual antenna is used to 'synthesise' a very long antenna. SAR allows the possibility of using longer wavelengths and still achieving good resolution with antenna structures of reasonable size [1].

SAR is an important tool for the collection of high-resolution all-weather earth images, from both airborne and space-borne platform. The potential of SAR in a diverse range of application such as sea and ice monitoring [2], mining [3], oil pollution monitoring [4], oceanography [5], snow monitoring [6], classification of earth terrain [7] etc. led to the development of a number of airborne and spaceborne SAR systems [8]. An extensive literature exists on various processing techniques for generating an image from the radar returns of a SAR [2, 9–14]. The SAR signal processing can be broken into two phases: range processing and azimuth processing. Most coherent radars use some form of modulation or coding of the transmitted waveform to improve resolution. Resolution enhancement is achieved by two-dimensional signal processing of the radar data. Range (across-track) resolution is improved by correlation of the pulse echoes with transmitted pulse in the range compression process. Azimuth (along-track) resolution is improved by synthetically generating a long antenna aperture, while the real aperture is relatively small. This operation is known as azimuth compression. Azimuth compression is based on the fact that each echo reflected from a single point target has a different phase shift. This phase shift appears to be quadratic in time and results in a linear frequency shift of the successive pulse echoes. The azimuth compression operation focuses the echo signal in such a way that a zero phase shift remains and integrates the focus echo. As a result the resolution is improved.

The generation of the picture out of the SAR raw data is a computational intensive task. Both range compression and azimuth compression can be summarised as time domain convolution with respective reference signal. In order to reduce the computational load, the time domain correlation processes are often completed in frequency domain. The transformation between time and frequency domain is performed by Fourier Transform (FT) algorithms and Inverse Fourier Transform (IFT) algorithms. They require most of the processing power of SAR signal processing. The block diagram of SAR signal processing in frequency domain is shown in figure 1. Although some architectures for SAR data processing have been developed to speed-up the processing time, powerful computing systems are still required to generate the image in real time. On the other hand, real time SAR imaging could play a very important role in applications as diverse as identifying man made objects on the ground, search and rescue operation or estimating earth surface activities. In this paper a modified algorithm for reducing the computational load of FT is proposed.

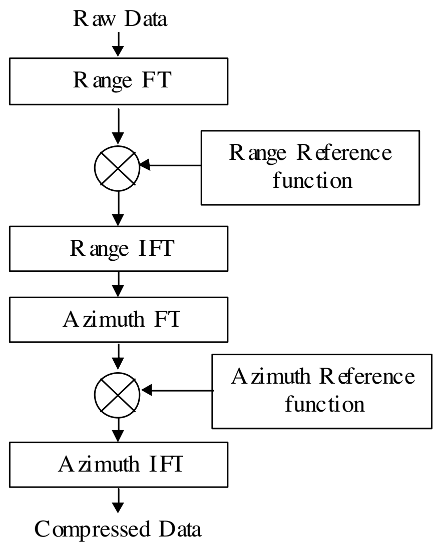

Figure 1. SAR processing in frequency domain via FFT.

2. PROBLEM STATEMENT

Fourier Transform (FT) is an important tool in SAR signal processing which plays a major role in convolution process of range and azimuth compression. Numerous textbooks devoted to the theory, properties and implementation of FT to digital processing [15–18] are available. In order to process the signal digitally either with computer or others dedicated digital processor, it is essential that the quantities involved be discrete. A sampled time signal satisfies this requirement. A FT that involves sampling both in time and frequency is called discrete FT (DFT). For a discrete-time signal $g(n)$ of length N, the DFT pair can be written as:

$$\text{DFT} : G(k) = \sum_{n=0}^{N-1} g(n) \exp\left\{-j\frac{2\pi kn}{N}\right\}, \quad k = 0, 1, \dots, N-1 \quad (1)$$

$$\text{IDFT} : g(n) = \frac{1}{N}\sum_{n=0}^{N-1} G(k) \exp\left\{j\frac{2\pi kn}{N}\right\}, \quad n = 0, 1, \dots, N-1 \quad (2)$$

The forward N-point DFT and its inverse, the IDFT, each requires an order of N^2 operations. To be specific, the total computational load of an N-point DFT is N^2 complex multiplications and $N(N-1)$ complex additions, where one complex multiplications consists of four real multiplication and two real additions, and one complex additions consists of two real additions. Thus each N-point DFT consists of $4N^2$ number of real multiplications and $4N^2 - 2N$ of real additions.

When N is a power of 2, fast FT (FFT) methods exist to implement the DFT or IDFT efficiently [15–18]. The most important fact about all FFT algorithms is that they are mathematically equivalent to DFT and FFT improves the DFT by reducing the computational load. The number of operations in the N-point FFT or its inverse, the IFFT, is the order of $N \log_2 N$, when N is a power of two. To be specific, the number of complex multiplications in radix-2 FFT is $(N/2) \log_2 N$, and the number of complex additions is $N \log_2 N$. FFT consists of $2N \log_2 N$ and $3N \log_2 N$ number of real multiplications and real additions respectively.

When the number of sample is not equal to a power of 2, a technique call zero padding can be used. Zeros are added to the sample signal to produce the length of the signal needed by FFT which is equal to a power of 2, i.e., 2^M where M is an integer. For SAR signal processing, the length of data in range or azimuth normally will not satisfied the condition of 2^M, thus zero padding is necessary. Padding a large number of zeros will greatly increase the computational load and reduce the processing efficiency. An effective FFT algorithm should be developed in order to reduce the computational load, thus reduce the hardware requirement for the realization of real time SAR imaging.

3. PROPOSED METHOD AND COMPUTATION COMPLEXITY

For a signal $g(n)$ with data length of N, if $N \neq 2^M$ but can be separated, let $N = N_1 N_2$ so that $g(n)$ can be divided into a number of N_2 arrays with data length of N_1. Thus an N point 2-dimensional DFT can be written as,

$$\begin{aligned} &G(k) \\ &= \sum_{n_2=0}^{N_2-1} \sum_{n_1=0}^{N_1-1} g(N_2 n_1 + n_2) e^{-2\pi \frac{(k_1 + N_1 k_2)}{N_1 N_2}} e^{-2\pi \frac{(N_2 n_1 + n_2)}{N_1 N_2}} \\ &= \sum_{n_2=0}^{N_2-1} \sum_{n_1=0}^{N_1-1} g(N_2 n_1 + n_2) e^{-2\pi \frac{N_2 n_1 k_1}{N_1 N_2}} e^{-2\pi \frac{k_1 n_2}{N_1 N_2}} e^{-2\pi \frac{N_1 k_2 n_2}{N_1 N_2}} e^{-2\pi \frac{N_1 k_2 N_2 n_1}{N_1 N_2}} \end{aligned} \tag{3}$$

Since $e^{-2\pi\frac{N_2 n_1 k_1}{N_1 N_2}} = e^{-2\pi\frac{n_1 k_1}{N_1}}$, $e^{-2\pi\frac{N_1 k_2 n_2}{N_1 N_2}} = e^{-2\pi\frac{k_2 n_2}{N_2}}$, $e^{-2\pi\frac{N_1 k_2 N_2 n_1}{N_1 N_2}} = e^{-2\pi N_2 n_1} = 1$, therefore Equation (3) can be further expressed as,

$$G(k)=\sum_{n_2=0}^{N_2-1}\left\{\sum_{n_1=0}^{N_1-1}\left[g\left(N_2 n_1+n_2\right)e^{-2\pi\frac{n_1 k_1}{N_1}}\right]e^{-2\pi\frac{k_1 n_2}{N_1 N_2}}\right\}e^{-2\pi\frac{k_2 n_2}{N_2}} \quad (4)$$

Therefore the DFT of a signal with data length of N can be processed in three steps: N_2 numbers of N_1-point FFT, follow by N_1 numbers of N_2 point complex multiplications and finally N_1 numbers of N_2-point DFT. If N_1 is power of two, then standard radix-2 FFT algorithm can be used to reduce the computational load. The total number of real multiplications and additions operations for the proposed method is summarized in Table 1. The selection of N_1 and N_2 will affect the computation efficiency. In order to minimize the computational load, N_1 should be a number much larger than N_2 and in the form of power of two so that FFT can be utilized to increase the computation speed.

Table 1. Computation load of N-point FFT and N-point proposed modified FFT method.

	Real Multiplication	Real Addition
FFT	$2N\log_2 N$	$3N\log_2 N$
Proposed Modified DFT	$2N_1N_2\log_2 N_1 + 4N_1N_2^2$ $-4N_1N_2 + 4N_1$	$3N_1N_2\log_2 N_1 + 4N_1N_2^2$ $-4N_1N_2 + 2N_1$

4. SAR PROCESSING IMPLEMENTATION

In SAR image formation, FFT occupied about 70% of the total computation operation. Thus through optimizing the FFT algorithm, the computational load can be reduced and the overall computation speed of SAR signal processing can be further improved. As an example, a SAR raw data contains 1200×2800 array of data (1200 range point and 2800 azimuth point) is considered. Figure 2 shows the required signal flow in the SAR signal processing involved particularly FT and IFT processing. During the Range compression process, it involved 2800×1200 point FT and 2800×1200 IFT. All the data will be feed to the corner turning memory for preparation of azimuth compression. In azimuth compression, another 1200×2800 point FT and 1200×2800 IFT is required.

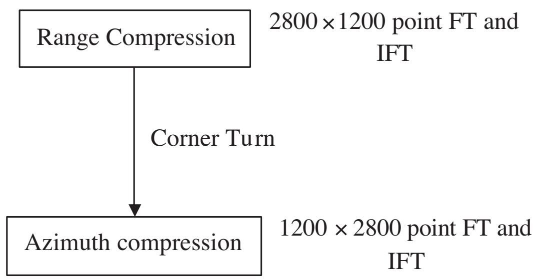

Figure 2. SAR image formation signal flow chart.

For conventional FFT method, 1200 range point need to be zero padded to 2048 point and for 2800 point in azimuth direction need to be zero padded to 4096 point in order to perform FFT and IFFT in both compressions. Therefore the required computation load will be greatly increased; the memory requirement and data bandwidth of the SAR processor have to be increase as well. The signal flow chart for conventional FFT and IFFT is shown in Figure 3.

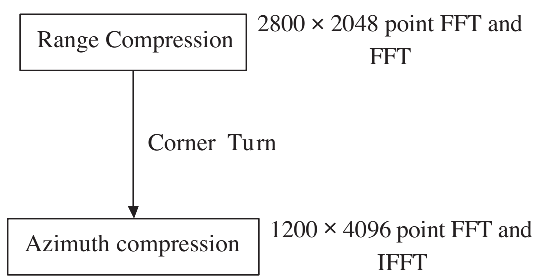

Figure 3. Conventional SAR image formation signal flow chart using FFT & IFFT.

4.1. SAR FFT Modified Algorithm

In SAR image formation, the number of N point required by FFT depends a lot on the radar system raw data and resolution required which normally will not be equal to order of power of two, therefore zero padding is necessary before performing FFT and IFFT. In order to minimize the computational load using the proposed method, selection for the number of zero padding must be followed the following principle: number of data point N' must be as small as possible which $N' = N_1 \times N_2$, N_1 should be as large as possible and possible in the order of power of two so that FFT can be utilized to increase the computation speed; and N_2 should be as small as possible and usually is a odd number. Therefore in order to minimize the computational load in range and azimuth direction, searching procedure of correct value of N', N_1 and N_2 is proposed as below:

(i) Initial value of M is determine as $M = \text{int}(\log_2 N)$, where int( ) means truncated to an integer number.

(ii) Zero padding so that $N' = N_1 \times N_2 = 2^{M-1} \times N_2$ where N_2 is an odd number. Besides the number of N' must satisfy the condition of $N \leq N' \leq 2^{\text{int}(\log_2 N)+1}$.

(iii) Let $m = m - 1$, repeat step (ii) until $m = 2$.

(iv) Compare the computational amount of all possible solution by using formula listed in Table 1, the smallest number of operation involved will determine the number of N'.

For conventional radix-2 FFT, $N = 2048$ and 4096 will be used for range and azimuth processing respectively. For the proposed method, let the range point to be decomposed as $N = 512 \times 3 = 1536$, therefore 336 zeros to be added. For azimuth direction, one can choose $N = 1024 \times 3 = 3072$ (i.e., 272 zeros to be added to 2800 data point). The propose scheme is illustrated in the figure below.

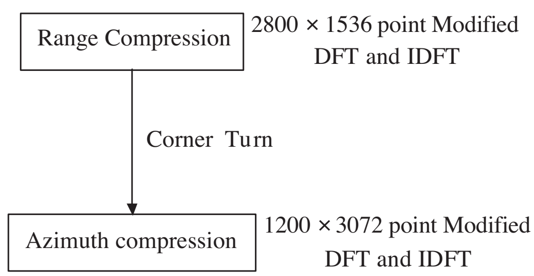

Figure 4. Modified SAR image formation signal flow chart using proposed method.

The number of operations for the proposed method is calculated and listed in Table 2. It is shown that the computation operations of the proposed method is significantly less than the conventional radix-2 FFT especially for number of data point which is much lesser than 2^M. In addition, the algorithm will support implementation of parallel processing hardware architecture where the various sub-arrays of data points are processed by separate units of microprocessor. This will further enhance the processing speed of real-time SAR signal processing.

Table 2. Case study of computation operation based on 1200×2800 array of data.

a) 1200 data point (range direction)

	Real Multiplication	Real Addition
FFT	45056	67584
Proposed Modified DFT	41984	54784
Percentage of improvement	6.81%	18.9%

b) 2800 data point (azimuth direction)

	Real Multiplication	Real Addition
FFT	98304	147456
Proposed Modified DFT	90112	118784
Percentage of improvement	8%	19.4%

c) Total number of operation to process 1200×2800 array of data for both methods

	Real Multiplication	Real Addition
FFT & IFFT	488243200	731364800
Proposed Modified DFT and Inverse	451379200	591872000
Percentage of improvement	7.55%	19.07%

5. CONCLUSION

A modified algorithm based on conventional FFT is proposed to optimize the computation efficiency. The number of data points is divided into a few sub-arrays to be processed separately. The computational load is analyzed and an example is given to illustrate the improvement provided by the proposed algorithm. In addition to increasing the computation speed, the algorithm also support the implementation of parallel processing hardware architecture. The implementation of such scheme into SAR system will greatly improved the processing efficiency for real-time SAR image formation.

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