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Signal Processing for Synthetic Aperture Radars

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Abstract—This paper presents the synthetic aperture radar principles. The introduction to signal processing for synthetic aperture radars is made using processing of coherent digitized radar. The SAR properties in range and azimuth directions are described and signal processing for target reflection is presented. The received signal is theoretically described. The SAR raw data, which represent the revived image is theoretically presented. The image formation algorithm is presented using pulse compression waveforms for high range resolution and optimal transmitter power, Doppler processing for clutter rejection and enhanced cross-range imaging is presented. The synthetic aperture radar image formation is described using range migration and chirp scaling algorithms.

Keywords-Synthetic Aperture Radar,raw data, focusing.

I. INTRODUCTION

The Synthetic Aperture Radar systems are all weather, day and night monitoring systems, which use the electromagnetic radiation for image retrieval. SAR is one of the most advanced engineering inventions systems in the last decade. Specific radar systems are imaging radars, such as side looking SAR and SAR. Practical restriction to the length of the antenna resulted in very coarse resolution in the flight direction. Using a fixed antenna, illuminating a strip or swath to the sensor's ground track, resulted in the concept of stripping mapping. Modern phased-array antennas are able to perform even more sophisticated data collections strategies, as ScanSAR, spotlight SAR, but the strip map mode is the most applied mode on current satellites [1]. The concept of using frequency (phase) information in the radar signal's along-track spectrum to discriminate two scatters within the antenna beam goes back to 1951 (Carl Wiley). The key factor is coherent radar,, where the phase and amplitude are received and preserved for later processing., but long antenna was required. The early SAR systems were based on optical processing of the measured echoed signal using the Fresnel approximation for image formation and are known as range-Doppler Imaging or polar format processing. The experience on airborne SAR systems in 60's and 70's culminated in L-band SAR system Seasat, a satellite launched in June 1978, primarily for ocean studies, the live time was 100 days, but the imaginary was spectacular, highlighting if geologic information and ocean topography information. Since 1981 Shuttle missions carried SAR systems. The first instrument was the Shuttle Imaging radar SIR laboratory and operated for 2.5 days. An improved version of SIR-A orbited the Earth in 1984 and was able to steer the antenna mechanically to enable different angels. Cosmos 1870 was the first S-band SAR satellite of former Soviet Union, launched in 1987 and orbited at a height of 270 km and operated for 2 years, ALMAZ-1 was the second satellite launched in 1991 and operated for 1.5 years. First European Remote Sensing Satellite ERS-1 was operational in 1991 and operated until March 2000. Japan sarted spaceborne SAR program in 1992 with JERS in 1992, SIR-C/X-SAR was developed by JPL, DLR and ASI operated with C, L and X band. Canadian Space Agency lounche Radarsat in 1995 in 2000 topography SRTM (Shuttle Radar Topography mission) was carried out between 11 and 23 February 2000.

II. SYNTHETIC APERTURE RADAR CONCEPT

The central idea of SAR processing is based upon matched filtering of the received signal in both the range and azimuth directions. Matched filtering is possible because the acquired SAR data are modulated in these directions with appropriate phase functions. The modulation in range is provided by the phase encoding of transmitted pulse, while the modulation in azimuth is created by the motion in the signal [2]. The point targets are arrayed in a Cartesian type Coordinate system space defined by range, azimuth, and altitude as analogs of x, y and z directions. The altitude direction is omitted in the two-dimensional simulation. The platform in this simulation is an antenna attached to a plane traveling at an orbital velocity, along the azimuth direction and at the midpoint in the flight, the distance to the target equals the range of closest approach or minimum range to target. As an satellite platform is used in the simulation, the curvature of the earth is considered negligible and the orbital velocity is approximately equal to the platform velocity.

The transmitted radar signal, x(t), is assumed to be a chirp pulse (linearly frequency modulated signal) given by [3]

$$x(t) = rec\left(\frac{t}{T_r}\right)\cos\left\{2\pi f_o + \pi K_r t^2\right\}$$

where f_o=9.43GHz, pulse duration Tr=25μs, $B_0 = K_t T_r$ (frequency bandwidth of the chirp)=300MHz, KR is range of the FM rate, measured MHz/ μs. The chirp signal in time domain and its impulse response are shown in Fig. 1.

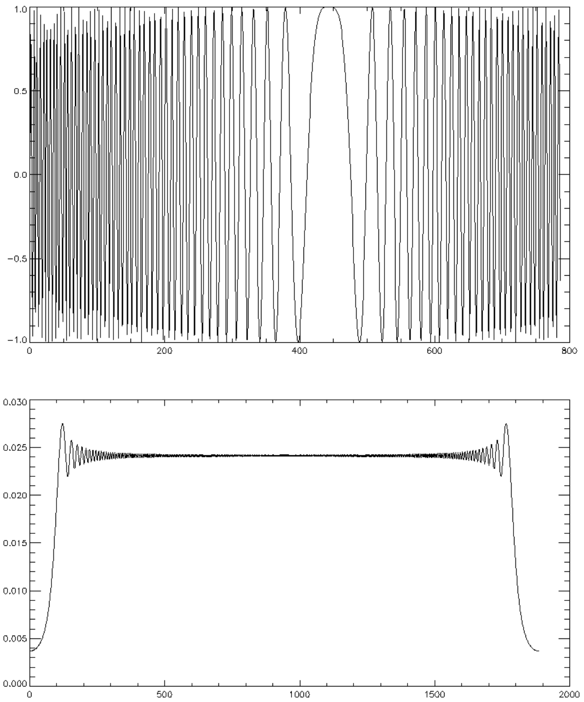

Figure 1. Chirp in time domain and its frequency response.

The range resolution of the transmitted signal is

$$\Delta R = \frac{c}{2B_0}$$

the transmitted radar signal as a cosine with a linearly ramping up frequency over a transmit duration followed by a null receive duration. The transmit window is called the pulse envelope, and defines the duration of the transmission. During the receive duration, the antenna waits to receive reflected radar signals from the targets contained in a one-dimensional range slice echo as function of quick time. One over the combined transmit and receive duration is called the pulse repetition frequency, PRF, and defines the amount of pulses transmitted per second..

The chirp signal is complex and has a complex envelope g(t) [4]

$$x(t) = g(\tau)\exp(j2\pi f_0 \tau)$$

Let a point scatterer has a dimension, smaller then the wavelength $\lambda = c/v_0$ be located at a distance R – range away from the radar. The radar platform has a velocity v. The point is seen at the elevation angle θ and azimuth angle β from the antenna main pointing direction. The received echo is proportional to the transmitted wave and delayed by the round-trip delay 2R/c.

$$a_\theta(\theta)a_\beta(\beta)g(\tau - 2R/c)\exp\left\{2j\pi v_0(\tau - 2R/c)\right\}$$

Here we assume that the antenna pattern is separable: $a_\theta(\theta)$ and $a_\beta(\beta)$ are the amplitude two-way antenna patterns in elevation and azimuth. The azimuth pattern is sinc^2 for small angles β= λ/L $a_\beta(\beta) = \sin c^2(\beta L/\lambda)$. For TerraSAR-x wavelength is 0.032 m.

In the receiver the echo signal is coherently demodulated , i.e. carrier frequency is removed, resulting echo signal of the point scatterer:

$$a_\theta(\theta)a_\beta(\beta)g(\tau - 2R/c)\exp\left\{-4j\pi R/\lambda)\right\}$$

The phase term depends on R, governs the interference of echoes from different scatterers. The shape of the pulse envelope g(τ) determines the range resolution of the radar, it is the ability of radar to distinguish two scatterers at slightly different ranges.

$$g(\tau) = \sin c(\tau B)$$

And its Fourier transform

$$g(\tau) = rec(\tau B)$$

The achievable range resolution defined as half power width of g(τ)

$$R = 0.885\frac{c}{2B_0}.$$

To avoid high peak transmit power, long duration phase coded pulses are prefer to short sinc functions, the ideal is chirp function.

The chirp functions can be compressed to a sinc function by correlation with a chirp function with the same frequency rate, thus leading to the resolution as given in xx. This so-called range compression is often the first step in SAR data processing. The only relevant parameter influencing on range resolution is range pulse bandwidth.

In range only one pulse was considered for explanation. As the sensor advances along its path, subsequent pulses are transmitted and received by radar. The pulses are transmitted every 1/PRF (pulse repartition frequency). The target is illuminated by many pulses. The strength of each pulse varies, primarily because of the azimuth beam pattern.

The signal strength decreases until target lies in the first null of the pattern beam. The energy in outside the main beam contributes to the azimuth ambiguities in the processed image. The received signal ahs the same waveform as transmitted signal, but it is much weaker and has a frequency shift governed by the relative speed of the sensor and the scatterer. If the distance between target and antenna is decreasing, the frequency of the received signal decreases. This effect is called SAR Doppler frequency. The beam pattern is approximately sinc function and the received power is square of $a_\beta(\beta)$.

$$a_\beta(\beta) = \sin c \frac{vL}{\lambda r_0}$$

The received signal from the target consists of several parameters, which depicts azimuth chirp and range migration effect. The received signal consists of (i) amplitude range dependence and the elevation antenna pattern, (ii) part which reflects 2-way antenna pattern of the sensor, which represents the synthetic aperture length and is proportional to range r_0, (iii) echo signal envelope and its position in fast time, (iv) the factor, wich translates the range trajectory of the point scatterer into a phase history, it is called azimuth chirp and its frequency is given by

$$f_D = \frac{1}{2\pi}\frac{d}{dt}\varphi(t-t_0) = \frac{-2}{\lambda}\frac{v^2}{r_0}(t-t_0)$$

It is also called Doppler frequency. The Doppler frequency at the beam center is Doppler Centroid f_{DC}

$$f_{DC} = f_D(t+t_c) = \frac{-2}{\lambda}\frac{v^2}{r_0}t_c = FM \cdot t_c$$

Where FM is frequency modulation rate of the azimuth chirp. The FM rate is always negative.

$$FM = \frac{-2}{\lambda}\frac{v^2}{r_0}$$

Coarse approximation can be written as

$$h_a(\tau,t) = C(r_0)a_\beta(v(t-t_0)/r_0)g(\tau)\exp(j\pi FMt^2)$$

The azimuth resolution is given by

$$A = \frac{0.866v\cos\theta}{f_{DC}} \approx \frac{L}{2}$$

The azimuth resolution is independent of range, velocity or wavelength. The actual resolution is a function of how much of the bandwidth is processed and the combined shape of the beam pattern and the weighting function. The received and demodulated radar signal is referred to as the SAR signal space as it is still in its raw form and the two-dimensional image of the magnitude of the two-dimensional imaginary signal would not allow recognition of targets.

III. RANGE MIGRATION FOCUSING ALGORITHM

The range Doppler algorithm (RDA) [5] was developed in 1976-1978 for processing SEASAT SAR data. Later it was used to digitally process space borne SAR image in 1978 and it is still the most widely used algorithm today. RDA operates in range and azimuth frequency domain, but it has the simplicity of one-dimensional operations. The reflected energy from areas on the earth's surface in the same range but in different azimuth, are located on the same azimuth frequency. So, when this frequency is adjusted, the whole target areas with the same frequency (which means in the same range) are adjusted. RDA uses the large difference in time scale of range and azimuth data and approximately separates processing in these two directions using Range Cell Migration Correction (RCMC). RCMC is the most important part of this algorithm. RCMC is performed in range frequency and azimuth frequency domain. Since, azimuth frequency is affected by Doppler Effect and azimuth frequency is bonded with Doppler frequency, it is called Range Doppler Algorithm. RDA can be implemented in three different ways. But they all have similar steps and their difference is only in Secondary Range Compression (SRC). The main steps of RDA are: 1- Range compression 2- Azimuth FFT (transform to range Doppler domain) 3- RCMC 4- Azimuth filtering 5- Inverse FFT (return to range azimuth time domain) 6- Image formation.

Range compression is implemented using matched filter. The filter is generated by taking the complex conjugate if the FFT of the zero padded pulse replica, where the zeros are added to the end of the replica array. The output of the range matched filter is the inverse transform between range Fourier transformed raw data and the frequency domain matched filter. Each azimuth signal is Fourier transformed via an azimuth FFT and RCMC is performed before azimuth matched filtering in the range-Doppler domain. After azimuth matched filtering of each signal and azimuth inverse fast Fourier transforms (IFFTs), the final target image is obtained.

IV. CHIRP SCALING FOCUSING ALGORITHM.

The chirp scaling algorithm (CSA) was developed specifically to eliminate the interpolator used in RCMC it is based on the scaling principle where a frequency modulation is applied to a chirp-encoded signal to achieve a shift or scaling of the signal. Chirp scaling uses a phase multiply to equalize the range migration of all target trajectories. Since the data is available in two dimensional frequency domain, this algorithm has the benefit of making the SRC dependent to azimuth frequency. The steps of CSA are: 1- Azimuth FFT which transforms data to range Doppler domain 2-

Applying Chirp Scaling 3- Range FFT which transforms data to two-dimensional frequency domain. 4- A phase multiply applies range compression, secondary range compression and RCMC at the same time 5- Range IFFT which returns data to range Doppler domain 6- Another phase multiply applies azimuth compression with a range-dependent matched filter 7- Azimuth IFFT which returns data to range azimuth time domain.

V. EXPERIMENTAL RESULTS

The goal of the experimental results is to show some simulation of the TerraSAR-X data. The parameters for TerraSAR-X data are shown in Table 1. The real part of the chirp signal in range is shown in Fig. 1 and its Fourier transform.

TABLE I. PARAMETERS FOR SPOTLIGHT MODE

Parameter	
Carrier Frequency F_0	***9.65GHz***
Wavelength λ	0.032m
Chirp duration Tp	11.428µs
Chirp Bandwidth B	150MHz
Range Sampling frequency Sf	165MHz
PRF	3500
Range Chirp rate Kr=B0/Rp	13125G
Platform velocity	7300
Length of antenna La	4.8

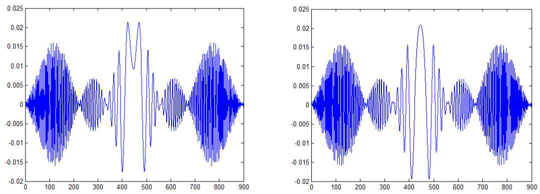

Figure 2. Real and imaginary part of the received signal

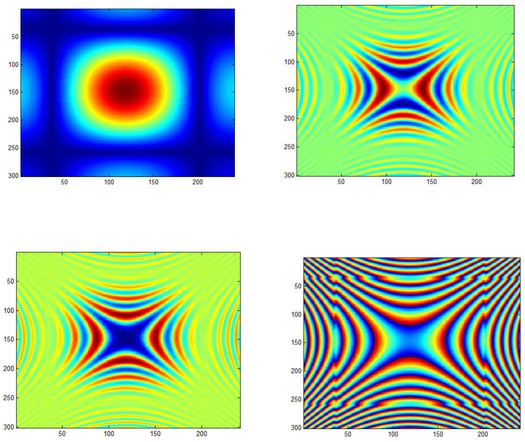

Figure 3. Simulated SAR raw data: amplitude, real part, imaginary and phase

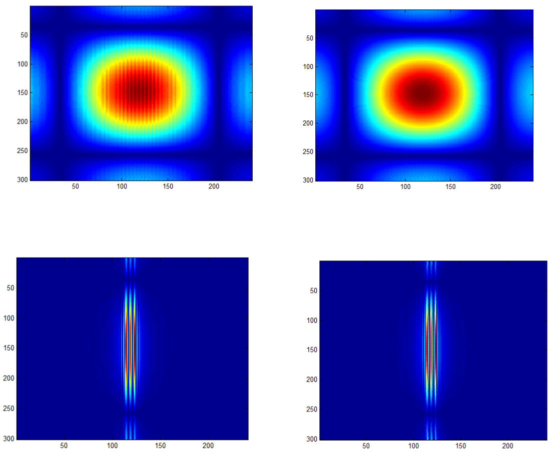

Figure 4. RDA: Range FFT, Range Matched Filtered, Range IFFT, Azimuth IFFT of RCMC

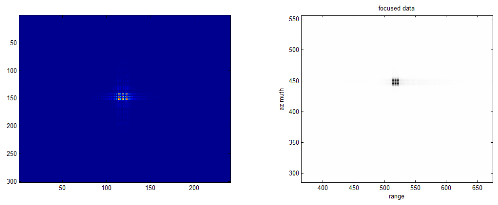

Figure 5. The final result with the RDA and chirp scaling

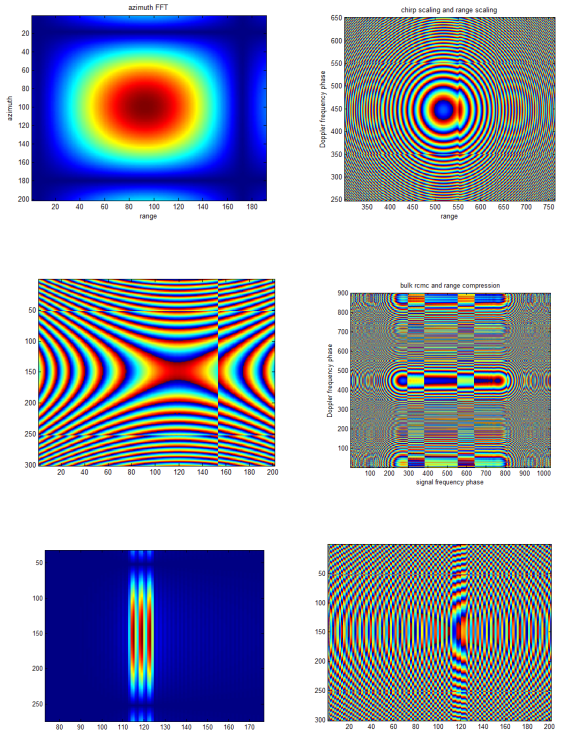

Figure 6. Azimuth FFT, phase of Chirp Scaling, range FFT, range compression,range IFFT, phase pf range doppler after phase correction

The response from the target is shown in Figure 2, where one line of the image, depicted in Fig. 3 is shown. Fig. 1 can be also represented by Fig 2, where the azimuth range migration can be noticed. Fig 3. Shows the SAR raw data obtained form the target with 10×10 pixels. The Range FFT image, Range Matched Filtered image, Range IFFT image and Azimuth IFFT of RCMC are shown in Fig. 4. Those responses belong to the RDA focusing algorithm. The responses of the chirp scaling algorithm are shown in Fig. 6. Fig. 7 shows the responses of the stationary and moving targets, where the velocity is depicted with the movement of the target. According to the movement and smeared of the target the velocity can be measured.

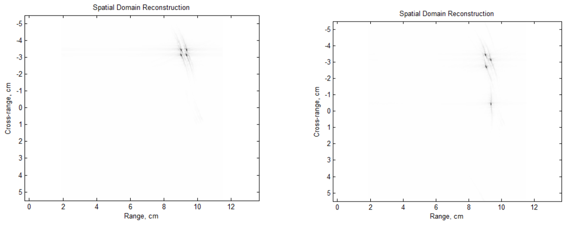

Figure 7. Simulation of Stationary and moving targets in SAR image.

VI. CONCLUSION

This paper presents the Synthetic Aperture Radar theory from generating signal to final image forming process. The chirp generation and properties in range and azimuth directions are shown, as well the response form the target is presented in order to collect received data and store them in the RAW data format. The RAW data can not be visually presented, therefore the focusing algorithm is required. range migration and chirp scaling algorithms for focusing of SAR data are presented.

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