SYNTHETIC APERTURE RADAR IMAGE FORMATON PROCESS: APPLICATION TO A REGION OF NORTH ALGERIA

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ABSTRACT

Synthetic aperture radar imaging provides high resolution images of large areas. The intensities of pixels in a SAR image are based on the spatial orientation, roughness, and dielectric constant of the surface imaged.
SAR is an active sensor, transmitting its own energy, and then measuring the return scattered by the earth's surface back to the satellite's antenna. SAR processing is the transformation of raw SAR signal data into a spatial image. In this communication, we present a contribution concerning implementation of a SAR image formation with the IDL language. This process is performed in a frequency domain correlation of the received signal including range compression, range migration, and azimuth compression.
The output is the final step in which the data is transposed back into its original format and written to an output file.
The data used are raw SAR image of scene of north Algeria of size 5616*28000 pixels of the 16 of February 1996. Evaluation of the method studied here is made on a Region of Reghaia lake (near of Algiers city) of 2048*5616 pixels.

1. INTRODUCTION

An intuitive introduction to basic SAR theory is given by Stimson [1]. More advanced treatments on basic SAR theory are provided by Sack and *al.* [2]. A theoretical basis for understanding SAR images and other texts with a treatment of SAR theory are offered by Curlander and McDonough [3].
The data for a SAR image is collected by a satellite with a sidelooking antenna, which transmits a stream of radar pulses and records the backscattered signal corresponding to each pulse. The rate or pulse repetition frequency (PRF) at which pulses are transmitted and received may be constant or may vary over time. Since the moving antenna beam covers a strip of the earth's surface, this type of SAR imaging is referred to as strip-map SAR.
SAR processing algorithms include the range-Doppler algorithm [4], the chirp scaling algorithm [5][6], and the range migration algorithm [7][8]. A comparison of SAR processing algorithms is given by Bamler [9].
The starting point for this research consists of three basic steps of SAR processing: range compression, range migration, and azimuth compression and the different contributions in the literature in the field of SAR image formation. For our part, the contribution is the implementation of the SAR process with the IDL language tested with Raw SAR data of Algerian zones.

2. IMAGE FORMATION

2.1. Geometry of SAR system

There are basically three operating modes of SAR system [10]: Stripmap scan and spot. The most popular is probably the strip mode. In this case, the radar antenna point along fixed position direction with respect to the flight platform path, and the antenna footprint covers a strip on the illuminated surface as platform moves (figure 1).

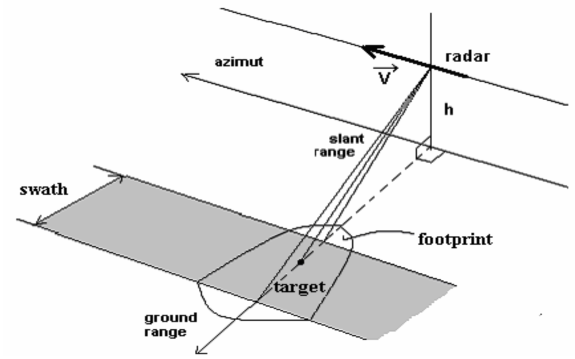

Figure 1: Side-looking strip-map SAR geometry.

The radar transmits pulses at the pulse repetition frequency, PRF, and for each pulse the backscatter return from the ground is sampled in range at the analog to digital (A/D) sampling frequency. The radar operation is coherent, which means that both the return magnitude and phase (with respect to the transmitted signal) are sampled. For each range sample the in-phase and quadrature values (I and Q) are stored. The raw data file is thus a two-dimensional array of complex values (with I as the real part and Q as the imaginary part). This two-dimensional data set is then processed to form an image.

2.2. Pulse Compression

Let us consider a radar system transmitting at microwave frequency, electromagnetic pulses of time duration Δt . The sensor range resolution is given by:

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$$\Delta R = \frac{c.\Delta t}{2} \tag{1}$$

Range resolution for a given radar can be significantly improved by using very short pulses. Unfortunately, using short pulses decreases the average transmitted power. Since the average transmitted power is directly linked to the receiver SNR, it is often desirable to increase the pulsewidth while simultaneously maintaining adequate range resolution. This can be made possible by using pulse compression techniques.

Pulse compression allows us to achieve the average transmitted power, while obtaining the range resolution corresponding to a short pulse.

If we consider the popular waveform referred to as chirp pulse (i.e., linearly frequency modulated signal) given in complex notation:

$$x(t) = \begin{cases} A \cdot \cos\left[2.\pi\left(f_0.t + K \cdot \frac{t^2}{2}\right)\right] & |t| \le \frac{\tau_p}{2} \\ 0 & otherwise \end{cases} \tag{2}$$

Where : τ_p : pulse duration

K : Chirp slope

f_0 : Carrier frequency

A portion of the chirp for the ERS- radar as well as its power spectrum and impulse response is shown below (figure 2).

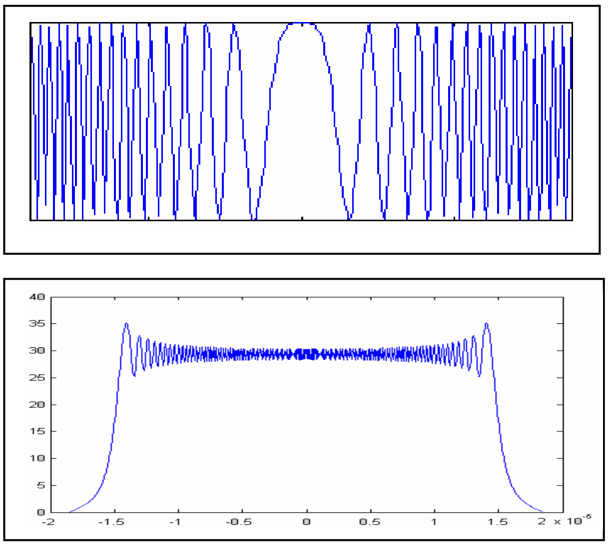

Figure 2: generation of a chirp signal (time and frequency)

Then the range resolution becomes:

$$\Delta R = \frac{c}{2.B} \tag{3}$$

Where $B = K \cdot \tau_p$ (frequency bandwidth of chirp)

Digital pulse compression techniques are routinely used for both the generation and the matched filtering of radar waveforms. The matched filter may be implemented by using a digital correlator for any waveform or else a "stretch" approach for a linear-FM waveform.

2.3. Azimuth compression

Azimuth compression or azimuth focusing involves generation of a frequency-modulated chirp in azimuth based on the knowledge of the spacecraft orbit (figure 3) [11].

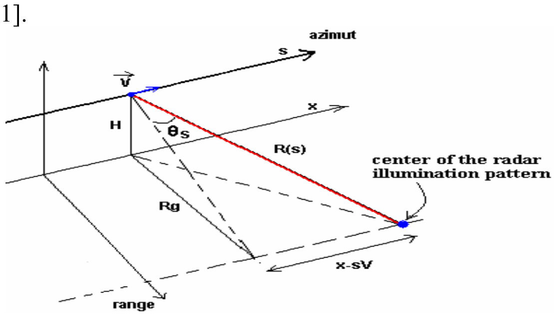

Figure 3: phase of azimuth signal

The phase of the return echo is:

$$\varphi(s) = 2 \cdot \frac{2.\pi}{\lambda} \cdot R(s) \tag{4}$$

So the complex phase is:

$$C(s) = \exp\left[i \cdot \frac{4.\pi}{\lambda} \cdot R(s)\right] \tag{5}$$

Where the range $R(s)$ is:

$$R^2(s) = (x - sV)^2 + R_g^{\ 2} + H^2 \tag{6}$$

with:

s :Slow time along the satellite track

x : ground-track position

V : Ground track velocity

s_c : Time when the target is in the center of the radar illumination pattern

H : Spacecraft height

Rg :Ground range

R(s) :Range from spacecraft to target

It is helpful to expand the range function $R(s)$ as a Taylor series around $s_c = \frac{x_c}{V}$:

$$R(s) \approx R_c + \dot{R}_c \cdot (s - s_c) + \ddot{R}_c \cdot \frac{(s - s_c)^2}{2} \tag{7}$$

R_c is the range to target , so:

$$C(s) = \exp\left[i \cdot \frac{4.\pi}{\lambda} \cdot \left(R_c + \dot{R}_c \cdot (s - s_c) + \ddot{R}_c \cdot \frac{(s - s_c)^2}{2}\right)\right] \tag{8}$$

Finally we obtain:

$$C(s) = \exp\left[i \cdot \frac{4.\pi.R_c^{\ 2}}{\lambda}\right] \cdot \exp\left[i.2.\pi.\left\{f_{DC}.(s - s_c) + f_R \cdot \frac{(s - s_c)^2}{2}\right\}\right]$$

$$\text{with} \quad |s - s_c| < \frac{S}{2} \tag{9}$$

Note that this function is a frequency-modulated chirp where there are two important parameters:

the Doppler centroid :

$$f_{DC} = -\frac{2.V}{\lambda} \cdot \frac{(x - s_c.V)}{R_c} \tag{10}$$

The Doppler frequency rate :

$$f_R = \frac{2.V^2}{\lambda.R_c} \quad (11)$$

This is called an azimuth chirp and the demodulation, also called azimuthal focusing or azimuth compression can be done in analogous ways to the range compression.

3. SAR PROCESSING

SAR processing is the transformation of raw SAR signal data into a spatial image. In its most abstract form, this is the process of performing a frequency domain correlation of the received signal with a 2-D system transfer function. In practice, this process is performed in several 1-D steps, including range compression, range migration, and azimuth compression.
These three processing steps are each displayed graphically in figure 4. For a complete description of SAR processing please refer to [3] or [10].

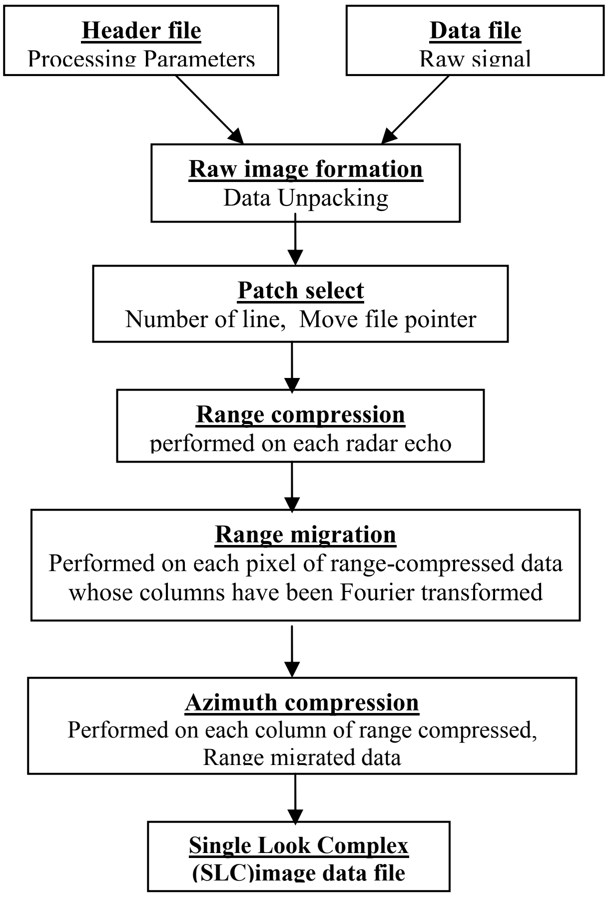

Figure 4: SAR Processing

3.1. Data Format and required parameters

The CEOS-format SAR raw data nominally consists of a volume Directory File, SAR Leader File, Raw Data File, and a Null Volume File. The Volume Directory File describes the arrangement of the data on the storage media. The SAR Leader File provides pertinent information about the specific SAR data set: Raw Data File size, spacecraft height and velocity, scene center latitude, longitude and time of acquisition, etc.
The first step performed by the SAR processor is to read in the SAR processing parameters. Sufficient parameters for SAR processing of ERS data and some representative values are shown in Table 1. The next step is to read in a block of data whose rows correspond to an area larger than the radar footprint in the along-track direction and whose number of rows is a power of 2 for efficient use of Fast Fourier Transforms (FFTs).

When image formation is processed directly from raw data, only a few parameters are required.
• Platform state vectors;
• Time of reception for each pulse;
• Slant range offset (corrected for internal delay in the radar);
• Reference squint angle.
In conjunction with other processing parameters, e.g., processing window offset. The SAR focusing additionally requires:
• Carrier frequency;
• Sampling frequency;
• Knowledge of pulse encoding, e.g., chirp length, and bandwidth.

Processing parameters	
Range pulse code specifier	Linear FM Chirp
Range sampling rate *fs*	18.9624680 MHz
Range pulse length τ_p	37.120 microseconds
(Chirp) phase coefficient Quadratic term *K*	4.17788e+11 Hz/sec
Radar frequency	5.300 GHz
Radar wavelength λ	0.0566660 eters
Pulse Repetition Frequency (PRF)	1679.9020 Hz
Incidence angle at first range pixel (at mid-azimuth)	19.386 degrees
Quantization per channel I & Q	**5** bits
fd 1	326.23 Constant coefficient of Doppler centroid frequency
fdd 1	0.0 Linear coefficient of Doppler centroid frequency
fddd 1	0.0 Quadratic coefficient of Doppler centroid frequency

Table 1: *SAR processing parameters*

Additional parameters required throughout the image formation process are:

- near range :

$$R_0 = \frac{C.T_0}{2} \quad \text{with} \quad T_0 = 5.541034 \text{ ms} \qquad (12)$$

(Zero-Doppler range time (two-way) of first range pixel)
R_0 = 831115.1 m

- spacecraft hight :

$$\cos\alpha = \frac{H}{R_0} \quad \text{so} \quad H = R_0 \cdot \cos\alpha \qquad (13)$$

With α = 19.386 degrees (α: Incidence angle at first range pixel (at mid-azimuth))
H = 783994,025 m

- space craft relative velocity :

$$V = \sqrt{V_X{}^2 + V_Y{}^2 + V_Z{}^2}$$

and $$V_{ST} = V \cdot \sqrt{1 + \left(\frac{H}{R_E}\right)} \qquad (14)$$

where RE = 6367.4515 m (middle radius of earth)
V_{ST} = 7126.14 m/s

Prior to image formation, the SAR raw data must be *unpacked*, a procedure whereby the distribution of values from each channel is adjusted to be zero-mean.
It involves converting each SAR raw data sample component from a quantized integer to a real number and removing a bias from each channel. For ERS SAR raw data, the nominal in-phase and quadrature biases would be 15.5.

3.2. Range compression

After reading in the processing parameters and a block of data, the range reference function (RRF) is calculated. The RRF is a replica of the transmitted radar pulse that will be used as a matched filter to be correlated with each row of raw SAR data. The RRF is constructed by first computing the number of points in the filter, N, using the range sampling frequency and the pulse duration ($N = fs.\tau_p$). The RRF is expressed as:

$$RRF[i] = \exp(\pi * k * t^2[i]),\ -\tau_p/2 \le t[i] \le \tau_p/2 \qquad (15)$$

Where, if $t[i] = -\tau_p/2$ and $\Delta t = 1/fs$,

Then $t[i] = t[i-1] + \Delta t,\ i = 1,2, \ldots, N$;

and K is the chirp-slope parameter (Table 1).

Where the sampling rate is: $\Delta t = \frac{1}{f_s}$

The RRF is then calculated according to the parameters (Table 1). After padding, the RRF is transformed into the Fourier domain using an FFT algorithm, multiplied by each row of similarly padded. Fourier transformed raw SAR data, and the product is transformed into the time domain to complete the range compression operation.
A radar pulse is recovered by deconvolution of the chirp. There are 5616 points in the ERS-2 signal data and the chirp is 703 points long.

3.3. Estimation of the Doppler centroid frequency

The Doppler centroid frequency may vary with range. It can then be expressed:

$$f_{DC} = fd\ 1 + fdd\ 1 * R + fddd\ 1 * R^2 \qquad (16)$$

Without knowing the attitude of the spacecraft, it is impossible to compute the Doppler centroid frequency directly. Instead, it may be estimated using an autocorrelation algorithm such as described by *Madsen et al.* [12].

3.4. Range migration

A point target will appear as a hyperbolic shaped reflection as it moves through the synthetic aperture. In addition, there could be a pronounced linear drift due to an elliptical orbit and earth rotation. In other words, the target will migrate in range cell as a linear trend plus a hyperbola. The shape of this migration path is calculated from the precise orbital information.
The range migration correction is accomplished with shifting the bin cell in the range direction with a value**:**

$$DR(s) = R(s) - R_c \qquad (17)$$

Where:

$$R(s) - R_c = -\frac{\lambda \cdot f_{Dc}}{2} \cdot (s - s_c) - \frac{\lambda \cdot f_R}{4} \cdot (s - s_c)^2 \qquad (18)$$

The maximum shift is given by: $DR = \frac{\lambda^2 .R_c}{16.\Delta X^2}$ where ΔX is the azimuth resolution. So it can constitute a criterion for range migration correction.
With: $DR \ge \Delta R$ and ΔR is the range resolution

In the case of ERS radar, we have $DR < \Delta R$.

3.5. Azimuth compression

The final step in the processing is to focus the data in azimuth by accounting for the phase shift of the target as it moves through the aperture. This is done by generating a second frequency-modulated chirp where the chirp parameters depend on the velocity of the spacecraft, the pulse repetition frequency (PRF), and the absolute range. The chirp is Fourier transformed into Doppler space and multiplied by each column of range-migrated data.
The length of the synthetic aperture l_{sa} depends on the length of the radar ground footprint in the azimuth direction which is approximately

$$l_{sa} = \frac{\lambda}{L_a} \cdot r \qquad (19)$$

Where: λ = 5.66cm and L_a = 10m
If we take r as near range: r = 831115.1 m we obtain: l_{sa} = 4704.1115 m
The length of the aperture in terms of radar echos is given by:

$$n_{sa} = \frac{PRF \cdot l_{sa}}{V} \quad (20)$$

PRF = 1679.9 Hz = 1679.9 impulsions /second

And V_{ST} = 7126.14 m/s

For near range l_{sa} = 4704.111 m , n_{sa} = 1109 pulses

For far range l_{sa} = 4955.781 m, n_{sa} = 1169 pulses

After range migration, the transformed, range-migrated columns of radar data are passed to the azimuth compression processing. First, the SAR aperture is computed and the SAR integration time can be computed from the bandwidth as a function of resolution, and the Doppler rate.

$S = l_{sa} \cdot V$ or $S = l_{sa} \cdot V$ and $l_{sa} = \frac{\lambda}{L_a} \cdot r$

$$\text{So, } S = \frac{\lambda \cdot r \cdot l_a}{V} \quad (21)$$

The along-track reference function for $s_c = 0$ is:

$$g(s) = \exp\left[i.2.\pi.\left\{f_{DC}.s - f_R \cdot \frac{s^2}{2}\right\}\right] \quad \text{for } |s| < \frac{S}{2} \quad (22)$$

$$\text{So: } ARF[k] = \exp\left[i.2.\pi.\left\{f_{DC}.s[k] - \frac{1}{2} \cdot f_R.[k].s[k]^2\right\}\right]$$

$$\text{for } -\frac{S}{2} \le s[k] \le +\frac{S}{2} \quad (23)$$

Where the sampling rate is: $\Delta s = \frac{1}{PRF}$

The product is inverse Fourier transformed to provide the focused image.

3.6. Single-Look Complex (SLC) Image

The data are processed in patches consisting of 2048 azimuth lines by the full width of range samples (5616). Processing continues until all input patches are completed. Each output pixel combines returns from an area equal to the length of the range reference function times the length of the azimuth reference function. Typical reference function sizes are 800 in azimuth and 700 in range. This means that for each 2048 x 5616 patch of raw data, approximately 1250 lines of 4900 samples of valid output are created.

4. RESULTS

Our SAR processor consists of following modules: parameter-setup program, range compression program, azimuth compression program, and resulting to a SLC image. One can change following parameters in this algorithm: processing area, processing size, image resampling size per pixel, output data type (real image / complex image), and number of looks.

The test area Algiers is situated in northern Algeria. The area includes several land-use classes like agricultural fields, urban areas and lakes. The overall relief is quite low, elevation is well below 200m, but not flat because of small hills.

ERS-2 RAW SAR image used in this study was taken on February, 16 1996 within ESA AOE-programme.

The figures below (figures 5a, b and c) show a small patch of ERS-2 data for an area near of Algiers city (Algeria). The range-compressed data shows vertical streaks due to the reflectivity of the targets as they migrate through the synthetic aperture. The fully focused image shows the reflectivity associated with the Different targets of the image and particularly the Reghaia lake in the left of the figure 5c.

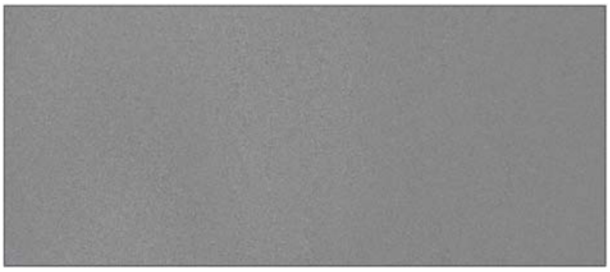

Figure 5a: Raw image

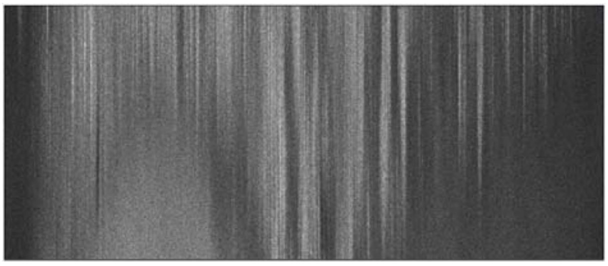

Figure 5b: range compressed image

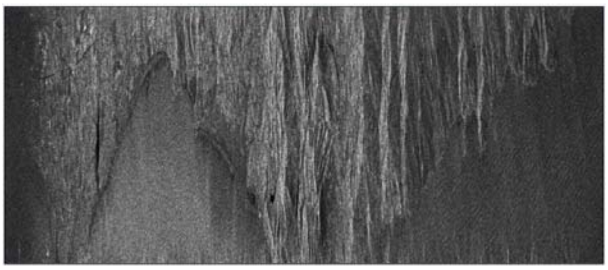

Figure 5c: range and azimuth compressed image

5. CONCLUSION

Our SAR image algorithm is currently available only for ERS images, and its image reconstruction procedure is 2-stage FFT (Fast Fourier Transform)-IFFT(Inverse Fast Fourier Transform) method. This method first executes range compression in Fourier domain, the next step is to execute azimuth compression in Fourier domain. It is the most standard method of SAR image reconstruction.

In this above presentation of SAR image formation, number of approximations and simplifying assumptions were introduced. These make the formulas used in signal processing geometrically inexact and so require corrections, usually to the pixel locations of the processed data.

One such resampling requirement is to obtain uniform ground range sample spacing. By digitizing uniformly in time (at 18.96 MHz), the samples are uniformly spaced in slant range at about 7.9 m, which implies ground range spacing that varies from 24 m to 18 m with increasing range. Thus the nominal 12.5 m range pixel size represents an interpolated resampling.

The first sidelobes are about -13dB lower than the main peak and this can cause problems. Therefore, instead of using a box-like weigthing function, an improvement to reduce these sidelobes is to use other shapes like the so-called HAMMING-weighting.

6. AKNOWLEDGMENTS

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