A New Method for Wide Field Synthetic Aperture Radar Processing

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Abstract

Synthetic Aperture Radar (SAR) data focusing can be carried out by filtering the raw signal in the two-dimensional Fourier domain and by applying a change of variables often referred to as Stolt interpolation. Basic idea of the paper is to present a new algorithm based on a non standard Fourier transform which allows the exact implementation of the Stolt change of variables. Efficiency of the presented procedure is due to the possibility of applying fast Fourier transform (FFT) codes. Moreover the algorithm doesn' t require any modification if the data are already range compressed and also if the SAR system transmits a signal different from a linear FM chirp.

Introduction

A fully focused and geometrically undistorted SAR image can be obtained by filtering the raw data with a space-variant, two-dimensional (2D) function representing the system impulse response. If the filtering operation is carried out in the time-domain, the space-variance of the system response can easily be taken into account but the overall procedure is computationally inefficient.

A more efficient solution is obtained by carrying out the filtering operation in the two-dimensional frequency domain. However, in this case, compensation of the space-variant nature of the system impulse response requires a change of variables pioneered by Stolt [1] and digitally implemented in the past with a complex interpolator.

Recently, a new approach for the compensation of the above menctioned space-variance has been presented; it is usually referred to as chirp scaling. This algorithm is based on a filtering operation carried out in the 2D-Fourier domain coupled with two phase multiplication steps. The multiplications are respectively carried out in the range-Doppler frequency domain before and after the 2D-filtering operation [2-3]. Note that the basic chirp scaling algorithm must be modified if the SAR system doesn' t transmit a chirp signal or if the data are compressed in range.

In our case we have developed a new procedure which allows the implementation of the exact Stolt change of variables without interpolation. The basic idea is to apply to the data spectrum a Doppler frequency-dependent scaling effect obtained by using a non standard Fourier transform. Efficiency of this non standard transform is high due to an *ad hoc* modification of the Bluestein chirp transform algorithm [4].

Main goal of this approach is the possibility to apply it independently from the type of transmitted signal and also to range-compressed data.

The flexibility of our approach is evident and computational performances are also interesting.

Signal Analysis in Frequency Domain

Starting point of our analysis is the evaluation of the two-dimensional Fourier Transform (FT) of the raw signal represented by [5]:

$$\begin{aligned} H(\xi,\eta) &= \iint dx'\,dr'\,h(x',r')\,exp(-jx'\xi - jr'\eta) \\ &\simeq \iint dx\,dr\,\gamma(x,r)\,exp(-jx\xi - jr\eta)\,G(\xi,\eta;r), \end{aligned} \tag{1}$$

wherein $G(\xi,\eta;r)$ is the system transfer function, $\gamma(x,r)$ the backscattering coefficient of the illuminated scene, (ξ,η) are azimuth and range frequencies respectively and the coordinate systems (x,r) and (x',r') have been considered accordingly with ref. [5].

Let us to assume the exact knowledge of the system transfer function computed in refs. [2,3,6] by applying the stationary phase method. We can decouple the r-invariant part of the $G(\cdot)$ function from the r-dependent one as follows:

$$G(\xi,\eta;r) = G(\xi,\eta;0)\cdot\Delta G(\xi,\eta;r) = G_0(\xi,\eta)\cdot\Delta G(\xi,\eta;r), \tag{2}$$

wherein:

$$\Delta G(\xi,\eta;r) \simeq exp(-j\Psi_1) \tag{3}$$

and:

$$\Psi_1 \simeq \mu(\xi)\,r + \nu(\xi)\,\eta\,r\,. \tag{4}$$

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Complete expression for function $\mu(\xi)$ and $\nu(\xi)$ is here omitted but can be founded in [3,6]. Note also that we neglected in eq. (3) a radiometric term which is inessential for the following analysis. Substituting eqs. (2), (3) and (4) in eq. (1), we get:

$$H(\xi,\eta) = G_0(\xi,\eta)\iint dx\ dr\ \gamma(x,r)\,exp(-jx\xi - j\mu(\xi)r - j\Omega(\xi)r\eta) = G_0(\xi,\eta)\Gamma[\xi,\Omega(\xi)\eta+\mu(\xi)], \tag{5}$$

being $\Omega(\xi) = 1 + \nu(\xi)$ and $\Gamma[\xi,\Omega(\xi)\eta+\mu(\xi)]$ the FT of $\gamma(\cdot)$ in the variables $(\xi,\Omega(\xi)\eta+\mu(\xi))$. This non linear mapping of the range frequencies is often referred to as Stolt change of variables. In particular we note in $\Gamma[\cdot]$ the presence of two factors: a scaling $\Omega(\xi)$ and a shifting term $\mu(\xi)$. For moderate angular bandwidths and low squinted SAR geometries we may ignore the scaling factor by taking $\Omega(\xi) \approx 1$ and we can apply to the squinted raw data the processing approach of ref. [7]. In this case the space-variance of the system transfer function is compensated by computing either the 2-D spectrum of the raw data on a deformed grid or by applying to the $\Gamma[\cdot]$ function a ξ-dependent shift in the η direction via a phase multiplication.

For wide swath and/or high squinted SAR geometries the $\Omega(\xi)$ factor cannot be neglected therefore an interpolation operation must be carried out on the $\Gamma[\xi,\Omega(\xi)\eta+\mu(\xi)]$ function in order to compute $\Gamma[\xi,\eta]$. In this case a complex interpolator can be applied but no long data windows can be used otherwise the computation time will drastically increase. On the other hand a too short data window interpolator can cause aberrations in the scenes and expecially in the phase of the complex SAR images.

In order to overcome these limitations we will consider a different approach. First of all we multiply the two-dimensional spectrum $H(\xi,\eta)$ by $G_0^{-1}(\xi,\eta)$ within the bandwidth of the signal:

$$\hat{H}(\xi,\eta) = H(\xi,\eta)G_0^{-1}(\xi,\eta) = \Gamma[\xi,\Omega(\xi)\eta+\mu(\xi)]. \tag{6}$$

We compute now the inverse Fourier transform of eq. (6) in the η direction by using the new kernel $exp(j\Omega(\xi)\eta r')$ instead of the usual one $exp(j\eta r')$. As a result of this opearation (that we will refer in the following as $SCFT^{-1}$) we will have:

$$SCFT^{-1}(\hat{H}(\xi,\eta)) = \frac{1}{2\pi}\int \hat{H}(\xi,\eta)exp(j\Omega(\xi)\eta r')d(\Omega(\xi)\eta) = \frac{1}{2\pi}\int \Gamma[\xi,\Omega(\xi)\eta+\mu(\xi)]exp(j\Omega(\xi)\eta r')\, d(\Omega(\xi)\eta) \simeq \Gamma[\xi,r']exp(-j\mu(\xi)r'). \tag{7}$$

The function $\Gamma[\xi,r']$ of eq. (7) represents the estimate of the backscattering coefficient in the azimuth frequency-range domain; note also that we have assumed (as usual) in eq. (7) a hign signal bandwidth in range. As final step we multiply eq. (7) by $exp(j\mu(\xi)r')$ within the azimuth signal bandwidth and we finally carry out a standard inverse FT with respect to the ξ variable. The overall procedure is shown in the block diagram of fig. 1.

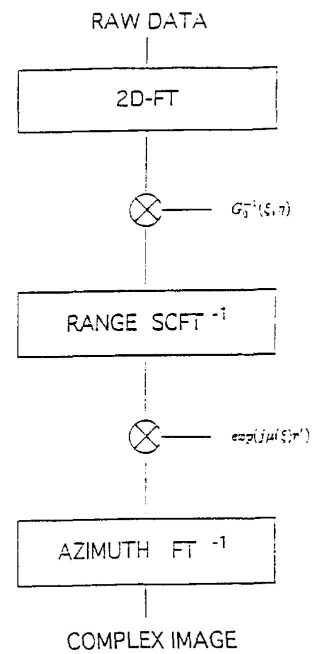

Fig 1 Flow-chart of the SAR processing procedure.

It is evident that the efficiency of the algorithm is strongly depending on the possibility to efficiently carry out the $SCFT^{-1}$ operation which compensate for the scaling factor appearing in the backscattering spectrum. The solution that we consider is based on the extension of the Bluenstein formula [4] which allows to rewrite eq. (7) as follows:

$$\frac{1}{2\pi}\int \Gamma[\xi,\Omega(\xi)\eta+\mu(\xi)]exp(j\Omega(\xi)\eta r')d(\Omega(\xi)\eta) = \frac{1}{2\pi}\Omega(\xi)exp(j\Omega(\xi)r'^2/2)\int(\Gamma[\xi,\Omega(\xi)\eta+\mu(\xi)]exp(j\Omega(\xi)\eta^2/2))\, exp(-j\Omega(\xi)(\eta-r')^2/2)d\eta. \tag{8}$$

Following eq. (8), we will carry out the $SCFT^{-1}$ operation by applying two phase multiplications and one convolution. In particular the backscattering spectrum will be first multiplied by the chirp function $exp(j\Omega(\xi)\eta^2/2)$; following this operation (that can be combined with the 2D-filtering step) the obtained function will be convolved with the term $exp(-j\Omega(\xi)\eta^2/2)$.As a last step again a phase multiplication step is required and again the used function will be a chirp multiplied by an amplitude factor. This final stage can be joined with the compensation of the $exp(-j\mu(\xi)r')$ factor of eq. (7). The new block diagram of the overall processing procedure is shown in fig. 2. Let us note that the convolution operation of fig. 2 can be efficiently carried out by using FFT codes.

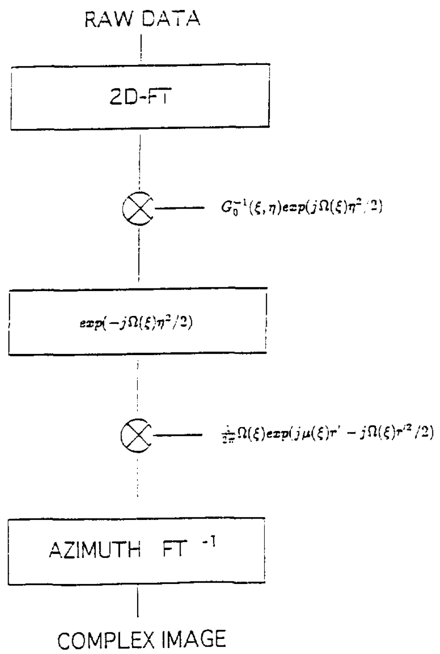

Fig 2 Efficient implementation of the SAR processing procedure

As a final remark let us to underline that the presented procedure is fully general in the sense that it doesn' t require any modification if the data are already range compressed and also if the SAR system transmits a signal different from a linear FM chirp. Obviously, depending from the transmitted signal or if the data are already range compressed the $G(\cdot)$ function must be modified but the procedure remains the same.

Experiments

In order to verify the performances of our algorithm we have processed a C-band raw data set of the German airborne sensor E-SAR. Sensor parameters are descibed in table I, moreover let us underline that in this case the squint angle was $\simeq 13.5°$ (quite large !). Obtained image is shown in fig. 3.

Conclusions

It is well known that SAR data focusing can be carried out by filtering the raw signal in the 2D-Fourier domain and by applying a change of variables often referred to as Stolt interpolation. We presented in this paper a new algorithm based on a non standard Fourier transform which allows the exact implementation of the Stolt change of variables. The presented procedure is efficient because it is based only on matrix multiplications and FFT codes. Moreover the algorithm doesn' t require any modification if the data are already range compressed and also if the SAR system transmits a signal different from a linear FM chirp.

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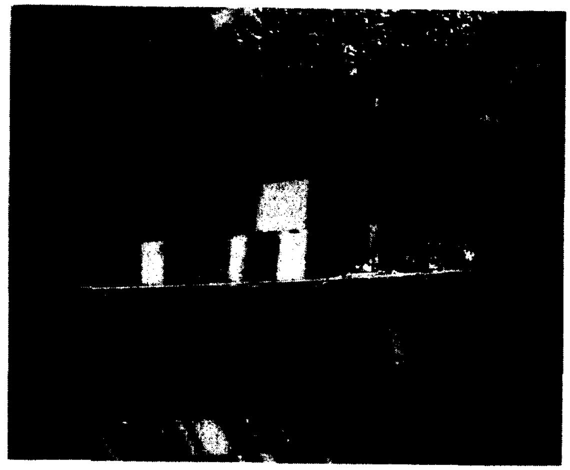

Fig 3 C-band SAR image with squint angle $\phi = 13.5°$

E-SAR C-band configuration

- RF-center frequency: 5.3 GHz
- Azimuth antenna 3 dB-beamwidth: 19°
- Elevation antenna 3 dB-beamwidth: 33°
- Antenna depression angle: 40°
- Sampling frequency: 100 MHz (I/Q)
- Range delay: 30.5 μs
- Pulse repetition frequency: 952 Hz
- Pulse duration: 5 μs
- Squint angle: 13.5°
- Location: Lechfeld area
- Mission date: 20/5/1992
- Platform type: Dornier-228

Table I