EFFICIENT SIMULATION OF EXTENDED-SCENE SAR RAW SIGNALS WITH ANY ACQUISITION MODE

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ABSTRACT

Synthetic Aperture Radar (SAR) systems are active sensors able to generate microwave images by using different acquisition modes. The classical one is the stripmap mode, the other ones are chosen based on the trade-off between spatial resolution and coverage. In this paper, we will present a unified formulation able to express raw signals for all acquisition modes and we will employ it into an approach to show that both sliding spotlight and TOPSAR raw signals of extended scenes can be simulated. This approach consists of a 1D range Fourier-domain (1D-FD) processing, followed by a 1D azimuth time-domain (TD) integration, and it can also take into account for sensor trajectory deviations. Numerical examples are then shown in order to verify the effectiveness of the simulation scheme.

Index Terms— Synthetic Aperture Radar (SAR), SAR simulation

1. INTRODUCTION

The SAR system can use different techniques to acquire data from ground surfaces. The simplest one is the well-known *stripmap* mode [1-2]: in this case, the azimuth resolution is equal to a half of the real antenna azimuth length. The *spotlight* mode [1-2] can be used in order to obtain a better azimuth resolution at the expense of ground coverage. A compromise is provided by the *sliding spotlight* mode [3-5]: this technique allows to obtain an azimuth resolution better than the one of the stripmap case and an azimuth coverage better than the one of the spotlight mode. Instead, in *scanSAR* [1-2] mode the range coverage increases by periodically switching the antenna beam elevation to illuminate different range subswaths. So, the azimuth resolution becomes worse and two drawbacks appear: the first is the so-called *scalloping* effect; the second one is an azimuth-varying ambiguity ratio. To overcome these effects, it is possible to use the *TOPSAR* [6] configuration: the antenna beam elevation is still switched along the range dimension, but within each sub-swath the beam is also steered from backward to forward. In this way all points on the ground are illuminated by the whole antenna azimuth pattern, so the above-cited drawbacks are avoided. At the state of the art, there are many different algorithms devised to process data

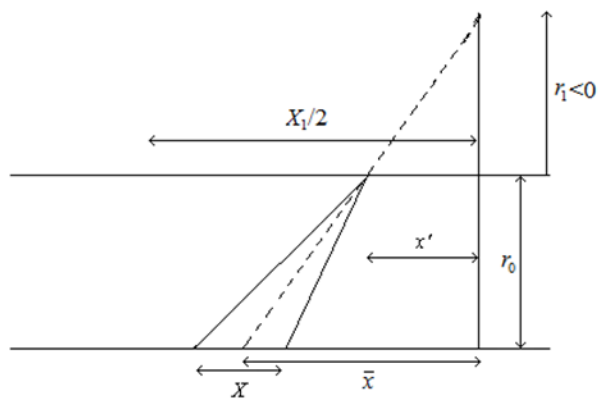


Fig.1: TOPSAR geometry

from the different operational modes [1-8]. However, a unified formulation able to express raw signals for all acquisition modes would be very attractive. The presentation of such a unified formulation is the first contribution of this paper. The second contribution is the use of our formulation to show that both sliding spotlight and TOPSAR raw signal simulation of extended scenes can be achieved by using a 1D range FD processing, followed by 1D azimuth TD integration. Finally, the proposed simulation approach can also take into account for SAR sensor trajectory deviations.

2. UNIFIED RAW SIGNAL FORMULATION

Let us consider a SAR sensor flying with velocity v along a straight line and call X_1 the portion of the trajectory to acquire the raw data. Let us define r_0 the distance from the line of flight to the centre of the illuminated area and r_1 the *orientend distance* from the line of flight to the beam rotation centre, assumed positive if the beam rotation centre is below the sensor (as in the sliding spotlight case), and negative if the beam rotation centre is above the sensor (as in the TOPSAR case, see Fig.1). For the sake of simplicity, we will assume that no squint is present and also that $X_1 \ll |r_1|$. So, we can now introduce the factor

$$A = \frac{r_1 - r_0}{r_1} \quad . \qquad (1)$$

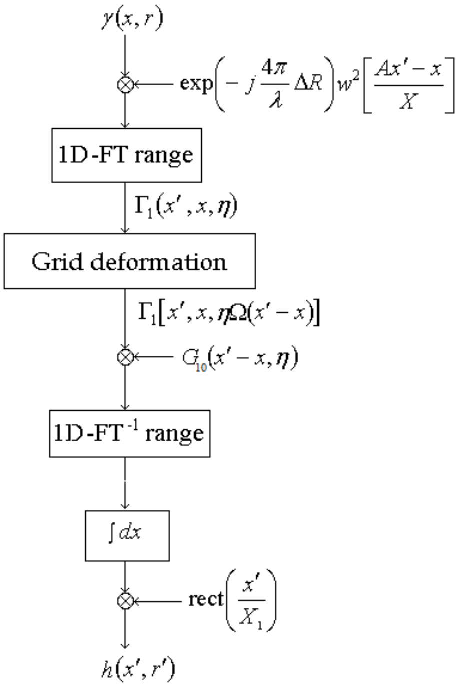


Fig.2: Flow chart of SAR raw signal simulation

Assuming a chirp modulation of the transmitted pulse (with bandwidth Δf and pulse duration time τ), the raw signal $h(\cdot)$ can be expressed as the space-variant convolution of the scene reflectivity pattern $\gamma(\cdot)$ (assuming that it does not change as the sensor moves) and the SAR system impulse response $g(\cdot)$. Useful information can be gained by expressing $h(\cdot)$ in the 2D FT domain and performing a stationary phase evaluation on it. In fact, we obtain that the SAR system transfer function (STF) is

$$G(\xi,\eta;x,r)=\exp\left[j\frac{\eta^2}{4b}\right]\exp\left[j\frac{\xi^2(r/r_0)}{4a\left(1+\eta\lambda/(4\pi)\right)}\right]\cdot$$
$$\cdot\mathrm{rect}\left[\frac{\eta}{bc\tau}\right]\mathrm{rect}\left[\frac{B(\xi-2ax)}{2aX}\right]w^2\left[\frac{A\xi-2a(A-1)x}{2aX}\right] \quad , \quad (2)$$

where

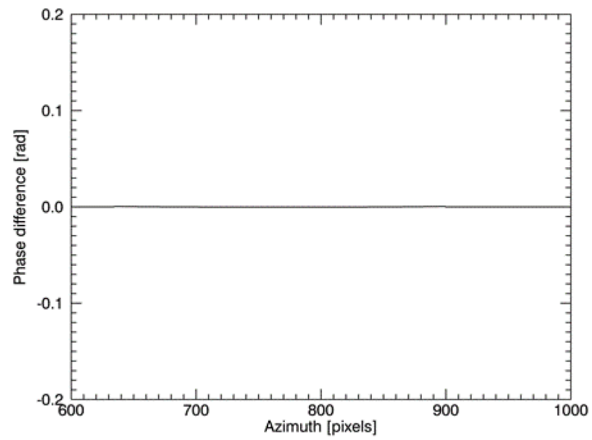
$$B=\frac{X}{X_1} \quad , \quad a=\frac{2\pi}{\lambda r_0} \quad , \quad b=\frac{4\pi}{\lambda}\frac{\Delta f/f}{c\tau} \quad , \quad (3)$$

with λ and f the carrier wavelength and frequency of the transmitted signal, respectively, and c the speed of light.
By analyzing the last three factors of (2), it is easy to get the range and the azimuth bandwidth of the each fully focused ground point and, finally, the SAR system slant range and azimuth resolutions (being L the azimuth antenna size):

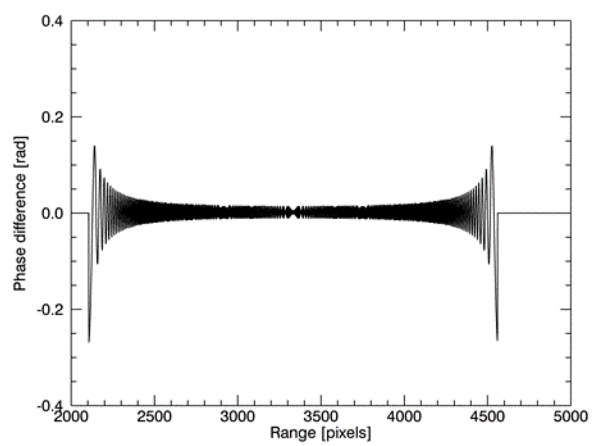
$$\rho_r=\frac{c}{2\Delta f} \quad , \quad \rho_a=\frac{L}{2}\max\{|A|,B\} \quad . \quad (4)$$

TABLE I
VALUES OF A AND CORRESPONDING ACQUISITION MODES

Range of values	Acquisition mode
$A = 0$	Staring Spotlight
$0 < A < 1$	Sliding Spotlight
$A = 1, \; B \ll 1$	Stripmap
$A = 1, \; B > 1$	ScanSAR
$A > 1$	TOPSAR
$-1 \le A < 0$	Inverse Sliding Spotlight
$A < -1$	Inverse TOPSAR



(a)



(b)

Fig.3: Azimuth (a) and range (b) cuts of the phase difference between the raw signals simulated by using the proposed approach and the full TD one. Point scatterer placed at $(x = 0, r = r_0)$.

The eqs. (2, 4) hold for any positive real value of B and for any real value of A, and, by varying it, all acquisition modes can be obtained, as summarized in Table I. Note that negative values of A are obtained if the beam rotation centre is between the sensor and the ground.

3. SIMULATION OF SAR RAW SIGNALS: SLIDING SPOTLIGHT AND TOPSAR MODES

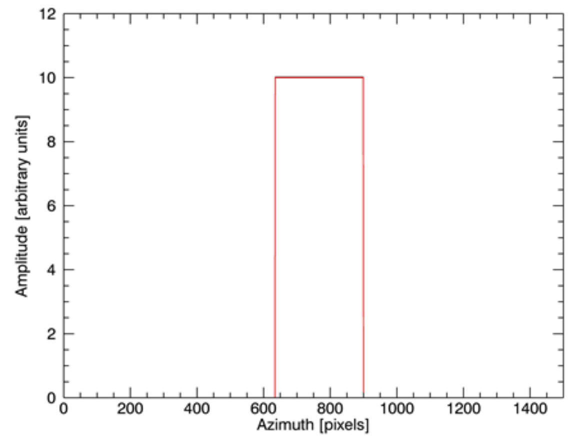
Contrary to what has been done in [2, 9-10], for the sliding spotlight and TOPSAR modes no procedure can be implemented to manage the x-dependence of the SAR STF. And an efficient simulation algorithm cannot be devised in the 2D FT domain. The method proposed here, described in Fig.2, is based on 1D range FT and, thanks to the range-Fourier domain interpolation step ("grid deformation" block in Fig.2), it can relax the limited-range-swath assumption made in [11]: therefore, it can be used for any acquisition mode. All the quantities, appearing in Fig.2 and not yet described, are here defined:

- x,r and θ are the coordinates in the cylindrical coordinates system whose axis is the sensor line of flight;
- x' is the generic sensor position along the flight path;
- r' is $c/2$ times the time elapsed from each pulse transmission;
- X is the azimuth antenna footprint;
- $\Delta R = R - r$ where R is the distance from the generic sensor position and the generic ground point;
- $w(\cdot)$ is the azimuth illumination diagram;
- $\Omega(x' - x) = r_0/\sqrt{r_0^2 + (x' - x)^2}$;
- $G_{10}(\cdot) = exp\left[j\frac{\eta^2}{4b}\right] rect\left[\frac{\eta}{bc\tau}\right] exp(-j\eta\Delta R_0)$ where $\Delta R_0 = R - r_0$.

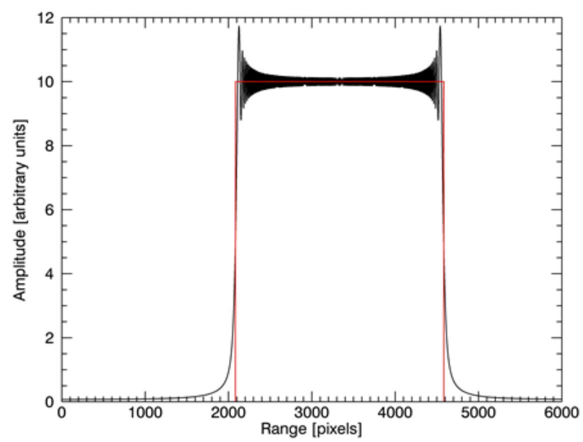
Note that the presented procedure not only is appropriate to spaceborne sensors, but also to airborne ones (for which deviations from the ideal trajectory can be appreciable) since the azimuth processing is performed in time domain. In this case, it is sufficient to include in the expression of ΔR the term $\Delta r(x', x, r)$, that is the projection along the local line of sight of the deviation with respect to the nominal trajectory at the sensor azimuth position x'. In addition, at variance with [12-13], no constraints on trajectory deviation amplitude are necessary (except that they are small compared to r_0, as it always happens in practice).

4. PERFORMANCE EVALUATION

Before moving to show some simulation examples, it's suitable to spend a few words on computational complexity of the proposed approach compared to the one of a full TD approach. In fact, because of our method is based on 1D range FT, an efficient 1D FFT algorithm can be exploited. If we measure the computational complexity by the number of complex multiplications (let's call it N_{1DFD} for the 1D-FD approach and N_{TD} for the TD one), then it's possible to verify that the processing time of our scheme is reduced by the factor $\frac{N_{1DFD}}{N_{TD}} = \frac{2+\log_2 N_r}{N_\tau}$ with respect to a TD one (where N_r and N_τ are the number of range pixels within the slant range swath S_r and the number of samples of the transmitted pulse



(a)



(b)

Fig.4: Azimuth (a) and range (b) cuts of the amplitudes of the raw signals simulated by using the proposed approach (black line) and the full TD simulation (red line). Point scatterer placed at scene centre ($x = 0, r = r_0$).

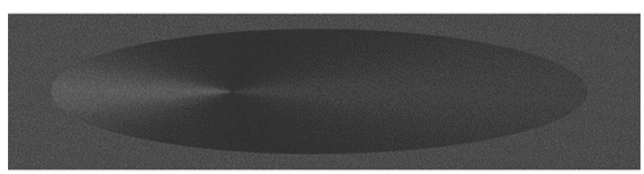


Fig.5: Amplitude image obtained by focusing a simulated raw signal of a canonical extended scene constituted by a cone over a flat plane.

duration τ, rispectively). Finally, if we consider the trajectory deviations, the computational complexity results to be similar to that of the method in [12].

We can now present some results. Let us start to verify that the raw signal corresponding to a single scattering point, simulated by the proposed 1D-FD approach, agrees with theone obtained directly from the TD expression.

We consider system parameters very similar to those of the Sentinel-1 spaceborne, operating in the TOPSAR mode, and simulate the raw signal from a point scatterer placed at the centre of the illuminated area. First, the phase difference between the raw signal simulated by using the proposed approach and the one obtained via full TD simulation is considered: the results are shown in the plots of Fig.3. It can be noted that the absolute value of this phase difference is always smaller, and often much smaller, than $\pi/10$, thus leading to negligible effects. Moreover, fast small oscillations in the range cut are due to the stationary phase method approximation. Raw signal amplitudes are considered in Fig.4. Only small oscillations around the exact constant value can be noted in the range cut, due to the stationary phase method approximation, whereas the two azimuth cuts are almost perfectly overlapped.

Similar comparisons for a point scatterer located at the azimuth and range borders of the illuminated scene provide very similar results: the only differences with respect to the previous case are very slight, negligible oscillations in the azimuth amplitude and phase cuts. Similar results are also obtained for different values of the system parameters.

A simulation relevant to an extended scene is now in order. We use the previous spaceborne SAR system data and a "canonical" extended scene, constituted by a cone over a flat plane. In this experiment, we assume that outside the fully resolved area the scene is perfectly absorbing. Corresponding raw signal has been generated and in Fig.5 we show the image that can be obtained by using a TOPSAR focusing algorithm.

5. CONCLUSION

In this paper, a unified analytical formulation able to express raw signals of all SAR acquisition modes has been presented. This formulation has been then employed to devise a sliding spotlight and TOPSAR raw signal simulation scheme for extended scenes. This approach implies a 1D range FD processing, followed by a 1D azimuth TD integration, and it can also account for sensor trajectory deviations. We have also discussed about the computational complexity, thus showing the enormous advantage of the proposed FD approach with respect to the TD one in terms of computing time. Finally, accuracy of the proposed simulation scheme has been assessed by comparing the raw signals that it generates with those generated by using the exact TD approach.

6. REFERENCES

[1] J. C. Curlander and R. N. McDonough, *Synthetic Aperture Radar: Systems and Signal Processing*. New York: Wiley, 1991.

[2] G. Franceschetti and R. Lanari, *Synthetic Aperture Radar Processing*. New York: CRC Press, 1999.

[3] D. P. Belcher, C. J. Baker, "High resolution processing of hybrid stripmap/spotlight mode SAR", *IEE Proc., Radar Sonar Navig*., vol.143, pp.366-374, 1996.

[4] R. Lanari, S. Zoffoli, E. Sansosti, G. Fornaro, F. Serafino, "New approach for hybrid strip-map/spotlight SAR data focusing", *IEE Proc., Radar Sonar Navig.* vol.148, pp.363-372, 2001.

[5] J. Mittermayer, R. T. Lord, E. Boerner, "Sliding Spotlight SAR Processing for TerraSAR-X using a new formulation of the extended chirp scaling algorithm", *Proc. IGARSS* 2003, Toulose, France, pp.1462-1464, 2003.

[6] F. De Zan, A. Monti Guarnieri, "TOPSAR: Terrain Observation by Progressive Scans", *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 9, pp.2352-2360, Sept. 2006.

[7] P. Prats, R. Scheiber, J. Mittermayer, A. Meta, and A. Moreira, "Processing of sliding spotlight and TOPS SAR data using baseband azimuth scaling," *IEEE Trans. Geosci. Remote Sens.*, vol. 48, no. 2, pp. 770–780, Feb. 2010.

[8] G. Sun, M. Xing, Y. Wang, Y. Wu, Y. Wu, and Zheng Bao, "Sliding Spotlight and TOPS SAR Data Processing Without Subaperture", *IEEE Geosci. Remote Sens. Letters*, vol. 8, no. 6, pp. 1036–1040, Nov. 2011.

[9] G. Franceschetti, M. Migliaccio, D. Riccio, G. Schirinzi, "SARAS: a SAR raw signal simulator", *IEEE Trans. Geosc. Remote Sensing*, vol.30, pp.110-123, 1992.

[10] S. Cimmino, G. Franceschetti, A. Iodice, D. Riccio, G. Ruello, "Efficient Spotlight SAR Raw Signal Simulation of Extended Scenes", *IEEE Trans. Geosc. Remote Sensing,* vol.41, pp. 2329-2337, 2003.

[11] G. Franceschetti, R. Guida, A. Iodice, D. Riccio, G. Ruello, "Efficient Simulation of Hybrid Stripmap/Spotlight SAR Raw Signal From Extended Scenes", *IEEE Trans. Geosci. Remote Sens.,* vol.42, no.11, pp. 2385-2396, Nov. 2004.

[12] G. Franceschetti, A. Iodice, S. Perna, D. Riccio, "Efficient Simulation of Airborne SAR Raw Data of Extended Scenes", *IEEE Transactions on Geoscience and Remote Sensing,* vol.44, no.10, pp. 2851-2860, 2006.

[13] G. Franceschetti, A. Iodice, S. Perna, D. Riccio, "SAR Sensor Trajectory Deviations: Fourier Domain Formulation and Extended Scene Simulation of Raw Signal", *IEEE Transactions on Geoscience and Remote Sensing,* vol.44, no.9, pp. 2323-2334, 2006.