Efficient Hybrid Stripmap/Spotlight SAR Raw Signal Simulation

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Abstract **- Recently, a new operating mode for Synthetic Aperture Radar (SAR) system, referred to as hybrid stripmap/spotlight mode, has been presented [1-2]. In the hybrid acquisition mode the radar antenna beam is steered about a point farther away from the radar than the area being illuminated, thus generating microwave images with an azimuth resolution better than that achieved in the stripmap configuration, and a ground coverage better than the one of the spotlight configuration.**

The subject of design, processing and data interpretation for the hybrid SAR mode is gaining an increasing interest in the remote sensing scientific community.

Consequently, a hybrid SAR raw signal simulator is strongly required, especially when real raw data are not available yet, to test processing algorithms and to help mission planning. In addition, to analyse the effects of processing errors and to verify the impact of different system design choices on the final image for different kinds of imaged scenes, an extended scene SAR raw signal simulator is very useful and it is what we present in this paper.

I. INTRODUCTION

Hybrid stripmap/spotlight configuration is a new mode in which a Synthetic Aperture Radar (SAR) system can image an area over the ground. In the hybrid acquisition the radar antenna beam is steered about a point farther away from the radar than the area being illuminated, see Fig.1. That is why it results to be 'hybrid' between the well-known stripmap mode, in which the radar antenna is pointed along a fixed direction with respect to the platform flight, and the spotlight configuration in which the radar antenna beam is steered during the overall acquisition time. Such a system allows the generation of microwave images with an azimuth resolution better than that achieved in the stripmap configuration, and a ground coverage better than the one of the spotlight configuration.

A number of different processing procedures for hybrid mode have been proposed in the last years [1-2] and, although spaceborne SAR sensors operating in the hybrid mode are not yet available, some are currently under design, e.g., SAR 2000 within the Cosmo/Skymed project or TerraSAR-X.

But any effort in planning SAR hybrid systems or testing processing algorithms requires the support of a SAR raw signal simulator, being real raw data available not yet.

Even if a time domain SAR raw signal simulation is always possible and easy to conceive, it turns out to be enormously time and memory consuming when extended

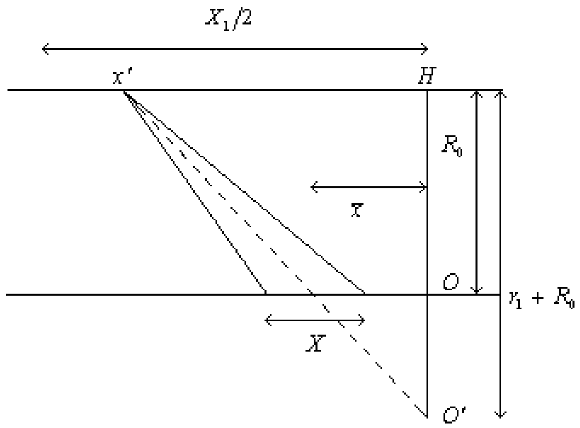

Fig.1: Geometry of the problem.

scenes are considered. Accordingly, an efficient frequency domain approach would be highly desirable. Efficient simulators, based on a frequency domain approach, have been presented for the stripmap and spotlight operational modes [3-4] but, to the best of our knowledge, no efficient extended scene SAR simulator for the hybrid mode is currently available. Only simple time domain simulators, able to deal with point targets or small scenes, can be found in literature [5].

In this work, a new transfer function for the hybrid case is defined and analytically evaluated via an asymptotic expansion. After showing that in this case a 2D Fourier domain approach is not viable, we demonstrate that a 1D range Fourier domain approach, followed by 1D azimuth time domain integration, is possible when some approximations, usually valid in the actual cases, are accepted.

We show that this method is still much more efficient than the time domain one, so that extended scenes can be considered. Some simulation examples, relevant to actual extended scenes assess the effectiveness of the simulator and are here presented.

II. HYBRID MODE

In this Section we consider the hybrid stripmap/spotlight mode: we firstly evaluate its transfer function and then present a raw signal simulation procedure.

Transfer function

In order to evaluate the SAR raw signal for the hybrid configuration, we have to introduce the factor [1-2]

$$A = \frac{r_1}{r_1 + R_0}, \tag{1}$$

where R_0 is the distance from the line of flight to the centre of the scene and r_1 is the distance from the ground to the beam steering point position beneath, so that r_1+R_0 is the distance from the line of flight to the steering point position, see Fig.1. It can be shown that in this case the resolution is increased by a factor $1/A$ with respect to the stripmap case, whereas the fully resolved covered area is increased by a factor $A(X_1/X)-1$ with respect to the spotlight case.

For a given sensor position x' the illuminated area is centred around a point with azimuth coordinate $\bar{x} = Ax'$ and has an azimuth size equal to X, see Fig.1. Accordingly, the azimuth illumination diagram of the real antenna is of the form $w\left(\frac{Ax'-x}{X}\right)$ that leads to the expression of the hybrid SAR raw signal given below:

$$h_{hybrid}\left(x',r'\right) = \iint \gamma\left(x,r\right) g_{hybrid}(x'-x,r'-r;x,r)\,dx\,dr\,, \tag{2}$$

where

$$\begin{aligned} g_{hybrid}(x'-x,r'-r;x,r) &= \\ &= \exp\left[-j\frac{4\pi}{\lambda}\Delta R\right]\exp\left[-j\frac{4\pi}{\lambda}\frac{\Delta f/f}{c\tau}\left(r'-r-\Delta R\right)^2\right]\cdot \\ &\cdot w^2\left(\frac{Ax'-x}{X}\right)\mathrm{rect}\left[\frac{x'}{X_1}\right]\mathrm{rect}\left[\frac{\left(r'-r-\Delta R\right)}{c\tau/2}\right] \end{aligned} \tag{3}$$

In eqs.(2-3), x, r and θ are the coordinates in the cylindrical coordinate system whose axis is the sensor line of flight; $S\equiv(x',0,0)$ is the antenna position; $\gamma(x,r)$ is the scene reflectivity pattern[1] including the phase factor $\exp[-j(4\pi/\lambda)r]$; λ and f are, respectively, the carrier wavelength and frequency of the transmitted signal; R is the distance from S to the generic point $(x,r,\theta(x,r))$ of the scene; $\theta=\theta(x,r)$ is the soil surface equation; R_0 is the distance from the line of flight to the centre of the scene; Δf is the chirp bandwidth; c is the speed of light; τ is the pulse duration time; $X=\lambda R_0/L$ is the real antenna azimuth footprint (we assume that $w(\cdot)$ is negligible when the absolute value of its argument is larger than 1/2, and that it is an even function); L is the azimuth dimension of the real antenna; rect[t/T] is the standard rectangular window function, i.e., rect[t/T]=1 if $|t|\le T/2$, otherwise, rect[t/T]=0; r' is $c/2$ times the time elapsed from each pulse transmission.

As expected, in the limiting cases A=1 and A=0, eqs.(2-3) reduce to the expression of the SAR raw signal in the stripmap and spotlight acquisition modes, respectively. Unfortunately, in the intermediate cases ($0<A<1$) the integral in eq.(2) cannot be expressed as a 2D convolution, and cannot be efficiently evaluated in the 2D Fourier transformed domain. In fact, a stationary phase evaluation of the FT of eq.(2) leads to

$$H_{hybrid}\left(\xi,\eta\right) = \iint \gamma\left(x,r\right) G_{hybrid}\left(\xi,\eta;x,r\right)\exp\left[-j\xi x\right]\exp\left[-j\eta r\right]dx\,dr \tag{4}$$

where

$$\begin{aligned} G_{hybrid}\left(\xi,\eta;x,r\right) &= \exp\left[j\frac{\eta^2}{4b}\right]\exp\left[j\frac{\xi^2\left(r/R_0\right)}{4a\left(1+\eta\lambda/(4\pi)\right)}\right]\cdot \\ &\cdot\mathrm{rect}\left[\frac{\eta}{2bc\tau/2}\right]\mathrm{rect}\left[\frac{\xi-2ax}{2aX_1}\right]w^2\left[\frac{\xi-2a\left(1-1/A\right)x}{2aX/A}\right] \end{aligned} \tag{5}$$

The particular x-dependence does not allow the implementation of an efficient simulation algorithm in the frequency domain while a time domain approach would be computationally expensive. A new method involving 1D range FT's is what we propose in the section below.

Simulation process

Let us start with an usually acceptable approximation in the second exponential of eq.(3): let us replace ΔR with its value at the scene centre (i.e., at $r = R_0$) thus neglecting only the effect of space variance on range curvature. In such a way eq.(2) can be rewritten as follows:

$$\begin{aligned} h_{hybrid}\left(x',r'\right) &\cong \int dx\, w^2\left[\frac{Ax'-x}{X}\right]\mathrm{rect}\left[\frac{x'}{X_1}\right]\cdot \\ &\cdot\left\{\int dr\,\gamma_1\left(x'-x,x,r\right)g\left(x'-x,r'-r\right)\right\} \end{aligned} \tag{6}$$

where

$$\gamma_1(x'-x,x,r) = \gamma(x,r)\exp\left[-j\frac{4\pi}{\lambda}\Delta R\right] \tag{7}$$

$$g(x'-x,r'-r) = \exp\left[-j\frac{4\pi}{\lambda}\frac{\Delta f/f}{c\tau}\left(r'-r-\Delta R_0\right)^2\right] rect\left[\frac{r'-r-\Delta R_0}{c\tau/2}\right] \tag{8}$$

and

$$\Delta R_0 = \Delta R(r=R_0) = \sqrt{R_0^2+\left(x'-x\right)^2} - R_0 \tag{9}$$

In eq.(6), the last term in the graph parentheses is recognized as the range-convolution between $\gamma_1\left(x'-x,x,r\right)$ and $g\left(x'-x,r\right)$. Therefore, eq.(6) can be also written as:

$$\begin{aligned} h_{hybrid}\left(x',r'\right) &= \int dx\, w^2\left[\frac{Ax'-x}{X}\right]\mathrm{rect}\left[\frac{x'}{X_1}\right]\cdot \\ &\cdot\left\{\Im^{-1}\left[\Gamma_1\left(x'-x,x,\eta\right)\cdot G\left(x'-x,\eta\right)\right]\right\} \end{aligned} \tag{10}$$

where $\Gamma_1\left(x'-x,x,\eta\right)$ and $G\left(x'-x,\eta\right)$ are the 1D range FT of $\gamma_1\left(x'-x,x,r\right)$ and $g\left(x'-x,r\right)$.

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1 Hereafter we will assume $\gamma\left(x',x,r\right)\approx\gamma\left(x,r\right)$. Actually, the reflectivity pattern of still ground point changes as the sensor moves, but the approximation is acceptable for the distances involved.

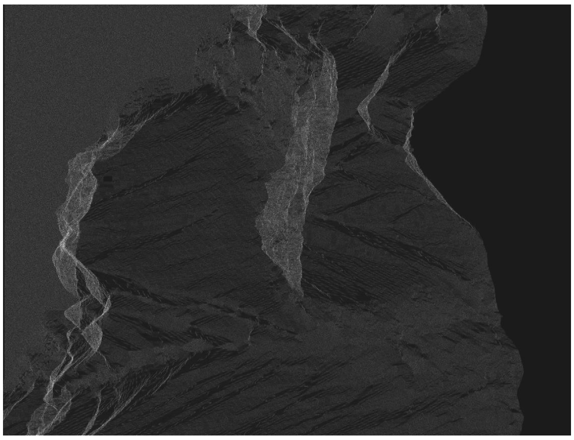

Fig.2: Image of an actual complex scene (Maratea), obtained by ideal hybrid processing. Near range is on the left. A=0.50, Q=6.

Eq.(10) suggests the steps we have followed to perform the simulation of hybrid SAR raw signals.

III. SIMULATION EXAMPLES

Raw signals simulation, relevant first to single scattering points and then to complex scenes, is now in order to test the effectiveness of the simulator proposed.

In the first case, phase errors, i.e. the phase differences between the raw signals simulated by using the proposed approach and the ones obtained via full time-domain simulation, have been considered. It can be shown that the absolute value of these phase differences is always smaller, and often much smaller, than $\pi/10$, thus leading to negligible effects. As far as concerns raw signal amplitudes, only small oscillations around the exact constant value can be noted.

Now, let us consider an actual complex extended scene given by an area of Maratea, Italy. In Fig.2 the corresponding image, obtained processing the raw signal with a hybrid focusing algorithm, is reported. Comparison with the image of Fig.3, obtained by processing the simulated raw signals with a Fourier domain focusing algorithm conceived for stripmap raw signals, shows a good agreement except for the appearance of some replicas, due to the Fourier Domain stripmap focusing algorithm.

IV. CONCLUSIONS

In this paper a new method to simulate hybrid SAR raw signals has been proposed, based on a 1D range Fourier domain approach followed by 1D azimuth time domain integration. Compared with a full time domain approach, it appears much more efficient, so that extended scenes can be considered.

Effectiveness of the simulator has been verified by comparing simulated raw signal corresponding to a single scattering point (placed at different positions in the illuminated scene) to the corresponding available time domain exact expression.

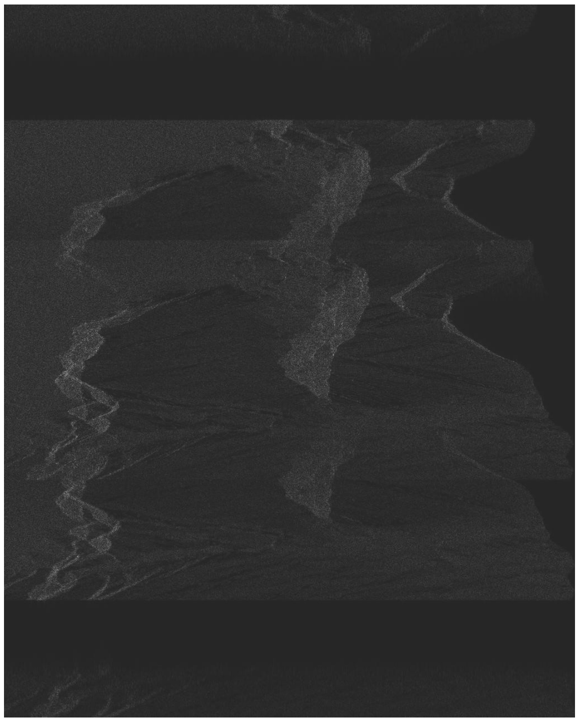

Fig.3: Image of an actual complex scene (Maratea), obtained by processing the simulated hybrid SAR raw signal via a Fourier domain stripmap focusing algorithm. Near range is on the left. A=0.50, Q=6.

Hybrid SAR raw signals corresponding to extended canonical scenes have been also simulated. Results confirm the consistency of the proposed simulation scheme and allow to highlight some interesting properties of the hybrid stripmap/spotlight SAR signals.

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