A TOOL FOR PLANNING OF HIGH RESOLUTION / WIDE COVERAGE IMAGING RADARS

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Abstract

The hybrid stripmap/spotlight operating mode for Synthetic Aperture Radar (SAR) system is able to generate 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, thanks to the radar antenna beam steering about a point farther away from the radar than the area being illuminated. In the last years the attention of remote sensing scientific community for the hybrid SAR mode is increased and, consequently, the subject of design, processing and data interpretation is gaining a growing interest.

SAR spaceborne sensors operating in the hybrid mode are still under design, as SAR 2000 in the Cosmo/Skymed project or TerraSAR-X, while airborne ones are already available as the wide band sensor SAR/MTI PAMIR.

Consequently, a hybrid SAR raw signal simulator is strongly required, especially when real raw data are not yet available, to test processing algorithms and 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.

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 Figure 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. In many cases, this is of paramount importance because a flexible operational mode as hybrid one allows to look at a wide range of scenarios every time with the best ‘eye’, that is with the most right couple of values of azimuth resolution and ground coverage.

In order to support the planning of SAR hybrid systems currently under design [1] or to test processing procedures proposed, in the last years, for hybrid mode [2-3] we need of a SAR raw signal simulator, being real raw data not yet available.
A frequency domain approach, being time and memory saving, would be highly desirable when extended scenes are considered. While efficient extended scene SAR simulators, based on a frequency domain approach, have been presented for the stripmap and spotlight operational modes [4-5], no one, to the best of our knowledge, is currently available for the hybrid geometry. In this work, the definition of a new transfer function for the hybrid case and its analytical evaluation via an asymptotic expansion are crucial steps for our aim.

After showing that in the hybrid 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.

Theoretical statements are followed by a simulation example, relevant to an actual extended scene, which confirm the effectiveness of the simulator here presented.

The hybrid stripmap/spotlight mode

In order to evaluate the SAR transfer function for the hybrid configuration we need to first evaluate the corresponding raw signal. At this aim we have to introduce the factor [2-3]

\[ A = \frac{r_1}{r_1 + R_0} \]  

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 Figure 2.

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 \( A(X_1/X) \) 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 Figure 2. Accordingly, the azimuth illumination diagram of the real antenna is of the form

\[ w \left( \frac{Ax' - x}{X} \right). \]

Usually, a SAR raw signal can be seen as the superimposition of all the elementary returns from the illuminated surface while each return is given by the scene reflectivity pattern \( \gamma(x,r) \) weighted by SAR impulse response function \( g(\cdot) \). This leads to the generic expression of the SAR raw signal given below:

\[ h(x',r') = \iint \gamma(x,r)g(x'-x,r'-r;x,r)dxdr, \]

which can be particularized for the hybrid case letting

\[ g_{\text{hybrid}}(x'-x,r'-r;x,r) = \exp \left[ -j \frac{4\pi}{\lambda} \Delta R \right] \exp \left[ -j \frac{4\pi}{\lambda} \frac{\Delta f}{c} \frac{f}{ct} (r'-r-\Delta R)^2 \right] w^2 \left( \frac{Ax' - x}{X} \right). \]  

In Equations [2]-[3], \( x, r \) and \( \theta \) are the coordinates in the cylindrical coordinate system whose axis is the sensor line of flight; \( S=(x',0,0) \) is the antenna position; \( \gamma(x,r) \) is the scene reflectivity pattern\(^1\) including the phase factor \( \exp[-j(4\pi/\lambda)r] \); \( \lambda \) 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

\(^1\) Hereafter we will assume \( \gamma(x',x,r) = \gamma(x,r) \). Actually, the reflectivity pattern of still ground point changes as the sensor moves, but the approximation is acceptable for the distances involved.
centre of the scene; $\Delta f$ is the chirp bandwidth; $c$ is the speed of light; $\tau$ 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; $\text{rect}(t/T)$ is the standard rectangular window function, i.e., $\text{rect}(t/T)=1$ if $|t| \leq T/2$, otherwise, $\text{rect}(t/T)=0$; $r'$ is $c/2$ times the time elapsed from each pulse transmission.

A stationary phase evaluation of the FT of Equation [2] leads to

$$H(\xi, \eta) = \int \gamma(x,r) G(\xi, \eta; x, r) \exp[-j\xi x] \exp[-j\eta r] dx dr$$

where, for the hybrid configuration,

$$G_{\text{hybrid}}(\xi, \eta; x, r) = \exp \left[ \frac{\eta^2}{4b} \right] \exp \left[ -j\frac{\xi^2 (r/R_0)}{4a(1+\eta^2/(4\pi))} \right] \text{rect} \left[ \frac{\eta - 2ax}{2aX_i} \right] \text{rect} \left[ \frac{\xi - 2a(1-1/A)x}{2aX/A} \right].$$

As expected, in the limiting cases $A=1$ and $A=0$, Equations [2]-[5] reduce to the expression of the SAR raw signal and transfer function in the stripmap and spotlight acquisition modes, respectively. Unfortunately, in the intermediate cases $(0<A<1)$ the integral in Equation [2] cannot be expressed as a 2D convolution, and cannot be efficiently evaluated in the 2D Fourier transformed domain. In fact, the particular $x$-dependence in Equation [5] does not allow the implementation of an efficient simulation algorithm in the frequency domain while a time domain approach would be computationally expensive. With an approximation usually acceptable in actual cases we demonstrate that an efficient simulation procedure, involving 1D range FT’s, is still possible and is here proposed in the section below.

**Simulation procedure**

Let us examine the second exponential of Equation [3] and replace $\Delta R$ 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 Equation [2] can be rewritten as follows:

$$h_{\text{hybrid}}(x', r') = \int dx \text{rect} \left[ \frac{x' - x}{X_i} \right] \cdot \left\{ \int dr' \gamma_1(x', x, r) g(x' - x, r' - r) \right\}$$

where

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

and

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

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

$$h_{\text{hybrid}}(x', r') = \int dx \text{rect} \left[ \frac{x' - x}{X_i} \right] \cdot \left\{ \mathcal{F}^{-1} \left[ \Gamma_1(x', x, \eta) \cdot G(x', x, \eta) \right] \right\}$$

where $\Gamma_1(x', x, \eta)$ and $G(x', x, \eta)$ are the 1D range FT of $\gamma_1(x', x, r)$ and $g(x' - x, r)$. Equation [10] suggests the
steps we have followed to perform the simulation of hybrid SAR raw signals.

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 a central area of Naples, Italy. The corresponding Digital Elevation Model is reported in Figure 3 where brightest pixels are related to higher altitudes. On the bottom left we can recognize the delightful hill of Posillipo while, on the top right the more level port area.

A 3-dimensional view of the same area is shown in Figure 4. On azimuth and range axes the number of pixels is reported. Pixel dimensions are about 15x15 m$^2$ so the imaged area has an extension of 8.6x6.4 km$^2$. An height of about 450 m corresponds to the brightest pixels on the top left of Figure 3, which major altitude is also shown in Figure 4.

In Figure 5 the image corresponding to the scene represented in Figures 3-4, obtained processing the raw signal with a hybrid focusing algorithm, is reported. A SAR system, flying at about 800 km, with a set frequency of 5.3 GHz, a look angle of 23 degrees and an azimuth antenna dimension of 15 m, has been employed in the simulation process. Layover and shadow effects, expected for the hill area, are evident. Comparison with the image of Figure 6, 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.

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.

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.

References

Captions and figures

Figure 1 - The hybrid stripmap/spotlight mode.

Figure 2 - Geometry of the problem.
Figure 3 - Digital Elevation Model of Naples, Italy.

Figure 4 - Digital Elevation Model of Naples, Italy: 3-dimensional view.
Figure 5 - Image of an actual complex scene (Naples), obtained by ideal hybrid processing. Near range is on the left.
Figure 6 - Image of an actual complex scene (Naples), obtained by processing the simulated hybrid SAR raw signal via a Fourier domain stripmap focusing algorithm. Near range is on the left.