Interferometric SAR Signal Analysis in the Presence of Squint

Marc BARA *, Rolf SCHEIBER *, Antoni BROQUETAS *

* Universitat Politècnica de Catalunya (UPC). Campus Nord, C/ Jordi Girona, 1-3, 08034 Barcelona, Spain.

Phone / Fax: +34 93 401 1065 / +34 93 401 7232. E-mail: mabara@volor.upc.es

* DLR-Deutsches Zentrum für Luft- und Raumfahrt e.V., Institut für Hochfrequenztechnik, D-82230 Oberpfaffenhofen, Germany. Phone / Fax: +49 8153 28 2319 / +49 8153 28 1449. E-mail: Rolf.Scheiber@dlr.de

ABSTRACT

In the following paper an analysis of the SAR impulse response signal from the interferometric point of view is expounded, with the intention of studying its phase behaviour in the presence of high squint values. The work will be focused on the development and verification of some methods for the generation of precise geocoded Digital Elevation Models (DEM) in high squinted geometries.

INTRODUCTION

It is well known that the geocoding techniques are oriented to the production of DEM's of the Earth's surface, starting from interferometric data recorded by a SAR system [1]. Their final accuracy is affected by errors coming from different sources, some of them directly relating to features of the SAR signal itself.

First, the paper will show that in the squinted case a phase ramp is present in the compressed impulse response function in the range direction, which, in combination with a certain degree of misregistration between the two channels, induces an offset in the generated interferometric phase. This behaviour, if not compensated, imposes strong limitations on the performance of the interferometric techniques.

Therefore, the next step described in this paper is the development of two new methods, which are appropriate to correct the phase bias coming from this source. The first one is based on a modification of the azimuth compression filter, while the second approach is oriented to estimate the expected misregistration. Both new correction methods have been tested with real airborne data coming from the DLR E-SAR system [2].

IMPULSE RESPONSE CHARACTERISTICS IN A SQUINTED GEOMETRY

It is well known that the impulse response of a SAR system can be considered as a two dimensional weighted-sinc function, obtained after the process of compression of the raw data coming from an individual target [3]. In this section a more general expression of the impulse response will be expounded, including the effects introduced by a squint angle, not only in the signal modulus but also the phase.

Equation (1) gives the expression of the signal in the range-Doppler domain [3], before the focusing step in azimuth, for a

target located at a minimum range time τ_0 (closest approach), and with a Doppler centroid (f_c) different from zero:

$$S(\tau, f_a) = C_0 \cdot s_r(\tau - \tau_0) \cdot w_a \left(\frac{f_a - f_c}{f_r} \right) \cdot \exp \left[-j 2\pi f_a t_0 \right] \cdot \exp \left[-j \frac{4\pi}{\lambda} r_0 \sqrt{1 - \left(\frac{\lambda f_a}{2v} \right)^2} \right] \quad (1)$$

where τ is the range time variable, f_a is the azimuth frequency, f_r is the Doppler rate, t_0 is the azimuth position of the target, λ is the wavelength value and v is the platform forward velocity. The functions named s_r and w_a are the envelopes in range time and azimuth frequency domains, respectively, while C_0 is an arbitrary complex constant. The following step of the processing chain consists of the multiplication with the azimuth-compressing filter:

$$H_{az}(\tau, f_a) = \exp \left[-j \frac{4\pi}{\lambda} \left(r_{ref} + \frac{c\tau/2 - r_{ref}}{\alpha} \right) \left(1 - \sqrt{1 - \left(\frac{\lambda f_a}{2v} \right)^2} \right) \right] \quad (2)$$

where α and r_{ref} are the well-known factors applied by the Extended Chirp Scaling (CS) algorithm [3]. ($\alpha = 1$ in the standard CS version). After the multiplication of (1) with (2), the response in range for a position located at a $\Delta\tau$ distance from the its maximum is:

$$S_c(\tau = \tau_0 + \Delta\tau, f_a) = C_2 \cdot s_r(\Delta\tau) \cdot w_a \left(\frac{f_a - f_c}{f_r} \right) \cdot \exp \left[-j 2\pi f_a t_0 \right] \cdot \exp \left[j \left[\phi_0 + \phi_1(f_a - f_c) + \phi_2(f_a - f_c)^2 \right] \right] \quad (3)$$

On one hand, the quadratic term ϕ_2 appears due to the fact that the sidelobes in range are compressed with a filter tuned to other distances and, therefore, it has no noticeable effect on the mainlobe of the signal. On the other hand, the linear term ϕ_1 is responsible for the shift of the sidelobes, which can be appreciable in a squinted response and zero-Doppler geometry, but it has no effect on the range phase. Finally, the constant term ϕ_0 represents a linear evolution along range. The final expression, after transforming back to the image domain, is given by

$$s_c(\tau, t) = C \cdot s_r(\tau - \tau_0) \cdot s_a \left(t - t_0 - \frac{c \tan \beta(r_0)}{v} (\tau - \tau_0) \right) \cdot \exp \left[-j \frac{4\pi}{\lambda} r_0 \right] \cdot \exp \left[j 2\pi f_c (t - t_0) \right] \cdot \exp \left[-j 2\pi f_0 (\tau - \tau_0) (1 - \cos \beta(r_0)) \right] \quad (4)$$

where f_0 is the radar central frequency, and β is the squint angle which can vary over range (point target at r_0). The last

exponential term of (4) includes the constant term ϕ_0 of (3), which induces a phase ramp in range. In the next section the effect of this factor on the interferometric phase is analysed.

EFFECTS OF THE SQUINT ANGLE ON THE PHASE

As we obtained in the previous section, in the squinted case the SAR signal is affected by a phase ramp in both dimensions. It can reach high values and introduce topography-dependent phase bias when combining both interferometric channels if they are not correctly coregistered. Taking into account that both channels are coregistered in azimuth in a single-pass scheme, the phase ramp to be considered is given by the last term of (4). When combining two responses, the following interferometric offset appears:

$$\phi_{\text{offset}} = \phi_{\text{real}} - \phi_{\text{ideal}} = \frac{4\pi}{\lambda} \Delta r \cdot (1 - \cos \beta) \quad (5)$$

where Δr is the existing misregistration and β the squint angle for that distance. This effect can not be considered as negligible since Δr is dependent on the topography and, therefore, it is not possible to compensate this bias by means of calibration with a single ground control point. Moreover, Equation (5) can reach high values in typical situations for airborne platforms.

METHODS FOR OFFSET COMPENSATION

In order to minimize the phase bias given by (5), two new and more effective solutions are presented.

1. Modification of the Azimuth-Compression Filter

We propose a modified version of the SAR azimuth-compressing filter, including a factor called β_g , in order to prevent the appearance of the phase ramp in (4):

$$H_{az}(\tau, f_a) = \exp \left[-j \frac{4\pi}{\lambda} \left(r_{\text{ref}} + \frac{c\tau/2 - r_{\text{ref}}}{\alpha} \right) \left(\cos \beta_g - \sqrt{1 - \left(\frac{\lambda f_a}{2v} \right)^2} \right) \right] \quad (6)$$

By means of this change, it can be shown that the phase ramp of (4) can be cancelled for one specific squint angle, yielding a reduced phase offset:

$$\phi_{\text{offset}} = \frac{4\pi}{\lambda} \Delta r \cdot (\cos \beta_g - \cos \beta(r)) \quad (7)$$

This factor, applied to both images, affects also the interferometric phase itself:

$$\phi = \frac{4\pi}{\lambda} (r_2 - r_1) \cdot \cos \beta_g \quad (8)$$

but this change can be taken into account during the geocoding stage.

2. Precise Geocoding with Estimated Misregistration

In cases we have to deal with variable squint over range, we suggest the use of another approach based on the estimation of

the existing misregistration for every point of the interferogram. This can be done if the features of the coregistering process are well known, as it is the case when using the ECS algorithm. In this case, the final position of a target located at r_2 from the slave antenna is scaled with:

$$r_{2,\text{scl}} = \alpha \cdot (r_2 - r_{\text{ref}}) + r_{\text{ref}2} \quad (9)$$

where $r_{\text{ref}2}$ is slightly different from r_{ref} because it contains the term which accounts for the coarse coregistration and the differential delay of the second channel.

Starting from the inaccurate value of the interferometric phase ϕ , it is possible however to obtain a first approximation for the distance r_2 with:

$$r_2 = r_1 + \frac{\lambda \phi}{4\pi} \quad (10)$$

where r_1 is the known distance to the master antenna. Then, considering (9), a estimation of the misregistration can be performed:

$$\Delta r_{\text{est}} = r_1 - r_{2,\text{scl}} \quad (11)$$

This value can be substituted in (5) to obtain a refined value:

$$r_{2,\text{corr}} = r_2 - \Delta r_{\text{est}} \cdot (1 - \cos \beta) \quad (12)$$

Indeed, this process can be repeated in an iterative way:

$$r_{2,n+1} = r_{2,0} - \left[r_1 - \left[\alpha (r_{2,n} - r_{\text{ref}}) + r_{\text{ref}2} \right] \right] \cdot (1 - \cos \beta) \quad (13)$$

and also in combination with the modified filter of (10) by considering $(\cos \beta_g - \cos \beta)$ instead of $(1 - \cos \beta)$.

RESULTS WITH REAL AIRBORNE DATA

The theoretical methods have been verified with real data of the DLR E-SAR system from the test area of Oberpfaffenhofen, Germany, taken with a squint angle of 3 degrees approximately. After processing with the ECS algorithm including motion compensation techniques, a DEM which contains five corner reflectors (Fig. 1) has been generated with a direct geocoding step. The obtained height accuracy in the five control points has a standard deviation of only 25 cm.

In order to assess the impact of the expressions expounded above, the data set has been re-processed introducing a controlled misregistration between both SAR channels. This distortion can be easily achieved by changing the co-registering parameters while processing the second image.

The misregistration which has been imposed for every real reflector is shown in Table 1. We use the notation P_i for describing the reflectors, with the index i increasing with range. After combining both images, a phase offset referred to the perfect co-registration case has been detected (Table 2).

As we can see, this offset is slightly different from the expected one from (5), considering a constant squint value of 2.7 degrees used during the processing.

Figure 1. Elevation Model with overlaid reflectivity

Table 1. Misregistration in Ground Control Points

Target	Misregistration (m)
P0	-0.31466
P1	-0.15934
P2	-0.00077
P3	0.16248
P4	0.32970

Table 2. Phase Offset in Ground Control Points

Target	Existing Phase Offset (deg)	Theoretical Offset (Eq.5) (deg)	Theoretical Offset (Eq.15) (deg)
P0	-7.01	-8.05	-5.18
P1	-1.94	-4.07	-2.77
P2	-0.14	-0.02	0.01
P3	2.12	4.15	3.05
P4	5.22	8.43	6.40

This discrepancy can be attributed to the motion compensation step. During this process, the signal is multiplied with a range-varying factor with the form:

$$H_{2nd}(t, r) = \exp \left[j \frac{4\pi}{\lambda} \Delta d(t, r) \right] \quad (14)$$

which introduces a range spectral shift, yielding an additional phase in the compressed response:

$$\phi_{offset} \approx \frac{4\pi}{\lambda} \Delta r \cdot \left((1 - \cos \beta(r)) - \frac{\partial \Delta d(r)}{\partial r} \right) \quad (15)$$

Equation (5) predicted a phase ramp value of about 25 deg/m, while with the introduction of this new contribution the resultant value is about 18 deg/m, which agrees much more accurately with the real existing phase ramp.

With this new expression for the predicted phase offset, it is possible to apply the iterative method. The results, after two iterations, are shown in Table 3. The obtained values agree with (15) (last column of Table 2), what confirms the possibility of estimating the misregistration to cancel the offset. Moreover, with only one iteration the approximation is sufficient, lessening in this way the computational time.

Table 3. Estimated offset with iterative method

Target	Estimated Offset (deg)	
	1 st iteration	2 nd iteration
P0	-5.29	-5.30
P1	-2.87	-2.87
P2	-0.14	-0.14
P3	2.93	2.94
P4	6.28	6.29

After subtracting the estimated values of Table 3 from the real offsets displayed in Table 2, the remaining biases are below 1.7 deg. It is possible to conclude, therefore, that this approach yields a high improvement of the final accuracy. The remaining errors could be attributed to an existing quadratic term of the motion compensation phase along range, or from the fact that it depends on azimuth time and affects the synthetic aperture in a variable way.

CONCLUSIONS

A complete interferometric signal analysis has been carried out, considering squinted geometries and also some effects of the motion compensation step. Two new methods for the compensation of existing phase offsets allow the generation of precise elevation models. Both methods have successfully shown their validity to improve the results in a real scenario.

ACKNOWLEDGMENT

The authors would like to thank the CIRIT Commission of the Catalan Government for the financial support of Marc Bara during his three-month stay at DLR. Special thanks also to Dr. Alberto Moreira from DLR for his technical support.

REFERENCES

- [1] D. Carrasco, D. Esteban, F. López, J. Tena, O. Rodríguez, M. Bara, A. Broquetas, "Precise geometry techniques for ERS SAR Interferometry", European Conference on Synthetic Aperture Radar, May 1998.
- [2] R. Horn, "The DLR Airborne SAR Project E-SAR", IGARSS'96.
- [3] A. Moreira, J. Mittermayer, R. Scheiber, "Extended Chirp Scaling Algorithm for Air- and Spaceborne SAR Data Processing in Stripmap and ScanSAR Imaging Modes", IEEE Trans. Geoscience and Remote Sensing, vol. 34, September 1996.