Phase preservation in SAR processing: The Interferometric Offset Test

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Abstract- SAR Interferometry requires a high accuracy processing of the phase information. The paper describes a practical method to check the phase preservation of a SAR processor. Test results for four different ERS SAR processors are presented.
Keywords: interferometry, phase preserving processing.

INTRODUCTION

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This article presents the current phase preservation tests [7] performed by the European Space Agency following a study described in [1]. Phase preservation tests results are presented for several ERS SAR processors.

PHASE DECORRELATION

The quality of an interferogram is usually represented by the coherence γ between a pair of complex products. Phase aberrations are translated in a coherence degradation and modify the interferogram statistics. Several factors contribute to the interferometric phase decorrelation. For our purposes, they can be divided in two kinds of decorrelation sources:

1. The factors inherent to the SAR system and to the interferometric scenario (as the spatial mis-registration, the temporal decorrelation, the variations in the propagation path or the spectrum mis-alignment): γ_{sys}
2. The factors introduced during the data processing, i.e. the processor phase preservation factors: γ_{proc}

Their contribution to the total coherence can be expressed as:

$$\gamma = \gamma_{sys} \cdot \gamma_{proc} \qquad (1)$$

As our purpose is to analyse the quality of the processor phase preservation, we need to isolate γ_{proc}. This leads to the Interferometric Offset test, which was originally proposed in [1] as a method for checking the phase preservation of SAR processors.

THE INTERFEROMETRIC OFFSET TEST

The test consists basically in:

a. Generate two complex products independently processing the same raw data set twice, but starting at different azimuth and range positions. Usage of the same raw data set will prevent from phase aberration due to inherent SAR effects (γ_{sys}).

b. Evaluate the statistics of the generated interferogram. Since it should ideally have a constant phase of zero, the obtained interferometric phase reveals processor induced aberrations.

Products generation

In generating the products, some points must be carefully observed in order to obtain an appropriated pair for the test:

- Range compression is performed using a nominal chirp or the same chirp replica in both cases.
- The number of offset lines and samples are not integer multiples of the processing blocks dimension (nor in azimuth nor in range). It causes the existence of interferometric areas generated from the same processing data block (which will be referred as *regions a*) and from different data blocks (referred as *regions b*). Their co-existence allows to check the noise level at the processing block boundaries.
- Since usage of different Doppler centroid would produce an spectral envelope misalignment (i.e. it would simulate a system decorrelation source), the same doppler centroid parameters are used to process both products.
- Starting processing positions are chosen, whenever possible, in such a way that the offset between products is an integer value in both directions. If it is not possible, a subpixel misregistration remains with the need of a subpixel coregistration, which increases the phase noise.

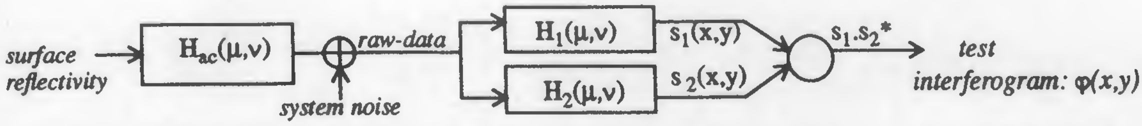

Fig.1 There is a unique acquisition process (H_{ac}) whose output is processed twice (H_1,H_2). Focused signals (s_1,s_2) are combined to form the test interferogram (s_2^* represents the complex conjugate of s_2).

Phase statistics evaluation

A theoretical study on the decorrelation due to the end-to-end SAR system response and on the interferometric phase statistics is carefully presented in [2,3,6]. The analysis is given for the case of an expected interferometric phase equal to zero and therefore it applies for the offset test interferogram if the system considered is the one represented in Fig.1.

The only difference between both transfer functions is the phase term $\phi(.)$, which represents the differential focusing under evaluation:

$$H_2(\mu,\nu) = H_1(\mu,\nu)\cdot e^{-j\phi(\mu,\nu)} \qquad (2)$$

Therefore, the coherence between tested products can be expressed as follows [2,3,4]:

$$\gamma = \frac{E\{s_1\cdot s^*_2\}}{\sqrt{E\{|s_1|^2\}\cdot E\{|s_2|^2\}}} = \frac{1}{B_\mu\cdot B_\nu}\cdot\int_{-B_\mu/2}^{B_\mu/2}\int_{-B_\nu/2}^{B_\nu/2} e^{j\phi(\mu,\nu)}d\mu d\nu \qquad (3)$$

where μ,ν,$B\mu$ and $B\nu$ represent the azimuth and range frequency, and the azimuth and range bandwidth respectively.

From this basis, an analytical expression for the phase p.d.f., the phase bias and the phase variance can be derived [2,3]. The interesting result for our analysis is that the interferometric phase decorrelation introduced by the processor can be characterised by:

1. A phase bias value (φ_0) corresponding to the systematic phase errors and equal to the argument of the coherence coefficient. Since it depends on both transfer functions but not on the SNR, it cannot be reduced by averaging.
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As a consequence, these two statistical parameters are the parameters to be estimated in the offset test interferogram.

The next important point is to identify the contribution of the different processing decorrelation sources on these parameters. The differential focusing phase can be expressed as Taylor series [2,6], where each term represents a different processing decorrelation source:

$$\phi(\mu,\nu) = \phi_{00}+\phi_{10}\cdot\mu+\phi_{01}\cdot\nu+\phi_{11}\cdot\mu\nu+ \\ +\phi_{20}\cdot\mu^2+\phi_{02}\cdot\nu^2+\phi_{21}\cdot\mu^2\nu+\ldots \qquad (4)$$

The meaning of each term together with their evidence in the test results is summarised in Table 1.

Therefore, measured phase bias and standard variation over the generated interferogram correspond to the following phase aberrations:

$$\varphi_0 = \varphi_{00}+\varphi_{20}$$
$$\sigma_\phi^2 = \sigma^2_{11}+\sigma^2_{21}+\sigma^2_{subpixel-mis}+\sigma^2_{proc-impl} \qquad (5)$$

where $\sigma^2_{poc\_impl}$ stands for the phase noise due to the processor implementation. This phase noise is consequence, for instance, of an insufficient amount of data discarded during processing operations which produce only a partial amount of valid data (e.g. when a linear correlation is .

Table 1: Measurable processing phase aberrations

	Constant phase offset: ϕ_{00}	Geometric misregistration azimuth: ϕ_{10} & range: ϕ_{01}	Uncompensated range migration linear: ϕ_{11} & quadratic: ϕ_{21}	Defocussing in azimuth: ϕ_{20}	Defocussing in range: ϕ_{02}
φ_0	φ_{00}	*Effect avoided by test conditions*	*No impact*	φ_{20}	*Effect avoided by test conditions*
σ^2_φ	*No impact*		$\sigma^2_{11}+\sigma^2_{21}$	σ^2_{20}	

obtained from a circular one). This noise can be visually detected as a cyclic pattern of regions with high noise (the so-called *regions b*). The presence of $\sigma^2_{subpixel\_mis}$ is not due to a processor induced aberration but to the difficulty to generate a testing pair with integer offset values. This noise term represents the noise introduced by the sub-pixel coregistration step needed in such a case.

Test Acceptance Criteria

The test acceptance criteria are based on a maximum systematic error (maximum phase mean) and on a maximum level noise, partially related to the system SNR [1]. The criteria are the following:

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TESTS RESULTS

The Interferometric Offset test was applied to four ERS SAR processors: the Verification Mode Processor (VMP) [Range-Doppler], the Italian PAF processor (I-PAF) [Range-Doppler], an experimental Chirp Scaling Algorithm (CSA) and an ωk Processor (ωk).

During the analysis of the statistical parameters, special care has been taken in:

- Avoiding very low backscattering coefficient areas. First part of Table 2 gives the results for the complete generated interferogram, i.e. with 100% of the input data. Second part of Table 2 gives the results obtained when discarding samples corresponding to low backscattering coefficient (equivalent to use about 95% of the input data). This insures a more accurate estimation of the processor induced aberrations.
- Independently measuring the parameters over both kinds of regions previously identified (*regions a* and *b*). No significant difference between these results have been found.

Comments

The results demonstrate that the four SAR processors are phase-preserving. However it is worth mentioning that the first results for the ωk and I-PAF processors were outside the acceptance criteria. This was due to processing inaccuracies and led to slight modifications in the processor design. The last results (Table 2) are obtained after the processor modifications.

The tested processors do not have the same flexibility to follow the test processing recommendations. In some cases, the processor implementation makes difficult the generation of the products required for the test. For example, the VMP processor, which is the main operational ERS processor, indicates the along track position by its associated azimuth time. When the VMP operational mode is used, it is difficult to get an integer azimuth shift between products. Therefore a corregistration step at subpixel level is needed and this is considered to be the main responsible of the measured phase noise. Using the VMP test mode enables the genetation of a pair of products shifted by an integer number of lines. In such a case much lower phase noise is obtained.

OTHER TESTS

The Interferometric Offset Test insures that a SAR processor is phase preserving. However the test does not insure that two phase preserving processors are able to provide compatible complex products for interferogram generation. Two possibilities exist and need further investigation:

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This test is proposed in [1] as a different approach for the offset test and is based on the phase quality analysis of the impulse response function. It is a complement to the classical SAR processing quality analysis.
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Different processors may implement slightly different transfer functions. The processor differences may not only be related to their phases but also to their modules (e.g. different weighting functions or different weighting coefficients). Therefore, the theoretical statistical analysis for the Offset Test is no more applicable and its independent accomplishment does not guarantee interferometric compatibility. The Cross-Offset overcomes this limitation by performing the Offset Test with a pair of products generated by two different processors (with the same processing requirements as for the Interferometric Offset Test).

CONCLUSIONS

A method to check the phase preservation of a SAR processor has been presented, with special emphasis on its practical aspects. The test was applied to four different ERS SAR processors, demonstrating the test capability to detect processing inaccuracies. Results prove the phase preservation capability of these processors. The test limitations for insuring the quality of an interferogram generated with different phase-preserving processors was pointed out. Additional tests to check this feasibility were proposed.

Table 2: Offset Test results. All phase values are given in degrees.

	VMP	I-PAF	CSA	ωk
Azimuth offset [lines]	332	6718	700	799
Range offset [samples]	99	300	300	300
100 %				
Coherence Module: $\lvert\gamma\rvert$	0.996621	0.999861	0.999786	0.999514
Coherence Phase: $\arg\{\gamma\}$	0.056222	0.000010	0.001010	0.004480
Phase mean: φ_0	0.063588	0.001200	0.002127	0.005300
Phase standard deviation: σ_φ	1.908490	1.233000	2.613000	4.583000
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Coherence Module: $\lvert\gamma\rvert$	0.998080	0.999866	0.999799	0.999558
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Phase mean: φ_0	0.060897	0.000960	0.000880	0.004370
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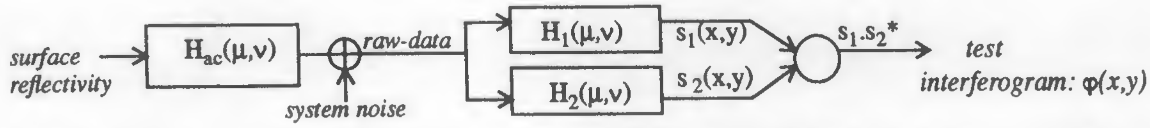

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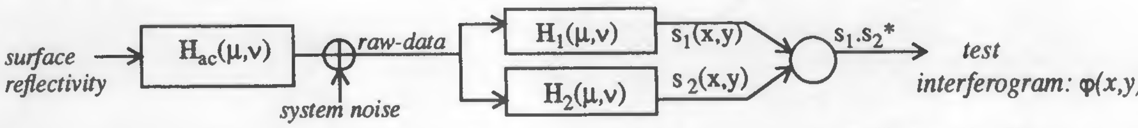

Fig.1 There is a unique acquisition process (H_{ac}) whose output is processed twice (H_1,H_2). Focused signals (s_1,s_2) are combined to form the test interferogram (s_2^* represents the complex conjugate of s_2).

Phase statistics evaluation

A theoretical study on the decorrelation due to the end-to-end SAR system response and on the interferometric phase statistics is carefully presented in [2,3,6]. The analysis is given for the case of an expected interferometric phase equal to zero and therefore it applies for the offset test interferogram if the system considered is the one represented in Fig.1.

The only difference between both transfer functions is the phase term $\phi(.)$, which represents the differential focusing under evaluation:

$$H_2(\mu,\nu) = H_1(\mu,\nu)\cdot e^{-j\phi(\mu,\nu)} \qquad (2)$$

Therefore, the coherence between tested products can be expressed as follows [2,3,4]:

$$\gamma = \frac{E\{s_1\cdot s^*_2\}}{\sqrt{E\{|s_1|^2\}\cdot E\{|s_2|^2\}}} = \frac{1}{B_\mu\cdot B_\nu}\cdot\int_{-B_\mu/2}^{B_\mu/2}\int_{-B_\nu/2}^{B_\nu/2} e^{j\phi(\mu,\nu)}\,d\mu d\nu \qquad (3)$$

where μ,ν,$B\mu$ and $B\nu$ represent the azimuth and range frequency, and the azimuth and range bandwidth respectively.

From this basis, an analytical expression for the phase p.d.f., the phase bias and the phase variance can be derived [2,3]. The interesting result for our analysis is that the interferometric phase decorrelation introduced by the processor can be characterised by:

1. A phase bias value (φ_0) corresponding to the systematic phase errors and equal to the argument of the coherence coefficient. Since it depends on both transfer functions but not on the SNR, it cannot be reduced by averaging.
2. A phase variance (σ^2_φ) depending on the module of the coherence coefficient, on both transfer functions and on the SNR. It is very sensitive to data manipulations, but it can be reduced by averaging.

As a consequence, these two statistical parameters are the parameters to be estimated in the offset test interferogram.

The next important point is to identify the contribution of the different processing decorrelation sources on these parameters. The differential focusing phase can be expressed as Taylor series [2,6], where each term represents a different processing decorrelation source:

$$\phi(\mu,\nu) = \phi_{00}+\phi_{10}\cdot\mu+\phi_{01}\cdot\nu+\phi_{11}\cdot\mu\nu+ \\ +\phi_{20}\cdot\mu^2+\phi_{02}\cdot\nu^2+\phi_{21}\cdot\mu^2\nu+\ldots \qquad (4)$$

The meaning of each term together with their evidence in the test results is summarised in Table 1.

Therefore, measured phase bias and standard variation over the generated interferogram correspond to the following phase aberrations:

$$\varphi_0 = \varphi_{00}+\varphi_{20} \\ \sigma_\phi^2 = \sigma^2_{11}+\sigma^2_{21}+\sigma^2_{subpixel-mis}+\sigma^2_{proc-impl} \qquad (5)$$

where $\sigma^2_{poc\_impl}$ stands for the phase noise due to the processor implementation. This phase noise is consequence, for instance, of an insufficient amount of data discarded during processing operations which produce only a partial amount of valid data (e.g. when a linear correlation is

Table 1: Measurable processing phase aberrations

	Constant phase offset: ϕ_{00}	Geometric misregistration azimuth: ϕ_{10} & range: ϕ_{01}	Uncompensated range migration linear: ϕ_{11} & quadratic: ϕ_{21}	Defocussing in azimuth: ϕ_{20}	Defocussing in range: ϕ_{02}
φ_0	φ_{00}	*Effect avoided by test conditions*	*No impact*	φ_{20}	*Effect avoided by test conditions*
σ^2_φ	*No impact*		$\sigma^2_{11}+\sigma^2_{21}$	σ^2_{20}	

obtained from a circular one). This noise can be visually detected as a cyclic pattern of regions with high noise (the so-called *regions b*). The presence of $\sigma^2_{subpixel\_mis}$ is not due to a processor induced aberration but to the difficulty to generate a testing pair with integer offset values. This noise term represents the noise introduced by the sub-pixel coregistration step needed in such a case.

Test Acceptance Criteria

The test acceptance criteria are based on a maximum systematic error (maximum phase mean) and on a maximum level noise, partially related to the system SNR [1]. The criteria are the following:

- maximum phase mean: 0.1 degrees
- maximum phase standard deviation: 5.0 degrees

TESTS RESULTS

The Interferometric Offset test was applied to four ERS SAR processors: the Verification Mode Processor (VMP) [Range-Doppler], the Italian PAF processor (I-PAF) [Range-Doppler], an experimental Chirp Scaling Algorithm (CSA) and an ωk Processor (ωk).

During the analysis of the statistical parameters, special care has been taken in:

- Avoiding very low backscattering coefficient areas. First part of Table 2 gives the results for the complete generated interferogram, i.e. with 100% of the input data. Second part of Table 2 gives the results obtained when discarding samples corresponding to low backscattering coefficient (equivalent to use about 95% of the input data). This insures a more accurate estimation of the processor induced aberrations.
- Independently measuring the parameters over both kinds of regions previously identified (*regions a* and *b*). No significant difference between these results have been found.

Comments

The results demonstrate that the four SAR processors are phase-preserving. However it is worth mentioning that the first results for the ωk and I-PAF processors were outside the acceptance criteria. This was due to processing inaccuracies and led to slight modifications in the processor design. The last results (Table 2) are obtained after the processor modifications.

The tested processors do not have the same flexibility to follow the test processing recommendations. In some cases, the processor implementation makes difficult the generation of the products required for the test. For example, the VMP processor, which is the main operational ERS processor, indicates the along track position by its associated azimuth time. When the VMP operational mode is used, it is difficult to get an integer azimuth shift between products. Therefore a corregistration step at subpixel level is needed and this is considered to be the main responsible of the measured phase noise. Using the VMP test mode enables the genetation of a pair of products shifted by an integer number of lines. In such a case much lower phase noise is obtained.

OTHER TESTS

The Interferometric Offset Test insures that a SAR processor is phase preserving. However the test does not insure that two phase preserving processors are able to provide compatible complex products for interferogram generation. Two possibilities exist and need further investigation:

1. The Point Target Test
   This test is proposed in [1] as a different approach for the offset test and is based on the phase quality analysis of the impulse response function. It is a complement to the classical SAR processing quality analysis.
2. The Cross-Offset Test
   Different processors may implement slightly different transfer functions. The processor differences may not only be related to their phases but also to their modules (e.g. different weighting functions or different weighting coefficients). Therefore, the theoretical statistical analysis for the Offset Test is no more applicable and its independent accomplishment does not guarantee interferometric compatibility. The Cross-Offset overcomes this limitation by performing the Offset Test with a pair of products generated by two different processors (with the same processing requirements as for the Interferometric Offset Test).

CONCLUSIONS

A method to check the phase preservation of a SAR processor has been presented, with special emphasis on its practical aspects. The test was applied to four different ERS SAR processors, demonstrating the test capability to detect processing inaccuracies. Results prove the phase preservation capability of these processors. The test limitations for insuring the quality of an interferogram generated with different phase-preserving processors was pointed out. Additional tests to check this feasibility were proposed.

Table 2: Offset Test results. All phase values are given in degrees.

	VMP	I-PAF	CSA	ωk
Azimuth offset [lines]	332	6718	700	799
Range offset [samples]	99	300	300	300
100 %				
Coherence Module: $\|\gamma\|$	0.996621	0.999861	0.999786	0.999514
Coherence Phase: $\arg\{\gamma\}$	0.056222	0.000010	0.001010	0.004480
Phase mean: φ_0	0.063588	0.001200	0.002127	0.005300
Phase standard deviation: σ_φ	1.908490	1.233000	2.613000	4.583000
95 %				
Coherence Module: $\|\gamma\|$	0.998080	0.999866	0.999799	0.999558
Coherence Phase: $\arg\{\gamma\}$	0.056000	0.000106	0.001003	0.004470
Phase mean: φ_0	0.060897	0.000960	0.000880	0.004370
Phase standard deviation: σ_φ	0.972000	0.599000	1.355000	2.301000

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