PERFORMANCE SIMULATOR FOR BISTATIC SAR MISSIONS

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ABSTRACT

This paper presents a Synthetic Aperture Radar (SAR) simulator designed to assess the performance of bi-static SAR missions. It is a modular software able to simulate realistic SAR data (including injection of the system non-idealities), to estimate the SAR performance at radiometric and interferometric level. In order to ensure accurate measures of the bi-static performance, it simulates raw data exploiting a time-domain approach, without assumptions on the acquisition geometry. This feature makes the simulator a useful tool for the design of new SAR missions concepts. We also report sample results considering the SAOCOM-CS mission case as an example of application of the simulator.

Index Terms— SAR, Simulation, Bistatic SAR, InSAR

1 INTRODUCTION

The last few years have seen the rise of interest into new spaceborne SAR missions concepts for Earth observation. In particular, the concept of passive receive-only companion satellites, paired to a monostatic illuminator for bistatic SAR imaging is subject of several studies (e.g. [1],[2]). The European Space Agency (ESA) has performed a series of studies that have addressed the feasibility of such bi-static missions. For example we cite the SAOCOM-CS [3], a passive follower of the SAOCOM satellite and the CompSAR [4], a receive-only satellite in formation with Sentinel-1.
The bi-static SAR observation brings new challenges such as the synchronization in time and phase between the instruments and the imaging geometry. The development of new tools becomes necessary, starting already in Phase-A, to ease the mission requirements definition and, in the successive phases, to address the trade-offs at system level. In response to this need ESA supported the development of the Performance Simulator for Bistatic SAR Missions (PSBSM). The PSBSM is an end-to-end simulator of SAR data, allowing the simulation of all the SAR products, from the raw data to the interferometric coherence, passing through Single Look Complex (SLC) and co-registered data. One main requirement is the capability to simulate both monostatic and bi-static data without limits in terms of geometric configurations. Concerning the raw data simulation, two approaches are normally on the table: the time-domain and the frequency-domain. The latter is an efficient way to simulate data exploiting the standard focusing algorithms "in reverse" [5]. The time-domain approach is based on a more "simple" algorithm, which mimics the actual timeline of the SAR system. This allows much more flexibility and accuracy, but generally a heavier computational cost. After the evaluation of the advantages and drawbacks of each approach, the time-domain was selected.
The developed PSBSM allows to inject directly into the raw data the non-idealities of the instrument (central electronic, antenna, orbit, etc.…) and of the propagation medium (Ionosphere). Concerning the L1 processor, the PSBSM framework provides the raw data focusing feature for monostatic ad bi-static data, and an independent verification processor exploiting the back-projection. Eventually, as final output the tool estimates the SAR performances in terms of Impulse Response Function (IRF) and quality of the interferometric phase. This is made possible thanks to the availability of a set of tools, performing co-registration, interferogram formation and SAR data quality analysis.
In the following sections, we provide an overview of the PSBSM architecture including a brief description of its buiding blocks (Section 2). Then we report some sample results (Section 3). In particular, we focus on the SAOCOM-CS case.

2 SIMULATOR ARCHITECTURE

As shown in Figure 1, the PSBSM is a modular software. This structure eases its evolution through the mission phases and the upgrade of the single modules with new features. We can identify the three main modules: Raw Data Simulator, L1 processor, Co-registration & analysis tools.

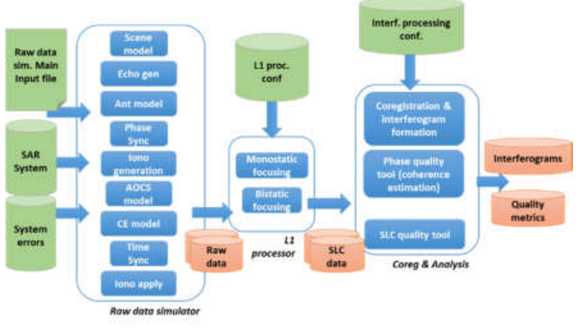

Figure 1 PSBSM architecture and interfaces

2.1 Raw Data Simulator

The Raw Data Simulator exploits a time-domain approach, i.e. for each PRI the module computes the round-trip path between transmitter and receiver for all targets in the scene. Accordingly, for each target it generates a chirp pulse with a proper delay, phase and gain and sum all of them together coherently. The raw data is generated collecting all the echoes for each PRI in a 2D matrix.
The time-domain approach just described is potentially very time-consuming (in particular for distributed targets). For this reason, the core of the module has been designed and implemented exploiting High Performance Computing (HPC), in particular it uses both the multi-threading and the multi-process paradigms.
In order to simulate the data, the module needs as input:

- The "SAR systems" representing the Tx and Rx satellites. Each "SAR system" is a collection of files that allow the description of potentially any SAR instrument. (pulse description, orbit, attitude, timeline, antenna patterns, ecc…)
- The description of the scene.
- The system errors, i.e. the characterization of the non idealities affecting the SAR acquisition (noise, radiometric and phase distortions, baseline and pointing errors,etc.).

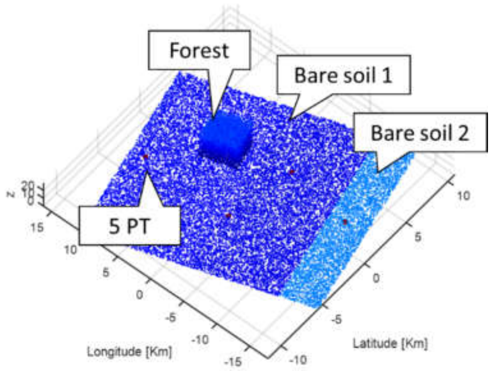

Figure 2 Output of the scene generator

Concerning the description of the scene, the module allows to simulate, isolated point targets (PT), 2D distributed targets (e.g. bare soil) and 3D distributed targets (e.g. forest). According to the target parameters provided by the "scene descriptor" (kind of target, moisture, biomass, etc.) and the acquisition geometry, the scene generator module defines a list of PTs with a proper density and Radar-Cross-Section (RCS). The look up tables to interpolate the sigma zero values and the vertical power spectrums (for forest targets) are based on state of the art wave-targets interaction models (the second order approximation of the SSA model [9] for soil, the solution of Radiative Transfer Equation based on the Matrix Doubling algorithm for vegetated areas and the model developed by Hwang and Fois [8], that is based on the SSA2 model, for water). The implementation of such models have been done by "CRAS - La Sapienza", Rome. In Figure 2 we display an example of a scene generated with the Scene Generator.
For the considered specific case of the SAOCOM-CS, the "SAR systems" and the "System errors" databases have been filled with realistic values thanks to the cooperation with Thales Alenia Space Italia (TAS-I) and Airbus DS CASA.
Overall, a realistic raw data matrix can be generated including the targets in the scene described above and the non-idealities that can be injected in the raw data:

- Central electronic non-idealities.
- Antenna errors.
- Time and phase mis-synchronization between transmitter and receiver sensors.
- Error in the orbit and attitude.
- Wave propagation effects due to the ionosphere.

2.2 L1 processor

The L1 processor module is devoted to perform the focusing of the data simulated by the Raw Data Simulator. In particular the main steps are: range compression, Doppler estimation, Azimuth focusing and radiometric calibration.
For the cases where the hypothesis of stationary acquisition [10] is valid, two possible algorithms for azimuth focusing have been selected:

- The "classical" Ω-k algorithm [7]: with analytical kernel for addressing, with the maximum efficiency and robustness, stationary configurations of the bi-static acquisitions with small baselines.
- An advanced version of the Ω-k algorithm: implementing a kernel computed numerically from orbits as in [6]. This second algorithm is more complex and a little bit more computationally demanding. Anyway, it is able address a wider range of bi-static configurations and maintains a very good level of computational efficiency.

Both algorithms are complemented with a block processing strategy that allows the correct update of processing parameters and ensures the maximum processing accuracy.

2.3 Co-registration & analysis tools

The third module of the end-to-end simulator allows the formation of SAR interferograms and offers a set of tools to measure the performance of the system directly on the simulated data, in terms of both IRF quality and InSAR phase quality. Hereinafter the list of the adopted figures of merit for the IRF quality:

- Resolution (azimuth/range)
- PSLR, ISLR
- Localization error
- Radiometric error (the difference between the expected and the measured radar cross section (RCS) of the target).

Concerning the performances of InSAR applications (InSAR, Tomography and PolInSAR) they strictly depend on the capability of the system to provide accurate measurement of the complex interferometric coherence in all the available interferometric pairs. Accordingly, the retrieval performance is assessed in all cases as a function of system-induced errors on the InSAR coherence magnitude and phase. We define:

- γ_{sys} as the bias of the coherence magnitude due to system-related effects (system coherence), such as noise, ambiguities, mis-registration, de-focusing, etc.
- σ_{α} as the standard deviation of the phase noise. This arises from e.g. a non-perfect compensation of clock drifts, orbits, and from approximate bistatic focusing.

For Tomography, the simulator allows the prediction of the impact of system-induced errors on the radiometric accuracy of the tomogram. For PolInSAR, the accuracy of the forest height and of the ground topography retrieval can be predicted.

3 SAOCOM-CS CASE SAMPLE RESULTS

In this section we collect some sample results generated by the PSBSM, obtained considering the SAOCOM-CS mission as a reference case. The results reported hereinafter have been simulated exploiting the scene displayed in Figure 2 and the parameters of the SAR systems reported in Table 1.

Table 1 Parameters of the SAR systems implemented in the PSBSM.

SAR system	Beam	Bistatic baseline Km		PRF	Chirp bandwidth
		along	across		
SAOCOM-CS tomographic phase	DS1	6	1.2, 2.4, 3.6, 4.8, 6	1840 Hz	38.3 MHz
SAOCOM-CS bistatic-1 phase	QS3	250	0	2149 Hz	37.1 MHz

Figure 3 displays the raw and SLC data intensity of SAOCOM-CS in Bistatic-1 configuration, whereas in Figure 4 the phase of the simulated single-pass bistatic interferogram is displayed.

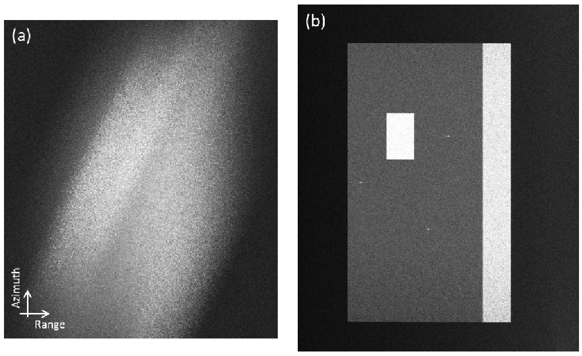

Figure 3 Example of SAOCOM-CS data in Bistatic-1 configuration, (a) raw data (b) SLC.

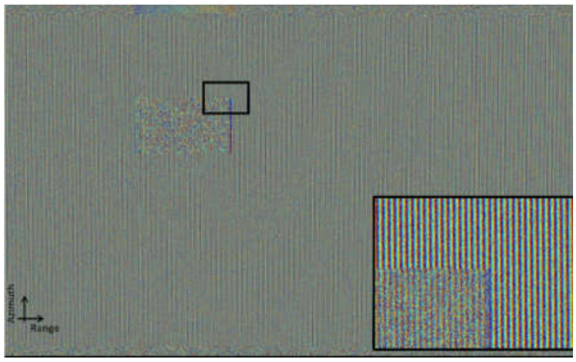

Figure 4 Example of raw interferogram between SAOCOM and SAOCOM-CS in tomographic configuration.

In this last figure, we display a zoom over a small area containing the transition between the bare-soil and the vegetated area. Note that the interferogram has not been flattened, to highlight the worse standard deviation of the InSAR phase in the forest area (w.r.t. the base soil around) due to the volumetric decorrelation. It is noted that this result was obtained only by proper simulation of the data (i.e., no decorrelation was "injected" in the forested area).

3.1 Mission Performance Assessment

One of the main applications of the developed simulator is to run a wide set of simulations to investigate the key performance figures and the sensitivity of each figure of merit to the system non-idealities. The tool allows to switch on and off each single contribution, so that its effects can be followed through the entire chain, from raw data to interferometric phase.

During the SAOCOM-CS Mission Performance Assessment (MPA), a large amount of data was generated, trying to cover as much as possible all the possible configurations and non-idealities. Due to the limited space we report here just some examples of the results. In particular, the subplots of Figure 5 from *(a)* to *(c)* display the IRF performances estimated for the Tomographic Mission Phase. In subplot *(d)* we report the sensitivity analysis of the coherence γ_{sys} in a bare soil area and with an across-track baseline of 1.2 Km.

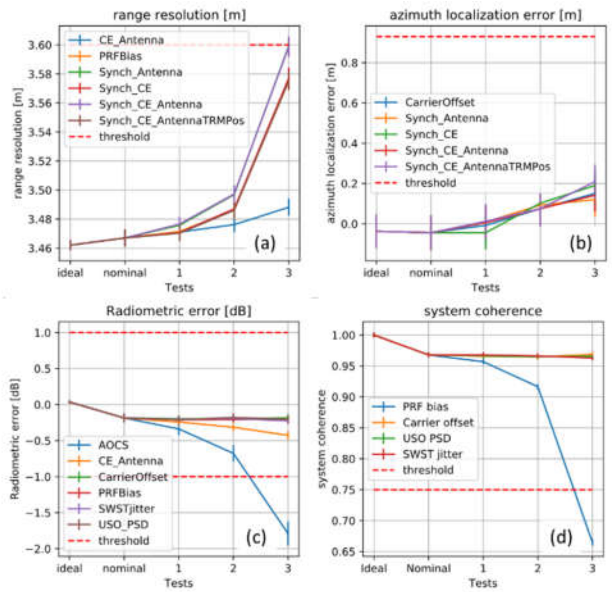

Figure 5 Examples of performance analyses obtained during the Mission Performance Assessment of the SAOCOM-CS.

On the horizontal axis of the plots we can find the different tests: in the "ideal" case, all the non-idealities are disabled. In the "nominal" case, all the non-idealities are enabled with their nominal values. This case should then represent the "typical" operational conditions. In the tests identified by the numbers "1,2,3", all the errors are enabled (as in the nominal case) except for some of them, which have been set to an "exaggerated" level, to perform the sensitivity analysis. The numbers represents increasing levels of "stress" of the particular error, which is simulated e.g. 2x to 10x its nominal value. The different lines in the plot identify which non-ideality is being stressed: for example the blue line shows the range resolution sensitivity to the combined effects of Central Electronic (CE) and Antenna non-idealities. The dotted red line corresponds to the acceptable threshold as defined in the System Requirement Document.
From the obtained results, we can notice a general robustness of the system to the errors, breaching the threshold only for exaggerated values of the injected errors (stress case 3).

4 CONCLUSIONS

The developed Performance Simulator for Bistatic SAR Missions has been presented, providing an overview of the architecture and some description of its building blocks. It was successfully exploited to assess the performance of the SAOCOM-CS mission. For the future woks, it would be of interest to evolve the framework by adding new simulation capabilities, to obtain a general and flexible tool that can be easily adapted and configured to support the analysis of novel SAR mission concepts.

5 ACKNOWLEDGEMENT

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