BIOMASS END-TO-END MISSION SIMULATION AND PERFORMANCE ASSESSMENT

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Abstract

This paper discusses the implementation of an end-to-end simulator for the BIOMASS mission. An overview of the system architecture is provided along with a functional description of the modules that comprise the simulator.

Key words: BIOMASS, Simulator, SAR.

1. INTRODUCTION

Biomass is a biophysical property of vegetation that relates to the amount of carbon stored in the terrestrial environment. While the world's forests contain the largest proportion of carbon in living vegetation global and accurate quantification of stock and dynamics - occurring as a consequence of, for example, deforestation, regrowth, management or fires - remains a significant but pressing challenge.

This uncertainty remains because of the lack of a systematic and reliable mechanism for differentiating biomass levels across large areas. In this context, European scientists proposed in the frame of ESA's 7th Earth Explorer [1] program BIOMASS[2][3], a mission with the objective to reduce the uncertainty in the worldwide spatial distribution and dynamics of forests leading to improved present assessments and future projections of the carbon cycle.

BIOMASS is based on a P-band Synthetic Aperture Radar that will systematically acquire fully- (quad-) polarized image data in an interferometric mode over all major forested areas on the globe. The inversion methodology is then based on backscatter intensity measurements at different polarizations and interferometric coherence measurements at different polarizations.

BIOMASS is currently in the Phase-A stage, in parallel with the two other competing mission proposals: CoReH$_2$O and Premier. A common critical key element for the final selection procedure is an End-to-End mission performance assessment, for which an End-to-End Simulator (E2ES) tool is being implemented. This BIOMASS E2ES (BEES) needs to go beyond the straightforward (but fundamental) radiometric sensitivity analysis and include disturbances or errors due to:

- The radiometric accuracy and stability, and radiometric biases.
- Ionospheric artifacts: Faraday rotation and scintillation effects.
- The effect of range and azimuth ambiguities.
- Phase stability (within an acquisition but also within channels or within repeat pass acquisitions)

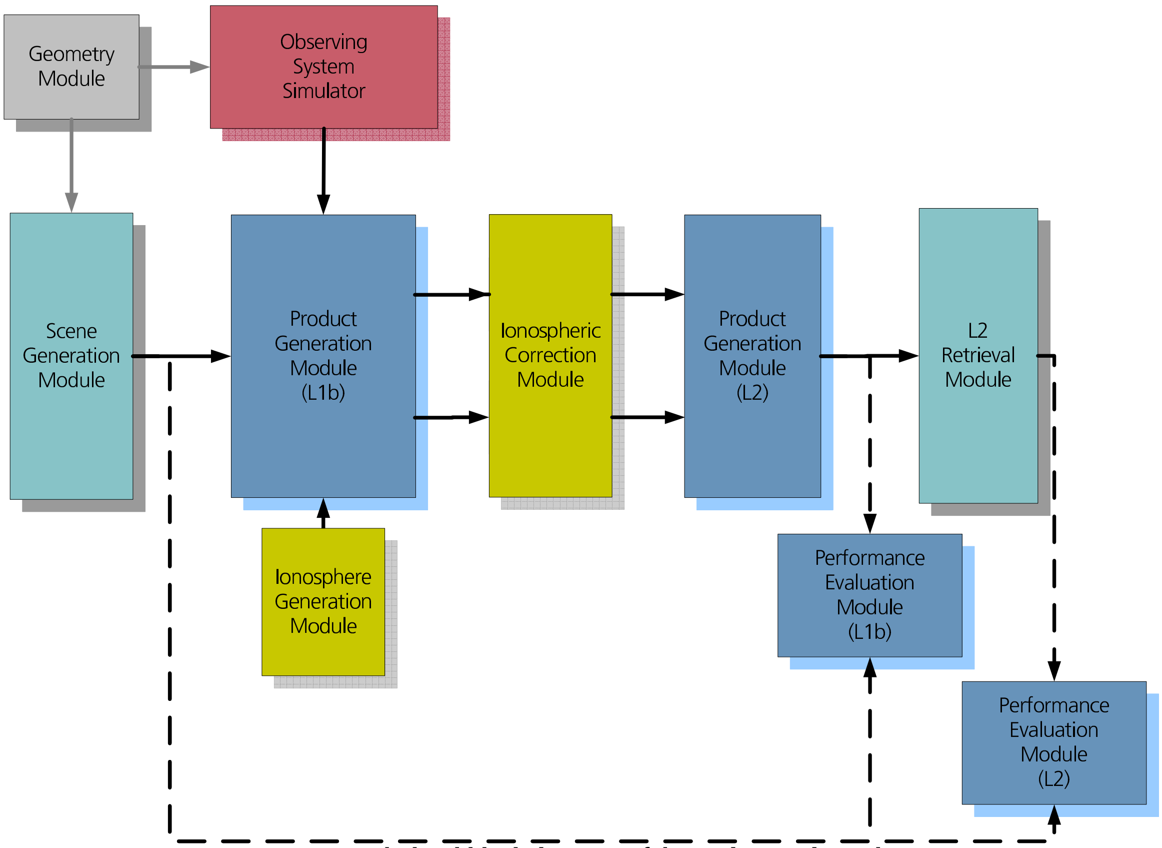


Figure 1. Hight level block diagram of the End-to-End simulator

- Channel imbalance and cross talk.
- Decorrelation sources: temporal and spectral shift.

The End-to-End nature of this tools means that the starting point of the simulation are maps providing a (simplified) geophysical descriptions of forest scenes, for which the main parameter of interest is the biomass (in mass per surface unit). Likewise, the final output of the tool are the estimates of this biomass parameter.

2. END-TO-END SIMULATOR ARCHITECTURE

This section describes the architecture of BEES, which is illustrated in Fig. 1. The modular structure of the E2ES corresponds not only to a logical breakdown of the simulation process, but reflects also the fact that the most of the modules are being developed by different research groups in the context of specific studies. To streamline the integration of these heterogeneous modules into a single tool, the E2ES is built using ESA's Open Simulation Framework (OpenSF) [4]

An important architectural aspect of BEES is the attempt to find a balance between physical fidelity to the system being simulated, and computational efficiency.

These modules are briefly discussed in the following sub-sections.

2.1. Geometry Module

This module calculates the common geometric relations needed by all the other modules. Basically, on a common ground range grid, and for all simulated acquisitions, it calculates the slant range, look and incidence angle, the cross-track interferometric baseline (expressed as $k_z = 2\pi/h_{amb}$), etc.

2.2. Observing System Simulator (OSS)

It characterizes the simulated BIOMASS SAR system. This module is divided in two independent modules:

2.2.1. IRF Module

This sub-module provides the end-to-end impulse response function (IRF) of the system considering the sensor physical characteristics (antenna pattern, orbit height, pulse bandwidth, etc.) and the SAR processing (processed Doppler bandwidth, range/azimuth windowing used, etc.).

The use of the end-to-end IRF is a key aspect of the E2ES, as it avoids generating raw data, which is computationally very costly, in particular at P-band due to the very long synthetic aperture. Likewise, it avoids the equally computationally intensive SAR processing step.

It is worth emphasizing that the IRF partially represents the radar and the processing chain at the ground segment. A natural consequence of this approach is that the errors and disturbances introduces during the simulation should be residual (post-calibration) ones, since the ground-segment will apply all known calibration factors to the data as part of the standard processing.

2.2.2. System Error and Sensitivity (SES)

The SES sub-module returns the different parameters describing the performance of the system:

- Noise equivalent σ_0 (NESZ)
- Range and azimuth ambiguity to signal ratios. In addition, an ambiguity mapping is provided, giving the location and relative amplitude of the individual ambiguities.
- Phase and amplitude stability (long and short term).
- Residual channel imbalance and cross-talk.
- Localization accuracy.

These values are calculated as a function of range.

Two different OSSs have been developed to simulate the two different Phase-A designs.

2.3. Scene Generation Module (SGM)

This module provides the scene as a map of the second order statistics of the scene, tying a specific extended covariance matrix to each position on the ground. The simulated forest is described by a forest type (currently Tropical and Boreal forests are considered), a mean biomass level, and a gradient. As a first step, the SGM generates 1 km^2 patches of forest with uniform biomass levels. Within each patch, the mean biomass level is converted to a tree-dimension distribution (Weibull or exponential). Using this distribution, a random collection of trees with different diameters and heights is generated. These trees are then clustered to form either a uniform tree distribution (typical of Boreal forests) or a clumpy one (associated to Tropical forests). The resulting forest patches are then converted to a 10x10 grid giving the biomass level and tree height (expressed as H100, the mean height of the 100 tallest trees per hectare) in a 1 ha square.

These 1 ha averaged biomass levels and tree-heights are then passed to a forward model derived from experimental data. As additional input parameters this model requires the nominal incidence angle, the vertical wavenumber (k_z), the temporal baseline between acquisitions and the biome id. Optionally, the model can also ingest a digital elevation model (DEM).

2.4. Ionosphere Modules

BEES incorporates an ionosphere generation module (IGM), which simulates ionospheric disturbances, and an ionospheric correction module (ICM). The IGM provides a map of Faraday rotation (FR) across the SAR image based on the satellite and radar geometry, a model of total electron content (TEC) along the propagation path and a model geomagnetic field. The IGM also simulates phase fluctuations due to ionospheric scintillation (the process of scattering from electron density irregularities in the ionosphere). This is provided as a two-dimensional thin phase screen, pseudo-randomly generated from a database of spatial phase spectrum parameters derived from the WBMOD model [5] for a variety of geomagnetic activity indices and over a solar cycle (1995-2005).

The ICM provides interfaces to a range of FR estimation and correction algorithms, which estimate the FR angle from the covariance between polarization channels but with an ambiguity of typically +/- n pi/2 , where n is an unknown integer. A model estimate of FR is therefore used to resolve the ambiguity in the FR estimates. The ICM will also estimate and correct the azimuthal shift in multiple-acquisition images by means of either an intensity correlation analysis for sub-windows within the image, and/or by determining the difference in TEC gradient and subsequent azimuth shift from the difference in FR estimates (between slave and master image) using a model geomagnetic field estimate.

Further details of both ionospheric modules are provided in [6].

2.5. Product Generation Module (PGM)

The PGM is the *heart* of BEES, as it is the connecting node of all the other modules. It generates simulated SAR data from the scene provided by the SGM, using the system characterization provided by the OSS and including (if so required) the IGM generated ionospheric distortions. An important aspect of the PGM is the capability to select which subset of disturbing phenomena are included in the simulation. The module is divided in two sub-modules:

PGM-L1a: generates coregistered multi-channel SLC SAR images without the Ionospheric Correction.

PGM-L1b: performs the multi-looking operation (estimation of the covariance matrices) and projection to ground range.

The PGM-L1a performs the following steps:

1. Calculates the Cholesky decomposition of the input covariance matrices.
2. Generates correlated multi-channel noise, by multiplying vectors of independent randomly distributed jointly Gaussian complex random vectors by coloring matrix obtained from the previous step. The resulting data is over-sampled w.r.t. the final SLC resolution.
3. Applies the interferometric phase to the interferometric data-pairs. This implicitly introduces a spectral shift in the image, which will cause a coherence loss.
4. Convolution with the OSS-generated IRF. In general, this is a range-dependent function.
5. The images are decompressed in azimuth to Ionospheric height where the ionospheric effects are introduced (for the equivalent SAR system flying at ionospheric height, the ionospheric distortion can be applied directly pixel by pixel to the range compressed data).
6. Interferometric phase flattening (removal of flat Earth phase) and, optionally, common band filtering. Note that this common-band filtering is a critical step given the low available pulse bandwidth in combination with a PolInSAR requirement for significant interferometric baselines.
7. Introduction of range and azimuth ambiguities. This implies adding a number of ambiguous images tot the main image. Each ambiguity is generated following the previous steps.
8. Introduction of system disturbances: random noise, phase and amplitude errors due to long and short term system stability, polarimetric channel imbalance and cross-talk. These errors are considered post-calibration residual errors.

The result of these steps is a set of SLC images typically representing the in total 8 channels of a PolInSAR acquisition. These images are then passed to the ICM, which returns an equivalent set of ionospheric-corrected SLCs, which are the input to the PGM-L1b sub-module. The PGM-L1b module estimates the extended covariance matrices from the data by applying a Gaussian spatial multi-looking window to all the co- and cross-channel products.

2.6. L2 retrieval module (L2RM)

This implements the inversion algorithm, producing biomass and forest heights estimates from the PGM supplied L1b data. The L2RM produces two independent biomass estimates. The first is derived from the HV (cross-polar) backscatter coefficient, using the empirical Above-Ground Dry Biomass (AGDB) to σ_0 relations derived during the BioSAR-1 campaign. The second estimate is generated from the PolInSAR data inverting a Random Volume over Ground (RVoG) model to obtain a H100 estimate and applying the H100-to-biomass allometric relations derived during BioSAR.

The two estimates are combined using a Bayesian MMSE approach.

2.7. Performance Evaluation Modules

In addition to the previously described modules, which comprise the actual E2ES, BEES includes a pair of Performance Evaluation Modules (PEMs):

PEM-L1b: generates statistics of the difference between the SGM-generated covariance matrices describing the scene, and the PGM-L1b estimated ones. Biases and standard deviations of the estimated NRCSs, and the PolInSAR coherences and phases are estimated. All statistics are calculated as scene averages and as a function of range. The goal of this L1b-level performance evaluation is to characterize the fidelity of the SAR system.

PEM-L2: generates error statistics of the estimated biomass levels and canopy height. The estimated biases and standard deviations are calculated as scene averages, as a function of range, and as a function of biomass level. These statistics predict the end-to-end performance of the system.

3. IMPLEMENTATION

As discussed, the overall system is implemented using the OpenSF framework. OpenSF provides a Human-machine interface (HMI) to set-up the simulator out of a collection of OpenSF-compliant modules, and also to configure a particular run of the simulator by editing the configuration parameters for each module (physically these are stored as xml files). It also runs the simulation, keeping track of the simulation status and error reporting. In addition, OpenSF allows configuring and executing a batch of simulation, optionally varying some parameters according to some pre-defined rule. This feature can be used, for example, for perturbation analysis or, as in the case of BEES, to generate multiple random realizations of a given simulation in a Monte Carlo approach.

The individual modules are developed in an heterogeneous combination of several programming languages and environments (mainly C, MATLAB and IDL). The entire simulator is designed to run on a standard Linux work-station.

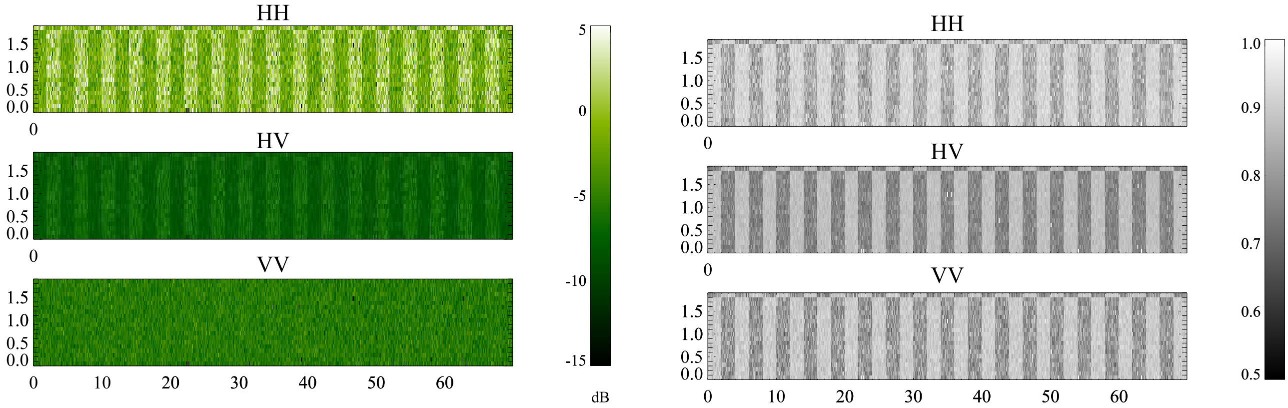
Although at time of writing BEES is not fully implemented, a preliminary computational performance analysis has been made. Currently, the simulation of a 200 km^2 scene requires in the order of 200 seconds simulation time. With the missing features included, this computation time is expected to stay under 300 seconds, thus allowing running hundreds of Monte Carlo repetitions in a time span of hours.

4. RESULTS

This section illustrates the simulation process by showing some example results.

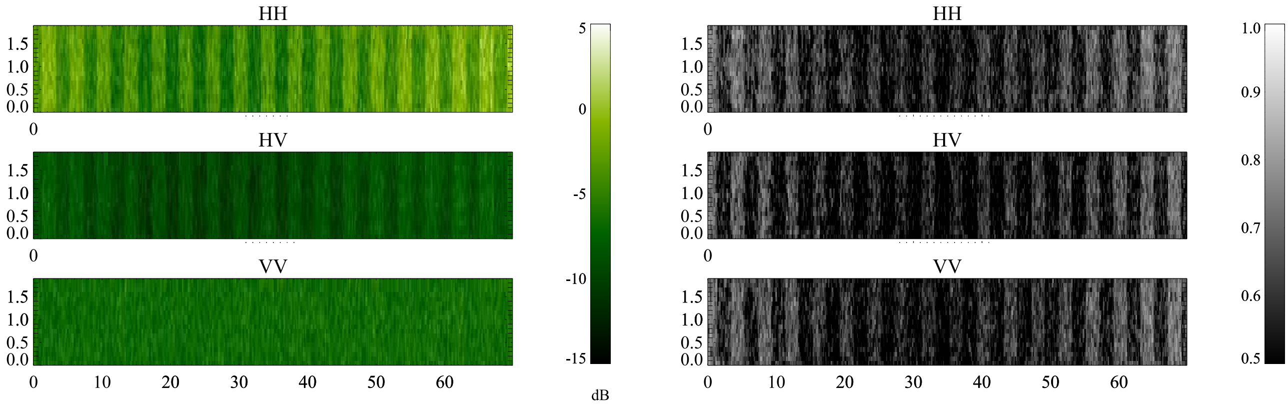
Fig. 2 illustrates the SGM generated inputs to the PGM. The left panels show an example of generated reflectivity maps showing the HH, HV, and VV channels, respectively, of the first PolInSAR acquisition. The horizontal and vertical axis represent ground range and azimuth, respectively, both given in km. The pattern visible in the HH and HV channel corresponds to a periodic variation of the mean biomass levels. The right panels in the figure show the corresponding interferometric coherences for the HH, HV, and VV channels, respectively.

Fig. 3 shows the equivalent variables estimated by the PGM-L1b module. The most visible effect with respect to the σ_0 is the smoothing effect caused by the multilook processing. However, a very significant significant drop of the coherence can be observed. This is caused, for this particular execution of BEES, by uncorrected ionospheric effects. In particular,



(a) σ_0 (b) ρ

Figure 2. Left: example of SGM generated reflectivity maps showing the HH, HV, and VV channels, respectively, of the first PolInSAR acquisition. Right: corresponding interferometric coherences for the HH, HV, and VV channels, respectively.



(a) σ_0 (b) ρ

Figure 3. Like Fig. 2 but showing the PGM-L1b estimated values.

the ionospheric phase screen introduces phase gradients that cause azimuth co-registration errors, hence reducing the interferometric coherence. This can be confirmed by looking at Fig. 4, which shows the coherence without introduction ionospheric errors (which is equivalent to having a perfect correction by the ICM). The resulting coherences are now much closer to the theoretical values in Fig. 2.

Fig. 5 illustrates the outputs of the PEM-L1b module for this latest Ionosphere-free simulation, showing some error statistics vs. range of the L1b products. In particular, the top panel shows the bias of the estimated HV σ_0 values for the master and slave acquisitions as a function of range. There is an average down bias as a result of the common band filtering process (this bias will be compensated in the final version of BEES). On top of this bias, the estimated σ_0 values also reveal the antenna elevation pattern: the lower NESZ in near and far range result in a overestimation of σ_0 due to the added noise power. The modulation of the bias can be explained as the result of the smoothing inherent to the multi-looking operation on data with sharp periodic discontinuities. The lower panel shows the bias of the corresponding interferometric coherences. There is a relatively small down-bias of the estimated coherences most likely due to noise.

The previous results also illustrate one of the main advantages of the end-to-end simulator approach: effects can be selectively turned on and off, which allows identifying the performance bottle-necks.

5. OUTLOOK

BEES is currently virtually completed and undergoing a careful verification process. It is scheduled to be verified and ready to use for the BIOMASS Mission performance assessment in September 2011. During the remainder of 2011, it

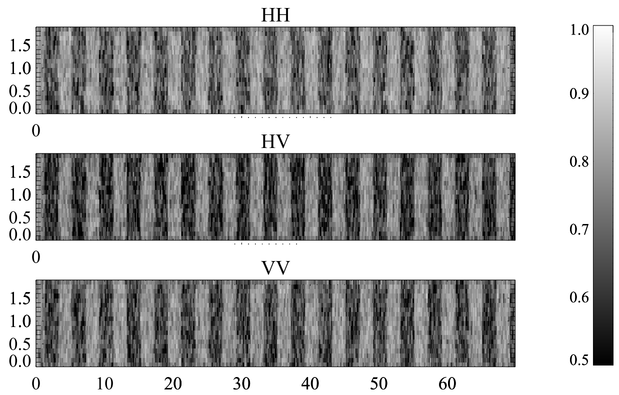


Figure 4. Like Fig. 3(b) but showing the coherence without ionospheric distortion.

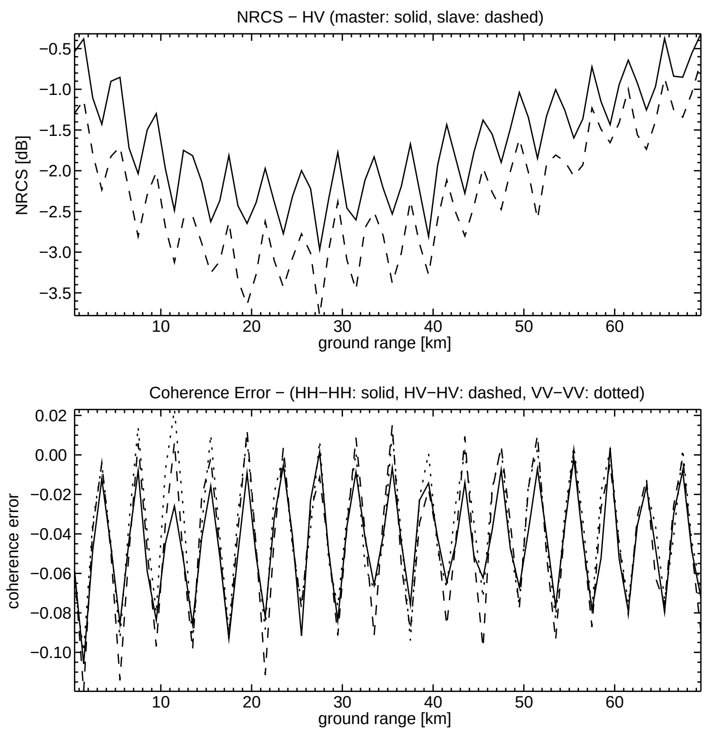


Figure 5. Example L1b PEM outputs

Index	Distribution	Clark/Evan Index	Notes
1	Weibull	1.8	Boreal Forest
2	Weibull	0.8	No ecosystem
3	Exponential	1.8	No ecosystem
4	Expoinential	0.8	Tropical Forest

Table 1. Forest types defined for reference scenarios

will be used to evaluate the expected performance of BIOMASS for the two alternative SAR system designs proposed during the Phase-A study. To perform this evaluation a set of reference scenarios have been defined, corresponding to 4 forest types (see Table 1) and a range of average biomass levels.

For each scenario, the system will be evaluated at two levels:

1. The fidelity L1b products will be evaluated by comparing the elements of the covariance matrices generated by the SGM to those estimated by the PGM-L1b module.
2. The end-to-end performance of the mission will be assessed by comparing the biomass an H100 tree height generated by the SGM and estimated by the L2RM.

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