

The ROSE-L End-To-End Performance Simulator and Ground Processor Prototype Tools: An Overview

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Abstract

This paper provides an overview as well as more specific details on the up-to-date implementation status of the ROSE-L End-to-End (E2E) Performance Simulator and the Ground Processor Prototype (GPP), which are fully representative tools of the E2E system behaviour for the upcoming ROSE-L mission, and will be used to support the overall verification of the ROSE-L mission performance. The software architecture of both tools is introduced along with a functional description of the modules, with focus on ROSE-L specific features. Finally, some first-cut but relevant results will be presented.

1 Introduction

As part of the Copernicus Spacecraft Expansion Programme, the European Commission (EU) approved in 2020 for implementation the so-called ROSE-L (Radar Observing System for Europe in L-band) mission [1], which is planned for launch in 2028.

ROSE-L will carry an L-band Synthetic Aperture Radar (SAR), acquiring high-resolution data. This mission is meant to provide advanced capabilities compared to those of the existing Sentinel-1 satellites, to grant enhanced continuity for diverse operational services and to address observation gaps as well as new and emerging user needs [2].

The primary objectives of the mission are [1]: 1) to complement the monitoring of European and global geohazards by extending the observation from space to vegetated areas as well as flooded areas below vegetation, 2) to enhance the monitoring of land use, land use change, forestry and agriculture, 3) to enable high-resolution monitoring of soil moisture below the vegetation canopy, 4) to increase the observations over the Arctic and cryosphere with focus on sea ice mapping, iceberg detection, glacier and ice caps monitoring, and snow water content (SWE) retrieval, and 5) to improve maritime surveillance in terms of sea state, surface wind and swell information retrieval.

To achieve this, ROSE-L is being designed to operate in a combined mode (i.e., same orbit, possibility of same swath coverage) with Sentinel-1, providing unique dual-frequency information and mapping capabilities. Three

main imaging modes are currently foreseen: dual-pol (either the so-called ROSE-L Interferometric Wide Swath – RIWS -, for overlap with Sentinel-1 IW, or dual-pol NWS), quad-pol (QWS) and Wave Mode (RWM). The main characteristics are summarized in **Table 1**.

Table 1: ROSE-L SAR Modes overview

	RIWS	NWS	QWS	RWM
Swath width	260 km	260 km	260 km	2 vignettes of 20km x 20km
Ground res. cell size	50 m ²	50 m ²	100 m ²	50 m ²
Access range	~ 30° - 45° (overlap with S1 IW)	~ 24° - 41°	~ 25° - 42°	~ 25° - 26.5° ~ 45° - 46°
Polarisation	Dual	Dual	Quad	Single
Sub-swaths	3	3	6	2

The specific and challenging needs of each acquisition mode lead the ROSE-L instrument towards an active phased array antenna with digital beamforming (DBF) capabilities. In more detail, ROSE-L will be a multi-channel system operated under the Nyquist rate, with five azimuth channels being independently acquired. Due to the decrease of the operation pulse repetition frequency (PRF), the Doppler spectrum of the received data of the single channels appears strongly aliased and needs to be resolved via azimuth reconstruction.

In order to support the verification of the mission during the Phases B2 and C/D in terms of instrument design, pre-launch mission performance assessment, ground segment development, ground processor simulation, development of calibration and L2 algorithms and in-orbit mission performance verification, a complete end-to-end simulation tool, named C-REEPS (Complete ROSE-L End-to-End Performance Simulator), is being implemented.

2 C-REEPS Architecture

In terms of software (SW) architecture, C-REEPS can be divided into 3 main blocks [3], as depicted in **Figure 1**:

- **ROSE-L E2E Performance Simulator (E2ES)**, in charge of the generation of raw data of extended and distributed scenes as provided by the ROSE-L instrument, and incorporating the observation geometry of ROSE-L and all relevant effects into the data quality as conditioned by the platform, instrument and environment;
- **Ground Processor Prototype (GPP)**, in charge of generating the ROSE-L Level-1 products;
- **Performance Evaluation Module (PEM)**, generating the statistics of the quality parameters investigated in the simulation, including a cross-check with the mission requirements.

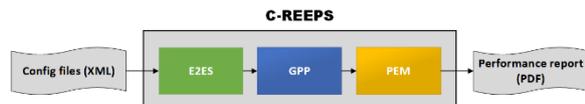


Figure 1: The C-REEPS high-level architecture.

Further details concerning these three blocks are provided in the following.

2.1 E2ES

The ROSE-L E2E Performance Simulator (E2ES) of raw data follows the general modular concept described in [4]. Its architecture and functionalities are depicted in **Figure 2** and summarized in the following, as per E2E flow [3]:

- **Mission and Acquisition Planning (MAP)**: This module is in charge of the computation of the exact location of the scene corners (for the overall scene and for each of the bursts of the simulation) according to input information, the returning of the start and end times of the acquisition, and the extraction of the timing and other relevant parameters (based on the scheme of the acquisition extracted for an external radar database) for each of the Tx/Rx events. The MAP also initialises the nominal orbit and attitude products, which will be used by the sub-sequent modules.

- **Instrument Characterisation (InC)**: The InC generates the instrument-related variables, including e.g., antenna patterns, linear and nonlinear descriptors of transmitter and receiver, digital and on-board processing parts, system noise and polarimetric imbalances. This module shall incorporate all states, channels, imaging modes, characterisation and calibration paths of the ROSE-L instrument. The handling of antenna patterns will be however performed in a dedicated (and standalone) sub-module, named **Antenna Model (AnM)**.
- **Platform Characterisation (PIC)**: The PIC generates realisations of platform-related variables to be included in the simulation of the raw data for all acquisitions. In particular, the PIC shall simulate the impact of the AOCS on the attitude and the true orbit, as well as the impact of the GNSS on the orbit knowledge and other relevant navigation products.
- **Back-Geocoding Module (BaM)**: For all acquisitions, the BaM imports the external DEM and computes the scene topography in the absolute and differential radar observation geometry, i.e., back-geocoded XYZ, interferometric offsets and vertical wavenumber κ_z , and makes it available to sub-sequent modules.
- **Scene Generation (ScG)**: The ScG computes the polarimetric covariance matrices of the simulated scenes, in the following also named multi-looked complex reflectivity images (e.g., MLC) consistent with the user input and derives from them the extended covariance matrices, or MLCs for all cycles, according to a polarimetric and interferometric forward model configurable by the user.
- **Atmospheric Generation (AtG)**: The AtG generates background and turbulent components of the troposphere and the ionosphere with geographical and cli-

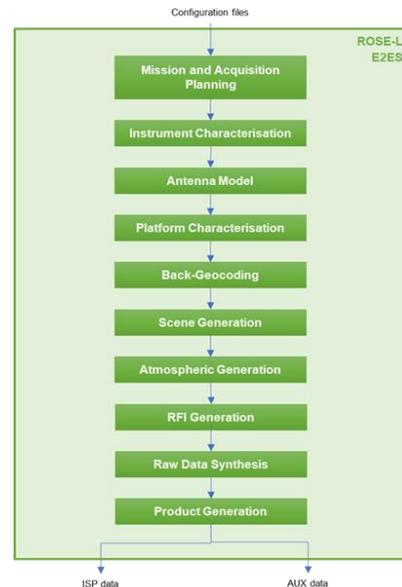


Figure 2: The ROSE-L E2ES architecture.

matological representability. These will be later incorporated into the simulated data by the Raw Data Synthesiser (RaS) module.

- **RFI Generation (RFG):** The RFG initialises radio frequency interferences (RFIs) with L-band representability both in power and spectral and temporal support.
- **Raw Data Synthesis (RaS):** The RaS generates the simulated raw data of all polarimetric channels of all cycles of the acquisition consistent with the output of the ScG and including the geometrical migration of the survey by means of a reverse SAR/InSAR processing chain, as well as a dedicated time-domain generation step for the simulation of point-like reference targets. The RaS is responsible for including the impact of the propagation, RFI, instrument and platform into the data.
- **Product Generation (PrG):** The PrG generates all internal and external products of C-REEPS. In particular, the PrG will perform the packing of the raw data into ISPs as per ROSE-L format, the ancillary instrument data ANC, and the ancillary platform data HTKM and NAVATT. This module shall also generate other relevant auxiliary data for the GPP and for the Performance Evaluation Module (PEM).

2.2 GPP

The ROSE-L Ground Prototype Processor (GPP) is a SAR processor in charge of generating L1 products starting from the raw data simulated with the E2ES described in the previous sub-section or directly generated by the ROSE-L instrument during the system Commissioning Phase. For this reason, the GPP is both a component of the C-REEPS and a standalone tool as well.

The architecture of the ROSE-L GPP is reported in **Figure 3**. The following processing steps are performed in order to generate the ROSE-L L1 products [3]:

- L1 Pre-Processor performs the ingestion of the L0 data and implements integrity checks and raw data corrections. The Instrument Source Packets (ISP) downlinked from the instrument and encapsulated in the L0 products are decoded and all the relevant metadata (including orbit and attitude information) are extracted. The raw data are decoded according to the selected Block Adaptive Quantization (BAQ) compression scheme and the I/Q channels bias, imbalances and orthogonality are corrected.
- RFI Filtering performs the RFI detection and mitigation on the RAW data in order to provide ‘clean’ SAR data to the remaining processing steps. The RFI detection is performed both in time and frequency domain in order to remove all the possible interfering signals. This is a critical processing step due to the high probability of RFI contamination occurrence in L-band.
- Internal Calibration algorithms defined for ROSE-L are applied in order to derive the corrections to be applied to the raw data. The extracted information includes: the chirp replica to be optionally used for the range compression of the data, the gain and phase drifts affecting the data due to the instrument (e.g., due to temperature changes) and the channel imbalances.
- Range compression with either an ideal chirp replica (generated from the chirp parameters annotated in the ISP) or from the chirp replica derived from the internal calibration. A chirp pre-distortion step is also foreseen to compensate for ionospheric effects affecting the range IRF (delay, resolution loss and side lobes degradation) [5] [6].
- Multi Aperture Recombination performs the recombination of the five azimuth channels that are acquired by the ROSE-L instrument in order to suppress azimuth ambiguities and maximize antenna gain for the imaged scene.
- Image Formation implements the ‘SAR focusing’ process, that transforms the image from the acquisition domain to the 2D image domain (Zero-Doppler coordinates). The following processing steps are implemented within this module:
 - Doppler Centroid estimation either based on the geometric information included in the ISPs (or externally provided in an attitude file) or from the data.
 - Doppler Rate estimation based on orbit and attitude information.
 - Azimuth compression of the SAR data based on the Baseband Azimuth Scaling (BAS) algorithm [7], an efficient approach for the processing of ScanSAR data. The proposed algorithm allows the selection of the sampling step of the focused data allowing to focus the different sub-swaths on a common azimuth grid to ease de-bursting and swath merging operations.
- Antenna Pattern Correction is specifically designed to cope with the Scan On Receive (SCORE) approach [8] implemented in ROSE-L mission. Additionally, spread losses are compensated in this module.
- Polarimetric Calibration implements the polarimetric corrections required to properly align the different ROSE-L channels. It is worth recalling that ROSE-L mission will be operated both in dual pol and in full-pol mode (where HH, VV, HV and HV are acquired at same time). This step performs the correction of fixed offsets that have been derived during the on-ground characterization of the instrument or during the Commissioning Phase activities.

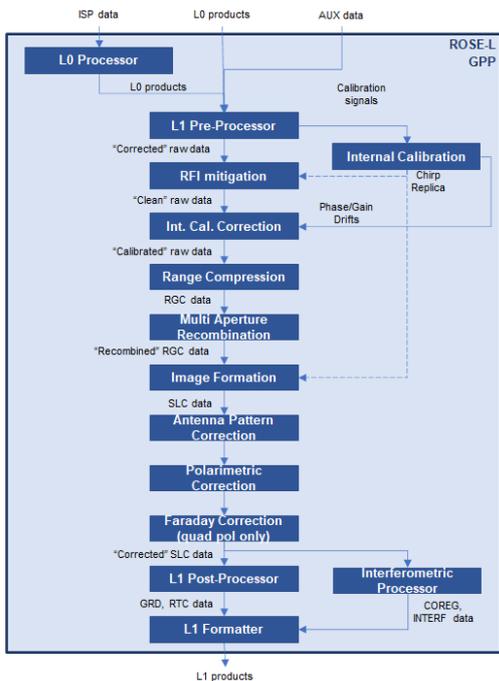


Figure 3: The ROSE-L GPP architecture.

- Faraday Correction module is specifically designed to implement the estimation and the correction of the Faraday Rotation effect [9] for full-pol data only.
- L1 Post-Processor covers all the image processing tasks that need to be performed on ROSE-L data in order to generate higher level data. The processing steps include:
 - de-bursting and swath merging;
 - frequency multi-looking with configurable central frequencies, bandwidths and weighting windows;
 - time domain multi-looking;
 - de-noising;
 - fine radiometric calibration exploiting imaged scene topography (RTC products) [10];
 - ground range re-projection;
 - geographic coordinates re-projection.
- L1 Interferometric Processor is in charge of:
 - generating the “ready for interferometry” SLC products;
 - the interferograms and coherence maps.
- L1 Formatter performs the data and meta-data formatting and acquisition quick-look generation in order to generate the final ROSE-L L1 products family.

Regarding the formal products, the base ROSE-L L1 product is the L1a Single Look Complex (SLC), generated for all the acquisition modes.

The L1a data will consist then of a SLC image in the slant-range plane and in zero-Doppler geometry with the

associated metadata. The products will be radiometrically calibrated and with the spread losses and antenna patterns (including SCORE approach) compensated.

The radiometric products, generated starting from the L1a products, will include:

- Ground Range Detected (GRD) L1b products: provided as de-bursting and swath merged, multi-looking (configurable factors) and de-noised (optional step) values projected in ground geometry.
- Radiometric Terrain Corrected (RTC) L1c products: provided as de-bursting and swath merged, multi-looking (configurable factors) and de-noised (optional step) values projected in geographic coordinates. The external calibration factor is in this case applied. Fine radiometric corrections are computed and applied exploiting a DEM of the imaged scene. Topography and incidence angles corresponding to each pixel of the data are provided as additional binary files.

Finally, the interferometric products, generated by the Interferometric Processor module, will include:

- Co-registered (CRG) L1b ready for interferometry products: provided as SLC data not yet de-bursting and swath merged. They are provided in Zero Doppler geometry to allow users to further process the data. The CRG products are co-registered w.r.t. ROSE-L reference orbit and the topography phase contribution, based on a DEM of the imaged scene, is annotated but not compensated. Topography and phase corrections corresponding to each pixel of the data are provided as additional binary files. Two interferometric CRG products can be directly combined to form interferograms but additional corrections could be required to improve interferogram quality.
- Interferograms (INT) L1c products: generated from pairs of corresponding CRG products after correction of the differential ionospheric phase contribution estimated with the split-spectrum technique [11] and the correction of the residual azimuth co-registration errors exploiting the Enhanced Spectral Diversity technique [12]. The products are provided de-bursting and swath merged and re-projected in geographic coordinates. Additional information (e.g. DEM, phase correction maps, coherence maps, ...) is included in the products as additional binary files.

2.3 PEM

The Performance Evaluation Module (PEM) is a dedicated module responsible for the evaluation of the performance of the system in the simulated mission scenario. It is based on the analysis and comparison of the final products delivered by the GPP with respect to nominal values and data. As the main output, the PEM produces a report summarizing all main results and outcomes.

3 C-REEPS SW Implementation

To ensure both efficiency and general-use, the individual modules of E2ES and GPP are being developed using a combination of Python and C programming languages. Python is used for the computationally cheaper activities, including the simulation flow, profiling, logging, plotting, and disk access operations, whereas the most demanding computational blocks (e.g., 2-D interpolations, FFTs, back-geocoding, reverse and direct SAR and InSAR kernels) are being coded in C with more advanced multi-threaded implementations. The entire simulator is designed to run on a standard Linux multi-core work-station.

In terms of software versioning, C-REEPS has been conceived as an incremental tool of tools, with functional early versions of the software to which functionalities are added. This approach is especially relevant to adapt to the overall development of the ROSE-L mission and, particularly, of the ROSE-L instrument. So, until the mission launch, four SW deliveries (V1 to V4) are planned to support the main system reviews, named: 1) Preliminary Design Review (PDR), 2) Critical Design Review (CDR), 3) Intermediate Qualification Status Review (IQSR) and 4) Qualification and Acceptance Review (QAR).

4 C-REEPS First Demonstration Data

At the time of writing, the C-REEPS implementation towards V2 is under way. Therefore, only results generated with the first version of the software (V1), delivered for the ROSE-L PDR last 2022, are presented here.

In terms of functional capabilities, C-REEPS V1 has consolidated interfaces but with limited simulation and processing skills (e.g., simulation of just point targets imbedded in noise, simulation and processing at a certain height but without real topography, no antenna pattern compensation, no official data formatting of products, etc.). However, the V1 available functionalities were tailored to verify geometrical and instrument-related effects on the SAR impulse response (IRF analysis) in order to support the instrument pre-development model test result evaluation at PDR stage.

Figure 4 shows the scene corners of a simulated data set with C-REEPS V1 for the RIWS mode, with user selected location. The red arrow illustrates the satellite ground track for reference. In this case, three sub-swaths and two bursts per sub-swath are considered, with some overlap among them. The brown dots represent the location of the point targets in the scene (nine point targets uniformly distributed in each sub-swath and burst).

All relevant system, acquisition geometry and timing parameters for the proper raw data simulation are consid-

ered as per user configuration. **Figure 5** shows the observation geometry of the simulation, including the incident angle as well as the elevation angle (with respect to beam center) as a function of the slant range distance. The three different colours illustrate the three sub-swaths.

After the raw data simulation by the E2ES, the GPP focuses the data and generates all relevant products, as described in Section 2.2. **Figure 6** shows two quick-looks corresponding to: (a) L1a SLC data of the first sub-swath, first burst and VV polarisation, and (b) the corresponding L1b GRD data at VV polarisation.

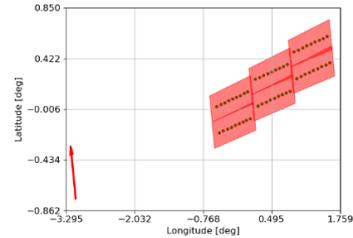


Figure 4: Corners of the simulate scene, in longitude and latitude (degrees) coordinates.

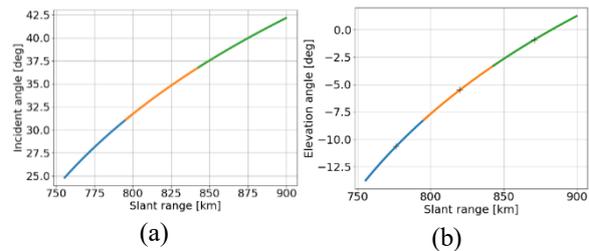


Figure 5: Observation geometry. (a) Incident angle and (b) elevation angle (both in degrees) as a function of the slant range distance (in km).

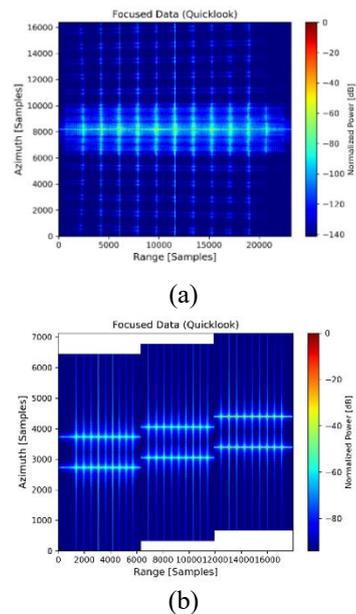


Figure 6: Quick-looks of focused data: (a) L1a SLC (first sub-swath, first burst, VV pol) and (b) corresponding L1b GRD (VV pol).

Finally, the PEM evaluates the overall system performance based on the resulting simulated data and generates a report with the most relevant results. **Figure 7** displays an example of generated IRF contour plots for one of the simulated point targets at two different ROSE-L products: (a) L1a SLC data and (b) the corresponding L1b GRD data. Instead, **Figure 8** shows a summary table of the IRF analysis when considering all point targets on a particular sub-swath and burst. For this specific simulation run, the raw data was generated assuming a given baseline scenario under ideal conditions (i.e., no instrument or platform errors, no RFIs or atmospheric contributions considered), and the GPP did not apply any correction. Hence, the IRF analysis shows compliance with the ROSE-L RIWS specifications.

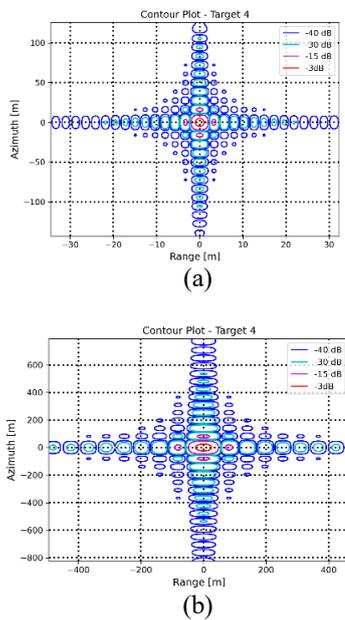


Figure 7: IRF contour plot at: (a) L1a SLC and (b) L1b GRD, for the point target located in the middle of the first sub-swath and first burst (VV pol).

	Value (VV)
Single-look Azimuth Resolution (3σ) [m]	9.84
Azimuth Position Error (3σ) [m]	0.0
Azimuth PSLR (3σ) [dB]	-13.27
Azimuth ISLR (3σ) [dB]	-10.08
Single-look Ground range resolution (3σ) [m]	4.64
Ground Range Position Error (3σ) [m]	0.0
Range PSLR (3σ) [dB]	-13.24
Range ISLR (3σ) [dB]	-10.0
Multi-look Azimuth resolution [m]	49.96
Multi-look Range resolution [m]	49.97

Figure 8: IRF summary table reported by the PEM (first sub-swath, first burst, VV-pol).

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