# SS-E2E: MISSION PERFORMANCE SIMULATORS FOR SPACE SCIENCE MISSIONS

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## ABSTRACT

A number of EO End-to-End Simulators (E2ES) have been developed in the past and are currently being developed. Although for Space Science (SS) this is often done external to the Agency by the scientific community, there can be a use for E2ES in this domain too and the framework, architecture and models defined in earth Observation (EO) could be reused to a large extent, making the definition and development of E2ES affordable even as internal independent engineering and validation tools. Moreover, for some space science missions it is more difficult to develop a clear mission plan and little funding is available in early design phases: therefore the availability of standard simulator architectures and a library of building blocks to enable the development of simulation scenarios without too much effort, would be highly appreciated.

The SS-E2ES activity is framed into this context, with the main objective to analyse which (type of) science missions can benefit from the E2ES concept, what is similar to EO (and therefore reusable), and to define a SS E2ES generic user requirements, architecture and building blocks, which could then be used for different payloads and planetary bodies [1].

The rationale behind this Reference Architecture (RA) is promoting reuse in the development of mission performance simulators by:

- Categorising past, current and planned ESA SS missions to identify the main elements affecting mission performance and having an impact over the simulator architecture.
- Identifying the architecture elements required to model the mission and proposing a generic RA that could be adapted for the different mission particularities.
- Describing the architecture elements, in particular those that can be generalized for the various mission categories.
- Evaluating the RA by comparing the development of an E2ES using this new concept vs. simulator development.
- Defining a roadmap to reach an operational concept for the development of E2ES based on the presented RA.

This paper will present the outcome of the SS-E2ES activity for the points listed above, and it will address - in particular - the proposed RA and building blocks, including its main architectural elements and how it suits the development of E2E mission performance simulators adapted to several missions and types of instrument for SS.

The SS-E2ES activity is being carried out by a consortium led by GMV (Spain) and including the following institutions: Airbus Space and Defence (Germany), Università di Roma “La Sapienza” (Italy), University College of London (UK).

## INTRODUCTION

While in EO domain the use of E2ES to assess mission performances is very common and well established through several years of successful applications, i.e. Earth Explorer and Copernicus programs, in SS the appeal of such tools is much more limited and their use is not typical at all. It is then worth to globally consider similarities and differences between EO and SS missions design practices, to have a clear indication on the reason why E2ES would have to be (eventually) used also for missions looking beyond our planet.

### Differences and Commonalities between Space Science and Earth Observation Missions' Design

A first factor to be considered is of course the difference in the frequency of missions launched between EO and SS. The high number of missions designed to observe our planet entails that different spacecraft could cover the same goals and/or use the same instrument of their predecessors: this pushes the need for a common approach for mission design as well as the interest to reuse what it has already been proved to be successful. Instead in SS the variety of targets generally causes the profusion of unique and dedicated mission design processes, while the high mission costs cut down the number of launched missions with respect to EO, reducing then the E2ES employment for missions' performances assessment and comparison.

Another important aspect to be surely taken into account is that in EO ESA is responsible for the instrument data processing: this stimulates the dissemination of ESA driven practices, with the consequent diffusion of Agency defined standards aiming at both mission design procedures harmonisation and common design modules reusability. On the other hand in SS the instrument data processing responsible is usually represented by the scientific team, who does not necessarily deal with more than one mission and does not then need to reuse the mission and instrument design analyses. Moreover, even if these teams could be in principle available to partially or fully disseminate their studies, it is less frequent to incur in the employment of standard and common framework for missions' simulation.

Nevertheless in the last years a common aspect between EO and SS missions rose up in ESA practices and it should be particularly considered within the context of the current study: the use of competition for missions' selection. This kind of approach, employed for example by the Earth Explorer or by the Cosmic Vision programs, relies on the possibility of a straight comparison of missions' performances, which are usually based on E2E simulation results analysis through a "Mission Assessment Report". Therefore this is a clearly common feature among EO and SS missions' design where the E2ES play a major role.

### E2ES Added Value for space science

It is then important to raise a critical question: would an E2ES be an added value for evaluating the performance of SS missions? SS missions design makes use of a different approach with respect of EO practices, an approach which demonstrated to be successful for many years and through many very complex missions. Introducing then the use of E2ES in this community will surely face a comprehensible reluctance and could lead to the typical programmatic complications entailed in any modus operandi modification.

Nevertheless for some SS missions it is more difficult to develop a clear mission plan and little funding is available in early design phases: therefore the availability of standard simulator architectures and a library of building blocks to enable the development of simulation scenarios without too much effort, would be highly appreciated.

It seems therefore that the main added value of E2ES use in SS would be the partial or global reusability of some of the simulator modules and possibly of the simulator architecture. Due to the big variety of targets, objectives, instruments and architecture of SS missions, it is very unlikely to find a solution valid for all analysed aspects and for all the considered missions. The question proposed at the beginning of this paragraph needs then to be reformulated as follow and to be solved in two different and consecutive steps.

- Would an E2ES be an added value to evaluate the performance of the considered SS mission category?
- Which are the building blocks that can be considered generic and therefore reused?

## MISSION AND INSTRUMENT SURVEY AND CATEGORISATION

To define a generic architecture suitable to different mission categories or several categories of mission architectures, it is necessary to perform a detailed review of past, current and planned SS missions. This review shall focus, at a first level, on the different mission options and their implications on the definition of the RA, such as the possibility of using common blocks or defining independent processing chains.

**Mission and Instruments Survey**

The categorization criteria definition for SS missions requires then some additional consideration with respect to EO: it is in fact true that also the missions dedicated to study our planet present a considerable diversity of scientific objectives and could then be classified according to them. Nevertheless in SS a preliminary categorisation naturally arises from its target objects assortment and has therefore been historically used to delineate the SS missions' taxonomy. The first step has consisted in distinguishing between missions looking at object inside or outside the Solar System; then, among the missions dedicated to study the Solar System bodies other than Earth, another division has been set between studies dedicated to the Sun or investigations targeting bodies in orbit around our star (planets, natural satellites, asteroids and comets). Therefore this first classification is built around the mission target objects, which are usually classified in three main classes:

- ASTROPHYSICS
- SOLAR SCIENCE
- PLANETARY SCIENCE

The missions have then been analysed under different aspects and criteria:

- Mission configuration, where the following categorizations have then to be taken into account: spacecraft orbit, number of platforms and number of instruments
- Scientific data retrieval, where three elements are considered critical in mission categorization: the acquisition technique, the science requirements and the performances achievements strategy
- Instruments categorization, which took into consideration both mission objectives and instrument acquisition technique

This large survey result has been summarised in statistical representations (i.e. the mission objectives for astrophysics class in Fig. 1, or the instruments usage in planetary missions in Fig. 2, or again the orbit selection for solar science missions in Fig. 3) that allowed to properly weighting the impact of each category on the overall analysis.

**Mission and Instruments Categorisation**

According to the team experience and to the survey realized different categorisations have then been proposed within the three mission classes and also across them (Fig. 4 and Fig. 5):

- astrophysics missions have been classified into observatories missions (i.e. Hubble, XMM), survey missions (i.e. Planck, Gaia) or hybrid missions (i.e. Kepler, Plato)
- planetary missions have been classified in two main categories: missions mainly orbiting around a central body (i.e. mars express, Bepi Colombo) or missions performing science exploration through one or several fly-bys (i.e. JUICE)

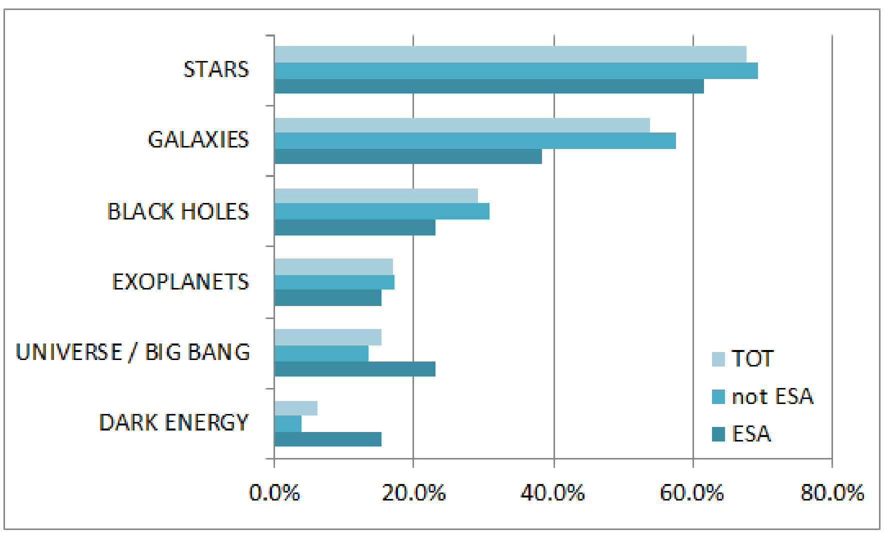


Fig. 1. Survey of 65 astrophysics missions objectives

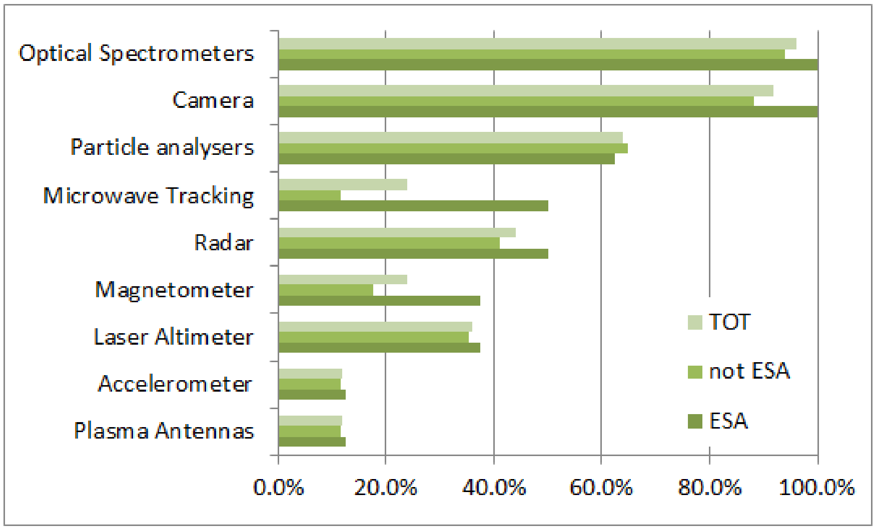

Fig. 2. Survey of 25 planetary science missions instruments usage

- SS missions could also be categorised analysing how the science requirements are defined and how they are broken down to quantitative system requirements for ESA and industry; in this case they would be split into missions having quantitative science requirements (i.e. Athena, Gaia) or missions having qualitative science requirements (i.e. Euclid, Planck)
- a part form the categorisation within each mission class (i.e. optical spectrometers, imagers, radars, etc.), instrument can be divided into three main groups considering their performances contributors: stand-alone instruments (almost all SS instruments), instruments closely coupled with the spacecraft (i.e. Euclid imager) and instruments requiring overall mission performance beyond single satellite (i.e. radio science experiments)

**Mission and Instruments Commonalities**

Identify commonalities within such a wide domain as SS missions set is, represents a key issue for the E2ES RA definition: if the sharing of common elements is demonstrated between all the missions, or at least within certain clearly identified groups of missions, then a categorization could be defined and the simulator common building blocks would then be defined within the correspondent category.

*Orbit Simulation*

The orbit simulation for SS represent a very different task with respect to the EO case, because of the much higher variety of orbit geometries, central bodies and perturbations to be considered, but this long list could be narrowed down

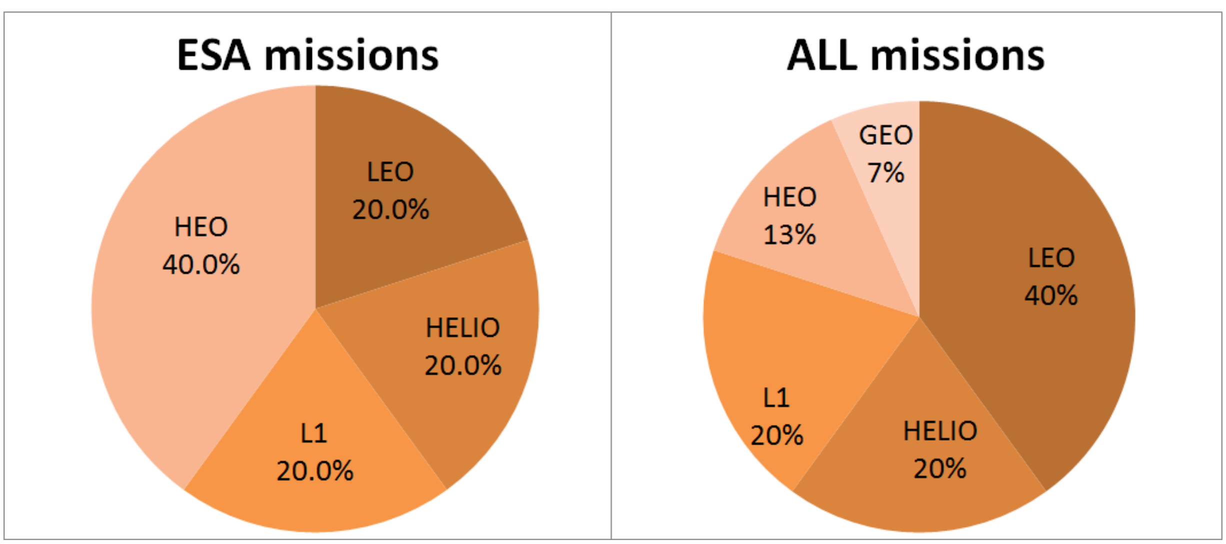

Fig. 3. Survey of 15 solar science missions orbits

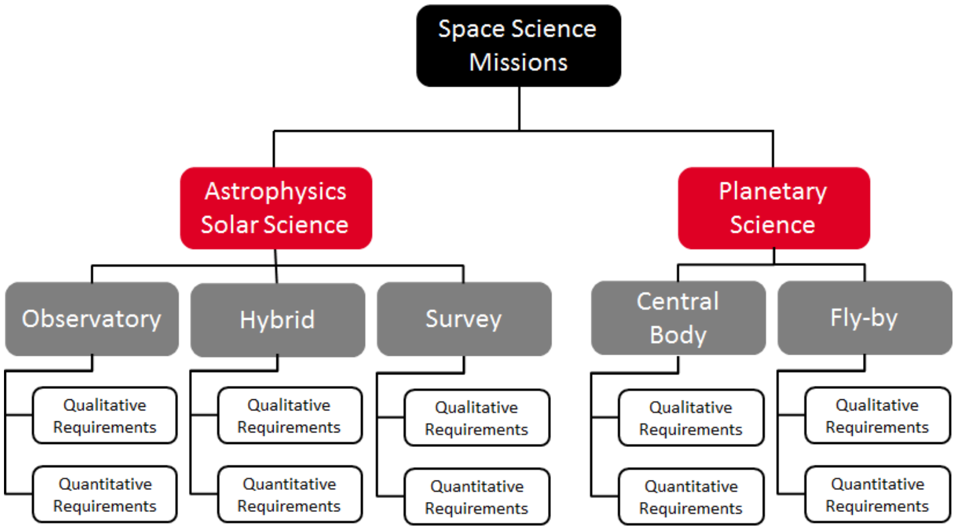

Fig. 4. Categorization of space science missions

through the statistical analysis and categorisation performed. Solar science and astrophysics missions, in particular, almost fully rely on geocentric or Lagrangian orbits while planetary science missions always have an orbit defined around a specific central body (also the cases of planetary fly-by could be treated as a sequence of different body-centred orbits through the patched-conics approach). A good level of commonality can be then individuated in the high level configurations of such missions: the base models (e.g. gravity, rotation, tides, drag, radiation pressure, etc.) can be reused from a simulation to another, with adjusted configurations and checking that the level of accuracy is compatible with the mission requirements. Other geometric modules also have a wide reusability: significant examples are the transformations among different reference frames and different coordinate systems, the tools to calculate spacecraft visibility from ground stations, occultation, solar elongation, etc.

*Attitude*

There are certainly criticality thresholds for attitude simulation in astrophysics missions, with possibly considerable stringent requirements in pointing definition and simulation, depending on mission target and instrument characteristics. Missions can be grouped as missions with strong mass limitations and consequently small instrument apertures, observatory missions and higher pointing stability missions. Under the attitude simulation point of view, the planetary science missions behave pretty similarly to EO missions: the pointing strategy is quite linked to the observation geometry of the instrument and the simulation of platform vibration and pointing errors, very important for the end-to-end simulation, could be done in similar way for most of the platforms and missions.

*Scene Generation*

When the scene generation is considered, astrophysics missions turn out to be a case apart with respect to solar and planetary science because of the nature of the objects they target. Even if some commonality can be extracted within this missions' class (i.e. 57.1% of missions are dedicate to stars observation and 42.9% target galaxies), the scenario

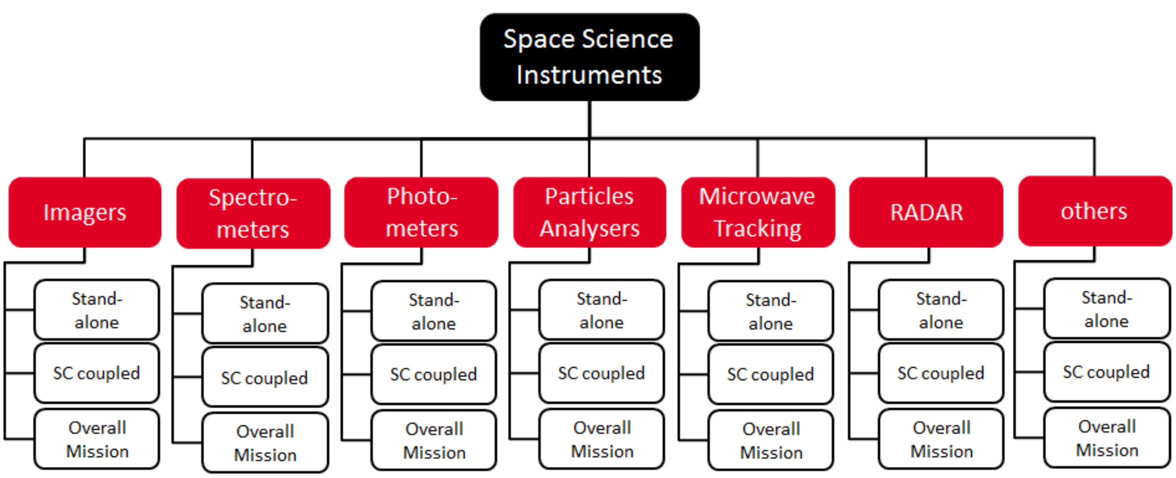

Fig. 5. Categorization of space science instruments

becomes much more complex when the amplitude of investigated sky portion is taken into account: another degrees of freedom comes into play distinguishing between missions dedicated to survey a small portion of the sky and missions that targets the whole celestial sphere, resulting in an atomised classification of missions dedicated to astrophysics studies. On the other hand solar and planetary sciences share the observation of many phenomena, but, once more, when one looks at the details of the objective scene generations many differences comes into play between the phenomena effects to be reproduced for a correct E2E simulation. What could be found to be common are the basic models of physical properties description and calculation: therefore models such the Radiative Transfer Models designed for Earth could in principle be used for other planets and atmospheres once the different atmospheric layers properties are properly modified.

*Instruments*

The models of the specific instruments have much lower commonalities among missions, because the level of detail of the model required to fulfil the specific mission requirements usually changes from mission to mission. There are at least two main factors that can contribute: one is the evolution of the instruments with time and the other one is the different environment in which they have to operate. This implies that the models of the instruments and part of the models required to simulate the scenario must be updated or, in some cases, re-designed from scratch in order to hit the scientific targets of a new mission. Moreover, these updates cannot be fully provided before the mission is flying and the data is collected, but they are completed by the scientific teams responsible for the data analysis during the process of the data analysis itself. Such data analysis is an adaptive process that relies on the experience of the specialists of each instrument.

*Data Processing and Retrieval*

In SS it is not at all trivial to properly discriminate between observed data processing and data retrieval simulation, because the two processes are often strictly related due to the close relations existent between the requirements definition at the different levels. This aspect of commonalities analysis is closely related with the scene generation one and it shows the presence of very few common aspects in data processing and retrieval between different missions. Commonalities could be identified only in some processing and retrieval method or inversion algorithms, such as least square filters or sequential filters, often used to obtain the quantities of scientific importance from the collected data, but hardly in the entire process

**REFERENCE ARCHITECTURE FOR E2E SIMULATORS**

The application of the RA to all types of missions/instruments supports the decision of defining certain elements at high level that would be present in all simulators, independently of the category of the mission and the type of instrument. This process will be very similar to the one established for EO missions and described in [2]: in the RA concept these high-level elements are called modules, and they could be identified as the simulator Stages (or even more, simulator Modules) that could be integrated into a simulation framework.

The main premises of the RA, illustrated in Fig. 6 are:

- The RA defines a series of six high-level modules and the interfaces among them that are common to all type of missions and instruments.
- Although the RA is generic, it is flexible to be adapted for the different mission particularities.

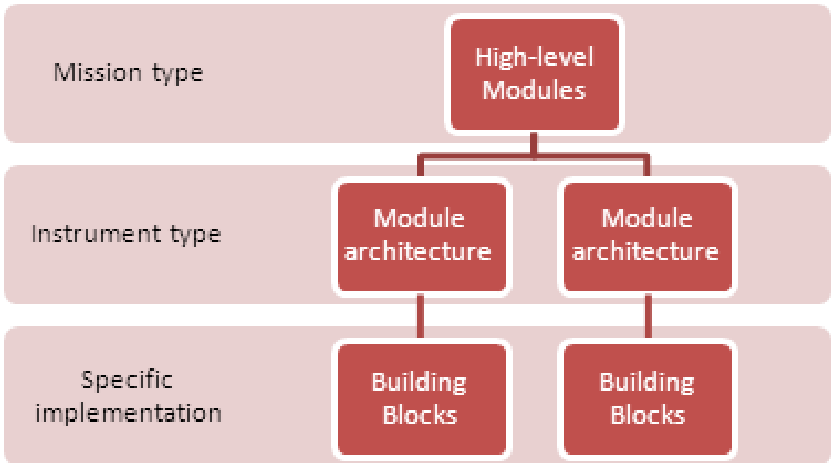


Fig. 6. The Reference Architecture Concept

- Depending on the type of instrument to be simulated each of the six high-level modules will have an internal architecture broken down in building blocks. This internal architecture is, for most cases, generic across instrument types.
- Different implementations of the same building blocks account for mission parameters, evolution of algorithms throughout the different mission phases, etc.
- Some of the high-level modules a——nd lower-level building blocks will be generic across missions and instruments

Including the high-level modules and the lower-level building blocks, the E2ES can be decomposed in three main elements:

- Modules (or Building Blocks): software objects that implement the chosen models.
- Data: input/output information for the models; exchanged among then different Modules.
- Configuration: defined by the user depending on the simulation to be run. Divided in:
    - Configuration parameters, used to configure the Modules in order to process the data under the desired conditions (i.e. instrument characteristics, data sampling, etc.).
    - Activation flags, used to enable/disable the execution of a subset of models or to select the algorithm to be adopted when the E2ES is run. These activation flags could also be used to select a particular implementation of the building block if it is shared by different types of instruments.

**High-Level Elements of the Reference Architecture**

The identification of the high-level elements of the RA has been done from the categorization of missions and analysis of commonalities, and takes into account the project team’s experience in the design and implementation of E2ES. Each of these high-level modules, six in total, implements a certain functionality of the E2ES, and has defined interfaces and configuration parameters. Table 1 summarises the purpose of each module and its main interfaces. Similarly to what is described in [2] for EO missions, the main RA will present a typical generic data flow as the one illustrated in Fig. 7

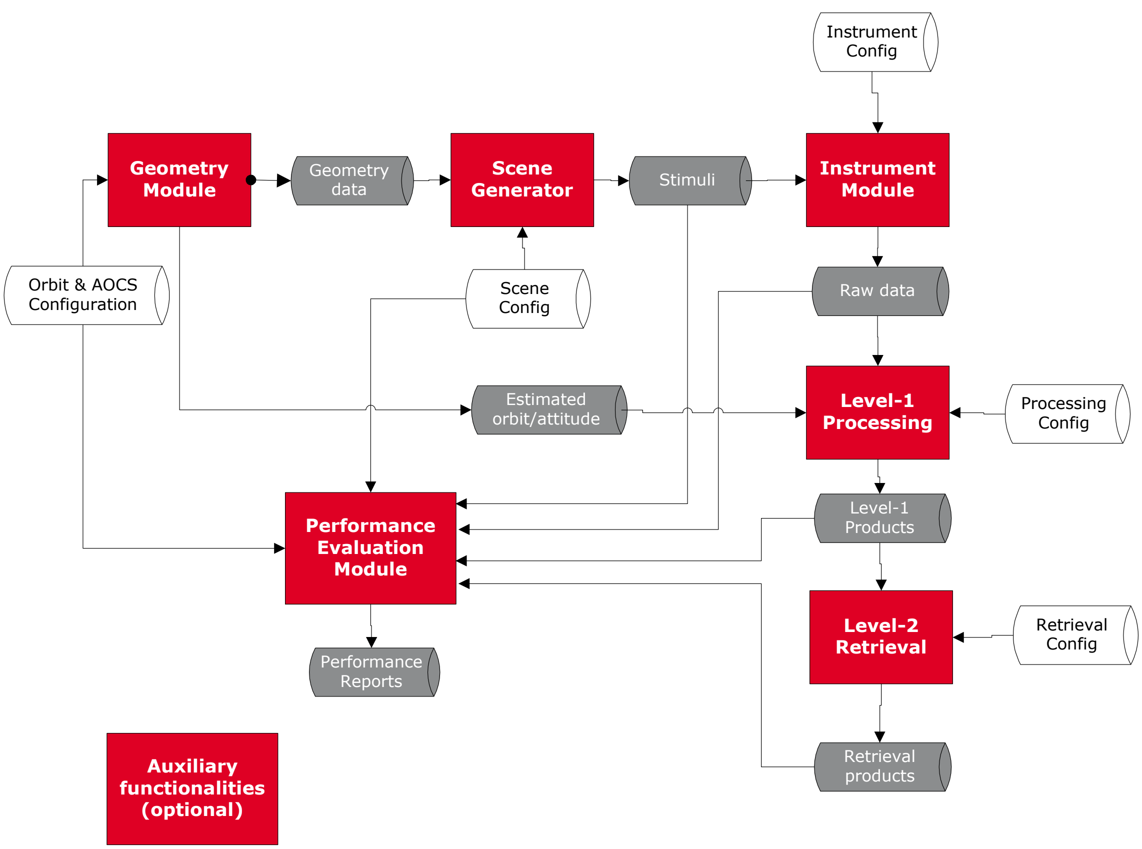


Fig. 7. Generic data flow at the highest level of the Reference Architecture

| Module | Purpose | Configuration | Inputs | Outputs |
|---|---|---|---|---|
| Geometry | Simulates SC orbit and attitude and observation geometry of each instrument | Orbit & AOCS configuration | N/A | Geometry data |
| Scene Generator | Simulates scene to be observed and environmental effects needed for generation of stimuli to enter instrument model. | Scene configuration | Geometry data | Stimuli |
| Instrument | Simulates sensor behaviour, having different outputs depending on type of instrument. | Instrument configuration | Stimuli | Raw data |
| Level-1 Processing | Generates Level-1 products. | Processing configuration | Raw data | Level-1 products |
| Level-2 Retrieval | Performs retrieval of geophysical parameters objective of the mission/instrument. | Retrieval configuration | Level-1 products | Retrieval products |
| Performance Evaluation | Performs analysis of simulator outputs to evaluate mission performances. It could be run at different points of the simulation chain. | Orbit & AOCS configuration<br>Scene configuration | Stimuli<br>Raw data<br>Level-1 products<br>Retrieval products | Performance reports |

Table 1. Details of the high-level modules of the Reference Architecture

**Building Blocks**

Following the RA concept presented, each of the different high-level modules has been broken down in a series of building blocks. The granularity of the building blocks has been determined after the identification of the elements to be modelled and a thorough analysis of commonalities. Once the preferred option (or options) for the definition and implementation of a building block has been identified, the building block itself has been defined.
To ensure the adequate level of detail in the definition of the building blocks, a custom template will be developed as already proposed in [2]. This level of detail is important to allow composability (i.e. reuse) of the architectural elements, both at syntactic (engineering) level and at semantic (modelling) level.

## CONCLUSIONS AND NEXT STEPS

An extensive review of SS missions and their instruments has allowed deriving a RA for E2ES in the frame of this missions' category, where a potential interest is identified: the use of competition for mission selections (i.e. in the Cosmic Vision programme) requires in fact a comparison between mission performances in early design phases, exactly when the low funds availability would take advantage of common libraries and architecture for mission performances simulations. The use of this RA has thus the potential of reducing the reengineering process associated to the evolution of the simulator throughout the different mission phases and the identification of common elements for different types of instruments enables reuse of the architectural elements across several mission simulators.
The next step will be to evaluate the RA to gain an understanding of the advantages of the RA approach with respect to the current approach. This evaluation will be done through a two-step approach:

- Analyse the process of designing and developing specific instruments simulator by applying RA using JUICE as case study
- Evaluate the proposed RA concept compared to ad-hoc E2E simulators development, using as case studies BepiColombo and EUCLID

The final task to be performed in the SS-E2ES activity will be the definition of a roadmap to reach an operational RA, including the identification of priorities in implementing generic building blocks and improvements to existing simulation frameworks and model repository.

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[2] Cristina de Negueruela, et al., "ARCHEO-E2E: A Reference Architecture for Earth Observation end-to-end Mission Performance Simulators", *SESP 2012*