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Analytical and Simulation-based V&V techniques applied to the ExoMars 2020 Cruise GNC

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Abstract

This paper presents an overview of DEIMOS Space's activities, with SENER as subcontractor, within the Cruise GNC activities of the ExoMars 2020 program. DEIMOS Space primes the independent V&V activities, supporting the analysis and verification of the Cruise Guidance, Navigation and Control (GNC). The Validation & Verification (V&V) campaign shall ensure, to the maximum extent possible, that the Cruise GNC can adequately control the SpaceCraft (S/C), and hence that the Descent Module (DM) accomplishes its objective of reaching the separation point with the required accuracy. The outcomes of the independent analysis, materialized as simulation reports and performance assessments, allows the customer to early identify possible bugs and unexpected problems, timely taking the necessary actions to ensure the adequate quality of the GNC product. Finally, the Software (SW) simulation framework (Cruise GNC Functional Engineering Simulator) enabled the efficient selection and investigation of test cases whilst maximizing functional coverage, to support the definition of the test cases to be executed, as part of the V&V activities, on the System Avionics Test Bench (ATB).

1. Introduction

The ExoMars 2020 mission [1], co-managed by ESA and ROSCOSMOS, consists of a Spacecraft Composite (SCC) to be launched in July 2020 by a Proton-M Launch Vehicle (LV) and is primed by TAS-I. The mission will demonstrate key flight and in-situ enabling technologies in support of the European ambitions for future Mars exploration missions, and will pursue fundamental scientific investigations. The mission objective for Europe is exobiology using a drill system and an elaborated laboratory that will sever 3 payload instruments (Micromega, MOMA, Raman, for a total of 9 payload instruments embarked on the Rover), while for Russia the interest is to have a static scientific platform on Mars to monitor the planet external and surface environment. The SCC includes the Carrier Module (CM led by OHB Bremen) and the Descent Module (DM), which accommodates the Rover Module (RM led by TAS-I with the Rover Vehicle led by Airbus UK). The CM will transport the DM during the cruise phase, covering the transfer orbit form Earth to Mars, starting at the separation of the SCC from the Launcher, and ending at the separation of the DM from the CM, a few days prior to the Entry, Descent and Landing (EDL) phase of the DM in Mars. Once the DM has landed on the Martian surface and after the egress of the RM the landed part of the DM will remain operational as a long-living Surface Station, while the RM will perform its nominal surface science operations.

DEIMOS is the prime contractor of the independent V&V activities, carried on with the collaboration of SENER as subcontractor. The activity is aimed at supporting the full analysis, verification and validation of the Cruise Guidance, Navigation and Control (GNC) algorithms, against the applicable requirements, during the phases C/D of the project.
The paper is organized to describe the activities performed to ensure an adequate V&V of the Cruise GNC algorithms reaching a proper Performance Assessment:

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- Analysis and analytical verification of the Cruise GNC algorithms, including activities of prototyping, unit testing and robust control techniques, to ensure the full understanding of all functionalities that have been included, is described in Section 2;
- Preparation and maintenance of a pointing budget, including the analysis of the Cruise GNC pointing error sources, non-linearities and non-idealities, considering the SC, its units and environment, and the GNC algorithm properties, is described in Section 3;
- Construction and validation of a Functional Engineering Simulator (FES), specifically designed to support the verification of the Cruise GNC algorithms, and implementing high-fidelity models of the SC, Actuators and Sensors, is described in Section 4
- Development of a Cruise GNC Verification Plan and the execution of the verification campaign in the FES, is described in Section 5.

The process has been iterated during the consecutive design loops, while the algorithms and the available data were progressively refined, starting from data retrieved by the units specifications, then using the declared units performance, and finally the measured units performance. A representation of the work logic of the V&V campaign and its loops is shown in Figure 1.

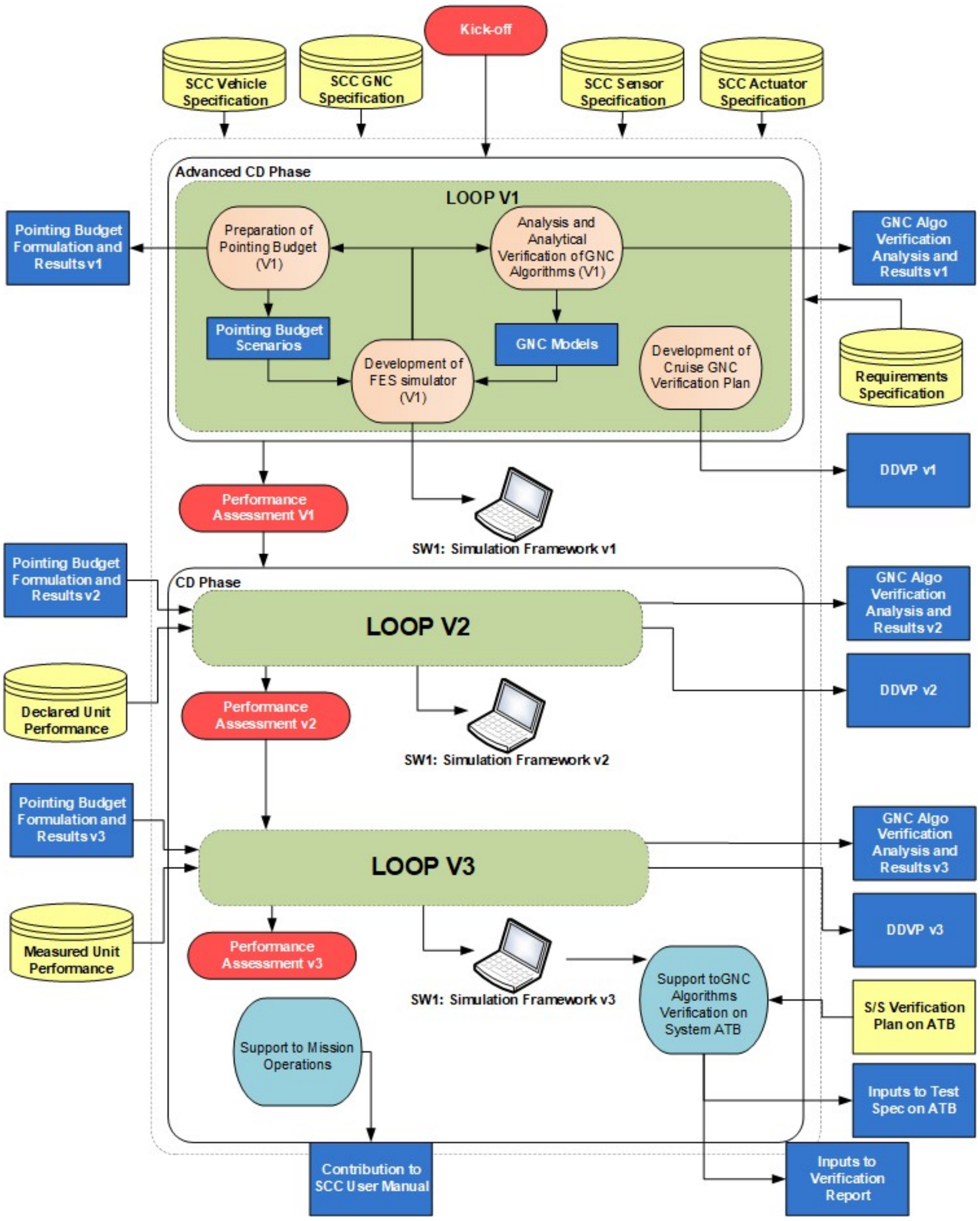

Figure 1: Workflow of the V&V campaign

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2. Analysis and analytical verification of the Cruise GNC Algorithms

The algorithm specification, provided by TAS-I, has been studied, understood and reviewed in terms of functionalities and parameterization, performing activities of prototyping, unit testing and robust control techniques, to detect deficiencies in the nominal functioning.

The tasks of the activity comprise, but are not limited to:

- Reviewing Cruise GNC algorithms specification and GNC requirements;
- Reviewing and evaluating any change in algorithms formulation, as well as in applicable parameters and constants;
- Identifying, through inspection, possible non-conformities or missing elements in the specification;
- Identifying changes in GNC modes, mapping each mode to each Cruise sub-phase.

A first loop of analysis is done on each of the GNC sub-functions separately, and is focused on verifying the consistency between its requirements, its design and its implementation. In some cases, unitary tests of the sub-functions are performed to support the analysis.

A broad number of tests have been carried on especially to verify the sub-functionalities of Navigation and Guidance. Some examples are reported hereafter:

- Navigation subfunction for Attitude estimation (Figure 2): the function has been tested independently from the rest of the GNC to assess its performance, configuring a certain delay on the Star Tracker (STR). This example shows that this subfunction performs as expected.
- Guidance subfunction for Reference trajectory generation (Figure 3): the function is tested independently of the others to assess its correct performance. In this case, the function is fed with the flag defining the required target the SCC shall point at, and an arbitrarily assigned final pointing axis direction; furthermore, the SCC is assumed to be spinning at the nominal spinning rate. The reference and true pointing axis direction, as well as pointing velocity, angular velocity and time-to-go for the slew manoeuvre are shown, demonstrating that, even if the test is conducted in open-loop, the function performs as expected.
- The Control function has been extensively analyzed by SENER through review of design, inspection analysis and functional verification of each sub-function, but also to assess robust stability of the system in a variety of scenarios considered representative of the flight environment. In [1] "ExoMars Mission (2020)," ESA, 2 May 2016, URL: http://exploration.esa.int/mars/48088-mission-overview/
- [2] details on the formal verification of stability and robustness are presented.

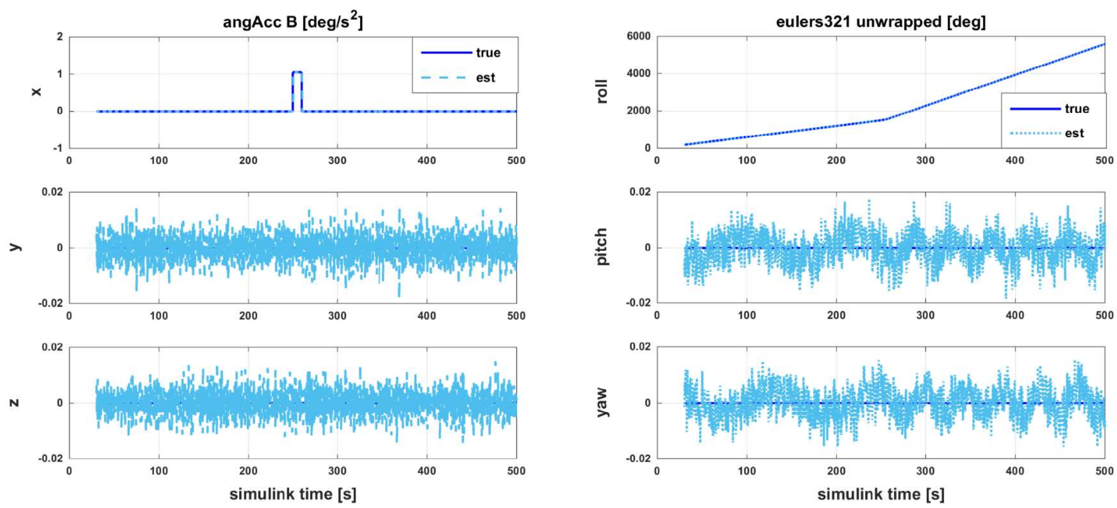

Figure 2: Example of Navigation Unit testing (Attitude Estimation)

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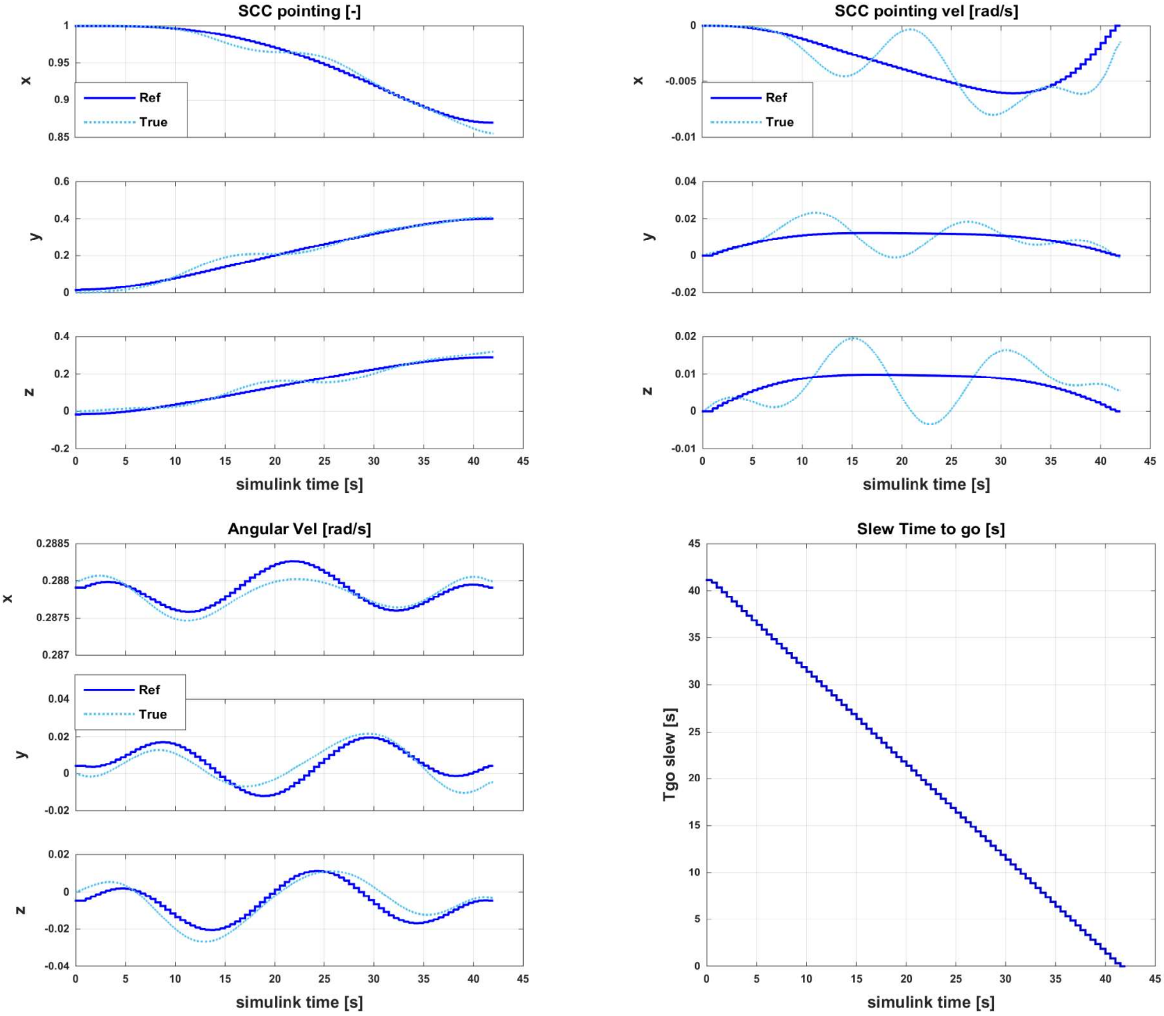

Figure 3: Example of Guidance Unit testing (Reference trajectory generation)

After all the specified sub-functions of the GNC algorithms have been prototyped and tested, following the specification, the entire GNC shall be tested. Prior to the integration inside the Cruise Functional Engineering Simulator (FES), some tests have been agreed with TAS-I, to ensure the coherence between the specification and the prototyped and integrated version of the algorithms. This is done through open-loop tests, conducted on different scenarios, with inputs/outputs provided by TAS-I. This cross-validation allows validating the prototyping performed by the independent GNC V&V team, and identifying possible deficiencies in the specification provided.

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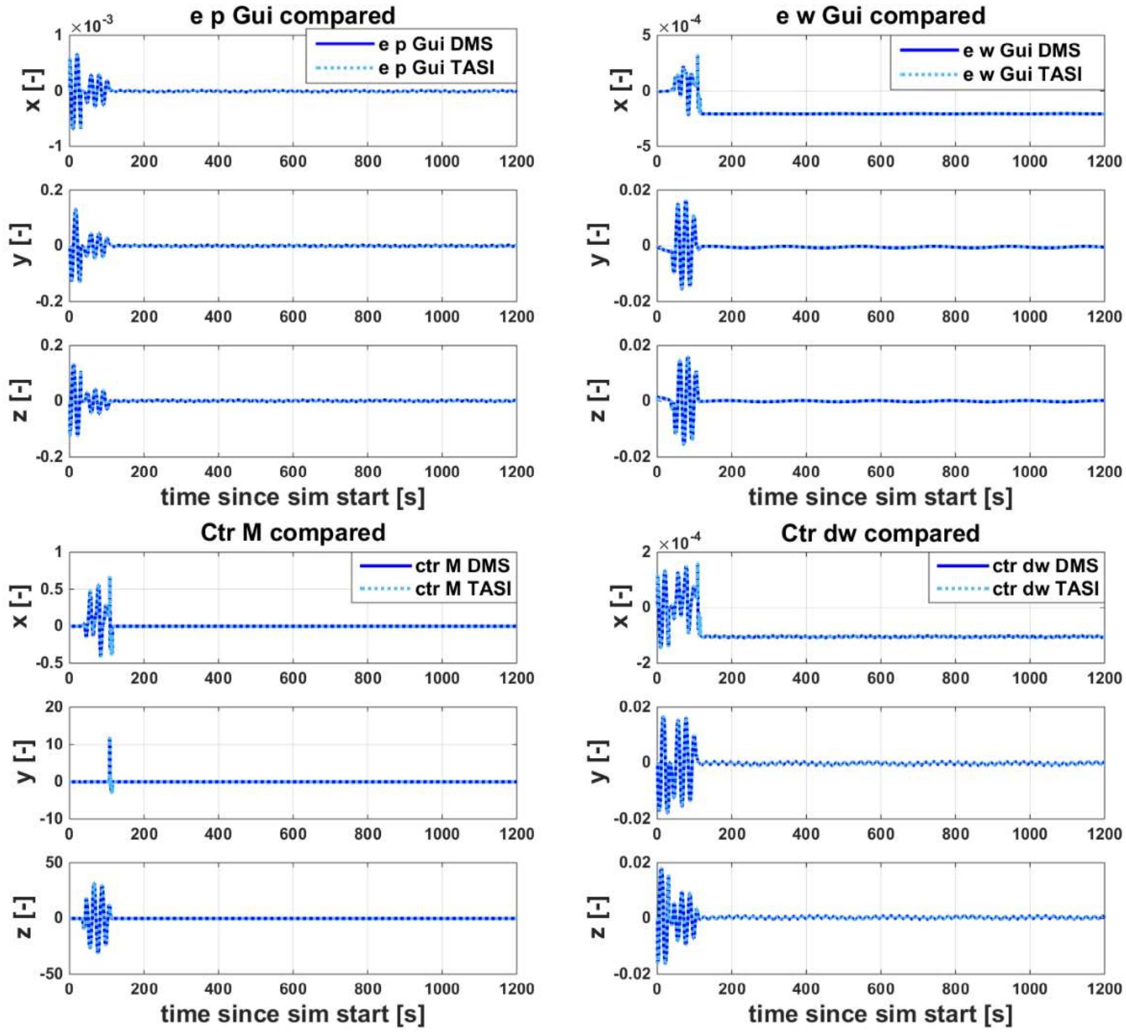

Figure 4: Open loop comparison, DEIMOS prototyping vs TAS-I specification

This rigorous process ensures, to the maximum extent possible, that the GNC prototyped by DEIMOS following TAS-I's specification reflects all the functionalities and behaves as expected. This, with the tests performed to each sub-function separately, and the review of the various functionalities, ensures that DEIMOS as independent V&V authority, is able to identify and isolate deficiencies and bugs in the proposed implementation, as well as suggesting ad hoc improvements.

3. Preparation and maintenance of a pointing budget

Within the activity of independent V&V of Cruise GNC for ExoMars 2020 program, the error budget was included in order to estimate the effect of the chosen navigation sensors, intrinsic SCC structure, environment perturbations, characteristics and tuning of the GNC subsystem on the pointing and translational accuracies of the SCC. In particular it will depend on the GNC subsystem algorithms, which can be separated in the following sub-algorithms:

- The Attitude Navigation, which fuses the measurements of the star tracker and the IMU. Besides filtering the sensors noise, the navigation is able to estimate (and compensate for) the IMU gyro's measurement bias.
- The Delta-V Navigation, which corrects (bias, centripetal acceleration), filters and integrates the IMU translational measurements.
- The MCI estimation, which uses the Dispatching function information to estimate the fuel consumption and in turn estimate the current mass, CoG location and inertia matrix.
- The Attitude Guidance, which computes the attitude error, desired pointing (autonomous, based on Earth and Sun ephemerides computed on-board) according to the current GNC mode and the estimated attitude.

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- The Delta-V Guidance, which computes the delta-V error based on the high-level ground command and the estimated delta-V to be applied.
- The Control and Dispatching, which combines the Guidance and Navigation information and converts it into on-time actuation commands for the RCS to simultaneously (if applicable) exert the commanded torques and forces.

The structure of the Navigation algorithm affects the error budgets through the Kalman-filter-based attitude estimation process and the angular velocity filtering.
The structure of the Control algorithm also directly affects the error budgets, through its main operations:

- Linear feedback;
- Attitude control dead-bands;
- Dynamic inversion;
- Dispatching.

The following metrics are considered for the attitude pointing budget analysis:

- Pointing Absolute Performance Error (APE): Corresponds to the angular difference between the SCC X-Axis and the ideal spinning axis for perfect pointing. Perfect pointing refers to the true Earth/Sun/Inertial direction.
- Rate APE: Corresponds to the modulus of the angular rate error obtained as the difference between the true angular rate and the spinning reference rate.
- Pointing Absolute Knowledge Error (AKE): Corresponds to the angular difference between the true SCC frame and the estimated one.

The attitude pointing budget covers multiple scenarios for different mission phases and GNC modes. The scenarios are selected with the aim of covering the GNC requirements that are related to the attitude pointing metrics. The pointing budget assumes that the GNC is actively controlling the SC spinning axis. This means that its results will apply to the attitude and angular rate pointing errors at the end of the repointing manoeuvre.

The pointing budget analysis has been performed resorting to the Pointing Error Engineering Tool (PEET) tool, by ESA. The PEET allows the engineer to build control systems error models and analyse specific error metrics. Therefore, a dynamic model has been built for each error source. Each dynamic model represents the SC plant with its controller, which accepts as input the Pointing Error Source (PES) modelled as e.g. an actuator torque error, rate sensor error or inertia matrix dispersion and it outputs the Pointing Error Contribution (PEC). Therefore, the transfer analysis from PES to PEC is moderately accurate and respects the ECSS guidelines for high performance systems and/or tight requirements.

The dynamic system is provided to the PEET as a state-space model which changes according to the type of error source. It shall be noted that the PEET provides a pointing error analysis in continuous-time, meaning that it cannot take into account the discrete characteristics of the controller (not an issue if the characteristic time of the system is much larger than the sample time). However, error sources can be characterized as discrete with their sample time.
The approach used by PEET to compute the PEC is based on frequency-domain analysis. This approach is restricted to Gaussian processes and linear time-invariant (LTI) systems (as per PEET constraints). The dynamic system is therefore converted to a transfer function and the output signal is analysed.
The results of this analysis, allowed having an estimation of the Pointing Error contribution of each error source, finally providing the estimated total APE and evaluating the percentage it represents of the applicable requirement.
Eventually, due to all the aforementioned considerations and assumptions, the results of PEET analysis are a rough order of magnitude (ROM) of pointing and translational error budget. These results are preliminary to any V&V campaign.

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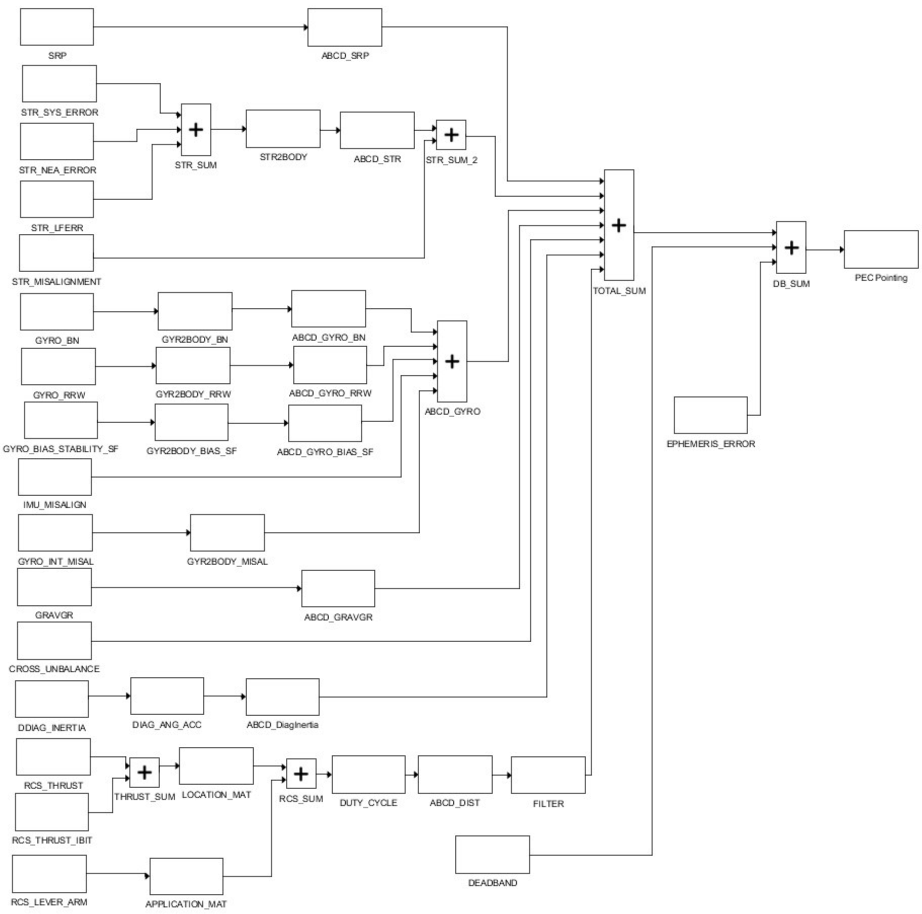

Figure 5: PEET Diagram implemented to obtain the Attitude Pointing Budget.

Table 1: Attitude Pointing Budget Results for angular APE in example scenario

PEC Family	Contribution [mdeg]	Percentage of applicable req [%][a]
GNC deadband	48.3	9.66 %
STR Measurement Error	30.6	6.12 %
IMU Gyro Measurement Error	247.5	49.51 %
Uncertainty on the principal moments of inertia	0.9	0.17 %
SRP	2.9E-3	0.00059 %
Gravity Gradient	0.2	0.04 %
RCS thrusters noise and lever arm dispersions	41.7	8.34 %

[a]Requirement is not satisfied if the sum of those contributions overcomes 100%

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Table 2: Total angular APE wrt requirement in example scenario

PEC Family	Total APE [mdeg]	Percentage of applicable req [%][b]
Ensemble of PEC	468.8	93.76

[b]Requirement is not satisfied if this overcomes 100%

4. Construction and validation of a Functional Engineering Simulator (FES)

The Functional Engineering Simulator (FES) developed is based on DEIMOS SIMPLAT infrastructure built on the MATLAB™/Simulink™ modeling & simulation environment, specifically designed to support the verification of the Cruise GNC prototype. To achieve the desired level of accuracy, high-fidelity models of the SC, actuators and sensors have been developed, including all the envisaged uncertainty sources.

DEIMOS SIMPLAT is a simulation infrastructure designed and developed using internal funds by DEIMOS Space for the production of functional engineering simulators for GNC and AOCS subsystems, and other related engineering activities. It has been used in a number of ESA programs to provide the program simulator (FES), for example for AOCS subsystems in EUCLID [3], and for GNC subsystems in PROBA-3 RVX [4] and IXV [5], in addition to DEIMOS' own programs for AOCS simulators, such as for the DEIMOS satellites programs, and for aeronautical applications (e.g. [6]). SIMPLAT's architecture is outlined in Figure 6. There are six main SW components in the architecture:

- **Simulation Engine**: responsible for the complete definition of a simulation, including the definition of the mission and the configuration of the models to be simulated. It loads the parameters of the mission from the Configuration Data Files (XML files). The parameters of the mission are pre-processed to obtain model and simulation parameters, and the models are configured accordingly by setting their mask parameters. This component also controls the execution of the simulation.
- **Simulation Core**: it is the main block where the numerical integration of the system dynamics is carried-out. In general, it will consist of a Simulink template, which is customized for each operation mode by replacing the applicable models taken from various Simulink libraries.
- **Monte Carlo Simulation**: comprises a number of functions that manage the configuration and control of Monte Carlo simulations. It generates perturbed values of the model parameters (applying dispersions and uncertainties) and controls the storage of the raw data so that they can be further processed.
- **Man Machine Interface (MMI)**: provides user interface functions that give access to the principal functionalities of the simulator, namely simulation, post-processing and visualization. In the case of the GNC FES, the implementation of the MMI is a GUI.
- **Visualization**: its purpose is to generate graphical representations or plots of the simulation raw data and of the post-processed data (system budgets and Figures of Merit). The graphical outputs will be integrated into the MMI for user convenience.
- **Post-Processing**: it provides functions for processing the raw data obtained in the simulations. They will compute system budgets and performance indexes.

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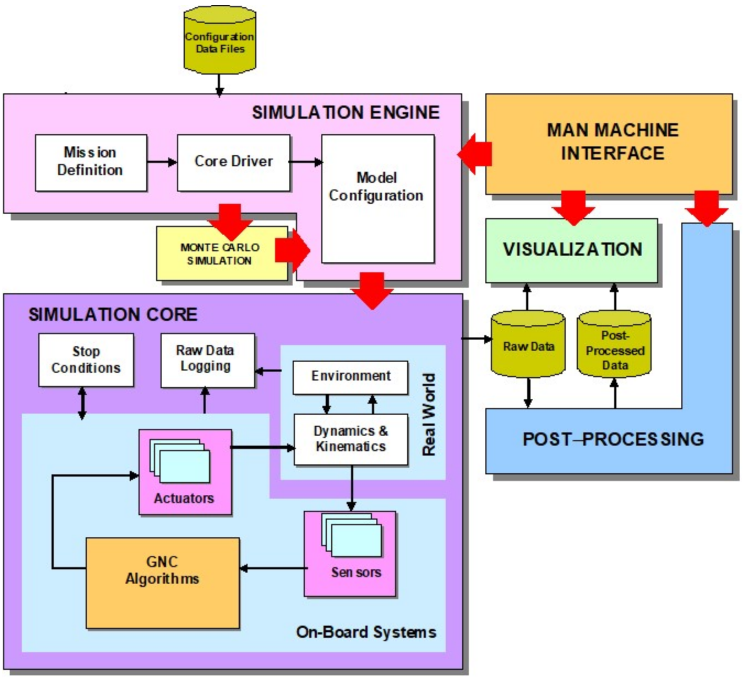

Figure 6: DEIMOS SIMPLAT architecture for EXOMARS 2020 Cruise FES

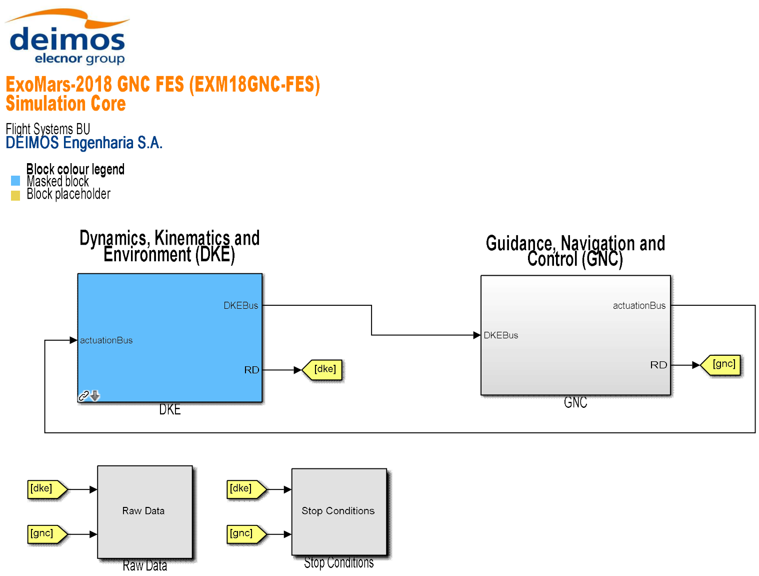

Figure 7: FES architecture for EXOMARS 2020

All the models in the FES have been specified and aim at guaranteeing the highest possible fidelity level between simulation and reality. This is especially true for the sensors and actuator models, which have then been integrated into the Attitude and Orbit Control – Guidance Navigation and Control – Special Check Out Equipment (AOC-GNC SCOE) facility.

The validation of the FES Test-bench software consists of the following tests:

- Unit testing: As the GNC algorithm prototype has to pass through all the testing process, before being integrated in the FES, all the DKE and GNC equipment models specifically developed for the study are subjected to unit testing (covering each major functionality or feature). To this aim, debug signals and

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variables of the models can be accessed if needed. Various pass criteria can be used, depending on the nature of the model under test:
   - Comparison with expected output: in some cases the expected output can be determined by an alternative tool or implementation of the model equations (e.g. J2 gravity equations coded in MATLAB).
   - Comparison with expert opinion: for complex models, when there is not an existing system to compare with, we can rely on the review of the outputs for reasonableness by an expert.
   - Comparison with another model: the model outputs can be compared with the outputs of a similar model (e.g. atmosphere models)
- Integration testing: It is aimed at verifying that the GNC equipment models have been correctly integrated into the FES together with other models. This is mainly applicable to sensor and actuator models. The pass criteria are normally based on the comparison with expected outputs for given input conditions.
- Functional testing: The functional tests are applied to the whole simulator and will be performed in two steps:
   - Open-loop: aimed to verify the correct propagation of the spacecraft dynamics under the effects of the considered perturbations.
   - Closed-loop: intended to check the correct operation of the GNC algorithms in nominal conditions and also with model uncertainties through Monte Carlo simulation.
   -

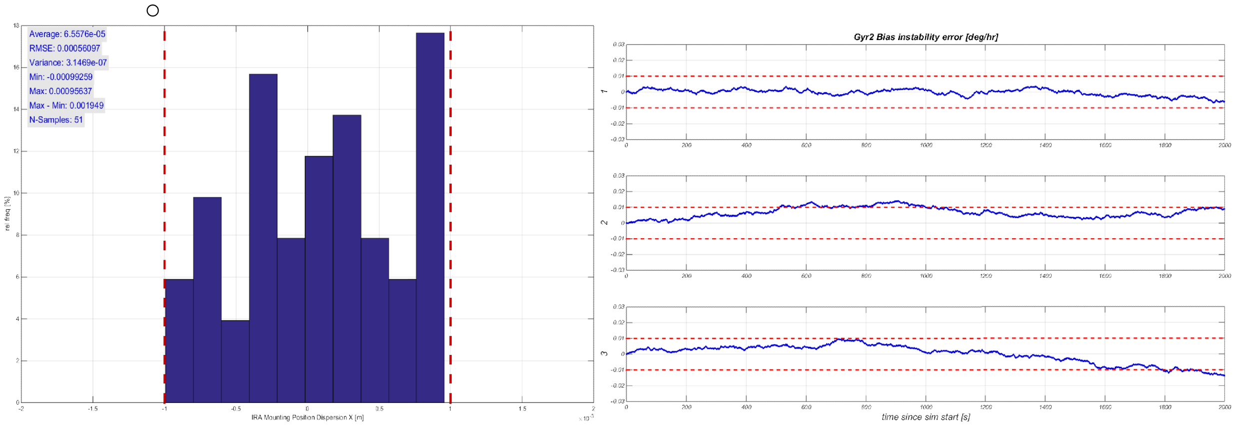

Figure 8: Examples of DKE unit testing, “Comparison with Expected output” type

5. Development of a Cruise GNC Verification Plan and execution of the Verification Campaign in the FES

The FES simulator is used for the following purposes:
- Functional and performance testing of the Cruise GNC algorithms
- Validation of the pointing budget
- Generation of test sequences and pass/fail criteria for subsystem verification.

A limitation which has been identified for FES simulations is related to the capability of performing E2E tests, especially for the cases of parametric analyses (such as Monte Carlo runs). It has been considered that running simulations with total durations of several months (duration of the cruise phase) and high levels of fidelity, leads to prohibitive simulation durations. For this reason, the test plan does not envisage E2E simulations. Instead, those functionalities which need to be tested in the FES are identified a priori, so that batch simulations may be run around the required mission phases.

The following list summarizes some of the main characteristics of the FES:
- Initialization at any stage of the cruise phase. For this purpose, the simulator states need to be specified.
- Parametric configuration of those variables which may introduce uncertainties: separation conditions, MCI, sensor & actuator performance, etc.
- Capability to run batch simulations with statistical parameter variations (Monte Carlo).
- Clear identification of the interfaces between the algorithms which will be a part of the OBSW with sensors & actuators, and also between sensors & actuators and DKE.

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- Capabilities to inject errors in all models in order to trigger the desired mode transitions, and/or FDIR recovery actions.

The analysis of the mission trajectory allowed performing a smart selection of test cases to be simulated, covering all the possible manoeuvring scenarios and functional modes that the GNC may encounter during the Cruise phase, leading to the definition of a certain number of test cases, depending on the possible combination of modes and submodes that may occur.
The main modes foreseen during the Cruise phase are:

- Stand-By Mode (SBM) ;
- Spin-Up Mode (SUM) ;
- Sun Pointing Mode (SPM) ;
- Earth Pointing Mode (EPM) ;
- Delta-V Mode (DVM) ;
- Inertial Pointing Mode (IPM) ;
- Pre-Separation Mode (PSM);
- Safe Mode (SM);
- Survival Mode (SVM).

It is foreseen that, during flight, each mode cannot be reached autonomously, but they will have to be triggered by Telecommand (TC). In the same fashion, many of the parameters can be updated through proper TC in some specific phases of the flight. One of the main difficulties of the V&V campaign preparation has been to identify and replicate the logic of those commands provision, in order to provide a realistic reproduction of what is the real flight expectation.
Sets of Monte Carlo, including all the possible uncertainties and dispersions that have been foreseen for the system, have been run and processed, in order to determine the status of compliance of the applicable requirements, both if they are quantifiable (see Figure 9) or qualitative (see Figure 10).

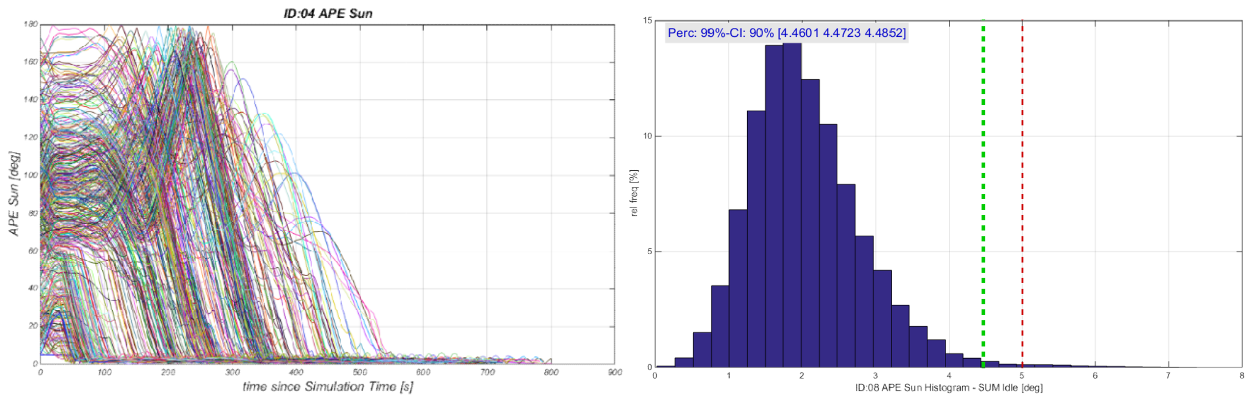

Figure 9: Example of APE behaviour, against time and statistic at required percentile (in green) wrt requirement (in red), for a test scenario.

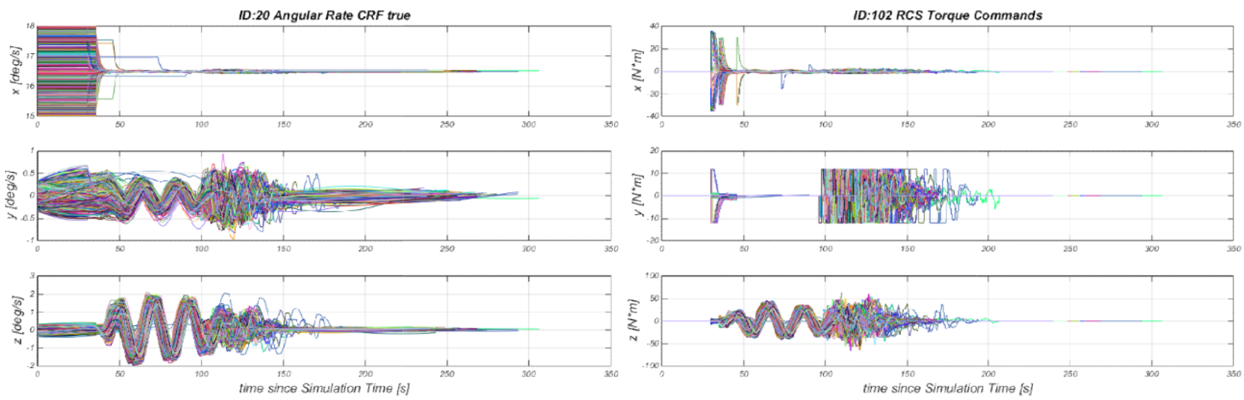

Figure 10: Example of Angular rate behaviour and RCS Torque Commands against time, for a test scenario.

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6. Conclusions

The process put in place for the Cruise GNC algorithm independent V&V campaign, confirms a fruitful collaboration between DEIMOS, with SENER as subcontractor, and TAS-I, and demonstrates the capability of DEIMOS to exploit its GNC and AOCS capabilities in interplanetary missions such as EXOMARS.

The outcomes of the V&V activities were composed of simulation reports and performance assessments, produced for successive versions of the GNC algorithm specification, progressively refined using at first data from requirement specification, then the declared unit performance and finally the measured unit performance. The analysis and simulation results allowed the customer to early identify possible bugs and unexpected problems, timely taking the necessary actions, for example redefining portions of algorithms, introducing protections and timeouts to avoid infinite loops and manoeuvres without a reachable exit condition, retuning GNC parameters, and re-evaluating the logic of some commands to be provided.

Additionally, the SW simulation framework (Cruise GNC FES) proved to be a powerful and flexible tool for the EXOMARS program. The re-use of the well known and consolidated DEIMOS' SIMPLAT infrastructure allowed for the rapid configuration of the EXOMARS 2020 FES at the beginning of the activity, to meet the demanding schedule, while providing a complete simulation environment. The same environment has been able to evolve in a fast and efficient way according to the needs of the program in the successive revisions of the GNC algorithm.

Cruise GNC FES has been demonstrated to be strict and rigorous in terms of validation, but allowing enough particularization to cover the whole range of flight conditions, from the separation of the SCC from the Launch Vehicle, throughout all the Cruise phase, until the CM/DM separation. Furthermore, it permitted efficient selection and investigation of test cases whilst maximizing functional coverage, to support the definition of the test cases to be executed on System Avionics Test Bench (ATB). This will be the last step of the V&V campaign leaded by DEIMOS, prior to the real mission, as the ATB will be the most realistic simulation environment available to this project.

Acknowledgements

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