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The IXV program FES: MIL and SIL simulation environment for GNC design, development and verification

Jose Ospina, Gabriele De Zaiacomo*, Vicente Fernández*, Murray L. Kerr*, V. Marco***
** Deimos Space (murray.kerr@deimos-space.com)*
Ronda de Poniente 19, Edificio Fiteni VI, 28760 Madrid – Spain
*** SENER Ingenieria y Sistemas, 28760 Madrid – Spain*

Abstract
This paper describes the Functional Engineering Simulator (FES) developed for the ESA Intermediate eXperimental Vehicle (IXV) program, and its use in the different program phases, from phase B to phase F. The IXV-FES, a validated tool developed following its own design, development and verification (DDV) plan, was the unique simulation environment for verification of the GNC subsystem by analysis in the IXV program. In particular, with the inability in the IXV program to perform incremental flight envelope testing, and the lack of a safe-mode due to the nature of the sub-orbital flight, extensive simulations of the IXV flight and its GNC were required, both for formal GNC verification, and to support GNC design, development and testing. As such, the IXV-FES played a key role in the IXV program in providing the confidence that the IXV would fly right, first time, and achieve the mission objectives.

1. Introduction

The Intermediate eXperimental Vehicle (IXV) program achieved a major success for Europe, when the IXV was launched on the 11th of February, 2015, and returned to Earth, with a flawless re-entry and recovery. IXV was an ESA re-entry lifting body demonstrator built to verify in-flight the performance of critical re-entry technologies during the re-entry phase ([1],[2]). The IXV´s flight and recovery represents a major step forward with respect to previous European re-entry experience (e.g. [3]). In particular, the increased in-flight manoeuvrability achieved from the lifting body permitted the verification of technologies over a wider re-entry corridor, the re-entry flight from orbital speeds with the lifting body aeroshape was a first for Europe and worldwide, and the combination of thrusters and aerodynamic surfaces for control was a first for Europe.

A key part of the IXV developments and advances was the IXV GNC ([4],[5]). The IXV GNC represents a step forward from previous European GNC solutions for re-entry vehicles. It provided a fully autonomous GNC subsystem that operated during the full sub-orbital flight from the Guiana launch-pad, a few minutes prior to Vega lift-off, to splashdown in the Pacific, through the entire set of flight phases (Figure 1); pre-lift-off, ascent, orbital coasting, re-entry and descent.

In the IXV mission, the re-entry phase was termed the experimental phase, as the key developments in the mission were those tested during the hypersonic and supersonic phases of the re-entry. This entry phase started at the Entry Interface Point (EIP) conditions of altitude 120km and co-rotating velocity of about 7500 m/s (~Mach 25), and terminated shortly after the supersonic drogue opening at Mach 1.5 and an altitude of 27km. The IXV shape and size is as shown in Figure 1. The aeroshape, having no wings, provides a lift-to-drag ratio of about 0.7 in the hypersonic regime. The planned IXV mission is sketched in Figure 1. Its execution was very similar to that planned [7], in terms of timings and the vehicle state.

The IXV GNC included the guidance algorithm for the lifting body, the use of the IMU measurements with GPS updates for navigation, and the flight control by means of a combination aerodynamic flaps and reaction control thrusters ([4],[5],[6]). The need to fly right, first time, played a key role in the IXV program and particularly for the IXV GNC Design Development and Validation (DDV). Due to the inability to perform incremental flight envelope testing, and the lack of a safe-mode, extensive simulations of the IXV GNC were required, both for formal verification and to support GNC design, development and testing. This was performed using a dedicated Functional Engineering Simulator (FES), in the IXV-FES.

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The IXV-FES is a validated tool, which was developed following its own DDV cycle. The IXV FES was developed by DEIMOS for the IXV program [8], using a proprietary simulation environment in SIMPLAT, first in Phase B1, and then it was continually adapted, re-validated and employed in all phases of the program (B1/B2, C, D, E1/E2 and F).

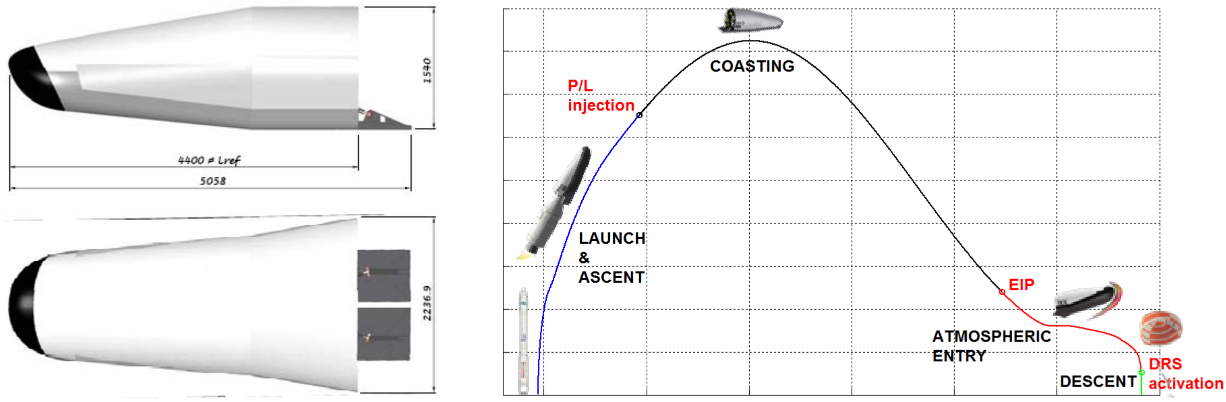

Figure 1: IXV vehicle shape and dimensions (left) and mission overview (right)

This paper presents the IXV-FES and in particular the final configuration of the IXV FES, as achieved at the end of the IXV program in phases D, E and F, where it provides both model-in-the-loop (MIL) and software-in-the-loop (SIL) simulation capabilities and supports ongoing post-flight analyses. This paper focuses on the IXV FES' role in phases D, E and F of the program, its different configurations for GNC requirements verification and GNC flying qualities worst case and stress testing, and in particular its SIL configuration, which was a novel and highly valued contribution to the program. Notably, a SIL configuration of the FES developed and verified as part of the IXV FES DDV activities. This was comprised of the implementation of the GNC ASW for the GNC modules (see Figure 2) within the IXV FES. This SIL IXV FES configuration follows recent ECSS recommendations (see ECSS-E-ST-60-30C, Section 5.4.3, Note 3), and was found to be a key tool and verification environment for the program.

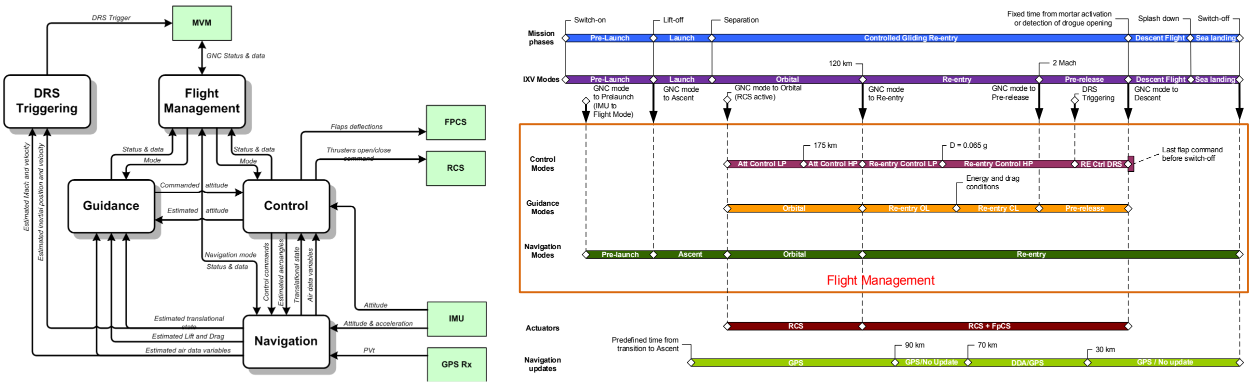

Figure 2: (left) IXV GNC functional architecture and (right) IXV phases and GNC modes

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1. IXV FES Role in the IXV Program

The basic purpose of the IXV-FES for IXV activities from phase B to E was twofold:

- To serve as the representative test and simulation environment for the IXV GNC, supporting the design and assessment, including formal verification, of the GNC subsystem and its algorithms.
- To support the definition and serve as the source of models for the real-time test bench (RTTB) and test environment facility (TEF), in which to validate the real-time performances of the on-board GNC system.

A further purpose of the IXV-FES for phase E2/F is to support post-flight analysis activities, via a tool to integrate, visualise and compare the IXV post-flight data, for what relates GNC activities, and to reconstruct the GNC outputs for such purposes.

The IXV-FES tool and simulator was designed to support and enable the IXV GNC engineering activities through the B, C, D and E phases of the IXV project life cycle [9], as per its specification. The IXV-FES tool, models, simulations and verification results and their statistics, were used throughout the project life cycle in different ways, depending on the active phase (see also [8]):

- **B2/C1 Phase:** the first fully functional release of the IXV-FES (V2.1), as a MIL simulator, was provided in this phase. This was used to validate the performance of the GNC preliminary design at S/SPDR.

- **C2 Phase:** the IXV-FES was used during the consolidation phase in support of the design and evaluation of the new GNC baseline at the consolidation key point (CKP). The FES supported the detailed design of the GNC subsystem and was upgraded for the validation of the GNC performance at the S/SCDR. Furthermore, at the end of phase C2, the FES evolved to generate, by autocoding, the dynamic and environmental models for the Real-Time Test Bench (RTTB), where the real-time performance of the GNC was pre-validated.
  In phase C2 the FES also supported the vehicle model identification (VMI) activities, and the specification of the GNC units.

- **D Phase**: during phase D the IXV-FES evolved to include the measured performance of the GNC units, and to provide both a MIL and SIL simulation environment, with the inclusion of the GNC ASW in the IXV-FES using the retrofitting process. The SIL IXV-FES version supported the verification of the GNC at each tuning loop in phase D, and the qualification and acceptance of the of the GNC subsystem as part of the subsystem and system QRs.
  In phase D (and phase E), the IXV-FES also supported the OBSW SVF and GNC SCOE facilities, providing the DKE and units models, which were auto-coded to provide the simulation environment for both facilities. The IXV-FES was used also to generate reference cases for the verification of the GNC ASW against its specification.
  In phase D, the IXV-FES also supported the final specification and verification of the GNC units.

- **E Phase:** during phase E the IXV-FES was used exclusively in its SIL configuration. This configuration was updated for the different GNC ASW versions, and for their flight parameters, that resulted from the final GNC tunings. The IXV-FES was also updated for the final flight units measured parameters, and the environmental parameters for the day of the flight. These IXV-FES versions served for regression testing, to assure the verified status of the GNC prior to flight, and to predict the GNC flight performances.

- **F Phase:** In addition to the B to E phases, for which the IXV-FES was designed to support via its specification, the IXV-FES has also played a key role in the post-flight analyses performed, following the successful IXV flight in February of 2015. This role continues to date (see, e.g. [6],[14]).

Throughout these phases of the program, the IVX-FES and its models were adapted and matured following the increasing maturity of the vehicle and GNC design, to arrive at a very high fidelity tool at the end of the program. Subsequently multiple releases of the IXV-FES were provided, from V2.1 in Phase B to V2.13 in phase E, with the IXV-FES serving as a key tool both for the GNC DDV and to support the IXV system activities.

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2. IXV FES Description

a. FES ARCHITECTURE

To meet the needs of the IXV program over the different phases (B to E) for which the IXV-FES was designed, and in an efficient manner to meet the program needs and constraints, a DEIMOS internal software infrastructure called SIMPLAT was employed to provide the basis for the IXV-FES. The SIMPLAT architecture was selected for the simulator (see Figure 3), which allowed for a fast sequence of product deliveries at the beginning of the program in phase B, while also supporting the evolution of the IXV-FES for the remainder of the program phases.

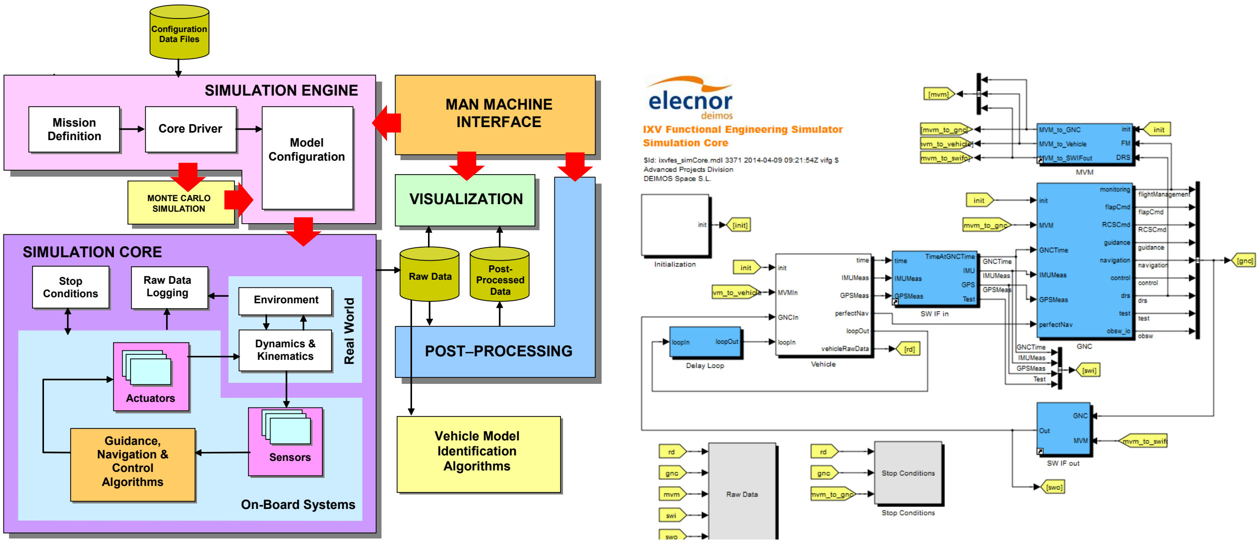

Figure 3: (left) IXV-FES software architecture, layout and features, and (right) its MATLAB/Simulink implementation of the IXV-FES (MIL version) within the simulation core layout

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 [10] and EXOMARS 2020, and for GNC subsystems in PROBA-3 RVX [11] and IXV [8], in addition to DEIMOS' own programs for AOCS simulators, such as for the DEIMOS satellites programs, and simulators for aeronautical applications (e.g. [12]).

The SIMPLAT infrastructure is based on the MATLAB™/Simulink™ modelling & simulation environment and provides all the basic functionalities needed by a FES tool, so that project-specific elements can be rapidly built on top of it. SIMPLAT operation largely relies on its XML database, which stores model, scenario and simulation parameters. SIMPLAT includes Monte Carlo simulation and analysis capabilities and many generic toolboxes and blocksets. The implementation in MATLAB/Simulink permits faster than real-time simulation, as necessary for extensive Monte Carlo simulation, for the verification of statistical performance requirements.

The main components of the FES architecture are the following ones:

- Simulation Engine: responsible for the complete definition of a simulation scenario, 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 represents where the numerical integration of the system dynamics is carried-out. In general, it consists of a Simulink template, which is customized for each operation mode by replacing the applicable models taken from various Simulink libraries.

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- 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.
- 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 menu-based 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 are integrated into the MMI for user convenience.
- Post-Processing: it provides functions for processing the raw data obtained in the simulations. They compute system budgets and performance indexes.

b. FES FEATURES AND DESIGN

The IXV-FES software design was performed so as to meet the IXV program needs in all program phases, as reflected in the IXV-FES specification. Specific features were inspired by the objectives of the project and the intended use of the simulator, always within the context of maximum cost-effectiveness and adherence to the project schedule. The basic features are.

- Representative numerical end-to-end simulation environment of the IXV mission and its GNC
- Validation and performance assessment of GNC algorithms
- Validation and assessment of VMI (Vehicle Model Identification) and other on-board algorithms
- High fidelity environment supporting GNC units specification and assessment
- Autocoding-ready modelling for real-time assessments during verification campaign

The main capabilities of the IXV-FES that supported the latter Phase D and E activities of the IXV program are:

- Multiple phase End-to-End simulation from Vega separation to supersonic DRS triggering in 6DOF, followed by 3DOF for descent until splashdown under parachutes, including:
  - Simulation of the GNC and Flight Management
  - Simulation of DRS triggering algorithm, as part of the GNC
  - Emulation of the SW scheduling of GNC-FM and avionics delays
- Monte Carlo simulation and automatic analysis
- Stress Cases simulation and automatic analysis
- Flying qualities Worst Cases (FQWCs) simulation and automatic analysis
- Automatic post-processing of simulation outputs and generation of figures of merit (see Figure 4), including:
  - Automatic generation of simulation output plots defined in the XML database.
  - Automatic statistical analysis, for Monte Carlo simulations.
  - Automatic computation of figures of merit (FOM): maximum, time of occurrence, condition, duration. The simulator can generate FOM reports.
- User defined plots and post-processing functions.
- XML database for simulator and model configuration
- High fidelity simulation models, including:
  - Detailed environmental models: atmosphere, winds, wind turbulences, gravitational harmonics
  - Detailed Mass, CoG & Inertia (MCI) model, including TPS and fuel consumption models
  - Detailed IXV vehicle hypersonic and supersonic/transonic aerodynamic (AEDB) data set
  - Detailed GNC actuator and sensor models: flap actuator, RCS, IMU, GPS (inc blackout)
  - Detailed DRS models
- Rapid simulation mode (auto-coding to Rsim target executable) for efficient Monte Carlo simulation. This feature significantly shortens the required simulation time, which is extremely useful for the Monte Carlo analyses performed in the multiple design loops.
- Auto-coding compliant

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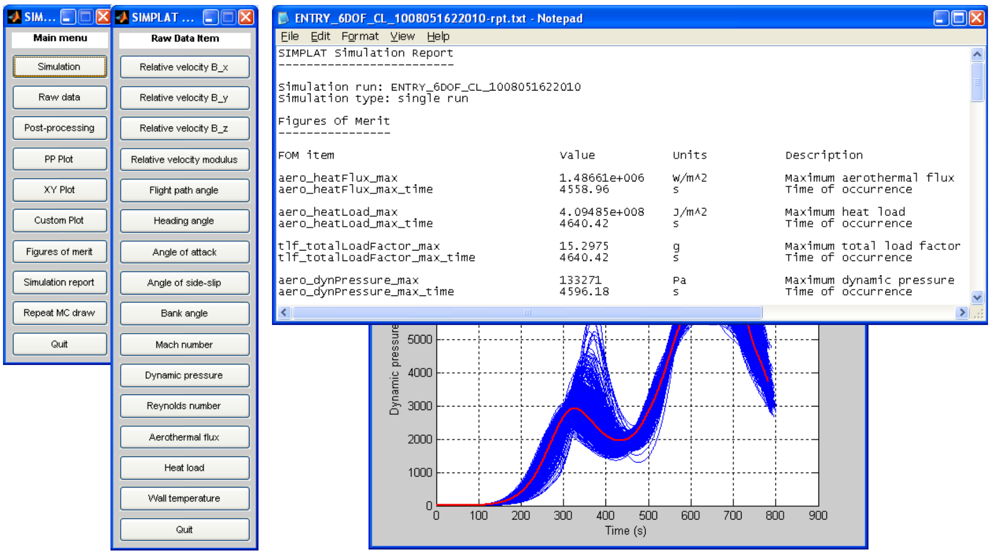

Figure 4: IXV-FES MMI and results

In addition to these capabilities, that supported the latter Phase D and E activities of the IXV program, the IXV-FES is being extended in the post-flight phase of the program to include additional capabilities to support GNC post-flight analysis. These extensions are shown in green in Figure 5, and will allow deeper analysis of the GNC's flight performance and its comparison to the flight predictions and re-predictions. It will provide the capability to integrate, visualise and compare (with predicted data) the IXV flight data, for what relates GNC activities for the following basic features. These capabilities are:

- A post-flight analysis simulation core, comprised of a zero DOF FES configuration. This zero DOF configuration will contain the GNC algorithms only in the OBSW retrofitted form.
- The ability to integrate the flight recorded GNC inputs and outputs in the FES using the post-flight analysis simulation core. This will enable their storage in the raw data format of the IXV-FES, permitting the visualisation and post-processing of the flight data using the established IXV-FES capabilities.
- The ability to stimulate the GNC algorithm, being the retrofitted OBSW with the flight GNC parameters, with the flight recorded GNC inputs. This will enable the re-generation (reconstruction) of the GNC outputs, over all the flight phases where GNC is active (pre-launch, ascent, orbital, re-entry and descent). It will also enable the storage of internal variables, signals and states of the GNC algorithm, beyond those available from the flight GNC outputs recorded in the telemetry, giving the potential for deep quantitative investigations for what concerns GNC performance in-flight
- A flight data comparison function, giving the ability to compare the flight GNC data (signals and states), with the same data generated by the IXV-FES via simulation. This can be used for visual inspection and also flight animation. Additionally, the ability to determine the difference between such data is considered a key asset for the quantification of the behaviour of the GNC in-flight against the predicted behaviour.

Figure 5 below shows the processes and capabilities that will be provided in the IXV-FES with these upgrades for post-flight analysis. The existing processes, being simulation multi configuration (via xml), simulation (6DOF, 3DOF) and raw data storage, processing and visualisation, are highlighted in blue. The new capabilities are highlighted green.

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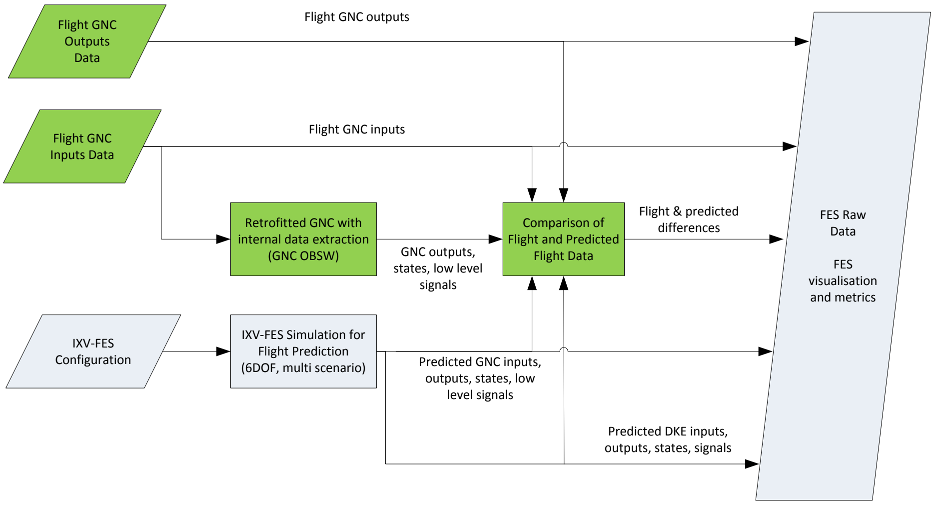

Figure 5: IXV FES Updates (Green) to support post-flight analysis activities: Flight GNC Data input and output integration, outputs reconstruction based on flight GNC inputs, and the comparison of predicted and flight GNC data

c. FES Basic Models

The specifications for the models in the IXV-FES either formed part of the FES specification, or were based on CFIs information from either the requirements for the GNC units or from their declared/measured performance from the unit suppliers.

The FES includes the following environment and vehicle models:

- Equations of motion: 3-DOF and 6-DOF dynamics.
- Atmosphere model: tabular models based on the USSA-1976 and NRLSISE00 models, including atmospheric dispersions, taking into account temporal and spatial variability with respect to the reference splashdown site and time.
- Wind model: the user can select two models. The tabulated wind model is a horizontal wind model based on a look-up table where wind speed components are interpolated as a function of the altitude. Wind nominal and dispersed values are derived from the HWM93/07 models taking also into account the Quasi-Biennial-Oscillation (QBO) phenomenon. The turbulent wind model implements a spectral representation of continuous wind turbulence similar to the Dryden model.
- Gravity model: takes into account the J2 zonal harmonic term.
- Force and moment perturbations: this model allows the injection of force and moment perturbation profiles as a function of the flight time, representing perturbations due to unmodelled effects, e.g. mortar firing.
- IXV aerodynamic database: full AEDB model for the vehicle, including flow field interaction effects and the blending of continuous and rarefied AEDB models.
- Mass centring and inertia (MCI): the total mass of the vehicle varies as the RCS propellant and TPS is consumed, in addition to outgassing. The position of the centre of gravity and the inertia matrix are interpolated in a look-up table as a function of the total mass.
- Reaction Control System (RCS): this actuator model receives on/off commands and considers various non-ideal effects like varied fuel consumption rates, minimum impulse bit, response delay, maximum thrust depending on the static pressure of the propellant tank, plume effects modelled as output moment uncertainty. It also includes the measured mounting and final individual unit performances.
- Flaps: the flap actuator model takes into account saturations, maximum deflection rates, bias, dead zone, hysteresis, response dynamics, and the change in the dynamic response with the change in hinge load.
- Inertial Measurement Unit (IMU): the IMU sensor model produces velocity increments and attitude measurements, taking into account misalignment, scale factor error, bias, noise, delay and quantization.
- Global Positioning System (GPS): the GPS model is a performance model based on adding bias, noise and quantization effects to the ideal measurements. It importantly models the time delays the different PVT signals.

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- OBDH: the FES includes an emulation of the different on-board times (e.g. OBET, GPS), the different delays in the sensor and on-board data acquisition, and the OBSW scheduling of the different GNC functions are their operating frequency, and delays coming from the actuator synchronous and asynchronous commands.

A Simulink modelling requirement included in the FES development specification was that the initialisation and treatment parts of the models had to be separated. This requirement facilitated the autocoding of the models for real-time assessment. Consequently, all the models were provided with initialisation blocks that define the model parameters and constants, which are wired through signal buses to the treatment parts of the models.

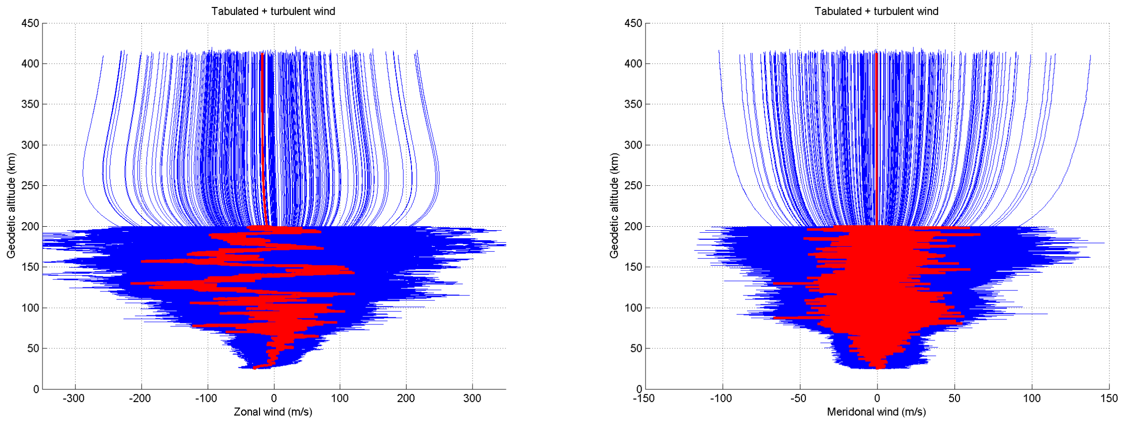

Figure 6: IXV atmosphere winds models, with turbulence added below 200km altitude

d. SIL Version

During phase D of the IXV program, a SIL version of the IXV-FES was developed, in which the code of the GNC algorithms, as implemented in the IXV on-board software (OBSW), was retrofitted in the GNC portion of the IXV-FES, to permit software-in-the-loop (SIL) GNC simulations. The GNC ASW was developed by an IXV third-party contractor, as part of the overall OBSW development, based on the control algorithm specification (CAS) developed by the IXV GNC core team. Notably, thanks to the modular design of the GNC ASW, following the GNC CAS, a SIL configuration within the FES was possible, and was performed and verified as part of the IXV FES DDV activities under DEIMOS responsibility.

The retrofitting process to construct the SIL version of the IXV-FES consisted in extracting the higher level GNC functions from the OBSW GNC ASW and implementing them in MATLAB/Simulink as MEX S-Functions (see Figure 7). This was comprised of the implementation of the GNC ASW for each of the five main GNC modules (G, N, C, FM, DRS triggering) within the IXV FES, without modification in any way (see Figure 8). The extraction process is shown in Figure 7, where it can be seen that only the GNC algorithms were extracted from the GNC ASW, while other portions of the OBSW, related to task call-back functions, and proper of OBC execution and real time operating systems, were not extracted, but rather functionally recreated in the IXV-FES. The simulation core with this SIL is shown in Figure 8. In addition, the retrofitting process included the extraction and manipulation of OBSW data structures needed by the GNC algorithms to store the parameters and states, and to transfer data from one function to another.

Through the migration of the FES to a Linux environment, this further allowed to compile and use the GNC ASW with the same basic mathematical routines as used in the flight SW. This further improved the representatively of the SIL environment.

The correct retrofitting of the GNC algorithms was validated by running the CAS reference test cases with the retrofitted MEX S-Functions. The correct initialization of the parameters and states was validated by comparing the parameter and states values used by the GNC algorithms at runtime with the CAS specification.

The SIL IXV-FES configuration follows recent ECSS recommendations (see ECSS-E-ST-60-30C, Section 5.4.3, Note 3), and was found to be a key tool and environment, supporting GNC verification in phases D and E, flight prediction in

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phase E and post-flight analysis in phase F. Figure 10 highlights the link between the OBSW development and its retrofitting in the FES to give the IXV-FES SIL version.

Notably the SIL IXV-FES version was the only AIT facility that permitted extensive simulation campaigns (e.g. Monte-Carlo) running the GNC ASW in its flight version, with the flight parameters. Hence it was the tool that provided confidence in the IXV GNC performance in flight, in the days leading up to the flight.

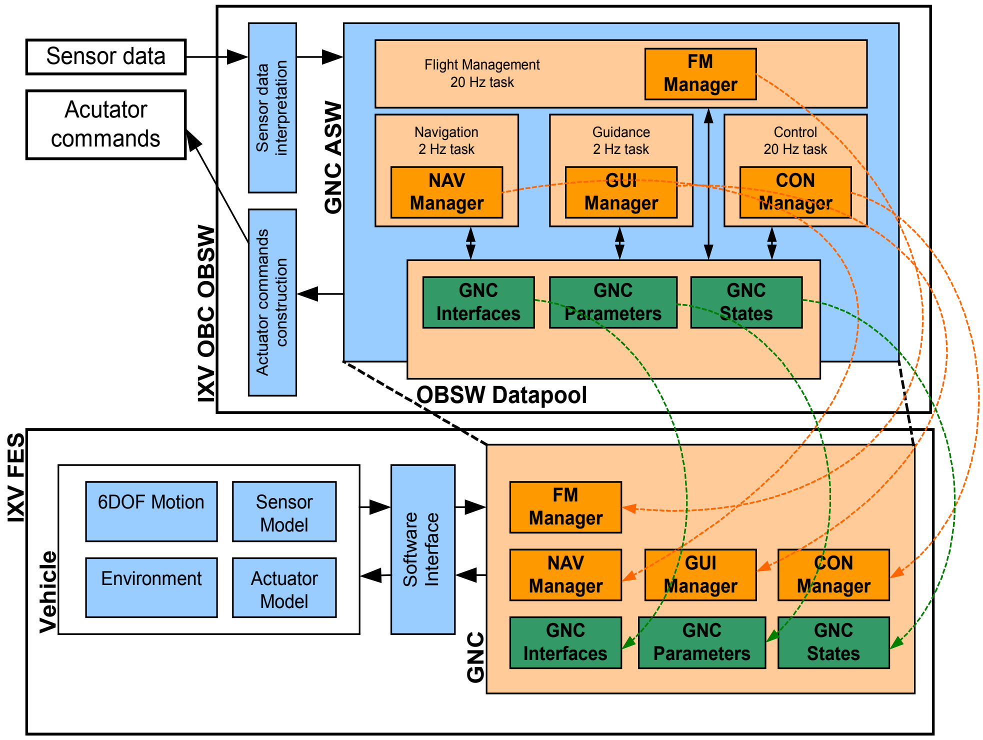

Figure 7: Retrofitting of the GNC ASW from the IXV OBSW to the IXV-FES SIL version

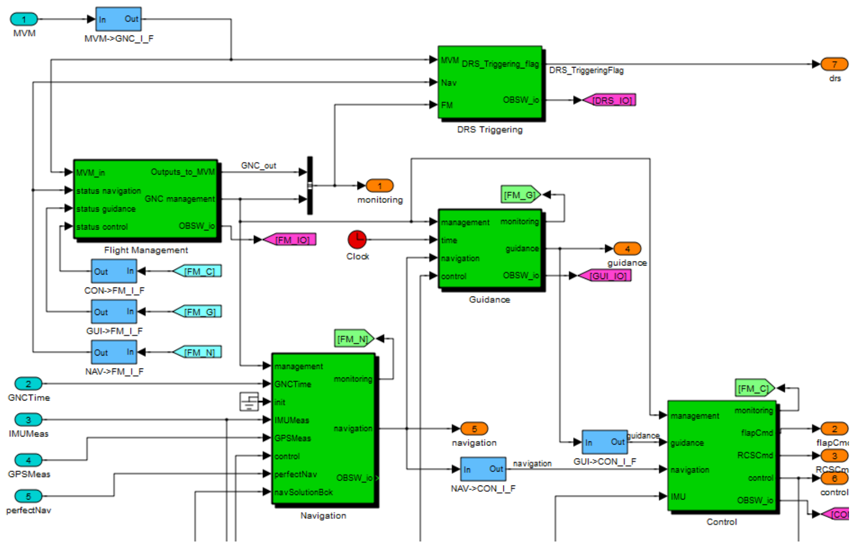

Figure 8: MATLAB/Simulink implementation of the IXV GNC ASW within the IXV-FES (SIL version). GNC ASW MEX S-Functions shown in green

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3. IXV FES DDV

The IXV-FES was specified, designed, verified, validated and accepted during Phase B, in order to serve Phase C and the later program phases for GNC verification and validation activities. Its SW Development Plan was proposed and followed during the Phase B, and repeated in subsequent phases.

That is, within the frame of the IXV Phase B/C1 activity, the IXV-FES underwent a systematic verification and validation campaign. The applied software verification and validation plan comprised of the unit testing of all the IXV models, and the functional validation of the simulator, with respect to the reference trajectory generated by an external trajectory optimisation tool.

Figure 9 presents the FES development logic followed in Phase B to reach an IXV-FES fully validated tool, following an agreed ECSS tailoring in terms of SW documentation followed during the IXV-FES development and qualification. Please note that the FES QR was performed against the technical spec and the FES AR was performed against the requirements baseline.

The IXV-FES simulator was validated according to a thorough Software Verification and Validation Plan. The plan complies with the ECSS-E-40 standard and comprises the following test designs:

- Model Test Design: unit testing of all the vehicle and environment models with the exception of the aerodynamic database model, which was already validated.
- FES Unit Test Design: unit testing of the project-specific toolboxes of MATLAB functions (e.g. the rigid body kinematics toolbox).
- FES Functional Test Design: functional validation of the simulator with respect to the IXV reference trajectory in open-loop, testing the capability of the FES to reproduce it.
- FES Integration Test Design: validation of the correct integration of GNC-relevant IXV models (e.g. RCS, flaps) into the FES.
- FES System Test Design: system tests for validation with respect to the Technical Specification.
- FES Regression Test Design: selection of tests to be re-run for the detection of regression errors.

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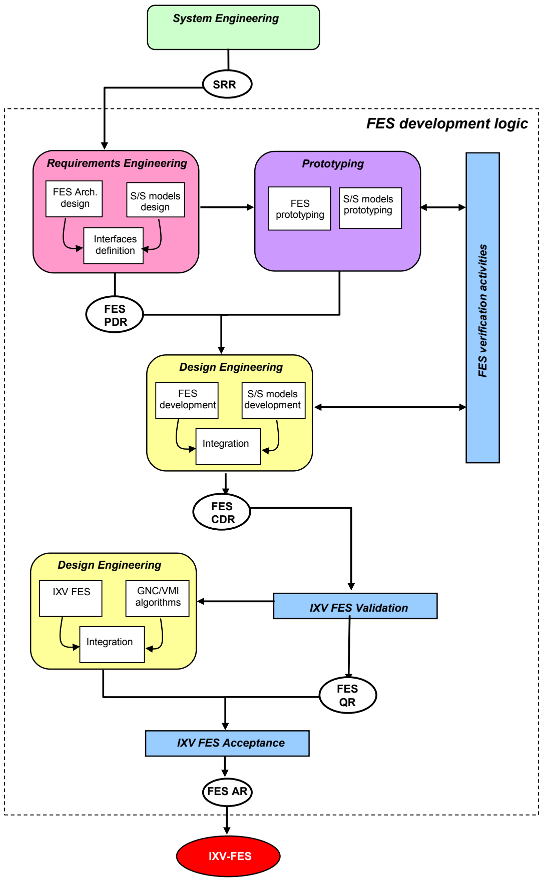

Figure 9: IXV-FES development cycle, showing the tailored development process for the FES in IXV

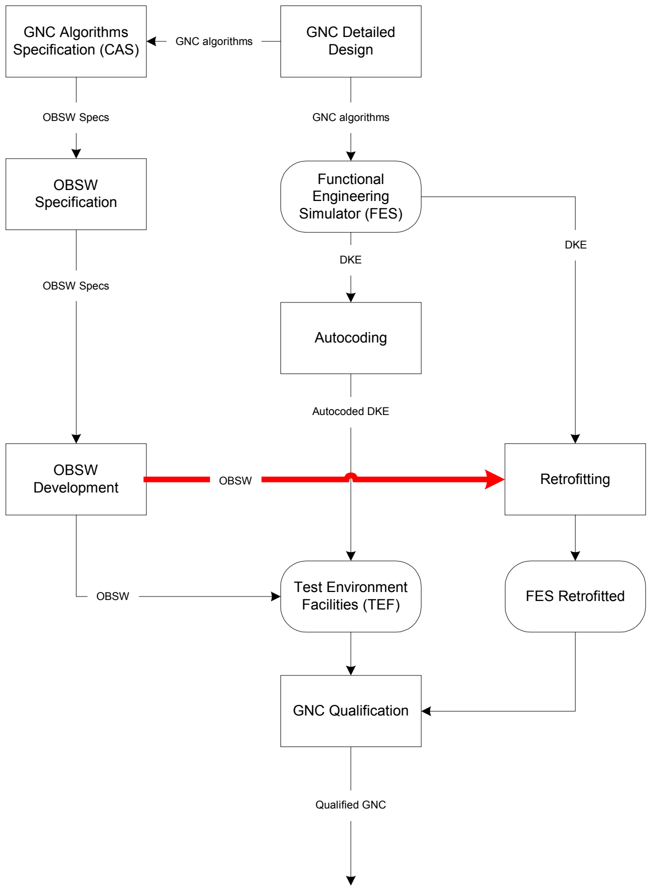

Figure 10: Highlight of the OBSW Retro-fitting in the IXV GNC and SW development cycle

4. IXV-FES for GNC Verification and Validation

The IXV-FES was used in phases C, D and E for formal verification of the GNC against is requirements. This section provides an example of the types of outputs and metrics provided by the tool for this purpose (see Figure 11to Figure 14), using as the example the SIL IXV-FES results from the final verification campaign performed in Phase E, shortly prior to the IXV flight.

In the final phase prior to flight (Phase E of the IXV program), it was necessary to both perform regression testing to ensure the verified status of the GNC, with its final flight parameters, remained valid and also to verify the correct functioning of the SW versions prior to flight, using the different OBSW parameters and states (P&S) for the GNC in the SIL IXV-FES. In particular, testing was performed with five different OBSW P&S for the GNC, tailored to the five different GNC parameters chosen to cover the range of wind scenarios that was considered as possible on the day of flight.

Moreover, these pre-flight verification activities had to be carried out under tight time constraints. This was successfully achieved thanks to abovementioned automatization of FES simulation and analysis processes.

For this verification, the following simulation campaigns were employed, as shown in Table 1.

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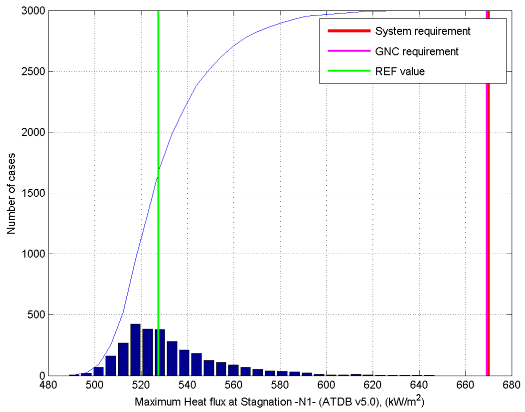
Table 1: IXV-FES Simulation Campaigns for GNC V&V in Phase E

	Description	# Shots	GNC Requirements Applicable
Requirements Verification in Baseline Configurations			
Monte-Carlo E2E 6DOF	6DOF simulation from Vega separation to Supersonic Chute, 2 GPS updates All dispersions in design range	3000	Yes
Monte-Carlo E2E 6/3DOF	6DOF simulation from Vega separation to Supersonic Chute, plus 3DOF simulation to splashdown, 2 GPS updates All dispersions in design range	100	Yes (for descent phase)
Monte-Carlo E2E 6DOF Predicted Winds	6DOF simulation from Vega separation to Supersonic Chute, 2 GPS updates All dispersions in design range On-board wind profile fixed to most probable	1000	Yes
Requirements Verification in Stress Case			
Monte-Carlo Re-entry Stress Case - AEDB	6DOF simulation from EIP to Supersonic Chute, No GPS updates All dispersions in design range, except AEDB dispersions increased by 50%	200	Yes
Monte-Carlo Re-entry Stress Case - MCI	6DOF simulation from EIP to Supersonic Chute, No GPS updates All dispersions in design range, except MCI dispersions increased by 50%	200	
OBSW Versions for Onboard Wind Tables Check			
Winds Grid E2E 6DOF OB wind tables #1	6DOF simulation from Vega separation to Supersonic Chute, 2 GPS updates All dispersions in design range, expect that winds are swept in a grid of 5x5 for the {±3, ±2, ±1}-σ dispersion	25	No (only comparison to baseline)
Winds Grid E2E 6DOF OB wind tables #6		25	
Winds Grid E2E 6DOF OB wind tables #7		25	
Winds Grid E2E 6DOF OB wind tables #8		25	
Winds Grid E2E 6DOF OB wind tables #9		25	



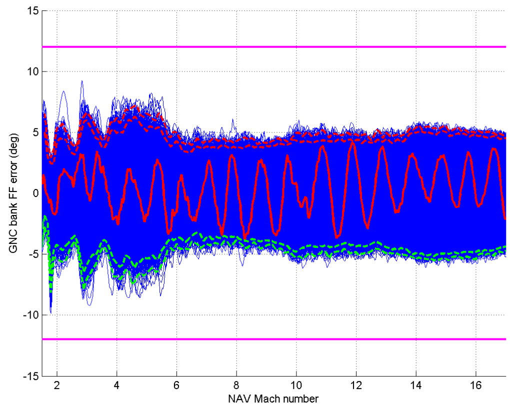


Figure 11: Phase E IXV GNC verification: examples from the Monte-Carlo E2E 6DOF (MC 3000, baseline configuration); (left) histogram and cumulative distribution of the heat flux at stagnation vs. requirement, (right) bank angle tracking error during re-entry vs. requirement, showing Monte-Carlo shots with overlaid (99%,90CI) lines

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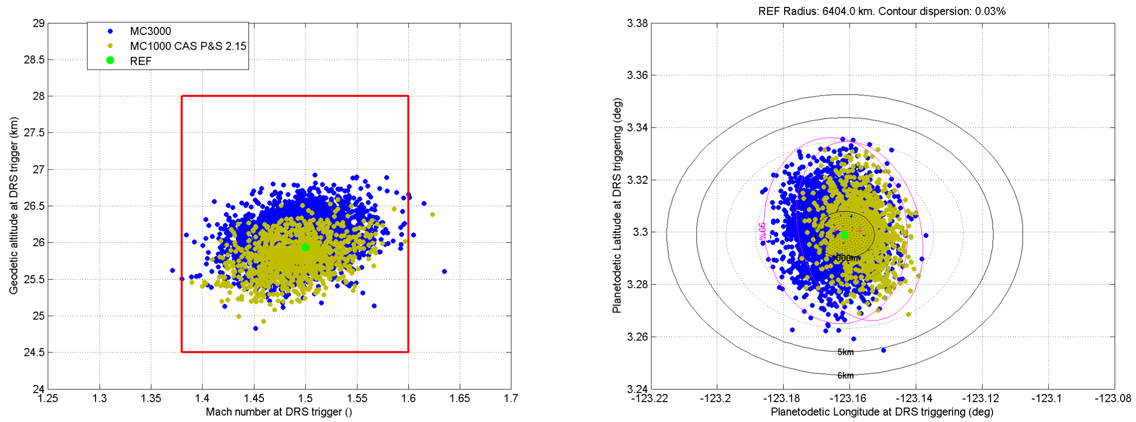

Figure 12: Phase E IXV GNC verification: examples from the Monte-Carlo E2E 6DOF Predicted Winds (MC 1000, baseline configuration), compared to the Monte-Carlo E2E 6DOF (MC 3000, baseline configuration); (left) Real Mach vs. Geodetic altitude at DRS triggering, and the constraint box, (right) position accuracy (with respect to target) at descent recovery system (DRS) triggering

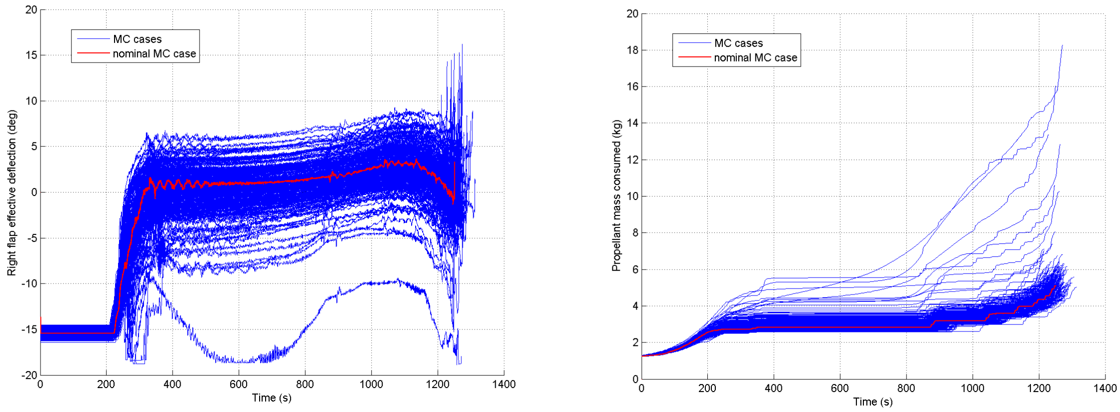

Figure 13: Phase E IXV GNC verification: examples from the Monte-Carlo Re-entry Stress Case - AEDB (MC 200, 50% increase in AEDB dispersions); (left) flap deflection in extreme trim cases, showing correct handling of aero surface saturations, (right) fuel consumption within the requirement in extreme trim cases

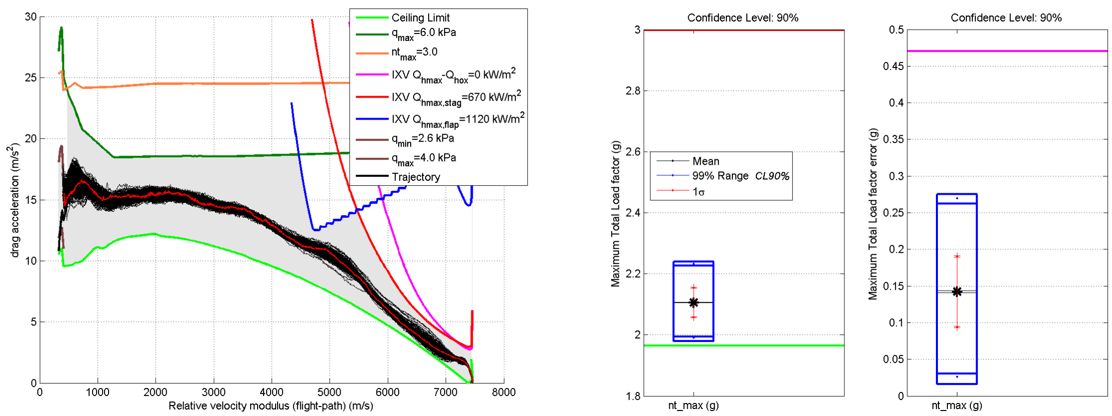

Figure 14: Phase E IXV GNC verification: (left) drag profile vs. re-entry corridor mission constraints for Monte-Carlo Re-entry Stress Case - AEDB, (right) total load factor statistics vs. constraints for Monte-Carlo E2E 6DOF

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5. IXV-FES for Flight Prediction and to Support Post-flight Analysis

The IXV-FES supported in Phase E the prediction of the IXV flight, using the models and data for the day of the flight. It has also supported since the IXV flight in February 2015, post-flight analysis activities, especially those focused on the GNC. In particular, it is the unique facility used to support the post-flight analysis of the GNC, including the re-prediction of the flight ([6],[13],[14]).

This section provides an example of the types of outputs and metrics provided by the tool for this purpose of flight prediction, re-prediction and post-flight analysis, using the SIL IXV-FES, complemented with additional features to support the post-flight analysis, as per Figure 5. Figure 15 (left) shows the trim performance seen in-flight versus that predicted prior to flight. Figure 15 (right) shows the internal components of the flap (trim) commands, reconstructed post-flight to support the analysis. Figure 16 (left) shows the guidance (GNC) bank commands seen in-flight, versus that predicted prior to flight, and that re-predicted using updated initial conditions at the EIP for the latitude and longitude, and the fuel consumption. Figure 16 (right) shows the on-board drag profile generated on-board in-flight, versus that predicted prior to flight, and that re-predicted using updated initial conditions at the EIP. Figure 17 shows the controller tracking errors during the low performance and high performance phases of the re-entry flight, for that in-flight, that predicted prior to flight and that re-predicted post-flight.

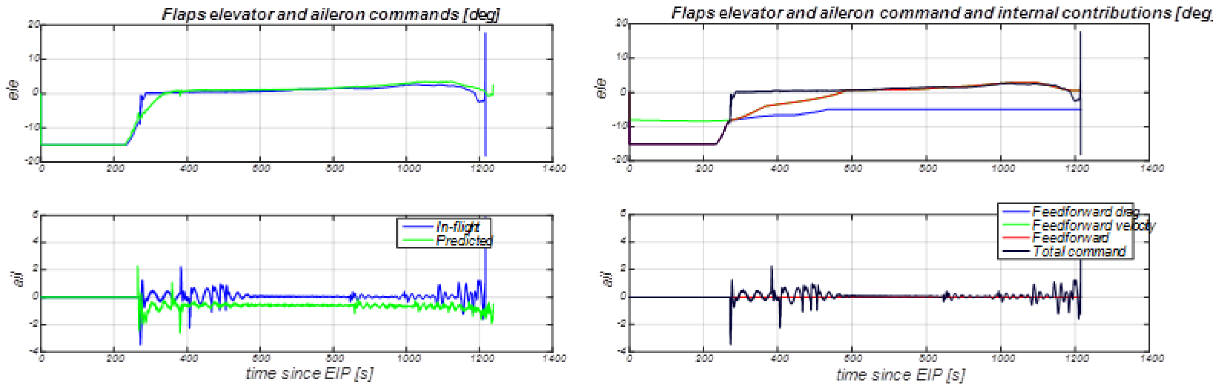

Figure 15: Phase F IXV flight prediction and flight results: (left) Re-entry controller flap trim command vs. that predicted, and (right) the contributors to the trim on-board controller trim command, showing the correct functioning of the on-board trim and small differences to the expected flaps trim values [6]

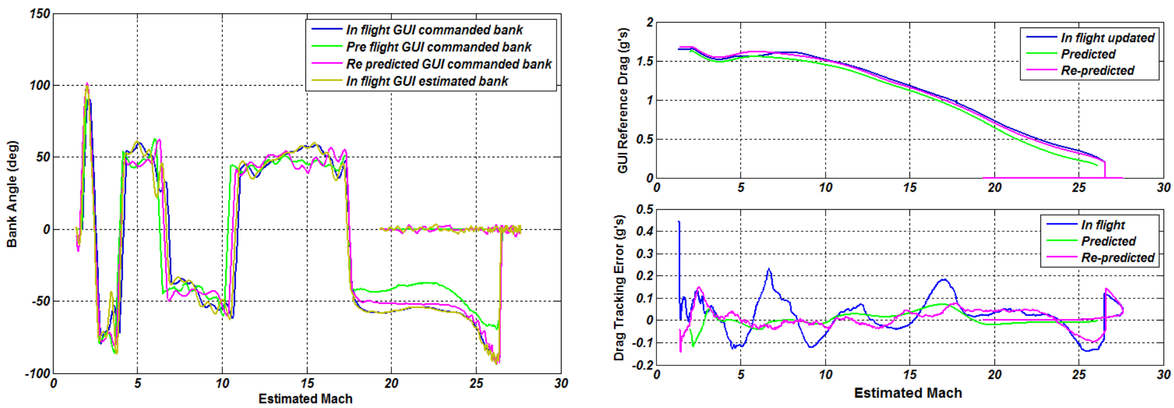

Figure 16: Phase F IXV flight prediction, re-prediction and flight results: (left) Guidance bank commanded, bank angle flown by the Control and that predicted and re-predicted to be flown, (right) Guidance drag tracking: reference drag profile, on board updated, predicted and re-predicted

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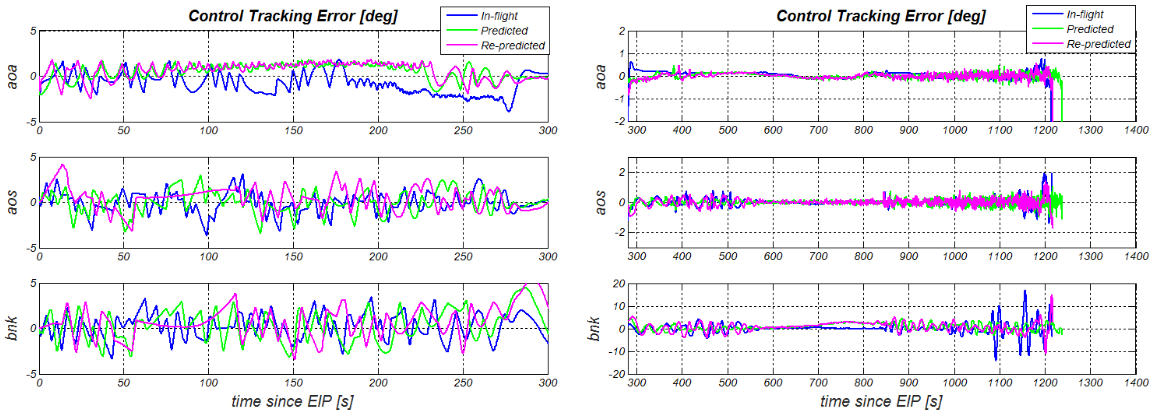

Figure 17: Phase F IXV flight prediction, re-prediction and flight results: (left) Low Performance re-entry control phase and (right) High Performance re-entry control phase Angle-of-attack, Angle-of-sideslip, and Bank angle tracking error flown, predicted and re-predicted to be flown

6. Conclusions

The IXV-FES served the ESA IXV program from Phase B to Phase F, with its use on-going in post-flight analyses. Two versions of the IXV-FES were used in the IXV program; MIL for early GNC design, prototyping and verification activities, and SIL for the final verification, qualification and acceptance of the GNC, and for the flight predictions and post-flight analyses. The IXV-FES was the unique tool to support verification by analysis of the GNC, and the only AIT tool in the IXV program that permitted the extensive validation of the GNC ASW, through Monte-Carlo campaigns using the GNC flight software in its final configuration prior to flight.

The IXV-FES proved to be a powerful and flexible tool for the IXV program. It met fully the challenging needs of the IXV program, that covers a very high range of flight conditions, from atmospheric ascent (launch), exoatmospheric costing and pointing (orbital arc), hyper and supersonic flight (reentry) and subsonic flight under chutes (descent and splashdown).

The re-use of DEIMOS' SIMPLAT infrastructure provided for the rapid configuration of the IXV-FES in the early program phases, to meet the demanding schedule, while providing a complete simulation environment that was able to evolve to the needs of the program in all the final phases (D, E and F), where it incorporated the GNC units measured performances and the final IXV parameters.

The IXV-FES was a key tool in the design, development and verification cycle of the IXV GNC. It also provided key outputs for other AIT tools (SVF and GNC SCOE) and insights into the performance and adequacy of the GNC ASW, through the testing of the GNC Application Software (ASW) in the IXV-FES SIL version.

On-going activities also show the flexibility of the tool, in supporting post-flight analysis activities for the analysis and re-prediction of the IXV flight.

The IXV-FES, and its DDV approach, in their now "flight qualified" status, provide a solid basis for future European atmospheric flight activities. This is of importance for current and future European GNC activities, such as SPACE RIDER, which takes as a basis many of the European technologies, tools and processes developed and proven in IXV, including the IXV-FES.

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