IXV GNC VERIFICATION FROM INSPECTION TO FLIGHT DEMONSTRATION

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ABSTRACT

The Guidance, Navigation and Control (GNC) of the Intermediate eXperimental Vehicle (IXV) had a dual role. On one side its objective was to ensure the safe flight of the vehicle in order to collect the experimental data, which was mainly related with hypersonic aerothermodynamics. On the other, to qualify himself in flight as re-entry GNC for a pure lifting body, as it was not available in Europe. Therefore, the GNC was considered part of the experiments onboard the IXV. The whole GNC development chain followed a rigorous process in order to pass the Qualification Review before flight, whose verification requirements increased along the lifecycle, starting from the analysis and functional tests up to the real time tests with hardware in the loop. The successful flight of IXV in February 2015 constituted the final step in this qualification process and the closure of the verification chain. This paper summarizes the GNC verification process, including the tools and techniques, as well as a first insight into the post flight results. The final conclusion is that Europe has qualified in flight the GNC for a re-entry vehicle controlled with elevons and RCS.

1. INTRODUCTION

The Intermediate eXperimental Vehicle (IXV) is an ESA re-entry lifting body demonstrator built to verify in-flight the performance of critical re-entry technologies. The IXV was launched on February the 11th, 2015, aboard Europe's Vega launcher. The IXV´s flight and successful recovery represents a major step forward with respect to previous European re-entry experience with the Atmospheric Re-entry Demonstrator (ARD), flown in October 1998. The increased in-flight manoeuvrability achieved from the lifting body solution permitted the verification of technologies over a wider re-entry corridor.

Among other objectives, which included the characterization of the re-entry environment through a variety of sensors, special attention was paid to GNC aspects, including the guidance algorithms for the unique lifting body, the use of the inertial measurement unit measurements with GPS updates for navigation, and the flight control by means of aerodynamic flaps and reaction control thrusters.

From a wider perspective, the development chain for the GNC starts from the shape conception, which implements the control authority needed during orbit and atmospheric flight, up to the production of the flight software which implements the GNC design. In IXV, the design and verification of the GNC has followed an ECSS based approach in which analysis (ex: Monte Carlo simulations) and test (processor and hardware in the loop) have been the main elements of validation to deliver a Qualified product and to verify the GNC for the last set of parameters before flight.

The successful flight of IXV has constituted the final verification of the GNC and hence a significant milestone for Europe: the ARD flight demonstrated the GNC for a capsule and the flight of IXV has verified the GNC for a lifting body using active flaps. The flight constitutes not only the final verification stage of the GNC but also a valuable source for validation and tuning of methods and tools. Several steps in the postflight analysis are foreseen which incrementally will exploit the flight performance using different tools and techniques. An initial postflight analysis has been conducted using several inspection, simulation and reconstruction techniques. This paper describes on one side the overall design, verification and missionisation process for IXV with emphasis in the tools and techniques that have been applied, which include either engineering tools to formal analysis tools like the Functional Engineering Simulator (FES) or the Real Time Test Bench (RTTB) facilities. On the other, the techniques used to derive the initial in-flight verification of the GNC will be presented as well as the main results and conclusions.

2. OVERVIEW OF THE IXV MISSION

The IXV is a 5 m long lifting body weighing 1.9 Tons with a lift-to-drag ratio of 0.7 in the hypersonics and, distinct from other re-entry vehicles such as ARD, is actuated through the combination of two body flaps mounted at the aft windward side of the vehicle acting as elevens and a Reaction Control System (RCS) mounted in the back cover.

The IXV flown mission is presented in Figure 1 with indication of the main events as recorded on-board. The vehicle was launched from Kourou onboard the Vega launcher (flight VV04) and then injected into a suborbital trajectory after separation of the upper stage (AVUM).

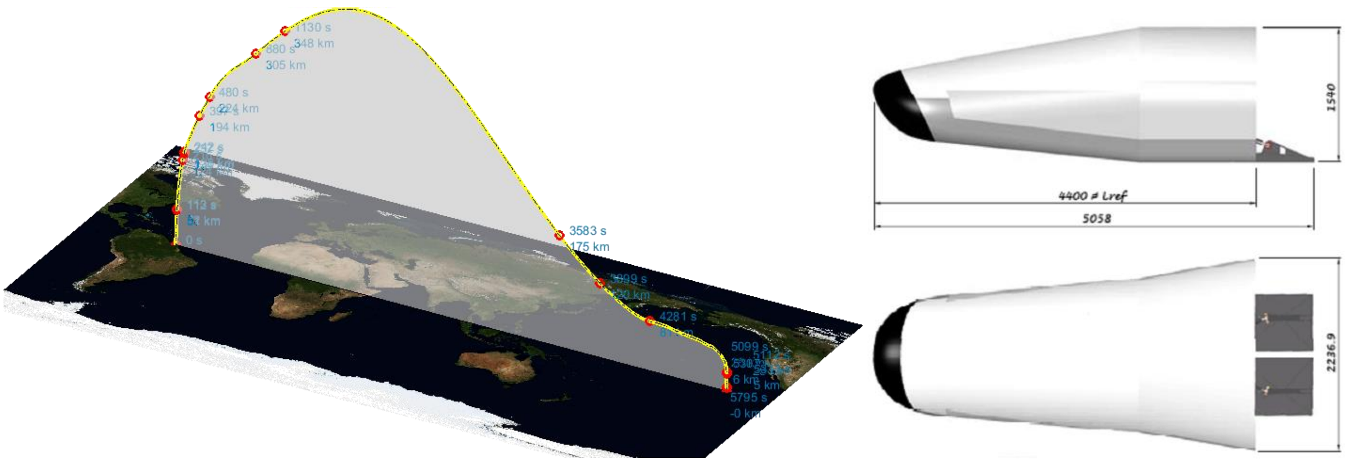

Figure 1: IXV flown mission profile and vehicle shape and dimensions

The IXV then performed a ballistic phase with an apogee of about 413km, coasting up to the Entry Interface Point (EIP), defined at 120 km altitude, which defines the boundary of the sensible atmosphere. Attitude control during this orbital phase is carried out by means of the Reaction Control System (RCS). The conditions at the EIP are typical of LEO return missions, with co-rotating velocities beyond 7.4 km/s (26700 km/h). The IXV then performed a guided gliding re-entry from the EIP until reaching the conditions for the Descent and Recover System (DRS) triggering, at which time the supersonic chute is inflated. Attitude control during the re-entry phase is carried out by means of flaps primarily, combined with the RCS.

The supersonic chute was deployed at the DRS triggering conditions of about Mach 1.5 at an altitude of 25.5 km, shortly after which the descent phase of the flight begun with a 3 stages parachute system. The flight terminated at splashdown in the Pacific Ocean, with a flotation system maintaining IXV in conditions suitable for the ship recovery.

3. GNC WITHIN RE-ENTRY VEHICLE DESIGN

The design of a re-entry vehicle is a highly coupled multidisciplinary process whose main difference with respect to an orbital system is the presence of the atmosphere which impact several subsystems and hence interconnects them. A substantial difference with respect to orbital vehicles is that aerodynamics becomes an actuator rather than a perturbation.

One privileged chain in the overall design process is build-up by the aerodynamics, mission analysis, flight mechanics and GNC. The aerodynamics provides the main actuation means during the atmospheric flight both for trajectory and attitude control. The mission analysis describe the scenario and the flight Mechanics the plant to be controlled. In this context, the GNC provides the function that implements the intended scenario using the aerodynamics and the RCS as control actuators, as depicted in Figure 2. This chain is iterative not only at system level due to the interaction with other disciplines but also internally to consolidate the response in a single loop.

During the first steps of the design this chain provides early feasibility at Mission & System level before activation of other disciplines and hence is used to consolidate requirements and to characterize the performances. The main tool at this step is the functional verification using, for instance, the FES. In advanced design phases, this chain becomes a formal procedure for qualification of the GNC as subsystem, whose product is the application software (ASW) to be loaded onboard. Tools and techniques gain in fidelity and the functional analyses are extended to reach real time testing using the flight software. An innovative verification chain has been setup in IXV as explained in the following sections, which includes the retrofitting of the ASW into the functional simulation chain as main novelty. It has been proven effective not only for the Qualification and Acceptance review but also for the missionisation required before launch.

Finally, the flight constitutes the final verification step not only for the GNC but also for the rest of disciplines that do not translate into a physical subsystem.

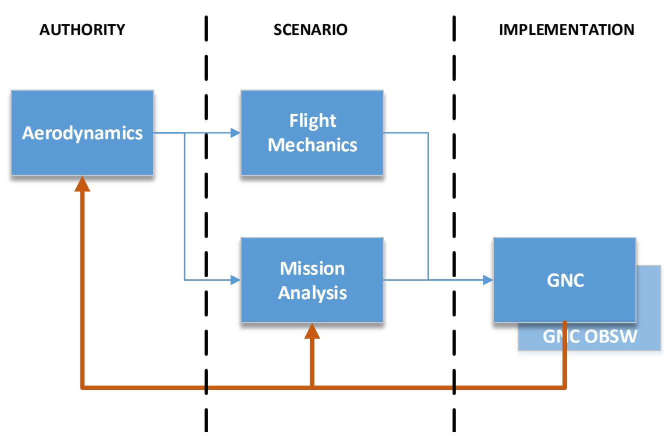

Figure 2: GNC as part of the aeroshape to flyability loop

4. THE GNC OF IXV

The IXV GNC and Flight Management (FM) subsystem is responsible for controlling the vehicle after separation, and taking it to the desired location for parachute triggering. The GNC&FM makes use of an Inertial Measurement Unit (IMU) and GPS measurements to estimate the state vector of the vehicle along the flight, from pre-launch to splashdown, as well as four 400 N thrusters and two aerodynamic flaps as actuators to control it. A brief overview of the GNC&FM subsystem is provided in the following sections, while a more detailed description can be found in [1] and [2]. The GNC&FM is active before the lift-off since the activation of the IMU and takes effective control of the vehicle after separation once the RCS start-up period finishes by enabling the Guidance and Control functions. The GNC is still active after the deployment of the parachutes to provide location information for the recovery operations, but without guiding or controlling the vehicle during the 26 km descent.

The GNC is composed of the core functions Guidance, Navigation and Control, and the Flight Management function which manages the changes of the G, N & C modes based on the estimated data and information exchanged with the Mission and Vehicle Management (MVM) subsystem. The functional architecture of the IXV GNC subsystem is presented in Figure 3 which illustrates the functional and physical architecture of the GNC subsystem, the dataflow between the G-N-C functions and the relationship with external entities, represented in green rectangular boxes (actuators, sensors and other OBSW components).

The main responsibility of the FM function is to command the right GNC mode according to the current MVM authorization, taking into account a sequence of acceptable internal transitions between GNC modes. It operates at 20Hz and basically sets the right mode for each Unitary Function (G-N-C) according to the current GNC mode and the flight conditions.

The Navigation function is in charge of computing the navigation solution, i.e. inertial position and velocity vectors, and a set of navigation derived parameters to be used by Guidance and Control functions to accomplish IXV mission based on the input data provided by the navigation sensors, namely an IMU and a GPS receiver. It operates a 2 Hz. The core of the Navigation function is the inertial navigation based on the IMU incremental measurements. When the receiver provides valid GPS data, it replaces the IMU (GPS updates). A drag derived altitude function is available during entry to improve the navigation solution during the black-out phases. The attitude estate estimation is performed within the control function using the direct IMU attitude rate measurements.

The Guidance function computes the commanded vehicle attitude to be tracked by the attitude control. During the orbital phase, it is based on a scheduled quaternion stored on board derived from the nominal attitude profile provided by Mission Analysis required on-board to ensure visibility from ground stations and GPS constellation.

During the entry the guidance commands angle of attack, bank angle and sideslip. It is initially open loop until the atmosphere is dense enough to allow aerodynamic manoeuvring, around 81 km. Then a close-loop trajectory control is triggered that updates the on-board trajectory reference to compensate for range deviations and that provides the vehicle attitude tracking commands to ensure flight within the entry corridor up to Mach 2, where the attitude needed at the deployment of the parachute system is commanded. The close-loop re-entry guidance is based on an evolved drag tracking algorithm using energy as independent variable and with a high degree of adaptation. It operates at the same frequency of the navigation.

The control implements a close-loop attitude control function with two major modes: orbital and entry. The orbital phase is characterized by negligible aerodynamic effects, so it fully relies on the RCS to detumble the vehicle after separation and to keep the vehicle aligned with the commanded attitude. For each axis a classical PD controller is implemented in combination with a dedicated thruster based dead-band control. Low Performance and High Performance subphases are sequenced in order to narrow the control error requirements as the vehicle approaches the Entry Interface Point (EIP).

The re-entry control function actuates the vehicle such that its attitude follows the attitude commands issued by the re-entry guidance, within a given accuracy, from the EIP to the supersonic chute inflation. The controller is classical, being based on the separation of the basic functionalities of trim, feedforward and feedback. A control allocation module is employed to combine these functionalities and a module for thruster management is required. The control function is executed at 20Hz.

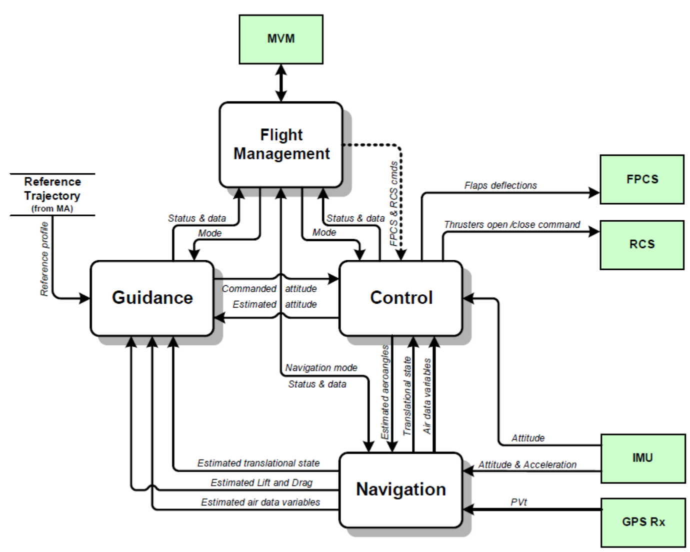

Figure 3: GNC functional architecture

5. IXV GNC VERIFICATION AT QUALIFICATION

The GNC of IXV operates autonomously starting from pre-launch up to splashdown, i.e. without any commanding from ground. Thus, as no override is possible, the verification requirements for the Qualification and Acceptance of the GNC are demanding to comply with the required mission success probability (99% with 90% confidence level).

Verification comprises the overall GNC as a subsystem as a whole and hence the scope is wider than the single verification of the underlying algorithms normally performed in early design stages reaching TRL 3.

In the frame of IXV, the GNC&FM subsystem validation and verification approach went through an incremental verification process which was optimized by ensuring the maximum representativeness and reuse through all stages. It permits to easily identify any GNC algorithm malfunctioning and to isolate and trace those errors through all stages of the GNC design, from the development until the qualification, locating the source of the deviation. Thus, the verification process was designed in 3 incremental stages. The associated method of verification as well as the facilities used are summarised in Table 1. A detailed description of these steps during Phase D is provided in [4].

The subsystem validation and tuning stands for the initial verification to the performed at functional level. It is the main source of validation during the design phase (Phase C2) but also during Phase D to perform the required tuning loops in order to adapt the GNC to the mission and system evolutions. This stage is based on two steps: first, a local validation using the design & validation environments of each function; afterwards, all the functions are integrated in a formally verified simulation environment: the Functional Engineering Simulator (FES). The FES was the main source of formal GNC design validation by the CDR.

In phase D, the functional analyses performed with the FES were extended by integrating the GNC application software into the FES Simulink environment (retrofitting). This application software was previously verified at pure software level in the Software Verification Facility (SVF) and integrated by the GNC team within the FES. This approach allowed to fill the gap between the functional validations using high-fidelity simulation but without the flight software and the qualification campaign in the Avionics Test Facility, where there is no capability to perform intensive functional test like Monte Carlo analysis. Some representative performance results are presented from Figure 5 to Figure 10.

For some functions like the Guidance, early functional validation was provided in the frame of Mission Analysis activities. Guidance was highly parametric and adaptive and hence suitable for integration and rapid tuning and testing during the mission analyses loops. This anticipation of the performances was demonstrated useful to increase the confidence during the GNC tuning loops, whose characteristic time was longer. An example of this performance anticipation is detailed in [3].

The IXV GNC verification is the last step before the GNC Subsystem is Qualified for flight. The verification approach is designed to allow a sequential and parallel development of the verification process (Test Environments and Test Specifications) and of the test facilities needed to implement each test campaign. This step is also incremental and covers from the Processor In the Loop (PIL) simulations using emulator facility instance up to a complete Real Time environment with the OBSW running in the On Board Computer (OBC) and with GNC elements (sensors and actuators) as Hardware In the Loop (HIL) and a retrofitting of the GNC application software into the Functional Engineering Simulation.

The facility used for this step is the Test Environment Facility (TEF), which depending on the involving equipment is able to perform PIL tests (TEF-1) or HIL test (TEF-2). The heart of the GNC Verification Facility is the GNC Special Check-Out Equipment (SCOE), designed to run in Real Time a High Fidelity simulation of the IXV flight. It includes high fidelity models of the atmosphere, aerothermodynamics effects during the reentry and all GNC units. Simulations are used to provide inputs to the GNC either using the simulated sensors outputs or via stimulation of the real sensors (IMU and GPS). The Simulation Loop is closed by acquiring the GNC actuations (pulses to thrusters and deflections to flaps) to be propagated in the RTS. The TEF-2 was also used for test with the PFM using the flight hardware. The overall GNC verification process is sketched in Figure 4.

Stage	Method	Tool & Facility
Subsystem Validation and Tuning	Review of design Analysis	– Local design environments. Ex: SENERIC (SENER, Figure 11) Endosim (DEIMOS, Figure 12) – FES
Performance requirements verification	Analysis	FES with retrofitted GNC ASW
GNC subsystem Verification	Test	– Processor in the Loop (PIL): TEF-1 – Hardware in the Loop (HIL): TEF-2 – Proto Flight Model (PFM): TEF-2*

Table 1: Incremental verification steps

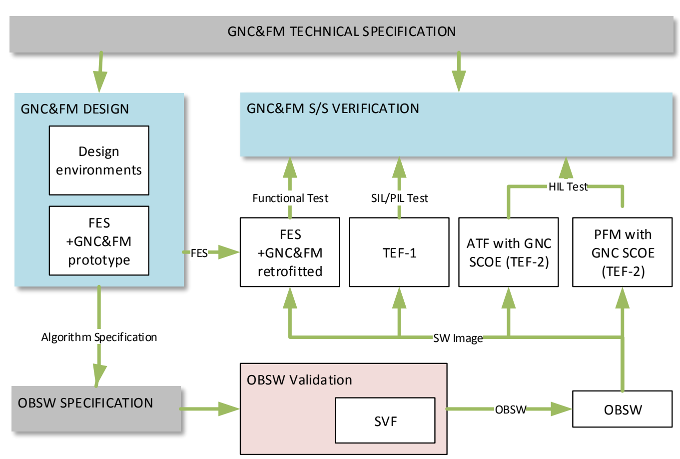

Figure 4: GNC verification process

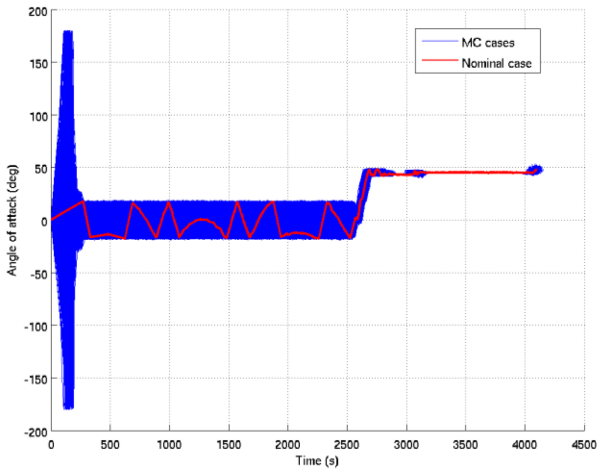

Figure 5: Angle of Attack vs Time

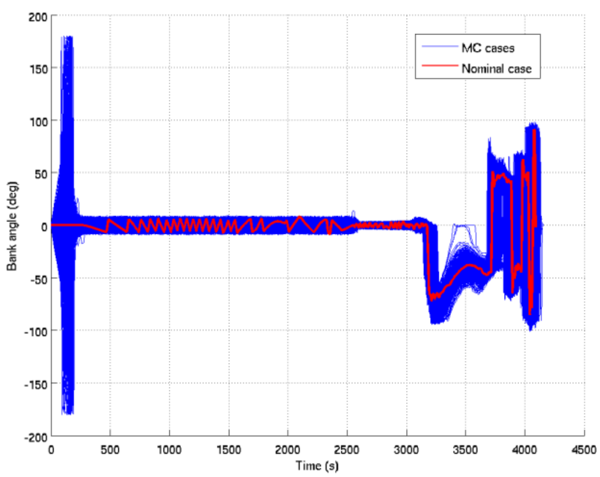

Figure 6: Bank Angle vs. Time

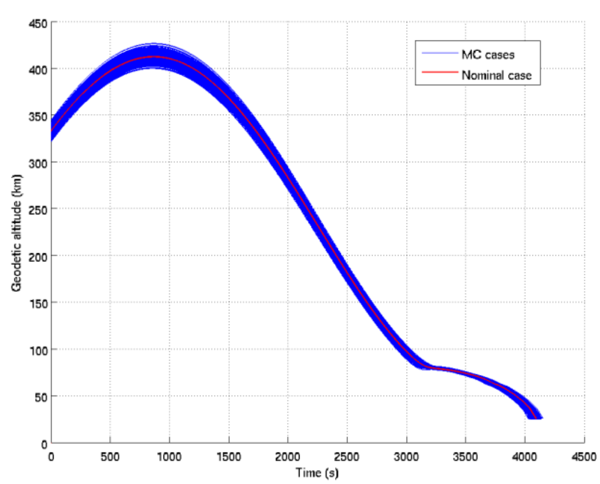

Figure 7: Geodetic altitude vs. Time

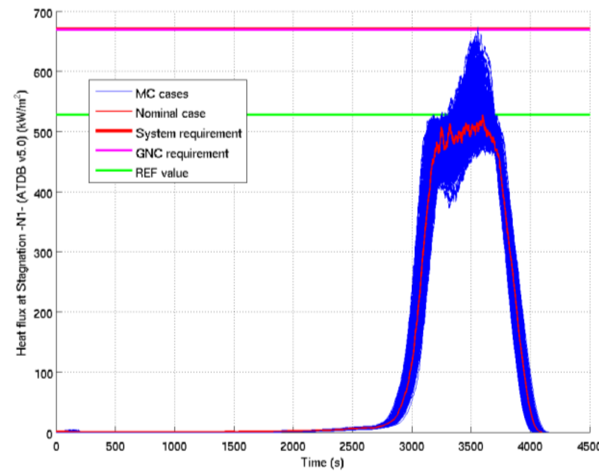

Figure 8: Heat flux at stagnation vrs. time

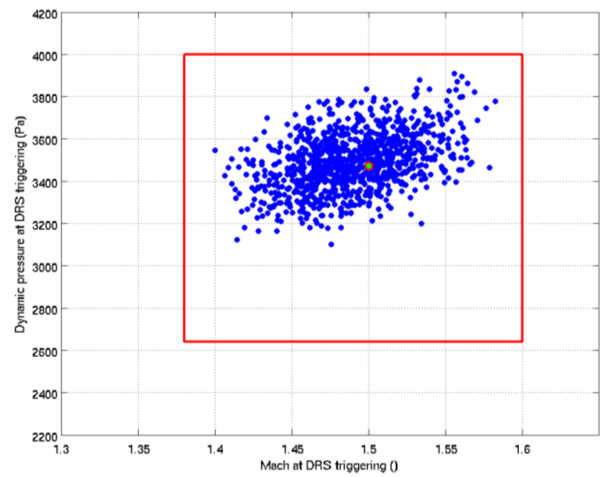

Figure 9: Real Mach vrs. Dynamic pressure at DRS

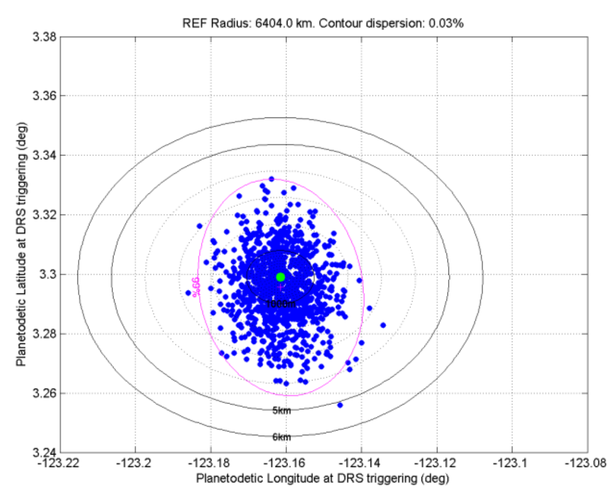

Figure 10: Latitude vs. Longitude at DRS triggering

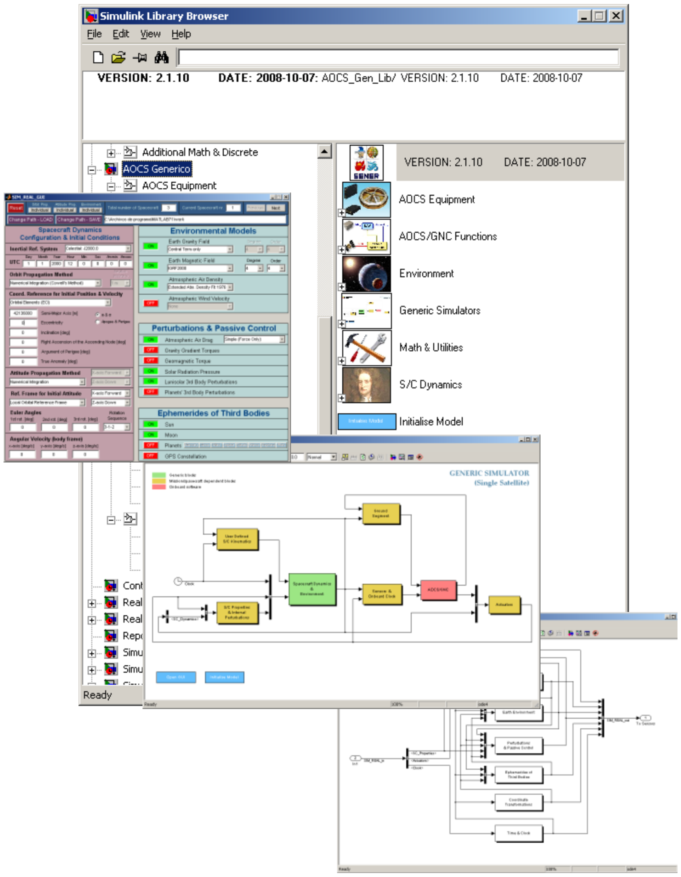

Figure 11: SENERIC simulation infrastructure

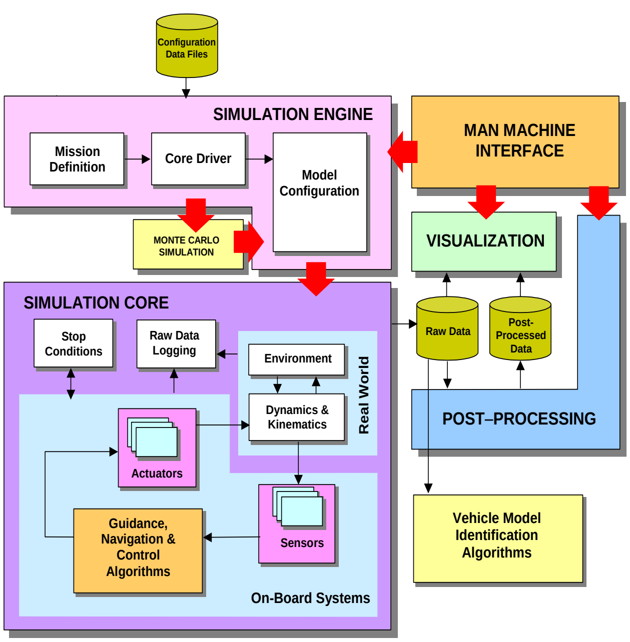

Figure 12: IXV-FES architecture

6. IXV GNC VERIFICATION AT PRE-LAUNCH

The System Qualification and Acceptance Review of IXV was successfully passed in September 2014. However, it is not the last step in the verification of the IXV GNC.

During Phase D, the verification of the GNC was devoted to the demonstration of the compliance of the GNC requirements. Therefore, the models and tests were designed to provide nominal performances, stress cases, worst cases as well as off-nominal simulations but not day of launch predictions. Once the launch date is frozen and the vehicle is assembled, several uncertainties shrink or even disappear leading to reduced dispersions and hence different performances. Moreover, some parameters are selected and fixed depending on the launch epoch, which builds-up what is known as flight prediction, [5].

One example are the wind tables. In order to improve the accuracy of the Descent and Recovery System (DRS) triggering, nominally specified at Mach 1.5, an on-board wind table was implemented to refine the on-board Mach estimation. This table was specified by the Mission Analysis team and is highly dependent of the launch epoch as explained in [5]. For the System Qualification and Acceptance Review (SQAR) the GNC was tested both at functional and subsystem level using dedicated dispersion models to emulate the discrepancy between the on-board wind table and the real winds but not the candidate ones as they were not available until few weeks before launch.

Thus, tests using the candidate wind tables occurred after the SQAR once the date was frozen and the wind predictions prepared. It required not only a verification of the software, as numerically these tables were different from the tables used for the verification, but also at GNC functional and subsystem level. The delay in the launch from November 2014 to February 2015 introduced an additional element, which was the impact of the updated launcher performances, namely injection conditions, into the IXV GNC performance.

Thus, a missionisation process was required with a tight schedule before the updated launch date to verify the GNC parameters upgrades. A coordinated action between System, Mission Analysis, GNC, software and avionics teams built-up a procedure that was successfully carried-out on time with the following objectives:

- Identification and functional validation at Mission Analysis level of the updated scenario.
- Selection of the candidate wind table.
- Functional GNC validation using the retrofitted FES.
- Confirmation of final GNC parameters to be uploaded.
- Software verification at SVF and creation of images.
- GNC subsystem validation at the ATF performing nominal simulations with final the flight parameters.
- Confirmation of the preselected wind table during launch campaign.

This process was successfully executed within the last 5 weeks before the launch.

7. IXV GNC VERIFICATION AT POSTFLIGHT

7.1. Post flight analyses

The final stage of the GNC verification process is the post-flight analyses, in which the performance is assessed. IXV was successfully launched at 11th February 2015 13:40 UTC. The mission was successful and the vehicle was recovered as planned. The vehicle separated, performed the controlled orbital and hypersonic/supersonic flight and descended under parachutes to reach the designated landing point.

First findings using the real time telemetry data displayed at the Mission Control Centre (MCC) controls showed a performance close to nominal with the key elements of the chain (launcher, TPS, GNC, parachutes, balloons, communications and recovery) performing nominally.

A level 0 post-flight analyses was conducted at system level to collect all the available information stored on-board to build a consistent data package of flight data. Waiting for the formal funding of the post-flight activities of IXV, an initial inspection beyond the Level L0 has been conducted internally. The objective is to identify the main highlights of the flight as first step before the detailed reconstruction and analyses to be conducted during level L1 activities.

A post-flight data suite was setup in order to perform an initial reconstruction from the raw flight data, covering:

- Data synchronization, filtering and rejection
- Trajectory reconstruction based on cleaning navigation profiles considering the GPS and IMU performances.
- Additional parameters (ex: air data, dynamics)
- GNC flight performance analyses

An example of reconstruction is shown in Figure 13. The onboard position and velocity is corrected with the GPS data as the navigation rejected part of the GPS signal during flight. Two flight performance analyses have been conducted:

- GNC performance: comparison of the flight with the predicted performance before flight
- GNC prediction: prediction of the flight created with the FES with updated environment and initial conditions as measured during the flight.

7.2. GNC performance

The first analysis is related to the separation event, which is the first key event. The injection was highly accurate and the attitude close to nominal with a very low residual angular velocity (< 0.25 deg/s, Figure 14). The injection was delayed in terms of time wrt pre-flight nominal value, but well within the expected range. Separation was properly detected on board, as shown in Figure 15. The next relevant event is the Entry Interface Point. It was noticed a shallower orbital arc leading to an eastwards and shallower entry conditions than predicted but within the expected dispersions. The re-entry guidance compensated this shift during the entry.

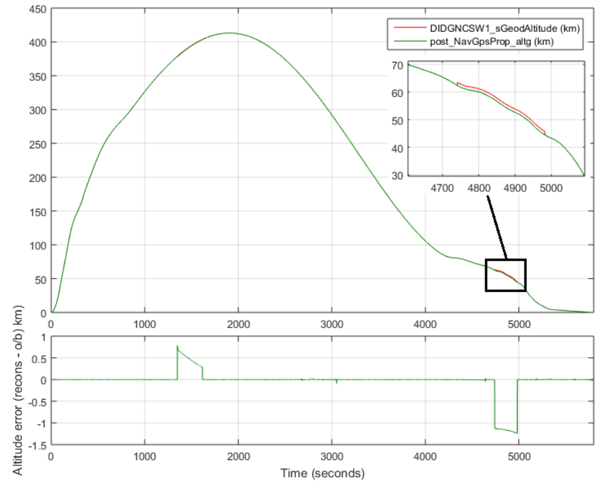

Figure 13: reconstructed altitude vs onboard value

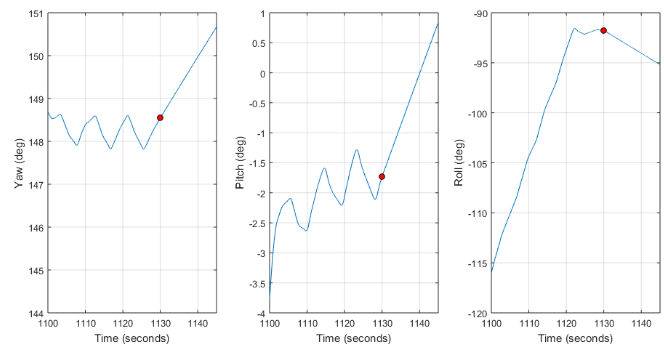

Figure 14: IXV attitude at separation

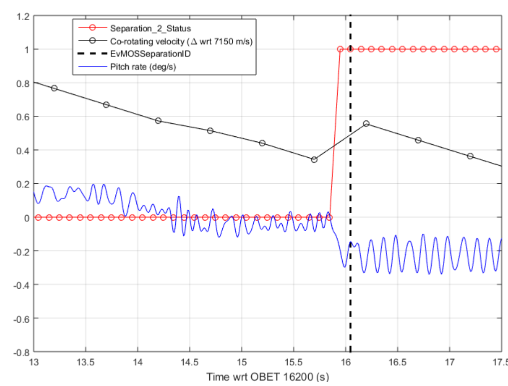

Figure 15: Separation event detection

The parachute was triggered at 25.4 km altitude and Mach 1.49, close to the target of Mach 1.5. Figure 16 shows the reconstructed Mach number and the onboard estimation. The availability of the GPS and the good track of the atmosphere conditions before flight ensured that the uploaded wind table was adequate. The estimated position error at DRS with respect to the predictions is ~1300 x 250 m (alongtrack x crosstrack). GPS was available down to splashdown, showing an accuracy of ~1-2 km with respect to the last prediction performed at the MCC 1 hour before launch. The descent (uncontrolled) was shorter than predicted but within bounds.

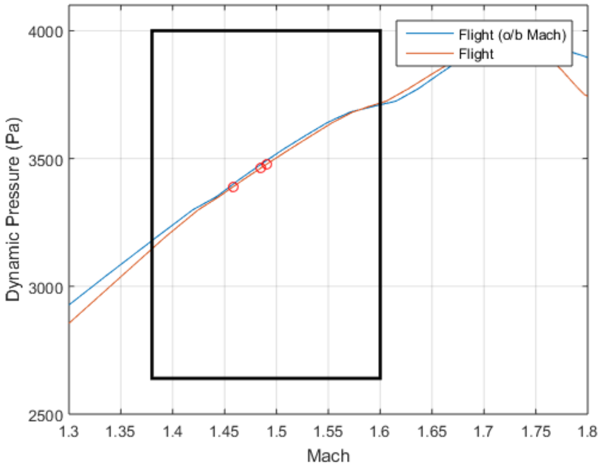

Figure 16: DRS triggering within the DRS box

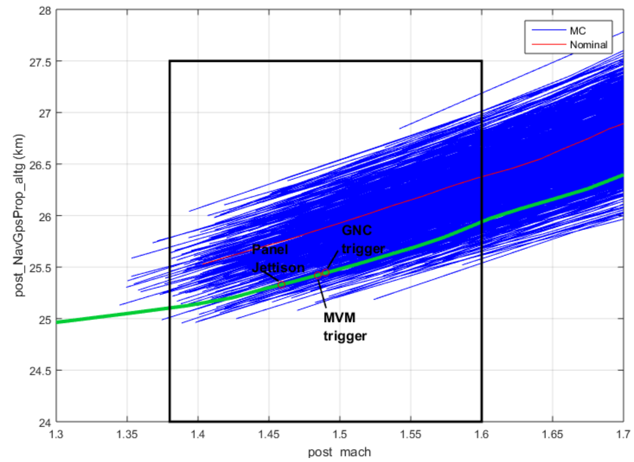

Figure 17: DRS triggering within the DRS box

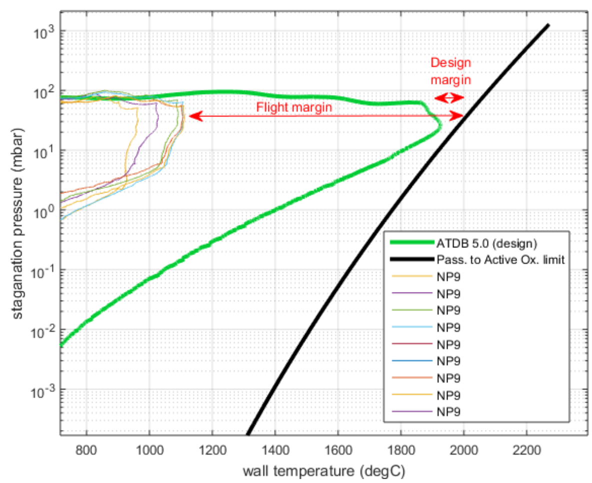

Figure 18: Passive to active oxidation transition assessment

Figure 19 to Figure 26 show some representative flight profiles (green line) compared with the variability band (blue lines) coming from the Monte Carlo campaign used for the Qualification. The nominal pre-flight trajectory is indicated in red. This variability band is narrower than the available corridor for all the variables. The red marker indicate the relevant mission events: separation, transition from low Precision to High Precision mode, Entry Interface Point, close-loop re-entry guidance and DRS triggering events.

All these figures show that the vehicle was successfully guided, navigated and controlled down to the parachute deployment box within the Qualification dispersion envelope. The shallow entry was corrected by the guidance once it entered into close-loop mode to steer the trajectory within the corridor, as shown in Figure 20. As a result of the compensation of the eastwards shallower entry carried out by the guidance, the ground track was closer to the boundary of the variability, but inside. This guidance compensation is also noticed in terms of the flight envelope (Figure 22), leading to a steeper flight close to the Monte Carlo boundaries but with significant margins with respect to the entry corridor.

The attitude control keeps the vehicle attitude within bounds. The duty cycle during the orbital coasting is shorter leading to a larger number of firings than predicted. The reason is a larger authority from the RCS that the attitude controller is able to absorb at the price of more actuation.

During the entry flight, the angle of attack is close to the nominal value of 45 deg in hypersonic, ensuring good aerothermodynamic performances. The angle of sideslip is smaller the 0.5 deg in most of the re-entry. There is a small pitch-up just before parachute deployment. The bank angle during entry (Figure 26) confirms the need of a steeper manoeuvre at the beginning of the entry to compensate the orbital arc deviations. Afterwards, the guidance steers the vehicle towards the nominal path and attitude and the difference with respect to the pre-flight trajectory is small. The bank manoeuvres magnitude and the location of the reversals are close to the pre-flight value, which confirms the observations made in real time at the MCC.

For what concerns the parachute deployment, Figure 17 shows the altitude - Mach deployment window besides the flight trajectory and the Qualification variability, showing wide margins. The deployment occurs within the expected band. There is a slight reduction in altitude with respect to the pre-flight prediction caused by the abovementioned pitch-up below Mach 1.8 during pre-release.

The Aerothermodynamic Database Tool (ATDB, [6]) has been used to compute the design heat fluxes and temperatures at the nose and at the flap using the flight conditions. These predictions are conservative as they include margins. They can be compared with the temperatures measured by the thermocouples mounted all along the Thermal Protection System of IXV. Figure 18 shows the passive to active oxidation transition boundary for the ceramic TPS of IXV (black line) in terms of temperature and stagnation pressure. The design prediction provided by the ATDB tool (green) is conservative with respect to the values measured in flight for all the stations. Thus, the flown entry corridor is wider than the one used for Qualification. Peak temperatures are below 1120ºC, while design predictions were 500 ºC higher. These results suggest a revisiting the ATD margins used for design.

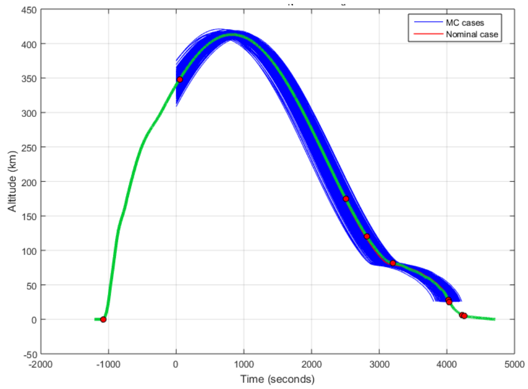

Figure 19: altitude profile and MC range

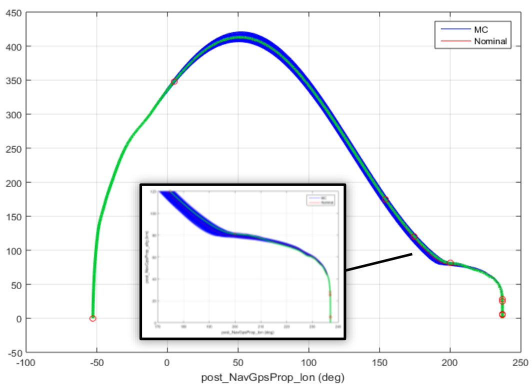

Figure 20: altitude-longitude and MC range

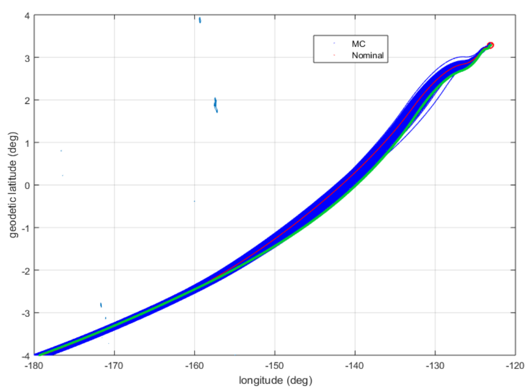

Figure 21: ground track and MC range

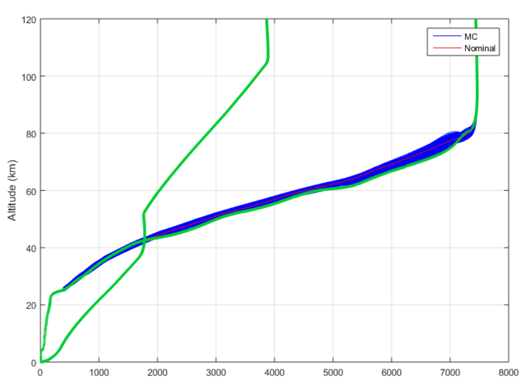

Figure 22: flight envelope and MC range

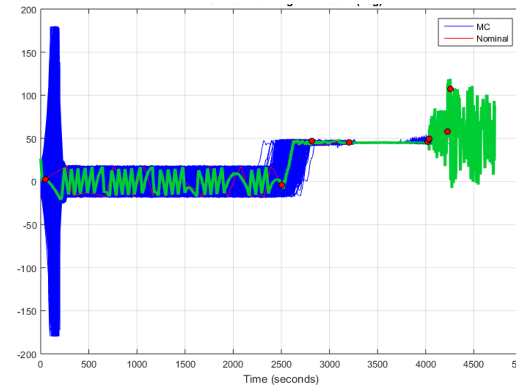

Figure 23: angle of attack profile and MC range

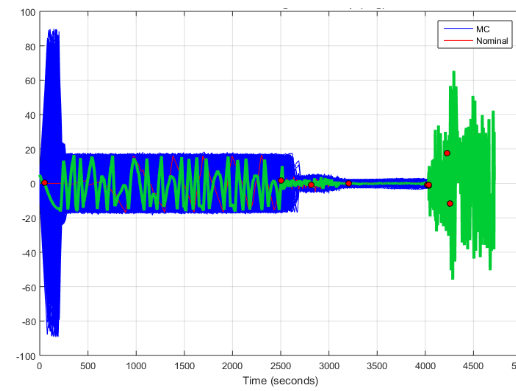

Figure 24: angle of sideslip profile and MC range

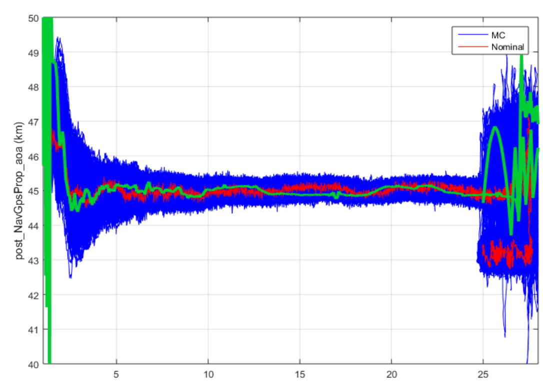

Figure 25: angle of attack-Mach during entry and MC range

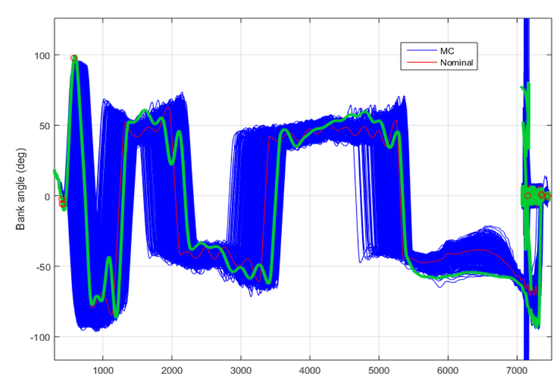

Figure 26: bank angle-velocity during entry and MC range

8. GNC PREDICTIONS

The next step in the verification of the performance is to compare the flight performance with the post flight prediction using day of launch data. Thus, the reconstructed initial conditions and environment (atmosphere and winds) during the flight as well as the GPS availability have been injected into the Functional Engineering Simulator to simulate the flight.

In terms of aerodynamics, the flown lift-to-drag ratio is very close to the prediction using the IXV Aerodynamic Database (Figure 27). The lift-to.-drag ratio drives the guidance authority during the hypersonic flight.

Figure 28 shows that the predicted bank profile (FES simulation) matches very well with the flight beyond first manoeuvre. The oscillations are due to the different RCS authority with respect to the pre-flight predictions. As mentioned in previous section, the initial bank is manoeuvre stronger than predicted, but within the dispersion range, to compensate the shallower and Eastwards entry conditions.

Figure 29 shows the angle of attack for the whole flight. There is more actuation than predicted with a shorter duty cycle. It has been caused by a larger RCS authority than predicted. This excess of authority caused on one side overconsumption, particularly during High Precision mode and early reentry, as well as eastwards and shallower entry conditions. The attitude controller handles the shorter duty cycle meeting the requirements. Simulations have been run with higher RCS authority that reproduce the orbital arc drift.

The actuation of the RCS has been analyzed. Figure 30 is a zoom showing the first RCS command after separation. Figure 31 shows the angular acceleration response of IXV after the first RCS ON command of 50 ms. The dotted line is the predicted angular acceleration (FES simulation), while the blue continuous line is the measured flight data. The integrated profile is a measure of the impulse imparted by the RCS. This figure confirms the higher authority for the same command and justifies the shorter cycle, the increase in firings during the orbital arc and the orbital shift due to the residual delta V of the RCS. All these deviations have been absorbed by the GNC to provide an almost nominal mission performance.

The flaps of IXV behave as elevons, i.e. perform an elevator and an aileron function at the same time. Thus, the elevator (δ_e) and aileron (δ_a) deflections are defined as follows

$\delta_a = ½ (\delta_R - \delta_L)$

$\delta_e = ½ (\delta_R + \delta_L)$

Figure 32 presents the elevator profile. It is close to the prediction particularly if we consider that the higher fuel consumption of the RCS causes a forward shift of the centre of gravity alleviating the deflection. In terms of aileron, practically no deflection was noticed beyond the bank reversal manoeuvres, which might indicate smaller lateral CoG offsets during flight than predicted.

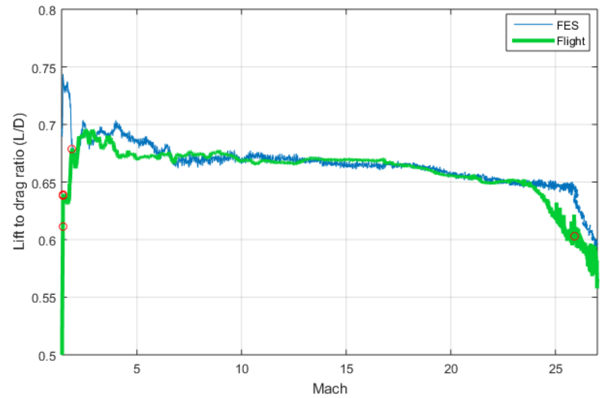

Figure 27: lift-to-drag ratio: flight and prediction

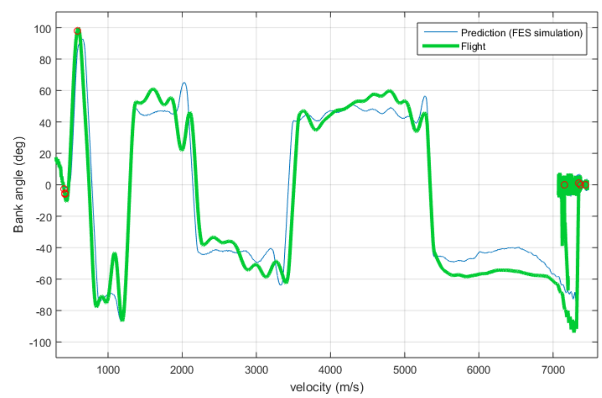

Figure 28: bank angle: flight and prediction

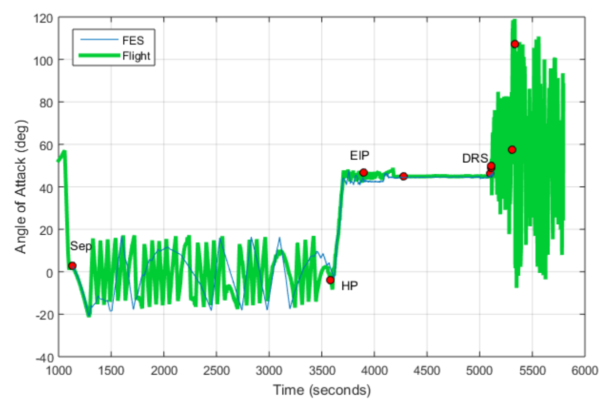

Figure 29: angle of attack: flight and prediction

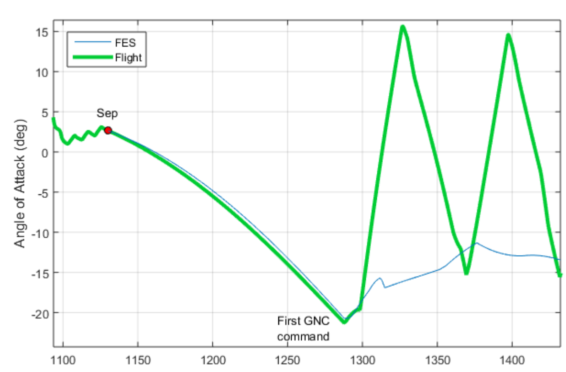

Figure 30: angle of attack at separation: flight and prediction

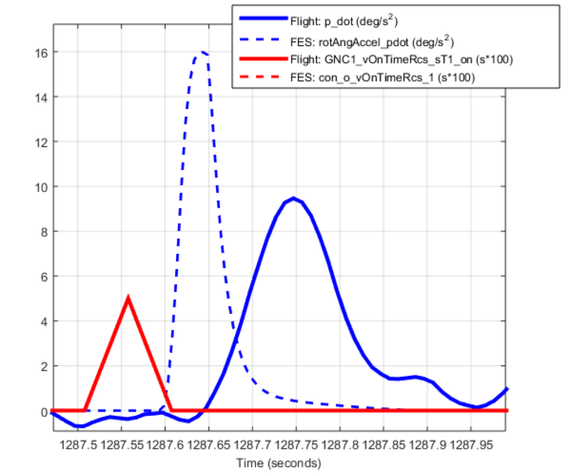

Figure 31: RCS command and angular acceleration

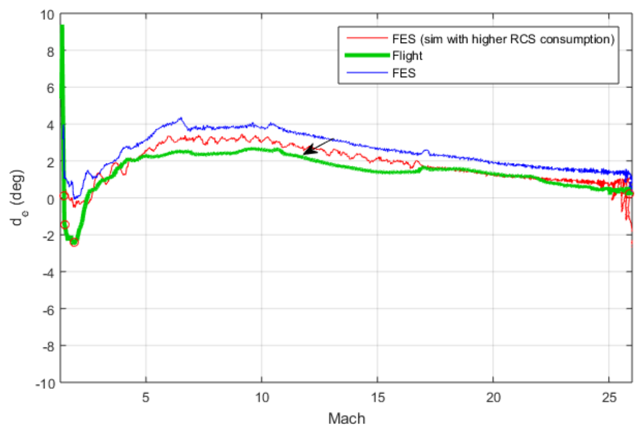

Figure 32: elevator deflection: flight and prediction

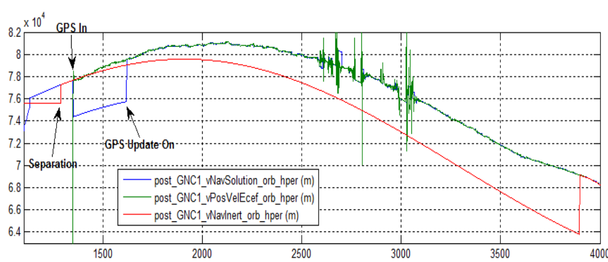

Figure 33: pericentre from GPS, IMU and Navigation

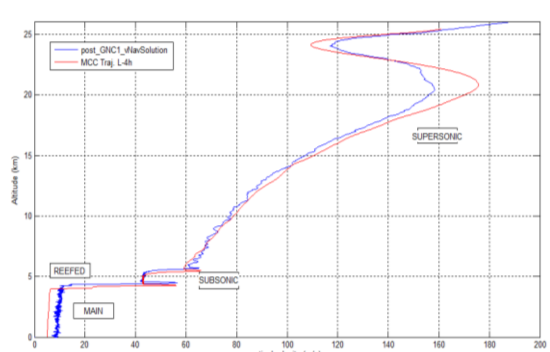

Figure 34: descent profile under parachutes

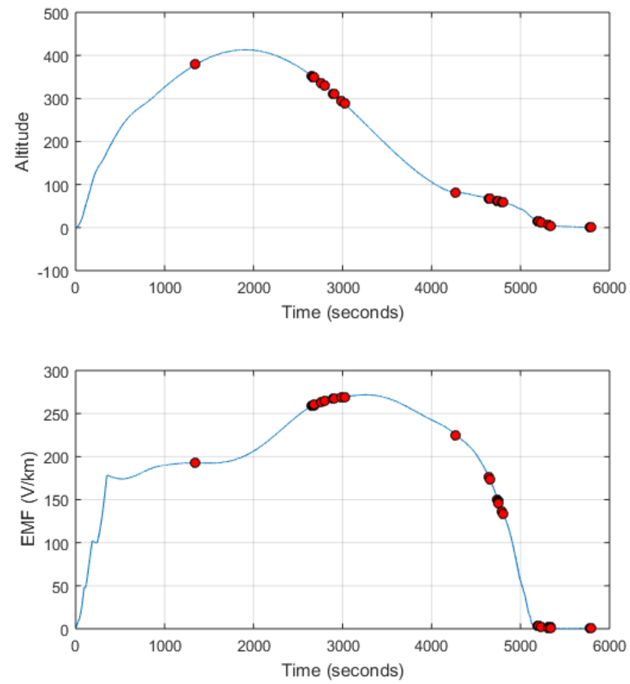

Figure 35: GPS acquisition/loss events

Regarding Navigation, the GPS was available most of the flight and hence it was the source of the Navigation solution. It was noticed that the initial GPS measurement provided by the receiver after separation was labelled as valid, but it was not still not properly converged, which caused a delayed acceptance of the GPS measurements by the on-board navigation. Figure 33 presents the altitude of the pericentre derived from the raw GPS data (green) , the IMU (red) and the Navigation solution (blue), showing the drift in the navigation solution caused by the inaccurate labelling of the first GPS signal.

The trajectory under parachutes is quite close to the pre-flight prediction computed at the MCC 4 hours before lift-off, [5]. It indicates that the wind profiles behave as measured by the balloons launched before flight. After the disreef of the main parachute, a higher vertical velocity was observed.

The GPS was available most of the time. The black-out of the GPS antenna extended from 81 km up to 60 km, with intermittent reacquisitions starting from 68 km. This range shows wide margins, as expected, with respect to the conservative blackout window used for communications and GNC design (100 to 50 km). The black-out window derived from dedicated non-equilibrium CFD predictions was also conservative, which is consistent with the wide margins that have been noticed in general in terms of ATD predictions.

Figure 35 shows the timeline of acquisition and loss of the GPS signal during the IXV flight. In addition to the blackout period and the intermittencies during the descent due to the oscillations under the parachutes, it was noticed an unexpected loss of the GPS signal during the orbital arc. It is potentially linked with Earth magnetic field.

9. CONCLUSIONS

IXV has been successfully flown past 11th February 2015, setting a new milestone in European Re-entry technology demonstration. The IXV programme is tasked with the development, maturation and demonstration of European knowledge and expertise for re-entry systems. The GNC of IXV is challenged by several factors like the coupling between all the mission phases due to the suborbital nature of the flight, the narrow corridor driven by aerothermal constraints to be guaranteed by the guidance and the large uncertainties and margins inherent to an experimental vehicle.

The Guidance, Navigation and Control system of IXV has followed a rigorous development and qualification process to move the conceptual design from paper to a subsystem designed to work in real time interacting with sensors and actuators. Special emphasis has been put on the interactions between the GNC and the System, Avionics and software development lifecycles and how an integrated and incremental verification process has been implemented by ensuring the maximum representativeness and reuse through all stages. The verification chain involved different tools and techniques ranging from design and functional simulation tools to the avionics test facilities

The flight has shown that the GNC subsystem has successfully performed its main tasks: to control the vehicle trajectory and attitude from Separation up to the DRS deployment. Initial post-flight analysis show a flight performance within the expected variability band. The excess of performance of the RCS subsystems has been absorbed by the GNC at the price of a larger consumption.

The GNC verification during post-flight shows that the GNC has been robust against the larger authority from the RCS subsystem and the overconsumption, compensating the deviations accumulated in orbit to steer the vehicle towards the expected target safely, ensuring nominal fulfilment of the mission objectives.

Pending on detailed aerodynamic assessments, main aerodynamic performances have behaved as expected. Further analyses of the RCS, aerodynamics and vehicle configuration are expected to consolidate the initial findings.

This verification confirms the in-flight qualification in Europe of the GNC for a lifting body re-entry vehicle using elevons and RCS as actuators.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

[1] Gherardi, D. et al, "IXV GNC Subsystem Design and Performances", Proceedings of the 8th International ESA Conference on Guidance, Navigation & Control Systems, Karlovy Vary, Czech Republic, 2011

[2] M. Kerr et al. "IXV Re-entry Guidance, Control & DRS Triggering: Algorithm Design and Assessment". AIAA Guidance, Navigation, and Control Conference. 2012

[3] Haya, R. et al, "The design and realisation of the IXV Mission Analysis and Flight Mechanics". Acta Astronautica, 2016.

[4] Contreras, R. et al. "IXV GNC&FM Subsystem Phase D Activities: Towards a Successful Qualification Review". 9th International ESA Conference on Guidance, Navigation & Control Systems, 2 - 6 June 2014, Oporto, Portugal

[5] Haya, R. "Flight Predictions for the IXV Mission". 8th European Symposium on aerothermodynamics for space vehicles, 2-6 March 2015, Lisbon, Portugal

[6] Mareschi, V. et al. "Intermediate Experimental Vehicle, ESA Program IXV. ATDB Tool and Aerothermodynamic Characterization". 7th Symposium on Aerothermodynamics for Space Vehicles, 2011, Brugges, Belgium.