FUNCTIONAL VALIDATION AND QUALIFICATION OF THE AUTOMATED TRANSFER VEHICLE (ATV) FLIGHT CONTROL

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I ABSTRACT

In nominal autonomous flight, ATV control is achieved by a flight control function (using computers, sensors and actuators) which is a part of the Flight Application Software (FAS) and includes nominal Guidance, Navigation and Control (GNC) algorithms. For validation and qualification of on-board algorithms included in the FAS, non real time and real time simulators have been developed. The GNC functional validation and qualification process on those simulators followed a step-by-step approach. This paper provides an overview of the methodology used from the simulations of the first algorithms driven on development simulators (containing simplified GNC mock-ups) up to the final validation phase of the complete integrated GNC software on different real time test benches. The methodology illustrated in this paper has been eventually completed with cross-comparisons between the first flight telemetry and on-ground closed loop tests.

II INTRODUCTION

The European Automated Transfer Vehicle (ATV- see Fig 1.) is an unmanned transport spacecraft designed to dock with the International Space Station (ISS) and to contribute to the logistic servicing of the ISS (dry cargo, water & gas delivery, ISS refueling, ISS reboost, contribution to ISS attitude control, and waste disposal).

The ATV Flight System development and qualification is managed by ASTRIUM Space Transportation as prime contractor, under ESA contract.

Fig 1. Picture taken during first ATV mission, named Jules Verne (31st of March, 2008).

The ATV is a very complex automated system designed to cope with multiple mission phases, operational & safety constraints, and high level of flight control performances. Therefore, the Flight Application Software (FAS) is a complex software to develop and validate, and so is the nominal Guidance, Navigation and Control (GNC) software, using 6 different kinds of sensors, and 32 thrusters as actuators.

In order to enable the validation and qualification of on-board GNC algorithms included in the FAS, non real time and real time simulators have been developed in order to be representative of ATV, ISS and their environment. The GNC validation/qualification process on those simulators is a step-by-step approach. The complete requirements coverage is achieved using all performances checks, which are obtained at the level of:

- Unitary functional studies with GNC stand alone mock-ups,
- Integrated GNC software (called LN3_FES) validation with the Functional Engineering Simulator (FES),
- FAS validation, including GNC, with the real time facility Software Validation Facility (SVF-FAS),
- The complete representative ATV flight system qualification using the Functional Simulation Facility (FSF), which is a real time facility including ATV real equipments.
- Additional qualification tests performed with real GPS receivers (IVF Moscow platform) or real videometers and telegoniometers optical equipments (IVF-EPOSX platform – Val de Reuil).

III ATV NOMINAL GNC DESCRIPTION

From Ariane 5 injection, when GNC becomes active, up to the docking with the ISS, the GNC objectives are:

- To perform early orbit operations: ATV angular rate reduction after Ariane 5 separation, possible slew manoeuvres to acquire star tracker first measurements, attitude control before solar arrays deployment.
- To perform progressively ATV Phasing w.r.t ISS: 3 successive Hohmann transfers with yaw steering attitude between the boosts (peculiar attitude law w.r.t Sun in order to optimize solar arrays power generation, thermal control, and attitude motion), slew manoeuvres from yaw steering attitude to boost direction, and vice versa. It allows reaching S0 point in ISS vicinity, around 30km away from ISS.
- To perform rendezvous from S0 (radio proximity link with ISS available) up to docking: pre-homing phase with relative GPS navigation (ATV/ISS) and guidance initialisation, Homing phase with 4 successive boosts up to S2 station keeping point, Closing phase up to S3 station keeping point, a slew to a Local Vertical Local Horizontal (LVLH) attitude and a final approach in the LVLH attitude up to S4, and then last meters in the ISS Docking port attitude (see Fig 2.).

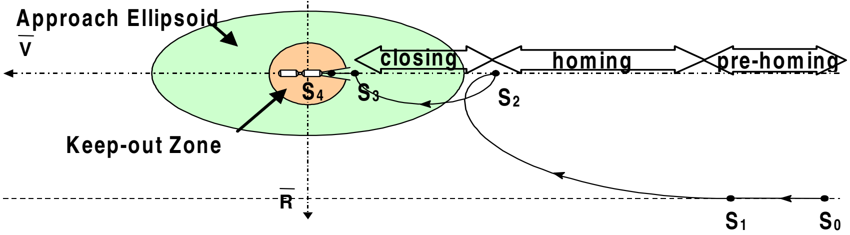


Fig 2. Relative ATV-ISS trajectory during Rendezvous

From ISS dedocking to atmospheric destructive re-entry, the role of the GNC is:

- To perform the single 4 m/s departure boost to move away from ISS and go out of the approach ellipsoid.
- To control ATV in a yaw steering attitude, and perform 2 deorbitation boosts.
- To control the re-entry manoeuvre, before destruction in atmosphere.

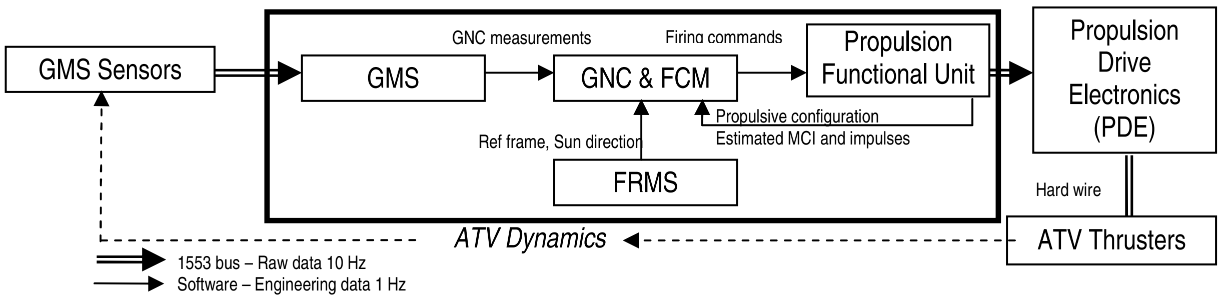


Fig 3. ATV GNC loop

ATV flight control software can be separated into 5 main sub-functions (see Fig 3.):

- The GNC Measurement System (GMS) is in charge of GNC sensors management, measurements processing and Failure Detection, Isolation & Recovery (FDIR).
- The Navigation (N) algorithms process GMS outputs and estimates ATV state vector. ATV attitude and angular rate are estimated with Kalman filters using gyrometers and star tracker measurements. ATV position and velocity estimation are provided by Relative GPS (ATV/ISS) navigation in Homing & Closing. In final approach from S3 way-point, videometers optical sensors are used.
- The Guidance & Control (GC) algorithms are in charge of attitude control whatever the phase, orbital and deorbitation boosts realization, Homing & Closing boosts calculation and realization, position and velocity control in final approach w.r.t reference trajectory based on Hinfinity optimal robust controller.
- The Reference Frame Service (FRMS) gives Sun direction and Local Orbital Frame estimation.
- The Flight Control Monitoring (FCM) monitors ATV kinematics main parameters using as much as possible dissimilar sensors and triggers an alarm if pre-defined corridors are overpassed.

In order to simplify, the GMS/N/GC/FRMS algorithms will be further called by the wording “GNC”. “FCM” wording will be kept in stand-alone. ATV GNC algorithmic blocks have been designed depending on the sub-function and the used mode. There is a total of 62 blocks.
If ATV flight system encounters serious anomalies, FAS may be reset and/or MSU software may be in charge of ATV control (managing then a Collision Avoidance Manoeuvre); in parallel, FAS goes to Survival mode. When FAS takes ATV control back, GNC has the objective to put ATV in a safe configuration in terms of power/thermal/communication (via a Star tracking manoeuvre and a Sun tracking manoeuvre).

IV DEVELOPMENT OF SIMULATORS FOR VALIDATION PHASE

Development of the Functional Engineering Simulator (FES)

In order to validate the GNC software w.r.t its functional & performance requirements, the Functional Engineering Simulator (FES) has been designed and validated in stand-alone, following the classic watershed approach (same one as for the Product Under Test: LN3_FES).

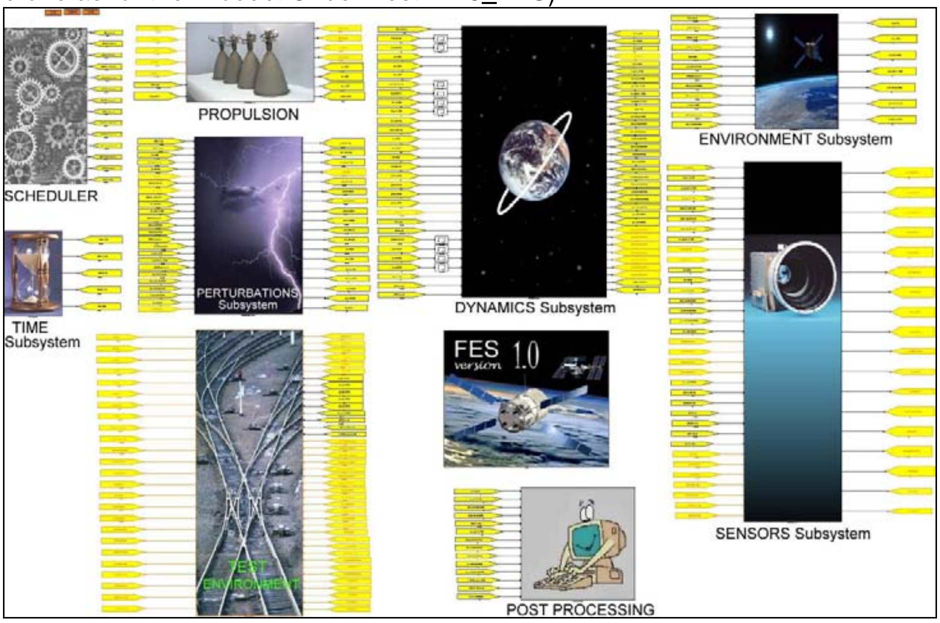


Fig 4. FES level 1 architecture under SIMULINK®.

The FES is composed of 25 SIMULINK® models (see Fig 4.), which have been developed following specific rules in order to be integrated in FES, but also in the ATV real time simulators for FAS validation (SVF-FAS) and ATV Flight System Qualification (FSF). All the FES models have been unitary validated with respect to their specification, and, sometimes, a complementary cross-validation with respect to another reference has been carried out: for instance comparison with a JAMES® model for ATV dynamics integration model in order to check correct fuel sloshing effects and solar arrays flexibility modeling/integration.

FES integration / validation in stand-alone (i.e. without facing GNC software) is carried out by:

- The non-regression for all the models when they are all integrated in the same SIMULINK® scheme,
- The consistency of the interfaces between models using SIMULINK® internal verification means,
- The validation of the scheduling of the simulator’s components,
- The global functional validation: compliance with the FES technical specification and validity of outputs with respect to inputs on simple cases (ATV free drift for instance) or with cross-comparison with other ASTRIUM-ST validated numerical simulators.

Development of the ATV Real Time Simulator (ATVsim)

The different test benches used for FAS qualification integrate the real time simulator called ATVsim. SIMULINK® has been chosen for the development and EUROSIM® as the Simulator Platform. The development, integration and validation of the different models developed under SIMULINK® environment follow the same rules as FES ones. Moreover, when possible, all numerical models used for FES simulator building were officially delivered for integration in ATVsim simulator. Using this approach allows having less costly developments, but also easier use of common postprocessings for both non real time and real time facilities. Nevertheless, numerous models have been developed for ATVsim needs only (communications, Thermal Control Unit, power…) but did not impact the GNC qualification.

The SIMULINK® and EUROSIM® tools cover all the cycle activities:

- SIMULINK® is used during the specification and design phases of the numerical models, the coding phase and during the models validation phases on host machines.
- Real Time Workshop® is used for generating ANSI C code and MOSAIC® is used during the integration of the models into EUROSIM®.
- EUROSIM® is used for the design of the simulator, for the real time integration of the numerical models and finally for the validation of the overall simulation software.

Common use of post-processings

For the processing of tests performed on real time bench, it has then been chosen to reuse the post-processings developed for FES validation (see Fig 5.) for the following reasons:

- The fact that the real time ATVsim simulator uses numerical models, some of which are common with FES simulator, allows a direct analysis of ATVsim output data files by FES post-processings, without any additional processing.
- The telemetry outputs can be treated, using a dedicated tool (called "GNC_tool"), in order to compute most of the variables issued during real time simulation by the LN3_FES. The GNC_tool has been developed under MATLAB® environment in order to use its significant interpolation performances.

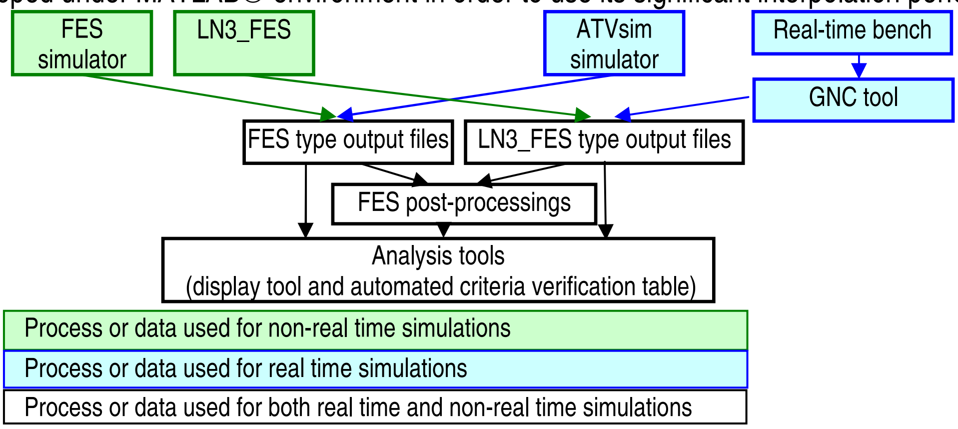
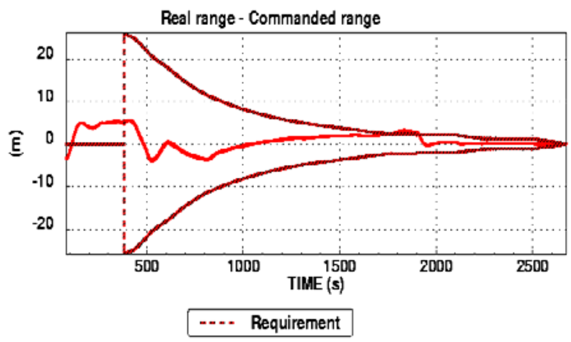


Fig 5. Common post-processings used for both real and non real time facilities

Requirements verification for both real time and non-real time facilities

The first way to verify the different requirements is to represent all the associated variables and specifications and visually check that none of the plotted variables goes beyond authorized values. This method allows observing the general behaviour of the ATV Flight Control and can reveal suspicious behaviours even when they do not lead to a requirement violation. For Monte Carlo tests, minimum, maximum and 3σ values are plotted to be compared with the requirements. The main drawback of this method is that the number of graphs to analyze can be significant (up to 400 curves for CLOSE rendezvous phase). It is thus impossible to quickly provide a diagnostic on the success of a simulation.



				GNC_ mode1	**GNC_ moden**
			Time(s)	80,1	1897,1
Parameter description	**TS0001**	**Item**	**unit**		
GNC attitude and attitude rate error	**GNC**	**Rq #**		**AAA**	**BBB**
		REF frame	**-**	**LVLH**	**LVLH**
		$\Delta\theta$	deg	8,10	5,10
		min	deg	-0,04	-1,35
		max	deg	9,10	-0,01

Fig 6. Examples of specific FES graphics and of automated criteria verification tool

The goal of the automated criteria verification tool is to summarize, in one table, the information related to the respect of the requirements. It was decided to gather in a table the maximum and minimum values for each parameter over each mode of a simulation and automatically compare them to their associated requirement. If there is a requirement violation, the incriminated parameter is automatically highlighted in red (see Fig 6.).

V ATV GNC QUALIFICATION DETAILED PROCESS

This part deals with the overall numerical validation philosophy. The main driver is to validate in an incremental and iterative manner GNC software from the unitary blocks up to the final product integrated in the real FAS and tested on a real time bench:

- When GMS/N/GC/FRMS/FCM blocks have been designed, they have first been validated separately on mock-up and specific unitary simulators. Functional analyses (for instance harmonic studies for controller) and simulations have been carried out in order to have separated demonstrated performances. Those results have been presented at ATV Critical Design Review (CDR).
- Afterwards, all the GNC unitary blocks have been ADA coded, unitary tested on host computer, and integrated in LN3_FES, representative of the GNC part of the on-board FAS.
- The FAS GNC formal numerical non real time validation is achieved via simulations of the LN3_FES integrated in FES facility: the implementation solution is to have two separate sets of code, i.e. two executable processes, one developed under SIMULINK® (FES), the other being an independent ADA process (LN3_FES), communicating with each other using the UNIX based socket mechanism.
- The FAS GNC formal real time validation is achieved via tests performed mainly on two tests benches: the SVF-Q and FSF platforms. The Product Under Test from the point of the qualification campaign is primarily composed of the FAS and the MSU softwares and all on-board flight segment equipments. Whatever the test platform, they run on target computer machines: 3 DPU and 2 MSU, and use real MIL-1553 Data Busses. These softwares run in real time and manage combinations of electrically and functionally representative equipments, and numerical models.
    - The FSF (see Fig 7.) embeds a maximum number of real equipments: it is either EQM (Electrical Qualification Model), EM (Electrical Model), or even FM (Flight Model).
    - The SVF-Q is the all-digital version of FSF, except for the 3 DPU & 8 1553 data busses, and the two MSU that are kept real.

Fig 7. View of FSF platform in ASTRIUM-ST Les Mureaux with the docking port in the foreground and the avionic bay in the background.

- A cross-validation has been performed between dedicated FES and SVF-Q or FSF tests, for each ATV flight phase, to show that the level of differences between non-real time and real time tests is a level of magnitude under the GNC requirements. To prove this allows considering the FES tests as “qualificative” ones.
- The IVF-EPOSX test bench (see Fig 8.) is used to check the correct behaviour of the ATV system in a representative optical environment. This bench uses the Flight Control main function, with the real rendezvous sensors and a Service Module mock-up with the Rendezvous Target. IVF is a facility similar to SVF-Q, allowing running, on a real DPU, the FAS with an ATV flight simulator. It is interfaced with EPOSX facility, providing mainly a command interface to drive EPOSX kinematics with IVF calculated trajectory.


Fig 8. Service Module Mock-up and Payload Carrier Platform - test on IVF-EPOSX platform (Val de Reuil).

- A cross-validation between FSF and IVF-EPOSX results has been performed as far as videometers and telegoniometers data are concerned, using the same ATV and ISS trajectories (injected in open loop on FSF).
- The IVF-Moscow platform test bench is used to check the correct behaviour of the ATV system involving the Flight Control main function, including the real GPS ATV and ISS receivers, as well as real RF link. As far as GNC is concerned, the major difference in this case is that the ISS motion is computed by a RSC-Energia model. The GPS front-end is in charge of simulating the GPS constellation and the GPS signals, and is connected to a Low Noise Amplifier instead of GPS antennas, from a radio frequency point-of-view. The signals are simulated in dynamics and attitude conditions determined by the simulators through antenna pattern. The front-end is based on a SPIRENT, composed of a RF generation rack and a control station.
- No formal FSF versus IVF-M results cross-validation has been performed. Nevertheless, the levels of error on ASN outputs have been compared to the inputs generated by the simulator, for example. These levels have also been measured in flight by RSC-Energia before the first Jules Verne Mission. However, a feedback on MODASN numerical model representativity, through a comparison with IVF-M, or even flight results, would be necessary to complete the validation process (for example, for a better characterization of the ionospheric effects, which have been revealed as particularly influent by the first post flight analyses).
- Finally, outside properly speaking qualification process and in an experience feedback goal, cross-comparisons have been performed between Jules Verne Mission telemetry and FES non-dispersed closed loop tests and also cross-comparisons between the Jules Verne telemetry and open loop tests with LN3_FES component.

Purposes of the FAS GNC function validation on non real time platform (with FES facility)

The purposes of the FAS GNC function validation on non real time platform are:

- To validate once more the algorithms coding: the validation tests complete the ones performed on unitary blocks. By activating those unitary blocks in a complete GNC loop, the tests may reveal coding issues in situations that could not be covered or that were not envisioned by the previous unitary tests.
- To validate the interfaces between the functions (integration tests).
- To confirm algorithms principles and design with respect to requirements.
- To evaluate the complete GNC loop algorithms global performances and check the associated requirements: the FES simulator allows producing a representative environment of the ATV flight, with real flight conditions and equipment characteristics. In particular, sizing biases or failures can be injected and the robustness and performances of the GNC loop algorithms in any conditions can thus be assessed.
- To analyze coupling effects induced after algorithm integration: the coupling effects can be produced by the coding of the unitary blocks themselves but also by the data of the modeled equipments. Particular hazardous combinations may thus be revealed.
- To validate all the GNC algorithm modes and their transitions: a GNC mode corresponds to the activation of a certain set of unitary blocks. When a transition from a mode to another is performed,

there is a risk that the activated blocks are not correctly initialized or that a peculiar coupling effect is revealed for instance.

- To perform some reference cases for real time facilities qualification tests: the simulations run on FES are used as references for cross-comparison with all real time facilities. Once the FES representativity is demonstrated (with respect to real time facilities), all FES tests can be considered as “qualificative” for GNC and participate then, in a significant manner, to the ATV flight control qualification.

To achieve these different purposes, two types of tests have to be run: FES unitary tests (sizing cases tests) and Monte-Carlo tests:

- **FES unitary tests (sizing cases)**

A sizing case test corresponds to a particular scenario i.e. flight sequence for which all simulations parameters are set to their maximum or minimum values and during which failures might be injected. A validation campaign begins with the identification of the sizing cases necessary to cover all possible GNC modes and mode transitions, to cover all existing vehicle configurations (propulsion, tank and sensors configurations), to verify all applicable requirements, to test the raising of all mission events, to test the raising of all alarms through the injection of failures, to test the impact of sizing failures, to test multiple combinations of simulations parameters, to minimize the number of simulations.

- **FES Monte-Carlo tests**

The Monte-Carlo tests are a set of multiple simulations respecting the same flight sequence but with input parameters randomly drawn using their probability density law. For a given Monte-Carlo, only one sequence of GNC modes is tested. A Monte-Carlo being, in general, time-consuming, it was decided to test the nominal sequences (no injection of failure) of three flight phases on FES: FAR rendezvous, CLOSE rendezvous and Departure. An additional contingency Monte-Carlo has also been run to test the particular ESCAPE sequence (manoeuvre which is triggered by FAS in certain contingency cases to move ATV away from ISS). This way the behaviour of the ATV and the performances of the GNC algorithms in multiple environments during the nominal sequence can be assessed. Moreover, the fact that all the parameters are randomly drawn also allows testing multiple combinations of parameters and may reveal hazardous situations.

The Monte-Carlo simulations challenges are very different from the unitary tests ones. Indeed, the goal is not to test all the transitions, modes and alarms but to run the same sequence with as many different conditions as necessary to deduce the ATV GNC performances.

Performing a Monte-Carlo sets many issues since running more than 1000 tests can be time and space consuming, if the process is not optimized. Thus, a specific platform has been built to parallelize the different unitary simulations. For example, thanks to the parallelization method, the total time for a FAR rendezvous Monte Carlo falls from 56 days (if all simulations were performed in series), to 7 days. This specific platform also allows identifying the simulations that led to worse cases w.r.t a specific requirement and to rerun them.

Purposes of the FAS FLC function validation on real time platform (SVF-Q and FSF facilities)

The goal of the tests performed on real test benches is the validation in a real time environment with real hardware of the correct functioning of the overall ATV system, i.e with most of the Functional and System Units integrated together.

As far as the GNC is concerned, all GNC test objectives related to the direct mechanical behaviour of ATV are permanently checked during the qualification campaign, if applicable. A maximum number of tests are run on FSF, in real time, with real hardware (except dedicated Rendezvous and some CAM tests on SVF-Q). The use of real hardware prevents extensive check of the Flight Domain, because the tests are already degraded cases due to Front End Equipment (FEE) latency times and signal distortion.

All tests are run with « nominal » data: no dispersion on thrust, sloshing frequencies, damping, MCIs etc. Performance of GNC is then not extensively tested. A few specific dispersed scenarios covering all flight phases have however be run on FSF. However, tests regarding GNC emphasize on:

- The respect of all requirements during tests performed with the real sensors and hardware.
- The potential synchronisation problems in a real time environment (for relative GPS navigation for example)
- The respect of hardware reconfiguration delays and other (potentially associated) switches to alternate plans.
- The capability of the FLC function to cope with the software or low level commands sendings which were only emulated on FES facility.
- The global FLC behaviour facing failures which could not be tested on FES facility.

VI ATV GNC CROSS-VALIDATION RESULTS

Comparison of the docking performances between unitary blocks and FES validations

The compliance of the GNC with requirements concerning the lateral position and velocity of the ATV at the instant of docking was tested for CDR on a Monte-Carlo of 1000 cases with mock-ups of the GNC blocks. The same performance has been studied on FES with a Monte-Carlo of 2330 cases. The GNC requirements are respected in both cases (see on Fig 9. - RS and DUP frames are tilted with a 45° angle), but the FES Monte-Carlo obtained a maximum lateral position higher than the worst-case of the CDR study. Indeed, the environment simulated on FES is much more complete than the mock-up which may lead to worst-cases. However, one can see that the majority of the simulations have a lateral position below 6cm in both cases.

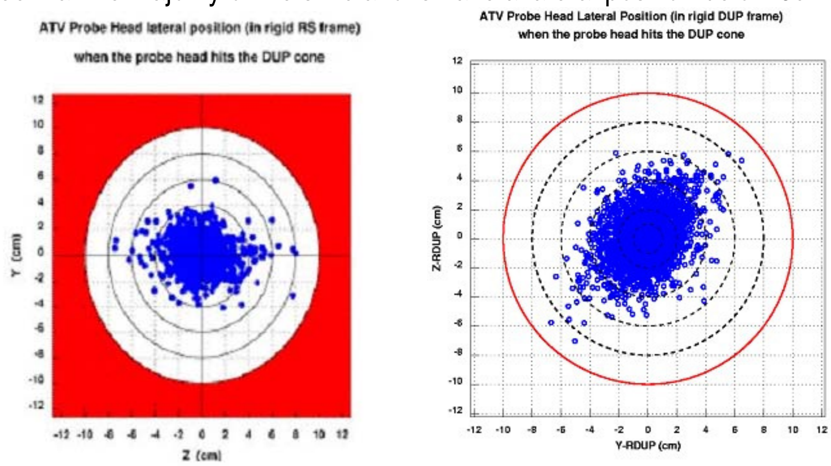


Fig 9. Distribution of lateral positions at docking for CDR and on FES.

Comparison of the trajectory during Rendezvous test between FSF and FES validations

A cross-validation has been performed between real time and non real time tests to prove that non real time and real time facilities are very close in terms of behaviours, and, therefore, to prove that FES tests can be considered as qualificative. For each ATV flight phase, one official test performed on FSF facility has been taken as a reference and a corresponding FES test has been built and run in conditions as close as possible from this reference. The goal of this cross-validation is to check that all differences between the real time and non real time results are one order of magnitude less than the corresponding GNC requirements (see Fig 10.).

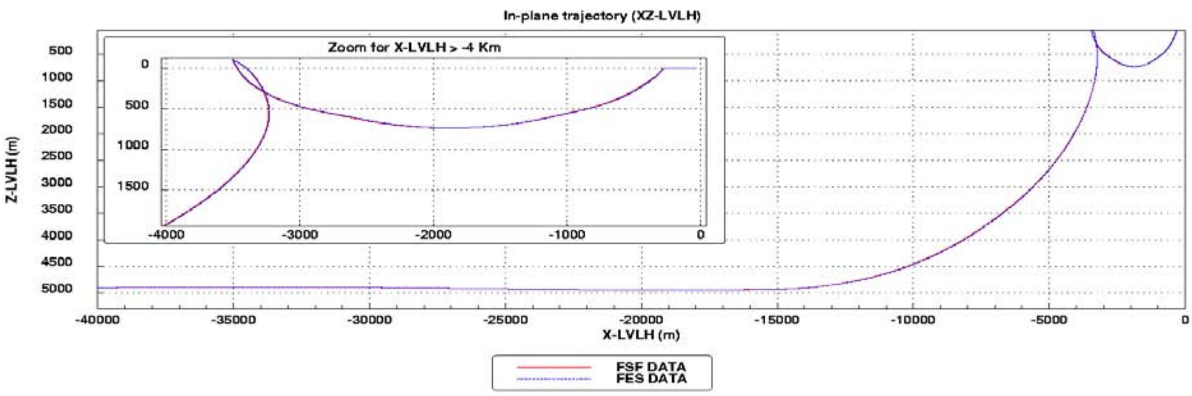


Fig 10. In-plane trajectory obtained for the Far Rendezvous during a test performed on FSF and FES facilities.

Comparison of the TGM retro-range during final approach FSF and IVF-EPOSX validations

The following curve (Fig 11.) shows the difference between the TGM retro-range during a final approach measured during an IVF-EPOSX and a FSF tests using the same trajectory.

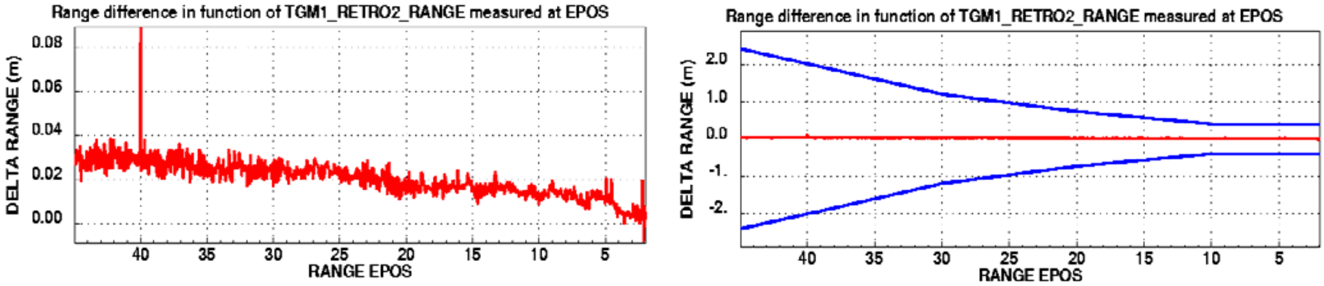


Fig 11. TGM 1 Retro 2 range obtained for the final approach during a test performed on FSF and EPOS-X facilities.

Comparison of the VDM sensors outputs during the 20 last meters of Jules Verne rendezvous day between FES and ATV flight housekeeping telemetry data

The following curves (see Fig 12.) show the difference between a FES closed-loop nominal simulation, using Jules Verne flight scenario, and the ATV flight telemetry. The VDM1 was the active VDM during this phase. The ISS rigid motion has been taken as representative as possible to get a match between FES IPC ISS attitude w.r.t LVLH attitude estimation and equivalent flight Housekeeping Telemetry. Nevertheless, FES simulation still seems to be a bit pessimistic w.r.t in-plane lateral off-set. The obtained FES performance at docking is 2.3 centimeters (see Fig 13.) whereas the ATV Jules Verne flight on-board estimated performance at docking is better than 2 centimeters (considering relative VDM close navigation data).

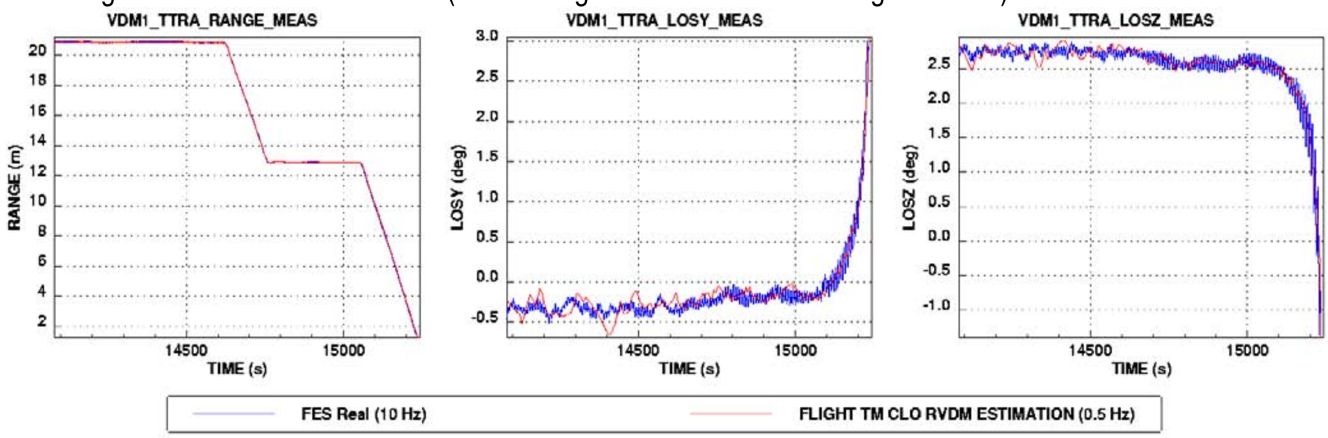


Fig 12. Close Rendezvous navigation position estimation and VDM sensors outputs obtained for the last 20 meters of the rendezvous day on FES closed loop simulation and in ATV flight housekeeping telemetry.

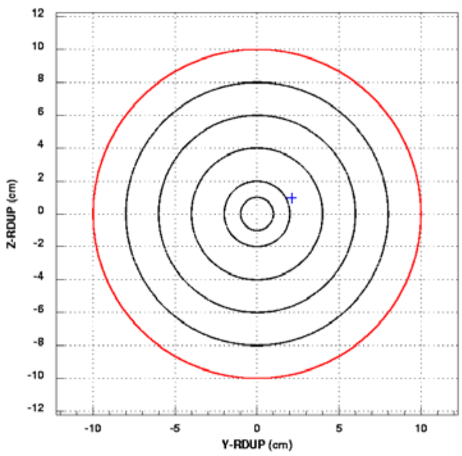


Fig 13. Transverse $O_{DUP} - O_{probe\ head}$ in DUP frame at contact obtained for the “flight like” FES simulation.

Analysis of GNC in flight behaviour thanks to open loop tests with the LN3_FES based on Jules Verne flight housekeeping telemetry

In the frame of post-flight analysis, open loop tests with LN3_FES component have been performed with the non real-time tool LN3_FES_OL on different flight phases: Launch and Early Orbital Phase, Survival, Demo Day 1 and 2. This tool uses flight housekeeping telemetry, which is interpolated to run the LN3_FES component in open loop. It allows performing deep analysis of GNC/GMS/FCM/FRMS in flight behaviour by checking reconstituted internal parameters and allows monitoring more parameters than those already sent in the telemetry. For example, during Demo Day 1, the LN3_FES_OL tool has rebuilt internal failure detection and isolation (FDI) consistency equations used by the sensors to detect potential failures which were not part of the telemetry (see Fig 14.). Of course, in case of GNC problem during the flight, which was not the case for ATV Jules Verne, this tool would be of great interest for investigations.

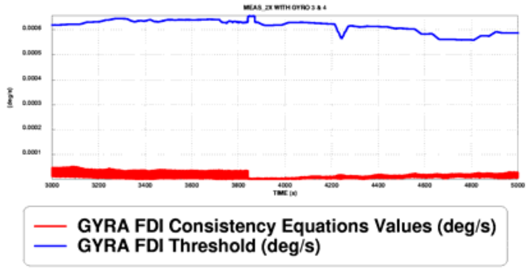


Fig 14. One of the FDI consistency equations for gyrometers during DD1 reconstitution on LN3_FES_OL tool

VII CONCLUSION

A complete strategy has been perfected by Astrium-ST in order to perform in an incremental and iterative manner the ATV GNC software qualification, from the unitary mocks-up, to the unitary and Monte-Carlo test on non real time facility and finally to the qualification on real time test bench. The same methodology applied on the complete process, the common development of numerical models and post-processings tools between real time and non real time facilities have allowed to show, in an effective way, the complete coherence between simulations at unitary blocks level, non real time and real time tests. Moreover, this complete and rigorous qualification process has allowed not discovering any problem of GNC performances during the ATV qualification campaign on real time benches. Finally, it has largely contributed to the first successful ATV mission, with three successful demonstration days and a docking of centimetric precision on the 3rd of April, 2008, 14:45 GMT.

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