Automated Transfer Vehicle Flight Dynamics System Lessons Learnt

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On March 23rd 2012, the third ESA Automated Transfer Vehicle (ATV), called Edoardo Amaldi, lifted off from Kourou aboard the Ariane 5 launcher towards the International Space Station (ISS) to which it docked on March 28th. ATV is designed to provide the crew with food and materials, ISS with propellant gas and water, to rise up the ISS altitude by several re-boosts and finally to unload ISS waste for a final burning into the atmosphere. The first mission, Jules Verne, had to demonstrate its capability to dock autonomously and safely to the ISS. So, it included additional mission phases as rendezvous demonstration days. The second mission, Johannes Kepler, was the first "recurrent mission". It docked directly to the ISS after an 8 days direct phasing to ISS. Thanks to the two first missions, FDS (Flight Dynamics Subsystem) has learnt lessons and implemented them. They cover various topics, such as mission analysis, software, operational baseline, procedures and manning. This paper describes the different lessons learnt by FDS and how their implementation allowed to optimize and simplify the operations.

I. Introduction

THE ATV is a program funded by the European Space Agency (ESA): the spacecraft is designed and build by ASTRIUM Space Transportation and operated by the French Space Agency (CNES) at ATV Control Center (ATV-CC) in Toulouse.

On 23 March 2012, the third Automated Transfer Vehicle (ATV) of the Edoardo Amaldi mission lifted off from Kourou aboard the Ariane 5 launcher towards the International Space Station. It was the third European automated spacecraft which has docked autonomously to the ISS. The ATV flights to the ISS are dedicated to provide the crew with food and materials, to provide the ISS with propellant gas and water, to raise up the ISS altitude by several reboosts, and finally to unload ISS waste for a final burning into the atmosphere.

Due to a launch delay and the closure of the docking opportunity window on April 2nd, this third mission experimented a short phasing in 5 days and a half.

II. Context

The ATV life in orbit is nominally divided into three main parts: the ascent phase, the attached phase, the undocking and re-entry phase. An example of nominal ascent phase scenario is the following (the number of Mid-Course and Transfer to ISS vicinity maneuvers depends on the phasing angle):

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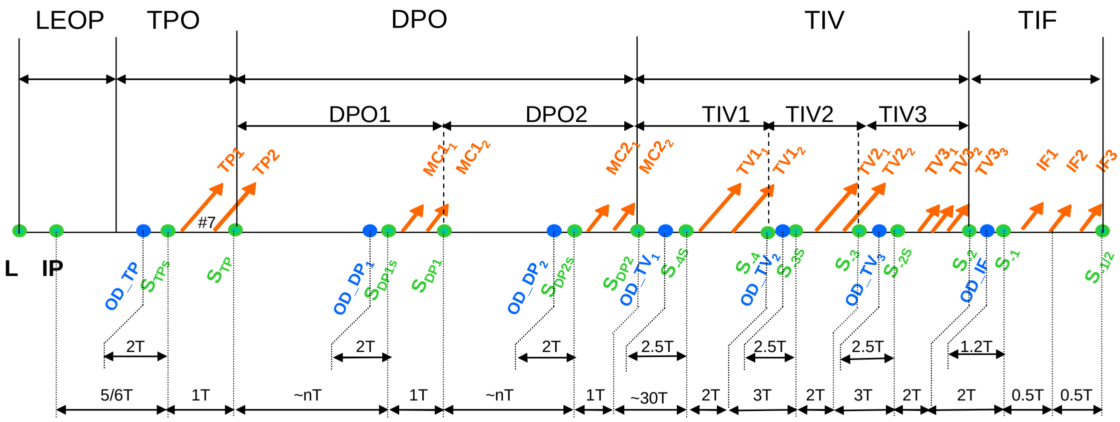

Legend:

LEOP	*: Launch and Early on-Orbit Phase*
IP	*: Injection Point*
TPO	*: Sub-phase Transfer to Phasing Orbit*
DPO	*: Sub-phase Drift on Phasing Orbit composed of 2 parts*
DPO1	*: Sub-phase Drift on Phasing Orbit with 1st Mid-Course maneuver cycle*
DPO2	*: Sub-phase Drift on Phasing Orbit with 2nd Mid-Course maneuver cycle*
TIV	*: Sub-phase Transfer to ISS Vicinity composed of 2 or 3 according to phasing angle*
TIV1	*: Sub-phase Transfer to ISS Vicinity-part 1, can be cancelled according to phasing angle*
TIV2	*: Sub-phase Transfer to ISS Vicinity-part 2*
TIV3	*: Sub-phase Transfer to ISS Vicinity-part 3*
IF	*: Sub-phase Transfer to RDV*
TP_1 *to* TP_2	*: Maneuvers*
$MC1_1$ *to* $MC2_2$	*: Mid-Course Maneuvers*
$TV1_1$ *to* $TV1_3$	*: Maneuvers*
$TV2_1$ *to* $TV2_3$	*: Maneuvers*
$TV3_1$ *to* $TV3_3$	*: Maneuvers*
IF_1 *to* IF_3	*: Maneuvers*
S_{TPs}	*: Start of the TPO sub-phase maneuvers range*
S_{TP}	*: End of the TPO sub-phase maneuvers range*
OD-TP :	*: Orbit Determination delivery for TP maneuvers calculation*
S_{DP1s}	*: Start of the DPO1 sub-phase maneuvers range*
S_{DP1}	*: End of the DPO1 sub-phase maneuvers range*
OD-DP1 :	*: Orbit Determination delivery for DPO1 maneuvers calculation*
S_{DP2s}	*: Start of the DPO2 sub-phase maneuvers range*
S_{DP2}	*: End of the DPO2 sub-phase maneuvers range*
OD-DP2 :	*: Orbit Determination delivery for DPO2 maneuvers calculation*
S_{-4s}	*: Start of the* TIV_1 *sub-phase maneuvers range*
S_{-4}	*: End of the* TIV_1 *sub-phase maneuvers range*
OD-TV1 :	*: Orbit Determination delivery for TIV1 maneuvers calculation*
S_{-3s}	*: Start of the* TIV_2 *sub-phase maneuvers range*
S_{-3}	*: End of the* TIV_2 *sub-phase maneuvers range*
OD-TV2 :	*: Orbit Determination delivery for TIV2 maneuvers calculation*
S_{-2s}	*: Start of the* TIV_3 *sub-phase maneuvers range*
S_{-2}	*: End of the* TIV_3 *sub-phase maneuvers range*
OD-TV3 :	*: Orbit Determination delivery for TIV3 maneuvers calculation*
OD-IF :	*: Orbit Determination delivery for IF maneuvers calculation*
S_{-1}	*: Soonest* IF_1 *location*
$S_{-1/2}$	*: Targeted final phasing point*
nT	*: n revolutions*

Figure 1. Phasing scenario overview

Since the first Jules Verne Mission was an in-flight demonstration mission, the ATV did not dock to the ISS at first rendezvous attempt. To ensure the safety of the ISS, the Jules Verne docking did not occur before the third rendezvous attempt. The demonstration concept consisted in approaching closer and closer to the station for each attempt before triggering an Escape maneuver in order to come back 48 hours later to perform a new attempt. At third attempt, the ATV ran the final approach until the end and docked to the ISS.

The second mission, Johannes Kepler, was the first "recurrent mission". It docked directly to ISS after an 8 days direct phasing.

For the third mission, Edoardo Amaldi, the preliminary hypothesis on launch date and docking date led to a first reference mission corresponding to a 8 days phasing towards parking point 2000 km behind the ISS, a 9 days station keeping at parking point and then the rendezvous phase. A few months before launch the launch date was readjusted and the reference mission turned into a 10 days direct phasing followed by the rendezvous phase. This reference mission was robust up to 3 days launch report by adjusting the phasing duration down to 7 days. On March 2nd, a routine inspection concluded that additional measures were required to ensure the maximum readiness of the third Automated Transfer Vehicle for launch. It was finally delayed to March 23rd, and the phasing duration decreased to 5 days and 13 hours, in order to be robust to two rendezvous attempts, due to the closure of the docking window on April 2nd.

The FDS (Flight Dynamics Subsystem) is in charge of all the flight dynamics functions required to watch over and reconfigure the ATV mission during the execution phase. It computes the maneuvers and the actual trajectory of ATV for all the phases of the mission, while determining the orbit, forecasting the events, screening the debris and monitoring the on-board GNC functions, especially during rendezvous. So, until $S_{-1/2}$ (interface between phasing and rendezvous) and after undocking, the maneuvers are computed and loaded by the ground.

As the missions went along, some improvements revealed necessary to be implemented in FDS:

- complementary mission analysis studies, to cover a bigger flight domain for long or short phasing duration
- software robustness and improvement increase
- operational baseline consolidation by preparation of backup scenario
- procedures improvement since it is a key tool used by all the operations
- manning generation automation which was very heavy to produce for Jules Verne Mission since it was manual
- team reduction

III. Lessons Learnt

A. Complementary mission analysis studies

1. Long duration phasing

The first ATV mission showed that it was necessary to increase the initial flight domain covered by the Generic System Mission Analysis: the extension of the covered flight domain at each mission permitted to propose more direct phasing strategy scenarios without having to go systematically to parking when phasing duration is greater than the maximum studied duration (8 days for Kepler, 13 days for Amaldi).

In order to demonstrate the robustness of maneuver scenarios, several End-To-End Monte-Carlo simulations have been performed. At each mission, the flight domain of the current mission has been covered, which finally results in a large flight domain covered after Edoardo Amaldi. The parameters checked throughout the analysis were: TP value dispersions, MC value dispersions, check of the TV maneuver sliding, compliance of the IF values and dispersions at $S_{-1/2}$ arrival.

Fig. 2 shows the End-to-End simulations that have been performed and the perimeter of the ATV missions that has been covered with these simulations. This perimeter is expressed in mission duration (days) and ISS targeted invariant altitudes.

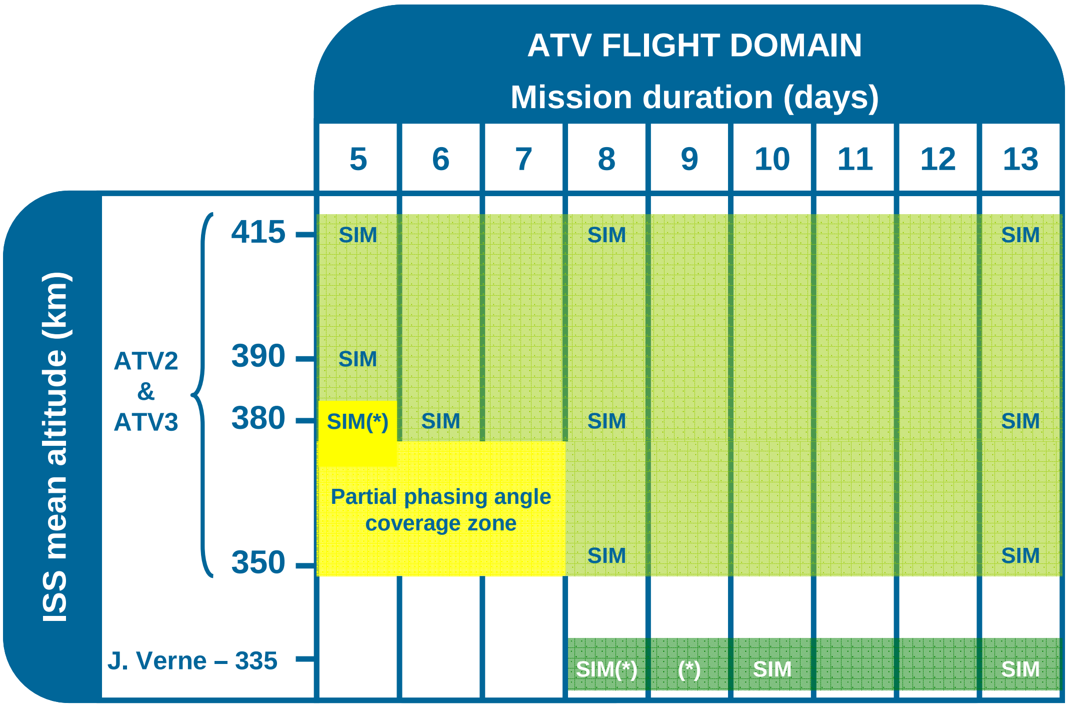

Figure 2. Monte-Carlo simulations and Mission perimeter overview

Fig. 2 must be read as follows:

- The light green color stands for the perimeter covered by the Monte-Carlo simulations performed within the mission analysis. All the simulations confirmed the feasibility of the ATV missions.
- The dark green color stands for the perimeter covered by the simulations performed for Jules Verne mission
- The yellow color stands for the "Partial phasing angle coverage zone" (belongs to the short duration phasing zone), no Monte-Carlo simulations have been run on this region, but an approached study on the feasibility of ATV missions within this region has been performed and is presented later.
- "SIM" capital letters stand for the performed scenarios in the simulations End-to-End (performing simulations at the limits of a zone permits to ensure the feasibility in the entire zone).
- The (*) symbol stands for those scenarios that, being feasible, have presented negative TP maneuvers

For scenarios between 8 and 13 days of duration, the feasibility of the selected phasing strategy for ATV missions has been demonstrated for any phasing angle and any ISS mean altitude between 350 and 415 km.

2. Short duration phasing

A sufficient number of scenarios has been selected to run nominal phasing trajectories, all of them for short phasing durations (4 to 8 days) at low and medium altitudes (from 350 km to 420 km). Then a linear interpolation from these reference simulations has been performed for intermediate altitudes. The objective of this analysis was:

- to identify, for a given ISS altitude and phasing duration, the phasing angle interval that can be covered by the ATV vehicle, even if this interval is smaller than [0;360 deg]
- to determine, for a selected duration, the minimal ISS altitude for which the ATV is able to perform the phasing whatever the initial phasing angle.

The covered perimeter is described in the next table.

Phasing angle (°)	Altitude		Phasing duration (days, approx)				
			4 d	5 d	6 d	7 d	8 d
	350 km	ΦMin	188	234	296	344	396
		ΦMax	314	430	529	648	773
		Φmax –Φmin	*126*	*196*	*233*	*304*	*377*
	360 km	ΦMin	192	238	300	348	400
		ΦMax	347	473	585	716	853
		Φmax –Φmin	*155*	*235*	*285*	*368*	*453*
	370 km	ΦMin	197	243	304	352	404
		ΦMax	380	517	641	785	934
		Φmax –Φmin	*184*	*274*	*337*	*433*	*530*
	380 km	ΦMin	201	247	308	356	408
		ΦMax	413	560	697	853	1014
		Φmax –Φmin	*213*	*313*	*389*	*497*	*606*
	390 km	ΦMin	205	251	312	361	412
		ΦMax	447	604	754	922	1095
		Φmax –Φmin	*241*	*353*	*442*	*561*	*683*
	400 km	ΦMin	209	255	316	365	416
		ΦMax	480	647	810	990	1175
		Φmax –Φmin	*270*	*392*	*494*	*625*	*759*
	410 km	ΦMin	214	260	320	369	420
		ΦMax	513	691	866	1059	1256
		Φmax –Φmin	*299*	*431*	*546*	*690*	*836*
	420 km	ΦMin	218	264	324	373	424
		ΦMax	546	734	922	1127	1336
		Φmax –Φmin	*328*	*470*	*598*	*754*	*912*

Table 1. Minimum and Maximum phasing angles (°)

For green-dyed cases $\Phi_{max}-\Phi_{min} \geq 372°$, a valid maneuver scenario can be built for the whole phasing angle range.

The specific case of 5 days and 390 km of ISS mean altitude (Edoardo Amaldi case) has been placed out of the green zone of this table, this is caused by the safety margins, however a dedicated end-to-end Monte-Carlo simulation has been performed, showing that this limit case is feasible for any phasing angle with TP and MC posigrade maneuvers.

Table 2 hereafter presents the minimum ISS invariant altitudes at which the ISS can be reached for all initial phasing angles:

	Phasing duration (days)				
	4	5	6	7	8
Minimum ISS mean altitude (km)	greater than 420km	390	380	370	350

Table 2. Minimum ISS altitude for short phasing durations

B. Software robustness and performance improvement

3. GNC monitoring

The FDS is responsible during the whole ATV mission for the monitoring of the on board GNC functions. The requirements for the GNC monitoring come from three different sources:

i. **ATV-ISS Joint Flight Rules.** Joint rules agreed with the International Partners. They prescribe a continuous monitoring from $S_{-1/2}$ that has to be able to provide GO/NO GO at any hold point or be able to detect off nominal situations at any time. The main objective of ATV-ISS Joint flight rules is to ensure ISS Safety.

ii. **ATV Vehicle User's Manuals.** Specified by ATV Design Authority (ASTRIUM ST). They request a monitoring all along the mission with the biggest part in rendezvous. The main objectives of these requirements are to assure mission success.

iii. **ATV-CC Monitoring document.** Specified by ATV-CC. This document states the monitoring to be performed all along the mission with the biggest part in rendezvous. The main objective is to give a complement to the previous two sources to increase mission and operation reliability.

These requirements are implemented at FDS level through real-time consistency checks between on board data and ground tools that implement comparable functions, but trying to be the most independent possible. Depending on the monitoring, on board or ground data can also be compared to predicted absolute/relative trajectory and attitude profiles or boost commands. The implementation logic is reported in Fig. 3, where T-XXX represents the different tools that are implementing or contributing to the GNC monitoring.

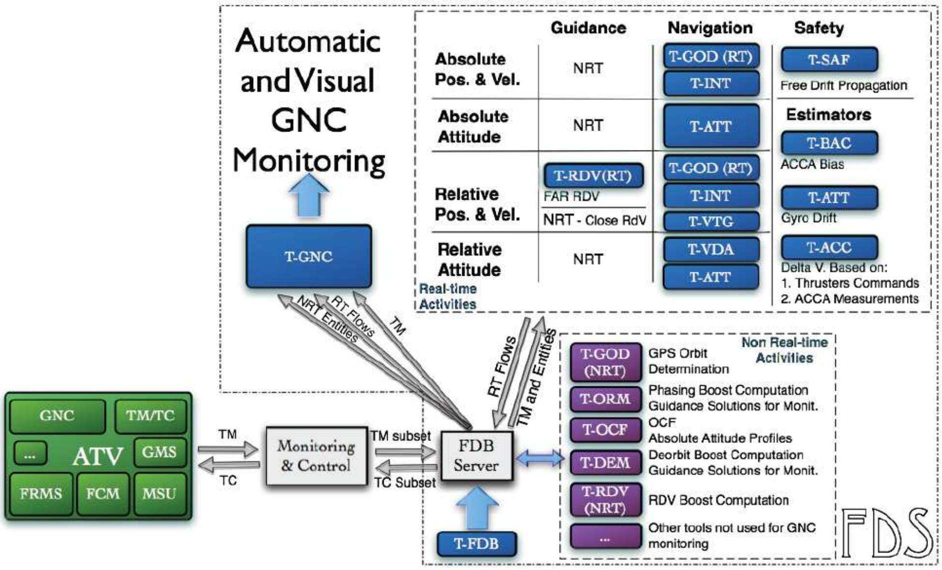

Figure 3. GNC monitoring implementation at FDS level

After the first ATV flight (Jules Verne mission), the GNC monitoring has been improved in the concept as well as in the implementation, taking particular advantage of some lessons learnt. The main improvements are:

- It has been observed during the first ATV flight that the comparisons and the thresholds were not homogeneous. After the first flight, the GNC monitoring thresholds have been completely reassessed and retuned. All the Joint Flight Rules thresholds have been recomputed by the FDS taking into account the three-sigma GNC flight envelope from the on board software Monte-Carlo simulations. They have been agreed later by the international partners and are now embedded in the Joint Flight Rules. In addition, the reference for all the most important monitoring is now the relevant FDS ground tool
- Before each ATV flight, the performance of the FDS ground tools is assessed, if needed, based on the on board corresponding Monte-Carlo simulation. For the first flight this activity has been very intensive and expensive in terms of resources. After the first flight, all the activity has been reengineered. The tasks that could have been automated have been. Now, when the new Monte-Carlo campaign is provided to FDS, there are three main tasks to be performed: (1) FDS context preparation from data (2) tools running (3) post-processing. The post-processing generates an automatic Latex report that has to be revised and commented by the operator. Almost all the other parts are now automatic
- During the Jules Verne mission, it has been observed that the MMI of the GNC monitoring master tool (T-GNC) was not fully adapted to the need, in particular in terms of ease to use and response. After the flight, it has been rewritten having in mind these particular aspects. The result for the Kepler and Amaldi missions is quite satisfactory. Now T-GNC is not limited to the FDS team, but is also used to share information with the other teams of ATV-CC and to be shown in the control centre wall screen
- To take into account some observations during the previous missions and simulation tests, the robustness of some tools has been increased. In particular: (1) the tool that performs the ground absolute and relative navigation in position and velocity based on GPS measurements (T-GOD) has been improved to take into account accelerometer measurements for the theoretical model. This allows the tool to be less sensitive to the position and duration of the boosts. Before this implementation, the theoretical model used the predicted boosts. In the case of an under/over boost or other contingencies, the ground navigation diverged. (2) The tool that computes the ground guidance solution in position and velocity during far rendezvous (T-RDV) has been improved to be able to start anywhere during the far rendezvous. In the previous implementation, it had to be started during pre-homing (between $S_{-1/2}$ and S_1) catching up to the current time. In the case of a repetitive behavior facing to a specific problem at a given point, it was unable to finish the rendezvous phase. (3) The management of switched-off sensors has been improved on all the relevant tools.

4. *Operational forecast*

After Jules Verne mission, in order to improve the timing performances of operational forecasting tool and also to avoid the trouble which caused in Flight Dynamics data base contents the large amount of space disk required by the output files of the tool, the following modifications on FDS system have been performed:

- The MMI has been modified to include the selector to generate or not some secondary output files which are not needed for timeline (orbital events, visibilities,…) or constraints plots
- In order to reduce the size of the output files, a new parameter has been included in the MMI giving the frequency wrt the computation time-step for the output file generation.

5. *Debris screening*

During the ATV-Jules Verne operations, external tools to FDS had to be used and operated by an external team in order to assess the collision risks with debris.

The objective of the debris screening evolution was to increase the autonomy and the means in the ATV-CC in relation to the collision risk assessment. The main evolutions of the tool (T-ARC) were:

- To be able to use an "Historical TLE (Two-Line element)" file to do the assessment of collision risks/tendency analysis with a specific debris. This "Historical TLE" file contains all TLE stored for a specific debris during a given period of time.
- Plot in collision plane for every detected conjunction (C1 and C2 relative distance and ATV exclusion area). Include the ATV and debris dispersion projected in collision plane.
- Add a new mode dedicated to the analysis of the effect of maneuver on separation distance of a conjunction.

This improvement has permitted to perform a debris avoidance maneuver during a critical phase, few hours after Edoardo Amaldi undocking.

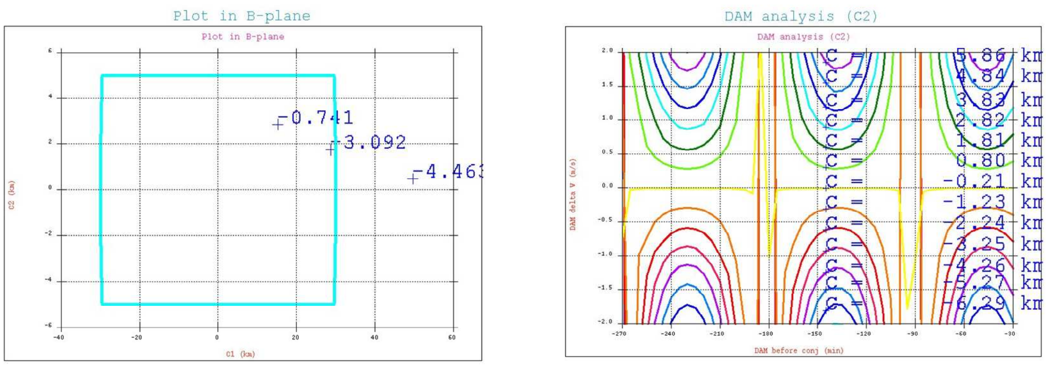

Figure 4. risk with a debris in the B-plane – trend analysis and analysis of the effect of a maneuver

6. *Interface management*

The aim of this evolution was to ensure a better distribution of functions between software. Before this evolution the input/output interfaces generation and sending was managed at the same level by the same tool. After this evolution, the generation and sending of the products (telecommands, forecasting events,…) were separated.

This added a lot of advantages in operations:

- Get the traceability for external interfaces and telecommands generation
- Clarify the GUI to make it homogeneous with the other software GUI
- Gather in one tool centralised FDS functions
- Allow validation and automated non regression tests
- Give a higher flexibility for changes in products generation

Fig. 5 shows the separation of function for a telecommand generation and sending:

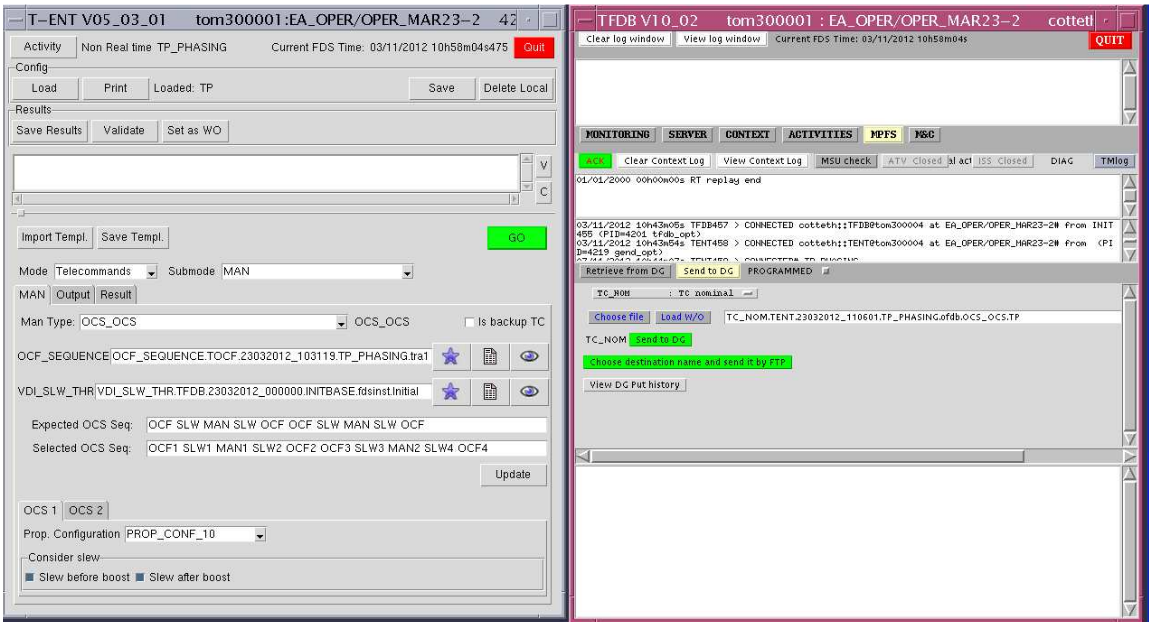

Figure 5. MMI of the two software in charge of sending and generating the products: example of telecommand

7. Plots and GUI

All the FDS tools share a common base architecture. One part of this architecture is the graphics engine called Xtrace that is developed by CNES. Another part is the GUI framework called Genesis, also developed by CNES. For the Jules Verne mission, each tool had an MMI created in Genesis that embedded into the MMI an Xtrace frame. In that implementation, all the tools needed an own controller to the graphics engine and provided a very basic control to the plotting functions. After the first flight, this solution was considered as a limit to take full advantage of the graphics engine. Moreover it was not easy to be kept up to date, due to the fact that Xtrace was embedded into each tool MMI. Even in terms of operability, that solution was not the best, because the graphic window, embedded in the MMI, did not allow having control at the same time on the tool MMI and on the plots.

In parallel, after the first flight, a new framework, based on Tcl/Tk, has been developed to create MMI's. It has been applied in particular to the T-GNC and T-ENT (generation of the products) MMI's because better than Genesis for performances and ease to use. At that time it was also decided to remove Xtrace from the tools MMI and to create a common tool that controls all the Xtrace instances from any running tool. This tool has been named DALI.

In Fig. 6 an example of the DALI MMI is reported. On the left the DALI Window Manager is shown. It allows capturing all the DALI instances for each running tool, having the possibility to show or hide any of them. On the right a specific instance for T-GNC is shown.

Since the mission Johannes Kepler, DALI has proved more robustness and flexibility in providing control on Xtrace. In particular it allows also having multiple graphic windows, frames and curves shown at the same time for each tool.

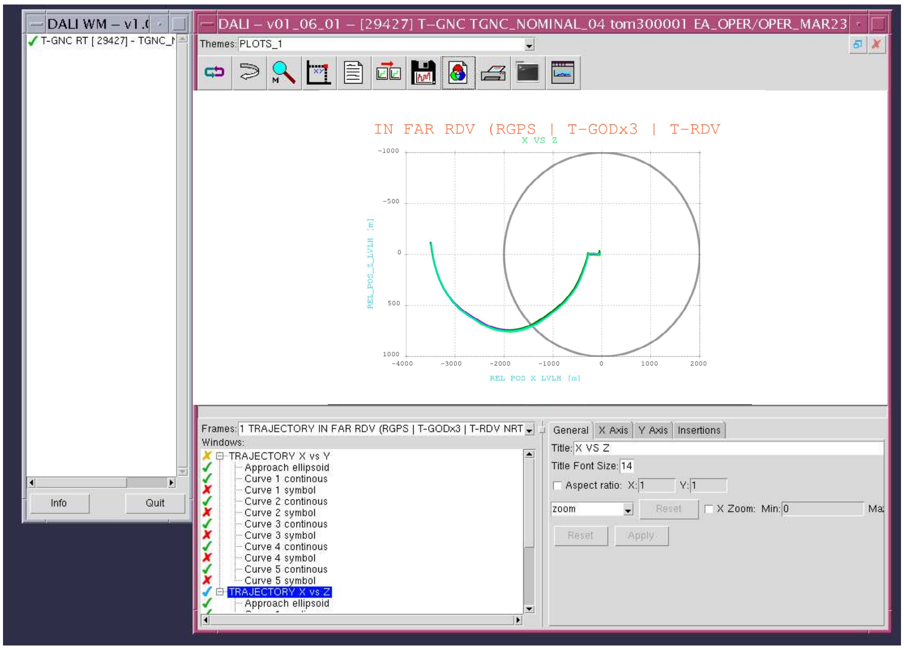

Figure 6. DALI MMI. On the left the DALI Window Manager and on the right the DALI for a specific tool (in this case T-GNC)

C. Operational baseline consolidation

After Jules Verne, FDS have found necessary to set up operational backup solutions when it was possible and when the baseline relied on external means:

In rendezvous phase, the relative on-board GPS initialization nominally relied on ISS ephemeris delivered by Russian partners in non real time. In order to increase our level of autonomy and to get additional information permitting to cross-check the results, it has been possible since Johannes Kepler to use the GPS measurements from American receiver available in the telemetry.

In undocking phase, the monitoring of the departure was previously based on absolute GPS measurements from ATV and ISS ephemeris delivered by Russian partners in non real time. The nominal solution now consists in processing the GPS measurements from American receiver available in the telemetry instead of the ISS ephemeris.

In both cases the previous solution is now used as a backup.

D. Procedures improvement

For ATV1 and ATV2 missions, the procedures were only standalone Excel files.

For ATV3, all FDS procedures have been gathered in a database which can be read using a dedicated Tcl/Tk tool. This tool also presents functionalities to built, edit and modify procedures. It is also used in control room to ease consultation of procedures and to allow operators to know at any time which step has been done (network functionality).

A procedure is a list of steps which indicates the global task sequencing of the procedure. For each step, following information is given:

- Operator
- Previous step: operator must wait that previous step is done before starting the current step. It can be last step of the operator or last step providing and entry
- Latest time for the task to be performed
- Duration allowed for the task (duration since previous step)
- Description of the task
- Tool to use
- Name of the activity in which the result must be validated
- Name to be given to the result

- Flag to set result as Working Occurrence (current status of the data base) or not
- Specialist Procedure to use

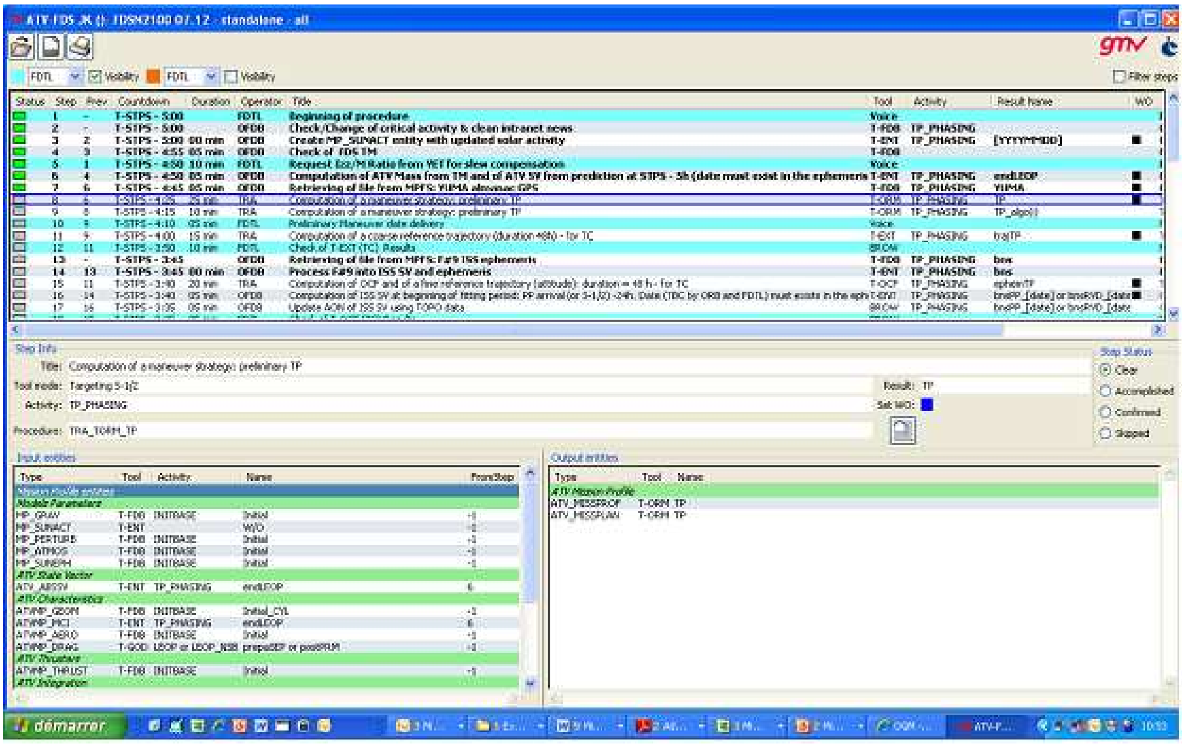

Figure 7. Example of operational procedure

E. Manning generation automation

On Jules Verne mission, producing a manning for 29 operators and more than 25 days operations was a very tedious activity which finally took several days!

For Johannes Kepler, we took these lessons learnt into account by producing the manning in a more automatic way: a visual basic program was developed and the steps were run in the following way:

- Positioning of all the procedures to be played over the period
- Definition of the operating team corresponding to the procedure to be played, depending on the phase
- Definition of the status of the other available teams: either on-call, or on rest (short or long)
- Global check of the work hours regarding the French legislation, re-loop if necessary

The program was designed to automatically place the operator status (On-call or on Rest), respecting all the constraints such as:

- French legislation work hours
- Change to on-call status outside night periods
- In case of a contingency, at least 2 teams must be available

Even if this method considerably lightened the manning production, the maintenance of the visual basic tool was very heavy, because of many specific cases to handle. Moreover, it did not cover some cases were the mission was too long, simply because no solution was found by the macro to fulfill all the constraints, resulting in frequent manual interventions.

Finally another method was developed for Edoardo Amaldi: it consists in manually positioning the rest periods first, which is the more restrictive constraint. The automated part is left to placing the 'On-call' status of the operators, according to a specific scheme and fulfilling the work hours of the French legislation. The team to be on-call can also be manually changed. This method avoided to fall into unsolved loops and proved to be very efficient. Furthermore the tool is easier to maintain: for Edoardo Amaldi, producing a manning took less than one hour.

F. Team reduction

One FDS team is currently composed of five FDS positions. Three FDS teams are necessary to ensure a full 24h manning in the last part of the ascent phase. The different positions roles are described hereafter:

- FDTL
    - Coordination of Flight Dynamics activities and responsible for the results provided by FDS
    - Operational interface (CNES and external) for FDS (except particular waiver)
    - Provides GO / NO GO before critical maneuvers according to the dedicated sequential procedure
    - Updates the manning during the operations in real time according to the planning of briefings/debriefings and keeps the team informed
    - Monitors the timing of external data arrival (Partners, Mission,..)
    - Updates the operations logbook in order to ensure operations continuity during shifts and to provide the most updated information during debriefings
- ORB
    - Determines the injection point from Ariane 5 telemetry and its validity
    - Determines the orbit from GPS measurements (absolute localization during phasing then relative during rendezvous)
    - Compares the GPS ephemeris with those obtained from TDRS measurements in order to validate internal orbit determination
    - Determines in real time the speed increments and the corresponding trajectory from accelerometer measurements and thrusters on-time
    - Computes the collisions risks with debris
- TRA
    - Computes the orbital maneuvers for the following phases of the mission: phasing, interface between phasing and rendezvous, parking, post Escape or post CAM, re-entry
    - Validates the foreseen maneuver plan (computed on ground or on board) wrt ISS safety
    - Computes the slew maneuvers
    - Computes the reference local orbital frame and the necessary updates
    - Computes the reference trajectories including the relative ATV/ISS trajectory during rendezvous
    - Computes the debris avoidance maneuvers if necessary
- GNC
    - Monitors the on-board functions: assess during all the phases of the mission the behavior of the main navigation and guidance functions of GNC and the whole GNC loop
    - Continuous monitoring of ISS safety on a "free drift" trajectory of the ATV
- OFDB
    - Management of the Flight Dynamics Data base
    - Archiving and delivery of the data to FDS tools
    - Broadcasts through video circuit the trajectory and the attitude of ATV and ISS, and the relative trajectory of ATV wrt ISS
    - Computes the geometrical and radio electrical visibilities of the ATV wrt ground stations, TDRS, GPS and ISS
    - Computes the sun eclipses by the earth
    - Computes the sensors dazzling (ISS camera, Star Tracker)
    - Computes the launch, docking, undocking opportunities

The different FDS teams' composition along the three missions is described hereafter:

	FDTL	TRA	ORB	GNC	OFDB	OPF	FDB	GRA	shadow	Total
Operations ATV1	3	5	5	5	0	3	3	1	4	29
Operations ATV2	3	4	4	3	3	N/A				17
Operations ATV3	3	3	3	3	3	N/A				15

Table 3. FDS team composition along the missions

For ATV Jules Verne mission, the main drivers were:

- During critical phases, two shifts were required plus a shadow team for complementary analysis, back-up and/or contingency cases
- Some positions were doubled during critical phases (LEOP, rendezvous and undocking)

After Jules Verne mission, the shadow team was integrated in the operational team thanks to the debris screening software improvement (described in paragraph B.). Thanks to operational forecast software improvement (described in paragraph B.), the position OPF, FDB and GRA could be merged into the position OFDB. The lessons learnt, the procedure improvement and the good behavior of maneuvers computations algorithms and orbit determination algorithms permitted to relax the constraint of doubling the TRA and ORB during all the phases. Since then TRA and ORB positions are only doubled in RDV phase.

After Johannes Kepler mission, the amount of tasks and studies in operations preparation at TRA and ORB positions level have been lighter and therefore it was possible to decrease the number of TRA and ORB operators to three even if their position is doubled in RDV phase.

IV. Conclusion

The experience acquired during the first three missions as well as the maturity level achieved by the mission analysis, the software and the operational products has permitted to FDS team to reach a high level of skill, and to prepare the last two future missions with great confidence.

Appendix A
Acronym List

ATV	Automated Transfer Vehicle
ATV-CC	ATV Control Center
CAM	Collision Avoidance Maneuver
FDS	Flight Dynamics Subsystem
GNC	Guidance, Navigation and Control
GUI	Graphic User Interface
ISS	International Space Station
MMI	Man Machine interface
TDRS	Tracking and Data and Relay Satellites
TLE	Two Lines Element
Wrt	With respect to

Appendix B
Glossary

B-plane	Perpendicular plane to the relative velocity of the two objects and centered on the ATV at the date of the closest distance
Docking	The docking brings the ATV safely from the conditions achieved jointly by ATV and ISS at the end of the final approach to the “attached to ISS” configuration, stable and safe, enabling to proceed with the ATV-ISS attached operations
Invariant elements	A set of mean Keplerian orbital elements that display only slight variations over the period of a given orbit
LEOP	Launch and Early Operations Phase
Phase angle $\Delta\Phi$	The phase angle $\Delta\Phi$ is defined as the difference of both vehicle positions on orbit
Phasing	The phasing starts at the LEOP completion and stops when the ATV reaches the vicinity of the ISS at the point named $S_{-1/2}$
S_1	S_1 is defined as the waypoint where the ATV trajectory crosses the Hohman line
$S_{-1/2}$	The way point $S_{-1/2}$ is located 39 km behind and 5 km below ISS
Timeline	Ascii file gathering the operational forecast events: orbital or vehicle events of the mission (for example: begin, end of maneuvers, begin and end of half lobe visibility , begin and end of eclipse and penumbra , begin and end of dazzling of ATV star trackers ….)

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