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ARTICLE 2

V.20 September, 2011

Title

ATV Jules Verne: a Step by Step Approach for In-Orbit Demonstration of New Rendezvous Technologies

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ATV Jules Verne: a Step by Step Approach for In-Orbit Demonstration of New Rendezvous Technologies

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In order to gain enough confidence in the behavior of the first Automated Transfer Vehicle “Jules Verne” (ATV-JV), the European Space Agency (ESA) defined a set of objectives and criteria to be met during the demonstration phase of the first mission prior to docking. ATV rendezvous sensor data, on-board navigation, trajectory and corridors have been in-orbit cross verified using available independent operational means as part of the demonstration objectives of ATV-JV mission. ATV-JV successfully met all demonstration criteria showing accurate relative navigation, a very robust control and a trajectory behavior well within the agreed criteria (up to 70% smaller in some cases). With the gained confidence the vehicle was authorized to complete on the 3rd of April 2008 the rendezvous, performed flawlessly and safely until docking. This paper addresses the definition of demonstration criteria, their operational implementation and the in-flight results.

Nomenclature

σ = standard deviation
ΔV = increment of along track velocity acquired during a maneuver
ESCAPE = automated maneuver (4 m/s retrograde ΔV) controlled by ATV’s on-board GNC and intended to move ATV away from ISS in case of contingency
CAM = Collision Avoidance Maneuver (5 m/s retrograde) controlled by dedicated ATV Hardware (HW) and software (SW) independent of nominal ATV Guidance, Navigation and Control (GNC) and intended to move ATV away from ISS in case of major ATV failure (e.g. on-board computer reset)

I. Introduction

The Automated Transfer Vehicle (ATV) is designed to provide the International Space Station (ISS) with several services like uploading pressurized cargo (experiments and crew supplies), transferring propellant, gas and water to ISS, providing propulsive support for ISS attitude and orbital control and unloading ISS waste, before returning in a destructive re-entry into the atmosphere. ATV is a program funded by the European Space Agency (ESA): the spacecraft is designed and built by ASTRIUM Space Transportation and operated by the French Space Agency (CNES) at ATV Control Center (ATV-CC) in Toulouse.

ATV “Jules Verne” (ATV-JV) has been the first European spacecraft to autonomously rendezvous and dock to ISS. Even if ATV is an unmanned vehicle, the GNC and relative trajectory safety requirements are human rated during proximity operations. The demonstration of safety critical functions has been one of the major objectives of the ATV-JV mission which, with its successful demonstration, has inaugurated the recursive servicing of ISS with ATV.

In general new technologies which are mission critical for human space safety are demonstrated in dedicated demonstration flights (e.g. for Shuttle and Soyuz vehicles) prior to being used in recursive operations. For ATV it was decided to include in the first flight the demonstration, the docking and the full servicing of the station: this required gaining a sufficient level of confidence in the safety functions during the vehicle’s way of docking. Since ATV-JV has been designed and built to be identical to the subsequent ATVs for recursive missions, no specific design requirement (e.g. involving additional HW and SW) was taken into account for demonstration purposes. The first mission was planned to achieve the demonstration objectives and to provide the nominal services to ISS. The implementation of demonstration objectives needed to comply with several constraints and with available on-board sensors and operational SW. This led the involved control centers to build up a general demonstration philosophy to be applied to different phases of the flight. The final demonstration plan and “GO” criteria were discussed and agreed upon between ATV-CC, Mission Control Center Houston (MCC-H) and Mission Control Center Moscow (MCC-M).

The general approach of demonstration focused on the safety aspects of ATV dynamics (mainly relative trajectory and attitude) aiming to provide confidence in the overall ATV system behavior as opposed to trying to assess in-orbit GNC performance: the existing onboard rendezvous (RDV) sensors, Videometers (VDM) and Telegoniometers (TGM), have the same order of accuracy, and they are not accurate enough to completely observe GNC performance.

The demonstration timeline has been organized in a step-wise fashion in order to demonstrate in an earlier phase safety critical functions used in rendezvous steps that follow closer to ISS. This approach has prevented ATV-CC from taking the risk of flying ATV safety critical functions prior to their being demonstrated in-orbit.

The level of confidence in the safety of the vehicle given by the ensemble of demonstration methods at each step of the demonstration has been analyzed, quantified and documented. Time critical operations to produce demonstration reports and to analyze and review demonstration results have been implemented.

The operational system and procedures required to execute the demonstration objectives have been carefully prepared and trained by ATV-CC in coordination with MCC-H and MCC-M in order to ensure effectiveness of the control centers' coordination and timeline compatibility for the report production and review with the mission phase sequence.

The methodology defined for this demonstration has been implemented in the Jules Verne flight: all the demonstration steps have gradually increased the confidence in all safety critical functions of ATV during proximity operations leading to a flawless rendezvous and docking on the 3rd of April 2008. The analysis and conclusions of demonstration report reviews anticipated the very stable and smooth dynamic behavior performed by ATV on the final rendezvous and docking.

As part of the ATV-JV flight while attached to the ISS, the ATV propulsive support function for ISS attitude and orbital maneuvers has also been demonstrated. These functions are safety critical because they are required in case of an ISS Debris Avoidance Maneuver. An ISS maneuver using other thrusters would be not optimal and too expensive in term of propellant consumption when ATV is docked to ISS Service Module (SM). This last part of the ATV demonstration is not addressed in this paper, as it is not relevant to rendezvous technology.

II. ATV-JV Mission Overview and Operational Constraints

In this section a layout of the ATV mission[1] is recalled with highlights on ATV-JV specific mission phases and operations requirements. See Fig. 1 for a sketch of the different flight phases of ATV-JV.

The ATV generic mission covers six phases:

(1) Launch and Early in Orbit Phase (LEOP)
(2) Phasing
(3) Rendezvous and Docking
(4) Attached Phase
(5) Departure
(6) Re-entry

However, because ATV Jules Verne also involved demonstration of ATV functionalities which are required to guarantee ISS safety, additional demonstration phases were planned:

- Execution of a CAM maneuver deliberately triggered by ATV-CC in the absence of vehicle failures during Phasing; it is called “CAM Demo”.

- Two additional rendezvous followed by commanded ESCAPE and post ESCAPE maneuvers prior to the final rendezvous and docking; they are called Demonstration Day 1 (DD1) and Demonstration Day 2 (DD2).

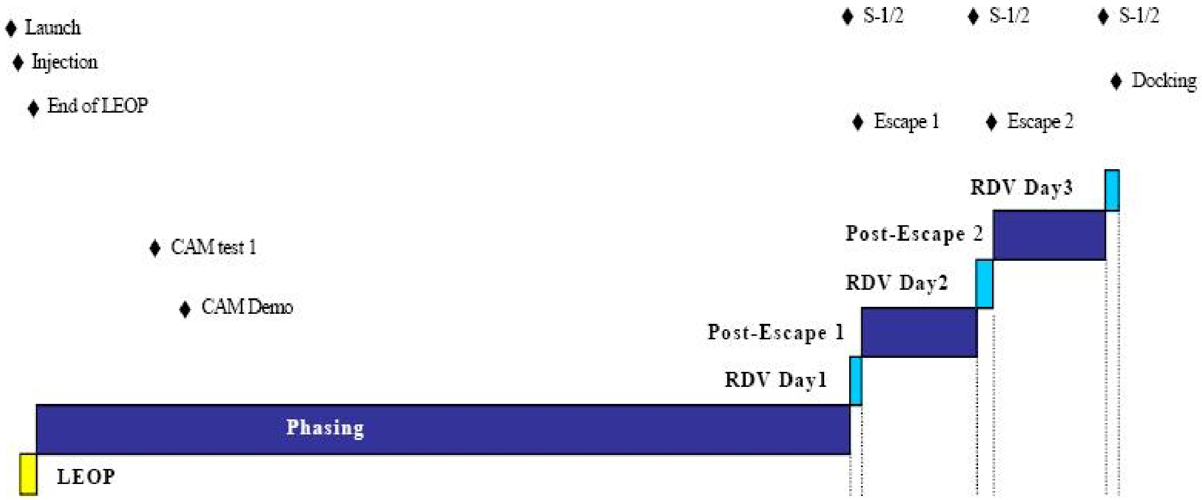

Figure 1. ATV Jules Verne ascent phase timeline

The LEOP phase covers the mission activities which bring the vehicle from launcher separation until fully operational status with Solar Wings deployed, propulsion system primed and navigation sensors activated.

The Phasing phase is dedicated to transferring ATV from the ATV delivery orbit (260 km altitude circular orbit) to the vicinity of ISS with a trajectory accuracy such that ATV's onboard GNC is able to initiate the rendezvous with the ISS. The targeted interface point is called $S_{-1/2}$. It is located 39 km behind and 5 km below the ISS. The errors on arriving to this point are about 3300 m in the along track direction and about 500 m cross-track. This accuracy is required for a good initialization of GNC at the beginning of rendezvous. Main drivers of trajectory accuracy performance are the accuracies of ATV and ISS orbit determination, trajectory prediction and ATV maneuver execution.

ATV orbit determination is performed by the ATV-CC Flight Dynamics (FDS) team based on ATV GPS pseudo-range measurements. ISS orbit determination is performed by the MCC-M ballistic team based on Russian ground station ranging and time stamped Position and Velocity (PVt) from the ISS receiver (ASN-M). Based on the two orbit determination solutions, the Phasing transfer maneuvers are computed and commanded by ATV-CC until ATV reaches the $S_{-1/2}$ point at a planned epoch. During Phasing and prior to $S_{-1/2}$ arrival, the CAM capability of thrust firing is checked (CAM test).

ATV flies autonomously from acquisition of the proximity link at $S_{-1/2}$ until docking. A few minutes after $S_{-1/2}$ arrival, ATV-CC uploads the relative ATV-to-ISS position and velocity estimated by ATV-CC FDS using precise orbit determination. The prediction accuracy needs to be better than 800 m (along track) in order to guarantee the on-board convergence of the on-board Relative GPS (RGPS) filter in time for the correct execution of the first maneuvers of rendezvous. This part of rendezvous prior to the beginning of the first maneuver is called Prehoming.

The rendezvous sequence (see Fig. 2) is characterized by station keeping points at different distances from ISS where ATV executes mode transitions and the Control Centers perform telemetry verification, on-board SW configuration and operational coordination with MCC-M and MCC-H:

- S_2 is 3500 m behind the ISS slightly above the local ISS horizontal
- S_3 is 250 m behind the ISS on the local ISS horizontal
- S_4 is 20 m from the ISS SM docking port on the local ISS horizontal
- S_{41} is 11 m from the ISS SM docking port on the longitudinal axis of the docking port

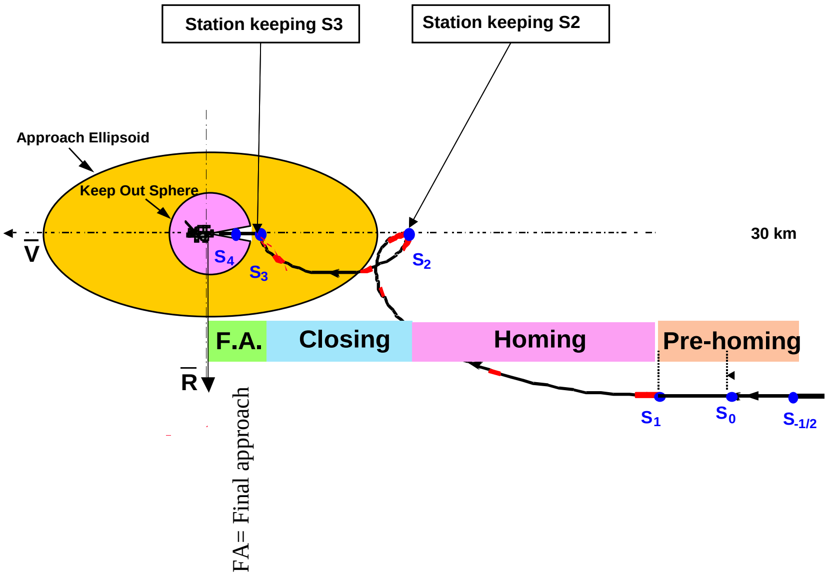

Figure 2. ATV rendezvous sequence

Between $S_{-1/2}$ and S_3 the on-board position navigation is based on RGPS and the guidance is a Homing-like sequence of maneuvers targeting S_2 first and then S_3 after leaving S_2; the Yaw Steering (YS) attitude is controlled for optimal power generation and communication. The part of rendezvous between $S_{-1/2}$ and S_3 is called Far rendezvous: Homing is from $S_{-1/2}$ to S_2, and Closing is from S_2 to S_3.

At S_3 the rendezvous sensors become the prime source of on-board navigation and the guidance performs a forced translation along the local horizontal direction until S_4; the attitude is controlled along the local horizontal direction. At S_4 the relative attitude navigation starts and the guidance performs a forced translation along the ISS Service Module docking port longitudinal axis until docking. The part of rendezvous between S_3 and docking is called Close rendezvous. Final Approach 1 (FA1) is from S_3 to S_4 and Final Approach 2 (FA2) is from S_4 to docking.

Along the whole rendezvous a dedicated on-board function named “Flight Control Monitoring” (FCM) checks that the ATV trajectory is within expected *safety* corridors: for this task the vehicle state is estimated with navigation means different from the Navigation used by on-board Guidance and Control.

During rendezvous the crew has independent means (video and the Russian radio navigation system named Kurs) to monitor that ATV remains inside the ISS safety corridor. The crew has also the capability to send very high level commands to ATV (e.g. Abort, ESCAPE, RETREAT, HOLD and RESUME).

With tools developed on the ground, ATV-CC assesses in real time GNC performance and trajectory against predefined thresholds during the whole rendezvous phase. At station keeping points ATV-CC verifies that ATV GNC behaved within expected envelopes prior to authorizing the vehicle to proceed in approaching the next station keeping point: corridors and monitoring thresholds are trilaterally (MCC-H, MCC-M and ATV-CC) agreed upon and documented in Joint Flight Rules.

III. ATV Spacecraft Design

In this section the main characteristics of ATV design[2] are recalled. A brief description of ATV rendezvous technique[3] implemented in ISS proximity operations is also included.

ATV weight is about 20 tons, the vehicle's largest diameter is equal to 4.5 m and its length is about 10 m. The solar arrays span 22 m. ATV is composed of a pressurized Cargo module and a Service Module. Communications are provided via Tracking and Data Relay Satellite System (TDRSS) and Artemis links during the whole mission.

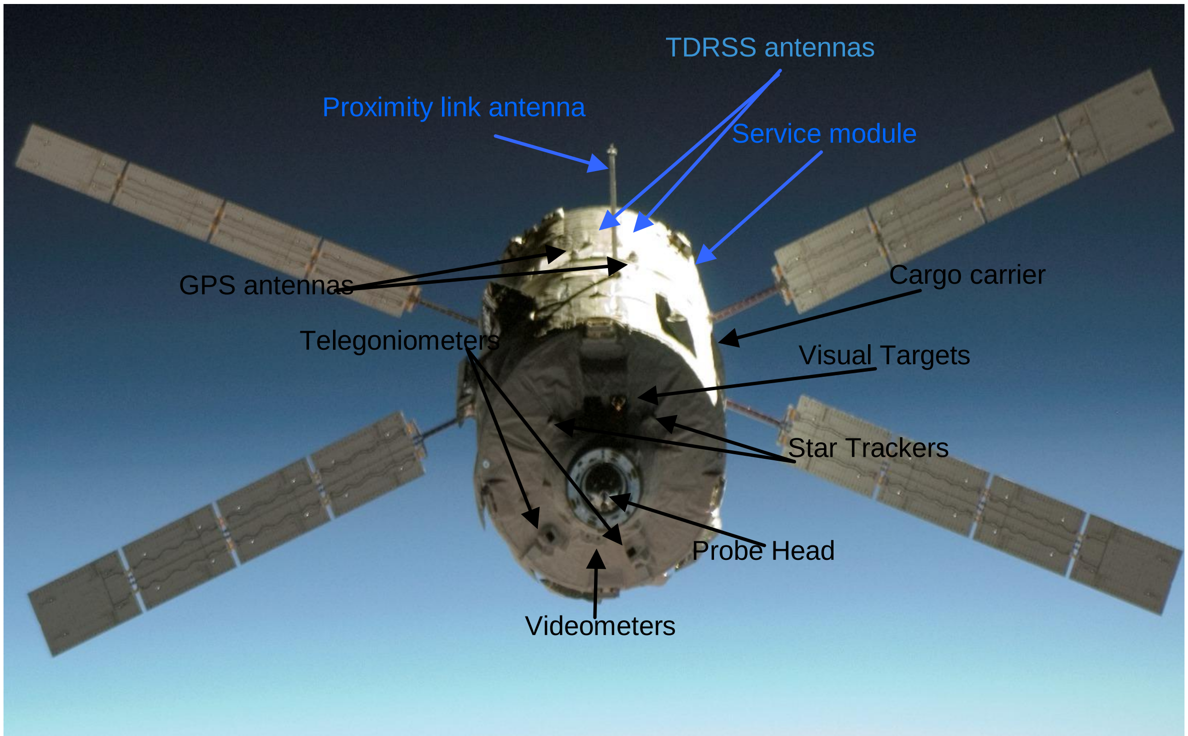

Figure 3. ATV-JV: picture taken from ISS during rendezvous

During ISS proximity operations a Proximity link antenna supports direct transfer of data between ISS and ATV. The GNC sensors include 2 GPS receivers mounted on ATV and two similar receivers (ASN-M) mounted on ISS service module, optical rendezvous targets (3 external and a three-dimensional inner target) mounted on ISS, 2 Videometers (VDM) and 2 Telegoniometers (TGM) for final approach navigation, and a standard gyrometer assembly (GYRA) of 4 2-axis gyrometers, 6 accelerometers and two Star Trackers. Figure 3 is a picture of ATV-JV taken from ISS: some vehicle components may be recognized.The propulsion system is composed of 4 Orbital Control System (OCS) thrusters of 490 N and 28 Attitude Control System (ACS) thrusters of 220 N for attitude control (3 degrees of freedom) and for small orbital maneuvers (6 degrees of freedom) including rendezvous trajectory guidance and control: both sets of thrusters can be used to provide propulsive support to ISS during the attached phase.

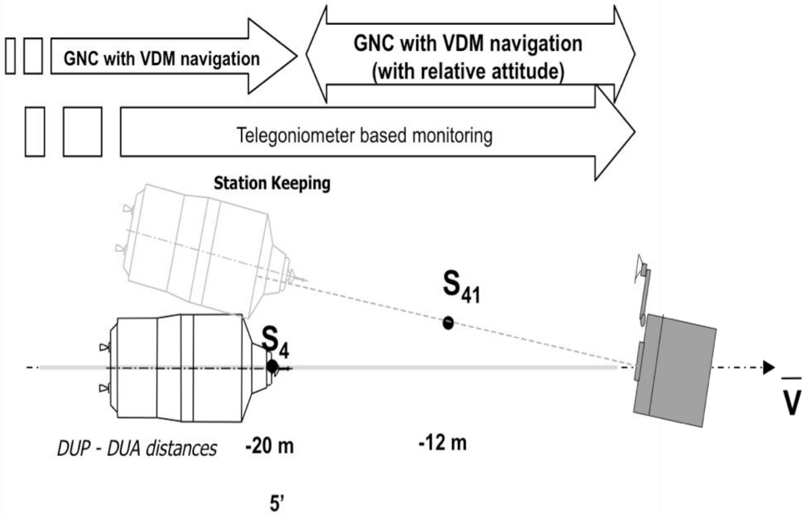

Figure 4. ATV Final Approach Guidance

ATV-JV was loaded with about 6 tonnes of propellant to support both demonstration flight and ISS propulsive support. ATV-JV also carried 860 kg of fuel, 270 kg of Water and 20 kg of Oxygen which was transferred to ISS during the attached phase together with a total of 1.3 tonnes of dry cargo.

Far rendezvous navigation is based on RGPS: the relative state vector is estimated from an optimal linearized Kalman filter which processes ATV and ISS GPS raw measurements (pseudo-range and Doppler count) synchronized and differentiated. This technique leads to canceling ionosphere errors and to achieving performance better than 5 meters for relative position and 3 cm/s for relative velocity. The navigation output is used at 1 Hz frequency by a robust guidance and control algorithm based upon Clohessy-Wiltshire equations. This algorithm implements a 2-boost strategy which targets S_2 and S_3 through optimal and safe maneuvers.

During Far rendezvous, PVt solutions (synchronized and differentiated) of ATV and ISS receivers are used by the FCM function for assessing in real time the relative position; accuracy is improved by integrating information on current thrust acceleration as measured by accelerometers. This navigation (□PVt) is sufficiently independent and accurate to allow FCM monitoring of the Far rendezvous trajectory.

From 250 m until docking ATV navigation uses brand new technologies based on optical sensor and laser pulses: VDM for guidance (GNC) and TGM for monitoring (FCM). Two VDMs and two TGMs are located on the front cone of ATV. Retroreflectors are part of the rendezvous sensors and are located on the aft end of the Russian Service module: a first set is a large 1.5 m sided triangular shape, and the second set is a smaller pyramidal shape 8.5 cm in height. The VDMs emit pulsed laser beams, which are passively reflected by retroreflectors. The VDMs analyze the image formed by the pattern of light spots and estimate range and line of sight. At ranges closer than 20 m VDM estimates relative orientation of the target with respect to the sensor. TGM emits laser pulses (at a different wavelength than VDM) towards the retroflectors and computes range and line of sight in a way similar to radar. Navigation algorithms differ from far range (250 m to 30 m without measurements of relative attitude) to close range (30 m to contact with measurements of relative attitude). Sensor noises and navigation accuracy improve when range decreases: accuracy goes from a few meters at 250 m down to a few millimeters at contact.

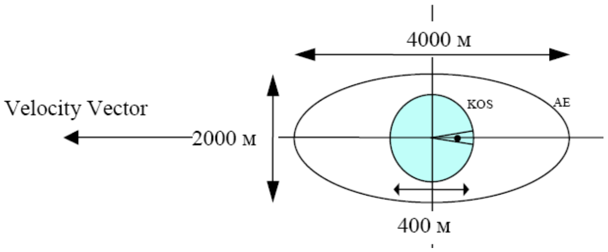

Figure 5. ISS safety volumes

The final approach guidance (see Fig. 4) from 250 m (S_3) until 20 m (S_4) is a forced translation along the orbital velocity direction following a range rate profile which is a function of range: in general the approach velocity decreases as the spacecraft closes to the Docking Port, also called Docking Unit Passive (DUP). From 20 m until docking the forced translation is performed along the direction of the DUP longitudinal axis aiming to align the Probe Head, also called Docking Unit Active (DUA) to DUP: this requires a robust control of relative position translation coupled to the relative attitude motion. The onboard controller compensates for ISS attitude motion (similar to a saw tooth motion), navigation sensor noises, Mass and Inertia (MCI) uncertainties, propulsive thrust dispersions, flexible modes of the ATV rotating solar panels, ATV sloshing and ISS flexible modes.

IV. ATV-JV Demonstration Approach

The Demonstration objectives of the ATV-JV mission have been defined[3] according to the following recommendations from the Flight Operation Review board:

(1) ATV spacecraft functionality is demonstrated prior to the use of that functionality in safety critical operations

(2) Success criteria for each demonstration objective will ensure that ATV is performing in a safe manner

(3) The demonstration mission sequence shall be safe throughout all phases

ISS main safety volumes are illustrated in Fig. 5 and their definitions are re-iterated below:

- The Approach Ellipsoid (AE) corresponds to an ellipsoid of 4 km x 2 km x 2 km, centered at the Space Station center of Mass, with the long axis along the V-bar direction. All 3σ trajectories prior to the Approach Initiation (AI) maneuver must stay outside of the Approach Ellipsoid.
- The Keep Out Sphere (KOS) is a safety sphere centered around the Space Station center of mass, with a radius of 200 m, which shall be entered only following pre-defined approach corridors.

The corridor for nominal ATV rendezvous approach is shown in Fig. 6. It consists of two cones around the DUP axis, of 8 deg for distances (DUP-DUA) between 200 m and 20 m and of 4 deg for distances (DUP-DUA) smaller than 20 m (until docking).

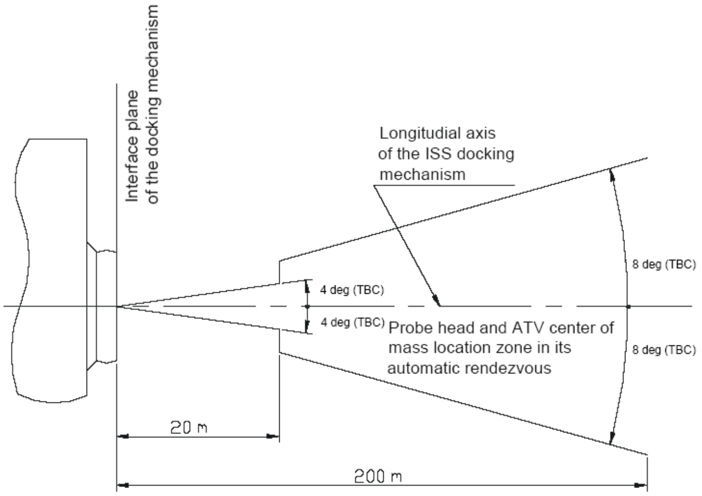

Figure 6. Corridor for nominal ATV rendezvous approach

The main safety requirements driving rendezvous trajectory and GNC design during proximity operations are re-iterated below:

Req. I. The ATV trajectory shall be such that, during rendezvous and proximity operations, the natural drift including 3σ dispersed trajectories ensures that prior to the AI burn, ATV stays outside the Approach Ellipsoid for a minimum of 24 hours in the absence of ground intervention;

Parameter	**Unit**	**Performance**
Relative longitudinal closing velocity	m/s	0.05 - 0.10
Relative lateral velocity	m/s	< 0.02
Relative angular rate (yaw/ pitch)	deg/s	< 0.15
Relative angular rate (roll)	deg/s	< 0.4
Angular misalignment of longitudinal axes (yaw / pitch)	deg	< 5
Roll misalignment	deg	< 5
Lateral misalignment	m	< 0.1

Table 1. ATV Initial Docking Contact conditions

Req. II. After the AI burn and prior to the ATV's stopping at the arrival point on V-bar inside the AE, the ATV stays outside the keep-out sphere (KOS) for a minimum of 4 orbits;

Req. III. During any retreat out of the Approach Ellipsoid, the ATV maintains a positive relative range rate until it is outside the Approach Ellipsoid and thereafter stays outside the Approach Ellipsoid for a minimum of 24 hours.

Req. IV. The ATV shall implement active collision avoidance maneuver strategies in addition to safe free drift trajectories, as a means to avoid collision with the ISS in case of contingencies up to docking.

Req. V. The ATV shall be capable of performing active docking to the ISS-RS Service Module V-bar docking port with initial docking contact conditions as specified in Table 1.

The main safety critical functions which are used during proximity operations are the following:

- Autonomous GNC controls the ATV trajectory inside safety corridors during Far and Close rendezvous. Monte-Carlo analysis has been performed for the ATV qualification campaign in order to verify that dispersed trajectories (at 3σ) are compliant with ISS safety requirements (e.g. Req. I on safe free drift trajectories).

- FCM function is used during ISS proximity operations and it performs on-board real-time monitoring of ATV dynamical behavior (trajectory, attitude and maneuver) using navigation means (sensors measurements and SW filters) which are independent of the nominal GNC. Monte-Carlo rendezvous trajectories were simulated during vehicle qualification and the resulting analysis showed that 3σ trajectories resulting from an ESCAPE issued by FCM are compliant with ISS safety requirements (e.g. Req. I on safe free drift trajectories) in worst cases of detection of FCM threshold trespassing.

- ESCAPE is a retrograde maneuver aiming to move ATV away from ISS and to reach a 24 hour safety trajectory. This maneuver may be issued by FCM when trajectory corridor thresholds are trespassed. The maneuver is executed by the on-board Fault Tolerance Computer (FTC) using GNC SW and with ACS thrusters which are also used during the rendezvous.

- CAM is a Collision Avoidance Maneuver which represents the last on-board action to move ATV away from ISS on a safe trajectory. The maneuver is retrograde and is performed by a completely segregated system (HW and SW) which is completely independent of the GNC and FTC. CAM may be issued by the Proximity Flight Safety (PFS) function, a dedicated class A SW running on dedicated fault tolerant computers (MSU) on-board ATV.

Besides the listed functions some brand new technologies have been used on the ATV vehicle. Particular attention has been paid to the demonstration of the following rendezvous sensors and technique:

- Relative GPS technique with ATV GPS and ISS ASN-M, used by autonomous ATV on-board guidance to get inside the AE until close to the KOS.

- Optical rendezvous sensors (VDM and TGM) which allow ATV to guide relative attitude and trajectory from inside KOS up to docking, autonomously controlling and monitoring the vehicle inside ISS approach corridors.

For each demonstration objective, three demonstration methods provided the evidence that ATV GNC was operating as designed and the confidence that the system performance was within the qualified domain:

(1) *Navigation coherence*. The primary onboard navigation was checked using a secondary means (e.g. during Final Approach: GNC against FCM, MSU, etc.) to ensure that both navigation methods were consistent. The navigation coherence has been checked by comparing the on-board navigation outputs from the nominal primary sensors with independent navigation based on the available Telemetry (TM). The differences have been checked against criteria based on onboard navigation performance.

(2) *GNC onboard confidence*. The integrated GNC was demonstrated by checking that the ATV primary GNC state was within its 3σ envelope. The GNC onboard confidence was provided by verifying that the onboard trajectory parameters that were directly controlled by the ATV onboard GNC and that were measured by onboard nominal navigation from primary sensors were within the expected 3σ domain.

(3) *Trajectory behavior.* The trajectory was further evaluated by checking that independent state measurements were within criteria based on the 3σ rendezvous trajectory envelopes plus the measurement errors of the independent means. The state parameters that have been checked are based on the list of required safety conditions (e.g. see Table 1).

V. ATV-JV Demonstration Objectives Selection

The rendezvous demonstration sequence[5] has been divided into three main phases: Phasing, DD1 and DD2.

Phasing demonstration main objectives were to provide confidence on ESCAPE and CAM and to check the good behavior of sensors and actuators involved in Far rendezvous GNC (e.g. for attitude control and for small orbital maneuvers). This demonstration has been performed before entering into ISS proximity operations. By doing this demonstration we gained enough confidence in the two main rendezvous abort functions and in the quality of GPS data from the ATV receiver to be used in the Far rendezvous by ATV GNC. The good in-orbit behavior of the ATV GPS receiver and the capability of ATV-CC to properly process ATV GPS raw data (ASN-M data have been already tested in-orbit) have been extensively experienced. Successful testing of ATV attitude and orbital control functions confirmed the vehicle performance required to achieve the needed trajectory accuracy at the beginning of rendezvous ($S_{-1/2}$). The trilateral agreement on the criteria achievement for this first part of the demonstration allowed ATV to initiate the first Proximity operation on DD1 executing the autonomous rendezvous until S_2.

DD1 was mainly focused on demonstration of ATV-ISS relative GPS navigation (RGPS by GNC and □PVt by FCM) and of good dynamic behavior of the ESCAPE maneuver. FCM □PVt and ESCAPE are the key functions which ensure safety outside KOS. On DD1 CAM and ESCAPE could be considered available since they were fully or partially demonstrated during Phasing. The ground capability to process ATV GPS and ISS ASN-M raw data was also exercised providing confidence in ATV-CC FDS real time monitoring of the Far rendezvous trajectory[6]. Demonstration of DD1 objectives were planned to be performed far enough from ISS and outside AE with the ISS safety ensured by the availability of CAM and ESCAPE which could be triggered by FCM, PFS or ATV-CC upon real-time monitoring of ATV trajectory and vehicle status. DD1's successful in-orbit demonstration provided enough confidence in FAR rendezvous GNC and safety functions (FCM and ESCAPE) to allow authorizing of ATV to enter AE and KOS in the next demonstration day (DD2).

DD2 lets the vehicle approach until S_{41}, and it was dedicated to the demonstration of rendezvous techniques used for final approach from S_3 to docking. All the safety functions on board used until S_3 (FAR rendezvous) were previously demonstrated during Phasing and DD1. Some critical functions used after S_3 (Final Approach) could not have been demonstrated prior to DD2 (e.g. Final Approach navigation used by GNC and FCM). Due to the nature of the rendezvous sensors which improve performance as the vehicle closes relative to ISS, the demonstration of those functions could not have been performed on DD2 without entering in the KOS and getting as close as 11 m (S_{41}).

On DD2, CAM and ESCAPE could be considered available since they had been fully demonstrated during Phasing and DD1. The ATV GNC behavior and ISS safety corridors were closely monitored by both Crew and ATV-CC with dedicated displays and automated real-time checks: crew and ATV-CC reactivity in case of an on-board anomaly or failure was considered sufficient up to S_{41} in order to cope with a not yet demonstrated ATV Final Approach. With these prerequisites ATV was allowed to fly rendezvous up to S_{41} during DD2. ATV GNC performance observed in the last meters of DD2 were analyzed offline and interpreted in order to get a sufficient level of confidence that ATV would meet the tight safety requirements at docking (see Req. V and Table 1) on the docking day.

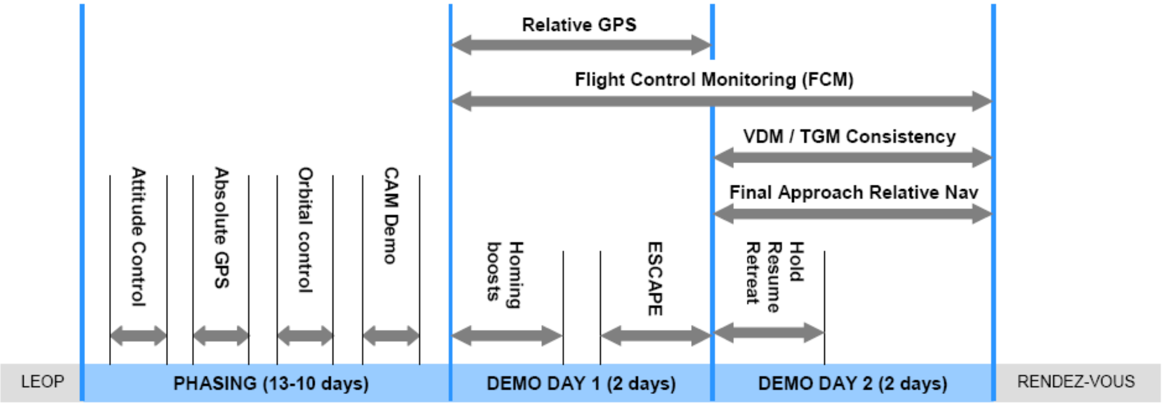

Figure 7. Demonstration Objectives Timelines

A brief description of the demo objectives selected per phase is recalled (see fig. 7) in this section.

During Phasing the following demonstration objectives were selected:

(1) CAM. The complete execution of a CAM maneuver following ATV-CC Telecommand (TC) and resulting in the vehicle's acquiring its "Survival" mode has been planned: this demonstration has been requested by the ISS program in order to show the complete capability of ATV to execute the retrograde maneuver in a timely fashion and within the attitude envelope observed in ground simulations. In fact the attitude dynamics during the CAM maneuver are very strong and require a significant control effort. ATV attitude is quite safety sensitive when ATV is very close to the station (e.g. in case of ATV FTC reset in the last meters of Final Approach) due to the large dimension of ATV appendages like the Solar Arrays. Aside from attitude the executed ΔV was estimated by ATV-CC in order to confirm the availability of a sufficient retrograde impulse to guarantee the safety drift trajectories. Due to the numerous and long automated recovery maneuvers after the CAM execution and the vehicle's entering in and exiting from Survival mode, the independent observation (using ATV-CC Orbit Determination) of the actual ΔV was very limited in accuracy and only a qualitative

assessment was possible: this was sufficient due to the big margin in the selection of the CAM ΔV value.

(2) Attitude. The GNC execution of the desired attitude profiles is a function extensively used by all (but CAM) safety critical functions. The observed attitude and attitude rate were statistically compared with the envelopes from the qualification simulations over an extended period of time in YS attitude. A few slew maneuvers, representative of the first part of an ESCAPE execution, have been also selected for attitude performance assessment.

(3) Small Orbital Maneuver. Most of the SW and HW components used for the execution of small orbital maneuvers are shared by the ESCAPE function. For this demonstration a dedicated test maneuver with ΔV magnitude of 3.3 m/s (close to the 4 m/s ΔV of an ESCAPE) has been selected for demonstration in the phasing maneuver sequence prior to arriving at $S_{-1/2}$. Performance in ΔV magnitude and direction have been assessed and compared to the expected ESCAPE maneuver performance.

(4) Absolute GPS. The quality of ATV GPS measurements (as well as ASN-M data) is a key factor in the successful RGPS navigation used by Far rendezvous guidance. ASN-M data could be extensively tested in-orbit prior to ATV flight while ATV GPS flight raw data were collected and processed by ATV-CC for the first time during ATV-JV phasing. ATV-CC assessed the quality of GPS measurements in the ATV orbit determination process by computing the residuals of ATV orbit determination and by comparing ATV orbit estimations over overlapping periods. The ATV-CC estimation of the ATV orbit has been also checked for consistency with an independent ATV orbit determination performed by NASA based on TDRSS tracking data. By checking ATV absolute orbit determination we gained sufficient confidence in ATV-CC computing of ATV relative position by differences of orbit determination solutions (obtained using ATV GPS and ISS ASN-M data). The ATV relative position estimate from ATV GPS and ASN-M data were used by ATV-CC for FCM ΔPVt and RGPS off-line assessment and real time monitoring during DD1 from $S_{-1/2}$ until S_2.

During DD1 the following demo objectives were demonstrated:

(5) RGPS. Relative GPS is a recently developed rendezvous navigation technique which was not yet flight proven prior to the ATV-JV mission. The mishap[7] of the DART demonstration flight in April 2005 was an example of the difficulties in fine tuning the RGPS algorithms and the associated collision avoidance logic: unexpected large discrepancies between estimated and measured positions caused the DART on-board guidance to fail to reach the desired aimpoint with the side effect of a collision with the MUBLCOM satellite. For ATV-JV it was important to carefully check this technique prior to getting too close to the ISS. GPS data from both ATV and ISS receivers are available on-ground no later than arrival at $S_{-1/2}$. Prior to authorization of the first Homing maneuver, the on-board RGPS solutions (from both GNC and FCM) were checked in real-time against the ATV relative state estimated with ATV-CC developed SW. ATV-CC and FCM real-time monitoring of the ATV trajectory continued until S_2, protecting the mission from unexpected GNC behavior. Two major limitations were identified in this demonstration: a) the accuracy of the navigation filters from ATV-CC was of the same order of magnitude and worse than GNC and FCM filters; b) the relative state

estimations from ATV-CC, GNC and FCM were using data from the same receivers (ATV GPS and ASN-M). The off-line analysis of RGPS data that occurred during the post-ESCAPE phase was required to capture the statistic aspects of this navigation performance and to increase the confidence in GNC and FCM navigation via an extensive (3 hours between $S_{-1/2}$ and S_2) consistency check.

(6) FCM □PVt. The FCM was compared with ATV-CC relative state estimation between $S_{-1/2}$ and S_2. During station keeping in S_2 the range rate measurements from KURS were compared as an independent consistency check. The safety aspects of the Far rendezvous trajectory were mainly covered by this demonstration objective. It was demonstrated that once the FCM could properly control the safety envelopes of FAR RDV trajectories and once the point S3 was safely reached then this covered the majority of the RDV trajectory which was a prerequisite for the Final Approach Demonstration. The most feared aspect of this functionality was the □PVt navigation used by FCM to trigger an ESCAPE in case of a violation of FCM safety trajectory corridors. Demonstration criteria were set to values larger than the actual FCM performance due to the contribution of navigation accuracy of FCM (better than 13 m and 0.07 m/s) and of ATV-CC (26 m and 0.18 m/s). It was proved by analysis[6] that the worst case of FCM threshold detection (derived from FCM observable performance) would not result in a dangerous violation of the KOS in case of an ESCAPE triggered by FCM during DD2 approaching S3.

Parameter	**Units**	**Acceptable upper bound**	**GNC performance**	**FCM/AADE performance**	**Docking conditions**	**ATV-JV observed S_4 -S_{41}**
Relative longitudinal velocity	m/s	0.095	0.08	0.015	0.1	0.07
FCM relative lateral velocity	m/s	0.05-0.03	0.03-0.01	0.02	0.02	0.015
Angular rate (yaw/ pitch)	deg/s	0.15	0.13	0.0017	0.15	0.04
Angular rate (roll)	deg/s	0.08	0.08	0.0015	0.4	0.03
FCM PH lateral misalignment	m	1.1-0.7	0.7-0.4	0.4-0.3	0.1	0.1-0.2
Roll attitude	Deg	4.2	2.7	1.5	5	0.4
Lateral (Pitch/Yaw) attitude	Deg	5	2.5	1.3	5	0.9

Table 2. Final Approach success criteria between S4 and S41, Trajectory behavior

(7) ESCAPE. This maneuver was assessed in the station keeping point S_2 by comparing the observed state (attitude and velocity increment) estimated by ATV (GNC or FCM) and by ATV-CC with the expected profile and criteria were based on expected observable performance. The criteria values selected for this demonstration were compatible with the ESCAPE performance analysis which proved that worst cases were still meeting ISS safety requirements. The full demonstration of the ESCAPE maneuver was requested as early as possible in the demonstration sequence since this function represents the first safety barrier of ATV rendezvous and can be triggered by ATV (FTC or MSU), ATV-CC or ISS crew. A trade-off[8] was performed between different scenarios. The choice of an ESCAPE demonstration at S_2 was based on considerations that on DD1 the CAM was fully demonstrated and that at such distances from ISS (larger than 3500 m) only a major ESCAPE malfunction could eventually cause a hazard to ISS in 90 minutes or longer, which would allow ATV-CC or the crew the time to adequately react (e.g. by triggering a CAM), if not already covered by an ATV onboard automated action (e.g. from PFS).

During DD2 the following objectives have been demonstrated:

(8) Final approach. The purpose of this demonstration was to show that different ATV modes used in Close rendezvous up to contact were functioning correctly prior to S_{41} departure. The main challenge of this demonstration was that, by design, ATV performance improves significantly between S_{41} and contact and ATV performance at S_{41} (the closest point during DD2) is not yet within all safe docking conditions as per Table 1. As an alternative the goal of the Final Approach demonstration was to gain confidence in ATV behavior by showing that the ATV was operating as designed between S_4 and S_{41}. The three methods described in section IV were applied: Navigation coherence (consistency of VDM and TGM measurements), GNC onboard confidence (onboard commanded against estimated positions) and trajectory behavior (trajectory parameters against expected envelopes). For the trajectory behavior the independent navigation used for estimating the trajectory was FCM for position and velocity and Absolute Attitude navigation (AADE) based on a Gyro stellar filter.

The challenge of this demonstration may be understood in the Trajectory behavior example by comparing (see Table 2) ATV GNC performance and success criteria between S_4 and S_{41} with the mechanical conditions to be met at docking. The criteria in this method were either within the safe contact conditions or they represented performance that, by design, would improve to meet safe contact conditions as the distance was decreasing.

During Final Approach FCM parameters were collected in the report, and the Crew capability of commanding HOLD, RESUME, and RETREAT was tested.

VI. ATV-JV In-Orbit Demonstration Objectives Results

In this section the main in-orbit results[9,10,11] of the ATV-JV demonstration are briefly reported.

Phasing. All the defined demonstration objectives were met with large margins. Differences less than 37 m between ATV-CC orbit determination and GPS PVt have been observed showing a good and stable quality of GPS PVt solution. ATV-CC capability to perform a correct ATV orbit determination has been confirmed by the good matching with NASA computations which differed by 32 m at 3σ. The accuracy of ATV-CC orbit determination during this phase has been estimated to be better than 23 m. The observed ΔV of the small orbital correction was accurate to about 1% in magnitude and 0.26 deg in direction, which was a much better performance than expected.

ATV attitude during the CAM demo maneuver was characterized by an intense dynamics and thrust firing during a relative short transition which rapidly (in less than 75 seconds) converged to the targeted profile (see Fig. 8), as in the ground prediction. In spite of the limited observation of the maneuver velocity increment due to the expected loss of telemetry, the CAM boost ΔV was estimated by ATV-CC at 5.5 m/s in the retrograde direction, which was well within the expected performance.

Demo day 1. The ATV–ISS GPS Relative Orbit computed by ATV-CC was compared with the ATV RGPS (differences of 10 m) and FCM solutions (agreement better than 5 m); ATV RGPS was checked against KURS data (differences less than 0.05 m/s in range rate and 12 m in range). Confidence in RGPS and FCM ΔPVt navigation was achieved at the end of DD1. ATV attitude and attitude rate during ESCAPE were according to the prediction, and achieved ΔV differed from the commanded ΔV by only 3 cm/s along track and 1 cm/s cross track. Thus, the ESCAPE functionality was successfully demonstrated in orbit.

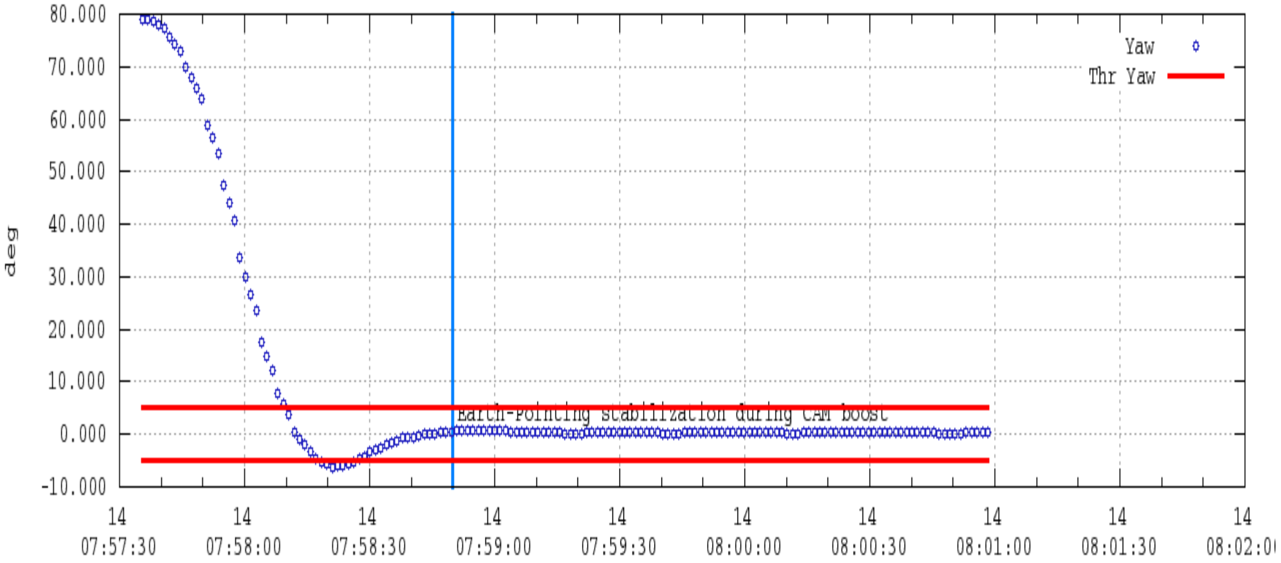

Figure 8. ATV-JV attitude (yaw) during CAM demo execution

Demo Day 2. ATV-JV GNC behavior in the Final Approach exceeded the expected performance, easing the control centers' task to review and approve the final report. The four rendezvous sensors (VDM1, VDM2, TGM1 and TGM2) showed very good consistency in delivering position measurements (range and line of sight), and only a small bias of 0.2 deg was noted between the nominal VDM and the other 3 sensors (see Fig. 9).

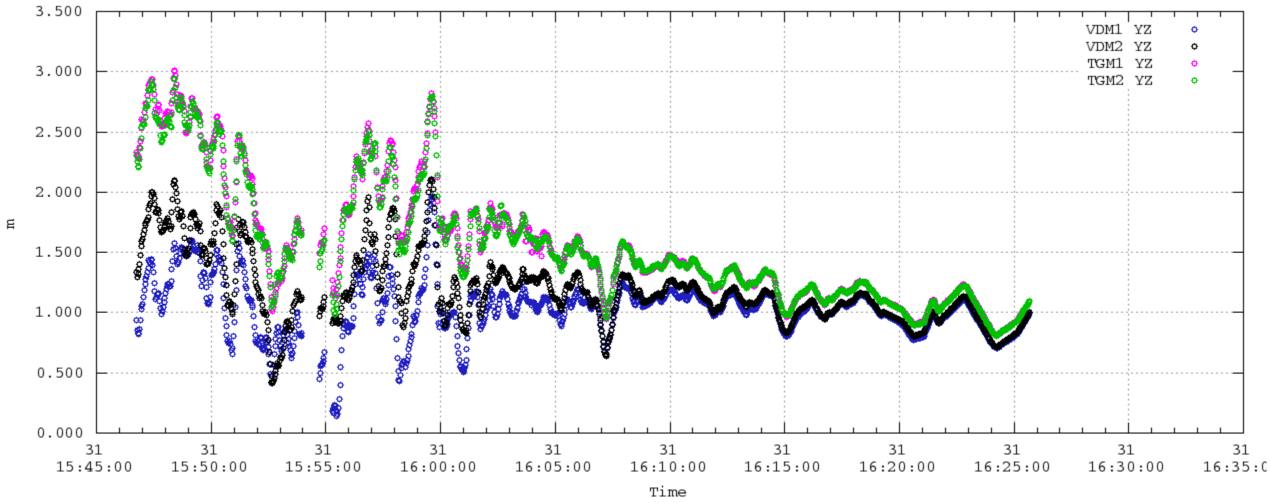

Figure 9. Lateral RDV Video Target (RVT) positions computed using VDM1, VMD2, TGM1 and TGM2 during Final Approach

The rendezvous trajectory performance showed a relative position and attitude control behavior between S_4 and S_{41} (at 12 m from the docking port) so good and stable that all trajectory parameters monitored in the trajectory behavior criteria were within the demanding conditions required at docking (see Table 2 and Fig. 10): at S_{41} closing range rate was less than 7 cm/s, lateral misalignment less than 10 cm, lateral velocity better than 0.004 m/s and relative attitude less than 1 deg.

The Retreat, Hold, Resume dynamical behavior perfectly matched the expectations.
The outstanding GNC performances of ATV-JV demonstrated during Demonstration Days were again confirmed by the flawless rendezvous and docking on the 3rd of April 2008.

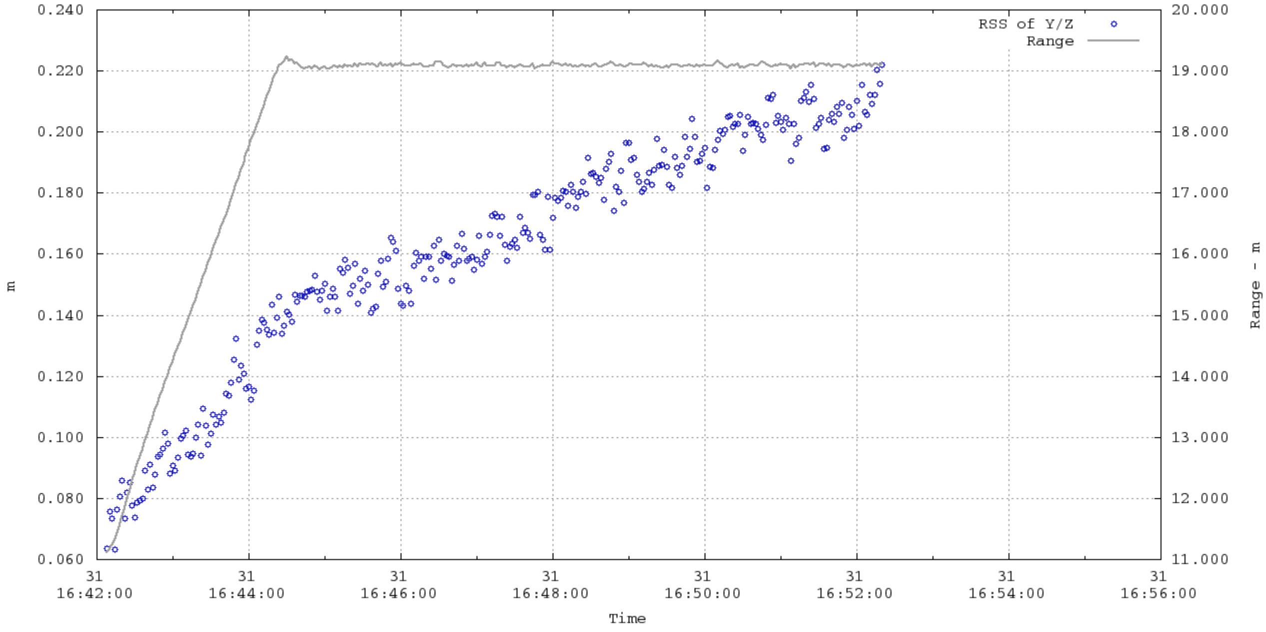

Figure 10. Probe Head to Docking Port lateral position (FCM) during RETREAT from S_{41} to S_4

VII. Conclusion

New GNC technologies implemented in a severe environment (like manned space) often need in-orbit demonstration to prove their compliance with safety requirements and to provide adequate confidence in the expected GNC and trajectory performance.

The case of ATV-JV has been presented in this paper, and the philosophy for the development of demonstration objectives has been explained. The problem of assigning success criteria which are acceptable from a safety point of view and achievable with the limited observation accuracy has been addressed, and the selected compromises have been justified.

The ATV spacecraft and generic mission were not originally designed for observing in-orbit GNC and trajectory performance: this increased the challenge of performing an ATV-JV demonstration. A good compromise has been reached between changes to the ATV mission plan, the use of available spacecraft resources and the capability of assessment of the ATV critical functions. Avoiding any changes to the spacecraft design (already under qualification) required a careful definition and preparation of demonstration operations, and a challenging inter-agency (ESA, NASA and RSC-E) coordination during the flight for time critical review of the observed spacecraft behavior.

The demonstration philosophy (*Navigation consistency*, *GNC onboard confidence* and *trajectory behavior*) adopted in the ATV-JV mission can be used as an example for new technology demonstrations for future spacecraft: it has proved to be effective and compatible with the demonstration of functionalities used to ensure ISS safety.

As a lesson learned from ATV-JV, the author recommends that for future missions the need for demonstration requirements and the definition of success criteria be assessed, if possible, early enough in the spacecraft design in order to avoid compromises potentially detrimental to the real operations.

Acknowledgments

The definition and finalization of ATV-JV demonstration objectives has been possible thanks to the professional and challenging support of GNC specialists from the ATV-CC Flight Dynamics team (CNES), from the Engineering Support team (ASTRIUM/ESA), from MCC-M (RSC-E), and from VVO and TOPO teams (NASA). Acknowledgment for their contribution is also expressed to the ATV-JV Flight and Mission Director's leads of the Control Centers.

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