Atv Jules Verne: in-flight demonstration of new RDV technology

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Abstract

On the 3rd of April, 2008, the Automated Transfer Vehicle Jules Verne (ATV-JV) successfully docked to the International Space Station (ISS). One of the mission objectives was to demonstrate the new technology developed to perform autonomous rendezvous (RDV) to the ISS with particular focus on functionalities critical for guaranteeing the ISS safety. ATV RDV innovative technology has been in flight demonstrated. Some of those technologies have potential application to formation flight: phasing manoeuvres to fly ATV to a precise position in proximity of ISS, accurate relative GPS autonomous navigation with proximity link communication, innovative RDV sensors, RDV guidance via station keeping points and final approach.

An ESA-lead team based at ATV-CC in Toulouse has performed a near real-time assessment of GNC critical functions of RDV during two dedicated demonstration days.

Successful trilateral reviews of the reports, involving teams from ESA, CNES, Astrium in ATV-CC, ISS Mission Control Centre in Houston and in Moscow have confirmed the good behaviour of ATV GNC resulting in a GO from ISS Management Team for the continuation of ATV-JV mission. The proposed paper presents a summary of results of in-flight experience which are related to the assessment of RDV technology with emphasis on observed performance of those functionalities which could be applied to formation flights.

1. Introduction

ATV is a European Space Agency (ESA) funded program: the spacecraft is designed and build by EADS ASTRIUM Space Transportation and operated by the French Space Agency (CNES).

ATV-JV is the first European spacecraft to achieve automated rendezvous and docking in the context of Human Spaceflight. Beside the complexity of the mission ATV has accomplished high system performances in term of RDV trajectory and docking accuracy while coping with the sever safety constraints imposed by ISS manned rated safety rules.

ATV-JV inaugurates a set of several flights to the ISS dedicated to provide the crew with supplies, to provide the ISS with propellant, gas and water, to raise up the ISS altitude, and finally to unload ISS waste and return in a burning re-entry into the atmosphere

ATV-JV has been launched by Ariane 5 from Kourou on the 9th of March 2008 with a perfect injection into a circular orbit of 260Km altitude in the same orbital plane of ISS. During several days of commissioning flight the Collision Avoidance Manoeuvre system which is the ultimate safety critical function to abort RDV has been demonstrated. On 29th of March the Far RDV functionalities have been successfully demonstrated getting ATV just behind the ISS safety zone (Approach Ellipsoid) as close as 3500m from ISS. On the 31st of March the ATV capability to perform the Final approach within the tight 4 Deg corridor have been successfully demonstrated after an accurate and stable approach to ISS reaching the close distance of 11m between Probe Head and Docking Port. The analysis of trajectory results have confirmed the very good behaviour of the RDV trajectory control leading the ISS Mission Management Team to authorise the final GO for ATV to approach and dock ISS.

ATV-JV docked to ISS Service Module on the 3rd of April 2008 after a flawless RDV.

During ATV free flight (“ATV phasing to ISS”) a technique based on Orbit Determination (OD) using ATV and ISS GPS receivers has been implemented at ATV Control Center (ATV-CC) in order to maintain the accurate knowledge of absolute state vectors of the two Spacecraft objects. Dedicated ATV manoeuvres have been computed based on the OD solutions and implemented by ATV-CC in order ATV-JV to get to an accurate relative position behind the ISS. This task is quite similar to positioning satellites in a constellation configuration.

Satisfactory quality of ATV receiver Position and Velocity solution has been demonstrated together with the good accuracy of Orbit Determination and Manoeuvre execution. The final targeted relative point has been reached well within the specified dispersion box.

During proximity operations between 40Km and 250m relative distance from ISS, ATV and ISS GPS receiver’s measurements acquired via proximity link between the two vehicles have been processed real-time by ATV on-board SW for an accurate estimation and control of relative position and velocity. This technique is applicable to system of tandem S/Cs which requires navigation and controlling accuracy on the order of few meters for a wide range of relative distances. Both ATV navigation and guidance during this phase have been in flight demonstrated against ATV-CC difference of ODs and relative range and range rate measured by Russian radar-based system (KURS).

For proximity operations at relative distance closer than 250m dedicate RDV sensors have been used onboard ATV. The GNC control was based on estimation of relative position and attitude from Videometer (VDM) measurements. An independent autonomous on-board function (FCM) has monitored the aimed approach corridor and the range rate profile using Telegoniometer (TGM) measurements.

VDM and TGM are brand new technologies based on optical sensor and laser pulses. Position estimation reaches accuracy of few tens of cm at 20m distance: accuracy in general improves at closer distance as function of range getting down to few millimetres at docking. This technology designed and developed to support RDV can be applied to formation flight with very demanding accuracy in relative position. VDM and TGM output have been successfully in flight demonstrated comparing them each other and against measurement from Russian radar-based system (KURS): the expected performance has been confirmed. The fine ATV GNC control of the relative trajectory along the docking port axis has been also demonstrated showing a very good accuracy on both lateral misalignment and relative range rate control.

In the next sections after a quick recall of ATV-JV mission profile and main ATV GNC features, the demonstration results which are of more interest for formation flights applications will be presented.

2. ATV spacecraft and RDV technique

ATV weight is about 20 tons, its largest diameter is equal to 4.5m and its length is about 10m; the solar arrays span 22m.

ATV is composed of a pressurised Cargo modules and a Service Module. Communications are provided via TDRSS and ARTEMIS link during the whole mission and during proximity operations a Proximity link antenna supports direct transfer of data between ISS and ATV.

The GNC sensors includes 2 GPS receivers mounted on ATV and two similar receivers (ASN-M) mounted on ISS service module, optical RDV targets (3 external and a 3D inner target) mounted on ISS, 2 Videometers (VDM) and 2 Telegoniometers (TGM) for final approach navigation, a standard gyrometers assembly (GYRA) of 4 2-axis gyrometers, 6 accelerometers and two Star Trackers.

The propulsion system is composed of 4 Orbital Control System thrusters of 490 N and 28 thrusters of 220 N for attitude control, small orbital manoeuvres and RDV: both set of thrusters can be used to provide propulsive support to ISS during attached phase.

In Figure 1 location of some S/C components are indicate on a real photo of ATV-JV in flight.

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

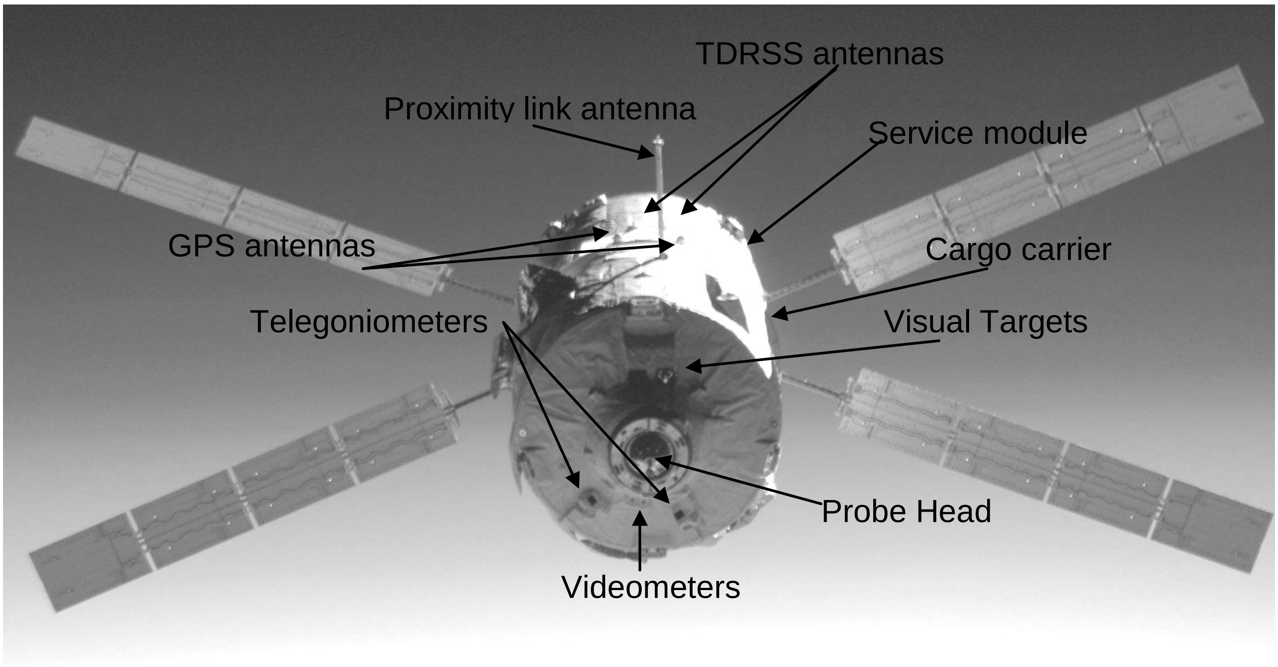

Figure 1 ATV-JV: picture taken from ISS during RDV.

ATV flights autonomously from acquisition of proximity link at S-1/2 point approximately 40 Km behind and 5Km below ISS until docking. During RDV phase ATV-CC performs mandatory uploads of flight parameters, it monitors ATV to ISS relative state and it uploads high level commands (e.g. GO, navigation mode transition) at key points of ATV RDV in coordination with MCC-M and MCC-H. During RDV the crew has independent means (video and KURS radar) to monitor ATV inside of ISS safety corridor and has the capability to send very high level commands to ATV (e.g. Abort, ESCAPE, Retreat, Hold, Resume).

During Far RDV from S-1/2 until 250m from ISS S3 ATV on-board navigation is based on Relative GPS (RGPS) on-board solution from an optimal linearized Kalman filter processing ATV and ISS GPS raw measurements (pseudo-range and Doppler count) synchronised and differentiated. This technique leads to cancelling ionosphere errors and to achieving performance better than 5 meters for position and 3cm/s for velocity.

The navigation output is used at 1Hz frequency by a robust guidance and control algorithm based upon Clohessy-Wiltshire equations, and implements a 2-boost strategy to target the aim points. ATV is guided trough optimal and safe manoeuvres from S-1/2 until S3 with intermediate station keeping at 3500Km behind the station and final station keeping at S3. Position control performance at S3 are better than 15m at 3 sigma on the along track direction.

An estimation of the relative position with a different technique is in parellel performed by an on-board Safety monitoring function (FCM) which filters real-time PVt solutions (synchronised and differentiated) of ATV and ISS receivers and integrates information on current thrust measured by accelerometers. This technique results in a relative position solution which is accurate up to 8m in position and it is robust to possible transient of non availability of valid GPS measurements.

Both navigation techniques can be applied to formation flights for a wide range of relative distances. Multipath effects can be an issue at distances closer than 250m if the two S/C are not designed (like for ISS structure) to minimise such effect. Navigation accuracy is quite stable after filter convergence and is not sensitive to the distance (on the contrary of optical devices) for a large set of ranges (e.g. from 40Km to 250m). The autonomous guidance and control based on RGPS provides an effective and accurate mean to optimal transfer the S/C in the vicinity of the companion S/C and to maintain the relative CoG position in a tight Station Keeping box.

From 250m until docking ATV navigations for trajectory guidance and safety monitoring use brand new technologies based on optical sensor and laser pulses: VDM for guidance and TGM for monitoring (FCM). Two VDMs and two TGMs are located on the front cone of ATV. Retroreflectors are part of RDV 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 analyse 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 emit laser pulses (at a different wavelength to VDM) towards the retroflectors and computes range and line of sight in a similar way as a radar. Navigation algorithms differ from far range (250m to 30m without measurements of relative attitude) to close range (30m to contact with measurements of relative attitude). Sensor noises and navigation accuracy increase when range decreases: accuracy goes from a few meters at 250 m down to a few millimetres at contact.

The final approach guidance from 250m until 20m is a forced translation along the orbital velocity direction following a range rate profile which is function of range: in general the approaching velocity decreases as the S/C closes to the docking port. From 20m until docking the forced translation is performed along the direction of the Docking Port longitudinal axis aiming to align the Probe Head to the Docking Port (see Figure 2): 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 sawtooth motion), navigation sensor noises, MCI uncertainties, propulsive thrust dispersions, flexible modes of the ATV rotating solar panels, ATV sloshing and ISS flexible modes.

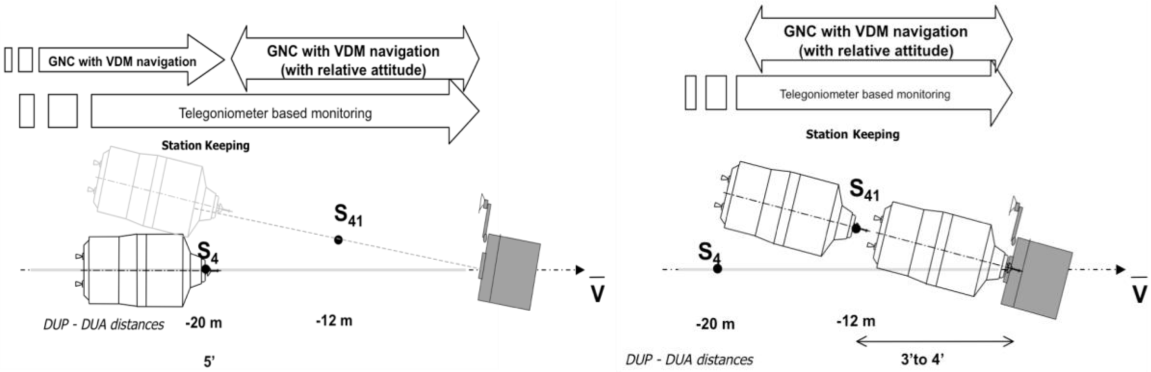

Figure 2 ATV Final Approach Guidance.

This new technology can be applied to science experiments based on multiple platforms flying at close distances and requiring high relative position and pointing accuracy. The draw back is the high demand on attitude and position control in order to assure that the target remains in the FOV of the optical sensor: an adequate filtering of coupled attitude dynamics shall be taken into account by the guidance and control algorithms.

3. ATV-JV Mission operations

The generic ATV mission covers six phases:

1) LEOP (Launch and Early in Orbit Phase)
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, two additional rendezvous followed by ESCAPE and post ESCAPE manoeuvres (instead of docking) have been planned and called Demonstration Day 1 (DD1) and 2 (DD2).

The phasing is dedicated to transfer the ATV with a required accuracy from ATV delivery orbit (260Km circular orbit) to the vicinity of ISS (flying on a circular orbit of about 337Km altitude) such that the onboard GNC is able to perform autonomously the Rendezvous and docking with the ISS. The transfer manoeuvres were computed and commanded by ATV-CC in Toulouse. The demonstration of CAM manoeuvre is also performed during this phase after successful check of CAM capability of thrust firing (CAM test). The final targeted interface point is called S-1/2, located 39km behind and 5km below the ISS.

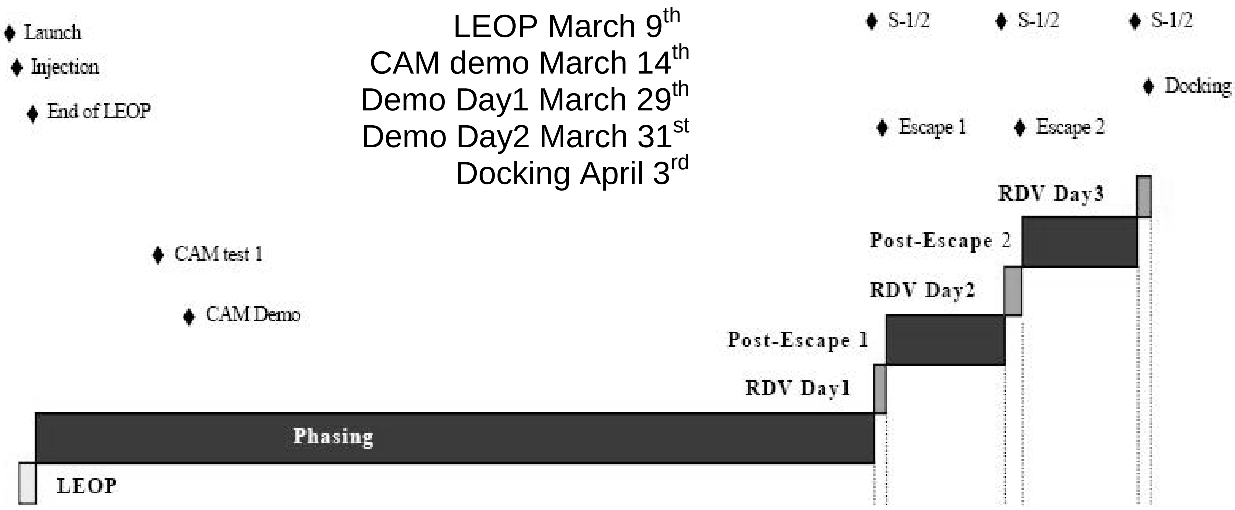

Figure 3 ATV Jules Verne ascent phase timeline

During ATV free flight the estimation of ATV orbit was regularly performed by ATV-CC Flight Dynamics (FDS) team based on ATV GPS Pseudo range measurements. ISS orbit was regularly estimated by MCC-M Ballistic team based on different means: Russian Ground Station ranging and PVt solutions from ISS receiver (ASN-M) on ISS Service Module. The two orbit determinations have been used by ATV-CC for computing several operational products including the commanded manoeuvres. The observed accuracy of the two orbit determinations is on the order of 50m 3σ and the trajectory prediction errors over few orbits are better than few hundreds of meters.

ATV-CC FDS team, using ATV and ISS orbit determination, computed the optimal sequence of manoeuvres aiming to the final ATV to ISS relative point S-1/2 at a planned epoch. The errors on arriving to this point are required to be within a box which is about 3300m on along track direction and 500m on cross-track. The accuracy is required in order to guaranty the good initialization of RDV GNC. Main drivers of trajectory accuracy performance are ATV/ISS OD accuracy, trajectory prediction and manoeuvre dispersions. During DD2, the observed error on arriving in S-1/2, based on ISS ephemeris, ATV GPS measurements and ATV accelerometer measurements, was 131m in along track direction and -7m on the delta of mean semi-major axes.. Based on GPS measurements from both ATV and ISS, the error on the delta of semi-major axes was updated to 8m.

Few minutes after S-1/2 arrival ATV-CC uploads on-board the predicted estimated ATV to ISS relative position and velocity for RGPS filter initialization. ATV onboard filter requires prediction accuracy better than 800m (along track) in order to converge quickly enough for the initialization of RDV. The estimated relative state is computed by ATV-CC about one hour before the actual implementation on-board: ATV-CC uses ATV and ISS precise orbit determination (based on GPS measurement filtering) and propagates the relative state vector modelling ATV and ISS dynamics. For the three rendezvous days, the accuracy of the relative state vector was below 163m with RGPS filter conversions in less than 2 minutes. During DD2, the error of the relative state vector was 68m and the filter converged in less than 1minute.

During ISS proximity operations ATV-CC has monitored ATV/ISS relative trajectory and main ATV GNC functions. At key points of RDV approach GO telecommands to proceed toward the station have been sent by ATV-CC after real time successful checks of corridors and boxes predefined and trilaterally agreed in Joint Flight Rules. In all RDV attempts (DD1, DD2 and Docking) ATV has shown trajectory performances largely inside the thresholds defined in Joint Flight Rules. Figure 4 illustrates the approach angle of the ATV Probe Head along XLVLH in S3SK based on RVDM not exceeding 0.5deg, largely within the 7.5deg corridor, required per Flight Rule as part of the GO/NO-GO for Final Approach 1.

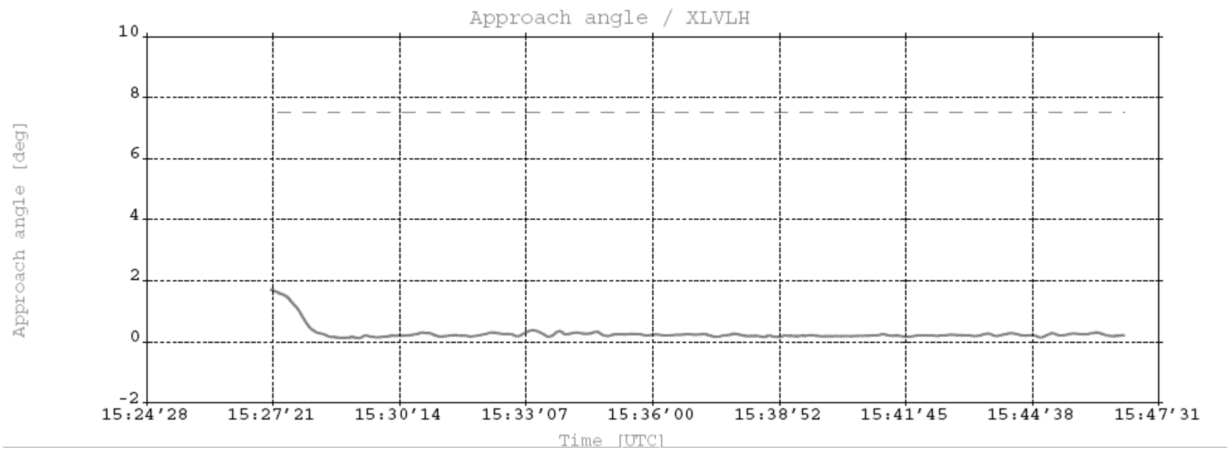

Figure 4 ATV approach angle during DD2 along XLVLH axis during S3 Station Keeping

4. ATV-JV demonstration objectives

The Demonstration objectives of ATV-JV mission have been defined (see Ref. [1]) according to the following Flight Operation board recommendations:

- ATV spacecraft functionality are demonstrated prior to the use of that functionality in safety critical operations
- The success criteria for each demonstration objective will ensure, as a minimum, that the spacecraft is performing in a safe manner
- the demonstration mission sequence is safe throughout all phases

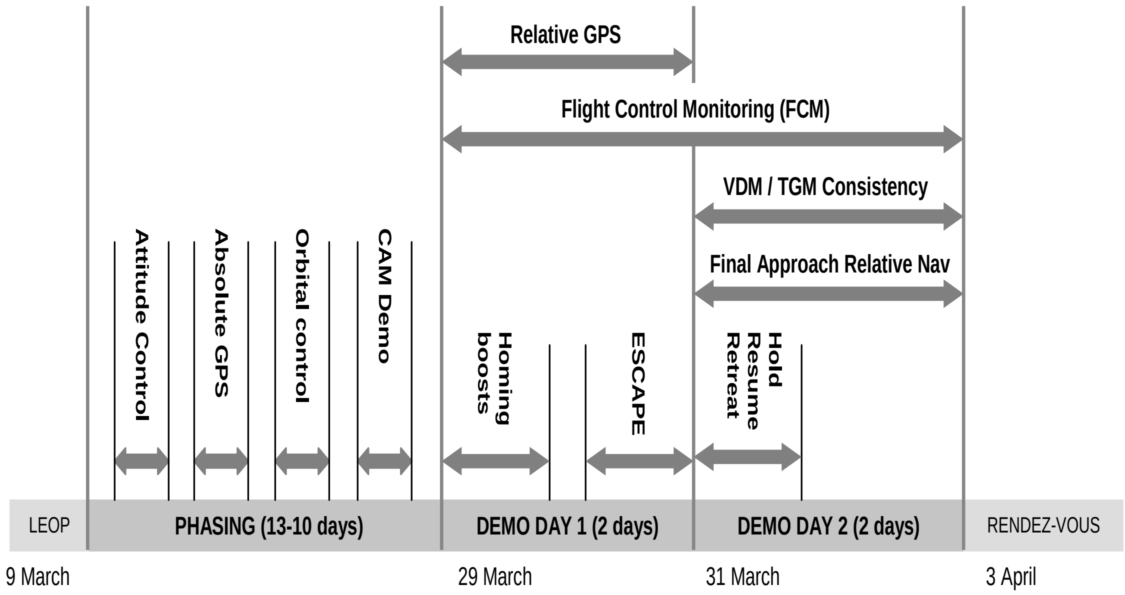

Figure 5 Demonstration Objectives Timeline

The timing for the assessments of the different demonstration objectives is recalled in the sketch of Figure 5.

For each demonstration objective, the evidence that ATV GNC was operating as designed was accomplished via three methods:

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

2) GNC onboard confidence. The integrated GNC was demonstrated by checking that the ATV primary GNC state was within its 3σ profile. The GNC on-board confidence has been

provided by verifying that the onboard trajectory parameters that were directly controlled by ATV onboard GNC and that were measured by onboard nominal navigation from primary sensors were within the expected 3σ domain.

3) Trajectory behaviour. The trajectory was further evaluated by checking that independent state measurements were within criteria based on the 3σ GNC profile + the measurement error of the independent means. The state parameters that have been checked are based on the list of required safety conditions.

5. ATV-JV demonstration: Phasing

During Phasing, ATV functionalities which are critical to perform a safe approach until S2 during DD1 have been demonstrated, namely: Attitude Control, Absolute GPS, Orbital control, CAM manoeuvre. Results have been documented in JADOR report for Phasing (see Ref. [4]).

At the end of the phasing period, the CAM has been shown available and its correct functioning has been verified; the attitude control, the Orbit Control and all functionalities required for the ESCAPE manoeuvre have been verified individually.

The three main attitude profiles (Yaw Steering, Earth pointing and Slew) have been demonstrated by comparing on-board GNC attitude estimation with the ground filter solution and with the predicted attitude profile. For all attitudes a good matching of ATV and ATV-CC attitude estimation results has been confirmed with differences of few tens of degrees. Attitude control has shown nominal pointing errors: 2 Deg (pitch and yaw) and 3.5 Deg (roll).

ATV Orbit Determinations have been computed by ATV-CC based on ATV GPS pseudo range measurements and GPS PVt solutions during quiet phases (no maneuvers). For the same period NASA (GSFC) has provided ATV Orbit Determination based on TDRSS tracking data. ATV ephemeris from ATV-CC and NASA has been compared with each other and with on-board PVt solution with satisfactory results.

Differences of 37m at 3 sigma between ATV-CC OD and GPS PVt have been observed showing a good and stable quality of GPS PVt solution (see Figure 6). ATV OD computed by ATV-CC has been confirmed by the good matching with GSFC computation which differed by 32m at 3 sigma. The accuracy of ATV-CC OD during this phase has been estimated with RSS better than 23m at 3 sigma and RMS equal to 9m (see Figure 7).

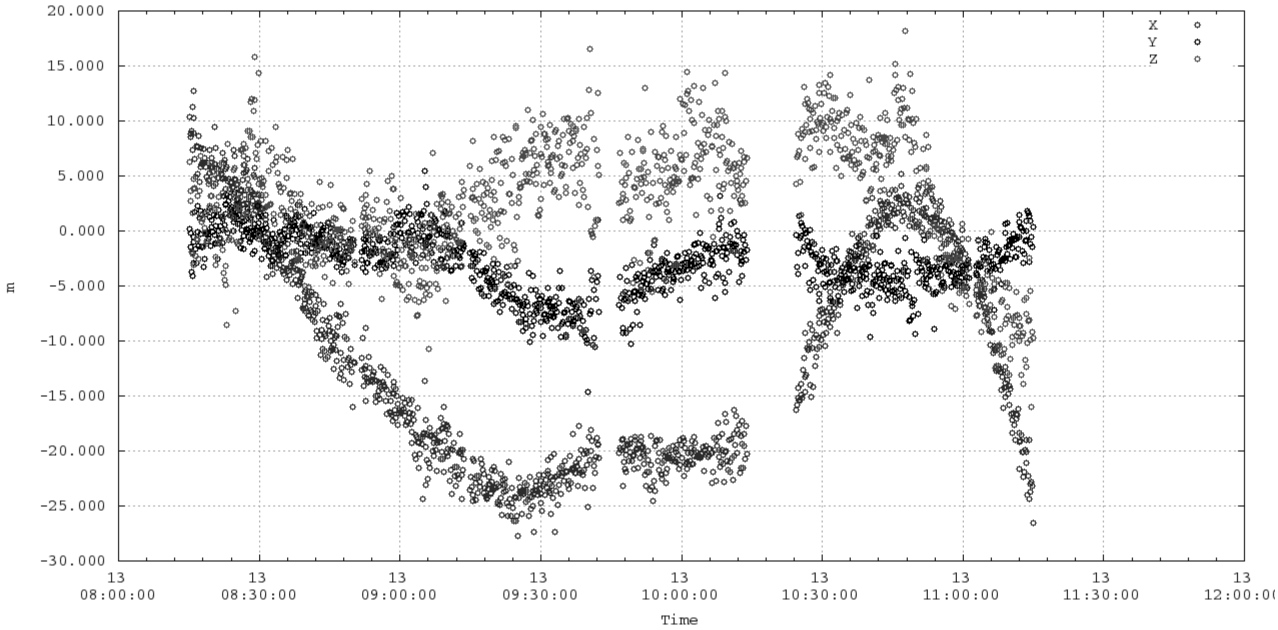

Figure 6 Difference between ATV ephemeris computed by ATV-CC using GPS raw measurements and ATV PVT measurements from ATV GPS receiver.

By checking ATV Absolute Orbit determination we have gained sufficient confidence on ATV-CC computing ATV relative position by differences of orbit determination solutions (using ATV GPS and ISS ASN-M data). ATV relative position estimated by ATV-CC using ATV GPS and ISS ASN-M data have been used for FCM ΔPVT and RGPS assessment during Demo Day 1 until S2.

A dedicated manoeuvre of 3.3m/s in the along track direction (representative of an ESCAPE manoeuvre) has been planned during phasing and its accuracy assessed comparing the actual measured DV against the commanded one.

The ability of ATV to execute an ESCAPE like manoeuvre has been confirmed by the observed very good performance: about 1% in magnitude and 0.26 Deg in direction.

The capability of thrusters firing under MSU control has been tested as part of nominal ATV operations during CAM test: a very small DV has been commanded by MSU and short thrusters firing have been observed.

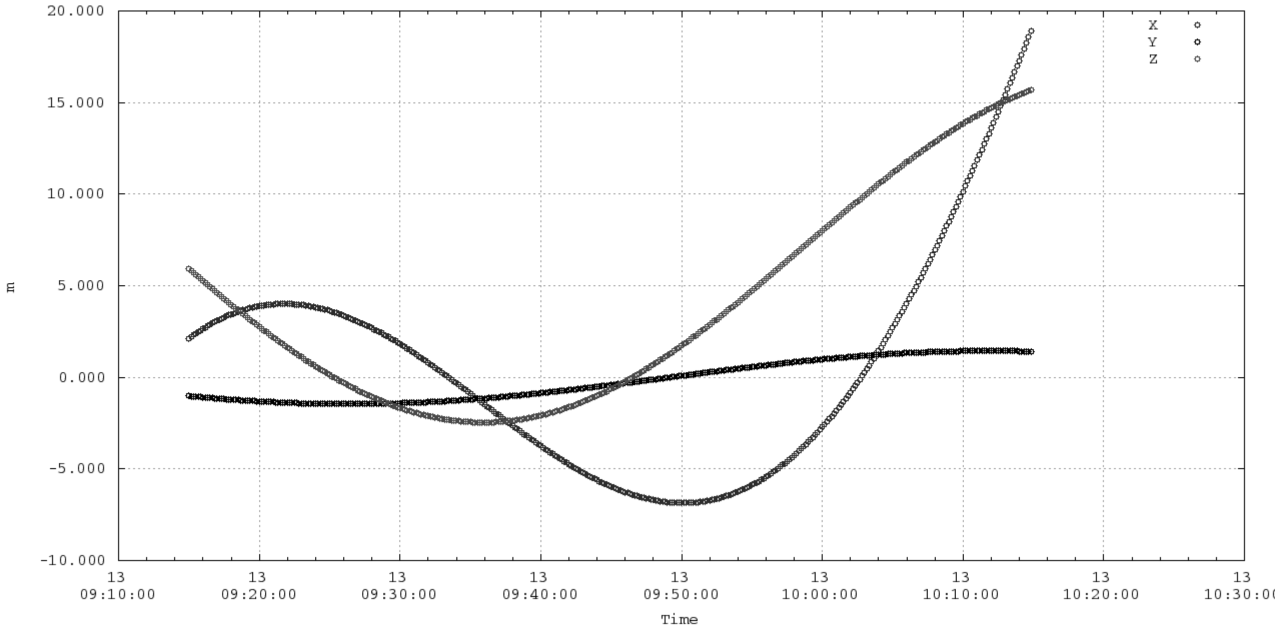

Figure 7 Difference between ATV ephemeris based on GPS raw measurements on two different periods over the overlapping arcs

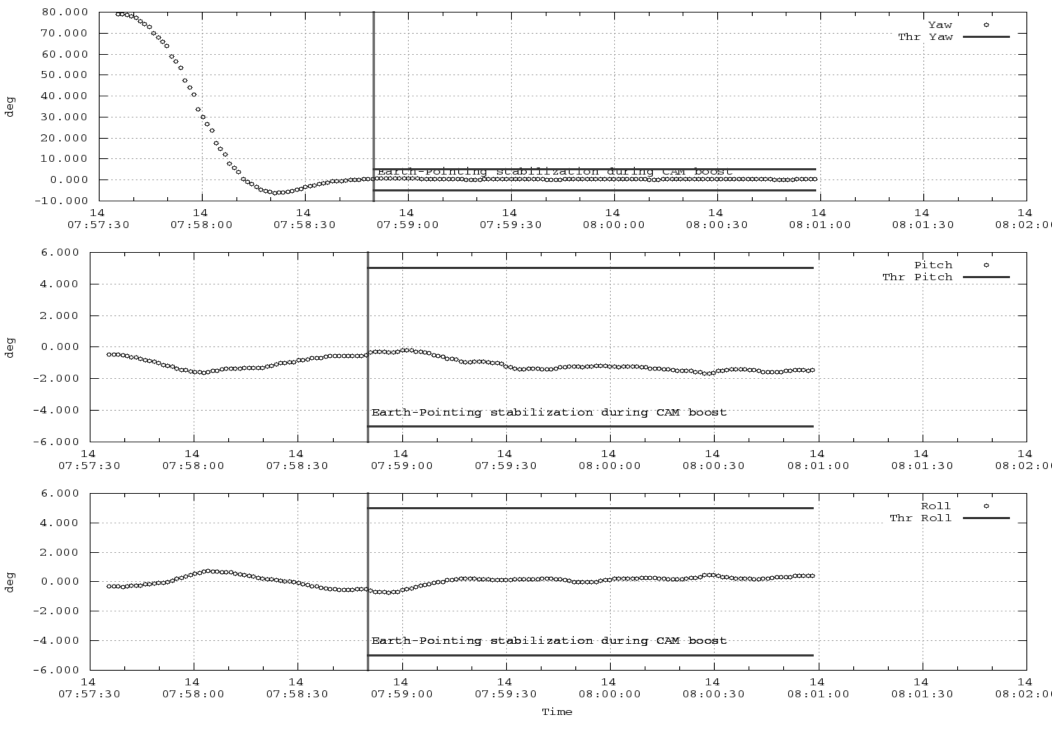

Figure 8 ATV attitude during CAM boost

The full execution of a CAM manoeuvre has been also executed as part of ATV-JV mission in order to completely demonstrate the ATV capability to execute the Collision Avoidance Maneuver (CAM), which is one of the means ensuring the ISS safety.

ATV attitude during this manoeuvre is characterized by an intense dynamics and thrust firing during a relative short transition which may last up to 100s. Figure 8 shows the observed attitude behaviour resulting in less than 75 second attitude slew and stabilization which is very similar to the average results of simulations for qualification campaign. In spite the limited observability of the manoeuvre due to nominal loss of GNC TM, the CAM boost DV has been estimated by ATV-CC at 5.5m/s in retrograde direction which is well within the expected performance.

6. ATV-JV demonstration: Demo Day 1

Before ATV executed the first RDV maneuver ATV-CC verified with real-time monitoring that ATV computed maneuvers were targeting the S2 point (located at 3.5km behind the ISS) and met the ISS safety requirements.

Therefore prior to ATV-CC authorization for ATV to execute the maneuvers to reach S2, the following has been demonstrated:

1) The ATV planned maneuvers lead to the targeted point and are safe with respect to ISS.

2) ISS safety is ensured from the demonstrated CAM and the partially demonstrated ESCAPE (no ESCAPE maneuver yet performed but all means (hardware and software) required for the ESCAPE maneuver have been demonstrated during phasing).

During Demonstration Day 1, the demonstration objectives consisted in verifying that:

1) ATV could perform accurate navigation (during free drift and orbital maneuvers) using Relative GPS

2) The FCM was monitoring relative trajectory estimated with an accuracy according to success criteria

3) The ESCAPE maneuver brought ATV in a safe orbit against ISS

4) Homing boosts allowed to reach the targeted S2 point and the ATV actual trajectory was safe with respect to the ISS.

At the end of Demonstration Day 1, the ESCAPE was fully demonstrated and all necessary means to ensure ISS safety (FCM until S3, ESCAPE and CAM) were also demonstrated.

Results have been documented in JADOR report for Demo Day 1 (see Ref. [5]).

The RGPS assessment consisted in verifying ATV GNC navigation solution (relative position computed from data from ATV GPS and ISS ASN-M receivers).

By checking RGPS we gained sufficient confidence on ATV controlling FAR RDV trajectory (by computing closed loop maneuvers) in order to reach S2 and S3SK points. Safety aspects of the FAR RDV trajectory are covered by FCM ΔPVT demonstration. ATV-CC determines the ATV–ISS GPS Relative Orbit and compared it with the ATV RGPS data resulting in differences of about 10m per axis at 3 sigma. ATV RGPS data was also assessed against KURS data showing and agreement better than 5m.

Demonstration of FCM trajectory monitoring during Far RDV has been performed during DD1 by comparing the FCM parameters (X, Z, VX, VZ, Zm) with the same parameters computed by ATV-CC using GPS Relative Orbit determination. Differences better than 12m in position and 7 cm/s in velocity have been observed showing a good agreement of the two solutions.

Technical analysis (Ref [2] and Ref. [3]) shows that FCM delta PVt navigation performances observable by ATV-CC prevent ATV from getting too close to ISS.

The ESCAPE demonstration was performed by executing and assessing the ESCAPE maneuver required to depart from the S2 hold point during Demo Day 1. The ESCAPE was triggered while in Yaw Steering attitude with a yaw angle of about 90deg.

ATV-CC assessed the ATV attitude and attitude rate during ESCAPE, as well as the components of the maneuver estimated by FCM which differed from the commanded DV of only 3cm/s along track and 1 cm/s cross track.

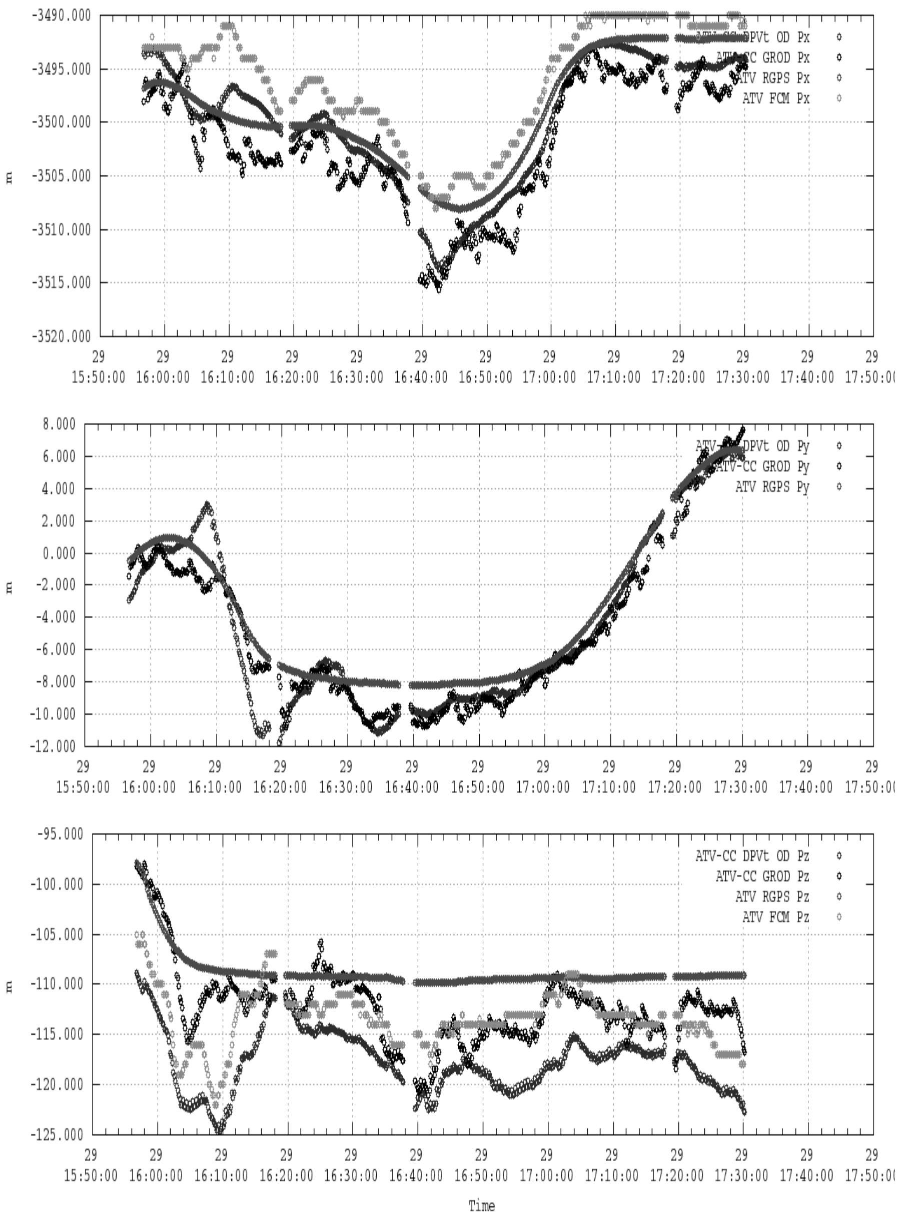

Figure 9 Relative position during S2 station keeping (RGPS, FCM and ATV-CC)

After having passed successfully the criteria on FCM DPVt and the assessment of Escape during DD1 the confidence on ATV FCM to protect ISS safety during ATV approach until S3 was considered acceptable and we could safely proceed to execute Demo Day 2.

7. ATV-JV demonstration: Demo Day 2

At the beginning of Demonstration Day 2 (shortly after departing S3 at a distance of about 150meters) the capability to RETREAT, HOLD and RESUME to the previous station keeping point, commanded either by ATV-CC or by the crew, was demonstrated. This gave confidence for proceeding further with a close approach towards the ISS.

During Demo Day 2, the demonstration objectives consisted in:

1) Assessing that VDM and TGM provide consistent data.
2) Verifying that nominal navigation perform accurately within the safety limits
3) Verifying that FCM functions correctly.
4) Demonstrating the ATV capability to perform forced translations and relative attitude navigation during the Final Approach.

At the end of demonstration day 2, FCM and ATV GNC performances in rendezvous have been fully demonstrated. Thus all necessary means, both in terms of on-board GNC, safety (FCM, ESCAPE, CAM), ground and crew monitoring and control have been demonstrated and allowed to proceed with the actual rendezvous and docking. Results have been documented in JADOR report for Demo Day 2 (see Ref. [6]).

The purpose of Final Approach demonstration was to show that the ATV modes that are used from S4 to contact were functioning correctly prior to S41 departure. By design, the ATV performance improves significantly between S41 and Contact, and the ATV performance might not have been yet within all safe docking contact conditions at S41. As a result, safe contact conditions might have not been explicitly demonstrated prior to departing S41. As an alternative, the goal of the Final Approach demonstration was to gain confidence in the ATV behavior by showing that the ATV was operating as designed between S4 and S41.

ATV-CC assessed the VDM/TGM consistency, differences between onboard estimated and commanded parameters regarding position and attitude, as well as typical trajectory behavior parameters.

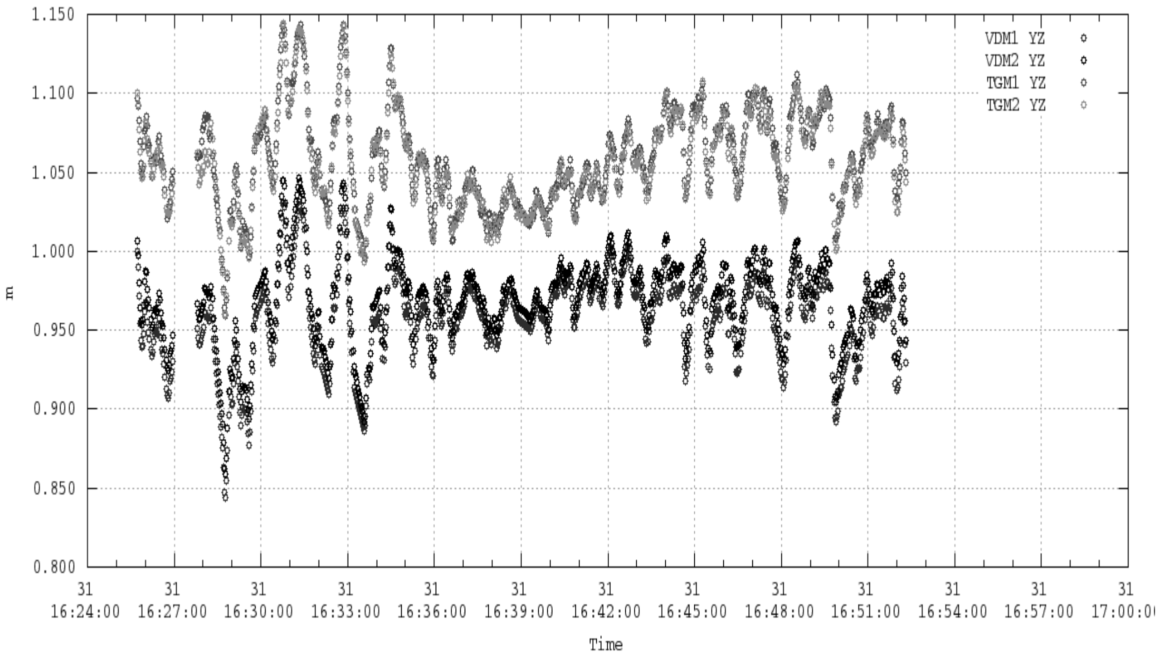

Figure 10 Lateral RVT positions computed using VDM1, VMD2, TGM1 and TGM2 during Final Approach

Navigation coherence and GNC onboard confidence methods demonstrated that the ATV navigation was performing as expected and that the ATV guidance and control were performing as designed. As there are no changes in the ATV GNC modes and functions between S4 and Contact, it was assumed that the ATV continued to function correctly between S41 and Contact if it flew correctly from S4 to S41. The trajectory behavior method provided an independent confirmation that the trajectory was within expected boundaries. 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.

The safe conditions associated with contact are based on the ATV Flight Segment analysis.

The four RDV sensors (VDM1, VDM2, TGM1 and TGM2) showed a 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 Figure 10).

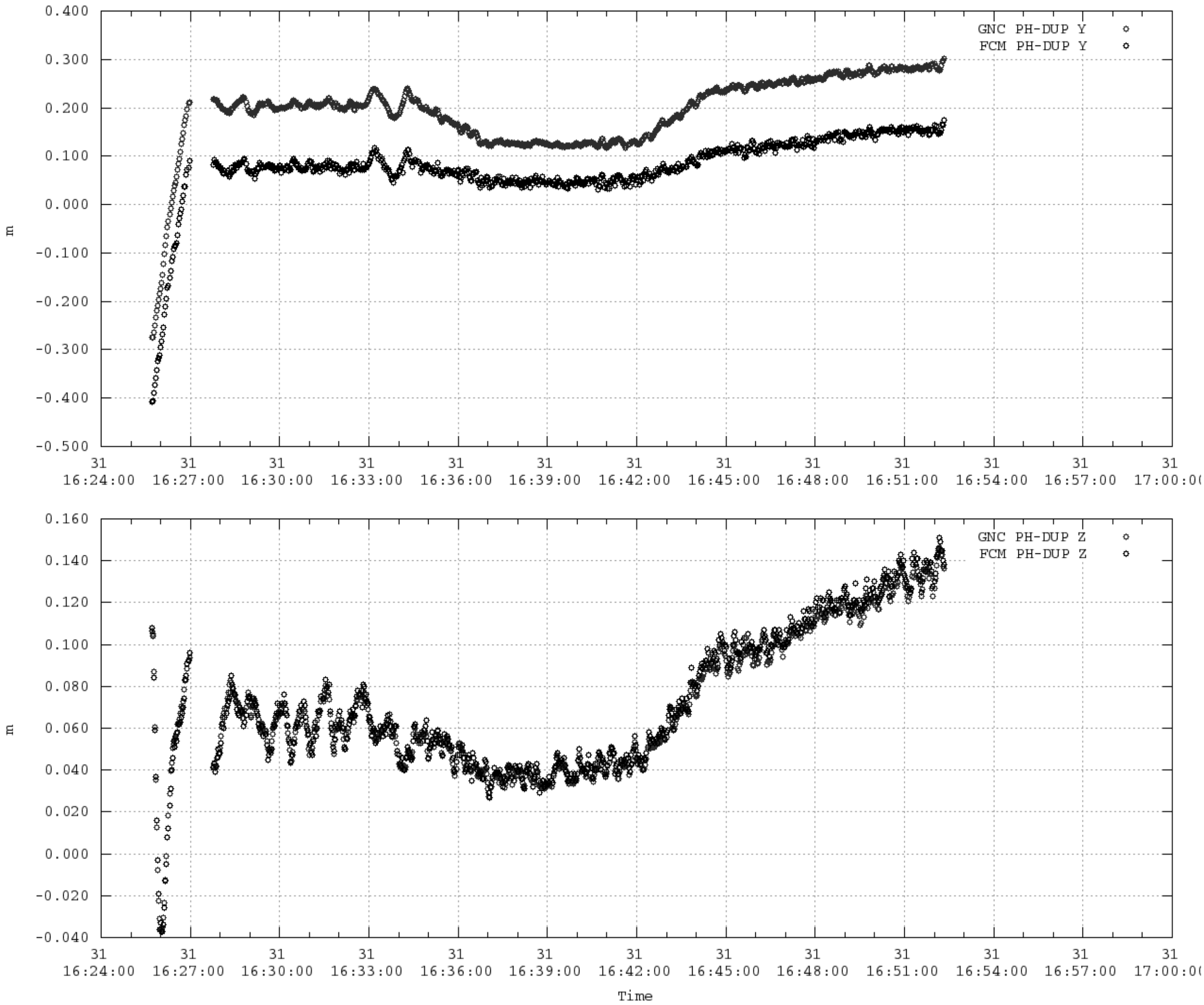

Figure 11 Probe Head to Docking Port lateral position (ATV GNC and FCM) from S4 to RETREAT (DD2).

The trajectory behavior estimated by FCM between S4 and S41 was largely inside the expected performance and it was so stable that all trajectory parameters were observed within the mechanical requirements at docking already at 12m from the docking port: closing range rate was less than 7cm/s (see Figure 12), lateral misalignment less than 10 cm (see Figure 11), lateral velocity better than 4mm/s and relative attitude less than 1Deg.

The assessment of RETREAT, HOLD, RESUME high level commands consisted in verifying that ATV braked, stopped and was station keeping at the defined stopping points and accelerated again towards S4 reaching its nominal translation velocity after the RESUME command.

The Retreat, Hold, Resume sequence is clearly visible in Figure 12 and the dynamics behavior was perfectly matching the expectations. One can also note the consistency between ATV estimated values and the values estimated by the independent means, i.e. ATV-CC and ISS KURS.

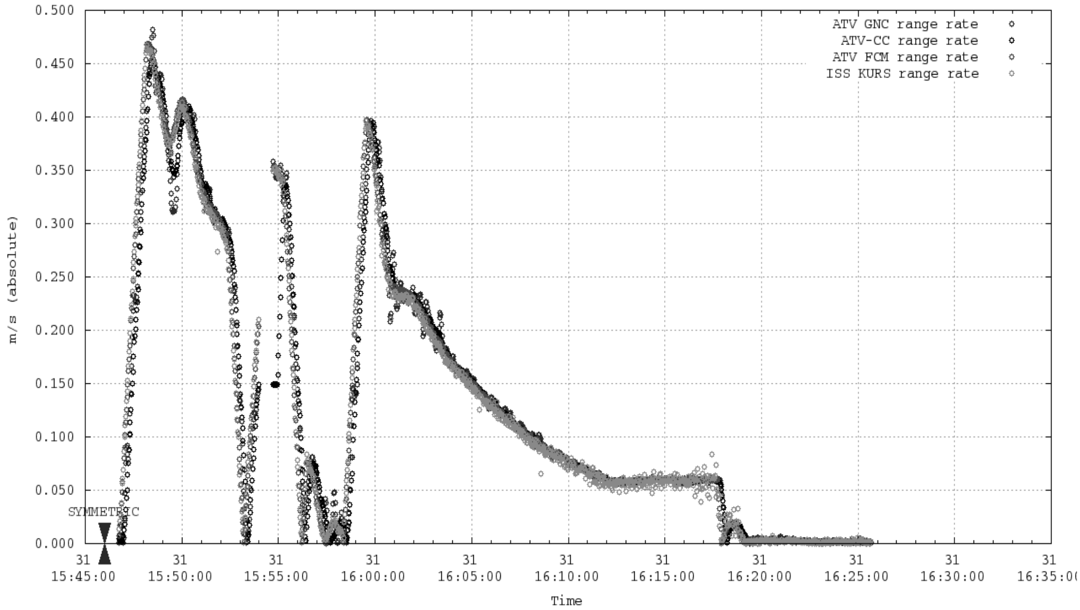

Figure 12 Range rate during Final Approach (S3-S4 DD2) from ATV GNC, ATV-CC, ATV FCM and ISS KURS.

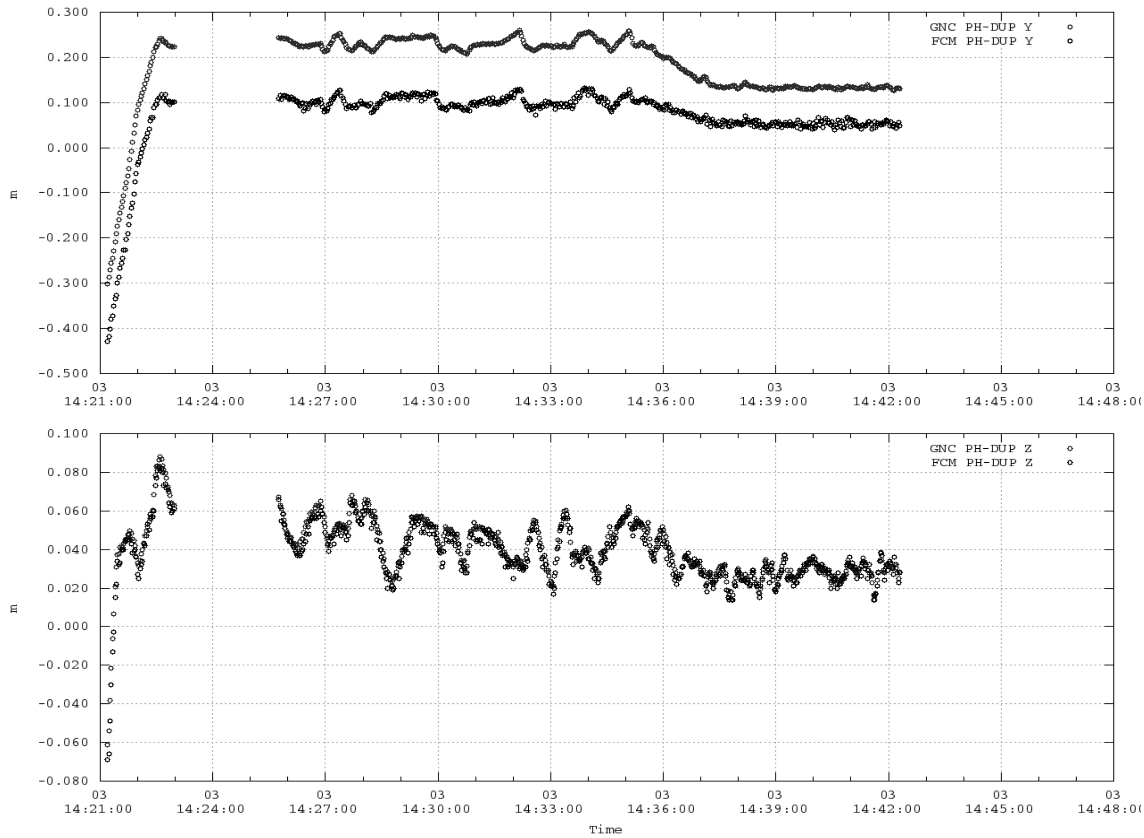

Figure 13 Probe Head to Docking Port lateral position (ATV GNC and FCM) from S4 to S41 (Docking Day).

The assessment of the FCM monitoring was limited to the assessment of the on-board computation of the parameters monitored by FCM by comparing it with the same parameters computed by ATV-CC.

A good consistency of the two computations was observed confirming the reliability of FCM monitoring.During RDV on Docking day the very same behavior seen in Demo Day2 was observed (see Figure 13 and Figure 14).

The outstanding GNC performances of ATV-JV demonstrated during Demo Days have been again confirmed by the flawless RDV and Docking on the 3rd of April 2008.

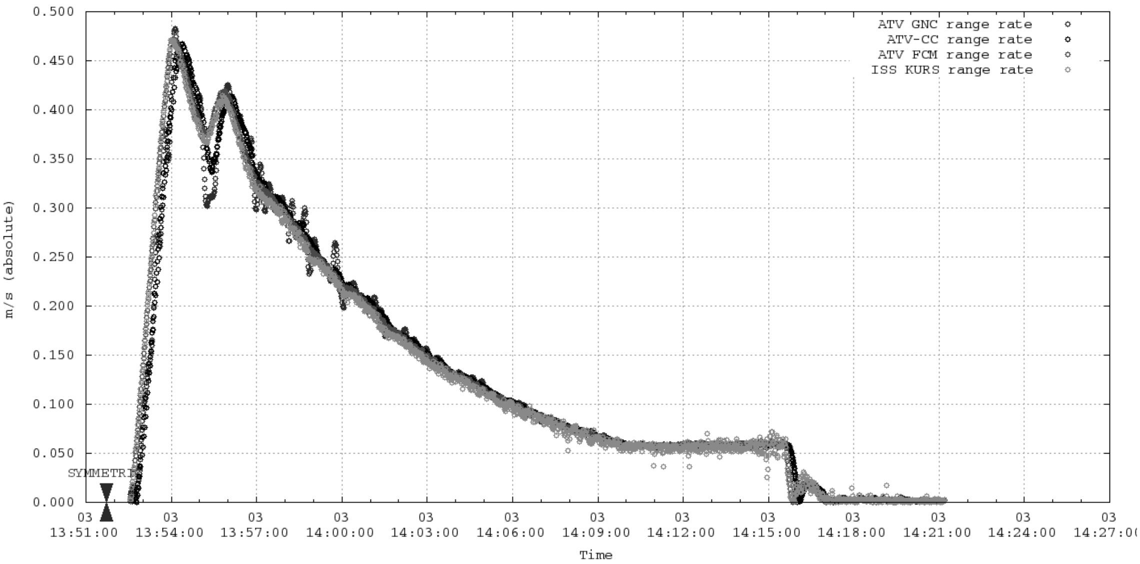

Figure 14 Range rate during Final Approach (S3-S4 Docking Day) from ATV GNC, ATV-CC, ATV FCM and ISS KURS.

8. Conclusion

This paper presented the results of ATV-JV demonstration which concern RDV technology which has potential applications to S/C formation flight and RDV. In flight results has shown that of ATV-JV is able to control relative position at 250m from ISS with accuracy better than 15m with a guidance based on Relative GPS navigation. This technique can be applied to formation S/C if the distance is sufficient to neglect multi-path effects.

Analysis of Final Approach TM has confirmed very good performance of brand new RDV sensors (VDM and TGM) based on laser pulses and optical devices: accuracy of few cm has been noted at 12m distance and it has improved up to few mm at docking. ATV Final approach forced translation has maintained the S/C aligned to the docking port trough the last 20m observing a maximum misalignment smaller than 10cm at station keeping point distant 11m from the docking port. The automated RDV technique has been demonstrated can be used for S/C system requiring connecting two modules in flight. These new RDV sensors can be also considered for applications of tandem S/C with strong requirements on relative position estimation and control accuracy.

ATV “Jules Verne” constitutes a major technological milestone for Europe, paving the way to further initiatives in the frame of autonomous safe rendezvous for space exploration, human spaceflight and formation flight experiments.

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Nomenclature

ASN-M	=	Satellite Navigation Equipment installed on the ISS Russian Segment
ATV	=	Automated Transfer Vehicle
ATV-JV	=	ATV Jules Verne

ATV-CC	=	ATV Control Centre
CAM	=	Collision Avoidance Maneuver
FCM	=	Flight Control Monitoring
FDS	=	Flight Dynamics Subsystem
GPS	=	Global Positioning System
ISS	=	International Space Station
JADOR	=	Joint ATV Demonstration Objectives Report
LVLH	=	Local Vertical Local Horizontal
NASA	=	National Aeronautics and Space Administration
RDV	=	Rendezvous
RGPS	=	Relative GPS
RSC-E	=	Rocket and Space Corporation Energia
TGM	=	Telegoniometer
TM	=	Telemetry
VDM	=	Videometer

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