ATV GNC flight performance and lessons learned

Olivier Mongrard, Bruno Cavrois**, Finn Ankersen*, Olivier Dubois-Matra*, Michel Zink **, Alizee Vergnol**, Eric Piquemal**, Guillaume Pionnier**, Ulysse Southivong***

** ESA-ESTEC, Noordwijk, Netherlands*

***Airbus Defence and Space, Les Mureaux, France*

Abstract
ESA's fifth and final ATV, Georges Lemaître, performed its fully automated rendezvous and docking with the International Space Station on the 12th August 2014. The ATV's navigation sensors have shown their worth docking the 20-tonne vehicles with aft port of the Space Station, manoeuvring into position and docking with an excellent accuracy. For the second consecutive time after ATV-4, the accuracy at docking was such that the ATV probe head was directly captured inside the Zvezda docking mechanism without contact with the receiving cone.
From 30km and down to a distance of 250m, ATV uses GPS information from its own receiver and the Station's that is transmitted over a radiofrequency link. As it moves closer, ATV switches to laser navigation, using the reflection of laser pulses on reflectors mounted on the Space Station.
This paper will present the achievements and performance of ATV GNC across the 5 missions for both types of navigation. It will also discuss the observations made during the various flights regarding unforeseen conditions such as space environment or target pattern contamination having a potential impact on performance and how they were resolved.

1 Introduction

The last Automated Transfer Vehicle (ATV) performed a controlled re-entry over the Pacific ocean on February 15th 2015, marking the end of the ESA ATV Programme. The ATV Programme has got no equals in the ESA history for technical and programmatic complexity as well as level and duration of the engaged resources. With five successful ATV cargo missions to the International Space Station (ISS), over seven years, the European spaceship has demonstrated its reliability as the largest and most versatile ISS cargo vehicle. It has been acknowledged by the ISS partners as a robust and extremely capable vehicle. ATV had the largest upload capability of all ISS visiting vehicles, as it can carry nearly 7 tonnes of dry and fluid cargo including water, gas, ISS refuelling propellant but also food and new experiments or spares. Together with the Russian Progress, the ATV during its 6 months stay at the ISS, was the only visiting vehicle that can perform ISS refuelling, ISS attitude control, ISS reboost and - whenever needed – debris avoidance manoeuvres. The ATV was a multifunctional spaceship, combining the automatic capabilities of an unmanned vehicle with human spacecraft safety requirements. New rendezvous technologies had been developed in the frame of the ATV programme to ensure such automated and safe docking to a manned facility. These new development paved the way for the other ISS visiting vehicles.
This paper will provide an overview of the performance of the ATV flight control during the automated rendezvous phase, comparing the five missions. Across the five ATV missions some anomalies have been encountered and resolved. The last part of the paper intends to provide some lessons learnt or recommendations based on this experience.

Figure 1 - ATV-4 prior docking to International Space Station

2 ATV Rendezvous GNC performance

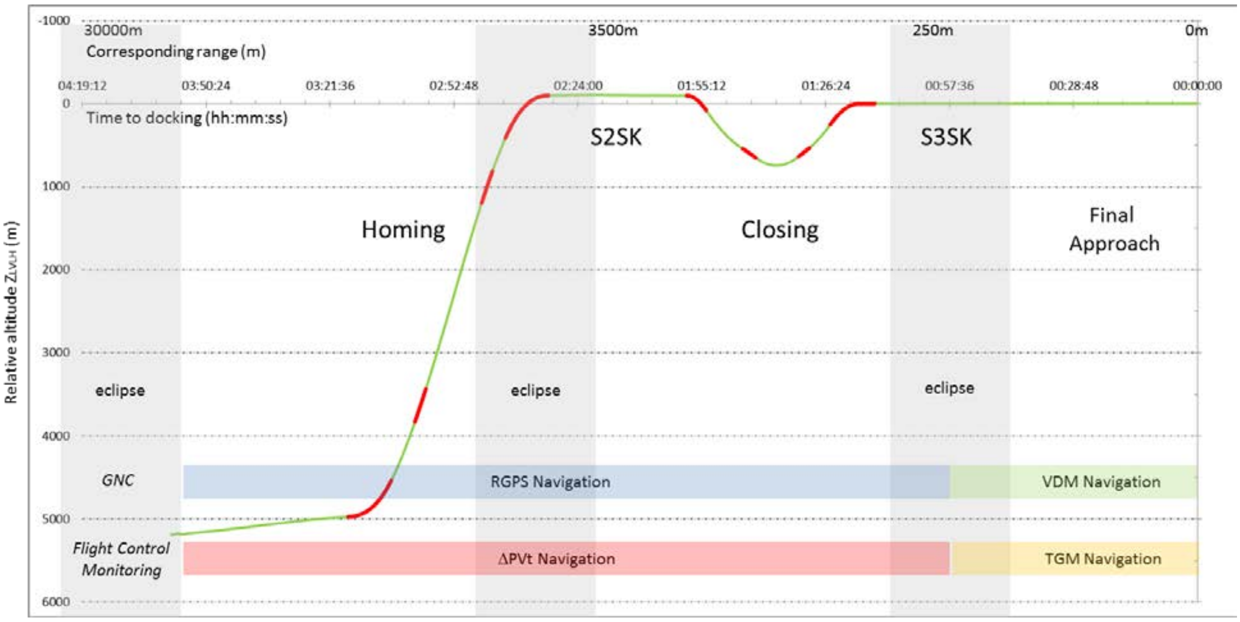

Figure 2 – ATV5 Rendezvous relative trajectory along Z_{LVLH} as a function of time to docking (red arcs represent boost phases)

ATV automated rendezvous is initiated about 30 km behind ISS along the local velocity vector and 5km below along nadir as illustrated on Figure 2. At such distance the Proximity Link with ISS can be established and relative navigation using ATV and ISS GPS receivers data (see Figure 3) initialized. GPS relative navigation is used by ATV up to a station keeping point located 250m behind ISS Zvezda service module. To meet its safety requirement toward ISS, ATV implements both the nominal Guidance, Navigation and Control (GNC) [1] function that is steering the vehicle toward docking with ISS and on top a dedicated Flight Control Monitoring function [2] that performs an independent monitoring of the trajectories to ensure safety [3]. During the far rendezvous, the GNC used Relative GPS navigation [4] that is processing raw GPS data from common GPS spacecraft observed by ISS and ATV receivers while FCM navigation relies on the comparison of the Position, Velocity and time (PVt) solution of each receiver. Having these two independent navigations being performed on-board allows to make comparison to assess their respective performance as will be described in the following chapters.

During the close rendezvous or final approach, ATV performs a translation along X_{LVLH} from S3 station keeping up to 20m, and then following a fly-around maneuver aligns itself with the ISS docking port axis for the final translation toward the docking port at a range rate of 6cm/s. During this phase, the nominal sensor used by GNC is the ViDeoMeter (VDM), while FCM uses the TeleGonioMeter (TGM) for monitoring. Both types of sensors are used in hot redundancy with a redundant equipment for each rendezvous. All sensors are using a unique optical target pattern, composed of multiple retro-reflectors and installed on the aft port of ISS service module (see Figure 3), to perform navigation measurements. More details over the rendezvous scenario and ATV Flight Control can be found in [5], [6].

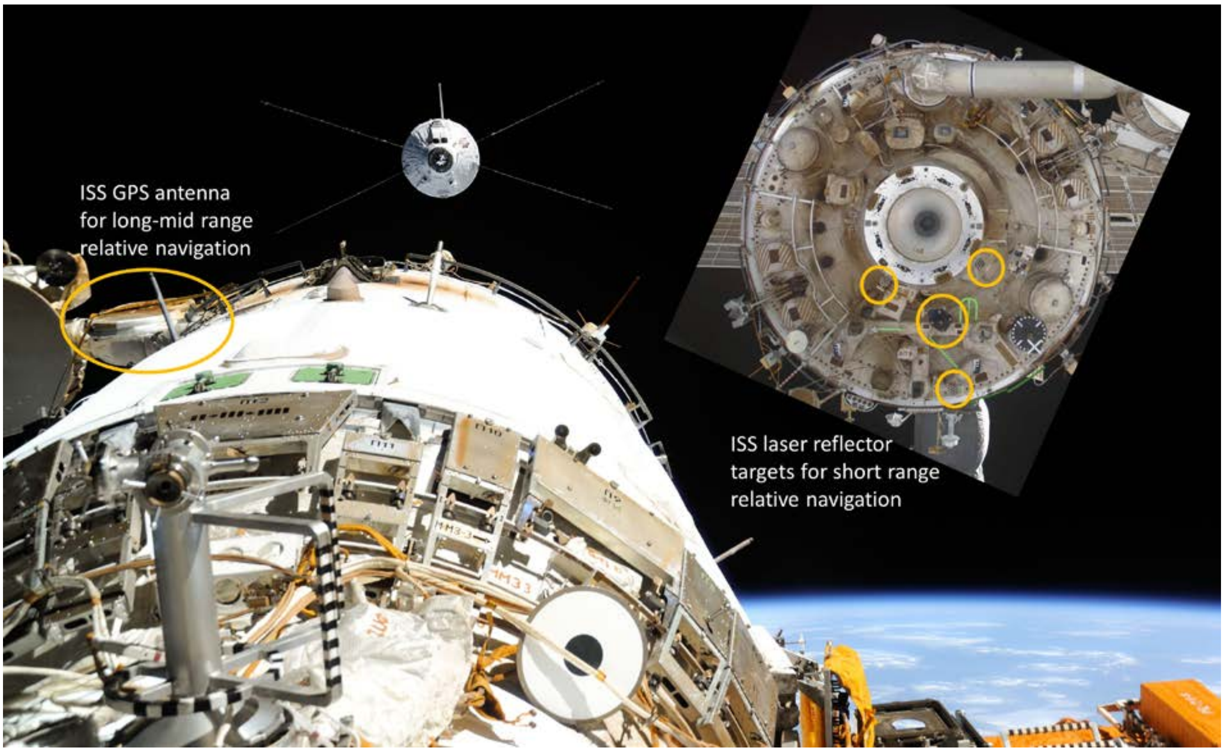

Figure 3 – ISS navigation hardware used for ATV Rendezvous. GPS receiver for navigation up to S3SK and laser reflector target pattern for Final Approach

2.1 Far rendezvous

For all flights, the initial convergence of the RGPS filter during the initialisation of the rendezvous has been much better than the specified 10min. The convergence was reached within about 1min for ATV-1 and ATV-2, 2min for ATV-3 and ATV-4 and 3min30 for ATV-5. The variability of the convergence time is expected based on the specific GPS constellation configuration at the beginning of the rendezvous and the accuracy of the initialisation performed by ATV-CC.

There is no possible comparison with a “perfect” reference to finely estimate the performance of the GPS navigation filter, but the comparison between the RGPS navigation and the ΔPVt navigation provides valuable information on the estimation capability.

The two graphs on Figure 4 present the estimation of position performed on-board by RGPS and ΔPVt for ATV-2 to ATV-5. Data starts with Pre-Homing and finishes with S_3 Station Keeping and has been synchronised among flights with respect to Equator crossing. Note that ATV-1 is not shown on these figures due to the fact that it is not directly comparable since the ISS GPS receiver was implementing some ionospheric corrections which were suppressed in subsequent flights. The plots show a similar and consistent behaviour across the various flights. During the initial phase, there is a slight decreasing bias on the radial component Z_{LVLH} that can be explained by the difference in definition of the relative frames used by RGPS and ΔPVt filters that is observable at large distance (~30km). Otherwise, both navigations are consistent with each other within less than 5m for both X_{LVLH} and Z_{LVLH} component during almost all the rendezvous, but for some specific peaks of 10m to 15m magnitude. In velocity, the consistency between the two navigations is within 0.02m/s of each others outside of the peaks.

ΔPVt algorithm does not perform any consistency control on the selection of the satellites taken into account to compute PVt solutions. It was confirmed for instance that satellites can be used by ISS GPS receiver and not by ATV GPS receiver. This phenomenon leads to some discrepancy between ATV PVt and ISS PVt, which is greatly amplified by the ionosphere effect. Figure 4 shows the correlation between the equator crossing during sunlight by the ATV and the observed peaks in difference between RGPS and ΔPVt. This confirms the influence of the ionosphere effect on the observed peaks.

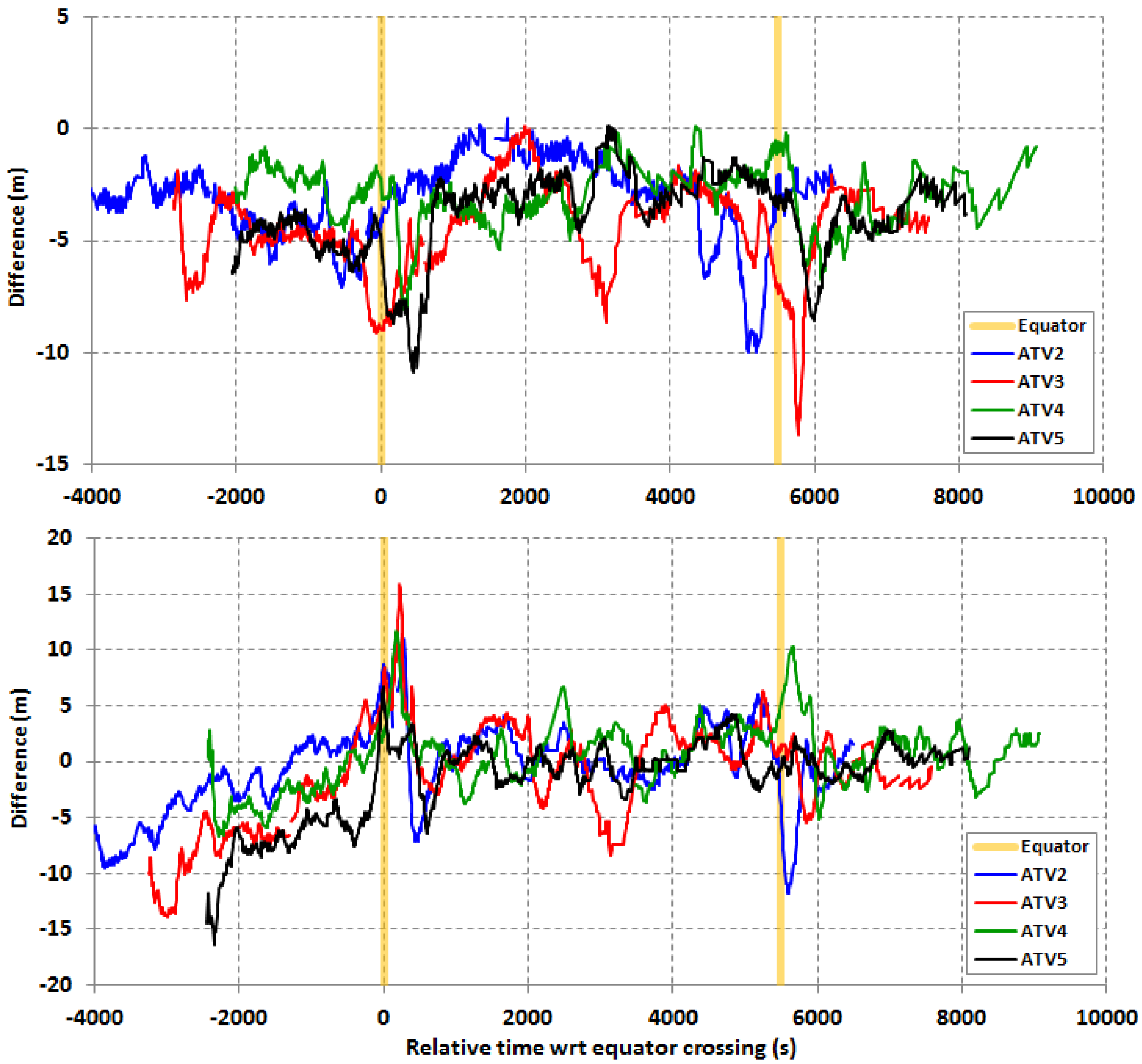

Figure 4 – Position difference (RGPS –ΔPVt) along X_{LVLH} (top) and Z_{LVLH} (bottom)

In conclusion, the observed peaks are due to ΔPVt increase error due to the combination of the ATV GPS and ISS GPS tracking list difference and the ionosphere effect at the equator.

For all flights trajectories are within less than 10m of each other in the final phase of the far rendezvous as can be seen on Figure 5. A margin of about 20m was always preserved with respect to on-board safety barriers [3] (red dashed line threshold on Figure 5). In general, the far rendezvous trajectories of all flights are comparable and well within the defined trajectory safety thresholds.

The robustness of ATV GNC was particularly illustrated during ATV-4 far rendezvous when a pressure sensor anomaly in a thruster triggered the isolation of one propulsive chain during the first boost of the Homing sequence (see Figure 2). This event led to the modification, within the next commanding cycle, of the propulsive configuration and hence thrusters available for the Thrusters Management Function (TMF) [7] to implement GNC commands. ATV was designed to ensure mission continuation after a first failure, and that incident had no impact on either the boost accuracy nor the attitude controller. ATV-4 pursued the remaining part of the rendezvous on the alternative propulsion configuration without any performance degradation.

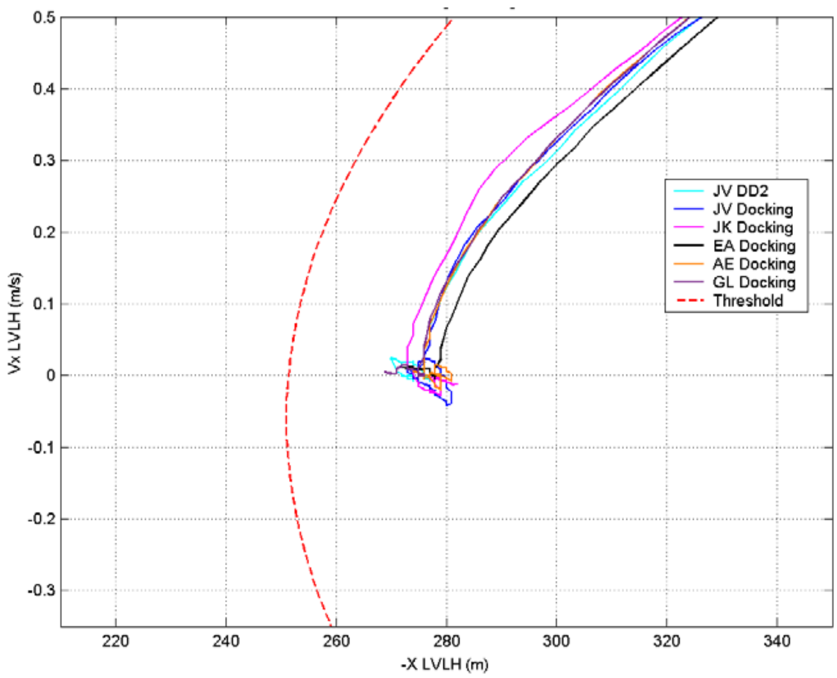

Figure 5 – ΔPVt Vx monitoring – Closing and S3 station-keeping trajectories in Vx-X plane

2.2 Close Rendezvous

The range-rate versus range profile from the S_3 station keeping point up to docking has been followed in a very similar and consistent way by all ATVs as can be seen on Figure 6. After an initial acceleration phase leaving S_3 up to a range rate of about 0.5m/s, ATV gradually decelerates to reach the final translation range rate of ~6cm/s. A slight controller overshoot is visible at the transition from the acceleration phase to the linear deceleration phase. It is similar for all spacecrafts. The station keeping points in S_4 at 20m and S_{41} at 12m are also visible on that chart as range rate is then temporary brought down to zero.

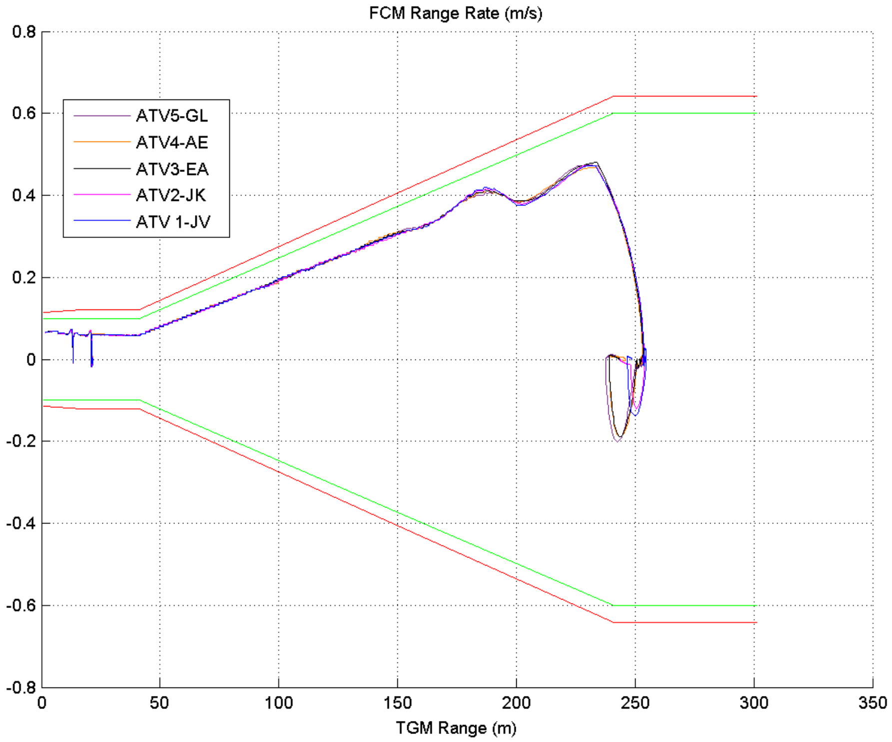

Figure 6 – Range rate monitoring – Final Approach trajectories in range-rate versus range

The range difference between the VDM sensor used by GNC and the TGM used by FCM provides an insight on the respective performance on the navigation during the final approach. Figure 7 shows that difference from S_3 up to docking for all 5 ATV missions. Above 200m, there is a clear bias between the 2 sensors of up to 2-3m, that is due to VDM range measurement performance. Closer than 200m, the difference between the two measurements remains smaller than 1m and is decreasing with range. Below 50m, the range provided by the two sensors are within 0.1m of each other, except for a small peak visible on all flights at 30m, due to a specific diffraction effect seen only by VDM-1 at such distance and still within specified range performance.

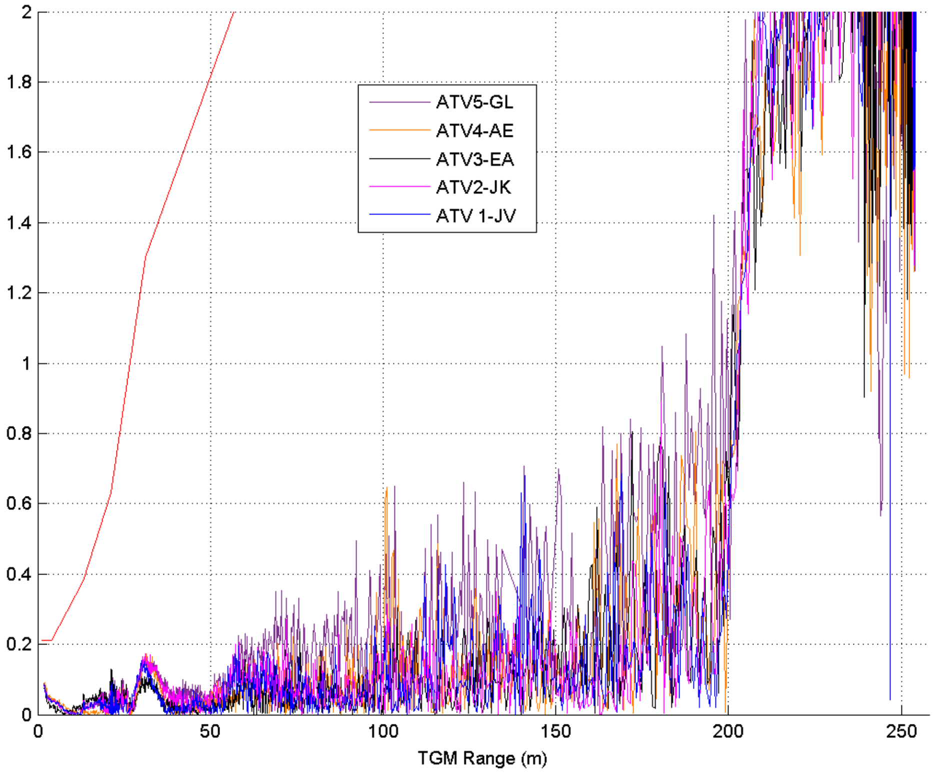

Figure 7 – Delta range (m) between TGM-1 and VDM-1 during Final Approach

During the ATV final approach, ISS is using its thrusters to maintain its attitude around an equilibrium point close to LVLH. Table 1 shows the average attitude profile of ISS during all ATV mission. Except for ATV-1, for which ISS assembly was not completed, the attitude profile followed by ISS has been similar. On Figure 8, the temporal evolution of ISS attitude in Yaw, Pitch and Roll during ATV5 final approach is reproduced. It can be seen that ISS maintains its attitude within 0.1deg of the reference. Hence the ISS attitude motion encountered in flight are very benign compared to the worst case attitude evolution considered for ATV qualification. The two-way motion specified for ISS worst case attitude motion during rendezvous is reproduced in black on Figure 8 and can be compared to flight data. Therefore, the ATV GNC controller design [8] that considered such motions for its qualification is very robust and handles the smooth ISS attitude evolution with ease.

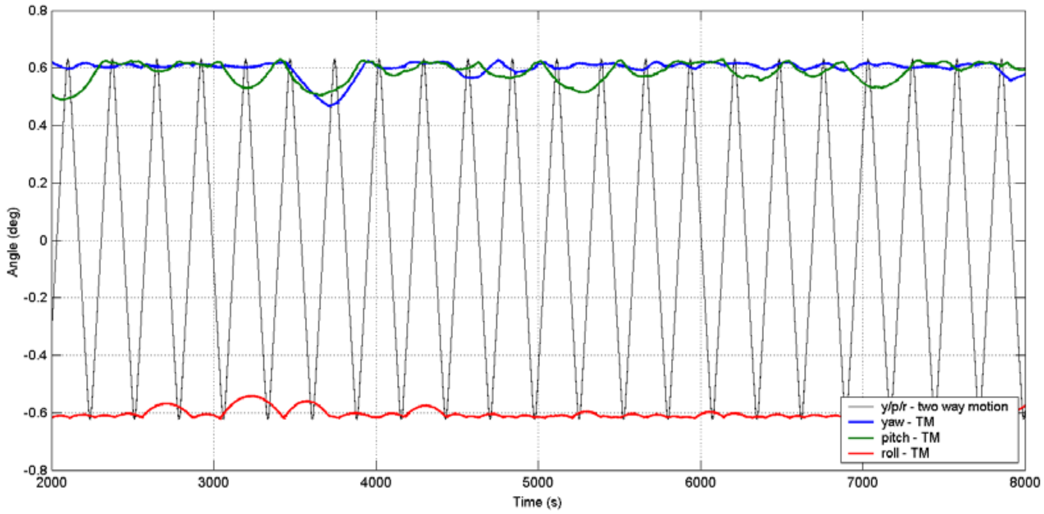

Figure 8 – ISS attitude wrt LVLH during ATV-5 rendezvous in Yaw/Pitch/Roll compared to specification used for ATV qualification

From the station keeping point in S_4 at about 20m from docking port, ATV start aligning itself with the ISS docking port. The position of the probe-head at the extremity of ATV docking port is then maintained along the ISS docking port axis. Figure 9 shows that after the transition from LVLH to ISS docking axis, the probe head has been kept aligned with a good accuracy for all flights during the last 20m. Despite the ISS attitude motion, the transverse motion of the probe head with respect to the ISS docking axis remains within about 1cm, which is much better than the 10cm error specified at docking.

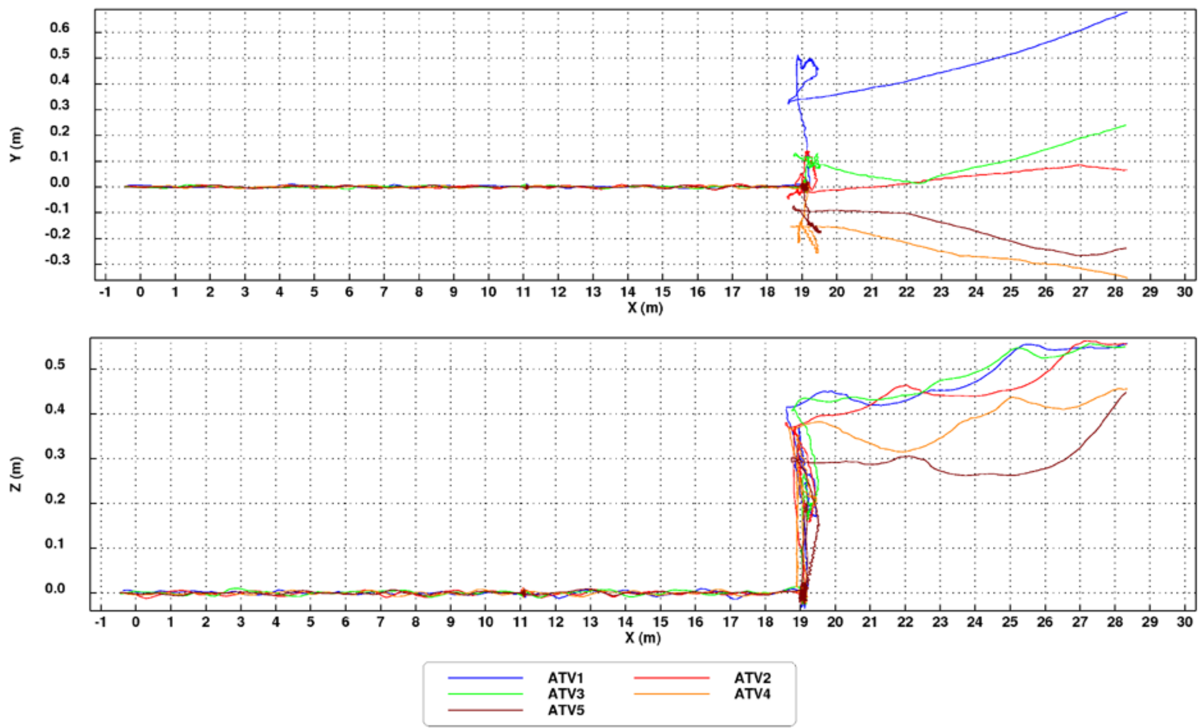

Figure 9 – Estimated ATV Probe Head position in ISS frame during last 30m

A zoom on the last 5m, shows that the transverse position of the probe head is indeed within 1cm, and even within 0.5cm when entering the docking cone (range equals zero) for all flights but ATV1. The accuracy at docking can be measured by the transverse probe head position at first contact and cross-checked versus the time between the first contact of the ATV probe head and the ISS docking cone and the capture of the probe-head inside the receiving cylinder in the centre of the docking cone. While for the first three ATVs, the probe-head touched first the receiving cone before being pushed inside the cone for capture within 0.76s to 0.4s, ATV4 and ATV5 achieved direct capture of the probe inside the docking mechanism (see Table 1). It means the probe-head touched directly the centre of the docking mechanism within only a couple millimetres. VDM measurements estimated the transverse position to about 2 mm for both flights.

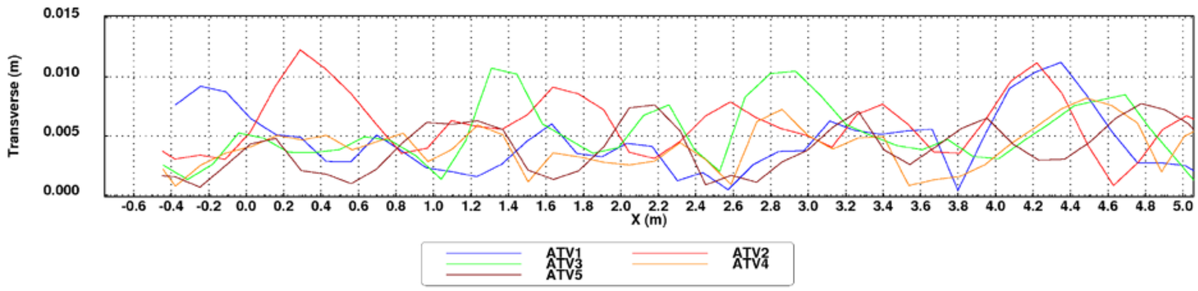

Figure 10 - Estimated ATV Probe Head position in ISS frame, zoom on last 5m

This extreme accuracy for such a large vehicle reached twice in a row, illustrates the high performance of the ATV GNC but also the proper pre-flight preparation including calibration and alignments of sensors during acceptance campaign and numerical simulations on test platforms to validate the mission and vehicle specific data for each flight.

Table 1: Synthesis Table – ATV Final Approach

	ATV1-JV	ATV2-JK	ATV3-EA	ATV4-AE	ATV5-GL
ISS average attitude [yaw pitch roll] (deg)	[-0.6; 0.6; 0.6]	[0.6; 0.6; -0.6]	[0.6; 0.6; -0.6]	[0.6; 0.6; -0.6]	[0.6; 0.6; -0.6]
Fly-around PH motion (Y axis) (cm)	50	0	10	15	12
Fly-around PH motion (Z axis) (cm)	40	37	40	37	30
Transverse position at contact (mm)	7.7	3.7	2.6	2.2	2.0
Time between first contact and capture (ms)	760 (~17mm)	500 (7-10mm)	400 (<10mm)	Direct Capture	Direct Capture

3 Lessons learned

3.1 Knowledge of ionospheric error for GPS measurements

During the far rendezvous, the ATV navigation (RGPS) and the Flight Control Monitoring (FCM) are based on GPS measurements difference provided by ATV and ISS GPS receivers. The knowledge of ionospheric error in terms of intensity and time evolution was a key element to survey along all ATV flights in order to confirm that predictions used for flight preparation and validation remained valid.

The different parameters which have an influence on ionospheric error level, are:

- ISS altitude (the lower the altitude is, the higher the ionospheric error level is): the altitude of ISS varied from 320km for ATV1 to 420 km for ATV5
- Year of flight: solar activity has a cycle period of 11 years, 2008 (ATV1 flight) was one of the lowest level, then solar activity increased to reach a maximum in 2012/2013 for ATV3/4
- Month of flight: the worst case month for ionospheric error level is around April (ATV1/2/3/4) then October
- Solar local time for rendezvous: worst case around 14h

- Equator crossing event: higher ionospheric error level around the magnetic equator, lower level at high latitude.

After post flight analysis of ATV1 flight, it appears that the numerical ionospheric error model used for qualification was sufficient for a flight in 2008, but not sufficiently representative to prepare and validate future ATV flights which have to be done in more severe conditions. The consequences were essentially identified in term of mission success probability reduction due to FCM false alarm rate increase and side effect on GPS satellites rejection by RGPS navigation filter.
For ATV production phase (ATV2 to 5) the ionospheric error model was improved to be more representative by taking into account the higher level of ionospheric error which can be encountered for all ATV missions in the worst conditions for year, month, local time but also by taking into account a variation of the level wrt latitude. For the maximum level, the reference was issued from IRI90 model with RZ=100 for solar activity, see Figure 11. For the variation with latitude, the same principle of ICD 200 for GPS concerning ionospheric error correction was used. The Figure 12 shows the level pseudorange lengthening due ionospheric error wrt elevation, considered for ATV1 and updated for ATV2-5.

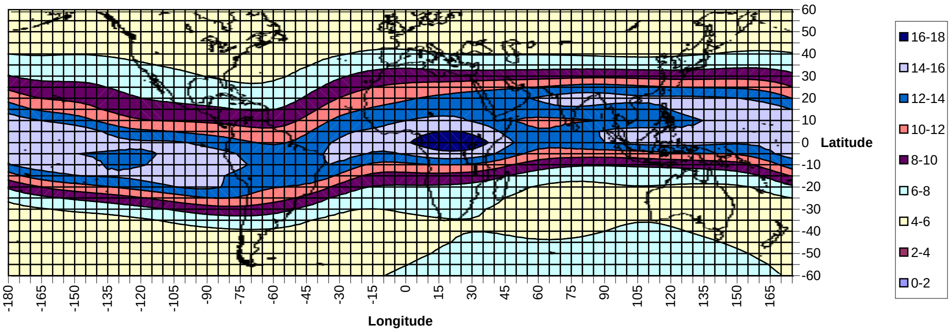

Figure 11 - Pseudorange lengthening due to ionospheric error from IRI90 RZ=100 14h30 local hour (m)

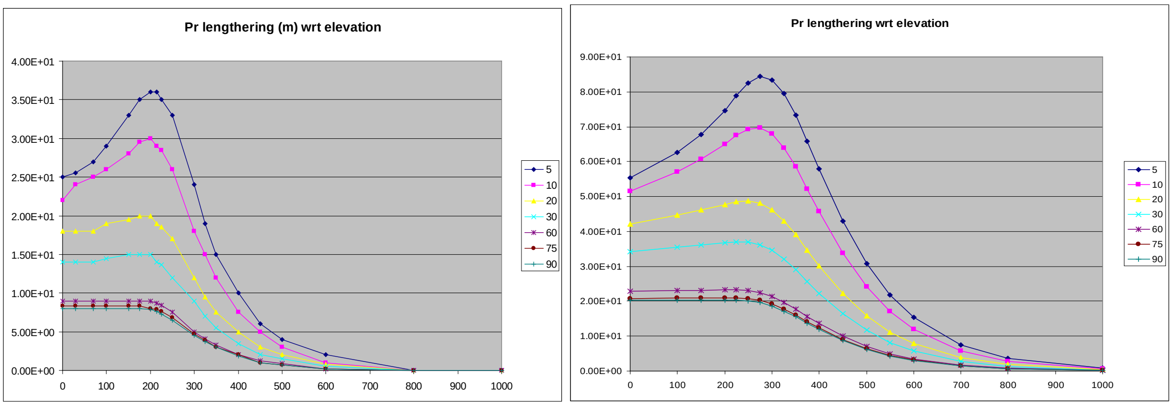

Figure 12 - Pseudorange lengthening due to ionospheric error wrt altitude (km) at different elevation (deg) used for ATV1 (left) and ATV2-5 (right)

Validation on ATV numerical platforms using this new ionospheric error model allowed to justify that with a new tuning of RGPS filter rejection threshold, the ATV GNC performance was not affected by the ionosphere impact even in the worst case conditions. Furthermore, due to system margin for the FCM, the degradation of mission success associated to potential false alarm was negligible and the safety of ISS was not impacted.
All these assumptions on ionospheric error modelling were confirmed by the different ATV flights. Figure 13 shows the ionospheric error effect in term of difference between Pseudorange and Doppler Count measured by ATV receiver during the worst case obtained for ATV3 (more than 50m).
Moreover a high day to day variability of ionospheric error was observed during the different ATV missions which also justify the margins considered to build the ionospheric error numerical model used for ATV2-5 wrt IRI90 model prediction.
During all the ATV production, the ionosphere evolution and possible impact on the mission were constantly surveyed and challenged with respect to the hypothesis taken for modelling. Therefore the behaviours of RGPS and FCM using GPS difference were flawless ensuring performance, rendezvous success and ISS safety without any false alarm caused by ionospheric error.

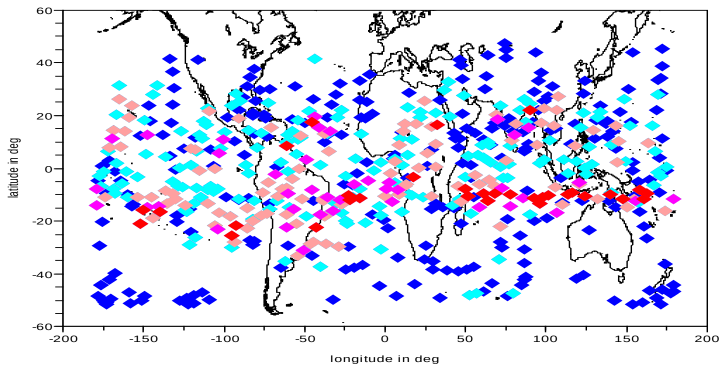

Figure 13 – ATV3 GPS Pseudorange minus Doppler Count (m) between 30 and 10deg of elevation

10-20m:blue, 20-30m: cyan, 30-40m: pink, 40-50m: violet, > 50m: red

3.2 Star trackers dazzled by thrusters plume

ATV used two star trackers for attitude navigation update and gyrometers drift estimation. ATV attitude navigation is initialized by using information coming from Ariane 5 at separation after lift-off or coming from ISS before undocking. But in case of survival flight phase following on-board major failures detection, attitude navigation is initialised by using star tracker measurement in a “lost in space” mode. The ATV survival mode was never automatically triggered during any ATV flight, but this mode was tested for demonstration purpose on the 14th March 2008 during the 1st ATV flight.
It was known that star trackers used by ATV (SED 16 SODERN) can be dazzled when a body such as Sun, Moon or ISS enters in the field of view. But during all ATV flights, unexpected star tracker dazzling were also observed when some thruster plume illuminated by Sun or Moon entered in the field of view, as shown on Figure 14.

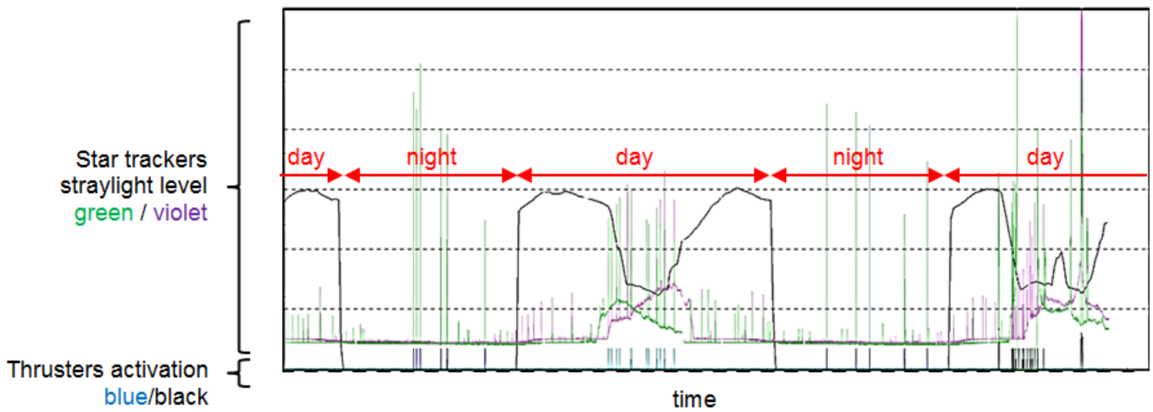

Figure 14 - Star trackers dazzling over day/night and thruster activations

Depending on the dazzling level, the plumes of the thrusters could induce a loss of tracking. However, once initialized, ATV attitude navigation was robust to these temporarily losses without impact on performance. The only critical phase was the survival exit phase experienced on March 2008. The controller design was such that it commanded permanently a set of thruster to perform an angular rate reduction followed by a specific sequence for star acquisition in order to initialise the attitude navigation. For ATV1, this operation occurred during daylight and unfortunately the selected thrusters dazzled both star trackers with the consequence to delay star trackers to go through tracking mode and therefore delaying the attitude navigation initialisation, see Figure 15.

For ATV1, there was no consequence for the demonstration, but considering other constraints like possible presence of bodies (Sun, Moon, Earth) in the field of view or robustness to one star tracker failure, it was not possible to prove that in all case the exit of survival would be successful leading to the potential definitive loss of ATV. Therefore, the robustness of survival exit was improved by modifying GNC survival guidance and control. During the star acquisition the thrusters activation was inhibited sequentially in order to avoid plume effect and then to allow the star trackers to go through tracking mode.

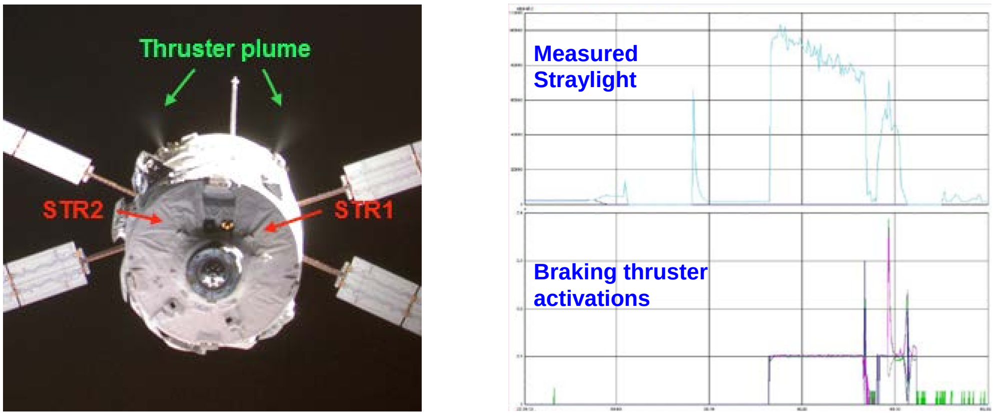

Figure 15 - Thruster plume on ATV1 approaching ISS (left) and star trackers dazzling and thruster activations on 14/08/2008 (right)

To minimize the impacts, the possible side effects and the requalification, the GNC algorithm was modified only during the star acquisition sequence when angular rate is stabilized. The duration T_{thrust}, when thrusters are activated, was chosen to allow the control of the vehicle, in accordance with the specifications. The duration T_{str}, without thruster activation, was chosen in order to allow star tracker acquisition in the worst case situation without any parasite object in the field of view and maximum angular rate consistent with GNC capabilities. A specific validation demonstrated that in all configurations of Sun, Moon, Earth, star tracker failure, the GNC performance in survival mode was conformed to specifications and attitude navigation was always correctly initialized. This GNC survival modification was implemented on ATV3, but was never used during remaining ATV flights.

3.3 GPS loss of tracking due to Equatorial anomaly phenomena

During ATV-3 post undocking free flight phase, a new observation was made on ATV GPS receivers tracking list. Sparse losses of tracking on several GPS satellites happened simultaneously, with a duration of max 90s for situations involving less than 5 remaining satellites. Associated with the loss of tracking, cycle-slips, i.e. discontinuities in the GPS measurements, were also detected. Such phenomenon was not observed during ATV2 flight, and looking back at ATV1 telemetry data only one occurrence of this phenomenon could be found.

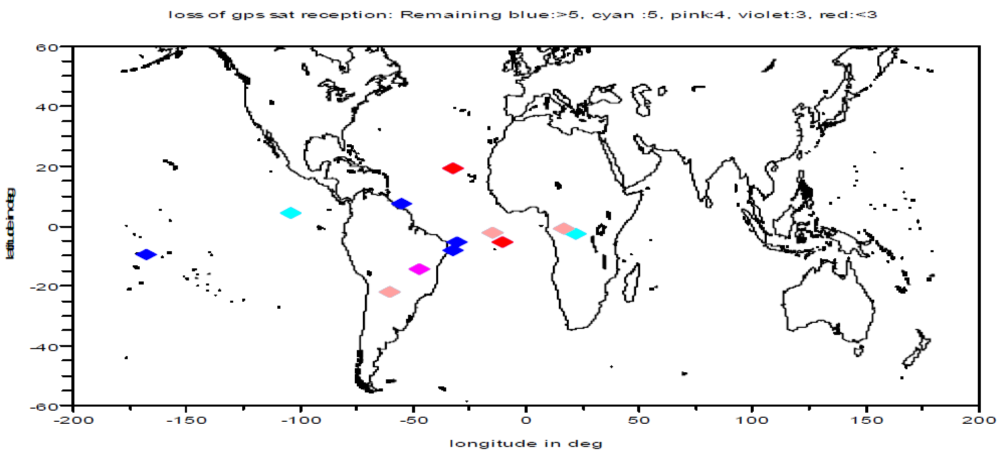

Figure 16 – Loss of GPS satellites tracking during ATV-3 descent phase

The worst case observed during ATV3 flight led to a complete tracking loss with no available satellite during at least 11s on both GPS receivers. Because a test on available satellites number is performed by the Flight Application Software (FAS) to ensure healthiness of receivers, such event could have had an impact on ATV mission. A satellite is considered as unusable if a cycle slip appears or at least 1 raw data measurement over the 2 ones (Pseudorange or Doppler Count) is unavailable. During ATV rendezvous, the GPS receiver is declared failed after 3 occurrences (3s) if no satellite is judged available by FAS. During free-flight, this test is disabled and hence there was no impact during this phase for ATV-3 mission. However, if such phenomenon would have appeared during rendezvous, potentially both GPS receivers could have been declared failed, which would automatically trigger an Escape manoeuvre and the abort of the rendezvous with ISS, while the navigation filters on-board ATV have been designed to handle un-availability of GPS measurements for durations larger than the ones of such events.

Looking closer at the data collected during ATV-3 flight, it has been observed that these events always occurred for a local time, relative to the Sun position at a given longitude, between 19h and 01h. Also when plotting the location of the losses of GPS reception on a map as see in Figure 16, it can be seen that these events occurred when ATV crossed two given latitude bands around the equator. From the particular characteristics of these events, associated with high ionosphere, crossing magnetic equator in eclipse, local hour between 19h and 1h, it was concluded that these could be attributed to the Appleton anomaly phenomena [9].

The Appleton or equatorial anomaly denotes regions of enhanced plasma density some 10° to 15° in latitude north and south of the dip equator, occurring from pre-noon through midnight hours. Appleton anomaly phenomena magnitude is linked to the level of ionosphere effect. On Figure 17 is an Earth map showing in red the geographical position of the enhanced plasma density during Appleton anomalies.

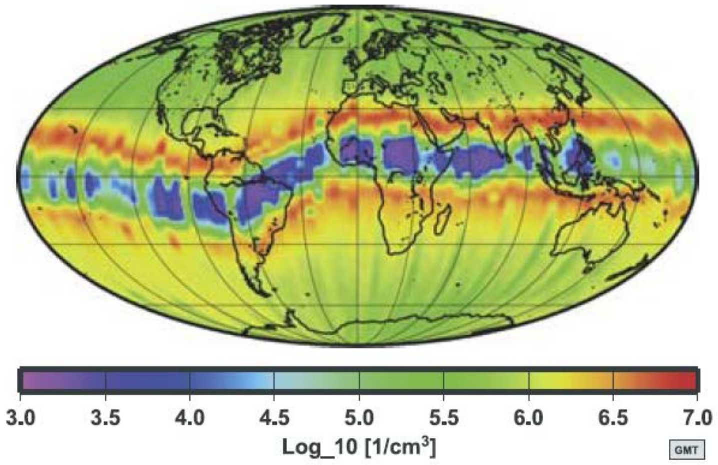

Figure 17 – Longitude variation of electron density in the 20 local time sector (Source [9])

Further investigations on ATV-4 post-undocking free-flight phase have been performed with an increased telemetry rate at 1Hz. The observed form of the perturbation is high frequency noise on signal to noise ratio, sometimes very limited in time as seen on Figure 18. Hence it can be stated that the loss of tracking is associated to a scintillation phenomenon. The analysis showed that the perturbation affecting GPS reception is roughly higher than ATV, stays in the same place with respect to an Earth-Centered Earth-Fixed (ECEF) frame, is localised along a precise latitude line, and affects the GPS satellites whose line of sight is precisely crossing that location line. Such observations confirmed the role of the Appleton anomaly in the observed GPS loss of tracking.

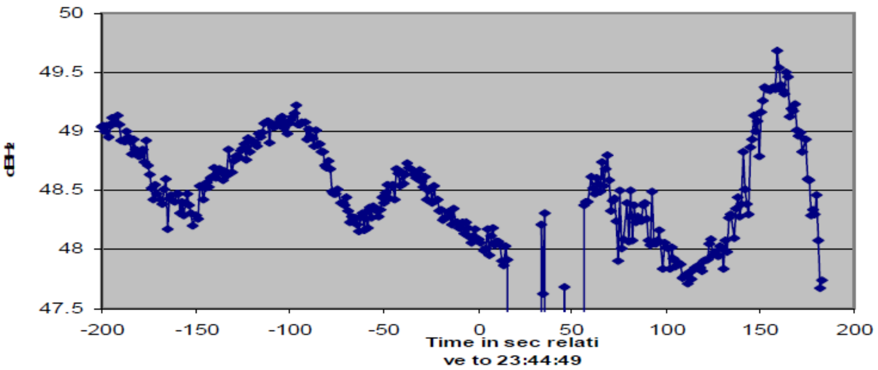

Figure 18 – ATV-4 GPS channel 1 signal to noise ratio at 1 Hz around an observed loss of tracking

Since the potential impact of the environment on the capability of GPS receivers to track GPS satellites had not been considered, the simultaneous loss of tracking of all GPS satellites was associated to a failure of the GPS receivers. To avoid an interruption of the ATV mission associated to the Appleton anomaly, the local time during forecasted rendezvous was checked to be outside of the risk zone for ATV-4 and this failure detection mode suppressed on ATV-5 as already covered by other detection means not sensitive to this effect.

3.4 ISS inner target contamination

During the last 20m of the final approach to the ISS, ATV used the ViDeoMeters (VDM) to perform 6 degree of freedom relative navigation. The VDMs are imaging the 5 corner cubes of the inner target (see Figure 20) installed on ISS as seen in Figure 3 to deduce the relative position and the relative attitude. The post-flight analysis of the performance of ATV-3 navigation sensors revealed an abnormal behaviour on relative attitude measurements. The yaw and pitch measurements for the redundant VDM (VDM-2) had been affected by errors well above the equipment specifications as illustrated on Figure 19. Furthermore, VDM-2 lost tracking of the inner target several times. However, there was no abnormal behaviour on all other measurements (position, roll…) and all health status of the equipment were correct.

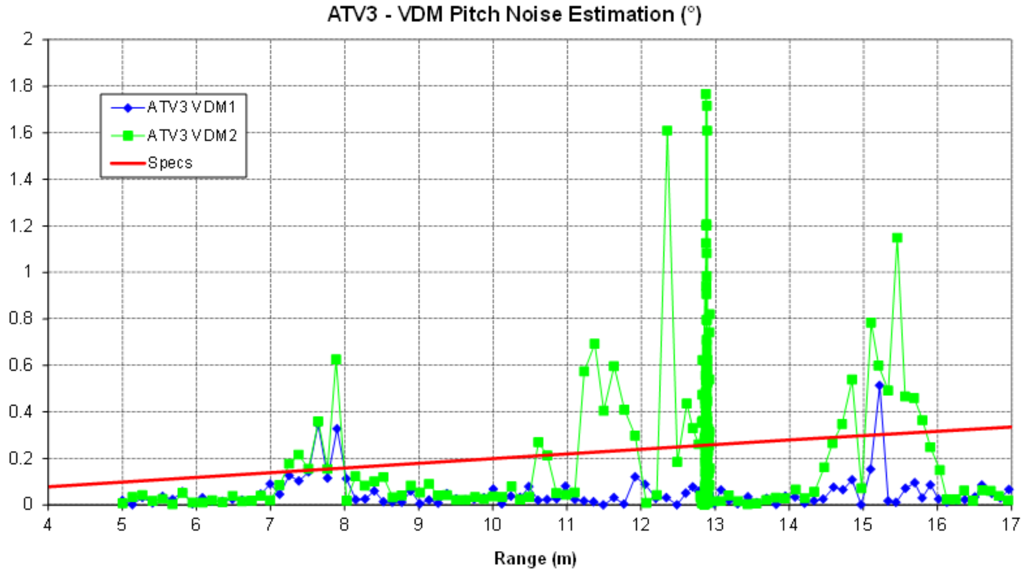

Figure 19 – ATV3 Post flight analysis – VDMs Pitch estimation noise

Further investigations have shown that the increased measurement noise was already encountered on ATV-2 but in a less severe way that did not led to loss of tracking, while for ATV-1 all measurements were within specifications.
Therefore, the analysis concluded that the inner target was likely affected by contamination especially on the centre retro-reflector that is used for Pitch/Yaw measurements. During previous ATV-2 undocking operations, the target may have been exposed to an oxidizer spill from the docking port refuelling line that is used by ATV to deliver ISS propellant. The refuelling line is close to the inner target and some droplets of oxidizer were observed by crew being vented from ATV line toward ISS.

These facts prompted a decision for recovering and exchanging the inner target with a spare unit from the exterior of the ISS prior to attempt ATV-4 rendezvous and docking. An Extra-Vehicular Activity (EVA) took place on 19th April 2013 (Figure 20) to perform the replacement operation. The old inner target that had already spent almost 9 years in space was recovered and stored within ISS and returned to Earth aboard Soyuz 34S on 11th September 2013.

The following docking operations of ATV-4 confirmed that the replacement of the inner target had been efficient in suppressing the measurements perturbations in Yaw and Pitch observed on ATV-2 and ATV-3. Meanwhile ground investigations on the retrieved inner target [10] have shown that there was an orange contamination on the surface of the baseplate and on the optical surfaces with a varying thickness across the surface (see Figure 20). No other damage from micro-meteoroid or other were found.

Another interesting finding was made looking at the right image on Figure 20 where a clear transition between the contaminated area (orange) and the original black plasmocer coating of the baseplate appears above the retro-reflectors. This demarcation line corresponds to the location of the EVA cover on top of the inner target which was used during ground operations, storage and EVA. Looking at similar images from the new inner target unit prior flight have confirmed that a "pre-conditioning" deposit on the plasmocer coating as already been made pre-flight due to the EVA cover. No evidence of a proper baking of the EVA cover, to remove volatiles and ensure absence of outgassing, prior to be in contact with the inner-target was found during investigations.

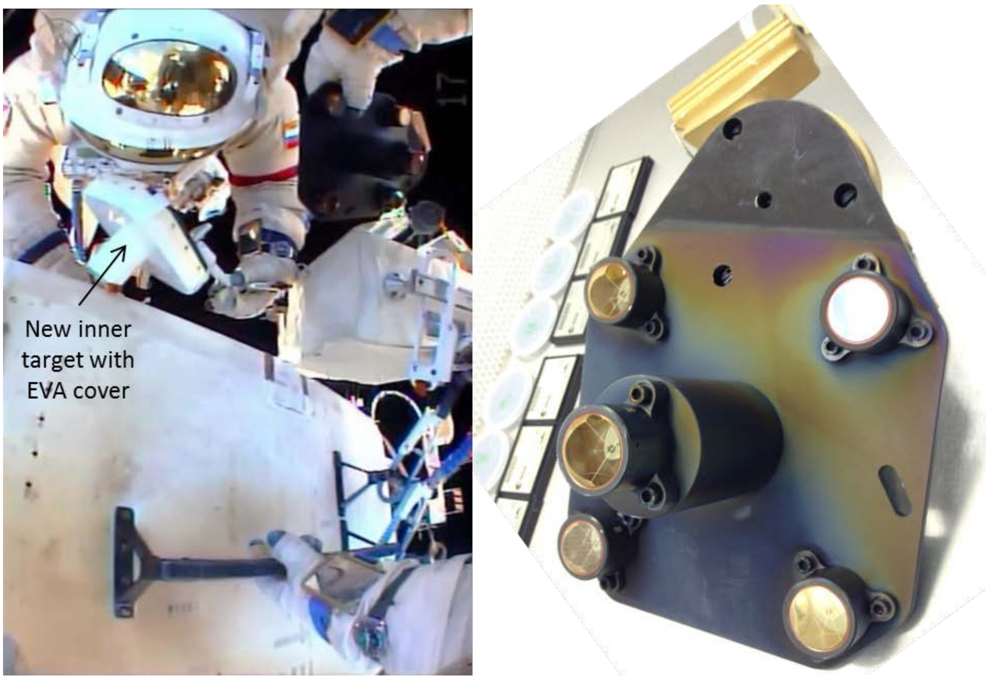

Figure 20 - Left: EVA to replace ATV inner target on ISS Service Module. New inner target is shown within its EVA protective cover while contaminated target is without cover (top right). Right: Contaminated inner target retrieved in ESA lab.

Optical measurements on the inner target have also been performed to characterize the contamination. The overall total reflectivity of the retro-reflectors was found not to be affected by the contamination at VDM wavelength. This result is consistent with flight observations that despite the contamination the overall magnitude of the signal returned by the inner target from VDM/TGM is not significantly impacted.

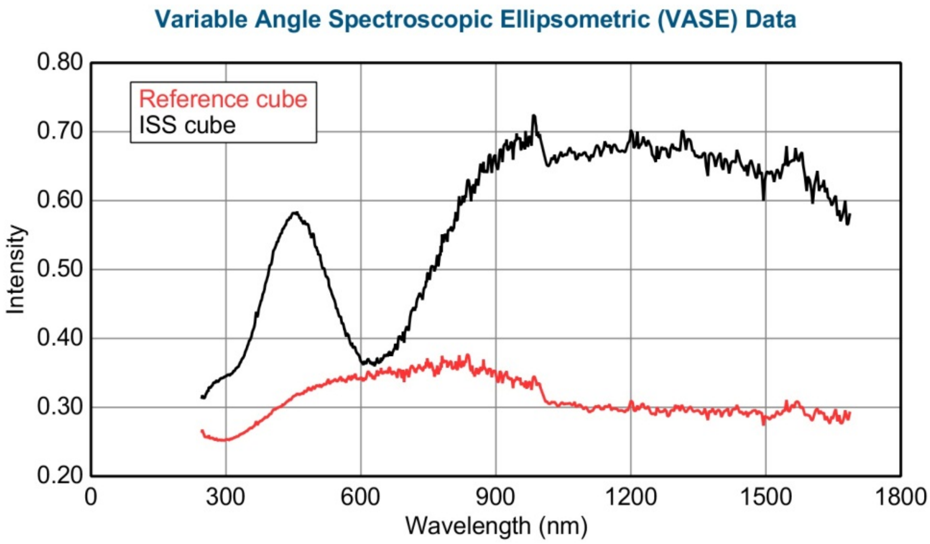

Figure 21 - Variable Angle Spectroscopic Ellipsometric data comparing a reference ground retro-reflector and a retro-reflector recovered from the replaced ISS inner target

Using Variable Angle Spectroscopic Ellipsometric (VASE) technique, the reflectivity of the front surface of the corner cubes of the inner target and properties of the layer deposited on these surfaces were estimated. The enhanced reflectivity of the replaced ISS inner target retro-reflector is quite evident (Figure 21). In particular, it can be seen that at the VDM operating wavelength (811nm) the enhanced reflectivity is of about a factor 1.6. Furthermore, using the same technique, it is possible to estimate the optical constants of the contaminated layer and deduce an estimated thickness. The estimated thickness of absorbing layer comes out to be 196 nm with a roughness of 3.6 nm.

Therefore, two different surface effects have been detected during replaced ISS Inner Target inspection. One linked to a molecular contamination pre-flight (also present on the inner-target currently on ISS) and a second one linked to ATV-Zvezda Oxidizer refuelling line that may have interacted. Further care shall then be taken when dealing with optical target to ensure the proper material selection for low outgassing and proper baking of all elements in contact with the target should be ensured [10]. Finally, any optical target should preferably be located away or shielded from potential contamination sources such as refuelling lines.

4 Conclusion

This paper presents the main performances of the ATV GNC during rendezvous by comparing the dissimilar navigations performed on-board. Overall, all ATVs have delivered a performance much better than its specifications and with a great consistency among the various flights. This performance culminated in achieving for the last two ATVs a direct capture with ISS docking port without first touching the receiving cone. The 2mm accuracy achieved by the fully automated docking ATV is an illustration of the European know-how developed in the frame of the ATV programme which has earned the ISS partners recognition.

Despite the achieved flawless dockings for the five missions, some observations and issues have arisen during the programme that required to be fixed in order to maintain mission success. The knowledge of the impact of the environment on GPS relative navigation has been improved and refined following analysis performed in the frame of the post-flight reviews. Observation of unforeseen dazzling of star trackers by thrusters plume led to modifications of survival mode to exclude potential interactions during this highly critical phase. And high perturbations on Pitch and Yaw measurements on VDM-2 during ATV-3 rendezvous led to an EVA to replace the ISS inner target that had been contaminated both pre-flight by its EVA cover and in-orbit by the spill of oxidiser from refuelling lines during previous ATVs undocking.

The authors of this paper would like to thank all the persons at the European Space Agency, the industrial prime Airbus Defence and Space and its subcontractors involved in the design, qualification, validation, operations and post-flight assessment of the ATV GNC. Their commitment and dedication all across the duration of the programme has been a key to the success of this programme.

References

[1] G. Personne, A. Lopez-y-diaz, P. Delpy. 2005. ATV GNC synthesis: overall design, operations and main performances. 6th International ESA Conference on Guidance, Navigation & Control Systems, Greece.

[2] B. Cavrois, S. Chavy, P. Delpy, S. Reynaud. 2005. ATV Flight Control Monitoring: A dedicated ATV function to ensure the safety of the ISS during Rendezvous. 1st IAASS conference.

[3] O. Mongrard, G. Bergez, B. Cavrois, F. Martel. 2005. ATV On-board Flight Control Monitoring design and trajectories safety assessment. 1st IAASS conference.

[4] Narmada. ATV Far Rendez-Vous navigation based on relative GPS. ION GNSS Congress, 13-17 September 2005, Long Beach.

[5] B. Cavrois, S. Reynaud, G. Personne, S. Chavy, S. Strandmoe. ATV GNC and Safety functions synthesis: overall design, main performances and operations. 2008. AIAAA Guidance, Navigation and Control.

[6] O. Mongrard, C. Santini, M. Powe, B. Cavrois, M. Zink and A. Donnard. 2012. ATV GNC for Rendezvous and Docking: principles, technology and experience. IAC-12.C1.2.1.

[7] N. Silva, F. Martel, P. Delpy. 2005. Automated Transfer Vehicle Thrusters selection and Management Function. 6th International ESA Conference on Guidance, Navigation & Control Systems, Greece.

[8] J. Bourdon, P. Delpy, M. Ganet, I. Quinquis, F. Ankersen. Application of H infinity design on ATV control loop during rendezvous phase. 2002. 5th International ESA Conference on Guidance, Navigation & Control Systems, Frascati, Italy.

[9] H. Lühr, M. Rother, S. Maus, W. Mai, and D. Cooke. 2003. The diamagnetic effect of the equatorial Appleton anomaly: Its characteristics and impact on geomagnetic field modelling.

[10] M. Malicki, A. Bolkhovitinov, Y. Butenko, D. Doyle, O. Mongrard, and G. van Papendrecht. 2015. Characterisation of surface properties of laser retroreflector retrieved from the International Space Station. 13th International Symposium on Materials in the Space Environment.