LESSONS LEARNED FROM THE PHASING STRAGETY DESIGN IN THE ATV PROGRAM

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Abstract: *The European Space Agency's (ESA) program, the Automated Transfer Vehicle (ATV), has finished its duty of supplying the International Space Station (ISS) achieving a 100% success with five accomplished missions. The last vehicle of its kind, the so-called ATV-5 "Georges Lemaitre", was launched end of July 2014, ending a five vehicle saga that started in March, 2008, with the launch of ATV-1 "Jules Verne". For the time being, the ATV has become the heaviest spacecraft ever injected into orbit by the European launcher Ariane-5, as well as the unmanned spacecraft carrying the highest quantity of dry cargo, liquid cargo and maneuver capacity to raise the ISS orbit.*

This huge and unique European program involved many well-known actors of the space industry in Europe and all around the globe. In particular, the Centre National d'Etudes Spatiales (CNES) was responsible for the development of the ATV Control Centre and execution of ATV Flight Operations and AIRBUS-DS (former ASTRIUM) was the prime contractor for the design, development and production of ATV Flight Segment. The present paper will focus on the design of ATV phasing strategies and will offer the reader a complete, synthetic and direct perspective on different ATV to ISS phasing problems.

Keywords: *ATV satellite, ISS logistics, Satellite operations, Maneuvers design, Phasing strategy, Re-phasing for reentry*

1. INTRODUCTION

In 1995, Europe officially started its participation to the International Space Station program providing several cargo vehicles (CV), under the name of ATV. The ATV mission was conceived to contribute to the logistic services of the ISS by transporting propellants, gases and other cargo to the Station for the common utilization. The ATV also provided the capability to dispose of ISS waste and to re-boost the ISS to a higher altitude as part of the ISS orbital strategy to compensate for the atmospheric drag.

The first ATV vehicle -the *Jules Verne*- was launched on March 9th 2008. It performed several in-flight demonstrations before docking to the ISS on April 3rd. Then, it remained attached to the ISS for about five months, after which it undocked and executed a safe destructive reentry above the uninhabited area of the South Pacific Ocean. Four more ATV missions followed achieving a full success. ATV *Johannes Kepler* was launched on February 15th 2010, ATV *Edoardo Amaldi* on March 23rd 2012, ATV *Albert Einstein* on June 5th 2013 and finally ATV-5 *Georges Lemaitre* ended the saga being launched on July 29th 2014. All of them were launched by the Ariane-5 launcher from Kourou, in the French Guyana, and injected in-orbit with accurate performances.

When one considers the reduced number of flights (5) performed by the ATV in comparison to the total number of missions (141) visiting the ISS in its first 15 years of functioning, the ATV figures reveal a surprisingly high contribution done to the ISS program. A good example is the work of the ATV on ISS maneuvering that reached the 28% of the total fuel expends of all the visiting vehicles in the same time period, only surpassed by the Progress CV with 39% of these expenditures, as exposed in [1]. The ATV-5 spacecraft, with a total weight of almost 20.3 tons at launch, became ESA's heaviest spacecraft ever injected into orbit by any Ariane launcher. With respect to the other CVs that were operational on the same period, the ATV was the largest, heaviest and more charged CV after the Shuttle retirement. It also procured a large integrated volume for ISS utilization during the attached phase (mainly used for temporary stowage and cargo transfer).

1.1. The ATV propulsion system

The propulsion system consists of 4 Orbital Control Thrusters (OCS) of 502 N each for large maneuvers and 28 smaller thrusters, called Attitude Control System (ACS) of 217 N each with a saturated global commanded thrust level of 150N achieved with On/Off modulation of the thrusters for small maneuvers and attitude control.

1.2. The phasing problem

The generic orbital mission of every CV is divided into 3 phases: the ascent phase, the attached phase and the descent phase. The ascent phase is sub-divided again in three parts: the Launch and Early Operations Phase (LEOP), the Phasing phase and the Rendezvous (RDV) phase.

This paper will focus on the phasing phase, which covers the orbital flight from the injection point until the interface point at the vicinity of the ISS, from which the autonomous rendezvous maneuvers are computed on-board.

The history of spacecraft (SC) phasing with orbital stations (OS) is long, very well-known and there is an extent bibliography on this topic (see [2] and [3]). It requires the fulfillment of three basic conditions: to provide a close coplanarity of the SC injection orbit and the OS orbit; to provide the necessary initial phasing angle, defined as

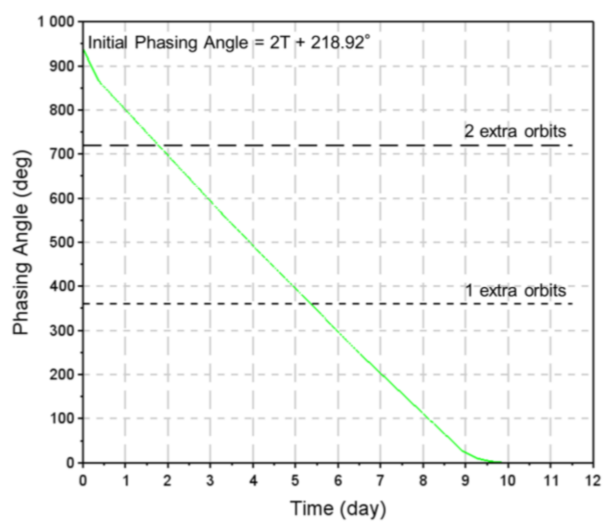

Figure 1 - ATV-5 Phasing Angle example

the phase between the SC and the OS; and to perform a maneuver strategy capable of reducing the initial phase angle to (almost) zero at the time of conjunction.

Figure 1 gives the phasing angle evolution along the flight for the ATV-5 phasing strategy that was computed two days before launch (L-2). ATV-5 performed two extra laps of 360° phase before arriving to the ISS, and presented an initial arc of 218.92° with respect to the ISS.

2. THE ATV PHASING DESIGN

2.1. Phasing scheduling

ATV mission had an impact on the two others major systems actors involved: Ariane-5 ECA LV and the International Space Station itself.

The LV had to cope with constraints on the launch date and time scheduling sometime in conflict with commercial launches. A certain flexibility of the ATV mission to resolve the Arianespace customer schedules was demanded: as result the final ATV launch windows were driven by the Flight Segment readiness and by the Arianespace launch schedule. As reported in [4] for the case of ATV-1 Jules Verne, also the traffic around the ISS of other un-manned CVs and manned SC such as the Soyouz-TMA or the Space Transportation Shuttle (STS) revealed to be major constraints for the selection of the date of ATV docking.

The selection of the feasible dates of ATV launch and docking determined the phasing durations. A minimum duration of ATV phasing should be considered in order to comply with Mission Analysis constraints and requirements. For long time intervals between launch and docking, a Parking Phase in the vicinity of the station would have been chosen after a standard phasing to the parking point. ATV station-keeping at parking point was light in terms operational of workload, and it absorbed potential launch delays.

2.2. Injection orbit and target orbit characteristics

For the ATV-1 mission the injection orbit was circular at 265 km osculating altitude. For the following ATVs the osculating altitude of the delivery orbit was 260 km. In the time interval from the first to the last ATV flight the ISS mean altitude evolved significantly: in 2007 the ISS mean altitude was at its lower point at 330 km and it was gradually raised up to 415 km in 2013 as described in [1]. ATV delivery orbit and ISS orbit were quasi-circular (eccentricity smaller than 0.003) and coplanar at a mean inclination of about 51.6°.

2.3. Phasing angle

For the ATV program, the initial phasing angle depended on the orbital positions of ATV and ISS at the epoch of ATV injection. The orbital position of ATV at the injection point was provided by Ariane-5: it was very stable in geocentric coordinates due to launcher trajectory design, with an AOL (Argument of Latitude) around 244°.

Generally, short phasing durations correspond to small initial phasing angles. Figure 2 compares the values from various CV missions extracted from [3] with equivalent values studied in the Generic System Mission Analysis (GSMA) document of the ATV. The blue lines correspond to the maximum and minimum initial phasing angles in the range, while the green lines represent the middle initial phasing angle in the range.

The capability to cope with any initial ISS to ATV phase angle (360° range coverage) was part of ATV System Requirements negotiated with the International Partners.

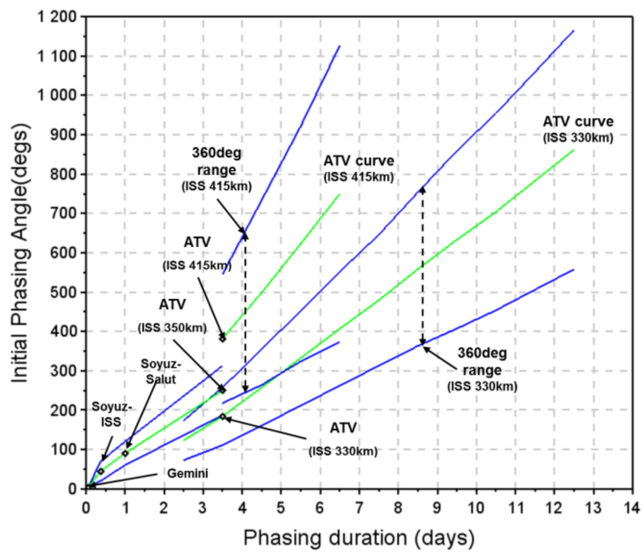

Figure 2 - ATV duration vs. Phasing angle

This requirement was established to avoid a reduced range of initial phasing angle that would lead to hard constraints on the launch window and to additional operations and maneuvers on the ISS prior to ATV docking.

ATV phasing strategy was designed in compliance to this requirement. There was no need of any dedicated ISS maneuver and launch opportunities were allowed at any day of the year. A relative long phasing duration (8-13 days) was initially selected: this was a good compromise between the Flight Dynamics Sub-system (FDS) constraints, the ISS altitude at the time (330 km – 360 km), and the goal to achieve a free flight to docking not too long. Following the experience and lessons learned from the first two ATV flights some assumptions were updated and ATV-3 performed a shorter phasing (5.5 days) that will be discussed in chapter 3.2.

2.4. Phasing strategy

In reference [4], [5], [6], [7] and [8] there are detailed technical descriptions of different aspects of the ATV phasing. The generic strategy consisted of:

- A *Transfer to the Phasing orbit* cycle (TP) consisting of 2 maneuvers
- 1 or 2 corrective *Mid-Course* (MC) cycles of 2 maneuvers each
- From 2 to 3 *Transfer to ISS Vicinity* (TIV) cycles (2 or 3 maneuvers each)
- *1 Transfer to the Interface orbit* (TIF) cycle consisting of 3 maneuvers

The ATV was transferred via a Hohman-like TP cycle from the injection orbit to an intermediate circular orbit called the Drift Phasing Orbit (DPO), at an altitude lower than the OS orbit: the relative phase angle reduced at a constant rate. Depending on the altitude at which the DPO was set the ATV reduced the phase angle with the OS faster or slower, zeroing the initial phasing angle at the desired conjunction date.

2.5. Target point

In opposition to the not co-elliptic approaches of the Soyuz or the STS, the ATV phasing had the objective to place the ATV into a co-elliptic approach to the station, which is achieved by matching a set of keplerian parameters called the $S_{-1/2}$ waypoint. The $S_{-1/2}$ waypoint was fixed at 4h and 8 minutes before the predicted docking opportunity, being "co-elliptical" to the ISS state-vector and in a relative position with respect to the ISS of 39km behind and 5km underneath in Curvilinear coordinates. Once arrived at this point with limited dispersions, the ATV-CC triggered the start of the automated RDV phase. More information can be found in document [5].

2.6. Maneuver Computation tools

The maneuvers computation tool T-ORM was part of the Flight Dynamics Sub-system (FDS) software at the ATV-CC. This tool was in charge of providing maneuvers strategy plans for both mission analysis and operations purposes [7]. Furthermore, the tool objectives included minimizing the propellant consumption under user-defined constraints, or computing the launch date and the associated injection state-vector at the injection time.

The origins of T-ORM's algorithm can be tracked back to the 90's when the CNES worked in direct collaboration with Russian specialists of the Keldyish Institute of Applied Mathematics (KIAM) and the MCC-M. One of the results of this collaboration was the CNES development of its own software of LEO phasing maneuvers computation, named DRAGON. T-ORM was then developed to comply with the ATV-CC specificities based on DRAGON principles. Further details can consulted in [10].

Since 1997, an upper-level software called OSCAR was developed to carry out Mission Analysis studies. This software uses DRAGON as a kernel enabling the conduction of Monte-Carlo analysis, simulating the maneuvers update process performed on-ground all along the mission by computing end-to-end simulations with the ATV-CC in the loop. OSCAR/DRAGON tool is intensively used today by the CNES in the positioning operations and mission analysis of the Galileo satellites.

3. THE ATV PHASING STRATEGIES

3.1. ATV program flight domain

The group of all the feasible ATV phasing scenarios was defined as the ATV flight domain, which is depicted in Figure 3 (blue polygon). The figure also presents the predicted phasing scenarios for each of the former ATVs (black crosses), and the final ATV phasing scenarios within this flight domain (green rhombi).

Their schedule plans were often modified and some of the changes can be identified in the Figure, as follows:

- ATV-1 and ATV2 were launched at L1 date (1 day after the nominal launch date, L0).

- ATV-3 was delayed 2 weeks due to a problem with the fixation of cargo. The final phasing duration was of 5.5 days, thanks to the fact that above 380 km all the initial phasing angles were covered by the strategy.
- ATV-4 was launched at L0 date, but it was let to drift 5 days at launch altitude before starting the phasing strategy with TP maneuvers on the orbit number (ON) 76 (red rhombus).
- ATV-5 was delayed 4 days during negative chronology before launch, as can be found in [11].

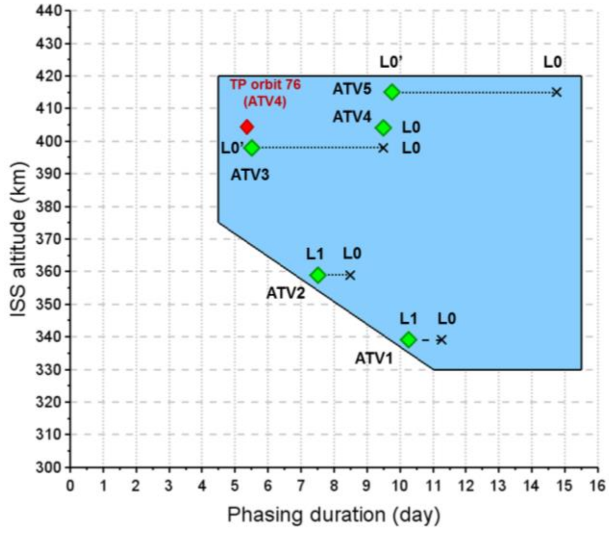

Figure 3 - ATV Flight Domain

The phasing parameters for the former ATV missions where the following:

- The targeted ISS mean altitudes were 335 km for ATV-1 and 415 km for ATV-5.
- The minimum duration of 5.5 days was performed by ATV-3 while the longest 10.25 days duration was experienced by ATV-1 (initially ATV-5 should have performed a duration of 14.8 days with a launch date prevision on the 25/07/2014 but the 5-days delay during the negative chronology decreased the duration to 9.8 days. GSMA studies were extended to 13.5 days of durations with some margins to perform even longer durations).

3.2. ATV phasing profiles

The phasing profiles to be described in the present paragraph correspond to the last trajectory baselines computed by the FDS team 2 days before launch (L-2) for each of the 5 ATV missions.

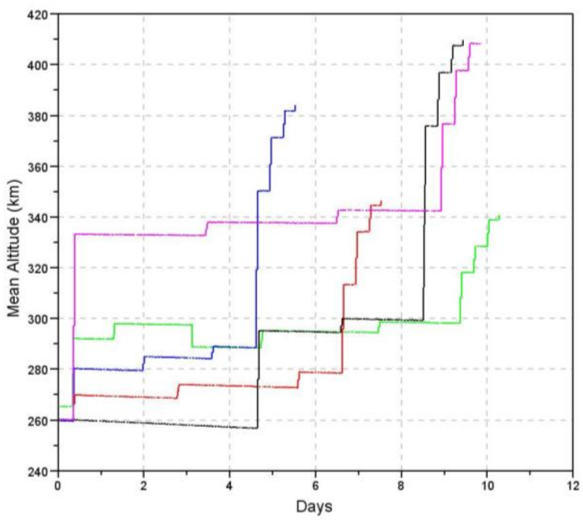

Figure 4 - ATV phasing profiles (L-2)

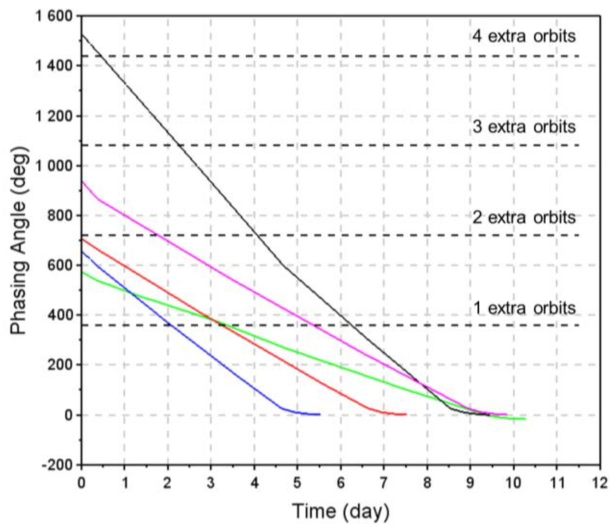

Figure 5 - ATV Missions Phasing Angle profiles

These baselines have been gathered in Figure 4 and Figure 5. The color code in the figures is the following: ATV-1 (green), ATV-2 (red), ATV-3 (blue), ATV-4 (black), ATV-5 (magenta).

The axes in Figure 4 present the mean ATV altitudes in function of time. The profiles begin at the injection point altitude and end at the targeted interface point covering the overall phasing duration. Each instantaneous change of altitude plotted in the figure corresponds to each of the maneuver cycles described in paragraph 2.4, while each of the free-flights before and after the cycles correspond to drifts in the following orbits: the injection orbit, the DPO, and the interface orbit.

Mission	ATV1	ATV2	ATV3	ATV4	ATV5
ISS altitude (km)	339	359	398	404	415
Duration (days)	10.25	7.5	5.5	9.5	9.75
Initial phasing angle ISS-ATV (deg)	213.89	347.09	297.19	85.29	218.92
Targeted point	PP4	$S_{-1/2}$	$S_{-1/2}$	$S_{-1/2}$	FU
ATV/ISS extra nb of orbits	1	1	1	4	2
TP cycle orbit number	7	7	7	76	7
Total DV (m/s)	55.19	52.41	73.09	89.07	87.22
Total Ergols (kg)	< 600	413.8	533.69	659.3	618.8

Table 1 - ATV Phasing main characteristics

Figure 5 displays the evolution of the phasing angle over time for each of the 5 ATV missions. The phasing angle at injection is computed as the initial phasing angle plus the number of extra orbits performed by the ATV with respect to the ISS multiplied by 360 degrees.

Table 1 contains the major characteristics of the 5 phasing strategies. The detail on the velocity increments (ΔV) of each phasing maneuver of each ATV mission has been placed in the Appendix or is available in previous literature [4] and [9].

ATV-1 *Jules Verne* L-2 baseline presented some characteristics which placed it out of the general case for the recurrent ATVs:

- It required a dedicated ACS test maneuver (AT) to check a long propulsion as it is performed for the Escape maneuvers.
- It had to demonstrate the capability to perform a Collision Avoidance Maneuver (CAM) with the ISS, followed by a drift in survival mode.
- The Shuttle STS-123 mission was re-scheduled to take place during the nominal phasing period of the ATV. To comply with the flight rules for vehicles visiting the ISS and to be robust to an Ariane-5 launch delay, a Parking Point was targeted after the phasing (PP4, +2000km), waiting for the “GO Decision” to initiate the proximity operations.

For a deeper knowledge on the technical details of this first ATV phasing mission plan, detailed information can be found in previous publications [8], [4] and [6].

ATV-2 *Johannes Kepler* phasing occurred nominally without suffering any important re-arrangement, so its characteristics were fully covered within the GSMA generic strategy. During the attached phase, the ATV-2 performed a re-boost maneuver which increased the ISS altitude from around 345 km to 380 km (the ISS + ATV weight was of about 405 tons at the time).

ATV-3 *Edoardo Amaldi* phasing occurred again nominally and within the flight domain of the generic strategy without any modification. The article [12] gives more information on this mission.

ATV-4 *Albert Einstein* L-2 baseline presented the following changes from the generic strategy, as stated in [5]:

- The launch date corresponded to a particular period of the year in which the Sun aspect angle on the orbit –the *beta angle*- was high (more than 64°) and the eclipse durations in the orbit remained very small (under 25 minutes) or disappeared completely. In such configuration the Solar Array Driving Mechanism could not perform the first gear cleaning after separation and this limitation was indirectly preventing the use of the main engines (OCS) for main manoeuvres: the impact on the mission was a delay of the TP cycle from orbit #7 to orbit #76.
- Consequently, the phasing scenario split into two sub-phases: a "free-drift sub-phase" (from injection to orbit 70) of 4 days and 5 hours of duration; and a "phasing sub-phase" (from end of the free-drift sub-phase to $S_{-1/2}$), of 5 days and 3 hours.
- The number of extra tours performed by the ATV with respect to the ISS within the overall period increased to 4 (see Figure 5 and Table 1).

ATV-5 *Georges Lemaitre* phasing profile was one-of-a-kind due to several reasons:

- ESA organized the "ATV-5 Laser Infra-Red Imaging Sensors (LIRIS) demonstrator" for which a new set of optical cameras was mounted at the exterior of the Integrated Cargo Carrier (ICC) of the ATV. Also, the targeted point was re-arranged (from -39km in front of the ISS to -71 km) to perform a safe free-drift under the station right after phasing, during which the IR camera recorded images of the ISS.
- Additionally, the ATV-5 phasing period overlapped with the Progress-55P SC undocking and deorbitation operations. A fast solution was found to avoid the crossing of trajectories between the two SC, which consisted of lowering the ATV's orbit altitude, performing one additional extra lap with respect to the ISS passing from 1 extra orbit to 2 (Figure 5 and Table 1).

To sum up, two L-2 phasings out of five were computed following 100% the generic strategy, while the other 3 had to be modified to adapt the strategy to the unforeseen constraints that appeared for reasons of 1) additional qualification maneuvers for the 1st flight, 2) impact of the ISS Visiting Vehicles traffic, 3) high values of the beta angles that are rare events of few days duration in a year, and 4) new in-flight experiences.

3.3. Ariane-5 ECA accuracy of ATV injection

The FDS Orbitography operational position at the ATV-CC (ORB) computed the accuracy state-vector of the delivered orbit of the ATV after the injection with respect to the predicted values. The errors, compiled in [11], were of a maximum of around 1 km for the semi-major axis, less than 0.03° for the out-of-plane and less than 0.25° for the AOL (see Table 2).

Parameter	ATV-1	ATV-2	ATV-3	ATV-4	ATV-5
dSMA (m)	-472.6	356.1	614.8	783.5	-1113.1
dECCx	7.19E-05	-1.97E-05	5.49E-05	8.32E-05	-7.55E-05
dECCy	4.49E-05	-2.63E-04	-2.67E-04	-2.51E-04	-8.83E-05
dINC (deg)	-0.020	0.009	0.019	-0.023	0.015
dRAAN(deg)	-0.002	0.001	0.002	-0.002	0.001
dAOL (deg)	0.207	0.230	0.145	-0.106	0.041

Table 2 - Ariane-5 accuracy at injection

Such errors did not exceed the predicted 1.1σ in eccentricity, the 0.8σ in inclination and the 0.6σ for the rest of orbital parameters (with respect to the ARIANE5 ECA specifications). This eased the work of the FDS team at the first beginning of in orbit operations during the LEOP when the phasing maneuvers strategy was updated with the actual delivered orbit estimated from ATV TM.

3.4. ATV in-operations contingencies during phasing

During the phasing operations several alarms were raised. From all of these alarms only a few of them had a potential impact on the maneuver strategy and only a few resulted in real modifications of the maneuver strategies.

Table 3 gives a synthetic view of the inflight observed ATV onboard alarms with potential impact on the maneuver plan together with the details on consolidated and non-consolidated contingencies.

Only ATV-1 phasing strategy had to be re-configured in real-time operations. Firstly, an isolation of the Propulsion Drive Electronic (PDE) occurred after separation from Ariane-5. This contingency operation caused a 3-days delay of the TP maneuvers, and the implementation of a new cycle (TE maneuvers) to test the propulsion system behavior prior to its full reintegration, the day before to the delayed TP cycle (see [4], [12], and [9]). As a consequence of these changes, MC2 cycle and TV1 cycle were cancelled.

ATV1	
Debris collision risk assessment (risk after TP manœuvres)	Cancelled alarm
PDE-2 chain is declared failed on ATV after separation	**Strategy modified**
Second debris collision risk detection	Cancelled alarm
Water flush of STS-123 flight (water icy spheres)	Cancelled alarm
Collision risk detection (after TP cycle)	**Strategy modified**
PDE-4 switch-off during MC boosts	Cancelled alarm
Explosion of Cosmos satellite the 14/03/2008	Cancelled alarm
ATV2	
Collision risk with debris 37354 (before launch)	Cancelled alarm
Prox-link deployment issue	Cancelled alarm
ATV3	
Collision risk with debris 33437 (during TV2 cycle)	Cancelled alarm
Prox-link deployment issue	Cancelled alarm
ATV4	
Collision risk with debris NORAD ID 89474	Cancelled alarm
SADM cleaning delayed 1 orbit	Cancelled alarm
Double conjunction risk (during MC cycle)	Cancelled alarm
Collision risk (during TV1 cycle)	Cancelled alarm
ATV5	
PDE 2 not working after separation with A5	Cancelled alarm
Artemis Ground Station of GUAM (subtropical storm)	Cancelled alarm
Collision risk before MC1 cycle	Cancelled alarm
Collision risk with debris 39069 (after MC2 cycle)	Cancelled alarm
Collision risk with debris 39268 (free-drift under the ISS)	Cancelled alarm
Collision risk with debris 31556 (free-drift under the ISS)	Cancelled alarm
Collision risk with debris 32467 (free-drift under the ISS)	Cancelled alarm

Table 3 - Raised alarms with potential impact in the strategy

During the final TP computation, a debris collision risk was detected causing the mitigation action of increasing each TP maneuver of 0.2m/s from around 5.9m/s to 6.1m/s (more detailed data are available in [14]). Although this change mitigated completely this risk, some perturbation was experienced on operations scheduling the TDRS service for ATV due to the unplanned changes of ATV orbit.

3.5. ATV maneuvers performances

The FDS Guidance, Navigation and Control operational position at ATV-CC (GNC) monitored the execution efficiency of ATV OCS and ACS maneuvers.
The missions ATV-2 to ATV-5 generated useful data on 35 OCS and 31 ACS maneuvers for assessing in-flight performance.

For the OCS, a negative small bias on the global ΔV of the maneuver has been found of about -0.43%. After *Jules Verne* mission a calibration process –also called *slew compensation*- was set, improving from mission to mission the prediction of the ΔV achieved by an OCS maneuver taking into account perturbations from attitude control firing. The resulting 3-sigma for the 35 OCS maneuvers was 1.7% of the commanded ΔV, below the ATV User's Manual (UM) specifications of 3% (without the slews effect). The ACS performances presented a 3-sigma deviation of 4.18% for the 31 maneuvers, having a maximum for ATV-3 mission of 7.13% (e.g.: for an ACS ΔV of 1.7m/s, the 3-sigma was 12cm/s).

Thrusters	Mission	Mean	3σ	Mean + 3σ
OCS	ATV2	-0.39%	2.87%	-3.26%
	ATV3	-0.56%	1.09%	-1.66%
	ATV4	-0.24%	0.52%	-0.77%
	ATV5	-0.46%	1.67%	-2.13%
	All ATVs	-0.43%	1.70%	-2.14%
	UM	*0%*	*3% + Slews*	*3% + Slews*
ACS	ATV2	1.05%	1.59%	2.64%
	ATV3	-0.38%	7.13%	-7.51%
	ATV4	-0.38%	1.12%	-1.50%
	ATV5	1.15%	2.26%	3.40%
	All ATVs	0.43%	4.18%	4.61%
	UM	*0%*	*9%*	*9%*

Table 4 - Propulsion systems performances

The in-flight monitoring of these maneuvers confirmed both the adequacy of the mission analysis assumptions and the excellent performances of the ATV propulsion systems.

3.6. Accuracy at the target

The accuracy at the interface point $S_{-1/2}$ was checked in real-time for each mission to give the "GO" to the automatic RDV phase. The ATV was delivered each time within the $S_{-1/2}$ safety box with very precise accuracy, showing large margins with respect to the assumptions of mission analysis that were used in the design of the phasing strategy.

Parameter at $S_{-1/2}$	ATV2	ATV3	ATV4	Safety box Thresholds
ΔX (m)	167	255	195	3300
ΔSMA (m)	12	36	8	480
ΔECCx (m)	23	58	20	480
ΔECCy (m)	49	1	48	480
Δh (deg)	5.0E-06	1.6E-05	6.0E-06	8.00E-05

Table 5 - Phasing accuracy at $S_{-1/2}$ waypoint

3.7. Mass prediction accuracy

The specific mission analysis predicts several months prior to the flight a propellant budget based on conservative assumptions in order fill the ATV tanks with a sufficient amount of propellant. More accurate prediction is performed by FDS when the mission profile is frozen (e.g from L-2)

	ATV-5		ATV-4		ATV-3	
	Mass (kg)	error (%)	Mass (kg)	error (%)	Mass (kg)	error (%)
T-ORM Pre-Launch L-2 baseline	556.75	-10.03%	571.948	-13.25%	471.7	-11.62%
T-ORM in-ops computation	557.155	-9.96%	575.941	-12.64%	476.59	-10.70%
TM Mass (w/o CAMT, YS, SLWS)	574.16	-7.21%	621.548	-5.73%	-	-
Total TM Mass	618.802		659.304		533.69	
Oscar Monte-Carlo Simulation	-	-	-	-	718.73	35%

Table 6 - Propellant consumption prediction accuracy

Table 6 compares the propellant budget predictions with the Telemetry data, for three ATV missions. T-ORM results offered the total consumption of nominal boosts without dispersion and without taking into account the Yaw Steering attitude law (YS), the slews (SLW), nor the other small vehicle operations such as the CAM Test (CAMT), the helium-line draining, etc. Errors with respect to the final estimated mass obtained from Telemetry (TM) data were between 10% - 13.25 % below the real consumption. For mission analysis purposes, additional dispersion coefficients were added to the Monte-Carlo runs performed by the Oscar/Dragon tool. These computations results added a margin of around 35% to the total consumption.

4. OTHER PHASING-RELATED STRATEGIES

4.1. ATV orbital missions overview

The experience demonstrated that no strict recurrence existed between ATV maneuver strategies except for ATV-2 and ATV-3 missions. Focusing on the ascent phase, ATV-2 to ATV-4 were fully recurrent performing a direct phasing to the $S_{-1/2}$ point, and then executing a nominal/automatic RDV (as shown in Table 7). Alternatively, ATV-1 and ATV-5 phasing strategy experienced several differences:

	Ascent Phase			
ATV1	Phasing to PP4	Parking at PP4	DEMO DAYS 1, 2, 3	RDV Phase
ATV2	Direct phasing			RDV Phase
ATV3	Direct phasing			RDV Phase
ATV4	Direct phasing			RDV Phase
ATV5	Phasing to Fly Under	Post-Fly-Under		RDV Phase

Table 7 - ATV orbital flights overview (Ascent phase)

- ATV-1 targeted the Parking Point 4 (+2000 km in front of the ISS), and then performed several parking maneuvers before entering in a three demonstration days phase (DEMO DAYS 1, 2 & 3), consisting of in-flight tests of functionalities critical for RDV safety and three fly around the station prior to the initiation of each demo day.
- ATV-5 targeted a different $S_{-1/2}$ waypoint to perform the LIRIS experience (avoiding the execution of TIF maneuver cycle). After the experience ATV performed a safe fly-around the ISS to initiate the final RDV phase.

The maneuver strategy used to fly-around the station in ATV-1 and ATV-5 was called Post-Escape due to the fact that this scenario was very similar to one firstly designed to be able to fly ATV back to the $S_{-1/2}$ point after an abort of the RDV executed with an Escape maneuver (-4m/s in the Local Orbital Frame).

For the descent phase ATV-2, ATV-3 and ATV-5 performed a fully recurrent strategy: the undocking was followed by a single departure maneuver and then a generic reentry strategy.

ATV-1, ATV-4 consisted of more phases to allow ATV reentry observation from ISS. This scenario was also planned for ATV-5 and cancelled before undocking due to an off nominal situation (Table 8):

	Descent Phase				
ATV1	Undocking	Re-phasing to Reentry			Reentry
ATV2	Undocking	-			Reentry
ATV3	Undocking	-			Reentry
ATV4	Undocking	Re-phasing to Reentry			Reentry
ATV5	Undocking	-			Reentry
ATV5 (cancelled baseline)	Undocking	Transfert to PP	Parking + OM maneuvers	Re-phasing to Shallow Reentry	Shallow reentry

Table 8 - ATV orbital flights overview (Descent phase)

- ATV-1 and ATV-4, after the undocking & departure, performed descending maneuvers in order to phase ATV with the ISS allowing an ATV reentry trajectory observable from the station. The objective of this observation was to gather unique scientific data concerning the hypersonic destruction of the SC when re-entering the denser layers of the Earth atmosphere, as presented in [18].
- ATV-5 descent phase baseline was designed to meet constraints of reentry stricter than for ATV-4, as it targeted a particular orbit of reentry – called the *shallow reentry* orbit (see [16] and [17]) – in order to improve the knowledge of the models in preparation of ISS disposal.

The strategies of Parking, Post-Escape and Re-phasing were designed using the phasing mission analysis tool Oscar/Dragon, and computed in operations using T-ORM tool. The following chapters provide some lessons learned on these "Phasing-related" strategies over the five ATV missions.

4.2. Parking

As the ATV-5 Parking phase was cancelled, only the in-orbit experience on ATV-1 Parking remains. Papers [4] and [8] explain the strategy principles that were used for the Station Keeping (SK) maneuvers during ATV-1 Parking: 1 cycle of 2 SK maneuvers each 2 days at maximum (under very conservative assumptions of the drag effect). The objective was to position the ATV in a box +2000 km +/- 250km during 8 days.

Finally, only two SK maneuvers were needed during the 8-day period due to low drag effects (March 2008), with a ΔV lower than 0.09m/s. The propellant consumption of these maneuvers was low, of 0.63 kg. The final ATV position with respect to the ISS at the end of the Parking period was around +1820 km with respect the ISS in X axis.

4.3. Post-Escape and Post-Escape-like strategies

During the ATV-1 Jules Verne mission 3 DEMO DAYS had to be preceded by 2 Post-Escape strategies [4]:

- The rendezvous DEMO DAY 1 required a return from PP4 to $S_{-1/2}$ strategy (red color in Figure 6).
- The rendezvous DEMO DAY 2 required a 48h -return (blue color) from demonstration Day 1 Escape after Homing to $S_{-1/2}$ of Demo Day 1.
- The rendezvous DEMO DAY 3 required a 72h-return (green color) from a demonstration escape triggered by the ISS crew on Demo Day 2 when the ATV was located at S4 (-40m from the ISS).

Similarly, after the LIRIS experience execution, ATV-5 performed a Post-Escape-like strategy flying back to RDV initiation in 60 hours (black color in Figure 6).

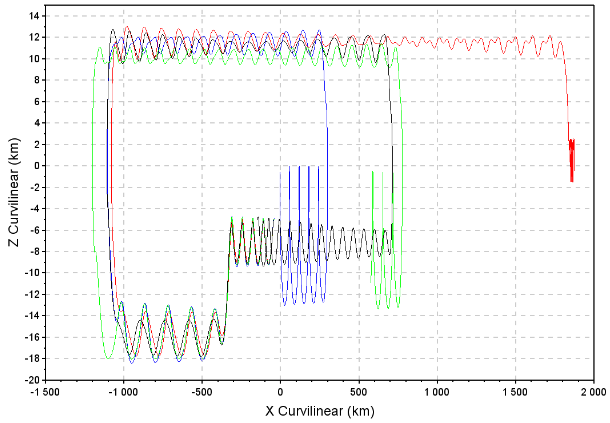

Figure 6 - ATV Fly-Around strategy profiles

Mission	ATV1 / DD1	ATV1 / DD2	ATV1 / DD3	ATV5
Initial DX (km)	2000	-3.5	-0.15	-71
Initial DZ (m)	0	+100 (above ISS)	0	-5000 (below ISS)
Duration (days)	2.75	2	3	3.5
Targeted point	$S_{-1/2}$	$S_{-1/2}$	$S_{-1/2}$	$S_{-1/2}$
Altitude of drift orbit (km)	10 - 13	10 - 12	9 - 12	10 - 13
Total DV (m/s)	28.28	32.09	30.89	31.17
Total Ergols (kg)	180.9	197.3	185	198.3

Table 9 - ATV Fly-Around strategies main characteristics

As stated in [6] every Post-Escape strategy consisted of the following cycles of maneuvers: a Transfer to orbit above the ISS (TA), a Transfer to orbit below the ISS (TB), a Transfer to ISS Vicinity (TV) and a Transfer to Interface waypoint (TIF).

Severe Flight Safety Rules applied when the ATV approached the station at close range. Each of the strategy cycles implemented up to the last 3 interface maneuvers were compliant with the safety requirement to not enter the Approach Ellipsoid (AE) in case of contingency free drift of 24h prior to the execution of each maneuver. The amplitude of each maneuver ΔV was constrained as well as the drift orbit altitudes after TA cycle. Table 9 summarizes the major characteristics of the 4 post-escape strategies. The ΔVs commanded for ATV-5 Fly-around have been placed in the Appendix.

4.4. The critical contingency that occurred during DEMO DAY 1

Document [13] describes the critical situation that ATV-CC had to cope with when the ATV-1 *Jules Verne* was approaching the $S_{-1/2}$ interface point for the first time. Around 5 orbits before the interface point, an off-nominal PDE switch to the redundant chain caused the cancellation of TV2 maneuver, leaving the ATV into a drifting trajectory with a relative speed too fast to reach the $S_{-1/2}$ waypoint according to ATV to ISS RDV opportunity with the nominal phasing scenario.

The solution was to compute a set of TV back-up maneuvers (*TV_BU*) and to modify TIF3 maneuver nominal value from 1.2m/s to zero. The reasons for this design were to raise the ATV orbit promptly, in order to match the required phasing angle and approaching relative speed at the arrival to $S_{-1/2}$. The details of this operation can be found in [13] and [14]. Figure 7 gives:

- the nominal trajectory (in light green),
- the *TV_BU* trajectory (in magenta),
- the *TV_BU* limit trajectory that was computed but rejected (red color).

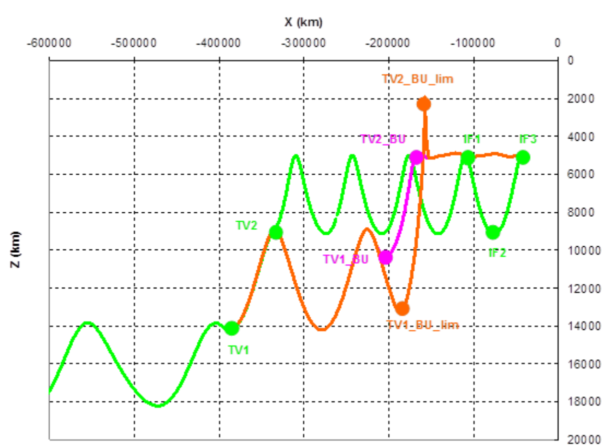

Figure 7 - ATV1 TV_BU critical contingency

The maneuvers *TV1_BU* and *TV2_BU* ΔV values were of 2.34 and 1.52m/s respectively.

4.5. Re-phasing to Reentry

As stated in [5], a "re-phasing to reentry strategy" was needed for those missions selected to perform an optical observation from the ISS of the ATV reentry. Three reentry observation campaigns were organized for ATV-1, ATV-4 and ATV-5 (although ATV-5 reentry observation was cancelled few days prior to ATV-5 undocking).
The problem consisted of re-phasing the ATV to re-enter hitting the Earth atmosphere (around 110-120 km of geodetic altitude) within the cone of observation of the optical instruments on-board the ISS. The strategy evolved mission to mission due to differences on the constraints: the initial altitude of the ISS, the duration of re-phasing, the possibility of performing back-up scenarios, the final altitude of the interface point towards re-entry and the acceptable dispersions at arrival.

By adapting the ascending phasing strategy to the case of a descending re-phasing, symmetrical solutions were found mainly consisting of tangential retrograde maneuvers. Figure 8 shows the two final trajectories in ATV-1 and ATV-4 missions, while Table 10 provides the main characteristics of these strategies computed before undocking (for more information on the final executed maneuvers in ATV-1 see [15]).

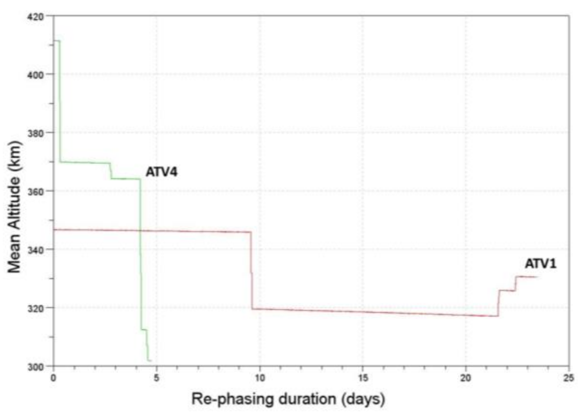

Figure 8- ATV-1 and ATV-4 re-phasing to reentry strategies

Mission	**ATV1**	**ATV4**
ISS altitude (km)	335	415
Targeted point Altitude (km)	330	300
Duration (days)	23.5	2
ATV/ISS extra nb of orbits	2	1
Total DV (m/s)	22.86	61.9
Total Ergols (kg)	104.5	370.8

Table 10- ATV-1 and ATV-2 re-phasing characteristics

4.6. ATV-5 baseline re-phasing to Shallow Reentry

As stated in reference document [16] *"the fifth ATV mission was selected to support a large re-entry observation campaign (...) which included three instruments on board ATV (ESA break up Camera BUC, NASA Reentry Break-up Recorder REBR-W and JAXA reentry data recorder i-Ball), several optical instruments on board the ISS operated by the crew, ground assets (radars and telescopes) and optical instruments carried on the NASA Ames DC8 aircraft in a joint ESA NASA observation mission). (...)"*. Unfortunately, a major on-board failure of the ATV happened, causing the cancellation of the observation campaign.

The ATV-5 cancelled baseline was nevertheless rich on challenges, the descent phase consisted of 5 parts: the undocking & departure phase, a transfer to PP4, a Parking with overconsumption maneuvers phase, a re-phasing to reentry phase and the shallow-reentry phase [17].

The retained strategy design was to re-phase the ATV in 48h and 1 extra tour with respect the ISS. If a phasing in 48h had to be engaged right after the departure phase, the minimum descent duration would have been done lasting for around 2.3 days (including reentry). Longer mission durations were envisaged thanks to a station-keeping phase at PP4 after departure. This configuration allowed adapting to eventual reentry delays scheduling up to 48h before the nominal reentry date.

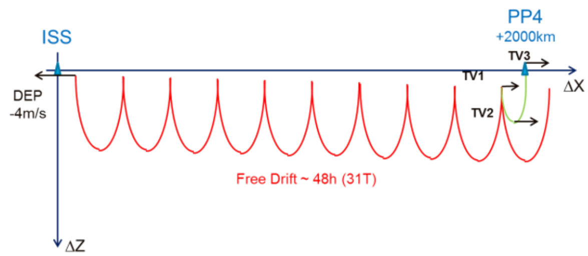

Figure 9 - Transfer to PP4 (ATV-5 cancelled baseline)

The transfer to PP4 strategy consisted of a free-drift arc after departure (DEP) maneuver during approximately 48h followed by a single 'TV-like' cycle of maneuvers, which would have allowed to stop the ATV drift with respect the ISS at the crossing of PP4 X-distance as shown in Figure 9.

The propellant at the beginning of the deorbitation phase should have been 652.5 kg in order to ensure the vehicle reentry safety constraints (ATV-5 "shallow reentry" specific constraint, refer to [16] and [17]). However, the propellant mass at the date of undocking was bigger, requiring the execution of "over-consumption" maneuvers (OM), to burn nearly 1200 kg of extra propellant prior to the deorbitation. In addition, to allow the automatic triggering of several payloads recording the ATV reentry, the maneuvers before the last deorbitation boost had to last less than 395 seconds, which was equivalent to maneuvers smaller than 20m/s. Each OM cycle consisted of 2 OCS maneuvers, in Y direction only, and always acting in opposite direction on the inclination of the orbit, but not on the RAAN. All over consumption expenses had to be done during the Parking Phase, within each of the 3-days loop of 2 cycles of SK maneuvers.

To determine the needed number of OM to consume the 1.2 tons of exceeding propellant, FDS and Vehicle experts performed a joint analysis of the previous ATV flights data on maneuvers consumption, which led to an improvement of the prediction accuracy on the residual propellant (results in Table 11).

Coefficient	UM value		In-flight data value	
	4 PDE	3 PDE	Both PDE configurations	
	Mean	Mean	Mean	3σ
OCS overconsumption	1.15	1.20	1.00	0.03
ACS overconsumption	2.15	3.25	1.49	0.81
SLW consumption (kg/slew)	1		0.65	0.35
YS consumption (kg/orbit)	0.7		0.18	0.52

Table 11 - ATV In-flight overconsumption data

Seven OM cycles (14 OM maneuvers under 20m/s) were finally needed in the baseline. Figure 10 and Figure 11 show the in-plane and out-of-plane relative trajectories and the effect of the SK and OM maneuvers during 1 station-keeping loop (3 OM cycles and 2 SK cycles).

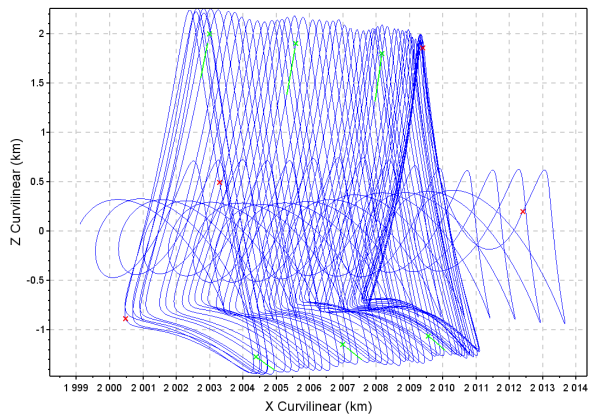

Figure 10 - SK loop with 3 OM cycles X-Z plane (ATV-5 cancelled baseline)

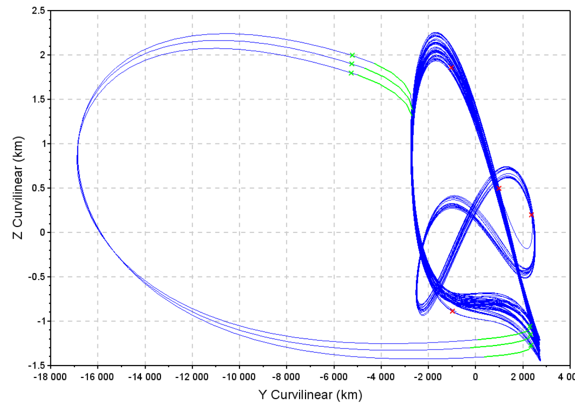

Figure 11 - SK loop with 3 OM cycles, Z-Y plane (ATV-5 cancelled baseline)

Once the ATV had achieved the necessary target mass, 48h prior the deorbitation opportunity, the re-phasing to the shallow reentry orbit had to be engaged.

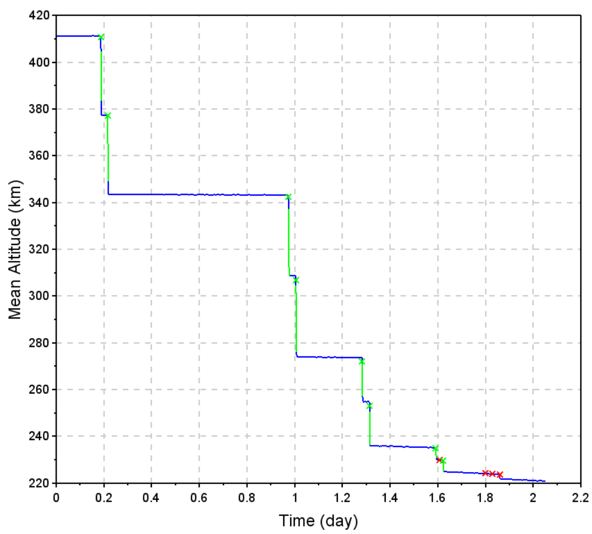

Figure 12 - ATV-5 re-phasing to shallow reentry profile (cancelled)

Mission	ATV5 (cancelled)
ISS altitude (km)	415
Targeted point Altitude (km)	215
Duration (days)	2
ATV/ISS extra nb of orbits	1
Total DV (m/s)	108
Total Ergols (kg)	679.1

Table 12 - ATV-5 re-phasing to shallow reentry characteristics (cancelled)

This phasing targeted an "$S_{-1/2}$ *Reentry*"point placed at an orbit of 215 km high, at 270 degrees of AOL and ~6h prior to the targeted orbit observation from the ISS. Figure 12 presents the nominal trajectory for re-phasing and Table 12 gives some of its main characteristics.

For further information on the shallow reentry see [16] and [17].

5. CONCLUSIONS

The ESA/CNES FDS teams of the ATV-CC were able, during the period from March 9th, 2008 to February 15th, 2015, to operate accurately and safely the flight dynamics aspects of 5 ATV missions to the ISS, fulfilling all the primary objectives and many other secondary, thanks to the extraordinary behavior of the ATV-CC organization, the ATV vehicle, the ISS, the Ariane-5 launcher, the Flight Segment specialist support and the International partner organizations.

The generic phasing strategy revealed to be accurate, robust and flexible, adapting to many contingencies and planned modifications during phasing, but also allowing descending re-phasings, which were developed for the 1st time during ATV-1 attached phase.

T-ORM and Oscar/Dragon tools, although not initially developed to compute the Station-Keeping of Cargo Vehicles neither the fly-around the ISS, were used with success to support these situations, avoiding the need of developing additional dedicated maneuver computation tools at the FDS.

However, no FDS tool in the ATV-CC allowed computing straight-away the over-consumption maneuvers to ensure a targeted mass at the arrival point before deorbitation (ATV-5). This problem required the development of specific and complicated procedures and the implementation of algorithms to help the operator prediction of the overall strategy. Unfortunately, these new means were not used in operations following the cancellation of the ATV-5's Shallow Reentry Observation Campaign.

In terms of mass prediction and maneuver calibration, it has been proven the advantages of updating methods when enough in-flight data exists. The recurrent models of any given CV should give similar performances to the first models, as ATV program experienced.

6. REFERENCES

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7. APPENDIX

The following Tables contain the final T-ORM computations for each of the maneuvers in each ATV mission with the exception of ATV-1, that has already been published in [4] and [9].

Mano.	Date	Hour	N	Aol(deg)	DV(m/s)	Vx(m/s)	Vy(m/s)	Vz(m/s)	Dur(s)	Thrusters
TP1	17/02/2011	07:19:53	7	112.89	4.76	4.52	0.00	1.48	92.99	OCS
TP2	17/02/2011	08:07:35	7	304.1	1.80	1.76	0.00	-0.40	236.73	ACS
MC1_1	19/02/2011	17:49:55	46	138.33	1.30	1.30	0.00	0.00	170.09	ACS
MC1_2	19/02/2011	18:28:53	46	294.36	1.29	1.29	0.00	0.00	168.93	ACS
MC2_1	22/02/2011	12:40:39	90	359.65	1.66	1.66	0.00	0.00	216.70	ACS
MC2_2	22/02/2011	13:22:36	91	167.67	1.66	1.66	0.00	0.00	216.32	ACS
TV1_1	23/02/2011	13:52:28	107	287.18	10.42	10.42	0.00	0.26	202.14	OCS
TV1_2	23/02/2011	14:37:37	108	107.21	10.46	10.46	0.00	0.00	202.18	OCS
TV2_1	23/02/2011	21:27:22	112	293.01	6.12	6.12	0.00	0.11	118.01	OCS
TV2_2	23/02/2011	22:13:20	113	115.1	6.00	6.00	0.00	0.00	115.41	OCS
TV3_1	24/02/2011	04:51:52	117	249.08	2.90	2.90	0.07	0.05	55.64	OCS
TV3_3	24/02/2011	05:38:02	118	71.15	2.80	2.80	-0.03	0.03	53.64	OCS
IF1	24/02/2011	09:58:30	121	17.54	0.34	0.34	0.00	0.00	43.66	ACS
IF2	24/02/2011	10:44:27	121	198.78	0.04	0.04	0.00	0.00	5.61	ACS
IF3	24/02/2011	11:29:16	122	15.18	0.90	0.90	0.08	0.00	115.64	ACS

Table 13 - ATV-2 Phasing (T-ORM final maneuver computations)

Mano.	Date	Hour	N	Aol(deg)	DV(m/s)	Vx(m/s)	Vy(m/s)	Vz(m/s)	Dur(s)	Thrusters
TP1	23/03/2012	13:56:53	7	88.12	5.93	5.91	0.00	-0.40	115.95	OCS
TP2	23/03/2012	14:21:46	7	187.97	6.19	6.14	0.00	0.86	120.96	OCS
MC1_1	25/03/2012	04:53:27	33	70.8	1.85	1.85	0.00	0.00	36.11	OCS
MC1_2	25/03/2012	05:31:24	33	222.8	1.86	1.86	0.00	0.00	36.13	OCS
MC2_1	26/03/2012	19:41:29	59	8.79	1.36	1.36	0.00	0.00	178.05	ACS
MC2_2	26/03/2012	20:24:32	59	180.82	1.36	1.36	0.00	0.00	177.31	ACS
TV1_1	27/03/2012	20:29:11	75	185.09	18.12	18.12	0.00	0.07	350.84	OCS
TV1_2	27/03/2012	21:14:37	76	5.18	18.21	18.21	0.00	0.00	350.84	OCS
TV2_1	28/03/2012	03:45:32	80	103.09	5.76	5.76	0.00	-0.06	110.36	OCS
TV2_2	28/03/2012	04:30:07	80	278.44	5.23	5.23	0.00	0.00	100.06	OCS
TV3_1	28/03/2012	11:34:17	85	139.91	2.90	2.90	-0.12	-0.04	55.41	OCS
TV3_2	28/03/2012	11:57:36	85	231.45	0.07	0.00	0.07	0.00	8.34	ACS
TV3_3	28/03/2012	12:17:03	85	307.49	3.41	3.41	0.15	0.00	436.94	ACS
IF1	28/03/2012	16:45:29	88	276.52	0.05	-0.05	0.00	0.00	6.08	ACS
IF2	28/03/2012	17:31:38	89	96.62	0.03	0.03	0.00	0.00	3.17	ACS
IF3	28/03/2012	18:16:21	89	271.68	1.21	1.21	-0.08	0.00	154.80	ACS

Table 14 - ATV-3 Phasing (T-ORM final maneuver computations)

Mano.	Date	Hour	N	Aol(deg)	DV(m/s)	Vx(m/s)	Vy(m/s)	Vz(m/s)	Dur(s)	Thrusters
TP1	10/06/2013	14:02:01	76	24.63	11.23	11.22	-0.52	0.00	220.71	OCS
TP2	10/06/2013	14:36:58	76	164.76	11.14	10.90	2.30	0.00	218.11	OCS
MC1_1	12/06/2013	12:45:30	107	36.72	1.67	1.67	0.00	0.00	219.48	ACS
MC1_2	12/06/2013	13:50:51	107	297.03	1.60	1.60	0.00	0.00	210.08	ACS
TV1_1	14/06/2013	11:31:34	138	46.78	22.45	22.45	-0.22	0.00	435.87	OCS
TV1_2	14/06/2013	12:18:25	138	232.09	22.32	22.32	0.00	0.00	430.26	OCS
TV2_1	14/06/2013	19:07:35	143	32.58	5.77	5.77	0.15	0.00	110.65	OCS
TV2_2	14/06/2013	19:53:39	143	212.68	5.63	5.63	0.00	0.00	107.82	OCS
TV3_1	15/06/2013	02:41:07	147	359.31	2.86	2.83	-0.20	0.33	366.73	ACS
TV3_2	Cancelled									
TV3_3	15/06/2013	03:29:30	148	187.99	3.18	3.13	-0.24	-0.48	407.78	ACS
IF1	15/06/2013	07:57:51	151	150.72	0.11	0.11	0.00	0.00	14.31	ACS
IF2	15/06/2013	08:44:23	151	331.1	0.02	0.02	0.00	0.00	2.46	ACS
IF3	15/06/2013	09:29:27	152	146.63	1.10	1.10	0.00	0.04	140.69	ACS

Table 15 - ATV-4 Phasing (T-ORM final maneuver computations)

Mano.	Date	Hour	N	Aol(deg)	DV(m/s)	Vx(m/s)	Vy(m/s)	Vz(m/s)	Dur(s)	Thrusters
TP1	28/10/2013	20:06:24	2253	153.79	11.79	-11.77	0.59	0.00	191.97	OCS
TP2	28/10/2013	20:48:29	2253	317.79	11.77	-11.73	1.02	0.00	190.94	OCS
MC1_1	31/10/2013	07:42:52	2292	127.03	1.84	-1.84	0.00	0.00	29.73	OCS
MC1_2	31/10/2013	08:30:51	2292	315.03	1.84	-1.84	0.00	0.00	29.67	OCS
TV1_1	01/11/2013	17:57:37	2314	269.45	13.14	-13.14	0.07	0.00	211.69	OCS
TV1_2	01/11/2013	18:44:14	2315	93.32	15.26	-15.26	-0.17	0.00	244.79	OCS
TV2_1	02/11/2013	01:59:20	2320	19.6	3.41	-3.40	0.00	0.11	54.43	OCS
TV2_2	02/11/2013	02:54:42	2320	239.55	3.48	-3.48	0.00	0.10	55.61	OCS

Table 16 - ATV-4 Re-phasing to reentry (T-ORM final maneuver computations)

Mano.	Date	Hour	N	Aol(deg)	DV(m/s)	Vx(m/s)	Vy(m/s)	Vz(m/s)	Dur(s)	Thrusters
TP1	30/07/2014	09:18:56	7	122.05	21.28	21.23	1.46	0.00	418.81	OCS
TP2	30/07/2014	10:07:08	7	314.28	21.26	21.25	-0.36	0.00	415.49	OCS
MC1_1	02/08/2014	11:42:11	56	118.87	1.77	1.77	0.00	0.00	34.43	OCS
MC1_2	02/08/2014	12:20:43	56	270.88	1.75	1.75	0.00	0.00	33.94	OCS
MC2_1	05/08/2014	12:35:24	104	97.9	1.43	1.43	0.00	0.00	187.14	ACS
MC2_2	05/08/2014	13:20:03	104	273.91	1.43	1.43	0.00	0.00	186.79	ACS
TV1_1	07/08/2014	23:16:12	142	297.11	9.38	9.38	0.16	0.00	181.61	OCS
TV1_2	08/08/2014	00:01:59	143	117.14	9.39	9.39	0.00	0.00	181.29	OCS
TV2_1	08/08/2014	07:05:22	147	333.86	6.72	6.72	-0.01	0.00	129.32	OCS
TV2_2	08/08/2014	07:51:26	148	153.89	6.69	6.69	0.00	0.00	128.57	OCS
TV3_1	08/08/2014	14:16:08	152	211.49	2.63	2.61	0.30	-0.16	50.37	OCS
TV3_2	Cancelled									
TV3_3	08/08/2014	14:58:52	153	17.54	2.54	2.52	0.32	0.20	327.24	ACS

Table 17 - ATV-5 Phasing (T-ORM final maneuver computations)

Mano.	Date	Hour	N	Aol(deg)	DV(m/s)	Vx(m/s)	Vy(m/s)	Vz(m/s)	Dur(s)	Thrusters
TA1	10/08/2014	03h19:02	176	207.96	3.30	3.30	0.00	0.00	63.12	OCS
TA2	10/08/2014	04h04:54	177	25.8	5.20	5.20	0.00	0.00	99.27	OCS
TA3	10/08/2014	04h50:42	177	203.31	1.38	1.38	0.00	0.00	176.57	ACS
TB1	11/08/2014	16h55:49	200	302.49	4.00	-4.00	0.00	-0.05	76.24	OCS
TB2	11/08/2014	17h47:20	201	142.48	8.08	-8.08	0.04	0.00	153.64	OCS
TB3	11/08/2014	18h44:10	202	3.19	2.87	-2.87	0.08	0.00	54.39	OCS
TV1	12/08/2014	01h57:42	206	250.89	2.53	2.50	0.07	0.37	47.97	OCS
TV2	12/08/2014	02h21:08	206	342.09	0.09	0.00	-0.09	0.00	10.87	ACS
TV3	12/08/2014	02h41:43	207	62.24	2.48	2.45	0.00	0.40	315.06	ACS
IF1	12/08/2014	07h41:34	210	147.34	0.03	0.03	0.00	0.00	3.15	ACS
IF2	12/08/2014	08h27:59	210	327.38	0.02	0.02	0.00	0.00	1.91	ACS
IF3	12/08/2014	09h13:01	211	142.65	1.17	1.16	0.00	0.10	148.36	ACS

Table 18 - ATV-5 Post-Fly-Under (T-ORM final maneuver computations)