HIGH REACTIVITY MANEUVER DESIGN IN ATV MISSIONS

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Abstract: *The Automated Transfer Vehicle (ATV) mission control has reached its peak of experience at the completion of the 4th mission supplying the International Space Station (ISS). The last vehicle of its kind, the so-called ATV-5 "Georges Lemaitre", will be launched in July 2014. The experience of the four first missions of the ATV shows that no real recurrence existed between each of the ATV maneuver strategies. In-flight demonstrations, new imagery experiences and change to protect from contingencies resulted in short-notice demands of revision and redesign of the phasing and deorbiting strategies. This paper focuses on the various maneuver strategies conceived along the past missions, and indicates the strategies designed for ATV 5 mission, which include several observation experiences during both ascent and deorbitation phases.*

Keywords: *ATV vehicle, Maneuver design, Mission analysis, ISS logistics, Satellite operations*

1. Introduction

The Automated Transfer Vehicle is an European Space Agency (ESA) funded program: the spacecraft is designed and built by Airbus Defence and Space and operated at the ATV Control Center (ATV-CC) by the French Space Agency (CNES). ATV-CC works in close coordination with the Mission Control Centre in Moscow (MCC-M) as the ATV docks with the Russian module, the Mission Control Centre in Houston (MCC-H) which coordinates the overall ATV-ISS joint operations, Goddard Space Control Centre providing communication service via TDRS constellation, Redu Control Centre providing communication service via ARTEMIS relay satellite, the on-board ISS crew who monitor the rendezvous and transfer the cargo and Kourou, the Ariane launch site.

The ATV is an unmanned space transport vehicle whose mission is to contribute to the logistic servicing of the ISS. By transporting propellants, gases and other logistic cargo to the Station for the common utilization, ATV becomes one of Europe's contributions towards Europe sharing of the International Space Station operating costs. ATV also provide the disposal of ISS waste and re-boosts the ISS to a higher altitude to compensate for the atmospheric drag.

The first ATV mission Jules Verne began with a successful launch by Ariane-5 on March 9th, 2008; after several demonstrations it docked to ISS on 3rd April and performed an attached phase of about 5 months, after which it undocked the station safely and executed a destructive reentry above the uninhabited area of the South Pacific Ocean.

Three more missions followed with success. ATV Johannes Kepler was launched on February 15th, 2010, ATV Edoardo Amaldi on March 23rd, 2012 and ATV Albert Einstein on June 5th, 2013. All of them were injected in-orbit by Ariane-5 launcher, from the French Guyana. The last vehicle of its kind, the so-called ATV-5 “Georges Lemaitre”, will be launched in July 2014. During the period between January 2008 and December 2014, the ATV program would represent 6% of the overall unmanned launches towards the ISS with logistics purposes. In terms of ISS refueling, it shall cover about the 14% of the launches in this period.

1.1. ATV spacecraft

The ATV main body is a cylinder, 10.3m long and up to 4.5m in diameter, that weighs about 20 tons at launch, representing the heaviest European spacecraft ever launched. Extending from the main body of the spacecraft are its characteristics X shaped metallic blue solar arrays.

The propulsion system consists of 4 Orbital Control Thrusters (OCS) of 502 N each and 28 smaller thrusters, called Attitude Control System (ACS) of 217 N each and with a saturated global commanded thrust level of 150N achieved with On/Off modulation of the thrusters. These thrusters also provide propulsive support to the ISS and they are commanded by the Service Module SW to perform ISS attitude control, debris avoidance maneuvers and re-boost maneuvers. ATV Navigation is performed with GPS, Dry Tuned Gyros and Star Trackers systems.

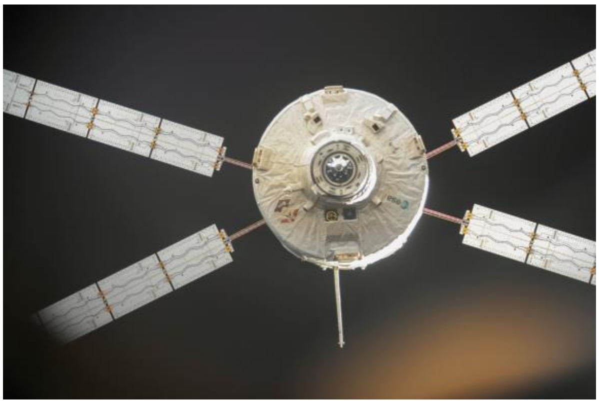


Figure 1. ATV4 Albert Einstein at the proximity of the ISS

For automatic docking, ATV is equipped with two videometers and two telegoniometers. Relay satellites TDRS and Artemis provide a continuous communication link between the ATV and the control center on Earth.

1.2. ATV-CC Flight Dynamics organization

Mission Analysis activities are conducted under ESA authority and they were split in two parts: Airbus Defence and Space took responsibility over the development phase of the flight segment, while the CNES is responsible for the development phase of the ground segment, the mission preparation and operations. At an early stage of the project, a controllability/reactivity trade-off was done to determine what parts of the Guidance, Navigation and Control system (GNC) shall be autonomous or computed on-ground. This trade-off resulted in a vehicle architecture allowing a complete autonomous relative navigation at the vicinity of the ISS until docking. Nevertheless, during the free flight from in-orbit injection to ISS vicinity, several major guidance functions of the ATV are computed on-ground in term of orbit determination, maneuver computation and attitude selection.

Within the ATV-CC teams, the Flight Dynamics team (FDS) is responsible for the orbit and attitude determination, the computation of the maneuver strategy and trajectory during the orbital flight phase, among other major tasks. The trajectory position (TRA) at ATV-CC in particular, computes the maneuver strategy and the trajectory during the orbital phases in which the ATV is guided based on absolute navigation. The TRA position activities towards the maneuver strategy computation include: Mission Analysis (MA), operational software development, preparation of operational products such as procedures and templates, simulation campaign, validation tests and operations.

1.3. Mission analysis at ATV-CC

The mission analysis activities performed by the ATV-CC are divided in two main branches:

- The Generic System Mission Analysis (GSMA) intends to support the ATV-CC technical qualification. It provides the justifications and demonstrations needed for ATV trajectory design. These analyses are, as far as possible, performed in a generic manner aiming to cover the ATV functioning domain in order to remains valid for future ATV flights.
- The System Mission Analysis (SMA), which aims to support the preparation of a specific mission, provides an end to end reference ATV trajectory, the associated orbital data and an estimation of the fuel consumption.

Besides these two kinds of documents specific internal technical notes may be written to demonstrate strategy robustness in case of very specific scenarios.

1.4. Problem justification

One of the most important characteristics of the ATV maneuver strategies is their high flexibility in terms of launch and docking scheduling. This flexibility leads to a complete disconnection between launch and docking dates scheduling, thanks to the following facts:

- Phasing strategy covering any phasing angle with respect to the ISS at launch
- Generic phasing strategy conceived to target any altitude within the expected range for the ISS
- Possibility to perform a parking phase as long as needed
- Orbital maneuvers until ISS vicinity computed on-ground

Concerning the undocking and de-orbitation phase, an equivalent flexibility is achieved by the ATV vehicle, easing the reentry operations scheduling and the ISS traffic planning with partners.

Despite this extremely flexible system no real recurrence existed between each of the ATV missions in term of maneuver strategies. Each mission demanded the revision and re-design of the maneuver strategy, that had to be performed in very short time, and carried out simultaneously to the rest of FDS critical activities. The TRA team is able to solve all these problems at maneuver design level thanks to an organization and a set of FDS techniques leading to a high reactivity of the TRA team, capable of re-computing, re-demonstrating strategies and renewing the optimum quantity of operational products in few days or weeks. This paper will focus on the Mission Analysis part of the strategy maneuver design and will present some past and current examples of non-recurrent maneuver strategies that had to be designed in order to solve each particular mission profile within ATV mission's experience.

2. ATV phasing strategy design

From the maneuver strategy design perspective, the ATV mission objectives decline into a simple question: how to command the ATV spacecraft safely from the injection point up to the docking port of the International Space Station. Such a rendezvous mission can be described as the deliberated conjunction of two spacecraft, in which one of them plays an active role being called the "chaser" while the second vehicle plays a passive role, acting as the "target". The different variables that define the rendezvous problem are: the initial date, the conjunction date, the state-vectors at these dates, the vehicle characteristics data and the environmental parameters (perturbation models, etc.).

A rendezvous (RDV) mission implies several phases that shall be regarded separately. In the case of the ATV missions, these phases are:

- Launch phase: Ariane-5 launcher injects the ATV in a Low Earth Orbit (LEO) circular at 260 Km altitude and 51.6° of inclination. The exact time of launch is computed with the objective to insert ATV vehicle in an orbit plane very close to the ISS orbital plane but not exactly the same, because the right ascension of the ascending node (RAAN) of the ATV will gradually drift due to J2 perturbations reaching the same orbital plane at the date of rendezvous with the ISS.

- Phasing phase: during this phase, two main objectives will be achieved, 1) to rise the ATV altitude until reaching the proximity of the ISS and 2) to reduce the phasing angle between the two vehicles (ATV and ISS) from its initial value at the time of A5 separation to about zero at the date of approaching the vicinity of the ISS (start of the autonomous relative navigation and guidance for docking). In the case of ATV mission this phase takes between 4.5 and 12.5 days.

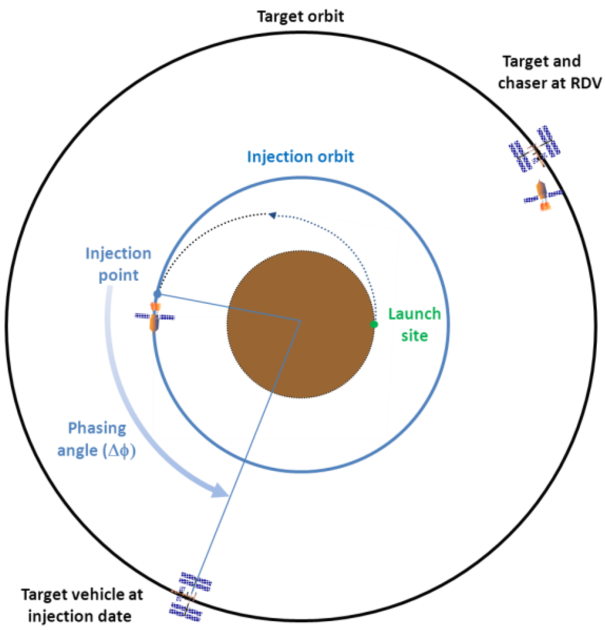


Figure 2. The phasing angle

- Rendezvous phase: once the vicinity of the ISS is reached safely, the relative GPS system is activated and the ATV-ISS RF communications link is initialized and consequently the ATV enters in automated mode. GNC functions are performed on-board in closed loop and are monitored by the ATV-CC. The rendezvous splits into several sub-phases (Far RDV, Close RDV…) ending at hold points where the ATV has almost fixed motion with respect to the ISS. The rendezvous phase ends with the docking completion. The duration of this phase, between the interface point with phasing and the is nominally 4h08m, but it may last longer depending on inflight the real time operations coordination and contingencies.

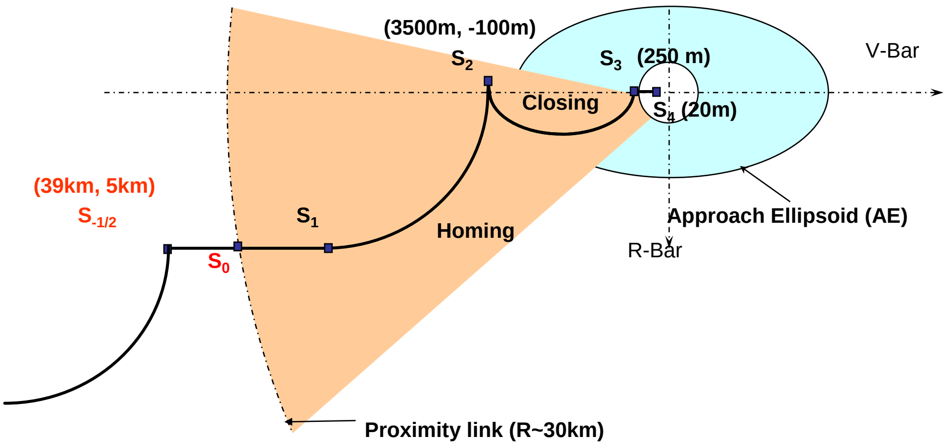


Figure 3. Rendezvous phase

- Parking phase: in the case of having a docking date later than 12.5 days after the launch, an additional phase of parking can be set up with no constraints of duration.

2.1. Phasing strategy basis

The launch trajectory is fixed and followed by Ariane-5. The RDV trajectory is executed automatically by the ATV vehicle. FDS team and TRA position in particular are responsible for the strategy design during the phasing phase only, that is, during the orbital phases between the injection point and the interface point ($S_{-1/2}$) that is the beginning of the onboard automated RDV navigation and guidance.

Generally, the optimal plan of maneuvers between two quasi-circular concentric orbits at different altitudes corresponds to a single Hohmann transfer. Such a strategy allows to reach a higher altitude (ISS altitude for example), but not to arrive to the exact point at which the target vehicle is placed at the same time for a given phasing duration.

To achieve this, an intermediate orbit shall be introduced; called the Drift Phasing Orbit (DPO). Depending on the altitude at which the DPO is set, a chaser placed on it will drift -in angular distance- faster or slower with respect to the target vehicle. Finding the right altitude for this orbit will serve to reach the station at the right date.

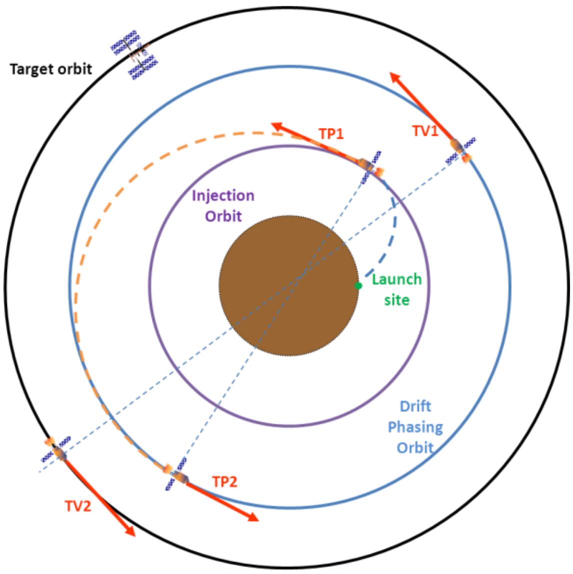


Figure 4. The Drift Phasing Orbit (DPO)

Then, two Hohmann transfers are theoretically enough to perform such strategy:

- 1st cycle : Transfer to the Phasing orbit (TP), from the Ariane-5 injection orbit.
- 2nd cycle : Transfer to ISS Vicinity (TIV) from DPO.

2.2. Former ATV phasing scenarios /ATV Flight domain

The altitude of the DPO as well as the values of the Hohmann transfers TP and TIV would depend, using the 3rd Keplerian law, only on 3 parameters: the ISS altitude, the phasing duration and the initial phasing angle between ATV and ISS. Any set of these three parameters describes a specific phasing scenario. The group of scenarios that can be demonstrated by mission analysis studies to be feasible becomes the ATV flight domain.

The general policy is to assure the capability of the ATV mission to dock safely with the station for all possible phasing angles between the ATV and the ISS at injection (from 0° to 360°). The targeted ISS mean altitude was 335 km for ATV1 and between 350 and 415 km for the following missions. The demonstrated phasing durations were between 10.5 and 12.5 days for ATV1 and between 4.5 and 12.5 for the following missions.

The GSMA document volume concerning the phasing flight domain had to be 1) updated after ATV1 mission following a rise of altitude of the ISS, 2) enlarged to cover shorter phasing durations (from 4.5 to 6.5 days) and 3) enlarged again to cover longer durations after ATV2 (11.5 and 12.5 days), remaining applicable for ATV3 to ATV5 missions.

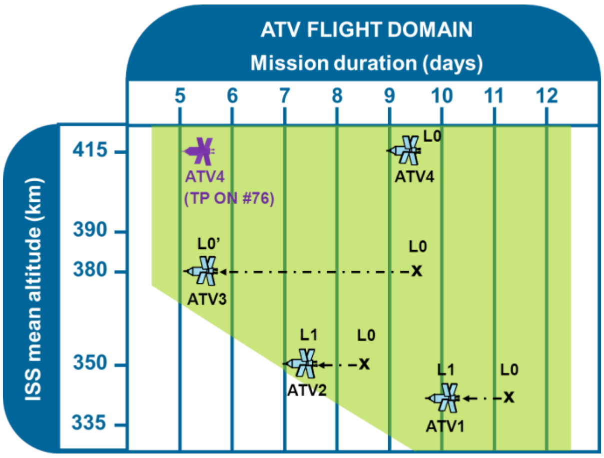


Figure 5. ATV Flight Domain and Former ATV mission scenarios

Figure 5 gives the ATV flight domain represented by a green zone. Inside the flight domain there are the predicted phasing scenarios for each of the former ATVs (black "X"), and the final ATV phasing scenarios within this flight domain (ATV icons). ATV1 and ATV2 were launched at L1 date (1 day after the nominal launch date, L0); ATV3 was delayed 2 weeks following a problem with the fixation of cargo, and ATV4 drifted 5 days at launch altitude before starting the phasing strategy with TP maneuvers on the orbit number (ON) 76.

Towards the objective of demonstrating the feasibility of such an important variety of scenarios following a common strategy design, it is imperative to test their robustness and then:

- To have tools able to perform Monte-Carlo simulations for phasing scenarios
- To cover the expected range of values of the input parameters for the ATV missions
- To use representative uncertainties and dispersions on the variables
- To simulate the ATV-CC operational delays and the ATV vehicle GNC system
- To achieve to put the ATV in the ISS vicinity with the necessary precision to start with the automatic relative navigation in RDV phase
- To respect the safety requirements of Human Flight Operations
- Not to produce unnecessary over-consumption
- Robustness toward potential prolongations of time of flight before docking (possibility of planning a Parking free-drift phase).

2.3. FDS Mission Analysis Tools for phasing

The tool used for ATV phasing mission analysis is OSCAR/DRAGON. This software uses DRAGON as kernel to compute the optimal maneuvers while OSCAR enables to conduct Monte-Carlo analysis, simulating how the maneuvers can be updated on-ground all along the mission by performing end-to-end simulations with the control center in the loop. Document [1] gives deeper information in OSCAR/DRAGON tool and its application in other major projects as GALILEO.

T-ORM, the FDS operational tool for maneuver optimization, has been developed for the ATV project inspired by DRAGON, and it is used both in operations and for SMA computations. Document [3] provides more information on this tool.

2.4. ATV's GNC system functioning in phasing

As it is stated in ATV User's Manuals and in document [4], during orbital phases –therefore during phasing- the ATV GNC behavior is the following:

- Geometrical center motion measured with a GPS receiver on-board
- Continuous Telemetry (TM) link via TDRS satellites with ATV-CC
- Navigation performed on-ground: absolute orbit determination (OD) based on Pseudo-Range measurements received in TM (non-real time/real time)
- Guidance performed on-ground:
  - Maneuver optimization
  - Trajectory extrapolation
  - Orbital Control Frame (OCF) based on OD and computed maneuver plan
- Attitude navigation performed on-board : star trackers and gyroscopes
- Attitude guidance performed almost entirely on-board :
  - Yaw steering (YS) attitude law performed nominally in free drift
  - ACS thrusters system used to :
    - perform YS permanently in free drift
    - perform small orbital maneuvers (<1.7m/s) simultaneously to YS attitude law
    - perform slew maneuvers before and after OCS maneuvers
  - OCS thrusters system used to :
    - Large orbital maneuvers (from 1.7 m/s to values greater than 60m/s)

2.5. Uncertainties in phasing strategy mission analysis

For mission analysis computations supporting the strategy design both the chaser (ATV) and the target (ISS) vehicles present a level of uncertainties that must be taken into account together with environmental uncertainties:

- ISS orbital parameters possible values
- ISS ephemeris uncertainties and ageing
- ISS ballistic coefficient : mass, surface, drag coefficient
- Ariane-5 dispersion at injection
- ATV orbit determination accuracy
- OCS and ACS maneuvers execution accuracy
- ATV ballistic coefficient: mass, surface, drag coefficient, attitude law effect
- Atmospheric conditions (sun activity, etc.)

2.6. Target point definition

When the established launch and docking dates fall within ATV flight domain valid duration, the phasing is direct, targeting a point within the ISS vicinity, result of an agreement between the different parts (CNES, Airbus Space and Defence and ESA). The arrival to this point, the so-called $S_{-1/2}$, will end the phasing phase and trigger the start of the automated RDV phase. The state-vector for $S_{-1/2}$ point must be reached with reduced dispersions in order to initiate safely the autonomous navigation of the ATV as already presented in [5].

	$S_{-1/2}$ LOCATION	ACCURACY REQUIREMENTS	COMMENTS
Δa	-5000 m	480 m	Mean parameter
$a_{ISS}\,\Delta e_{xp}$	0	480 m	Mean parameter
$a_{ISS}\,\Delta e_{zp}$	0	480 m	Mean parameter
ΔX	39000 m	3300 m	X osculating coordinate Cartesian frame (LVLH ISS)
Δh_{cin}	0 deg	0.005729 deg	(10^{-4} radians, osc. coordinate) ATV/ISS angular momentum errors

Table 1. Targeted point definition and requirements

A specific cycle of three interface maneuvers (TIF) will be also required right before reaching this point, which must be monitored to confirm a full safety.

	Tangential component (m/s)		Radial component (m/s)		Module (m/s)	Duration (s)
Maneuver	Mean - 3σ	Mean + 3σ	Mean - 3σ	Mean + 3σ	Mean + 3σ	Mean + 3σ
IF1	-1.879	1.857	0	0	2.288	387
IF2	-0.432	0.420	0	0	0.4534	102
IF3	-0.406	2.824	-1.158	1.110	3.5492	582

Table 2. Interface maneuvers values and limits

In case of phasing scenarios with a duration greater than those of the ATV flight domain (greater then 12,5 days), an intermediate parking phase should be planned so that the previous phasing will not target the $S_{-1/2}$ at first place. Instead, it will target one of the 4 possible parking points (PP) defined in the Figure 6. No TIF cycle of maneuvers is needed to reach the PP. The four parking points are placed at ISS altitude to cancel ATV-ISS relative drift towards X axis in local vertical local horizontal frame (LVLH).

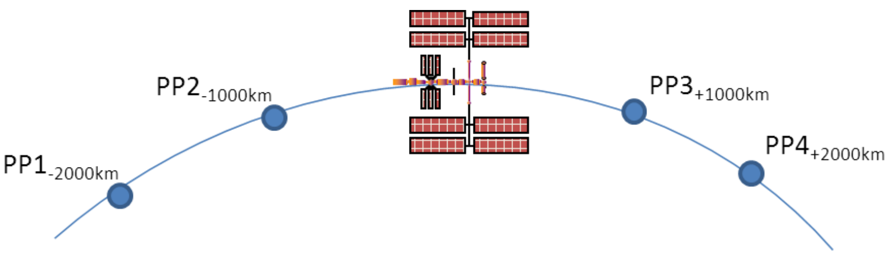


Figure 6. Parking points location

2.7. GSMA Phasing strategy

The level of detail of the strategy design is rather extensive, so this paper will only give the essential ideas. The GSMA document describes the phasing strategy design resulting from mission analysis simulations, as follows:

- 1 TP maneuver cycle: during the orbit number #7, two maneuvers (TP1 and TP2) are performed to reach the DPO. These maneuvers have commanded longitudinal and transversal components, the transversal components aim at correcting the injection errors. A minimum DV value is set to avoid nominal retrograde maneuvers after injection: 2 x 2.5 m/s

- 1 or 2 Mid-Course (MC) maneuver cycles: during DPO, 2 or 4 tangential maneuvers ($MC1_1$ to $MC2_2$) will be calculated and tuned to deliver ATV at S_{-3s} (before TIV cycles in case of 2 TIV cycles, Figure 7) within suitable dispersions. Nominal ΔV is set between 1 and 2 m/s to avoid dispersed retrograde maneuvers.

- 2 or 3 TIV cycles: located at the end of the phasing, it transfers the ATV from its Drift Phasing Orbit to the way point S_{-2} (before TIF cycle). This transfer must be able to catch up the dispersions mainly generated by the last mid-course maneuvers and drag dispersions; therefore a minimum ΔV is required. On another hand, it must not generate too many dispersions for the cycle TIF (less than ±13 km for the along track dispersion), then the upper maneuver values are limited.

- TIF cycle: three maneuvers as defined in the previous chapter.

Example of phasing strategy with 2 MC and 2TV cycles:

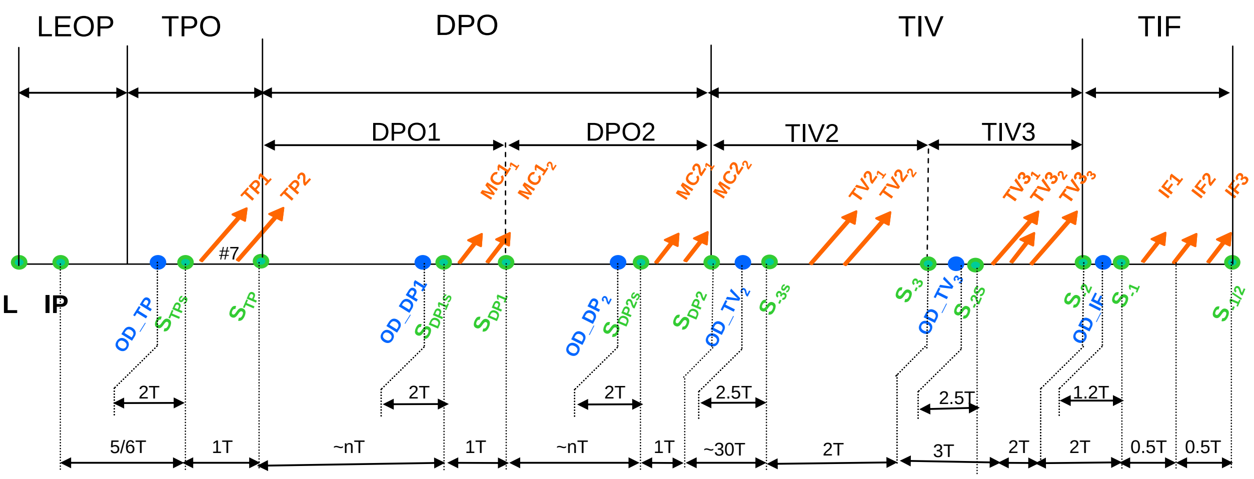


Figure 7. ATV phasing strategy example

2.8. Former missions phasing strategies

From ATV1 to ATV4 mission, every phasing strategy was computed using the generic strategy described on the GSMA, volume "Phasing".

Figure 8. Past ATV missions phasing profiles

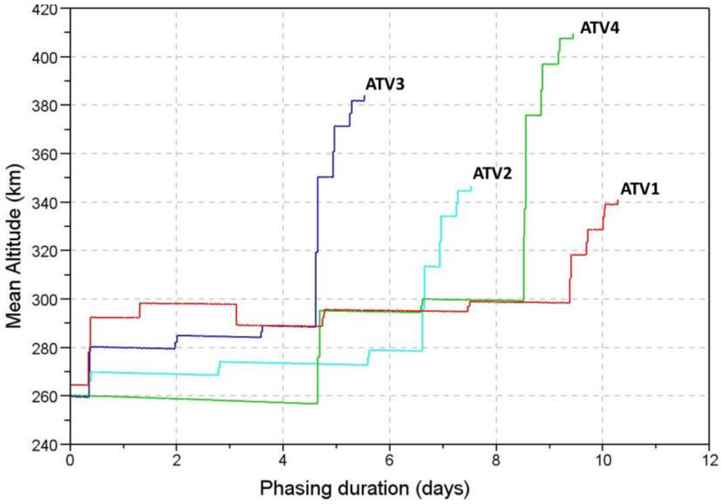


Table 3. Past ATV scenarios data

Phasing scenario	ATV1	ATV2	ATV3	ATV4
ISS altitude (km)	339	359	398	404
Duration (days)	10.25	7.5	5.5	9.5
Phasing angle at launch (deg)	146.11	12.91	62.81	274.71
Targeted point	PP4	S-1/2	S-1/2	S-1/2
ATV/ISS extra nb of orbits	1	1	1	4
TP cycle orbit number	7	7	7	76
Total DV (m/s)	55.19	52.41	73.09	89.07
Total Ergols (kg)	< 600	413.8	533.7	659.3

Nevertheless the missions ATV1 and ATV4 presented some characteristics which placed them out of the general case for recurrent ATV's. In the case of ATV1 Jules Verne:

- ATV1 differed from the generic mission as it involved in-flight demonstrations before docking.
- 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.
- As the Shuttle STS-123 mission was scheduled during the nominal phasing period, in order to comply with the flight rules for vehicles servicing ISS and to be robust to Ariane-5 launch delay, a Parking Point was targeted after the phasing (PP4, +2000km), waiting for the "GO Decision" to start the proximity operations.
- During operations, due to a failure of the Propulsion Drive Electronic (PDE), the experts required OCS test maneuvers so TP cycle was split into two cycles (TE/TP).

For a deeper knowledge on the particularities of this first ATV phasing mission plan, detailed information can be found in previous publications [2], [3], [5] and [6]. For deeper information on ATV3 mission see [11].

In the case of ATV4 Albert Einstein, the launch date was initially scheduled in middle March 2013 but, as result of the evolution of the project, the launch date was delayed several times until the final date of June, 5th. This particular date corresponded to a period of the year in which the Sun aspect angle on the orbit called beta angle was high (more than 64°, these high values are present only a few days in the year): this condition implied too short eclipse durations in ATV phasing orbit or even no eclipse at all. Having eclipses shorter than a certain duration (24 minutes and 10 seconds) forbids to perform operations for cleaning the

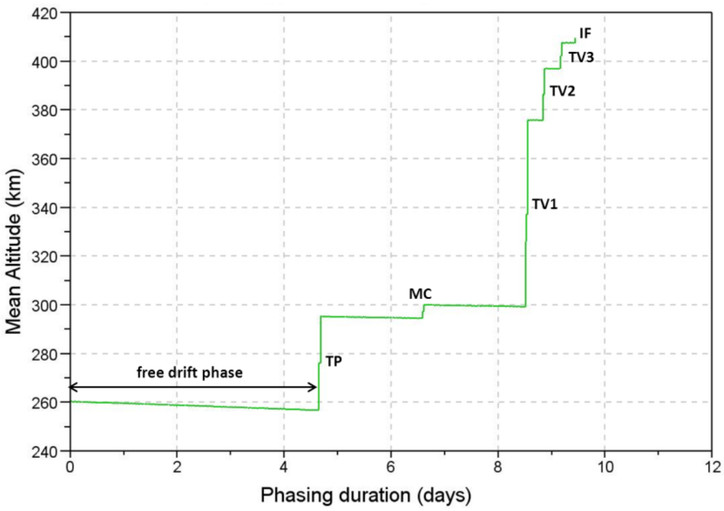
Solar Array Drive Mechanism (SADM), which are necessary before performing orbital maneuvers with OCS.

The first phasing maneuvers (TP cycle) had to be delayed until the 10th of June, from orbit #7 to orbit #76. Then, the phasing scenario can be seen as split into two sub-phases:

- Free-drift sub-phase (from injection to orbit 70, AOL ~244°): duration 4 days, 5 hours.
- Phasing sub-phase (from end of free-drift sub-phase to $S_{-1/2}$): duration 5 days, 3 hours.

The total phasing duration for the ATV4 mission (from injection to $S_{-1/2}$) was 9 days, 10 hours and 42 minutes. Some specific Monte-Carlo runs were performed by the FDS to validate the final scenario, as no computation with TP delayed maneuvers to orbit #76 is covered in the existing GSMA. In a second round of simulations, a reduction to only one MC cycle in the strategy was validated. The final results were gathered 20 days before the Launch Monday (LM-20), already in negative chronology.

Figure 9. ATV4 phasing profile - TP cycle delay to ON #76



2.9. ATV5 phasing strategy baseline

ATV5, the actual mission under preparation, still announce important modifications with respect to the generic strategy design established by GSMA documents. This time, the reason for the changes is the implementation of a new set of optical cameras at the exterior of the Integrated Cargo Carrier (ICC) of the ATV that will be used for future RDV sensor techniques.

In flight data from these visible (VIS) and infrared (IR) cameras will be recorded in order to offline assess on ground the accuracy and quality of the data and images at long range (around 15km to the ISS), checking the robustness of new navigation technique based on the cameras' images for various illumination conditions (since slow relative motion), and their ability of discrimination between the Sun and the ISS.

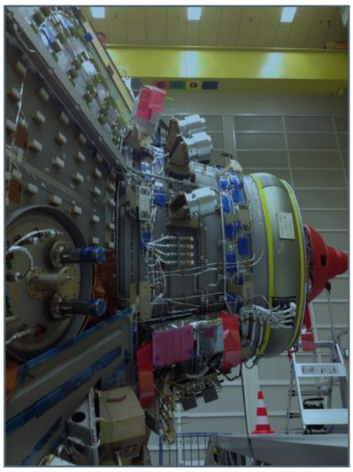


Figure 10. Optical instruments integrated on ATV5 in Bremen

The field of view (FoV) of the cameras is the following:

- VIS and IR cameras axis have a 15deg pitch from ATV main axis.
- IR Camera field of view in-plane 58.6deg (+/-29.3)
- VIS Camera field of view in-plane 57.5deg (+/-28.75)

The FDS has proposed a strategy allowing the observation of the ISS at long range distances for the given positions of the camera and their fields of view orientations. The chosen strategy allows performing a free-drift trajectory of fly-under the ISS, during which the long range experience will be performed. Such a fly-under scenario will be achieved as follows:

- No modification to the existing generic phasing strategy until the target point with no impact on operational procedures.
- Re-use of the TIF cycle cancellation scenario, with existing ATV-CC operations procedures and safety analysis already available in GSMA document.
- “Post-Escape-like” strategy after the fly-under free-drift, to re-engage 60h later, the RDV phase with the ISS.
- A new definition of the targeted point for fly-under (S-1/2_FU) is chosen to minimize ATV/ISS range when the camera acquisition of the ISS is lost. This point is ΔX = -71 km, Δa = -5 km in LVLH ISS. The minimum range will be 8-10 km if the trajectory is nominal and never greater of 15 km for dispersed maneuvers with a 90% of confidence.

Figure 11 depicts the ISS relative trajectory seen from the ATV inside the cone of visibility of the cameras during the optical experience called “Fly Under” (blue line), together with the 3-sigma dispersed trajectories (red lines). The green straight lines represent the IR instrument FoV limits and the dashed green line represents the camera axis direction.

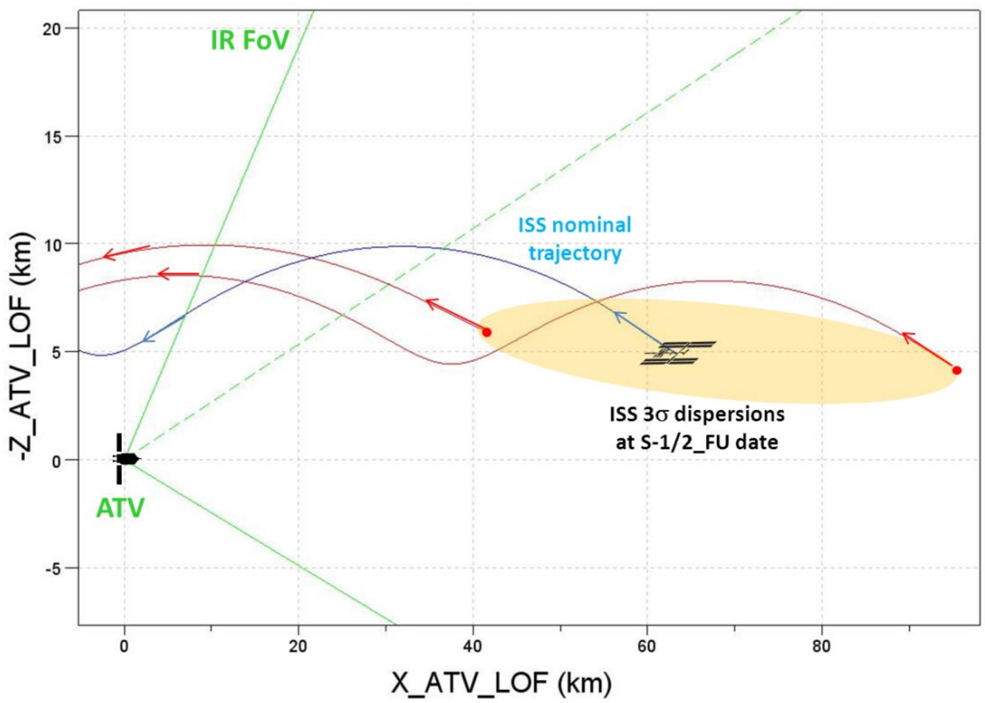


Figure 11. Fly-Under experience: ISS relative trajectory wrt ATV LOF

3. ATV "Return from Fly-Under" design

After performing the optical experience, the ATV5 will execute a strategy of maneuvers leading to "come-back" to the nominal $S_{-1/2}$ to engage the foreseen docking with the ISS.

Similar strategies were executed during the ATV1 Jules Verne mission to demonstrate the safety of the ATV operations during RDV approach and Escape contingency scenarios. Indeed, an Escape maneuver is performed if the ATV systems detect a violation of the Flight Safety Rules in the proximity of the station. It is a retrograde maneuver of -4m/s towards the X axis of the ATV, which leads the ATV in a drift orbit under the station.

Figure 12 presents the baseline Post Fly Under trajectory for ATV5 (red color) as well as the three similar trajectories performed during ATV1 Jules Verne Flight preceding each one of the three Demo Days (in cyan, light blue and dark blue colors):

- Demo Day 1 (DD1) was preceded of a Return from PP4 (+2000 km) strategy
- Demo Day 2 (DD2) was preceded of a Post-Escape in 48h
- Demo Day 3 (DD3) was preceded of a Post-Escape in 72h

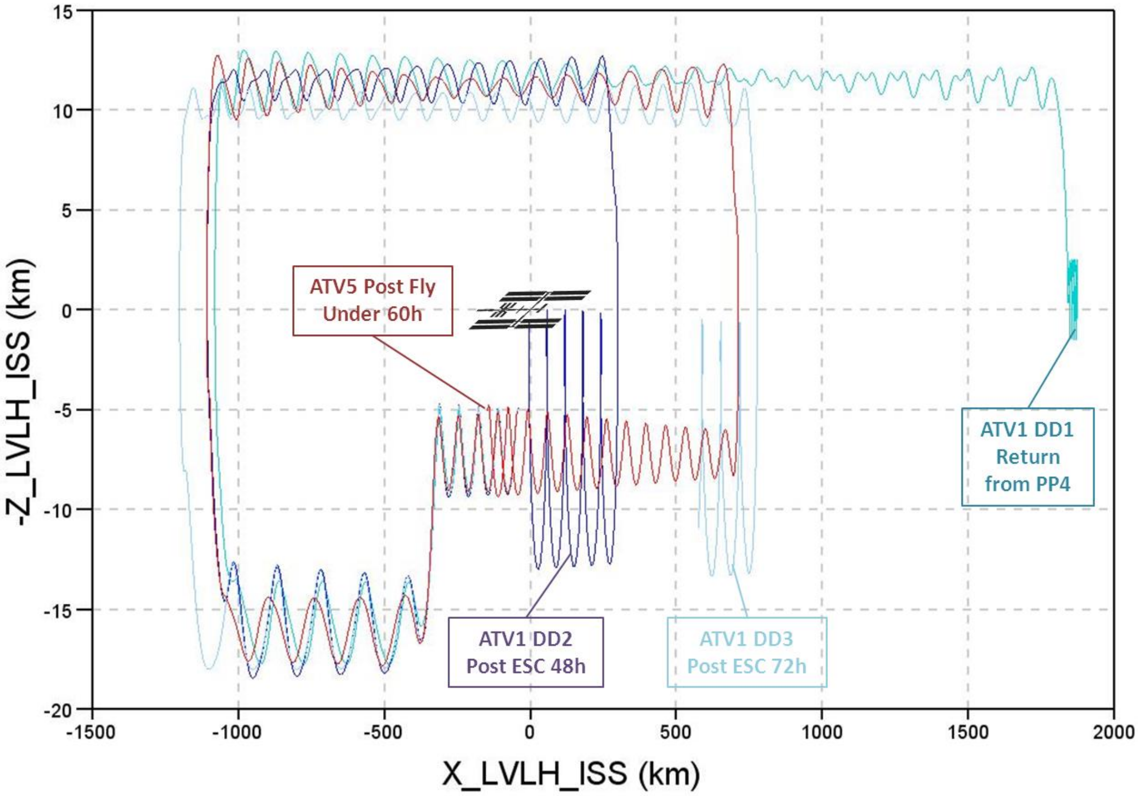


Figure 12. ATV1 Demo Days and ATV5 Post Fly Under trajectories

A full generic mission analysis documentation exists on this topic, allowing to re-use the existing strategy named "Post-Escape in 48h". The only difference is that the strategy would be performed in 60h and not in 48h. To solve this, TRA team has borrowed Post-Escape strategy and performed new Monte-Carlo runs specific to ATV5 mission. The scheme of maneuvers, composed of four cycles of maneuvers denominated TA, TB, TV and TIF, serves both for the Post-Escape and Post-Fly-Under scenarios. Figure 13 depicts the maneuvers positioning (T stands for "Orbital Period", OD for "Orbit determination").

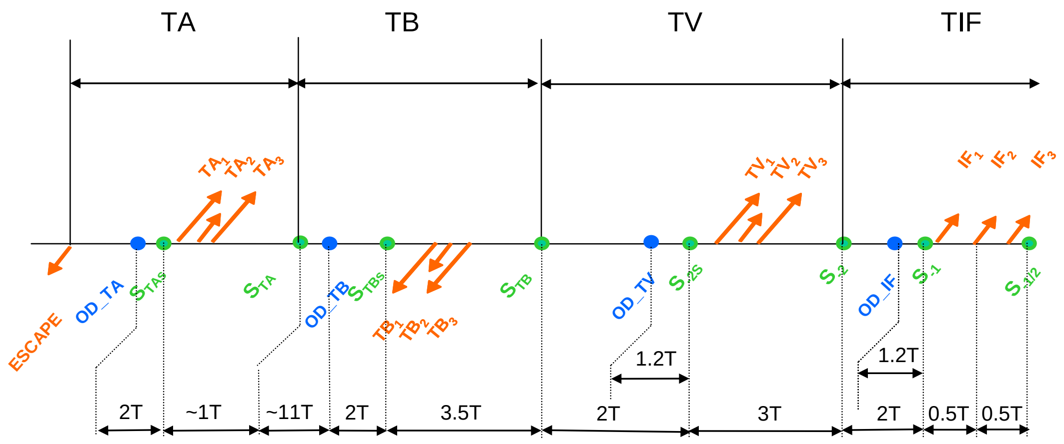


Figure 13. Post Escape recovery strategy

The results shows that the IF maneuvers are executed nominally below their limits, $S_{-1/2}$ is acquired within the maximum dispersions limits, and the ISS safety is not compromised.

4. ATV deorbitation strategy design

4.1. ATV deorbitation strategy basis

The purpose of the deorbitation is to make the ATV enter the atmosphere in order to fall into the ocean without any risk of damages for population and properties. Furthermore, it must be then guaranteed that, for each mission configuration, it is always possible to reach an impact zone with an adequate level of confidence. The ATV deorbitation phase begins nominally after the undocking from the ISS, as soon as the ATV has left ISS Approach Ellipsoid.

The GSMA document covers this phase, describing the strategy that facilitates to reach the impact point from a various range of altitudes and phasing with respect to the entry point.

The selected impact zone for ATV reentry is the South Pacific Ocean Uninhabited Area (SPOUA) which is bordered by the 175W and the 85W meridians and by the 29S and 60S parallels. This is the biggest uninhabited area in the world without emerged land.

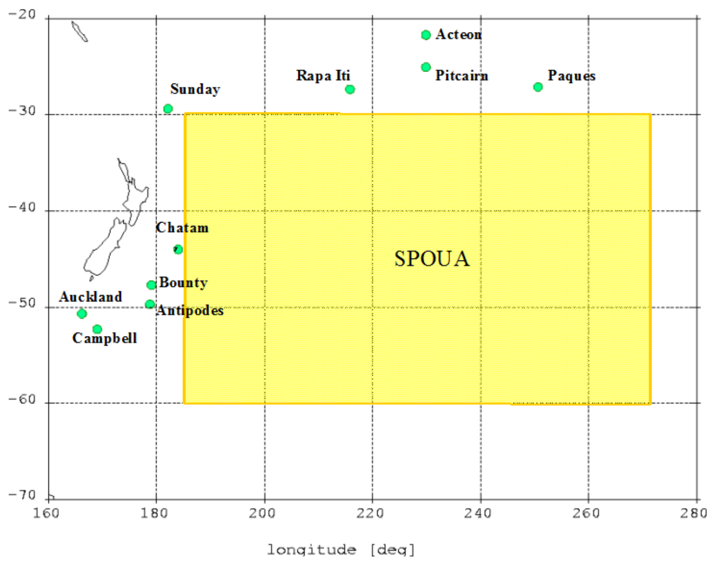


Figure 14. South Pacific Ocean Uninhabited Area (SPOUA)

In order to transfer the ATV from an orbital point to a ground point in the SPOUA by decreasing its perigee altitude a strategy with two deorbitation maneuvers have been selected. As it is shown in Figure 15, the first deorbitation manoeuver (DEO1) will have two objectives: 1) to transfer the ATV from a circular orbit to an elliptical orbit with the required apsides line orientation (phasing with the entry point), 2) to decrease the perigee altitude until 220km. The second deorbitation manoeuver (DEO2) is located at the apogee of the intermediary orbit and decreases again the perigee altitude from 220 km to 0km (nominally), forcing the ATV re-entry in the Earth atmosphere.

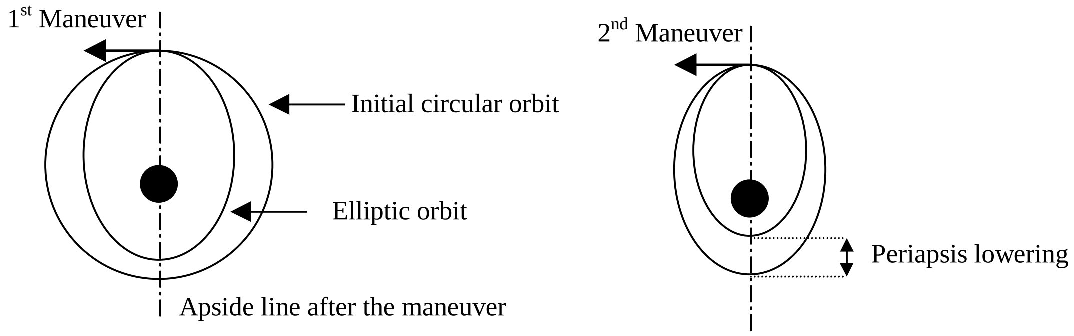


Figure 15. Deorbitation maneuvers principles

4.2. GSMA deorbitation strategy

A generic ATV deorbitation scenario is able to assure ground safety within the following flight domain:

- ISS mean altitude at undocking between 300 km and 460 km
- 1 Departure maneuver (DEP) of -5m/s with ACS ESCAPE thrusters 1 minute after undocking from the ISS
- Nominal reentry about 24h after undocking
- 2 OCS tangential & retrograde maneuvers (DEO1, DEO2) targeting the reentry arc as follows:
    - Apogee approximately at ISS altitude (after Departure maneuver and ~24h free-drift)
    - Perigee nominally at 0km (or -70km if high percentage of ergol filling in the tanks)

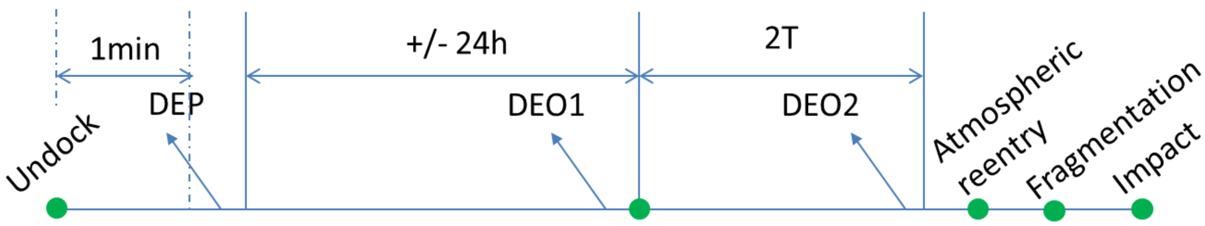


Figure 16. ATV deorbitation generic stratey

4.3. ATV reentry trajectory and safety analysis

After the final deorbitation boost, the ATV will begin its descent trajectory. As soon as the last maneuver has been completed, the attitude of the vehicle switches to a tumbling motion in order to cancel the eventual aerodynamic lift force in the highest layers of the atmosphere. The atmospheric interface at 120 km altitude is reached about 18 min after the end of the last boost. However, the ATV is not designed to undergo a re-entry and, as soon as the aerothermal conditions will become severe, a natural destruction process will begin. The possible explosion of the ATV may generate instantaneously several thousands of debris, but only the sizing debris will be extrapolated until impact.

The AIP (Aimed Impact Point for the mean fragment) is located in the South Pacific Ocean. However, due to the fragmentation phenomenon, the debris will impact the Earth surface at different points, generating an impact footprint. Therefore, the method will be to target with a theoretical trajectory of a single “mean fragment” the AIP, and then demonstrate that the corresponding impact footprint still lay within the SPOUA.

Statistics methods will establish the Safety Reentry Area (SRA), which is the area surrounding the footprint that corresponds to a 10^{-5} probability of debris impact outside of the area (see document [10]). Monte-Carlo simulations allow to demonstrate that the SRA lays within the SPOUA for the GSMA strategy, for the following initial ATV conditions:

- ISS invariant altitude from 300 km to 460 km
- Nominal reentry about 24h after undocking

In summary, the mission analysis for deorbitation and reentry for a spacecraft as the ATV requires to:

- To have tools able to the perform Monte-Carlo simulations for deorbitation and reentry taking into account the fragmentation of the vehicle
- To cover on the expected range of values of all the input parameters necessary for mission analysis computations
- To use representative uncertainties and dispersions for the input parameters
- To simulate GNC system modes in deorbitation and reentry
- To have precise models for fragmentation & explosion phenomena
- To be able to target with the ATV a given impact point
- To respect the safety requirements for controlled reentry operations

4.4. FDS Mission Analysis Tools for deorbitation and reentry

The deorbitation strategies are computed by the FDS operational tool T-DEM (see document [3]), and by DOORS, an internal mission analysis tool.

To perform global tasks of mission analysis for deorbitation phase, the FDS takes as inputs the altitude of fragmentation, the model of fragmentation and the deorbitation strategy. The tool ELECTRA (internal) simulates the fragments trajectories and performs dispersions of the reentry trajectory, as it is described in previous publication [8].

4.5. Former missions deorbitation scenarios

The experience on the past ATV missions is that, with the exception of ATV2 mission, each deorbitation scenario required modifications and complementary studies to be demonstrated before execution. In spite of the fact that the two deorbitation maneuvers scheme has never been altered, other changes and additional requirements to the reentry trajectory had to be taken into account rapidly by the flight dynamics team:

- ATV1 Jules Verne reentry was chosen to perform an experience of observation of ATV from the ISS. This experience had to be performed at the orbital night, with both ISS and ATV vehicles phased at the exact time of the atmospheric reentry of the ATV, implying a completely new “re-phasing” strategy design, along with a new target point definition for re-phasing and a new opportunity for reentry computation method.

- ATV2 was a fully generic deorbitation with DEO maneuvers executed 24h after undocking.
- A stop during ATV3 undocking negative chronology caused the postponement of the undocking, and as a result of that and for safety reasons the ATV had to enter in a free-drift phase of 4 days between separation with the ISS and starting the deorbitation sequence.
- During the ATV4 reentry, a new optical experience was performed, with a trajectory reentry also phased with the ISS at the orbital night. In this case, several modifications were introduced with respect to the ATV1 mission re-phasing strategy, the interface point definition ($S_{-1/2}$_REEN) and the opportunities computation.

4.6. Former missions re-phasing strategies

The re-phasing strategy will be needed if the ATV has to be used to perform optical observations of the vehicle reentry from the ISS, as it was the case of the ATV1 and the ATV4 missions. As no generic analysis deals with the re-phasing strategy as such, specific analysis must be developed case by case by the FDS team and particularly by the TRA operators prior to the operational execution of the strategy.

The problem here consists of re-phasing the ATV to exactly re-enter the Earth atmosphere (around 110-120 km of geodetic altitude) within the cone of observation of the optical instrument on-board the ISS. In order to do that, three aspects must be solved: a) define the target point that leads the ATV in the cone at the right time (S-1/2_REEN), b) evaluate the maximum dispersions at arrival of the interface point S-1/2_REEN, and c) design the maneuver strategy facilitating to achieve the previous two conditions. All of this must be done with the maximum re-use of operational products and previous mission analysis studies.

The solution to all this has been to re-use phasing GSMA phasing generic strategies in the frame of a descending re-phasing. Symmetric solutions to the ascending phase can be found building strategies with retrograde tangential maneuvers. TP maneuvers to transfer to the necessary drift orbit, MC maneuvers to cope with free-drift dispersions during the drift phasing orbit, several TV maneuver cycles to cope progressively with dispersions and reducing them gradually while approaching the interface point. The following table serves to compare the ascending phase maneuvers and the descending phase re-phasing maneuvers of ATV4 mission. The symmetries are evident.

	Tangential component of the maneuvers (m/s)										
	TP1	TP2	MC11	MC12	TV11	TV12	TV21	TV22	TV31	TV33	IF3
ATV4 Phasing	11.2	11.1	1.6	1.6	21.7	22.2	6	6	3	3	1.2
ATV4 Rephasing	-11.7	-11.7	-1.5	-1.5			-14.8	-14.7	-3	-3	

Table 4. ATV4 re-phasing maneuvers vs. phasing maneuvers

The ATV1 re-phasing took place between the 5th September and the 29th September 2008. It was a long strategy (about 23 days) during which each T-ORM computation was performed with the same targeted state vector J2000 coordinates, the targeting time was tuned to compensate for ISS trajectory variations.

The ATV4 re-phasing duration was shorter, taking approximately 5 days to go from the undocking date, the 28th October, until the interface point, which took place the 2nd November 2013. Equally to Jules Verne mission, T-ORM computations were performed with the same targeted state vector all along, but on this time T-ORM was used in 3D mode instead of 2D, being able to correct simultaneously in-plane and out-of-plane dispersions.

Figure 17. ATV1 and ATV4 re-phasing profiles

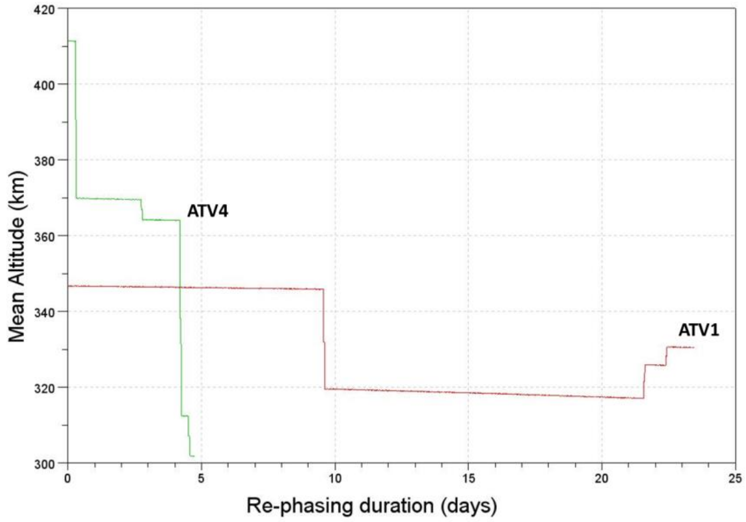


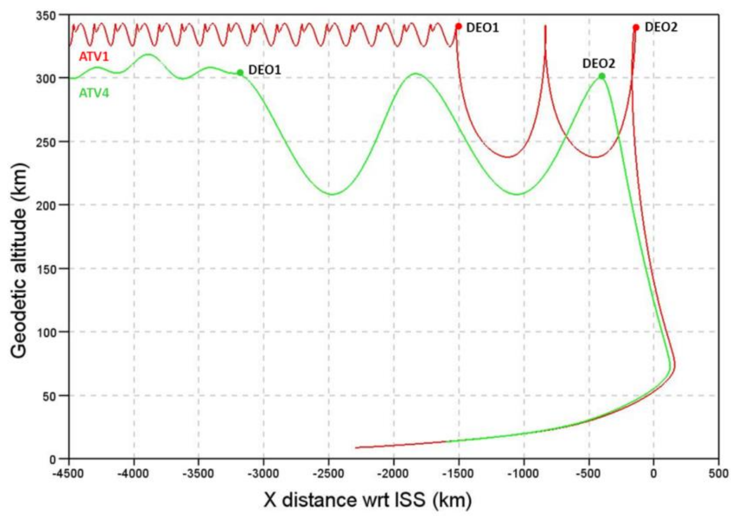
Table 5. ATV1 and ATV4 re-phasing strategy maneuvers

	Rephasing DV (m/s) per cycle			
	ATV1		ATV4	
Cycle	1st Man	2nd Man	1st Man	2nd Man
TP (or TR)	-7.9	-7.1	-11.7	-11.7
MC1	0.0	0.0	-1.5	-1.5
MC2	0.0	0.0		
TV1 (or TV)	2.5	2.5	-14.8	-14.7
TV2 (or IF)	1.4	1.4	-3	-3

4.7. Former reentry observation experiences

Concerning the ATV1 observation, previous publication [7] explains clearly the objectives of that experience: a) detection of explosion events (if any), b) estimation of altitude of main break-up events (explosion or fragmentation) with accuracy better than 5 km and c) analysis of trajectories, size, temperature and materials of the fragments.

Figure 18. ATV1 and ATV4 phased reentry trajectories



During this mission, TRA position at the ATV-CC established the essential procedures to build the target point from which the ATV shall start the deorbitation phase towards a phased reentry trajectory laying within the observation cone. This mission analysis work was performed during ATV Jules Verne attached phase, as the necessary inputs and project decision did not rise early in the mission.

The results of the ATV1 reentry campaign were fully satisfactory and they are available in the paper [7]. Figure 18 gives the reentry trajectory of ATV1 as seen from the ISS frame (red color).

The ATV4 observation (green color, Figure 18) pursued equivalent objectives to the ATV1 experience, with the following exceptions:

- ISS altitude is higher for ATV4, at around 415 km, than for ATV1 at 350 km.
- The apogee altitude of the reentry arc of ATV4 was 300 km, while for ATV1 it was around 330 km.
- The targeted perigee altitude of the reentry arc of ATV4 was -70 km, while for ATV1 it was 0 km.

An iterative procedure with T-DEM was developed to compute the targeted state-vector at S-1/2_REEN. The interpolation condition is to have the altitudes of interest [75 km – 120 km] within a cone with a Field of View (FoV) of +/- 35° underneath the ISS (towards Z_LVLH). Figure 19 and Figure 20 shows ATV4 results for ATV4 experience preparation.

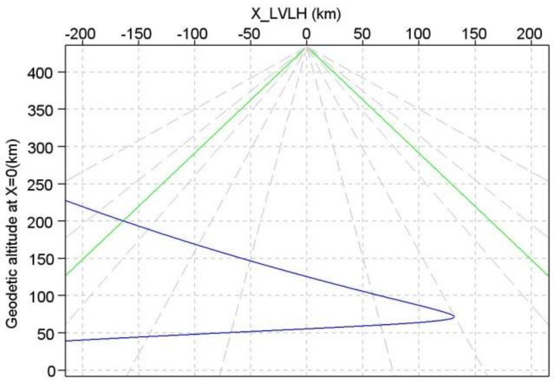


Figure 19. ATV4 reentry trajectory in X,Z plane within the observation cone of the ISS

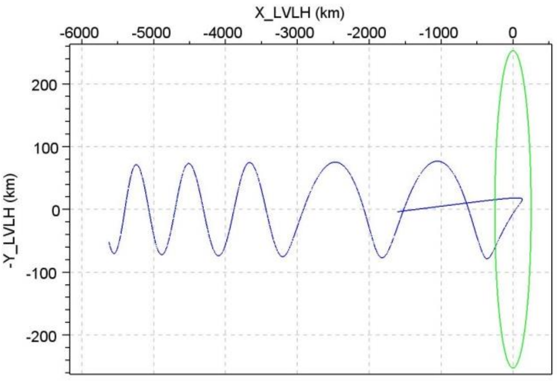


Figure 20. ATV4 reentry trajectory in X,Y plane within the observation cone of the ISS

The reason to lower to 300 km the apogee of the reentry arc in ATV4 was that the trajectory of interest today is the ISS deorbitation profile, also denominated “shallow reentry”, in reference to the small pitch angle at which the vehicle shall enter the atmosphere. No lower altitudes were covered by the generic mission analysis documents at that time.

A targeted perigee altitude of 0 km was proposed, but due to an overloading of propellant at undocking the perigee altitude had to be reduced to -70 km to ensure the safety requirements. It is important to say that all the ATV4 re-phased reentry planning had to be set up in less than 2 months prior to undocking, it was a clear demonstration on how fast must be the mission analysis work carried out. As a result of this experience, ATV fragmentation over a black pacific ocean was followed from the altitude of the ISS, obtaining much data on ATV reentry trajectory main events, and pictures as the one hereafter.

Figure 21. ATV4 reentry over the nocturne Pacific Ocean (picture taken from the ISS)

4.8. Former missions deorbitation strategies

The following Table 6 provides some figures of the past ATV deorbitation strategies.

Mission:	ATV1	ATV2	ATV3	ATV4
Deorbitation type	Phased	GSMA	GSMA Delayed	Phased
Ergols tanks filling	< 10%	< 10%	< 10%	> 10%
Duration	1 day	2 day	4 days	5h
ISS altitude (km)	351	395	408	417
Reentry orbit:				
Perigee alt	0	0	0	-70
Reentry path	-1.45	-1.65	-1.71	-1.63
DEO1 ΔV (m/s)	29.85	47.14	60.71	26.98
DEO2 ΔV (m/s)	70.2	66.93	66.73	88.4

Table 6. Past ATV missions deorbitation characteristics

4.9. ATV5 deorbitation strategy baseline

The actual working date for ATV5 undocking is January 2015. ATV5 Georges Lemaitre deorbitation baseline for a shallow reentry has not yet been established and whether it will be issue of an observation experience concerning ATV and ISS vehicles is still under discussion due to the unfavorable illumination condition in the south hemisphere during end of January. If the choice of a new observation is made, several new conditions will be considered and it is foreseen that they will be of great impact concerning the mission analysis domain. Targeting a phased observation of a “shallow reentry arc” requires:

- Modification of the operational baseline agreed with partners.
- New specific analysis for the re-phasing strategy.
- Renewal of the existent generic mission analysis for deorbitation.
- New products (including TC commands) to be made by other teams in ATV-CC.

5. Conclusion

The ATV-CC teams have successfully conducted ATV operations and mission analysis achieving the following results:

- A strategy design with the greatest flexibility towards launch, docking, undocking and reentry scheduling, even simultaneous flights with other visiting vehicles could be supported (Progress, Dragon and Cygnus).
- A system of generic mission analysis broad enough to cover the most number of possible strategies without any changes or with reduced modifications.
- An organization capable of realizing specific mission analysis in parallel to the mission campaigns of qualification and operations.

6. Acknowledgments

This publication would have not been possible without the collaboration of the actual and former members of the TRA, FDTL and ESA flight dynamics teams of the ATV-CC, that

have dedicated their work to accomplish the duty of the strategy design of ATV missions along the last decade.

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