STUDIES ABOUT A SHALLOW RE-ENTRY FOR ATV-5

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***Abstract** : For last Automated Transfer Vehicle (ATV), ATV-5* "Georges Lemaitre", *NASA, in the frame of International Space Station (ISS) program, requested the ATV Control Center (ATV-CC) to perform an experimental reentry observation to characterize the ISS reentry environment and fragmentation models prior to the ISS end of life. Therefore, to be as close as possible to the ISS re-entry conditions, ATV-CC had to change the ATV "steep" re-entry strategy, applied to the previous ATVs, into a new ATV "shallow" re-entry strategy. The paper will present the methodology followed and the studies performed to design an acceptable (science and safety wise) "shallow" re-entry strategy for ATV-5, focusing on the particularities of this kind of re-entry on the deorbitation and phasing phases.*

***Keywords:** ATV, Deorbitation, Impact footprint, Mission analysis, Maneuvers design.*

1. Introduction

After five successful missions, the Automated Transfer Vehicle (ATV) program ended last February with the safe ATV-5 "Georges Lemaitre" re-entry in the South Pacific Ocean in an uninhabited area. The role of the ATV was to provide supplies to International Space Station (ISS) with propellant, water, gas, dry cargo and to remove ISS waste. ISS cargo and liquid waste was destroyed during the atmospheric re-entry, as the vehicle itself. ATV provided also a propulsive support to ISS for attitude control, re-boost and debris avoidance. ATV was a project funded by ESA and the spacecraft was developed by AIRBUS-DS as prime contractor. CNES has developed the ATV Control Centre (ATV-CC) under ESA contract and has been responsible for the operations of the five ATV missions. The CNES team of the Flight Dynamics Sub-system (FDS) of ATV-CC, which is in charge of the System Mission Analysis (SMA), issued Generic SMA (GSMA) documents and designed the flight dynamics operations of the various phases of a regular ATV mission.

The ATV-5 re-entry was performed according to the principles of the deorbitation documented in GSMA: one minute after the separation with the ISS, a departure maneuver took away the ATV from ISS and, after 24 hours of free-flight, the deorbitation was performed by means of two deorbitation maneuvers lowering the perigee to the geocentric altitude of -70km. This kind of deorbitation can be described as "steep" because of the re-entry path angle in the dense layer of the atmosphere.

But this "steep" reentry profile differs from the initially planned scenario for the ATV-5 re-entry. Indeed in 2013, NASA ISS program requested the ATV Control Center (ATV-CC) to perform with the ATV-5 an experimental reentry observation to characterize the ISS reentry environment and fragmentation models prior to the ISS end of life. Therefore, to be as close as possible to the ISS re-entry conditions, ATV-CC had to change the generic ATV "steep" re-entry strategy into a new ATV "shallow" re-entry strategy.

Another new feature of the ATV-5 "shallow" re-entry was the attitude after the last deorbitation maneuver. For all of the four previous ATV missions, the vehicle was put in a tumbling attitude (10deg/s pitch rate). But, in order to improve the observation of aerothermodynamics phenomenon expected in an ATV and ISS "shallow" reentry, a fixed orbital Earth Pointing attitude was initially planned to be achieved after the completion of last deorbitation maneuver and to be held down to 125km geodetic altitude.
It was also planned to move the solar arrays in "knife" position in order to reduce aerodynamics force perturbation.
Because of that, some of the hypotheses, in particular those concerning the fragmentation, taken for the ATV deorbitation GSMA are no longer valid and new studies had to be performed in order to define new hypotheses for the assessment of shallow re-rentry footprint.
Furthermore, the fragmentation had also to be observable from the ISS, as it was done for ATV-4 and ATV-1, but the constraints on the phasing precision are not the same.
Many studies and iterations with NASA were performed to design a "shallow" re-entry strategy for ATV-5 acceptable with regards to the observation objectives and the safety. Indeed, the ATV had to be safe with regards to the ground population casualty risk: the probability that a debris, resulting of the ATV fragmentation during atmospheric re-entry, impacts dry lands and territorial waters had to be lower than 10^{-5}.

To define a whole scenario of "shallow" re-entry we had also to take into account the constraints on the dates of the undocking imposed by the ISS visiting vehicles traffic and of the re-entry induced by the ATV reentry observation experiments.
Another constraint linked to the safety of ground population was the maximum mass of propellant remaining in ATV tanks in order to limit the energy of a potential explosion during fragmentation and then the dispersion of the resulting fragments.
The manoeuver strategy had also to deal with the operating constraints of the three on-board recorders provided by international partners to characterize the ATV break-up: the NASA Reentry Break-up Recorder (REBR), the JAXA re-entry data recorder i-Ball and the ESA Break Up Camera BUC.

The scenario is divided in four successive phases as schematized in Fig. 1. The first one is the departure of the ISS which ends with the transfer to the parking point 2000km ahead the ISS. Then there is a phase of station keeping during which the extra propellant is burn, followed by the 48 hours phasing period and finally the deorbitation and re-entry phase. The scenario planned also branching on a "steep" deorbitation scenario in case of contingencies.

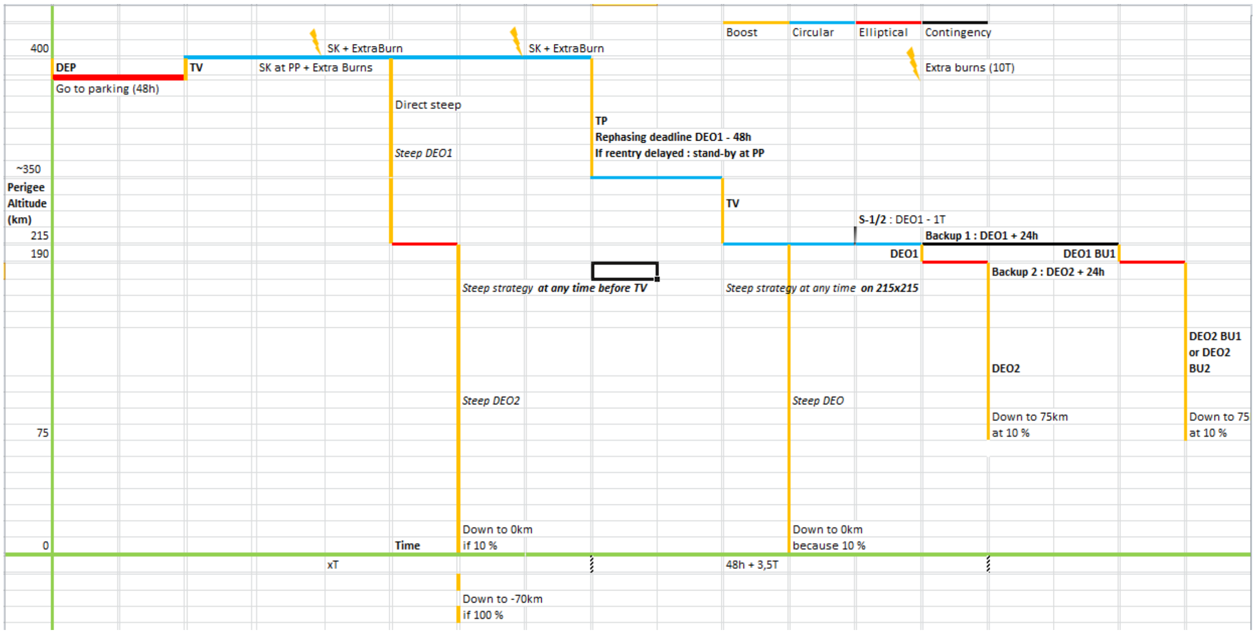

Figure 1: Shallow re-entry scenario

The paper will focus on the design of the last deorbitation and re-entry highlighting the differences with the GSMA hypotheses and results.

The first section presents the final specifications of the shallow reentry impacting the mission analysis. The various iterations between ATV-CC and NASA which led to these requirements are not described and can be found in [1].

The second section addresses the design of the deorbitation and re-entry phase. It details in a first part how ATV-CC defined the re-entry arc taking into account both experiments' objective and safety constraints with a focus on the new hypothesis concerning the fragmentation of ATV and on the verification of the compliance to the ground population safety requirements. The second part of this section gives a synthesis of the deorbitation phase: trajectory and impact footprint. The last part is about the opportunities of the re-entry constrained by the need to have a final ATV ground track covered by ground observation assets in Australia and New Zealand.

The third section is dedicated to the phasing with the ISS focusing on the particularities of the ATV-5 phasing. More details of re-entry phasing principle can be found in [2].

The last section addresses the subject of the extra propellant burning during the parking phase.

2. Specification of the shallow re-entry

The requirements for the shallow re-entry agreed with NASA were the following:

- The initial orbit before last deorbitation boost is a 190x215km geodetic altitude orbit.
- Targeted perigee after the last deorbitation boost is at 75km geodetic altitude and apogee at 190km geodetic altitude
- The Longitude of Ascending Node (LAN) of the ATV re-entry arc lies between 44 and 57.29 degree West to allow the observation by ground system assets in Australia and New-Zealand.

- The deorbitation is performed by two maneuvers and in between the spacecraft shall fly for at least two orbits in free drift.
- The visibility shall be guaranteed from ISS after last deorbitation boost at 110km geodetic altitude taking into account 3 sigma dispersions on the trajectory model.
- ISS instrument for observation is pointing towards the Nadir with a ± 5 degrees conic field of view.
- Minimum phasing duration is 4 days and 3 orbits.
- In case the re-entry is delayed, a strategy shall exist to allow rephasing with the station in 4 days minimum. The decision to postpone the re-entry shall be taken before the deorbitation boosts.
- Due to the REBR triggering strategy, last deorbitation maneuver shall be longer than 450s and the maneuvers before last deorbitation boost shall be shorter than 395s
- The maximum time allowed between activation of the REBR (resp. i-Ball) power systems and the end of battery life is 22 days (resp. 15 days).
- Shallow re-entry shall be performed only if the remaining propellant loading is lower than 774kg after last deorbitation boost
- The attitude after last deorbitation boost is different from the nominal tumbling attitude :
  ATV will target an Earth Pointing attitude after last deorbitation boost, with the solar arrays in “knife” position (no cross track area). This attitude shall be hold down to 125km geodetic altitude.

These requirements about the strategy of final deorbitation phase (orbit characteristics, number of maneuvers) are a compromise between the initial NASA requests, the ATV-CC constraints and the results of CNES mission analysis studies. Indeed, in addition to the experimentation constraints, several other constraints, common to all the ATV, are to be taken into account for the design of the re-entry: they are constraints intrinsic to the vehicle, to the ground population safety and to operations.

3. Deorbitation phase

To guaranty the visibility from ISS of the ATV when it crosses the geodetic altitude of 110km, it was decided to place, by phasing maneuvers, the ATV-5 in a circular orbit before the deorbitation maneuvers, like-wise the ATV-4.

The first task was then to define the altitude of the deorbitation rendez-vous point. To be compliant with the request to have an ATV-5 re-entry representative of the ISS re-entry, the altitude of this “deorbitation orbit” has to be as low as possible but compliant with the constraints of lifetime on the orbit, minimum altitude for ATV maneuverability and nominal boost dispersions. The initial requirement of the NASA was to have a re-entry arc with apogee at 160km and perigee at 70km altitude or higher, incompatible with this constraints.

The second step was to determine the highest targeted ATV orbit perigee after the last deorbitation boost ensuring a safe reentry with regard to the ground population. Several studies were needed to acquire enough confidence in the result. When the targeted perigee and the other reentry parameters were fixed, the accurate rendez-vous point could be computed according to observation constraints.

3.1. Altitude of the deorbitation rendez-vous

To assess the minimum initial altitude, the lifetime on a circular orbit at different mean altitude was studied. The solar activity taken into account was based on the predictions of the Marshall Space Flight Center's Solar Activity Site [3] for the planned re-entry dates.

The constraints, explained on the Fig. 2, were the following:

C1 : the orbit before reentry must be such as the mean altitude is higher than 180 km

C2 : in case of contingency before last deorbitation boost, the ATV shall be able to remain 24h free drift at mean altitudes higher than 180 Km.

C3 : the mean altitude after previous boost (circularization boost) must remain above 180 km in any cases of dispersions.

The constraint C1 means the circularization boost shall put the ATV on an orbit high enough in order to prevent the altitude decay during this possible drift. The study concluded that the ATV shall not be lower than a 205x205km orbit just after the circularization boost. Considering a dispersion of 5% on the circularization boost, the constraints C3 implies to take a 10 km margin on the target altitude.

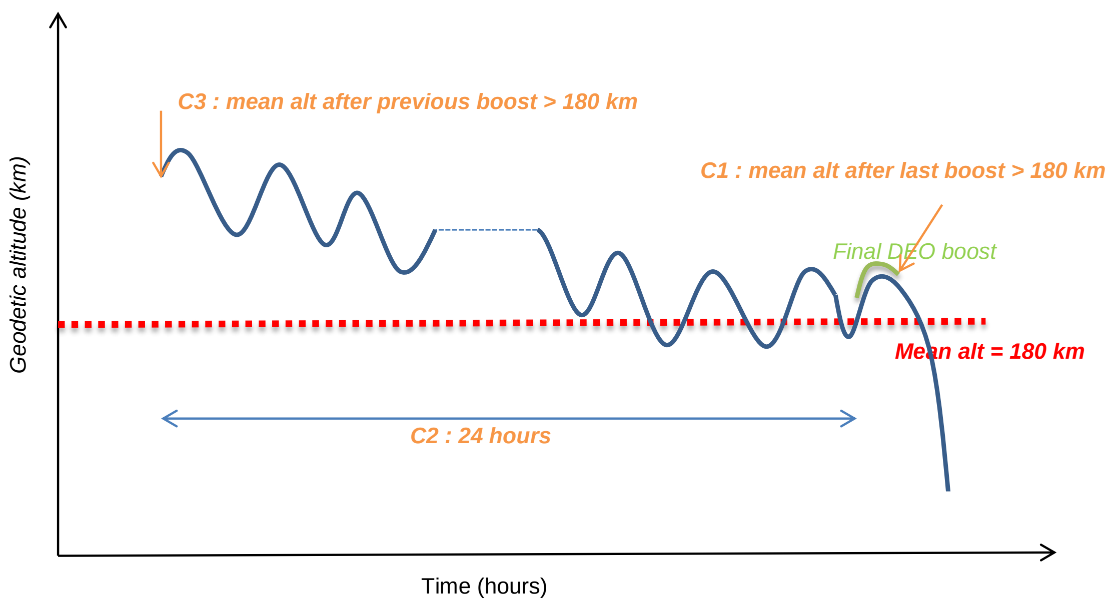

Figure 2. Constraints to define the deorbitation orbit altitude

Then the deorbitation rendez-vous point shall be on a 215x215km orbit.

A deorbitation with a single boost from this orbit with a safe targeted perigee doesn't allow obtaining duration for the exposition of the spacecraft to the re-entry environment on the key-heating region, close enough to the duration of the future ISS re-entry (730s).

The deorbitation has to be performed with two maneuvers: a first boost to lower the perigee to 190km and the second boost around the perigee for the re-entry to fix the apogee of re-entry arc at 190km of altitude. For the previous ATV, according to GSMA, the deorbitation boosts were always around apogee and we needed to adapt the tool T-DEM, used by the FDS to compute deorbitation strategies, to cope with this new feature.

3.2. Altitude of the targeted perigee

Like the apogee of 160km requested by the NASA was not possible, NASA requested a perigee at 75 km of geodetic altitude to meet the science objective.
Studies were performed to analyze the NASA request with regard to the impact footprints taking into account dispersions at the level of the vehicle (boost, altitude of fragmentation, mass) and at the level of the environment (solar activity, dispersion of the atmospheric density).

To compute the deorbitation strategy two parameters are fixed:
- an Aimed Impact Point (AIP), chosen to place the impact footprint inside the South Pacific Ocean Uninhabited Area (SPOUA),
- the perigee after the last deorbitation boost defined in geocentric altitude.

The SPOUA is located between New Zealand and Chili at the South of the Easter Island. It is bordered by the 185 deg. East and the 275 deg. East meridians and by the 29 deg. South and the 60 deg. South parallels.

GSMA plans an AIP at fixed longitude, but this implies an AIP moving in latitude in function of the day in re-entry and then a size of impact footprint and a geodetic altitude of targeted perigee depending of the day of the re-entry. For that reason, it was decided for ATV-5, to target an AIP at fixed latitude of 50.5 degrees South on an ascending ground track in order to have an impact footprint of the same size and the same geodetic perigee altitude of re-entry arc, for any day of re-entry (the re-entry and the impact footprint are simply translated in longitude).
To take into account safety with regard to the impact footprint, two kinds of boxes were defined for ATV with different probabilities to have a surviving fragment impacting outside the box: Declared Re-entry Area (DRA) for the probability of 10^{-2} and the Safety Re-entry Area (SRA) for the probability of 10^{-5}. The DRA is used to elaborate the NOTAM (cf 3.3.3) and the SRA is computed to determine if the targeted perigee is acceptable with regard to the safety. The SRA shall not cover totally or partly dry land or territorial waters.
The main sizing parameters of the SRA are the altitude of the targeted perigee (the higher is the altitude, the longer is the footprint) and the vehicle attitude and the position of solar arrays after the last deorbitation boost because of their effect on the fragmentation.

3.2.1. Altitude of fragmentation

For the previous ATV, a fragmentation altitude and the surviving sizing fragments were determined for the deorbitation GSMA, with the assumption that ATV orientation is tumbling (forced pitch rate of 10 Deg/s) after the last deorbitation boost and the targeted perigee is 0 km or -70km depending on the remaining propellant in the ATV tanks after the last deorbitation boost.
To study the ATV behavior from a fragmentation point of view, HTG (Hyperscall Technologie Göttingen) performed, under ESA contract, some simulations using SCARAB (SpaceCraft Atmospheric Re-entry and Aerothermal Break-up) tool. The simulations specific for the ATV5 shallow reentry had some assumptions different from previous SCARAB simulations for the generic ATV reentry: the attitude after last deorbitation boost (tumbling or EP), solar arrays position (canonical or “knife”), spacecraft mass (12t, 15t and 16t), solar activity and of course the targeted perigee altitude.
With regard to the results of these simulations, the GSMA fragmentation hypotheses for the generic steep reentry are not usable for the shallow re-entry. The Earth Pointing (EP) with the probe in the velocity direction modifies the occurrence of explosion because the ATV propulsion

bay, which is on the opposite side, is somehow protected from a large part of a heat flux at the beginning of the re-entry. Furthermore, the “knife” position of the solar arrays reduce the drag force and then extend the duration of the entire vehicle flight inside the dense layer of atmosphere (bellow 120km). After the assessment of the ATV-1 reentry observation data, the “explosion event” in SCARAB simulations of ATV fragmentation is associated to the complete separation of the propulsion bay from the main body of the spacecraft.
Figure 3 gives the synthesis of the simulation results binding the altitude of ATV explosion with the geodetic targeted perigee.

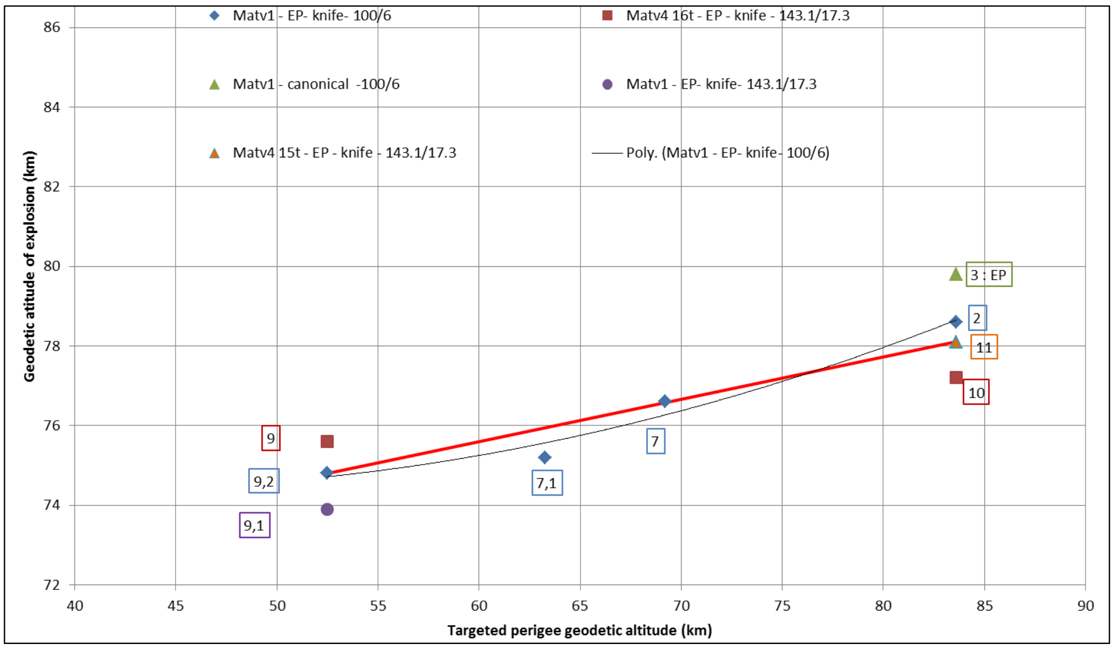

Figure 3. Altitude of explosion

HTG simulations assumptions were very different from one to another so all of them were not applicable to our study. But if we consider cases with EP attitude, “knife” position of solar arrays and solar activity close to the expected one, a trend can be extracted from the chart of Fig. 3. A rough law of dependency of explosion altitude on targeted perigee is given by the “black curve” approximated by the linear “red curve”. Then, for the shallow re-entry with a targeted perigee at 75km of geodetic altitude, the fragmentation altitude is considered equal to 77km (instead of the 75km used in GSMA). The 1σ gaussian dispersion of ±2km used in the GSMA is still considered applicable to the shallow re-entry.

3.2.2. Sizing fragments

Another point to be assessed is the list of surviving fragments that are sizing the SRA dimension and location. At the time of ATV-1 reentry analysis, the surviving fragments were issued from a CNES model called SEDIA and three sizing fragments for the SRA and DRA were selected among them, sizing in the sense that they were contributing to the heel and the toe of the footprint. The SEDIA fragments list is not modified by the shallow reentry and considered still applicable to ATV5 shallow re-entry, but some computations with all the SEDIA fragments showed that for shallow re-entry we have to consider six fragments for SRA sizing, three more than for GSMA.

The characteristics of the fragments are given on the Tab. 1. The fragments sizing the short point of the SRA ("heel" point) are highlighted in blue and the long point ("toe" point) in brown. The additional fragments to be considered for the shallow re-entry are shown in red.

Fragment Number	Mass (kg)	DeltaV (m/s)	Ballistic coefficient (kg/m²)	
			min	max
1	30	22	55	66
2	470	1	3952	5512
3	60	26	2	5
4	3	33	3	6
5	**5**	**26**	**5**	**10**
6	**109**	**5**	**1538**	**2456**
7	5	18	213	284
8	25	54	198	262
9	123	40	227	272
10	36	27	45	89
11	461	14	45	85
12	13	17	31	64
13	96	15	71	122
14	11	8	48	97
15	121	21	35	66
16	12	30	27	56
17	**607**	**28**	**156**	**244**
18	20	26	39	81
19	91	38	18	34
20	10	67	15	30

Table 1: Characteristics of SEDIA fragments

3.2.3. SRA

Estimation of the size of the SRA requires a statistical analysis. The aim is to provide the ground area limits, which assure that outside these borders the probability of a debris impact is less than 10^{-5}.

A 20 000 cases Monte-Carlo was performed with the tool ELECTRA [4] (tool developed by CNES in the framework of the French Space Operations Act) on the trajectory taking into account nominal dispersions on various parameters like the propulsion, the atmospheric density, the vehicle mass, the fragmentation altitude or the ballistic coefficient of debris.

For each one of the 20 000 computations, the fragment which goes the further ahead and the one that goes the furthest behind are selected and the distance from AIP is computed. Then a Generalized Pareto Distribution (GPD) law is fitted on the distribution of the "heel" points and on the distribution of the "toe" points for different thresholds to evaluate the quantiles (distances from the AIP in our case) associated to a given probability level. The fitting is considered acceptable when the quantile is stable with respect to the threshold. A Generalized Pareto Distribution (GPD) statistical law is used because our concern is the estimation of the distribution tail (low density regions). The details of the method to determine the SRA size can be found in [5].

We can see the result of the GPD law fitting in the case of the targeted perigee at 75km of geodetic altitude on the Fig. 4.

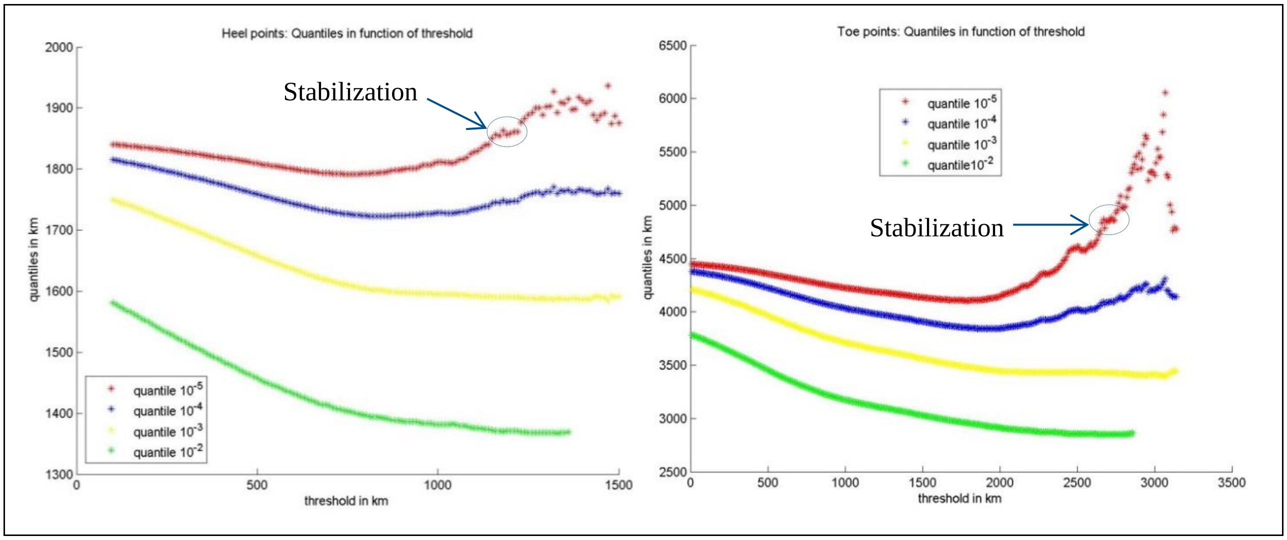

Figure 4: Fitting of the GPD law for the west limit trajectory

When the threshold is too high, there are not enough points to have a reliable estimation. That explains the shape of the curve for high thresholds. The size of the SRA is given by the red curve (quantile 10^{-5}). According to this fitting, the SRA is 6710 km long with a “heel” point distance from AIP of 1860 km and a “toe” distance of 4850km.

The impact ground track computed by ELECTRA and the corresponding SRA outline (in red) are shown on Fig.5, as well as the SPOUA outline (in green), for the limit west and east of the re-entry arc LAN and for a middle case. The diamond represents islands. We can see that the SRA goes outside the north of the SPOUA but without cover dry lands and that the size of the SRA doesn’t depend of the LAN of the re-entry arc. The west limit of the LAN was defined to protect the Easter Island.

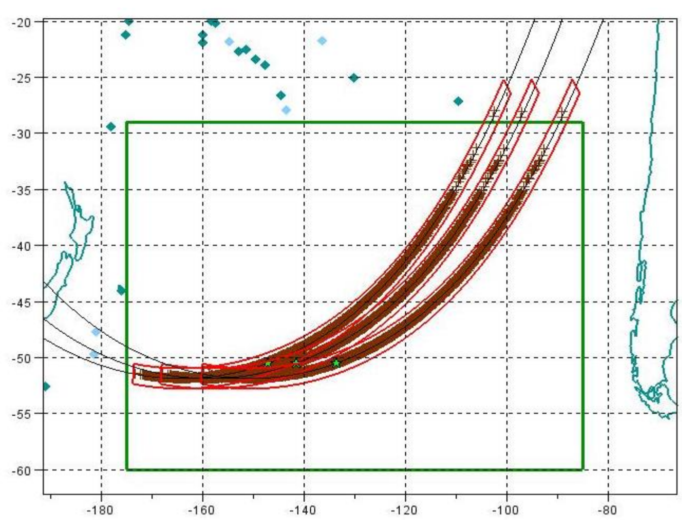

Figure 5: Impact ground track and SRA

3.2.4. Sensitivity analysis

To consolidate robustness of the safety compliance of ATV shallow reentry at a targeted perigee of 75km geodetic altitude, the CNES conducted sensitivity analysis to assess the effects of some uncertainties of the models and of the behavior of the vehicle during re-entry. The following parameters were examined with regard to their effect on the SRA for targeted perigees between 50km and 75km of geocentric altitude: atmospheric data (atmospheric model, solar activity, atmosphere density), fragmentation data (fragmentation altitude, fragments characteristics). For all these parameters, the evolution of the SRA size is smooth up to a targeted perigee of 70km of geocentric altitude and even if the hypotheses are modified, the SRA doesn't cover dry land. As, for the chosen AIP (latitude of 50.5 degrees south on an ascending ground track), a targeted perigee at 75km of geodetic altitude is equivalent to a targeted perigee at 66.5km of geocentric altitude, ATV-CC could positively answer to the request of NASA while guaranteeing the safety of the ground population.

3.3. Synthesis of the deorbitation strategy

3.3.1. Principles

Finally, the following strategy to compute manoeuvers and trajectories was proposed by the ATV-CC and agreed by NASA:

- The ATV is deorbited from a circular orbit at 215km of altitude,
- A first deorbitation manoeuver (DEO1) lowers the perigee to 190km to obtain a 215x190 km elliptic orbit,
- A second manoeuver (DEO2) around the perigee, lowers the apogee to 75km of geodetic altitude to place the ATV on a 190x75km re-entry arc,
- The AIP is located at 50.5 degrees South on the ascending track.

3.3.2. Trajectories

Four strategies were computed with the T-DEM tool to deorbit the ATV from its 215x215km deorbitation orbit: one nominal strategy and three back-up strategies. The back-up strategies were designed to answering contingency cases.

The nominal strategy consists of a DEO1 maneuver of 8.25m/s (duration 123s), one orbit after the deorbitation rendez-vous point ($S_{-1/2\_Reen}$) and of a second maneuver (DEO2) of 47m/s (duration 693s), two orbits and half later.

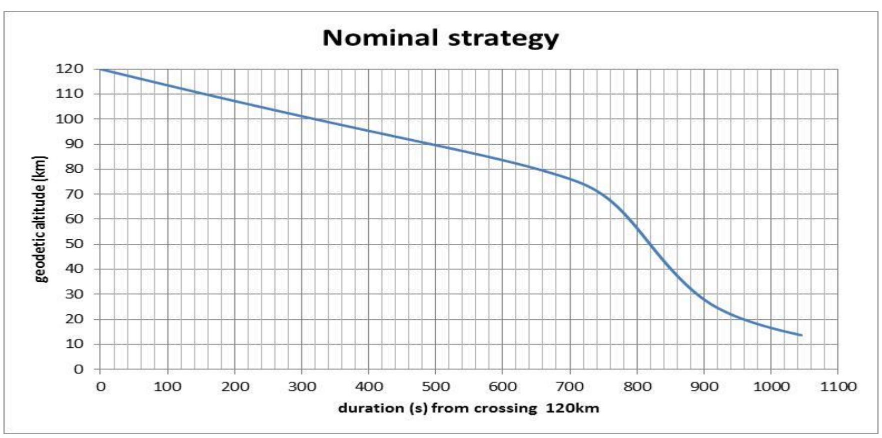

Figure 6: Altitude profile bellow 120km

The geodetic altitude profile of Fig. 6 gives the duration of the flight below 120km of geodetic altitude.
We can see on Fig. 7, the corresponding ground track with maneuvers in blue delimited by pink diamond and the SPOUA outline in red. Fragmentation and impact are represented by blue squares.

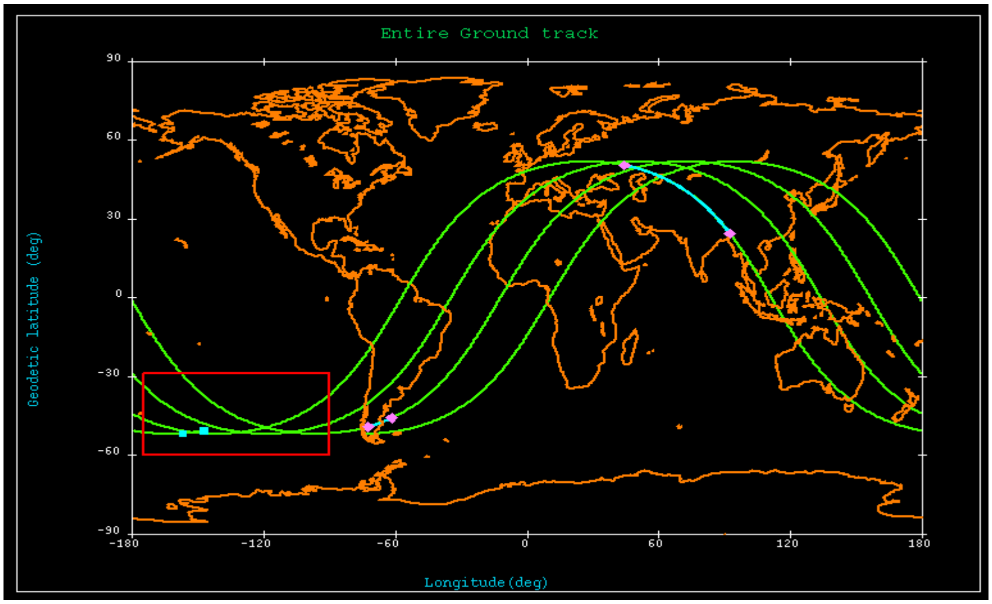

Figure 7: Ground track of the nominal re-entry

The nominal deorbitation from $S_{-1/2}$ to impact point lasts 6 hours.

In the Back-up 1 strategy (BU1), the two deorbitation maneuvers are postponed by one day and the re-entry is similar to the nominal one (with regard to the re-entry characteristics targeted perigee after DEO2 and AIP).

For the Back-up 2 (BU2), only the second maneuver is postponed by one day and the re-entry is similar to the nominal one like for BU1. The re-entry of these two back-up strategies is still shallow re-entries but no more phased with ISS observation. They are triggered if the maneuvers for some reasons cannot be realized on time. This kind of back-up strategy existed also for the previous ATV.

The last backup strategy, named “Steep”, was designed specifically for the ATV-5 and was planned in case of no authorization of shallow re-entry for safety reasons after the $S_{-1/2\_Reen}$ point. It consists in deorbiting the ATV from the 215x215 orbit with only one maneuver which lowers the perigee to an altitude of 0 Km, targeting the same latitude of 50.5° South on the same ascending ground track as the nominal ones. After the maneuver, the solar arrays are not put in “knife” position and a tumbling mode attitude is acquired with a rate of 10deg/s (Y-axis) like for the re-entry strategy studied in GSMA for the general ATV reentry. This strategy aimed to reduce as much as practical the size of the safety boxes.

3.3.3. NOTAM

The ATV planned re-entry debris footprint needed to be communicated to related national authorities for air traffic and sea traffic warning. The notification process is called NOTAM. The ATV-CC FDS was responsible for computing the debris footprint of the NOTAM which was directly sent by the ATV Mission Director to ESOC Space Debris Office, one week before the re-entry. This NOTAM area does not only correspond to the expected reentry area for the nominal day of reentry, it is an envelope of all the possible footprints of the re-entry domain. The re-entry debris footprint of the NOTAM corresponds to the DRA (10^{-2} probability). The area is then generic and computed once in the mission analysis.

Associated to the NOTAM area, ATV-CC had to communicate the dates with time slots when this area has to be cleared.

The NOTAM was required to be computed for nominal and backup strategies.

The NOTAM shall cover a period of 7 days, starting from the first planned re-entry opportunity. A “macro re-entry zone”, enveloping the DRAs of all the possible re-entry arcs (nominal and backup) was then designed for GSMA re-entry. For ATV-5 a new zone had to be computed for the shallow re-entry (cf. Fig 8.) because the DRA are quite different.

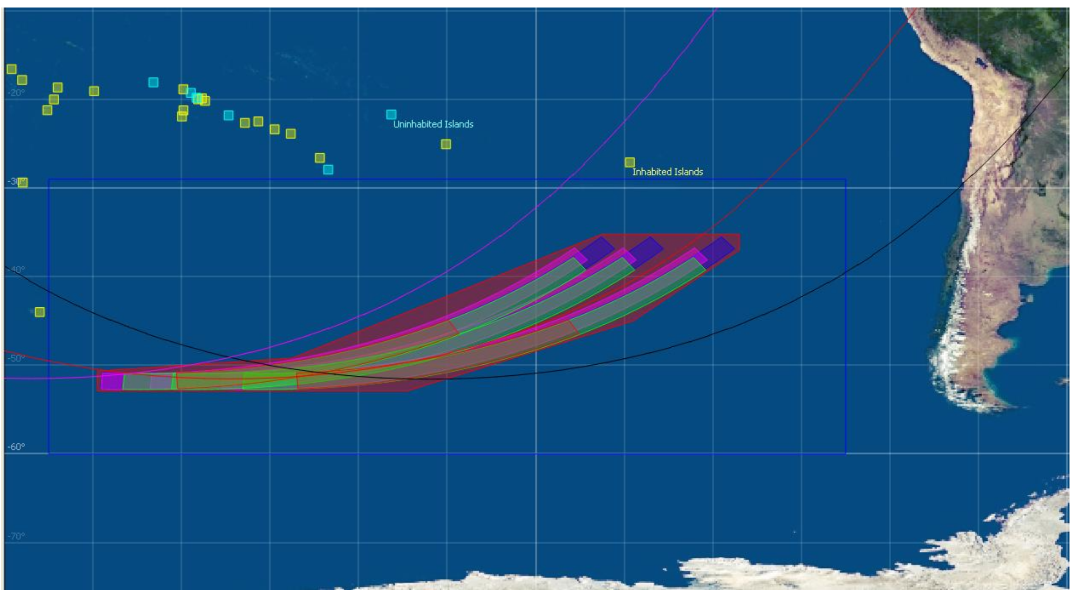

Figure 8: Generic NOTAM zone (in red) covering DRA of nominal, BU1, BU2 and Steep 215 re-entry

As the NOTAM is computed for re-entry phased with ISS, the temporal part was computed from the date of the first planned re-entry dates and ISS trajectory information.

3.4. Opportunities for the LAN of re-entry

Another new feature of the ATV-5 re-entry is the range of the re-entry arc LAN ([-57.29, -44.] degrees of longitude) for the re-entry arc required by observation constraints and safety reasons.

With the LAN constraints, there is not an opportunity of re-entry every day and when there is an opportunity, the re-entry orbit can be either from the ATV daily orbit #4 or #3, contrary to the generic ATV re-entry which is always on the daily orbit #4 without limitation of LAN. The limit between the re-entry from daily orbit#4 and #3 corresponds to a reentry LAN of -47.56 deg.

The LAN of a given ISS daily orbit number is moving to 6.5 deg. toward the East per day and because of the phasing with ISS, the ATV re-entry arc LAN does the same. When the ATV re-entry LAN becomes greater than -44 degrees of longitude (corresponding to a re-entry from the daily orbit #3), we have to target an orbit later for the re-entry (i.e. re-entry from a daily orbit #4) and the re-entry LAN moves to 22.52 deg. to the West and can be smaller than 57.29 degrees. In that case, there are no opportunities for the day.
For the period of the NOTAM sent for a nominal shallow re-entry the 27th of February, the re-entry opportunities are given in the Tab. 2.

Day	Opportunity
27/02/2015	Daily orbit #4
28/02/2015	Daily orbit #4
01/03/2015	No opportunity
02/03/2015	No opportunity
03/03/2015	Daily orbit #4
04/03/2015	Daily orbit #3
05/03/2015	No opportunity

Table 2: Re-entry opportunities

4. ISS phasing

4.1. Deorbitation Interface Point

One of the main purposes of the mission is to "phase" the ATV re-entry such as the explosion can be observed from the ISS. Similarly to the rendez vous with ISS for docking (when targeting the interface point $S_{-1/2}$), this can be achieved by aiming at a "deorbitation" interface point, called by analogy $S_{-1/2\_Reen,}$ before the deorbitation boosts. More details about interface point $S_{-1/2}$ can be found in [2].
The deorbitation interface point $S_{-1/2\_Reen}$ is located one orbit before DEO1 on a circular orbit at 215km of altitude.
As a latitude for the AIP (instead of a longitude) is targeted, the duration between the arrival at rendez-vous point $S_{-1/2\_Reen}$ and the impact is stable and equal to 6 hours. ATV re-entry being phased with ISS, the date of the ATV impact is roughly known and then the date of the $S_{-1/2\_Reen}$.
The $S_{-1/2\_Reen}$ point is built from the ISS mean inclination and the Right Ascension of the Ascending Node (RAAN) at that date. It is located on a circular orbit at 215km of altitude, with a mean inclination equal to the mean inclination of the ISS and a RAAN equal to the ISS RAAN added with RAAN drift during phasing transfer due to J_2. The AOL is fixed at 270 degrees to be one orbit before DEO1.
The precise date of the $S_{-1:2\_Reen}$ point is computed by an iterative method which corrects this date and recomputes deorbitation manoeuvers until the ATV is crossing ISS nadir at 110 km geodetic altitude with an error less than 1 km.

4.2. Maneuver strategy

The phasing scenario retained was a phasing in 48 hours with an extra tour with respect of the ISS. Indeed, the elevated difference in altitude between the ISS and the "$S_{-1/2\_Reen}$" implies a

strong drift of the RAAN during the phasing, and therefore, short phasing strategies are better for targeting the observation point with the expected accuracy.
However, the ATV undocking date was fixed the 14th of February because of constraints due to the ISS visiting vehicles traffic and the re-entry date on the 27th of February by NASA for the re-entry observation. Then a station keeping phase at the Parking Point PP4 placed 2000km ahead ISS, was added and the phasing strategy was designed from this point.
No maneuver is allowed to overwhelm 25 m/s because of the REBR triggering strategy. This leads to the phasing strategy from the parking point of the Fig. 9.

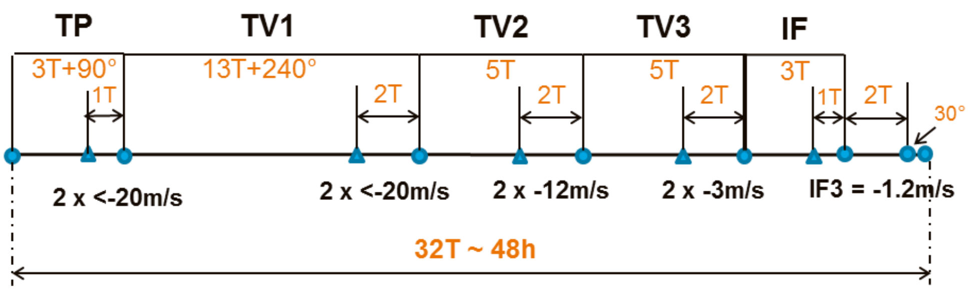

Figure 9: phasing strategy

The IF cycle was added to achieve the necessary accuracy at the $S_{-1/2\_Reen}$ point.

4.3. Accuracy at observation point

The driving constraint for the phasing was to reduce as much as possible the along track errors at $S_{-1/2\_Reen}$ crossing. Afterwards, the deorbitation boosts are performed and they induce along track dispersions on the observation point during re-entry that cannot be compensated.
The ±5 degrees field of view cone of the ISS represents ±27,41 km at 110 km and ±29,37 km at 90 km. Nominally, the strategy targets an altitude crossing right below the station (DX = 0km) but due to various sources of errors this can be dispersed as presented in the Tab. 3:

ΔX dispersions at observation point (Hgeod)			
Hgeod 110 km	Hgeod 90 km	Units	Contributor
1.00	1.00	km	FDS method error for $S_{-1/2\_Reen}$ SV computation
20.06	20.98	km	Phasing error propagation from $S_{-1/2\_Reen}$ to observation altitude
22.80	39.26	km	Max error due to DV dispersions in DEO1, DEO2 Maneuvers
23.70	23.95	km	Max error due to thrust level dispersions in DEO1, DEO2 Maneuvers
0.00	0.00	km	OD error (negligible)
0.45	0.45	km	$S_{-1/2\_Reen}$ Mass error (100kg)
4.16	4.16	km	Max solar flux error
39.75	51.72	km	3σ error (total geometric Sum. + FDS $S_{-1/2\_Reen}$ computation error)
26.5	34.48	km	2σ error (2/3 of 3σ)
13.25	17.24	km	1σ error (1/3 of 3σ)

Table 3: Dispersions at ISS observation point

When crossing 110 km altitude, the ATV is inside the field of view at 2σ and outside at 3σ. But the figures have to be considered as worst case as all the 3σ contributions are added. Furthermore, for the boosts, the considered dispersions are the dispersions design specifications and they are 4 times higher than those observed during ATV-5 flight. With the expected in flight dispersions, an observation point inside the cone for the 110 km case, even at 3 sigma dispersions, could then be expected.

5. Extra propellant burn

The fragmentation used for the SRA computation supposes a remaining propellant mass less than 774kg. But the propellant mass at the undocking was rather high and that implied to burn nearly 1200kg of extra propellant to allow a shallow re-entry. The solution to burn this extra propellant was performing cycles of two opposite out of plane maneuvers of same DV during parking phase. The problem was then to compute these "over-consumption" maneuvers (OM). It can seem easy to calculate, but it is not.

The goal is not only to achieve at the end of the mission a propellant mass less than 774kg, but also to keep a minimum propellant mass to perform the shallow re-entry as well as the possible contingency re-entry ("steep" back-up strategy from 215 km). Then we have a minimum and a maximum limit for the propellant remaining mass.

Some extra budgets have to be added or subtracted to these limits, as well as additional margins for uncertainties and dispersions.

The Tab. 4 summarizes the contributors to the definition of the propellant mass limits.

Propellant Mass at Reentry (PMR) Contributors			
FDS budgets & Margins			
Concept	**Value (kg)**		**Application to Authorized limits Max /Min**
	Budgets	**Dispersions**	
Margin : 3s Nominal strategy	-	42,00	Both
Margin : TORM-TM 3s difference	-	20,70	Both
Contingency budget : PDE failure	104	-	Min only
Contingency budget : steep reentry	85	-	Min only
VET Budgets & Margins			
Concept	**Value (kg)**		**Application to Authorized limits Max /Min**
	Budgets	**Dispersions**	
Non consumable : static	73,60	-	Min only
Non consumable : dynamic	-	113,20	Min only
Loading dispersions	-	3,20	Both
Leakage	65,30	-	Min only
Re-priming activities	23,75	-	Min only
Real Mass / TM Mass error	-	111,71	Both
MCI / TM Mass error	133,45	-	Min

Table 4: Contributors to the definition of targeted remaining propellant mass

Some contributors are intrinsic to the propulsion system of the vehicle or due to the difficulty to know the real on-board mass of propellant and are assessed by the ATV-CC Vehicle Expert

Team ("VET"). Beside the provisions for contingency scenarii, the "FDS" contributors are due to the fact that the realized manoeuvers are not exactly the same as those planed during the SMA (e.g. due to the variability of the environment) and that the consumption is not perfectly predicted by the FDS tools.
Finally, for the computation of the OM, the targeting interval for the mass of the remaining propellant is reduced to [652.8 ; 652.3], and we decided to retain the target of 652.5 kg.

Furthermore the VET team defined a tank switching strategy to maintain an offset of ATV Center of Mass lower than 0.085m.

The OM cycles were placed between the three Station Keeping (SK) Manoeuvers cycles. At the last negative chronology before the cancellation of the shallow re-entry, the following strategy was computed by the FDS, together with the VET, taking into account the tank switching:

- 1 cycle of OM of 20m/s before the first SK cycle
- 3 cycles of OM before the second SK cycle : of 20m/s, 17m/s et 20m/s
- 3 cycles of OM before the last SK cycle: of 14m/s, 9.38m/s and 10.31m/s.

The two last cycles of OM allowed adjusting the mass of propellant to burn, the value DV of the previous OM cycles being fixed.

6. Conclusion

An ATV "shallow" re-entry strategy phased with ISS was finalized with all the ATV operational products adapted to support it. The ATV-CC teams were fully trained to this new strategy and ready to support the experiment operations.
Unfortunately, one week before the undocking, this plan had to be cancelled due to a failure onboard ATV leading to the isolation of one of the four power chains. In these conditions, ATV was not fault tolerance to another failure on power chain for the functionalities required for a nominal ATV reentry and in order to limit the risk of another critical failure, the planned date for reentry was advanced to the earliest opportunity after undocking. Due to the large amount of unused propellant left onboard ATV, only a "steep re-entry" allowed to meet the safety objectives with regards to the ground population. The short time between ATV undocking and reentry did not allow the execution of enough ATV maneuvers for burning propellant in excess as required by a shallow reentry, nor even for the phasing with ISS as required for ATV fragmentation observation. The shallow re-entry was canceled in favor of a regular steep re-entry as documented in GSMA.
The cancellation of the shallow re-entry was disappointing for the operational teams involved because all the efforts devoted to best meet the objectives of that re-entry could not be completed by a successful reentry observation campaign, but the technical challenges that ATV-CC solved during the mission analysis were a rewarding experience.

6. References

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