DOI: 10.13009/EUCASS2019-638

Reusable Payload Fairings:

Mission Engineering and GNC Challenges

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Abstract

Recovery and reuse of launcher elements is revolutionizing access to space, reducing costs and environmental impact when compared to the classic expendable launchers solutions.
The recovery and reusability of Payload Fairings requires innovative technological solutions throughout the flight and ground segments of the mission. This paper presents the current status of the Reusable Payload Fairing (PLF) activities, focused on the Mission Engineering and GNC solutions. Mastering these technologies is critical to trade-off, design, test and fly technical solutions that balance complexity, reliability and costs. Following a general perspective at a programmatic and system level, Mission Engineering and GNC challenges to achieve the PLF recovery and reusability goals are discussed. Key aspects of modelling and simulation of the end-to-end mission – from launcher separation to touchdown – are presented, as well as the related GNC needs and envisaged solutions for the different mission sub-phases. The current high-level estimated mission success identifies the proposed technological solutions as a promising baseline, not only for reusable PLFs, but also for other launcher components.

1. Introduction

The optimization of a launcher ascent phase trajectory results in the need for minimizing inert masses and releasing them as soon as they are no longer needed. Both aspects usually drive the design of hardware elements, which are designed and optimized to the very end to fulfil their function, typically limited to a fraction of the launcher mission ascent phase. As a result, and focusing on the ascent phase only, the minimum launch mass solution is the fully expendable rocket. Adding functionalities to a launcher's element inevitably has an associated penalty in terms of mass, design and manufacturing costs. These considerations historically drove most of the launchers designs worldwide, but widening the analysis beyond the pure ascent phase, and considering the possibility of introducing a return phase for the dropped launchers elements, with the purpose of reutilizing them, opens up a much wider space of design solutions.
Recovery and reuse of dropped launchers elements becomes therefore the optimum solution if the extra costs of design, manufacturing, operations and refurbishment are compensated by the value of the recovered element. The economics could become beneficial after a number of launches, re-entry, recoveries and refurbishments, implying that the risk of a failure in any of these phases could result in a negative net value in comparison to the non-reusable design. Given the fact that extra costs and risks could be relatively high, compared with expendable launcher solutions, the interest in recovery and reuse of launcher elements is limited to the most valuable and easier to recover and refurbish ones. For these reasons, the market is currently focused on the recovery of liquid first stages, or their most valuable parts, such as the engines and the avionics.
Nowadays, recovery and reuse of first launcher stages is a reality: successful results in the USA from key players such as SpaceX and Blue Origin are revolutionizing the market of access to space with vertical landing of their first liquid stages [7]. ULA ([2] [3]) is also approaching the reusability problem with different and innovative solutions (inflatable heat shields for re-entry and mid-air retrieval for descent and landing): focusing the effort in recovering only the most valuable part of the first launcher stage (engines and the avionics), the plan is to maximise the benefit with the minimum extra costs. Europe is also working in research and innovation to increase the TRL of the technological solutions required for vertical landing of launcher's first stages [4], [5], [8] and in inflatable heatshields solutions for the recovery of upper stages [6].
While first stages are a clear choice for reusability, any other very valuable hardware elements could be potentially considered, if benefits are positive as discussed above. Within the other components worth recovering, payload fairings are among the most notable. These parts have the key function of protecting the payload from the aerodynamic, thermal and acoustic environments that the vehicle experiences during atmospheric flight, starting

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from the lift-off through the supersonic and hypersonic phases of the ascent flight. These flight regimes usually last few minutes, and when the launcher reaches altitude about 100 km and the resulting heat flux is below given values, the function of the payload fairing is complete. Becoming an inert mass, the last step is to separate cleanly from the launcher, posing no risks to the payload or to the launcher itself.
As a result of decades of continuous optimization, payload fairings evolved to the current state of the art solutions: extremely thin, lightweight and structurally efficient carbon fibre sandwich structures capable of protecting the payloads and separate cleanly from the launchers.
When the full mission of a payload fairing is considered, thus including in the scope the re-entry and refurbishment phases, new challenges are introduced, and the global design optimum point could move out of the currently mastered local optimum. Challenges at mission analysis and GNC levels, design solutions, modelling and simulation are discussed in this paper, focused but not limited to the PLF class of 5.4 m diameter.

2. Reusable Payload Fairings: mission overview

It is a requirement that the design solution for a re-usable fairing shall be such that it provides an economical advantage to the end customer, without losing the required functional and performance characteristics.
The mission goal is to recover and reuse, with minimum refurbishment, mass penalties, and operation costs, the two shells of the launcher payload fairing. The definition above carries several of the most challenging requirements the mission inherently sets. Moreover, taking into account the extremely lightweight structure, designed to withstand distributed inertial and pressure loads, the challenges for mission fulfilment increase even more.
The reusability goal is challenging. Achieving a recoverable PLF was set as the first step where it is demonstrated that the PLF can survive the entry and can be recovered for inspections. The mission and GNC engineering challenges are similar, in particular for what concerns surviving the re-entry, descent and landing phases. The main difference at mission level could be a relaxed landing accuracy in the case of a recoverable PLF which results in cheaper operations for a demonstration mission. An instrumented recoverable PLF enables a validation of the models used for the simulations during the design and pre-flight prediction phases. The post-landing refurbishment phase is another critical driver towards successful reuse.
In both recoverable or reusable options, at mission level, the PLF shall be able to withstand entry phase constraints, possibly with the minimum amount of dedicated equipment (either aerothermodynamic or RCS). Once hypersonic and supersonic deceleration is completed, with the PLF approaching the sound barrier, the aerodynamic stability (if present) decreases due to shifting of the aerodynamic centre of pressure. After the entry phase, a stabilizer / decelerator phase is therefore required. Given the need for a precise landing (high accuracy in position for recovery and velocity for reusability), active GNC solutions are likely needed to guide the vehicle towards the desired final point: this calls for controlling the aerodynamic lift produced by the PLF or by additional devices (e.g. parafoil) during the descent. The final phase of the mission, the landing and recovery, can either be fulfilled by a Mid Air Retrieval (MAR), by precise landing on a barge, by coordinated landing on a fast boat equipped with a capture system (SpaceX, Mr. Steven approach) or simply by a water landing: it is conceivable to specifically design a recoverable PLF to accept a water landing, specifically making it immune to interaction with salty water, thus reducing part of the complexity (and costs) of the landing and recovery phase.
This high-level mission overview was assessed considering the Mission engineering and GNC challenges, described in the next section. These challenges were the foundations on which the final design solution (presented in section 4.1) was built.

3. Mission Engineering and GNC challenges

3.1. Mission Engineering challenges

This section describes the most relevant challenges that arose during the mission design phase. Each challenge impacts several modelling and design aspects of the mission, and of the PLF design itself.

PLF separation from the rocket: initial conditions
The separation event from the launcher is defined and optimized on a per-mission basis; the variability of initial conditions results in a wide range of total energy (kinetic and potential) to be dissipated. Moreover, the launcher may or may not be in a thrusting phase, when the fairing separation occurs; therefore, the mission engineering challenge demands robust design solutions.
If PLF separation takes place during a thrusting phase, interactions with the launcher rocket plume induce relatively fast rotational rates on the PLF. In order to deal with these rates, an efficient de-tumbling solution shall be designed. Random tumbling motion during re-entry is extremely dangerous for the PLF, as the loads that an uncontrolled PLF

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will encounter are so high that it will likely break apart. Only if the PLF hits the denser layers of the atmosphere (when the dynamic pressure starts to rise) with suitable attitude and rates, it can survive the entry loads. A detumbling system shall be therefore designed so as to achieve the required attitude and reduce the rates before the increase in dynamic pressure.

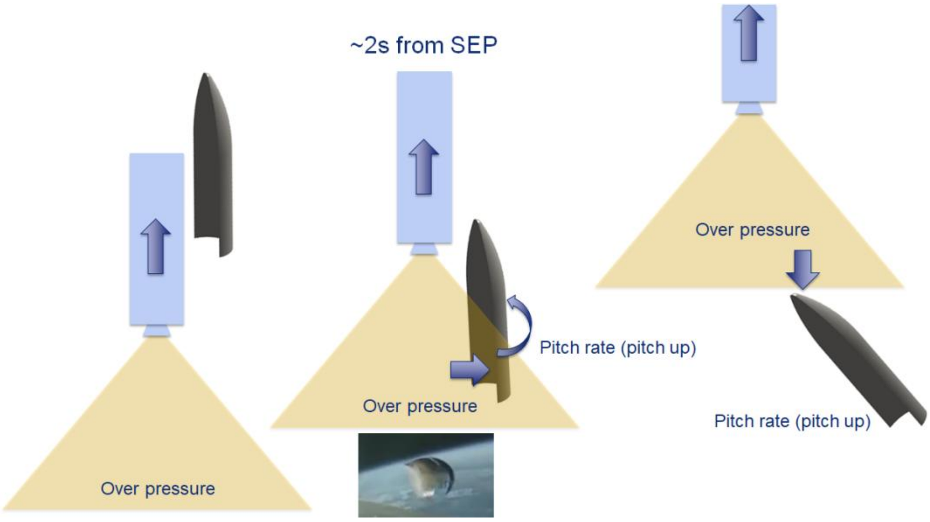

Figure 1 PLF interaction with the launcher plume

Aerodynamics: trim and stability

As aforementioned, the overall goal is to re-use PLFs with the minimum penalties in terms of refurbishment effort, mass, design and costs. The PLFs for today's large launch vehicles (5 m diameter class) have reference lengths in the order of 20 m, and are extremely lightweight (in the range of 1000-1500 kg), resulting in relatively low ballistic coefficients. For such a body, aerodynamics become the driver of the dynamics due to the large forces and moments generated, hence a successful design will tailor and exploit aerodynamic phenomena. A passive flight solution shall therefore be pursued, so to enable a feasible entry taking advantage of the vehicle's natural trim. Flying the PLF without external aids down to transonic regimes is also one of the challenges addressed: this possibility would restrict parachute operations in the subsonic regime only, leading to a cost and mass reduction. For these reasons the aeroshape alone shall be capable of reaching acceptable attitudes (trim) and longitudinal and lateral aerodynamic stability, throughout a wide set of flight conditions (Mach, angle of attack (AoA) and sideslip (AoS)). To adequately assess static stability and trimmability, a suitable aerodynamic model is required (either computed or measured through wind tunnel testing), covering both rarefied and continuum flow regimes.
To overcome these challenges, and to attain a suitable design, proper aerodynamic modelling and flying qualities analyses (trim and stability) are required to simulate the entry phase.

Mass and accommodation

The mass of the additional equipment needed for the PLF to survive the entry, descent and landing phases, and to enable its reusability, has a crucial impact on the business case. An additional challenge is identifying a suitable volume within the PLF to allocate this equipment, as the current design features only limited unused space in the upper (nose cone) part of the fairing. External shape modifications can be acceptable only in some areas, to reduce the impact on the launcher aerodynamics and structure. The added subsystems needed for surviving the entry, descent and landing phases and to recover the PLF have to be therefore optimized both in mass and volume.
Integration of these systems in the PLF structure leads to the challenge of load introduction. The PLF and the equipment is subjected to accelerations during the end-to-end mission, resulting in inertial loads bearing on the structure. The accommodation of the additional equipment needed for a recoverable PLF shall be defined so as to avoid excessive concentrated loads, leading to localized damage or even break-up of the PLF structure: this asks for relatively distributed solutions, achieved either by exploiting the nature of the components, or through suitable design of their attachment systems.

Descent and landing

The touchdown of the PLF is among the crucial events of the mission. Limiting the loads in this situation is necessary to ensure survivability with minimum structural mass. This translates into the requirement for a low speed

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at touchdown and results into the need of PLF velocity control. As discussed above, after the entry phase, a stabilizer / decelerator phase is required for stability reasons, but also to control vertical speed and to cope with landing loads.
The reusability of the PLF requires the use of additional external equipment to perform the search and recovery operations. Cost of operations are drivers in the overall reusability of the PLF, hence should be minimized. This translates into the need of limiting the PLF search and recovery area, attainable by actively controlling the trajectory of the PLF up to its touchdown. Considering the initial conditions dispersions, a relatively small but positive control authority during entry, and the requirements in search and recovery area, the decelerator device should also be capable of generating the required amount of L/D, hence a parafoil is considered a suitable candidate.

Recovery operations and safety
The reusability of the PLF requires the return to Earth of an object flying in suborbital conditions, but at the edge of space (approximately from the Karman line at 100 km altitude). A return mission has to be designed under the safety regulations applicable to avoid unacceptable levels of risk for the ground population, properties, or moving objects (aircrafts, vessels), therefore safety requirements shall be included in the mission design.
The safety requirements of the launch naturally ask for a water landing of the PLF and of the possible debris generated during a destructive re-entry. A change in the launcher trajectory, asking for ground landing of the PLF, would compromise launcher safety and overall performance. For these reasons, recovery operations are expected to happen in open water areas, relatively far from the launch pad. Operations complexity therefore rises, as it requires deploying moving objects, like aircrafts (mid-air-retrieval) or vessels (boats, movable platforms), or fixed floating devices (e.g. barges, pontoons, inflatables, nets or others), in open water areas. In addition, reusability of the PLF structure, made by carbon fibres and aluminium honeycomb, ideally asks for avoiding contact with salted water, or additional measures, implying additional costs. This can be traded-off against the extra cost of operating the aforementioned dedicated vehicles, capable of preventing contact of the PLF with water.

3.2. GNC Challenges

The presented Mission Engineering challenges prompted multiple discussions and analyses at system level, resulting in the definition of additional subsystems, and of the corresponding requirements. One of these subsystems, strictly connected to the Mission Engineering, is the GNC, for which DEIMOS Space is a recognized expert.
The re-entry of large PLFs poses several challenges at GNC level due to the need to detumble, orient and control a large structure while satisfying demanding requirements: both at system level, in terms of mass, cost, volume, safety, and interfaces, and at mission level, in terms of detumbling, orienting, and landing requirements.

Detumbling
One of the main GNC challenges stems from the requirement to detumble and orient the PLF before reaching the denser regions of the atmosphere, and the associated increase in dynamic pressure, to achieve the flight conditions enabling a stable re-entry. With the considered launch trajectories, less than 90 s are available to detumble the PLF from its initial angular velocities. These, due to the interaction of the fairing with the rocket plume at separation, could reach values of up to 60 deg/s. Additionally, the peculiarities of the fairing structure, which is characterized by extensive dimensions, high rotational inertia and limited available volume, pose additional constraints on the GNC system definition, especially in relation with the need to minimize its mass and cost.

Launcher constraints
A second important challenge lays in the necessity to minimize the impact of the PLF GNC on the launcher system in order to reduce the integration effort and make the system concept suitable for different launchers. In this perspective, an additional constraint consists in the passivity of the PLF up to separation, required to prevent affecting adversely the launcher safety. Due to these reasons, interfaces with the launcher shall be minimized and the PLF GNC system shall be kept passive from up to several hours before launch, and during the whole launcher ascent phase, up to separation. From the GNC perspective, this translates into the need to perform the system initialization and the attitude estimation without a reliable initial attitude solution, during a phase which could be characterized by high angular velocities.

Landing accuracy
Depending on the descent and landing concept selected, trajectory control will be needed during re-entry and/or descent and landing, in order to comply with the accuracy requirements enabling the recovery of the PLF. Challenges at GNC level arise, on one side, from the navigation problem, due to the difficulty of achieving accurate position and attitude estimates with a minimal set of sensors and considering also the absence of a reliable initial solution. On the other side, the control authority available, strongly limited by the stringent mass and cost constraints, restrict the PLF manoeuvring capability in the atmospheric phases.

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4. Design Solutions

4.1. Mission Engineering

As detailed in section 3.1, state of the art launchers are versatile platforms, hence provide the possibility to reach different orbits/payload configurations, therefore, the fairing deployment itself may occur during variable launcher phases (e.g. thrust / no thrust), and with variable initial conditions. That indicates the need of missionization of the Reusable Payload Fairings mission. Having in mind the requirement to design a system robust to the broad set of missions, and the necessity to adjust, for each mission, the overall chain of events, a summary of the most relevant phases and events is reported below (Figure 2), from a mission engineering design standpoint:

- Mission starts at Fairing separation (SEP).
- In the first seconds the payload faring system is still inactive, to avoid any interaction with the launcher mission. Once the PLF falls within the exhaust plume of the launcher (in case of thrusting phase), it will receive an aero(thermo)dynamic impulse from the gases, which may introduce a significant angular momentum in the system. Once the PLF has reached a sufficient distance from the launcher, system activation takes place (SA) and GNC actuations are possible.
- In case a tumbling motion was introduced during separation, either by the separation mechanism, or by the rocket plume impingement, a detumbling phase initiates. It is critical to achieve a detumbled vehicle with a stable attitude before the dynamic pressure rises, at entry point (EP).
- During atmospheric entry, the PLF aerodynamic drag decelerates the body, and a suitable PLF attitude is flown until a decelerator deployment takes place: pilot triggering (PT). This initiates the descent phase.
- The sequence of events subsequent to PT depends on the final configuration of the mission; nevertheless, a drogue triggering event (DT) is expected so as to increase the vehicle aerodynamic performance (stability) and to provide the extraction force for parafoil deployment (PFD).
- Once the parafoil is successfully deployed, landing or mid-air retrieval takes place.

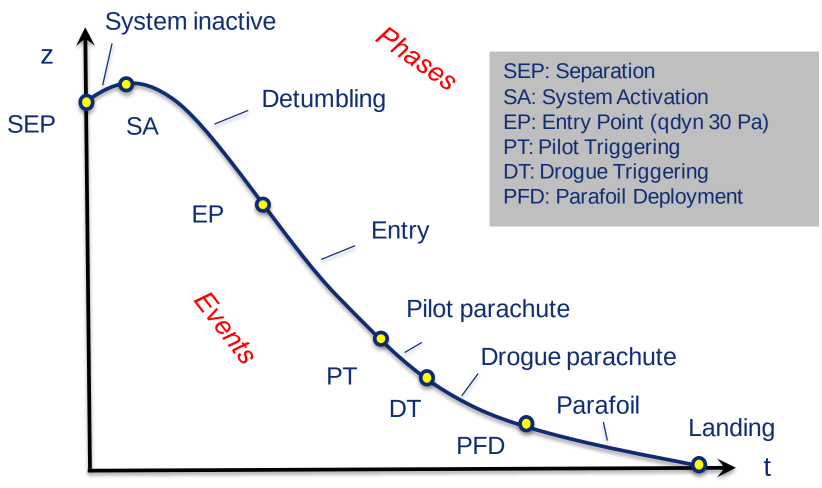

Figure 2: Mission Phases

The mission phases highlighted in Figure 2 leave open several trade-offs, related to the detumbling (see 4.2), entry descent and landing phases.

Entry Phase
Different entry phase concepts were considered, with trade-offs focused on improving the trim and stability on one side, and controllability on the other side. Several options have been explored to increase L/D, which would lead to an improvement in downrange capabilities.

Increasing the L/D of the PLF requires a passive system (to avoid unreasonable increment of the mass budget) which reduces the trim AoA during the re-entry phase. To this purpose, the following options were analysed:

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Aerodynamic means to pitch down the PLF during entry phase.
Within this approach, the three following options were analysed:

- Trailing solutions: based on the use of a drag device attached to the fairing bottom part which is deployed during supersonic phase. A trailing isotensoid ballute was identified as a possible solution (Figure 3, left). Assuming the conditions tested in [10], a reduction of the trim AoA of 50 degrees at Mach 5 is possible with a ballute diameter of 2.25 m.
- Attached solutions: consists on the deflection of the lower part of the PLF, in a manner akin to a flap, to produce drag (or lift, depending on the relative angle of attack) and thus reducing the pitch of the PLF (Figure 3, centre). Considering an objective of trim AoA of 50 degrees at Mach 5, an aerodynamic surface of 3.25 m^2 is required assuming a flap fully normal to the velocity.
- Removal of PLF access doors: consists of the removal of several access doors of the PLF to alter the overall Cp distribution (Figure 3, right). Nevertheless, it also introduces a change in the CoG towards the nose of the PLF, reducing the net effect to an improvement in the trim AoA of just 2 degrees at Mach 5.

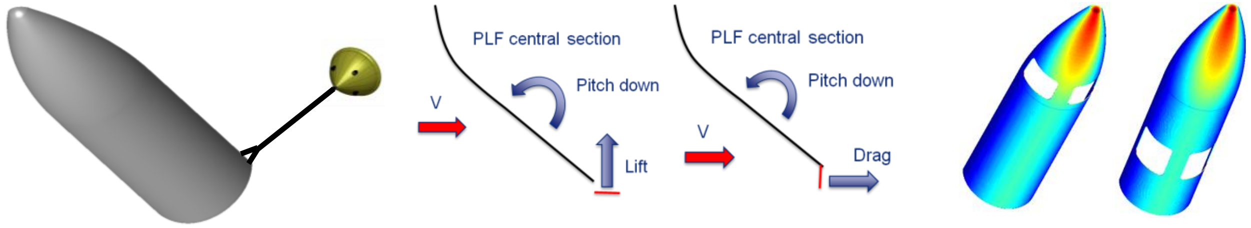

Figure 3 Aerodynamic means for L/D increment concepts: ballute (left), attached solutions (centre) and panels removal (right)

Adjustment of the PLF centre of gravity location.
A simple ballast located in a specific position allows the translation of the CoG with respect to the non-recoverable design. In fact, by placing the D&L subsystem in the right location, required position of the CoG can be attained. A reduction of the trim AoA of 50 degrees can be achieved if CoG is shifted 0.5 m forward (Figure 4). According to the PLF conditions, a ballast of about 80 kg located close to the PLF nose leads to a 0.6 m movement of the CoG towards the nose.

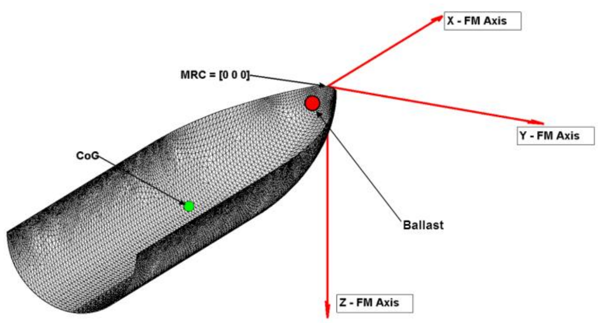

Figure 4 Ballast position

A trade-off of the previous concepts was performed considering a set of aspects such as mass, volume, power constraints, cost, complexity and efficiency (see Figure 5, in the table, where Efficiency* indicates whether the solution is effective to achieve a change in trim). As a result, it is obvious that the CoG solution is the preferable concept, resulting in a real advantage in terms of L/D and the corresponding increase in range capability.

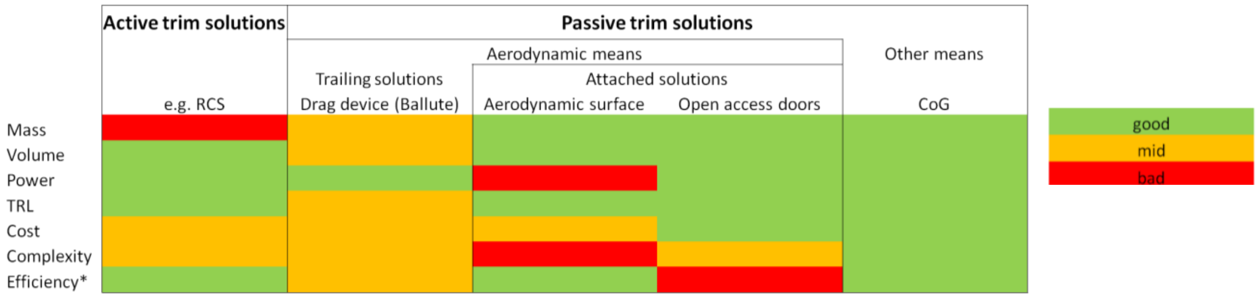

Figure 5 Entry concepts trade-off

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Descent phase

Different descent phase concepts were analysed (Figure 6), including 2- and 3-stage solutions. All the considered concepts rely on different combinations of decelerators or stabilizer parachutes and parafoil solutions.

All cases share the 1^{st} stage initial conditions: deployment of the first stage in the subsonic regime, extracted with a pilot and mortar system. Two main concepts were analysed: concept 1 (two stages), has different combinations of 1^{st} (drag parachute and stabilizer) and 2^{nd} (parafoil and parachute) stages, while concept 2 (three stages) adds a main parachute, before or after the parafoil stage, to have finer control on the terminal velocity.

Preliminary analyses indicate that Concept 1 is the most promising solution; in particular, using a drag parachute for the 1^{st} stage is the preferred option (1AA of Figure 6) due to: better free-stream conditions (less shadowing of the parachute due to the PLF), COTS availability (drag chute), possibly simpler connection of the fairing (by introducing mainly shear forces into its structure rather than normal loads), in turn resulting into a reduced number of lines and hanging points. Due to the PLF attitude under the drag parachute, its aerodynamic contribution is negligible. Consequently, the velocity profiles are fully verticalized. The drawback is that changes in PLF attitude are necessary to transition from the end of entry to the 1^{st} stage, and from the end of 1^{st} stage to the parafoil deployment.

Given these drawbacks, to identify with certainty the most suitable solution, a Monte Carlo simulation campaign (see Section 6) is performed.

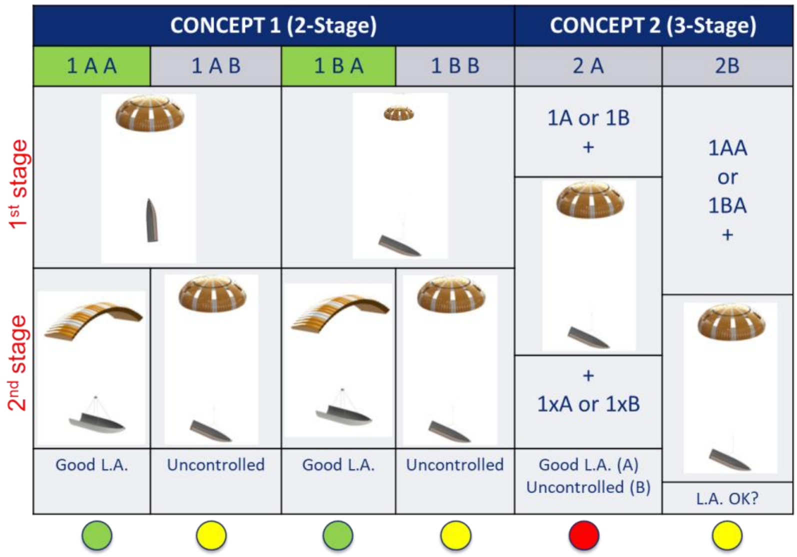

Figure 6: Descent phase tradeoff

Landing phase

The landing strategy tradeoff has been similarly analysed in detail and has been presented in [1]; given the proposed weighting, the promising concept called for a design with a splashdown controlled with a parafoil. This is fully compatible with a recoverable PLF mission as discussed in chapter 2.

4.2. GNC

In order to identify suitable GNC solutions suitable for the PLF mission needs along the different phases (see Figure 2), trade-offs have been carried out focusing on the definition of actuators and sensors concepts, taking into consideration mission, performance, and system criteria.

Actuators

The sizing condition for the actuators is the de-tumbling phase, requiring the dissipation of a high initial angular momentum in a short time, in a region characterized by low dynamic pressures. In this perspective, the use of RCS actuators emerged as the most promising solution in terms of performance and mass budget, as it allows exploiting the large dimensions of the PLF in order to generate the high torques needed during detumbling, while delivering high angular momentum capacity. Specifically, Cold Gas Thrusters in the 50÷100 N range are considered due to the operative needs of using non-toxic propellants and the lower system complexity with respect to Hot Gas Thrusters. Different thrusters layouts have been analysed in terms of torque authority, layout complexity, and ease of integration within the structure, which resulted in the selection of a candidate layout characterized by 8 thrusters placed in the nose of the PLF. This configuration offers the advantage of enabling to cluster the equipment in a small area, hence minimizing its complexity.

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Sensors
When it comes to the attitude determination, different sensors suites will be required for the various phases of the PLF mission.
For the detumbling phase, a set of sensors constituted by IMU and magnetometers was selected, since it enables the attitude estimation without requiring precise information for the initial (post-separation) attitude, while satisfying the accuracy requirements of the pointing phase at the end of detumbling.
On the other side, during the re-entry flight, the use of GNSS coupled with the IMU was selected to guarantee precise position accuracy and improved attitude estimation, thus permitting an effective trajectory control.
Finally, for descent and landing, further sensors, such as an altimeter, are envisaged depending on the consolidation of the mission concept.

5. PLF modelling

Section 3.1 and 4.1 defined the challenges and phases as far as mission engineering is concerned. To adequately assess all the mission phases, dedicated simulation environment and models were developed by DEIMOS Space. Given the key challenges highlighted in the previous sections, key modelling efforts and results are presented focusing on the areas of aerodynamics and GNC models (other relevant topics as: MCI, environment and Thermal, although analysed and implemented, will not be covered within this paper). They leverage on extensive experience in atmospheric flight and unique assets available at DEIMOS Space, including the Planetary Entry Toolbox [9].

Aerodynamics
DEIMOS was responsible for the computation of the aerodynamic database of the PLF end-to-end, from free-molecular to subsonic regime. Several proprietary tools were used to generate the complete aerodynamic database (Figure 7 shows the flowfield of a subsonic CFD simulation: Mach 0.6, AoA 70º, AoS 0º, top, and of a supersonic CFD simulation: Mach 2, AoA 70º, AoS 0º, bottom). The aerodynamic database, independently verified in a subset of flight conditions, features multiple dimensions, to account for Mach / speed ratio, angle of attack, angle of sideslip, and pressure coefficient (Cp) on the PLF surface mesh. Through the CFD analyses, a complete, 6-DoF (degrees of freedom) aerodynamic database (longitudinal and lateral forces and moments) was generated.
In addition to the aerodynamic database creation, CFD flow field analyses supported the sizing of the descent and landing system, in particular for assessing the chute canopy-PLF wake interaction.

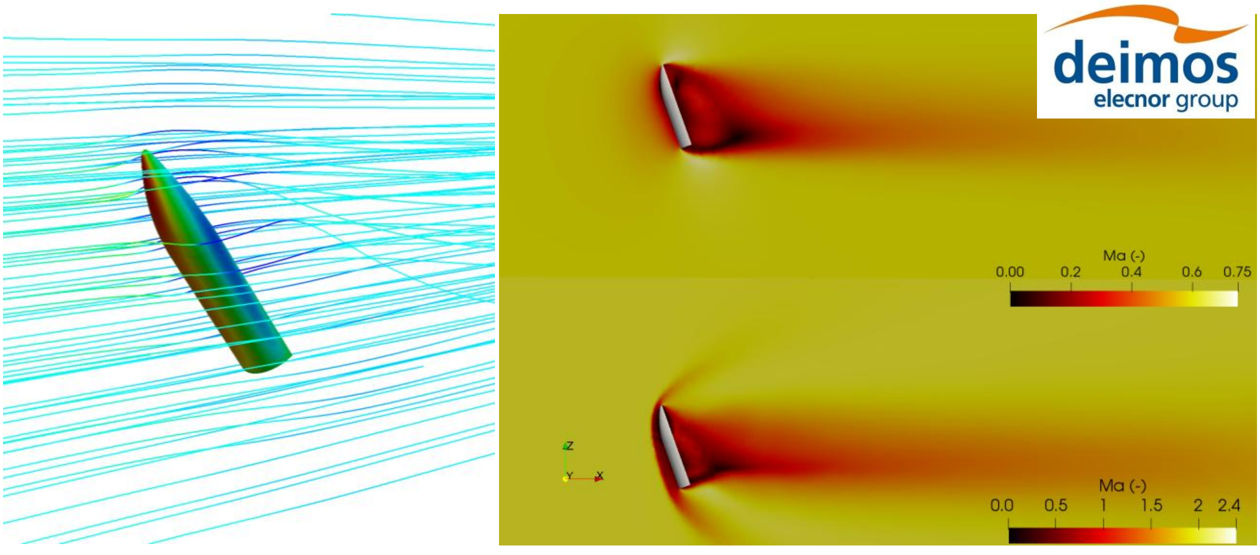

Figure 7: CFD computation of nominal PLF aerodynamics.

Endo-atmospheric simulator
The PLF aerodynamic models described in section 5 were integrated in the DEIMOS property endo-atmospheric simulation environment "endosim" which allows to design the planetary entry phase through trajectory simulations. The key characteristics of Endosim, for the problem at hand, are its ability to consider 6-DoF problems, its capacity of propagating exo/endo-atmospheric trajectories considering open- and closed-loop control laws in various GNC modes, as well as mass and drag variations (in this case, fuel consumption and parachutes deployment). Furthermore, by supporting the definition of dispersions for each value describing the problem, performance

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assessments can be performed through Monte Carlo campaigns. Figure 8 shows an instant of the resulting simulation, with the PLF – coloured according to the local pressure coefficient (Cp) – in a stable attitude during entry.

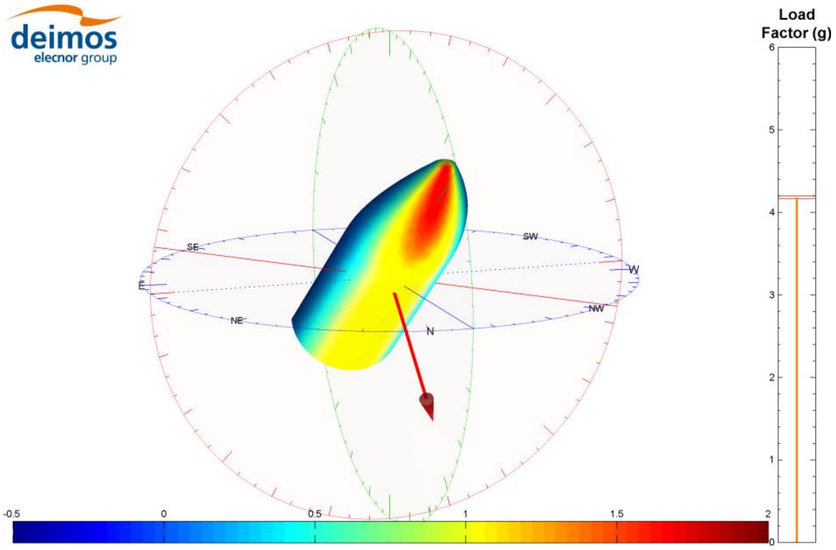

Figure 8: 6-DoF PLF Re-entry simulation. Aeroshape shaded with local pressure coefficient Cp.

6. Performance assessment

Flying qualities
By taking advantage of the aerodynamic database, flying qualities (trim and stability) assessments were done, as they permit to establish the trim conditions and L/D performance of the vehicle as a function of Mach and angle of attack (see Figure 9).

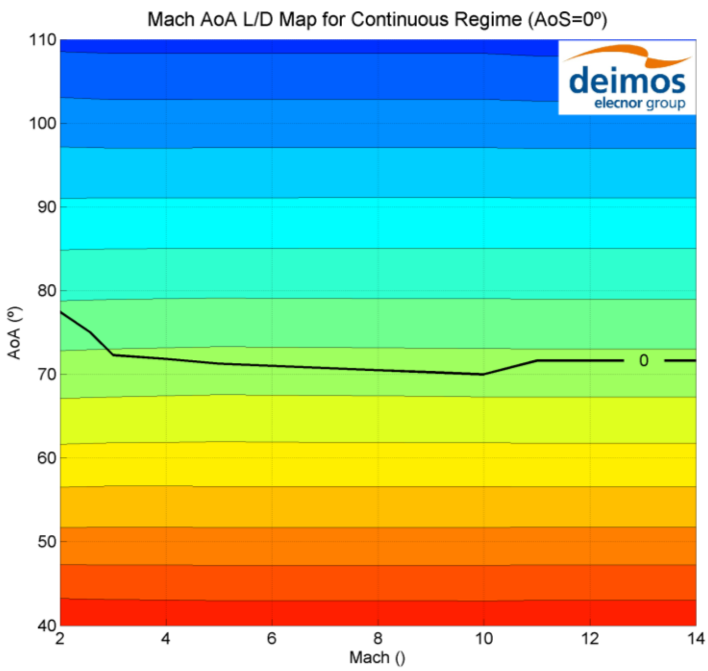

Figure 9: Example of nominal PLF aerodynamics: trimline (zero pitching moment) and Contours of L/D.

Monte Carlo entry simulation
Due to the considerable effects on the stability and dynamics caused by variations of the MCI, and to the variety of initial conditions associated to different missions, it was mandatory to perform end-to-end simulation campaigns, so to model the complex phenomena of the entry, descent and landing of the PLF.

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Taking advantage of the DEIMOS endo-atmospheric simulator, two Monte Carlo (MC) 6-DoF simulation campaigns have been performed, respectively in open- and closed-loop mode. The two campaigns assessed the ability of the GNC subsystem to control the PLF during entry, down to DRS conditions, as well as the PLF dynamics. The detumbling proto-GNC algorithm implemented for this simulation is a simplified prototype that fulfils the requirements outlined in sections 3.1, and 3.2 (in particular related to the dispersions of initial conditions: state vector, velocities and rates). A subsequent implementation of a complete and accurate GNC algorithm is planned, to confirm and validate the conclusions of the preliminary closed-loop campaign.
Taking advantage of Monte Carlo simulations, which rely on dispersions sets derived from mission, environment and system characteristics (e.g. initial conditions, aerodynamic, MCI, environmental...), the overall feasibility of the mission was assessed, with detumbling proto-GNC and without it. In particular, reference and dispersed shots provide key indicators on the attitudes and performance of the PLF during entry (e.g. total load factor as a function of time, and Mach as a function of time, in Figure 10). The dynamic pressure rise leads to a bell-shaped curve describing the load factor (time 0 is defined as the instant when the PLF encounters a dynamic pressure of 30 Pa). Together with the Mach number plot, these results indicate that the PLF is capable of crossing the sound barrier without losing aerodynamic stability.

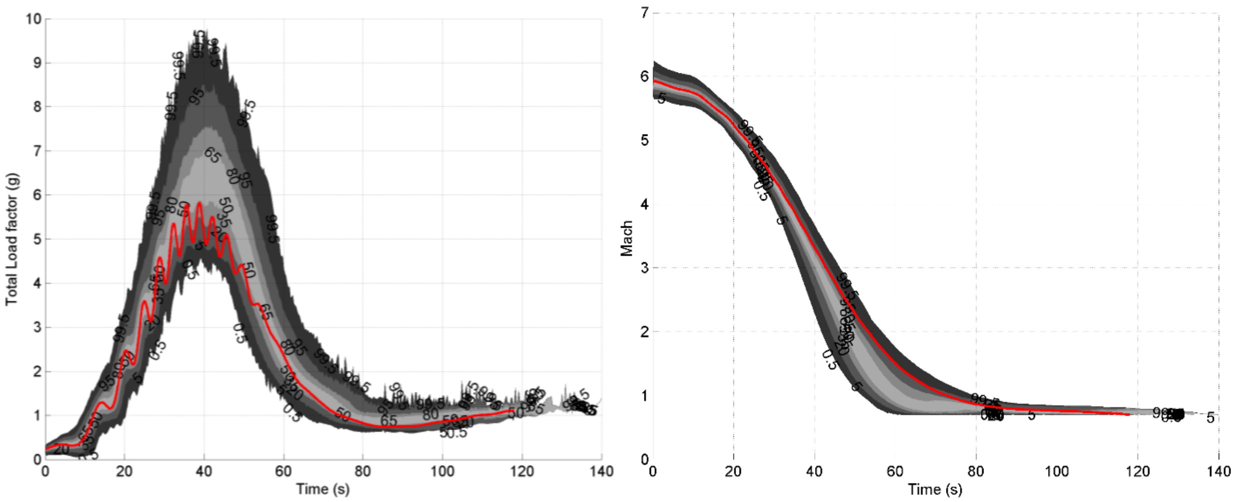

Figure 10: Load Factor as a function of time, Mach as a function of time: red nominal, grey: MC statistics.

Monte Carlo simulation campaigns of the entry phase have been run from a dynamic pressure of 30 Pa down to subsonic Mach, both in open-loop (without proto-GNC) and in closed-loop (with proto-GNC). A range of different simulation assumptions have been tested, mainly to understand the reasons for failure cases, the limits of achievable performance, and to identify the correlations between successful shots and dispersions.
The key conclusions from the closed-loop MC simulations is that the percentage of shots successfully reaching subsonic conditions is strongly dependent on the assumptions made at dispersions level. Without proto-GNC, only 3.3% of the cases is successful; therefore, the introduction of detumbling GNC is necessary during the entry phase. With GNC, an improvement in mission success figure of at least one order of magnitude is observed. In particular, 76% of the shots are successfully controlled by the proto-GNC during the entry phase, in case uncertainties in aerodynamic database and MCI are assumed to be in line to values typical of more advanced mission phases (B2). It is therefore recommended to concentrate future efforts in the reduction of critical dispersions that have been identified as the main drivers for mission success, namely aerodynamics and MCI properties (Y-CoG), as demonstrated by the sensitivity analyses performed (Figure 11).

DOI: 10.13009/EUCASS2019-638

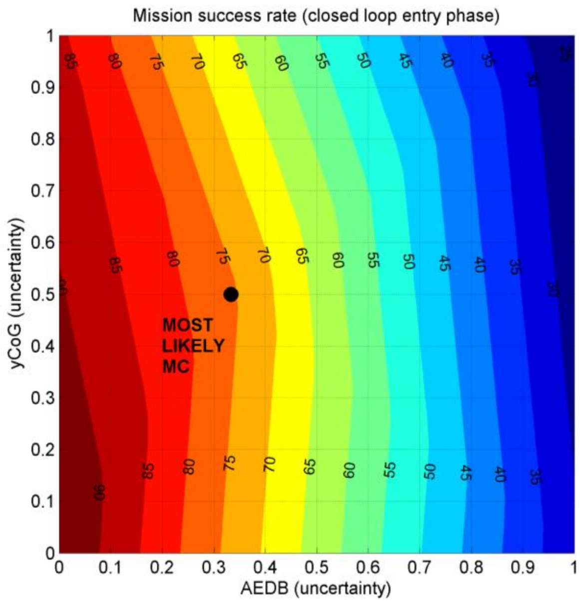

Figure 11: Entry phase mission success (closed loop MC) dependence on assumptions in key modelling dispersions

GNC

Concerning GNC performances, the detumbling phase is the driver for the sizing of the GNC system and, in particular, of the actuators subsystem, as it defines the authority needs of the PLF mission, as well the propellant consumption. This, in turn, has a significant contribution towards the GNC system mass budget. For these reasons, the performances of the proposed GNC concept have been analysed in MC simulations to show the feasibility of detumbling the PLF within the required time and mass budget. Figure 12 and Figure 13 show the results of a 400 shots MC campaign on the PLF detumbling phase. The graphs present respectively the percentile estimations of the angular velocity norm, and of the total propellant consumption. The results indicate that detumbling the PLF, with an initial angular velocity of 40 deg/s per axis, would require less than 60s and 11kg of propellant. It is evident that the PLF initial conditions directly impact the GNC concept and the associated mass budget; their accurate characterization will be thus crucial for the consolidation of the PLF reusability concept.

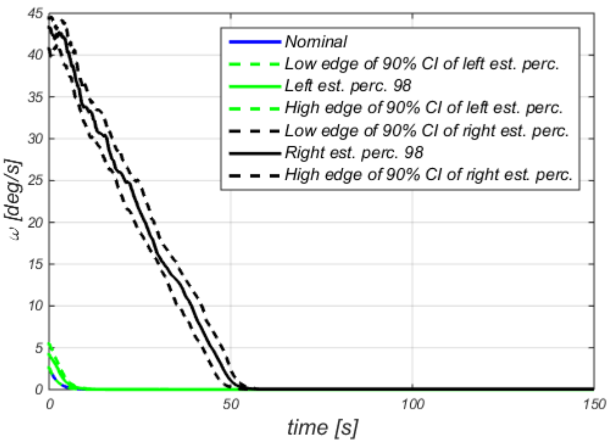

Figure 12: Angular velocity norm

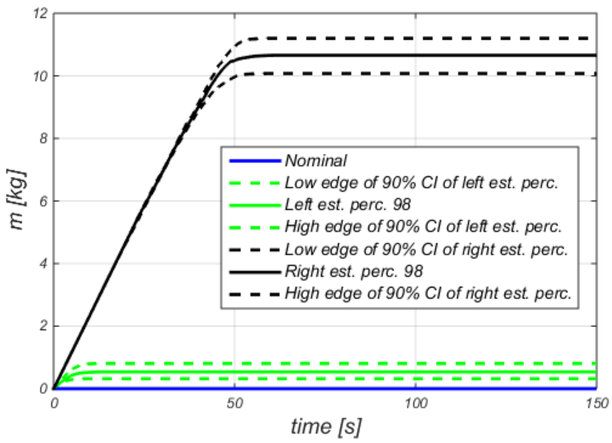

Figure 13: Propellant Consumption

Monte Carlo descent simulation

Following the trade-offs and down-selection of the descent phase concepts (described in 4.1), and the results of the Monte Carlo Entry simulation, a Monte Carlo campaign for the drag parachute and stabilizer 1st stage concepts was carried out. The analysis of the MC campaign results indicates that a successful descent down to an altitude of 6 km is achievable (End-to-end profiles are shown in Figure 14, combining the entry and the descent phases); at this point the Parafoil Deployment is triggered. Among the two 1st stage concepts (see 4.1), the drag parachute is the preferred option, as it allows more verticalized velocity profiles and less dispersion during descent (see Figure 15).

DOI: 10.13009/EUCASS2019-638

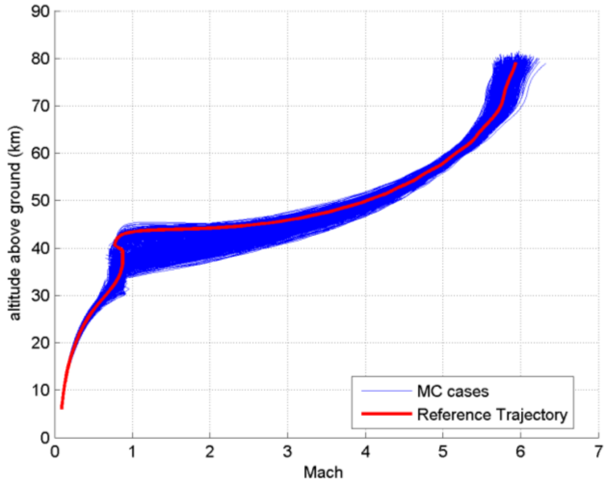

Figure 14: End to end MC mission profiles (altitude-Mach), from 30 Pa to PFD

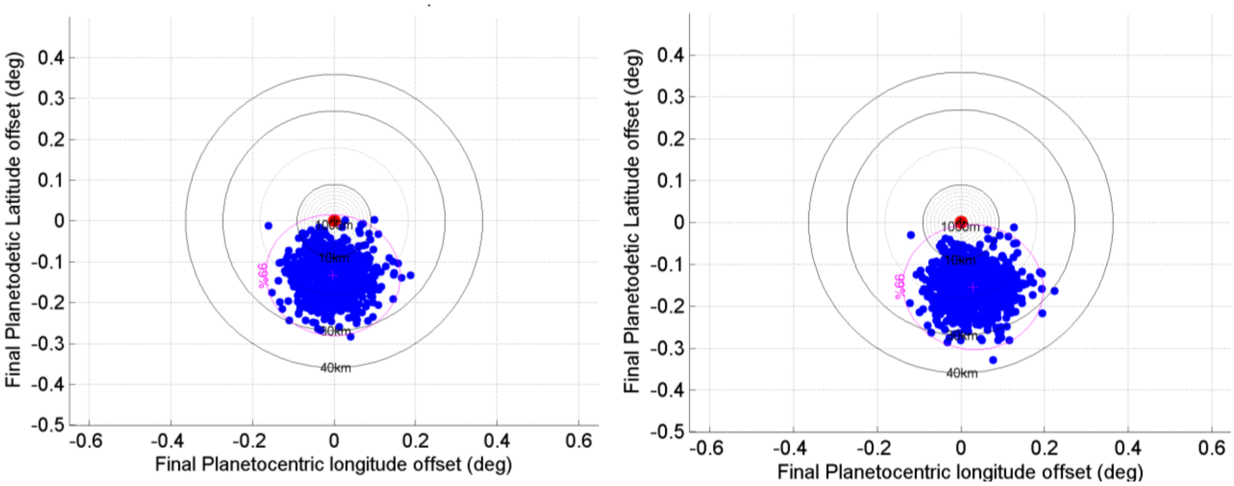

Figure 15: Final longitude, latitude dispersions of the drag parachute (left) and of the stabilizer concept (right)

Additionally, a range capability analysis for the descent 2nd stage under parafoil was carried out, and the analysis of the results indicate that more than 96 % of the MC shots at parafoil deployment are within the Parafoil Range Capability (500 m of altitude margin with respect to the target), indicating very high possibility of mission success (see Figure 16).

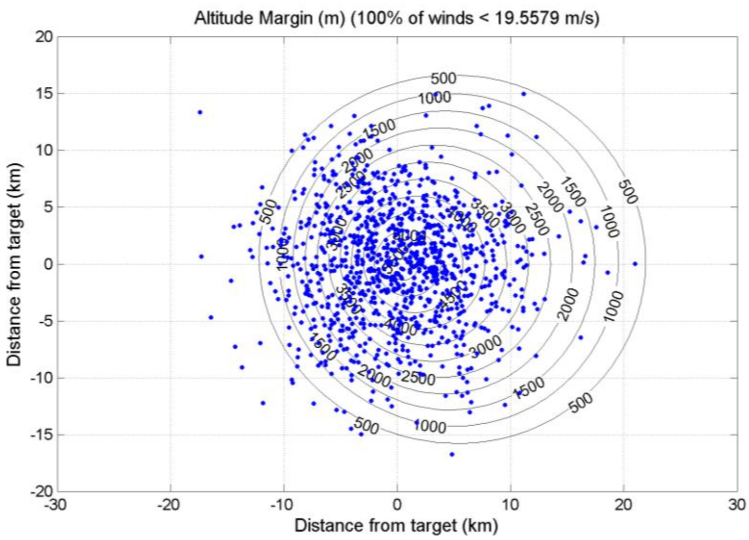

Figure 16: Parafoil Target Area results (drag parachute approach)

DOI: 10.13009/EUCASS2019-638

7. Conclusions

A comprehensive description of the status of the Reusable Payload Fairing activities, focused on the Mission Engineering and GNC solutions, was presented in this paper. Mission engineering and GNC challenges of the Reusable Payload Fairing mission provided the input to the definition of suitable design solutions and models. The implementation of the models into the endo-atmospheric simulator was the key enabler to support design trade-offs and to assess the mission performance through Monte Carlo simulation campaigns.

The main conclusion from the Monte Carlo simulations is that without a GNC solution to detumble and point the vehicle to the right attitude, less than 5% of the cases are successful. The introduction of GNC is therefore necessary during the entry phase, leading to a drastic improvement in mission success figure, up to about 80%.

As far as the descent phase trade-off is concerned, a feasible descent down to an altitude 6 km is achieved; at this point the Parafoil Deployment is triggered. The use of a drag parachute for the 1st stage is the preferred option. As more than 96% of the MC shots are within the Parafoil Range Capability, there is a very high likelihood of mission success.

The experience gained during this work on Mission Engineering, GNC, modelling and simulation, is well suited to tackle the challenges related to recovery of not only payload fairings, but also other elements of state-of-the-art launchers.

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