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# RETALT: Development of Key Flight Dynamics and GNC Technologies for Reusable Launchers

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**Abstract**

The capability to partially recover and reuse a launch vehicle is currently the most effective way of reducing the cost of access to space, which is a key endeavour to the commercialization of space. Despite this, it remains a great technical challenge, with only two US companies (SpaceX and Blue Origin) having developed the necessary technology to carry out routinely successful recovery missions, both using retro-propulsive vertical landing as the recovery strategy, and both reporting significant cost savings due to the reusability effort.

In this context, the RETALT (Retro Propulsion Assisted Landing Technologies) project, funded by the EC Horizon 2020 programme under grant agreement No 821890, had the goal of investigating and maturing key technologies to enable reusability in Europe. One of the great technical challenges in this endeavour lies in the capability to define a feasible mission to safely and robustly return the launcher, and to develop a recovery Guidance, Navigation and Control (GNC) system to perform a precision landing in a fast-dynamic environment, with extremely limited fuel margins, and with significant unknown dispersions accumulated during prior phases. In particular, the project aims to increase the Technology Readiness Level (TRL) of the GNC technologies needed for recovery up to 3.

The baseline configuration and the main focus of the project and this paper is RETALT1. The vehicle operates similarly to a typical launcher until separation, after which two scenarios for the first stage recovery are considered: Downrange Landing (DRL) and Return to Launch Site (RTLS). The latter differs in the use of a post-separation flip manoeuvre and boostback burn that modifies the ballistic arc to allow a landing at or near the launch site, while the former foresees a landing at sea on a floating barge. Both scenarios employ a re-entry burn, in order to reduce velocity and dispersions, and an active aerodynamic descent phase enabled by the use of control surfaces. Finally, the first stage recovery mission ends with an engine-powered descent, which slows the vehicle down to a pinpoint and soft vertical landing.

The focus of this paper will be the methodology implemented to assess the feasibility of the recovery mission, identify the mission design envelope for the wide range of launch missions that the system could target, and define a mission solution for representative re-entry conditions, as well as the design, development and test of the GNC solution, that was demonstrated capable of guaranteeing the necessary performance to recover the system.

**Keywords:** reusable launchers, reusability, guidance, navigation, control, flight mechanics, online optimisation.

## 1 Introduction

In RETALT, the mission engineering is a critical process of the design-for-reusability chain, and it is a discipline of excellence of DEIMOS Space. The objective of the mission engineering in RETALT is to define a mission baseline and derive reference trajectories for all return flight phases and for all the mission scenarios selected. In this way, flight and landing loads are derived to ensure total coherence among all requirements and to support the development of the key technologies considered in the study (aerothermodynamics, structural concepts and mechanisms, TPS, GNC).

To meet the study objectives, and based on Deimos' experience in atmospheric flight and re-entry mission analysis [1][2][3], the mission engineering for RETALT focuses initially on the definition of the concept of operations (CONOPS) for the return mission and the analysis of the capability of the launcher configurations to perform such a recovery mission. Once the flight envelope for the return mission has been identified, the mission design of the reference return mission can be performed in detail. The flying qualities analysis allows to evaluate the trimmability, stability, and controllability characteristics of the launcher configurations, and therefore characterize their capability to fly a return trajectory. The reference trajectories for the return scenarios considered are then optimised to support the development of the different technologies necessary to enable the recovery and therefore the reusability of the launcher, and in particular of the GNC.

The objective of the GNC design in RETALT is thus to develop key GNC concepts that would enable the recovery of the first stage of the TSTO launcher and target a TRL 3 for the most critical components at the end of the study.

To meet the study objectives, a baseline end-2-end solution is identified for the complete return mission. Critical algorithms are then defined and implemented, being the powered descent and landing GNC solution the main focus of the development, as it must allow the system to perform a high-precision landing in a fast-dynamic environment, with non-negligible aerodynamic forces, limited fuel margins, and with significant unknown dispersions accumulated during prior phases. Nevertheless, the design of GNC algorithms is also adapted to the other phases of the return flight.

A functional engineering simulator (FES) is developed to provide a high-fidelity simulations environment to test the proposed GNC concept. The GNC performance are thus verified with model-in-the-loop simulation for the landing phase, while the applicability of the proposed algorithms for the end-2-end return scenario is preliminary assessed testing the GNC functioning in the other phases of the re-entry.

## 2 Reference mission and configuration

The baseline configuration and main focus of the project and this paper is RETALT1, a 103 m tall two-stage to orbit (TSTO) launcher, shown in Fig. 1. The vehicle operates similarly to a typical launcher until separation, after which two scenarios for the first stage recovery are considered: Downrange Landing (DRL) and Return to Launch Site (RTLS), illustrated in Fig. 2. The latter differs in the use of a post-separation flip manoeuvre and boost-back burn that modifies the ballistic arc to allow a landing at or near the launch site, while the former foresees a landing at sea on a floating barge. Both scenarios employ a re-entry burn, to reduce velocity, and an active aerodynamic descent phase enabled by the use of Aerodynamic Control Surfaces (ACS). Finally, pinpoint soft vertical landing is enabled by an engine-powered descent. Different ACS configurations are considered for the RETALT1 concept, including interstage petals (IS), planar fins (PF), and grid fins (GF), see Fig. 1.

The concept configuration of the RETALT1 first stage was designed assuming the use of Vulcain-like engines [4], and has a dry mass of 59.3 tons and 57 tons of propellant available for the return manoeuvres (50 tons plus 7 reserve).


Fig. 1 – RETALT1 reference configurations

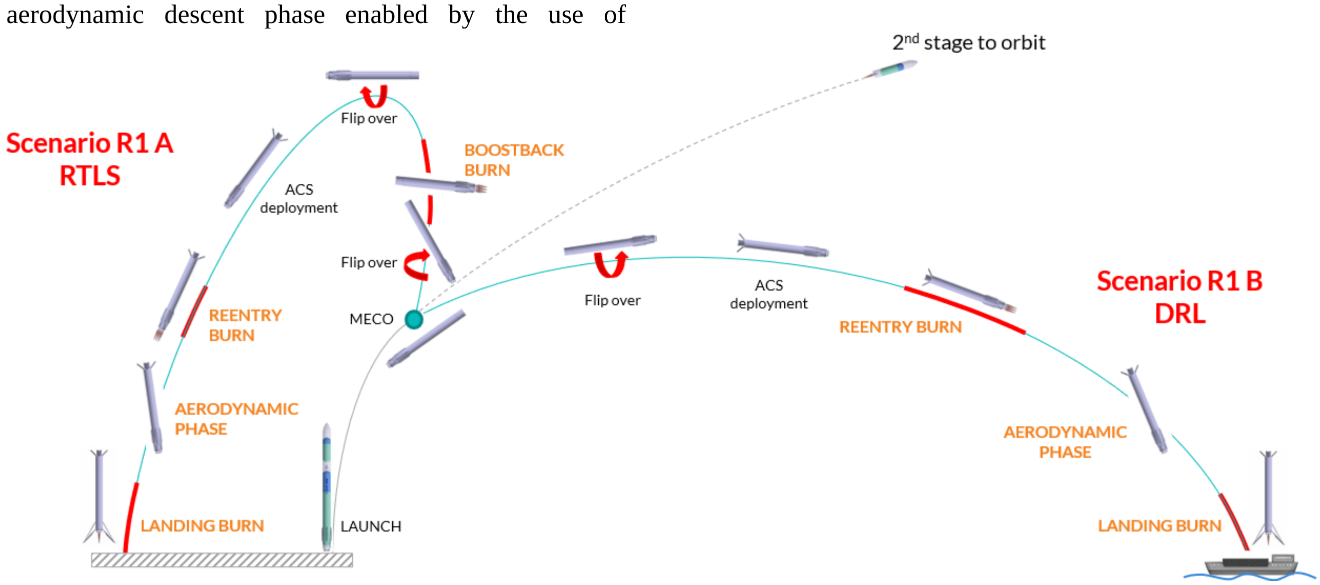


Fig. 2 – RETALT1 return mission concept

## 3 Mission feasibility analysis

The mission feasibility analysis of RETALT1 focuses on the assessment of the capabilities of the proposed configurations to perform a return mission.

At first, the analysis of the recovery capability is carried out exploring the conditions that the launchers will face during the return, and studying the different recovery manoeuvres to define the flight envelope and identify design drivers for the recovery mission. Then, based on the results of the recovery capability analysis, the mission needs are identified in terms of performance required to achieve the mission objectives and enable recovery and thus reusability. The propellant budget is thus consolidated and flight and landing loads derived, which contribute to the sizing of the aerodynamic actuators.

This assessment is based on the reference system configurations and the concept trajectories identified, but not limited to these trajectory conditions. Actually, the capability of recovering the launcher's first stage from a wide range of launch mission scenarios is key in enabling a broad combination of payloads and injection orbits, providing the launcher with the flexibility to meet the needs of different customers. For given conditions at MECO, a specific recovery strategy is possible (RTLS or DRL). The variability of conditions at MECO (velocity and FPA) expected for the RETALT launcher has been identified mapping characteristic conditions for typical LEO and GTO launch missions, which are the mission scenarios envisaged for RETALT1.

### *3.1 Analysis of the recovery capability*

The analysis of the recovery capability of RETALT is based on a bottom-up approach that starts focusing on the landing phase, then it addresses the aerodynamic phase, and finally the propulsive phases (re-entry and boost-back burns). The analysis of the landing and aerodynamic phases is common for all scenarios, while the analysis of the re-entry and boost-back burns depends on the mission scenarios considered.

The primary objective of the landing phase is to land the vehicle and target a precise landing site by compensating the residual trajectory dispersions and achieving pinpoint landing. The capability of providing lateral manoeuvring is therefore necessary, and it is obtained by changing the attitude of the thrust vector. The timing for the start of the landing manoeuvre is also important: the best timing is the one that combines effectively the use of the aerodynamic braking capabilities with the retro-propulsion manoeuvre. The different launcher configurations mainly affect the variability of the trajectory conditions at the end of the aerodynamic phase, and the capability to carry out a successful landing depends on the trajectory conditions, as well as the propellant required to land. The design of the landing manoeuvre is therefore a trade-off between the range capability that shall be guaranteed, driven by the capability of the GNC system to bring the launcher to the start of the landing phase within a certain accuracy, and the propellant that is required for a successful landing. For the RETALT1 return scenario considered, a promising design point has been found depending on the configuration [5]: the interstage petals configuration, which maximizes the braking capability during the aerodynamic phase, requires about 9 tons of propellant to perform a successful landing while the other configurations require about 2 tons of additional propellant, bringing the total propellant consumption for the landing phase up to 11 tons. This total consumption is on top of the reserve/margin propellant.

The objective of the aerodynamic entry phase is to slow the vehicle down to the desired initial conditions for the landing phase, while maintaining the thermomechanical loads within the required limits. In addition, it has to contribute to the trajectory control compensating the residual trajectory dispersions after the re-entry burn and the trajectory dispersions that could be accumulated during the aerodynamic flight due to uncertainties. The orientation of the vehicle with respect to the velocity vector during the aerodynamic phase determines the aerodynamic performance of the vehicle. In case of a ballistic flight lift is zero, and the capability to control the position is neglected. Deployable surfaces could be used to directly increase the drag coefficient, but they are also required to provide the capability to trim the vehicle at AoA different than 180º to enable trajectory control. The aero-thermo-mechanical loads during the aerodynamic phase depend on the drag characteristics of the vehicle and on the velocity conditions at the beginning of the aerodynamic phase, see Fig. 3. The drag coefficient range considered covers the expected variability from a clean vehicle configuration to the configuration with the interstage petals deployed. The performance of grid fins and planar fins configurations are in between [6]. Deploying the interstage petals will decrease the peak dynamic pressure during the flight, and in general decrease the loads. Anyhow, it is possible to maintain the dynamic pressure under the 100 kPa limit even with the clean configuration by either decreasing the initial velocity – i.e. performing a more aggressive re-entry burn – or by increasing the drag coefficient flying the vehicle with a trim angle different than 180º. Clearly, a stronger re-entry burn would imply a higher propellant consumption. A detailed analysis of the trim flight characteristics was carried out for the different configurations, considering variable initial conditions and AoA during the aerodynamic flight [5]. The conclusion was that flying with trim angles up to ΔAoA of 10º would be compatible with the set of path constraints defined in the study (with the goal to limit as much as possible the impact of the recovery needs on the launcher structure) and should allow compensating the trajectory dispersions accumulated.

The objective of the re-entry burn is to decrease the velocity of the vehicle making use of the propulsion system and thus maintain the aero-thermo-mechanical loads under control during the following aerodynamic phase. Also, the modulation of the thrust vector attitude would enable trajectory control, contributing to the compensation of trajectory dispersions accumulated during the high-altitude aerodynamic flight due to uncertainties or errors with respect to the reference conditions. The performance during the re-entry burn depends on the starting point of the burn, its duration, and the initial conditions at the start of the burn. In case a downrange landing (DRL) is performed, the re-entry burn is the only active manoeuvre occurring between MECO and the aerodynamic phase, and the initial conditions of the re-entry burn only depend on the conditions at MECO. The propellant consumption during the re-entry burn is comparable for the different aerodynamic configurations explored due to the low influence of aerodynamics on the trajectory during this phase.

In case a RTLS is targeted, a boost-back burn is required to change the direction of the velocity and correctly target the desired landing site: the launch pad, or an alternative landing pad close to the launch pad. The analysis of the recovery capability for the boost-back burn focuses on the identification of the propellant required to achieve the inversion of the velocity and the targeting of the landing site. As for the analysis of the re-entry burn in the DRL scenario, the recovery capability analysis of the boost-back burn is carried out considering the same variability in terms of conditions at MECO, but the distance from the launch site at MECO was also added as a mission design variable.

### *3.2 Identification of the performance needs*

Based on the results of the recovery capability analysis, the performance needs are identified for the two proposed recovery strategies (DRL and RTLS) to enable the re-entry and landing of the RETALT1 first stage.

The total propellant budget for each scenario and configuration is computed as function of the conditions at MECO taking into account the propellant consumption required for each phase, building end-2-end performance maps [5]. The region of FPA/velocity at MECO for which a recovery mission is compatible with the available propellant and the structural constraints is defined as the feasible domain for the return mission. For example, for the planar fins' configuration (Fig. 4), the maximum dynamic pressure limit prevents to perform a DRL of the first stage for launch missions that have very steep FPA and very high-speed conditions at MECO. The maximum propellant available of 50 tons limits the duration of the re-entry burn for very high speed and shallow conditions at MECO, characteristics of launch missions to GTO.

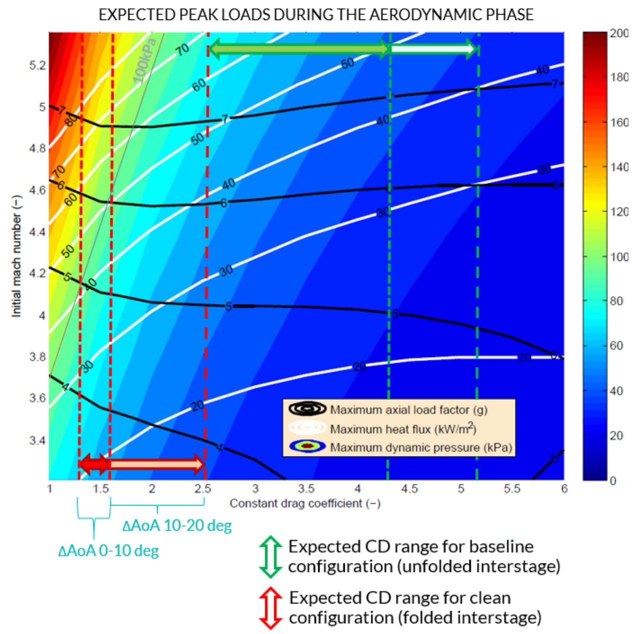


Fig. 3 – Expected peak loads during the aerodynamic entry, RETALT1 aerodynamic phase

Moreover, propellant available limits the feasible domain for the RTLS mission to low speed and steep conditions at MECO (Fig. 5). Also, if the MECO occurs more than 60 km downrange from the LS, RTLS is not possible for the range of conditions at MECO considered.

The use of grid fins allows saving on average up to about 5% of the total propellant budget for the same mission (any given set of conditions at MECO), but this gain in the propellant consumption is not enough to significantly change the feasible domain. The use of the interstage petals as aerobraking devices has a similar yet much stronger impact with a 13% saving on average for the same mission [5].

Also, a dispersion budget could be computed to define the characteristics of the trajectory control that shall allow a precise landing [5]. This dispersions budget can used to derive preliminary requirements for the GNC.

The ACS design and sizing activities showed that the use of the interstage petals as the main ACS for the current RETALT1 configuration is considered not feasible due to current structural and mechanisms design limitations [7]. Hence, the configuration with the planar fins was selected as the baseline configuration for RETALT1. Although deemed unfeasible for the RETALT1 vehicle, the impact of having the interstage petals on the overall propellant budget is significant in comparison to the planar fins. The use of such aerobraking devices is recommended for smaller launchers, when actuation loads are limited and feasible solutions could be designed.

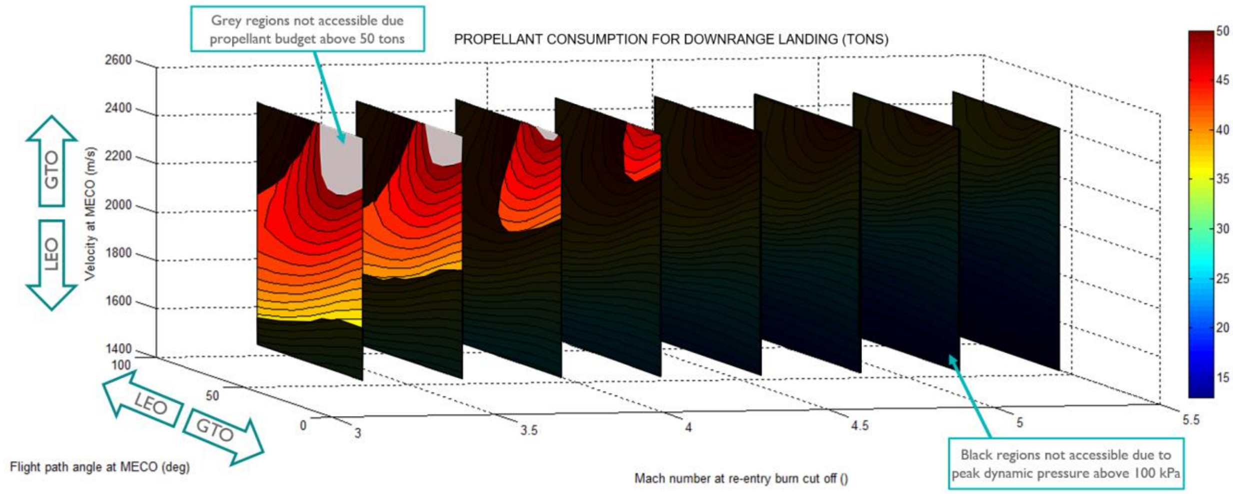


Fig. 4 – End-2-end propellant budget as function of conditions at MECO, RETALT1 PF configuration, DRL

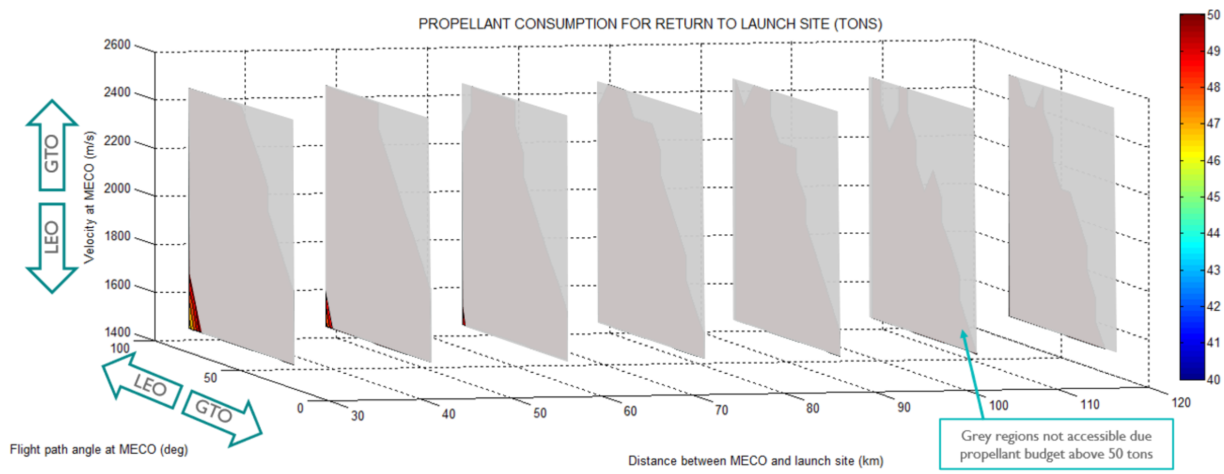


Fig. 5 – End-2-end propellant budget as function of conditions at MECO, RETALT1 PF configuration, RTLS

For the baseline planar fins configuration, an overall feasibility map is identified considering both the DRL and RTLS recovery strategies and as function of the velocity and FPA conditions at MECO. Fig. 6 shows the RETALT1 recovery feasibility map for the range of MECO velocity and FPA considered in this mission feasibility analysis. For the sake of comparison, the recovery map inferred for SpaceX's Falcon 9 [8] is also reported.

## 4 Mission design

### *4.1 Entry corridor analysis*

The trimmability and stability of the system - Flying Qualities Analysis (FQA) - are evaluated to support the definition of a trim strategy and a trim solution based on the mission needs. The AoA Entry Corridor (EC), defined as the region of the Mach-AoA plane compatible with the set of flight mechanics constraints considered, identifies

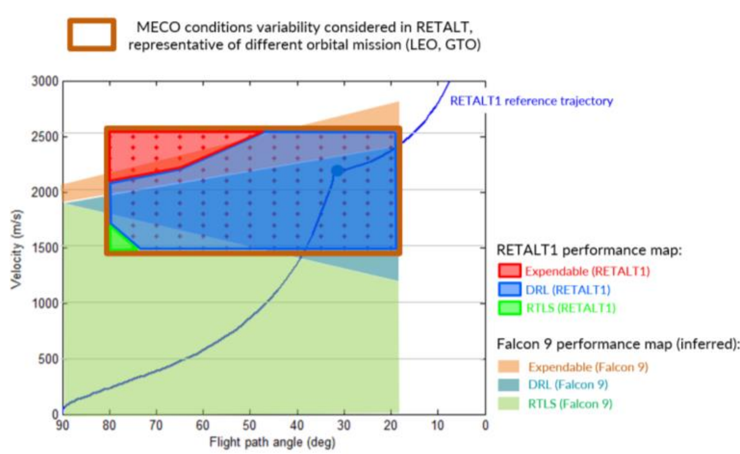


Fig. 6 – Feasibility map for the recovery of RETALT1 (and comparison with reconstructed F9 performance [8])

the region within which a trim solution can be found.

The trim design and the FQA are carried out for all phases of the return mission of RETALT1 when the aerodynamics is non-negligible: the landing burn and, most importantly, the aerodynamic phase. The FQA tool available in DEIMOS is used [1] for this analysis. Fig. 7 shows the longitudinal entry corridor during the aerodynamic phase for the planar fins' configuration for a CoG correspondent to the reference propellant consumption as obtained by the consolidated DRL reference trajectory. The corridor is obtained considering dispersions in the atmosphere, aerodynamics, and MCI. The result shows that a valid entry corridor (green region in the figure) can be identified for the region of interest in terms of Mach-AoA. In particular, the aerodynamic flight is expected to be fully trimmable and stable up to ΔAoA of 10º, in line with the mission needs. The fins deflection required to trim the vehicle is also reported. Similar results are obtained for the RTLS scenario, that has a lower mass during the aerodynamic phase, and therefore a slightly forward CoG.

With respect to preliminary results obtained with initial versions of the dataset [5], the consolidated aerodynamic database shows better stability performance of the vehicle during the aerodynamic phase, assuring full flyability of the first stage for all the mass range including with a full tank loading.

In RETALT the EC analysis was extended also considering different CoG locations to take into account the different propellant loading that the vehicle could have during the aerodynamic phase, obtaining a so-called feasible domain (FD) analysis that showed a trimmable and stable configuration for all the CoG envelope of interest [5].

A similar analysis has been carried out for the landing phase. In this case, the central engine is active and when the TVC is actuating the vehicle shall be trimmed taking into account the contribution of the thrust. Based on the models available, the planar fins are able to fully trim the vehicle during the landing phase [5]. Therefore, the FQA confirms the return mission to be feasible from a flight mechanics point of view, and the performance required to guarantee the recovery of the RETALT1 first stage could be met. These results have been used as input to consolidate the reference return scenario of RETALT1.

### *4.2 Mission consolidation*

The mission design consolidation for the RETALT1 return scenarios has been carried out focusing on the baseline configuration with planar fins. Consolidated reference trajectories have been optimized considering the flight envelope and mission requirement derived from the mission feasibility analysis. Different initial conditions for the two scenarios have been assumed in line with the feasibility domain reported in Fig. 4 and Fig. 5. Trajectory optimization is performed with a DEIMOS'

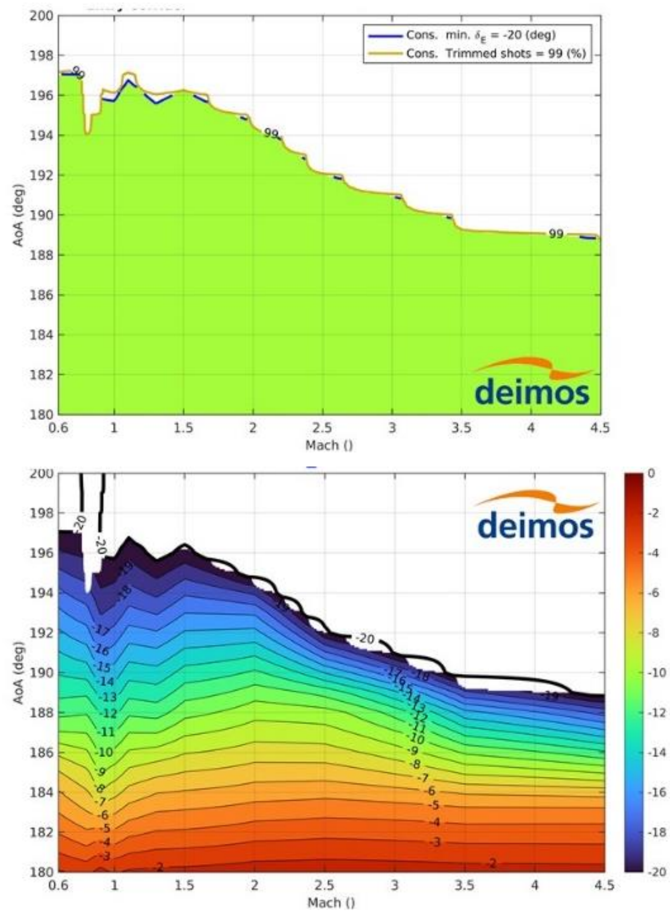


Fig. 7 – Dispersed (Monte Carlo) AoA entry corridor for the reference propellant loading, planar fins configuration, aerodynamic phase

DEIMOS' proprietary optimisation tool [1]. The objective is to define a reference mission compatible with the performance needs and the mission requirements and that minimizes the propellant consumption. The optimisation variables are the timing of the different burns (landing, re-entry, and boost-back for RTLS), the attitude during the aerodynamic phase, and the attitude profile during the boost-back phase for RTLS.

The consolidated trajectories respect all the mission constraints, with margins to compensate for uncertainties and dispersions. The angle of attack during the aerodynamic phase is optimized in order to have a different value to 180º and therefore obtaining two main benefits: increased drag acceleration which contributes to the braking allowing propellant saving, and creation of positive lift acceleration that can be used to control the trajectory and generate enough crossrange capability to steer the vehicle toward the landing site (Fig. 9). The consolidation of the reference trajectories with more detailed aerodynamic datasets confirms the feasibility of the mission solution, showing similar performance in terms of trajectory characteristics (Fig. 8). The consolidated propellant consumption for the DRL scenario is lower than 45 tons (Fig. 8), while for the RTLS scenario it is slightly lower than 50 tons as a result of the additional boost-back manoeuvre, and in line with the preliminary needs estimated in the mission feasibility analysis. However, the boost-back manoeuvre partially contributes to slow the 1st stage down reducing the propellant budget for the re-entry burn in case of RTLS by about 30% with respect to the DRL scenario. The trim AoA solution for the aerodynamic phase is within the entry corridor, therefore avoiding instability regions.

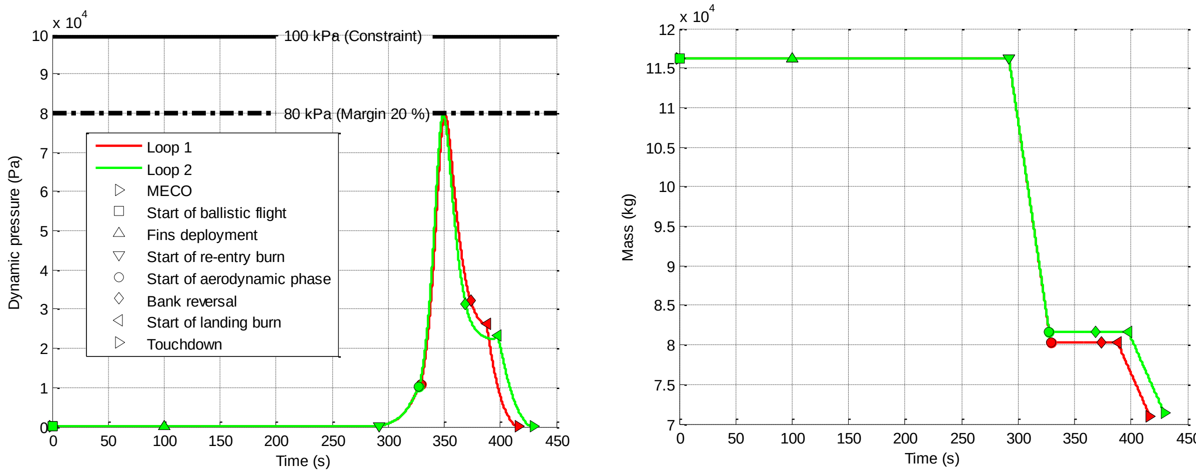


Fig. 8 – Dynamic pressure (left) and total mass profile for the DRL (R1 B) scenario

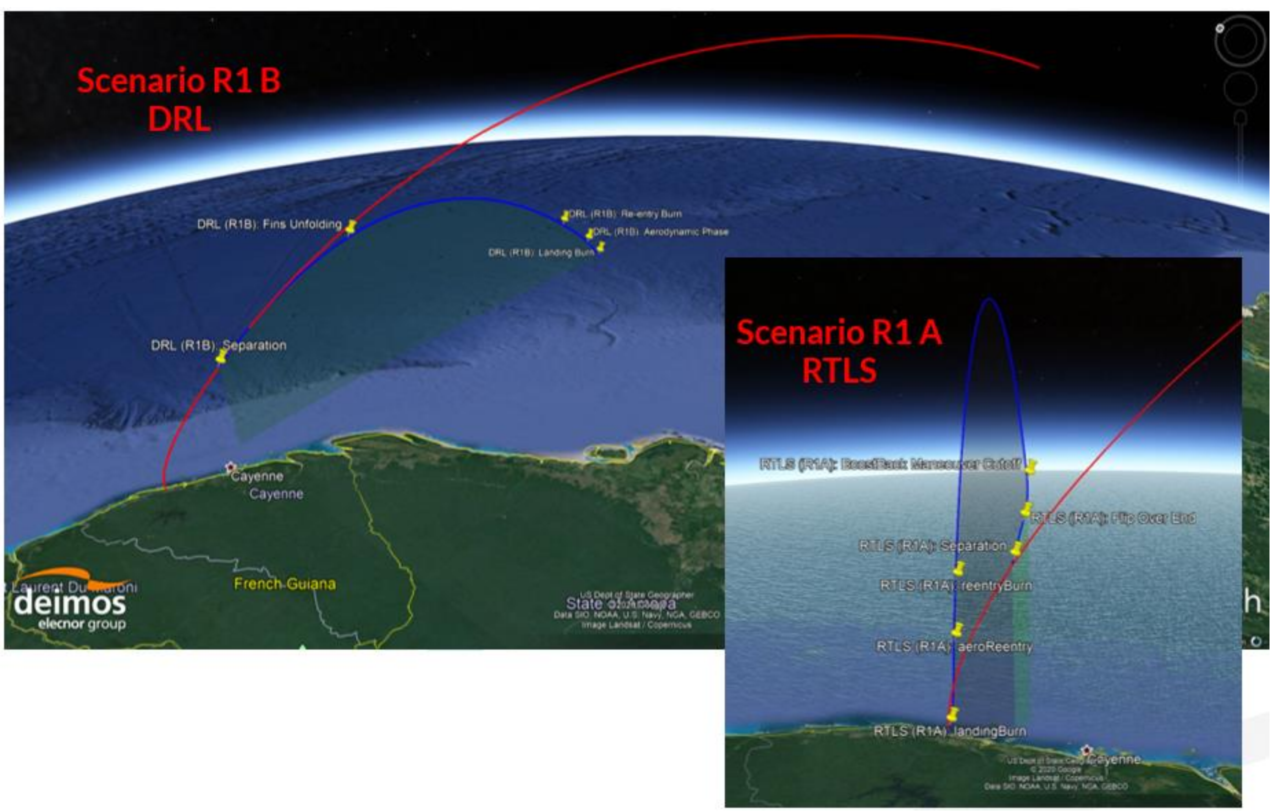


Fig. 9 – Google Earth representation of the consolidated return trajectories: RTLS (R1 A) and DRL (R1-B) scenarios

# 5 GNC design

## *5.1 Functional architecture*

The GNC is split into the following sub-functions:

- *Navigation*: it provides position, velocity and attitude estimates during the return phase, making use of Inertial Navigation System (INS), or IMU, products hybridized with a GNSS. The use of (D)GNSS/altimeter allows increasing the accuracy of the estimation close to landing.
- *Guidance*: it defines the re-entry, descent, and landing trajectories during the return phases. This serves to ensure the vehicle is able to perform a pinpoint landing, respecting the mission and flight path constraints.
- *Control*: it tracks the reference produced by the guidance and ensures a stable attitude, using the effective actuators for the phase. This includes the actuator management.

The end-2-end GNC architecture is illustrated in Fig. 10, where the interactions between each sub-function, the Flight Manager, the sensors and actuators are also included. The GNC operational modes are defined by the mission phase in Fig. 11, together with the sensors and actuators applicable for each mode. The guidance commands the attitude manoeuvres required in each phase of the flight, the modulation of the attitude during the re-entry burn and the aerodynamic phase to target the correct location at the start of the landing burn.

The Control takes care of executing these manoeuvres while rejecting perturbations, making use of Thrust Vectoring Control (TVC), Reaction Control System (RCS), and Aerodynamic Control Surfaces (ACS) based on their availability during the flight. The navigation could also use (F)ADS, or altimeter, if needed, to further improve the estimation accuracy close to the landing site.

## *5.2 Guidance*

The purpose of the guidance during the return mission is to steer the first stage to the desired landing site, either the launch site or a barge depending on the return scenario, and guarantee a pinpoint landing. The guidance strategy varies for each specific phase of the return mission, due to the different objectives and dynamics encountered for each of the phases, being the powered descent and landing guidance the key algorithm as it shall cope with the fast dynamics of the landing phase, where the aerodynamic contribution is still relevant, be robust to the vehicle and environmental uncertainties, and compensate residual position and velocity dispersions from the previous phases.

The solution for the RETALT powered descend and landing guidance relies on the definition of an Optimum Control Problem (OCP), that is optimized on-board. The OCP is defined with a dynamic model, an objective function, and a set of constraints; it is discretized and then

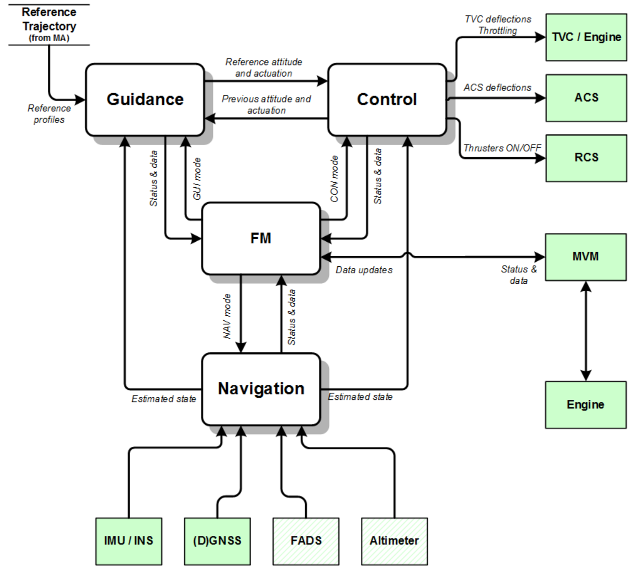


Fig. 10 – RETALT1 recovery GNC functional architecture

| Phase | Guidance | Navigation | Control | Maneuvers |
|---|---|---|---|---|
| Boostback burn | Landing site targeting | | Maneuvering, Pert. Rejection TVC / RCS | Quick Flip over Boostback burn |
| High altitude ballistic flight | - | Hybrid IMU/INS – (D)GNSS | Maneuvering, Pert. rejection RCS | Slow Flip over ACS deployment |
| Reentry burn | Trajectory corrections - powered | | Maneuvering, Pert. rejection TVC / RCS | Reentry burn |
| Aerodynamic phase | Trajectory corrections - aerodynamics | Hybrid IMU/INS – (D)GNSS- FADS | Maneuvering, Pert. rejection ACS / RCS | Trim control and bank control |
| Landing burn | Pinpoint landing - powered | Hybrid IMU/INS – (D)GNSS- FADS - altimeter | Maneuvering, Pert. rejection TVC / ACS / RCS | Pitch control Landing burn |

Optional

Fig. 11 – RETALT1 recovery GNC modes

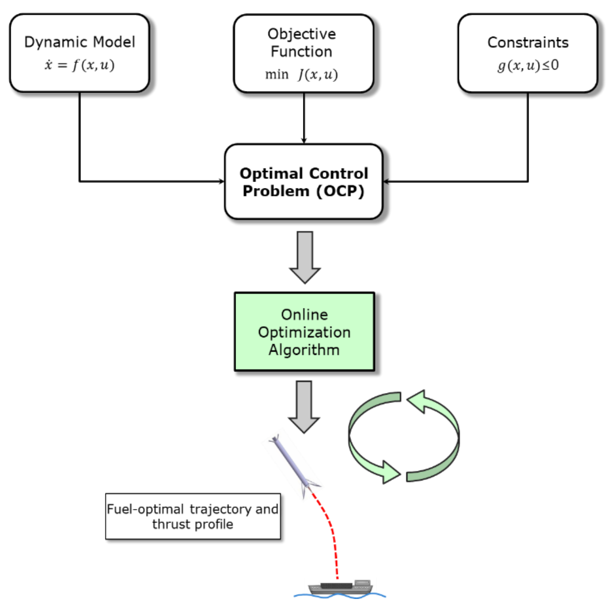


Fig. 12 – Powered descent and landing guidance strategy

solved at a low frequency in real-time using available optimization solvers (see Fig. 12). Extensive research has been conducted in the last years to study how this methodology can be applied to the powered descent guidance problem for Mars landing missions [9][10] aiming at fuel optimal solutions in presence of non-negligible aerodynamic forces [11]. The adaptation of these techniques to the launchers' recovery problem has been studied [12][13] and has been proposed for the CALLISTO experiment [14]. More notably, the guidance employed by SpaceX for the Falcon 9 landing also utilizes this type of strategy [15].

This type of online strategy is necessary especially for the landing phase due to its challenging nature, since a feasible trajectory must be computed from an initial condition which has accumulated considerable dispersions from previous phases, to a precise final position with an accuracy of a few meters. Moreover, several operational constraints exist that condition the feasibility of the generated reference trajectory, such as the available propellant, the thrust capabilities of the vehicle, and attitude constraints, including the maximum angle of attack and a near-vertical final orientation, which more traditional trajectory planning methods do not allow to implicitly satisfy.

The largest limitation of the selected strategy is the relatively high computational load necessary for solving the optimization problem, which must be sufficiently complex in order to capture the fast dynamics and constraints of the guidance problem. The dynamic modelling is the most critical step in the design of this algorithm: the model may be arbitrarily realistic and complex, which improves the fidelity of the guidance output, but also increases the computational effort required to obtain it. Therefore, the formulation of the optimal control problem is a trade-off between the fidelity and complexity of the problem, and the computational effort required to solve it [16].

The guidance solution implemented for RETALT [16] includes the modelling of non-linear aerodynamic forces, variable mass, and free manoeuvring time. It also allows for the implicit satisfaction of operational constraints such as: thrust throttle and attitude magnitude and rate, to consider limitations of the engine and TVC, terminal state, to ensure soft, vertical touchdown, glide slope and aerodynamic angles, to ensure the glidepath remains above a specified limit and the attitude copes with flying qualities. These characteristics result in a non-convex optimisation problem, that is solved with successive convexification techniques that compared to alternative solutions allows exploiting benefits such as good convergence properties and low computation effort [11].

The guidance solution is developed focusing mainly on the powered descent and landing phase, but its applicability is tested also for the other phases of the return mission.

### *5.3 Navigation*

To allow the pinpoint landing of the RETALT1 first stage the navigation system shall be able to produce extremely precise estimations of the vehicle states, to give margins to the guidance and control contributions to the GNC error (e.g., position estimation accuracy at landing below 1m, velocity estimation accuracy below 0.2 m/s).

The navigation solution identified to cope with these demanding requirements is an INS/GNSS coupled system, in which the INS solution is hybridized with the observations provided by the GNSS receiver through an EKF-based filter (Considered Kalman Filter). The navigation algorithm implemented autonomously and internally manages the applicable process based on the availability of measurements from the different sensors. This navigation solution has the advantage of simplicity and redundancy. In fact, this architecture can be used with any kind of INS and GNSS equipment and allows outage of GNSS measurements, as the two sensors work independently. Differential GNSS receivers could be used to complement or in alternative to the standard GNSS unit. Other available sensors (altimeter, FADS), could be integrated with an uncoupled architecture.

### *5.4 Control*

The objective of the control function is to actuate the vehicle in order to maintain its attitude stable, while rejecting disturbances, and to track the reference attitude as commanded by the guidance, within a given accuracy, as specified by the control requirements. This must be done over the full set of flight conditions while respecting the actuator limitations and constraints.

The control for the recovery of RETALT decouples the control of the pitch and yaw channels exploiting vehicle axis-symmetry through TVC/ACS commands, and controls independently the roll rate control using RCS / ACS. Multiple MIMO controllers are designed for different points of the trajectory by solving an optimization problem aimed to ensure the closed-loop robustness to model uncertainty and perturbations, following a well structure design methodology which consists in the derivation, at first, of reliable models obtained by using the so-called Linear Fractional Transformation (LFT) framework, which is particularly suitable for robust control design. The LFT framework allows the representation of the system to control by means of the feedback connection of the nominal plant G(s) and a block diagonal uncertainty $\Delta(s)$ gathering all the uncertain parameters of the system. Then, the controller is synthetized using robust control design techniques. The controller synthesis problem (Fig. 13) consists in finding the controller with transfer function K(s) that stabilizes the closed-loop system, while minimizing a given cost function. The structured $H\infty$ control synthesis will be applied in order to obtain a

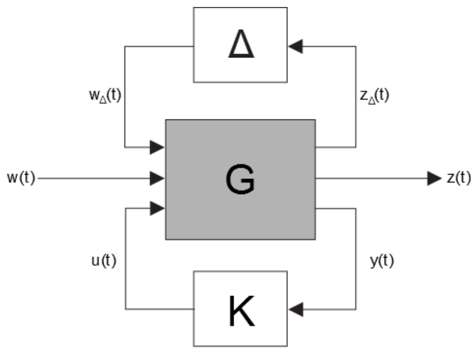


Fig. 13 – Control synthesis problem

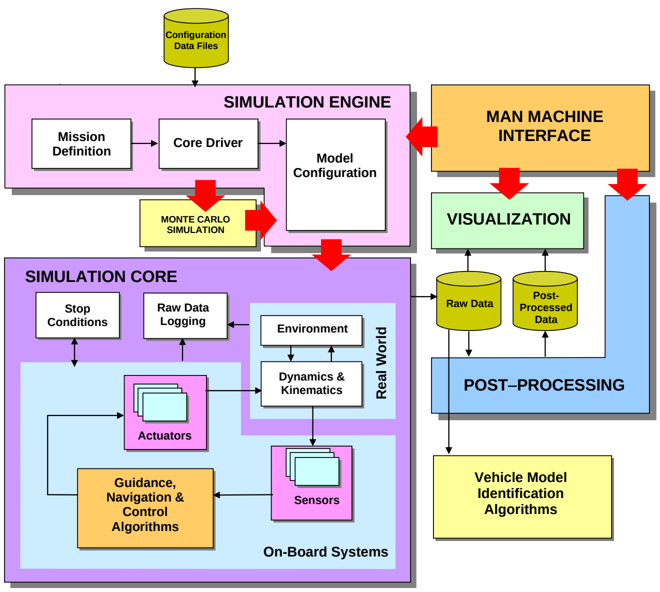


Fig. 14 – RETALT FES architecture

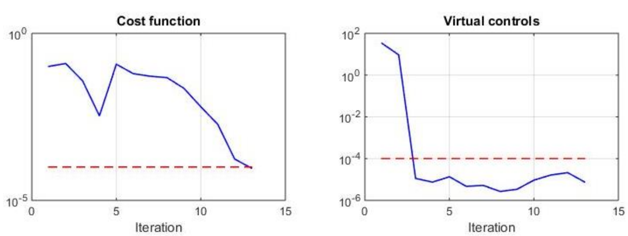


Fig. 15 – Convergence properties of the guidance solution, nominal case

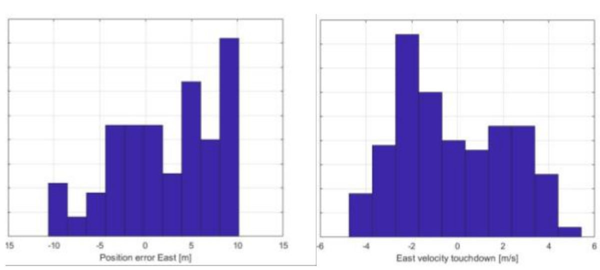

Fig. 16 – Statistics of position and velocity errors at touchdown

controller which guarantees the robust performance of the closed-loop system in the presence of the uncertainties, while keeping a low order predefined controller structure. Finally, μ-analysis techniques are used to assess the robust stability of the system in presence of dynamical and parametric uncertainties.

## 6 GNC performance

### *6.1 Functional Engineering Simulator (FES)*

A Functional Engineering Simulator (FES) has been used to support the GNC testing and evaluate the performance of the algorithms developed in RETALT. The RETALT-FES is a high-fidelity simulation environment based on SIMPLAT [17], that has been tailored to RETALT including detailed vehicle configurations and mission scenario models. It allows performing simulations in 3 and 6 DoF, with G-N-C algorithms in the loop, and performance models of sensors and actuators, see Fig. 14.

### *6.2 Guidance performance*

The optimised guidance is able to solve the descent problem guaranteeing good performance in terms of convergence and accuracy of the solution. In the nominal case for the downrange landing scenario, for example, the algorithm converges in less than 15 iterations, with the cost function defined reaching the desired threshold, with the virtual controls used to help the convergence decreasing rapidly below negligible levels, see Fig. 15.

The guidance is able to successfully recover uncertainties in initial conditions (in line with the trajectory control capability of the system) environment, aerodynamics and MCI, with very good accuracy at touchdown, as 99.5% of the shots (200 in total) below 15 m of position deviation from the target (including algo the contribution of the Control and Navigation to the GNC error), see Fig. 16 and Fig. 17. The velocity at touchdown is also kept under control, with about 80% of the cases below 3 m/s in terms of horizontal velocity and 99.5% of the cases below 5m/s.

Vertical landing is achieved with the controller being able maintain the verticality of the vehicle, with all the runs showing a final tilt angle less than 5 deg.

Moreover, the propellant needed to complete the phase is less than 10 tons, in line with the propellant budget estimated by mission analysis.

### *6.3 Navigation performance*

A trade-off of the navigation performance allowed the identification of a baseline sensors suite among state of art options: a class II IMU - LN-200E (Northrop Grumman) was used to provide reference performance –, and a differential GNSS – (D)GNSS – that acts as GNSS when outside the range of (D)GNSS operativity. For the latter, the strict requirements of RETALT mission,

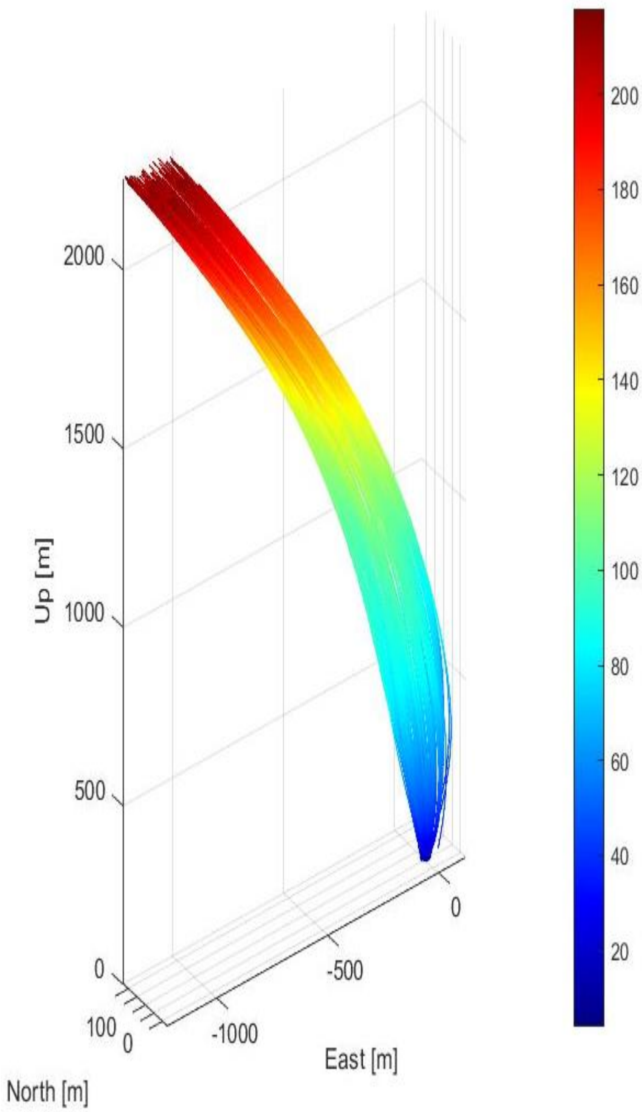


Fig. 17 – Trajectory path during the powered descent and landing phase

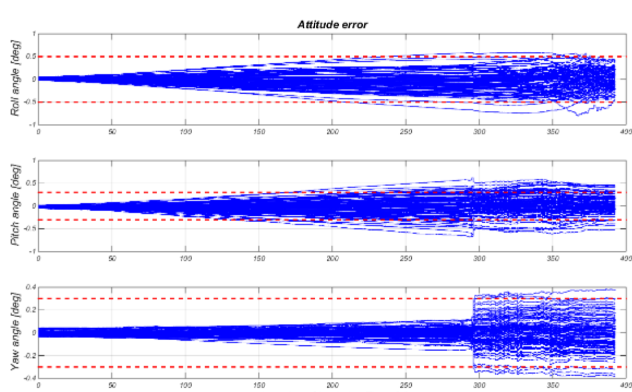


Fig. 18 – Attitude estimation accuracy, end-2-end return trajectory

suggest to limit the selection between the two more precise options:

- RTK (Real Time Kinematic) positioning, provides the most precise measurements, relative to a local surveyed base station network (ie. Ground station at landing site).
- PPP (Precise Pointing Positioning), which requires provision of real-time GNSS orbit and clock corrections from a dedicated service provider. (i.e. using data from the TerraStar correction service to deliver a globally available and reliable solution).

Given the specific nature of the landing problem in RETALT, the RTK method could be beneficial in the RTLS scenario, as the “base” antenna is well known and hence the position of the launcher can be precisely estimated. However, this kind of sensor may not be the most suitable in the case of DRL, if landing has to be performed on a barge. For the DRL on a barge, the preferred option would be to directly use the PPP technology, with the additional advantage of keeping the higher level of accuracy during the whole flight. Both scenarios have been analysed, using as (D)GNSS the Novatel OEM719, configured to be working as RTK or as PPP (TerraStar-C service).

Both allow to reach the desired level of accuracy at landing, being the PPP option more uniform as the performance are independent of the vehicle position, but requiring the acquisition of the TerraStar correction services, while the RTK is depending on the distance to the base antenna, with increasing level of accuracy while approaching it. In general, end-2-end results – obtained simulating from MECO until touchdown and considering uncertainties on sensors and navigation performance and mounting – showed that the navigation guarantees very good performance, in line with the requirements:

- Position errors < 0.5 m (3σ)
- Velocity errors < 0.2 m/s (3σ)
- Attitude errors < 0.5º (3σ), see Fig. 18

The navigation concept shows very good performance also in presence of winds, when an on-board wind table is used by the navigation. With a wind knowledge error assumed up to 15 m/s, the estimation performance are similar to the no wind case. The winds have a significant impact on the attitude throughout the flight, however the navigation performance are recovering the increased error during the propelled flight phase: roll angle estimation error is within the requirement, while pitch and yaw slightly exceed it. These results shows that the proposed navigation concept is able to provide the required estimation performance, and the use of additional sensors (e.g., (F)ADS) is not strictly necessary, even if their inclusion is not discarded a priori.

### *6.4 Control performance*

At design level, the performance of the controller are evaluated along the reference trajectory; indeed, given the high variability of the flight conditions for the mission considered, gain-scheduling is applied and the airspeed is used as scheduling variable. In addition, uncertainties in aerodynamics and MCI are considered for the assessment of the robustness properties of the controller. Before performing the synthesis, the control-oriented linear time-invariant models are compared with the FES (in open-loop) to ensure a good validity of the adopted modelling assumptions, while the achieved closed-loop performance are summarized in Fig. 19. The robustness of the designed attitude controller with respect to the considered uncertainties is proved by the mu-analysis, whose results are reported in Fig. 20: it can be seen that the upper bound of mu is below 1 for all the operating points, thus confirming robust stability for all the considered flight conditions.

The results with the integrated GNC in the loop confirmed the validity of the control solution defined, as the vehicle is fully controlled and stable during the complete flight. Moreover, the control is able to correctly track the manoeuvres commanded by the guidance and required to control the trajectory error. The control error, in fact, is always within 2 deg. The good behaviour of the controller allows the launcher to touchdown with a tilt angle below 2 deg for 99% of the cases (see Fig. 21), and rates always below 2 deg/s.

## 7 Conclusions

During the RETALT project key technologies for launchers reusability were developed in the domain of flight dynamics and GNC.

A mission engineering methodology for the return mission analysis and design of reusable launchers was developed. Applied to the RETALT1 configuration, it demonstrated that the recovery of the first stage of RETALT1 is feasible with strategy based on the use of retro-propulsion. The propellant budget assigned for the return mission enable the recovery of the RETALT1 booster for a wide range of launch missions, that can be performed either with a downrange landing on a barge, or with a return-to-launch-site depending on the conditions at MECO. This analysis allowed to define preliminary mission requirements that drove the consolidation of the return mission design. From the consolidated mission flight and landing loads were also computed to support the sizing of the aerodynamic actuators, and the design of the GNC solution.

The GNC concept for the recovery of the first stage of RETALT1 was also defined. In particular, an end-2-end GNC architecture was defined, and critical algorithms were defined to assure a precise estimation of the vehicles state and the capability to perform pinpoint landing while compensating for relevant uncertainties and with a fully

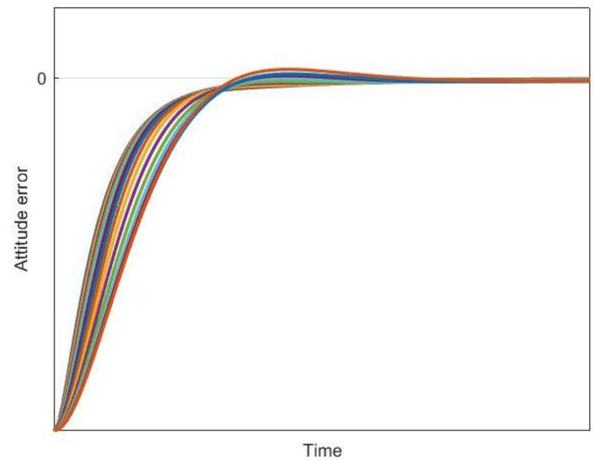


Fig. 19 – Pitch attitude controller time domain performance for different flight speeds; step response time history

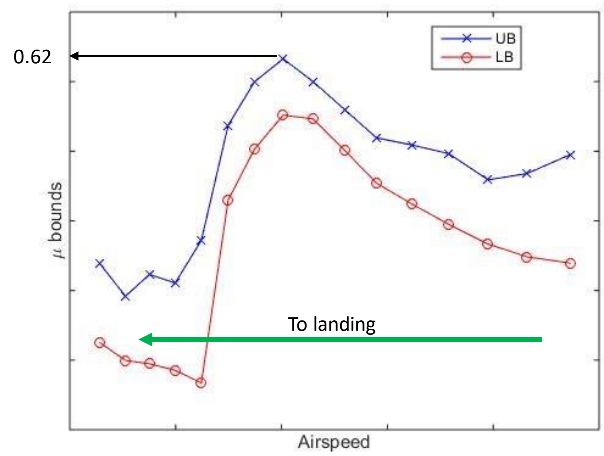


Fig. 20 – Structured singular value behaviour along trajectory

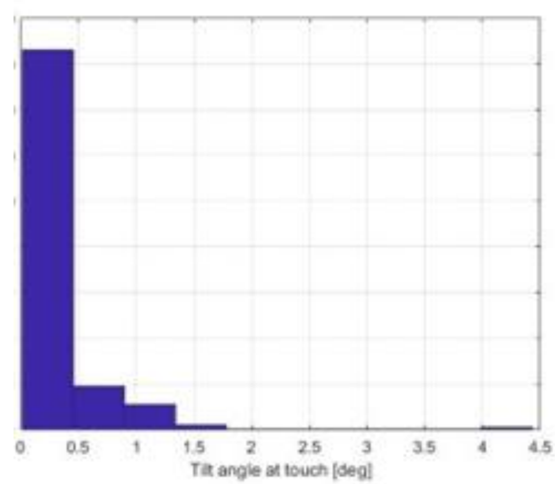


Fig. 21 – Statistics of launcher tilt angle at touchdown

controlled vehicle. The GNC solution relies on state-of-art sensors, and makes use of RCS, TVC, and ACS, depending on their availability during the return flight.

A high-fidelity functional engineering simulator framework was used to integrate the complex vehicle's models and the GNC algorithms, allowing the test of the proposed solution in a model-in-the-loop simulation environment. The results of the simulation campaigns showed good GNC functioning and promising performance. The main test campaigns focused on the powered descent and landing phase, that is the most critical part of the flight. For this phase, the proposed GNC solutions reached a TRL of 3. Further tuning and small improvements are necessary to be fully compliant with all the requirements, but the results obtained indicate that the solution proposed is valid.

Further development of the GNC shall focus on the consolidation of the end-2-end GNC solution for the complete return phase, including the management of the boost-back burn and the re-entry burn, for which preliminary tests were carried out but a fully integrated and coherent GNC solution is not yet fully consolidated. In particular, the focus should be the testing of the optimised guidance, as the hybrid navigation has been assessed for the complete return scenario, and the control synthesis also covered all phases of the return trajectory.

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