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Mission Engineering for Space Rider Maiden Return Mission

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Abstract

The ESA Space Rider programme is developing a European reusable space transportation system for routine access and return from Low Earth Orbit. The Space Rider system is composed of an expendable AVUM Orbital Module, and a reusable Re-entry Module designed to be flown multiple times. The latter must be a flexible system to carry a wide range of payloads, and robust enough to cope with a wide range of flight conditions, in compliance to the applicable safety constraints in case of failure. This is a critical challenge for Europe, beyond the state of the art in re-entry technology represented by the successful flight of the ESA Intermediate eXperimental Vehicle IXV.

This work presents the Space Rider Mission Engineering activities carried out during the phase D of the program, focusing on the baseline mission updates for the maiden mission, landing at Santa Maria, Azores. This study also provides an in-depth description of three specific advancements that have been introduced in the latest loop of mission analysis.

The first advancement provides feedback to verify that the trim-line is not only inside the bounds of the entry corridor but also ensures the largest possible margins from the constraints.

The second is the reduction of the number of trajectory optimisation variables due to the use of an on-board guidance model in the optimal control problem, reducing the gap between simulations and flight.

The last novelty jointly executes the entry interface point localisation and de-orbit manoeuvre optimisation with the same modelling fidelity of the mission performance verification, expanding the range of solutions for the de-orbit manoeuvre in 2 dimensions.

The engineering advancements that have been developed improve the mission design processes, by providing additional insights on the capabilities of the system and guiding the choices that affect the outcome of the mission verification.

Keywords: *Mission Engineering, Flying Qualities, Trajectory Optimisation, Space Rider*

1. Introduction

The Space Rider programme [1] progresses further in the main advancements developed and tested during the successful Intermediate eXperimental Vehicle (IXV) flight. This successful mission demonstrated the European independent capability to return from space. Critical technologies in hypersonic flight conditions, fully representative of an atmospheric re-entry from Low Earth Orbit (LEO) were also demonstrated, as a step toward future space applications.

The Space Rider main objective is to develop a European reusable space transportation solution for space access, extended orbital stay, and return missions. The vehicle provides alternative or complementary sovereign capabilities that do not rely on the soon to be decommissioned International Space Station. This affordable end-to-end transportation system benefits to the maximum extent possible from existing technologies and addressing where relevant progressive technological challenges with limited risks and minimal financial efforts for Europe. The shape of the Space Rider re-entry vehicle is thus inherited from IXV with a size scale-up. The VEGA C+ orbital launch vehicle covers the additional performances requirements, with increased payload fairing volume and payload mass capacity.

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Thales Alenia Space is the leader of the industrial consortium and co-prime, with AVIO, of the Space Rider mission. Indra-Deimos is responsible for the mission engineering activities of the operational flight presented in this study, but also for the drop test campaign mission analysis [2], and is contributing to the development of the GNC system [3] that governs the re-entry module's safe descent and landing.

This study provides the results for the mission engineering of the Santa Maria, Azores (SMA) baseline mission scenario and an in-depth description of the three specific advancements that have been introduced in the latest analysis loop, providing extra insights in the process. The Space Rider Mission Engineering activities of the phase D of the program are parallel to the manufacturing, qualification and testing campaigns, with the aim of flying the complete end-to-end return mission in the coming years.

1.1. Mission Engineering

Mission Engineering is a process that includes multiple activities in support of the mission and system design: flying qualities analysis, assessment of the deorbiting opportunities, reference trajectories optimisation, analysis of the vehicle flight capabilities during entry and under parafoil, assessment of the mission performance through Monte Carlo simulation campaigns, and safety analyses during all phases of the return mission.

Indra-Deimos leverages expertise in those fields inherited from the IXV development, through mission analysis tools which have continuously improved with advancements introduced over time. The mission engineering [4] activities are developed and enhanced in each analysis loop, fulfilling new requirements or integrating updated inputs received along the testing and qualification process.

1.2. Mission profile

The baseline mission starts with the insertion the Space Rider System, comprising both the AVUM Orbital Module (AOM) and the Re-entry Module (RM), into the target operational orbit with the launch vehicle. The Multi-Purpose Cargo Bay of the RM starts its active role at orbit acquisition, performing the in-orbit payload operations with the AOM support, and remaining active until experiment completion or landing. The AOM performs the orbital manoeuvres required from the injection after the launch vehicle upper stage separation, until the deorbit boost is executed to return to the Earth. The Separation (SEP) of the AOM from RM happens at 490 km of altitude, before the Interface Control Point (ICP) at 200 km.

The second coasting phase concludes at 120 km, at the Entry Interface Point (EIP), with the start of the Entry phase. The re-entry phase ends at Mach 2.5 and is the critical flight section where the vehicle is subject to the entry loads. At Mach 2.5 the RM enters at the Terminal Area Energy Management (TAEM) phase, until Descent System (DS) triggering, where the parachute pilot is deployed followed by the drogue deployment. The Parafoil Deployment (PFD) happens at 5500 m, led by the parafoil pilot deployment and followed by the parafoil reefing. Finally, the PGNC is activated at lower altitude guiding the vehicle to the designated location and landing on the island of Santa Maria, Azores.

2. Mission Design

The Mission design is a multi-step process required to identify the reference trajectory flown by the vehicle. It starts with the analysis of the vehicle capabilities, identifying the aerodynamic trim configuration during re-entry and margins with the Flying Qualities Analysis (FQA), and subsequently identifying the down- and cross-range capabilities of the system. Likewise, the performances under parafoil are investigated in the Parafoil Target Area (PTA) analysis, to position the DS and PFD locations while satisfying the safety and glide range constraints under uncertainties.

Once the location of the re-entry end is defined, the de-orbit analysis finds the optimal location for the de-orbit burn, and the ICP gate through which the vehicle must pass to be able to successfully complete the re-entry, given the range capability of the system and the orbital constraints. Given start and end conditions, the optimal control problem solution finds the optimal trajectory to be flown in the re-entry phase, identifying the reference trajectory.

2.1. Flying Qualities Analysis

The flight mechanics performance must satisfy the requirements defined for the entire re-entry phase, integrating both flight dynamics and vehicle flying qualities. From a flight mechanics perspective, the Flying Qualities Analysis receives inputs at system and vehicle levels and provides a framework to evaluate vehicle performance. These results are then assessed against system-level requirements and may be used to refine the system design.

The objective of the FQA is to evaluate and verify the open-loop performance of the re-entry vehicle, ensuring full compliance with mission requirements. FQA defines the trim, stability and control characteristics and associated, ultimately identifying the optimal Mach, Angle of Attack trim line. The resulting data is provided as input to the Guidance, Navigation and Control (GNC) subsystem. Additionally, this analysis plays a critical role in the design and verification process of the vehicle configuration, ensuring flight safety and controllability during both steady flight and manoeuvring. In the current design phase (Phase D), the aerodynamic dataset, the vehicle Mass, Centre of Gravity and Inertia characteristics, and mission constraints have been updated, and used to perform the FQA [5].

Leveraging on the well-established, and flight qualified IXV flight design methodology, vehicle performance is first estimated using the Entry Corridor Design Tools before trajectory performance is assessed. The estimation process involves:

- Design assessment: Design of the Trim Line (AoA as a function of Mach) within the AoA Entry Corridor, ensuring sufficient margins against imposed constraints.
- Design verification: Verification of the design through Monte Carlo simulations of vehicle Flying Qualities.

The AoA Entry Corridor defines the region of the Mach - Angle of Attack plane that complies with all design constraints. This initial analysis includes uncertainties in aerodynamics, AoA, MCI and drag, captured via a Monte Carlo campaign. Results are statistically presented as the 99 % variability range with a 90 % Confidence Interval across Mach values. A Monte Carlo sample size of 1000 simulations is considered optimal to balance computational effort, result significance, and confidence in mission assessment. Accordingly, 1000 samples are used for the design, and 4000 for the verification. The analysis spans all flight regimes from hypersonic to subsonic.

Results are categorized into two main regimes:

- Hypersonic Entry corridor (Mach > 3, Fig 1 top plot): The IXV trim strategy is applied from Mach 27 down to Mach 3. A small region around Mach 25 exhibits an undamped short period mode, primarily due to the low dynamic pressure. In the low hypersonics, the Hinge Moment threshold is reducing the available angle of attack range, but safe margin is kept with the current design. Control system is expected to handle this behaviour effectively, as demonstrated for IXV [4].
- Supersonic Entry corridor (Mach < 3, Fig 1 bottom plot): The IXV trim strategy is applied between Mach 3 and Mach 0.8. In this region, the short-period mode is consistently damped, with Time to half values of at least 5 seconds. The dE trim strategy is also applied from Mach 0.8 to Mach 0.5 for this regime. In this range, damping is maintained for Mach numbers between 1.2 and 0.8, with Time to Half values of at least 6 seconds.

The Entry Corridor serves as the baseline for trimline design. In the hypersonic regime the trimline must align closely to the TPS design solution requirements. In the supersonic regime, the design must simultaneously account for multiple constraints. To support the specialist in this complex task, visualizing the cost function (Fig 1, central plot) proves to be a valuable aid in guiding the design process. The cost function is computed by accounting for all constraints indicated in the Entry Corridor figure’s legend, with the addition of the angle-of-attack rate, to reflect the vehicle’s dynamic limitations.

Following the trimline design, a verification phase is conducted to ensure compliance with all design constraints.

Two trim strategies have been considered and assessed for the supersonic, transonic, subsonic regimes:

- IXV trim strategy: a conventional approach that follows a Mach-dependent AoA profile (including dispersions), identifying combinations of elevator deflection (dE), aileron deflection (dA), and sideslip angle (AoS) that reduce moment coefficients below a given tolerance.
- dE trim strategy: an alternative approach that follows a Mach-dependent elevator deflection profile, determining combinations of AoA, dA and AoS that achieves the same moment coefficient reduction.

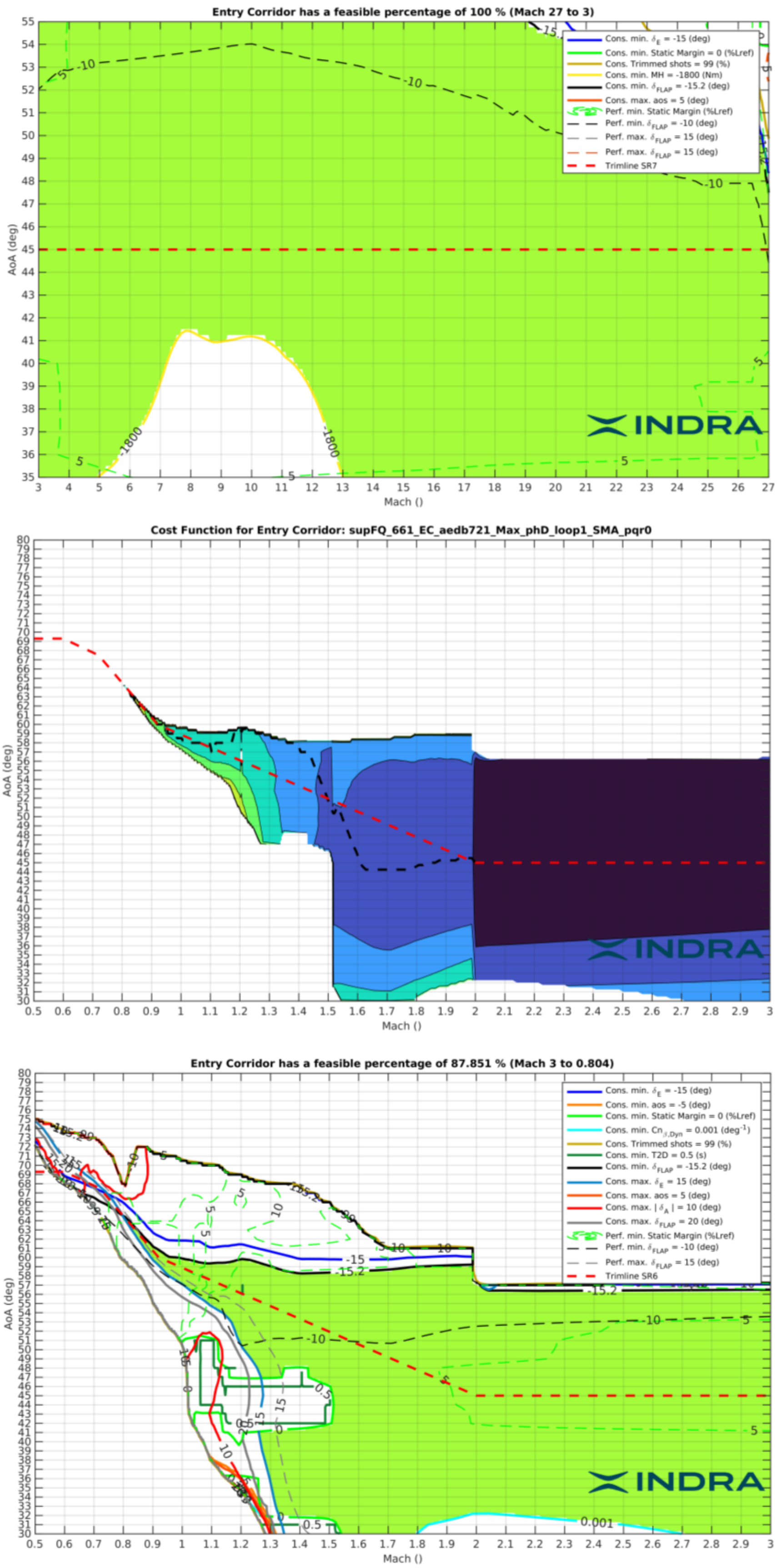
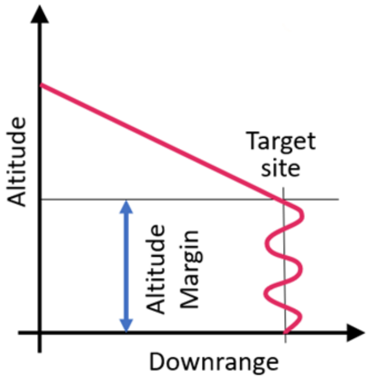


Fig 1. Entry Corridor, hypersonic (top) and supersonic (bottom) legs of entry phase (99 % variability range with 90 % CI). Trim Cost function (central), supersonic.

2.2. Parafoil Target Area analysis

The PTA is an analysis [5] used to define the location targeted by the vehicle during re-entry: the parafoil deployment (PFD) location. The PTA analysis computes the altitude margin (Fig 2), defined as the maximum altitude at which the system will reach the target landing site from a given starting position. Mapping the starting points in the area near the landing site identifies the altitude margin contours, obtained as a function of the waypoints and landing site locations, the parafoil aerodynamics, and the winds model.



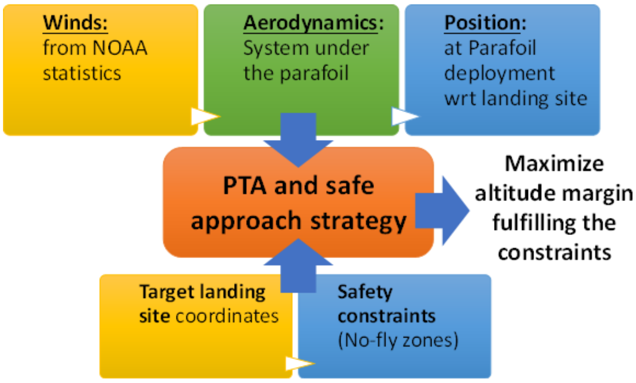


Fig 2. PTA altitude margin scheme (left) and contributing factors diagram (right)

The PTA process begins with the final item of the previous input list: the review of local wind databases, typically measured with sounding balloons or equivalent methods. These wind profiles are filtered according to the system's GO/NO-GO criteria, allowing identification of recovery opportunity windows and exclusion of profiles that violate operational constraints. Wind intensity and direction are extracted from the historical database of atmospheric profiles. A statistical analysis is then conducted to identify seasonal trends and potential dependencies on the time of the day. These wind patterns directly influence the selection of the DS triggering location and associated waypoints, aiming to balance the parafoil performances with the dispersion risk in the event of a failure. In particular, low-altitude wind conditions can significantly affect the potential landing area in off-nominal scenarios. The DS triggering location is chosen using data from previous analysis loops, specifically the failure dispersion ellipses, ensuring it remains clear of protected zones while maintaining a conservative altitude margin.

Waypoints are introduced when a specific approach strategy is required. In the Santa Maria Azores (SMA) scenario, for instance, Space Rider performs a loitering manoeuvre above the waypoint, gradually descending until landing conditions are met to proceed with the final approach, enhancing operational safety margins.

Fig 3 shows the results of the PTA for the scenario landing in SMA. It can be observed that the altitude margin contour is centred on WP1, as the Guidance will divert the vehicle from any place the parafoil inflates from to such location, but only if the altitude margin is sufficient to reach the landing site (LS). Although the PFD is triggered at 5500m, the altitude margin is reduced by the altitude lost travelled from WP1 to the LS and the highest contour line is 4500m.

The PFD target location has been positioned with knowledge coming from previous analysis loops. The ellipse shown in Fig 3 is updated with the results of the mission verification campaign of section 3, confirming a good placement. The PFD dispersion points are confirmed to be within the PFD accuracy assumed for the PTA definition, demonstrating the validity of the approach implemented.

All of the trajectories achieve a successful landing in proximity of the LS, and only 2% of the simulations skip WP1, heading directly to the LS. No trajectories cross safety boundaries (not shown), irrespective of the wind conditions and the safety analysis of section 4 finds no jettisoned item posing a threat to the ground.

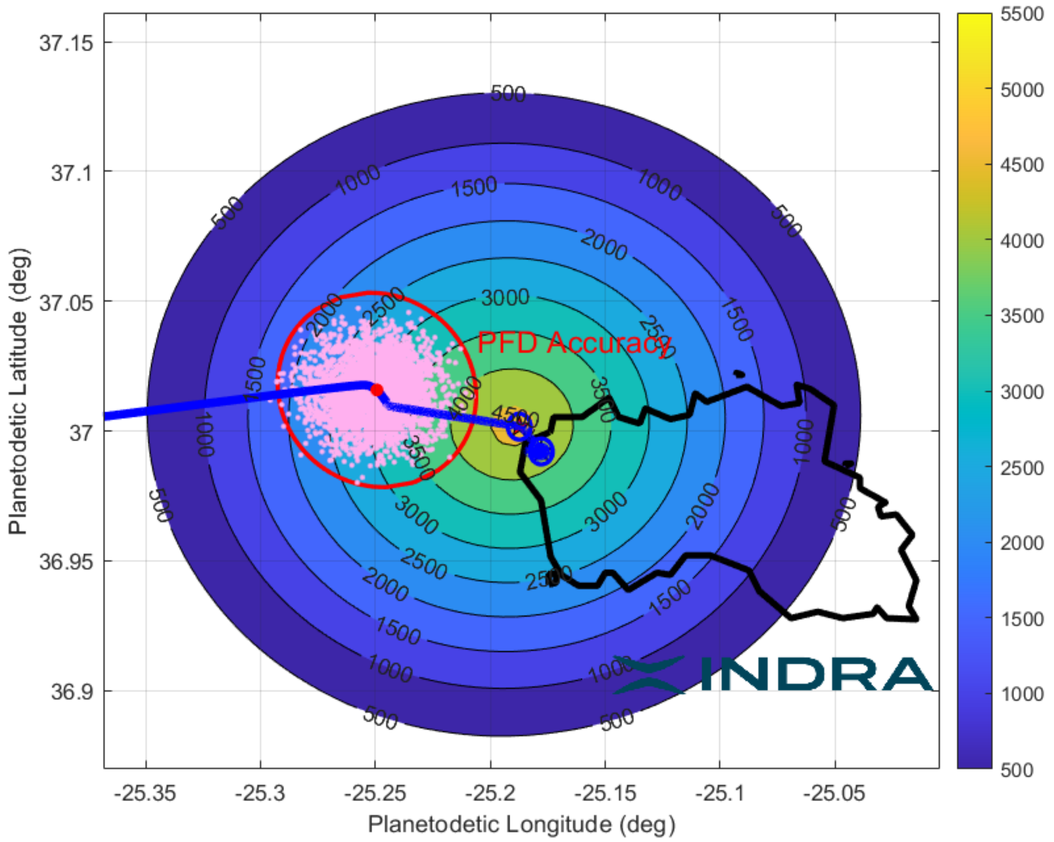


Fig 3. Parafoil Target Area analysis for the baseline scenario landing in SMA. Contours provide the altitude margin, Waypoint 1 (WP1) is marked with a red star.

2.3. De-orbit Analysis

As the PTA defines the target coordinates for the re-entry trajectory, the de-orbit analysis establishes the initial conditions of the reference trajectory. The analysis strategy is derived from the mission design requirements, considering the orbital parameters provided by AVIO, the vehicle characteristics, and the selected landing site. Within this framework, de-orbit gates are defined to enable the AOM to execute the manoeuvre at the appropriate conditions, ensuring that the RM enters the re-entry phase with the desired state to complete the return mission to SMA.

The analysis simulates both the de-orbiting and coasting phases, beginning with the initiation of the AOM de-orbit burn and ending at the EIP. It includes the following key mission phases and events:

- De-orbiting boost: propelled manoeuvre that targets the required initial conditions at the EIP.
- Coasting 1: from the conclusion of the de-orbiting boost to the separation of the AVUM from the RM, approximately 150 s after thruster cut-off.
- AVUM-RM separation
- Coasting 2: the RM flies to the target position, velocity, and attitude at the EIP.

The de-orbit analysis is initiated with a grid-based assessment, which provides the initial guess for the trajectory design. This step compares the downrange and crossrange capabilities of the system against the required target values with respect to the landing site location. A local optimisation is then performed, using as variables the burn duration, the RAAN, and the true anomaly for orbital phasing, while the inclination remains fixed by design. For the SMA scenario, the selected inclination is 34.3°, representing a compromise between launcher injection requirements and the crossrange manoeuvrability of the RM. Since this inclination is lower than the landing site latitude, the ascending and descending branches converge into a single return solution, which defines the reference return node and associated manoeuvre settings. The minimum crossrange correction required is approximately 300 km, within the RM capabilities.

The reference gate width is determined by identifying two bounding gates located on either side of the cross-track, within the crossrange capability of the vehicle. In the SMA case, the gate spans a crossrange between 307.3 km and 325 km, illustrated in Fig 4. These larger deviations drive the trajectory closer to the performance limits of the RM, with Monte Carlo campaigns highlighting violations of some outliers of the maximum allowable heat flux at stagnation and on the windward side. These are caused by the vehicle performing manoeuvres to correct a larger crossrange delta during the re-entry phase, compensating the initial EIP position to reach the DS triggering coordinates.

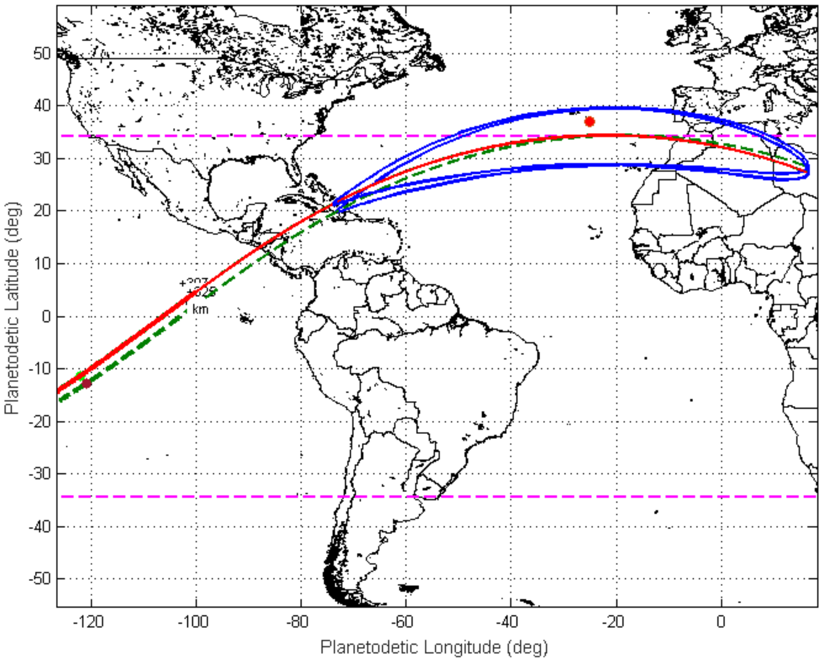


Fig 4. Deorbiting gate and reference trajectory for SMA scenario. Target landing site marked by a red dot, orbital limits in pink. Reference orbital trajectory in red, gate orbital trajectories in green, and range capability of the system in blue.

Additional considerations, such as the avoidance of overflight of restricted regions, such as U.S. airspace, are incorporated into the analysis. The gate width is finally set to guarantee at least one re-entry opportunity per week, satisfying the mission availability requirements while maintaining compliance with operational and geopolitical constraints.

The defined gate provides the target conditions for AVIO, within which the state uncertainty characterising the AVUM performance is applied. This uncertainty is then propagated in the Monte Carlo verification, ensuring that all trajectories initiated within the gate maintain sufficient margins to successfully reach the landing site in SMA.

In addition to the conventional gate definition based on crossrange capability, the Controllability and Reachability Set (CRC) methodology introduced in [6] has been applied to Space Rider to assess re-entry opportunities. Unlike the original study, which simplifies the problem formulation for the purpose of convergence, our approach preserves the full-fidelity simulation within the optimisation loop, sacrificing computational speed but ensuring that the system dynamics and entry path constraints are directly verified. The optimisation is set up with retrograde-only de-orbit burns, with RAAN, true anomaly, and burn time as the manoeuvre parameters, coupled with bank magnitude optimisation during entry.

The results shown in Fig 5 show that the CRC solutions span a wider range of orbits but do also raise potential issues with the U.S. airspace intersection.

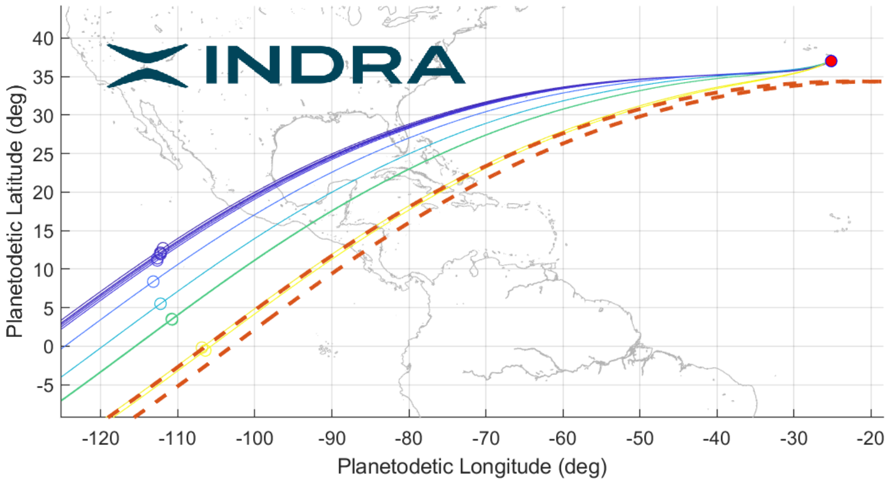


Fig 5. Comparison between entry gate boundaries derived from Controllability and Reachability Set (CRC) analysis (solid lines) and the conventional crossrange-based gate definition (dashed lines).

The CRC explores the RAAN-TA space, providing a broader set of reachable conditions compared to the gate derived from crossrange capability analysis. This results in a larger effective gate and more feasible re-entry opportunities. However, this expansion pushes the system closer to its performance limits and increases sensitivity to uncertainties. Consequently, while the CRC analysis is valuable as an informative tool for providing feedback and identifying potential opportunities, it is not adopted in the baseline mission design. Direct verification of feasibility is retained by running full trajectory simulations, as detailed in the following section on trajectory optimisation, ensuring robustness to dispersions and avoiding reliance solely on range capability estimates.

2.4. Trajectory optimisation

The portion of the end-to-end reference trajectory design covering the Entry and TAEM phases is obtained through an optimisation process from the EIP to the DS triggering event, nominally targeted at Mach 0.73. The resulting reference trajectory maximises margins for GNC operations during Entry and TAEM, remaining within the entry corridor while ensuring compatibility with both the orbital phases and the operative envelope of the descent system. Vehicle behaviour is governed by the angle of attack, defined as a function of Mach and constrained by the Trim Line identified in the FQA, while the bank angle controls lift generation. An increase in bank angle magnitude reduces lift and downrange capability while increasing crossrange deviation.

This trajectory phase is obtained through the solution of an optimal control problem, with the objective of determining the bank profile that satisfies the boundary conditions at the initial and final states while respecting path constraints from thermo-structural loads. These include peak entry load factor, dynamic pressure, stagnation and windward heat fluxes, flap heating, total heat load, and the dynamic pressure and Mach distribution at the DS triggering box. The optimisation problem is solved using HOpE [5], an optimisation framework designed as an algorithm-agnostic module interfacing with EndoSim [5], the proprietary high-fidelity exo- and endo-atmospheric simulator.

A new approach to reference trajectory optimisation has been introduced, embedding additional fidelity in the trajectory propagation. The GNC logic of the mission verification campaign is included in the simulator setup, with the angle of attack determined by the Trim Line, and the bank angle magnitude optimised by HOpE. The bank sign is determined by the azimuth error with respect to the landing site: when the azimuth error exceeds a threshold dependent on velocity, a bank reversal manoeuvre is performed to re-align the vehicle to the target.

The optimal control law obtained is post-processed to derive the reference drag-energy law, expressed as a piecewise polynomial spline, which is subsequently loaded into the GNC for mission verification.

By directly simulating full-fidelity models during optimisation, a seamless transition is achieved between the nominal trajectory and the Monte Carlo verification of perturbed trajectories.

3. Mission Verification

The objective of this activity is to verify the feasibility of the design for the SMA return mission, ensuring the required design margins are met. Building on the IXV experience, the identified trajectory solution is expected to demonstrate sufficient robustness to guarantee mission success when subject to design uncertainties and environmental dispersions. A campaign of 3000 Monte Carlo simulations is performed from AOM–RM separation to touchdown. To reproduce continuous end-to-end trajectories, uncertainties in mass, environment, and AEDB coefficients are consistently applied across all mission phases, from the orbital coasting arc to parafoil-guided landing. Path constraints and vehicle performance uncertainties are provided by TAS-I, while atmospheric and wind variability are obtained from validated models.

The feasibility of the complete trajectory is verified in terms of:

- **EIP conditions**: These affect the Entry Guidance performances, incorporating positional uncertainty from de-orbit errors provided by AVIO as initial parameter variations at separation. The Orbital Control Performance Model (OCPM) is included to characterise the GNC deviations during the coasting phase. Environmental and aerodynamic uncertainties, mass dispersions, and AEDB coefficients are set in this phase and kept consistent across the following ones.
- **Trajectory controllability**: The EIP dispersions must be compensated during re-entry and TAEM phases despite uncertainties, using a proto-Guidance derived from the Space Rider Entry and TAEM algorithms [7]. A Navigation Performance Model (NPM) is implemented to reproduce the behaviour of the navigation solution, while a Control Performance Model (CPM) is applied to represent actuator and control dynamics and associated uncertainties.
- **Trajectory margins**: The analysis verifies compliance with the thermo-structural path constraints defined during mission design. The dispersions caused by the NPM and CPM, with performances derived from subsystem-level GNC results, are applied to the simulations and their effect is evaluated.
- **Entry-TAEM interface**: conditions at Mach 2.5 are confirmed to ensure the flyability of the TAEM trajectory, with performance comparable to IXV.
- **TAEM-Descent interface**: the TAEM proto-Guidance correctly steers the vehicle through supersonic and transonic phases, aligning the heading and verifying that pilot triggering occurs within the DS box (Fig 6), with improved results when compared to the previous solution [8].

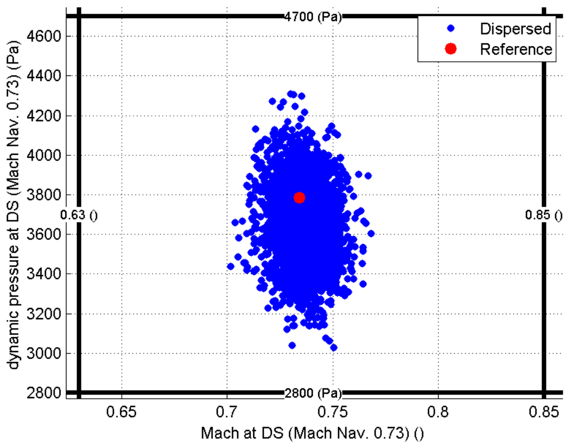


Fig 6. Mach and dynamic pressure performance at DS triggering (Mach = 0.73), full entry gate

- **Parafoil trajectory controllability**: position dispersions remain compatible with the parafoil's flight performances, and PGUID logic demonstrates robust controllability across arbitrary environmental conditions and subsystems' performance variability [9].

- **Descent under parachute phase**: from DS triggering to PFD at 5500 m. The system remains within the parachute operative envelope, and deployment accuracy at PFD is consistent with the parafoil's lift-to-drag ratio of 3.6.
- **Ballistic parafoil phase**: from PFD at 5500 m to PGNC activation.
- **Guided parafoil phase**: from PGNC activation down to touchdown. In all simulated trajectories, PGNC guidance ensures arrival at the landing site with a positive altitude margin, confirming the validity of PTA assumptions.

The predicted mission performance is consistent with 6-DoF GNC Monte Carlo results for Entry and TAEM [7], validating the mission analysis process and the assumptions applied. Overall, the end-to-end trajectory analysis confirms that the design solution for the SMA return mission is robust to uncertainties up to touchdown and is successfully verified.

4. Safety Analyses

Space Rider will return to Earth through a controlled re-entry, descent, and landing on an island close to a populated area. Any spacecraft returning to Earth can pose a casualty risk on the ground under contingency conditions. Consequently, a safety assessment is required to verify compliance with the applicable safety requirements defined for the Space Rider mission.

Specific safety analyses and simulations are performed to support this casualty risk assessment in the event of failures. Section 4.1 addresses the analysis of the RM during the Coasting and Entry phases, while Section 4.2 addresses the Descent phase. With respect to flight quantitative requirements, the probability of loss of life due to an event with catastrophic consequences shall remain below $1.9 \cdot 10^{-5}$ during the re-entry phase and below $1 \cdot 10^{-6}$ during the final approach. These thresholds are defined as the maximum permissible casualty risks for the population or for the generation of debris. Furthermore, the re-entry casualty risk assessment must include all fragments of the space system impacting the Earth's surface with a kinetic energy of at least 15 J. In addition, jettisoned elements must not fall beyond the safety limits defined in Section 4.2 for the Descent phase.

4.1. Re-entry safety

Safety assessment of the re-entry is performed using the DEBRIS tool [5].

The risk model assumes that the Re-entry Module (RM) suffers a GNC failure during aerodynamic flight, leading to uncontrolled motion and impact of the vehicle as a single object. The GNC failure is assumed to occur randomly at any point along the trajectory, between AOM-RM separation and DS triggering.

To ensure statistical reliability, 450,000 6-DoF failure trajectories are propagated, generating the consolidated footprint shown in Fig 7 for the SMA re-entry scenario. Once the failure impact footprint is estimated, the casualty risk is calculated by integrating the probability distribution function with the population density. The Gridded Population of the World v.4, extrapolated to 2025, is used to validate this risk assessment. The "casualty area" is defined as the projected area of the vehicle combined with the cross-sectional area of a human body.

Finally, the on-ground risk is obtained by integrating the impact footprint probability distribution with the population density at the re-entry epoch, weighted by the estimated Space Rider casualty cross-section. Four breakup scenarios are considered, from intact re-entry (smallest casualty area) to complete fragmentation (largest casualty area), all of which are verified as compliant with the safety requirements.

Accounting for flight failure probability, the results confirm compliance with the $1.9 \cdot 10^{-5}$ threshold. Notably, the casualty probability has decreased by at least four orders of magnitude compared to the already acceptable baseline [8] of landing in Kourou, owing to the ocean overflight instead of populated South American land.

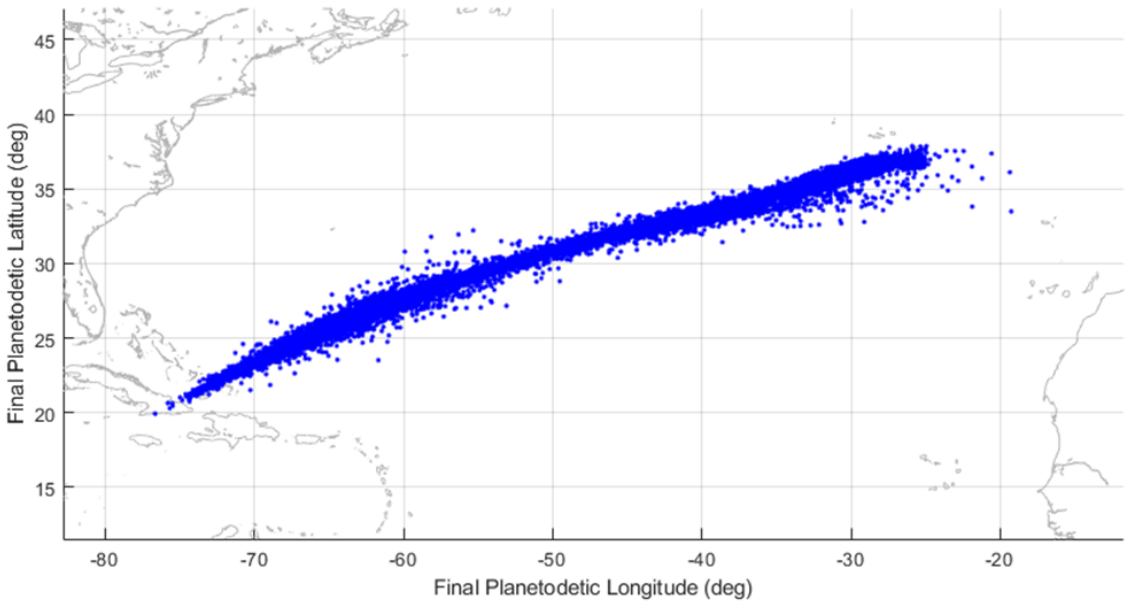


Fig 7. Re-entry failure impact footprint

4.2. Descent safety

During the descent phase, safety analyses consider potential failures occurring when the RM is flying under a drogue parachute or parafoil.

- Two dedicated 6-DoF Monte Carlo campaigns (3,000 shots each) cover:
  - failure of the DS triggering (free flight from DS to ground), and
  - GNC failure at PGNC activation (parafoil cut commanded, free flight from PGNC to ground).

- Two dedicated 3-DoF Monte Carlo campaigns (3,000 shots each) cover:
  - failure of drogue disreefing (descent with reefed drogue to ground, no parafoil deployment), and
  - failure of PFD triggering (descent under fully inflated drogue to ground).

Uncertainties for each campaign are inherited from the corresponding reference Monte Carlo analyses of the Coasting, Entry, and TAEM phases.

The results show a reduced casualty risk (below $1 \cdot 10^{-7}$) for all four descent failure models. The ellipse dispersions of the ground impact points remain well within the SMA safety limits. For DS and PFD failure estimations assumed in the PTA analysis, no further adjustments to the safety ellipses are required, as the centres show excellent agreement.

Additionally, a safety analysis is performed for all jettisoned items ejected from mortar triggering to splashdown: break-out patch, pilot bag, mortar piston, pilot panel, drogue chute, parafoil pilot, nose landing gear panel, and two main landing gear panels. Each item is analysed separately with a 3-DoF Monte Carlo campaign (3,000 shots) from release to touchdown. Associated uncertainties in mass and drag coefficients, as well as environmental dispersions, are applied to propagate the trajectories.

While the results confirm that the risk associated with jettisoned item impacts remains below the threshold, some footprint ellipses show minor overlaps with land areas. To further increase safety, the PFD target location has been shifted farther away from the island. The analysis loop for this modification is already in progress, and results will be published at the next opportunity.

5. Conclusions

The Space Rider re-entry mission solutions have been defined through multiple activities reported in this work and carried out during Phase D of the Mission Analysis. The feasibility of the complete return phase, from deorbiting to touchdown, has been verified using full-fidelity models directly simulated and optimised within the mission engineering process, leveraging consolidated tools and the expertise of

Indra-Deimos, both inherited from the IXV mission.

The design loop presented refers to the SMA scenario, and the reported analyses confirm the robustness of the proposed solution against uncertainties throughout the complete return mission. New approaches have been introduced in particular for: the definition of an optimal trim line maximising design margins; the reference trajectory optimisation using higher-fidelity models; and the sizing of the entry gate focused on constraint fulfilment.

Further refinements of the baseline solution will be undertaken in future iterations as part of the mission engineering process.

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