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Multidisciplinary Analysis Framework for the Mission Design of Reusable Space Transportation Re-Entry Vehicles

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Abstract

Analyzing space access and re-entry missions demands a multidisciplinary approach to meet diverse requirements while adhering to strict constraints. Disciplinary synergies help minimize early challenges, optimizing outcomes. Each mission is unique, requiring precision from swift estimations to intensive simulations. The multi-fidelity and multi-disciplinary framework developed by the Atmospheric Flight Competence Centre is designed to tackle such challenges. This paper delves into its components and methodologies, applications, and latest Multidisciplinary Design Optimization developments. These tools are crucial for the design of reusable re-entry vehicles, enabling safe and controlled descents respecting the mission constraints. Real-world case studies showcase the framework's adaptability and effectiveness in addressing mission-specific challenges.

Keywords: *mission analysis, multi-disciplinary, optimization, re-entry, reusability*

1. Introduction

Over the last two decades, the Atmospheric Flight Competence Centre (AFCC) in Deimos Space S.L. developed the Planetary Entry Toolbox [1] (PETbox), a set of multiple modules to support Mission Engineering and Flight Mechanics in the area of Atmospheric Flight. This modular, multi-fidelity analysis framework offers a systematic approach to the design and analysis of trans-atmospheric missions. The toolbox represents a vital component of an ongoing commitment to enhancing the analytical capabilities for innovative mission concepts supporting industry to solve problems in the present, and to advance the research of the European aerospace network towards future solutions.

PETbox has been intensively and successfully used in multiple ESA projects, EU projects and private initiatives covering a very wide range of vehicles (launchers, lifting bodies, capsules, UAVs, winged bodies, hypersonic transport vehicles, space debris…) in multiple environments (Earth, Mars, Titan) and in multiple flight phases (launch, coasting, entry, descent, landing, sustained flight). Practical example of use and key applications in multiple projects are presented with special emphasis on the use of PETbox in the ExoMars program (2016 and 2018 missions), the Intermediate eXperimental Vehicle (IXV) [2] that successfully flew on February 11th, 2015, its evolution SpaceRider [3], and the operations of the Orbex Prime launch vehicle from the Sutherland Space Hub.

1.1. Analysis Framework

PETbox is a modular and multidisciplinary framework that embeds several analysis modules to support the Mission Engineering process throughout the entire design lifecycle, from pre-phase A to Post Flight Analyses. The core module of this toolbox is EndoSim, an exo and endo-atmospheric simulator developed and used by the Atmospheric Flight Competence Center (AFCC) of Deimos Space. As reported in Fig 1, the application areas of PETbox cover a wide range of analyses, which are vehicle design, aerothermodynamics, flying qualities, trajectories design and optimization, guidance design and

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validation, sizing conditions, safety and risk, visibility, and post flight analyses. The toolbox is highly modular to facilitate maintainability, improvements, and modifications.

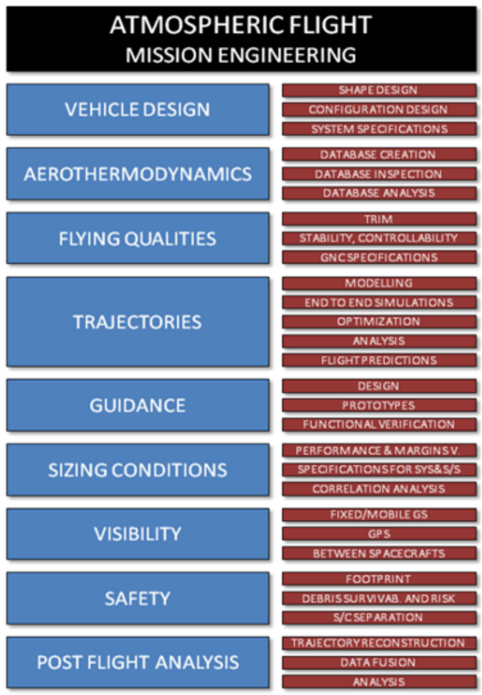


Fig 1. PETbox main application areas.

1.2. Simulation

EndoSim, the high-fidelity exo and endo-atmospheric simulator is a modular and versatile trajectory propagator that can handle end-to-end simulations characterized by single and multiple phases with several flight events, and with both open-loop and closed-loop guidance. Fig 2 shows the architecture of the simulation core with its three main building blocks:

- the Dynamics, Kinematics and Environments (DKE) module manages the equations of motion and models the environment and the external forces,
- the GNC System embeds the guidance strategies and provides the commands,
- the Phase Management Module (PMM) System manages the different phases and events along the simulation.

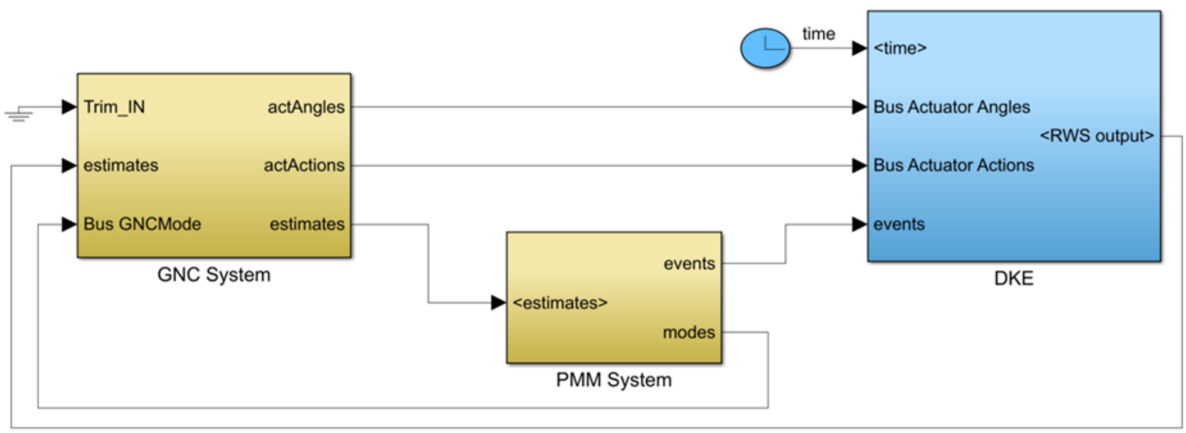


Fig 2. EndoSim: PETbox simulation core.

EndoSim is based on a wide library of models for dynamics and environment whose complexity ranges from simple models, like spherical gravity and exponential atmosphere for preliminary assessment, to state-of-art models, such as EGM96, NRLMSISE-00 and ablation mass loss models, for high fidelity performance assessment and design verification.

EndoSim guarantees an ideal flight qualified framework for the design, development, prototyping, and functional validation of a guidance solution. The modularity of PETbox and its simulation core allows to easily design and implement a guidance algorithm, and test it in a high-fidelity environment, in a sort of plug-and-play approach. These characteristics are crucial for performing trajectory controllability tests, nominal and Monte Carlo (MC) guided trajectory performance assessment, and sizing of attitude control system support by identifying realistic actuation profiles.

Through dedicated drivers it is possible to call the simulation core in multiple modes to perform nominal, worst cases, dispersed, Monte Carlo, or covariance propagations supporting the type of analysis needed, providing a great level of robustness and reliability to the Mission Analysis performance assessment.

An example is constituted by the design of a drag-tracking scheme that considers both trajectory generation (on-board trajectory planning) and trajectory control (trajectory tracking). It allowed assessing the performance of many vehicles in past activities, from capsules, to lifting bodies up to space planes. This algorithm was improved and adapted to the IXV vehicle and became the guidance solution eventually implemented in the GNC sub-system and tested in flight. However, any kind of guidance scheme can be added and tested within EndoSim.

1.3. Optimization

The increase of performances in computational capability of the last decade have introduced the possibility of solving the optimal control and other optimization problems directly with EndoSim in the loop. This development allows the simulation with vehicle subsystem models of varying fidelity, evolving with the projects, and have a reference solution that is ready to use at the time of convergence.

The optimal control problem is formulated with a direct transcription, single or multiple shooting method. The Hybrid Optimization Engine (HOpE) module of PETbox encapsulates the flight simulation performed by EndoSim, iteratively providing the decision vector, and analyzing the output key mission parameters to drive the solution within the search space. The optimization algorithm can be freely chosen from the selection available in MATLAB, with the choice often being the Particle Swarm Optimization (PSO). Such algorithm has demonstrated a good trade-off of exploration, exploitation, and parallel computational efficiency in many of the problems analyzed, characterized by many local minima, discontinuities, and tens of search-space dimensions.

Having the full fidelity models directly simulated during optimization, there is direct transition in the analysis loop from the guidance law of the nominal trajectory to the MC analyses of the perturbed trajectories. HOpE, while partially tailored on the interoperability with EndoSim, it treats the computation of the cost and constraints as black boxes. This adds the benefit of solving problems that extend beyond the optimal control, opening the possibility of performing Multidisciplinary Design Optimization (MDO) of multiple vehicle subsystems, calling external routines or tools to generate the required performance maps, as shown in sections 3, and 5.

1.4. Visualization

Along with the simulation and propagation, PETbox features a visualization module, Vistool, Fig 3. The module displays a 6-Dof 3D rendering of the spacecrafts' dynamics during entry. Vistool is fully customizable, handles events, plots, gauges, telemetry, maps, planet overlay, and can run in real time. Moving surfaces, OML deformation, RCS thrusters, and aerothermodynamic heating are also modelled, as they provide pivotal information to guide the analyst through the monitoring of the propagation output.

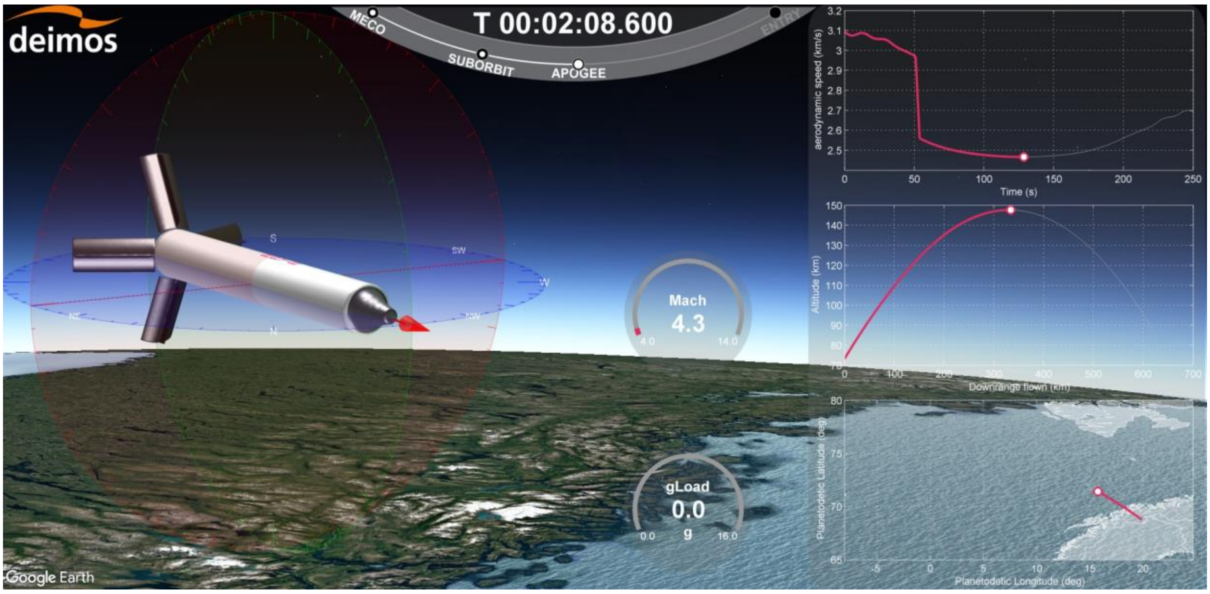


Fig 3. Vistool: PETbox visualization module.

1.5. Safety

Ascent and re-entry are flight phases characterized by large amount of energy being exchanged by the vehicle system and the environment, therefore likely to incur into destructive events.

DEBRIS

In some circumstances, these events are desirable, as it is the case for the demisability of re-entering satellites after the end of their useful life in orbit. Some fragments, e.g. titanium tanks and stainless-steel reaction wheels, may reach ground, representing a potential risk to the population. A spacecraft performing an uncontrolled re-entry must satisfy the expected casualty requirement of the applicable legislation to minimize the risk to human population.

The DEBRIS module leverages the PETBox building blocks to perform the required calculation of risk based on debris survivability analyses and footprint computations. DEBRIS runs fast analyses for the estimation of the impact area of the fragments produced by a vehicle breakup, its survivability, short- and long- term risk assessments, and recontact analyses. Recontact is a particular danger in case of service modules following a path similar to the re-entry vehicles that they detach from. Safety distance analyses have been performed by the AFCC team in several ESA projects of this class, remarkably in ARV and ExoMars2018.

The AFCC team employed DEBRIS [4] for the ESA/ESOC Space Debris Office contracts on D4D (Design For Demise [5]), analyzing system level solutions to ensure compliance to the risk requirement using uncontrolled entry, and on the upgrade of the official ESA's DRAMA (Debris Risk Assessment and Mitigation Analysis) software, where the AFCC team is responsible for the upgrade of the SESAM (Spacecraft Entry Survival Analysis Module) module.

Regulatory compliant flight safety analysis methodology

The Flight Safety Analysis (FSA) performed by Deimos Space follows the best industry practices for the quantification of the risk derived from flight activities. The FAA documentation provided the baseline algorithms to develop the structure of the Risk Analysis Tool, with two tiers of complexities developed for different use cases:

- A geometric approach based on the *FAA-AST Part 420 License to Operate Launch Site*, is used to estimate the Expected Casualty (Ec) associated with the launch and recovery operations from a specific location. This is usually employed when the knowledge level of the vehicle is low, or for cases where the launch vehicle provider is undefined. The low computational overhead allows the use within the trajectory optimization loop to identify safer trajectories.

- A computationally intensive MC campaign based on the state-of-the-art *FAA-AST Part 450 Launch and Reentry License Requirements* is used in programs that advance to a higher level of maturity. This methodology uses the MC capability of EndoSim through the DEBRIS tool driver to identify the breakup conditions, simulating the flight of the debris catalogue generated. The impact points and debris characteristics are used to quantify the risk of a trajectory, both in expected casualties (Ec) and in Individual Risk Per Annum (IRPA). The same approach extends to vessel in the sea and air, to identify the hazard areas that require special care.

The methodology has been developed and refined over time, following participation in the UK regulatory development studies, and frequent engagements with the UK's Civil Aviation Authority (CAA), to satisfy the licensing requirements of the Orbex Prime vehicle to launch from the Space Hub Sutherland in Scotland.

The architecture is based on the heritage and functionalities of multiple PETbox modules. Furthermore, thanks to the shared mission engineering framework, the FSA is designed to leverage the synergies naturally occurring with the Orbex Prime and PLD Miura GNC developments that occur in Deimos Space. This allows the inclusion of high-fidelity models accurately representing the vehicle performances.

Ground Visibility Tools

Communication with the Ground Segment or with other spacecrafts is one of the capabilities usually required during the atmospheric flight to transmit real time telemetry, updates, commands, or to receive GPS data. The existence of a line of sight between the vehicle and the required point is space (ground station or satellite), known as "Geometric Visibility" is the first step required to perform link budget analysis.

The Ground Visibility Tools (GVT) are a set of modules integrated with PETbox functionalities where it is also possible to include specific visibility masks on top of the vehicle (to address vehicle attitude effects on onboard antennas) or azimuth elevation masks (for ground stations). Preliminary models of plasma flow field interactions are available to estimate the extent of communications blackout periods directly affecting the link budget of the hypersonic re-entry phase.

The AFCC team integrated trajectory results (nominal, off-nominal and safety) with Geometric Visibility analyses to provide support to the IXV operations: the optimum recovery ship position has been designed to maximize visibility time, minimize risk and time to reach IXV post splashdown. The use of GVT is part of the analysis activities of section 2.

1.6. Sizing conditions

In the context of Mission Analysis activities, sizing conditions are of great importance to derive System and Sub-System design specifications design (during early stages of a project) but also for the assessment of performance and margins with respect to the requirements, and for qualification of the design solution. Within the PETbox, multiple functionalities have been developed to support the sizing conditions definition for the Mission Engineering of an atmospheric flight.

Local Entry Corridor

The Local Entry Corridor (LEC) is a 2-D set of analyses based on multiple trajectories simulations covering a parametric variation of entry Flight Path Angle (FPA), and Ballistic Coefficient (BC).

The tool explores a grid of n by m scenarios, being n the number of FPA values and m the number of BC points, re-entry trajectories, starting from the Entry Interface Point (EIP) until the completion of the entry phase. Those trajectories are calculated for a set of worst-case conditions for both the atmosphere and the vehicle aerodynamics. The results are postprocessed to extract the constraints under scrutiny in each study.

The objective of the LEC analysis is to determine the feasible region in terms of the design parameters to ensure that the re-entry of the spacecraft happens in a safe range of structural and aerothermal parameters and the vehicle is able to reach the landing point. Therefore, the constraints defined for the mission (typically heat flux, heat load, dynamic pressure, load factor and landing accuracy) are the variables that identify the mission feasible domain. Fig 4 shows an example of the afore mentioned concept, marking in grey the entry corridor region compliant with the re-entry constraints marked by the differently colored lines. In particular, the orange lines illustrate the results of the TPS sizing tool described in section 1.8.

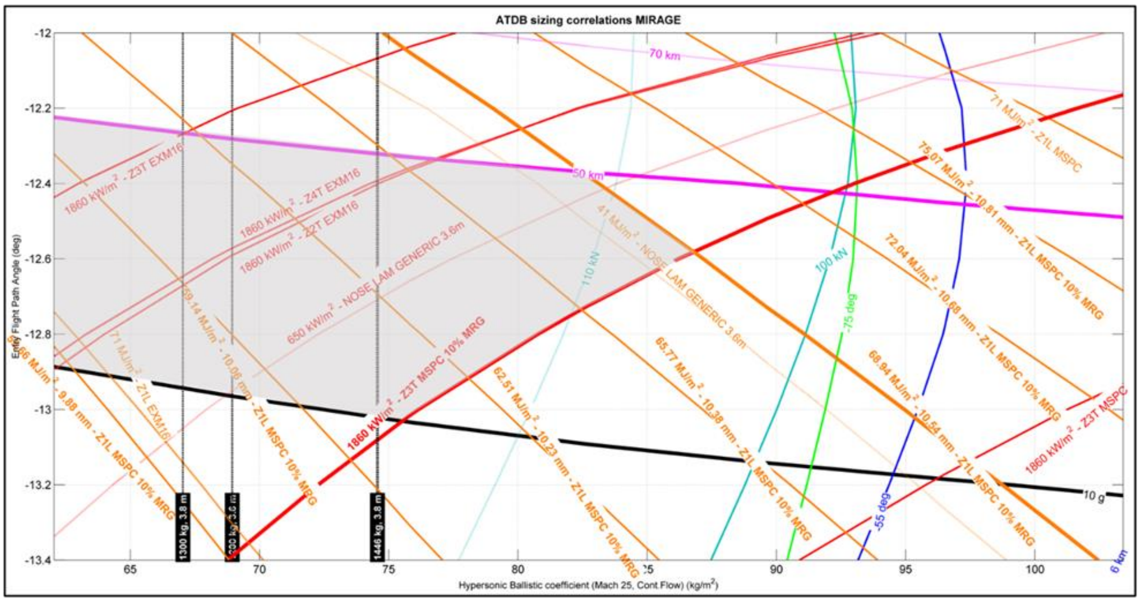


Fig 4. Example of TPS sizing tool application to LEC, MIRAGE project.

When additional dimensions are considered (e.g. Latitude and Longitude of the landing site), planetary Global Entry Corridor (GEC) analyses are performed.

PTAtool

The Parafoil Terminal Area analysis tool, is meant to provide a preliminary assessment of the Parafoil performance, estimating the range capability of the subsystem. The parafoil dispersion rejection performance is assessed in terms of altitude margin, illustrated in Fig 8. The altitude margin is defined as the altitude remaining once the parafoil reached the target site. In the computation of the margin, atmospheric variability is taken into account in terms of winds profiles, in addition to uncertainties in the parafoil aerodynamic performance, coordinates of the parafoil deployment, and position of the target landing site.

1.7. Vehicle design

Vehicle design is an area of engineering inherently characterized by multiple disciplines interacting together. The process follows the development of a vehicle, but it is especially important in the early project phases, where trade-offs are assessed, and major decisions taken. Deimos Space has been involved in multiple designs of vehicles (ranging from hypersonic vehicles to re-entry capsules for planetary exploration to UAVs) bringing its expertise in the field of atmospheric flight. One of the most relevant results in this area is the design of the vehicle aeroshape that is the result of an advanced multidisciplinary design optimization (MDO) expertise. The MDO is a crucial feature since it allows to simultaneously optimize multiple design parameters and objectives while taking into account a wide set of constraints. MDO, however, is not limited to aeroshape design. One crucial analysis of the vehicle design consists in the specification of Vehicle Centre of Gravity locations, with one application presented in section 4. In case of unpowered re-entry vehicles, indeed, the CoG position is a major driver for the definition of the system specifications, especially in terms of vehicle flying qualities (trim, stability and controllability) and thermo-mechanical flight performance overall. This system aspect is therefore optimized through Feasible Domain analysis.

A key aspect when dealing with MDO is the definition of the multidisciplinary design framework, where all disciplines are organized and the relationship between them are well-defined. Specific modules within PETbox, based on design structure matrix techniques [6], allow the engineers to build up relations within the different disciplines (analysis modules available and with external tools of different partners), to analyze and to optimize advanced designs. Then, multi-objective optimization modules help the designer by automatically identifying the subset of most promising (Pareto-dominant) solutions, focusing the efforts on final design refinements and verification.

Two main methodologies are available to assist the multidisciplinary design optimization (MDO), depending on the computational load of the case under scrutiny.

The first approach is based on ESAT (EDL&GNC Sizing and Analysis Tool), which exploits efficient metamodeling techniques to create and manage surrogate models of time-consuming analyses. ESAT uses Design of Experiments (DoE) techniques to run the analyses, seen as external black-boxes, in specific design points and interpolates the obtained responses with Gaussian Radial Basis Functions (RBFs). This tool has been successfully used by the AFCC for the MDO of EDL systems for Mars and Titan explorations, as well as for the evaluation of different design options of a space launcher covering the variability in terms propellant mass, number of engines and expansion ratio for each stage.

The second approach is part of the tool HOpE, an algorithm-agnostic optimization wrapper, that can solve the MDO problem with an all-at-once methodology [7]. The two approaches have also been combined to leverage the strengths and mitigate the limitations of both, as shown in section 3.

1.8. Aerothermodynamics

Aerothermodynamics is one discipline strictly coupled with vehicle design, especially with the aeroshape and CoG location. The numerical databases of aerodynamics (AEDB) at CoG and thermal coefficients (ATDB) represent the response of the aeroshape to a given flight condition in terms of aerodynamic forces, moments, and heat fluxes. Mastering the impact of modification in the vehicle aeroshape to changes in AEDB and ATDB is one of the keys to achieve an optimum vehicle design. Specific modules within PETbox (HYDRA, HADES) allow the team to perform preliminary estimations of AEDBs and ATDBs covering a wide range of flight regimes (free molecular flow, rarefied flow, hypersonic and supersonic) and applications (capsules, lifting bodies, space planes, satellites, space debris…). Additional modules are dedicated to low-speed flight (for UAV applications). Besides that, the team has got expertise in the use of CFD tools (internal and commercial solutions) to perform punctual verifications and tuning of the preliminary AEDBs and ATDBs at specific flight conditions.

HYDRA

The Hypersonic Database & Real-time Aerodynamics, referred to as HYDRA, is a module for the preliminary assessment of the hypersonic and Free Molecular Flow (FMF) aerodynamics on the aeroshape Outer Mold Line (OML). It focuses on the precise definition, implementation, and analysis of a modified Newton method tailored specifically for hypersonic aerodynamics. The core objective of HYDRA is to enable rapid computation of vehicle aerodynamics, utilizing a program written in the C programming language.

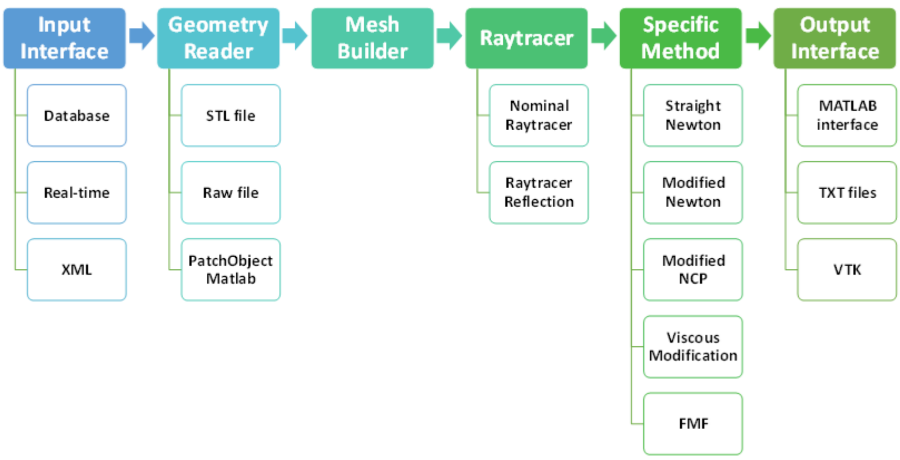
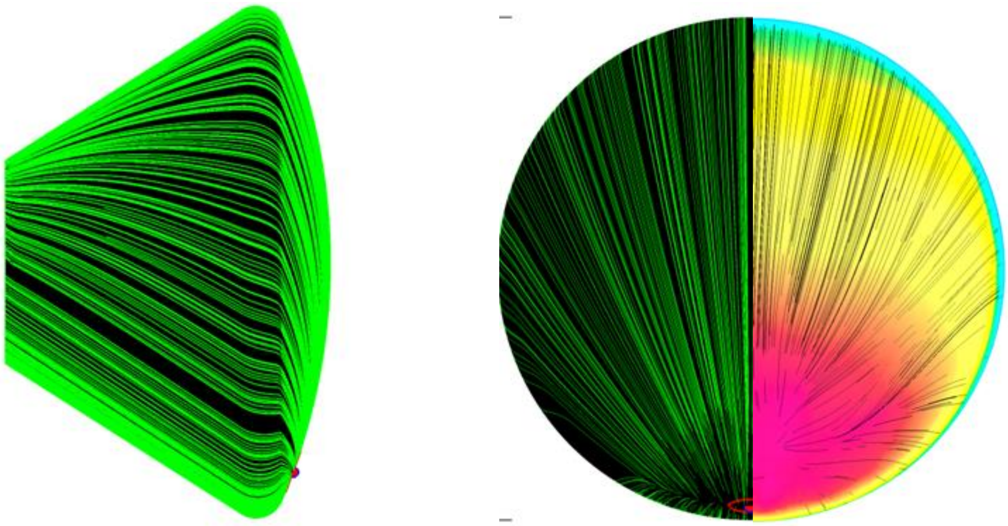


Fig 5. HYDRA Algorithm.

HADES

The Hypersonic Aerothermodynamics Database Estimation (HADES) is a module for the preliminary assessment of the aerothermodynamics on the aeroshape OML. There are relatively computationally inexpensive methodologies to assess the expected aerothermodynamic performance of primitive shapes (spheres, cones, wedges, cylinders), and their use is pivotal as well. Nevertheless, HADES' relative simplicity and fast computation, combined with the capability to estimate not only the stagnation point/region but also the complete OML at any desired attitude, make it suitable for use in the early design stages. It guides engineers through the high-level characterization of heat fluxes, loads, and temperatures on the complete aeroshape. By using this characterization as input, the preliminary estimation of the Thermal Protection System (TPS) stack-up and sizing can be performed.



A) B)

Fig 6. A) HADES Streamline Runge Kutta computation (green on black OML). B) Comparison with an inviscid solution (SU2).

Thermal Protection System sizing

During the atmospheric re-entry of a vehicle, the TPS (Thermal Protection System) has the role of protecting the internal structure from the extreme environmental conditions. The TPS is exposed to a convective heat flow over its outer surface, a portion of the heat is redirected towards the atmosphere due to radiation, and part of the heat transfers through the material is due to conduction.

The TPS sizing tool solves the 1D heat diffusion equation to assess the in-depth thermal response of a TPS material during the atmospheric re-entry for preliminary analyses. It allows modelling the effects of ablation by taking into account the material surface recession when subject to the convective heat flux.

The tool computes the effects of ablation with approximate correlations:

- The heat of ablation model is used to estimate surface recession. This effectively reduces the thickness of the TPS by the computed recession (conservative assumption).
- The reduction in heat transfer coefficient associated with the blowing of the pyrolysis gases into the boundary layer (blowing effect) is estimated by means of a blowing coefficient.

The tool can also perform an optimization analysis to estimate the minimum thickness of a material to thermally protect the vehicle during re-entry, for a range of heat flux profiles. The cost function is the material thickness, and the bond line temperature is set as a constraint. The minimum thickness depends on both the heat load and the duration of the atmospheric entry. An example of the use of this optimization is shown in Fig 4, where the orange lines identify the worst-case thickness required for a given heat load. These combinations of heat load and minimum thickness are included in the LEC analysis to find a feasible entry corridor.

1.9. Flying qualities

For an atmospheric entry system, Flying Qualities (FQ) are defined as the trim, stability and control characteristics of a vehicle that have an important bearing on the safety of flight and on the ease of flying a vehicle in steady flight and in maneuvers [8]. As such, flying quality analysis constitutes a critical step in the design and verification process of the vehicle aerodynamic shape, vehicle configuration (system) and of the GNC. For an automatic vehicle like IXV, Flying Qualities rather than Handling Qualities are addressed due to the absence of pilot-vehicle interaction. Flying Qualities for re-entry vehicles are not as standardized as for aircrafts. This is basically due to the reduced number of flown and projected re-entry vehicles, the single flight nature of most of them and the large differences in terms of aerodynamic configuration. The heritage of several studies for operational and experimental vehicles, conducted for ESA by the AFCC team over the years, allowed the development and application of a standardized methodology for re-entry Flying Qualities. The resulting product is the FQA Tool [9], enabled by additional modules, functionalities (AEDB inspections, Feasible Domain, Entry Corridor, Worst Cases) and direct interfaces with the rest of PETbox modules. This tool is a key module of PETbox and in the overall design methodology implemented by the AFCC in multiple projects. Remarkably, the successful IXV mission on 2015 marked the flight qualification of FQ analysis for re-entry vehicles, setting the highest level of TRL in Europe for the AFCC team in this discipline [10].

The Monte Carlo Flying Qualities Analysis [9] focuses on the re-entry phase of the spacecraft. The reference trajectory and vehicle geometry have previously been defined, similarly to the preliminary mission.

The Mission Analysis results cover the vehicle performance from a Flight Mechanics point of view, being the combination of the work reported in this section (focused on flight dynamics - vehicle flying qualities aspects).

As shown in Fig 7, within the frame of Flight Mechanics the Flying Qualities analysis receives inputs at system and vehicle level and provides the means to compute vehicle performance, which can be tested against system requirements and eventually fed back as inputs at the system level.

When a vehicle is controlled during entry, the FQA provides a valuable source to design a trimline which best deals with the entry requirements (either in terms of peak loads, or saturations), within the frame of the project a passive entry is foreseen, hence a nominal zero angle of attack and sideslip trimline is considered.

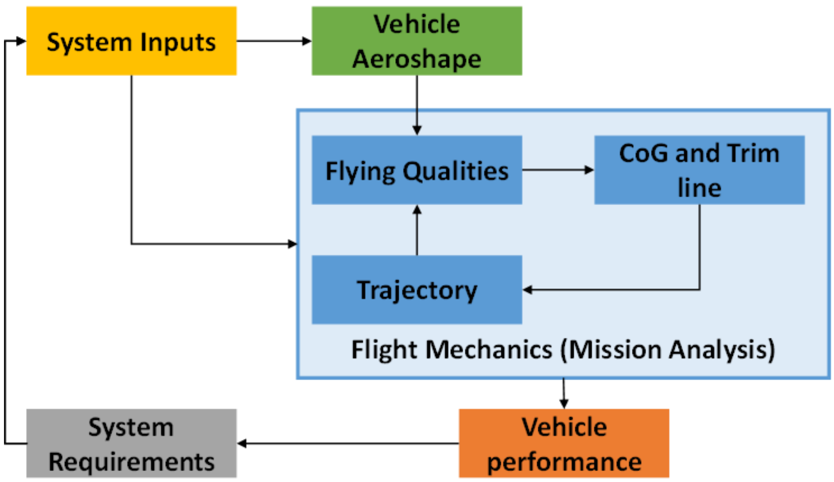


Fig 7. Context diagram: simplified interactions between System and Mission Analysis.

2. Application Case: End to end Mission Engineering

The Space Rider System is a reusable space transportation system composed of 2 flight modules that jointly operate for the orbital mission of the vehicle. The AVUM Orbital Module (AOM) detaches after the de-orbit boost and is demised in the atmospheric entry, while the Re-entry Module (RM) is designed to survive the aerothermal loads.

Deimos Space is responsible for the Mission Analysis of the Re-entry Module [3], which is end-to-end, i.e. covering all the flight phases from the AOM-RM de-orbit and separation to the RM landing. DEIMOS Space also provides support to the AOM-RM orbital mission analysis. The calculations of the launch and ascent phase up to the separation of the Space Rider vehicle from the VEGA launcher are covered by the Launcher Authority. Deimos Space is also responsible for the G&C for the Re-entry and for the GNC of the TAEM phases.

The first task for each loop of mission engineering starts with the analysis of the local environmental conditions, reviewing the local wind measurements and models. Protected areas and safety concerns are identified in this phase to locate the reference coordinates for the parafoil opening. These inputs converge in the PTAtool, that can generate a map of altitude margin as plotted in Fig 8. In the figure the center of the contours is located over water for safety purposes, and the vehicle is expected to glide to a landing site on solid ground.

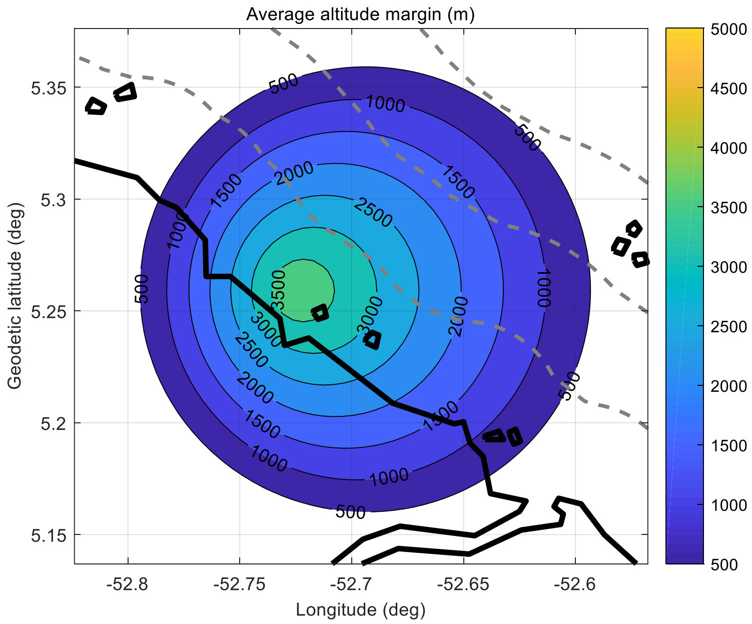


Fig 8. PTAtool analysis for parafoil deployment off the coast of Kourou CSG. The centre of the contours is located over water for safety purposed.

The location selected with the support of the PTAtool is then used as a target location for a de-orbit optimization, using the high fidelity EndoSim propagator. The problem is set up to find the optimal orbital states and burn characteristics to define the de-orbit conditions that would land the unguided RM at the desired crossrange distance from the target.

The de-orbit conditions identified are then used as the initial point for the optimal control problem solved by HOpE and simulated by EndoSim. The objective of the optimization is to minimize the flight loads experienced by the vehicle reaching the target location. The open loop guidance solution found is converted into the required format for the GNC performance model and verified comparing it with the closed loop results.

The MC capabilities of EndoSim are then leveraged to compute an extensive campaign of high-fidelity simulations including the exo-atmospheric phase, re-entry, terminal Area Energy Management (TAEM), deployment of the decelerators and parafoil guidance until touchdown. This analysis produces important results that stochastically put the vehicle in particularly challenging scenarios caused by combinations of vehicle uncertainties and environmental variability. The statistical postprocessing functionalities that are part of PETbox are used to analyze the MC campaign results and verify compliance with the mission constraints.

If the results are satisfactory, the MC trajectories are used as a starting point for the failure scenarios, set up and run by the DEBRIS tool described in section 1.5, with the EndoSim high fidelity simulation core propagating hundreds of thousands of failure trajectories to generate high resolution safety contours.

3. Application Case: Reusable launch vehicle trade-off analysis

In the RESOLVE project, led by DLR, Deimos was tasked with the mission engineering for the range of vehicle under scrutiny. The objective of the study was to analyze the options of partially reusable space transportation solutions to target the desired payload/orbit combinations, at approximately Ariane 5 levels of performances.

The AFCC team performed MDO for the vehicle types identified, sharing the common requirements of being capable of horizontal landing, but with multiple options:

- Take off method (Vertical/Horizontal)
- Landing location (DRL/RTLS)
- Propellant mixture (Kerolox/Hydrolox)
- Target orbit (LEO/GTO)
- Propulsion method (Rocket/Air breathing)

All the permutations of these missions and concepts were all singularly investigated, with 24 combinations being individually analyzed, compared, each requiring an intensive optimization and simulation campaign in a dedicated HPC due to the large scale of the problems. The vehicle design variables of each launch vehicle stage were its size (dry/wet masses, reference surface), geometry, propulsion (number of engines, thrust, expansion ratio).

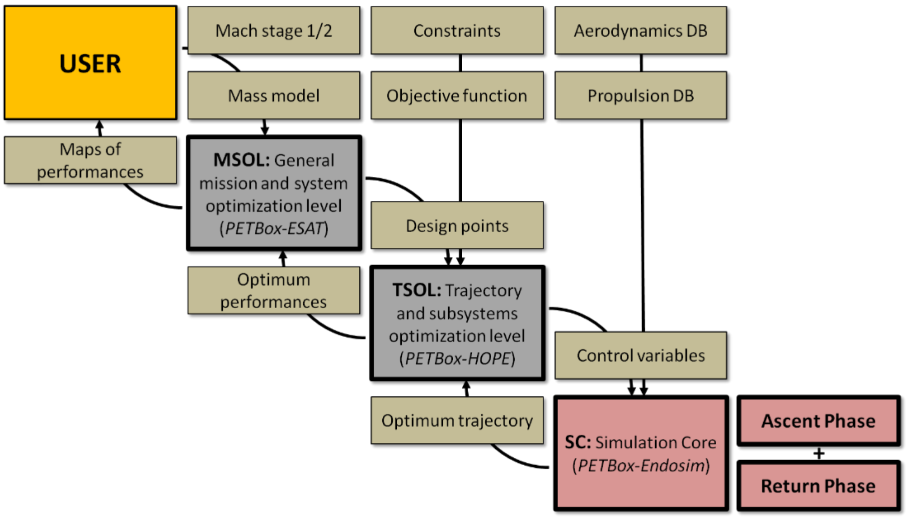


Fig 9. Architecture of the solution developed for RESOLVE, involving the tools of ESAT, HOpE, and EndoSim.

The selection of the vehicle propulsion sizing and mass budget was organized in a multi-level architecture of PETBox tools, illustrated in Fig 9. At the top level, the user was directly interacting with ESAT, the mission solver (MSOL), coordinating the design of experiments to construct the surrogate models, with the vehicle design parameters as inputs. ESAT performed the selection of the search-space design points that were consequently analyzed with trajectory optimization through HOpE, in the role of the trajectory solver (TSOL). At the center of it all, the high fidelity EndoSim propagated the full vehicle trajectory (both the ascent and the return missions) with the control profiles specified by the TSOL. An example of the sensitivity maps generated by ESAT is shown in Fig 10.

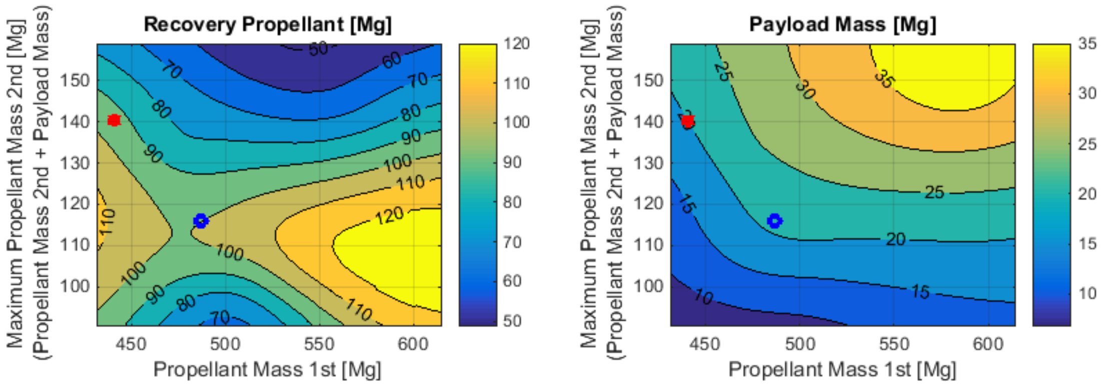


Fig 10. Example sensitivity map generated through the ESAT surrogate modelling, built with hundreds of independent trajectory optimizations. The red marker identifies the minimum operating cost vehicle, the blue mark identifies the minimum mass configuration achieving the mission objectives and satisfying the constraints.

In total, tens of thousands of trajectory optimizations were completed to generate the surrogate models with sufficient fidelity given the high dimensionality of the search-spaces. The most promising configurations, selected with a cost function accounting for reusability and refurbishment, were studied in more details by the consortium partners to obtain higher fidelity models. Once all the disciplines were ready, Deimos Space further refined the trajectories with the combination of HOpE and EndoSim. The trajectory optimization defined the guidance profile with the angle of attack, bank, and timing of the events of both the ascent and return mission profiles, leveraging synergies of the 2 legs of flight. The problem was constrained with path constraints (dynamic pressure, acceleration), initial/final constraints, and matching constraints at separation.

4. Application Case: Hypersonic point to point transportation vehicle

The task of the study was to assist DESTINUS, at the time a newly founded aerospace company, with the aim to develop hypersonic vehicles for intercontinental point to point cargo transportation. The tasks of Deimos Space included the preliminary vehicle sizing definition, mission analysis, and GNC engineering study of the reference vehicle. Additionally, Deimos performed a review of the regulatory compliance, and airspace interaction required for the execution of flight activities. The aeroshape was preliminarily set to the Hexafly (HXI-INT) prototype [11] to kickstart the initial development based on data availability, and similar target Mach regimes.

The process started from the review of the HXI-INT vehicle literature, integration of aerodynamic databases, and investigation of the available details on the GNC architecture. Having received the customer's inputs, such as propulsion system data and mission constraints, the simulation framework was integrated with the optimization routines. The objective of the reference design mission was for the vehicle to accelerate until the target Mach and fly back to the take-off runway.

The optimal control solution showed the vehicle leveraging the efficient air breathing engines climbing to commercial flight altitudes, where it accelerated to supersonic speed. This was followed by a dive and pull-up maneuver, typical of SSTO vehicles, and organically emerging from optimization, before the rocket engine ignition. The high thrust engine would then throw the prototype in a high-altitude arc where the vehicle would accelerate above the target Mach at MECO. The slowdown was then performed in a glide arc that served the purpose of correcting the heading back towards the runway for cruising back assisted by an air-breathing engine. The flight mission profile provided the first set of inputs for the GNC engineering activity.

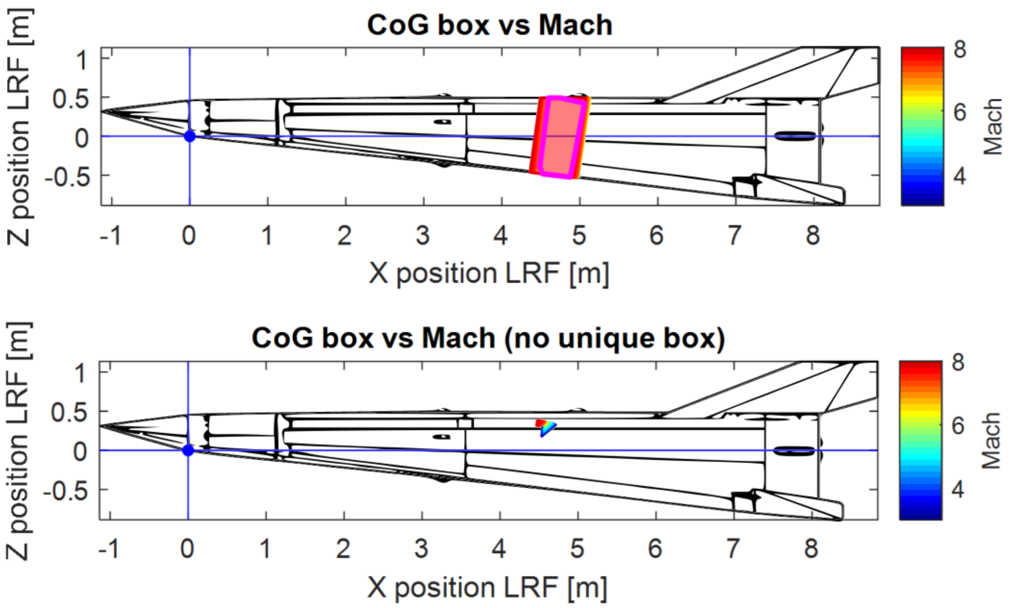


Fig 11. Conservative CoG box for the hypersonic glider and the HXI AEDB full Mach-AoA grid with (bottom) and without (top) the stability constraint. The blue dot represents the origin of the layout reference frame, the vertical unit vector is positive upwards and the horizontal unit vector is positive rearwards. The closed contour in magenta represents the edges of the final CoG box

The preliminary controllability analysis for the glide and rocket propelled phases of flight identified the CoG boxes, accounting only for the aerosurfaces to reduces the complexity of the engine mount. The definition of the CoG box allowed the identification of the most suitable internal layout of the vehicle, but one of the outputs highlighted that the box dimensions could shrink considerably when static stability is enforced. Nevertheless, the analysis highlighted the advantages of a statically stable vehicle, suggesting a consolidation of the aeroshape design and corresponding AEDB, and the use of TVC allows to significantly enlarge the CoG-box. The mission profile and the GNC concepts were evaluated starting from the review of the HXI-INT literature, but the low overlap of commonalities in the mission profiles hindered the reuse of the information, suggesting the need for a bespoke solution.

5. Application Case: Reusable launch vehicle MDO

The REVOLUTE consortium, led by SENER, is studying the common building blocks for future European reusable launch systems.

Deimos Space is involved to perform multiple steps of mission analysis to assess the flight segment, following the continuous evolution of the project, with the use of the highly modular EndoSim framework. The first step completed was in the preliminary sizing of the launch stages for the sizing missions: heavy and super-heavy class payloads inserted in orbits LEO to LTO (Lunar Transfer Orbit). This initial information provided the partners with an initial guess to prepare the vehicle subsystem models to be incorporated into the successive phase.

The flexibility and compatibility of EndoSim and the mission analysis framework with black box models allowed a quick turnaround from receiving the inputs, to delivery of the results of the multi-problem MDOs scenarios. The optimization, performed through HOpE with the All-At-Once (AAO) approach [7] provided both the optimal trajectories for ascent until orbit insertion, launcher stages recovery according to the desired CONOPS, in addition to sizing of the vehicle mass, aeroshape and propulsion configuration.

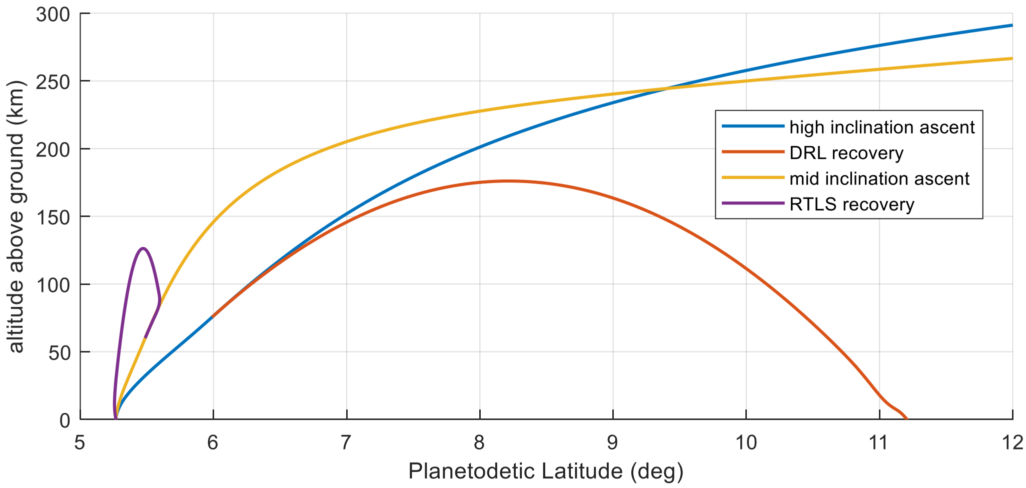


Fig 12. Latitude-altitude profiles for 2 vehicles launching from Kourou, going to a high inclination SSO and a mid-inclination LEO. Even accounting for the distortion effect of the selected abscissa, major drivers affecting the shape of the trajectories are the constraints applied by the selected first stage recovery strategies.

The project is currently ongoing, with continuous iterations with the partners to refine week by week the launch vehicles configurations, increasing the fidelity of the models, and providing always up to date mission analysis results. The modularity of the mission analysis framework has proven itself invaluable in projects requiring rapid iterations with multiple partners, such as the application case described.

6. Final Remarks

This document has described the key tools part of Deimos Space's AFCC for the purpose of endo- and exo-atmospheric mission engineering.

The selected application cases presented are of particular interest in the current space transportation industry landscape, currently undergoing major shifts. Those examples showcase the flexibility of the mission analysis framework to study and support the development of high-speed vehicles for vehicles that have flown and will fly.

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