PETBOX: FLIGHT QUALIFIED TOOLS FOR ATMOSPHERIC FLIGHT

Davide Bonetti, Cristina Parigini, Gabriele De Zaiacomo, Irene Pontijas Fuentes, Gonzalo Blanco Arnao, David Riley, Mariano Sánchez Nogales

DEIMOS Space S.L.U., Flight Systems Business Unit, Atmospheric Flight Competence Center
Ronda de Poniente, 19, 28760, Tres Cantos, Spain
davide.bonetti@deimos-space.com

ABSTRACT

The Planetary Entry Toolbox (PETbox) is a set of multiple modules developed by DEIMOS Space S.L.U. to support Mission Engineering and Flight Mechanics in the area of Atmospheric Flight.

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 current ExoMars program (2016 and 2018 missions) and in the recent Intermediate eXperimental Vehicle (IXV) that successfully flew on February 11th, 2015, [1].

***Index Terms*—** Atmospheric Flight, Flight Mechanics, Vehicles, Mission Analysis, Simulation

1. INTRODUCTION

The set of modules that composes PETbox allows a critical range of multiple analyses, a full "Mission Engineering process" that supports engineers at different levels, from Pre-Phase A studies to Post Flight Analyses. The core module of PETbox is an exo and endo-atmospheric simulator which is the simulation framework used by the Atmospheric Flight Competence Center (AFCC) of DEIMOS Space.

The toolbox is live and continuously evolving according to the improvements and modifications implemented daily in a centralized software repository under subversion control. It currently integrates more than 50 years of engineering work of the AFCC team of DEIMOS Space.

The applications range is wide, covering vehicle design (shape design, configuration design, system specifications…), aerothermodynamics (computations, inspection, analyses, support to databases refinements…), flying qualities (trim, stability, controllability, GNC specifications, …), trajectories (modeling, end to end simulation and optimization, analyses, flight predictions…), guidance (design, prototypes, functional validation, …), sizing conditions (performance and margins verification, specifications for system and subsystems, correlations analyses, …), safety aspects (nominal and off-nominal footprints, survivability and risk analysis of debris, separation analyses…), visibility aspects (with fixed or mobile ground stations, with GPS, between spacecrafts…), post flight analyses (trajectory reconstruction, data fusion, analyses, …), etc.

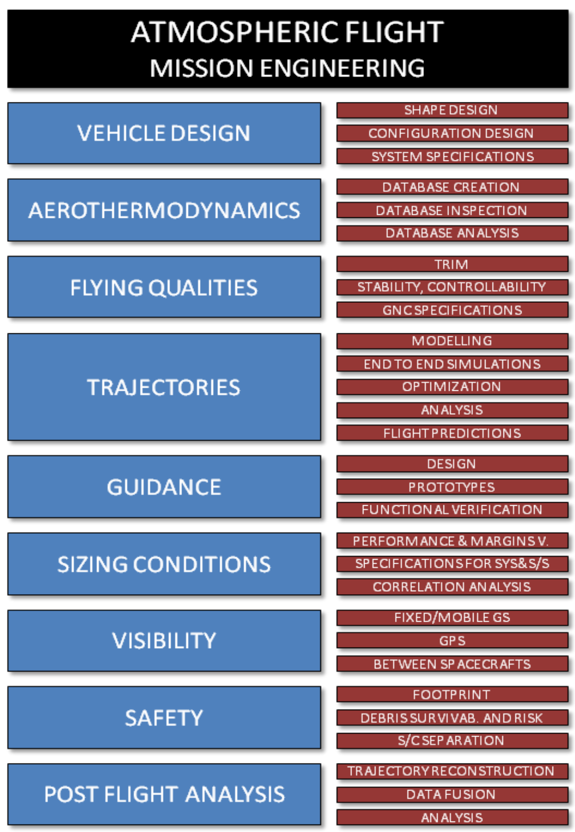

Figure 1: PETbox main application areas

Practical examples of use and key applications in multiple projects are presented with special emphasis on the use of PETbox in the current ExoMars program (2016 and 2018 missions) and in the recent Intermediate eXperimental Vehicle (IXV) that successfully flew on February 11th, 2015. IXV has represented a unique opportunity to increase the TRL level not only of re-entry technologies but it also marked a key milestone in the overall validation of the design methodology and tools implemented in the areas of Mission Analysis and Flight Mechanics; it confirmed the robustness of the approach and the maturity of PETbox which is now Flight Qualified and ready for future challenges in the European re-entry technology roadmap.

2. VEHICLE DESIGN

Vehicle design is an area of engineering where multiple disciplines contribute. 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 actually is the result of an advanced multidisciplinary design optimization (MDO) expertise.

Specific modules within PETbox, based on design structure matrix techniques, 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 (like hypersonic morphing vehicles, see Figure 2, [2]). Multiobjective optimizations modules help the designer by automatically identifying the subset of most promising (Pareto-dominant) solutions, focusing the efforts on final design refinements and verification.

Figure 2: Hypersonic Morphing solution from MDO

Even though the aeroshape is probably the most visual outcome of the MDO process, the team expertise is not limited to aeroshape design: specification of Vehicle Centre of Gravity locations is also a very important aspect of vehicle design. In case of unpowered re-entry vehicles it 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 one major design parameter typically optimized by the team through Feasible Domain analysis (see IXV, Figure 3, [1]) since it results in multiple specifications for the rest of subsystem typically involved in re-entry missions (TPS, GNC, Structure and Mechanisms…). A sub-optimum solution would imply higher costs and lower performance or even unfeasible designs.

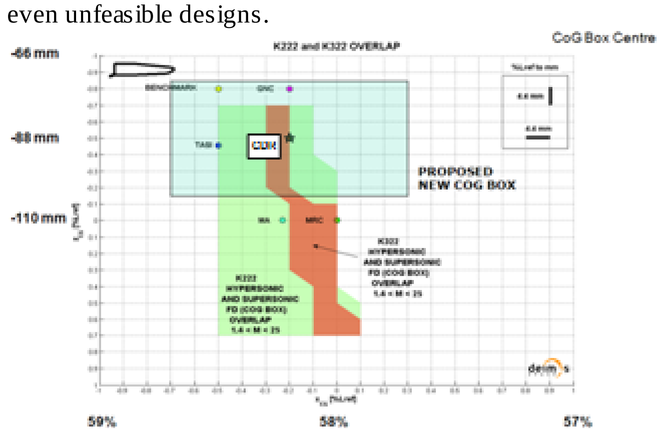

Figure 3: IXV CoG design

3. AEROTHERMODYNAMICS

Aerothermodynamics is one discipline strictly coupled with vehicle design, especially with the aeroshape and CoG location. Indeed 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).

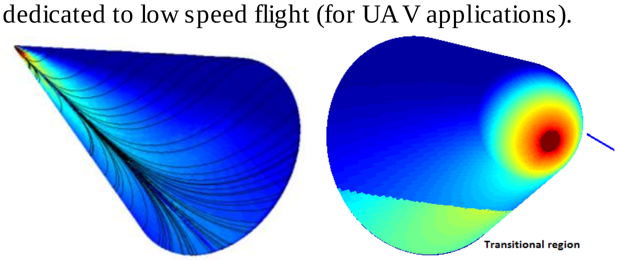

Figure 4: Examples of HYDRA - HADES (Cp, heat flux)

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 built, in interesting flight conditions.

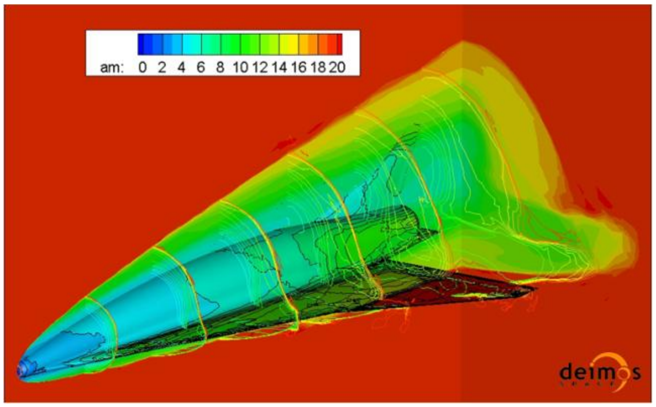

Figure 5: Example of CFD capabilities (FAST20XX)

4. 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. 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 conducted for ESA by the AFCC team in the recent years for operational and experimental vehicles allowed the development and application of a standardized methodology for re-entry Flying Qualities. The resulting product is the FQA Tool [3], 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 [1].

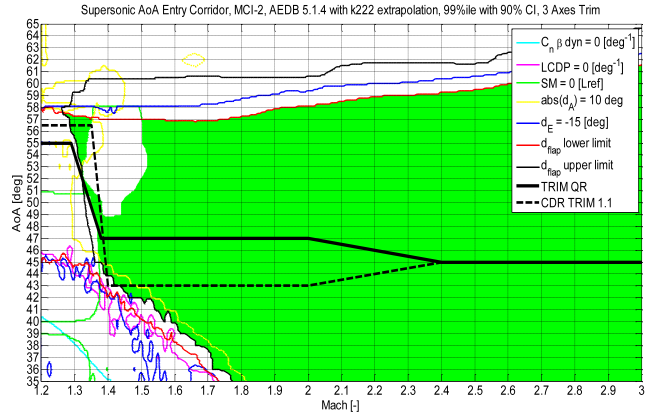

Figure 6: IXV entry corridor and trim line design

5. TRAJECTORIES

The PETbox simulation core allows performing end-2-end simulations of exo and endo-atmospheric trajectories. Modular and extremely versatile, it is based on a wide library of models for dynamics and environment whose complexity encompasses simple models (spherical gravity, exponential atmosphere, constant winds, etc) for preliminary assessment to state-of-art models (EGM96, GMM-2b, USSA76, NRLMSISE-00, EMCD, HWM93, CSPICE-based ephemeris models, MCI loss models due to outgassing/ablation/erosion, etc…) for high fidelity performance assessment and design verification.

It is strictly coupled with the rest of PETbox modules since it represents the centralized trajectory propagator for all the simulations performed in all the projects and studies of the AFCC team. 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.

Numerous post-processing and statistical tools are available, to provide the engineers with the capability for a detailed analysis of the trajectory performance. Additionally, a dedicated module allows the static or dynamic visualization of the trajectory, the vehicle attitude (from simulated or actual flight data) and the actuators (flaps, RCS…) in order to give to the mission engineer an insightful perspective.

Among the multiple modes available, a remarkable capability is that of performing trajectory optimization for the design of optimal or extreme solutions. One of the optimization algorithms available is the Sequential Gradient Restoration Algorithm (SGRA), an optimal control method that solve the Multiple Point Boundary Value Problem, and defines optimal solutions taking into account the constraints associated to the problem [4]. Other optimization methods are also available, based on Evolutionary Algorithms [5].

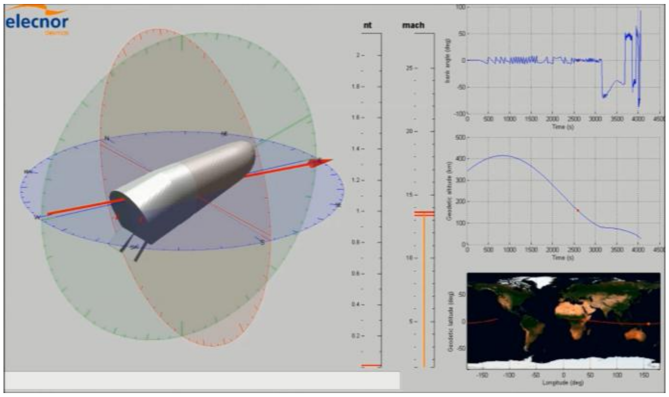

Figure 7: Example of IXV 6DOF end-2end trajectory visualization, with RCS and flaps actuation

During the IXV project, end-2-end optimization was performed with SGRA, including the optimization of the VEGA launcher trajectory to achieve the desired conditions for IXV release into suborbital trajectory, and optimization of the re-entry trajectory to reach the desired splashdown site by respecting the entry corridor, defined by the path constraints associated to the hypersonic flight and the constraint related to parachute deployment. Extreme steep and shallow trajectories, sizing for multiple IXV subsystems (e.g. TPS), have also been computed with SGRA.

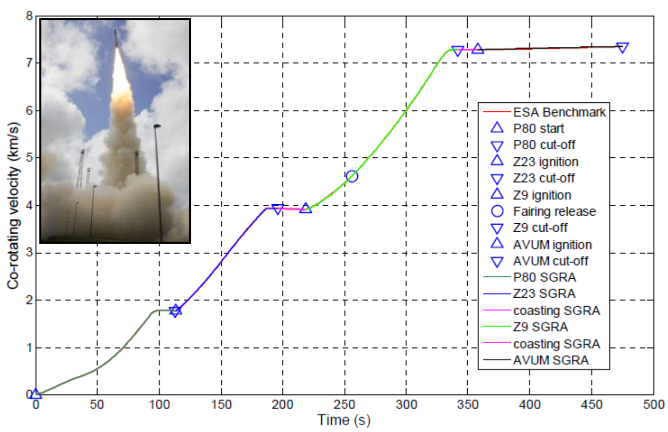

Figure 8: Example of trajectory optimization of VEGA launcher with SGRA (XV launch picture credits: ESA)

During the IXV project, closed loop trajectory simulations and analyses were intensively used during all the mission phases to support the full cycle from design to performance assessments, verifications and flight predictions: at this point, the latest models derived from actual measurements of MCI and winds were injected into the simulation chain, and accurate flight predictions were carried out. The tool had been able to predict the actual splashdown site of IXV with an error 1-2 km. Post flight trajectory analysis is currently ongoing to close the loop started with design [1].

The successful IXV mission on 2015 marked the flight qualification of this PETbox core module in its multiple modes, setting the highest level of TRL in Europe for the AFCC team also in the field of modeling and simulation.

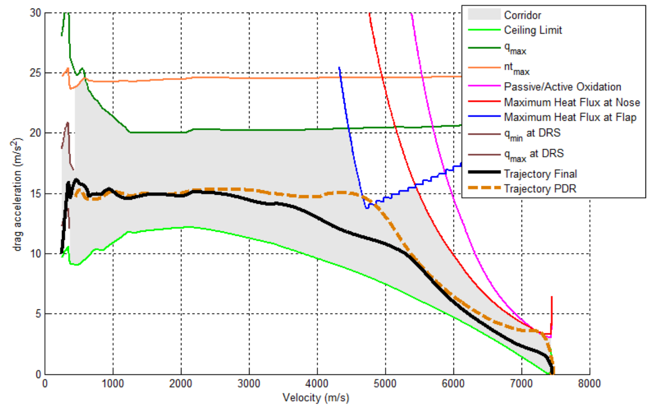

Figure 9: Example of IXV entry trajectory optimisation

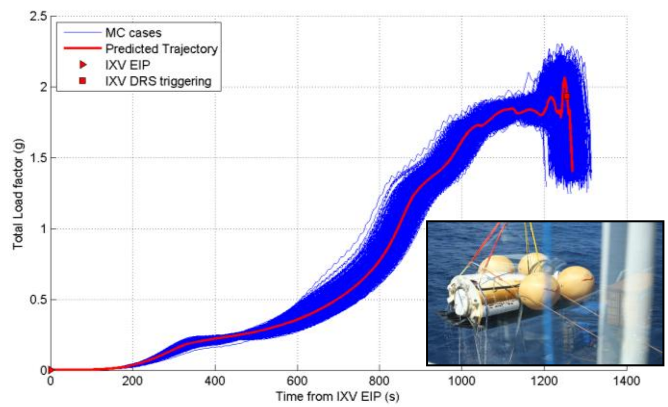

Figure 10: Predicted IXV entry trajectory wrt MC cases (IXV recovery picture credits: ESA)

Capabilities however are not limited to Earth: remarkably, during the phase E activities of the ExoMars 2016 mission, the Schiaparelli mission analysis design has been verified for the March 2016 launch windows, from TGO separation to touchdown, including the simulation of all the EDL events: separation mortar actuation, EIP crossing, drogue and DGB parachute inflation and deployment, front-shield jettison, parachute cut and back-shield release, and retrorockets activation. 3 DOF and 6 DOF results were obtained, to obtain both trajectory and attitude performance assessment and compute the margins with respect to the requirements.

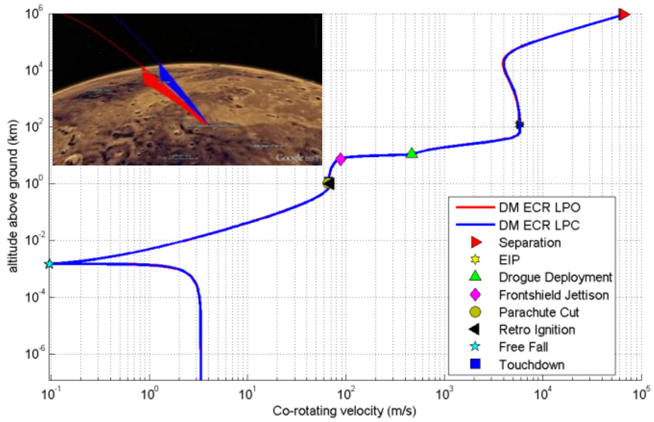

Figure 11: ExoMars 2016 nominal trajectories

6. GUIDANCE

The assessment of the guidance capability to fly a nominal trajectory in the presence of uncertainties and perturbations represents the basis of the performance evaluation of a vehicle during the atmospheric flight. The PETbox trajectory simulation and analysis capabilities presented so far guarantee an ideal flight qualified framework for the design, development, prototyping, and functional validation of a guidance solution.

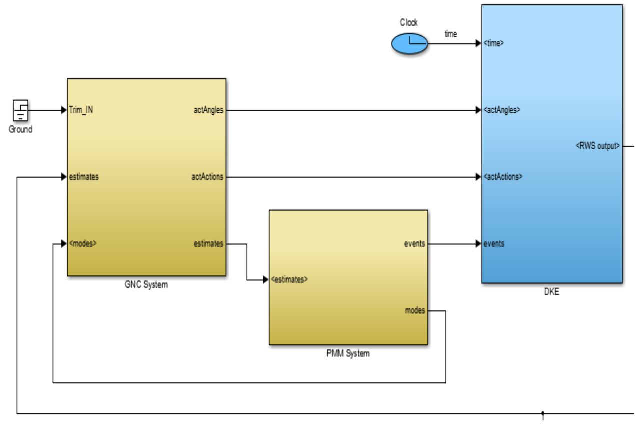

Figure 12: PETbox simulation core

A drag-tracking scheme that considers both trajectory generation (on-board trajectory planning) and trajectory control (trajectory tracking) was designed as a solution easily adaptable to different vehicles, with no restrictions regarding to the reference trajectory shape, and adaptive control. 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. In this way, it had been possible to perform the closed loop functional verification during IXV Mission Engineering with the same algorithm implemented at GNC level, providing a great level of robustness and reliability to the Mission Analysis performance assessment. Moreover, it guaranteed a smooth flowdown from Mission Analysis to GNC, from design to prototyping and eventually verification through test.

The modularity of PETbox, and in particular of the 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 allows performing trajectory controllability tests and assure controllability of a reference trajectory, nominal and Monte Carlo guided trajectory performance assessment, support sizing of attitude control system by identifying realistic actuation profiles.

Selected examples of these flexible capabilities are a skip entry guidance implemented in PETbox (derived from the Apollo approach, [6]) used to define the reference trajectories, nominal trajectories, and carry out the mission performance assessment of several exploration missions return scenarios from Moon (in the ESA CSTE study) and in the case of high energy entry (in the ESA BLAST study), or a entry guidance designed for high precision landing on Mars (in the ESA MREP HPEDLGNC study, [7]).

The BLAST study was particularly interesting because an exo-atmospheric guidance was developed within PETbox to perform the targeting of the desired orbital characteristics during a kick stage, demonstrating PETbox guidance module versatility and adaptability.

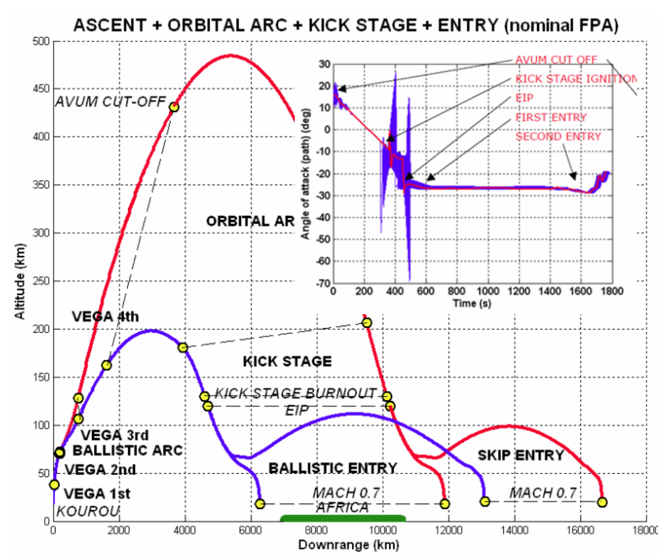

Figure 13: BLAST Mission phases and Guidance command during kick stage

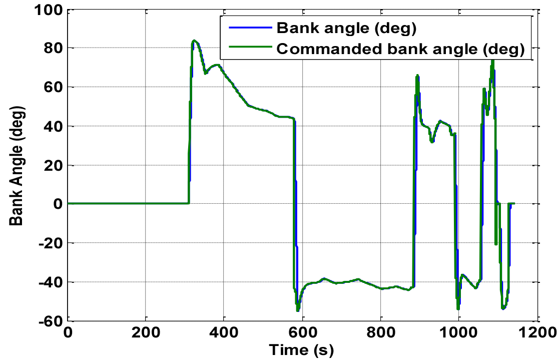

Figure 14: Guidance command for a re-entry lifting body

7. 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, 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.

For example, in the ExoMars programme, extensive use of these capabilities has been made, from early design phases (phase A/B/C in ExoMars 2016 and 2018) to the latest assessment prior to the launch (phase E1 in ExoMars 2016). Figure 15 shows an example of Local Entry Corridor (LEC) analysis for the ExoMars mission, where the margins with respect to the path entry constraints are computed as function of the flight path angle at EIP [5]. Extending the dimensionality of the analysis, dependency on the ballistic coefficient can be added (LEC 2D, applied to ExoMars, Phobos and Lunar Sample Return, and other exploration missions), in order identify sizing conditions to support the design of the entry vehicle as well as the design of the trajectory. When additional dimensions are considered (e.g. Latitude and Longitude of the landing site), planetary Global Entry Corridor (GEC) analyses are performed. Figure 16 shows an example of the GEC results obtained for the ESA MarsNEXT study.

In addition, correlation analysis methods are available to help addressing the identification of the performance driving factors. In the final phase of a study, performance and margins verification is the most important objective of Mission Analysis. In the IXV Mission Analysis activities during phase D and E multiple loops of verification were carried out as soon as updated inputs were available (MCI measurements, winds predictions, etc…) in order to assure that all the requirements were respected, in terms of aero-thermo-dynamic constraints during entry, as well as Descent and Recovery System triggering performance, and landing accuracy.

The sizing conditions module of PETBox provides therefore useful capabilities that are exploited during the complete development process of an atmospheric flight mission, connecting the entire loop from design to verification.

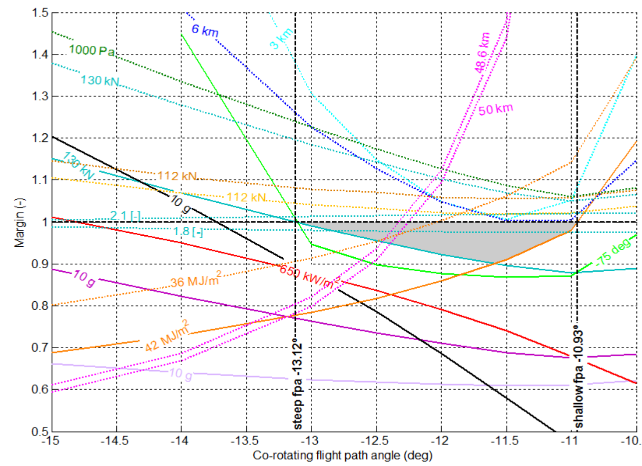

Figure 15: Local Entry Corridor analysis for ExoMars

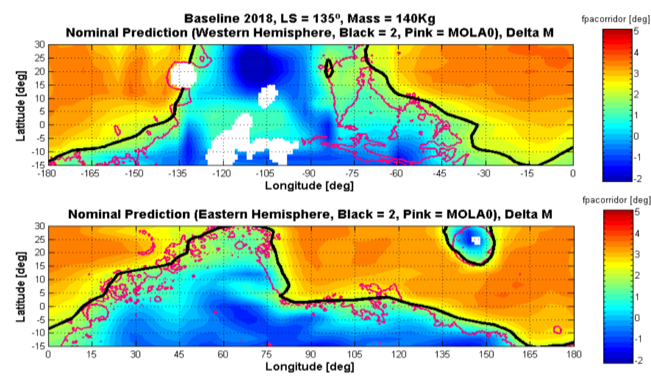

Figure 16: GEC analysis for MarsNEXT

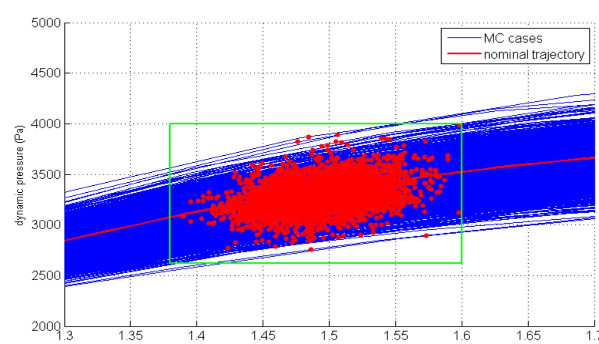

Figure 17: DRS triggering performance verification against qualification box, IXV

8. SAFETY ASPECTS

Safety is one of the most important aspects to take into account in the list trajectory performance. When safety is considered in the mission design phases, it covers activities related with design of the nominal trajectory and analyses of margins under off-nominal flight conditions or in case of vehicle failures (e.g. IXV footprint in case of flaps mechanisms lock, see Figure 18).

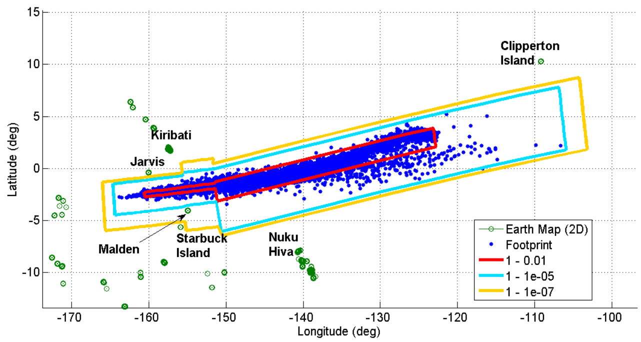

Figure 18: IXV footprint in case of flaps mechanism lock

Besides vehicles designed to fly in the atmosphere, that require the above design activities, many objects that are not specifically designed end up flying in the atmosphere when they re-enter from space: space debris.

The atmospheric flight and the breakup of space vehicles are characterized by a set of complex and coupled physical phenomena such as hypersonic aerodynamics, heating, ablation, fragmentation and fragments interaction. After the main vehicle breakup, most of its fragments demise during entry. However, some fragments, e.g. titanium tanks and stainless steel reaction wheels, usually reach ground, representing a potential risk to the population, in case of uncontrolled entry. To minimize the risk to human population, a requirement is imposed, at ESA level, on spacecraft which will re-enter that the risk of casualties must be below 10-4.

PETbox contains all the building blocks required to perform the required calculation of risk based on debris survivability analyses and footprint computations. This set of tools is known as “DEBRIS”. In particular, the purpose of DEBRIS is to run fast analyses for the estimation of the impact area of the debris produced by a vehicle breakup, its survivability, short- and long- term risk assessments and re-contact analyses. Thanks to the flexibility of the internal trajectory propagator, a wide set of analyses can be run for different re-entry scenarios (launcher stages fallout, vehicles in failure modes, planetary probes carriers, asteroids fragmentation, explosions of service modules etc.) and with different levels of details. DEBRIS has been used in the frame of several projects for running safety assessments during Phases 0 up to Phases E, [8].

Remarkably, the AFCC team is currently working under ESA/ESOC Space Debris Office contracts on D4D (Design For Demise, [9]), 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.

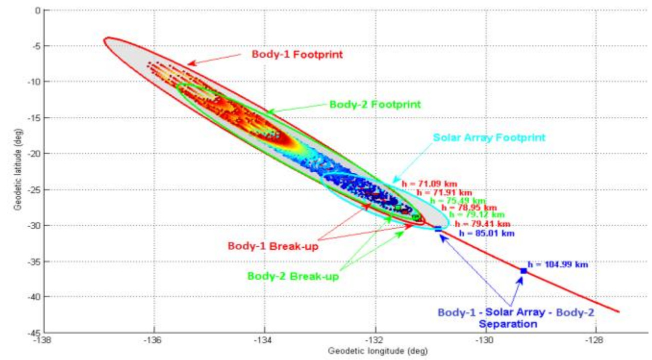

Figure 19: Example of footprint results from DEBRIS

In addition to the above analyses, special cases of interest from the safety perspective emerge in missions based on the use of service modules to bring re-entry vehicles to the right Entry Interface Point conditions. Unless fully autonomous and capable of performing additional delta V, the service module typically end up following a flight path close to the re-entry vehicle. Fragmentation of those modules during re-entry produces multiple debris with a range of ballistic coefficients that in some cases can end up posing a risk for the main re-entry mission. Safety distance analyses have been performed by the AFCC team in several ESA projects of this class, remarkably in ARV and ExoMars2018.

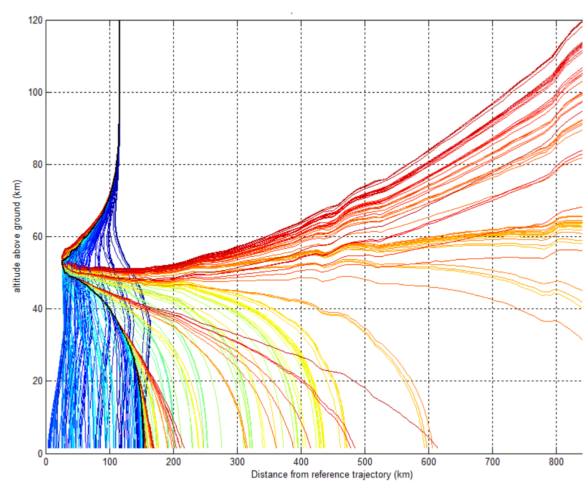

Figure 20: Distance of ExoMars18 carrier debris to DM

9. VISIBILITY ASPECTS

Communication with the Ground Segment or with other spacecrafts is one of the capabilities usually required during the atmospheric flight, for example to transmit real time telemetry, to receive 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) is known as "Geometric Visibility" and is the first step required to perform link budget analysis.

Geometric Visibility is supported by the 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). Besides that, preliminary models of plasma flow field interactions are available in PETbox to estimate the extent of communications blackout periods directly affecting the link budget of the hypersonic re-entry phase.

Based on the above capabilities, 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, [1].

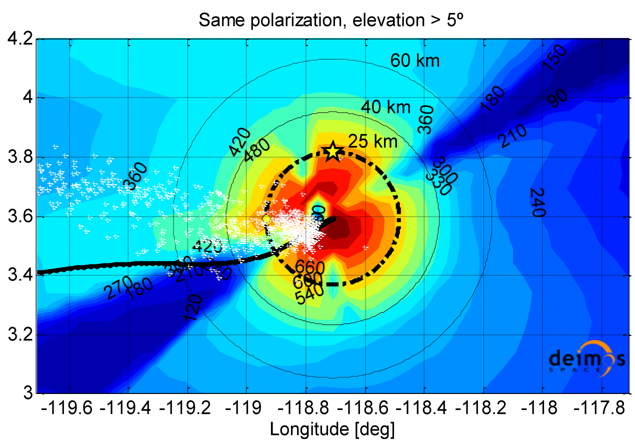

Figure 21: IXV Recovery Ship Optimization map

10. POST FLIGHT ANALYSIS

Post flight analysis represents the final step of vehicle life-cycle where numerical data recorded by the available sensors is analyzed. From the perspective of atmospheric flight, the mission performed by an exploration vehicle is in many senses unique and represents an experiment by itself (e.g. IXV or ExoMars). The information collected by sensors in terms of vehicle position, attitude or flight conditions in general is of fundamental importance in order to validate the results of previous design steps. From the numerical comparison of the design solution with real flight data the engineers can derive fundamental lessons and improve the design tools in the areas required.

In 2015 the AFCC team had the opportunity to test twice the quality of the design methodology and PETbox modules by comparing design solutions with real flight data. This occurred on two completely different missions: the first is the ESA IXV, a hypersonic lifting body designed to perform in-flight demonstration of key technology for re-entry and the second is PERIGEO (funded by CDTI, Spain), a subsonic blended-wing-body UAV designed to explore Titan's atmosphere and for which a scaled vehicle has been designed, built and tested on Earth under equivalent flight conditions, [10].

Figure 22: PERIGEO ready for take-off

Despite being so different, both made use of PETbox modules for design and analysis and both performed fully nominal missions perfectly validating the design results at their maiden (unique for IXV) flight.

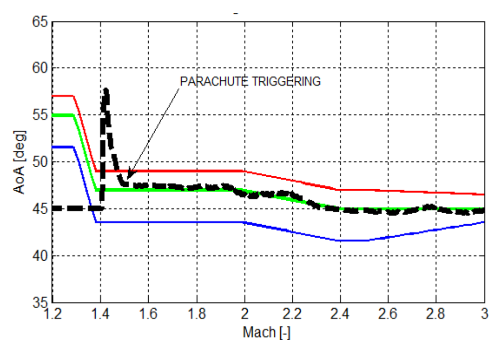

Figure 23: IXV AoA design band vs flight data (black)

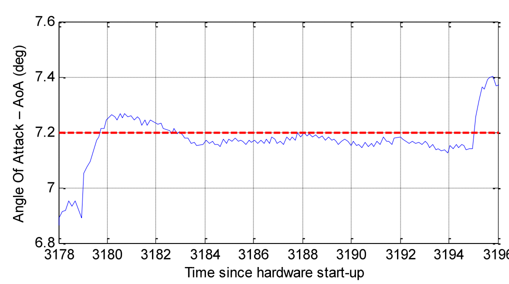

Figure 24: PERIGEO AoA design vs flight data (blue)

11. CONCLUSIONS

The Planetary Entry Toolbox (PETbox) developed by DEIMOS Space S.L.U. to support Mission Engineering and Flight Mechanics in the area of Atmospheric Flight has been presented. Practical examples of use and key applications of PETbox in multiple projects have been highlighted.

PETbox represents the current state of the art in Europe in terms of SW for Atmospheric Flight Mission Engineering. It demonstrated extreme flexibility and capability to support a very wide range of problems (different vehicles, flight phases, environments, analysis types) under the use and continuous upgrade of a team of expert engineers.

Recent successful flights of missions designed with PETbox allowed its validation in very different conditions, confirming the robustness of the design approach and the maturity of PETbox which is now Flight Qualified and ready for future challenges in the European re-entry technology roadmap.

12. AKNOWLEDGEMENT

The authors would like to thank past DEIMOS Space AFCC team members that contributed during multiple years to the creation, improvement and maintenance of the PETbox SW suite. Besides internal team working, continuous collaborations with ESA, EU Commission, CDTI, prime contractors, subcontractors, private entities and project partners played a fundamental role fostering continuous innovation to make PETbox a unique, state of the art tool at European level.

13. REFERENCES

[1] D. Bonetti et al. "IXV MISSION ANALYSIS AND FLIGHT MECHANICS: FROM DESIGN TO POSTFLIGHT" 23rd Conference of the Italian Association of Aeronautics and Astronautics, AIDAA2015, Politecnico di Torino, Italy, 17-19 November 2015.

[2] D. Bonetti et al. "HYPERSONIC MORPHING FOR A CABIN ESCAPE SYSTEM", Aerodays2015, 7th European Aeronautics Days, London, UK, 20-23 October 2015.

[3] R. Haya et al. "FLYING QUALITIES ANALYSIS FOR RE-ENTRY VEHICLES: METHODOLOGY AND APPLICATION", AIAA Guidance, Navigation, and Control Conference, Portland, USA, 8-11 August 2011.

[4] J.C. Bastante et al. "END TO END OPTIMIZATION OF IXV TRAJECTORY VIA MULTIPLE SUBARC SEQUENTIAL GRADIENT RESTORATION ALGORITHM", 61st IAC, Prague, Czech Republic, 27 September - 1 October 2010.

[5] D. Bonetti et al. "OPTIMUM SIZING FOR DESIGN OF MARS PROBES", 9th International Planetary Probe Workshop Toulouse, France, 18 – 22 June 2012.

[6] G. De Zaiacomo et al. "Robust Skip Entry Guidance and Control for a Capsule Returning from Lunar Orbit", AIAA Guidance, Navigation, and Control Conference, Chicago, USA, 10-13 August 2009.

[7] D. Bonetti et al. "HIGH - PRECISION LANDING GUIDANCE FOR MARS: DESIGN AND SYSTEM MDO", AIAA Guidance, Navigation and Control Conference, Boston, Massachusetts, USA, 19 – 22 August 2013.

[8] C. Parigini et al. "DEBRIS TOOL AND ITS USE IN MISSION ANALYSIS ACTIVITIES", 8th European Symposium on aerothermodynamics for space vehicles, Lisbon, Portugal, 2-6 March 2015.

[9] D. Riley et al. ""DESIGN FOR DEMISE" TECHNIQUES TO REDUCE RE-ENTRY CASUALTY RISK", 66th International Astronautical Congress, Jerusalem, Israel, 12-16 October 2015.

[10] D. Bonetti et al. "MDO, WIND TUNNEL AND FLIGHT TESTS OF UAVs FOR TITAN EXPLORATION", Data Systems In Aerospace, DASIA, Barcelona, Spain, 19-21 May 2015.