New concurrent design optimisation models of ASTOS

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INTRODUCTION

Recently the ESA contract for Mathematical Optimization Methods for Concurrent Early Design of Trajectories, Propulsion and Aerodynamics has been finalized. The activity analyzed the state-of-the-art capabilities of Multi Disciplinary Optimization (MDO) techniques for concurrent engineering and extended the Aerospace Trajectory Optimization Software ASTOS by more detailed design models. The design capabilities of ASTOS are especially dedicated to preliminary design phases and hence fit best to the working environment of concurrent design facilities as it has been proven at ESA's CDF since many years. This paper presents the progress of ASTOS since it has been presented at SECESA 2006 and gives an overview of MDO capabilities.

MULTIDISCIPLINARY OPTIMIZATION

Overview of Methods

MDO is most widely known from an approach where detailed design methods, like Navier Stokes and FEM, are coupled with a few parameters and constraints in combination with different levels of optimizers or parameterized method. MDO methods can be classified in three larger groups as depicted in Fig. 1 and described below:

- Calculus based methods depend on the computation of gradient information to find a path to the minimum solution. They are only suited for problems with smooth functions and continuous derivatives. Representative methods are: multi-discipline-feasible (MDF), individual-discipline-feasible (IDF), all-at-once (AAO) or simultaneous analysis and design (SAND), MDO based on independent surfaces (MDOIS) and the multi-level methods concurrent subspace optimization (CSSO), bi-level integrated system synthesis (BLISS) and collaborative optimization (CO). It shall be noted that the classical definition can be extended by replacing local optimization methods by global methods.
- Parametric methods map the design space by carefully selected design points and evaluate the response function at those points, resulting in a quick sampling of the whole design space. It is also possible to represent the design space by a surface in order to make a preliminary search for optimum solutions and robustness. These methods are thus well suited for studies that do no necessitate the real optimum solution but are satisfied with an approximation to the real solution, at least in a first analysis of the design space. However, the number of system level parameters should be lower than ten and the design space needs to be continuous. Typical representatives are design of experiments (DOE), response surface methods, Taguchi methods, central composite design (CCD).
- Stochastic methods are methods often applied when discrete variables are present. Such methods have the disadvantage that the number of optimisable parameters is highly limited, path and equality constraints are difficult to handle, the computation time is high and no sensitivity information is available. Stochastic methods are not further analyzed, as most discrete problems can be transferred into a continuous formulation and because vehicle design problems are not classical global optimization problems, which require necessarily such an approach. The selection among local minima lies more in the responsibility of an architectural decision than within the responsibility of an optimization method.

The mentioned MDO methods had been compared in several studies and are published in [1] to [16]. It can be summarized that the characteristic of the various MDO methods are their various advantages and disadvantages. Unfortunately the performance of each method is highly dependent on the test case, which makes very difficult to assess a fair comparison. In any case according to Hammond [7] the best approach is to stay with an All-At-Once approach as long as possible, as it guarantees convergence.

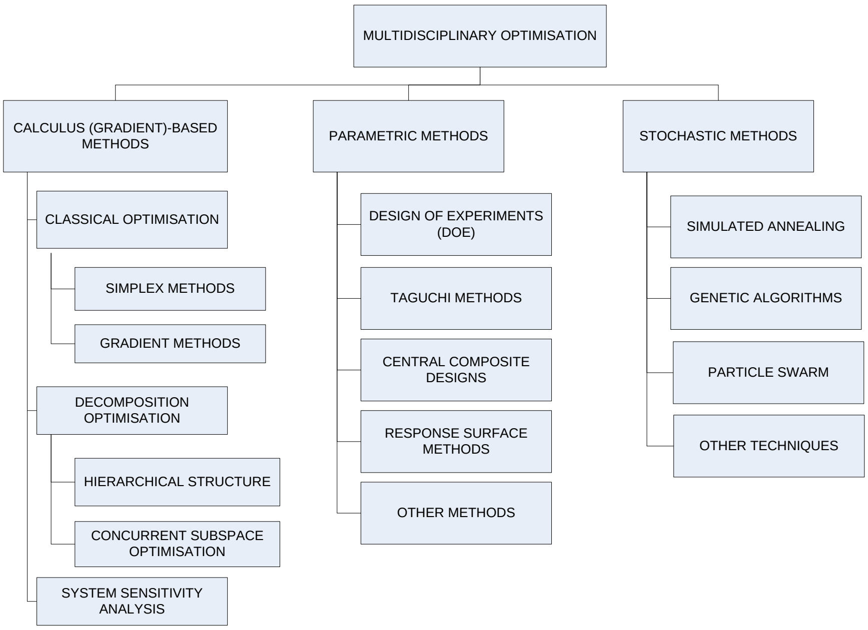


Fig. 1. Classification of MDO methods

In case the computation effort grows too much in one discipline it might be necessary to split the optimization process, which results in a decomposition. Fig. 2 shows an example of CO, where each discipline has its own optimization process with independent time scales. However, the difficulty lies in the coupling of the system parameters and constraints on system optimizer level. In reality mixtures of the different MDO methods might be the most useful choice.

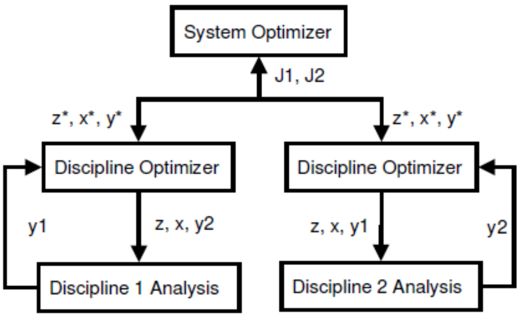


Fig. 2. The collaborative optimization method [14]

Utilization in a Concurrent Design Environment

A CDF environment has many similarities with MDO. Domain experts exchange their data similar to MDO disciplines. An architecture team controls the system level optimization and watchkeepers could be interpreted as the user of an MDO system. However, this comparison would only be valid if a multi-level optimization would work over all CDF domains and the system level optimizer would have some kind of artificial intelligence. It will take several decades before methods and hardware performance will be ready for an autonomous CDF based on MDO. Nevertheless, MDO fits into the general approach of a CDF and hence it is of considerable interest to understand parallel aspects.

A concurrent design environment lives from the exchange of information, the discussion of results, the assessment of feasibility and the decision making during a design. MDO fits into that process as it combines domains (disciplines) in one software environment. Moreover MDO need to consider the following guidelines to stay compatible with a CDF:

- The effort of preparation and computation time should be acceptably low, otherwise the solution process requires several weeks and does not fit into the schedule of CDF sessions. This results in relatively simple discipline models.

- The approach should return sensitivity information which is essential information for the engineering process. Different local minima (solutions) should be presented as different results. Calculus or parametric methods are preferable to fulfill this task if compared to stochastic methods.
- The number of links or interactions at system level should not be restricted. Otherwise the problem formulation could move too far away from the real problem formulation and the design process would not take advantage of the MDO results. This fact favors the use of AAO method as far as the computational effort remains within reasonable limits.
- The simplified models used for each discipline inside MDO should preferably allow a direct link with the CDF specialist's tool to allow verification and data exchange.

Considering those guidelines MDO offers various advantages for CDF:

- MDO can be used to create initial design points much closer to the final result
- MDO reduces the number of intermediate design loops, which are necessary to synchronize the scenario in all domains with respect to all constraints
- MDO might allow the analysis of additional important aspects which are often located beyond the available budget

Utilization in Space Applications

Typically an MDO solution is able to provide an optimal result considering dependencies between the disciplines and additional constraints, minimizing one or more objective functions. Theoretically, local and global minima can be computed using dedicated optimization methods as well as pareto-optimal fronts and sensitivities. In general local and global optimization methods can be combined for that purpose as it is also provided with ASTOS.

In space scenarios MDO is typically used for vehicle design considering mission and trajectory aspects. Most of the time it involves shape design, aerodynamics and structures; although in some cases it can include propulsion systems, thermal protection systems and costs. Moreover various load cases might occur along the trajectory, which together with various critical constraints related to the ground track create a strong link between the vehicle design and the trajectory design. In contrast to aeronautical MDO applications, space applications require many more load cases computations in different aerodynamic domains. Due to that it is difficult to directly transfer to space scenarios the success of MDO for airplanes shape design.

If MDO is applied to launcher applications, it is highly recommended that all trajectory related constraints, such as load constraints, separation constraints, station visibility constraints and splash down constraints are fully considered. Otherwise any design will run into local solutions either violating such constraints or representing an overdesigned vehicle. This fact is getting more important if a complete launcher family shall be designed for multiple missions. The requirement of a well designed trajectory is getting so important that the use of global optimization methods with their included simplifications is not well suited.

Based on that experience Astos Solutions follows an approach, which uses as far as possible approximation methods on MDO discipline level. Ideally, these models should be linked as good as possible with expert tools on CDF domain level for two purposes: fine tuning of the approximation method and generation of more accurate initial guess for the expert tool. Moreover the trajectory domain is fully represented with all constraints and therefore guarantees a feasible result within all engineering safety regions. Finally it should be noted that it is not important in the overall design process to produce the best result, which might lead to unrealistic designs wasting money and time, but the most robust result capable of successfully going through the detailed design loops, while ensuring mission requirements.

ASTOS MDO MODULE

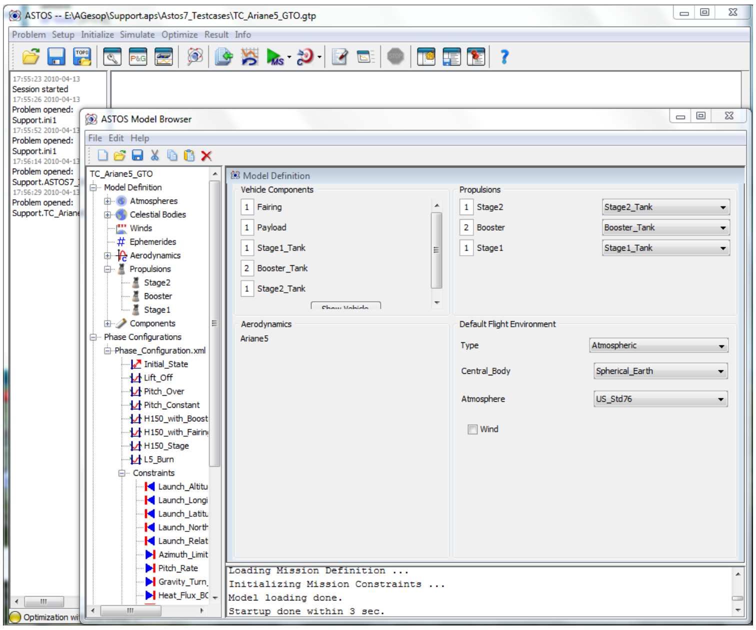
ASTOS Overview

The optimization software ASTOS can be used to optimize ascent trajectories of launchers and reentry vehicles as well as interplanetary trajectories. Before giving more details on trajectory optimization in ASTOS, the essence of a trajectory optimization problem shall be briefly explained.

Trajectory optimization is the process of finding a trajectory that minimizes or maximizes a specified objective function while fulfilling prescribed constraints. The optimization problem consists of equations of motion (EoM), attitude and throttle controls, cost function, initial, final and path constraints and optimisable parameters. It is essentially an optimal control problem.

The EoM describe the physical behavior and are ordinary differential equations (ODE) that lead to the time-varying position and velocity when integrated in time. The controls are the means to influence the EoM directly; they are to be optimized (e.g. the aerodynamic angles). The constraints put certain restrictions on the states or on model parameters and may be defined at the beginning (initial boundary constraint), the end (final boundary constraint) or along the entire trajectory (path constraint). Typical constraints in launcher ascent optimization are put onto the lift-off, the maximum

dynamic pressure and heat flux, the splash down of stages or the final orbit. Optimisable parameters are model parameters which are optimized together with the time-varying controls (e.g. initial propellant mass).
In ASTOS the user can define a launcher trajectory optimization problem in an easy-to-use software environment (see Fig. 3). A complete optimization problem definition includes the vehicle information with the stages and their properties, the propulsions and the aerodynamics, plus the environment definition including the planet and its shape and gravity field, the atmosphere and possibly the wind. The various top level objects are depicted in Fig. 4.



```
17:55:23 2010-04-13
Session started
17:55:26 2010-04-13
Problem opened:
Support.ini1
17:55:52 2010-04-13
Problem opened:
Support.ini1
17:56:14 2010-04-13
Problem opened:
Support.ASTOS7_
17:56:29 2010-04-13
Problem opened:
Support.TC_Ariane
```

Vehicle Components

1	Fairing
1	Payload
1	Stage1_Tank
2	Booster_Tank
1	Stage2_Tank

Propulsions

1	Stage2	Stage2_Tank
2	Booster	Booster_Tank
1	Stage1	Stage1_Tank

Aerodynamics
Ariane5

Default Flight Environment
Type: Atmospheric
Central_Body: Spherical_Earth
Atmosphere: US_Std76
☐ Wind

```
Loading Mission Definition ...
Initializing Mission Constraints ...
Model loading done.
Startup done within 3 sec.
```

Fig. 3. ASTOS Main window and Model Browser

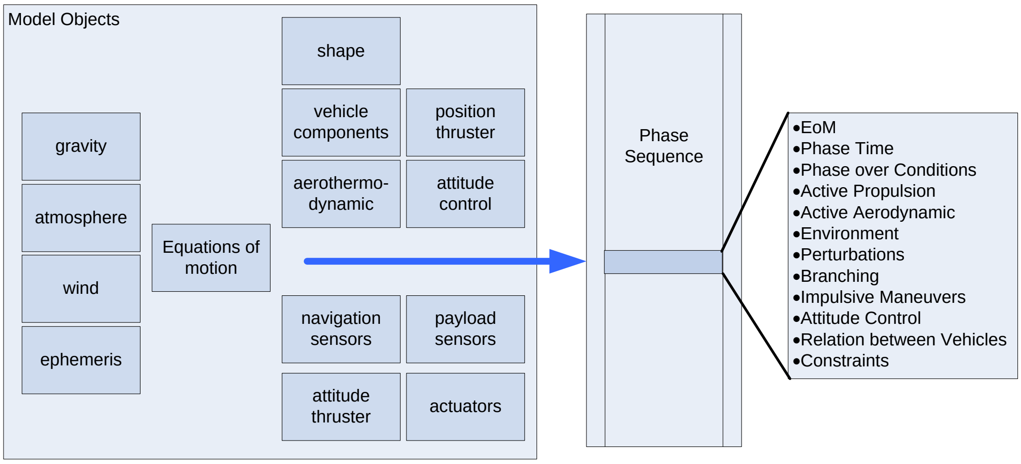


Fig. 4. Scenario Builder of ASTOS

The user can choose from several well-established optimizers. Most of these optimizers use a gradient-based method to numerically solve the optimal control problem. Two approaches can be distinguished here: the multiple shooting method and the direct collocation method. The multiple shooting method essentially discretizes the control while integrating the equations of motion (EoM) with a general-purpose ODE integrator whereas the direct collocation method discretizes both the control and the EoM. Resulting optimization problems are solved using the NLP solvers eNLP/WORHP, SNOPT or SOCS/SPRNLP, or by global optimization methods.

MDO Extension

The ASTOS capability of trajectory optimization has been enhanced to include launch vehicle design optimization. Therefore the disciplines aerodynamics, propulsion and weights have been improved for optimizability and higher fidelity and the disciplines geometry and structures have been added. The data exchange between these disciplines is considerable as many disciplines depend on input from many others (Fig. 5).

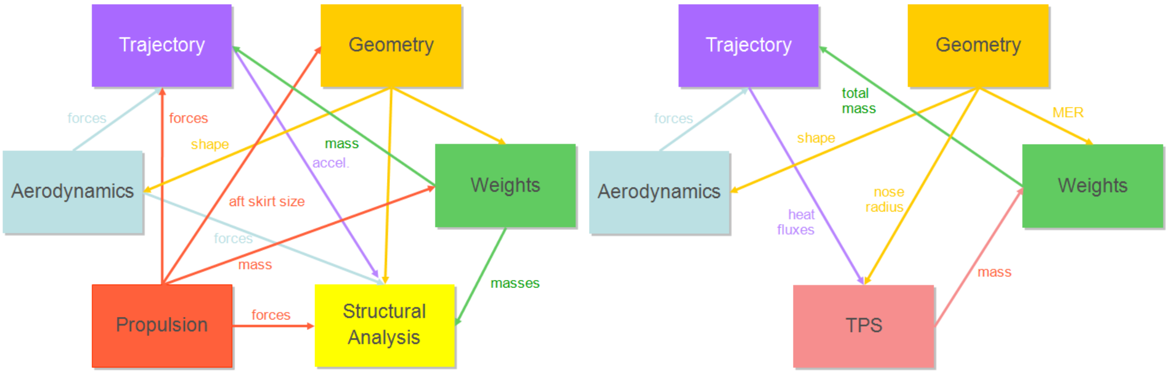


Fig. 5. Data exchange between disciplines for launch (left) and re-entry vehicles (right)

Launcher Module

The launcher scenario has been extended by a geometry model for all stages and the fairing, where lengths and diameters are optimisable. Interstages manage different stage diameters, which allow the modeling of hammerhead configurations. The aerodynamics is computed by Missile Datcom, where the shape is used from the geometry model including strap-ons. Missile Datcom provides full 6-DOF aerodynamic coefficients and supports the computation of the static stability. Tank models for separate, common bulkhead and enclosed tanks are provided to support the geometry model and the mass estimation. The mass estimation is based on regression, where a database of regression coefficients for most important components is provided. The mass estimation is refined with a One-Beam Approximation (OBAX), which performs a structural analysis based on external and internal forces and weights and which results in a minimum wall thickness and mass estimation. OBAX also returns the loading cases as function of flight time and helps to analyze critical loads of different vehicle designs in early design phases. Finally the models for propulsion systems have been extended. The liquid engine model computes the combustion at equilibrium conditions with the NASA tool CEA and adds efficiency factors based on regression. The regression factors have been derived from existing engines depending on the propellant type, the cycle type, the engine performance and the stage position. In a similar way the engine mass is estimated [17]. A module for solid propellant thrusters has been developed, which allows a preliminary design of the mass flow without detailed knowledge of the propellant grain. The approach is based on the assumption that modifications will basically follow the design comparable booster designs [18].

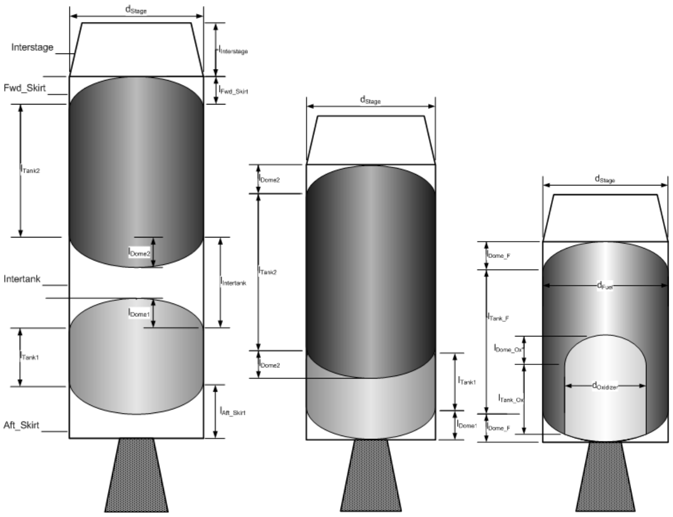


Fig. 6. Tank configurations

The concurrent design models in ASTOS allow a preliminary design for conventional and expendable launchers and are perfectly suited for collaboration with detailed design tools. The branching functions allows additionally the optimal stage design of a launcher for different target orbits and payload in one single optimization run and hence is perfectly suited for early design activities of launcher families [18].

Re-Entry Module

The re-entry module has been extended by five basic parameterized re- entry vehicles: sphere-cone, bi-conic, capsule, probe and ellipsled (see Fig. 7).

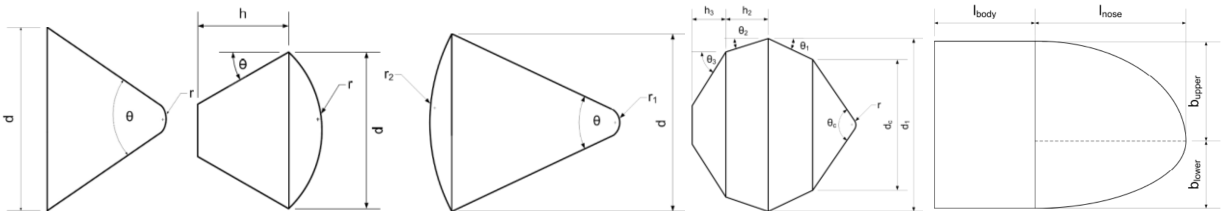


Fig. 7. Parameterized re-entry vehicle geometries

The aerodynamics has been extended by the surface inclination method SOSE of DLR. SOSE is configured by the geometry module for the whole flight regime, bounded by a Mach number range, an angle of attack range, and a yaw angle range. Parting from a geometry indicated by the geometry module it can calculate aerodynamic coefficients (CL, CD, CQ, Cl, Cm, Cn), and the surface flow variables of the vehicle (pressure coefficient, free stream pressure ratio and Mach number as a function of the location along the vehicle). The mass of the vehicle is estimated based on regression as function of the geometry [19].

Additionally the mass of the Thermal Protection System (TPS) is approximated based on one-dimensional transient heat conduction, which outputs also the maximum TPS temperature, where a multi-layer TPS material can be defined. Moreover a conservative model for ablation is provided implementing a transformed partial differential equation. Altogether the mass of the TPS system is estimated using an assumption for the surface distribution or alternatively a regression formula. The results have been verified against the STARDUST mission [19].

SENSITIVITY ANALYSIS

Sensitivity information is most important for the design process. It gives the expert an understanding of critical design parameters and allows him to cast doubt on estimated values in case the results depends highly on such a parameter. Moreover sensitivity information is used to evaluate the robustness of a solution. This is extremely important as the design space of space vehicles is small. A small overestimated regression coefficient or too high safety factor decides about the feasibility of a concept. Hence the mutually dependent weighing of such coefficients is perfectly supported by this functionality inside a CDF environment. ASTOS supports that functionality with an integrated batch process.

COUPLED MISSION & GNC ANALYSIS

Vehicle design and trajectory optimization is only one aspect. In a next step the feasibility has to be analysed considering aspects outside an optimization formulation. ASTOS provides for that purpose a coupled mission and GNC analysis, which allows detailed mission analysis tasks including high quality animations and GNC onboard computer modelling with Simulink. In all working steps ASTOS serves as scenario builder and central model library. This functionality is currently under development with funding from DLR in the frame of space robotics and will be presented on ESA's conference GNC 2011.

RESULTS

Sensitivity of Domains

Extensive sensitivity computations have been performed using the MDO models applied to a conventional launcher design. The following sensitivities were analyzed:

- stage diameter with influence on aerodynamic drag and structural mass
- engine Isp
- engine mass flow with influence on propellant and tank mass and aerodynamic drag
- structural mass
- burn profile of solid boosters

Assuming certain model uncertainties from the mathematical models themselves or from uncertainties of regression coefficients it has been determined that the largest sensitivity exists in the structural mass computation, followed by the Isp and the drag.

The study resulted in multiple sensitivity values. However, in the content of this paper it is important to integrate the sensitivity information into the working environment of a CDF. It can be summarized that this technique offers the possibility to set the known or estimated uncertainties of a discipline model in relationship to the obtained result and also the considered safety factors. This allows a better assessment of the quality of the obtained result.

FLPP Design Optimization

The Branching function of ASTOS has been used to perform a design optimization of a launcher family following the FLPP requirements. For the first time the Branching function has been applied to a multi-mission scenario. Several missions have been optimized at once determining the optimal stage size for all missions. These missions are 3, 5 and 8 tons to GTO, a maximum payload into SSO, LEO and MEO. The missions 5 tons and 8 tons to GTO include 2 and 4 solid boosters respectively, which have also been optimized during the computations. Fig. 8 depicts some results.

The all-at-once optimization of the multi-mission has shown a very good performance and important results. Fig. 9 shows, how the size of the first and second stage changes in case of a multiple mission design (left bar Branched Solution) in comparison to single solutions of each mission. While a classical approach only allows a launcher design for multiple missions in an iterative process, ASTOS can do that in a single optimization run. The advantage against an iterative process is that additional sensitivities can be computed and specific influence based on architectural design criteria can be directly considered during the optimization process.

A major capability of the multi-mission approach is that it allows the optimization of a most ideal maximum payload for the different configurations and missions. For example, in case of FLPP is not efficient to request 8to payload into GTO as it causes a complete overdesign of the launcher configuration for the other missions. With ASTOS it is possible to determine a payload distribution, which allows the most efficient launcher configuration for all missions.

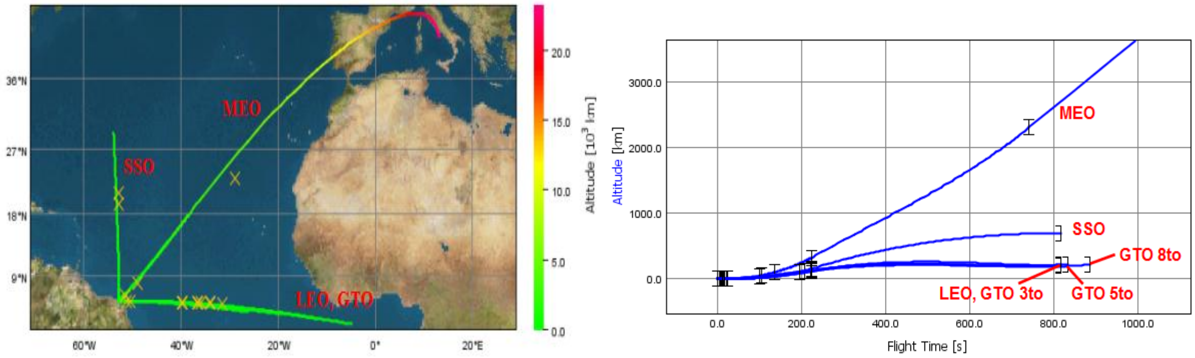


Fig. 8. Multi-mission groundtrack and altitude profile of multi-mission launcher design

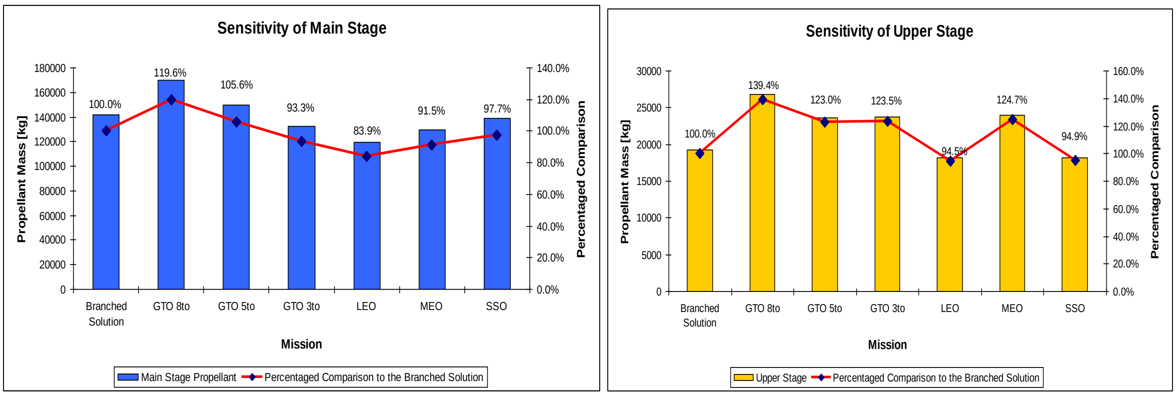


Fig. 9. Stage design of multi-mission design

CONCLUSION

The ASTOS capabilities for trajectory optimization have been enriched to perform multidisciplinary design optimization of expandable launchers and re-entry vehicles. The new disciplines and the complex vehicle parts have been integrated into the ASTOS core and the GUI seamlessly. The connection of trajectory and design optimization performed at the same time is a promising approach for preliminary design where the physical models used are still fast enough for such an approach.

The new models allow detailed stage optimization of launchers. It is possible to fix various systems of the launcher (e.g. existing solid propulsion boosters) and use the MDO capabilities to design upper stage engines or whole stages. Beside that it is possible to define constraints, which help to optimize a low cost design. Not only simple constraints (such as for example the maximum chamber pressure), but also more complex ones, like the same size of two stages or the same basic engine in two different stages, can be easily considered.

The design of the MDO module of ASTOS follows perfectly the needs of CDF working environments supporting interfaces with detailed design tools, preliminary design tasks, fast response time and providing additional valuable information for the design process.

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