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INNOVATIVE MULTI-DISCIPLINARY VEHICLE, MISSION AND GNC ANALYSIS

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The combination of multi-disciplinary optimization with mission and subsystem analysis and design is nowadays key to successful and low cost design for space missions. In particular, Mission Vehicle Management (MVM) plays a key role in the multi-disciplinary optimization design process. However, despite the improvements in computational speed, mathematical algorithms and software engineering, still the subsystem design dependencies are huge and the market expectations are growing. This paper presents an innovative approach, how the European space industry and ESA meets this challenge.

The multi-disciplinary design environment proposed in this paper is based on the newly ASTOS Guidance, Navigation, and Control (GNC) design software framework, which combines several optimization methods and propagators with a flexible environment for the definition of a complete space scenario, space vehicle, and its corresponding mission vehicle management. The ASTOS software suite presented here is composed of powerful trajectory and guidance optimizers, a full GNC system design, and the capability to realize multi-disciplinary design optimization for MVM problems. Following the lifecycle of space systems, the ASTOS software suite allows step by step refinement of the system models including switching from rigid to flexible body dynamics or from 3-dof open loop guidance to 6-dof closed loop control, etc. The new ASTOS version 8.0 comprises a fully integrated working environment, which allows the numerical optimization of vehicle and control parameters, optimal trajectory analysis and GNC analysis all at once. The ASTOS analysis functions can be used in a coupled mode, which allows the detailed analysis of complex scenarios like space robotic missions as well.

This paper further describes the engineering design and development tasks and the corresponding capabilities from Phase 0 till Phase C of the ASTOS suite. Furthermore, the ASTOS software framework is showcased by presenting the design process of 3 example cases: a launch vehicle, a space robotics mission, and a low thrust propulsion mission.

I. BACKGROUND

Multidisciplinary Optimization (MDO)

Multidisciplinary vehicle design optimization makes use of gradient-based methods like decomposition methods using single and multi level methods, Random Search Methods (RSM) or sophisticated parametric models like Design of Experiments or Response Surface Methods. Various designs have been implemented in the past in several engineering fields.

However, their industrial application in astronautics seems to lack in confidence that might be driven by the difficulties to integrate MDO results in the classical engineering process of space systems. An optimal vehicle design cannot be defined just by one (global) optimal solution. Rather it requires the feasibility analysis of several vehicle subsystems, which cannot be considered all together in MDO processes especially when using RSM based methods.

For that reason Astos Solutions GmbH has developed together with ESA/ESTEC a multidisciplinary design approach that allows quick optimization of mission vehicle management design. This development is based on the latest version of the ASTOS software suite. ASTOS focuses on the optimal trajectory and GNC related aspects of a mission and includes all relevant subsystems and disciplines like GNC/AOCS, power, thermal, structure, aerodynamics, to provide a complete analysis of loads and budgets for all analysis and design processes.

For such a design process it is mandatory that the ESA development engineering process is properly reflected in the tool. Since any design solution needs to be verifiable and justifiable it is of less interest to obtain one most global optimal solution, rather than a multi-objective solution. In this kind of MVM problems, many mission constraints have to be considered and a good system analysis is required to verify the feasibility of the final optimized concept.

To build the latest MDO release of ASTOS, our final choice was to use our existing Non-Linear Programming (NLP) based optimal control software, considering a multitude of constraints and extending the optimisable parameter set by various MDO models. The chosen optimization method is a single-level decomposition method called All-At-Once (AAO) method. This method is suitable for conceptual and preliminary design tasks. The implementation of discipline models themselves have to match in their level of fidelity and should not have a level of detail which requires extensive CPU-time.

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Verification and Validation by Simulation

The ECSS Technical Memorandum “System Modelling and Simulation” [1] describes in detail the need for Virtual Spacecraft Design methods to increase the confidence in early project phases. The aim is the cost reduction of the whole project. Moreover it defines the various simulators used during the space system lifecycle. The current paper focuses on the MVM design and development between phase 0 and phase C. Along those phases the main tasks are feasibility and performance analysis, requirements specification, design verification, system and mission performance verification, and partly functional subsystem verification and validation. The simulators proposed in [1] are mapped by the ASTOS software suite [2] as follows:

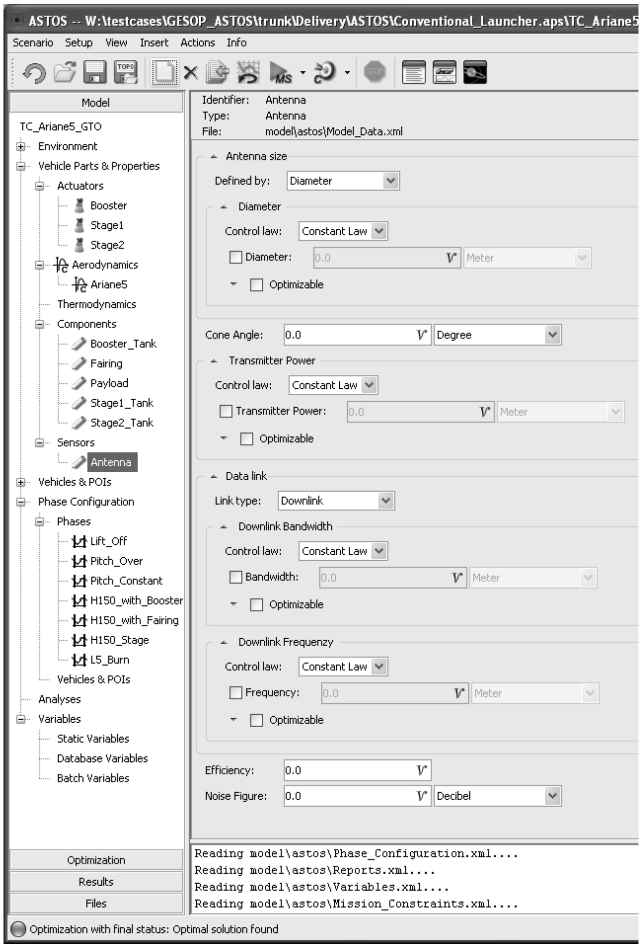
- System Concept Simulator (SCS)
- Mission Performance Simulator (MPS), also called End-to-End Simulator (E2E)
- Functional Engineering Simulator (FES)

II. ASTOS OVERVIEW

The current version of the ASTOS software is an industrial grade COTS optimization, mission and system analysis and design software. It combines a highly flexible scenario definition based on a graphical user interface and an extensive object oriented model library with tools for trajectory and vehicle design optimization using large scale direct optimization and random search techniques, short and long time propagation based on numerical and semi-analytical methods, and interfaces to various tools like Simulink for detailed GNC/AOCS design and analysis.

ASTOS is suited to model and analyze endo- and exo-atmospheric, orbital and interplanetary missions like launch, (re-)entry, planetary observation, satellite communication, rendezvous, formation flying, constellations, aero-assisted missions.

Originally established as optimization software [3], ASTOS has been newly extended to a powerful mission vehicle management analysis and design software. ASTOS now provides a virtual spacecraft designer including sensor specification (Fig. 1) and analysis and design for GNC systems with interface with MATLAB/Simulink^{TM}. The new ASTOS version [7] provides the capability to specify the space scenario using the well-known ASTOS user environment and provides the dynamics and environment simulation features as an S-function to any Simulink canvas. In this Simulink canvas, sensors and actuators can be modeled in detail and onboard algorithms can be implemented for later export to real-time C or Ada coded platforms. Moreover, ground station simulation and a simulation station for debugging and verification purpose complete the functionality.



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Optimization with final status: Optimal solution found

Fig. 1: Equipment definition in ASTOS

A Simulink library is provided to the user with equipment models and algorithms that reduce the configuration and development time. Finally, the 3D visualization and animation software VESTA (Virtual Environment for Space and Terrestrial Applications) complements ASTOS [4].

ASTOS is now able to solve MDO for MVM problems not only for rockets and re-entry vehicles, but also for conventional satellite missions as well.

ASTOS is currently used at the European Space agency and across Industry in the world. More than 200 licenses have been sold across Space Agencies, and industrial partners. In ESA, ASTOS is used at the ESA Concurrent Design Facility (CDF), at the Technical Directorate, in the Human Space flight and Operations Directorate, and at the Launcher’s Directorate. Its fully data driven approach it is highly suited for collaborative working environments and rapid prototyping tasks. ASTOS is also the basis for the Launcher GNC Simulation Sizing Tool [6] and it has been applied as Space Robotics Simulator to the German Orbital Servicing Mission (DEOS) [5], where it has proven its added value for future space projects. Especially for close approach maneuvers, like berthing maneuvers, the

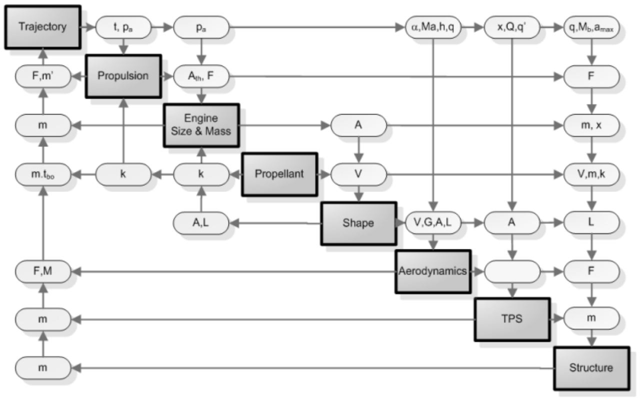

Fig. 2: Decomposition of discipline models

coupled analysis of ASTOS is able to give full confidence in proposed strategies or to expose its weak points.

The ASTOS virtual mission design capabilities are derived from the trajectory analysis including related simulations and subsystems. Those are primarily trajectory design and analysis, MVM design, GNC and related subsystems and disciplines like propulsion, aerodynamics, structure, power, thermal, communication, and data handling [8]. Such subsystems are considered in a relevant maturity to answer questions concerning the feasibility of a concept or mission analyzing loads and budgets.

III. MULTIDISCIPLINARY SYSTEM CONCEPT

The new ASTOS design approach [7]is based on a further extension and combination of the previous ASTOS functionality. MDO, MVM, GNC analysis and design and further consideration of the vehicle subsystems are combined into an integrated working environment. All this is complemented by functions for the evaluation of the results such as requirements management functions and verification functions as part of an automatic reporting capability.

The user driven approach of ASTOS allows the user to specify his own workflow and focus on the specific aspects of his mission. By selecting specific models and analysis functions, the user is able to focus either on the MDO problem, or on system concept design and verification, or on mission performance simulation, or on the functional engineering simulation aspects. ASTOS offers rapid configuration of the entire virtual system and maintenance of the models and scenario during the lifecycle of the space system, always staying in one single working environment with the same look-and-feel.

This workflow interprets the requirements of reusability in a unique way resulting in a high grade of efficiency to reduce costs.

IV. DETAILS OF THE NEW ASTOS DESIGN FEATURES

Multidisciplinary Optimization

The AAO approach used by ASTOS relies on direct optimal control software and sparse NLP solvers like the new European NLP solver WOHRP [12]. Problems with more than 100,000 parameters and constraints can be solved easily. A decomposition of the disciplines (Fig. 2) provides a robust optimization behavior. The considered disciplines are optimal trajectories (with branching capabilities), propulsion systems, structures, aerothermo-dynamics, shape, and thermal protection systems [11].

Specific subsystem models are used to mimic the behavior for design optimization [7]. The propulsion system uses chemical equilibrium algorithms and its efficiency depends on design criteria like low cost or high performance. The aerodynamics subsystem uses analytic methods for launcher drag and uses the shock expansion method SOSE from DLR [9] for entry vehicles. The mass of engines and structural components is based on regression. The data is obtained from existing designs or from the structural optimization software ODIN [10], which allows also the export of NASTRAN^{TM} models. The shape is parameterized using basic geometries. Results have shown that an error in the estimation of the structural mass has the largest impact on the vehicle design, followed by engine performance and aerodynamics drag. But this result does not consider dynamic effects that are discussed later.

Mission Analysis

Key feature of the mission analysis of ASTOS is the determination of the loads and budgets of a mission. Loads are required as input e.g. for the structural mass estimation in MDO processes. Budgets are relevant for the design specification. The new ASTOS version also allows the positioning of sensors on the vehicles. During the early phase of a project, most sensors functionality can be mapped by means of simply the field of view. But also more detailed sensor models can be implemented.

The combination with the 3D visualization engine VESTA allows the visual verification of the mission scenario (Fig. 3).

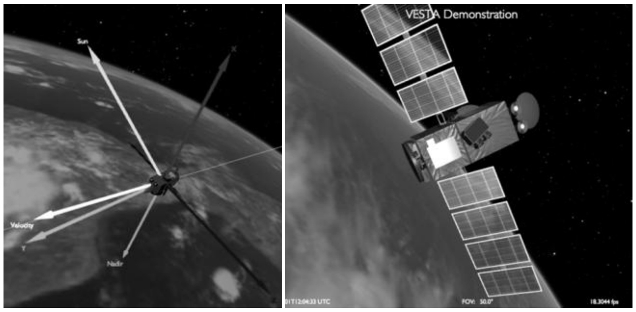

Fig. 3: VESTA showing visual helpers (left) and reflections (right)

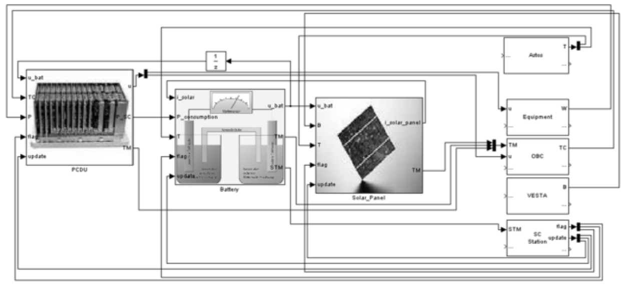

Fig. 4: Detailed model of power system with battery, solar panel and consumers.

System Analysis

Most system computation requires a set of detailed subsystem tools for a realistic full system analysis. This paper considers the features of the analysis and design process, which have a clear impact on the trajectory and GNC subsystem. This includes also the mass budget in case of design optimization. The considered subsystems are the propulsion system, the power system required for e.g. electric propulsion (Fig. 4), the thermal system, and the telemetry budget. All those subsystems are modeled in ASTOS but they may be modeled in a higher level of detail in Simulink as required for FES or MPS if so required. This way, any performance simulations and the verification and validation of the system requirements with respect to the mission objectives is possible.

GNC Analysis and Design

The GNC analysis and design module enables the user to specify the scenario through the ASTOS model browser and then export of the dynamics and environment as an S-function to Simulink, where the sensors, navigation, guidance, control and actuators are fully modeled (Fig. 5). The post-processing is done also in the ASTOS software, which knows the spacecraft and scenario definition and hence ASTOS is able to make use of it in an intelligent and automated process.

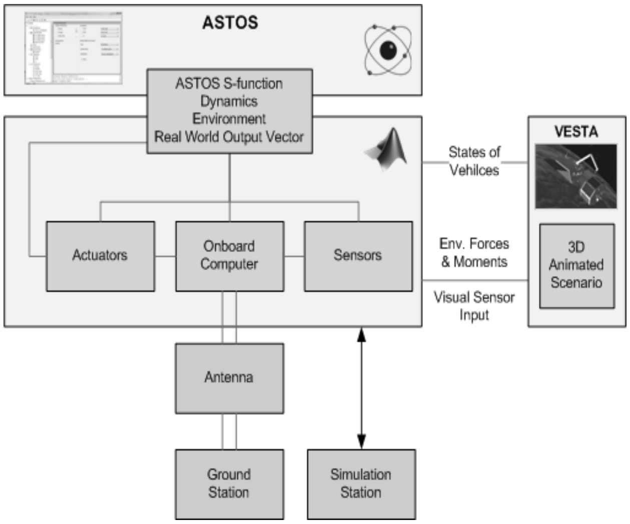

Fig. 5: ASTOS-GNC architecture

In the frame of ESA’s Launcher GNC Simulation Sizing Tools development [6], lead by Astos Solutions GmbH, the ASTOS tool is used for launcher missions. The GNC is implemented under MATLAB/Simulink. A controller design tool is implemented under MATLAB. Any flexible dynamics is simulated using the DCAP software [13] that is coupled. The computed load cases considers also dynamic effects like distributed aerodynamic drag and lift during oscillations. The data can be imported from ESA’s CDF infrastructure [14] or from ESA’s ALMA database [17].

Coupled Analysis

All previously discussed features can be combined in the same working environment. These combinations are here after detailed: Mission and GNC Analysis, Mission and System Analysis, and MDO and GNC Analysis.

Mission and GNC Analysis

ASTOS now provides the possibility to perform mission analysis and to consider in parallel aspects of GNC analysis e.g. for proper determination of the delta-V budget. Vis versa it is possible to activate the mission analysis functions like visibility, lightning conditions etc. during a detailed GNC analysis tasks. One possible application is the coupled computation of the fuel budget considering orbit and attitude control.

In addition, VESTA provides the capability to compute accurately differential forces and moments in a OpenGL environment and to feed them back into the GNC dynamics for accurate station keeping, e.g. during the mating procedure of two spacecraft (Fig. 6). The geometric relationships are computed on the graphical processor (GPU) of the computer considering solar radiation pressure and air drag. This is of special interest in case of partial shadowing, for example.

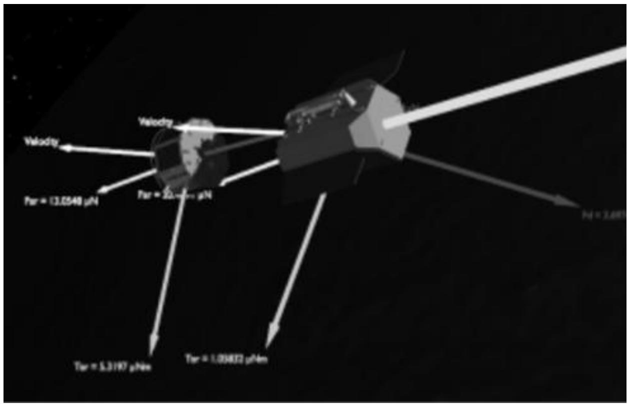

Fig. 6: DEOS scenario with partial shadowing; force and torque vectors caused by solar radiation pressure and air drag are shown.

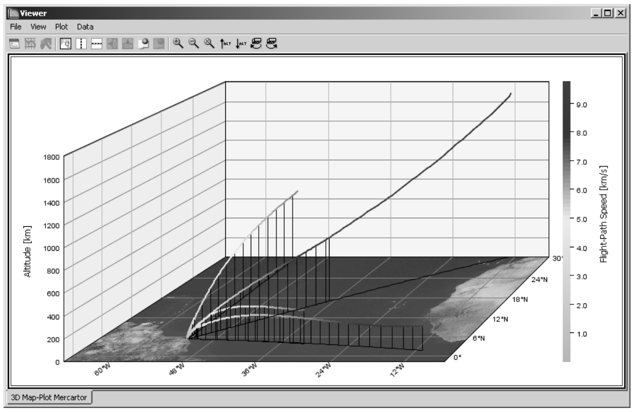

Fig. 7: Launcher family design for multiple orbits and payloads

Mission and System Analysis

The 3D rendering engine VESTA is used in ASTOS for visualization of the mission. The analysis capabilities of the user are supported by visual helpers, like vectors or sensor cones (Fig. 3, Fig. 8). Similar to the force feedback, a VESTA extension is able to compute the partial shadowing of solar panels and consider the cell structure and the depending performance characteristics. This information is used as input for the battery model.

Moreover, VESTA provides the detailed irradiation and radiation at the different surface elements of a satellite under consideration of partial shadowing effects. This way a detailed thermal model can be computed.

MDO and GNC Analysis

The feasibility of a MDO solution needs to be evaluated using information coming from the space vehicle subsystems. As MDO normally considers only rigid body dynamics and only translational motion, aspects like flexible dynamics, attitude control or aerodynamic stability are ignored for purpose of fast computation.

The GNC module of ASTOS allows the computation of the Eigenfrequencies based on the Dynamics Control and Analysis Package DCAP software [13]. Finally an approximation of the controllability can be performed based on the aerodynamic and thrusters efficiency [15]. This information can be considered in the MDO process if the user wishes.

DCAP is able to perform a modal analysis based on a beam approximation or NASTRAN model, which might be produced by the structural optimization software ODIN, which is part of the MDO process.

V. APPLICATION CASES

This section presents the current ASTOS capabilities using 3 distinctive analysis and design examples.

Launch Vehicle MDO and GNC

Considering just MDO for launcher design it is hardly possible to obtain a single solution which is suitable for engineering processes. It is essential to extend the available information as much as possible to the subsystem analysis in early design phases.

All ESA’s new launcher MDO and GNC coupled simulation developments are now using ASTOS as baseline. This provides a continuous workflow as follows:

- MDO for preliminary design, requirements specification and mission performance verification under consideration of maximum loads and multi-mission objectives [16] (Fig. 7).
- ASTOS for computation of guidance, reference trajectories, and payload performance tables.
- Safety and risk analysis.
- Navigation and guidance algorithms in Simulink using ASTOS S-function as dynamics and environment block with previously computed reference trajectory. MonteCarlo analysis and post-processing using the Batch Mode Inspector computing injection accuracy and ground track drift.
- Modeling of flexible dynamics using DCAP. Automatic initialization is done by ASTOS which keeps the scenario definition consistent.
- Controller design in MATLAB using information from either ASTOS or DCAP for state space linearization.
- Closed loop control simulation in Simulink using ASTOS or DCAP for rigid or flexible body dynamics and previously defined guidance.
- Post-processing in ASTOS with automatic reporting but also the possibility to export to MATLAB.
- Launch window computation with ASTOS.
- Automatic verification of testable requirements with ASTOS.

Orbital Servicing Mission

The German Orbital Servicing Mission DEOS has the objective to capture an non-cooperative target and to

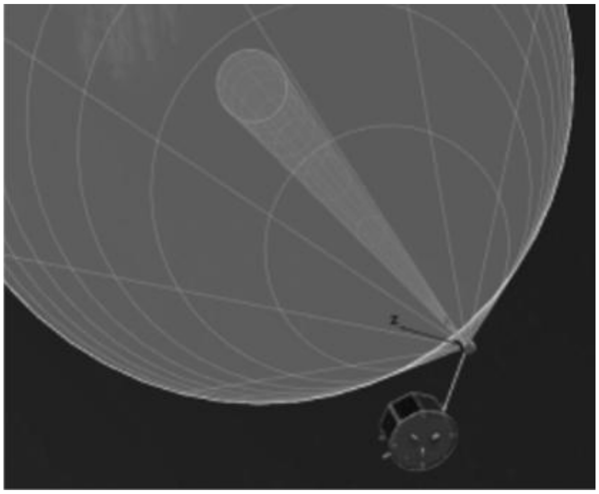

Fig. 8: Field of view of wide field camera and close field LIDAR in DEOS like scenario running in combination with search algorithm. Client is currently outside of both cones.

ensure its save de-orbiting [5]. This requires new GNC strategies as the non-cooperative client is not able to support the rendezvous and docking maneuver with additional navigation information. Specifically close approach maneuvers are required.

For such kind of scenario, ASTOS offers the following functionality:

- Maneuver optimizing for far and close approach.
- Mission analysis verifying visibility to ground stations and relay satellites, eclipse phases, and visual sensor field of view (Fig 8).
- Export of ASTOS dynamics and environment as S-function to Simulink and modeling of the GNC algorithms in Simulink.
- Simulation in Simulink and parallel visualization in VESTA implemented as Simulink block.
- Computation of environmental forces and moments in VESTA and feedback into Simulink.
- Computation of environmental input for subsystems like power in VESTA and feedback into Simulink.
- Extended use of VESTA for real-time visual 2D and 3D sensor simulation considering sensor characteristics and using hardware interfaces like CameraLink (Fig. 9).
- Detailed modeling of sensor signal processing based of sensor simulated data.
- Modeling of the kinematic of the manipulator arm and verification of the mission performance.
- In the future, flexible body dynamics of the coupled system of servicer and client using DCAP.
- Optimization of deorbit maneuvers.
- Computation of breakup, demise and impact during reentry as part of the safety and risk module.
- Automatic verification of testable requirements with ASTOS.

Low Thrust GTO-GEO Transfer

There is currently a high interest of the use of low thrust propulsion for conventional missions.

Especially of a high interest is the space mission phase from LEOP until injection into the GEO box of satellites. The objective is to improve the mass balance over life-time by using only electric propulsion for transfer, station keeping and disposal.

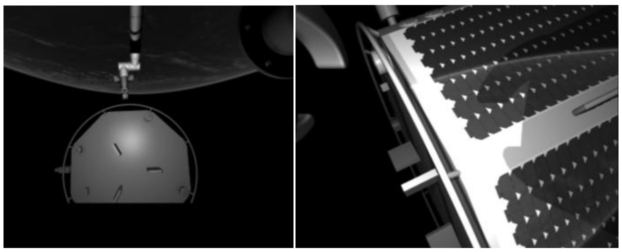

Fig. 9: Infrared camera simulator presenting client seen with two cameras, one mounted at the servicer directly (left) and one mounted close to the grabber at the end of the manipulator arm (right).

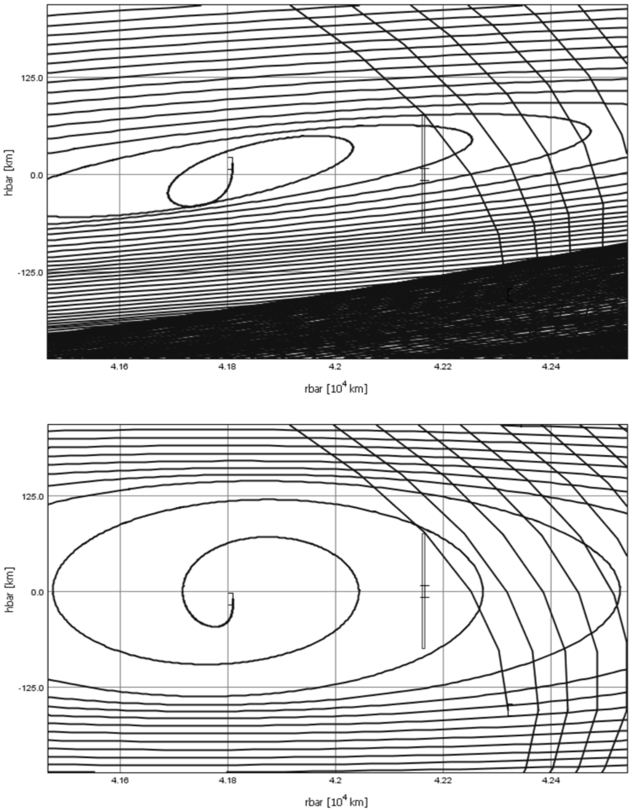

Fig. 10: GTO-GEO transfer with (top) and without (bottom) GEO-box (vertical line) crossing presented in radial-transverse frame; End point in the left part of the picture represents the target point 500km below the GEO box.

ASTOS supports the engineering work as follows:

- Trajectory optimization of the 6 to 12 month transfer using full state discretization and optimal control under the consideration of perturbations and power constraints.
- Detailed trajectory optimization of critical flight phases like collision avoidance during GEO-belt crossing (Fig 10) or reduction of degradation effects by fastest transfers through the van Allan belt including combinations of chemical and electrical thrusters.
- Analysis of ground station visibilities and navigation aspects, e.g. visible of GPS satellites.
- Optimal guidance considering different requirements on the navigation accuracy in specific flight phases, collision avoidance and operational aspects.
- Development of a Functional Engineering Simulator based on GNC module of ASTOS.

VI. CONCLUSION

This paper has shown how multidisciplinary analysis is combined in the newly ASTOS framework. The capabilities stretch from trajectory and vehicle design optimization to mission, system and GNC analysis and design including vehicle equipment simulation. The framework comprises all features under a single tool and allows the user to combine modeling and analysis tasks in a project. ASTOS provides a rapid configuration of the space systems and flexibility for MDO problems. It is possible to extend the scenario setup according to the user requirements and to maintain it during the space system lifecycle. Due to the new coupled analysis and design capabilities of ASTOS, it is possible to perform analysis and design of complex concepts in earlier phases, which improves the confidence in a space system as early as possible. As a consequence a tool has been presented which helps to reduce the total development costs.

ASTOS v8.0 is available at the following URL: http://www.astos.de. ASTOS is free of charge for education and non-commercial research.

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