LOTOS

Low-Thrust Orbit Transfer Trajectory Optimization Software

Astos Solutions

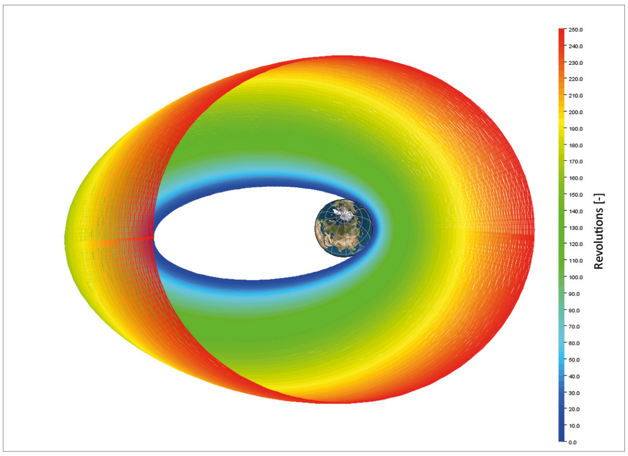
With the maturation of electric propulsion technology it has become attractive to exploit the high specific impulse and reduce the propellant budget for transfer from GTO to GEO. The majority of platform developments for telecommunication satellites include this transfer capability in their product list.

LOTOS is an advanced tool for trajectory optimization and analysis of electric orbit-raising scenarios and hybrid transfers, where the chemical orbit-raising is followed by an electric propulsion orbit transfer. It allows simulation, optimization, verification and analysis of orbit transfer trajectories with electric (low-thrust) propulsion. For preparation and support of the spacecraft operations during the orbit transfer, LOTOS features the re-optimization of pre-computed attitude histories and optimal trajectories, which has to be performed after an update of the spacecraft state by means of orbit determ-ination. Since initial and final orbit are user-defined, the tool is not limited to typical GTO-GEO transfers of telecommunication satellites but offers a wide range of possible applications for low-thrust transfers such as constellation deployment and graveyarding.
All user defined scenario input as well as the computed output and the results of the automatically run analyses are summarized in user customizable reports. Just one click and e.g. mission analysis engineers and project managers receive all relevant numbers, plots, tables and facts of the orbit transfer.

LOTOS is based on more than 10 years of experience supporting space agencies and commercial companies worldwide.

Key Features

- Optimization of reference trajectories
- Re-optimization of updated trajectories for spacecraft operations and autonomous transfers
- Hybrid transfers
- Verification of trajectories
- Full 6DoF attitude control
- Slew rate optimization
- Analyses related to transfer performance and spacecraft subsystem aspects
- Automatic mission analysis reports
- Built-in batch-processing
- Command-line interface for use at control centres



Optimized transfer from Ariane 5 GTO to GEO

Added Values

Productivity
- Rapid configuration
- First iterations for proposal preparations
- Requirements definition
- Mission and system concept specification
- Verification and validation

Reusability between Project Phases
Continuous maintenance and refinement of
- Mission configuration
- Model
- Algorithms
- Methods

Reusability between Working Groups
- Interdisciplinary exchange between user groups
- Dedicated support by technology groups
- Abstract reuse of technology results on program level

Risk and Cost Reduction
- Consideration of detailed models, operational and real-time relevant requirements
- Rapid prototyping using phase B/C technologies in phase 0/A
- Cost neutral analysis of critical mission aspects in preceding project phases
- Overall cost reductions

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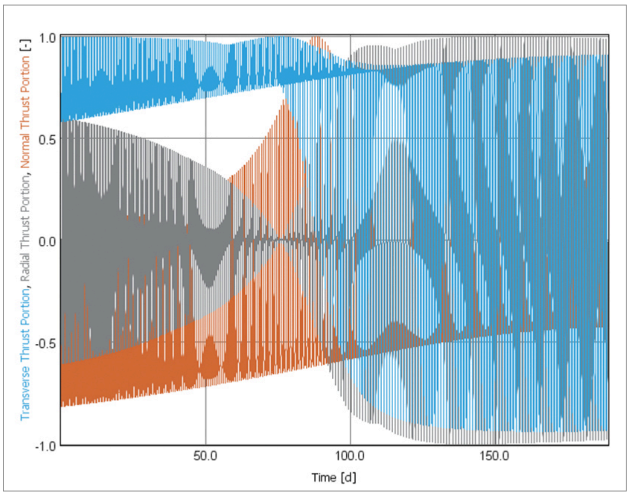
Modelling

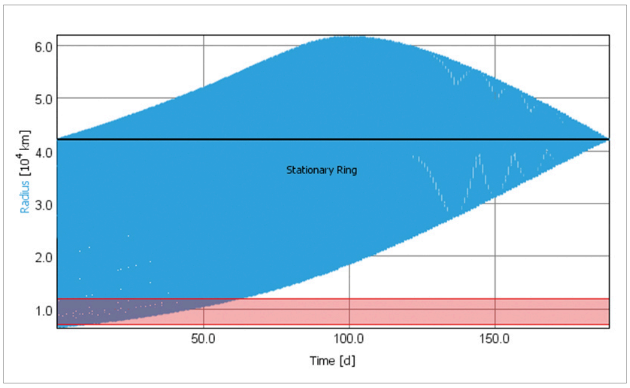
Hybrid Transfers
- Up to three user customizable chemical burns
- Optimisable burn duration
- Optimisable out-of-plane manoeuvres
- Minimum periapsis radius
- Maximum total transfer duration
- Dedicated report

Control Centre Mode
- Support of spacecraft operations
- Updated initial state after autonomous orbit transfer (e.g. after few days)
- Automatic identification of location on reference trajectory
- Re-optimization of remaining orbit transfer based on reference trajectory



Optimal evolution of thrust vector components

Environment
- Earth gravity field with zonal harmonics up to J6
- DE405 ephemeris library
- Analytic polynomial ephemerides for highest performance
- Atmospheric drag with Jacchia-Bowman 2008 or exponential atmosphere model
- Van-Allen belt integrated radiation flux
- Third body perturbation from sun, moon and planets
- Solar radiation pressure and solar wind



Evolution of spacecraft radius (blue) with radiation belt (red) and stationary ring (black)

Attitude Controls
- Unit vector components, Euler angles and Euler angular rates in inertial or local orbit frame (RTN)
- Spacecraft body rates (6DoF)
- Fully automatic initial guess generation with analytic laws or from external file (either control history or trajectory)

Spacecraft
- Mass and moments of inertia
- Power model incl. battery
- Propulsion parameters (Isp, Thrust) as function of power
- Propulsion time schedule (e.g. inactive on weekends)
- Propulsion shut-off during eclipses
- Thruster firing limitations (e.g. min./max. duration)
- Thruster on-off mode (bang-bang control)
- Disturbances of thrust direction and magnitude for robustness analysis
- Attitude and slew rate limitations
- Reference area, drag coefficient and reflectivity index

Dynamics
- Time or equinoctial element L as independent variable
- Normalized or un-normalized independent variable
- Equations of motion based on equinoctial elements
- Additional states: battery capacity, dwell time radiation belt, radiation dose, spacecraft attitude
- Several ODE solvers (variable-step RK4/5, RK7/8, MEBDFDAE and fixed-step RK4)

Optimization

General

- Graphical editor for optimization problem
- Iteration monitor for states, controls, objective function, constraint violation and much more
- Multi-phase optimization, e.g. for precise eclipses

Methods

- Direct collocation with SOS developed by John T. Betts, Applied Mathematical Analysis, LLC
- Direct collocation and multiple-shooting with CAMTOS developed by P. Gath and Astos Solutions
- Automatic mesh refinements (SOS, CAMTOS)

Solvers

- State of the art NLP solver SPRNLP (part of SOS) for several 100,000 parameters
- Alternative supported sparse NLP solvers are WORHP (developed by Steinbeis Research Center Optimization, Control and Adjustment Control) and SNOPT (from Stanford University)
- MIDACO: random search and mixed integer solver based on ant colony optimization algorithms developed by M. Schlueter
- CGA: classical genetic algorithm developed by D. Fischer and Astos Solutions
- PSO: particle swarm optimization

Constraints

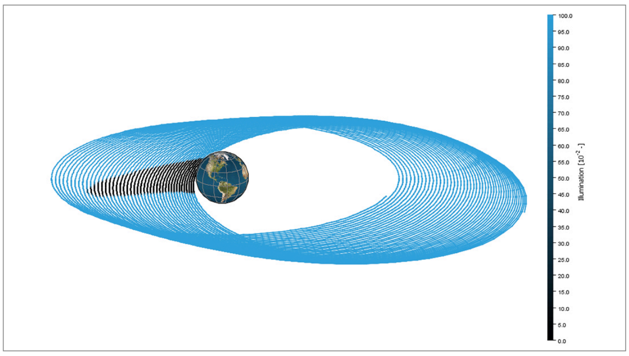
- Final Keplerian and equinoctial orbit elements
- Final geographic longitude
- Transfer duration
- Sub-synchronous transfer
- Slew rates during burn and coast arcs
- Eclipse begin and end conditions
- Battery capacity

Cost Functions

- Fuel consumption
- Transfer duration
- Final Keplerian and equinoctial orbit elements
- Final geographic longitude
- Van Allen belt dwell time
- Slew rates during burn and coast arcs
- Sub-synchronous transfer

Output

- Customizable output functions
- Several plots (2D, 3D, map plots, 3D map plots)
- Plots with value-based curve colour (gradient)
- User-defined step-size
- Sun eclipses from earth and moon as detailed output file
- Attitude progression (quaternions) as dedicated output file
- Output functions including position, velocity, orbital elements, accelerations, attitude, attitude rates, body rates, body accelerations, torques, wheel momentums, delta-V, dwell time in Van Allen belt, number of GEO belt crossing, distance to GEO belt, visibility from ground stations, etc.



Electric orbit-raising with eclipses (black)

Analyses

Several built-in analyses are customizable with user defined thresholds and are run automatically with each simulation action:

- Attitude constraint violations (thruster pointing in sun direction)
- Eclipses (number of eclipses up to 30 minutes, 30 to 60 minutes, average eclipse duration, longest eclipse duration, etc.)
- GEO belt crossings (number of crossings, time and longitude of each crossing, etc.)
- Slew rate violations (number, transfer time, peak value, etc.)
- Star tracker blinding (number of total blindings, occurrence of blindings, etc.)
- Thruster firings (minimum and maximum firing durations, minimum period between two firings for two different thruster modes, etc.)

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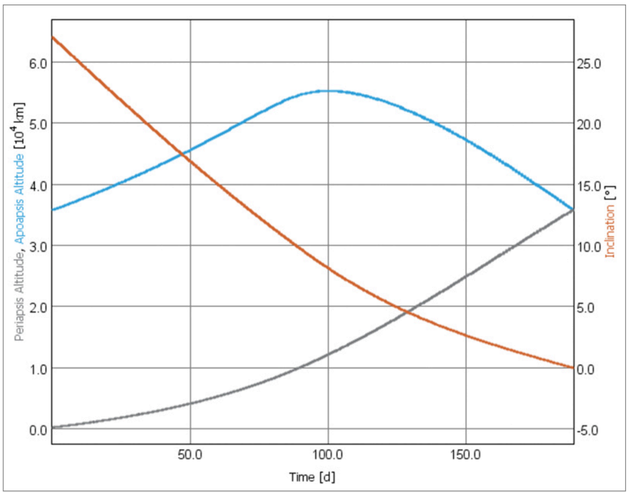
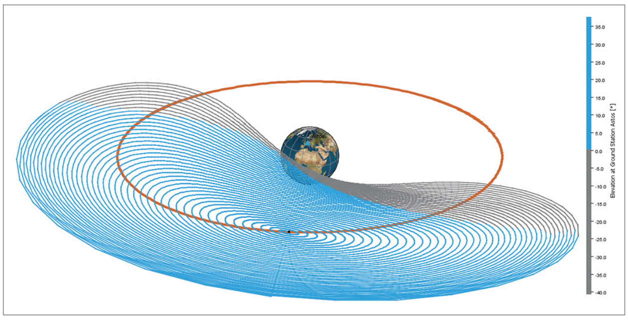
- Torque limit violations (number of violations and when they occur, etc.)
- Visibility analysis for ground stations (total and average time of ground station contact and loss, etc.)
- Wheel momentum limit violations (number of violations and time, wheel momentum dumping, etc.)



Progression of optimized orbital elements

Reports

- User customizable
- Automatic creation
- Pre-defined templates for hybrid transfers and electric orbit-raisings
- Access to scenario input
- Access to all output data
- Access to results of analyses
- Dynamic tables depending on output data
- May contain plot diagrams
- May contain external figures
- Header and footer with user CI



Synchronous orbit transfer (grey) in Earth rotating frame with ground station visibility (blue) and GEO ring (brown)

General Characteristics

- Completely data driven modelling solution
- XML based configuration files
- Graphical user interface
- Command line interface
- Built-in batch processing (e.g. for sensitivity analyses)
- Interactive help and PDF manual
- Content-sensitive manual
- Tutorial
- Prebuilt scenarios
- Operating systems: Windows 10/11 and Linux

Database

- User-customizable
- Pre-defined examples
- Comprises: orbital elements, environmental aspects (e.g. radiation belt, GEO ring), spacecraft characteristics (e.g. power, propulsion system like thrust and specific impulse profiles, AOCS like slew rates and star tracker), ground stations, cost functions, etc.

Performance

- Results within seconds
- Converged results within minutes

License Policy

- Perpetual node locked or floating license
- 20 hours of remote support
- Software updates for one year
- 5-day training in Stuttgart, Germany
- Optional yearly maintenance
- Hybrid Transfer and Control Centre Mode require dedicated license features

More Information

For more information please contact service@astos.de or visit our software product website https://www.astos.de/products/lotos

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