Low-Thrust Orbit Transfer Trajectory Optimization Software for Launcher Upper Stages

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- Electric propulsion upper stage
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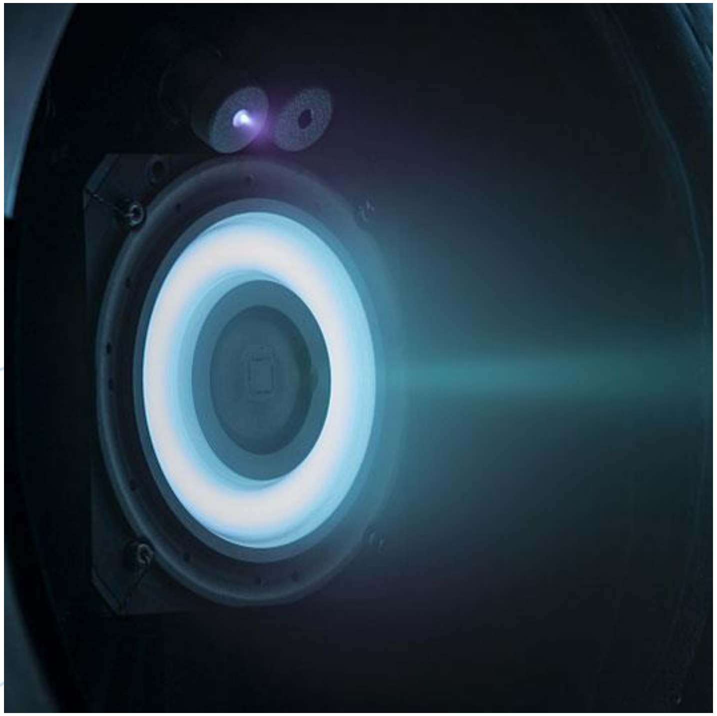


Credits: Safran

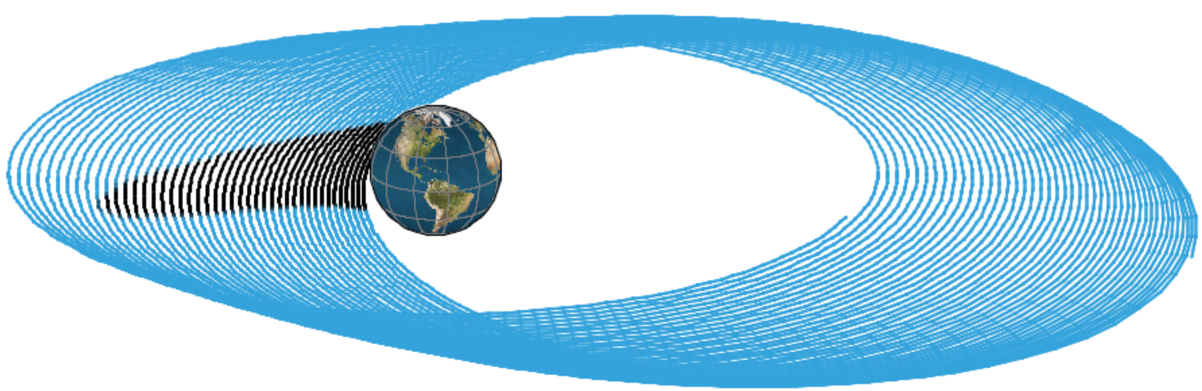
State of the art

Low-thrust is applied to several scenarios:

- Orbit raising till target orbit
- Position and Attitude control during operational phase
- De-orbit or graveyarding at end-of-life

Near future scenarios:

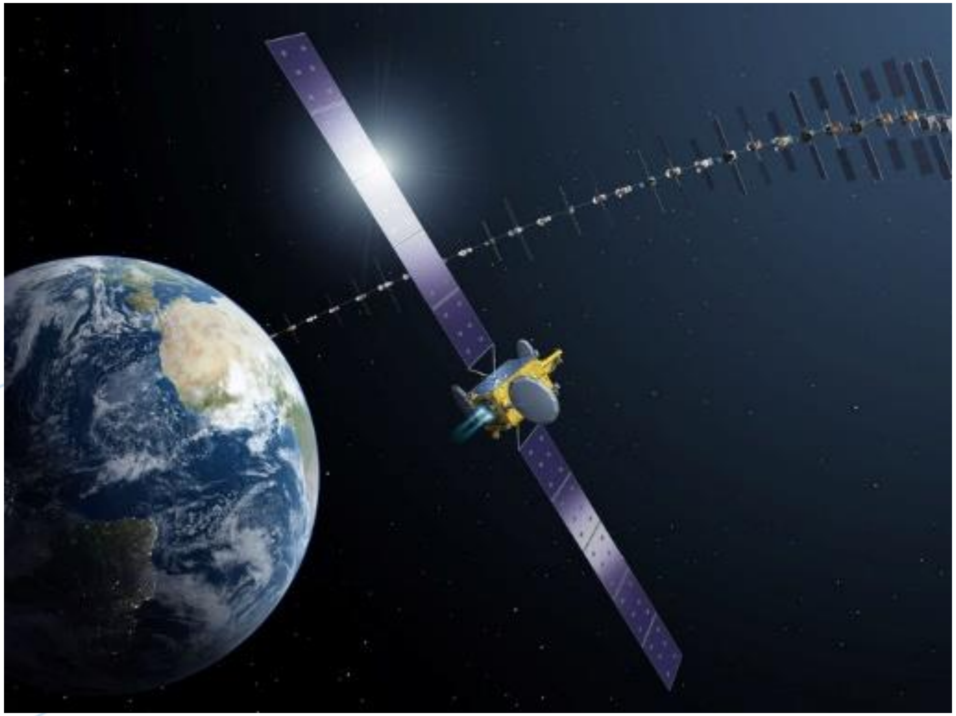
- Space tug for delivery and service
- Upper stage?



Motivation

All these scenarios requires:

- Optimization and analysis of high-fidelity transfer trajectories
- Optimized maneuver planning
- Software for Guidance & Navigation
- Mission analysis

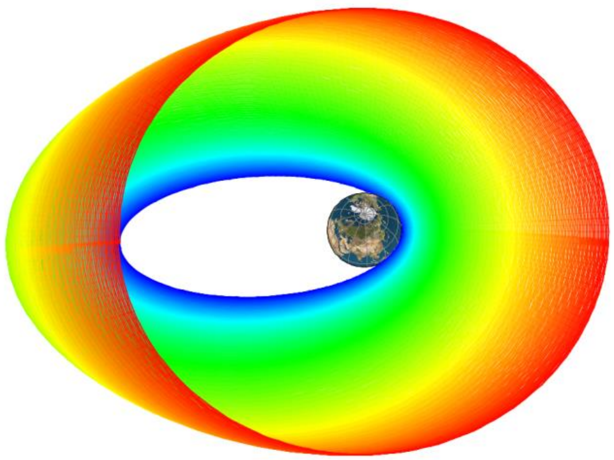


Credits: EPIC EU

Electric Propulsion for Orbit Raising

Most telecom spacecraft are launched into a transfer orbit

- GTO-GEO transfer
  - ~12% propellant consumption (vs. 40% chemical)
  - Transfer duration prolonged up to several months

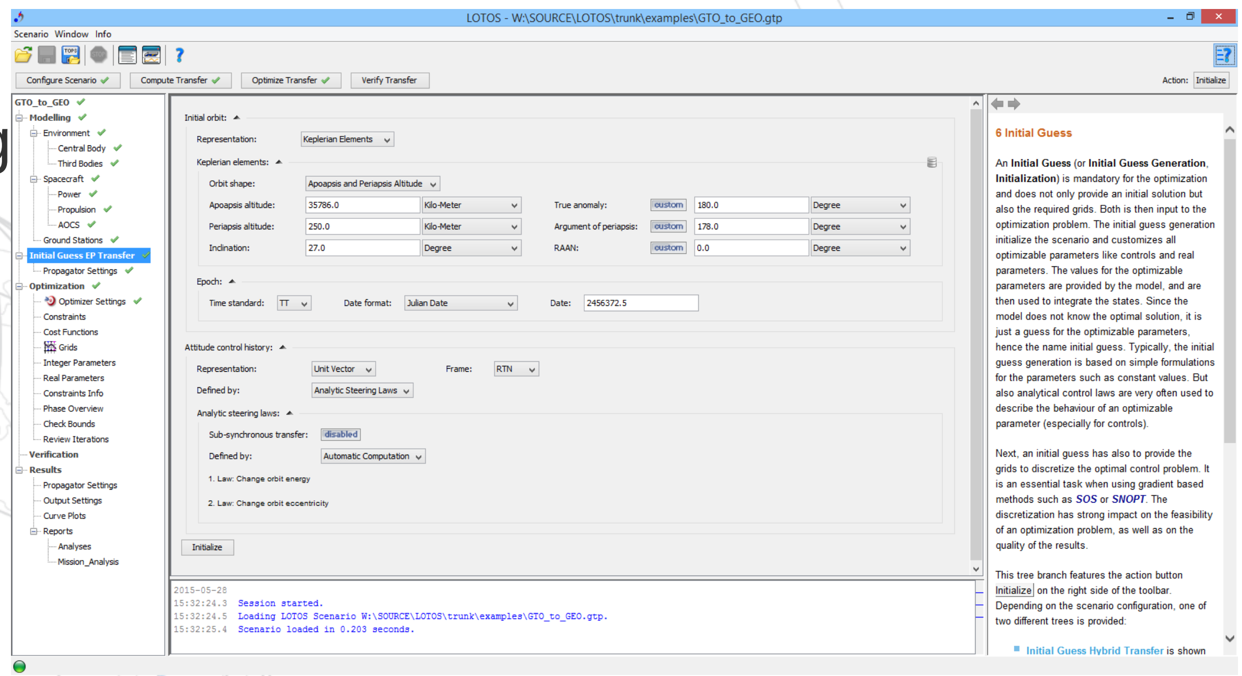


The use of "small" launchers can reduce mission cost

- LEO-LEO transfer
  - NEUTRINO on https://www.astos.de/news
- LEO-MEO transfer
  - http://www.esa.int/Our_Activities/Navigation/Electric_thrusters_may_steer_Galileo_in_future
- LEO-GEO transfer
  - https://artes.esa.int/news/vega-launcher-telecoms

LOTOS Key Features

- Hybrid transfers and pure electric orbit-raisings
- Support of operational trajectories
- Controlled 6DoF attitude
- Verification of trajectories
- Database
- Post-processing
- Reports
- Windows & Linux platform



LOTOS – Software Scheme

Minimum Time Transfer | Composite Objective | Minimum Fuel Transfer

↓

Starting Orbit | Mission Epoch | Target Orbit

Visibility Constraints

Transfer Constraints (e.g. GEO, Min. Radius)

Perturbations

Solar Eclipses

Radiation Damage

Constrained Slew Rates

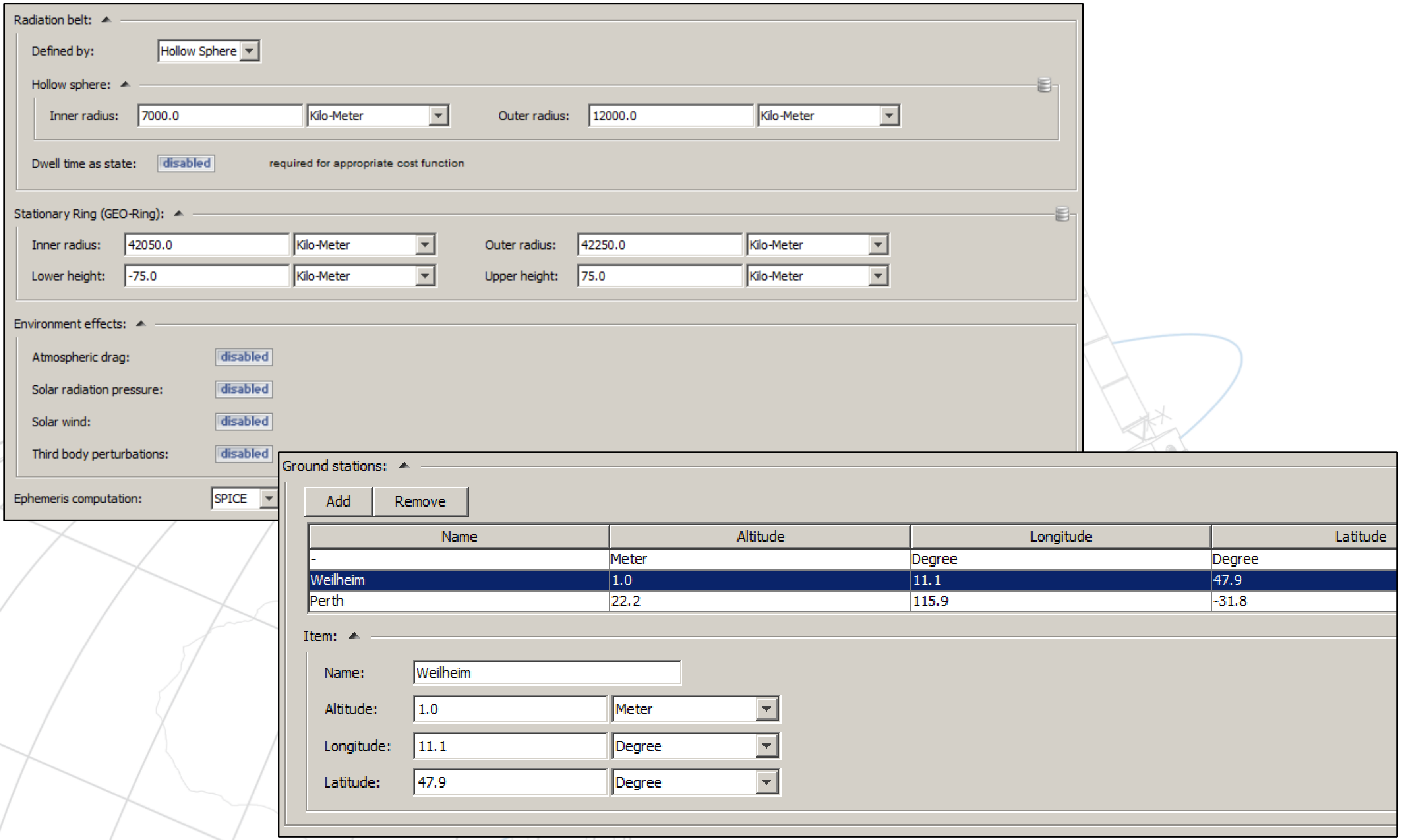
Managerial Constraints

Phasing | Intermediate Orbits

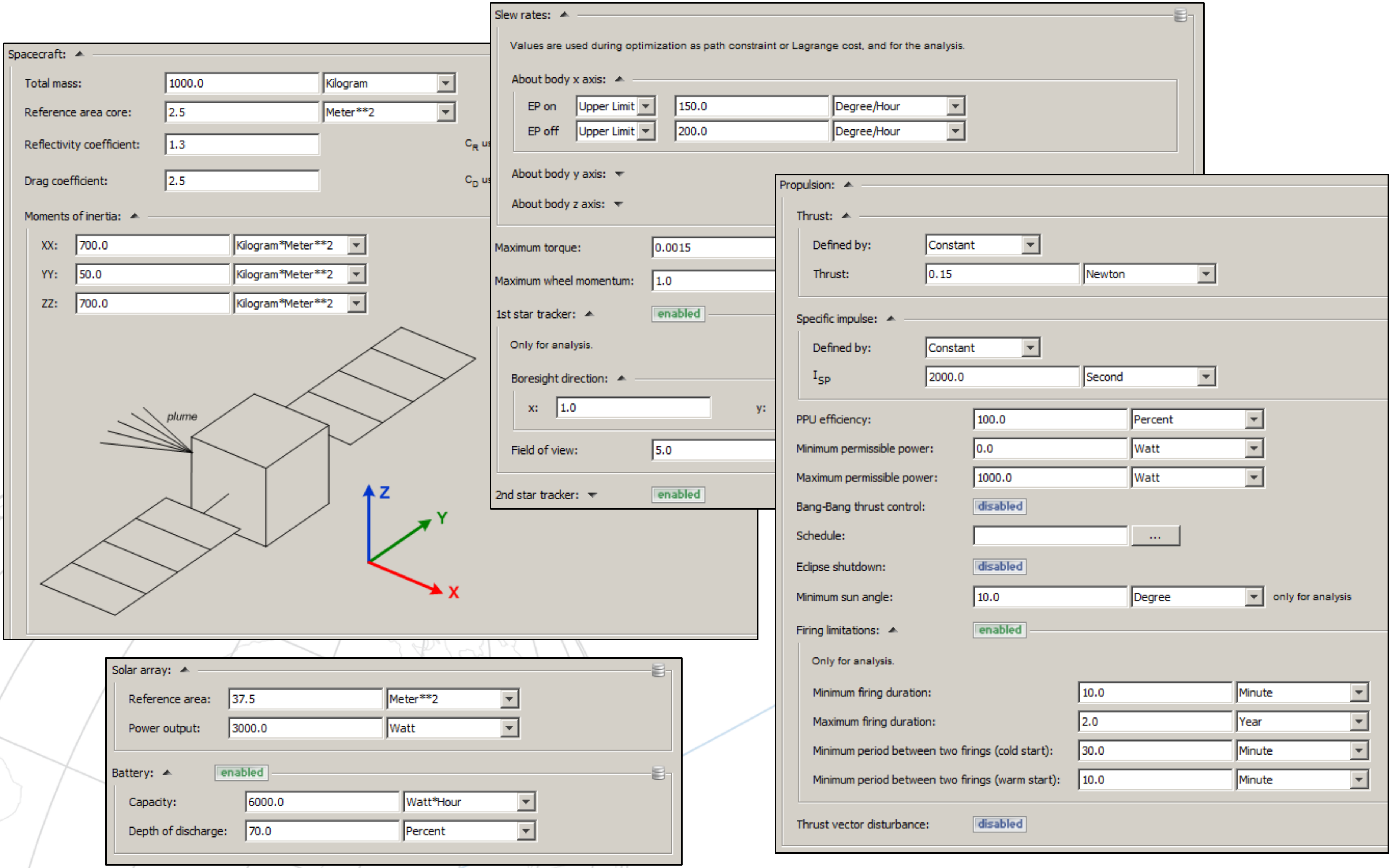
↓

Optimal Trajectory

LOTOS – Environment

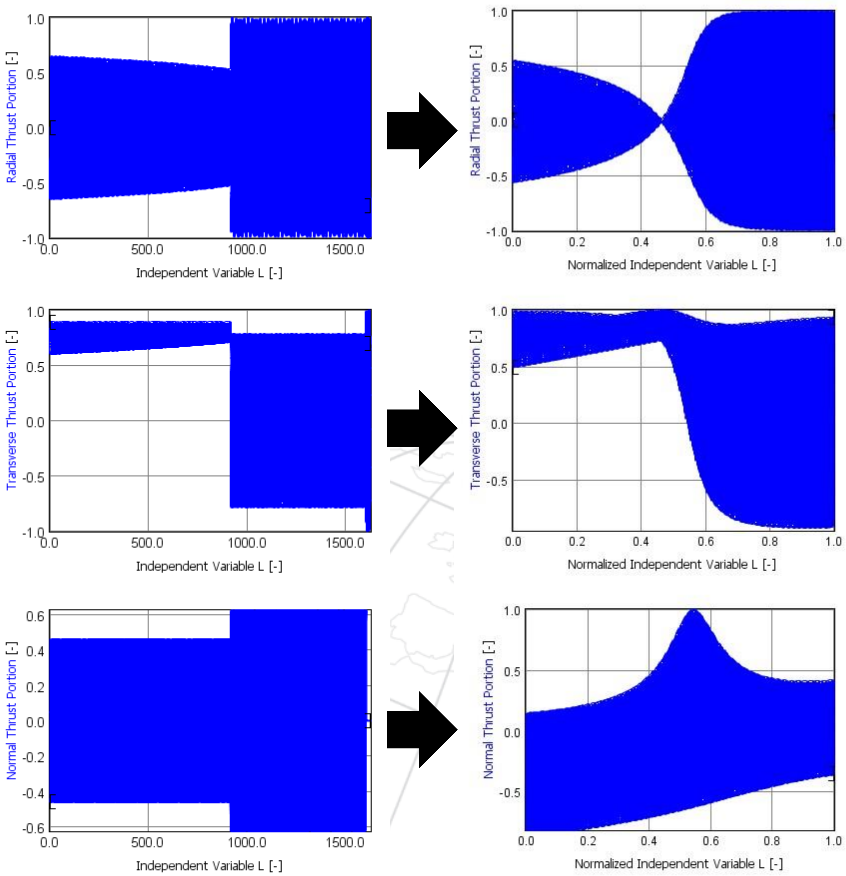


LOTOS – Spacecraft

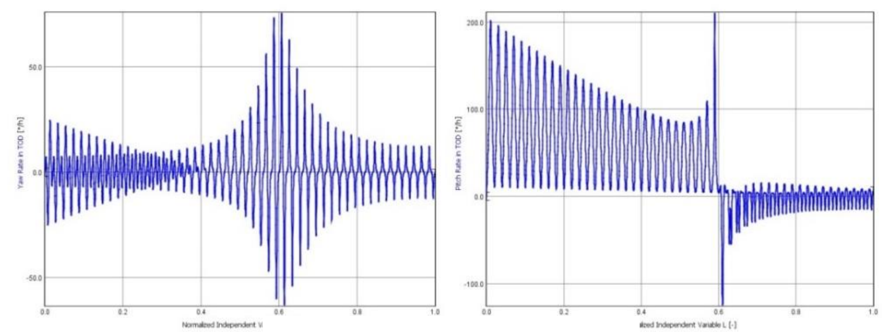


LOTOS – Dynamics

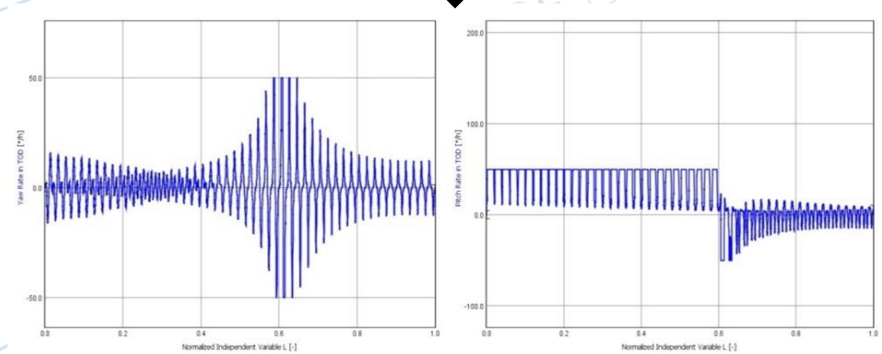
Thrust direction



Slew rates



unconstrained

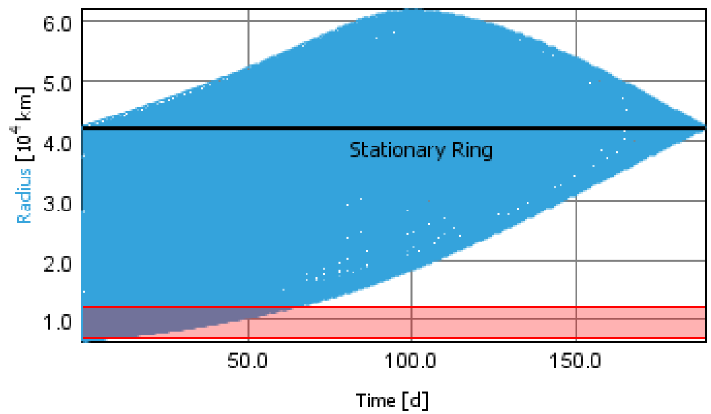


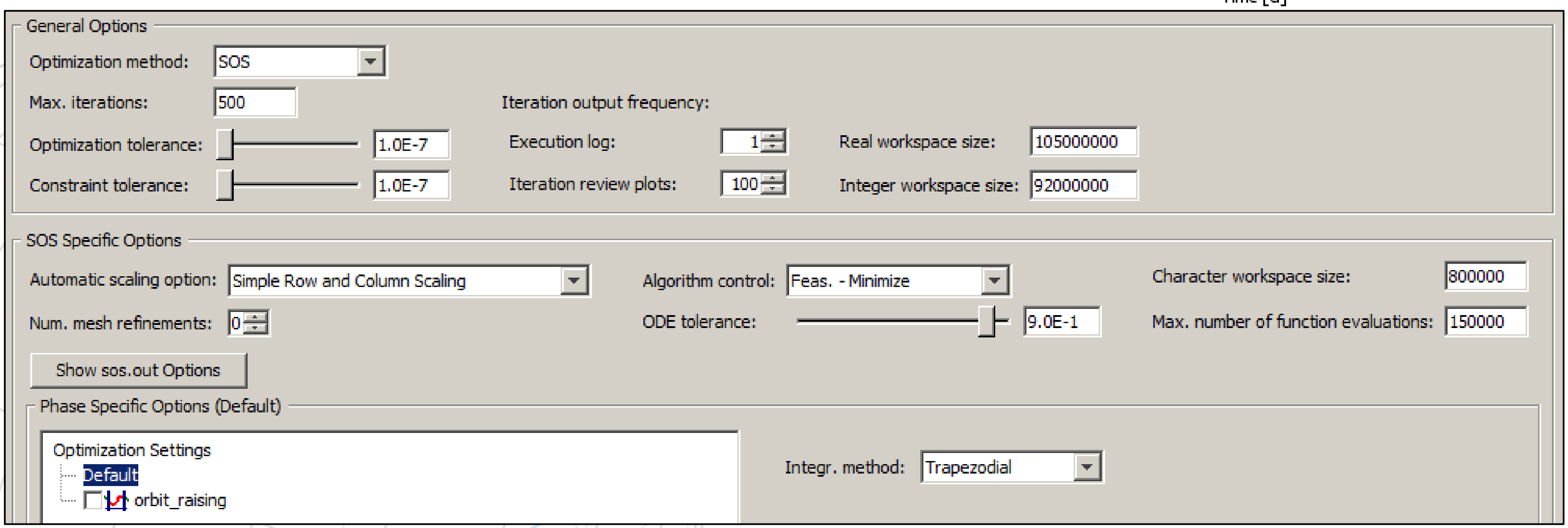
max. 50°/h

LOTOS – Optimization

Solvers

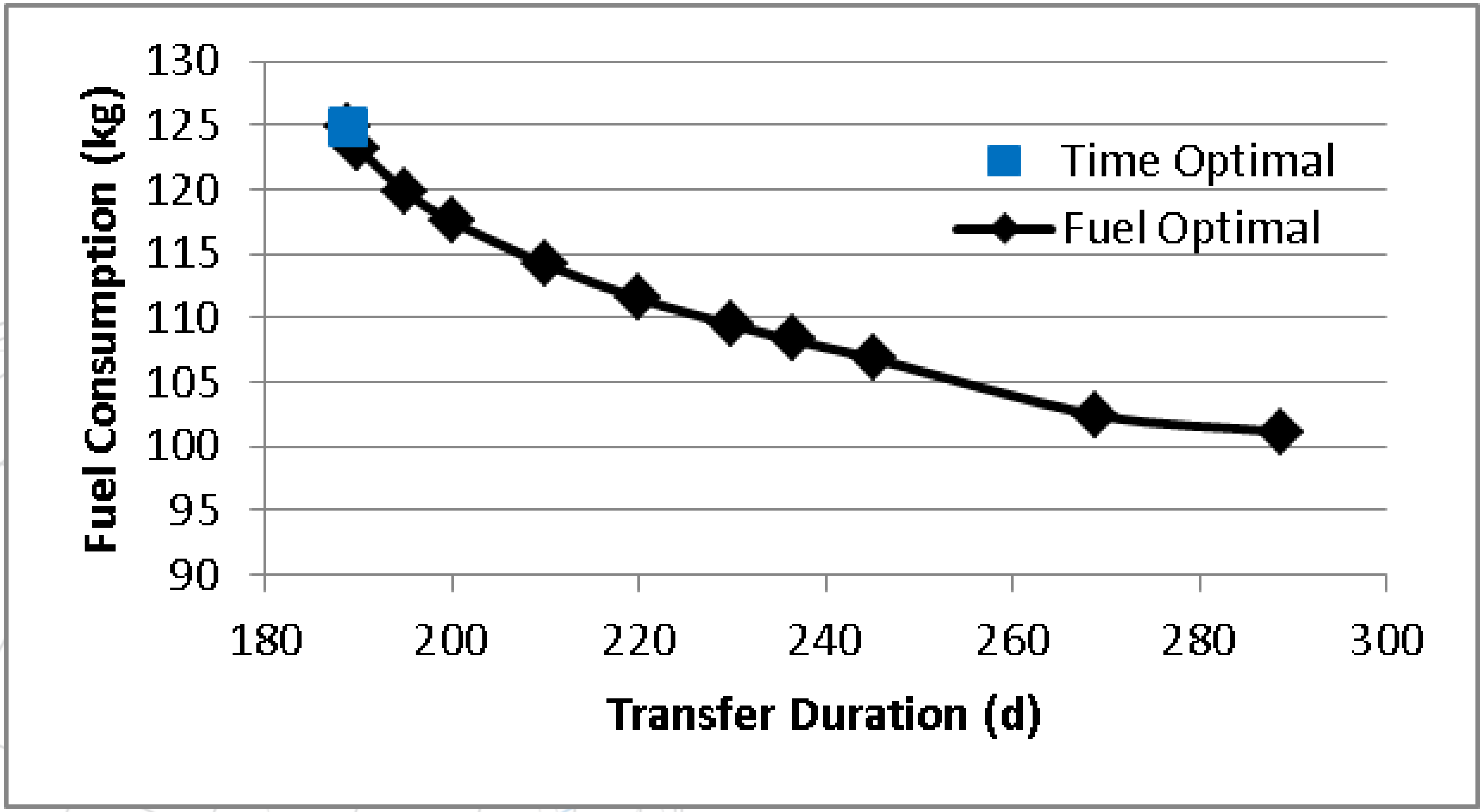
- MIDACO (ant colony optimization)
- SOS (Sparse Optimization Software)
- WORHP (European sparse NLP solver)





LOTOS – Objective Functions

Time Optimal vs. Fuel Optimal (with coast arcs).



LOTOS – User Interface

Front-end and command line interface

Customizable output

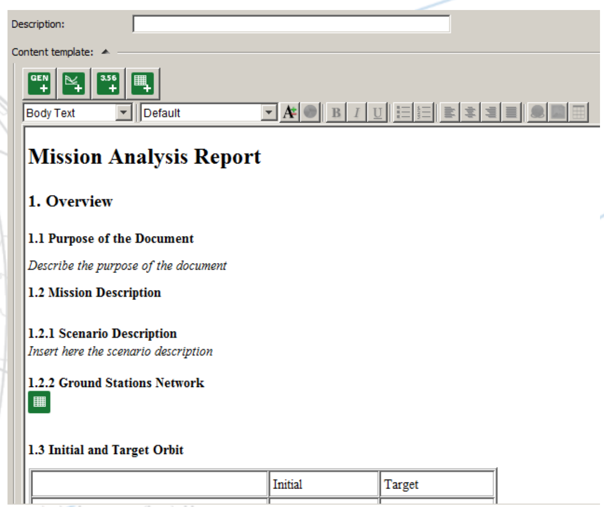
- Scenario input and output (scalars, functions,
- Maneuver plan and eclipses as output files

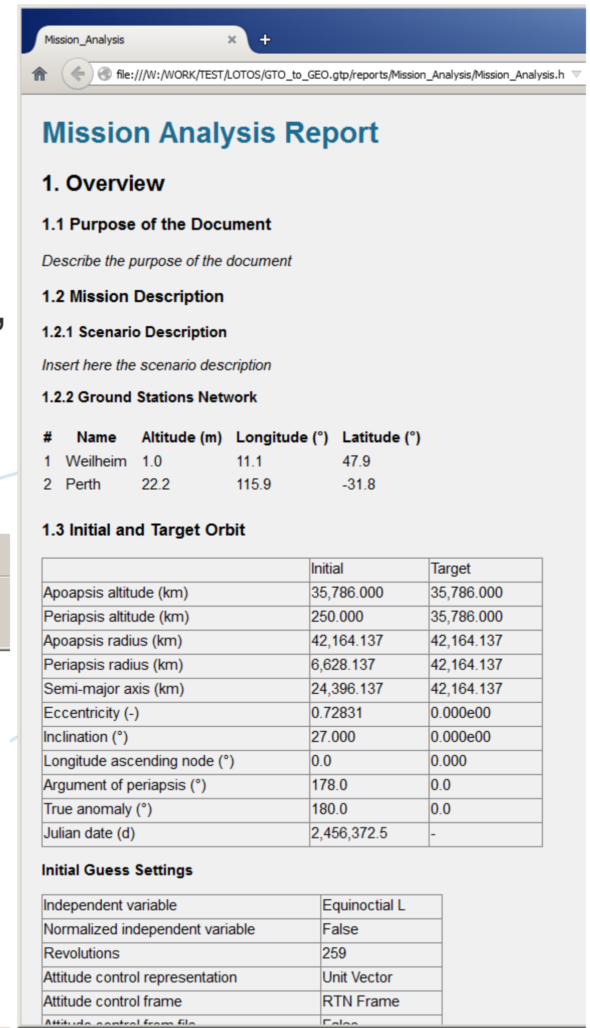
Automatic post-processing

- Customizable (e.g. AOCS, EP, eclipses,…)

Reports

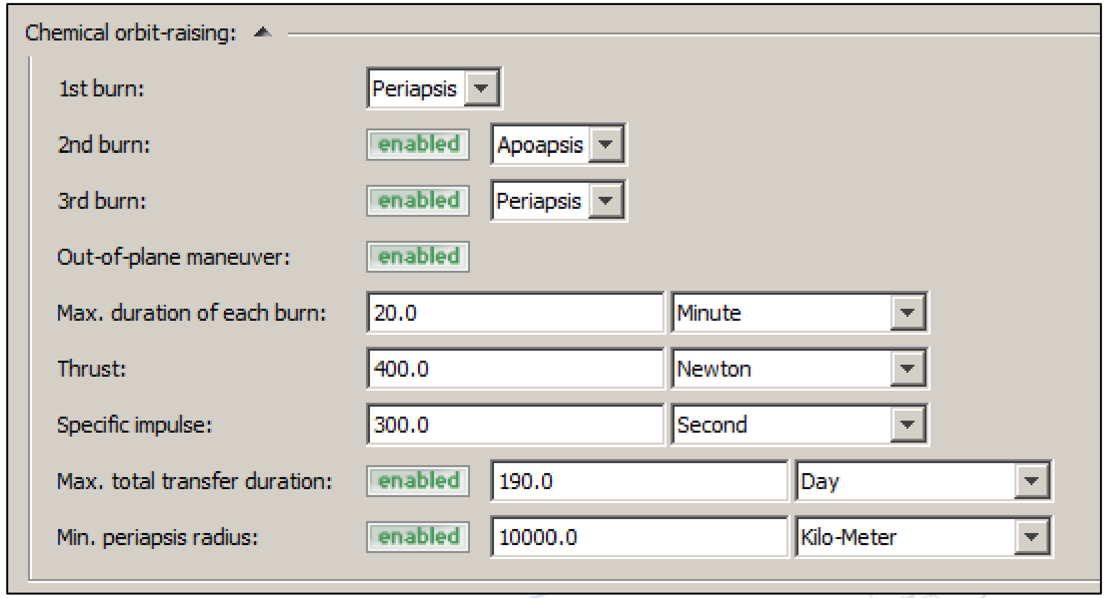
- Customizable
- Automatic generation



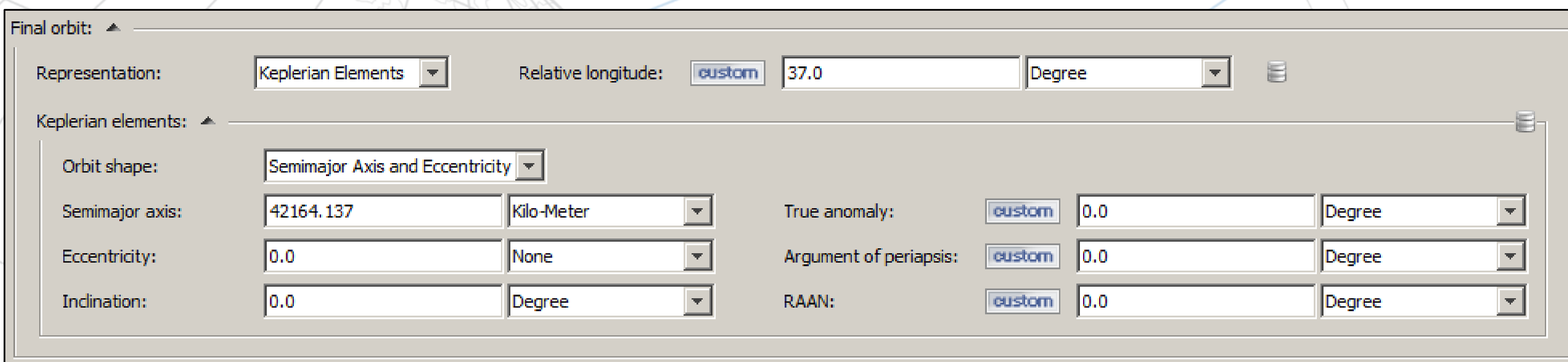


LOTOS – Hybrid Transfer

Chemical orbit-raising



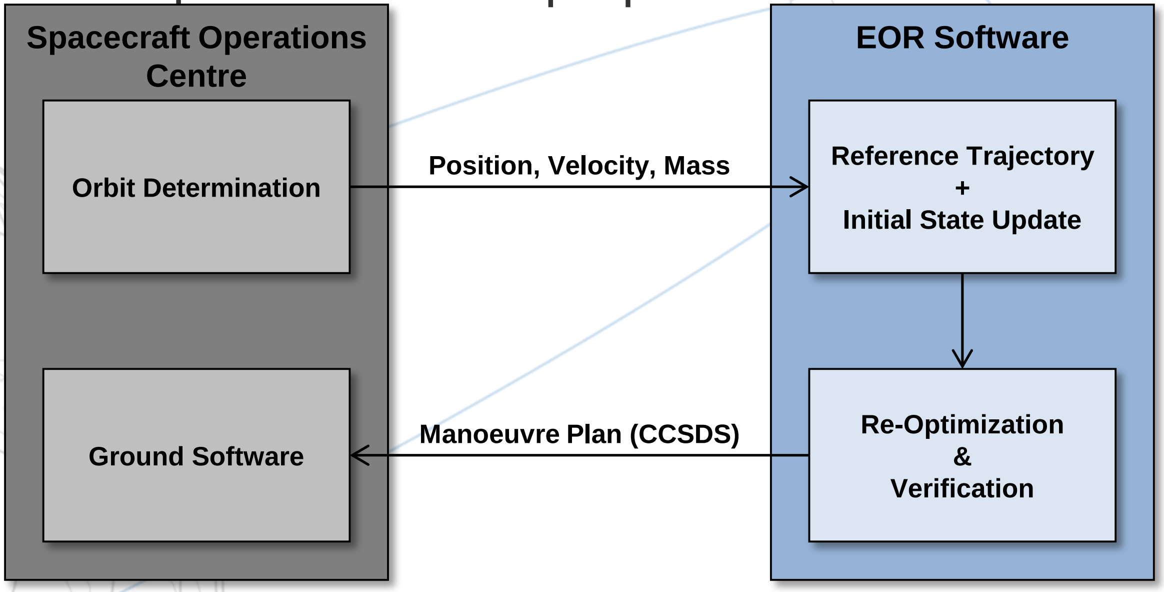
followed by electric orbit-raising to target orbit



LOTOS – Operational Aspects

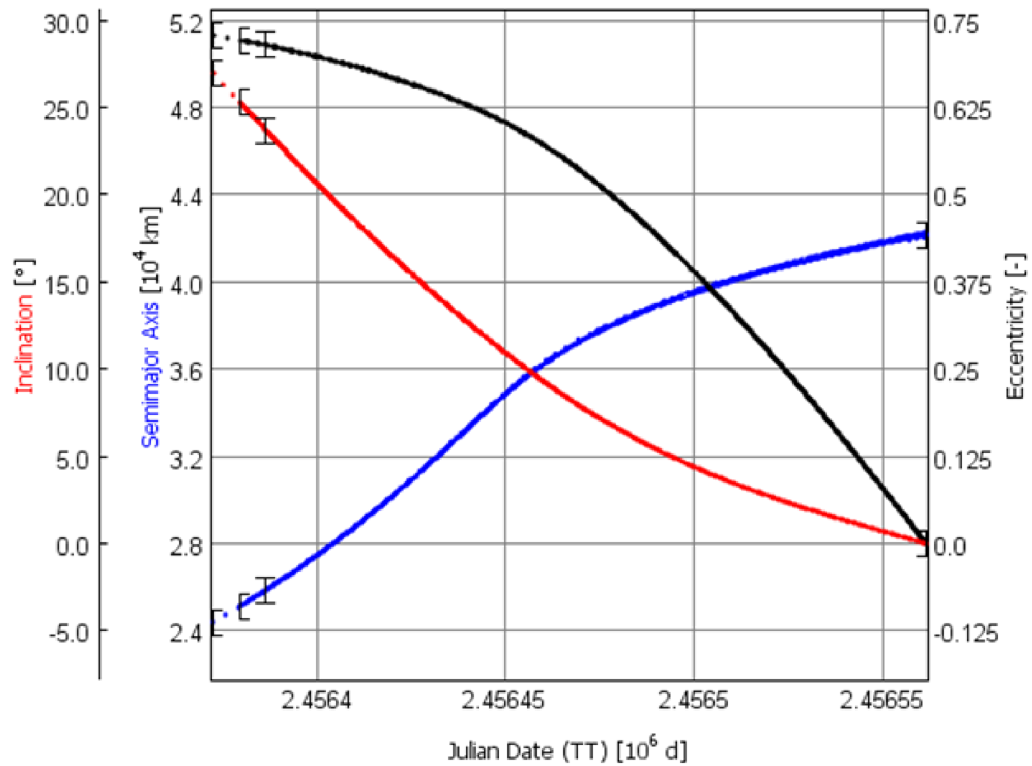
Once the trajectory (and satellite) is optimized, operational aspects have to be considered:

- Re-optimization of trajectory after separation from launcher to consider injection errors.
- Periodic re-optimization of trajectory to account for perturbations, attitude errors and underperformance of propulsion.
- New maneuver plan of next cycle is uploaded to the satellite.



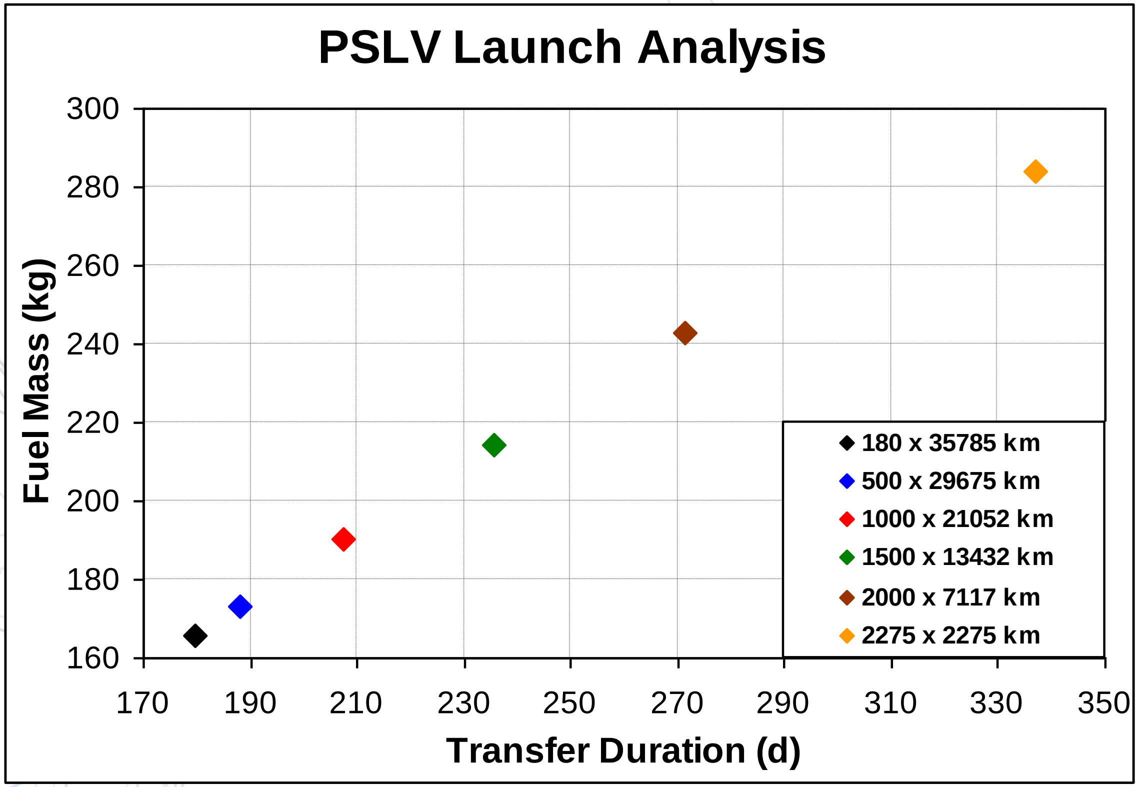
LOTOS – Operational Mode

- GTO to GEO
- Updated initial state (position, velocity, epoch, mass) after 7 days of transfer
- Perturbation was applied on initial state to simulate deviation from the reference trajectory



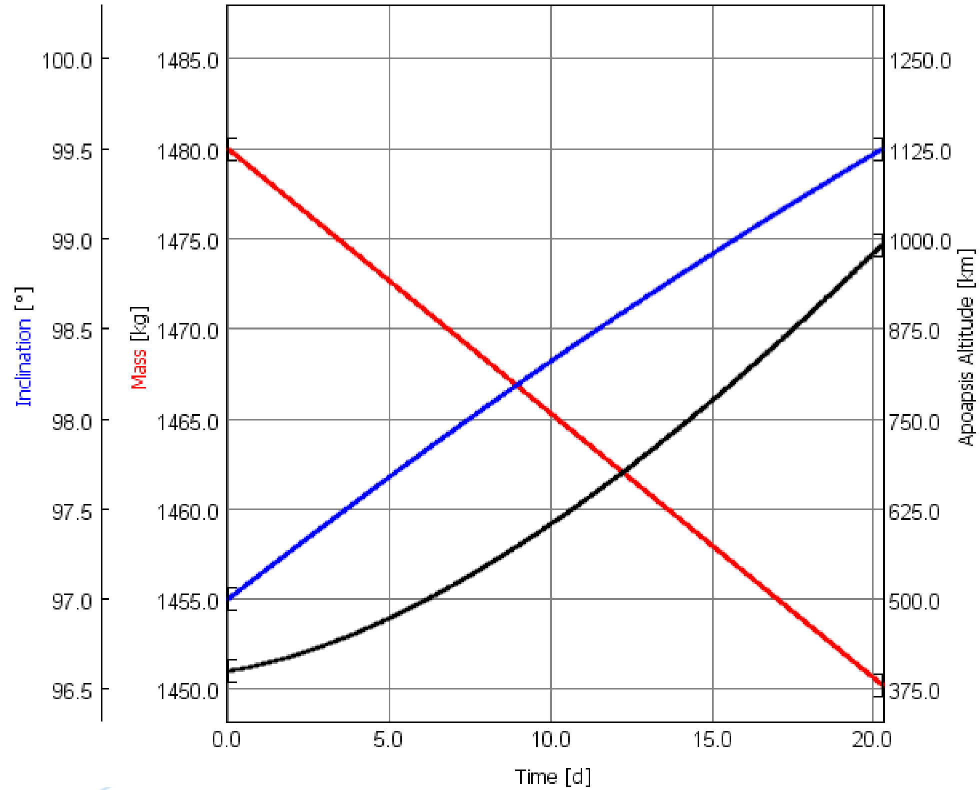
Launcher Injection Orbit

- For end-to-end trajectory optimization, the launcher part should be optimized to identify the optimal separation point.
- For most scenarios, GTO is the most efficient injection orbit.
- In case the launcher is not able to achieve GTO (e.g. VEGA), the driving factor is the transfer duration.



Electric Orbit Raising – LEO

- VEGA delivery at 400 km SSO = 1480 kg (VEGA User Manual).
- EOR to 1000 km SSO
  - Isp = 3000 s
  - Thrust = 0.5 N
  - Final mass = 1450 kg
  - Transfer duration = 20 days
  - Dwell time in radiation belt = 10 days



- VEGA delivery at 1000 km = 1140 kg (-310 kg)

Electric Propulsion for Upper Stage?

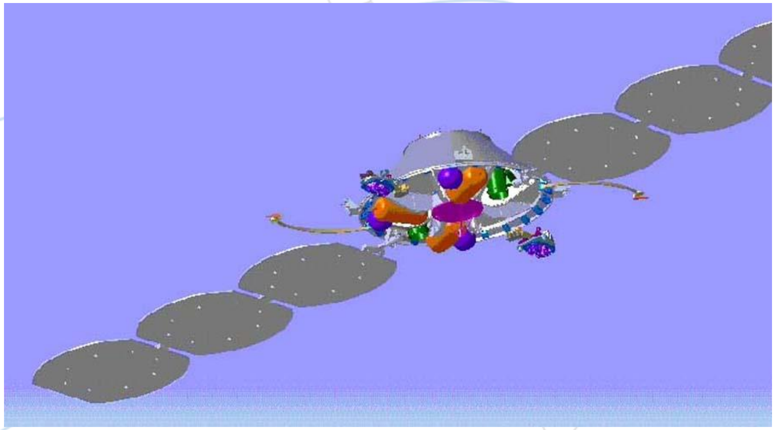
Low-thrust requirement:

- Electric power 30-15 kW/N

Efficiency 27-10 mN/m^2

Power generation requirement:

- Solar panel 0.3-0.4 kW/m^2



Credits: ESA

Problems:

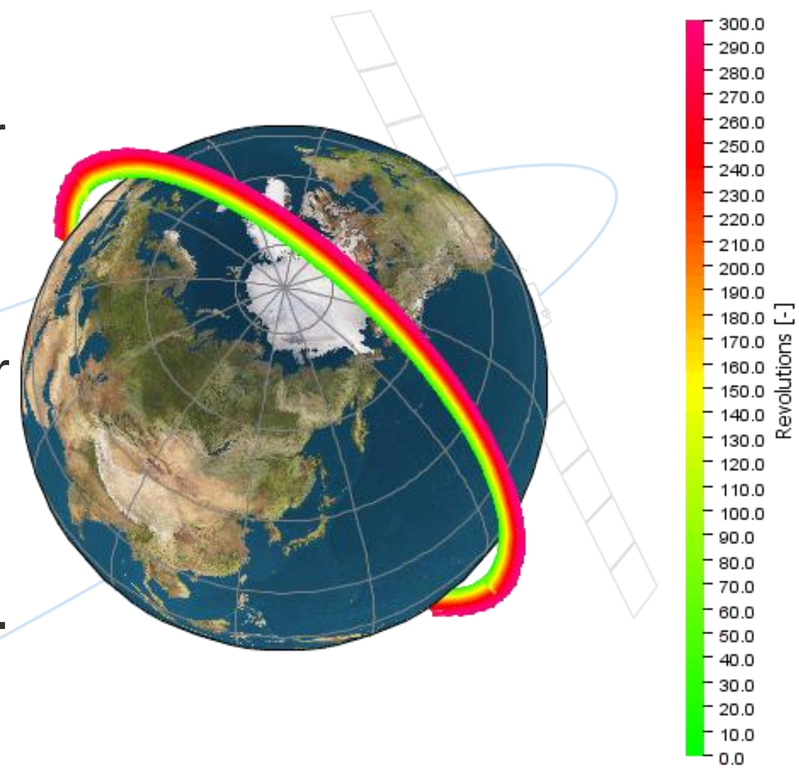
- Single use for expensive engine
- Single use for expensive solar panels
- Allocation of solar panels

Solution:

- Reusable Space Tug

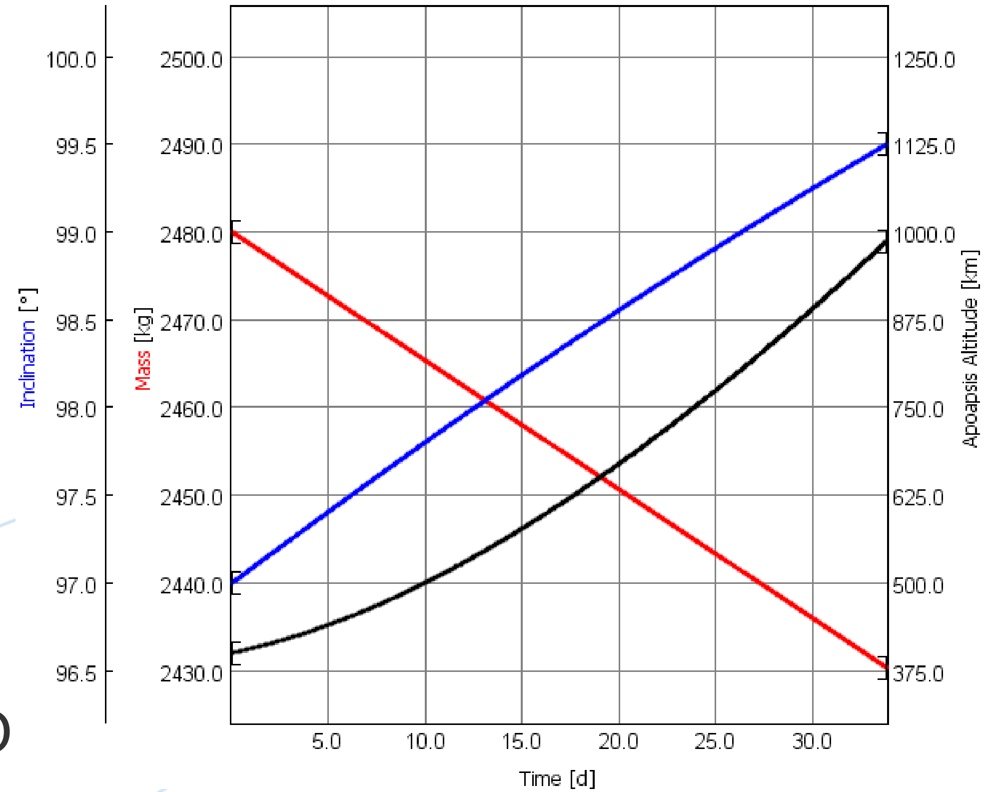
Space Tug – Applications

- Delivery of a satellite to its final orbit
- Constellation deployment without impacting life-time of satellites
- Cargo delivery to ISS
- Service of satellites in GEO for repositioning, life-extension, repair and graveyarding.
- Service of satellites in MEO for repositioning, life-extension, repair and graveyarding.
- De-orbit of not active satellites.



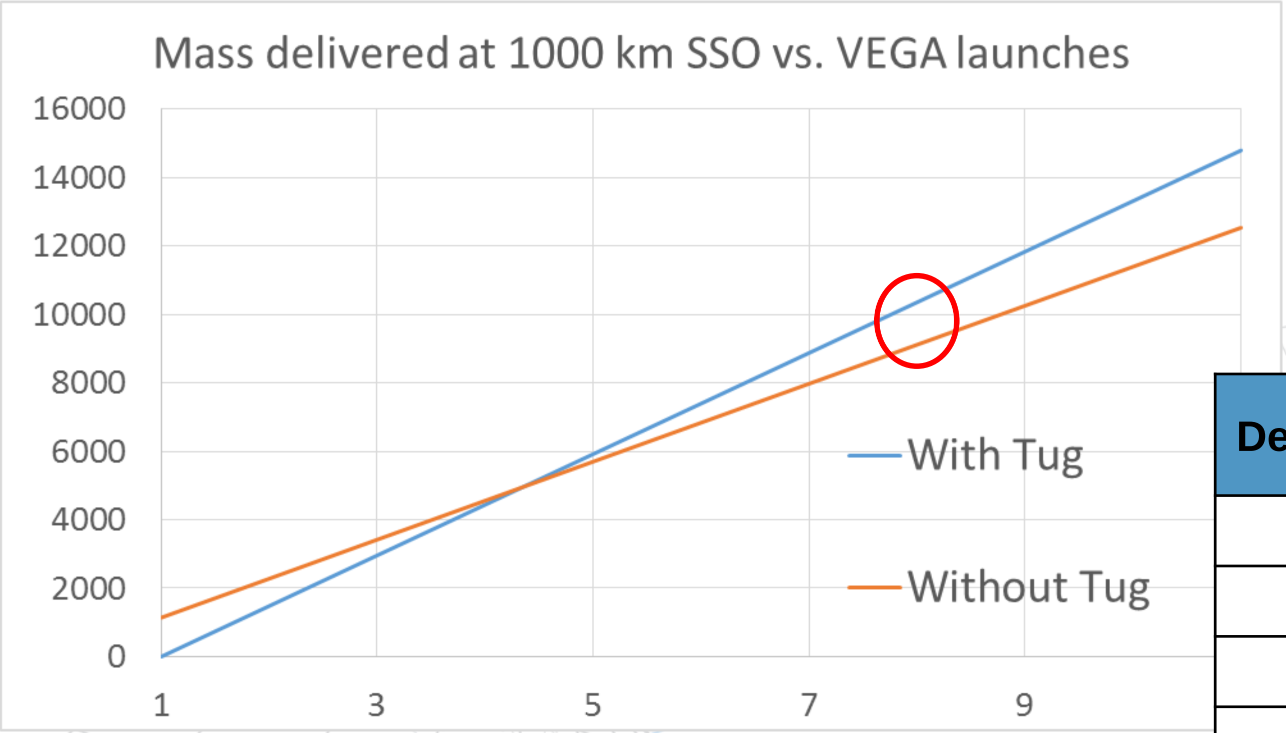
Space Tug – Single Delivery

- VEGA delivery at 400 km SSO = 1480 kg (VEGA User Manual).
- Tug to 1000 km SSO
  - Tug mass = 1000 kg
  - Isp = 3000 s
  - Thrust = 0.5 N
  - Final Tug mass = 950 kg
  - Transfer duration = 35 days
  - Dwell time in radiation belt = 16 days



- Tug return at 400 km SSO
  - Final Tug mass = 930 kg
  - Transfer duration = 12 days (Dwell time in radiation belt = 7.5 days)

Space Tug – Multiple Deliveries



Delivery	Propellant [kg]
1	70
2	140
3	200
4	260
5	320
6	375
7	430
8	480

- Example: Tug total propellant = 450 kg
  - Mass in 1000 km SSO = 7 x 1480 = 10360 kg
  - VEGA launches = 1 + 7
  - Equivalent VEGA launches at 1000 km SSO = 9 (x1140 kg)

Impact on Future Launchers

Conventional approach

- The available launchers were driving the design of a new satellite platform.
- The satellite future market was driving the design of a new launcher (family).

EOR available

- The telecommunication satellites can be launched by middle-, small-class launchers.
- Larger fairing volume is required to accommodate antennas, solar arrays and radiators.
- The mass-trend for telecommunication satellites has changed.

New set of requirements enters in the design of future launchers.

Conclusion

- EOR has radically changed the communication satellite platforms.
- The reduction of propellant mass is achieved with the increase of the transfer duration and overall mission complexity. Most of the aspects has to be considered during the transfer optimization phase (e.g. perturbations, constraints). New aspects impact the platform sub-systems.
- The increased complexity of mission analysis and trajectory optimization requires experience and powerful tools.

- LOTOS is the solution. It includes optimization and analysis features. It can be used for hybrid transfer and it can support spacecraft operations.
- LOTOS analysis have shown that a space tug can enhance the capability of small-middle launchers.

Leadership requires solutions

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Thank you!