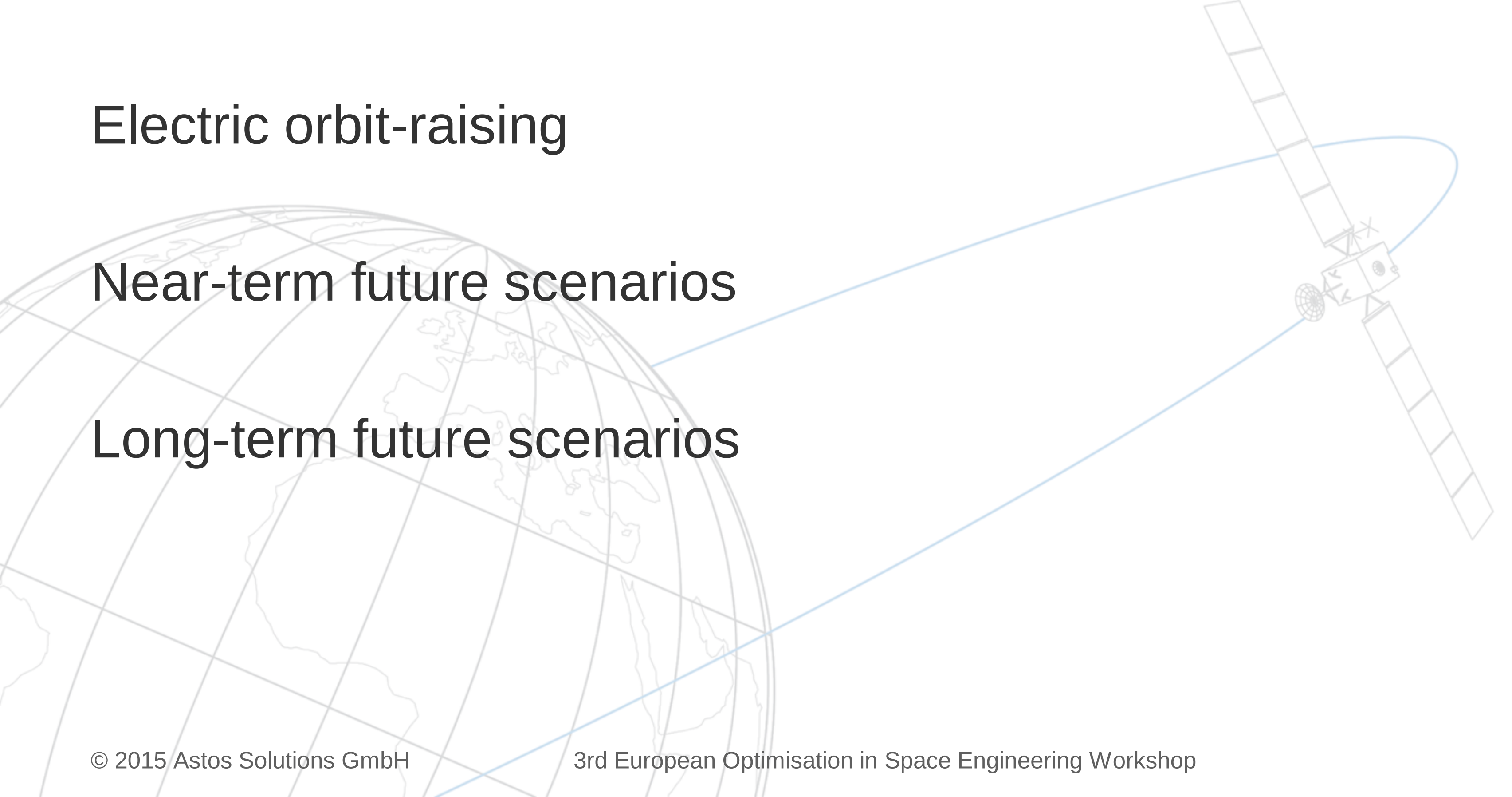
Missions Involing Low-Thrust Optimization

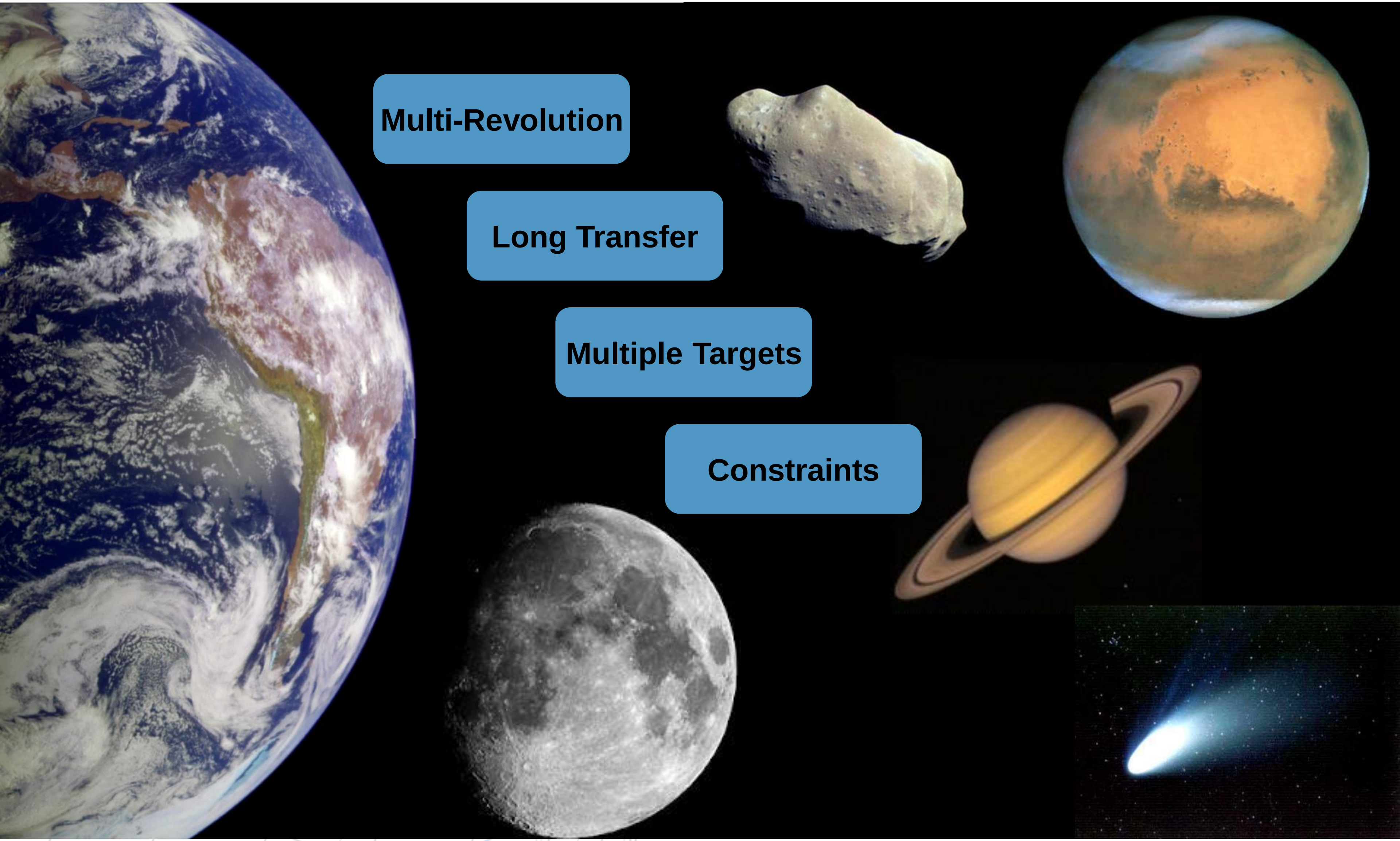
3rd European Optimization in Space Engineering Workshop

Glasgow, September 17-18, 2015

Outline



- Objectives for mission analysis
- Brief low-thrust model description
- Electric orbit-raising
- Near-term future scenarios
- Long-term future scenarios



Multi-Revolution

Long Transfer

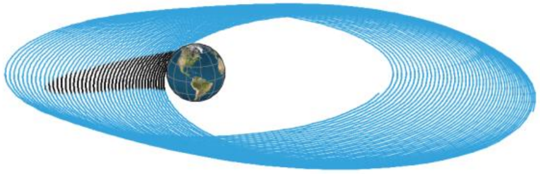
Multiple Targets

Constraints

Objectives for Mission Analysis

Determination of initial mission specifications is governed by varying levels of sophistication

- Perturbations (Earth oblateness effects, perturbational bodies, ...)
- Radiation belt modelling, power degradation modelling



Varying propulsion and system configurations

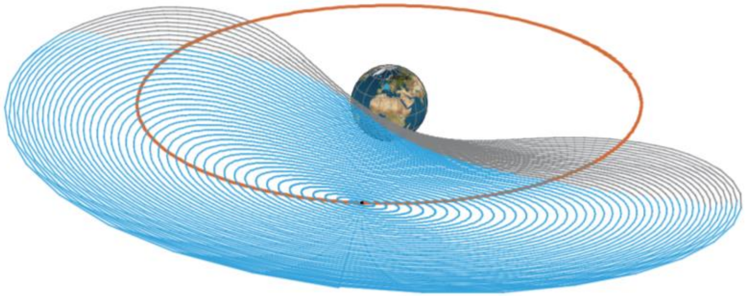
- Propulsion components, thruster characteristics
- System driven restrictions, e.g. solar cells orientation, recharge cycle

Trade-off aspects

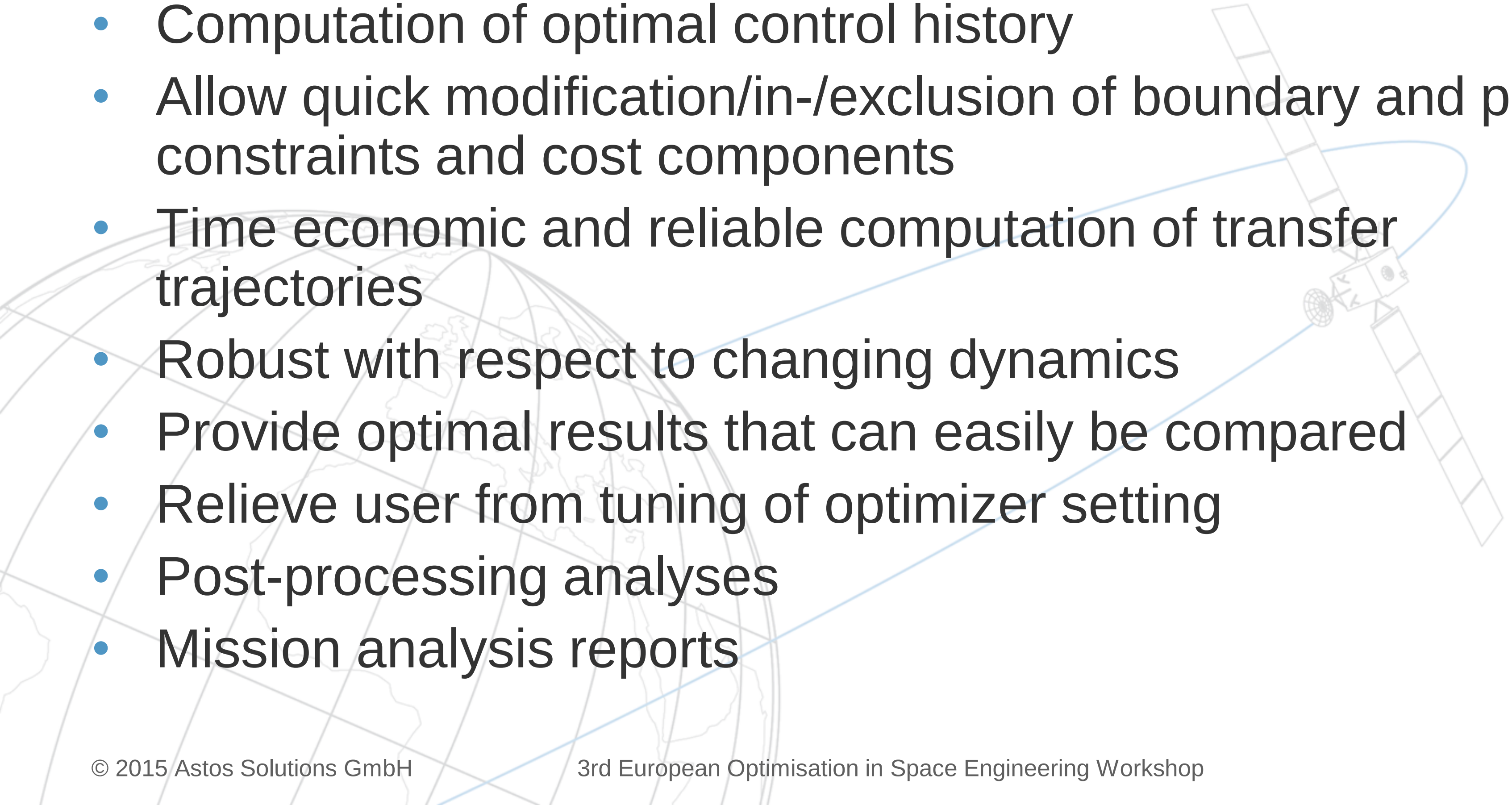
- Restrictions on orbit geometry, e.g. sub-synchronous transfers
- Changing objectives, e.g. power output, payload, fuel, trip time

Mission constraints

- Power management
- Geometrical path constraints i.e. radius
- Visibility and navigational constraints
- Target orbit definition



Objectives for Mission Analysis



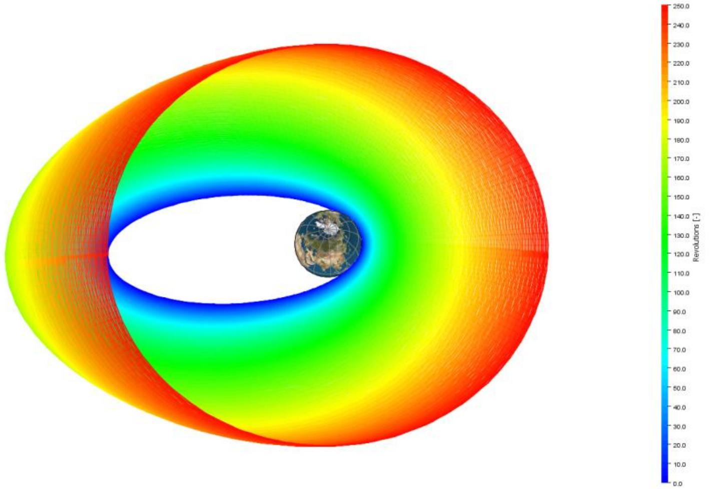
Requirements for mission analysis optimization software

- Utilization of low-thrust transfers (continuous thrust)
- Calculate time or fuel optimal transfer trajectories
- Computation of optimal control history
- Allow quick modification/in-/exclusion of boundary and path constraints and cost components
- Time economic and reliable computation of transfer trajectories
- Robust with respect to changing dynamics
- Provide optimal results that can easily be compared
- Relieve user from tuning of optimizer setting
- Post-processing analyses
- Mission analysis reports

Low-Thrust Software

Low-Thrust Tool for

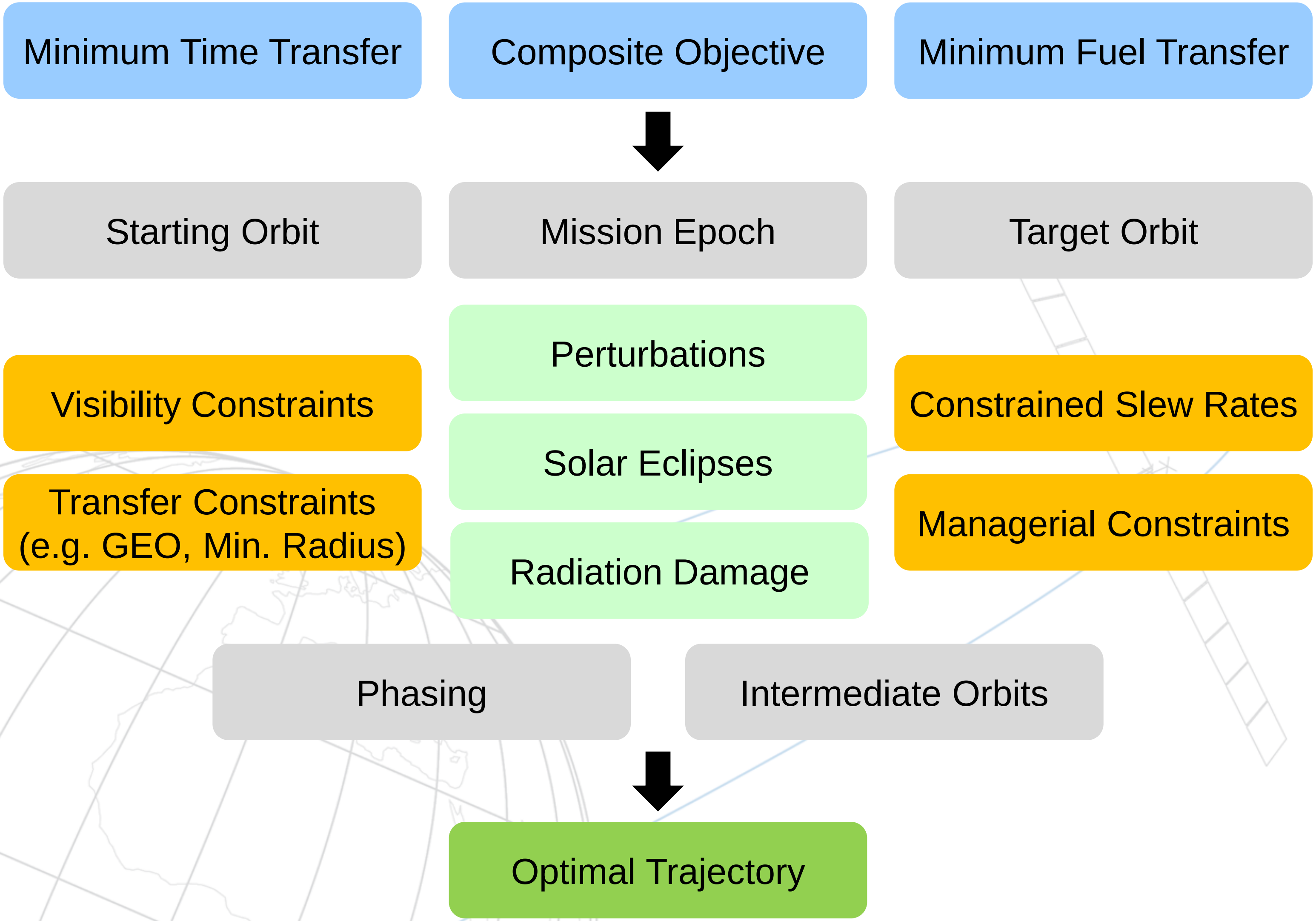
- Orbit transfers
- Moon transfers
- Interplanetary transfers



Model

- Perturbations (oblateness, 3rd bodies, solar radiation pressure, atmospheric drag, ...)
- Environment (radiation, eclipses, ...)
- Operational aspects (visibility, slew rates, GEO ring, ...)

Low-Thrust Software



Minimum Time Transfer

Composite Objective

Minimum Fuel Transfer

Starting Orbit

Mission Epoch

Target Orbit

Perturbations

Visibility Constraints

Constrained Slew Rates

Solar Eclipses

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

Managerial Constraints

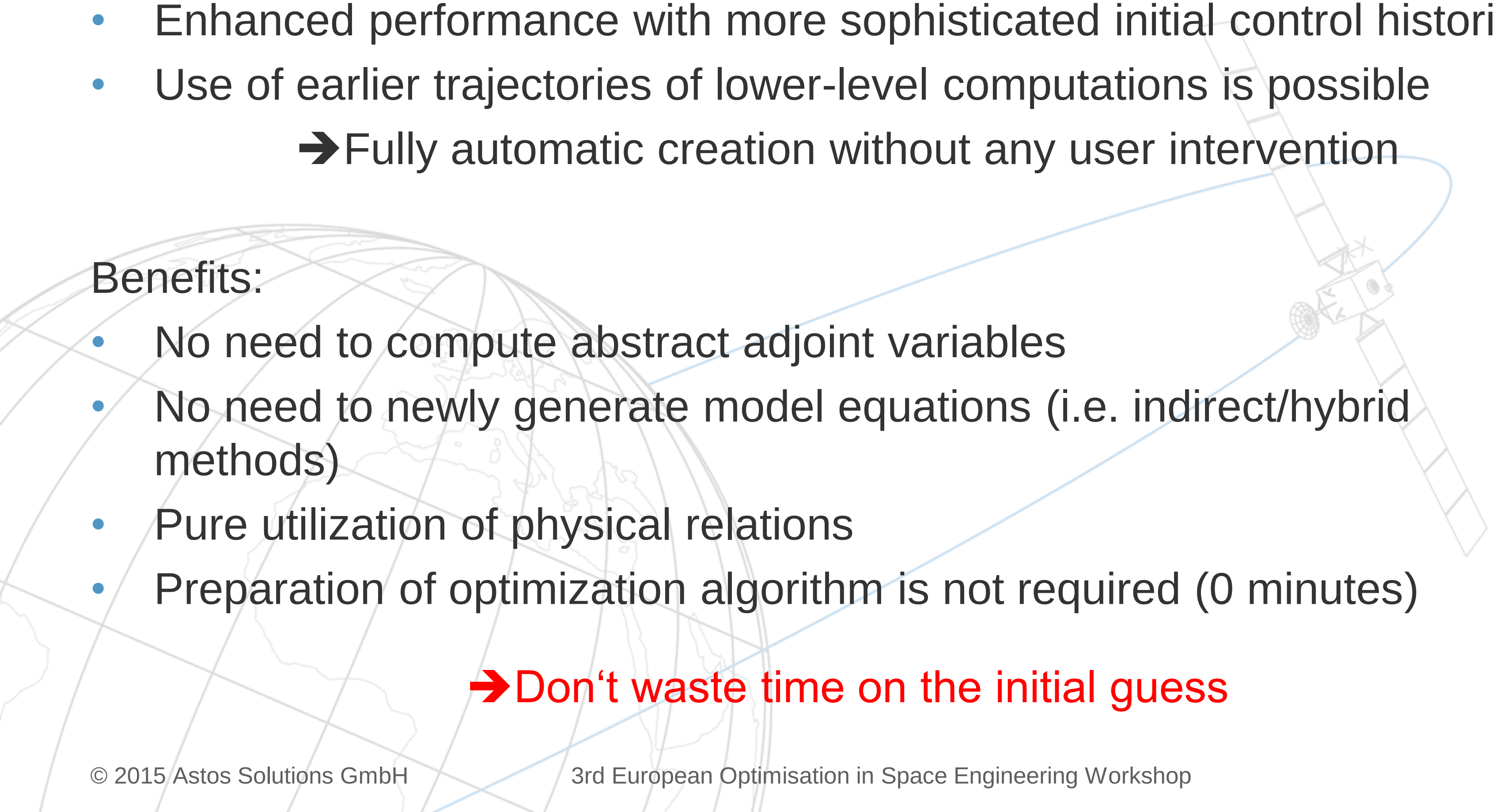
Radiation Damage

Phasing

Intermediate Orbits

Optimal Trajectory

Initial Guess Generation



Initial guess generation is based on a straight forward simulation

- Automatic construction using standard control laws
- Generic control history is sufficient to allow steady optimization
- Enhanced performance with more sophisticated initial control histories
- Use of earlier trajectories of lower-level computations is possible

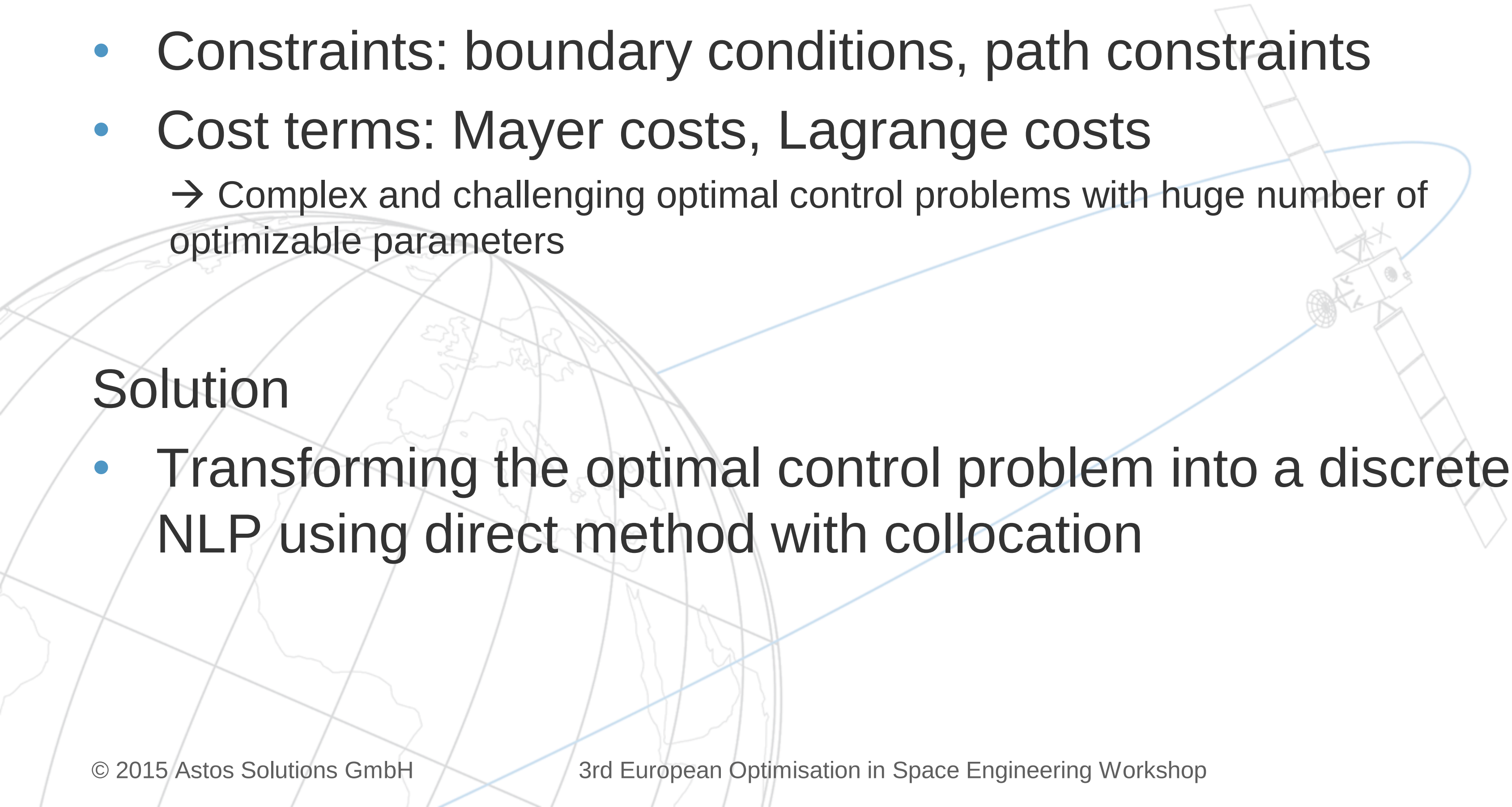
➔Fully automatic creation without any user intervention

Benefits:

- No need to compute abstract adjoint variables
- No need to newly generate model equations (i.e. indirect/hybrid methods)
- Pure utilization of physical relations
- Preparation of optimization algorithm is not required (0 minutes)

➔Don‘t waste time on the initial guess

Large Scale Optimal Control Problems



Challenge

- 10,000s of optimizable parameters, typically up to 200,000
- 10,000s of constraints
- Constraints: boundary conditions, path constraints
- Cost terms: Mayer costs, Lagrange costs

→ Complex and challenging optimal control problems with huge number of optimizable parameters

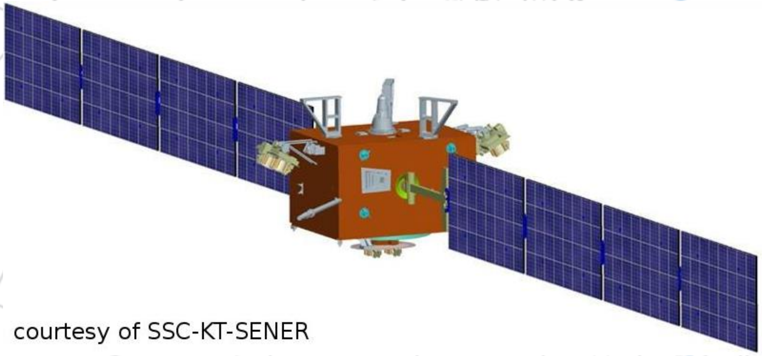
Solution

- Transforming the optimal control problem into a discrete NLP using direct method with collocation

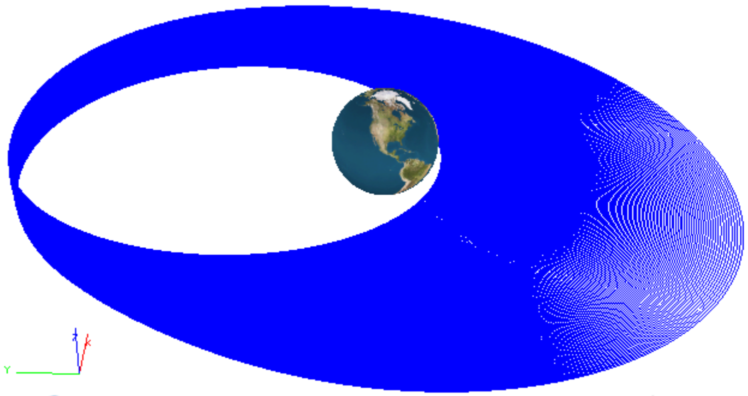
Electric Orbit-Raising

Orbital Life Extension Vehicle

- Spiralling from a transfer orbit (GTO) to the geostationary orbit (GEO) using low-thrust solar electric propulsion
- Docking with client spacecraft (telecommunication satellite in GEO) and taking over attitude and orbit control



courtesy of SSC-KT-SENER



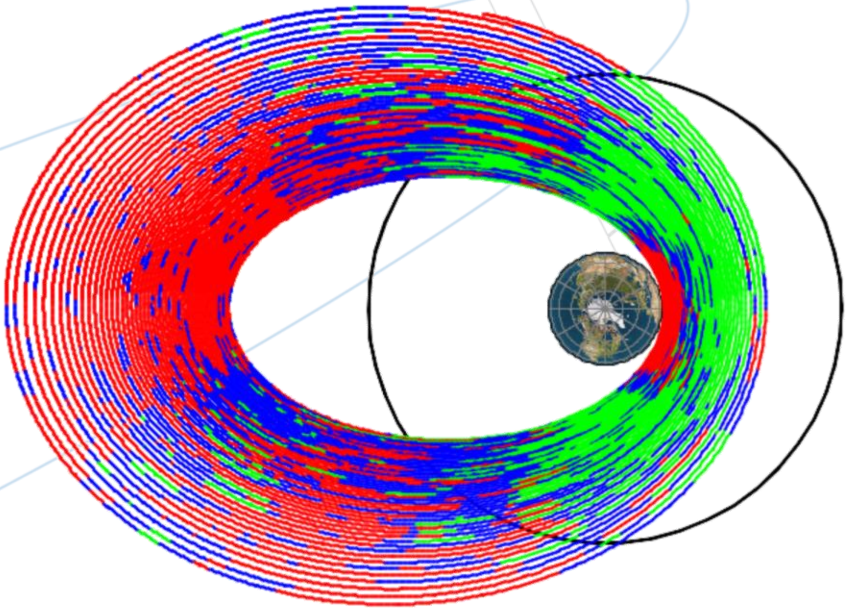
EOR Operational Aspects – Navigation

The long duration of EOR increase the cost of the ground station link.

An alternative could be autonomous navigation via GNSS:

- First half of GTO-GEO transfer with only one GPS antenna (nadir)
- Black line indicates GPS constellation orbit
- Green: > 3 GPS signals
- Blue: 2-3 GPS signals
- Red: <2 GPS signals

➤GPS alone is not enough!



		Near-Term Scenarios	Long-Term Scenarios
	**Earth-Moon System**	- Shipment of large payloads from low Earth orbit to Earth-Moon lagrangian point and low lunar orbit	
	**Near Earth Objects**	- Scientific missions to near-Earth objects	
	**Mars**	- Robotic Mars sample return	
	**Outer Planets**		

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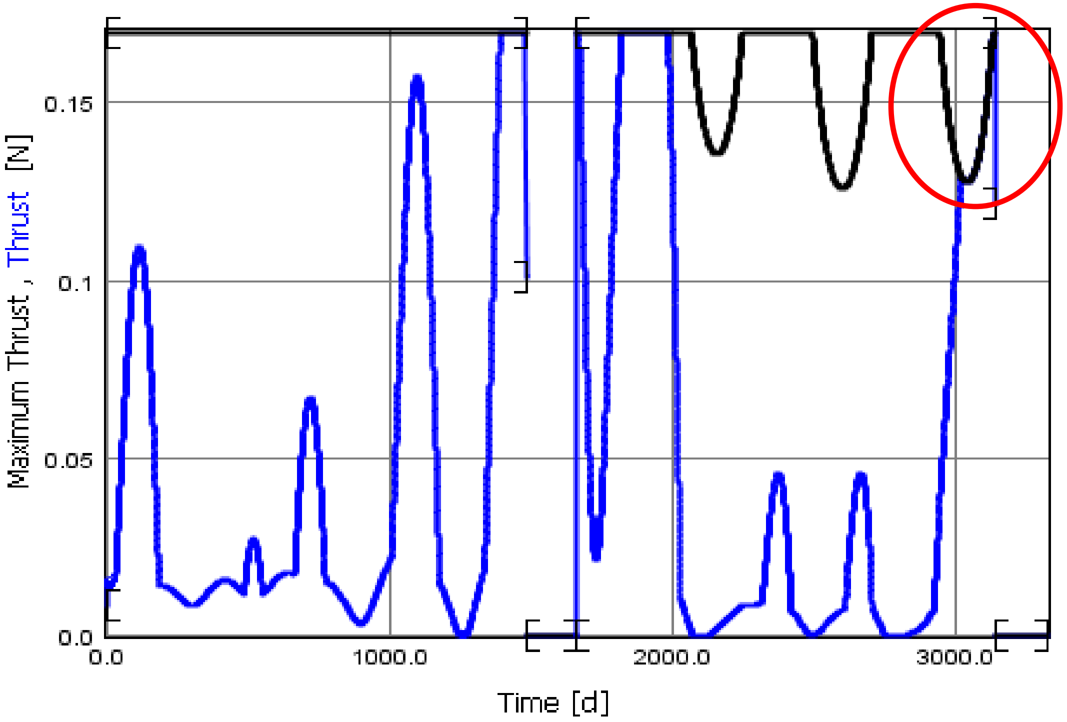
Asteroid Double Rendezvous

- Spacecraft visiting two near-Earth asteroids
- Solar electric propulsion
- Thrust level depends on available power

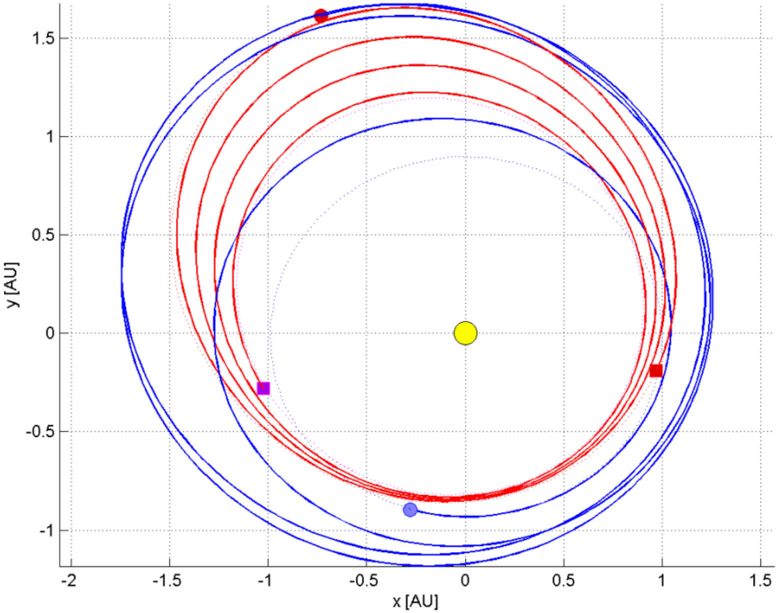


➢Restrictions in maximal usable thrustlevel

➢Thrust peaks used for e.g. inclination change

Asteroid Double Rendezvous

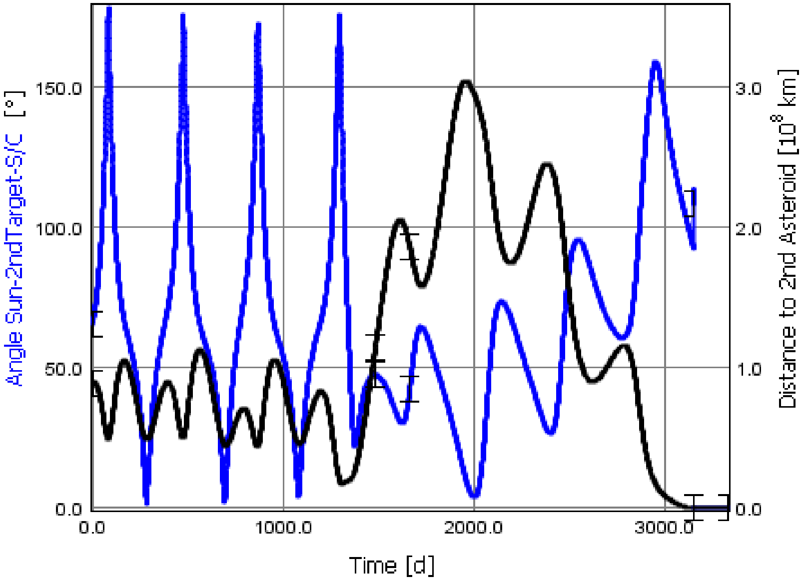
- Modeling of whole mission in one problem under consideration of all mission constraints Stepwise refinement of the trajectory under consideration of
- Operational constraints (e.g. station visibility)
- Navigational constraints (e.g. target visibility)

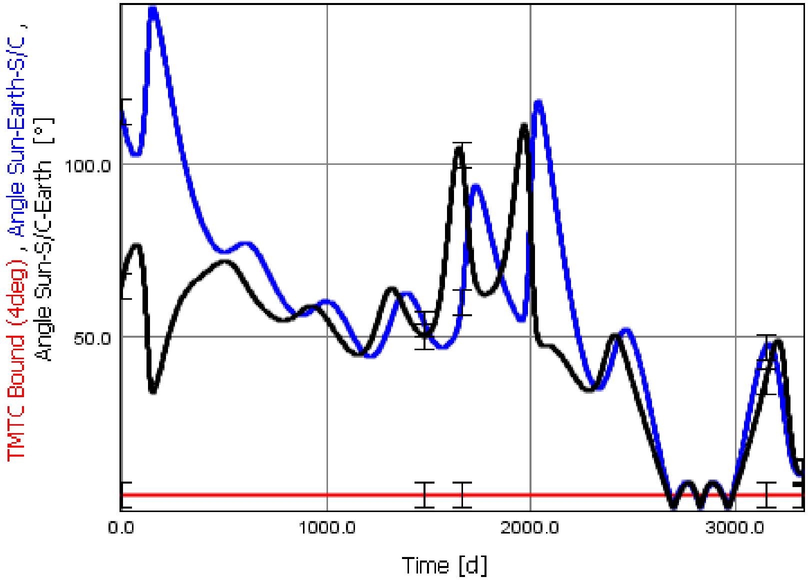


Asteroid Double Rendezvous

Left figure: angle Sun-2ndTarget-S/C (blue) and distance from S/C to 2nd target (black)

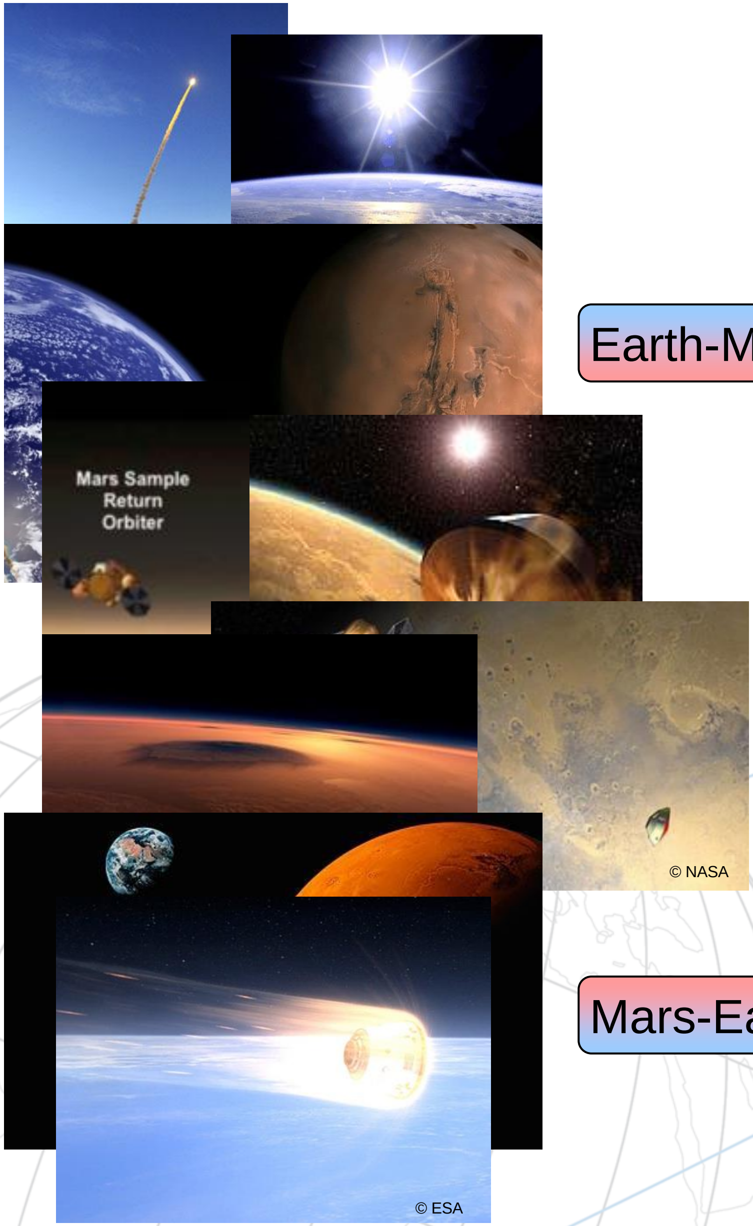
- ➢ For angles > 90° imaging of the asteroid by cameras becomes difficult during approach





Right figure: angle between Sun and spacecraft as seen from Earth (blue line), angle between Sun and Earth as seen from spacecraft (black line) and the minimum angular separation for safe uplink/downlink (red line)

Robotic Mars Sample Return



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Launch

Earth Escape

Earth-Mars (Min Time) | Earth-Mars (Min Fuel)

Mars Arrival (Payload Jettison)

Mars Stay

Rendezvous & Docking

Mars Escape

Mars-Earth (Min Time) | Mars-Earth (Min Fuel)

Earth Re-entry

Robotic Mars Sample Return

Mission analysis

- Specific impulse ranges from 2,500s to 5,000s
- Thrust ranges from 1.22N to 2.44N
- Time and fuel optimal transfers

Mission constraints

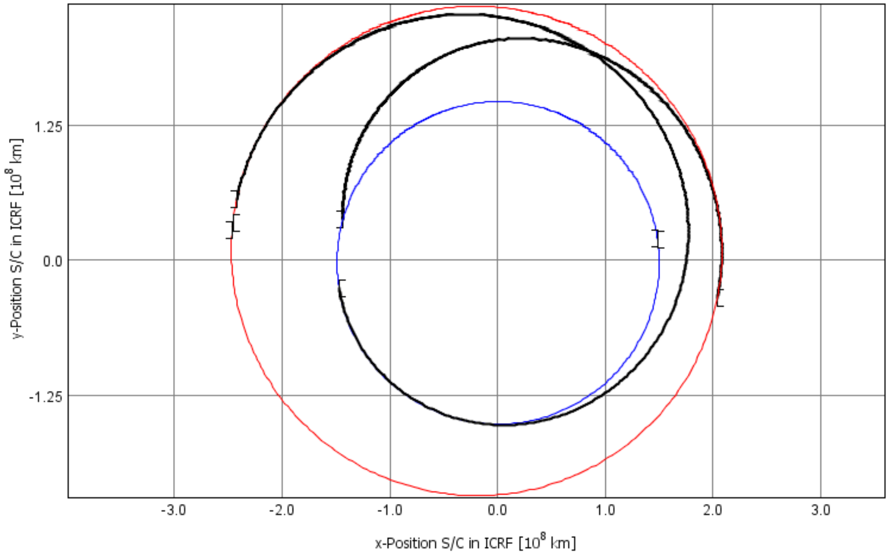
- Payload mass to be delivered to Mars is 3 metric tons
- Prevent landing on Mars during dust storm season
- Maximum duration of mission is 6 years

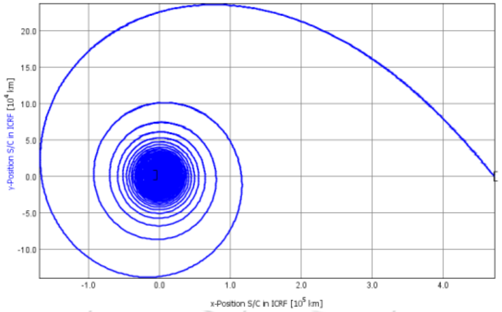
Case	Specific Impulse	Thrust	Issues for Time Optimal Result	Issues for Fuel Optimal Result
Case 1A	2,500 s	1.22 N	• Negative mass margin • Mission duration > 6 years	• Negative mass margin • Arrival at Mars during dust storm season • Mission duration > 6 years
Case 1B	2,500 s	1.5 N	• Negative mass margin • Mission duration > 6 years	• Negative mass margin • Mission duration > 6 years
Case 1C	2,500 s	1.75 N	• Negative mass margin	• Negative mass margin
Case 1D	2,500 s	2.0 N	• Negative mass margin	• Negative mass margin
Case 1E	2,500 s	2.44 N	• Negative mass margin	• Negative mass margin
Case 2A	5,000 s	1.22 N	• Arrival at Mars during dust storm season • Mission duration > 6 years	• Arrival at Mars during dust storm season • Mission duration > 6 years
Case 2B	5,000 s	1.5 N	• Mission duration > 6 years	• Arrival at Mars during dust storm season • Mission duration > 6 years
Case 2C	5,000 s	1.75 N	✓	• Mission duration > 6 years
Case 2D	5,000 s	2.0 N	✓	✓
Case 2E	5,000 s	2.44 N	• Negative mass margin	✓

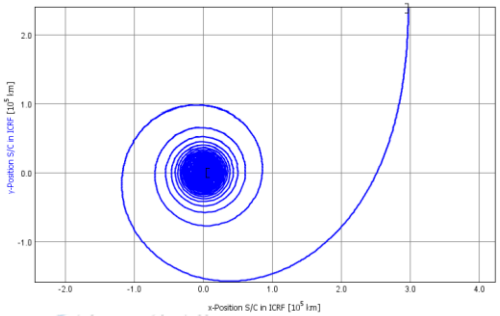
Robotic Mars Sample Return

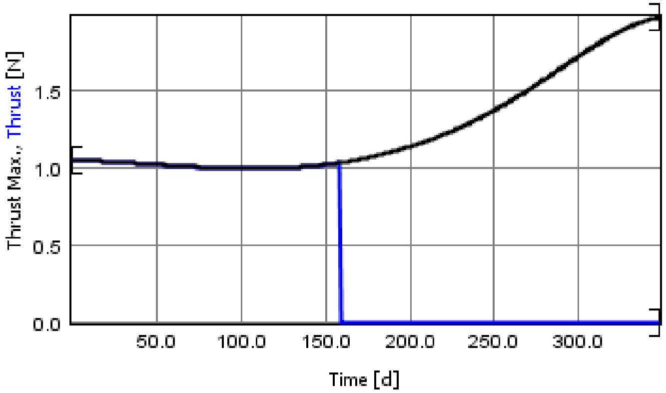
Results of time/fuel optimal transfers

- One Ariane 5 launch
- Initial mass 10 metric tons in GTO
- Launch in August 2019
- Mars stay 642 d / 515 d
- Re-entry March / April 2025
- Duration 5.5 y / 5.7 y
- Fuel mass 3,027 kg / 2,678 kg
- Delta-v 22.7 km/s / 18.8 km/s









	Near-Term Scenarios	Long-Term Scenarios
Earth-Moon System	- Shipment of large payloads from low Earth orbit to Earth-Moon lagrangian point and low lunar orbit	- Assembly of large telescopes in Earth-Moon lagrangian point to be shipped to Sun-Earth lagrangian point - Moon in-situ resource utilization for missions beyond the Earth-Moon system
Near Earth Objects	- Scientific missions to near-Earth objects	- Near-Earth objects exploration, exploitation, and risk mitigation
Mars	- Robotic Mars sample return	- Crewed missions to Mars, Deimos, and Phobos
Outer Planets		- Scientific/robotic missions to the outer planets to search for evidence of life

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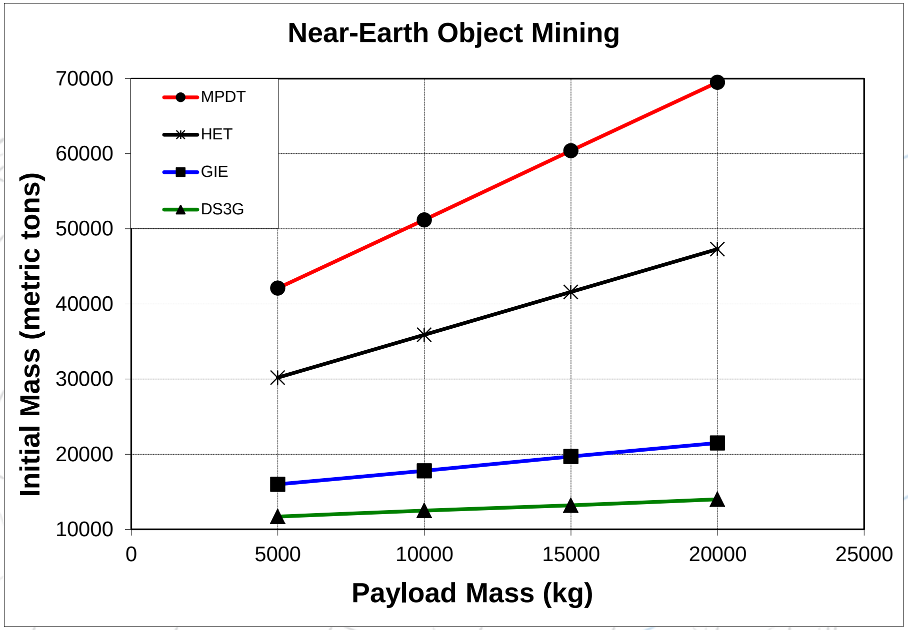
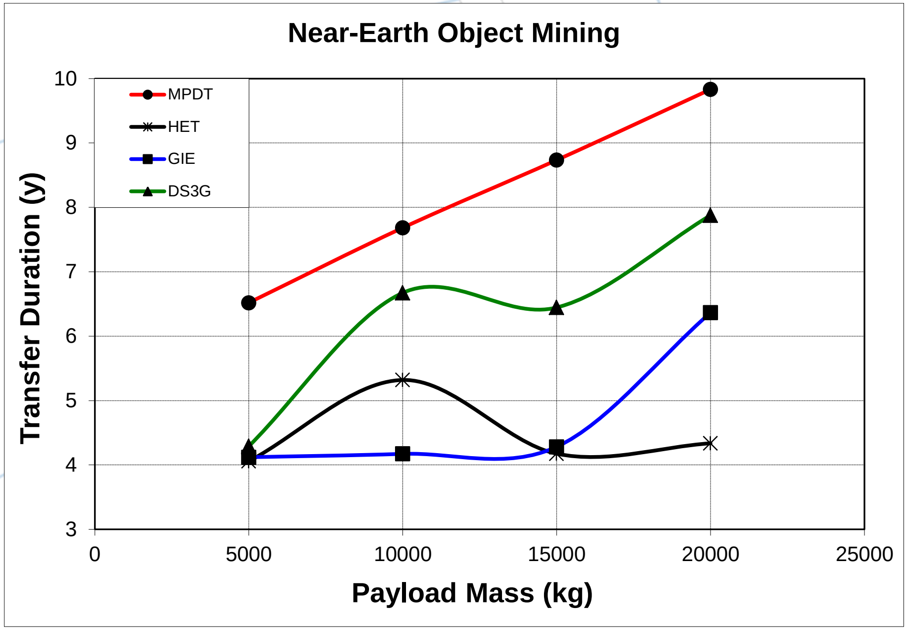
Asteroid Mining

- Transport of mined material (e.g. hydrocarbons)
- Example target asteroid (1685) Toro
- Nuclear powered spacecraft with 200 kWe
- 4 payload masses (5, 10, 15, and 20 metric tons)
- Specific impulse from 2,000s to 10,000s representing four thruster technologies (MPDT, HET, single grid GIE, dual stage 3 grid DS3G)



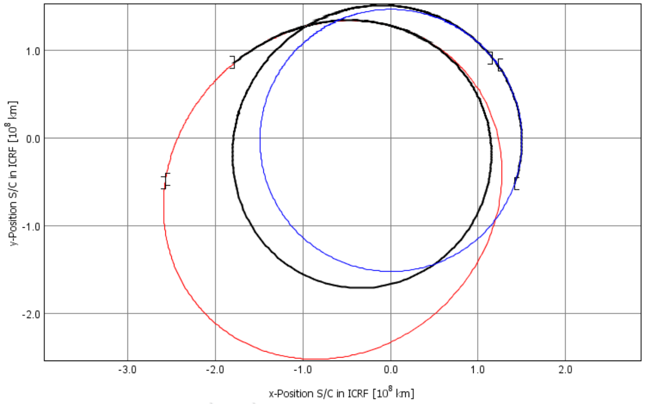


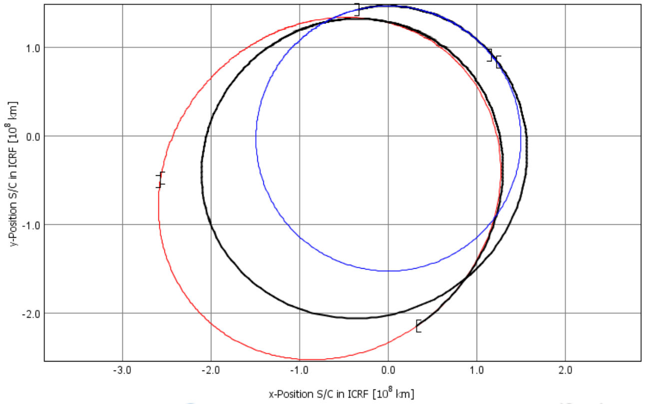
Asteroid Mining

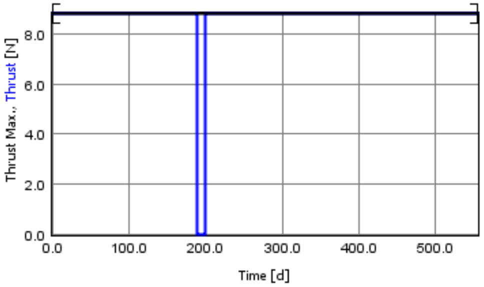
- Spacecraft assembled in lagrangian point
- Launch in 2030
- Stay time 1 year
- Minimum fuel transfers
- Mission delta-v is ~20 km/s
- Examples for Isp 2,500s (HET)

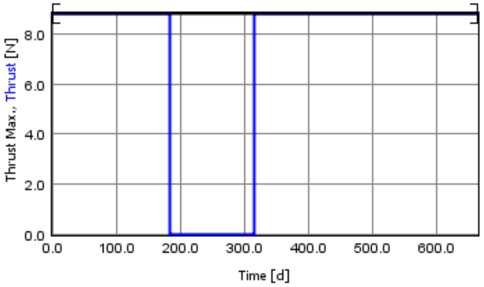
- Payload of 5 metric tons
  - Mission duration 4.1 years
  - Fuel consumption ~18 metric tons

- Payload of 20 metric tons
  - Mission duration 4.3 years
  - Fuel consumption ~33 metric tons



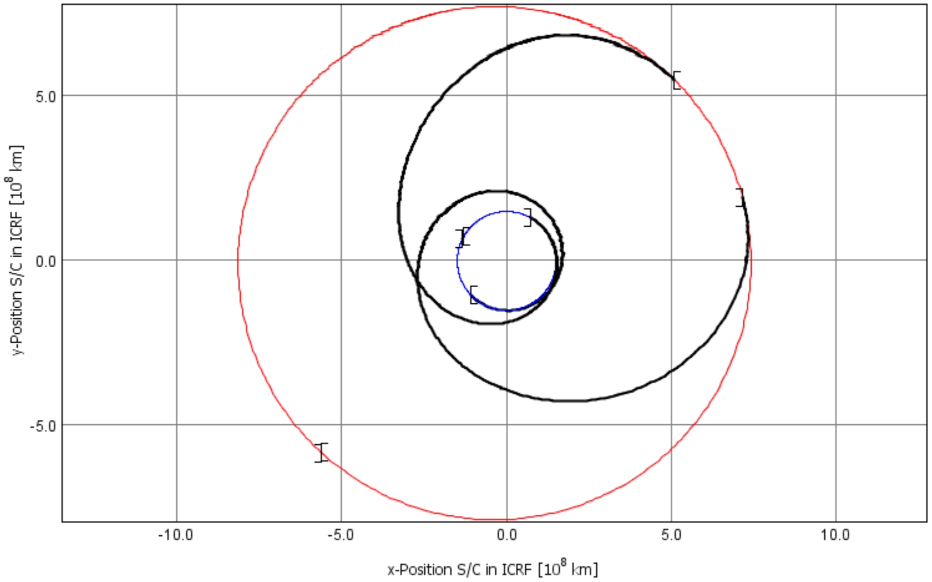


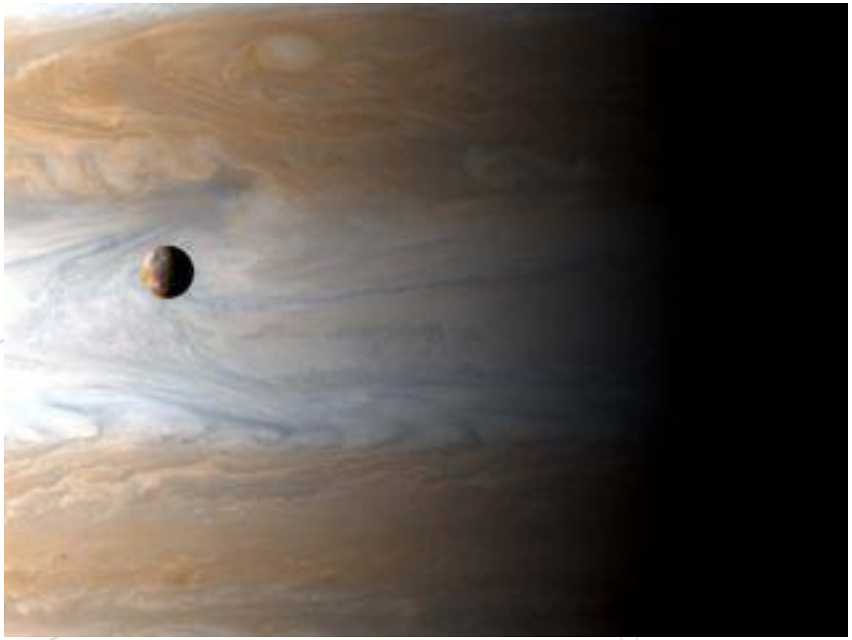




Jupiter Moons Sample Return

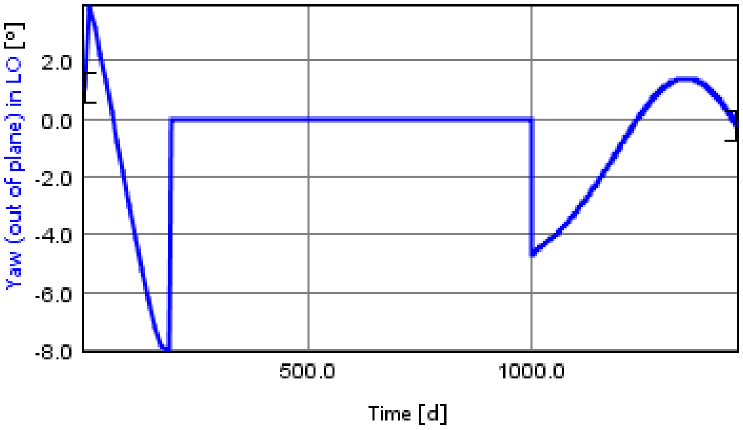
- Sample return mission from one of the Jovian moons
- Spacecraft assembled in one of the lagrangian points
- NEP driven spacecraft (200 kW$_e$)
- HET, GIE, and DS3G
- Payload of 2 metric tons
- Hohmann-like low-thrust transfers

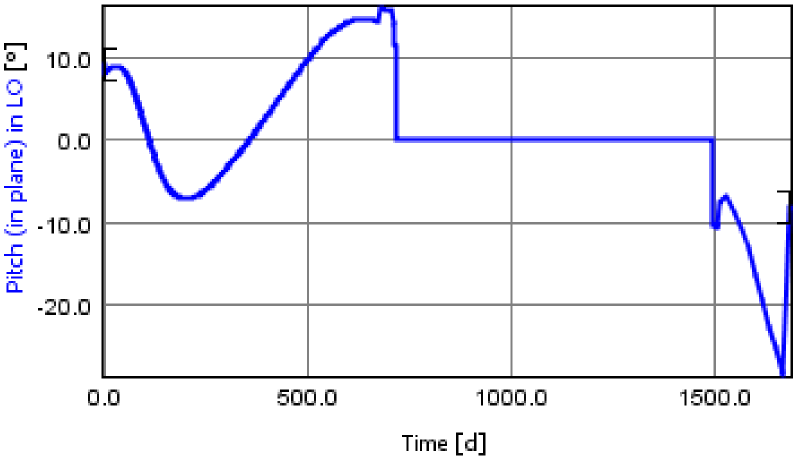


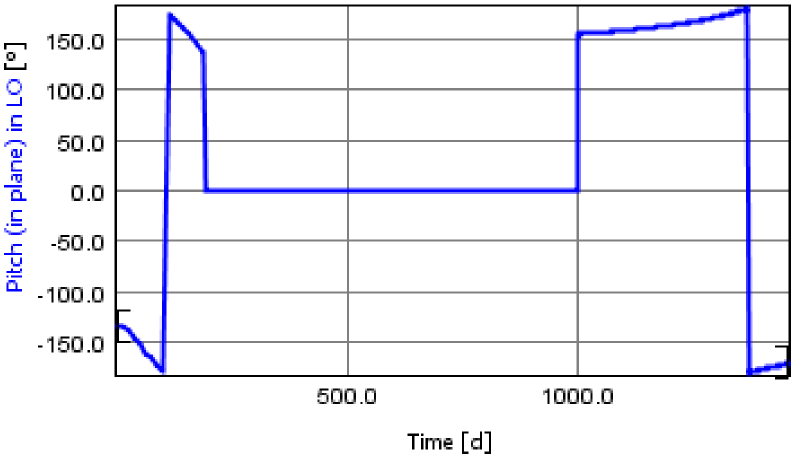


Jupiter Moons Sample Return

- Fuel optimal transfers
- Initial mass 15-51 metric tons
- Mission duration ~9-10 years
- Stay time 1-2 years
- Mission delta-v ~33 km/s
- Fuel mass ~9-36 metric tons



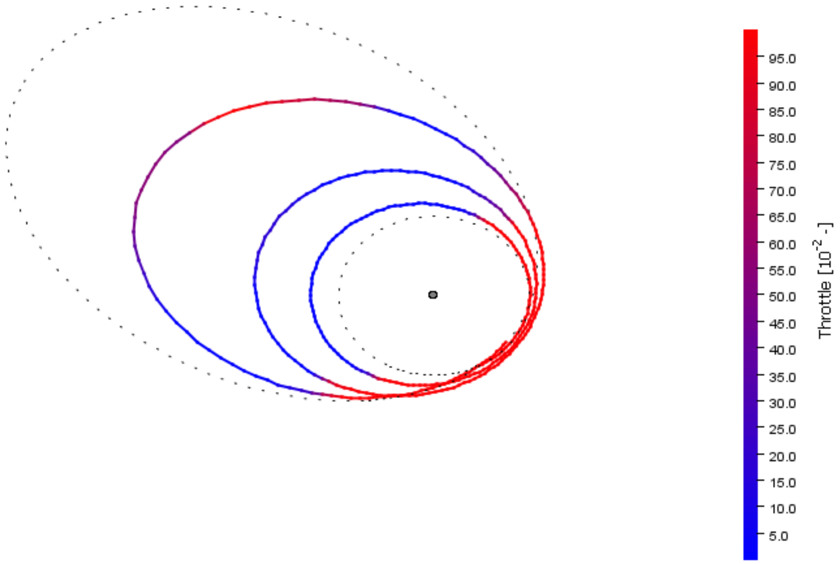


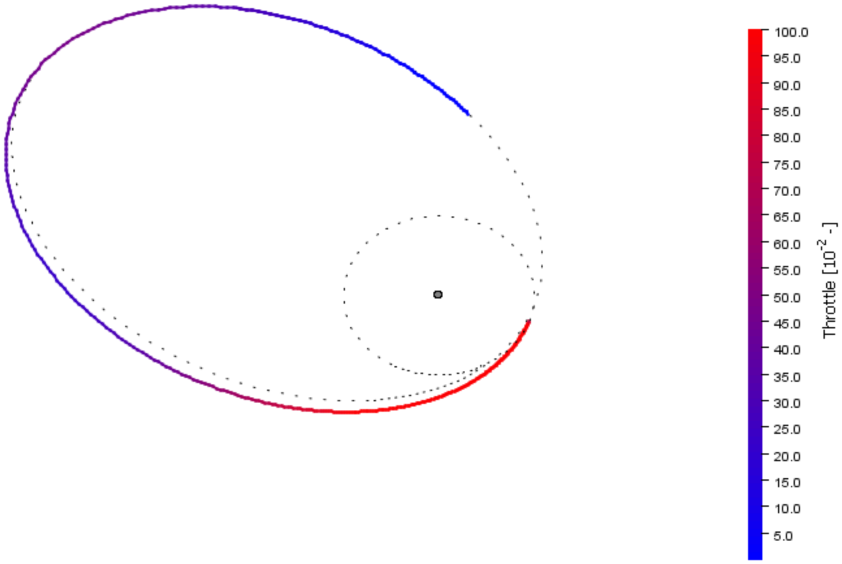


Comet Sample Return

Sample return mission from comet nucleus

- Solar electric propulsion (distance to Sun in aphelion!)
- Fuel optimal transfers
- Constrained comet arrival: during perihelion passage





Leadership requires solutions

Astos Solutions

Thank you!