

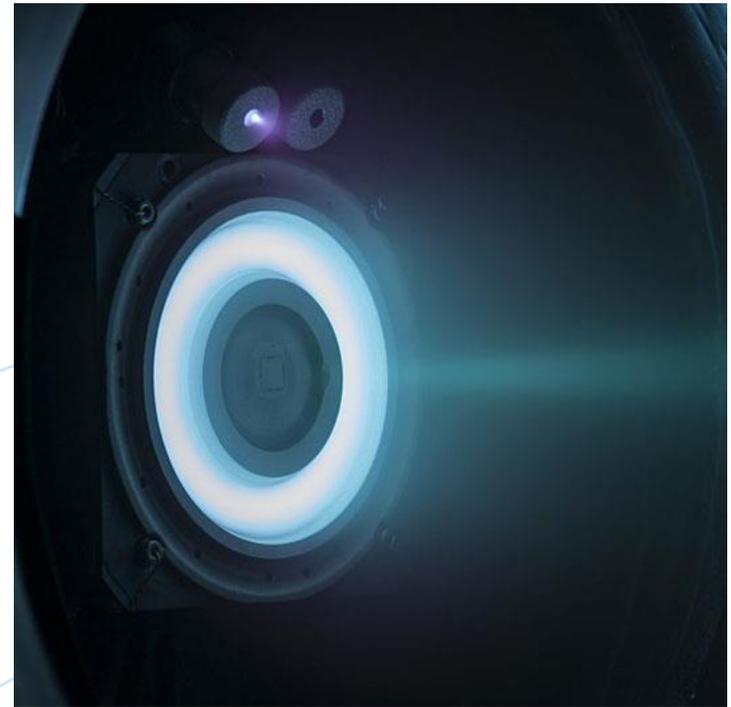
Low-Thrust Orbit Transfer Trajectory Optimization Software for Launcher Upper Stages

Space Engineering and Technology Final Presentation
Days, 23-24 May 2017, ESA-ESTEC (NL)

Francesco Cremaschi, Astos Solutions GmbH,
Stuttgart

Outline

- State of art
- Motivation
- EP for orbit raising
- LOTOS
 - Introduction
 - Hybrid transfer
 - Operational mode
- Launcher injection orbit
- EOR - LEO
- Electric propulsion upper stage
- Space Tug
- Conclusion



Credits: Safran

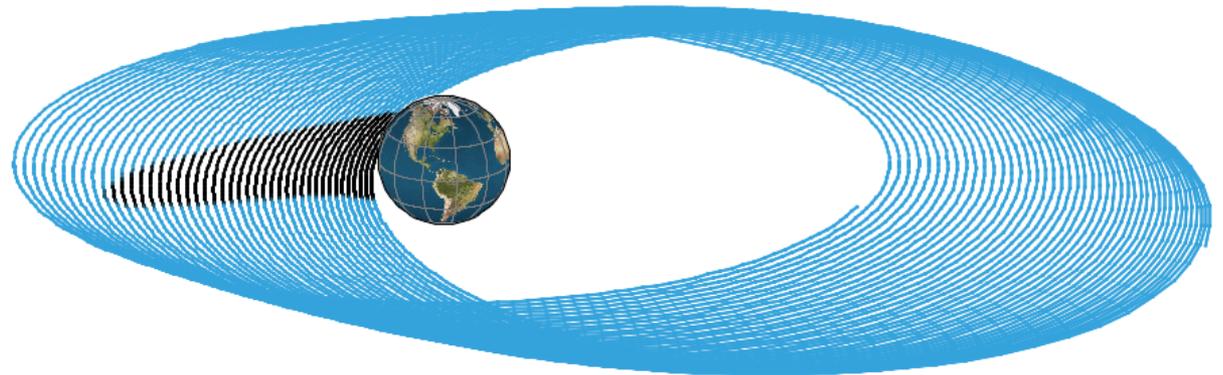
State of the art

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:

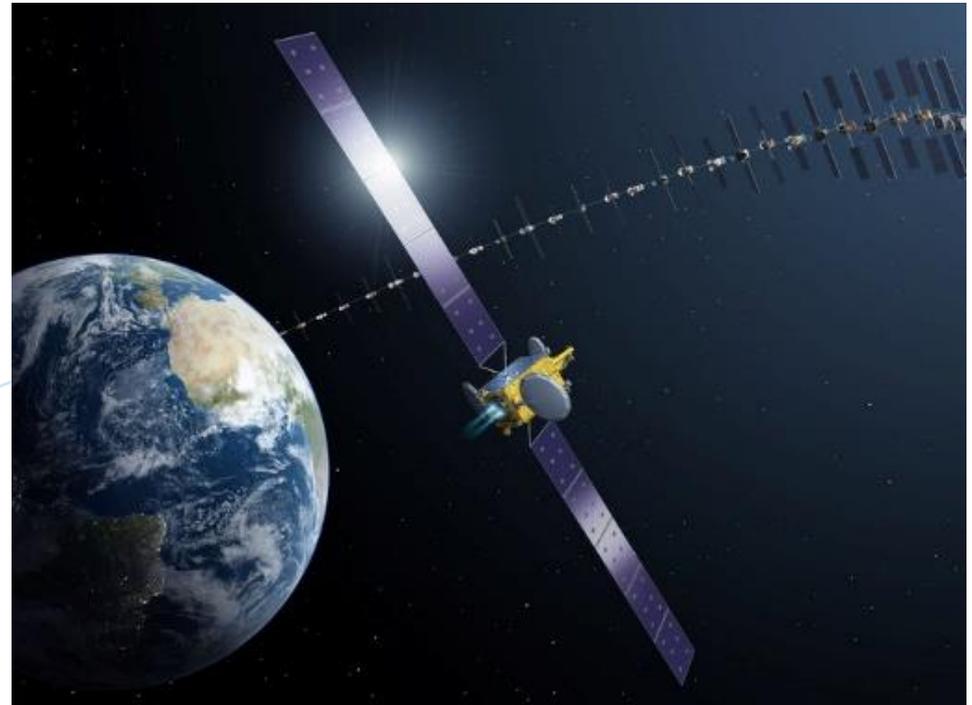
- Space tug for delivery and service
- Upper stage?



Motivation

All these scenarios requires:

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

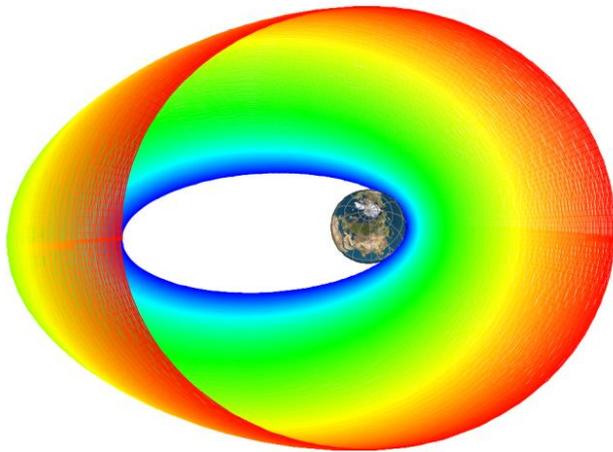


Credits: EPIC EU

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

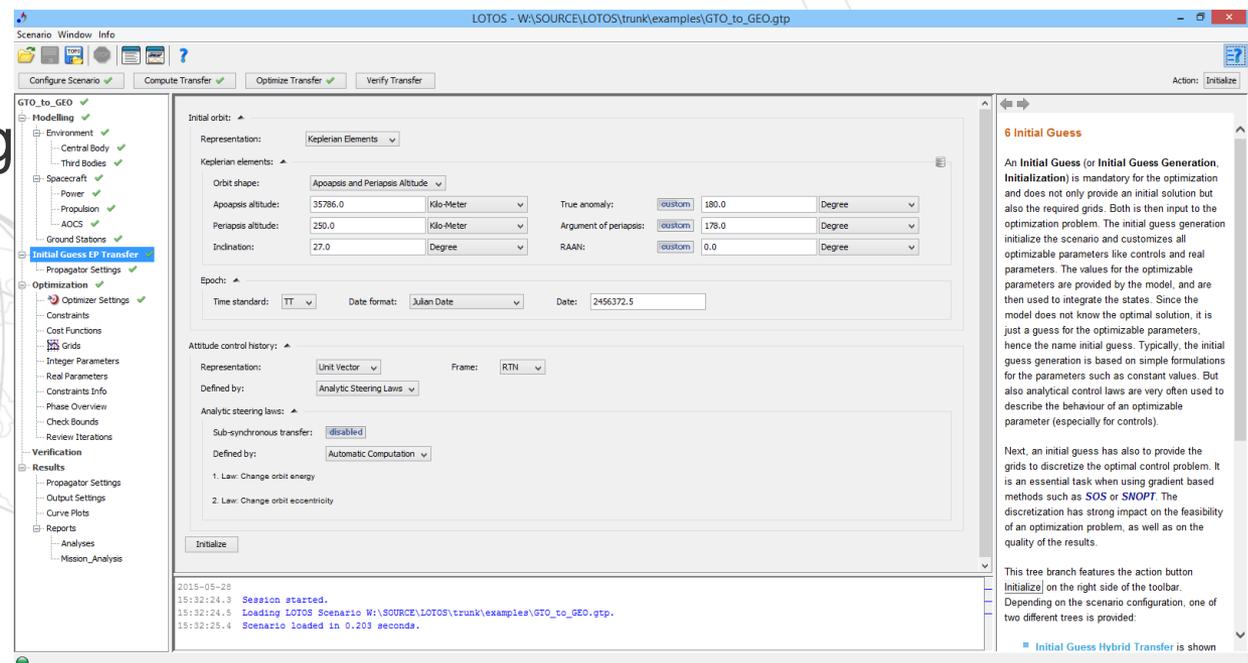


The use of “small” launchers can reduce mission cost

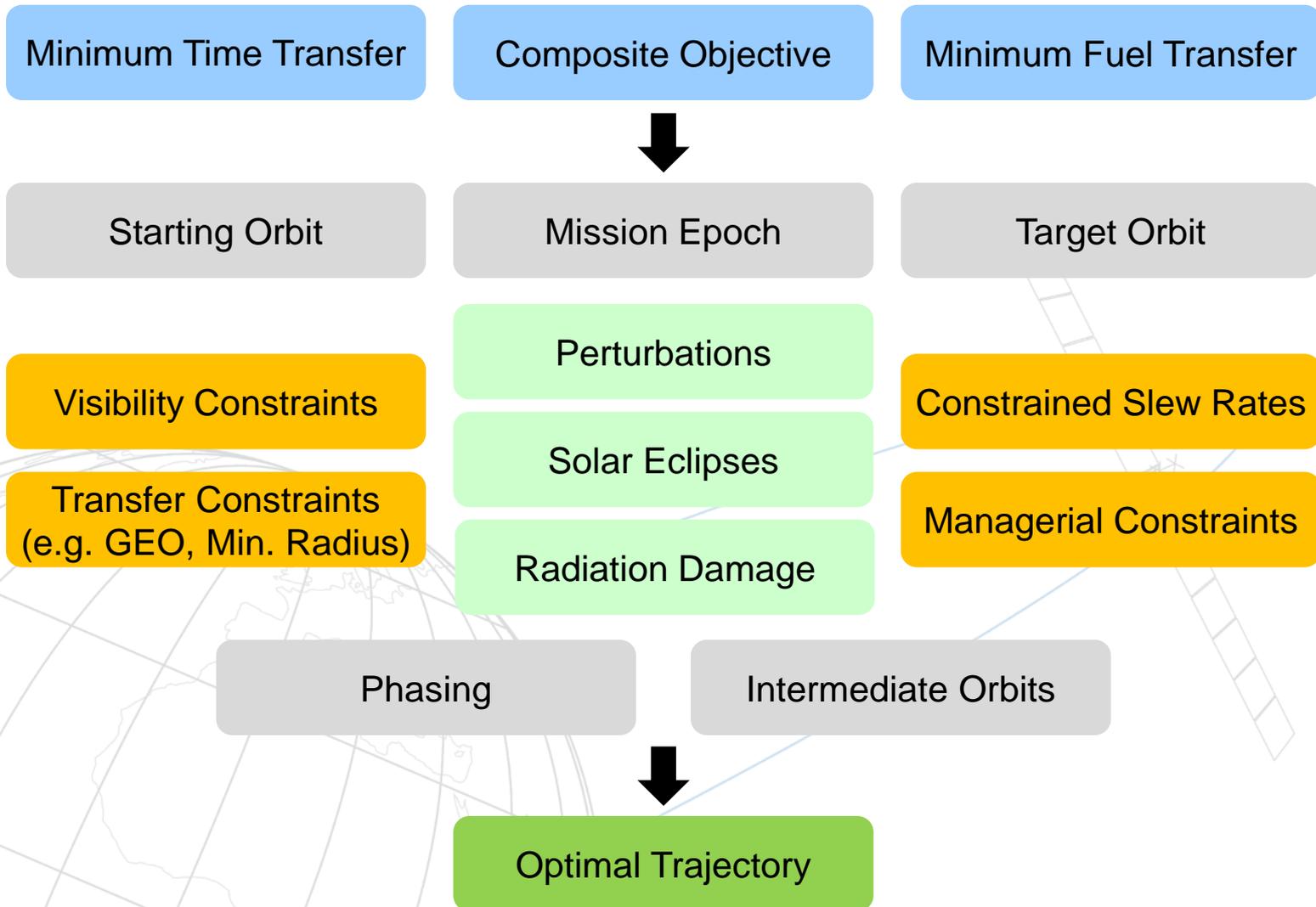
- LEO-LEO transfer
 - NEUTRINO on <https://www.astos.de/news>
- LEO-MEO transfer
 - http://www.esa.int/Our_Activities/Navigation/Electric_thrusters_may_steel_Galileo_in_future
- LEO-GEO transfer
 - <https://artes.esa.int/news/vega-launcher-telecoms>

LOTOS Key Features

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



LOTOS – Software Scheme



LOTOS – Environment

Radiation belt: ▲

Defined by:

Hollow sphere: ▲

Inner radius: Outer radius:

Dwell time as state: required for appropriate cost function

Stationary Ring (GEO-Ring): ▲

Inner radius: Outer radius:

Lower height: Upper height:

Environment effects: ▲

Atmospheric drag:

Solar radiation pressure:

Solar wind:

Third body perturbations:

Ephemeris computation:

Ground stations: ▲

Name	Altitude	Longitude	Latitude
-	Meter	Degree	Degree
Weilheim	1.0	11.1	47.9
Perth	22.2	115.9	-31.8

Item: ▲

Name:

Altitude:

Longitude:

Latitude:

LOTOS – Spacecraft

Spacecraft:

Total mass:

Reference area core:

Reflectivity coefficient:

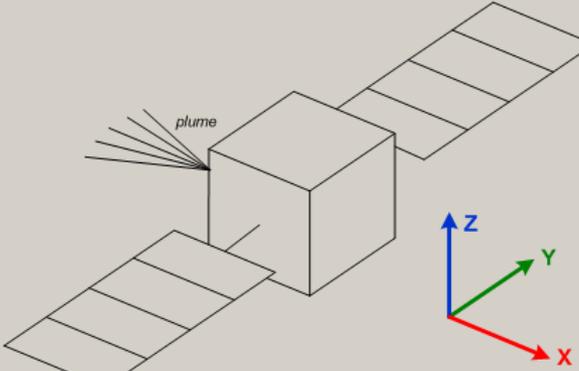
Drag coefficient:

Moments of inertia:

XX:

YY:

ZZ:



Slew rates:

Values are used during optimization as path constraint or Lagrange cost, and for the analysis.

About body x axis:

EP on:

EP off:

About body y axis:

About body z axis:

Maximum torque:

Maximum wheel momentum:

1st star tracker: enabled

Only for analysis:

Boresight direction:

x: y:

Field of view:

2nd star tracker: enabled

Propulsion:

Thrust:

Defined by:

Thrust:

Specific impulse:

Defined by:

I_{sp} :

PPU efficiency:

Minimum permissible power:

Maximum permissible power:

Bang-Bang thrust control:

Schedule:

Eclipse shutdown:

Minimum sun angle: only for analysis

Firing limitations: enabled

Only for analysis:

Minimum firing duration:

Maximum firing duration:

Minimum period between two firings (cold start):

Minimum period between two firings (warm start):

Thrust vector disturbance:

Solar array:

Reference area:

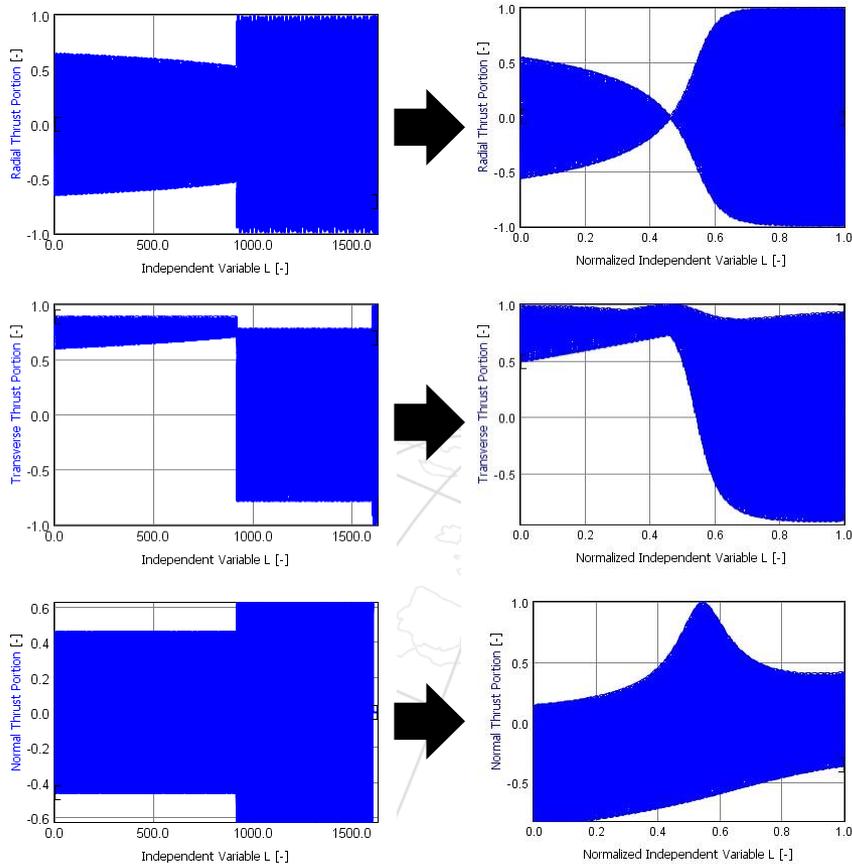
Power output:

Battery: enabled

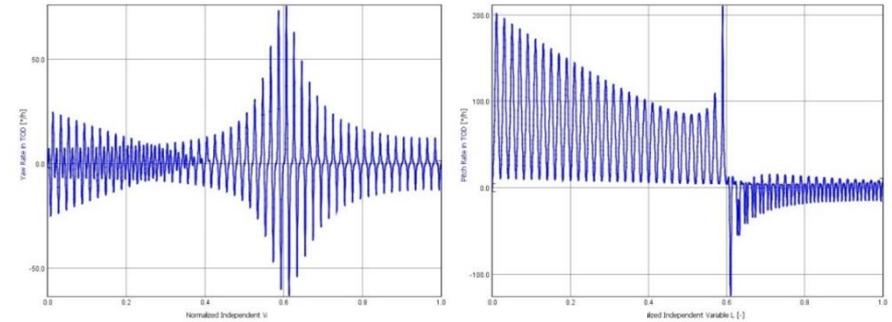
Capacity:

Depth of discharge:

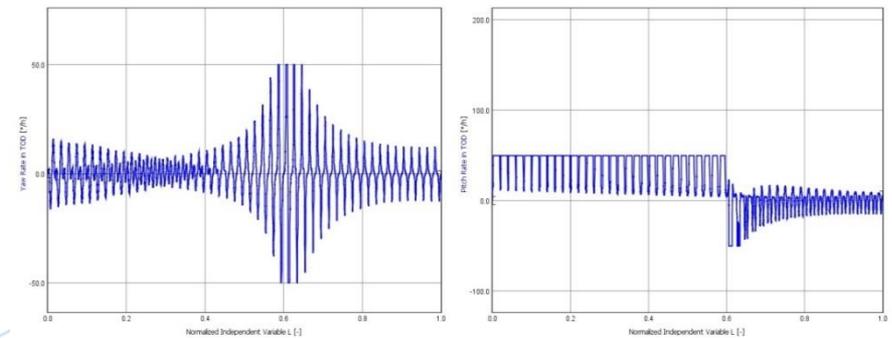
Thrust direction



Slew rates



unconstrained

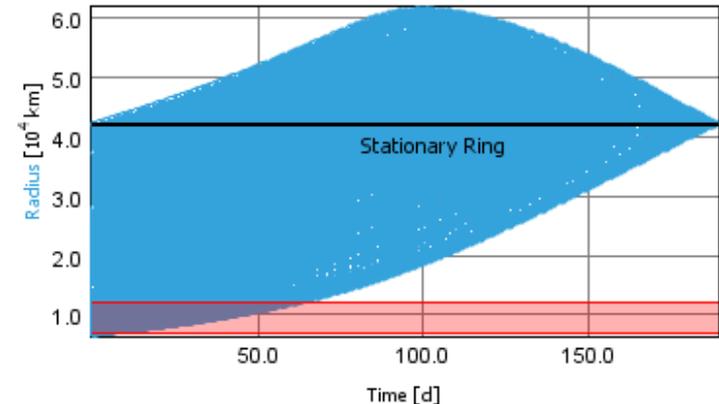


max. 50°/h

LOTOS – Optimization

Solvers

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



General Options

Optimization method:

Max. iterations: Iteration output frequency:

Optimization tolerance: Execution log: Real workspace size:

Constraint tolerance: Iteration review plots: Integer workspace size:

SOS Specific Options

Automatic scaling option: Algorithm control: Character workspace size:

Num. mesh refinements: ODE tolerance: Max. number of function evaluations:

Show sos.out Options

Phase Specific Options (Default)

Optimization Settings

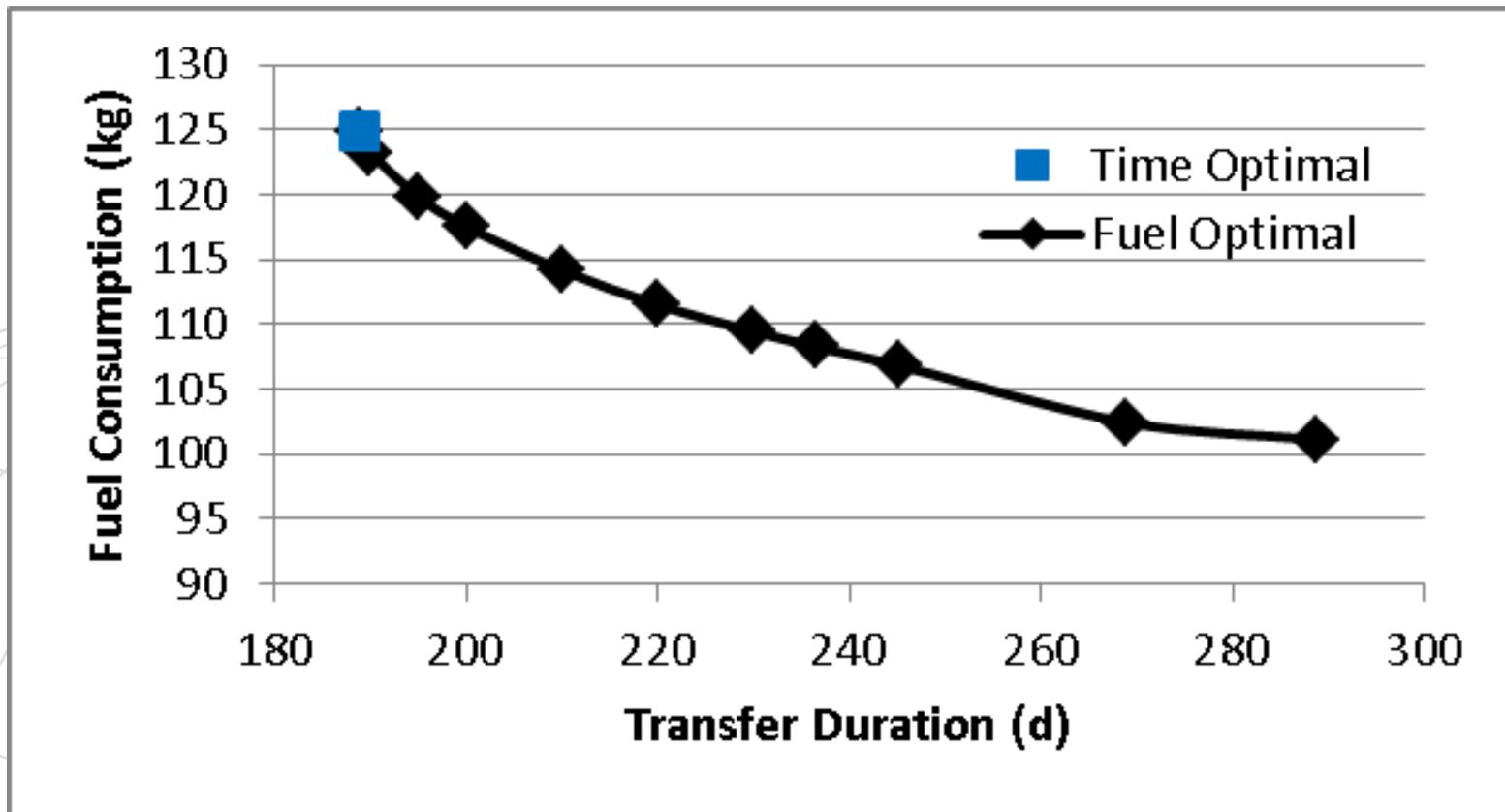
Default

orbit_raising

Integr. method:

LOTOS – Objective Functions

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



LOTOS – User Interface

Front-end and command line interface

Customizable output

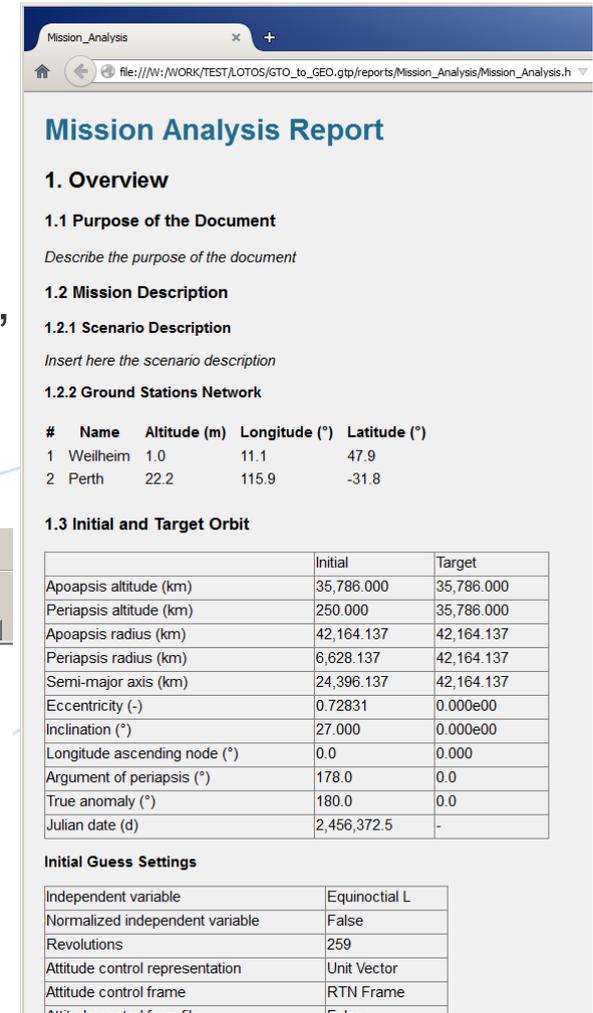
- Scenario input and output (scalars, functions,
- Maneuver plan and eclipses as output files

Automatic post-processing

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

Reports

- Customizable
- Automatic generation



Mission Analysis Report

1. Overview

1.1 Purpose of the Document

Describe the purpose of the document

1.2 Mission Description

1.2.1 Scenario Description

Insert here the scenario description

1.2.2 Ground Stations Network

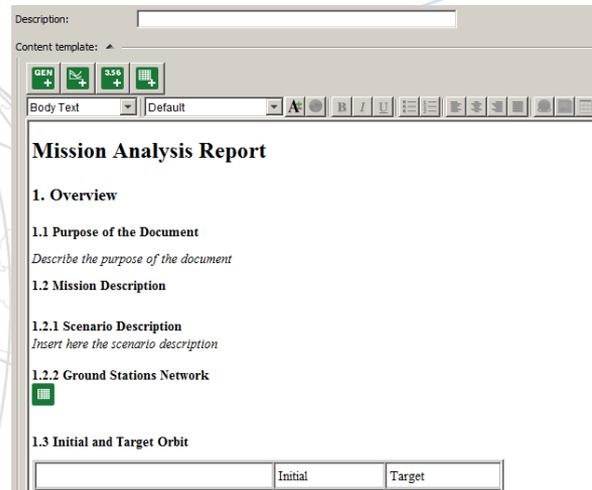
#	Name	Altitude (m)	Longitude (°)	Latitude (°)
1	Weilheim	1.0	11.1	47.9
2	Perth	22.2	115.9	-31.8

1.3 Initial and Target Orbit

	Initial	Target
Apoapsis altitude (km)	35,786.000	35,786.000
Periapsis altitude (km)	250.000	35,786.000
Apoapsis radius (km)	42,164.137	42,164.137
Periapsis radius (km)	6,628.137	42,164.137
Semi-major axis (km)	24,396.137	42,164.137
Eccentricity (-)	0.72831	0.000e00
Inclination (°)	27.000	0.000e00
Longitude ascending node (°)	0.0	0.000
Argument of periapsis (°)	178.0	0.0
True anomaly (°)	180.0	0.0
Julian date (d)	2,456,372.5	-

Initial Guess Settings

Independent variable	Equinoctial L
Normalized independent variable	False
Revolutions	259
Attitude control representation	Unit Vector
Attitude control frame	RTN Frame
Attitude control from file	False



Description:

Content template:

Body Text Default

Mission Analysis Report

1. Overview

1.1 Purpose of the Document

Describe the purpose of the document

1.2 Mission Description

1.2.1 Scenario Description

Insert here the scenario description

1.2.2 Ground Stations Network

#	Name	Altitude (m)	Longitude (°)	Latitude (°)
1	Weilheim	1.0	11.1	47.9
2	Perth	22.2	115.9	-31.8

1.3 Initial and Target Orbit

	Initial	Target
Apoapsis altitude (km)	35,786.000	35,786.000
Periapsis altitude (km)	250.000	35,786.000
Apoapsis radius (km)	42,164.137	42,164.137
Periapsis radius (km)	6,628.137	42,164.137
Semi-major axis (km)	24,396.137	42,164.137
Eccentricity (-)	0.72831	0.000e00
Inclination (°)	27.000	0.000e00
Longitude ascending node (°)	0.0	0.000
Argument of periapsis (°)	178.0	0.0
True anomaly (°)	180.0	0.0
Julian date (d)	2,456,372.5	-

LOTOS – Hybrid Transfer

Chemical orbit-raising

Chemical orbit-raising: ▲

1st burn:	<input type="text" value="Periapsis"/>
2nd burn:	<input checked="" type="checkbox" value="enabled"/> <input type="text" value="Apoapsis"/>
3rd burn:	<input checked="" type="checkbox" value="enabled"/> <input type="text" value="Periapsis"/>
Out-of-plane maneuver:	<input checked="" type="checkbox" value="enabled"/>
Max. duration of each burn:	<input type="text" value="20.0"/> <input type="text" value="Minute"/>
Thrust:	<input type="text" value="400.0"/> <input type="text" value="Newton"/>
Specific impulse:	<input type="text" value="300.0"/> <input type="text" value="Second"/>
Max. total transfer duration:	<input checked="" type="checkbox" value="enabled"/> <input type="text" value="190.0"/> <input type="text" value="Day"/>
Min. periapsis radius:	<input checked="" type="checkbox" value="enabled"/> <input type="text" value="10000.0"/> <input type="text" value="Kilo-Meter"/>

followed by electric orbit-raising to target orbit

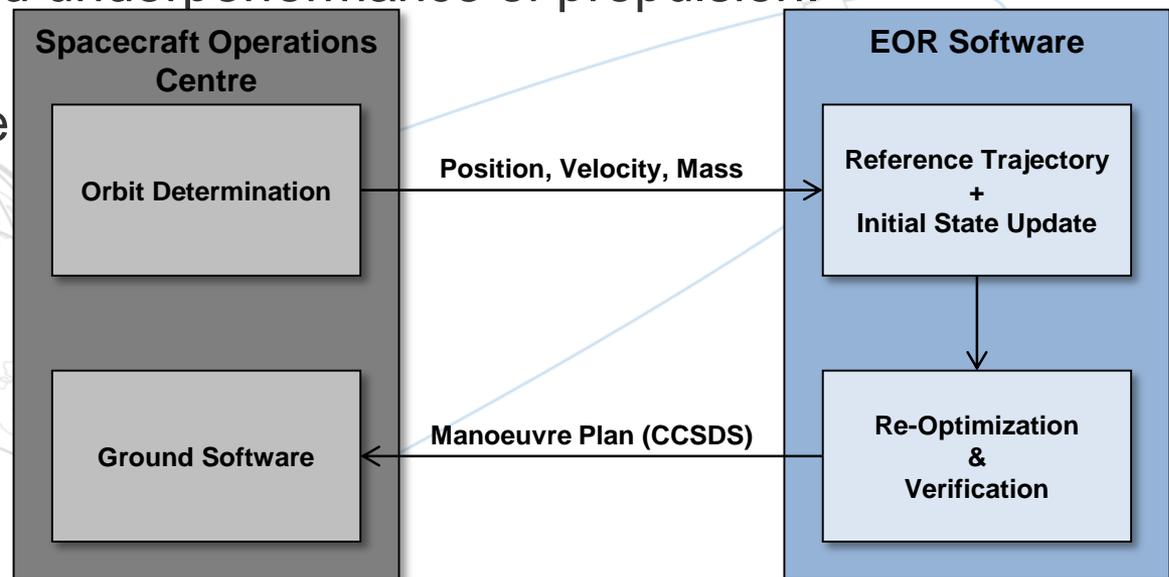
Final orbit: ▲

Representation:	<input type="text" value="Keplerian Elements"/>	Relative longitude:	<input checked="" type="checkbox" value="custom"/> <input type="text" value="37.0"/>	<input type="text" value="Degree"/>
Keplerian elements: ▲	<input checked="" type="checkbox" value="Semimajor Axis and Eccentricity"/>			
Semimajor axis:	<input type="text" value="42164.137"/> <input type="text" value="Kilo-Meter"/>	True anomaly:	<input checked="" type="checkbox" value="custom"/> <input type="text" value="0.0"/>	<input type="text" value="Degree"/>
Eccentricity:	<input type="text" value="0.0"/> <input type="text" value="None"/>	Argument of periapsis:	<input checked="" type="checkbox" value="custom"/> <input type="text" value="0.0"/>	<input type="text" value="Degree"/>
Inclination:	<input type="text" value="0.0"/> <input type="text" value="Degree"/>	RAAN:	<input checked="" type="checkbox" value="custom"/> <input type="text" value="0.0"/>	<input type="text" value="Degree"/>

LOTOS – Operational Aspects

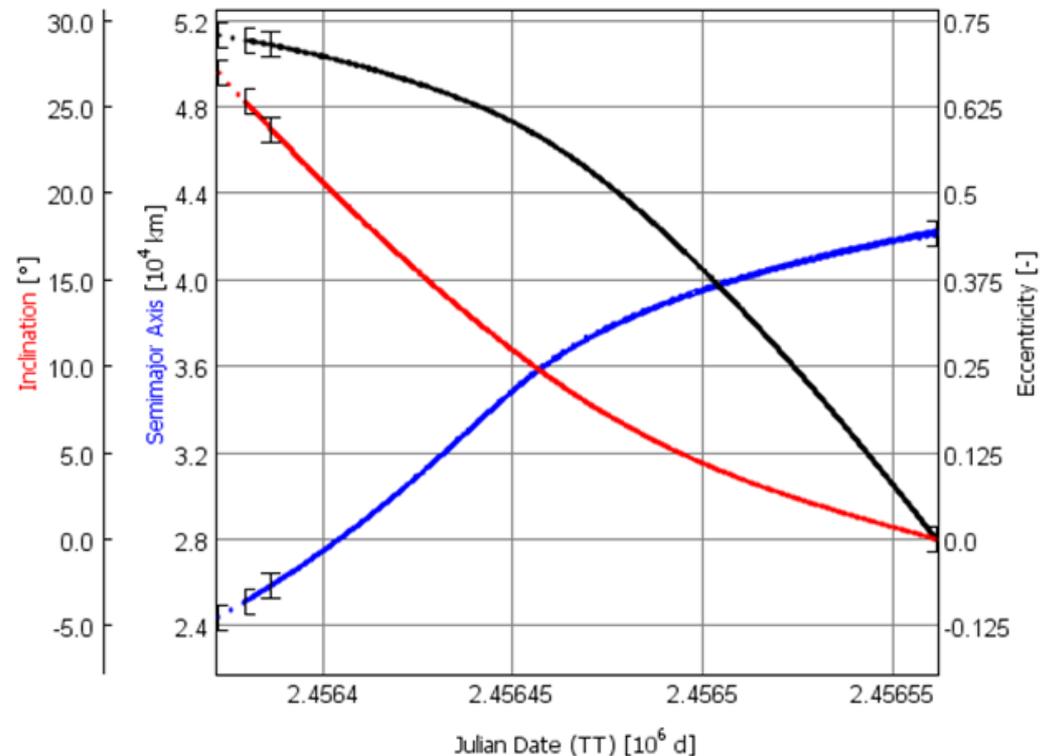
Once the trajectory (and satellite) is optimized, operational aspects have to be considered:

- 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.



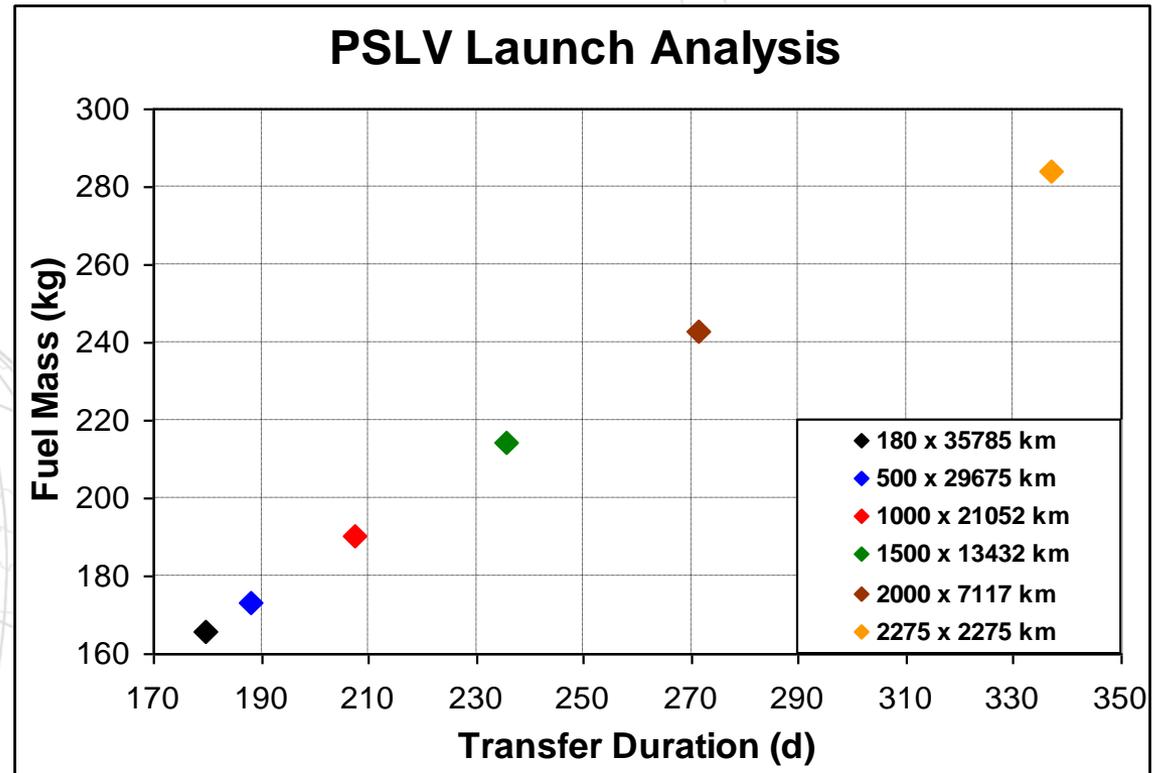
LOTOS – Operational Mode

- 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



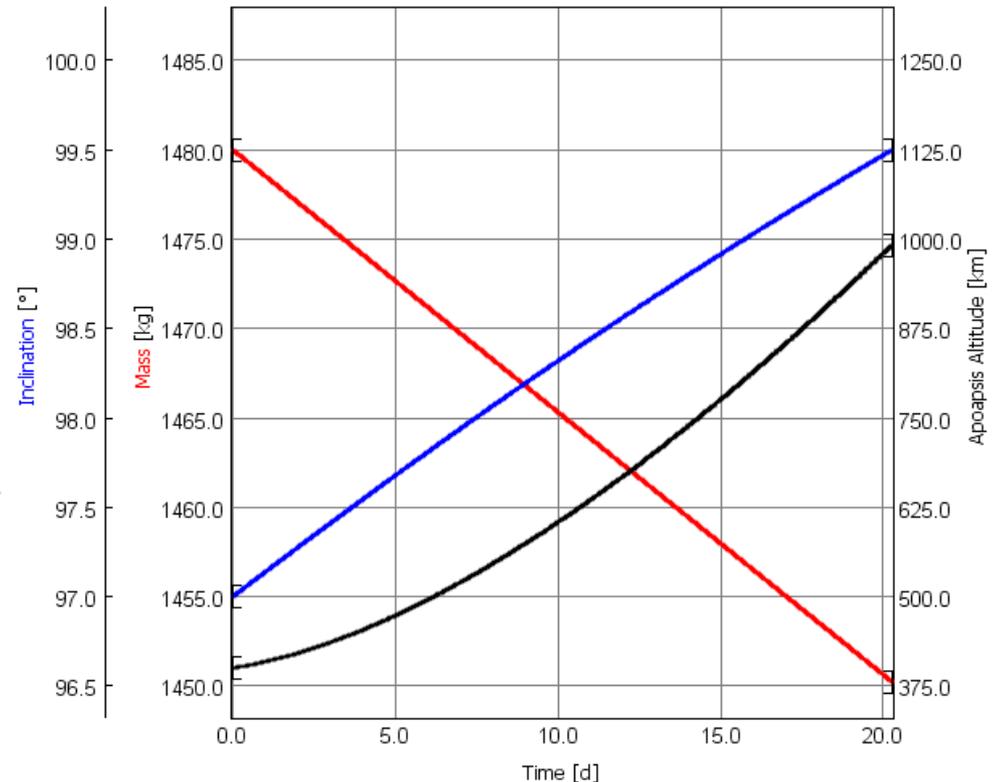
Launcher Injection Orbit

- 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

Power generation requirement:

- Solar panel 0.3-0.4 kW/m²

Efficiency 27-10 mN/m²

Problems:

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

Solution:

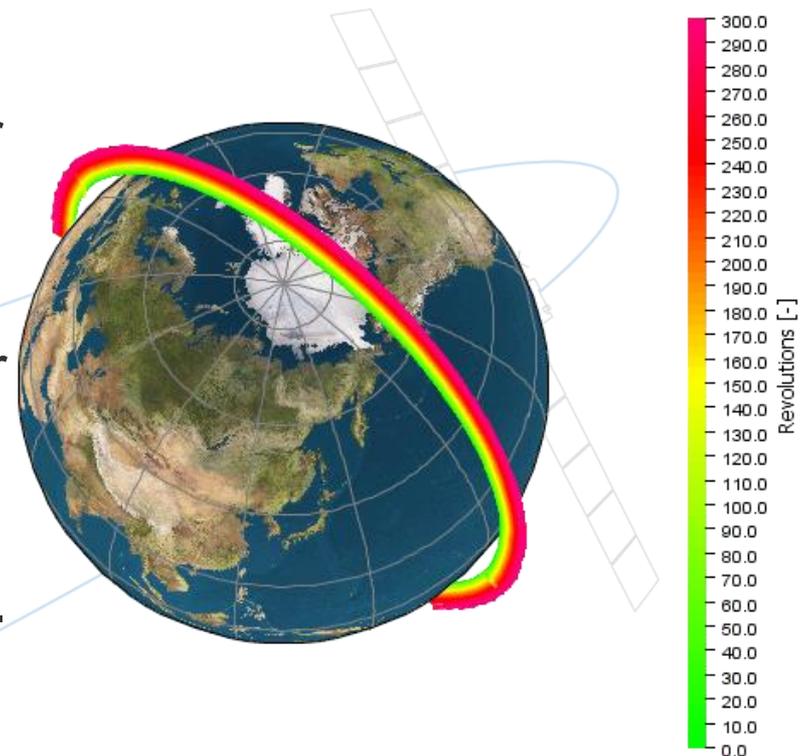
- Reusable Space Tug



Credits: ESA

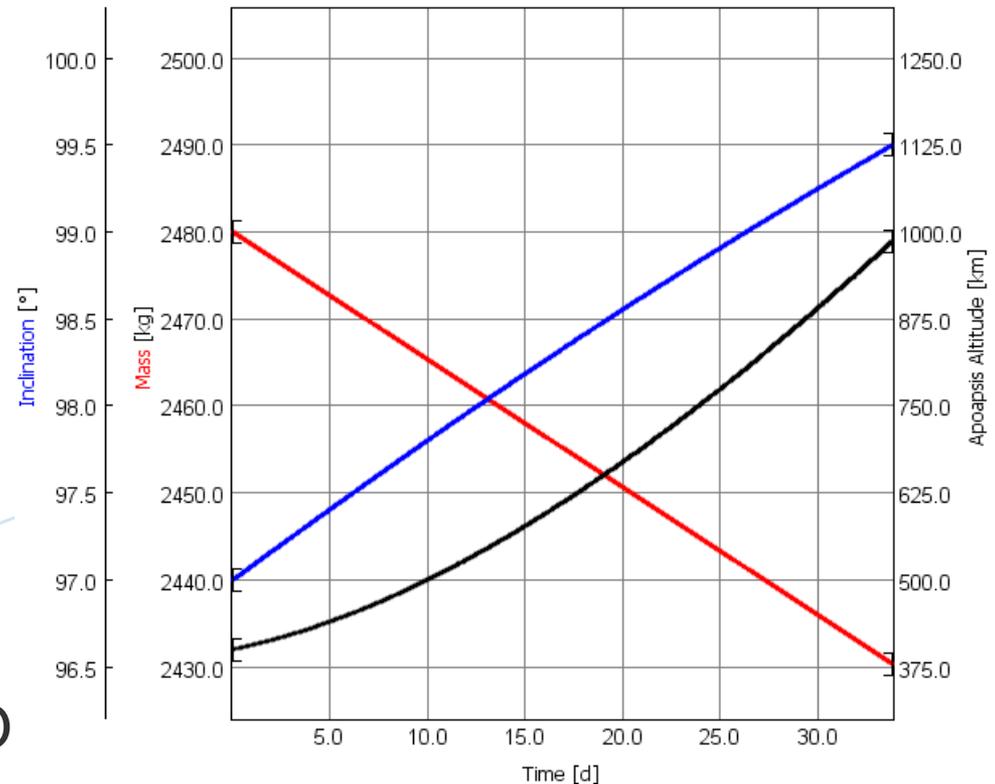
Space Tug – Applications

- 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.

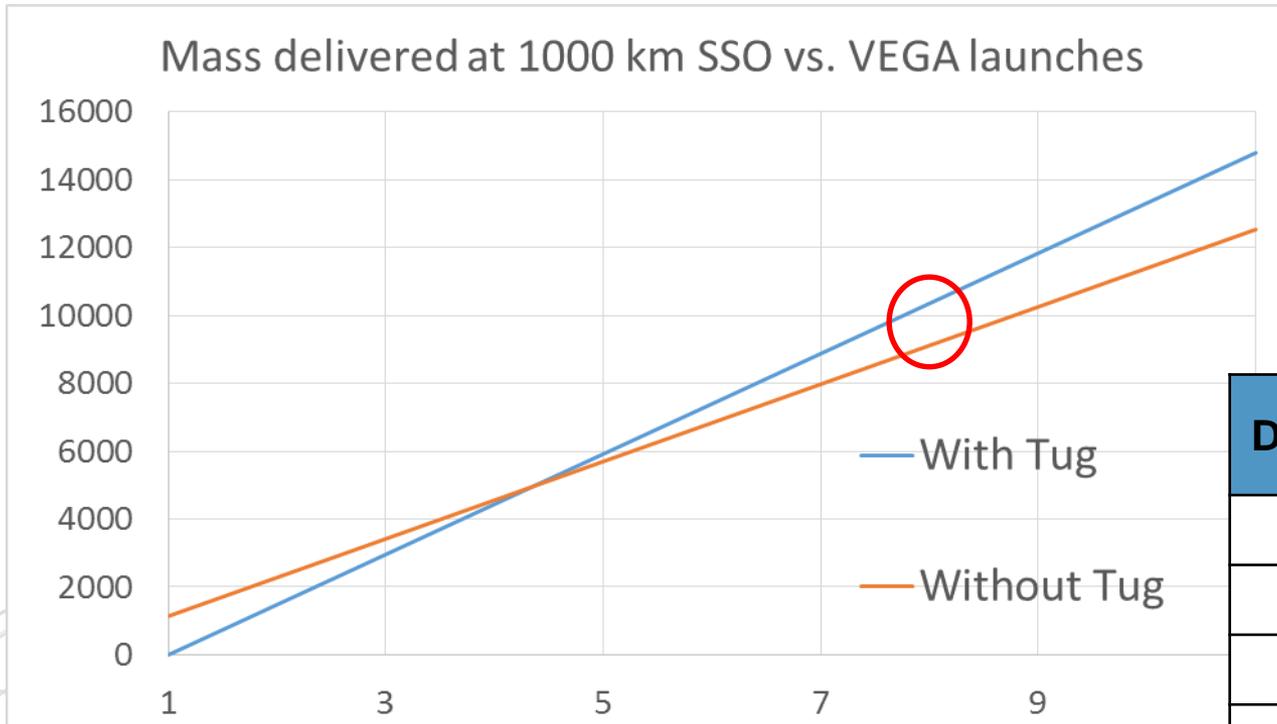


Space Tug – Single Delivery

- 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



Website: <https://www.astos.de/products/lotos>

Contacts: sven.schaeff@astos.de, francesco.cremaschi@astos.de

Thank you!

