

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

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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



- LEO-LEO transfer
 - NEUTRINO on https://www.astos.de/news
- LEO-MEO transfer
 - http://www.esa.int/Our_Activities/ Navigation/Electric_thrusters_m ay_steer_Galileo_in_future
- LEO-GEO transfer
 - https://artes.esa.int/news/vegalauncher-telecoms

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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

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todelling 🗸	Initial orbit: 🔺									Clattial Current	~
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Third Bodies	Keplerian elements: 🔺							E		An Initial Guess (or Initial Guess Generation	
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Power 🖌	Orbit snape:	Apoapsis and Penapsi	s Alutude 🗸							and does not only provide an initial solution but	
Propulsion 🗸	Apoapsis altitude:	35786.0	Kilo-Meter 🗸	True anomaly:	custom	180.0	Degree	~		also the required grids. Both is then input to the	
AOCS 🗸	Periapsis altitude:	250.0	Kilo-Meter 🗸	Argument of periapsis:	oustom	178.0	Degree	~		optimization problem. The initial guess generation	1
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nitial Guess EP Transfer 📝	and door.	27.0	ocyce v	100010		0.0	begree			optimizable parameters like controls and real	
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ptimization 🗸	cpoon									parameters are provided by the model, and are	
Optimizer Settings	Time standard: TT	 Date format 	: Julian Date 🗸 🗸	Date: 2456372.5						then used to integrate the states. Since the	
Constraints										model does not know the optimal solution, it is	
- Structures	Attitude control history:									hence the name initial quess. Typically, the initial	
Integer Parameters										quess generation is based on simple formulations	
- Real Parameters	Representation:	Unit Vector 🗸	Frame: RTN	~						for the parameters such as constant values. But	
Constraints Info	Defined by:	Analytic Steering La	ws 🗸							also analytical control laws are very often used to	
- Phase Overview	Analytic steering laws: 🔺									describe the behaviour of an optimizable	
Check Bounds										parameter (especially for controls).	
- Review Iterations	Sub-synchronous transl	fer: disabled									
rification	Defined by:	Automatic Compu	tation 🗸							Next, an initial guess has also to provide the	
tesults	1. Law: Change orbit en	ergy								grids to discretize the optimal control problem. It	
Propagator Settings		-								is an essential task when using gradient based	
Output Settings	2. Law: Change orbit ec	centricity								discretization has strong impact on the feasibility	
Curve Plots										of an optimization problem, as well as on the	
- Reports	Initialize									quality of the results	
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LOTOS – Software Scheme





LOTOS – Environment



Radiation belt: 🔺								
Defined by: Hollow Sphere 💌								
Hollow sphere: 🔺								
Inner radius: 7000.0	Kilo-Meter	Outer radius:	12000.0	Kilo-Meter	•			
Dwell time as state: disabled rec	quired for appropriate c	ost function						
Stationary Ring (GEO-Ring): 🔺								
Inner radius: 42050.0	Kilo-Meter	Outer radius:	42250.0	Kilo-Meter	Y			
Lower height: -75.0	Kilo-Meter	▼ Upper height:	75.0	Kilo-Meter	Y			
Environment effects:								
Atmospheric drag:)	
Solar radiation pressure: disabled								
Solar wind: disabled							\sim	
Third body perturbations: disabled	Ground stations:	A						
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\land \land \land	Latitude:	47.9	Degree	_				
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LOTOS – Spacecraft

	Slew rates: A
Spacecraft: 🔺	Values are used during optimization as path constraint or Lagrange cost, and for the analysis.
Total mass: 1000.0 Kilogram	About body x axis: 🔺
Reference area core: 2.5 Meter**2	EP on Upper Limit 💌 150.0 Degree/Hour 💌
Reflectivity coefficient: 1.3	EP off Upper Limit 💌 200.0 Degree/Hour 💌
	About body y avier
Drag coefficient: 2.5 C _D u	About body y axis.
Moments of inertia: 🔺	About body z axis: Thrust:
XX: 700.0 Kilogram*Meter**2	Maximum torque: 0.0015 Defined by: Constant
YY: 50.0 Kilogram*Meter**2	Maximum wheel momentum: 1.0 Thrust: 0.15 Newton
ZZ: 700.0 Kilogram*Meter**2 💌	1st star tracker:
	Only for analysis. Defined by: Constant
	Boresight direction:
	x: 1.0 y:
	PPU efficiency: 100.0 Percent
	Field of view: 5.0 Minimum permissible power: 0.0 Watt
	2nd star tracker: Maximum permissible power: 1000.0 Watt
	Bang-Bang thrust control: disabled
	Schedule:
	Eclipse shutdown: disabled
	Minimum sun angle: 10.0 Degree only for analysis
	Firing limitations:
Solar array:	Only for analysis.
Reference area: 37.5 Meter**2	Minimum firing duration: 10.0 Minute
Power output: 3000.0 Watt	Maximum firing duration: 2.0 Year
	Minimum period between two firings (cold start): 30.0 Minute
Battery: A enabled	Minimum period between two firings (warm start): 10.0 Minute
Capacity: 6000.0 Watt*Hour Depth of discharge: 70.0 Percent	Thrust vector disturbance: disabled

As⁻

LOTOS – Dynamics





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LOTOS – Optimization

Solvers

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

	·····	
General Options		
Optimization method: SOS		
Max. iterations: 500	Iteration output frequency:	
Optimization tolerance:	Execution log: 1 Real workspace size: 105000000	
Constraint tolerance: 1.0E-7	Iteration review plots: 100 - Integer workspace size: 92000000	
SOS Specific Options		
Automatic scaling option: Simple Row and Column Scaling	Algorithm control: Feas Minimize Character workspace :	size: 800000
Num. mesh refinements: 0	ODE tolerance: 9.0E-1 Max. number of function	on evaluations: 150000
Show sos.out Options		
Phase Specific Options (Default)		
Optimization Settings		
Default	Integr. method: Trapezodial 💌	
orbit_raising		

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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

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Mission_Analysis		× \+				
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1.2.2 Ground	Stations Net	work				
# Name	Altitude (m)	Longitud	de (°)	Latitude (°)	
1 Weilheim	1.0	11.1		47.9		
2 Perth	22.2	115.9		-31.8		
1.3 Initial an	d Target Or	bit				
			Initia		Target	
Apoapsis altitu	ude (km)		35,7	86.000	35,786.000	
Periapsis altit	ude (km)		250.	000	35,786.000	
Apoapsis radi	us (km)		42,1	64.137	42,164.137	
Periapsis radi	us (km)		6,62	8.137	42,164.137	
Semi-major axis (km)		24,3	96.137	42,164.137	7	
Eccentricity (-)		0.72	831	0.000e00	
Inclination (°)			27.0	00	0.000e00	
Longitude asc	ending node (°)	0.0		0.000	1
Argument of p	eriapsis (°)		178.	0	0.0	1
True anomaly	(°)		180.	0	0.0	-
Julian date (d)			2 45	3 372 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	Falsa

LOTOS – Hybrid Transfer

Astos

Chemical orbit-raising

Chemical orbit-raising: 1st burn: Periapsis 2nd burn: enabled Apoapsis 3rd burn: enabled Periapsis Out-of-plane maneuver: enabled Max. duration of each burn: 20.0 Minute Thrust: 400.0 Newton Specific impulse: 300.0 Second Max. total transfer duration: enabled 190.0 Min. periapsis radius:				
1st burn: Periapsis ▼ 2nd burn: enabled Apoapsis ▼ 3rd burn: enabled Periapsis ▼ Out-of-plane maneuver: enabled Max. duration of each burn: 20.0 Max. turation of each burn: 300.0 Specific impulse: 300.0 Max. turation: enabled 190.0 Day Min. periapsis radius: enabled 10000.0 Kilo-Meter	Chemical orbit-raising: 🔺 ——			
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Min. periapsis radius: enabled 10000.0 Kilo-Meter	Max. total transfer duration:	enabled 190.0	Day	-
	Min. periapsis radius:	enabled 10000.0	Kilo-Meter	-

followed by electric orbit-raising to target orbit

Final orbit: 🔺		16191						\	
Representation:	Keplerian Elements 💌	Relative longitude:	custom	37.0	Degr	ee 💌			
Keplerian elements: 🔺 -									
Orbit shape:	Semimajor Axis and Eccentric	ity 💌							
Semimajor axis:	42164.137	Kilo-Meter	Ŧ	True anomaly:	custom	0.0	De	gree	-
Eccentricity:	0.0	None	Ŧ	Argument of periapsis:	custom	0.0	De	gree	-
Inclination:	0.0	Degree	Ŧ	RAAN:	custom	0.0	De	gree	-

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.



GTO to GEO

LOTOS – Operational Mode

- 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/m^2

Problems:

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





Credits: ESA

Solution:

Reusable Space Tug

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Space Tug – Applications

Astos

- 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.



30.0 20.0 10.0 0.0

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





 Equivalent VEGA launches at 1000 km SSO = 9 (x1140 kg)

8

480

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-, smallclass 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 subsystems.
- 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!