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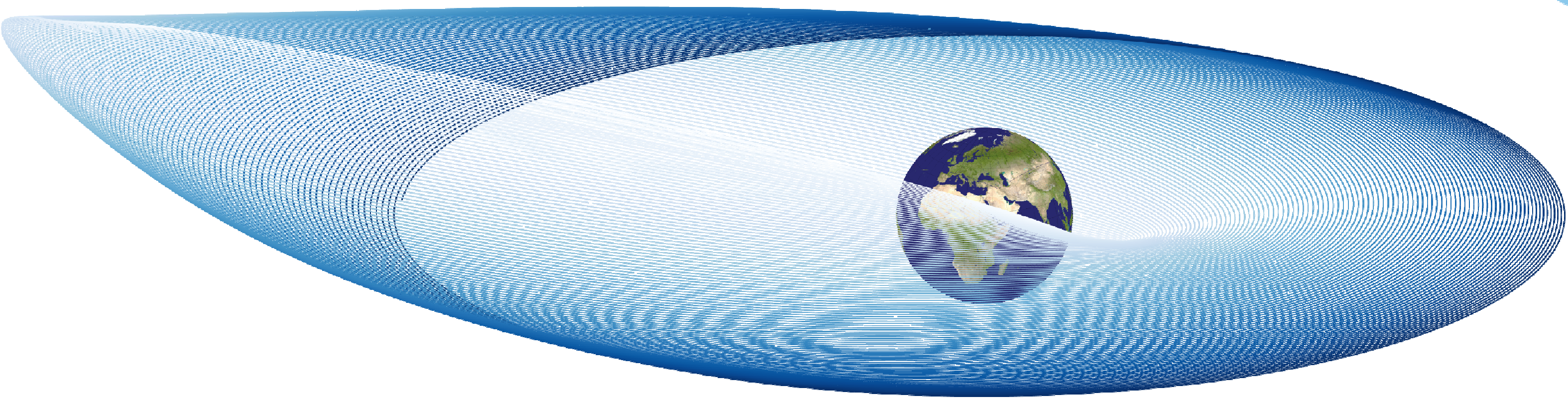


SPACE SYSTEMS

ELECTRO: A SW tool for the ELECtric propulsion TRajectory Optimisation

We. Create. Space.

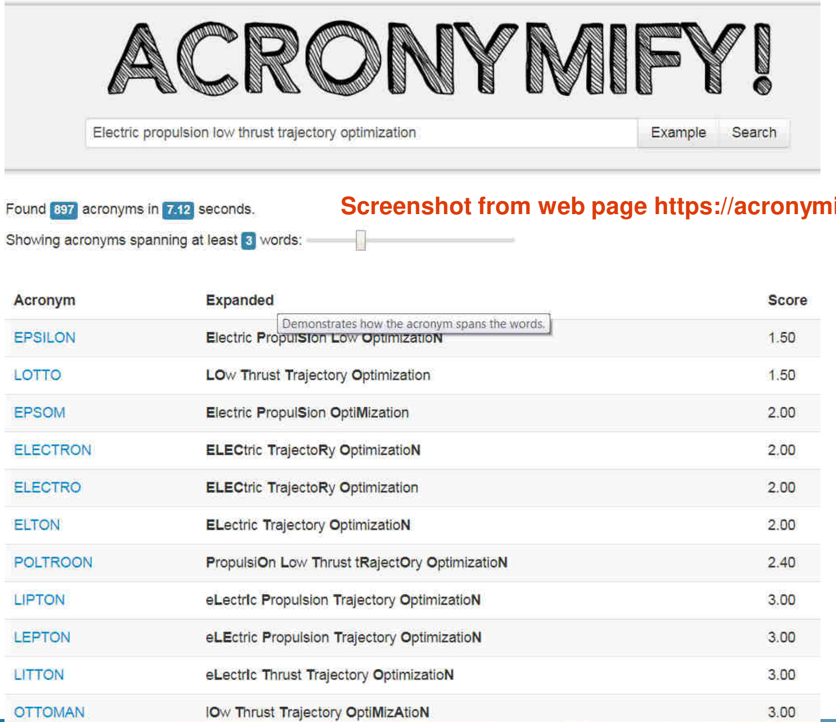
Outline

- Introduction
- Sequential Gradient Restoration Algorithm (SGRA)
- Some validation cases for the SGRA algorithm applied to this problem
- Tool outputs
- Conclusions

Why ELECTRO name??...

Image taken from Wikipedia:
https://en.wikipedia.org/wiki/Electro_(Marvel_Comics)

- ELECTRO is a Mission Analysis tool for low thrust trajectory design developed in OHB during last 5 years
- Latest push for development has been gained in the framework of the **Electra project** (OHB all-electric GEO platform, currently under development).


ACRONYMIFY!

Electric propulsion low thrust trajectory optimization Example Search

Found 897 acronyms in 7.12 seconds.

Showing acronyms spanning at least 3 words:

Acronym	Expanded	Score
EPSILON	Electric PropulSIon Low OptimizatioN	1.50
LOTTO	LOw Thrust Trajectory Optimization	1.50
EPSOM	Electric PropulSion OptiMization	2.00
ELECTRON	ELECtric TrajectoRy OptimizatioN	2.00
ELECTRO	ELECtric TrajectoRy Optimization	2.00
ELTON	ELectric Trajectory OptimizatioN	2.00
POLTROON	PropulsiOn Low Thrust tRajectOry OptimizatioN	2.40
LIPTON	eLectrIc Propulsion Trajectory OptimizatioN	3.00
LEPTON	eLEctric Propulsion Trajectory OptimizatioN	3.00
LITTON	eLectrIc Thrust Trajectory OptimizatioN	3.00
OTTOMAN	lOw Thrust Trajectory OptiMizAtioN	3.00

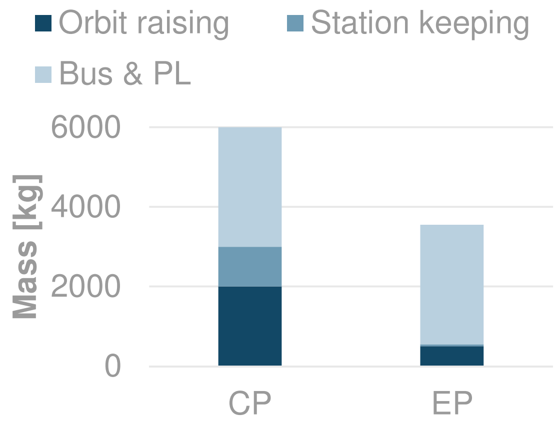
Demonstrates how the acronym spans the words.

Screenshot from web page https://acronymify.com

Electric propulsion & mission design

Electric propulsion applied to **GEO** satellites offers a significant **mass advantage**, which can be translated into

- increased revenue-generating payload performance *(e.g. SES-12)*
- launch vehicle savings to customers *(e.g. dual launch of Boeing 702SP satellites)*

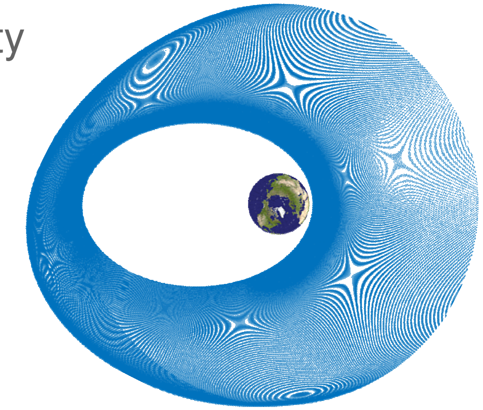


Typical mass breakdown for a GEO satellite with chemical propulsion (CP) or electric propulsion (EP)

Technology used since mid-1990s for station keeping; first **all-electric satellite** (station keeping & transfer) launched in **2015**

Low-thrust transfer: increased design and operational complexity

- Trajectory optimisation (and coupling with attitude control)
- **Long transfer** (4-6 months):
  - collision avoidance operations
  - permanence within the Van Allen Belts
  - cost of operations



Sequential Gradient Restoration Algorithm

Indirect method developed in the 60's-70's by Prof. Miele in Rice University (Houston)

State vector *x*, partitioned into vectors *y* (components prescribed at the initial point) and *z* (components not prescribed at the initial point). Given *x* modifiable by a control vector *u* and a parameter vector π:

$$I = \int_0^1 f(x,u,\pi,t)dt + [h(z,\pi)]_0 + [g(x,\pi)]_1$$

Cost function to be minimised

$$\dot{x} = \phi(x,u,\pi,t), \qquad 0 \le t \le 1$$

Differential constraints (dynamics)

$$y(0) = \text{given},$$
$$[\omega(x,\pi)]_0 = 0$$
$$[\psi(x,\pi)]_1 = 0$$

Boundary conditions

$$S(x,u,\pi,t) = 0 \qquad 0 \le t \le 1$$

Path constraints (equality or inequality)

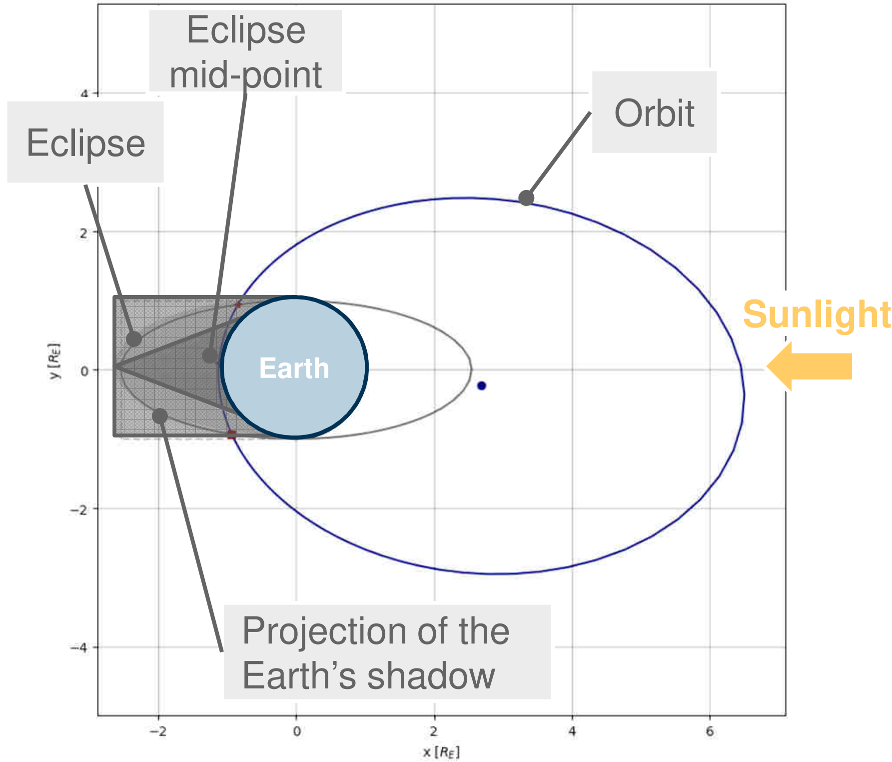
Main idea: alternate restoration / gradient phases for achieving feasibility / decreased cost function value, respectively.

Transfer optimisation

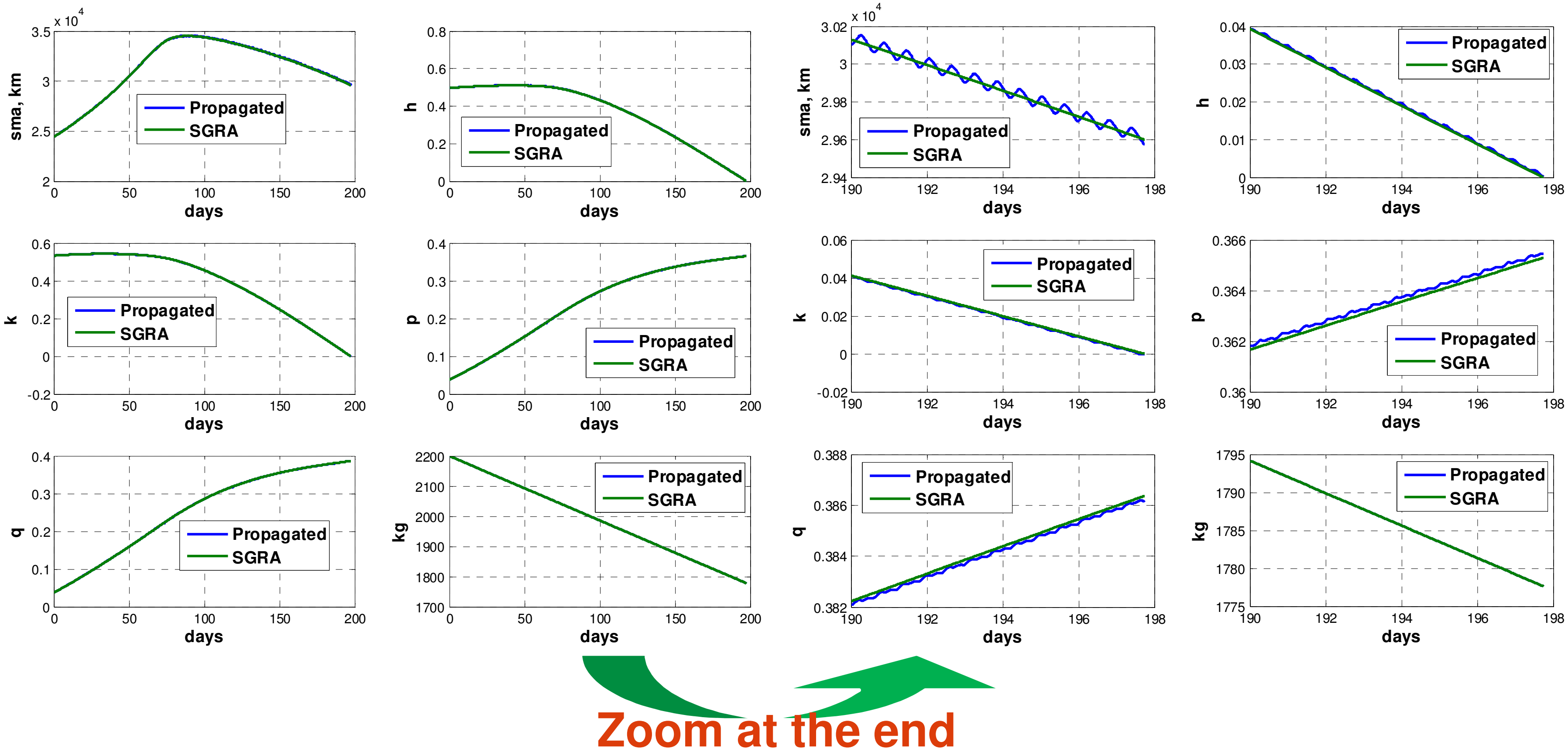
- **Problem statement**: minimize Δv between the injection orbit in GTO/SSTO to GEO.
  - State vector: 5 averaged equinoctial elements per orbit + mass;
  - Control vector: 5 Lagrange coefficients (1 per element) in the Hamiltonian
  - Parameters: Transfer time
- **Given inputs**:
  - Boundary t_0: injection orbit from launcher: GTO, SSTO, LEO, etc
  - Boundary t_1: circular @ GEO, Equatorial; MEO; IGSO; or any other target orbit
- **Constraints**:
  - Angular rate of thrust vector
- **Environment**:
  - J2 perturbation
  - EP off during eclipses
  - 3rd bodies & SRP

Analytical method for eclipse location

- Problem represented on the **orbital plane**: intersection of **two conics** (orbit and shadow)
- The **intersection points** can be found numerically, but we need also the derivatives of the intersection points wrt the state
- **Analytical formulation** based on the combination of two solutions:
  - rectangular
  - triangular case
  - weighting factor depending on the location of the eclipse mid-point
- Current implementation solves analytically the quartic resulting when trying to find the intersection of two ellipses

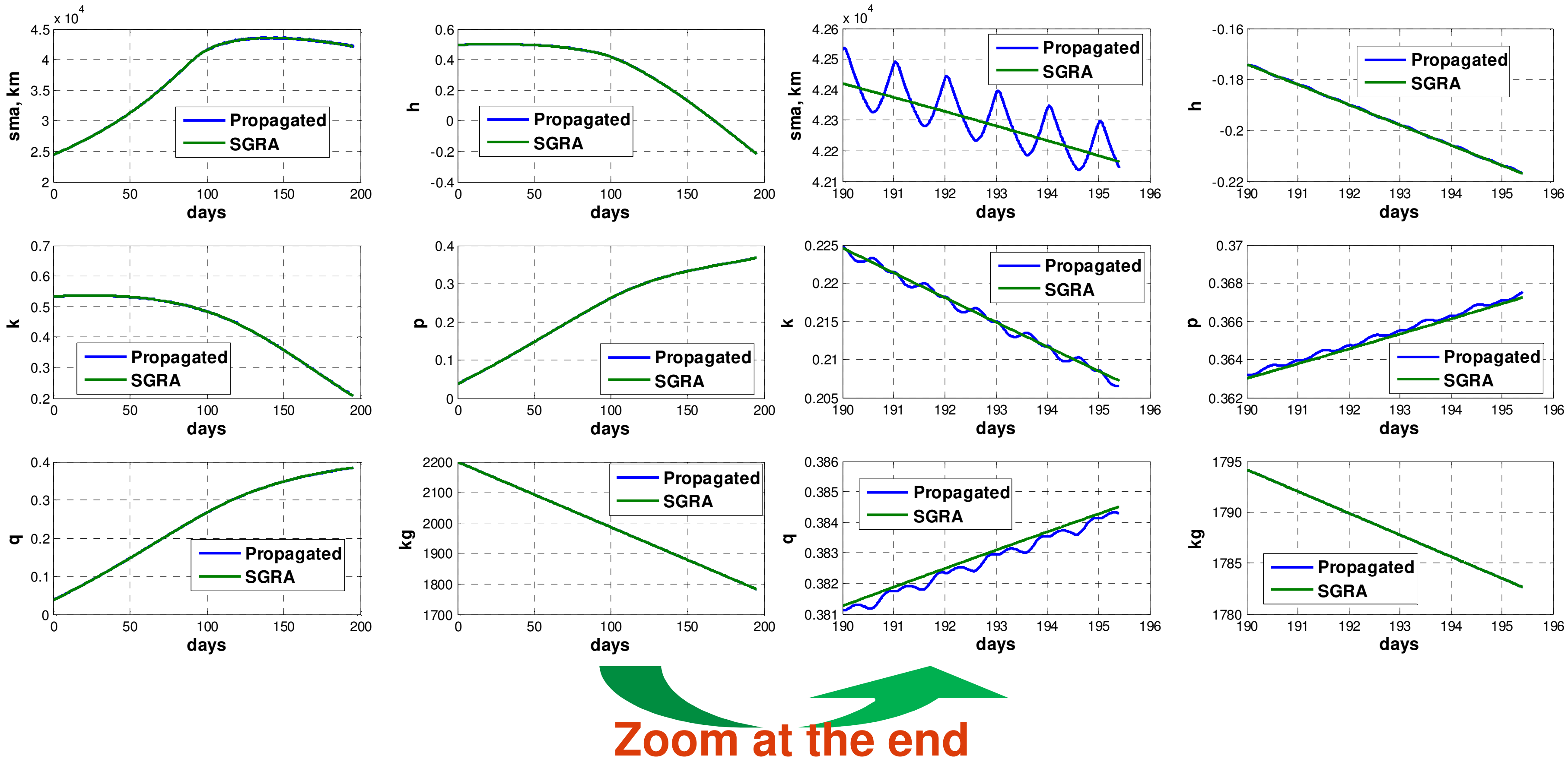


Some Validation cases: GTO to MEO @ 56°



- Computed Δv of 3449 m/s (versus 3447 from ESOC), in just ~100 iterations (~10 s/iteration), starting from scratch (constant Lagrange coeffs. in the Hamiltonian)

Some Validation cases: GTO to IGSO @ 56°, e=0.3, ω=270°



- Computed Δv of 3404 m/s (versus 3408 from ESOC), in just ~50 iterations (~10 s/iteration), starting from scratch (constant Lagrange coeffs. in the Hamiltonian)

ELECTRO provides…

Thrust profile (attitude guidance law)

Evolution of equinoctial elements

Evolution of position & velocity

Angular velocity in body axes

Eclipse profile (location & duration)

SADM profile (angle & rate)

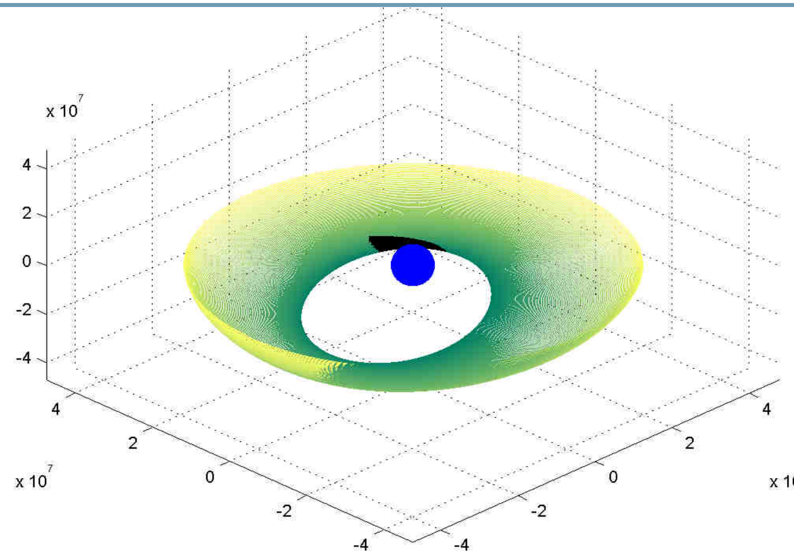
Star trackers blinding profile

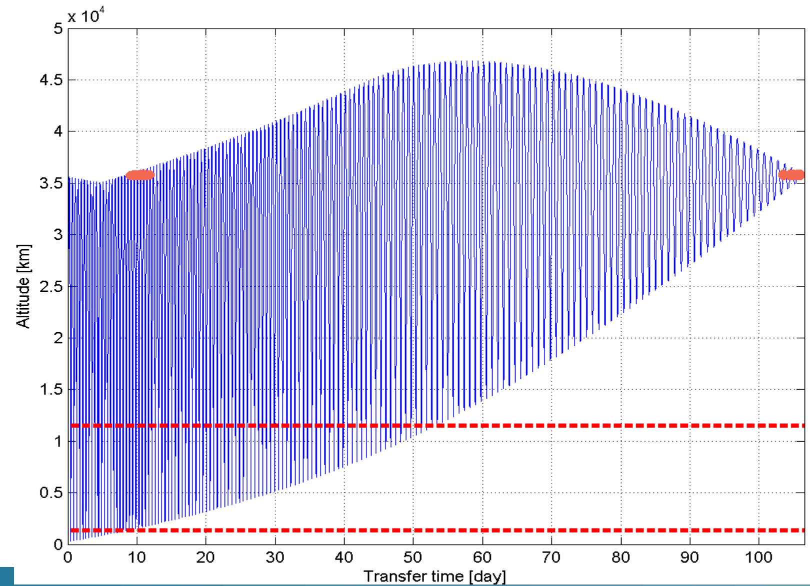
GEO (or MEO) ring # of crossings

Residence time in radiation belts

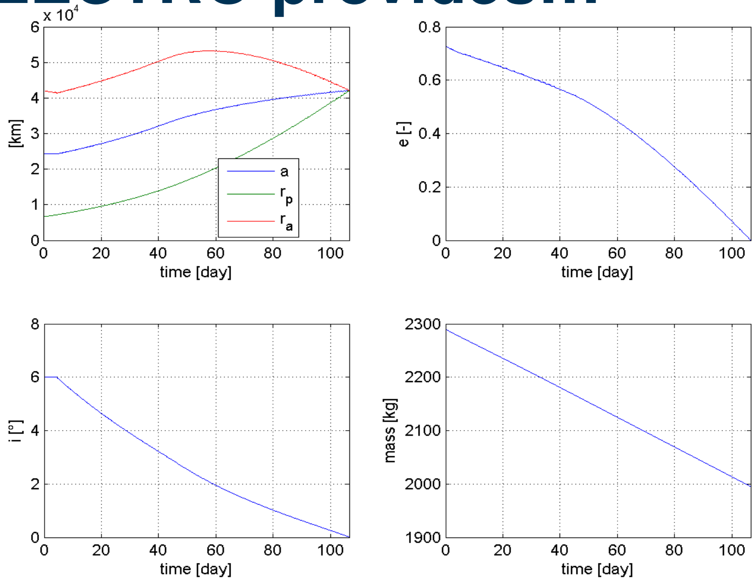
Preliminary collision probability (kinetic gas theory applied to a density function of height)

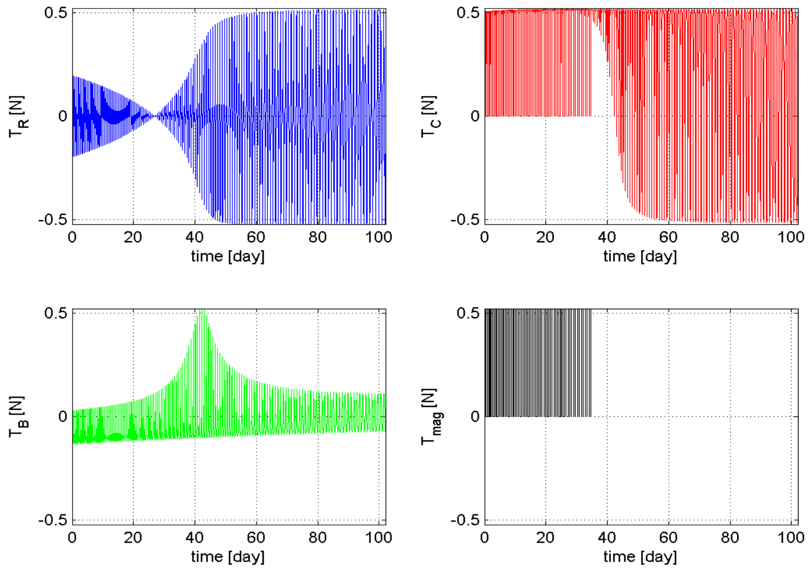
Support launch window analyses

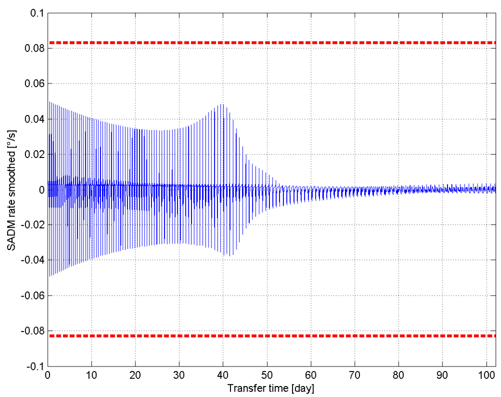


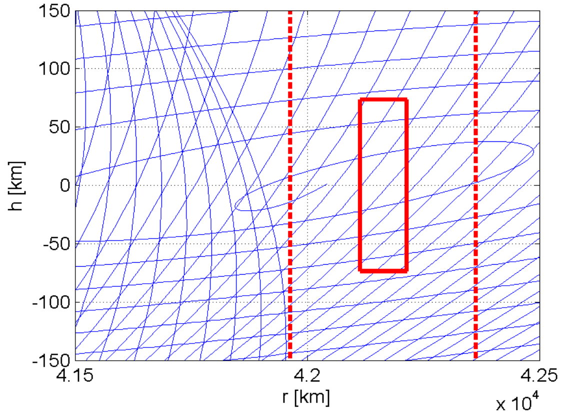


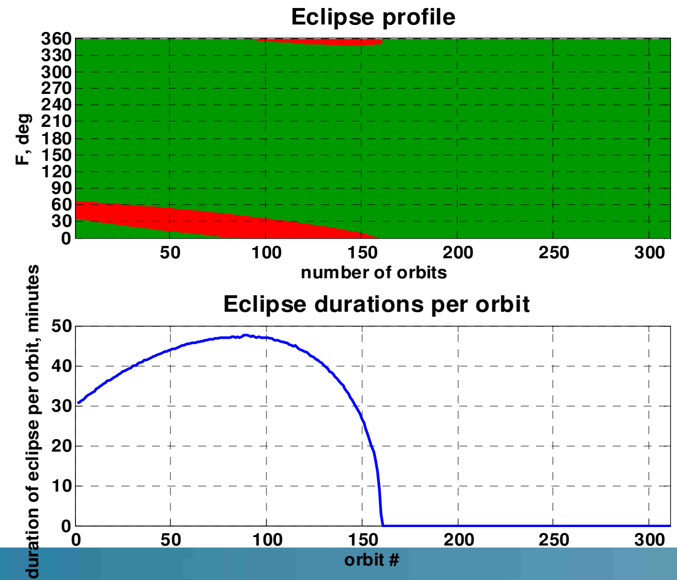
ELECTRO provides…







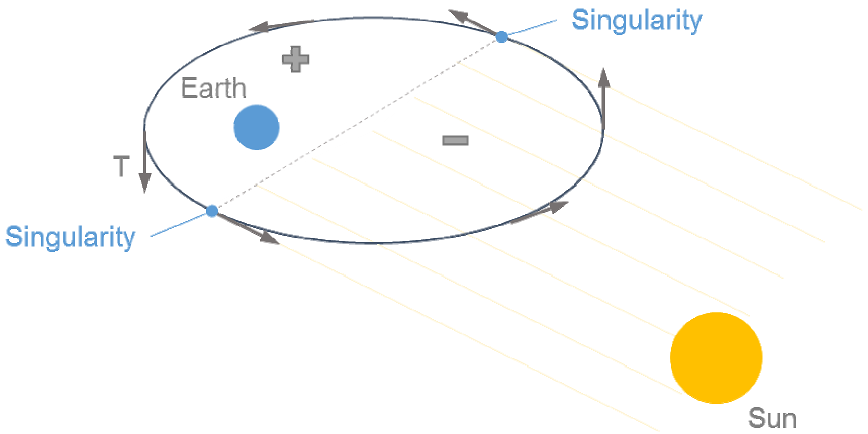


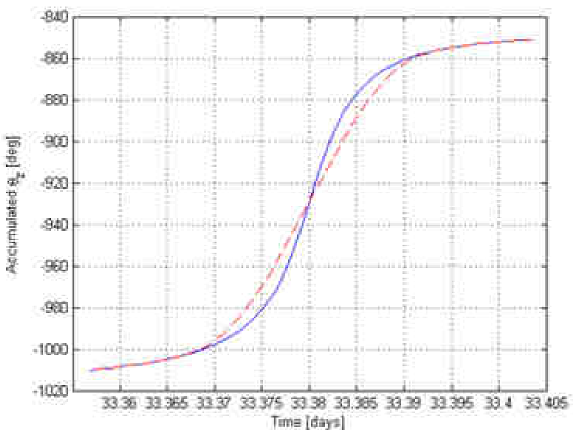


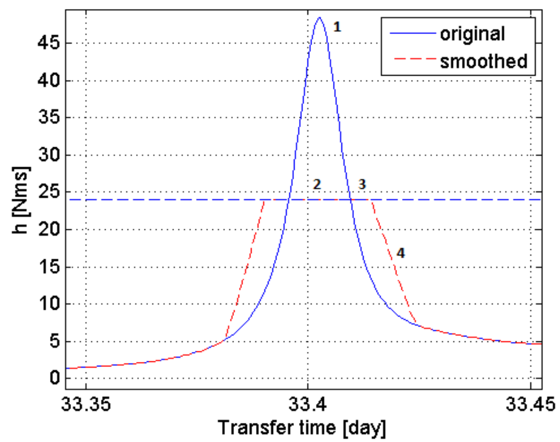
ELECTRO and the AOCS constraints

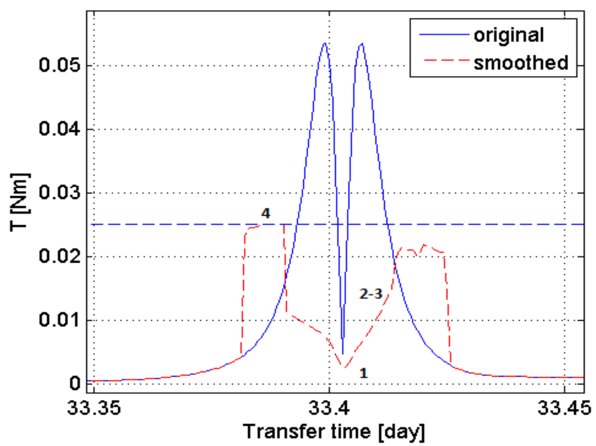
Rotation around thrust vector needs to be smoothed to avoid violation on AOCS constraints (angular momentum & torque)

The cost of such smoothing is a loss of Sun pointing during some few minutes → trade-off between power balance & AOCS design parameters (f.i. wheels size)

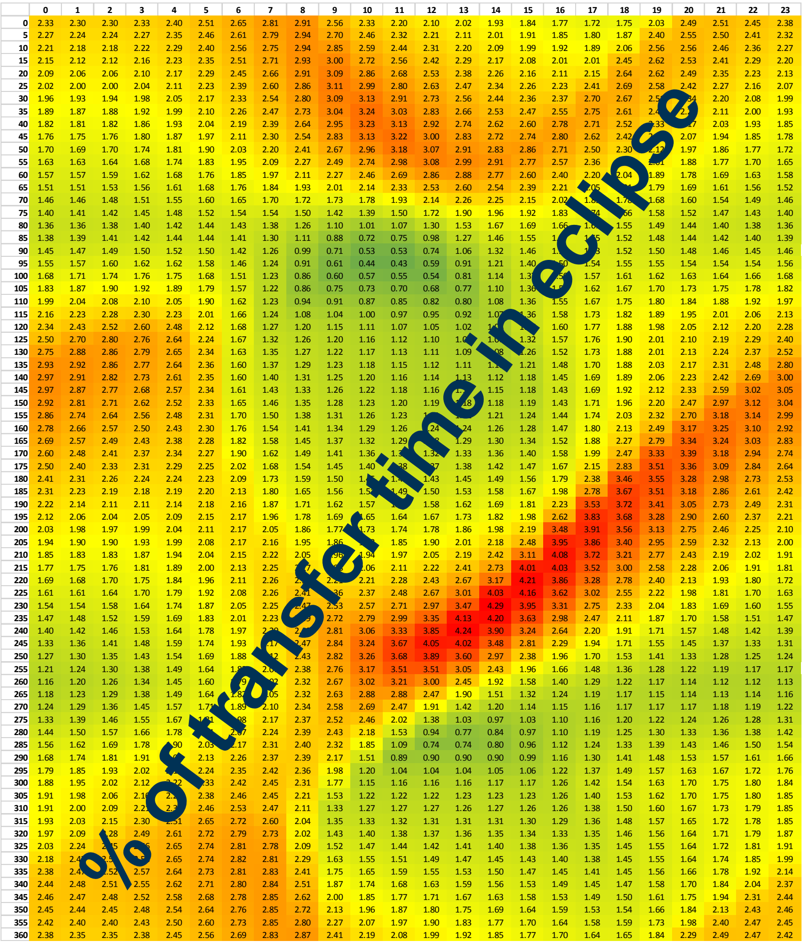


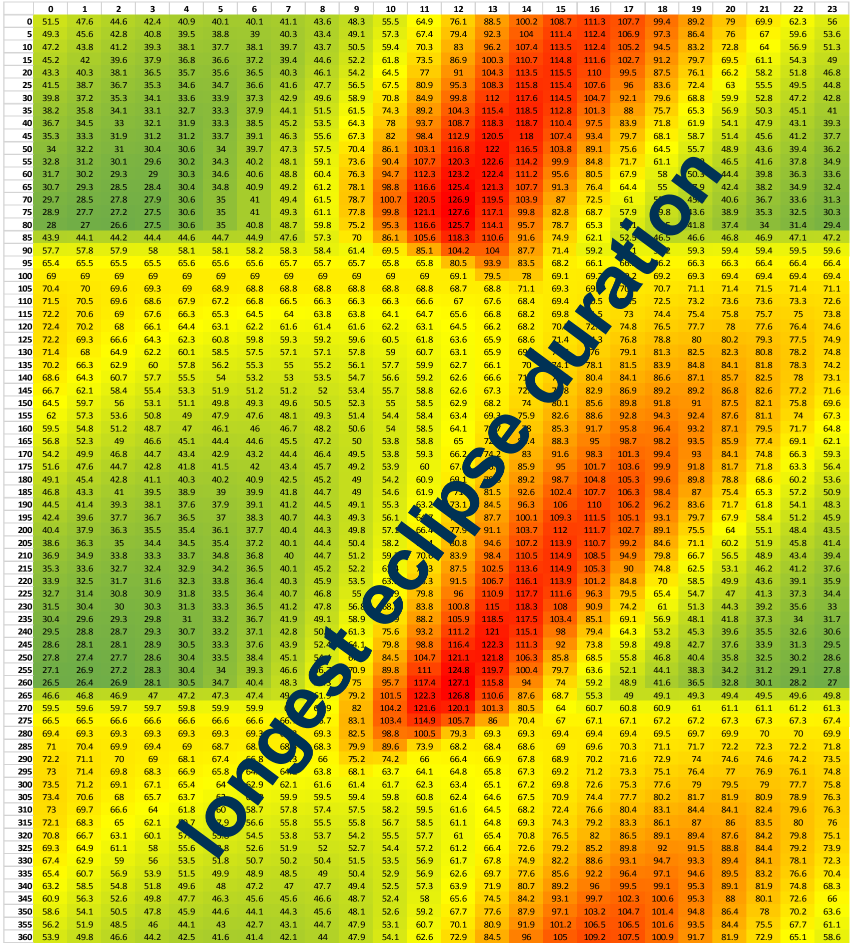






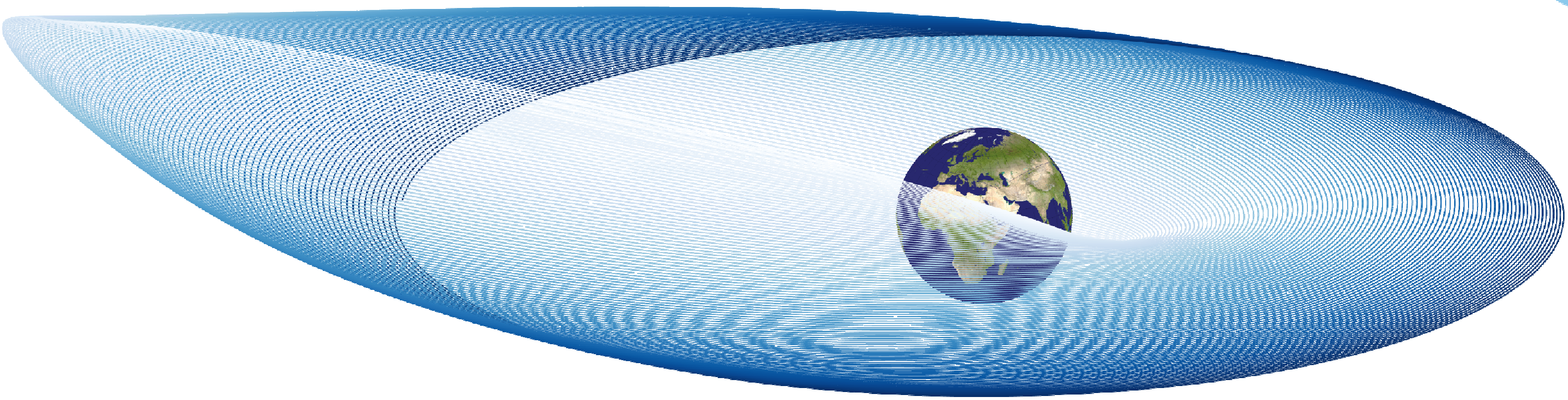
ELECTRO and the launch window analysis





Conclusions

- An indirect method (Sequential Gradient Restoration Algorithm) has been used for the generation of nominal low-thrust transfer trajectories and all related analyses, to support the mission scenarios trade off and subsystems design tasks
- The constraint that electric propulsion is off during eclipses needed to be included: this was done by developing an analytical approximation for the location of the extreme eclipse points
- Further, AOCS constraints (in **h** & **T** at guidance level) have been included, allowing the assessment of the impact of AOCS subsystem design on the satellite power balance
- The output of the optimiser is then processed to obtain all the relevant performance indicators of a transfer such as eclipse duration, spacecraft angular velocity, SADM profile, sensors blinding, etc
- The tool offers also the possibility of running launch window analyses and obtain general results related to epoch-dependent phenomena such as eclipses and sensor blinding.



Questions?

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