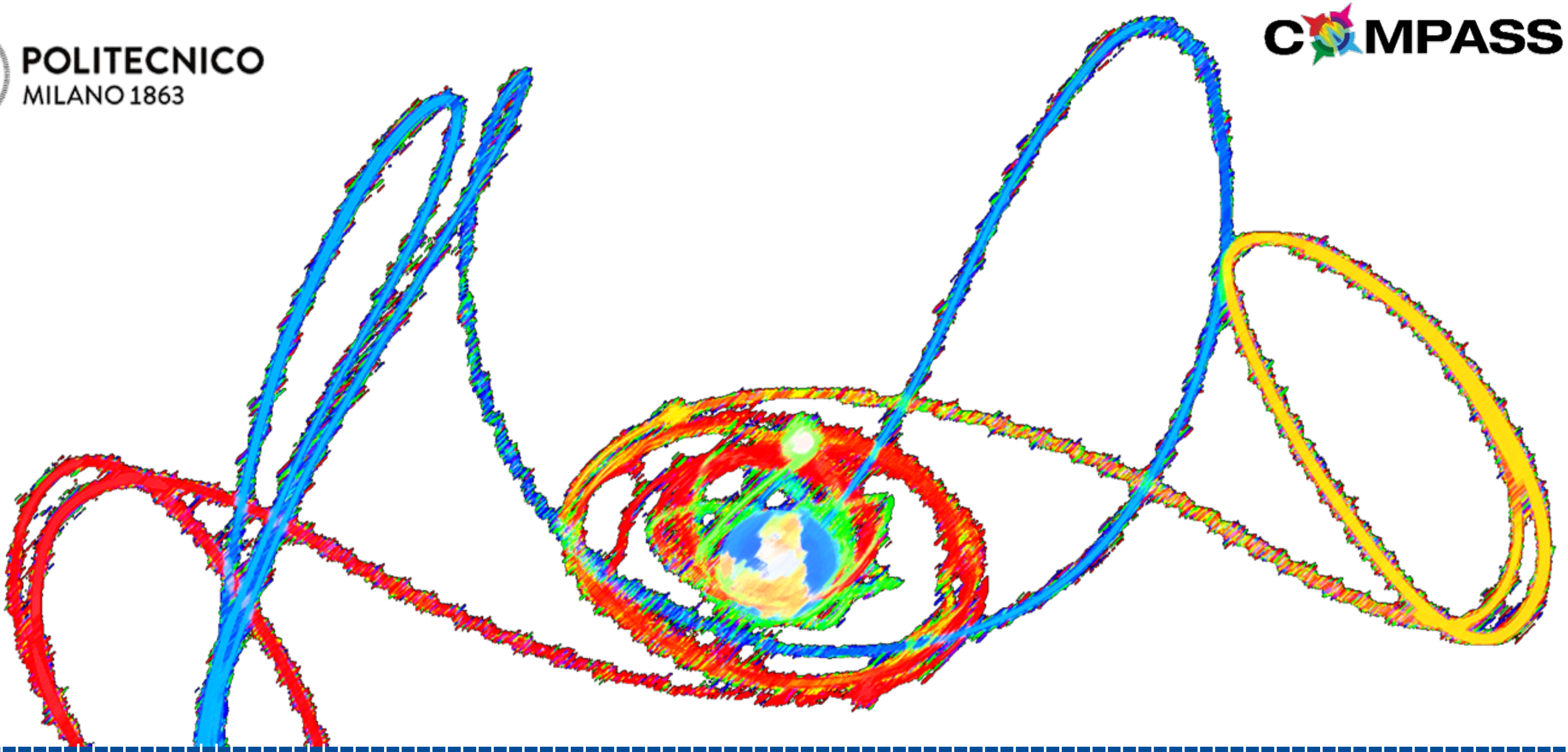


Design of end-of-life of disposal manoeuvres and re-entry modelling with PlanODyn

Stefan Frey, Ioannis Gkolias, Camilla Colombo

7th European workshop on satellites end of life - 25 Jan. 2018

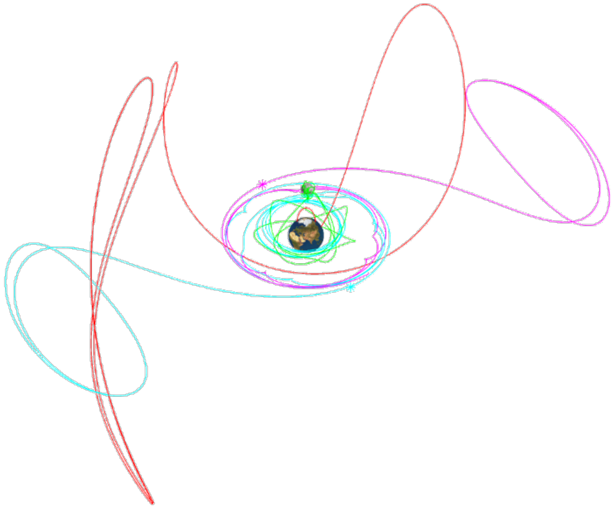
INTRODUCTION

Introduction

Trajectory design, orbit prediction and maintenance are a challenging task when the effects of orbit perturbations are relevant

- Design of planet centred orbits

- Space situation awareness
  - Design of end-of-life disposal trajectories
  - Graveyard orbit stability
  - Prediction of spacecraft re-entry
  - Modelling the evolution of space debris



Natural dynamics can be studied and leveraged to reduce the propellant requirements, thus creating new opportunities

Planetary Orbital Dynamics

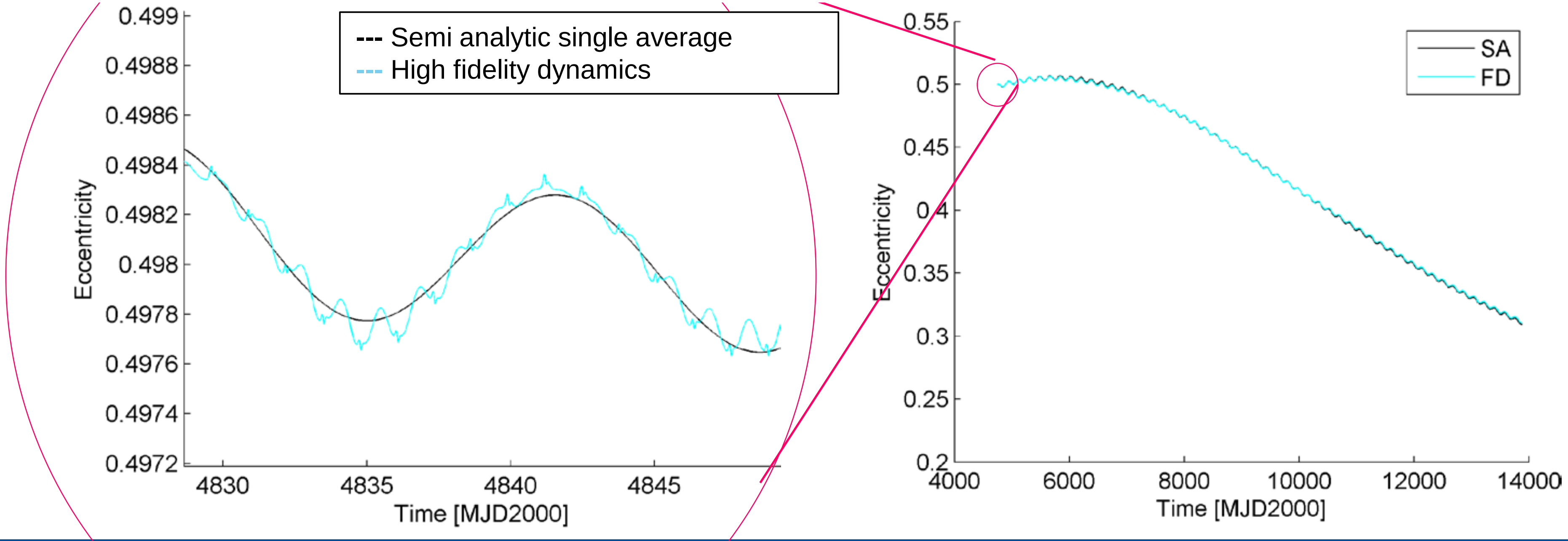
PLANODYN

Planetary Orbital Dynamics

Why averaged dynamics

Average variation of orbital elements over one orbit revolution

- Filter high frequency oscillations
- Reduce stiffness of the problem
- Decrease computational time for long term integration



Planetary Orbital Dynamics

Why averaged dynamics

Applications:

- Preliminary design where many initial conditions and spacecraft parameters have to be determined/studied
- Optimisations of EOL disposal
- Sensitivity analysis
- Propagation of many objects (clouds of debris fragments, space debris population)

Planetary Orbital Dynamics

PlanODyn suite

Space Debris Evolution, Collision risk, and Mitigation
FP7/EU Marie Curie grant 302270

End-Of-Life Disposal Concepts for Lagrange-Point, Highly Elliptical Orbit missions, **ESA GSP**

End-Of-Life Disposal Concepts Medium Earth Orbit missions, **ESA GSP**

EOL disposal in "Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies" **ReDSHIFT, H2020**

COMPASS, ERC "Control for orbit manoeuvring through perturbations for supplication to space systems"

Planetary Orbital Dynamics

Orbit propagation based on averaged dynamics

For conservative orbit perturbation effects

Disturbing potential function

$$R = R_{\text{SRP}} + R_{\text{zonal}} + R_{3\text{–Sun}} + R_{3\text{–Moon}}$$

Planetary equations in Lagrange form

$$\frac{d\boldsymbol{\alpha}}{dt} = f\left(\boldsymbol{\alpha}, \frac{\partial R}{\partial \boldsymbol{\alpha}}\right) \qquad \boldsymbol{\alpha} = \begin{bmatrix} a & e & i & \Omega & \omega & M \end{bmatrix}^T$$

Average over one orbit revolution of the spacecraft around the primary planet

$$\bar{R} = \bar{R}_{\text{SRP}} + \bar{R}_{\text{zonal}} + \bar{R}_{3\text{–Sun}} + \bar{R}_{3\text{–Moon}}$$

$$\frac{d\bar{\boldsymbol{\alpha}}}{dt} = f\left(\bar{\boldsymbol{\alpha}}, \frac{\partial \bar{R}}{\partial \bar{\boldsymbol{\alpha}}}\right)$$

Single average

Average over the revolution of the perturbing body around the primary planet

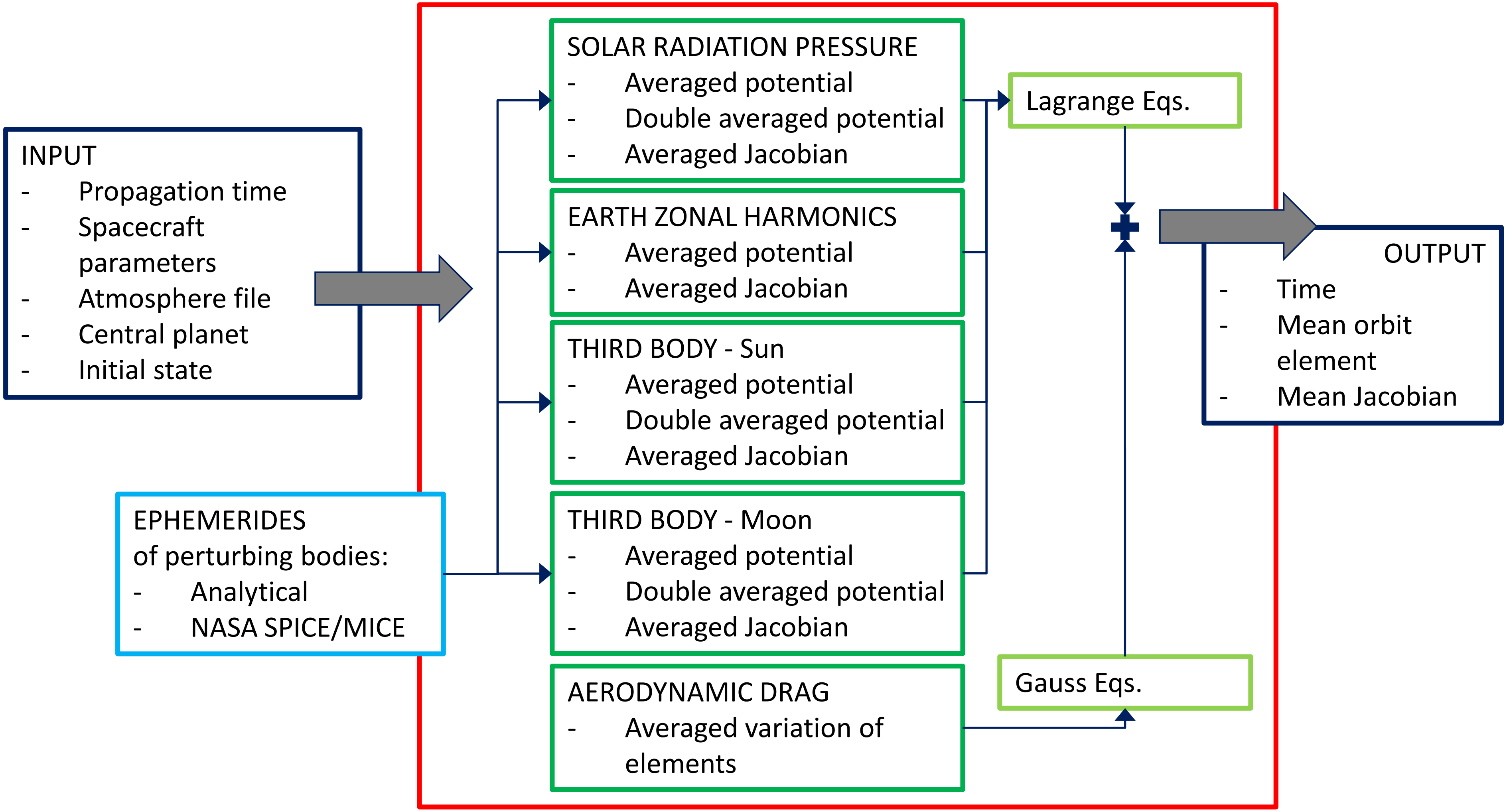
$$\bar{\bar{R}} = \bar{\bar{R}}_{\text{SRP}} + \bar{R}_{\text{zonal}} + \bar{\bar{R}}_{3\text{–Sun}} + \bar{\bar{R}}_{3\text{–Moon}}$$

$$\frac{d\bar{\bar{\boldsymbol{\alpha}}}}{dt} = f\left(\bar{\bar{\boldsymbol{\alpha}}}, \frac{\partial \bar{\bar{R}}}{\partial \bar{\bar{\boldsymbol{\alpha}}}}\right)$$

Double average

Planetary Orbital Dynamics

PlanODyn: Planetary Orbital Dynamics



INPUT
- Propagation time
- Spacecraft parameters
- Atmosphere file
- Central planet
- Initial state

EPHEMERIDES of perturbing bodies:
- Analytical
- NASA SPICE/MICE

SOLAR RADIATION PRESSURE
- Averaged potential
- Double averaged potential
- Averaged Jacobian

EARTH ZONAL HARMONICS
- Averaged potential
- Averaged Jacobian

THIRD BODY - Sun
- Averaged potential
- Double averaged potential
- Averaged Jacobian

THIRD BODY - Moon
- Averaged potential
- Double averaged potential
- Averaged Jacobian

AERODYNAMIC DRAG
- Averaged variation of elements

Lagrange Eqs.

Gauss Eqs.

OUTPUT
- Time
- Mean orbit element
- Mean Jacobian

► *Colombo C., "Planetary Orbital Dynamics Suite for Long Term Propagation in Perturbed Environment," ICATT, ESA/ESOC, 2016.*

Planetary Orbital Dynamics

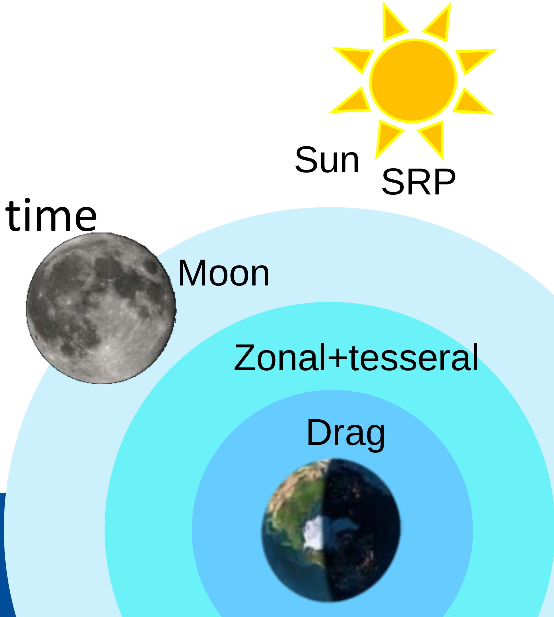
Perturbation in planet centred dynamics

- Atmospheric drag
  - Non-spherical smooth exponential model
  - J_2 short period coupling
- Earth gravity potential
  - Zonal up to order 6 with J_2^2 contribution
  - Tesseral resonant terms
- Solar radiation pressure with cannonball model
- Third body perturbation of the third body (Moon and Sun) up to order 5 in the parallax factor

Ephemerides options

- Analytical approximation based on polynomial expansion in time
- Numerical ephemerides through the NASA SPICE toolkit

Orbital elements in planet centred frame



Planetary Orbital Dynamics

Applications

In this presentation two applications will be shown

Disposal design in Geosynchronous orbits

Drag induced re-entry modelling

Conservative perturbations

DISPOSAL DESIGN IN GEOSYNRONOUS ORBIT

Dynamical model

Third body potential

Third body potential

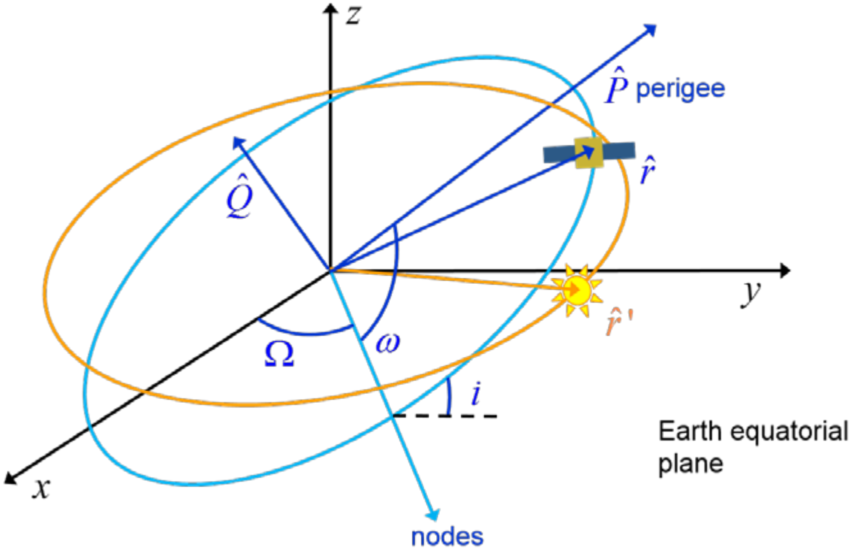
- Written in terms of the ratio between orbit semi-major axis and distance of the third body $\delta = \frac{a}{r'}$
- Composition of rotation in orbital elements
- Series expansion in δ

$$R_{3B}(r, r') = \frac{\mu'}{r'} \sum_{k=2}^{\infty} \delta^k F_k(A, B, e, E)$$

- Average over one orbit revolution

$$\overline{R}_{3B}(r, r') = \frac{\mu'}{r'} \sum_{k=2}^{\infty} \delta^k \overline{F}_k(A, B, e)$$

- Include averaged potential in Lagrange equations



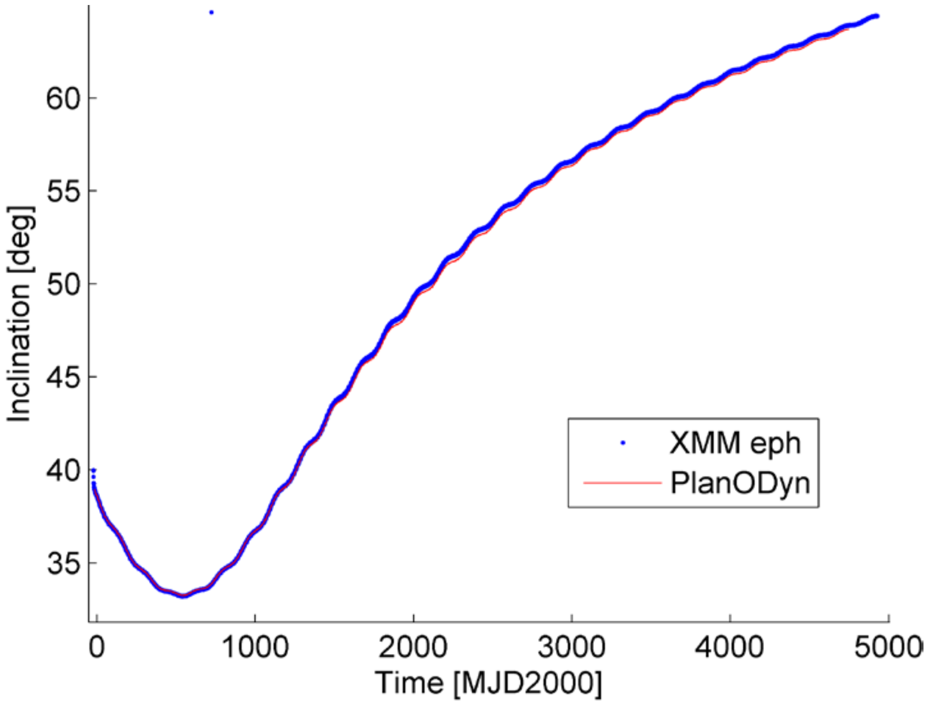
► *Kaufman and Dasenbrock, NASA report, 1979*

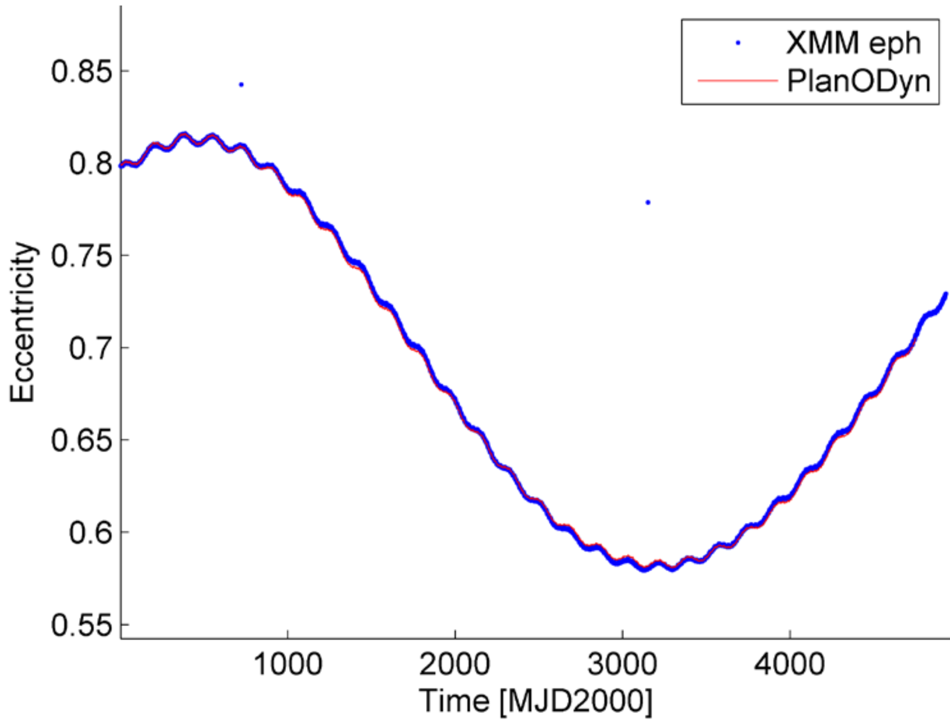
Validation

XMM-Newton trajectory

Propagation time: 1999/12/15 to 2013/01/01

Initial Keplerian elements from ESA on 1999/12/15 at 15:00:
a = 67045 km, e = 0.7951, i = 0.67988 rad, Ω = 4.1192 rad, ω = 0.99259 rad
System: Earth centred, equatorial J2000



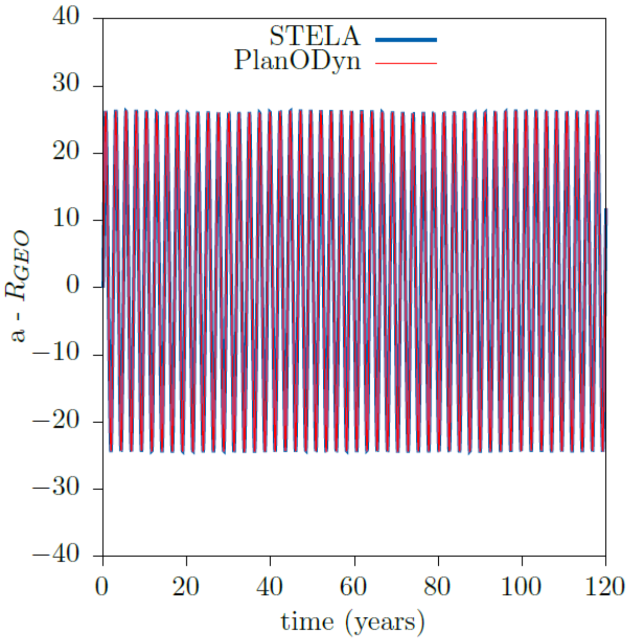


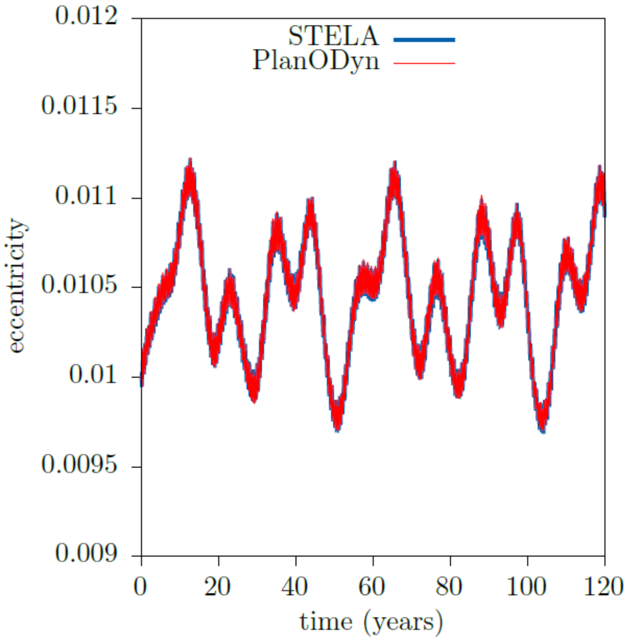
Validation

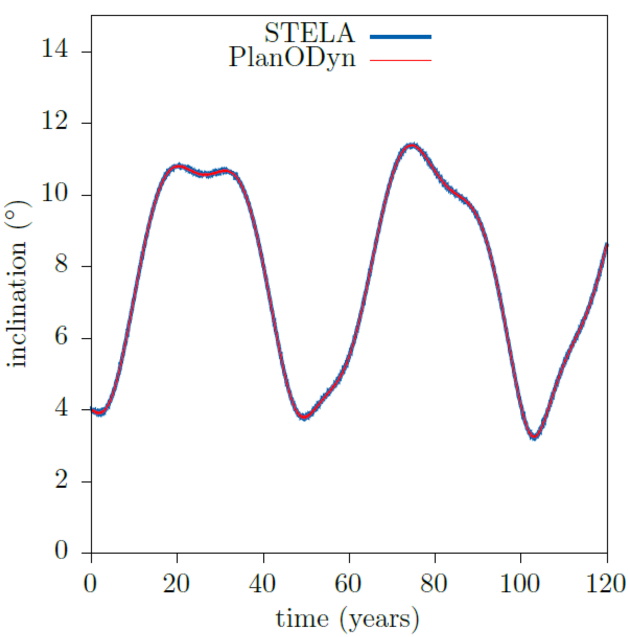
Geostationary orbit

a = R_{GEO}, e = 0.01, i = 4°, Ω = 0°, ω = 0°

4x4 Geopotential, 5th order lunisolar, cannonball SRP, Earth's precession







Disposal design

Strategy

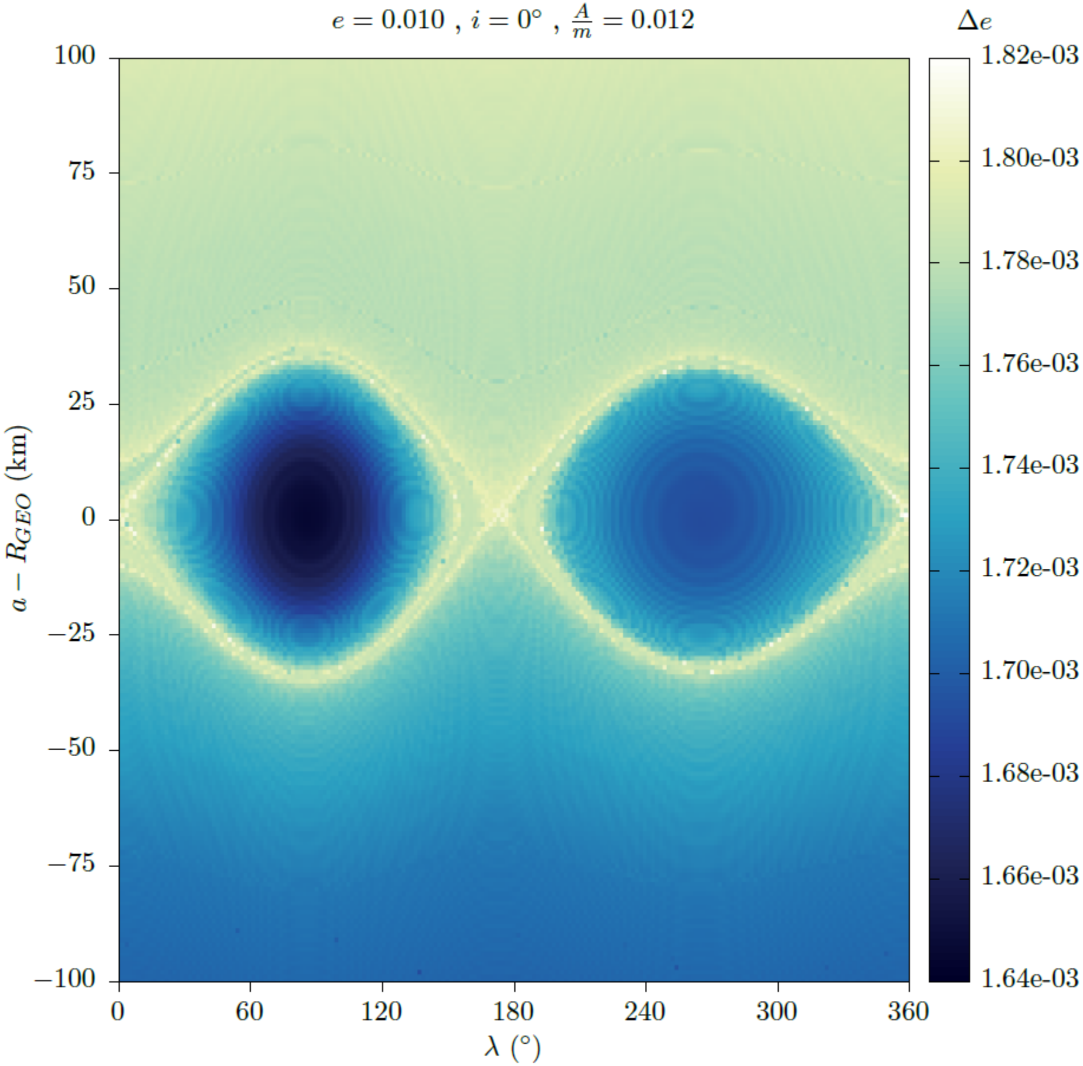
- Long-term orbit propagation from many initial conditions on a grid of orbital elements
- Different stating epochs (i.e., different orientation of s/c-Moon-Sun) and spacecraft parameters (i.e., *A*/*m* considered)

↓

- The variation of the orbital elements can be used as a measure of the orbit stability
- Optimal manoeuvre can be designed to target graveyard or re-entry solutions

Disposal design

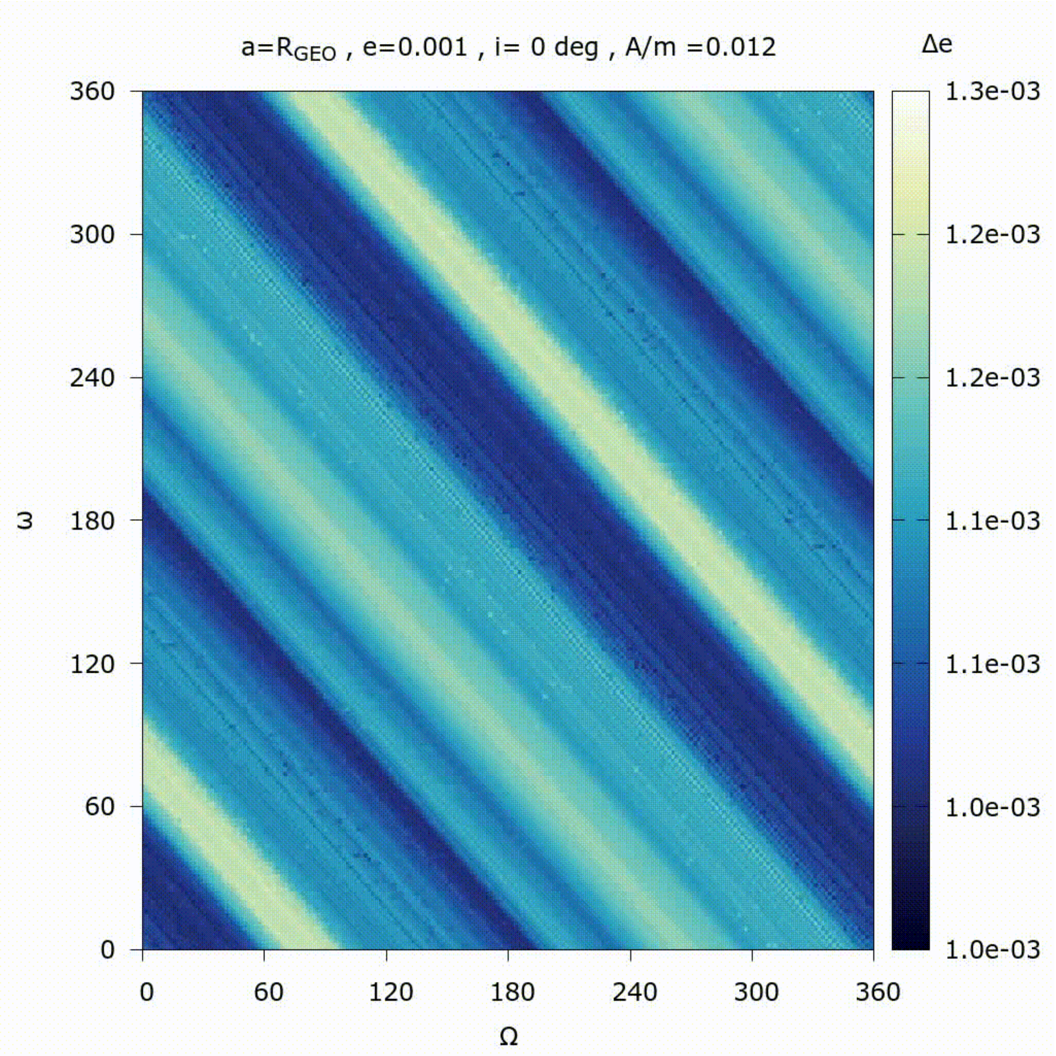
Effect of the Earth's triaxiality - Eye plots



Dynamics caused by Earth's triaxiality can be appreciated by propagating an initial GEO orbit for different starting values of the resonant angle λ

Disposal design

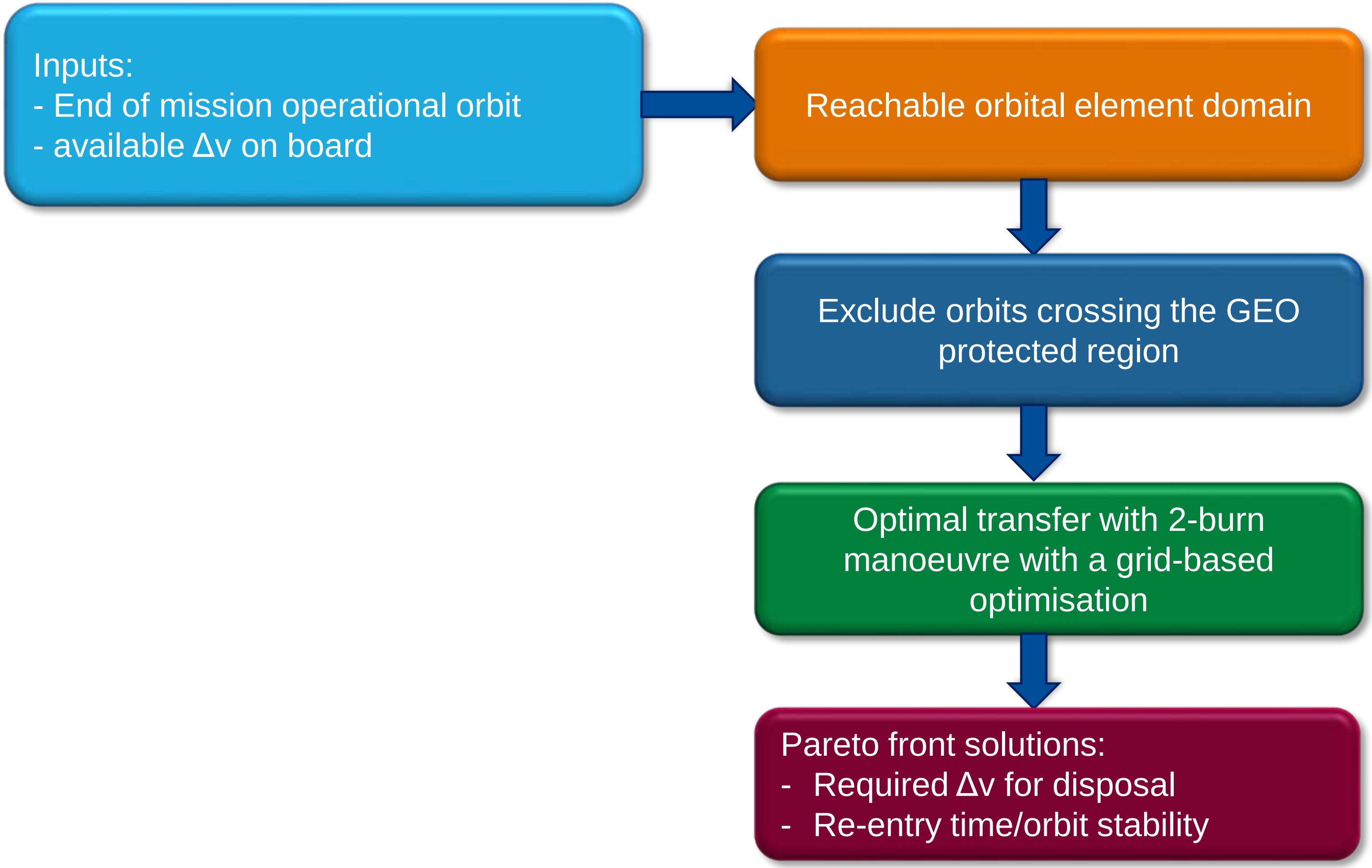
Luni-solar effects - *Ω*-*ω* plots



Coupling between J_2, luni-solar, and SRP effect.

Disposal strategy

Disposal design



Inputs:
- End of mission operational orbit
- available Δv on board

Reachable orbital element domain

Exclude orbits crossing the GEO protected region

Optimal transfer with 2-burn manoeuvre with a grid-based optimisation

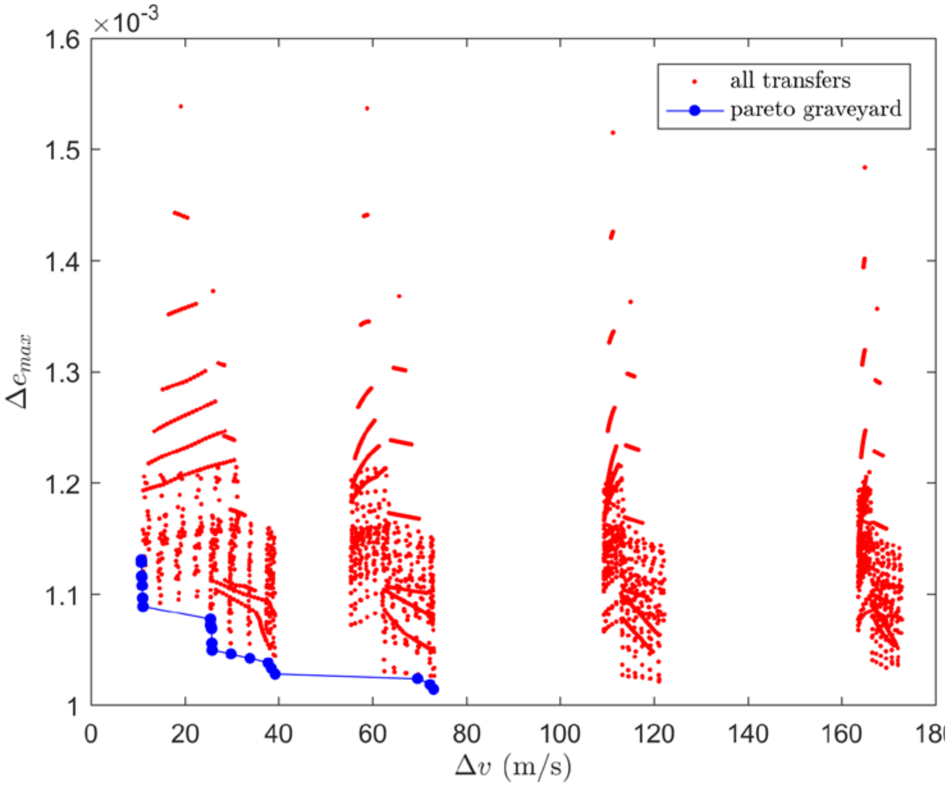
Pareto front solutions:
- Required Δv for disposal
- Re-entry time/orbit stability

- *Gkolias, I., Colombo, C., End-of-life disposal of geosynchronous satellites, Proceedings of the 68th IAC, 2017*

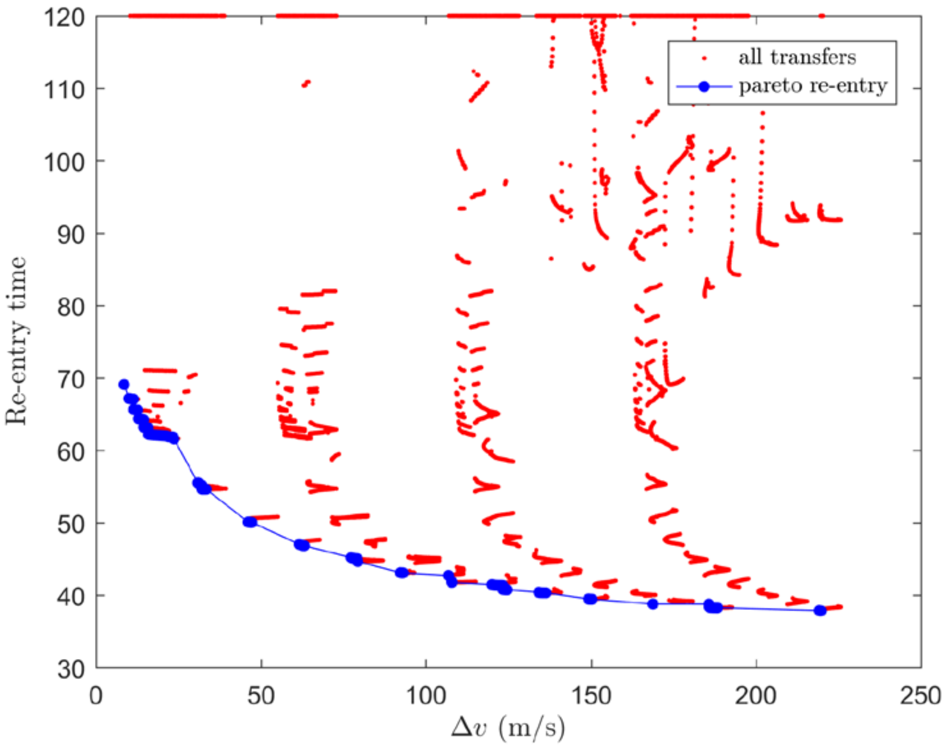
Disposal design

End-of-life of GEO orbits

Initial post-mission orbit: $a = R_{GEO}$, $e = 0.001$, $\Omega = 0°$, $\omega = 0°$, maximum available $\Delta v = 200$ m/s



Pareto front graveyard for regular GEO (i = 0°)



Pareto front re-entry for highly inclined GEO (i = 75°)

Non-conservative perturbations

DRAG INDUCED RE-ENTRY MODELLING

Dynamical model

Averaging

- Average out fast moving variable (f, E or M), assuming the other mean elements to be fixed

$$\bar{\dot{x}} = \frac{\Delta x}{P} = \frac{1}{P}\int_0^{2\pi} \frac{dx}{dE}\, dE \qquad\qquad x \in [a, e]$$

- The change $\frac{dx}{dE}$ is a function the Keplerian elements, $\boldsymbol{k}$, the density, ρ, at altitude, h, and the effective area-to-mass ratio, $\delta = c_D \frac{A}{m}$

$$\frac{dx}{dE} = f x(\boldsymbol{k}, \rho(h(\boldsymbol{k})), \delta) \qquad\qquad \boldsymbol{k}^{\mathrm{T}} = (\mathrm{a}, \mathrm{e}, \mathrm{i}, \Omega, \omega, E)$$

$$h = h_m + \Delta h_\varepsilon + \Delta h_{J_2}$$

Short periodic variation

Altitude above ellipsoid variation

Mean altitude

Dynamical model

Averaging method

- The integrals can be approximated quickly numerically or analytically
  - E.g. *Gauss-Legendre* quadrature
    - \+ Flexible: can work with any drag model
    - \+ Valid for any eccentricity, i.e. series expansion avoided
    - − Multiple density evaluations (usually $\mathrm{N} = 33$)
  - E.g. *King-Hele* (KH) method
    - − Requires exponentially decaying atmosphere model (next slide)
    - − Series expansion in eccentricity (solved for low and high eccentricities by KH)
    - \+ Only one density evaluation
    - \+ Analytical estimation of the Jacobian available
- Both are implemented in *PlanODyn*, with the (Superimposed) King-Hele method as default

➢ *Liu, J. J. F., Alford, R. L., An Introduction to Gauss-Legendre Quadrature, Northrop Services, Inc., 1973.*
➢ *King-Hele, D., Theory of Satellite Orbits in an Atmosphere, London Butterworths, 1964*

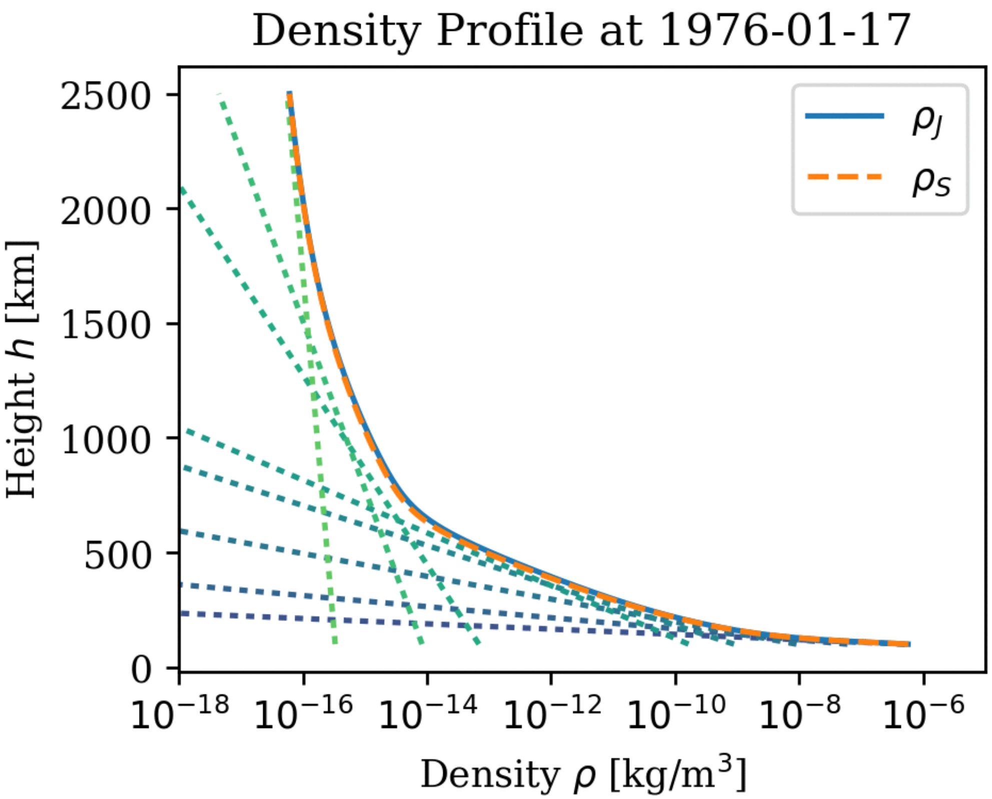
Dynamical model

Atmospheric model

- KH requires atmosphere to decay exponentially
- Fit superimposed partial exponential atmospheres to any desired model

$$\rho(h) = \sum_p \rho_{0,p} \exp -\frac{h}{H_p}$$

- Can include temporal or spatial changes
- E.g. fit to Jacchia-77 with solar activity



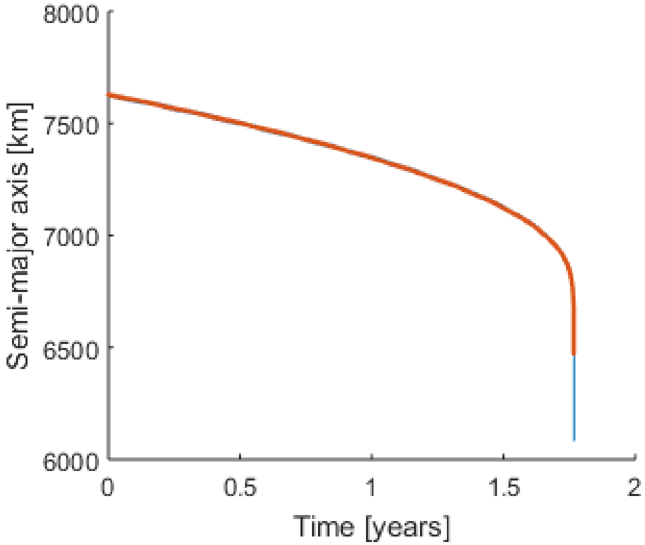
➢ *Jacchia, L. G., Thermospheric temperature, density, and composition: new models. SAO Special Report, 1977.*

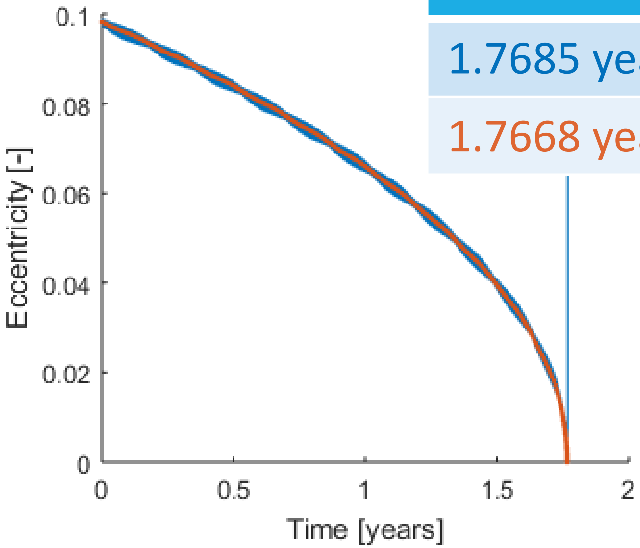
Validation

Drag representative example

- $h_p/\, h_a$=500/2000 km, $i = 90°$, $\Omega/\omega/f = 0°$, $\mathrm{A/m} =$ 1 m^2/kg, $c_D = 2.1$
- Perturbations: drag, Earth flattening and J_2
- Full numerical: Jacchia-77 (fixed, $T_\infty = 1000$ K)
- Semi-analytical: Smooth exponential atmosphere (fitted to aforementioned model) and superimposed King-Hele

Lifetime	CPU time
1.7685 years	118.89 s
1.7668 years	0.29 s



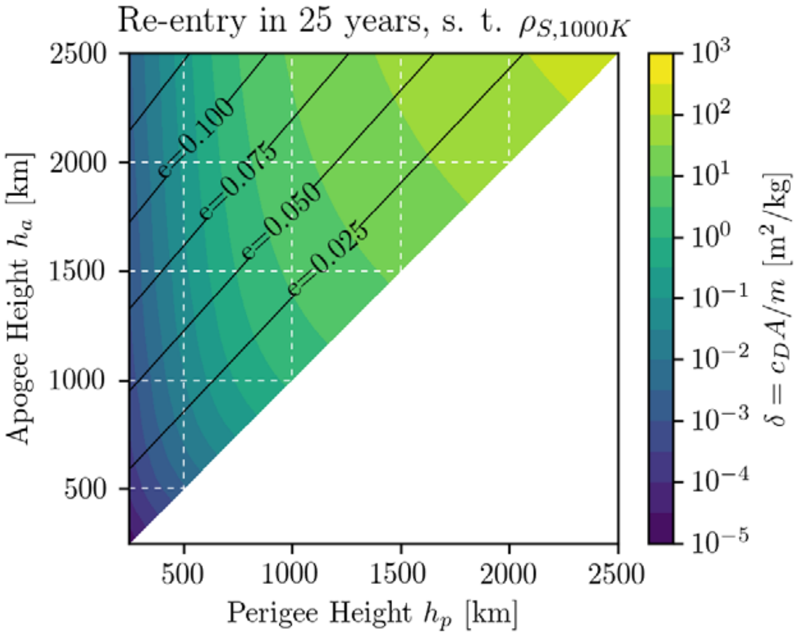


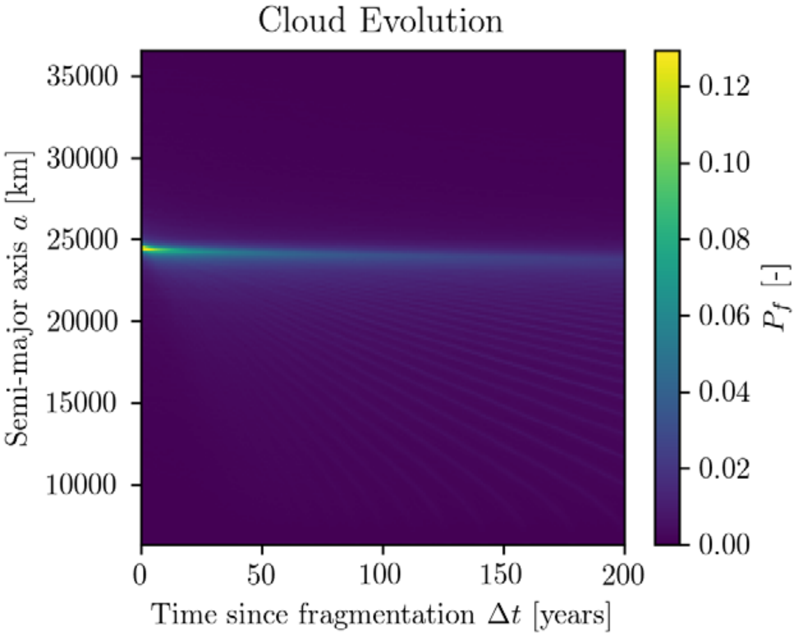
Using a variable-step/variable-order Adams-Bashforth-Moulton integrator (rel. tol. γ_{rel} = 10^{-9})

Applications

Drag induced re-entry: two examples

- Maps of effective area-to-mass ratio required for re-entry in x years (optimisation)
- Evolution of clouds of fragments (collision or explosion) or entire space debris population





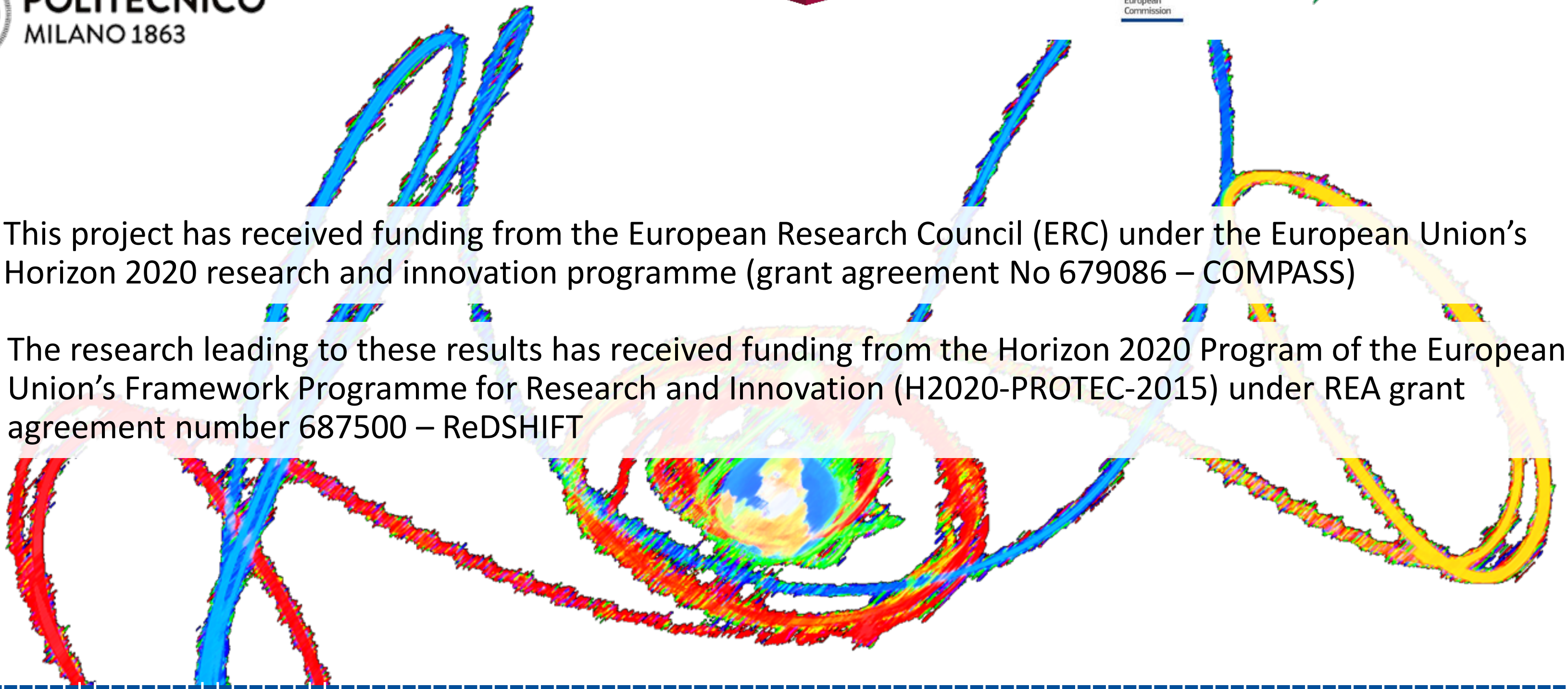
- *Frey, S., Colombo, C., Lemmens, S., Krag H., Evolution of Fragmentation Cloud in Highly Eccentric Orbit using Representative, Proceedings of the 68th IAC, 2017*

Conclusions

- Semi-analytical methods can be used to characterise the stability of graveyard orbits and identify re-entry options
  - Get an insight on the orbit evolution
  - Leverage the dynamics for end-of-life disposal

- Semi-analytical methods shows accuracy against numerical propagation
  - Especially for conservative forces
  - Also for drag induced forces up until shortly before re-entry

- Possible applications
  - Disposal trajectory design
  - Re-entry modelling and orbit determination
  - Sensitivity analysis to spacecraft parameters and model uncertainties



This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 679086 – COMPASS)

The research leading to these results has received funding from the Horizon 2020 Program of the European Union's Framework Programme for Research and Innovation (H2020-PROTEC-2015) under REA grant agreement number 687500 – ReDSHIFT

Design of end-of-life of disposal manoeuvres and re-entry modelling with PlanODyn

stefan.frey@polimi.it, ioannis.gkolias@polimi.it,
camilla.colombo@polimi.it