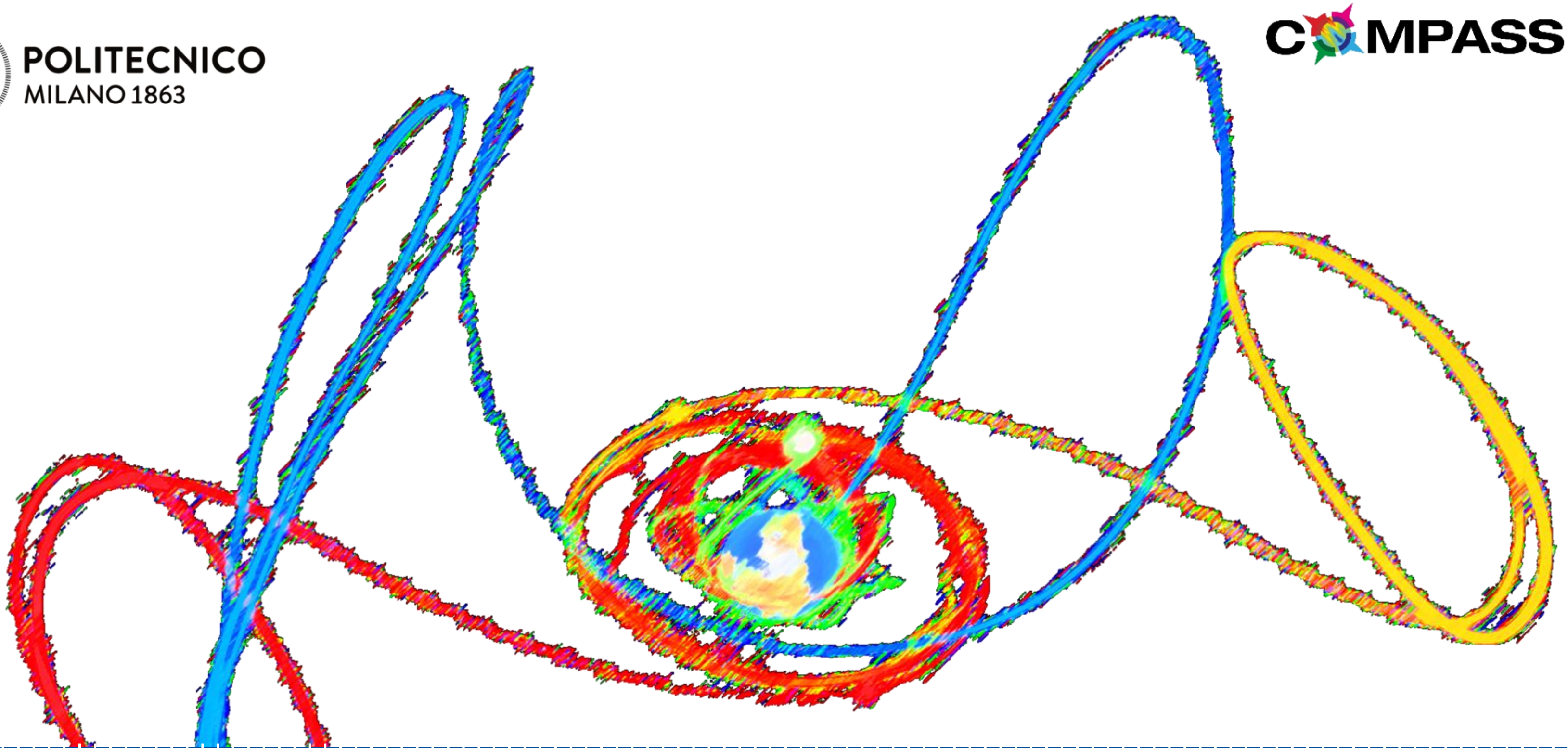


Control for Orbit Manoeuvring through Perturbations for Application to Space Systems

Camilla Colombo

ERC WEEK - ERC's 10th anniversary

Politecnico di Milano - 15 March 2017

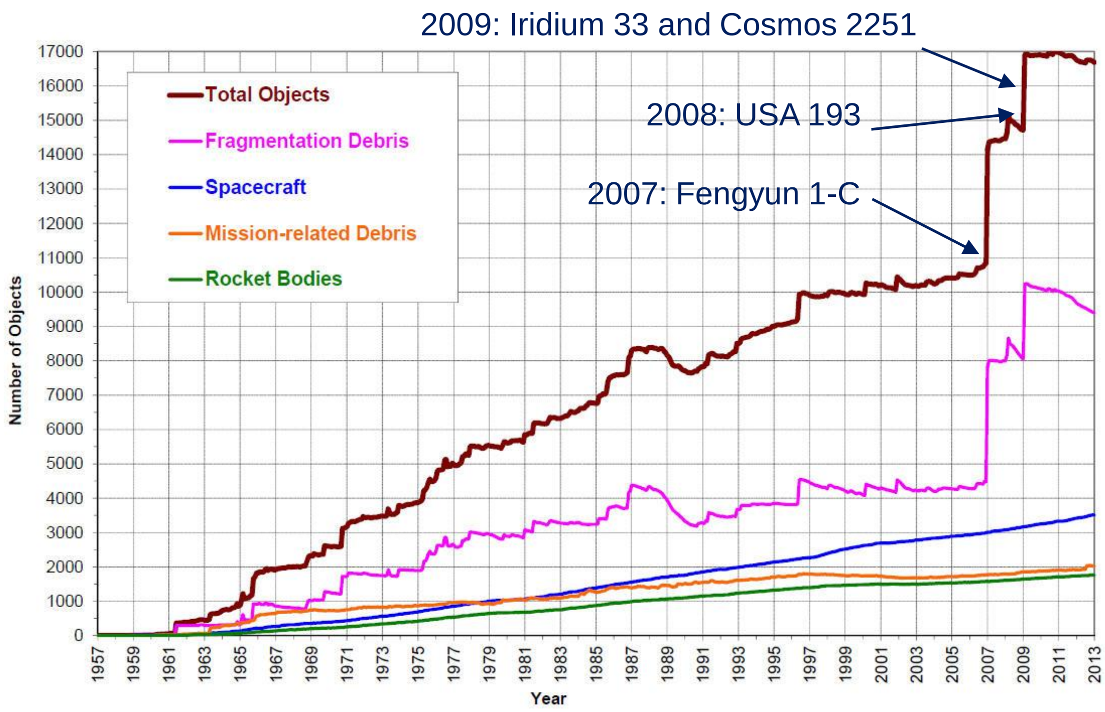
INTRODUCTION

Introduction

Space situation awareness

Space debris poses a threat to current and future space activities

- Currently 22000 objects > 10 cm and 500000 objects > 1-10 cm
  Breakups generate clouds of fragments difficult to track
- Fragments can collide at very high velocity and damage operating satellites
- Need to define debris mitigation guidelines



Introduction

Planetary protection

- On average a 10-km-sized asteroid strikes the Earth every 30-50 million years (Globally catastrophic effects)
- Tunguska class (100 m in size) asteroid impact every 100 years (Locally devastating effects)
- Very small asteroids are very frequent but generally burn in the atmosphere
- Spacecraft and launcher for interplanetary missions remain in resonance with the Earth and other planets


Chelyabinsk, Russia (2013), 17-30 m diameter asteroid


Tunguska, Siberia (1908), flattening 2000 km^2 of forest, 50-70 m asteroid


Breakup of the object WT110F during re-entry (November 2015)

Introduction

Space transfer

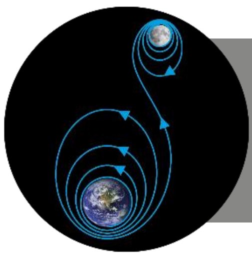
- Space transfer allows the colonisation of new habitats and reaching operational orbits for science missions and space services.
- Trajectory design and orbit maintenance are a challenging task
- The natural dynamics can be leveraged to reduce the current extreme high mission cost.
- As enabling technology, electric propulsion is increasingly selected as the primary option for near future missions, while novel propulsion systems for de-orbiting and orbit-raising are being proposed.
- New space system are under development (e.g. mega-constellation, nano and CubeSat)

Background and proposed approach

COMPASS erc

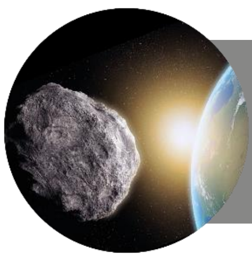
Services, technologies, science, space exploration

SPACE TRANSFER



Reach, control operational orbit

SPACE SITUATION AWARENESS



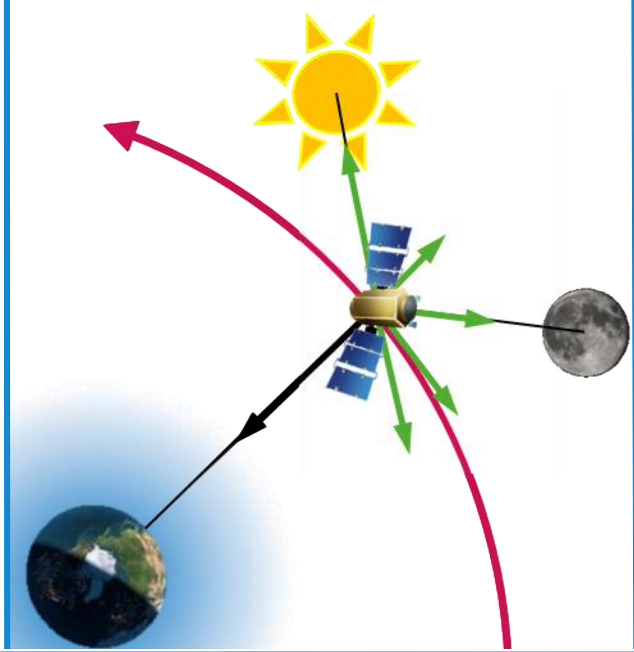
Asteroids. planetary protection

Space debris

ORBIT PERTURBATIONS

Traditional approach: counteract perturbations

- Complex orbital dynamics
- Increase fuel requirements for orbit control



COMPASS

Novel approach: leverage perturbations

Reduce extremely high space mission costs

Create new opportunities for exploration and exploitation

Mitigate space debris

Develop novel techniques for orbit manoeuvring by surfing through orbit perturbations

METHODOLOGY

Methodology and expected results

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Engineering

Optimisation

Dynamical system theory

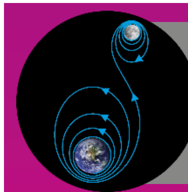
Orbital dynamics

TASK 1 — Semi analytical techniques for dynamics modelling

TASK 2 — Maps of long-term orbit evolution

TASK 3 — Optimisation in the phase-space of orbital elements

TASK 4



Low-thrust surfing
Station keeping
Planetary moon systems

Frozen orbit exploration
Space-based detection
Asteroid deflection

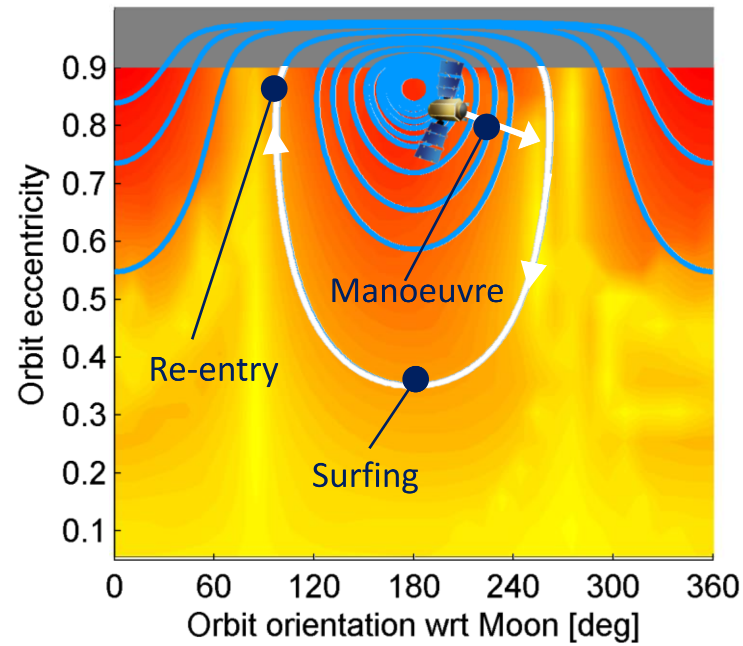
Evolution of debris clouds
End-of-life disposal
Collision avoidance

T1. Understanding of the spacecraft orbit evolution

T2. Topology of space of orbit perturbations (stability)

T3. Spacecraft surf these natural currents to the desired orbit

T4. Design of space missions

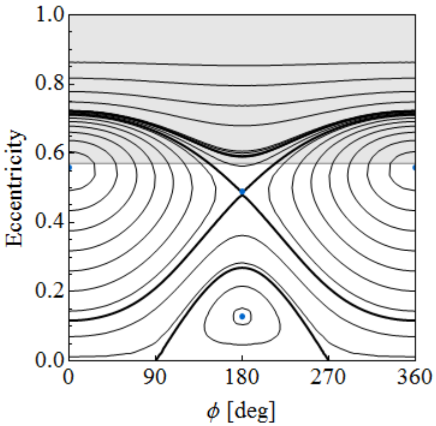


Task 1. Orbit perturbation modelling

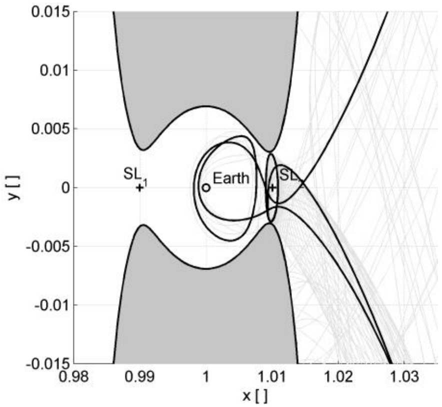
Understanding of the spacecraft orbit evolution

- Semi-analytical techniques to understand effects of natural and artificial orbit perturbations
  - in planetary systems (SRP, aerodynamic drag, third-body effect, generalised gravity potential, Lorentz force etc.)
  - in interplanetary space
  - artificial manoeuvres (low-thrust propulsion, impulsive manoeuvres, solar sails, etc.)

- Surrogate models with dynamics system theory
  - semi-analytical single and double-averaging techniques
  - manifold dynamics
  - domain of application



Solar radiation pressure and Earth's oblateness

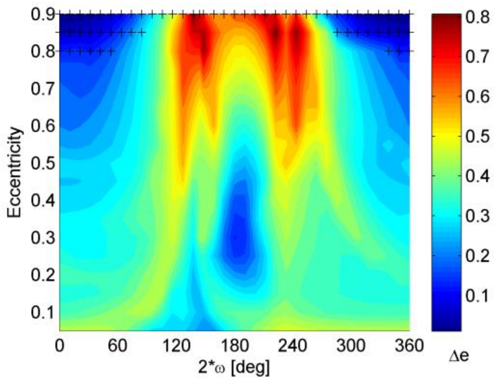


Three-body problem

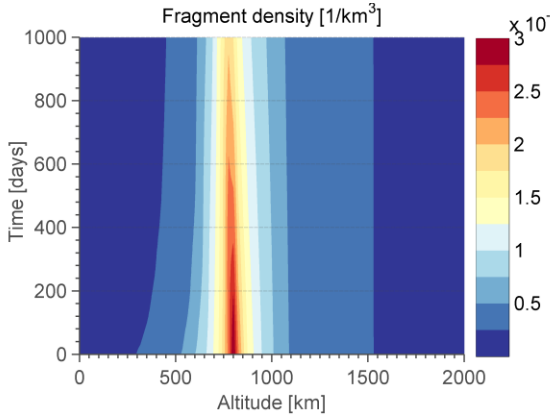
Task 2. Maps of long-term evolution

Topology of space of orbit perturbations

- Coordinate transformation
  - variables choice and formalism, normal forms
  - dynamics in the phase space
- Perturbation analysis
  - frequency analysis for autonomous on-board orbit prediction
  - dynamic indicators for orbital/attitude chaotic region definitions
  - high order expansions techniques with averaged dynamics
- Perturbation maps



XMM-Newton orbit evolution



Density of space debris in LEO

Task 3. Optimisation and control

Trajectory design through perturbation and artificial manoeuvres

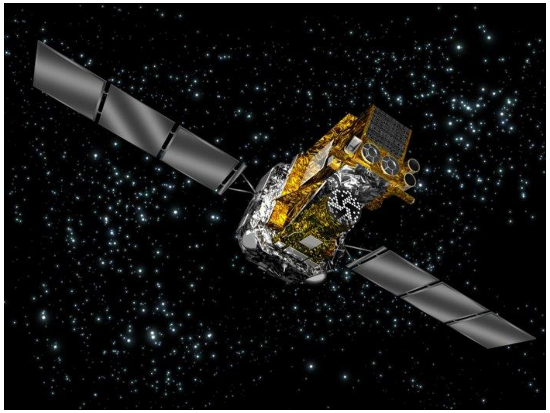
- Phase-space global optimisation (naturally or artificially perturbed trajectories)
  - multiple singular events (e.g., impulsive manoeuvres, gravity kicks)
  - multi-scale dynamics (i.e., escape and capture phases)
  - optimisation in the phase-space
- Phase-space local optimisation
  - continuation techniques
  - direct and indirect methods and hybrid techniques
- Blended optimisation
  - solution on different levels
  - automatic blending of dynamical models
  - optimiser explores the phase space and progressively learn its structure

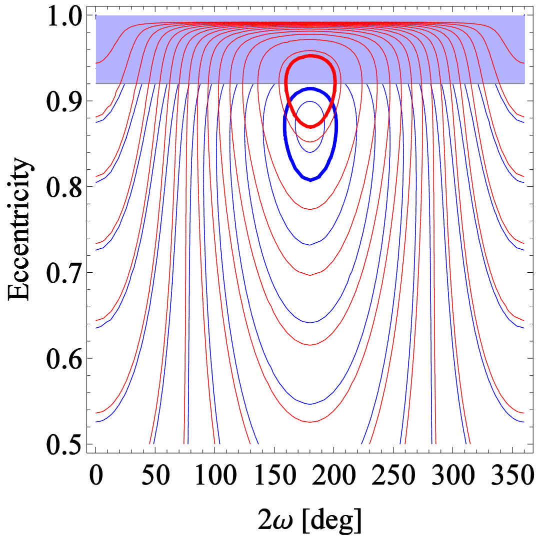
MISSION APPLICATIONS

Concept demonstration

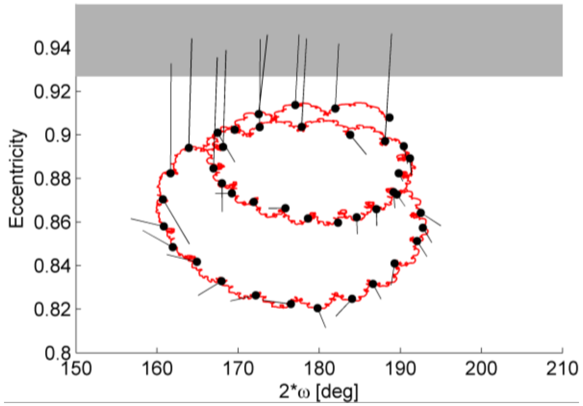
Perturbation enhanced end-of-life design of INTEGRAL mission

- Astrophysics and astronomy missions (e.g., INTEGRAL and XMM-Newton)
- Very complex dynamics under the effects of Moon and Sun perturbation and Earth's oblateness
- No end-of-life disposal



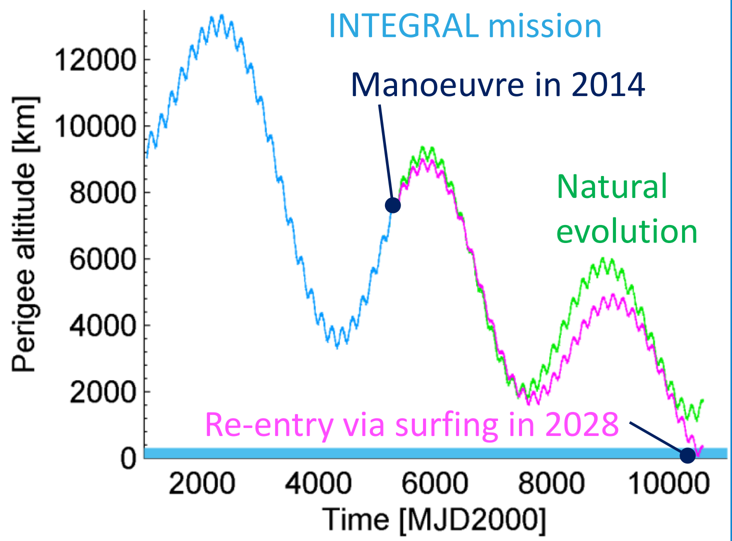


Orbit phase-space evolution



Trajectory design in the phase space

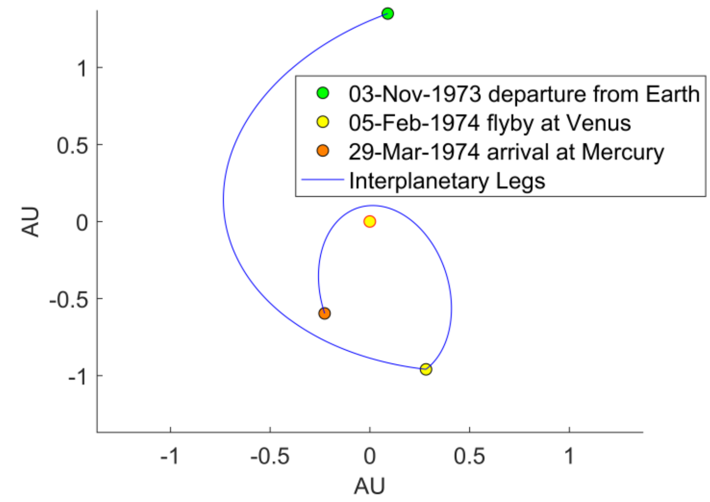
Luni-solar perturbation surfing made re-entry of INTEGRAL mission possible

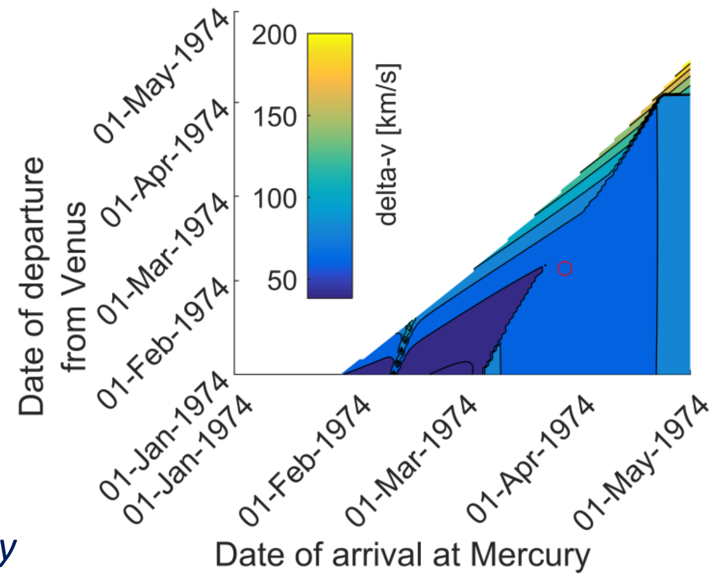


Space transfer

Interplanetary fly-by design through maps

- Solution of interplanetary trajectory optimisation problem
- Orbital phase design through well-known Lambert problem
- Tisserand energetic manner method to identify reachable bodies and encounter conditions
- Combined Lambert-Tisserand solution applied to the single flyby problem



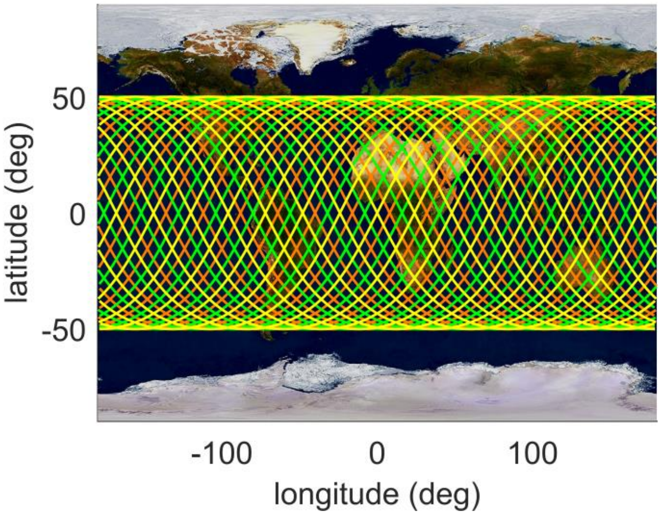


Mariner 4 trajectory

Space transfer

Design of spacecraft mega-constellations for space-based services

- Comparative assessment of different constellation geometries for space-based applications
- Optimisation of constellation design
- Debris interaction and end-of-life
- Perturbation enhanced frozen orbits



Constellation design in LEO and MEO

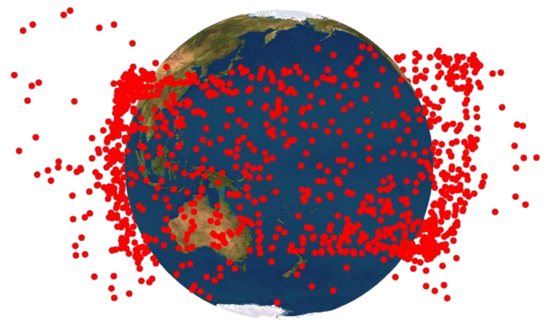
Space Transfer

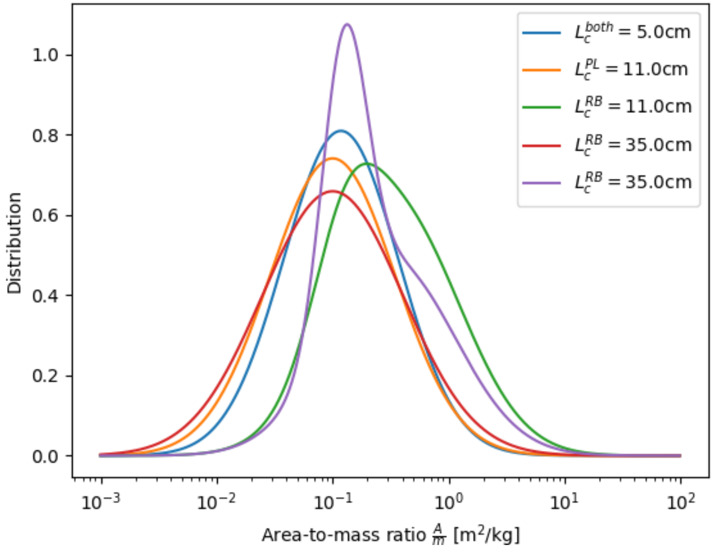
Space debris

Evolution and collision risk of space debris clouds

- Semi-analytical models to study the evolution of space debris in orbit
- Continuity equation approach: follow he evolution of the spatial density rather than each single object
- Challenging as dynamical problem is very complex
- Interaction of fragmentation clouds in highly elliptical orbit with the ow earth orbit environment

Distribution of debris fragments following a collision event





Space debris

End of life trajectory design

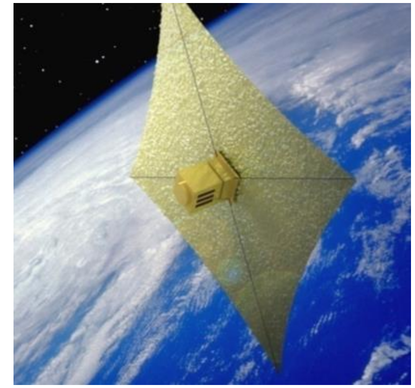
Solar sail deorbiting

- Solar sail for end-of life deorbiting in Earth centred orbit
- Novel technique for solar sailing to maximise deorbiting effect

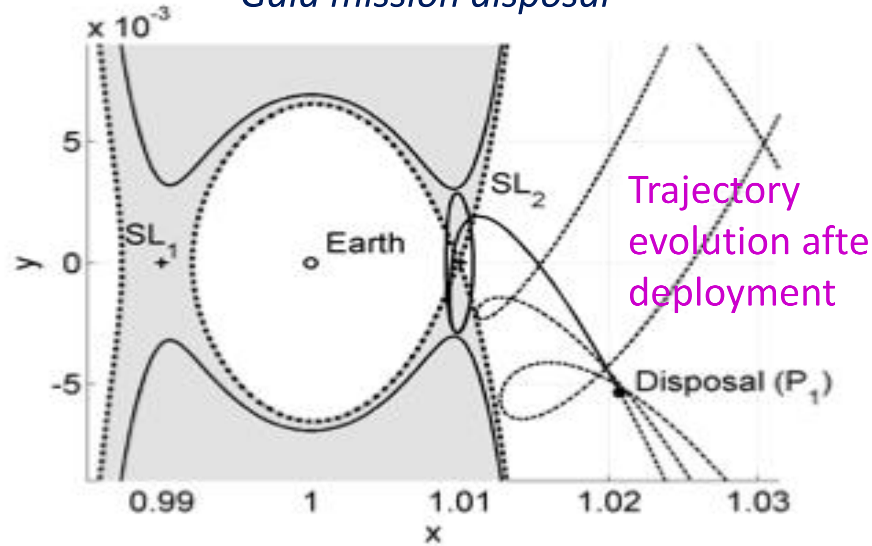
End-of-life for Lagrangian point missions

- End-of-life trajectory design for missions at the Lagrangian point
- Study of re-entry conditions
- Study of resonances
- Mission application to Gaia and Lisa Pathfinder missions

Solar sailing deorbiting



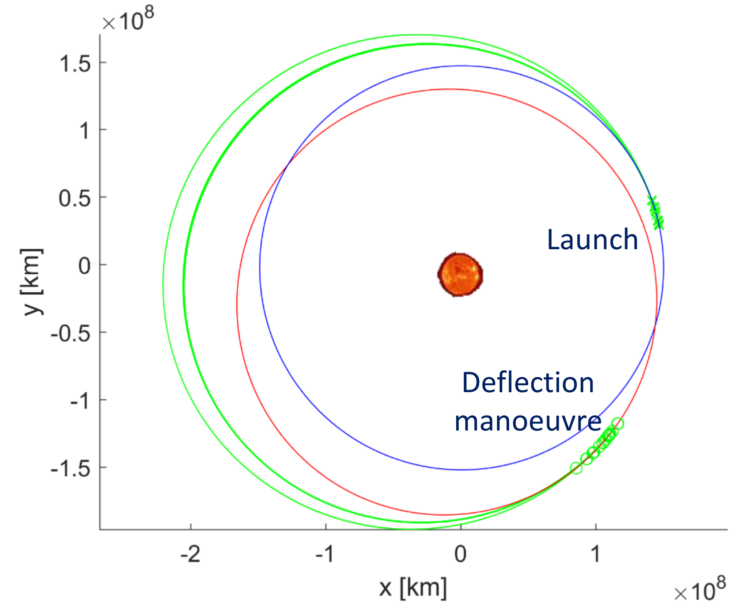
Gaia mission disposal



Planetary protection

Reference missions for different NEA threat scenarios

- Prepare a response to an Near Earth Asteroid (NEA) impact threat scenario
- Study mission design for NEA deflection mission
- Consider a diversity of cases: asteroids have different orbit and physical properties
- Study of selected case for direct and resonant encounter
- Design of robust deflection manoeuvre
  - Uncertainties on asteroid characteristics
  - Uncertainties on orbit determination and manoeuvre error

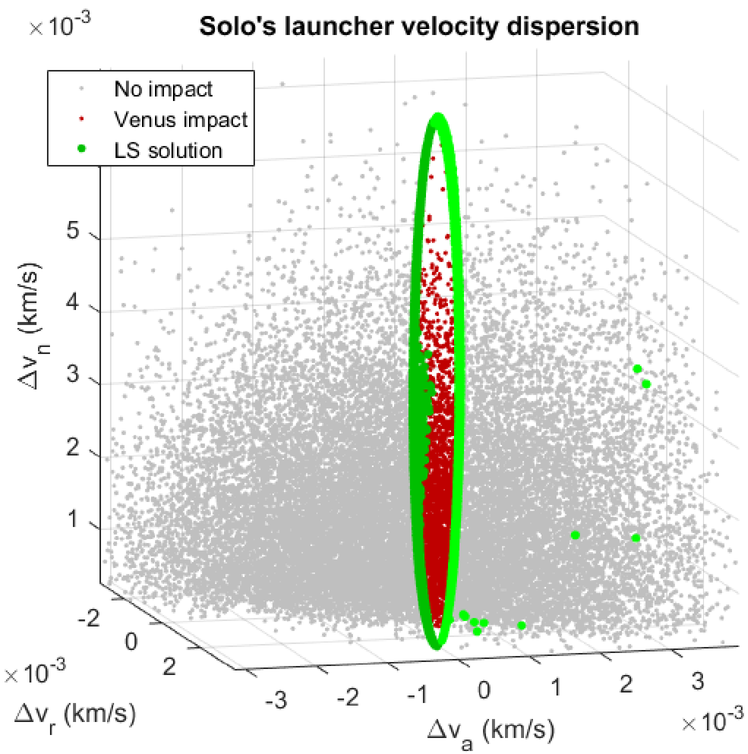


Direct deflection mission to 2010RF12

Planetary protection

Analysis of planetary protection requirements

- Spacecraft and launchers used for interplanetary missions and missions to the Lagrangian points may come back to the Earth or impact with other planets
- Planetary protection requirements: avoid the risk of contamination = check maximum impact probability with planets over 50-100 years
- Development of a tool for the verification of the compliance using a Monte Carlo approach and the b-plane representation



Solo launcher velocity dispersion: impact condition with Venus

Expected results

Work in progress

Space Debris

- Density based debris model
- Environmental index of space debris
- Semi-analytical coupled with high order expansions for cloud propagation
- End-of-life disposal
- Perturbation enhanced collision avoidance manoeuvres

Planetary protection

- Frozen orbits for asteroid exploration
- NEAs deflection and detection
- Planetary protection verification for interplanetary missions

Space transfer

- Small sat interplanetary missions
- Planetary moon missions
- Low-thrust/chemical optimisation under perturbations
- Station keeping
- Autonomous navigation

RESEARCH TEAM

Research team

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Scientific Advisory Board

- esa – European Space Agency
- NASA
- UK Space Agency
- cnes – Centre National d'Études Spatiales
- JAXA – Japan Aerospace Exploration Agency

Conclusions

Contributions

- Beauty: Understanding of perturbations dynamics
- Novelty: Surf by exploiting natural disturbances
  (Problem into opportunity)
- Impact: Perturbation-enhanced mission design

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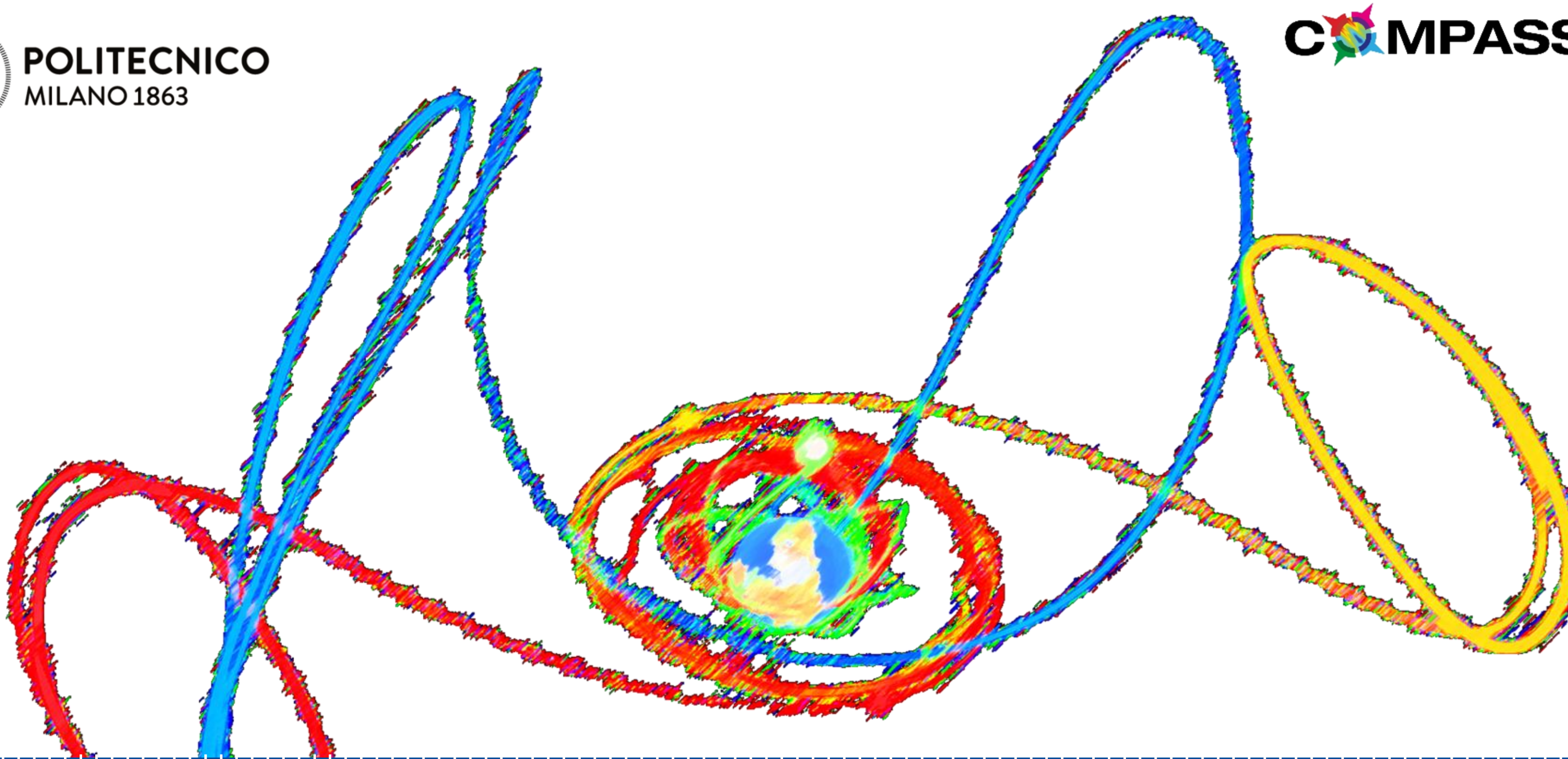

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