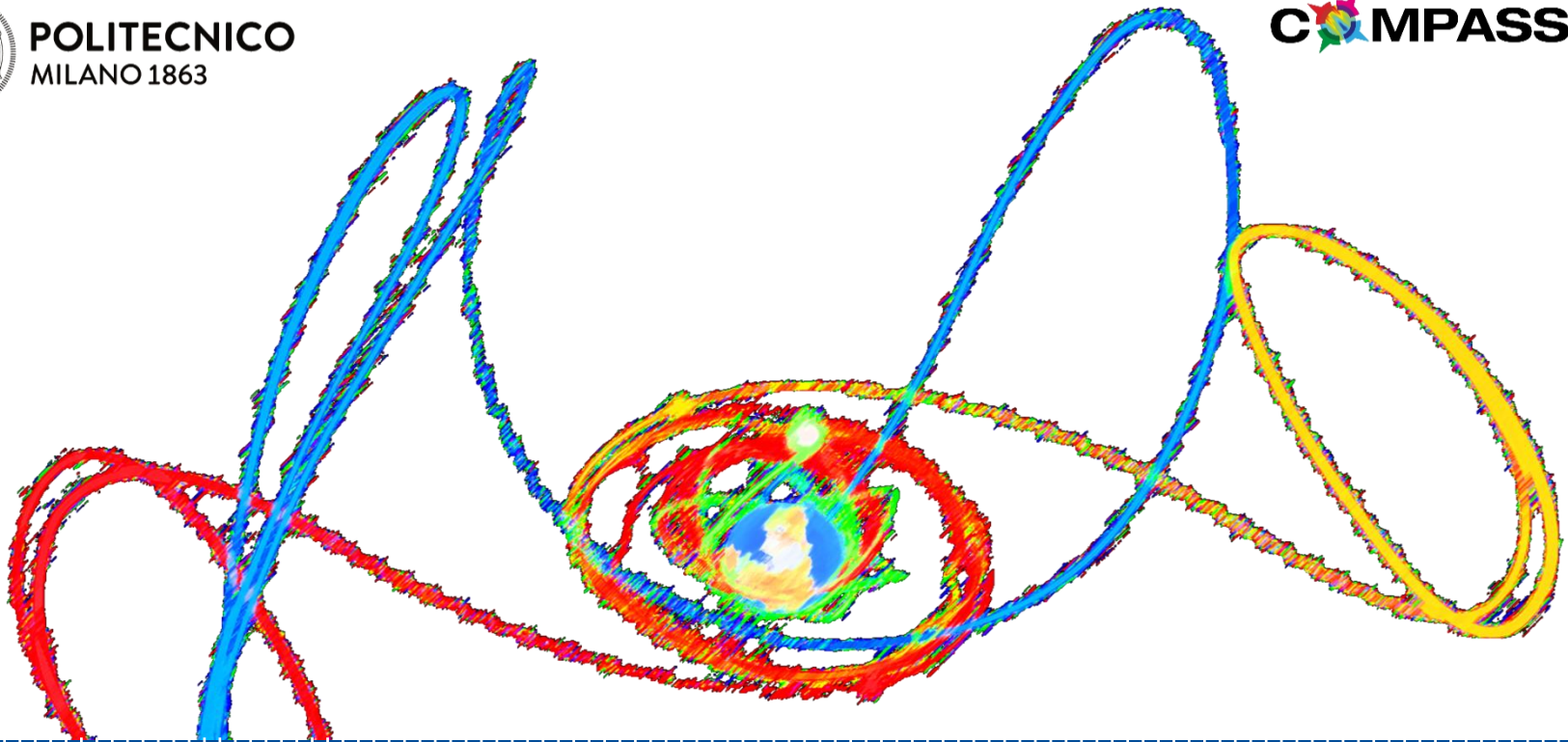




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COMPASS



COMPASS: Control for orbit manoeuvring enhancing natural perturbations

Camilla Colombo and COMPASS team

Numerical Models and Methods in Earth and Space Sciences

Università di Tor Vergata, Roma, March 2019



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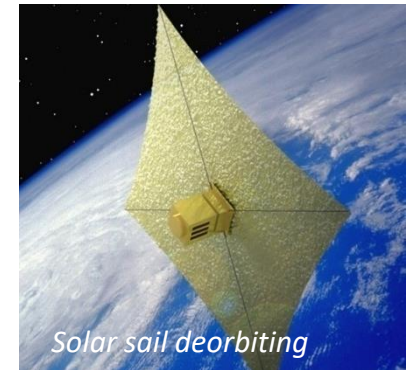


INTRODUCTION

Space transfer

Space transfer allows the colonisation of new habitats and reaching operational orbits for science missions and space-based services.

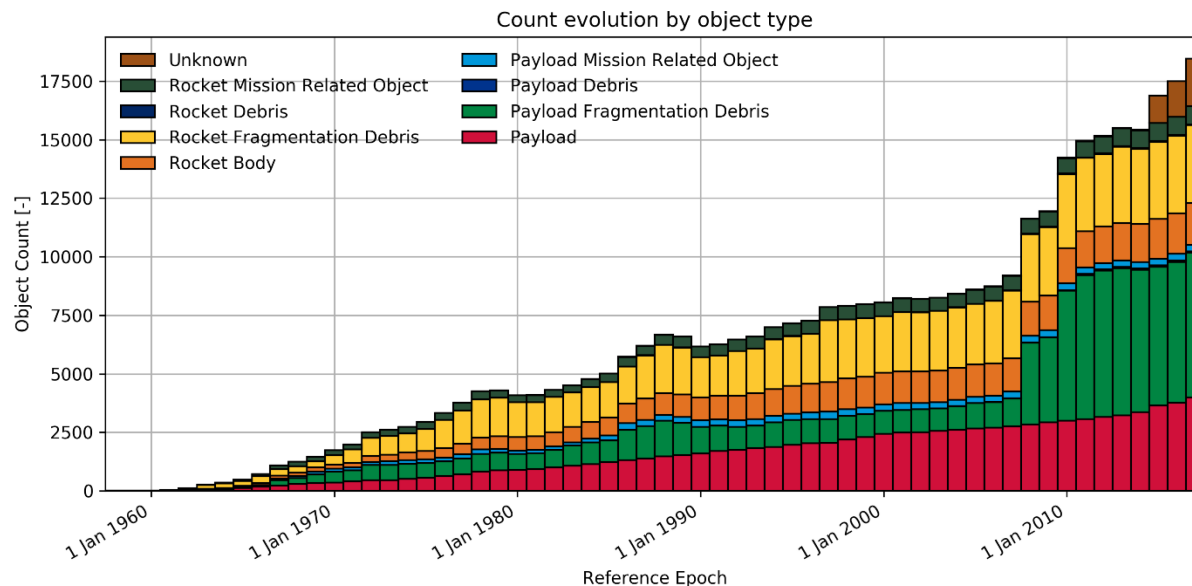
- **Trajectory design** and orbit maintenance are a challenging task
- **New Space development** towards great number of small satellites for distributed services (e.g. large-constellation, nano and micro satellites)
- As enabling technology, **electric propulsion** is increasingly selected as the primary option for near future missions, while **novel propulsion systems** (e.g., solar sailing) have some potential.
- **Natural dynamics can be leveraged** to reduce the extremely high mission cost.



Space situation awareness: space debris

Space debris poses a threat to current and future space activities

- Currently 34000 objects > 10 cm, 900000 objects from 1 to 10 cm
- Breakups generate clouds of fragments difficult to track: 128 million from 1 mm to 1 cm



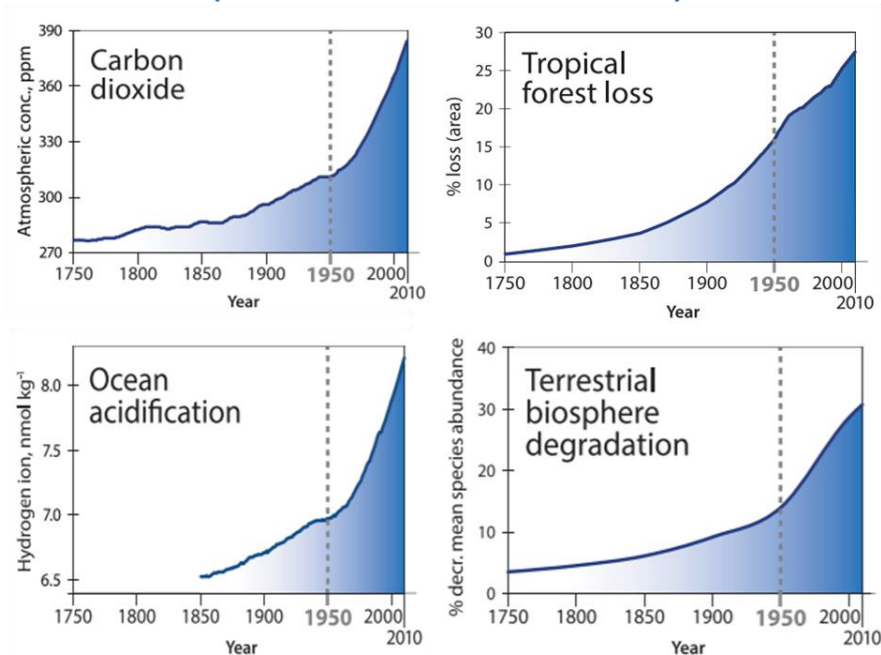
Artificial space object number from ESA Debris report 2018

➤ https://www.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/Space_debris_by_the_numbers

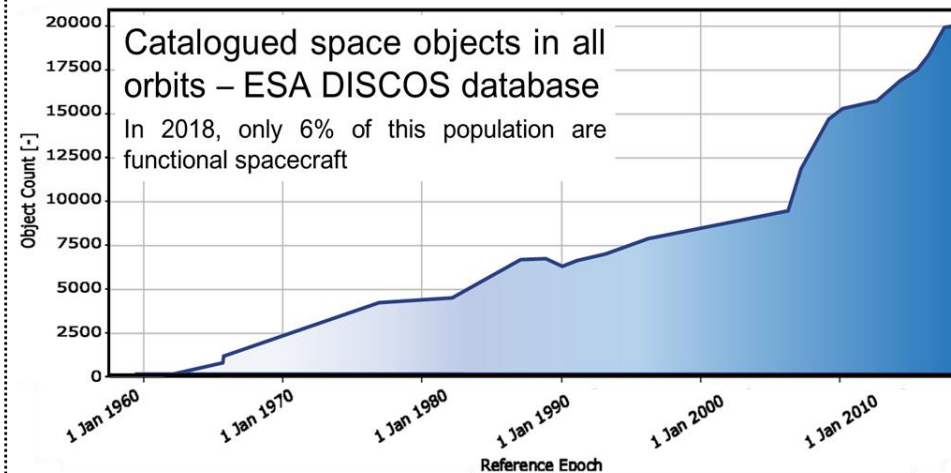
Space situation awareness: space debris

Space debris like other environmental issues

**Earth system trends
(environmental stressors)**



**Orbital environment trend
(space debris growth)**



- Maury T., Loubet P., Trisolini M., Gallice A., Sonnemann G., Colombo C., "Assessing the impact of space debris on orbital resource in Life Cycle Assessment: a proposed method and case study", Science of the Total Environment, 2019.

Space situation awareness: space debris

Space debris related challenges

- Fragments can collide at very high velocity (7-10 km/s) and damage operating satellites
 - Model the evolution of clouds of fragments and the whole space debris population
 - Plan collision avoidance manoeuvres
- Space is our outward ecosystem
 - Assess the capacity of the space environment
 - Need to define debris mitigation guidelines
- Sustainable use of space
 - Design end-of-life manoeuvres and strategies
 - Accurate re-entry prediction
- Development of small spacecraft on large scale
 - Orbit raising and end-of-life disposal
 - Space traffic management



Space situation awareness: asteroid missions and asteroid deflection

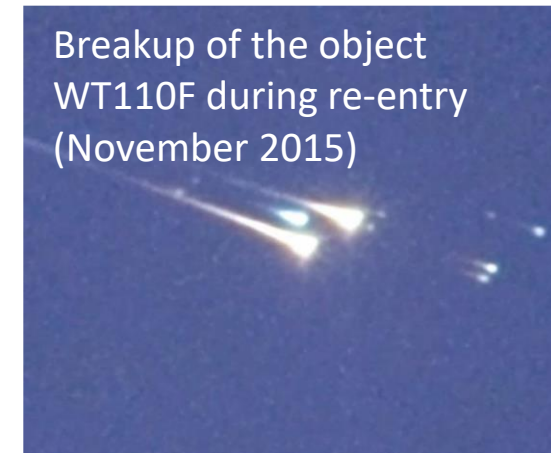
- On average a 10-km-sized asteroid strikes the Earth every 30-50 million years (globally catastrophic effects). Tunguska class (100 m in size) asteroid impact every 100 years (locally devastating effects)
- Near Earth Asteroids can be a **threat** but also an **opportunity** for science and material utilisation
- This is enabled by mission to asteroids and demonstration mission for asteroid deflection



Space situation awareness: planetary protection

Humans now routinely venture beyond Earth and send spacecraft to explore other planets.

- **With this extraordinary ability comes great responsibility:** do not introduce terrestrial biological contamination to other planets and moons that have potential for past or present life
- For interplanetary missions and missions at Libration Point Orbit, **planetary protection analysis** need to be performed



Background and proposed approach

Services, technologies,
science, space exploration

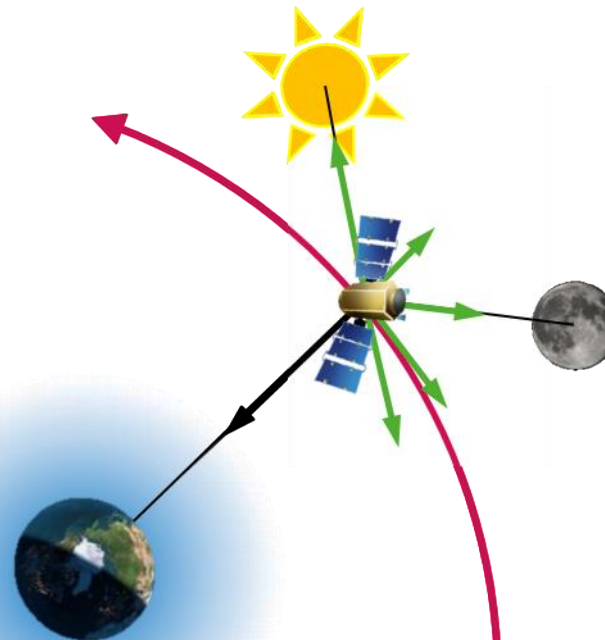
ORBIT PERTURBATIONS

Traditional approach:
counteract perturbations

COMPASS

Novel approach:
leverage perturbations

- Complex orbital dynamics
- Increase fuel requirements for orbit control



Reduce extremely high
space mission costs

Create new opportunities for
exploration and exploitation

Mitigate space debris

Reach, control
operational orbit

Asteroids.
planetary
protection

Space debris

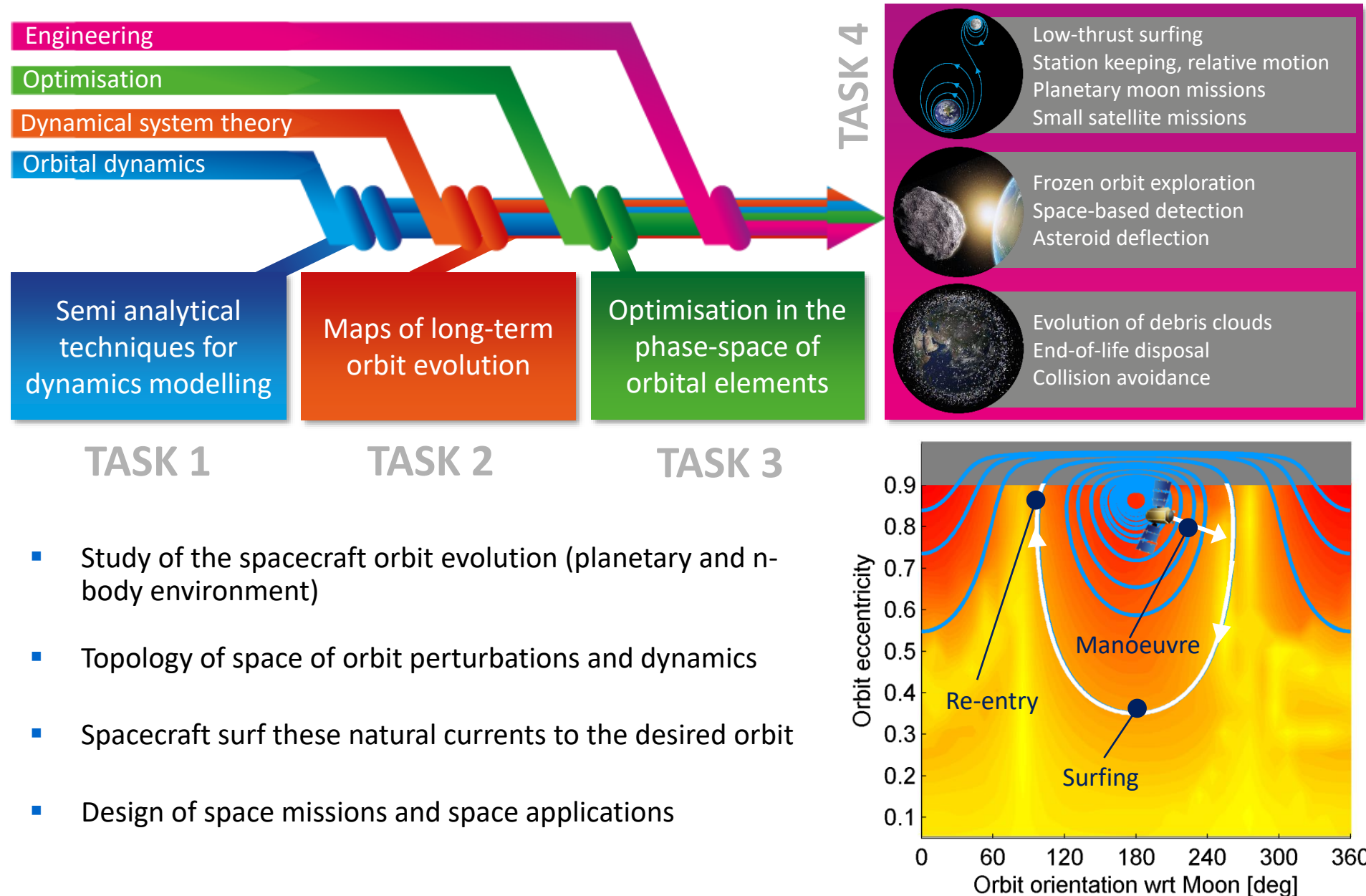
SPACE SITUATION AWARENESS SPACE TRANSFER

Develop novel techniques for orbit manoeuvring by surfing through orbit perturbations



METHODOLOGY

Methodology and expected results





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MISSION APPLICATIONS

Space debris evolution

And its collision risk

Problem

How to model such a large number of particles?

Model

Model it as a **continuum** and propagate through the **continuity equation**

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{F}) = g$$

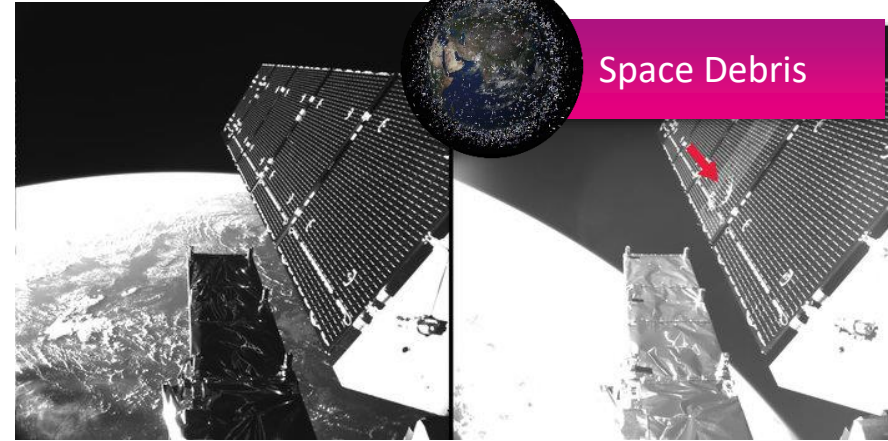
Density of fragments in the phase space of orbital elements $n(a, e, i, A/m)$

Slow phenomena: perturbations

Fast phenomena (sources, sinks): launches, collisions, explosions, removal

Numerically solve through the methods of the characteristics

- C. R. McInnes. An analytical model for the catastrophic production of orbital debris. *ESA Journal*, 1993.
- N. N. Gor'kavyi, L. M. Ozernoy, J. C. Mather, "A new approach to dynamical evolution of interplanetary dust", *The Astrophysical Journal*, 1997



Impact crater from millimetre sized space debris on Sentinel-1A solar panel. Credit: ESA

Space debris evolution

Explosion in low Earth orbit: evolution cloud of fragments

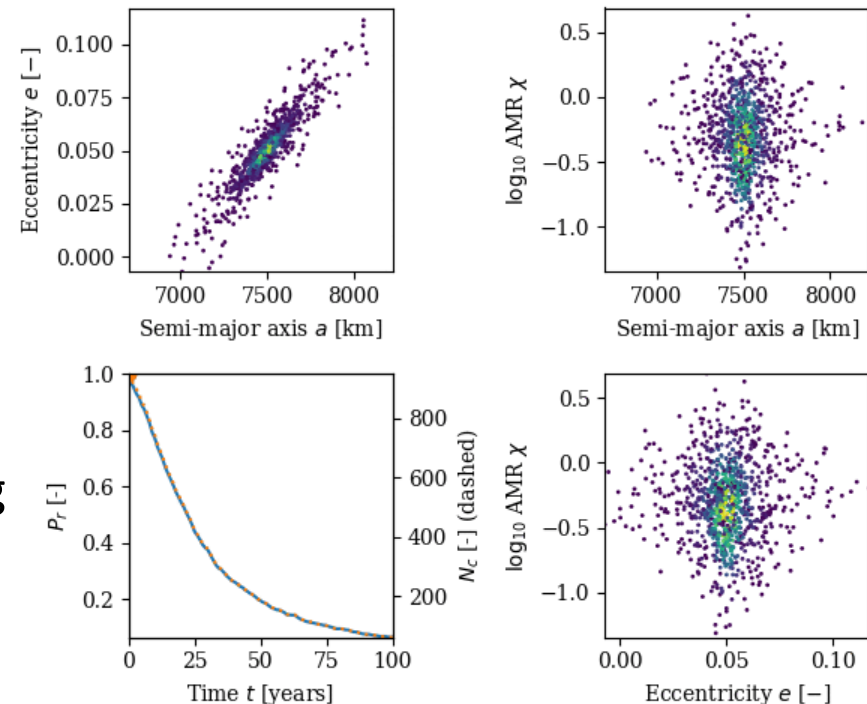


Space Debris

In general the dynamics is perturbed by solar radiation pressure, third body perturbation, Earth's oblate gravity field and atmospheric drag.

Example

- Explosion in Low Earth Orbit, using NASA standard break-up model: 380000 fragments > 1 mm
- Phase space: $x = \left(a, e, \frac{A}{m}\right)$
 - ← Semi-major axis
 - ↓ Eccentricity
 - Area-to-mass ratio
- Propagated with PlanODYn with only drag
- Number of characteristics drops from initially 1000 to below 200 after 50 years, e.g. 80% of fragments re-entered



➤ S. Frey et al. Interpolation and integration of phase space density for estimation of fragmentation cloud distribution, 29th AAS/AIAA Space Flight Mechanics Meeting, January 15, 2019 - Ka'anapali, HI, USA

Space debris evolution

Density interpolation

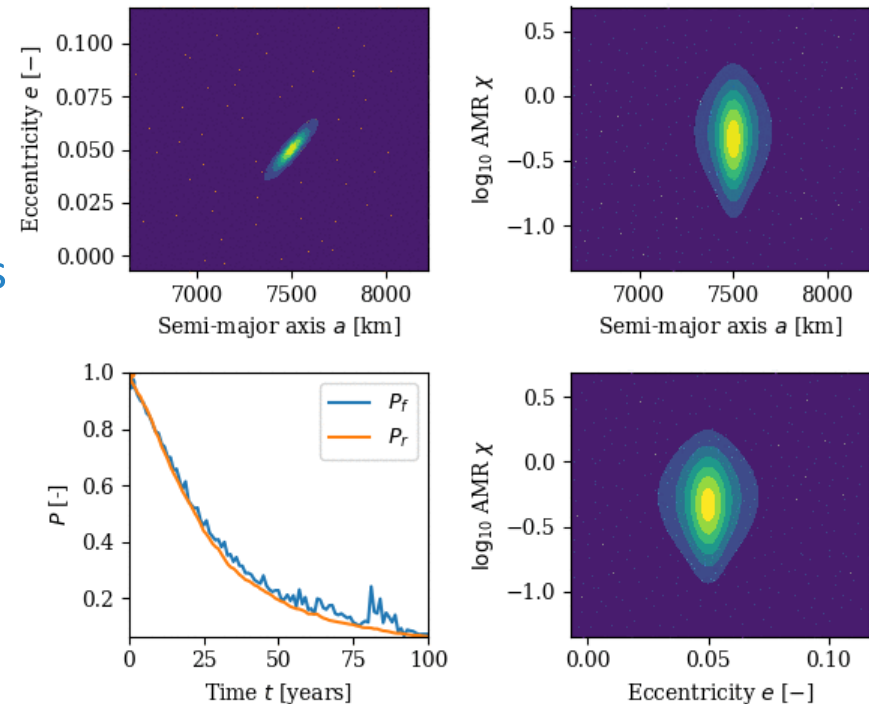


- Interpolation through **Gaussian Mixture Model**

$$f(\mathbf{x}) = \sum_{k=1}^K \pi_k \mathcal{N}(\mathbf{x} | \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)$$

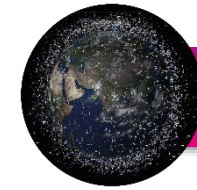
- Fitting routine: **regularised least squares in In-space**
- During time history slightly overestimates density, possibly due single data points being isolated
- Towards the end, becomes spikey as number of sampling points in same as number of fitting parameters
- Can be resolved by resampling density to increase characteristics population

➤ S. Frey et al. Interpolation and integration of phase space density for estimation of fragmentation cloud distribution, 29th AAS/AIAA Space Flight Mechanics Meeting, January 15, 2019 - Ka'anapali, HI, USA



Re-entry prediction

Density-based approach



Problem

- Propagation of re-entry uncertainties in the initial conditions and spacecraft parameters to predict spacecraft re-entries.
- Modelling of asteroids re-entries and the propagation of their fragments after break-up.

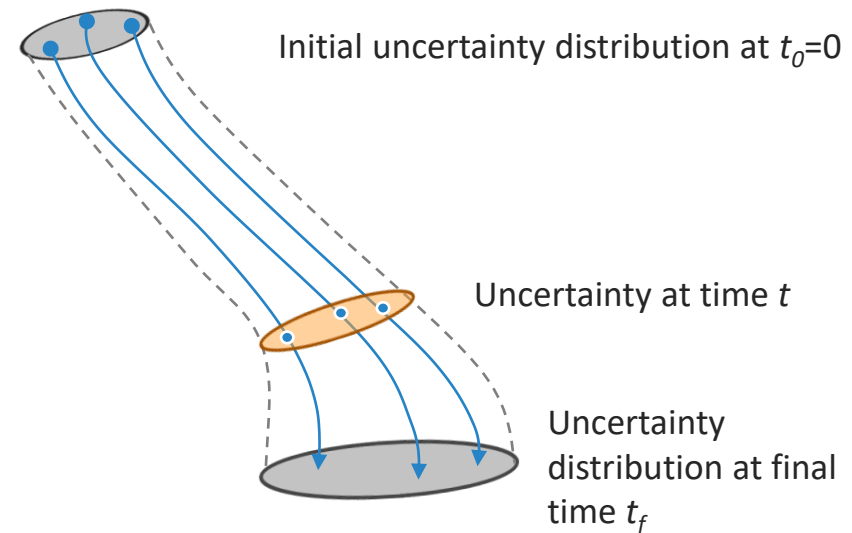


Artists impression of ATV-5 breakup and re-entry.
Credits: ESA-D. Ducros

Method

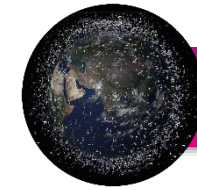
Continuity equation with the re-entry dynamics, the joint probability distribution function of the uncertainties is propagated

$$\frac{\partial n(\mathbf{x}, t)}{\partial t} + \nabla \cdot \mathbf{f}(\mathbf{x}) = \dot{n}^+ - \dot{n}^-$$



Re-entry prediction

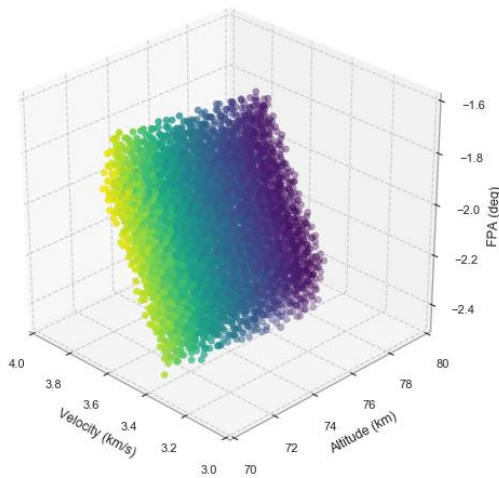
Methodology example



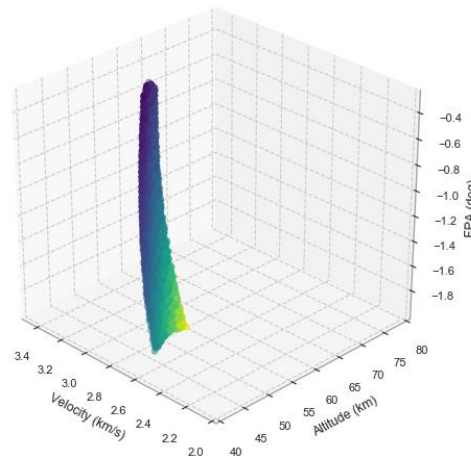
- Sampling of the initial distribution
- Numerical propagation of the density using the continuity equation
- Reconstruction of the 3D density and of the marginal densities



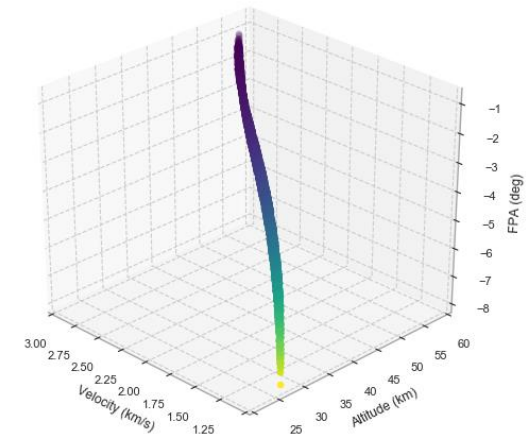
Compute the casualty area on ground



Density distribution at $t = 10$ s



Density distribution at $t = 120$ s



Density distribution at $t = 200$ s

➤ Trisolini M., Colombo C., "A density-based approach to the propagation of re-entry uncertainties", 29th AAS/AIAA Space Flight Mechanics Meeting, January 15, 2019 - Ka'anapali, HI, USA

End-of-life disposal design

Disposal design for distant Earth orbits



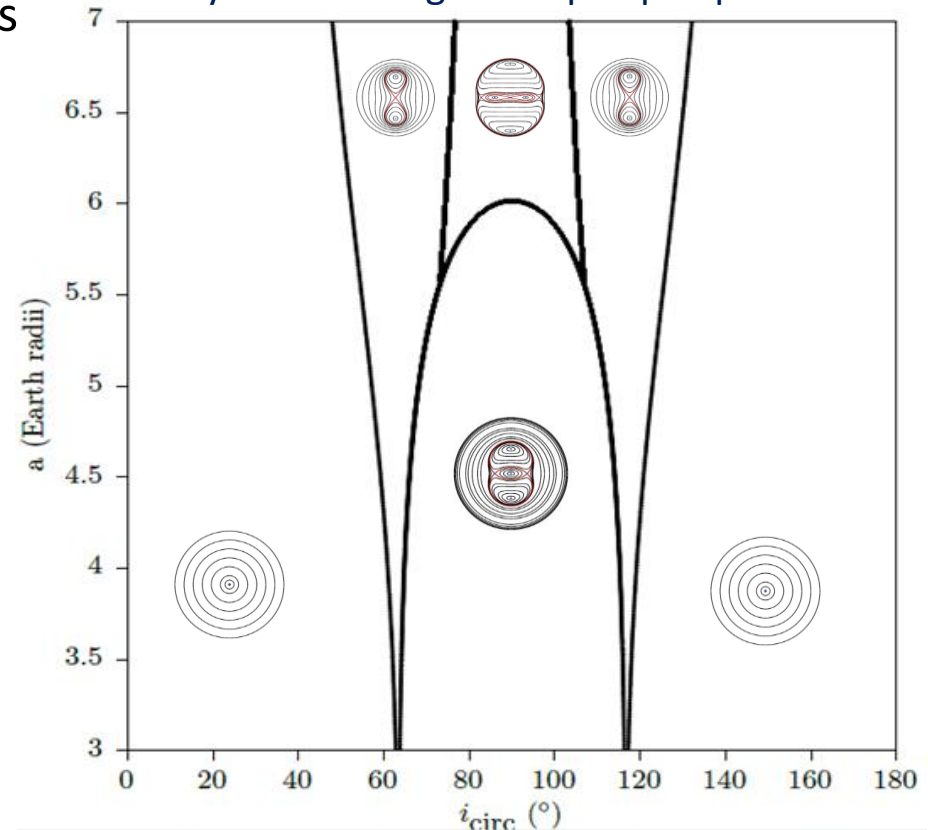
Problem

- Provide efficient disposal scenarios for distant Earth satellites
- Analytical model in the phase space

Methods

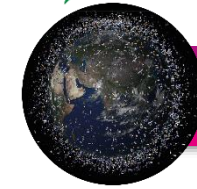
- Averaging techniques
- Analytical modelling
- Semi-analytical propagations

Analytical modelling of distant Earth satellites' dynamics using an ecliptic perspective



➤ Gkolias I., Lara M., Colombo C., "An ecliptic perspective to analytical satellite theories", AAS-18-370, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, AIAA/AAS Snowbird, Utah, 2018

Model formulation



Space Debris

The orbit of an Earth's satellite in high orbit (no drag) can be modelled as a perturbed Keplerian motion

$$\mathcal{H} = H_{\text{kep}} + H_{\text{zonal}} + H_{\text{third-body}}$$

- Keplerian part

$$H_{\text{kep}} = -\frac{\mu}{2a}$$

- Zonal harmonics

$$H_{\text{zonal}} = -\frac{\mu}{r} \sum_{j \geq 2} \left(\frac{R_{\oplus}}{r} \right)^j C_{j,0} P_{j,0}(\sin \phi)$$

- Third body attraction (Sun and Moon)

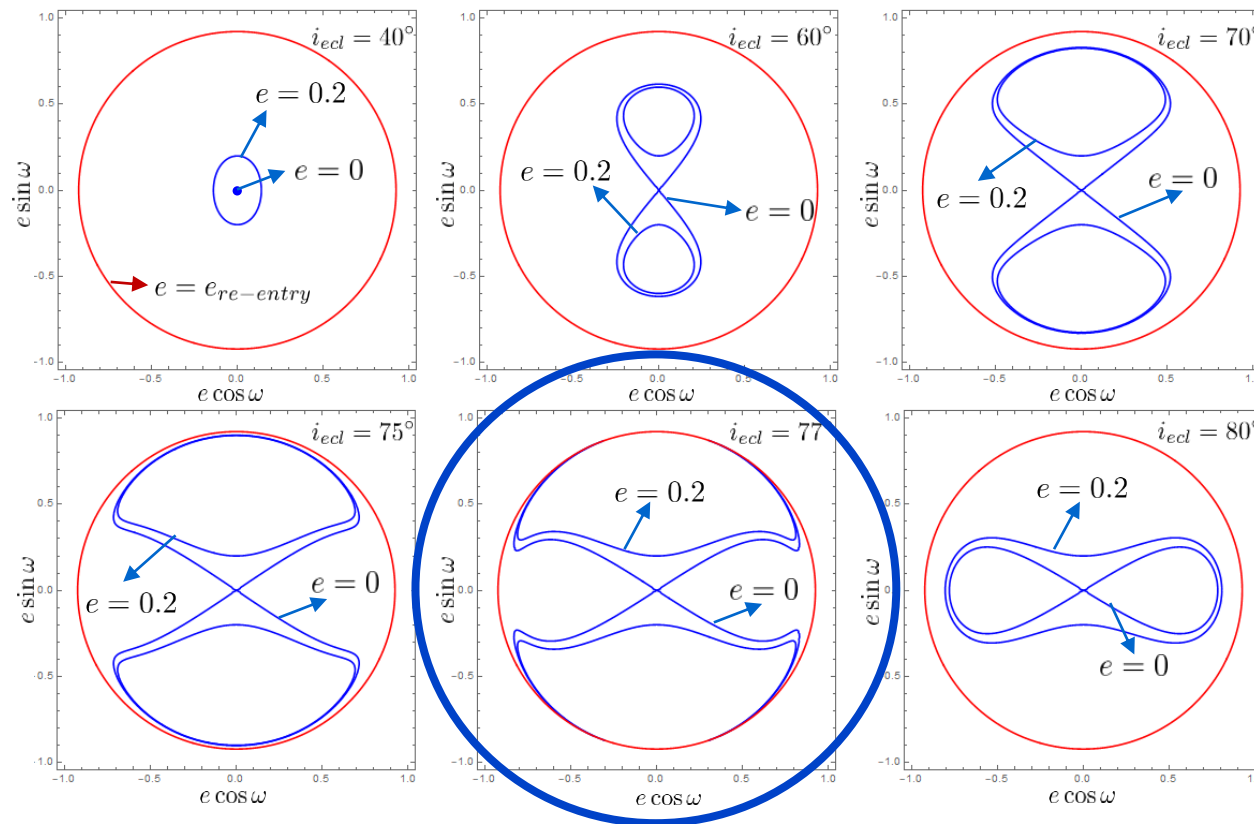
$$H_{\text{third-body}} = -\frac{\mu'}{r'} \left(\frac{r'}{\|\mathbf{r} - \mathbf{r}'\|} - \frac{\mathbf{r} \cdot \mathbf{r}'}{r'^2} \right)$$

$$\bar{\bar{H}} = \bar{\bar{H}}(a, e, i, \Omega, \omega, -, \Omega_{\odot}, \theta_{\odot}; \mu, J_2, R_{\oplus}, \epsilon, n_{\odot}, a_{\odot}, n_{\odot}, a_{\odot}, \eta_{\odot})$$

➤ Gkolias I., Lara M., Colombo C., "An ecliptic perspective to analytical satellite theories", AAS-18-370, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, AIAA/AAS Snowbird, Utah, 2018

End-of-life disposal design

Disposal design for distant Earth orbits

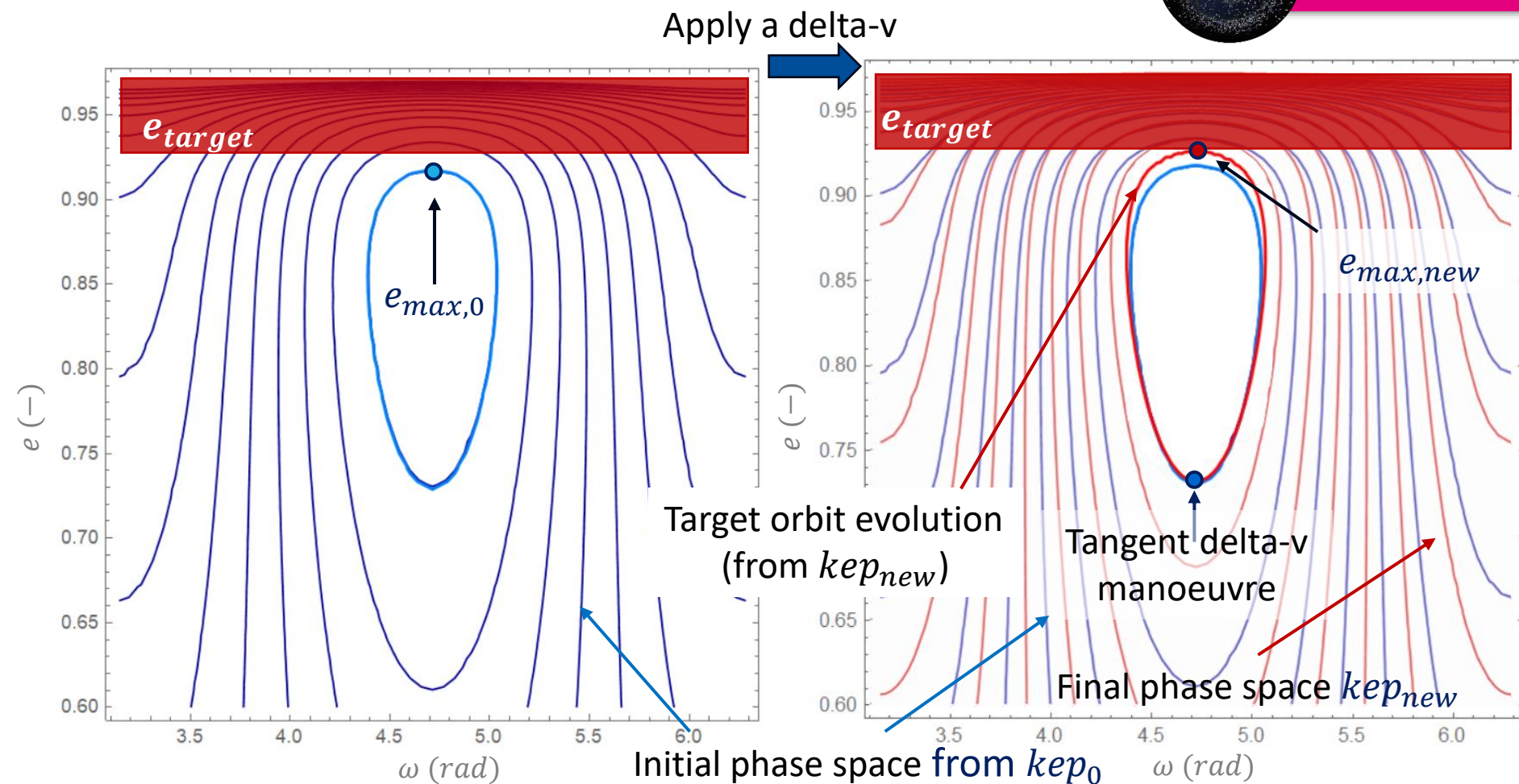
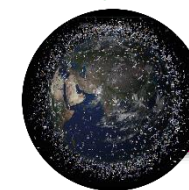


Exploitation of the analytical modelling in the design
of end-of-life disposal manoeuvres at GEO altitude

- I. Gkolias, M. Lara, C. Colombo, "An ecliptic perspective to analytical satellite theories", AAS-18-370, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, AIAA/AAS Snowbird, Utah, 2018

End-of-life disposal design

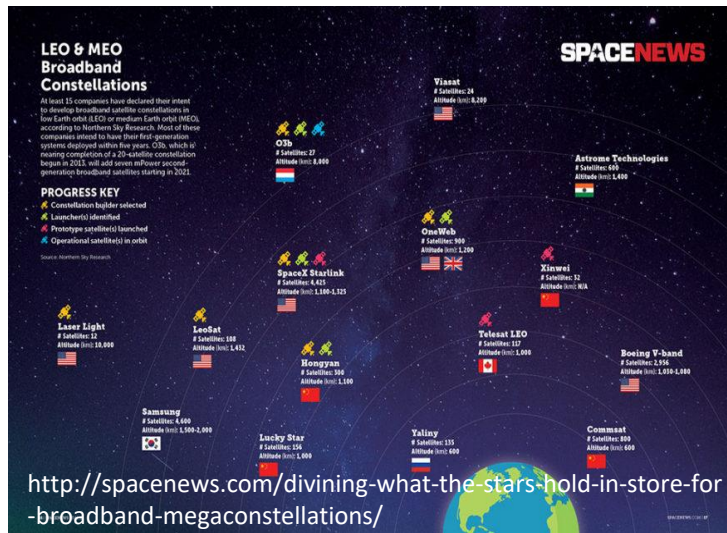
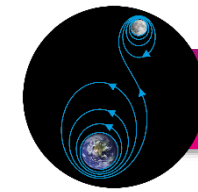
Manoeuvre design in the phase space



- F. Scala, C. Colombo, I. Gkolias, "Surfing in the phase space of Earth's oblateness and third body perturbation", AAS-19-484, 29th AAS/AIAA Space Flight Mechanics Meeting, January 15, 2019 - Ka'anapali, HI, USA

Large constellations

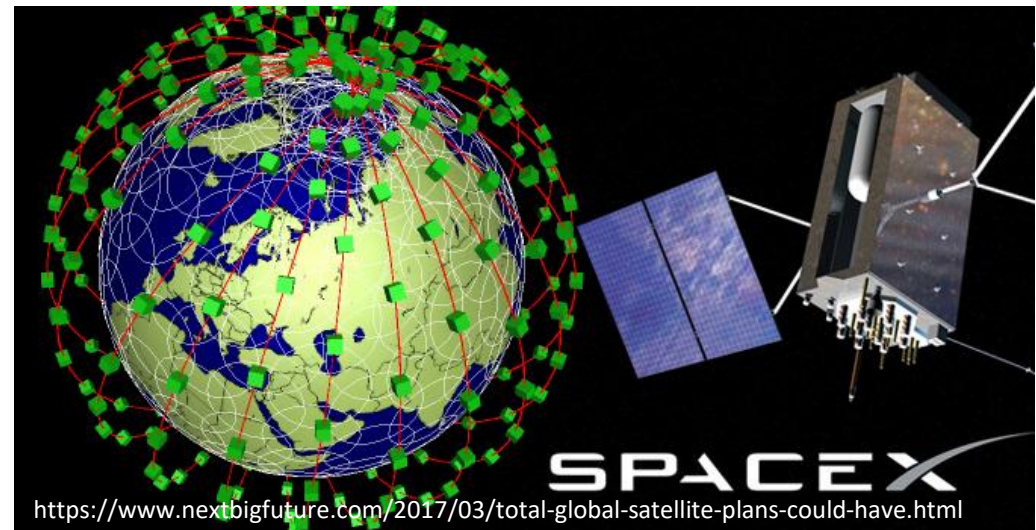
Design of large constellations for space-based services



Why

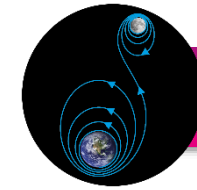
Large constellation of small satellites proposed for space based services

- Optimal design
- Space debris interaction
- Inner-constellation collision



Large constellations

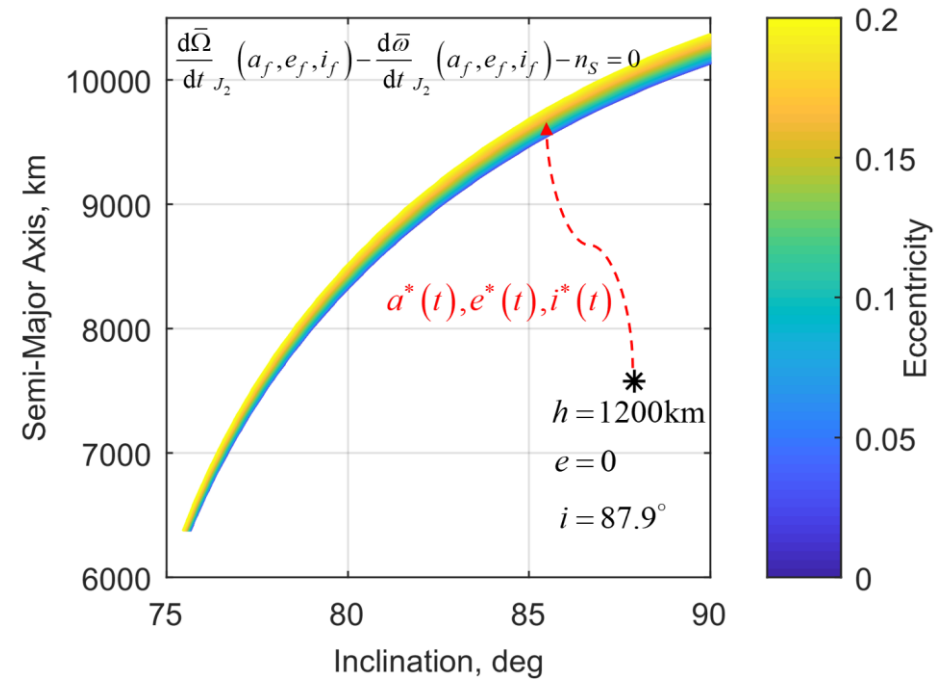
Design of large constellations for space-based services



Space Transfer

Methods:

- Comparative assessment of different constellation geometries for space-based applications
- Optimisation of constellation design
 - Optimal orbit raising or deorbiting design
 - Optimisation of the whole constellation plan
- Debris interaction and end-of-life
- Perturbation enhanced frozen orbits

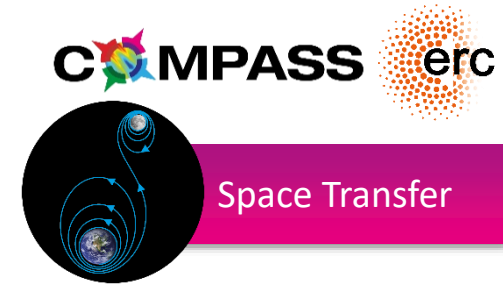


Deorbiting exploiting resonances

- S. Huang, C. Colombo and F. Bernelli-Zazzera, "Comparative Assessment of Difference Constellation Geometries for Space-Based Application." 68th International Astronautical Congress. Adelaide, Australia, 25-29 September 2017, IAC-17, C1, IP, 31, x41252.
- S. Huang, C. Colombo, E. M. Alessi, Z. Hou, "Large Constellation de-orbiting with low-thrust propulsion" 29th AAS/AIAA Space Flight Mechanics Meeting, January 15, 2019 - Ka'anapali, HI, USA.

Formation flying

Exploiting satellites which fly close to each other

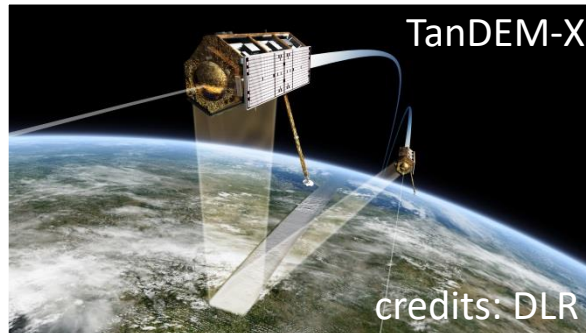


- Formation flying embraces several applications
 - Sparse instruments (e.g., Earth observation, communication ...)
 - On-orbit servicing
 - Active debris removal
- Several applications occur in low-Earth orbits (harsh environment)

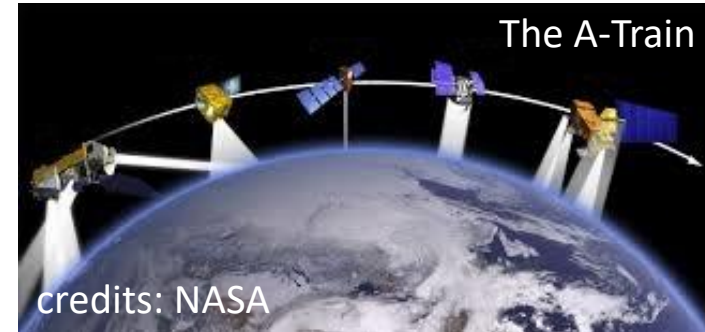
PRISMA



TanDEM-X

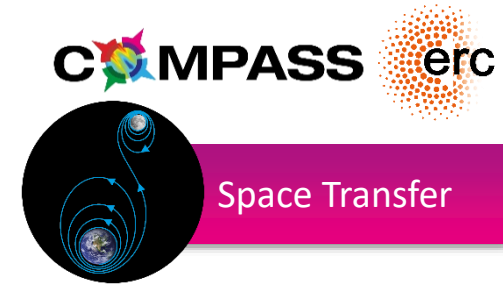


The A-Train



Formation flying

Focus on satellites' relative motion



Goal:

Understanding and use of the orbital perturbations in the relative motion to

- Enhance current Guidance Navigation and Control (GNC) algorithms that enable formation flying activities
- Improve the level of autonomy of such GNC systems

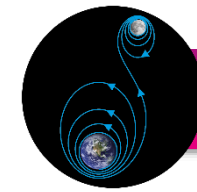
Method:

Use of orbital elements based semi-analytical approaches to

- Exploit the peculiarities of the orbital dynamics
- Develop a framework suitable to run on spaceborne processors

➤ Gaias G., Lara M., Colombo C., “Accurate Osculating/Mean Orbital Elements Conversions for Spaceborne Formation Flying”, Proceedings of the 18th Australian International Aerospace Congress , ISSFD 2019

Orbit and attitude of solar sails



Problem setting

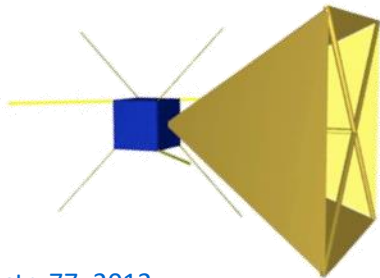
Problem:

- Fast orbit and attitude propagation of **uncontrolled spacecraft in strongly perturbed environments**.
- To be applied in the context of **passive mitigation strategies with the aid of Solar Radiation Pressure** acceleration.

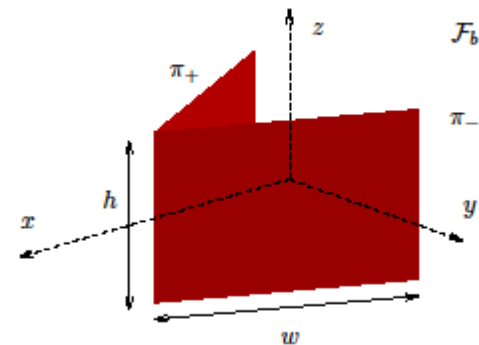
How:

- Strategies rely on attitude control (e.g., helio-stable shape).

3D concept



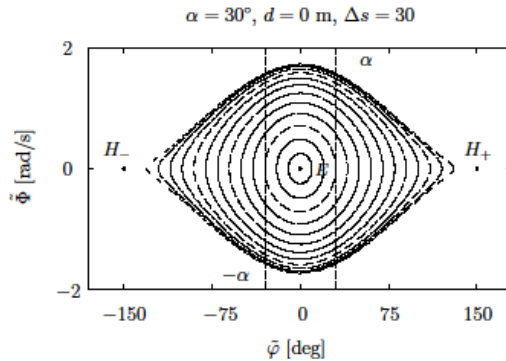
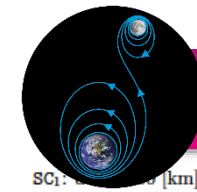
2D simplified



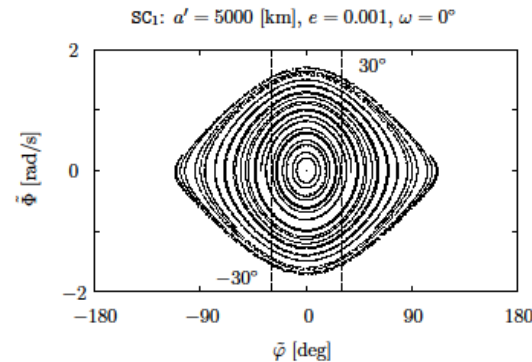
- Lücking et al. *Acta Astr.* 77, 2012
- Colombo et al. *Acta Astr.* 81, 2012
- Ceriotti et al. *Adv. Solar Sailing* 2014

Orbit and attitude of solar sails

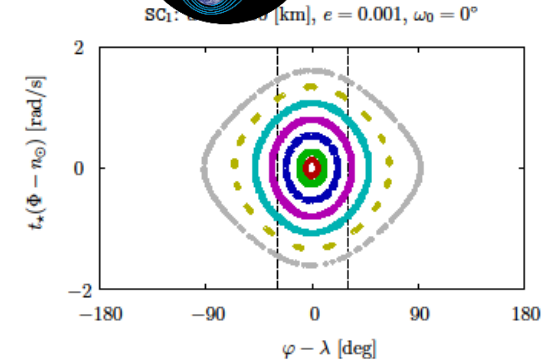
Dynamics close to Sun-pointing attitude



Only attitude, only SRP



Only attitude, SRP+ gravity gradient



Attitude + Orbit

- Dynamics: Orbit + fixed attitude and attitude + fixed orbit are **Hamiltonian systems**.
- Coupled dynamics: **Slow-fast system** (orbit-attitude, resp.).
- Analytical results in the planar case: explicit (and averaged) equations for a large family of spacecraft, static stability of Sun-pointing direction.
- Analysis depends on **shape, center of mass-center of pressure offset, area-to-mass ratio**.

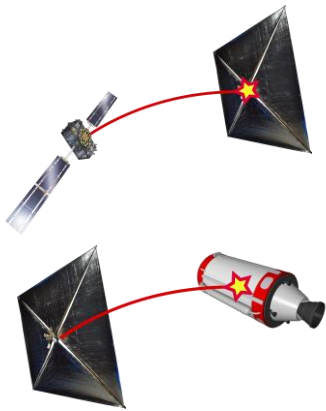
➤ N. Miguel, C. Colombo, "Planar orbit and attitude dynamics of an Earth-orbiting solar sail under J_2 and atmospheric drag effects", AAS-18-361, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, AIAA/AAS Snowbird, Utah, 2018

Solar sails and collision avoidance

Collision avoidance manoeuvres for solar sail missions

Solar sails are a **cost-effective alternative to reduce de-orbit** time for satellites reaching their end of life

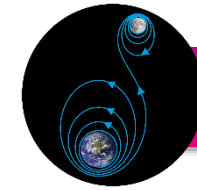
- Comply with space debris mitigation policies
- Reduce/eliminate need for additional fuel (costly)



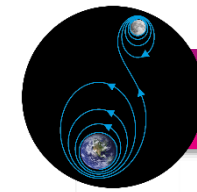
But their large cross-sectional area **increases collision risk**

New insights and tools on collision avoidance manoeuvres involving large objects (as sails) need to be developed

Results can be applied to other missions such as **asteroid deflection or redirection**



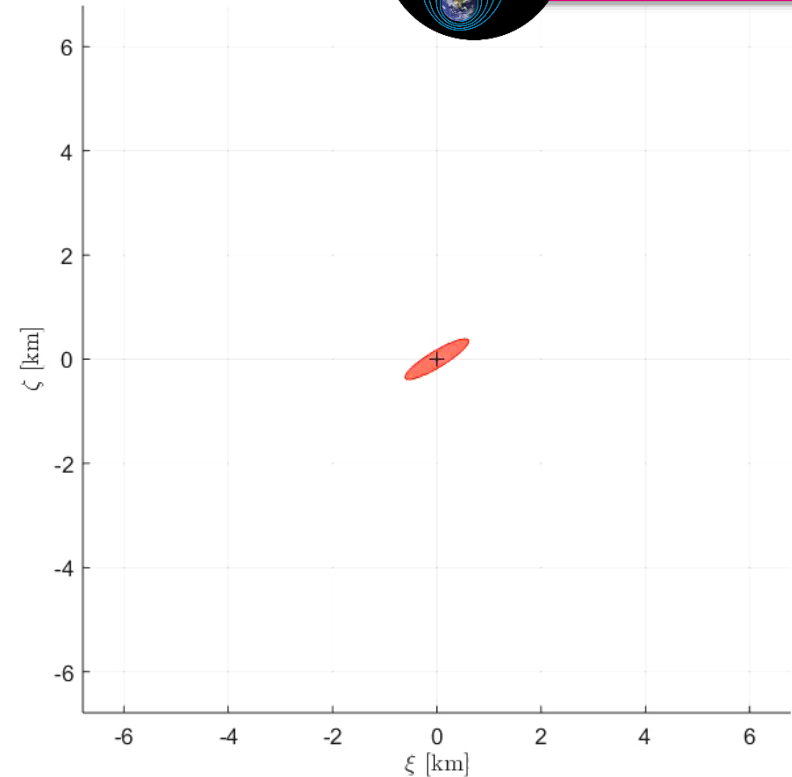
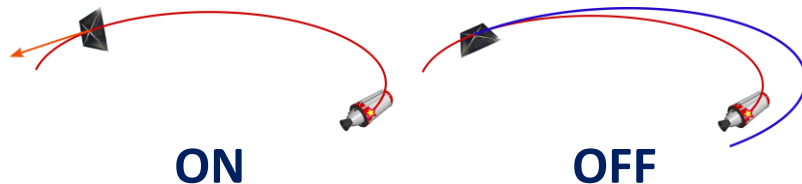
Solar sails and collision avoidance



Method and results

Analytic, semi-analytic and numerical approaches:

- Manoeuvring either the sail or the incoming object
- Representation of dynamics at the close approach (b-plane)
- Max. miss distance and min. collision probability strategies
- Taking into account the effect of the uncertainties



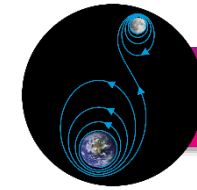
 Covariance ellipse, $\sigma = 1$  Min. collision probability  Max. miss distance

Max. miss distance vs min. collision probability manoeuvres, with time-evolving uncertainties

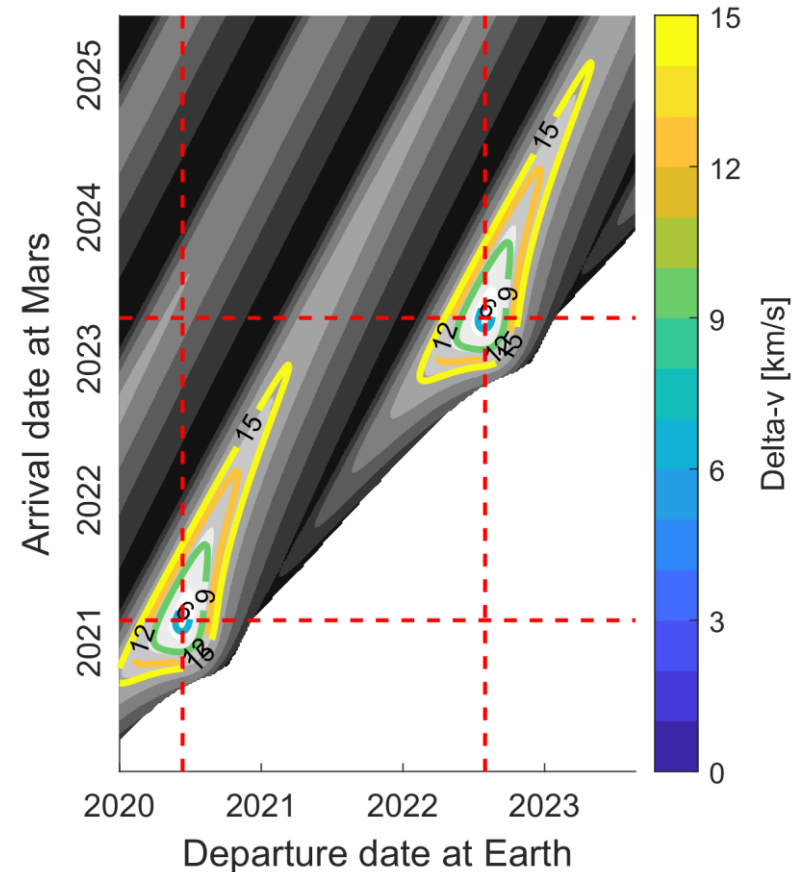
➤ J. L. Gonzalo, C. Colombo, P. Di Lizia, "Analysis and design of collision avoidance manoeuvres for passive deorbiting missions", AAS-18-357, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, AIAA/AAS Snowbird, Utah, 2018

Interplanetary transfer

Fly-by design through maps



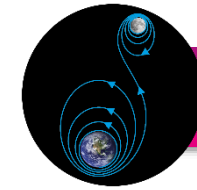
- Solution of interplanetary trajectory optimisation problem
- Tisserand energetic manner method to identify reachable bodies and encounter conditions
- Extension to 3D porkchop plot to allow elegant resolution for the flyby problem
- Syzygy function, borrowed from astronomy for designing gravity assists assisted trajectories



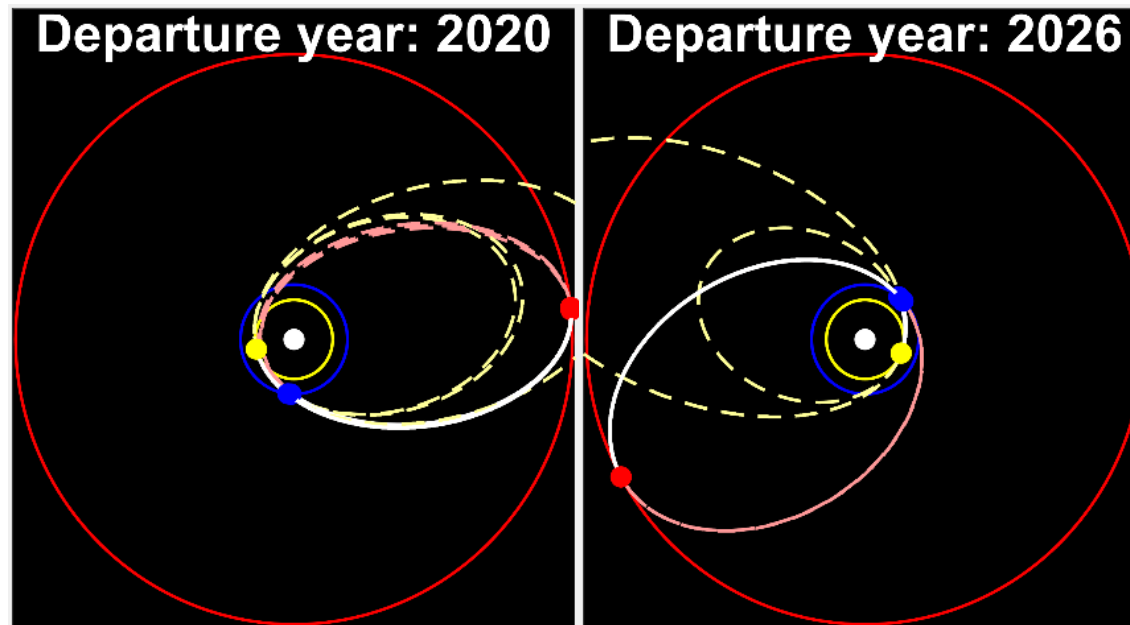
➤ D. Menzio, C. Colombo, "An analysis of the porkchop plot for direct, multi-revolution and flyby missions, DyCoSS conference 2018, IAA-AAS-DyCoSS 18-621

Interplanetary transfer

Fly-by design through maps



Syzygy function, borrowed from astronomy, extended to designing gravity assists assisted trajectories



- Menzio D. , C. Colombo, “Adapted Syzygy function for the preliminary design of multiple gravity assisted trajectories”, International Astronautical Congress 2018, Bremen, Germany.

Planetary protection

Analysis of planetary protection requirements

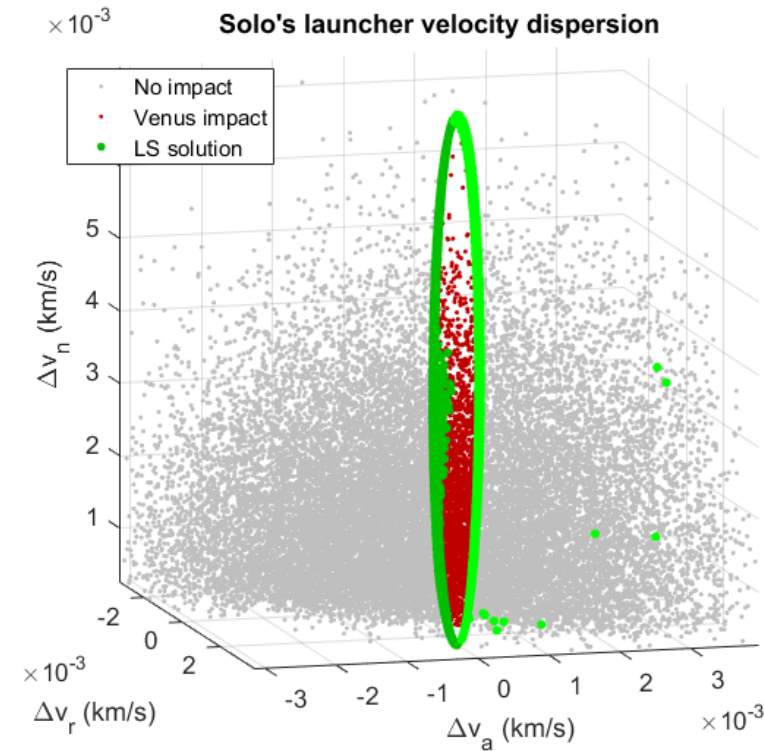


Problem:

Spacecraft and launchers used for interplanetary missions and missions to the Lagrangian points may come back to the Earth or impact with other planets

Method:

- 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 efficient sampling and integration techniques and smart representation (b-plane)



*Solo launcher velocity dispersion:
impact condition with Venus*

➤ Romano M., Camilla Colombo C., Jose Manuel Sánchez Pérez J. M., "Verification of planetary protection requirements with symplectic methods and monte Carlo line sampling", *International Astronautical Congress 2017*, IAC-17-C1.9.5.

Planetary protection

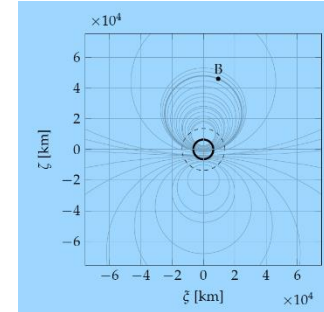
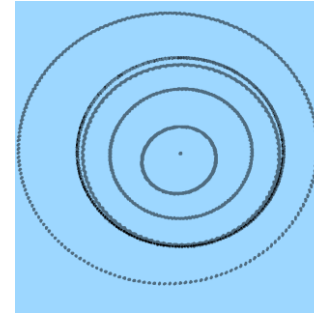
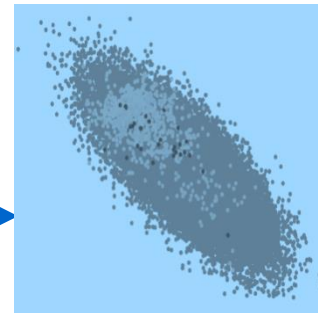
Suite for Numerical Analysis of Planetary Protection

Input:

Uncertainty distribution
Planetary protection
requirement: max
impact prob. and
confidence level

Number of MC runs
Initial conditions

Trajectory propagation



Monte Carlo
initialisation

Trajectory
propagation

B-plane
analysis

Increase number
of runs

NO

Verify
planetary
protection
requiremen
ts

Number of
impacts

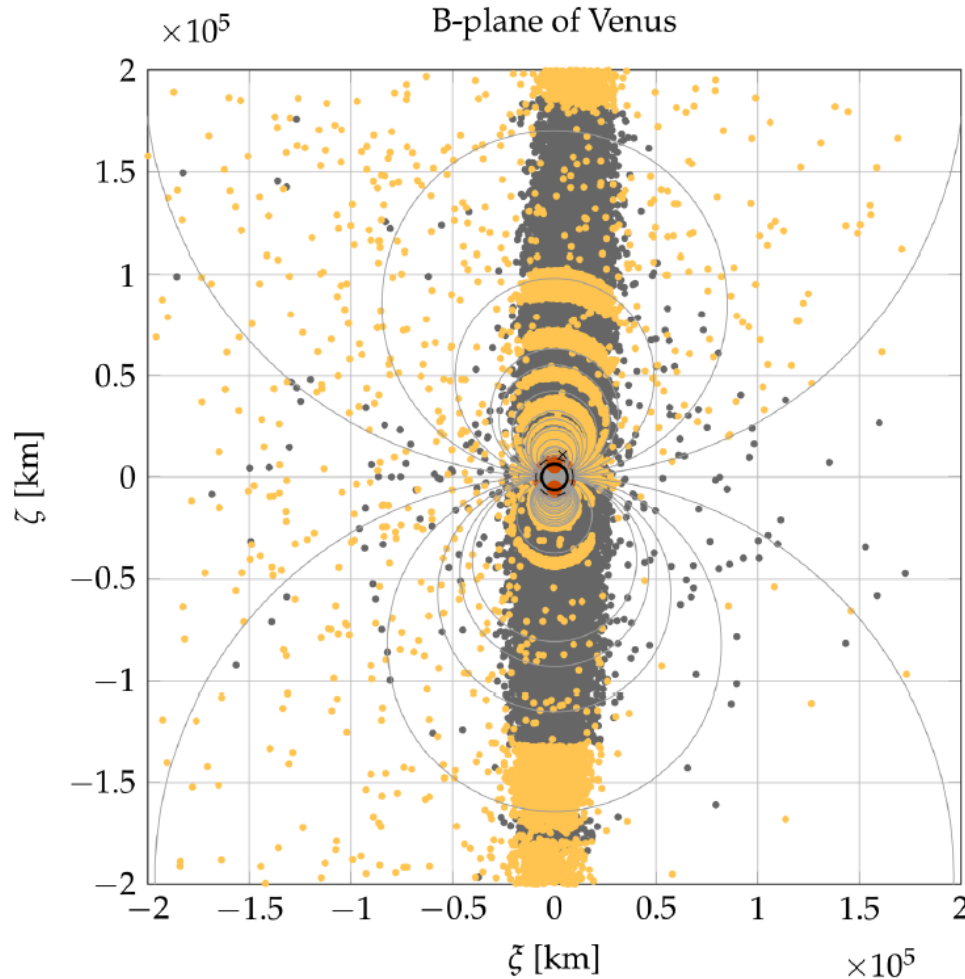
YES

Output and
graphics

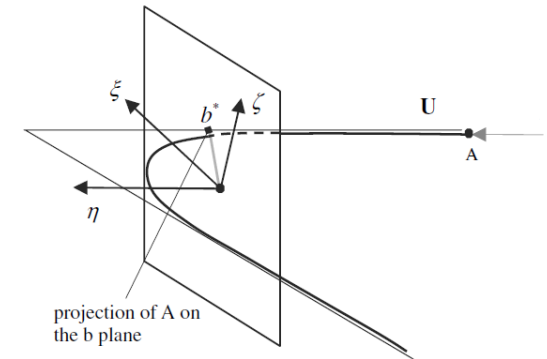
- Colombo C., Letizia F., Van den Eynde J., R., Jehn, "SNAPPSHOT: ESA planetary protection compliance verification software, Final report", ESA contract, Jan 2016

Planetary protection

Effect of launcher dispersion: Solo launcher



- Venus: CA
- Venus: Resonance
- Venus: Impact



Uncertainty: **state dispersion**
(**covariance matrix**)

Propagation: time 100 years,
Number of runs: 54114 (the
minimum number of runs required
to prove that planetary protection
verified with 99% confidence)

*Representation of the worst close
approaches for the 1000 Monte Carlo
runs of the launcher of Solo on the b-
plane of Venus.*



Camilla Colombo, Gabriella Gaias, Ioannis Gkolia, Juan Luis Gonzalo, Narcis Miguel, Mirko Trisolini, Stefan Frey, Simeng Huang, Davide Menzio, Matteo Romano

Research team



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MILANO 1863



Department of Aerospace Science and Technology



Camilla Colombo



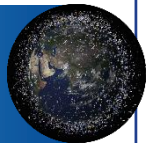
Mirko Trisolini
Space debris



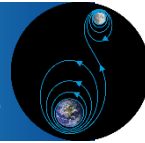
Stefan Frey
Space debris



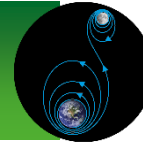
Ioannis Gkolas
Space debris



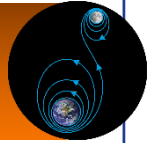
Gabriella Gaias
Space transfers



Davide Menzio
Space transfer



Narcis Miguel
Solar sails



Juan Luis Gonzalo
Space debris
Asteroids



Matteo Romano
planetary
protection



Simeng Huang PhD
Large constellations



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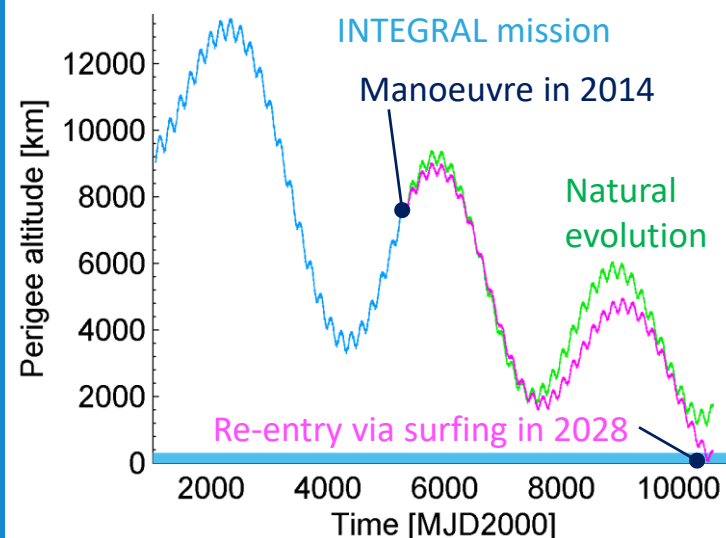
Orbital dynamics

Contributions

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



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





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