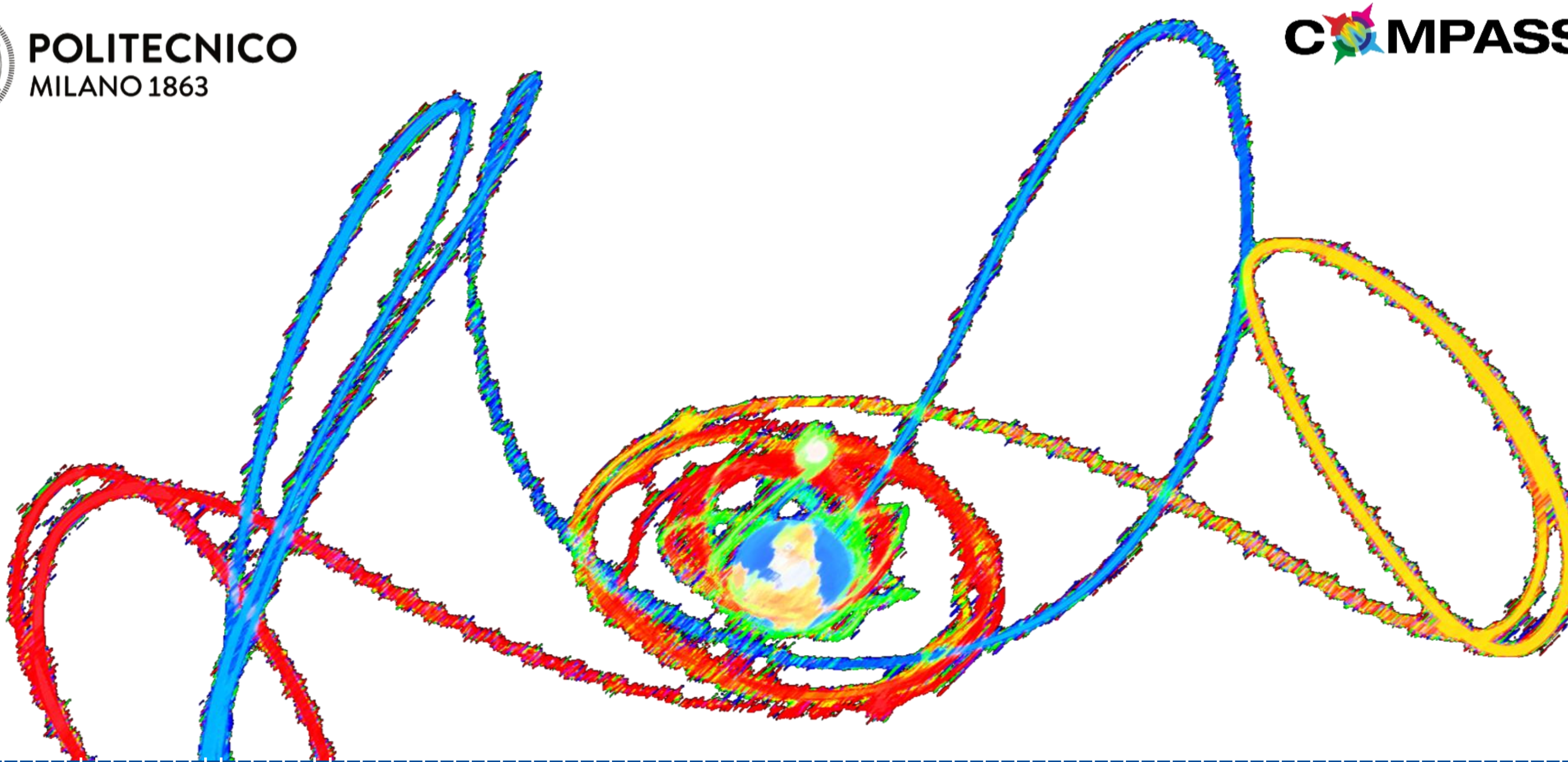
POLITECNICO
MILANO 1863



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

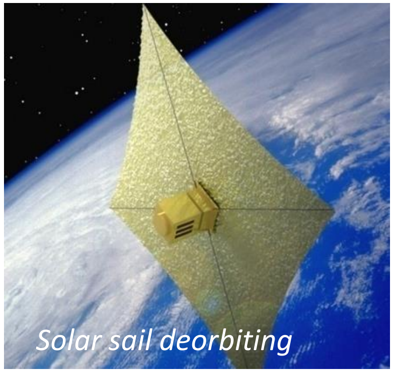
INTRODUCTION

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.


Solar sail deorbiting


Artistic rendering of OneWeb's satellites in orbit. Credit: Airbus

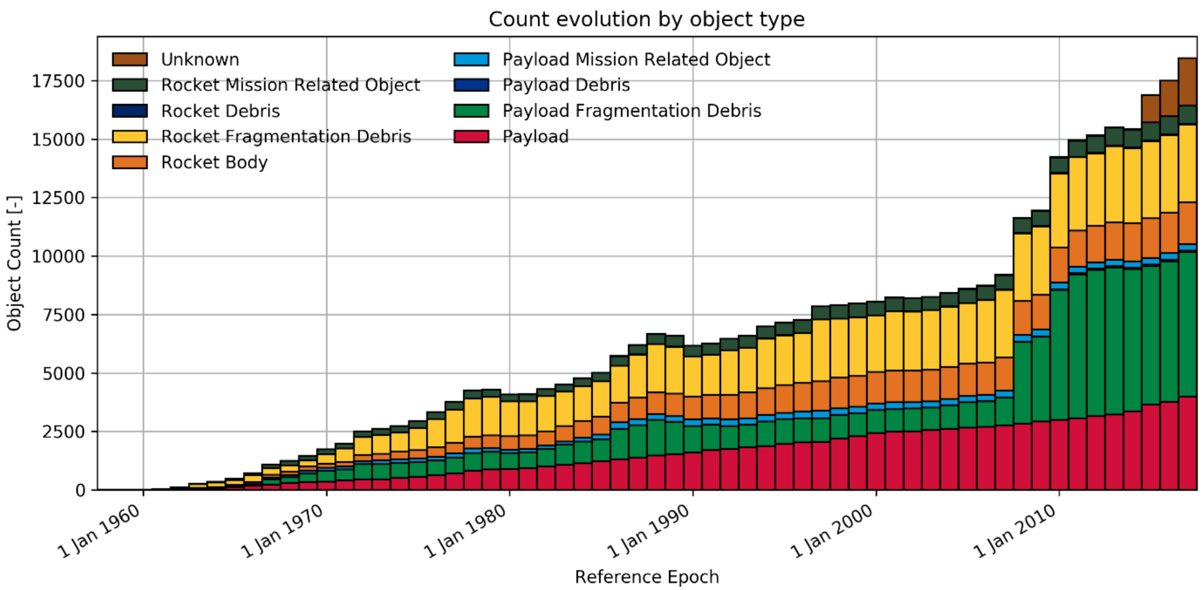

Credit: The University of Michigan

Introduction

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

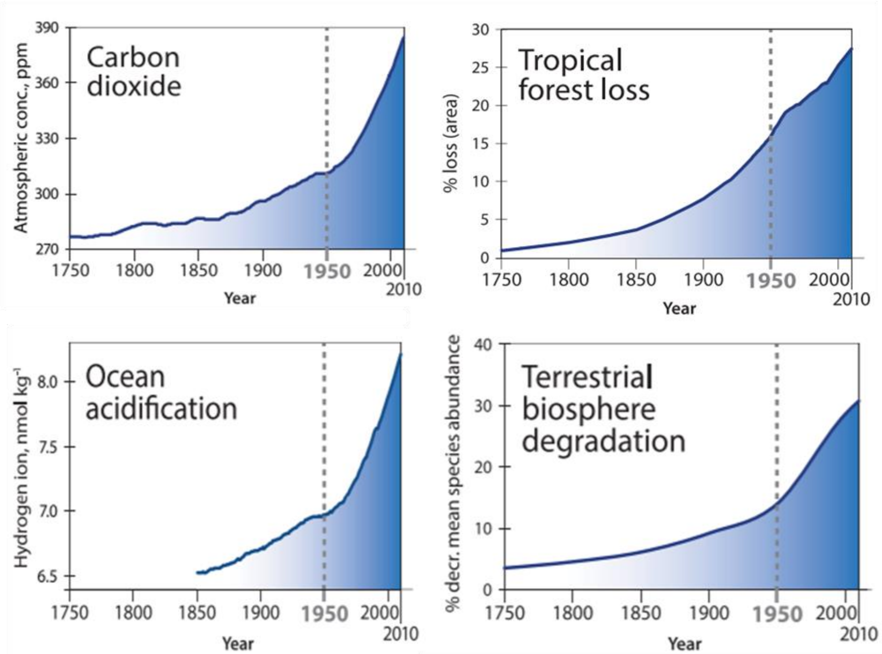
➢ https://www.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/Space_debris_by_the_numbers

Introduction

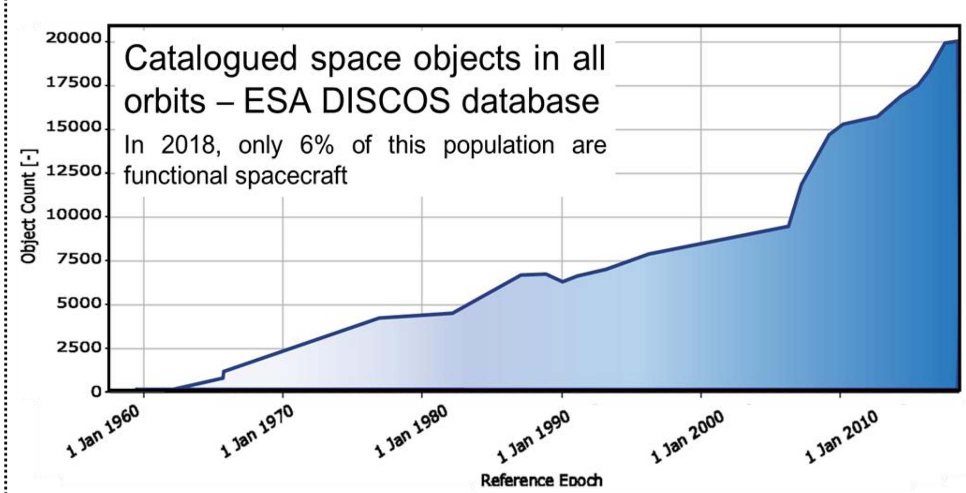
Space situation awareness: space debris

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.

Introduction

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

Introduction

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 enables by mission to asteroids and demonstration mission for asteroid deflection


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


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

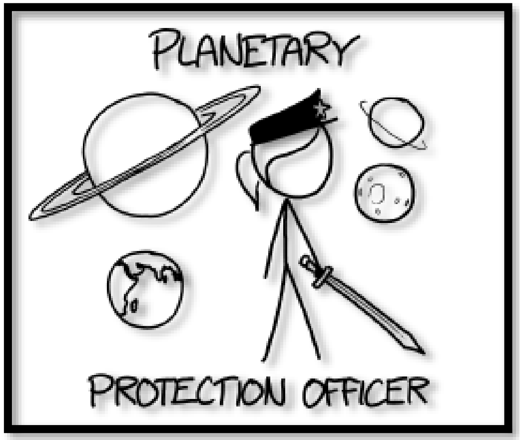

Asteroid manipulation

Introduction

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

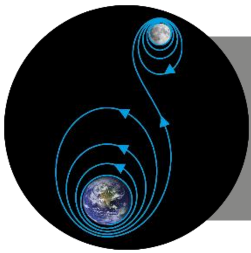


Background and proposed approach

COMPASS erc

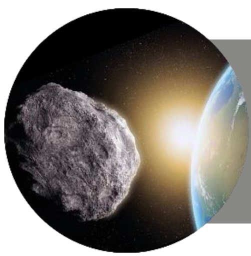
Services, technologies, science, space exploration	ORBIT PERTURBATIONS Traditional approach: counteract perturbations	COMPASS Novel approach: leverage perturbations

SPACE TRANSFER



Reach, control operational orbit

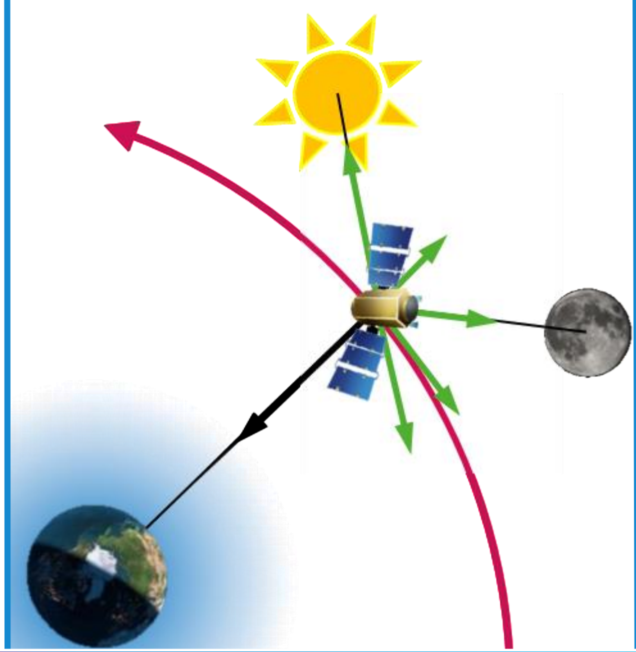
SPACE SITUATION AWARENESS



Asteroids. planetary protection

Space debris

- Complex orbital dynamics
- Increase fuel requirements for orbit control



Reduce extremely high space mission costs

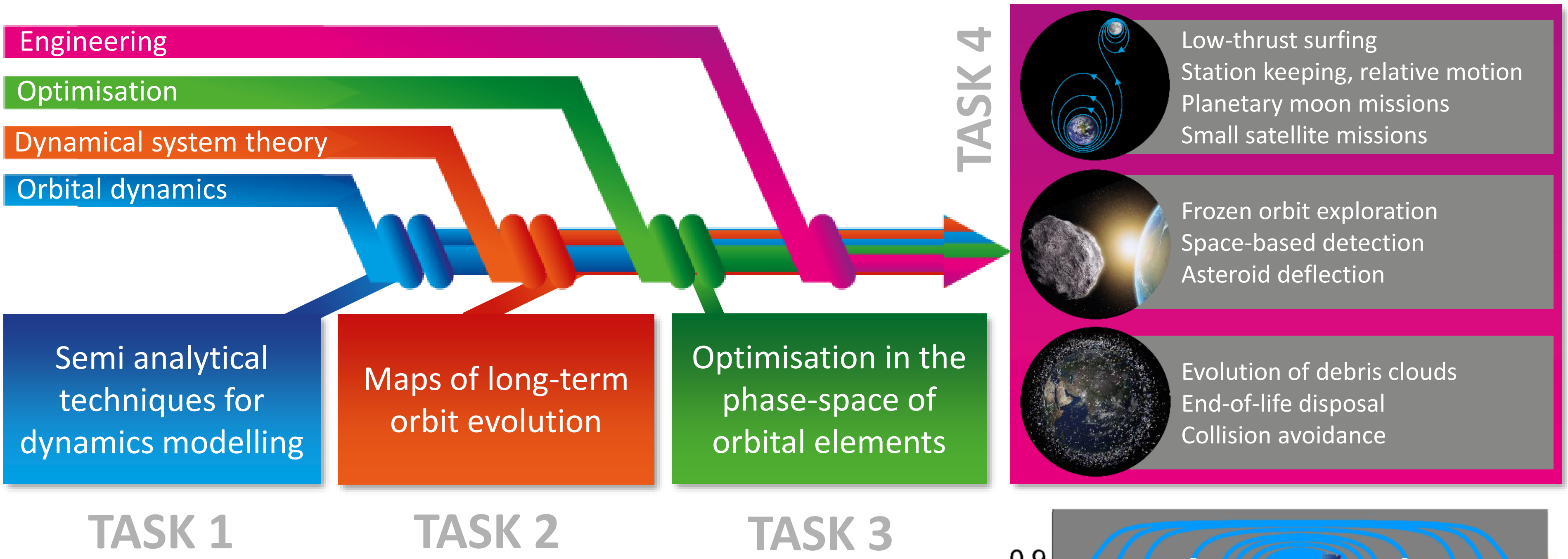
Create new opportunities for exploration and exploitation

Mitigate space debris

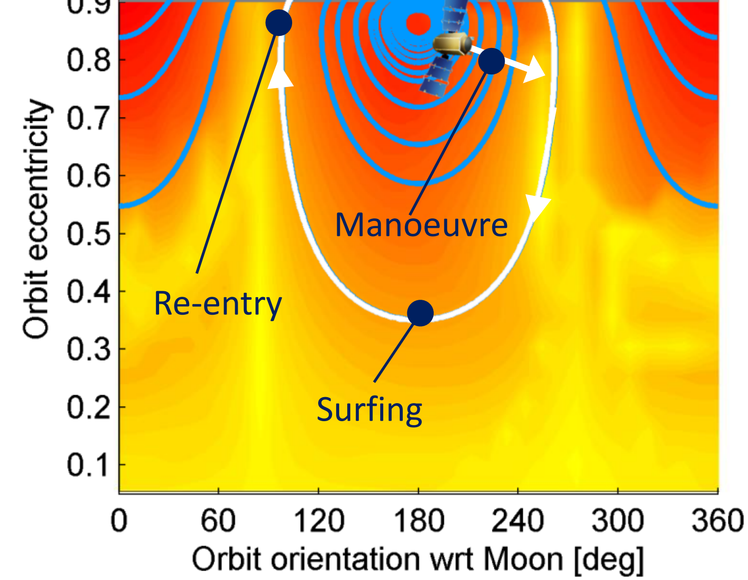
Develop novel techniques for orbit manoeuvring by surfing through orbit perturbations

METHODOLOGY

Methodology and expected results



- Study of the spacecraft orbit evolution (planetary and n-body environment)
- Topology of space of orbit perturbations and dynamics
- Spacecraft surf these natural currents to the desired orbit
- Design of space missions and space applications



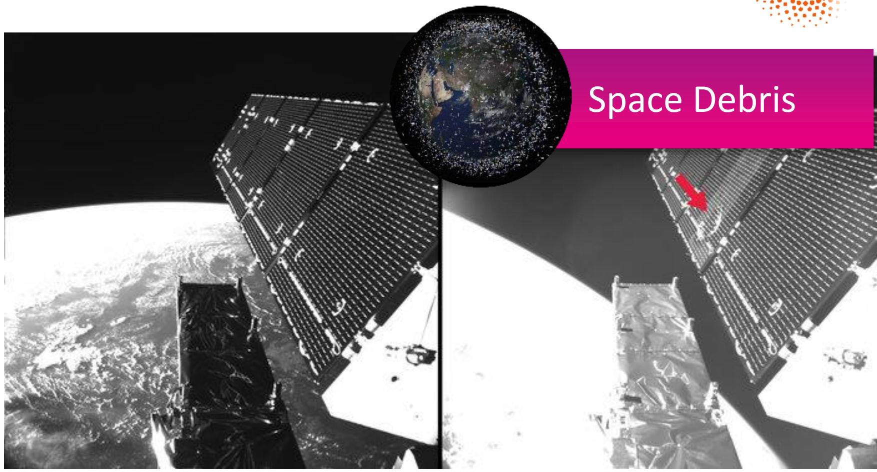
MISSION APPLICATIONS

Space debris evolution

And its collision risk

Problem

How to model such a large number of particles?



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

Model

Model it as a continuum and propagate through the continuity equation

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

- $\frac{\partial n}{\partial t}$ → Density of fragments in the phase space of orbital elements $n(a, e, i, A/m)$
- $\nabla \cdot (n\boldsymbol{F})$ → Slow phenomena: perturbations
- g → 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

Space debris evolution

Explosion in low Earth orbit: evolution cloud of fragments

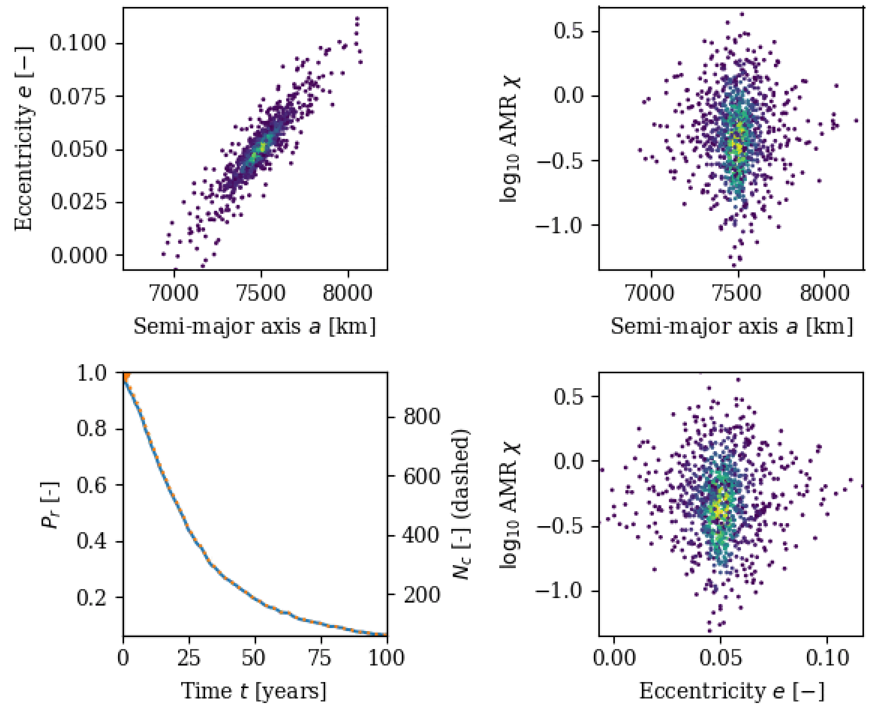
Space Debris

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

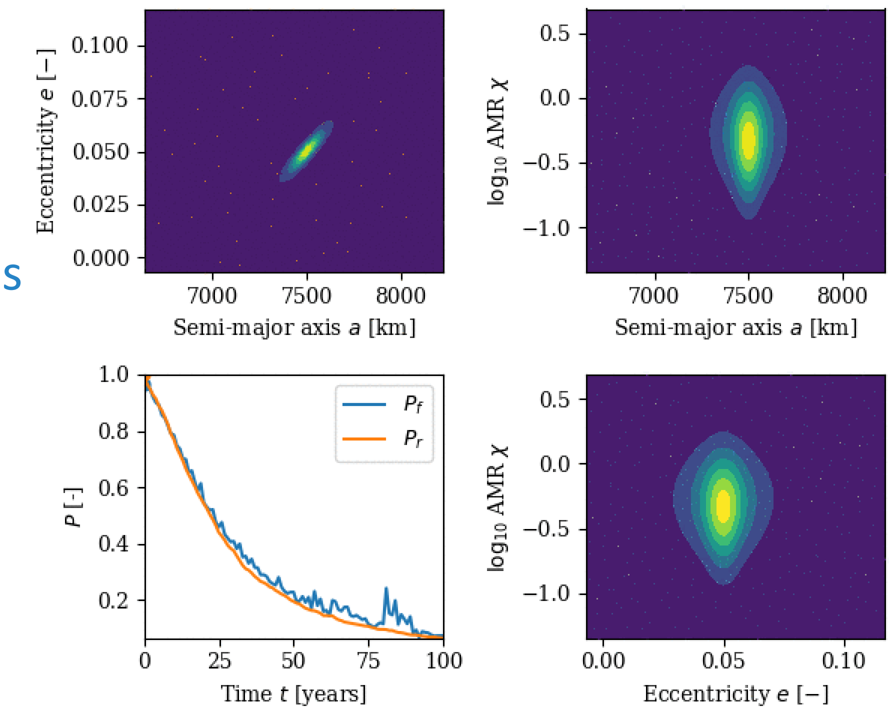
Space debris evolution

Density interpolation

- Interpolation through Gaussian Mixture Model

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

- Fitting routine: regularised least squares in ln-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

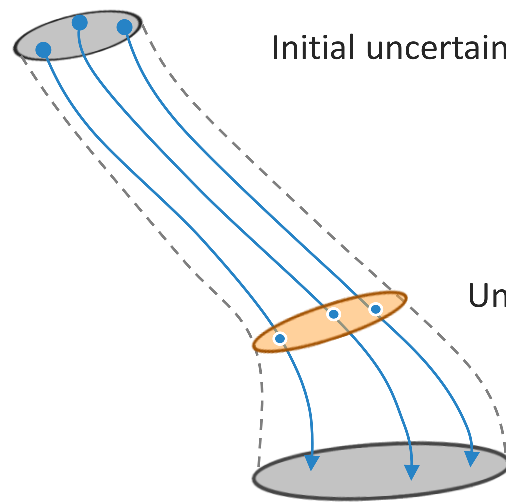
- Propagation of re-entry uncertainties in the initial conditions and spacecraft parameters to predict spacecraft re-entries.
- Modelling of asteroids re-entries and the propagation of their fragments after break-up.

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

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



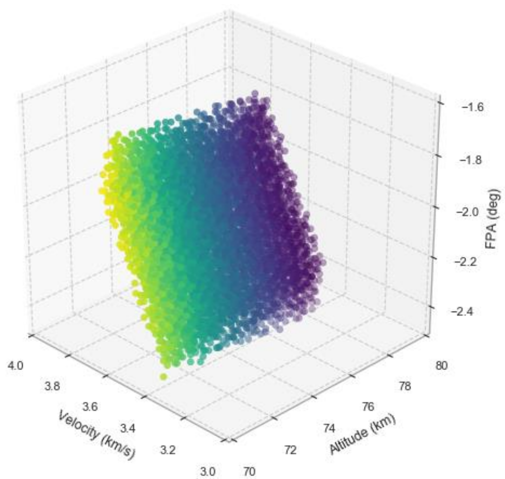
Re-entry prediction

Methodology example

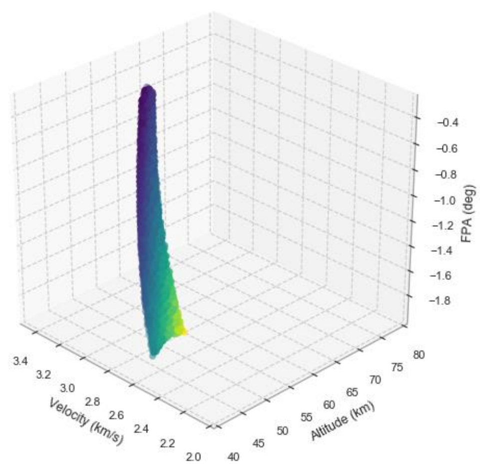
Space Debris

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

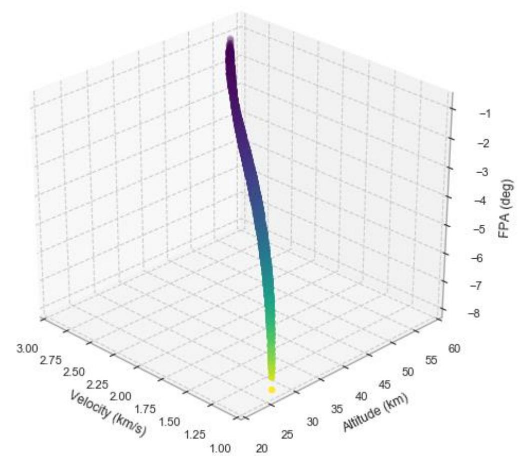
→ Compute the casualty area on ground



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

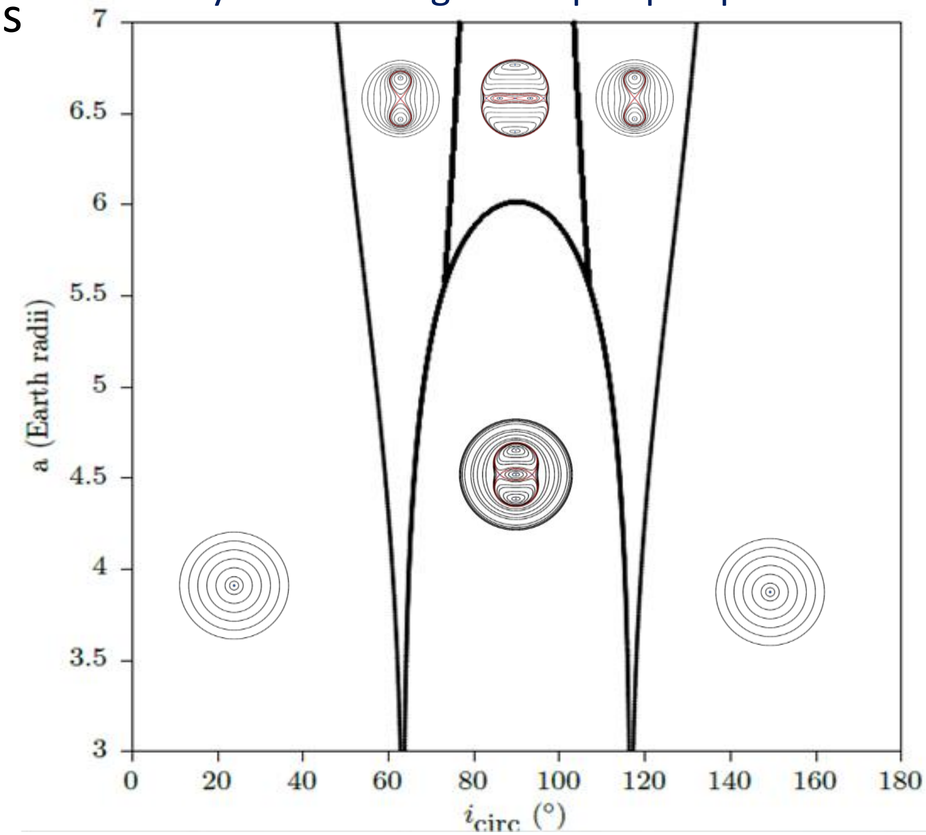
Problem

- 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

End-of-life disposal design

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)

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

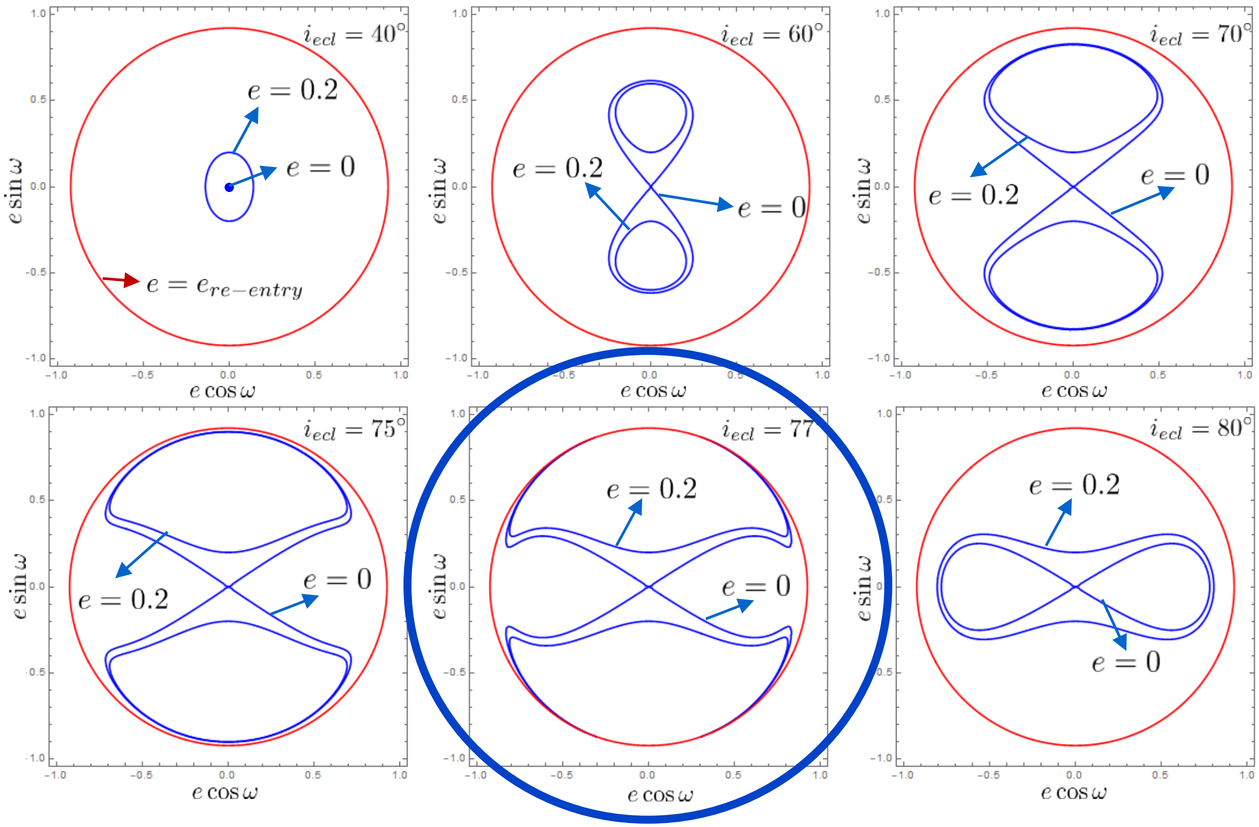
$$\bar{\bar{H}} = \bar{\bar{H}}(a, e, i, \Omega, \omega, -, \Omega_{\leftmoon}, \theta_\odot; \mu, J_2, R_\oplus, \epsilon, n_\odot, a_\odot, n_{\leftmoon}, a_{\leftmoon}, \eta_{\leftmoon})$$

➢ 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

Space Debris

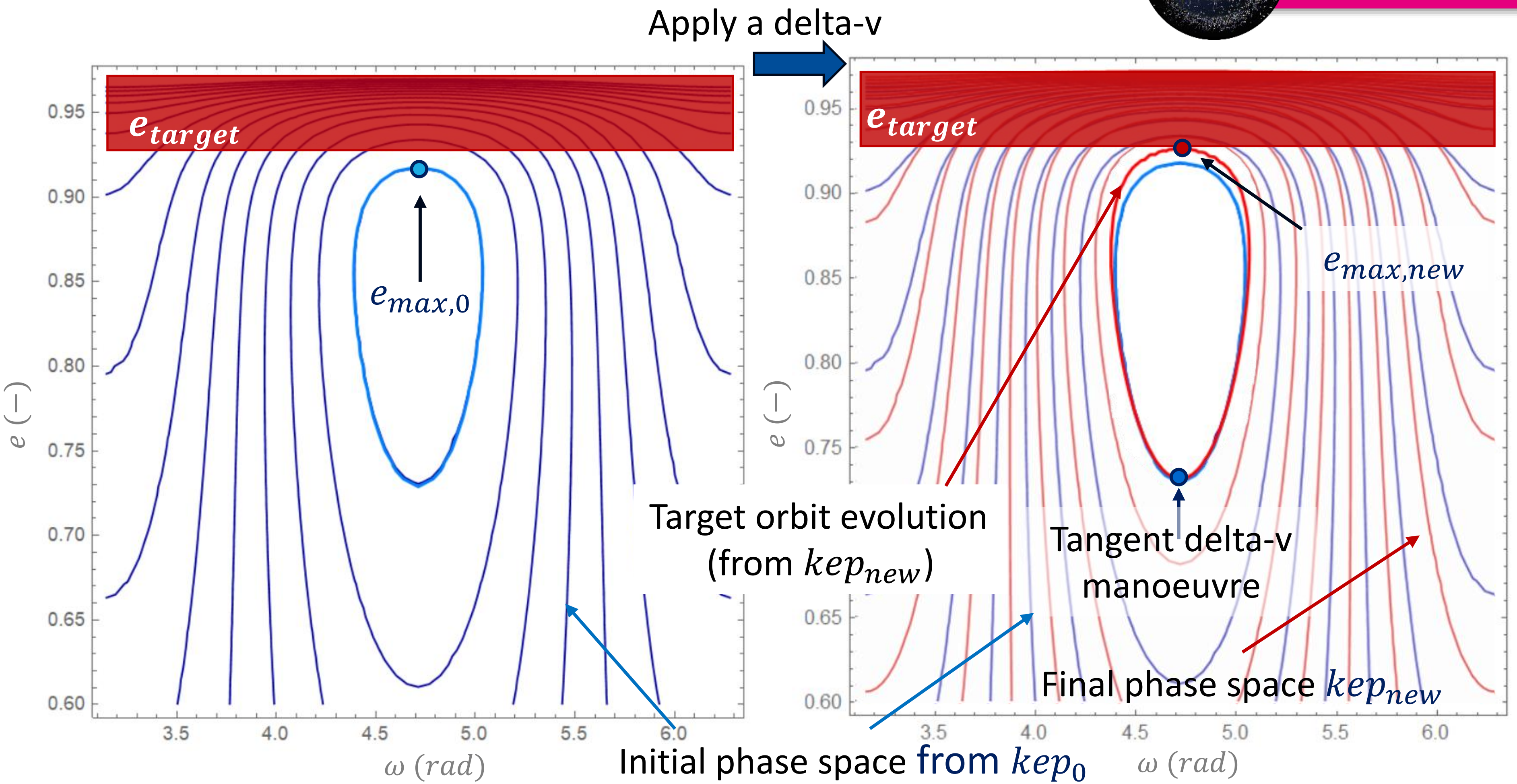


Exploitation of the analytical modelling in the design of end-of-life disposal manoeuvres at GEO altitude

- 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

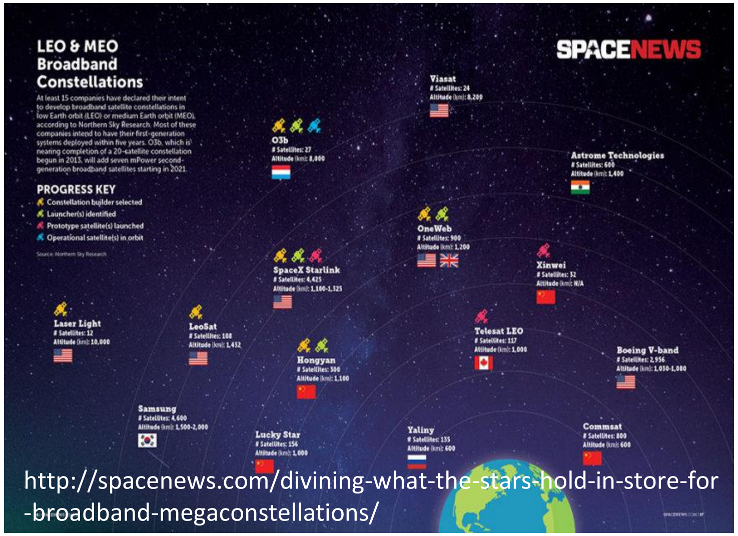


- F. Scala, C. Colombo, I. Gkolias, "Surfing in the phase space of Earth's oblateness and third body perturbation", AAS-19-484, 29th AAS/AIAA Space Flight Mechanics Meeting, January 15, 2019 - Ka'anapali, HI, USA

Large constellations

Design of large constellations for space-based services

Space Transfer

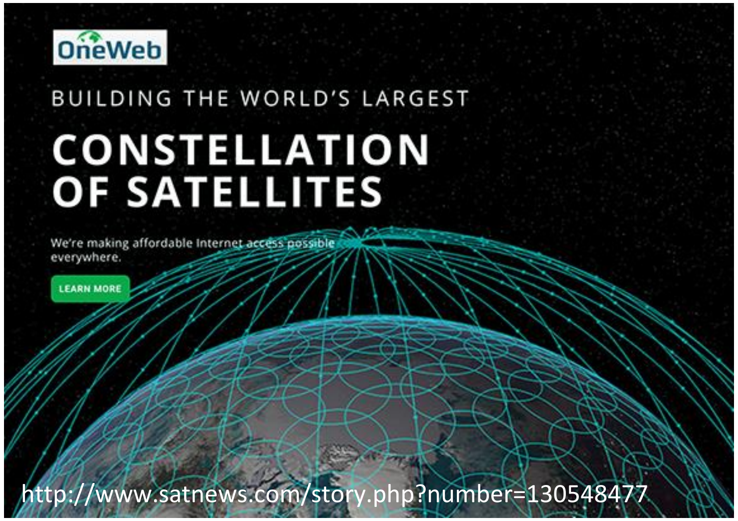


http://spacenews.com/divining-what-the-stars-hold-in-store-for-broadband-megaconstellations/

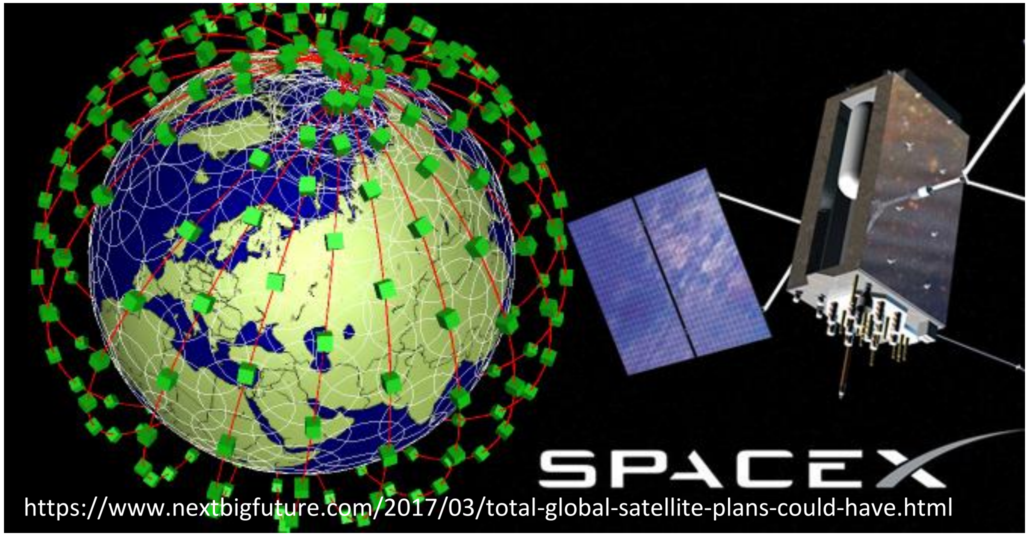
Why

Large constellation of small satellites proposed for space based services

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



http://www.satnews.com/story.php?number=130548477



https://www.nextbigfuture.com/2017/03/total-global-satellite-plans-could-have.html

Large constellations

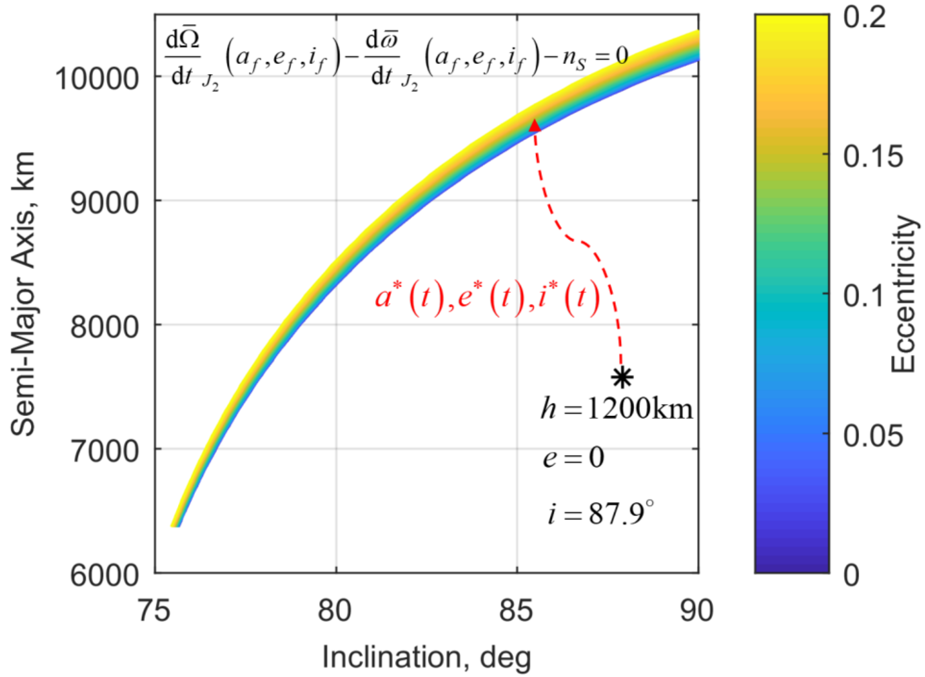
COMPASS erc

Space Transfer

Design of large constellations for space-based services

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.

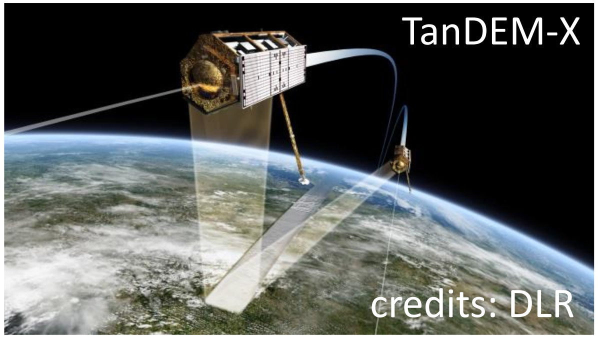
Formation flying

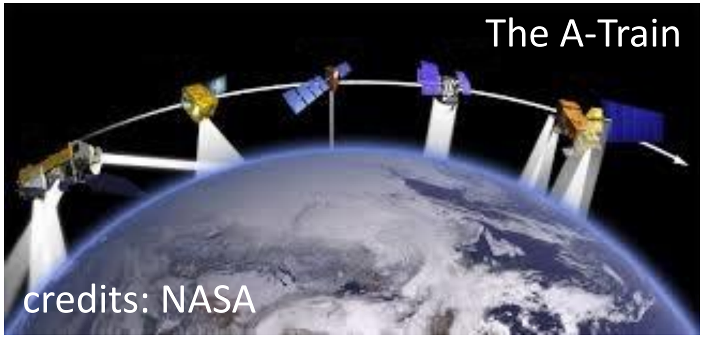
Exploiting satellites which fly close to each other

Space Transfer

- 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)





Formation flying

Focus on satellites' relative motion

Space Transfer

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

Space Transfer

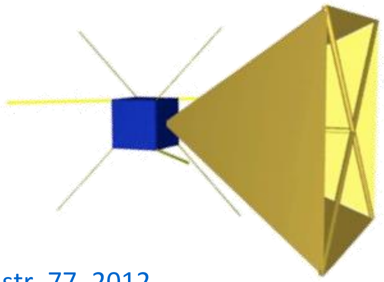
Problem:

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

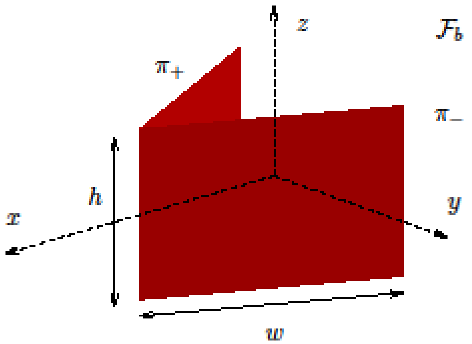
How:

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

3D concept



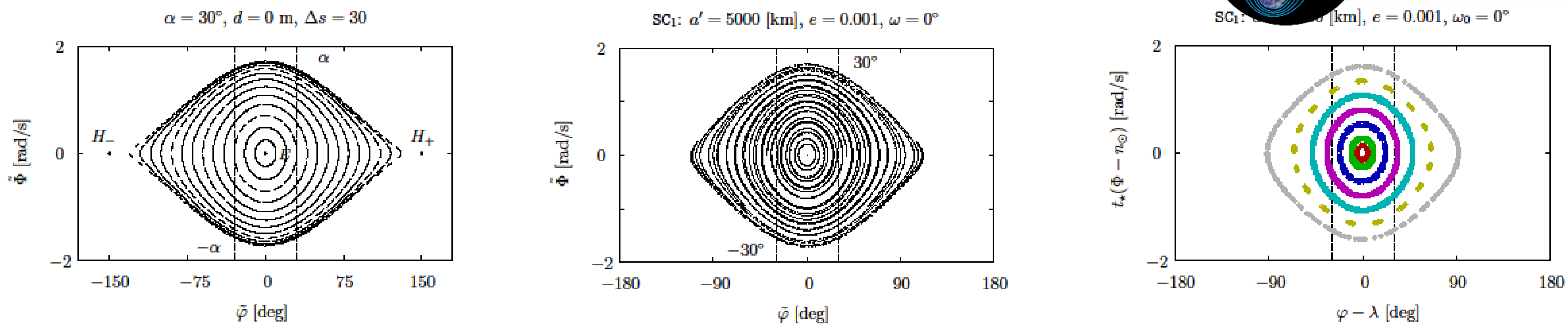
2D simplified



- 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

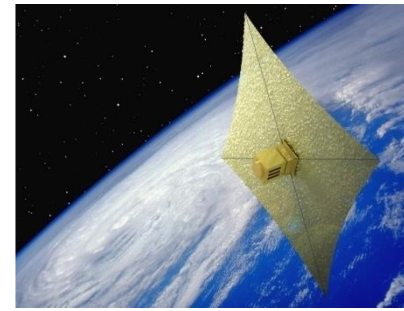
Solar sails and collision avoidance

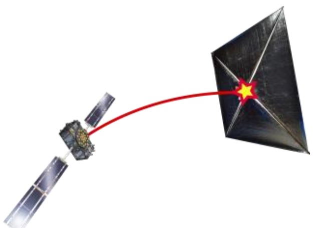
Collision avoidance manoeuvres for solar sail missions

Space Transfer

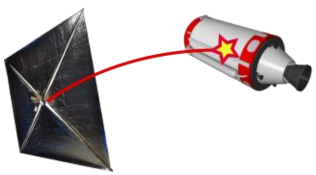
Solar sails are a cost-effective alternative to reduce de-orbit time for satellites reaching their end of life

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



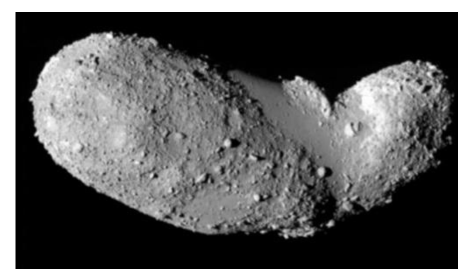


But their large cross-sectional area increases collision risk



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**

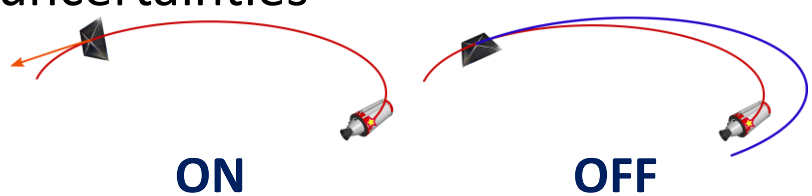


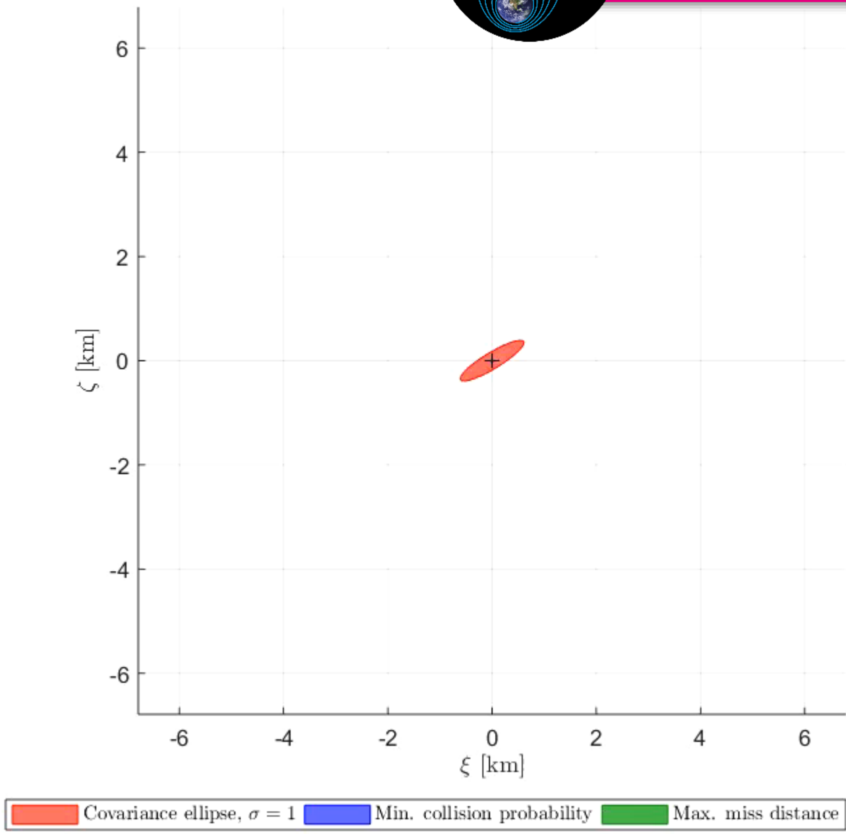
Solar sails and collision avoidance

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





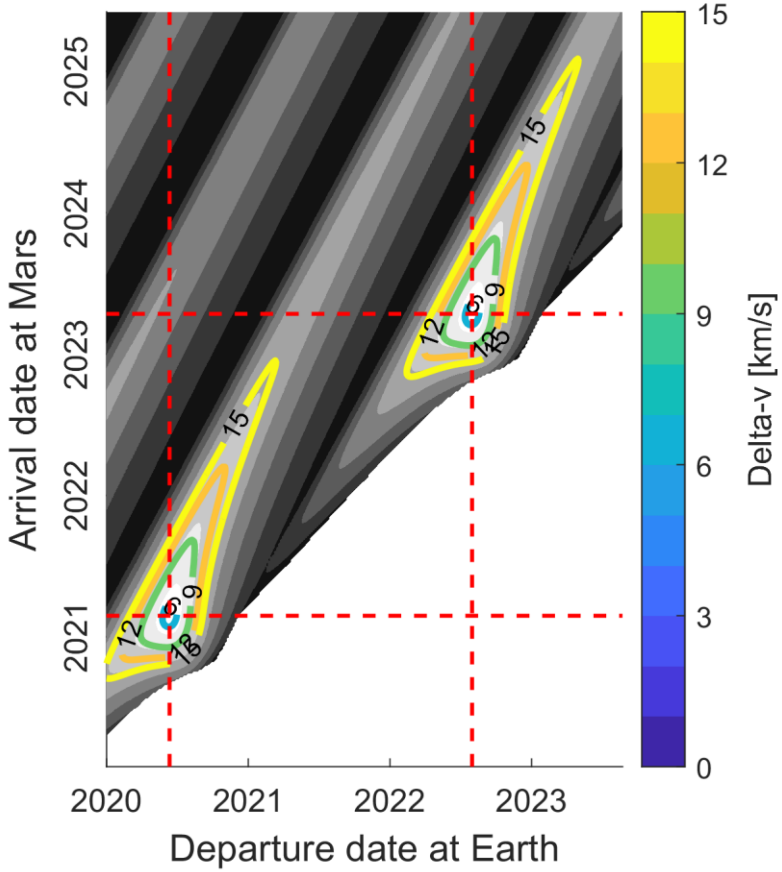
Max. miss distance vs min. collision probability manoeuvres, with time-evolving uncertainties

➢ 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



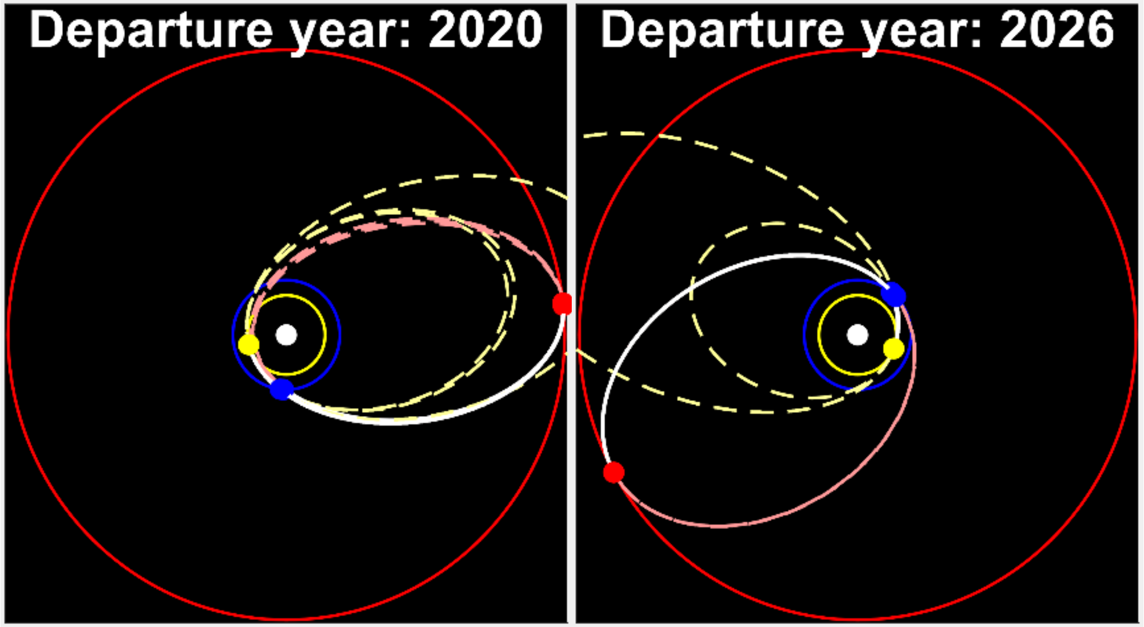
➢ D. Menzio, C. Colombo, "An analysis of the porkchop plot for direct, multi-revolution and flyby missions, DyCoSS conference 2018, IAA-AAS-DyCoSS 18-621

Interplanetary transfer

Fly-by design through maps

Space Transfer

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

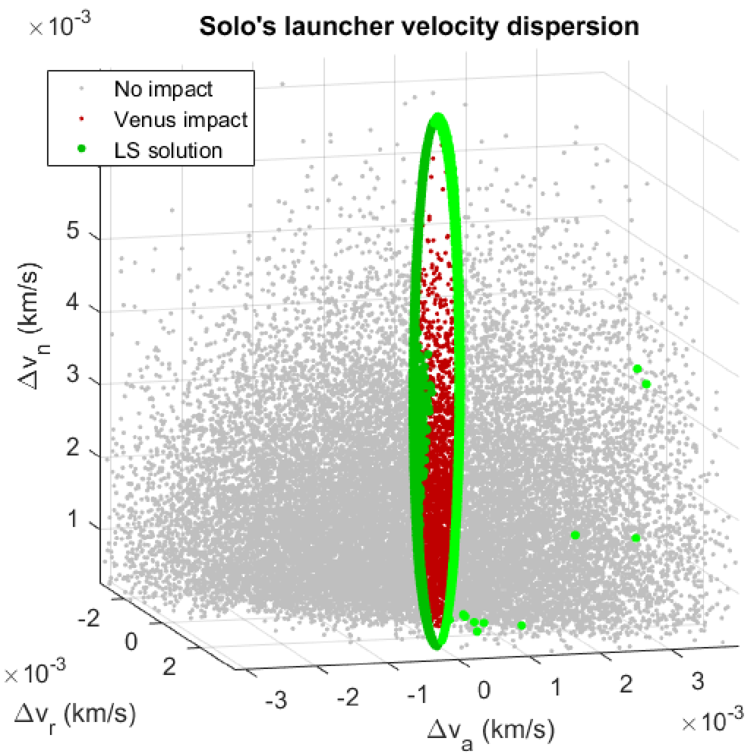
Planetary protection

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)

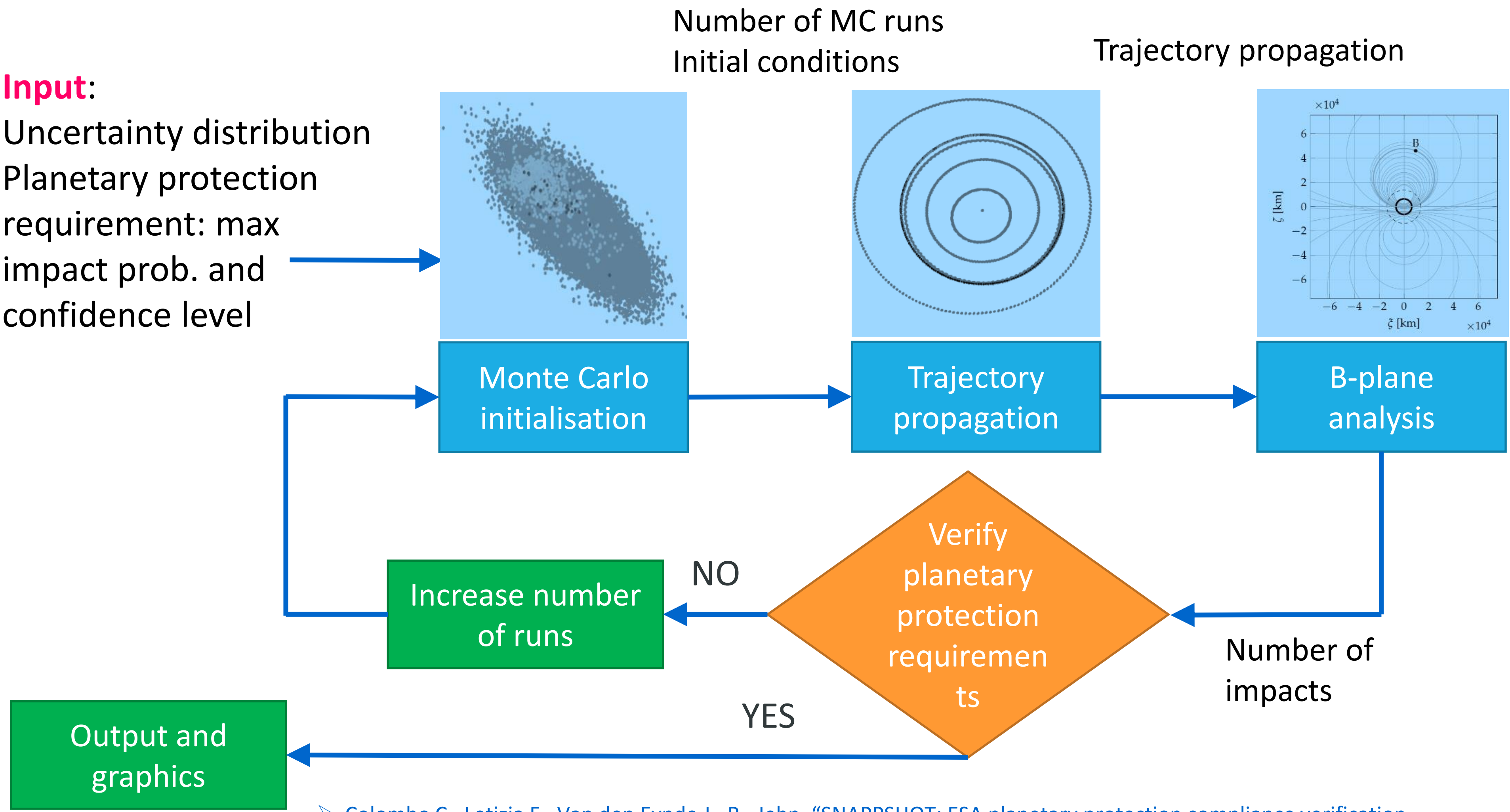


Solo launcher velocity dispersion: impact condition with Venus

➢ 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

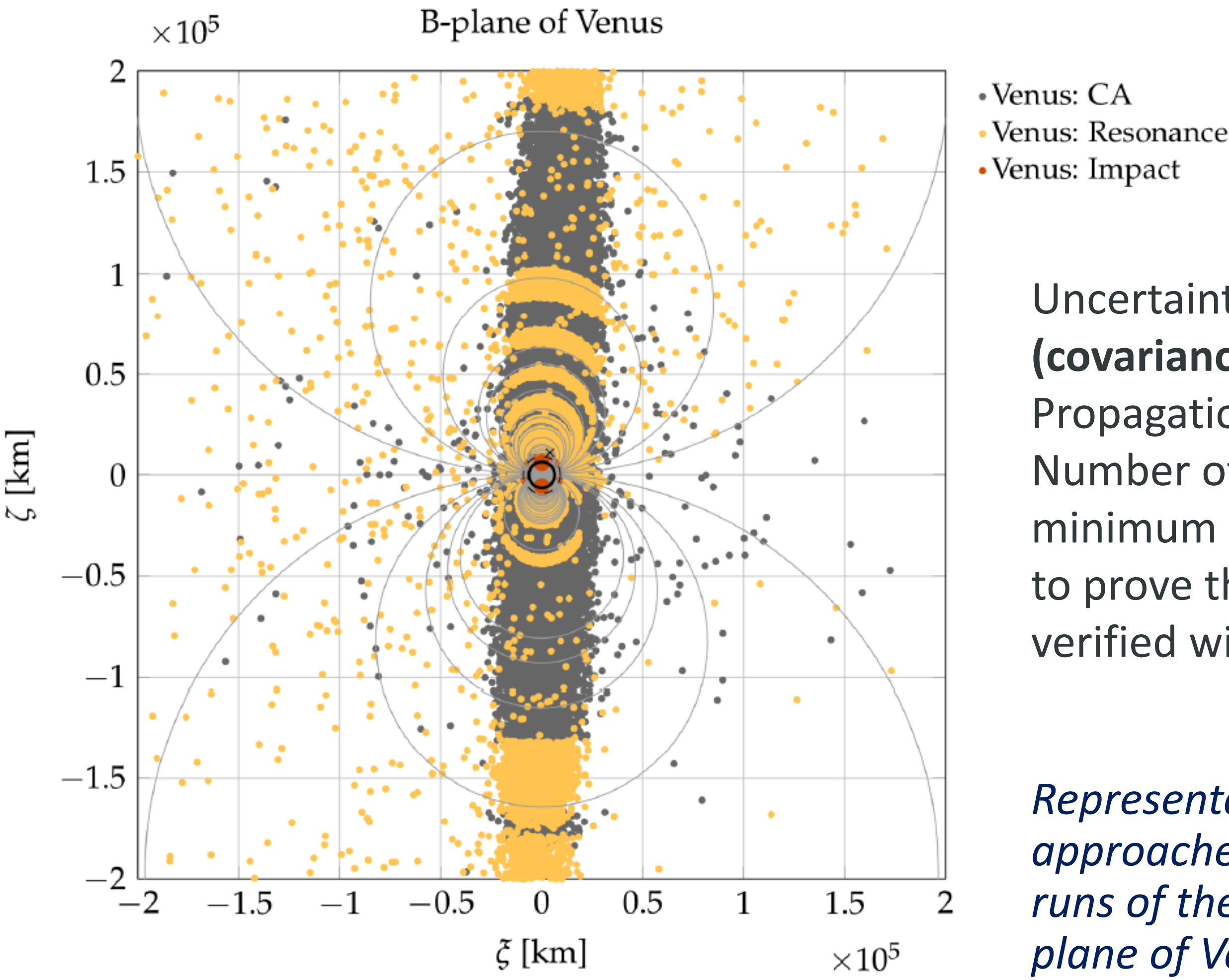
Suite for Numerical Analysis of Planetary Protection

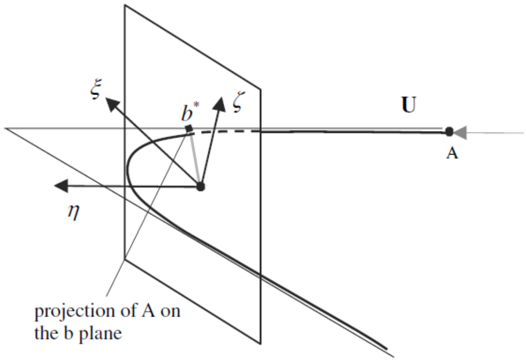


- Colombo C., Letizia F., Van den Eynde J., R., Jehn, “SNAPPSHOT: ESA planetary protection compliance verification software, Final report”, ESA contract, Jan 2016

Planetary protection

Effect of launcher dispersion: Solo launcher





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.

- Letizia F., Van den Eynde J., Colombo C., R., Jehn, 2016

Research team

Research team

POLITECNICO MILANO 1863

COMPASS erc

Department of Aerospace Science and Technology

COMPASS erc ReDSHIFT esa

Horizon 2020 European Union funding for Research & Innovation

Camilla Colombo

Mirko Trisolini
Space debris

Stefan Frey
Space debris

Ioannis Gkolias
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

Scientific Advisory Board

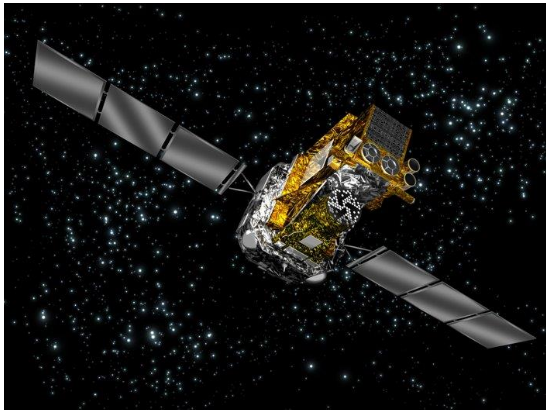
esa – European Space Agency	cnes – Centre National d'Études Spatiales
NASA – NASA	JAXA – Japan Aerospace Exploration Agency
asi agenzia spaziale italiana – Italian Space Agency	

- Engineering
- Optimisation
- Dynamical system theory
- Orbital dynamics

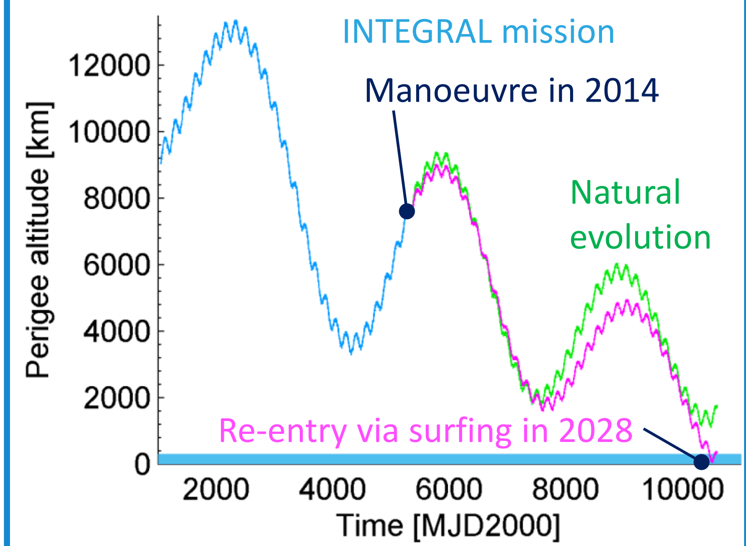
Conclusions

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



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)

Camilla Colombo and the COMPASS team

camilla.colombo@polimi.it

www.compass.polimi.it

@COMPASS_ERC