ACT
10 years event

Trends in Advanced Research on Mission Analysis

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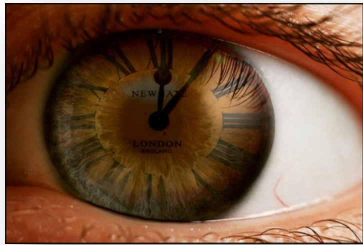
Agenda

A bit of ACT History

The Last 10 years: Methods and Tools

Trends in Advanced Research in Mission Analysis?



Future Perspectives

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A bit of ACT History

The Beginning

I arrived in **November 2001** because of the idea of a man

There was no office and no one knew about me

The ACT was a one man band…me, myself and I

Six months later Leo arrived

Andres was already a YGT in the CDF…

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The First Steps

The mandate was:

Start up the ACT… piece of cake

Find new ways to do Mission Analysis in ESA

That required a bit of thinking….

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Initial Observations

ESA not adventurous and risk-adverse even at low TRL

Little or no internal developments: heavy reliance on external parties.

Little publication output from ESA

Mission Analysis like cooking: don't tell the cook how to cook

American innovation syndrome: US seen as a reference from which to import proven technology

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First Ideas and Actions

Formalise the Problem

- Translate Mission Analysis problems into formal mathematical problems

Introduce New Techniques

- Computational Intelligence
- Global optimisation methods
- Validated and high order integration methods
- Distributed computing
- Robust design

Bridge the Gap

- Foster EU capabilities
- Avoid importing technology from the US

Forecast Future Needs

- Asteroids
- Small scale low cost
- New platforms

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A Few Initial Activities

Ariadna studies on:

- Global optimisation methods for Mission Analysis
- New applications for low energy transfers
- Interstellar travel

Small scale explorative study on:

- Computational intelligence techniques for integrated system design

Small internal studies on:

- Global methods for Mars mission design
- Asteroid deflection
- Robust trajectory design
- Interval analysis

Established contact with some non-space communities:

- Optimisation
- Uncertainty Quantification
- Validated integration and interval analysis

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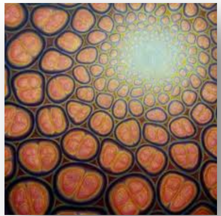
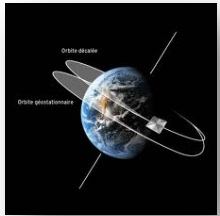
The Last 10 Years: Methods and Tools

The Last 10 Years: Methods and Tools

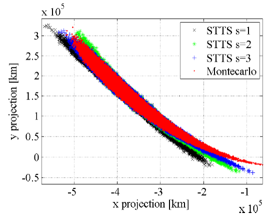


Global Optimisation Methods Became Popular

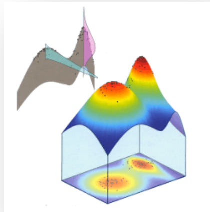
Improvements in the Solution of Optimal Control Problems



Dynamical System Theory Unveiling the World of NKO



High Order Expansion and Validated Methods



Concepts of Robustness and Reliability

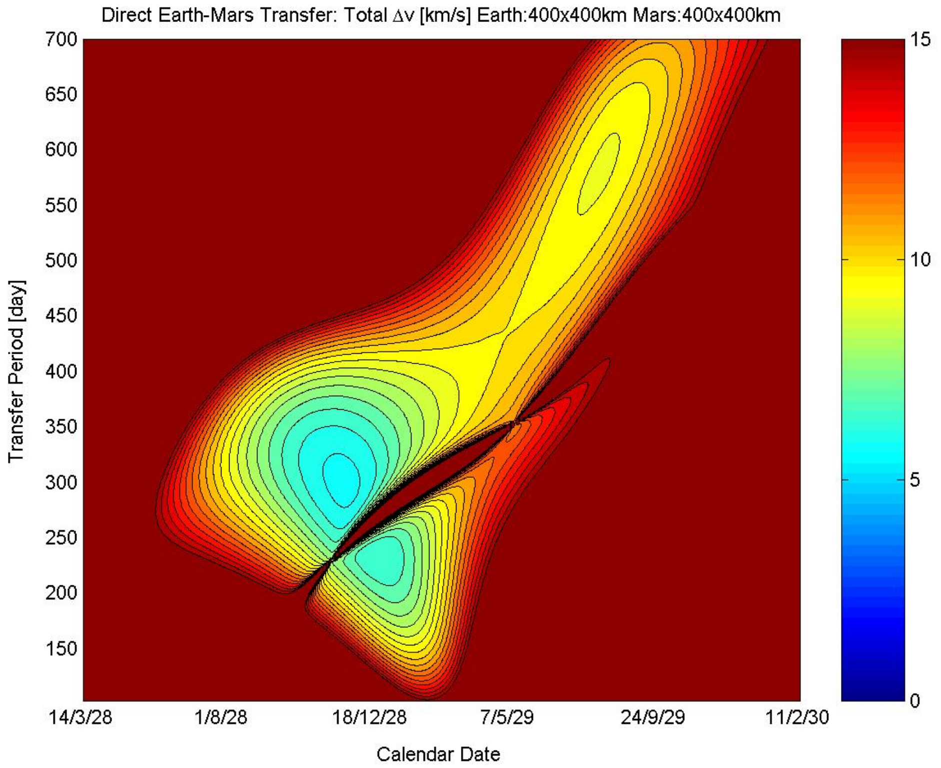
Have Emerged

Global Methods

Problem Statement:

Efficient exploration of the space of transfer options, for a given mission, to generate the set of optimal solutions fulfilling mission constraints.

Example 1: Design of a Transfer to Mars.



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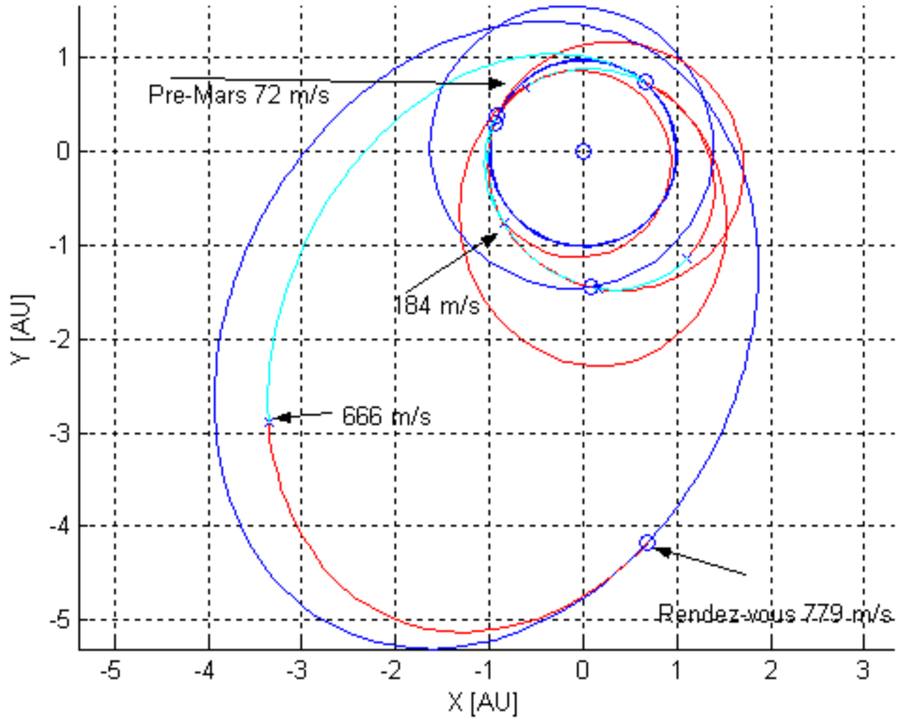
Global Methods

Problem Statement:

Efficient exploration of the space of transfer options, for a given mission, to generate the set of optimal solutions fulfilling mission constraints.

Example 2: Design of an Optimal Transfer for Rosetta.



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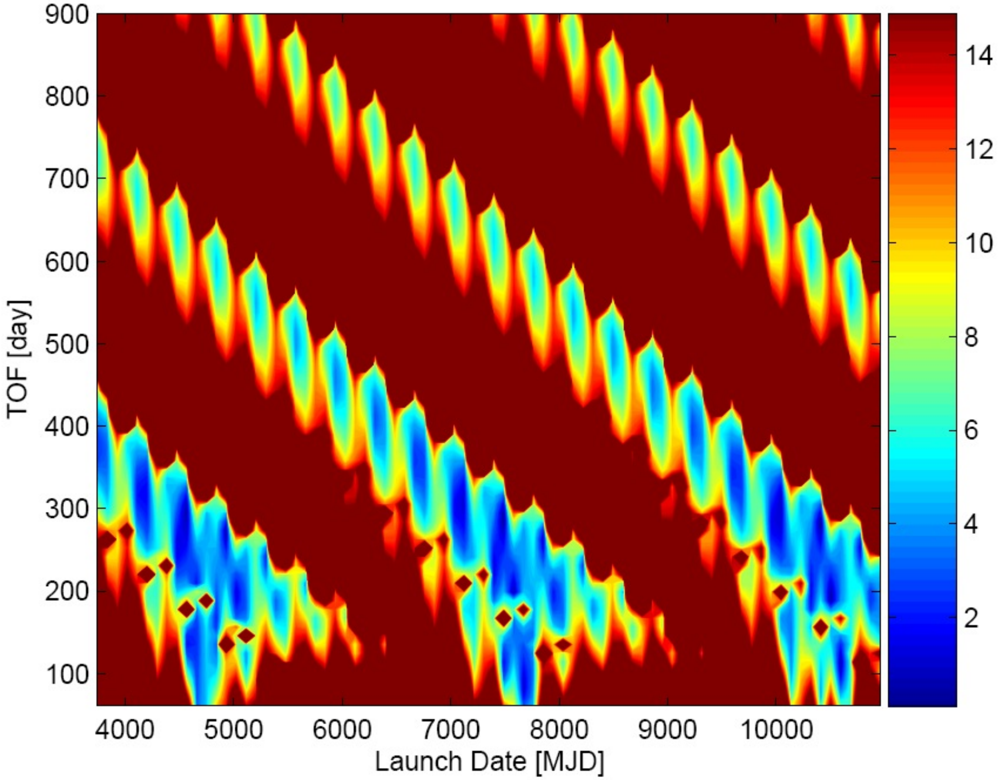
Global Methods

Problem Statement:

Efficient exploration of the space of transfer options, for a given mission, to generate the set of optimal solutions fulfilling mission constraints.

Example 3: Design of a Transfer to asteroid Apophis.



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Global Methods - Why bother?

Initial realisation of the potential improvement in mission objectives

	Ref	Sol.1	Sol.2
Launch Date	15/10/1997	20/10/1997	17/10/1997
Hyp Esc Vel (km/s)	3.93	4.04	4.03
E-V TOF	194 days	191 days	191 days
V-V deep space ΔV	471 m/s	432 m/s	414 m/s
V-V TOF	425 days	421 days	420 days
V-E TOF	54 days	53 days	53 days
E-J deep spaceΔV	0 m/s	132 m/s	0 m/s
E-J TOF	499 days	493 days	540 days
J-S deep space ΔV	376 m/s	0 m/s	0 m/s
J-S TOF	1267 days	1216 days	1656 days
Hyp Arr Vel (km/s)	5.36	5.58	4.59
Total ΔV (km/s)	10.14	10.18	9.06

Cassini-Huygens **Vasile & DePascale 2004**

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Global Optimisation Methods

Remarkable improvement in general methods:

GASP: Super-fast branch and prune algorithms that solve MGA problems in polynomial time.

Memetic Algorithms that can improve mission payload mass by 20% with over 80% probability

Hidden genes GA and Ant Colony for automatic MGA sequence selection.

Massive parallelisation and Ensemble methods (e.g. DiGMO).

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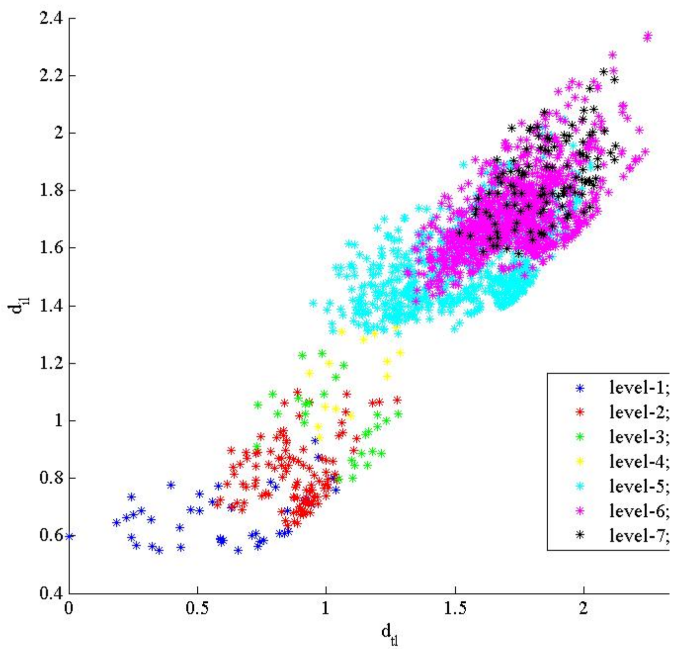
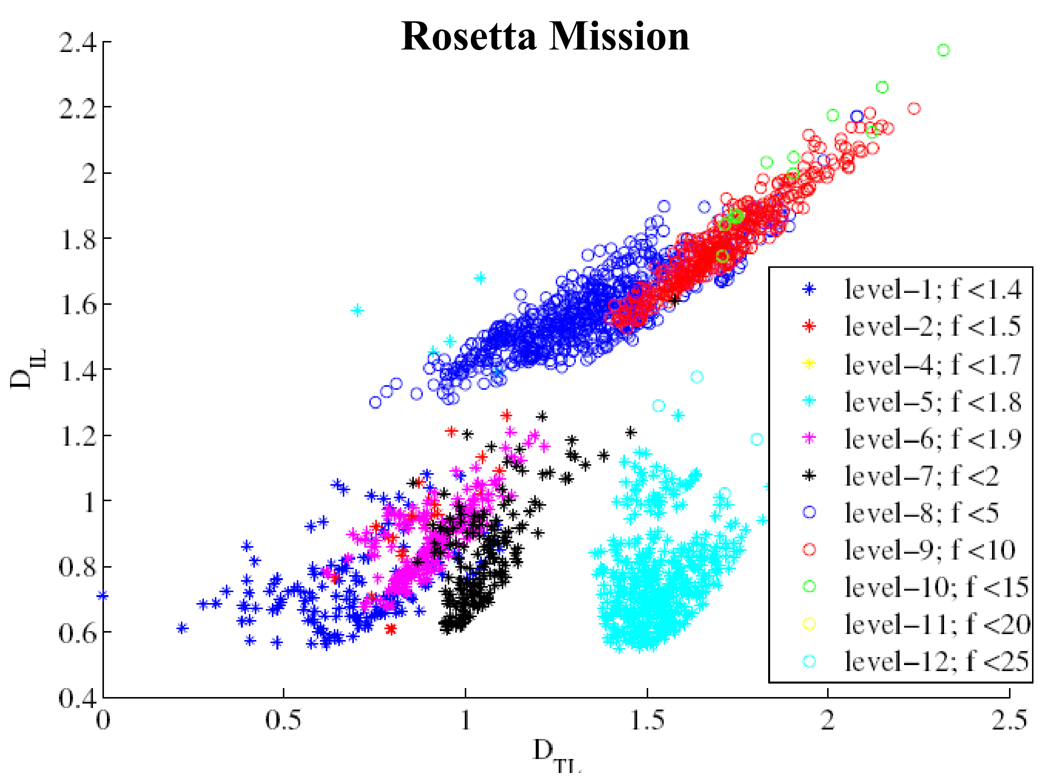
Where are we after 10 years?

Remarkable improvement in understanding of the structure of some problems:

- 2D D_{TL}-D_{IL} graphs of multidimensional spaces

Cassini





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Global Optimisation Methods

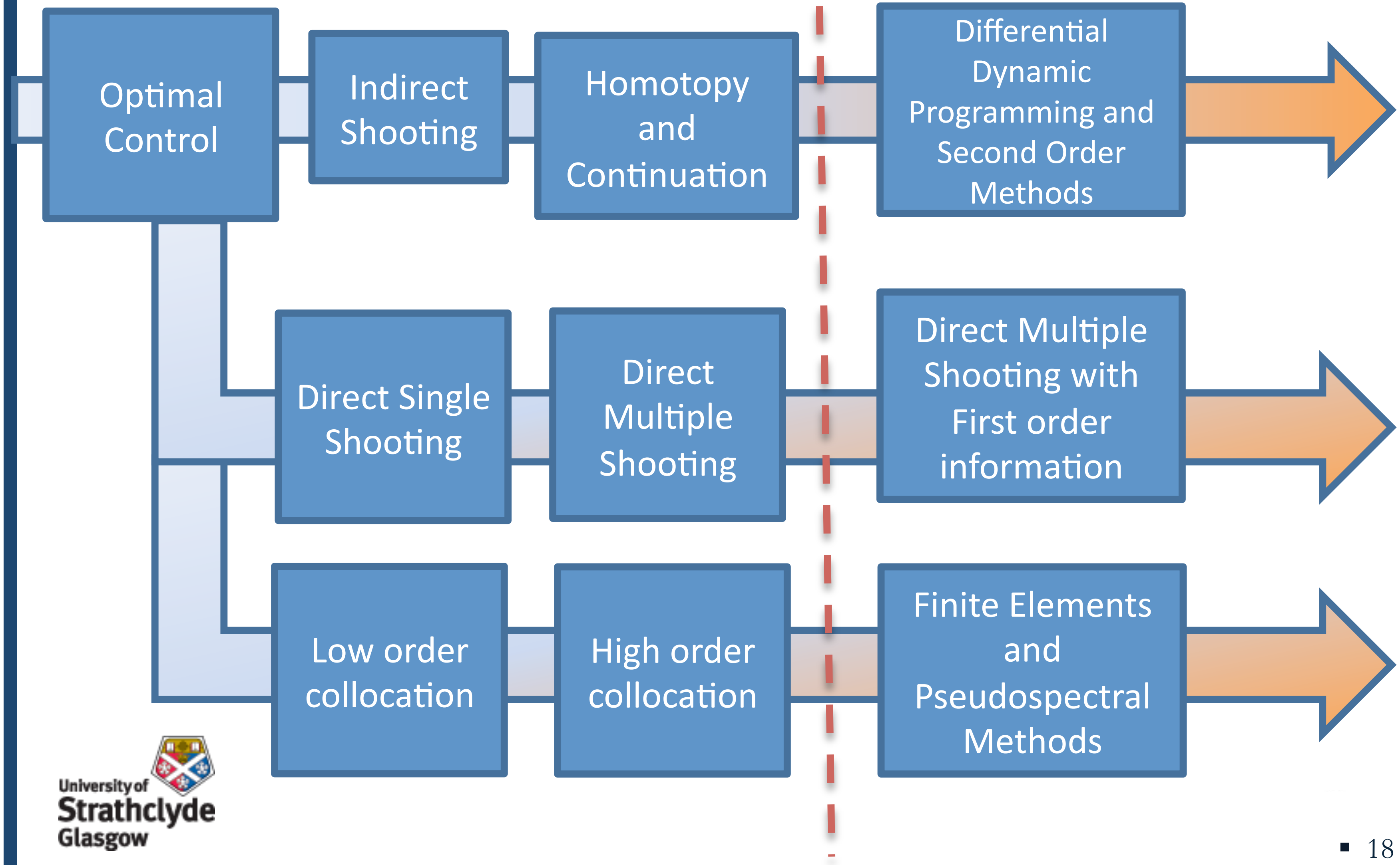
Remarkable lessons learnt from GTOC:

- Private sector can do it
- JPL certainly can do it
- Academia can do it
- Everybody went global

- **Can we do it better?**
- **Do we need to do it better?**

Optimal Control and Trajectory Design

With the advent of low-thrust propulsion, optimal control problems have become of primary importance in the design of space trajectories.



The Last 10 Years

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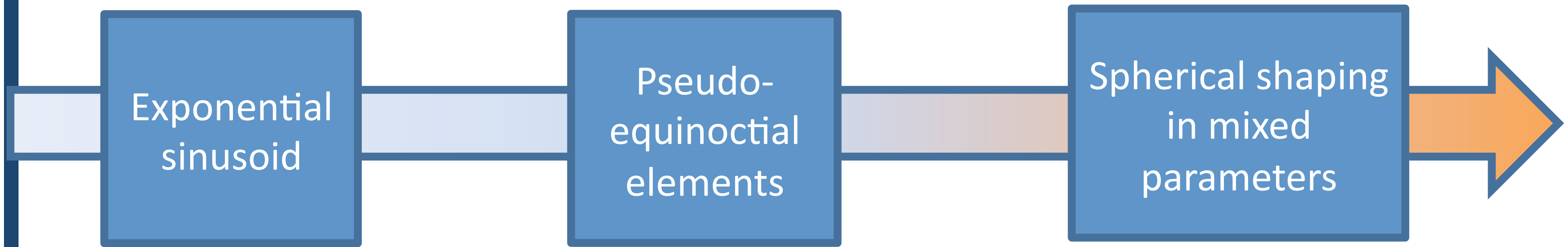
Inverse Approach to Optimal Control

- Optimal control is computationally intensive and requires a first guess
- Inverse approach to optimal control, AKA shaping approach in the space field
- Fast and robust exploration of low-thrust transfer options
- Difficult estimation of the correct peak thrust



Petropoulos et al. 1999

DePascale et al. 2006

Bradley et al. 2008
Novak et al. 2011

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Analytical Solutions

Analytical and semi-analytical solutions have recently shown to represent a valid tool.

Sims & Flanagan Approach (GALLOP, MALTO)

- Low-thrust modelled as series of impulses connecting Keplerian arcs

Stark Problem (Russell and Lantoine 2010)

- Solution of the Stark problem over extended arcs
- Rotation of the reference system for variable control direction

Perturbative expansions in non-singular elements (Zuiani et al. 2010)

- Fast analytical propagation of Gauss Planetary Equations under the effect of a low-thrust propulsion
- Multiple-shooting with forward and backward propagation

What is missing?

From **patched-conic** approach to **building-block** approach

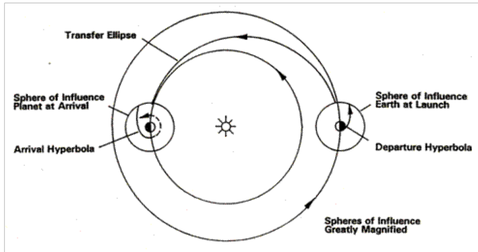
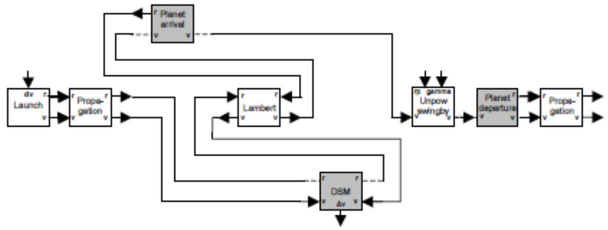


Fig. 6.2 Patched conic orbit.



- Started as part of an Ariadna study (Vasile & Ceriotti 2008) it would allow automated mission planning putting together elementary building blocks: launch, orbit raising, transfer, etc.

- Very fast building-blocks are now possible.

- Intersection between astrodynamics and computational intelligence

- Similar efforts already in the US, see the automaton of Conway et al.

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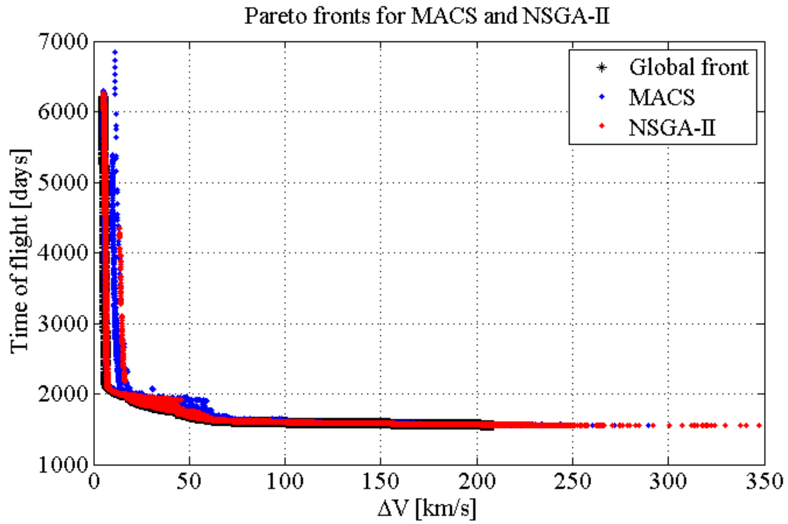
Set-Oriented Approach

The initial statement:

- Efficient exploration of the space of transfer options, for a given mission, to generate the **set of optimal solutions** fulfilling mission constraints



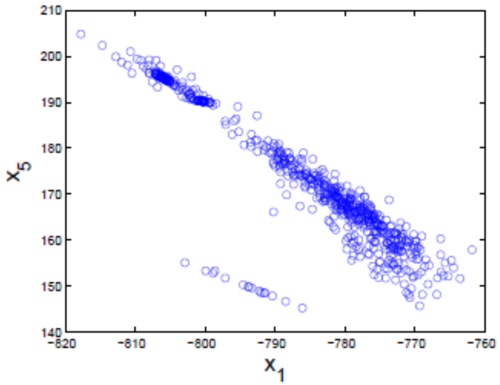
Optimise multiple criteria at the same time:

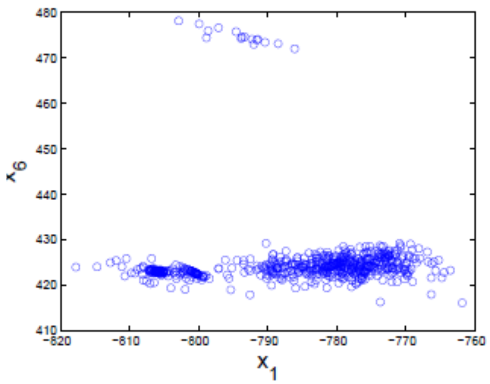
$$\min_{\mathbf{x}\in X} \mathbf{F} = \left[f_1, f_2, \ldots, f_m \right]^T$$

$$\mathbf{c}(\mathbf{x}) \le 0$$

Efficient archiving of optimal solutions:

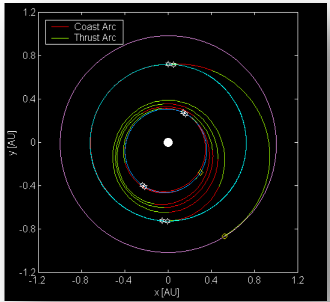
$$X = \left\{ \mathbf{x} \mid f(\mathbf{x}) < \varepsilon \wedge \mathbf{c}(\mathbf{x}) \le 0 \right\}$$





Robust and Integrated Approaches

Integrate Mission Analysis, Operations and System Design



Embed Uncertainty Quantification in the design process

- More commonly used in aircraft or automotive design
- Large impact on the manufacturing process
- Critical support to decision making

Optimal and Reliable

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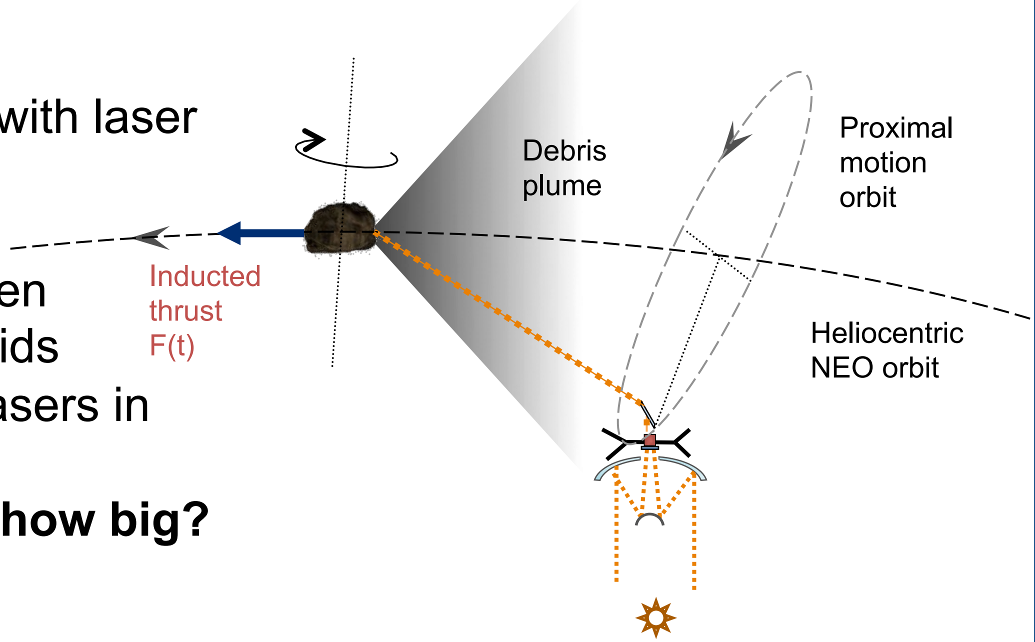
Why Integrated Robust Design?

Problem:

- I want to deflect an asteroid with laser ablation
- Highly uncertain process given current knowledge on asteroids and the use of high power lasers in space.
- **How many spacecraft and how big?**



Approach:

- Integrate system design with **Evidence-based Uncertainty Quantification**
- Fast long term propagation with **perturbative expansions** in non-singular elements
- Search for **the set of Pareto optimal solutions** minimising system mass and maximising asteroid deflection

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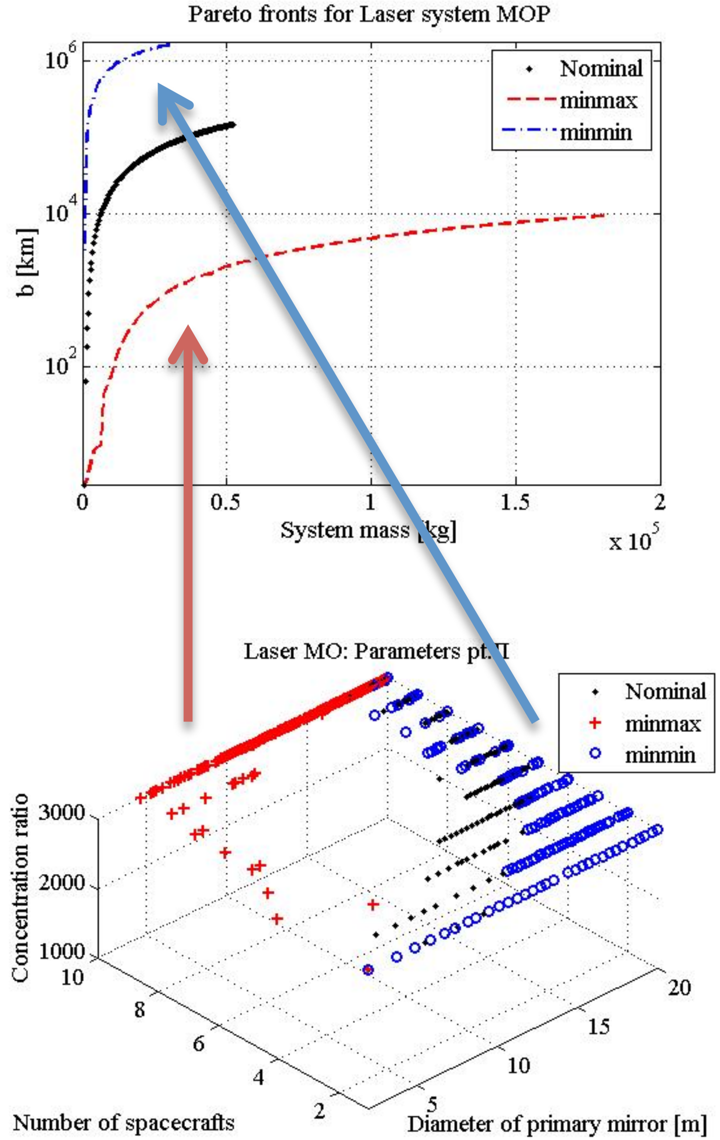
Why Integrated Robust Design?

Best Case $$\min_{x\in D}\left[\min_{u\in\bar{U}} m_{system} \quad \min_{u\in\bar{U}}(-b)\right]$$

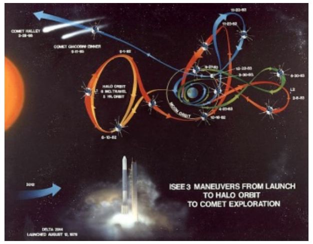
Worst Case $$\min_{x\in D}\left[\max_{u\in\bar{U}} m_{system} \quad \max_{u\in\bar{U}}(-b)\right]$$

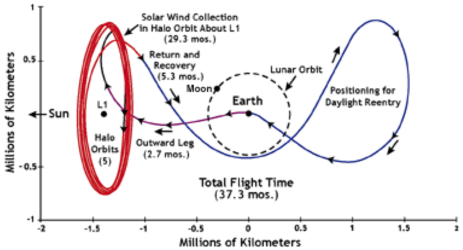
- The Pareto Sets show a switch between two families of designs:
  - In the **worst case**, solutions with a high number of spacecraft and a small primary mirror are preferred (many spacecraft to compensate for their lower individual efficiency)
  - In the **best case**, solutions with a low number of spacecraft and a large primary mirror are preferred (few spacecraft but very efficient)

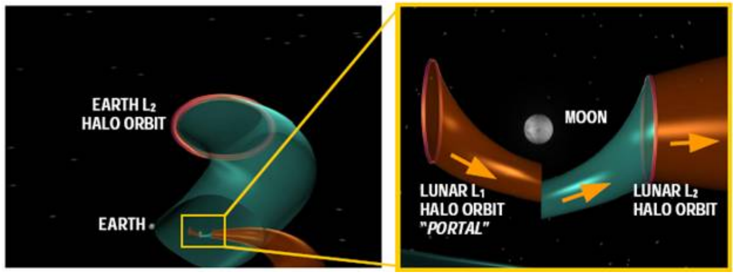


Dynamical Systems

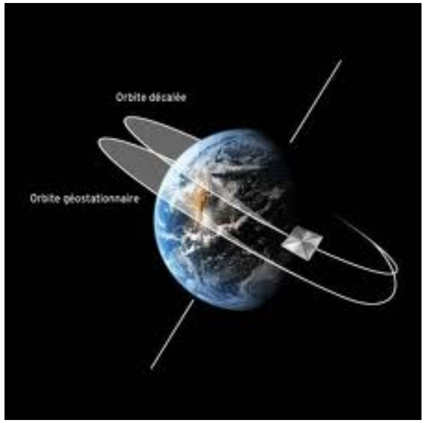
Mathematical theory for Non-Keplerian Orbits (NKO)





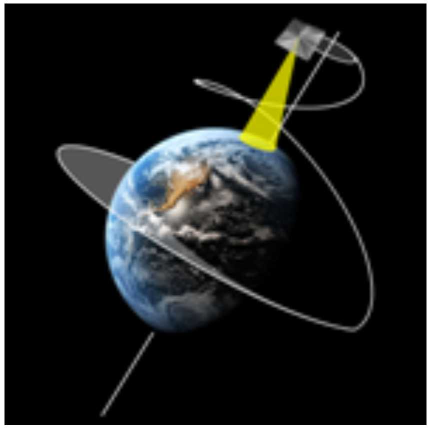


Natural extension to artificial NKO and to orbits around orbits:

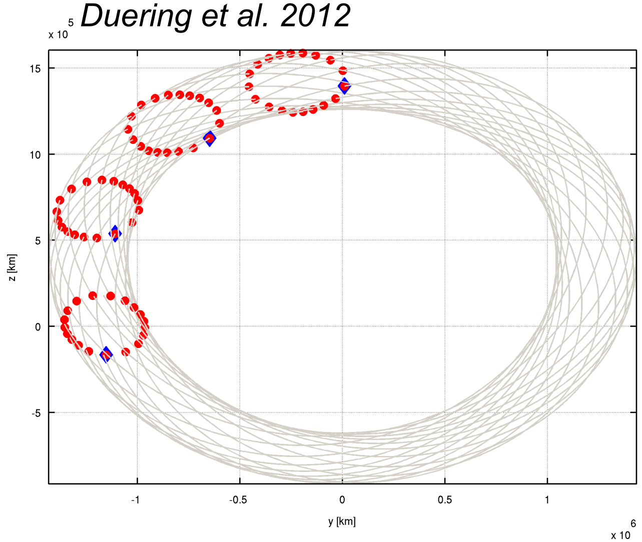


Displaced GEO ring
McInnes et al.

Pole sitter
McInnes et al.



Formations around Tori
Duering et al. 2012



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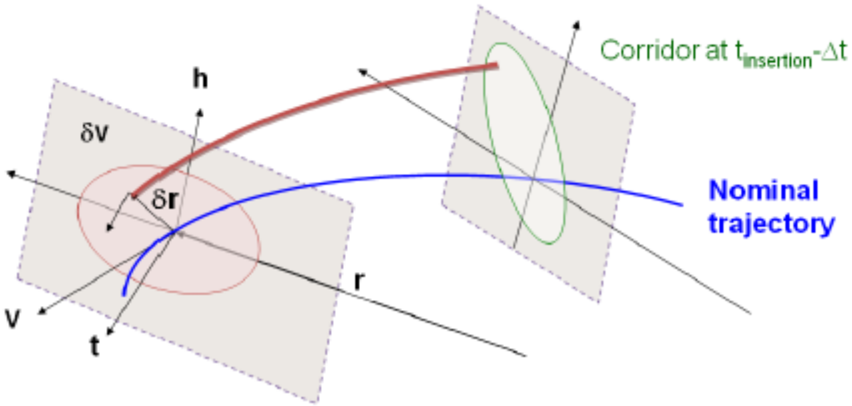
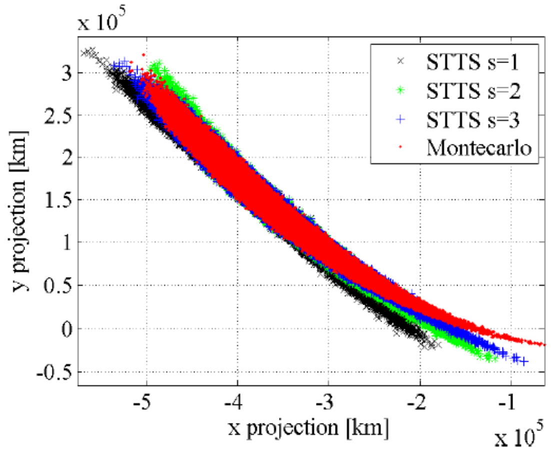
High Order Expansions

- High order expansion for nonlinear filtering in OD (Park & Scheeres 2006)
- Alternative to validated propagation (DiLizia, Armellin, Topputo 2008) and robust control (DiLizia 2008)
- High order expansions for navigation and robust trajectory planning (Vetrisano et al. 2012)





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New Trends in Mission Analysis?

What has changed in Mission Analysis the last 10 years?

No significant changes…

USA maintain a mix of Top-Down and Bottom-Up approach to the creation of new ideas with a self-sufficient attitude.
Mix of Up-stream and Down-stream research and development.

EU maintain an adventurous approach at local level and a Bottom-Up approach to the creation of new ideas. Limited Top-Down push still prone to importing solutions to limit the risk.

Japan has a very adventurous character with a strong support towards Up-stream research and development activities.

So no significant changes…except

China has demonstrated significant capabilities with a vertical ascent in their activities. China can create trends by supporting en mass a vast number of specific concepts.

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Can we talk about actual Trends?

The general answer is no because:

- Mission analysts tend to use their own tools. '*Don't tell the cook how to cook*' paradigm.
- Mission analysis depends on mission objectives and underpinning technologies

The question should be reformulated in a different way:

- Are there commonly valid techniques?
- Are there new trends in mission concepts
- Are there new technologies that need new analysis tools/ approaches?

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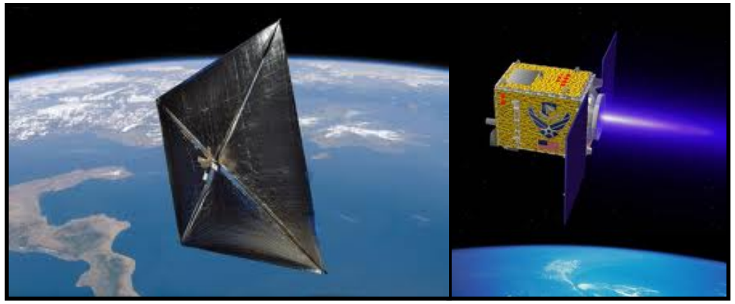
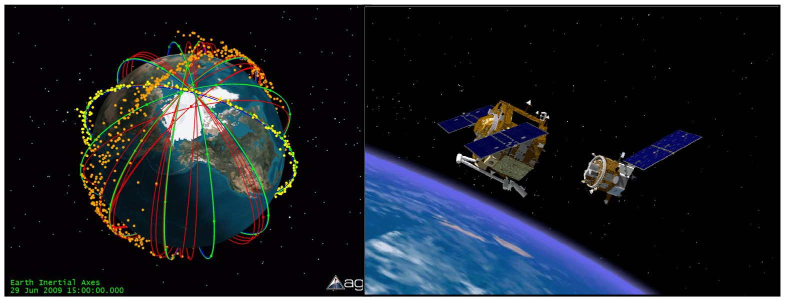
Emerging Areas

Nano-satellites
From mainframe
to PC



Fractionated Systems
From monolithic to
swarm intelligence

Satellite Disposal and Servicing
From dirty to tidy



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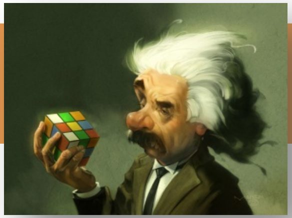
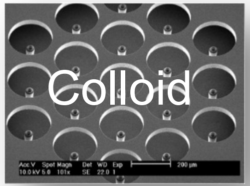
Low-cost Nano Missions

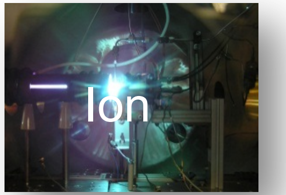


Nano-missions represent an interesting opportunity to open the access to space but need new solutions to go beyond LEO.

All about propulsion:

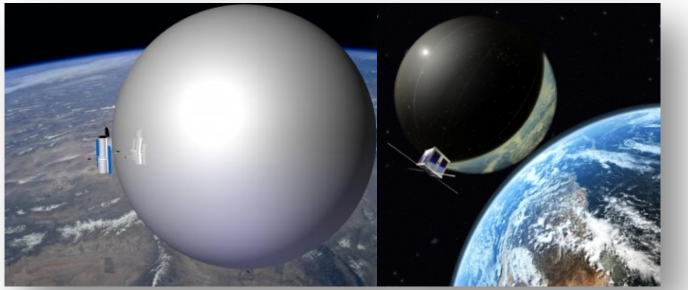
- New interesting micro-propulsion systems are under development to support nano-satellites





Non-gravitational forces:

- Nano-sat tend to have a very high density compared to standard satellites but their AMR can be easily increased by orders of magnitude with simple small scale devices.



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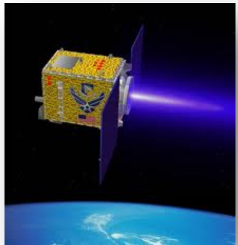
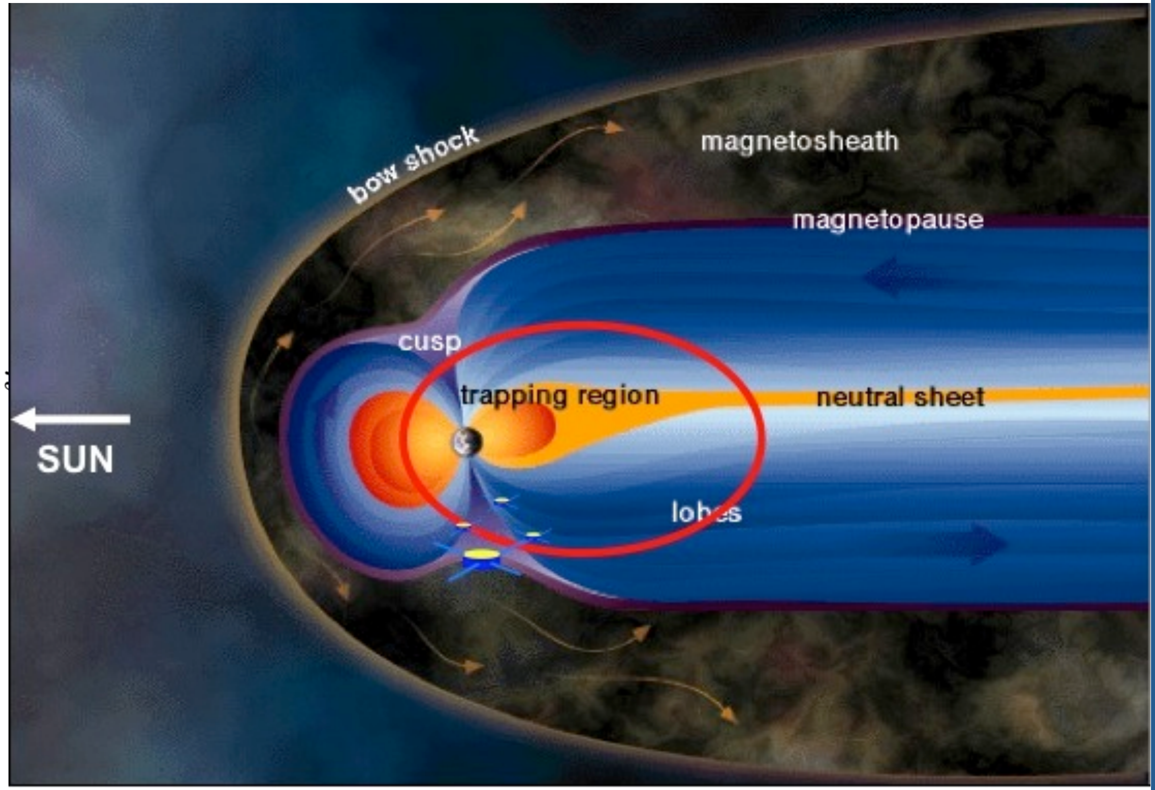
All about propulsion

Nano-satellites offer interesting possibility to hybridise propulsion systems.





Example of 3 year transfer with 31 manoeuvres and hybrid propulsion, <300g of propellant. During the journey a number of experiments can be conducted.

Conceptually new type of operations:

the journey becomes the destination.

All about propulsion… and POWER

Big issues in miniaturisation of the propulsion system are:

- Miniaturised power systems can only handle low power inputs (<100W), more power also means more mass
- Low-power engines have lower efficiency (5%-40%)

Engine	Thrust (mN)	Engine Mass (kg)	Isp (s)	Power (W)
MiXI	0.01-1.5	0.2	2500-3200	13-50
Colloid	0.03-0.3	0.3	~3000	1.5-15
CHT	3-6	<1	1200-2000	50-170

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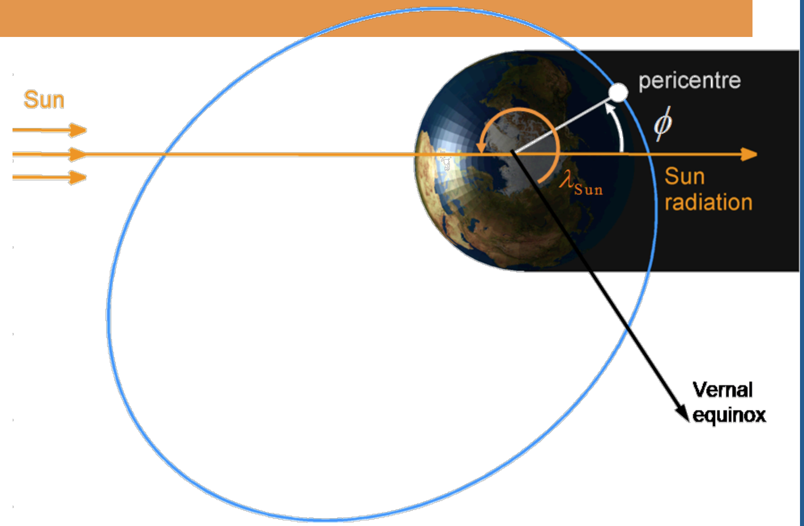
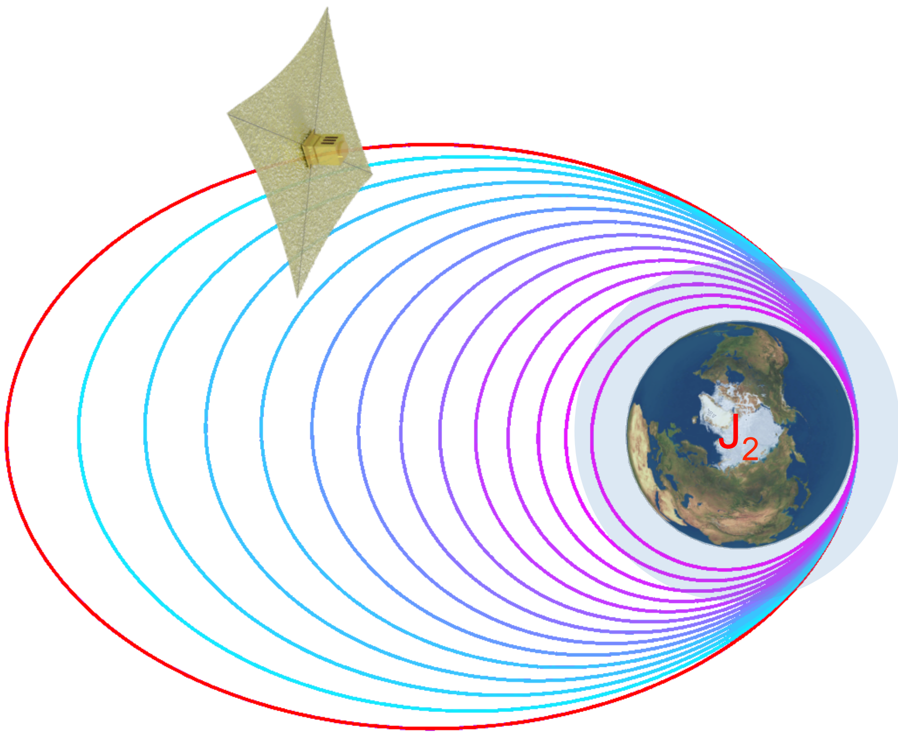
Exploiting Non-gravitational Forces

- Exploit natural perturbations to transfer for free from GTO to LEO:

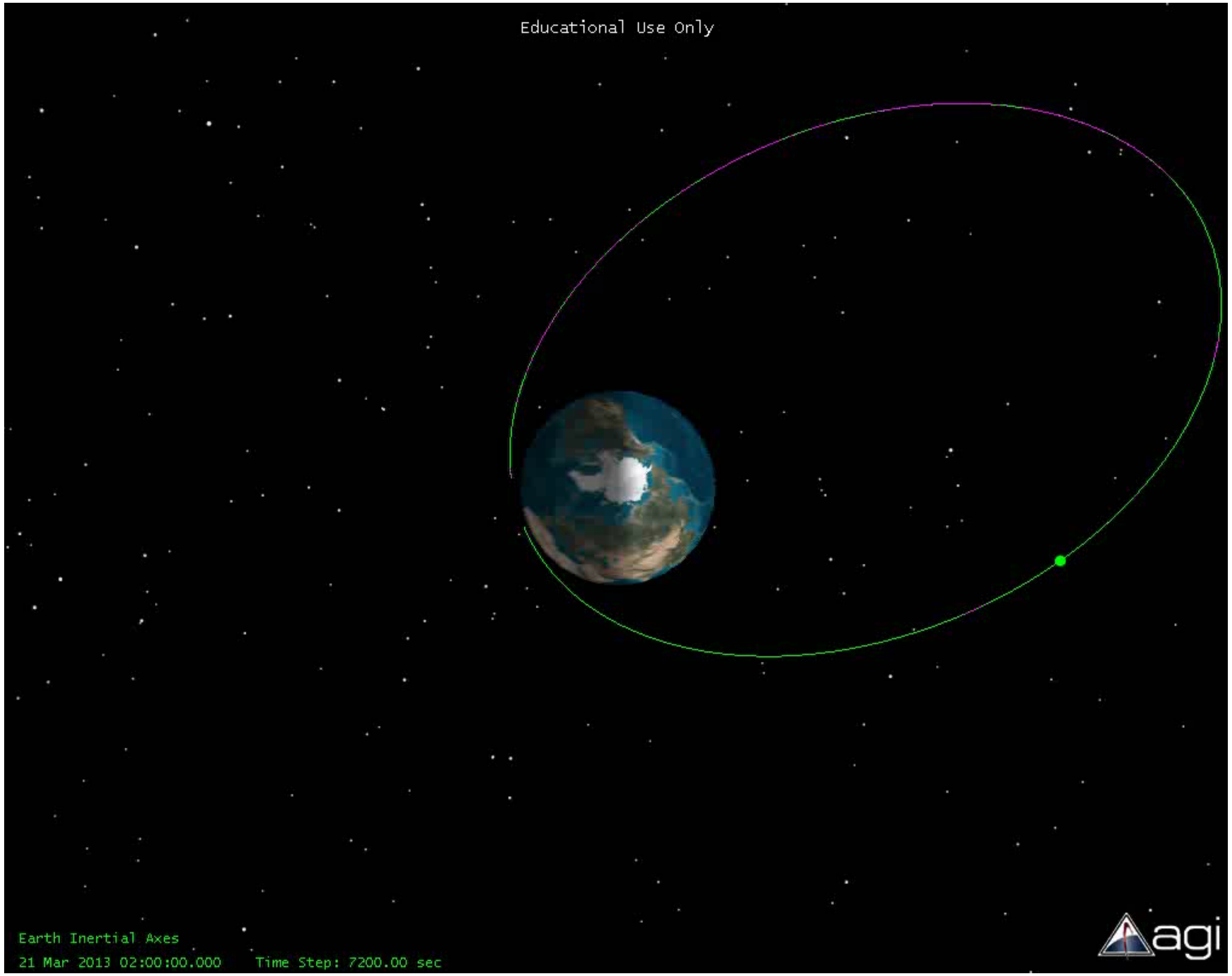


- Enhance atmospheric drag to decrease orbit energy

- Exploit J_2 effect and solar radiation pressure to increase final perigee



Exploiting Non-gravitational Forces



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Fractionated Systems

Fractionating a monolithic large system into a number of small inhomogeneous systems brings along new interesting problems:

Close cooperation and swarm intelligence:

- Relative motion control beyond normal formation flying is required
- Close interaction effects must be taken into account (e.g. Coulomb formations)
- Emerging behaviour due to large collectives (e.g. potential field control)

Non-gravitational forces become relevant:

- The AMR makes the spacecraft prone to high accelerations due to solar pressure and drag.
- Non gravitational forces can be exploited for orbit control

Macro-dynamics is the expression of the micro-dynamics:

- The shape of the fractionated system is coupled with its orbital motion
- The global behaviour of the fractionated system depends on the relative interaction of the components.

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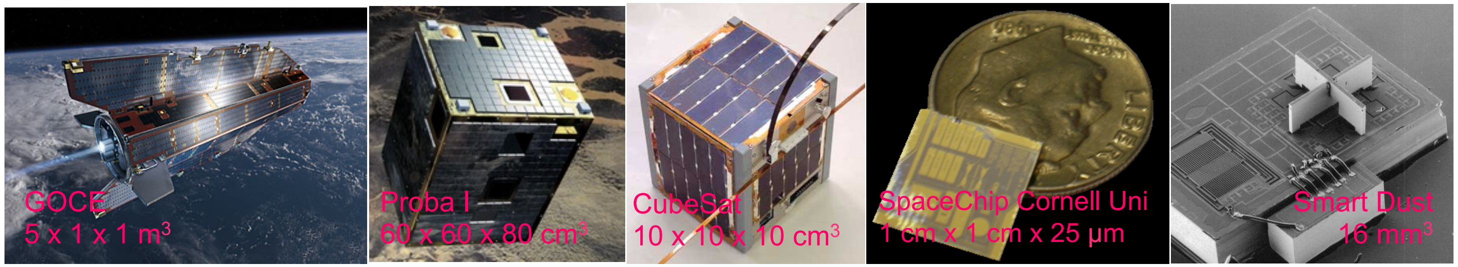
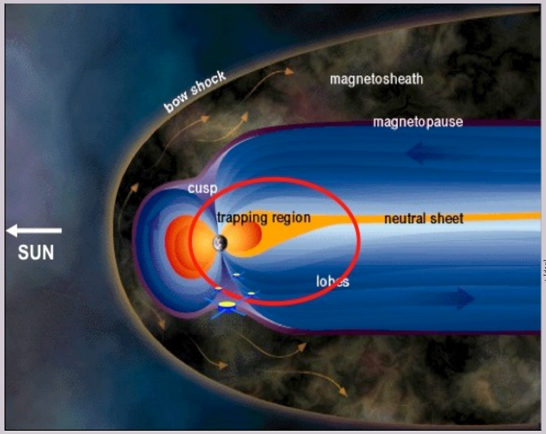
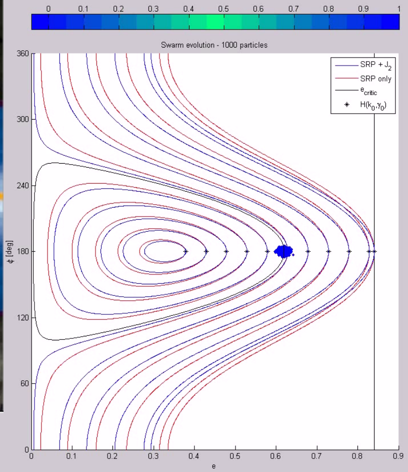
From single point mass dynamics to flow dynamics



AMR | $9.5\text{x}10^{-4}$ | 0.0038 | 0.01 | 17.4

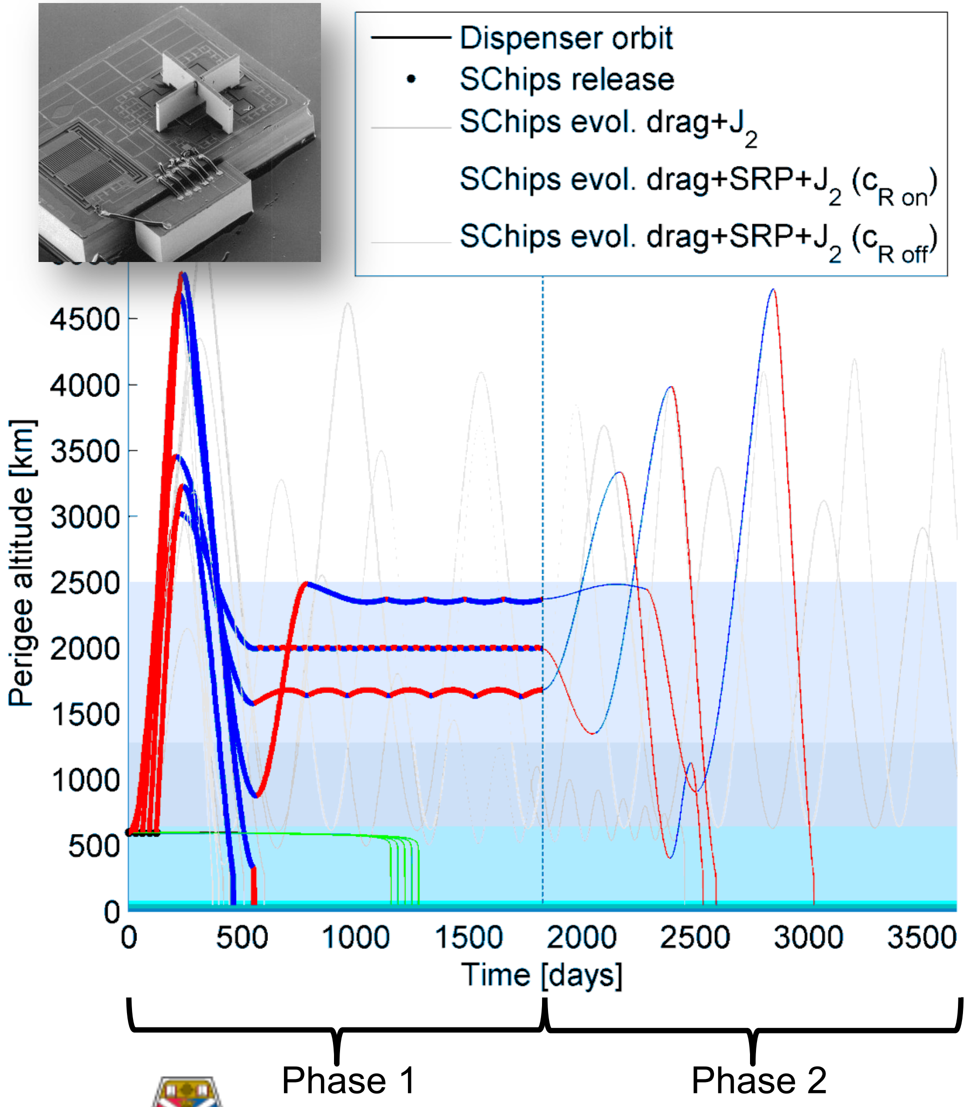
$$\frac{\partial n(\mathbf{x},t)}{\partial t} + \nabla \cdot (n\mathbf{v}) = N^{+}(\mathbf{x},t) - N^{-}(\mathbf{x},t)$$





New Trends

Electro-chromic control (Colombo et al 2012)



- Exploitation of SRP allows coverage of a more extended region of the atmosphere
- The swarm collects distributed measurements
- Effect of DRAG exploited to obtain a fast decay in the terminal phase of the mission
  - ensure end-of-life disposal
  - avoid creation of long-lived space debris

(Colombo, Lucking, McInnes, 2012)

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New Trends

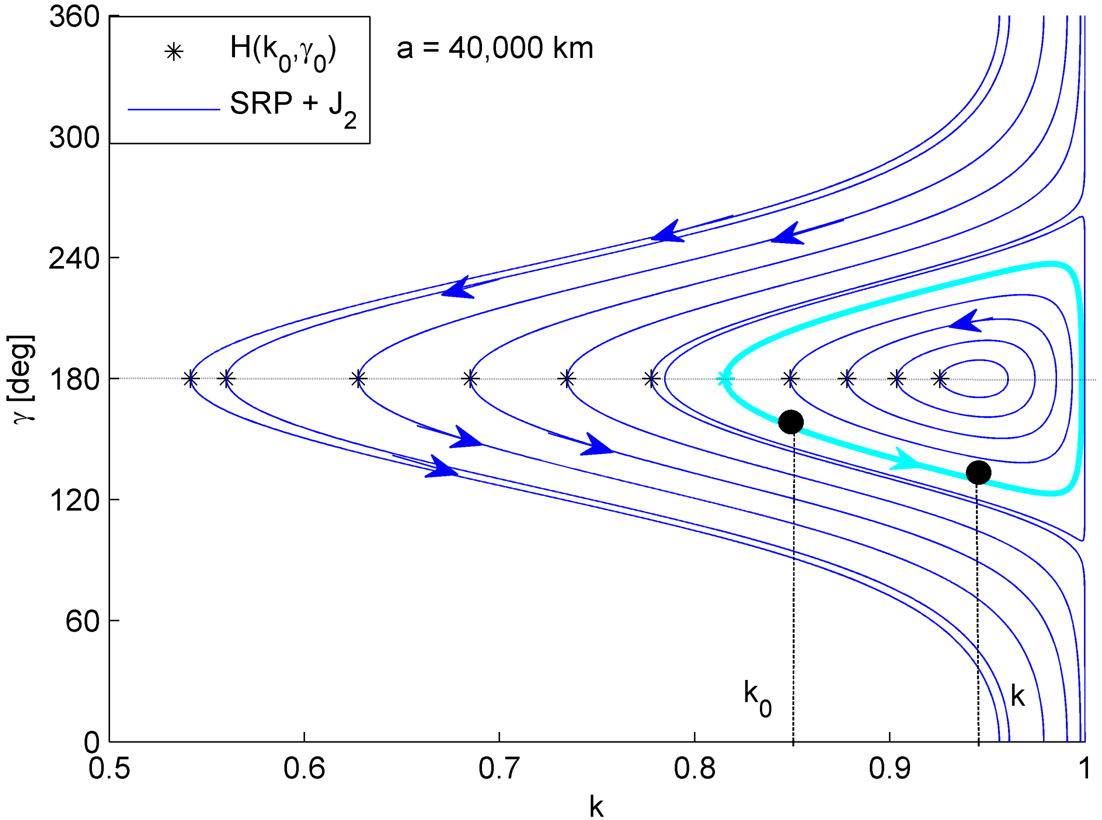
Cloud Evolution (Colombo et al.2012)

From single point mass dynamics to flow dynamics:

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

Hp: no fast processes

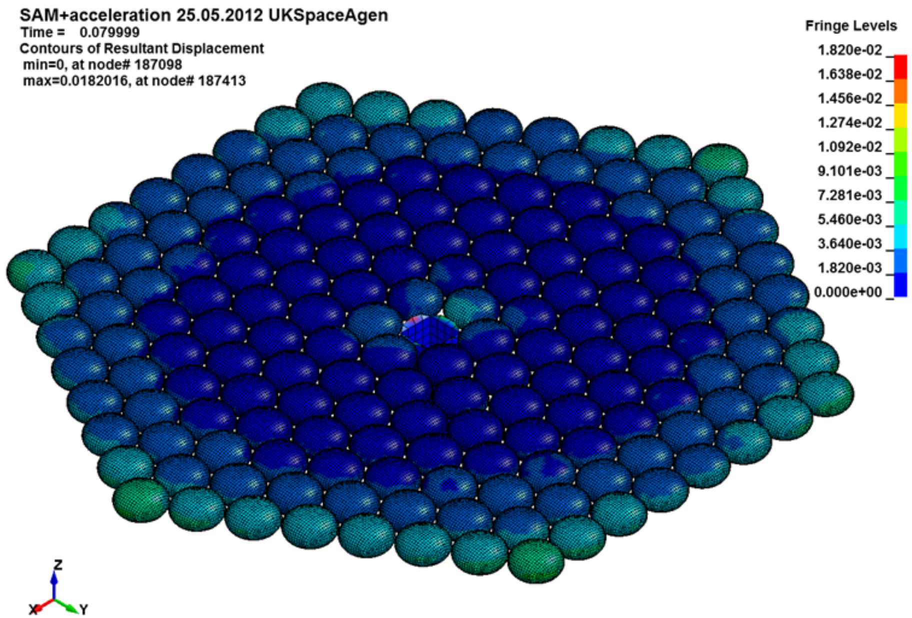
$$\frac{\partial n}{\partial t} + \frac{\partial n}{\partial e}\frac{de}{dt} + \frac{\partial n}{\partial \phi}\frac{d\phi}{dt} + n\left(\frac{\partial v_e}{\partial e} + \frac{\partial v_\phi}{\partial \phi}\right) = 0$$



- Ref. McInnes, 1998
- Ref. Gor'kavyi et al., 1997

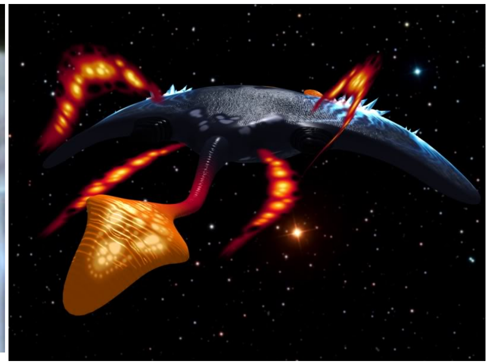
Cellular Structures (Sinn et al. 2012)

- Example of whole inflatable cellular spacecraft
- Cells are independent modules working together as a collective
- Conceptually similar to PETSATs



- Coupling between shape, attitude and orbital dynamics:

The shape of the orbit depends on the shape of the spacecraft



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Satellite Disposal and Servicing

The active removal of space debris and the on-orbit servicing of satellites pose new interesting problems:

- Fetch and deorbit analysis
- Recurrent transfers
- Close interaction with uncooperative objects
- Stable/reliable disposal solutions

Long term evolution beyond mission lifetime becomes relevant

The problem is combinatorial in nature

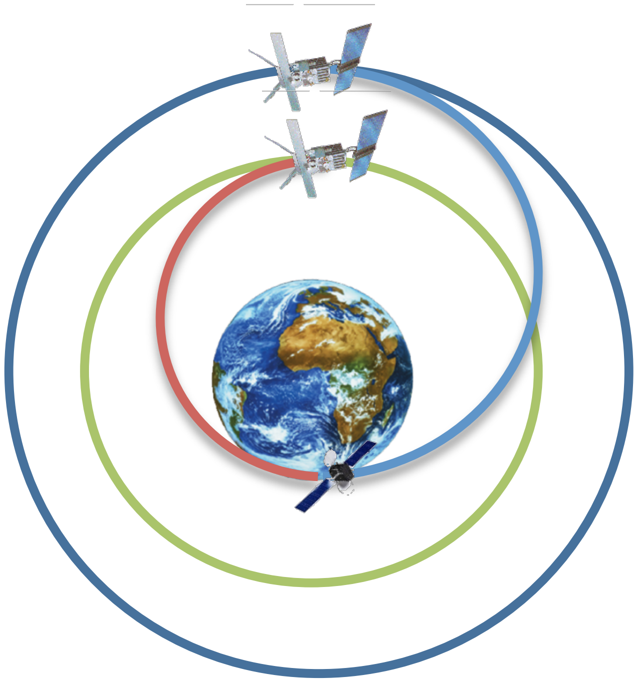
- Maximise the deorbited mass in a given time over a population of thousands of objects

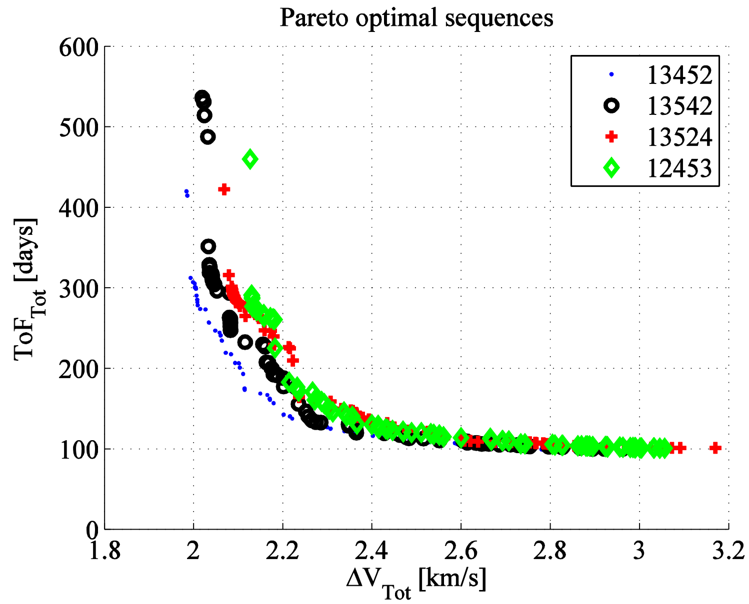
The interaction with the environment assumes a new dimension

- Transfers, trajectories and manoeuvres must account for obstacle avoidance and impacts

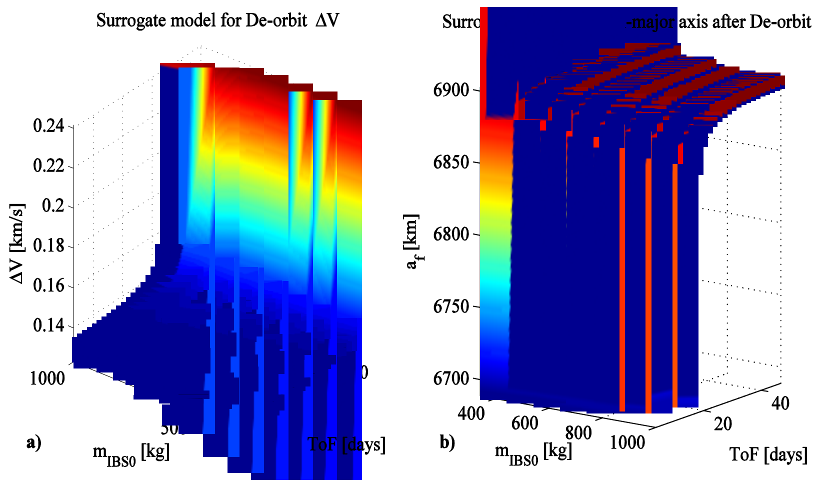
Maximum Debris Removal Problem (Zuiani et al. 2011)

- Optimal sequence of satellites to service
- Optimal compromise between time and propellant cost





Fast analytical propagation with perturbative elements.



Future Perspectives

Some Recommendations

- Be bold and invest in adventurous ideas:
  - being stingy at TRL 1-2 does not pay off.
- Define a pipeline for the development of new ideas:
  - having to relay on US or EC investment because there is nothing beyond and after the ACT seems odd.
  - NIAC has evolved establishing a pipeline
- Promote Top-down developments:
  - trust the innovation produced internally.

Move the ACT to our new Technology Innovation Centre

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What to do in the next 10 years?

- A change of paradigm from main-frame to PC requires new everything: mission concepts, operations, tools, etc.
- Look at new conceptually different platforms: different from a box.
  - Disaggregated/fractionated systems
  - All-inflatable spacecraft and morphing spacecraft
- On the short-to-medium term on-orbit servicing and active debris removal offers a new interesting variety of problems. Asteroid manipulation as well.
- Global methods still not completely exhausted but everybody does that: move on to set-oriented approaches and to automatic mission planning.
- Integrated robust approaches very interesting and a growing area in other sectors: don't take it for granted.

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Questions?

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