Mini-workshop on Global Trajectory Optimisation

ESTEC, 10th of September 2007

European Space Agency

Programme

10:00-10:10 **Opening** (Leopold Summerer , ESA-ACT)

10:10 - 11:00 **Global Trajectory Optimisation projects in the ACT** (Dario Izzo, Tamas Vinko and Claudio Bombardelli, ESA-ACT)

11:00 - 12:00 **Global Trajectory Optimisation: Can We Prune the Solution Space when Considering Deep Space Manoeuvres?** Ariadna Final Presentation, Politecnico di Milano and Michigan State University

12:00 - 13:00 **Global Trajectory Optimisation: Can We Prune the Solution Space when Considering Deep Space Manoeuvres?** Ariadna Final Presentation, Ecole des Mines de Paris

13:00 - 14:30 Lunch break

14:30 - 15:30 **Global Trajectory Optimisation: Can We Prune the Solution Space when Considering Deep Space Manoeuvres?** Ariadna Final Presentation, University of Glasgow and University of Reading

15:30 - 16:00 **An extension of GASP to DSM trajectories**, (Adam Zalcman, Jagiellonian University, Poland)

16:00 - 16:20 **ESOC plans on global trajectory optimisation** (Johannes Schoenmaekers, OPS-GFA)

16:20 - 17:00 Technical discussion and wrap-up

The increasing number of interplanetary missions that are proposed for the various ESA programs often requires a large number of trajectory/design options to be evaluated. At a preliminary stage this usually means the consideration of very large launch windows, different planetary fly-by sequences and of different design options. This small workshop wants to give an overview on different solutions that have been recently proposed by the spacecraft trajectory optimization community in response to the need of finding good preliminary solutions that may make the difference between a feasible and an unfeasible mission. The emphasis is put on global optimization

esa Advanced Concepts Team

Contents

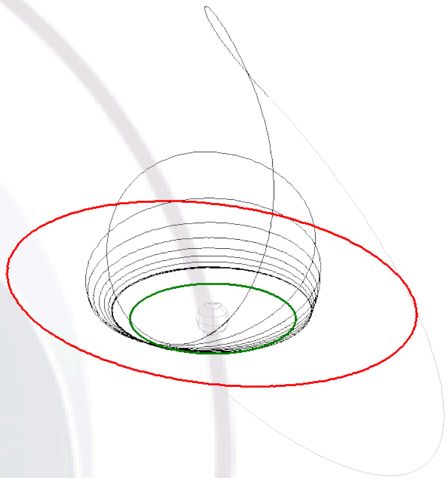
- Introduction to global optimisation for interplanetary trajectories
- The open source benchmark problems
- GTOC: past competitions overview
- The past Ariadna Projects
  - Global optimisation off-the shelf algorithms
  - Exponential sinusoids
  - GASP

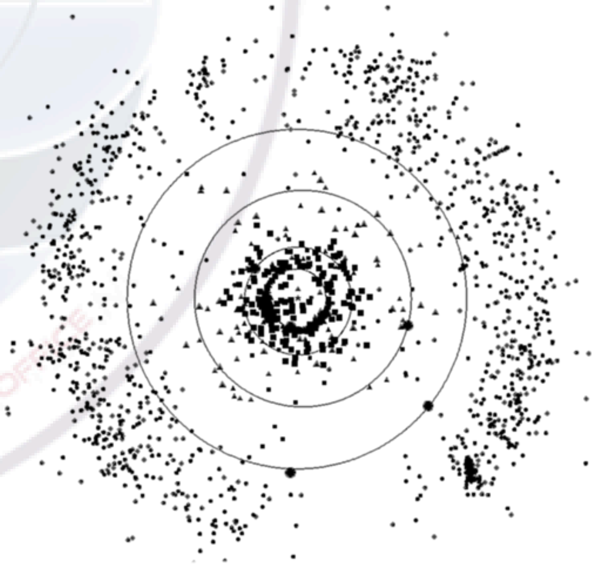
Interplanetary trajectories design

- An early step of any interplanetary space mission feasibility study
- Complex problem in its very mathematical nature:

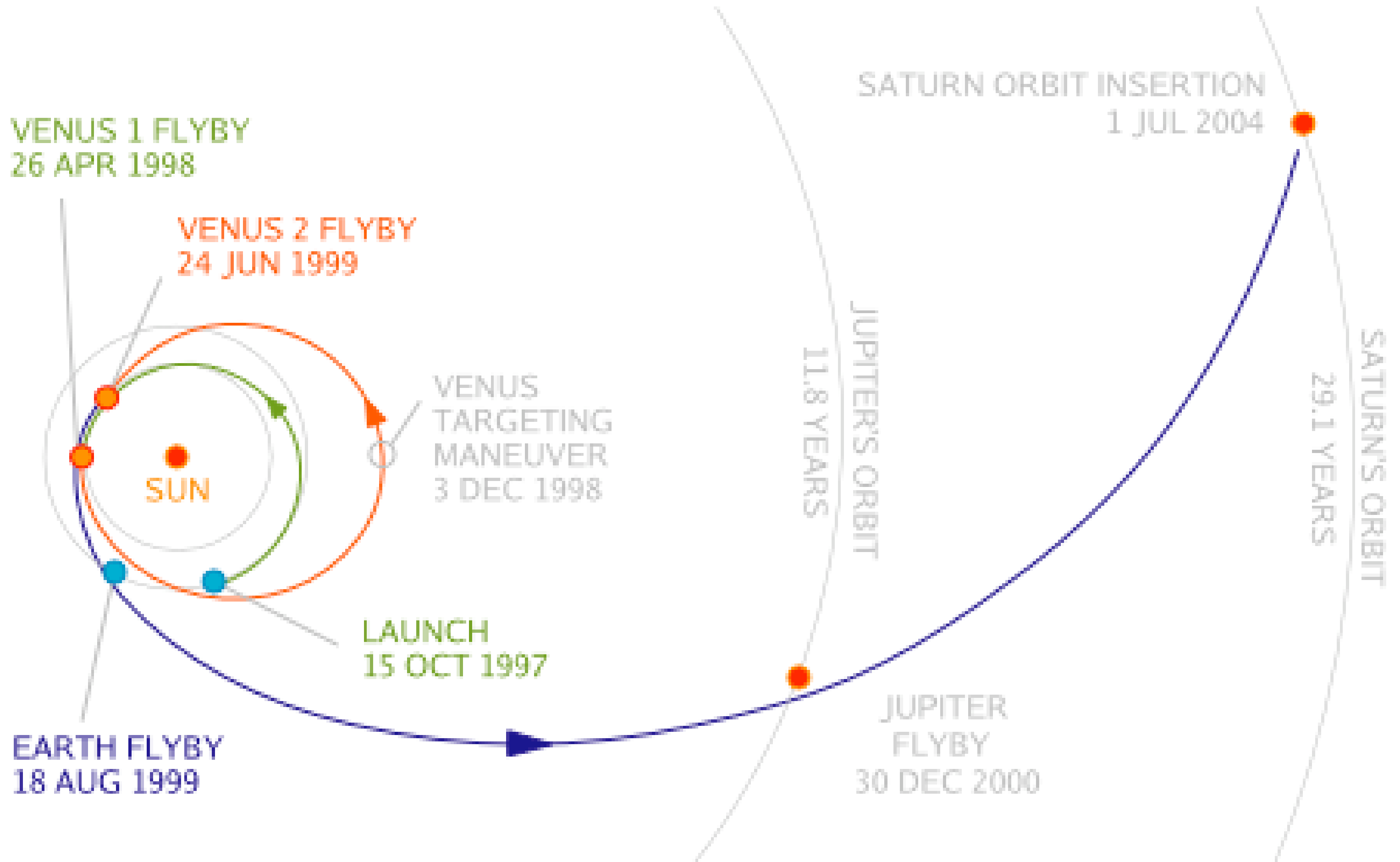
$$\begin{array}{ll} \text{Minimise:} & J(\mathbf{x}) \\ \text{Subject to:} & \mathbf{g}(\mathbf{x}) \leq 0 \end{array}$$

- There is more than meets the eye

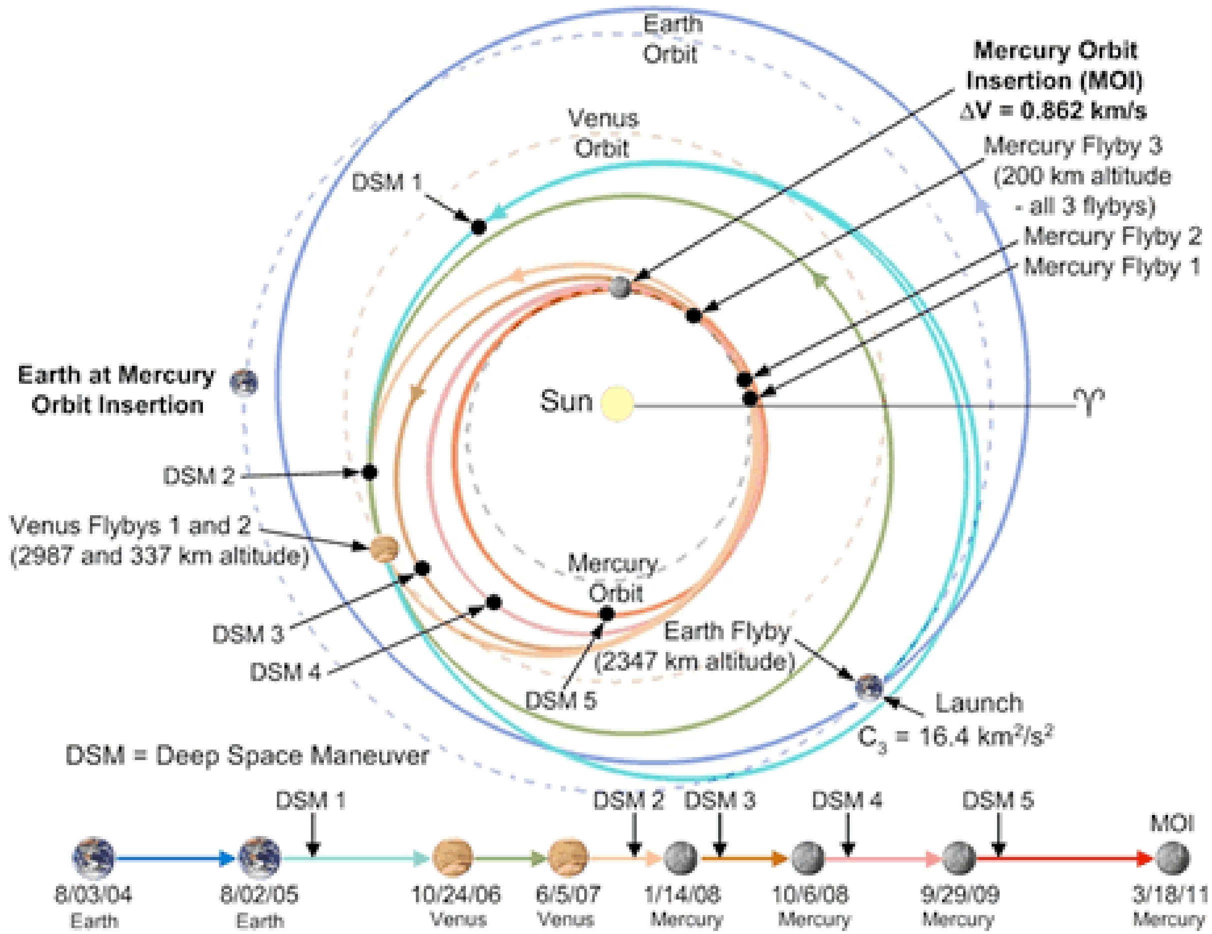




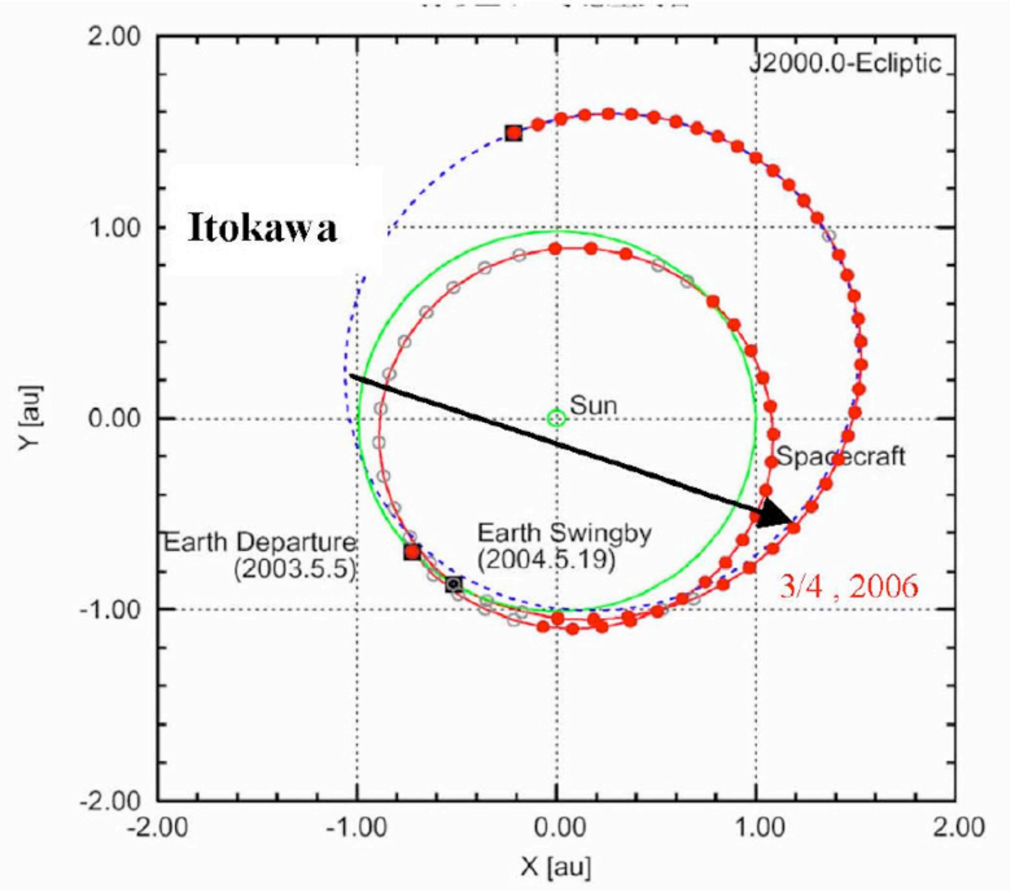
Cassini


VENUS 1 FLYBY
26 APR 1998
VENUS 2 FLYBY
24 JUN 1999
VENUS
TARGETING
MANEUVER
3 DEC 1998
SUN
LAUNCH
15 OCT 1997
EARTH FLYBY
18 AUG 1999
JUPITER'S ORBIT
11.8 YEARS
JUPITER
FLYBY
30 DEC 2000
SATURN ORBIT INSERTION
1 JUL 2004
SATURN'S ORBIT
29.1 YEARS

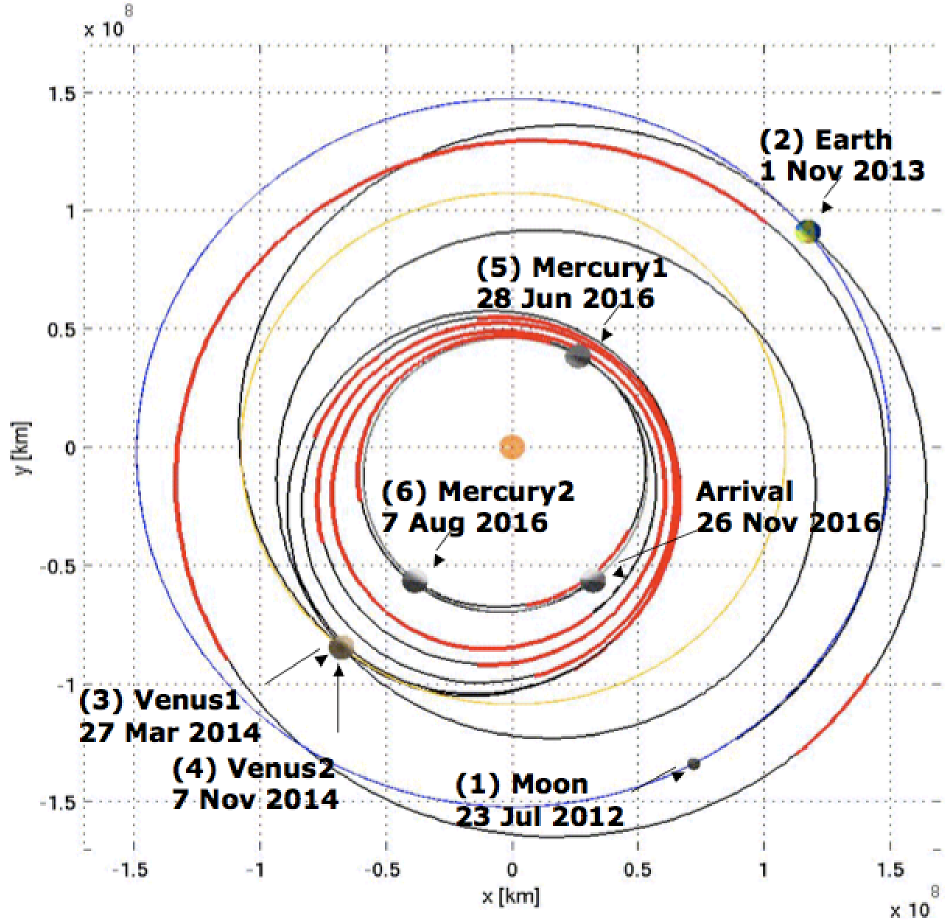
Messenger


Earth Orbit
Mercury Orbit Insertion (MOI) ΔV = 0.862 km/s
Venus Orbit
Mercury Flyby 3 (200 km altitude - all 3 flybys)
DSM 1
Mercury Flyby 2
Mercury Flyby 1
Earth at Mercury Orbit Insertion
Sun
♈
DSM 2
Venus Flybys 1 and 2 (2987 and 337 km altitude)
Mercury Orbit
DSM 3
Earth Flyby (2347 km altitude)
DSM 4
DSM 5
Launch
C_3 = 16.4 km²/s²
DSM = Deep Space Maneuver
DSM 1
DSM 2
DSM 3
DSM 4
DSM 5
MOI
8/03/04 Earth
8/02/05 Earth
10/24/06 Venus
6/5/07 Venus
1/14/08 Mercury
10/6/08 Mercury
9/29/09 Mercury
3/18/11 Mercury

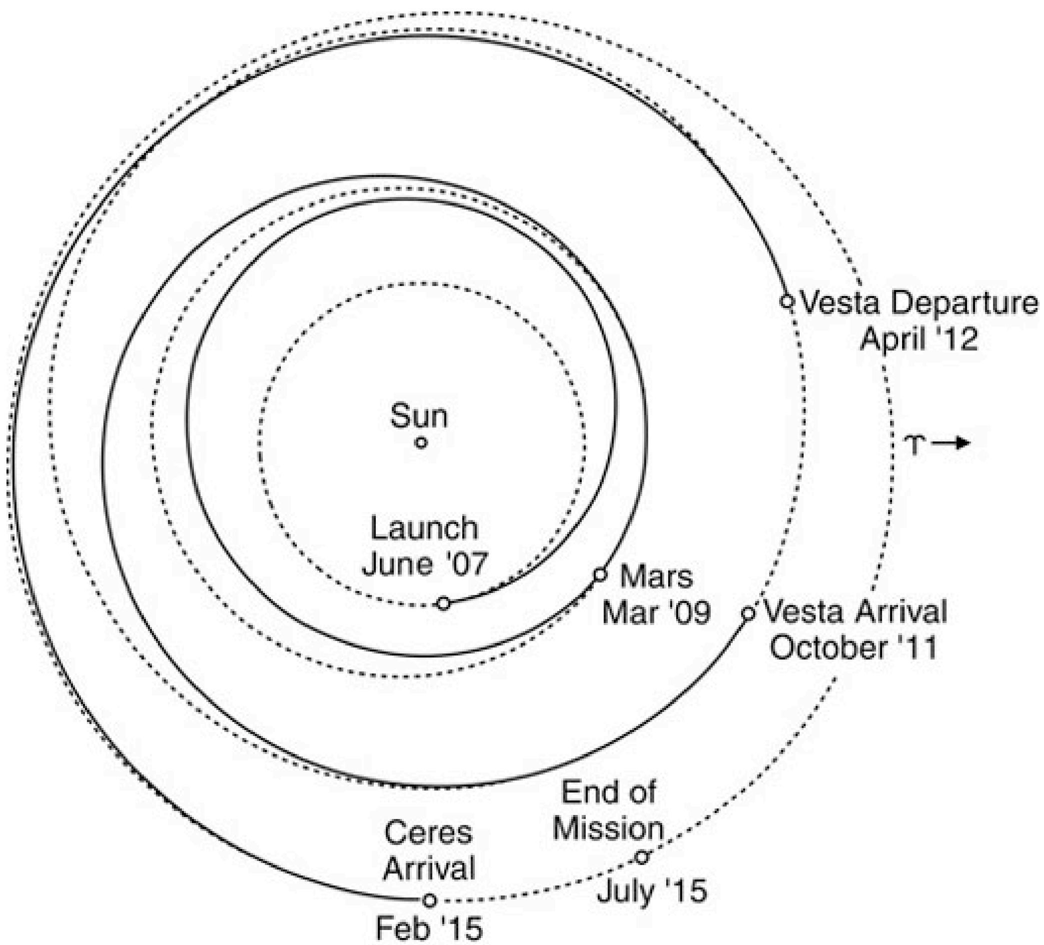
Hyabusa


J2000.0-Ecliptic
Itokawa
Sun
Spacecraft
Earth Departure
(2003.5.5)
Earth Swingby
(2004.5.19)
3/4 , 2006
Y [au]
X [au]
2.00
1.00
0.00
-1.00
-2.00
-2.00
-1.00
0.00
1.00
2.00

Bepi Colombo

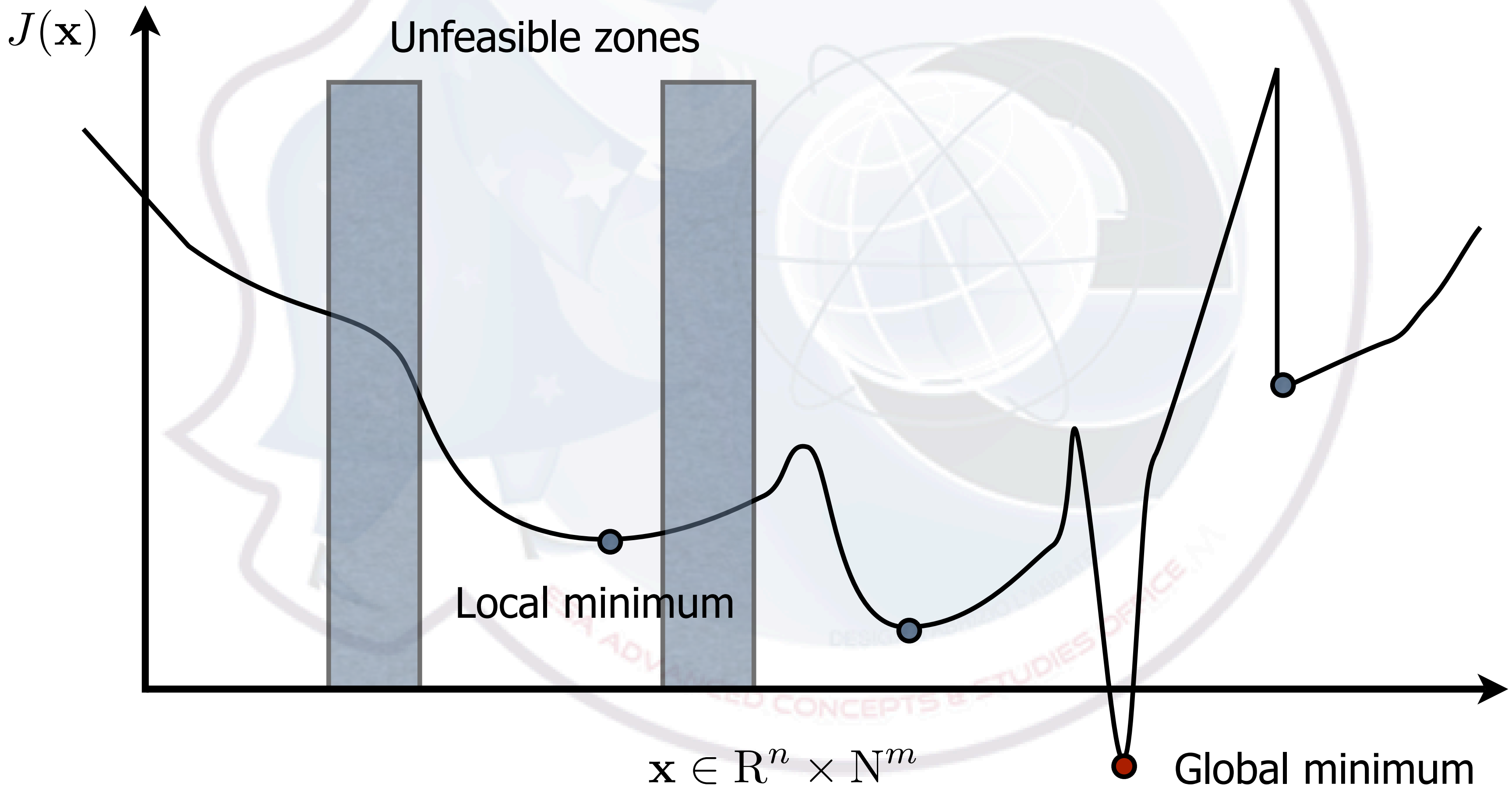


Dawn I


Vesta Departure
April '12
Sun
♈
Launch
June '07
Mars
Mar '09
Vesta Arrival
October '11
End of
Mission
July '15
Ceres
Arrival
Feb '15

Mathematical programming

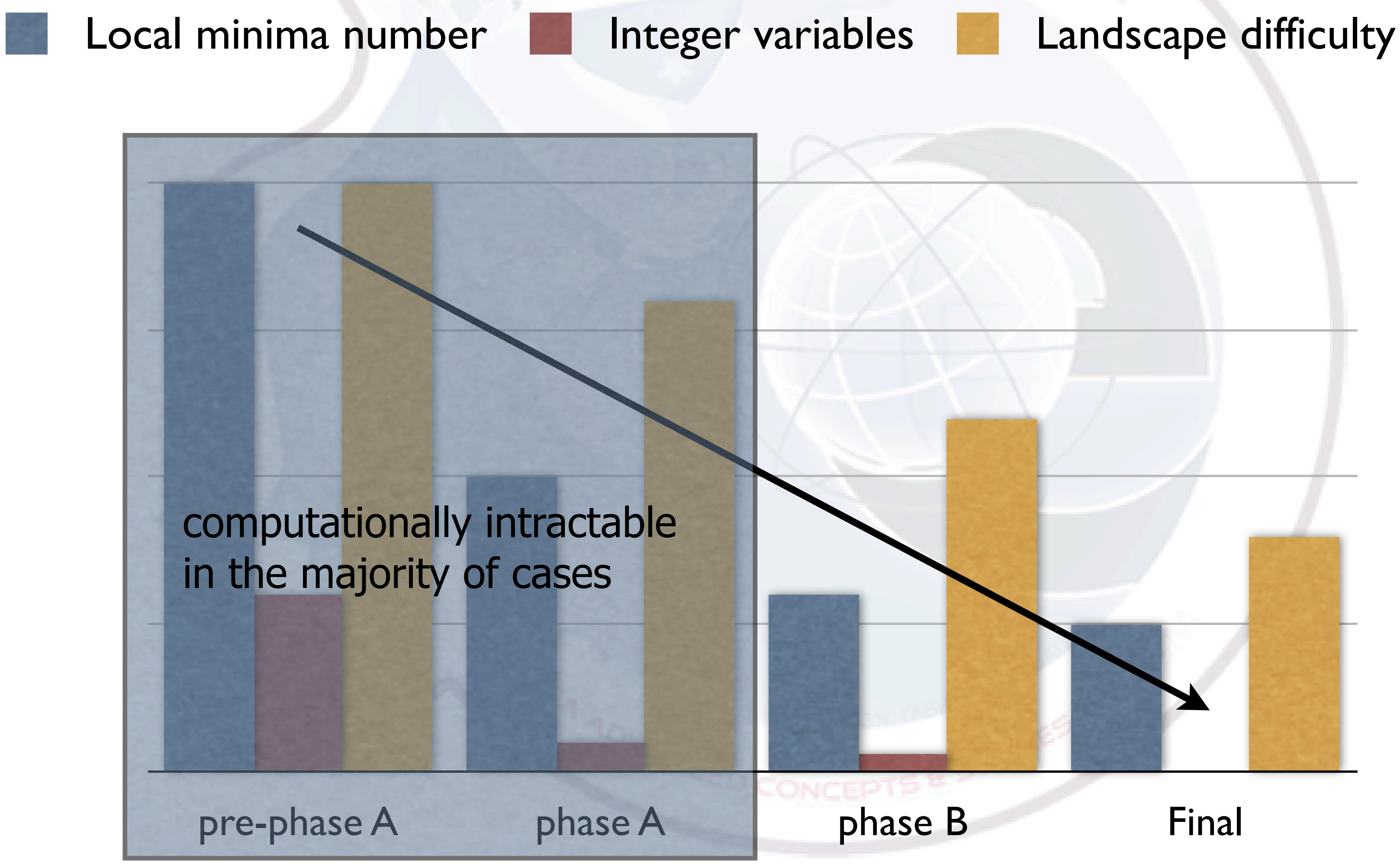
$$\begin{array}{ll}\text{Minimise:} & J(\mathbf{x}) \\ \text{Subject to:} & \mathbf{g}(\mathbf{x}) \leq 0\end{array}$$



Mathematical programming

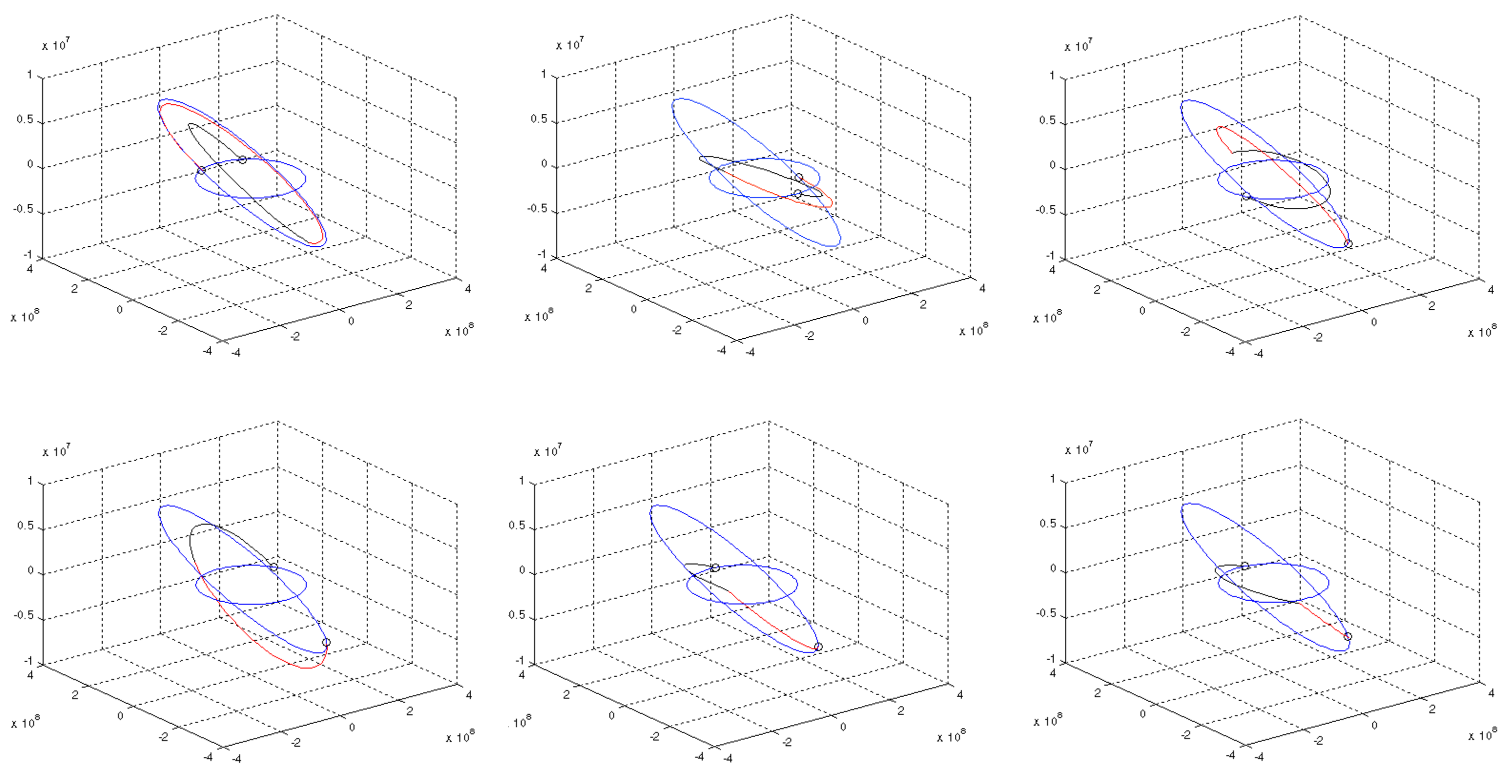
- There is no numerical algorithm able to tackle the mathematical programming problem in its generality
- The preliminary analysis of the problem structure suggests the most suited approach
- What makes the problem difficult/easy?
  - Dimensionality
  - Number of local minima
  - Topology of the feasible domain
  - Number of integer variables
  - Single or multiple objectives
  - Computational cost of the objective function evaluation
  - Convex or non convex constraints and objectives

Is trajectory optimisation difficult?

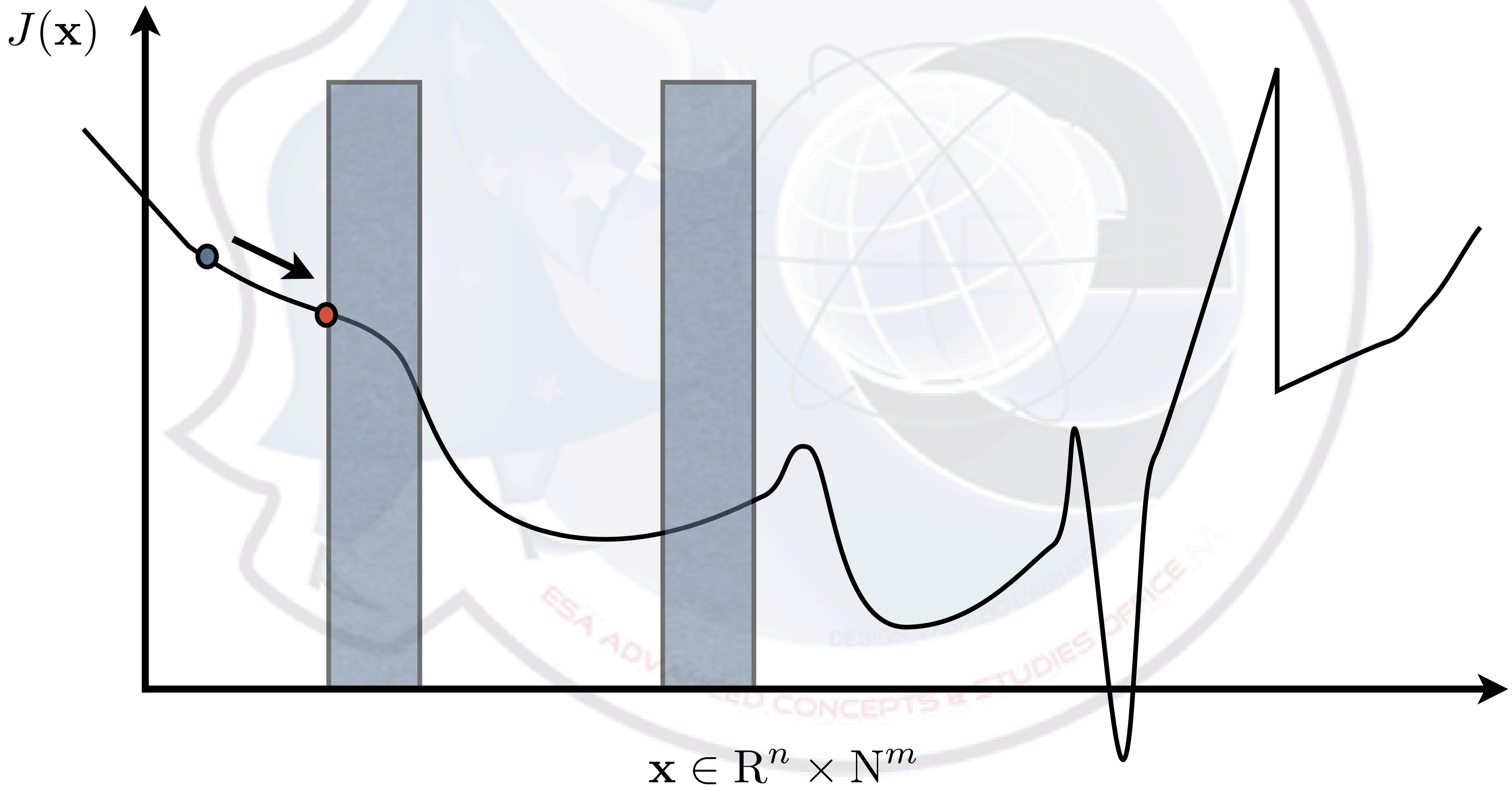


A schematic of the overall process

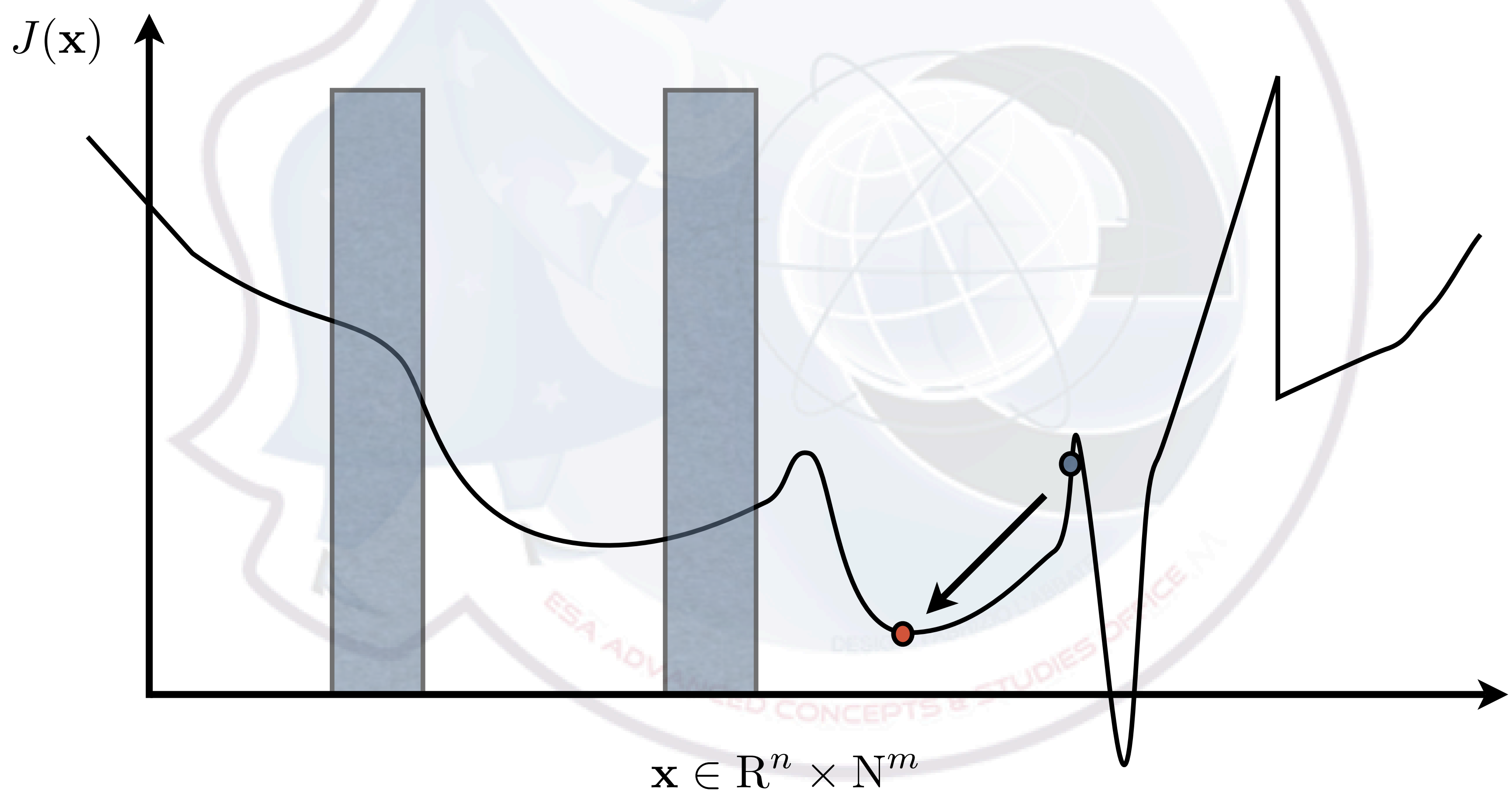
Initial Guess → Local Optimisation



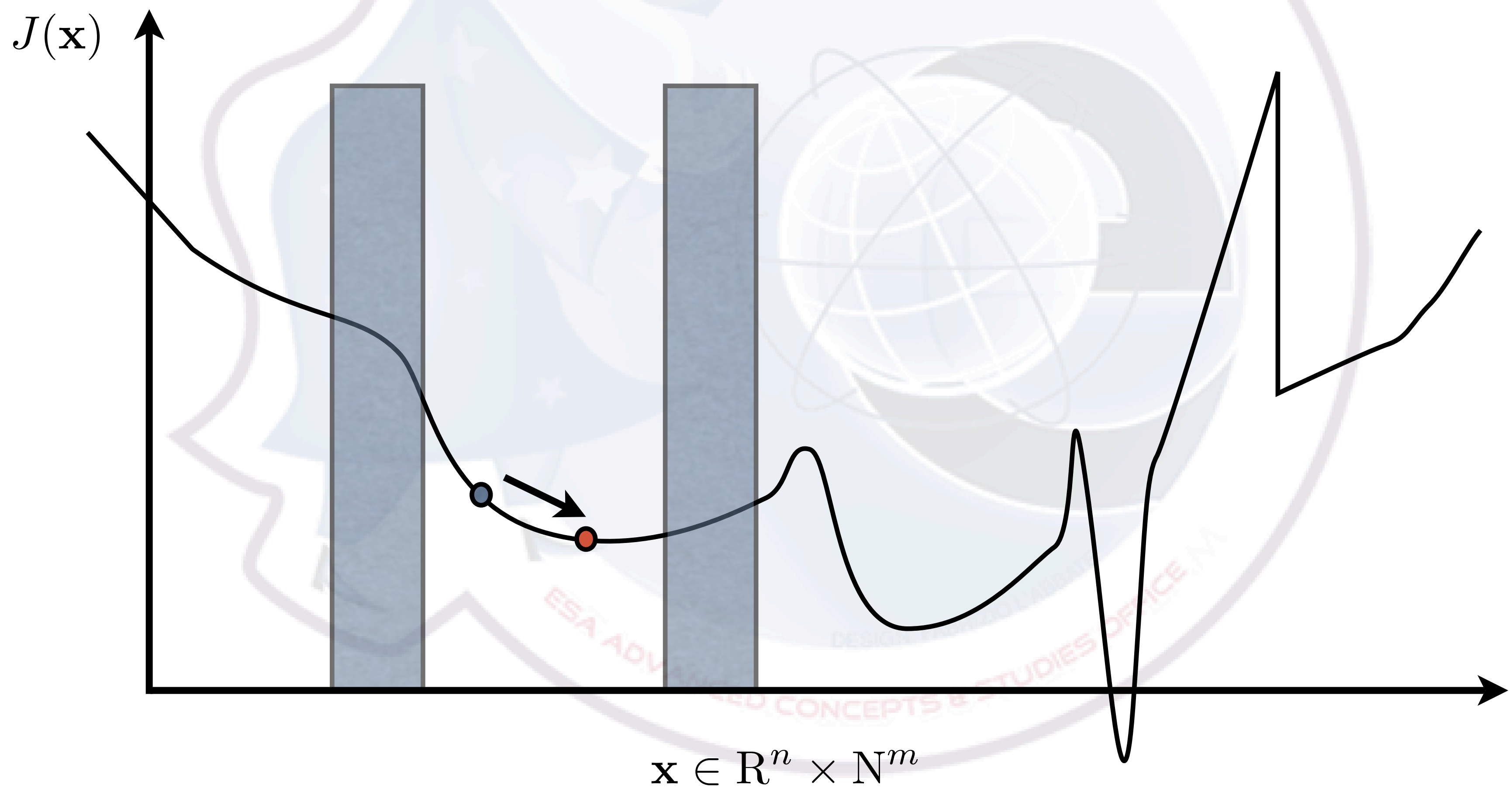
A schematic of the overall process



A schematic of the overall process

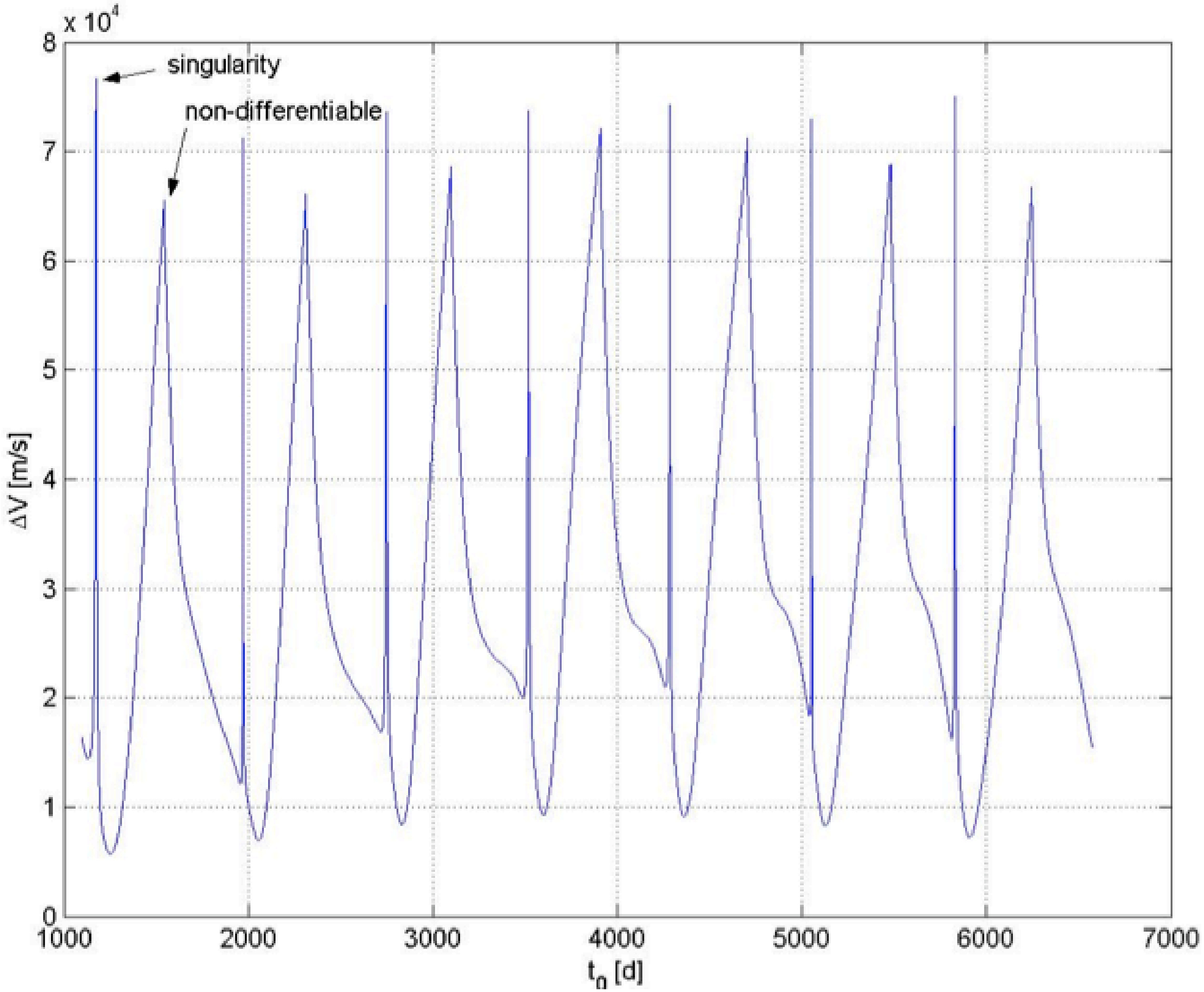


A schematic of the overall process



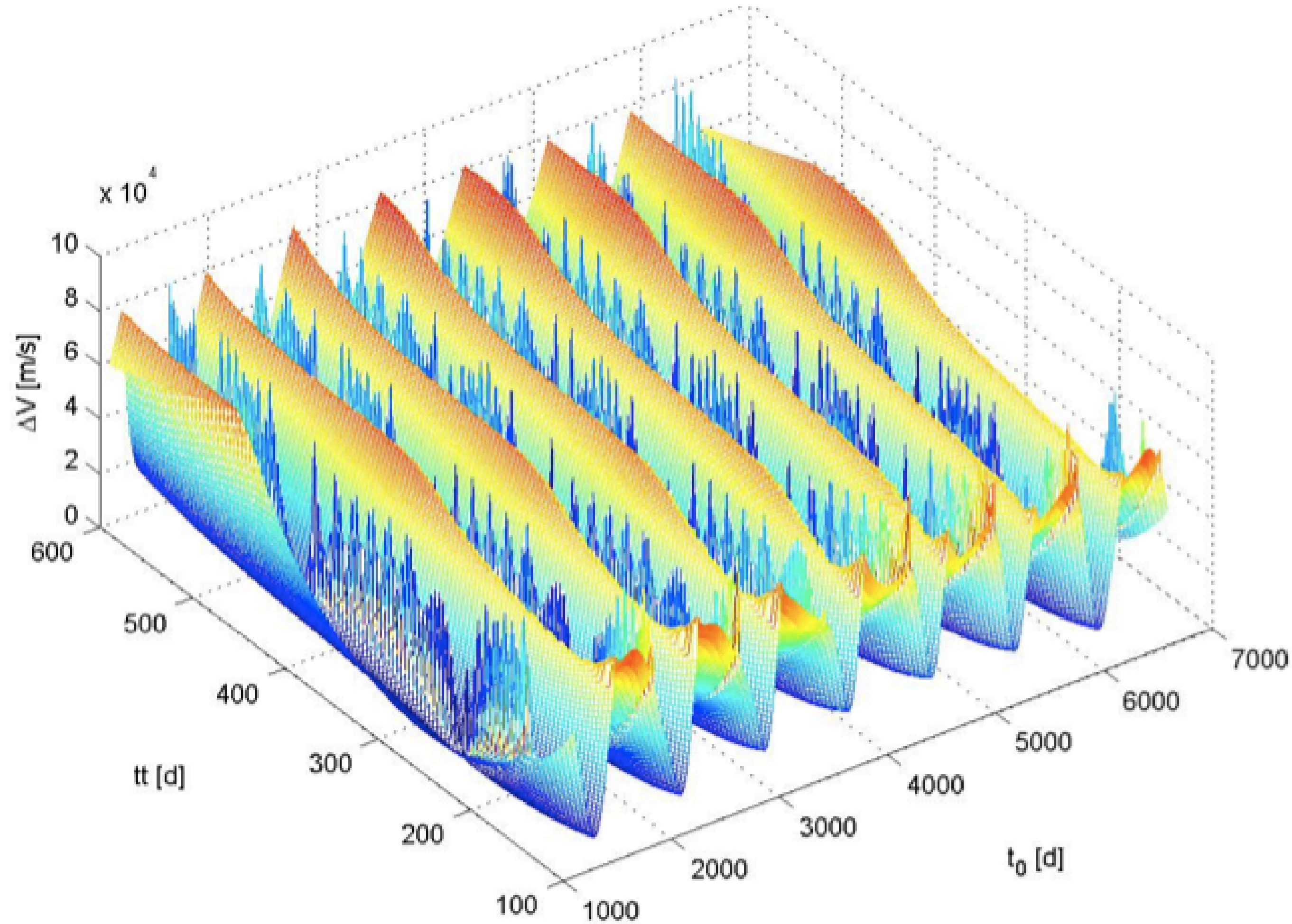
A "simple" example in 1D

- Earth-Mars transfer
- Chemical propulsion
- No deep-space manouvres
- 200 days of transfer
- MJD2000 used



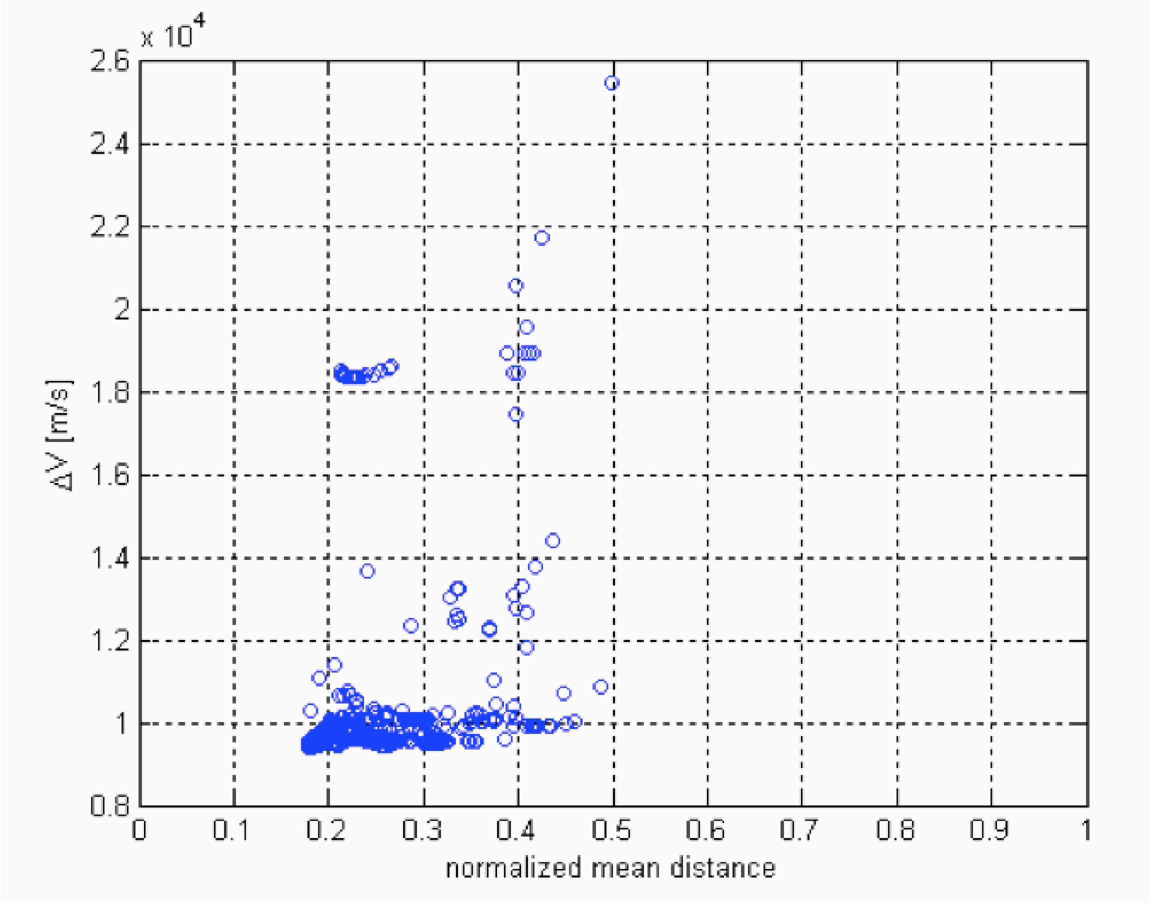
A “simple” example in 2D

- Earth-Mars transfer
- Chemical propulsion
- No deep-space manouvres
- Days and MJD2000 used



A "simple" example in 3D

- Earth-Jupiter-Saturn transfer
- Chemical propulsion
- No deep-space manouvres
- Local optima cluster together
- Better local optima are close to the global one



How large is the dimension?

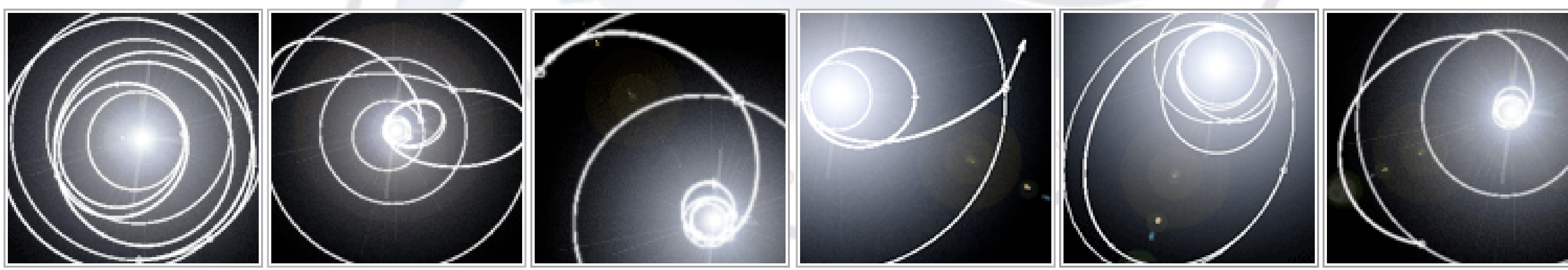
- Each trajectory optimisation problem is a different mathematical programming problem
- Complexity is different, dimension is different.... everything is different
- Dimension ranges from 2 to more than 100,000!!!! Need for dimension reduction
- We may, in a first simplification, distinguish between MGA problems, MGA with DSM problems, low-thrust problems, low-thrust with GA problems
- Although having a different complexity/structure each class has some common features

Benchmarks

Open source code containing solvers and problems is available!!!

Everything is on-line....

- We challenged the scientific community to find good solutions with original approaches by sharing the code for the black-box function on our web-site together with the best known solution
- A simple cooperative approach improves the performances of the stand alone solvers (IAF paper to be presented in Hyderabad)



GTOC

Global Trajectory Optimisation Competition

When we made them compete

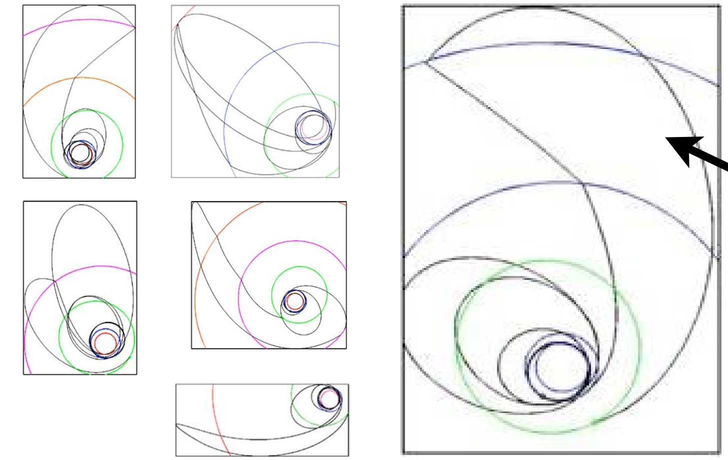
- September, 1st, 2005: GTOC1 announced
  - Open to world wide academia, industry and researchers
- October, 30th, 2005: Inscriptions closed
  - 17 Teams from Europe, China, Russia and the US
- November, 7th, 2005: Problem released
  - impact mission to TW229
  - designed to assure the diversity of the solutions returned and the interest of the problem
- December, 5th, 2005: Solutions returned
  - Twelve out of the seventeen teams returned a solution
- December, 20th, 2005: Solutions checked and definitive rankings formed
  - Only one solution could not be ranked
- February, 2nd, 2006: Workshop on Global Trajectory Optimisation
  - All the teams presented their methodologies and discussed upon the most promising trajectory optimisation researches

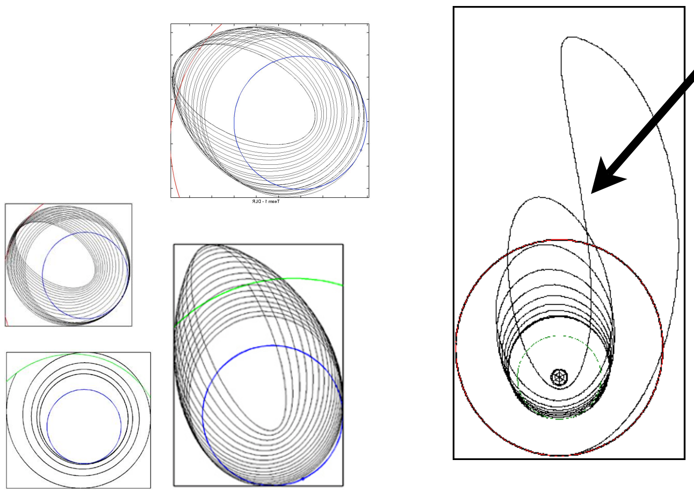
GTOC Trophy

Competition official home page

Special issue of Acta Astronautica

Final ranks (GTOC1)

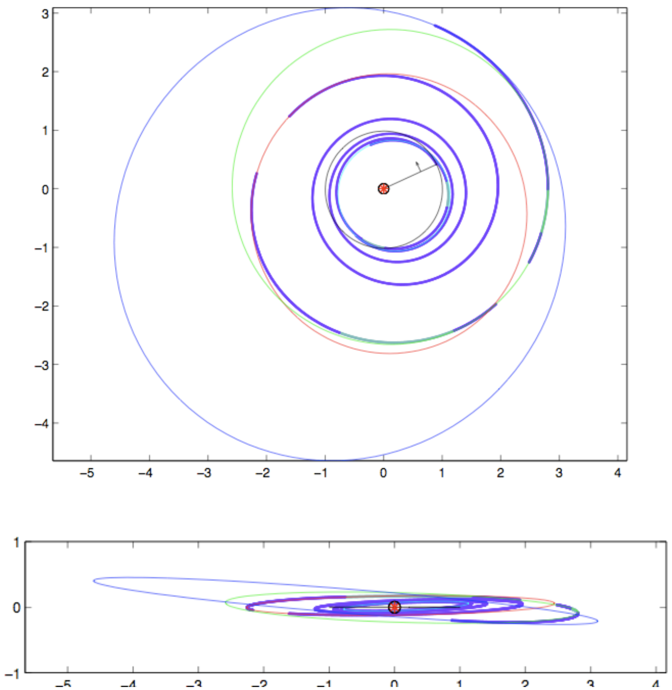




	Team name	Value
G	JPL (Team 11)	1,850,000
G	Deimos Space (Team 17)	1,820,000
G	GMV (Team 2)	1,455,000
L	Moscow Aviation Institute (Team 12)	1,364,000
L	Politecnico di Torino (Team 4)	1,290,000
L	CNES/CS (Team 7)	1,194,000
G	Glasgow University (Team 13)	385,000
L	Moscow University (Team 9)	351,152
L	Alcatel (Team 14)	330,385
G	DLR (Team 1)	330,000
G	Tsinghua University (Team 8)	89,000

And when we competed....

- The winner of the first edition (Jet Propulsion Laboratory) organized a second edition
- A grand asteroid tour was given as a problem
  - Four groups of many asteroids and a trajectory to reach them all....
  - 90 days of minimum stay on each asteroid
  - Low-thrust propulsion 0.1N NEP
  - Initial mass 1500 kg
  - Departure DV 3.5 km/sec
  - Minimisation of mass/time
- Thanks to Anastassios Petropoulos and to JPL for having organized the second edition!!



Winning trajectory from Turin Polytechnic

Final ranks (GTOC2)

Rank	Team		J (kg/yr)
1	4:	Politecnico di Torino	98.64
2	13:	Moscow Aviation Institute, and Khrunichev State Research and Production Space Center	87.93
3	10:	Advanced Concepts Team, ESA	87.05
4	15:	Centre National d'Etudes Spatiales (CNES)	85.43
5	1:	GMV Aerospace and Defence	85.28
6	2:	German Aerospace Center (DLR)	84.48
7	9:	Politecnico di Milano	82.48
8	19:	Alcatel Alenia Space	76.37
9	14:	Moscow State University	75.08
10	7:	Tsinghua University	56.87
11	18:	Carnegie Mellon University, J.J. Arrieta-Camacho	27.94
–	17:	University of Glasgow, *et al.*	73.87[a]
–	21:	Technical University of Delft and Dutch Space	15.95[b]
–	23:	Facultes Universitaires Notre-Dame de la Paix (FUNDP)	–[c]
–	26:	University of Maribor, Bostjan Eferl	–[d]

[a] Significant position and velocity violations at the asteroids and Earth

[b] Significant position and velocity violations at the asteroids and Earth, and flight time limit violation

[c] Only one leg computed (Earth to Group 4)

Interaction with the european academia: the Ariadna projects

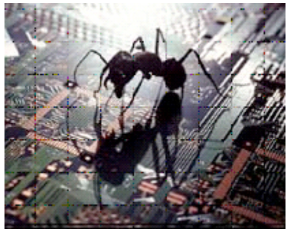
Cooperation with academia via Ariadna

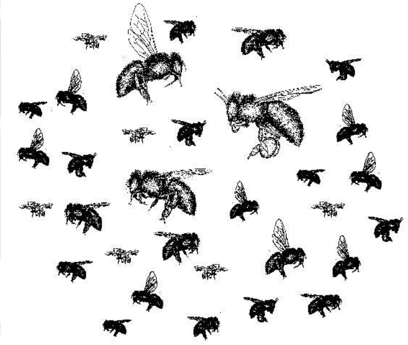
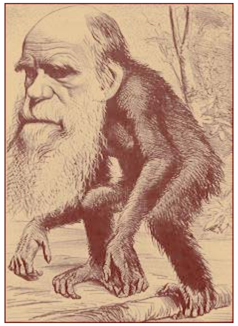
- 2003 - Advanced global optimisation tools for mission analysis and design
  - 4101a - Myatt, D.R., Becerra, V.M., Nasuto, S.J., and Bishop, J.M., Reading University and Goldsmith College
  - 4101b - Di Lizia, P., Radice, G., Glasgow University
- 2005 - Spiral trajectories in Global Optimisation of Interplanetary and Orbital Transfers
  - 4106 - Vasile, M., Schutze, O., Junge, O., Radice, G., and Dellnitz, M., Glasgow University and Paderborn University
- 2006 - Global trajectory optimisation: Can we prune the solution space when considering deep space manouvres?
  - 4110a - Ecole de Mines
  - 4110b - Politecnico di Milano and Mitchigan University
  - 4110c - Glasgow University and Reading University

Off the shelf GO algorithms

Which algorithms?

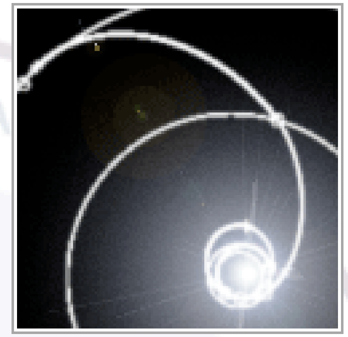
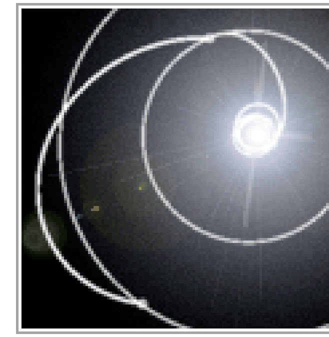
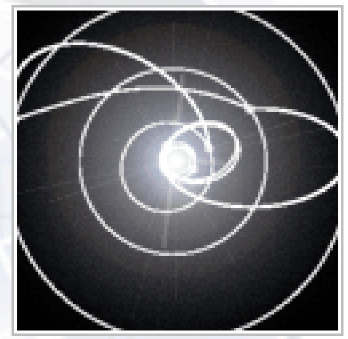
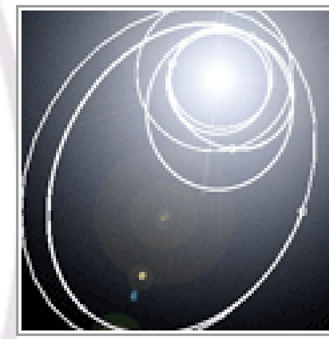
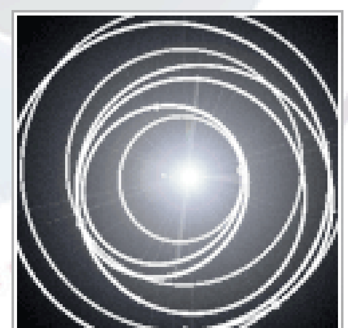
- Stochastic
  - Genetic algorithms and variants
  - Simulated Annealing (simple and adaptive)
  - Particle Swarm and variants
  - Differential Evolution (the 7 types)
  - Monte Carlo
  - Ant Colony over continuous space (Dorigo's version)
  - GLOBAL
  - others....
- Deterministic (or quasi)
  - DIRECT
  - Multi Coordinated Search
  - others....



What problems?

- MGA problem
  - Cassini
  - Apophis Deflection
  - GTOC1, with different sequences
- MGA with DSM problem
  - Cassini
  - Messenger with no mult. rev.
  - Rosetta
  - SAGAS
- MGA with simplified low-thrust shapes
  - Multiple asteroid rendezvous mission


Lesson Learned?

- Algorithms are difficult to compare
- We can say that for complex problems no simple algorithm work
- DE, PSO, GA and ASA have attractive characteristics for different problems. Our favorite is certainly DE
- A cooperative approach, implemented both in our distributed computing environment and in a single computer, allow to find good solutions by just ‘pressing a button’

Exponential sinusoids for low thrust

in cooperation with Glasgow University and Padeborn University

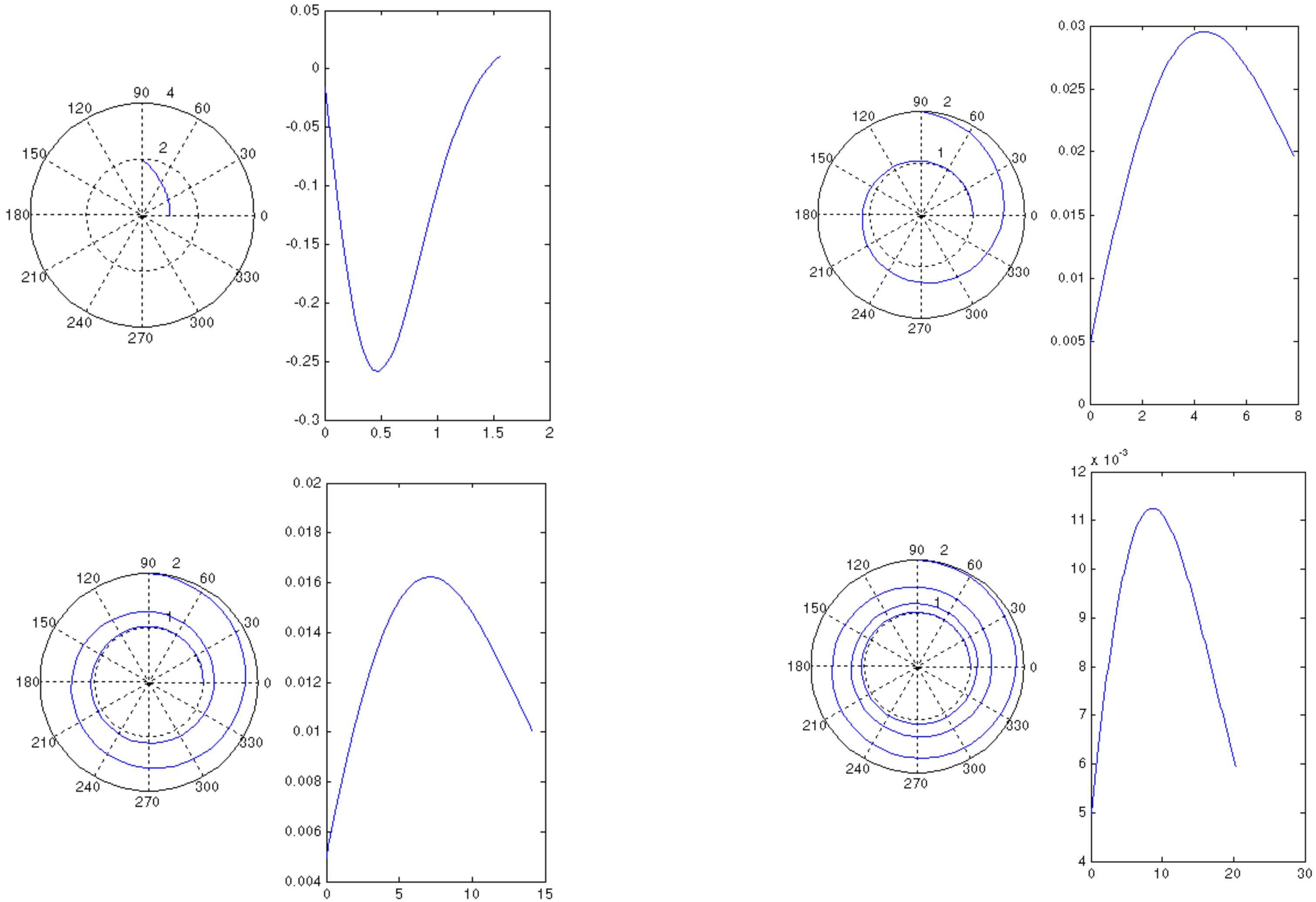
Going from A to B with low-thrust

- Taking into account that A and B are moving…..
- For low-thrust arcs there is no simple solution….. An infinite number of trajectories lead from A to B!!! We therefore consider only a restricted class:

$$\begin{cases} \ddot{r} - r\dot{\theta}^2 + \mu/r^2 = F \sin\alpha \\ \ddot{\theta} r + 2\dot{\theta}\dot{r} = F \cos\alpha \end{cases}$$

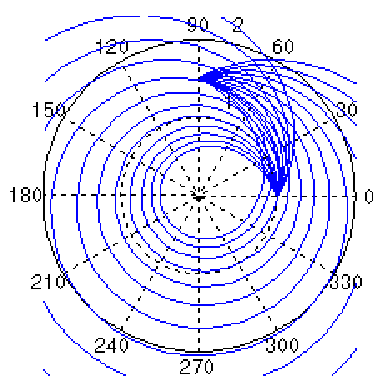
$$r = k_0 \exp[k_1 \sin(k_2\theta + \varphi)] \longrightarrow$$ Exponential Sinusoids

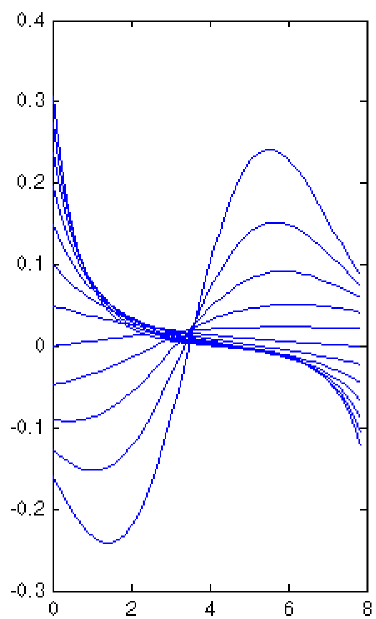
Going from A to B.....

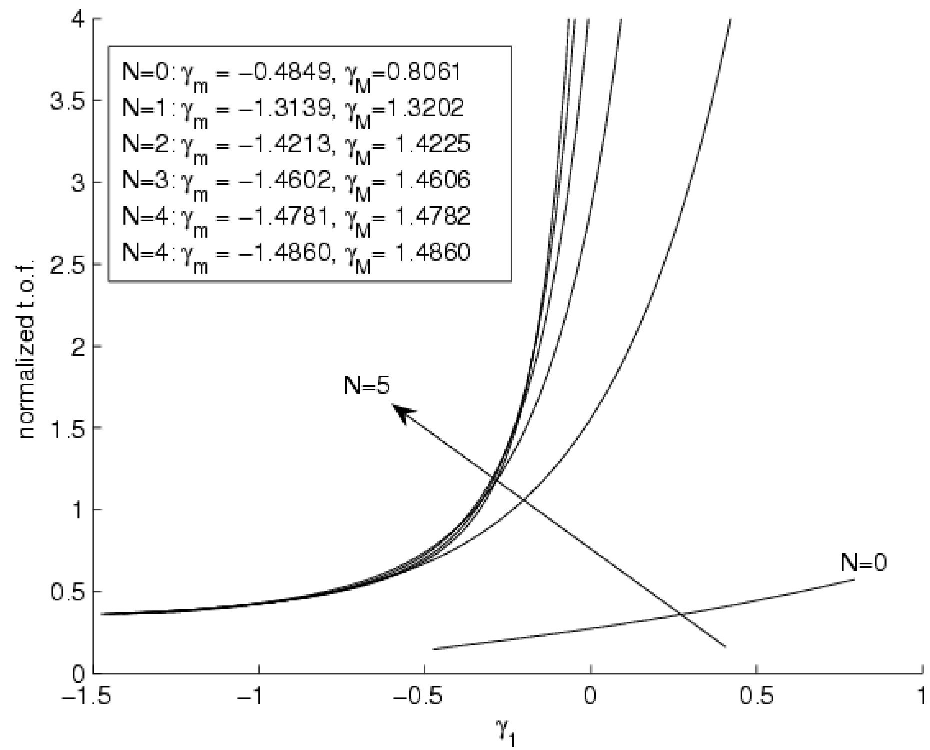


Good choice?

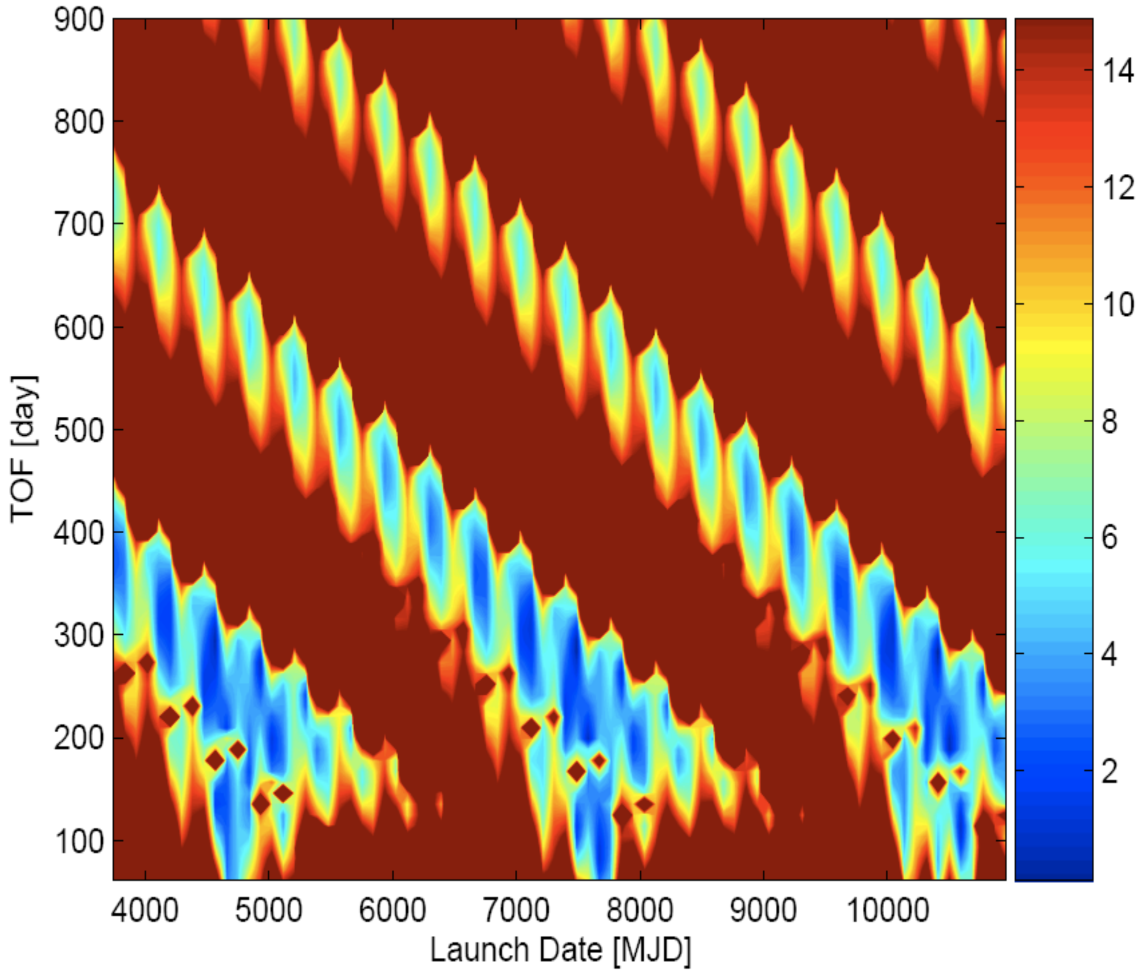
- We may restate Lambert's problem in a slightly different form (there may be no solution) and solve it efficiently (see graph below)
- Typical high thrust.
- Impossible to vary the boundary conditions





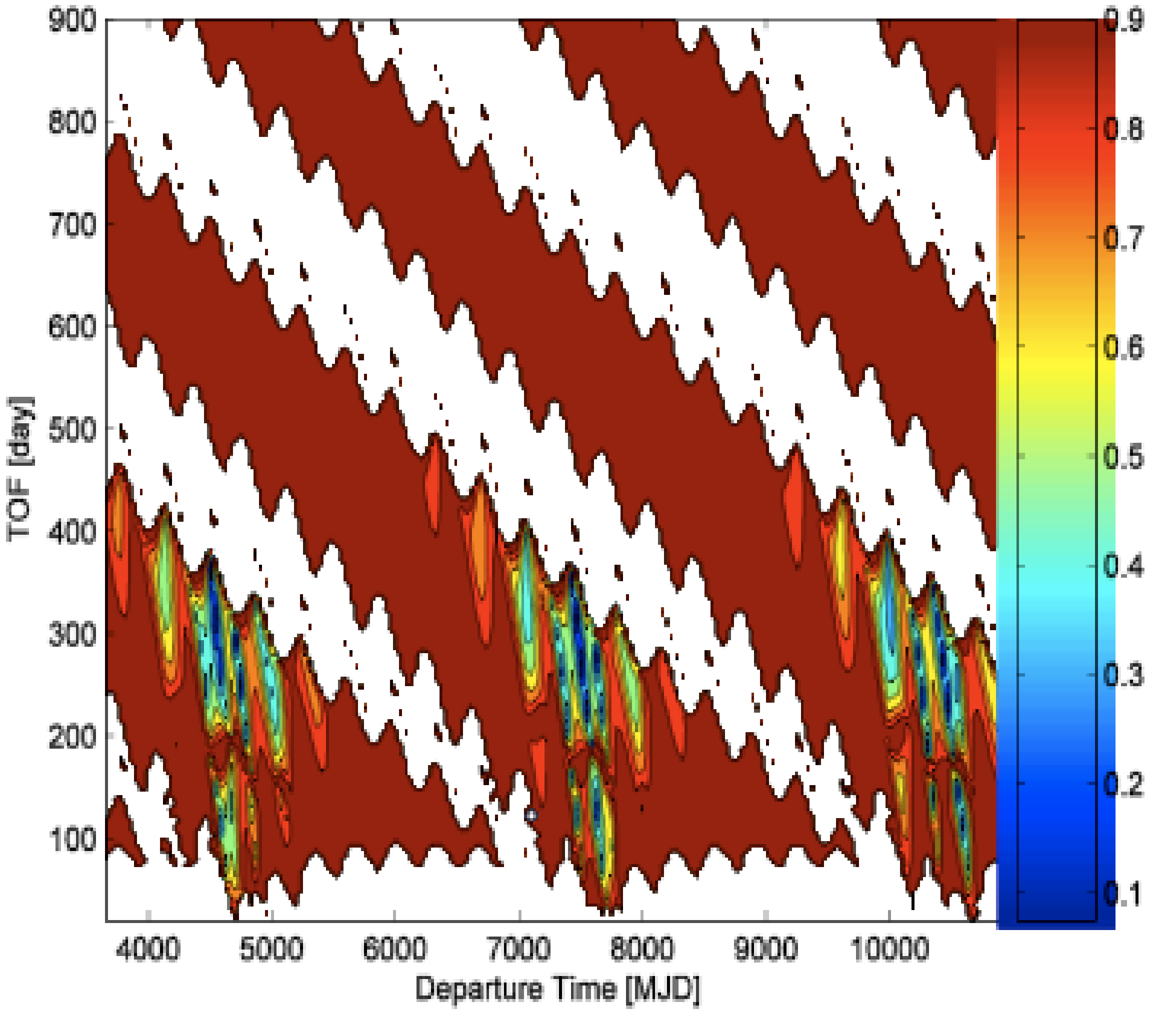


Good choice?



For N=0 no substantial advantages with respect to Lambert arcs! For N>1 exponential sinusoids are a possibility

Good choice?



For N=0 no substantial advantages with respect to Lambert arcs! For N>1 exponential sinusoids are a possibility

GASP!

Gravity Assist Space Pruning
In cooperation with Reading University

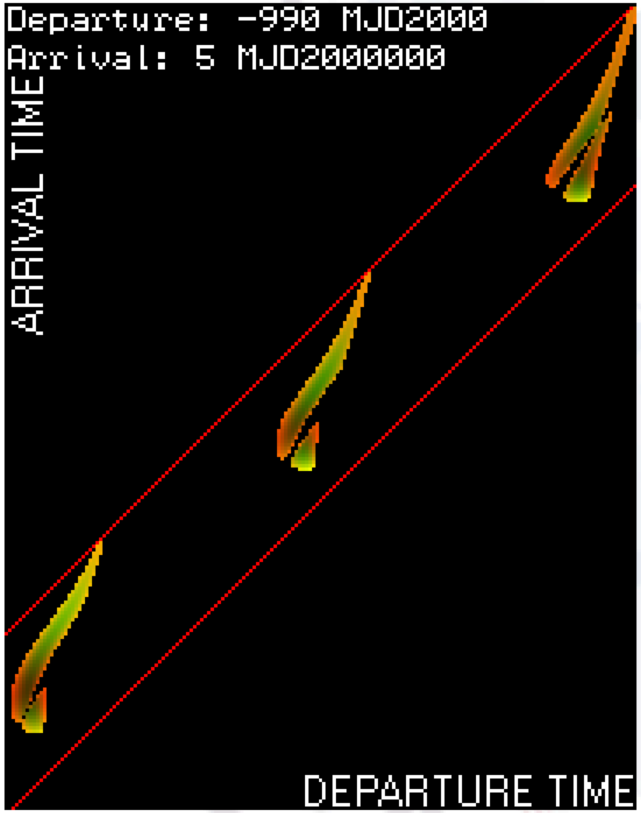
Overview of Gravity Assist Space Pruning

- Deterministic algorithm
- Transforms the N dimensional space into a cascade of 2D spaces
- Exploits domain knowledge to effectively constrain space
- User defined constraints on launch energy, gravity assist thrusts, swing-by periapsis radii, and braking thrust
- Provides intuitive visualisation of high dimensional MGA search spaces
- Allows simple identification of solution families
- Produces a set of reduced box bounds (between 6 and 9 orders of magnitude smaller than original space)

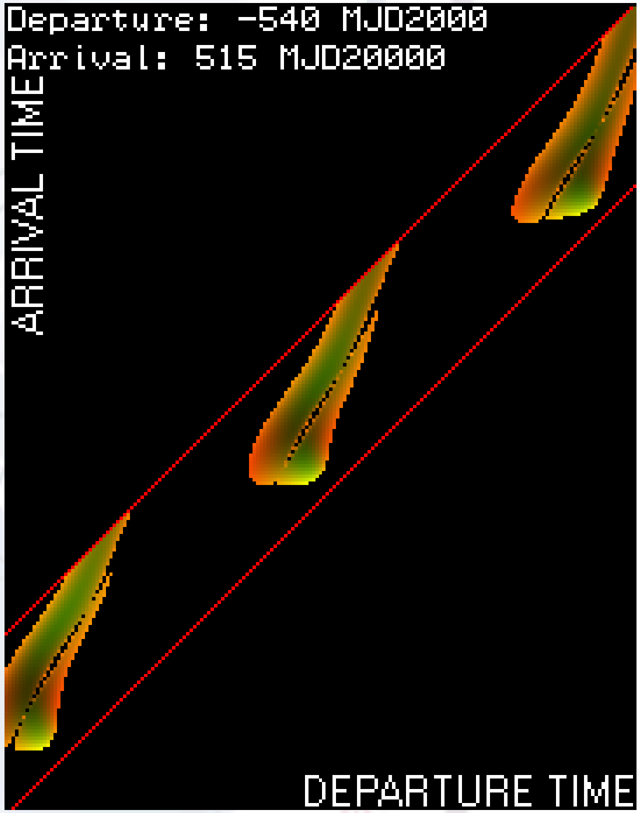
Example: Earth-Mars transfer

- Consider an Earth-Mars transfer
- -1200<t0<600 MJD2000
- 25<T1<525 days
- Grid sampled at resolution of 10 days

Effect of launch velocity constraint



pruned at 5km/sec



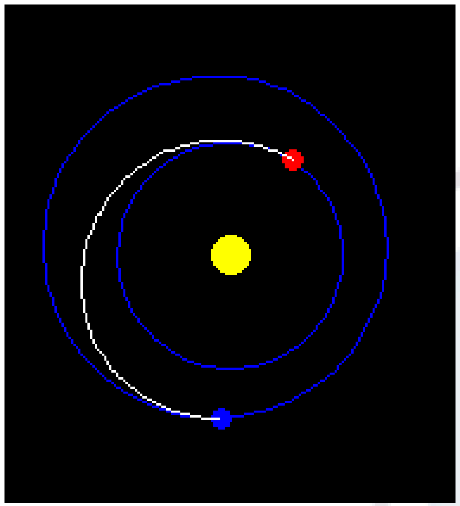
pruned at 10km/sec

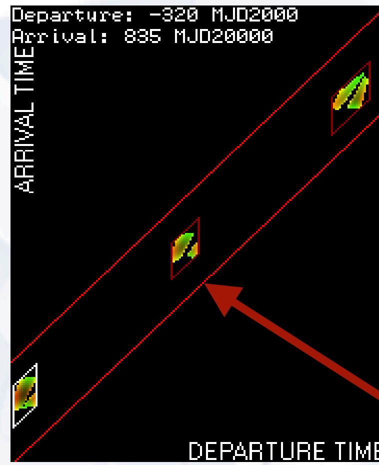
Note: Arrival time = Departure time + transfer time (t0+T1)

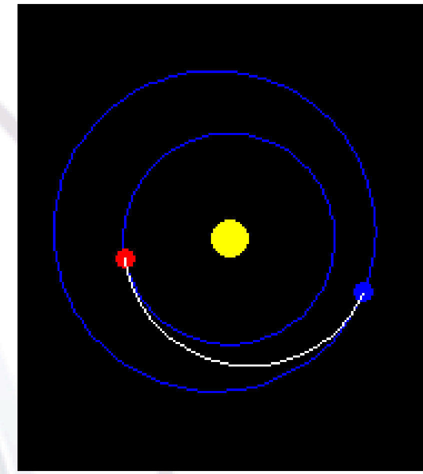
Adding a Braking Constraint

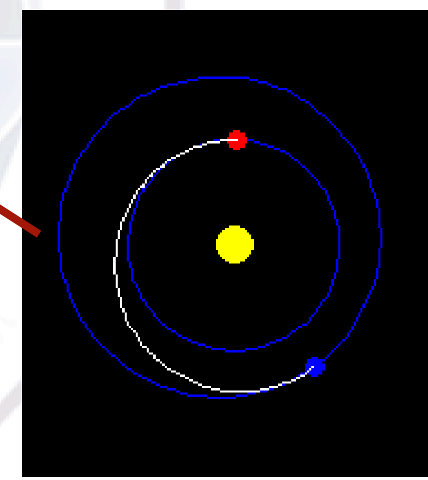
- Adding a braking manoeuvre constraint at Mars of 5 km/s yields only 4% of the search space valid.

Optimising launch windows



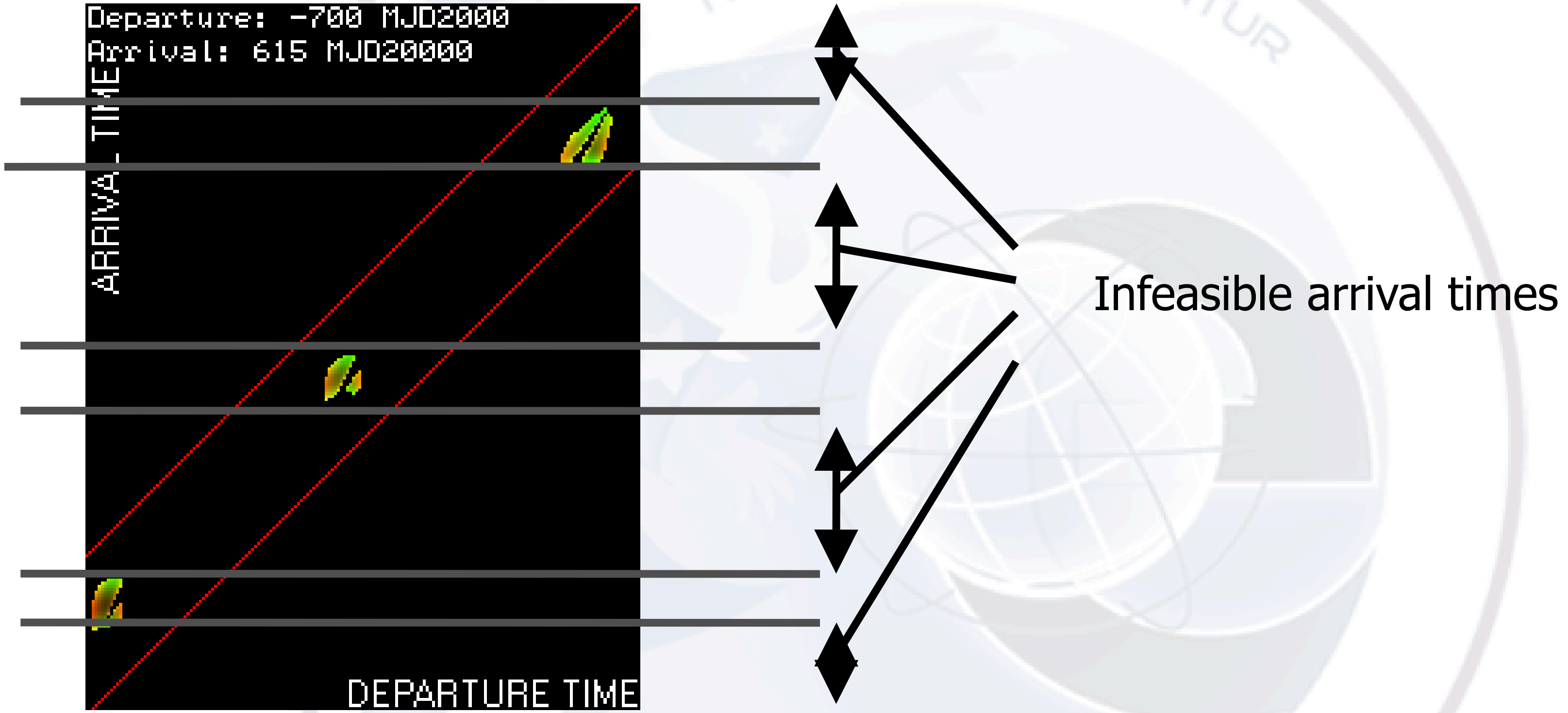






- Reduced box bounds automatically calculated for each launch window
- Each launch window can been optimised separately using a global optimisation scheme, e.g. Differential Evolution
- Different solution families can be examined separately and then the most appropriate chosen

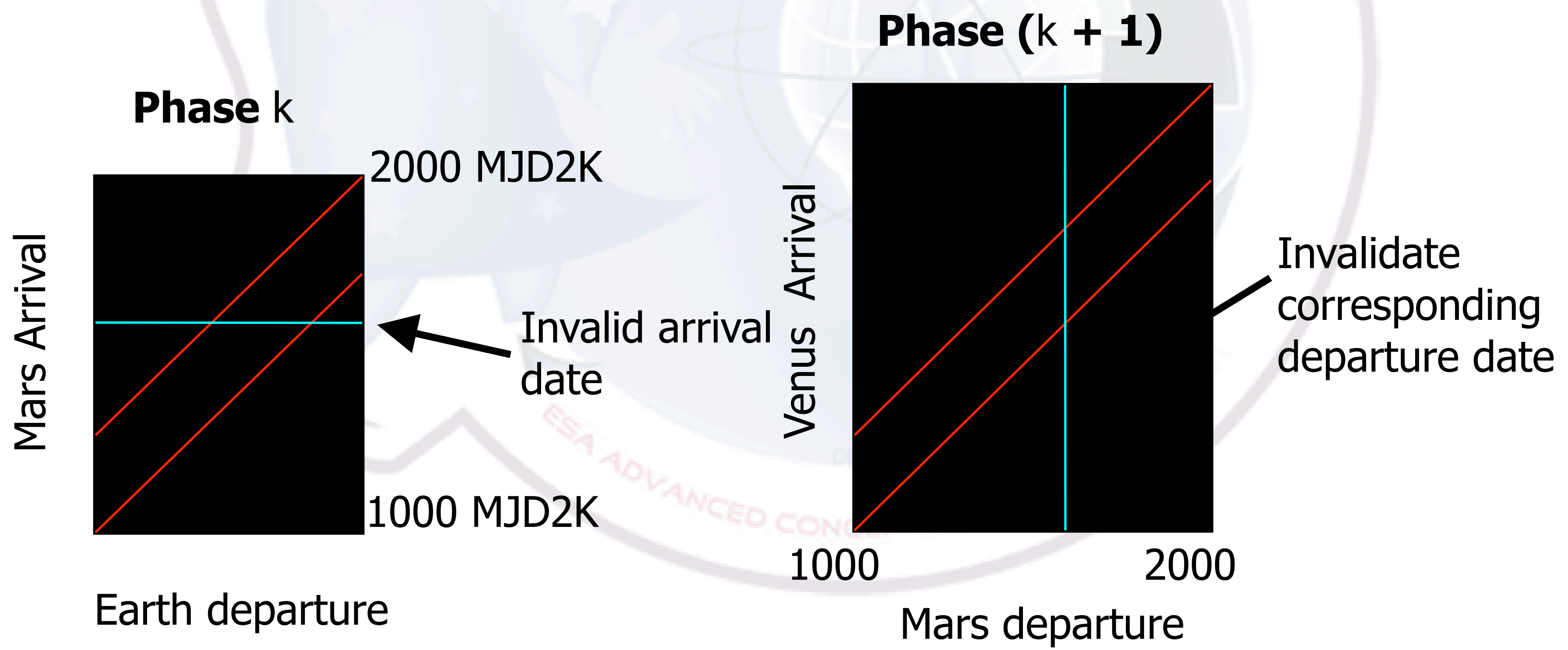
Two and more phases…



Therefore, it must be infeasible to depart from the next planet on these dates…

Forward constraining

- Infeasible arrival date constrains departure from the planet on that date
- Horizontal axis constrains vertical in the next phase



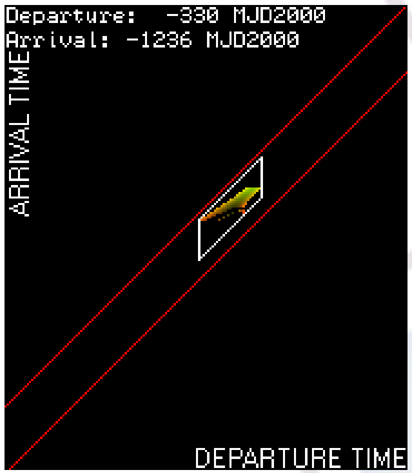
Complete GASP Algorithm

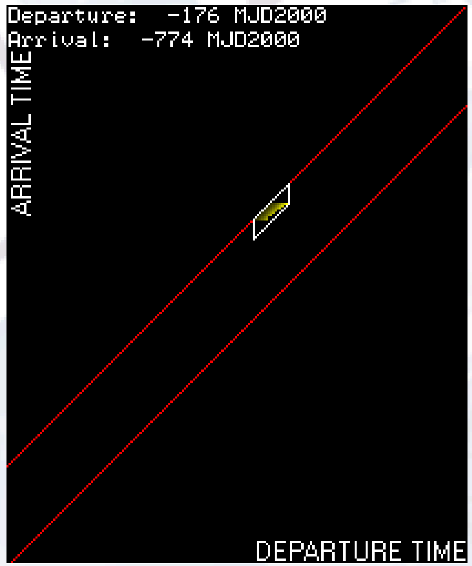
- Perform sampling as sequence of 2D spaces
  - Earth departure/Mars arrival
  - Mars departure/Venus arrival
- Apply initial velocity constraint to first phase
- Forward constraining through all phases
- Apply braking manoeuvre constraint
- Backward constraining through all phases
  - Invalidate arrival dates based on departure dates

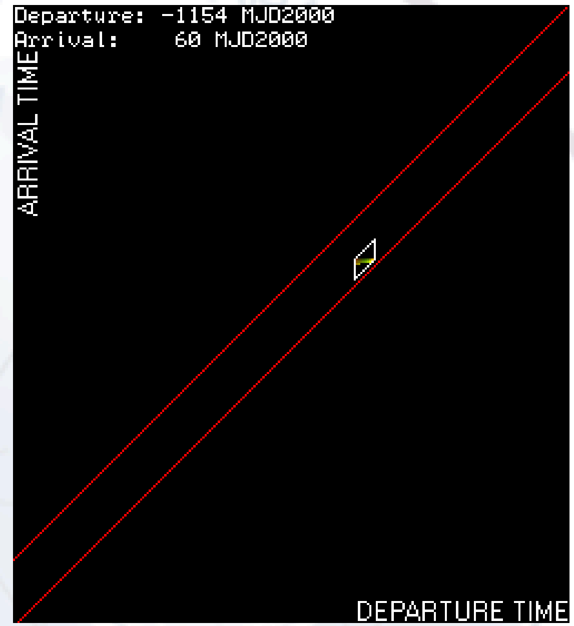
Scaling of GASP algorithm

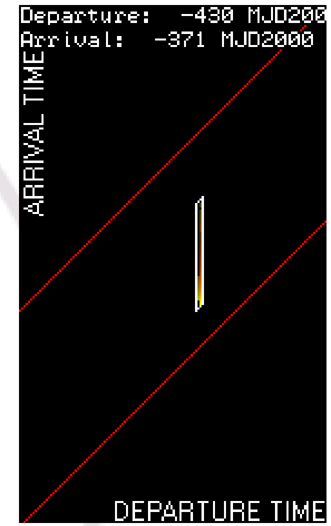
- GASP algorithm scales polynomially – this is due to the characterisation of the search space as a sequence of connected 2D search spaces
- This is true both in memory requirements and computational expense
- Copes well with the curse of dimensionality

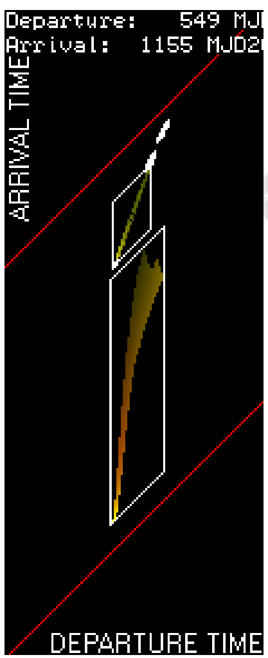
EVVEJS With New Bounds



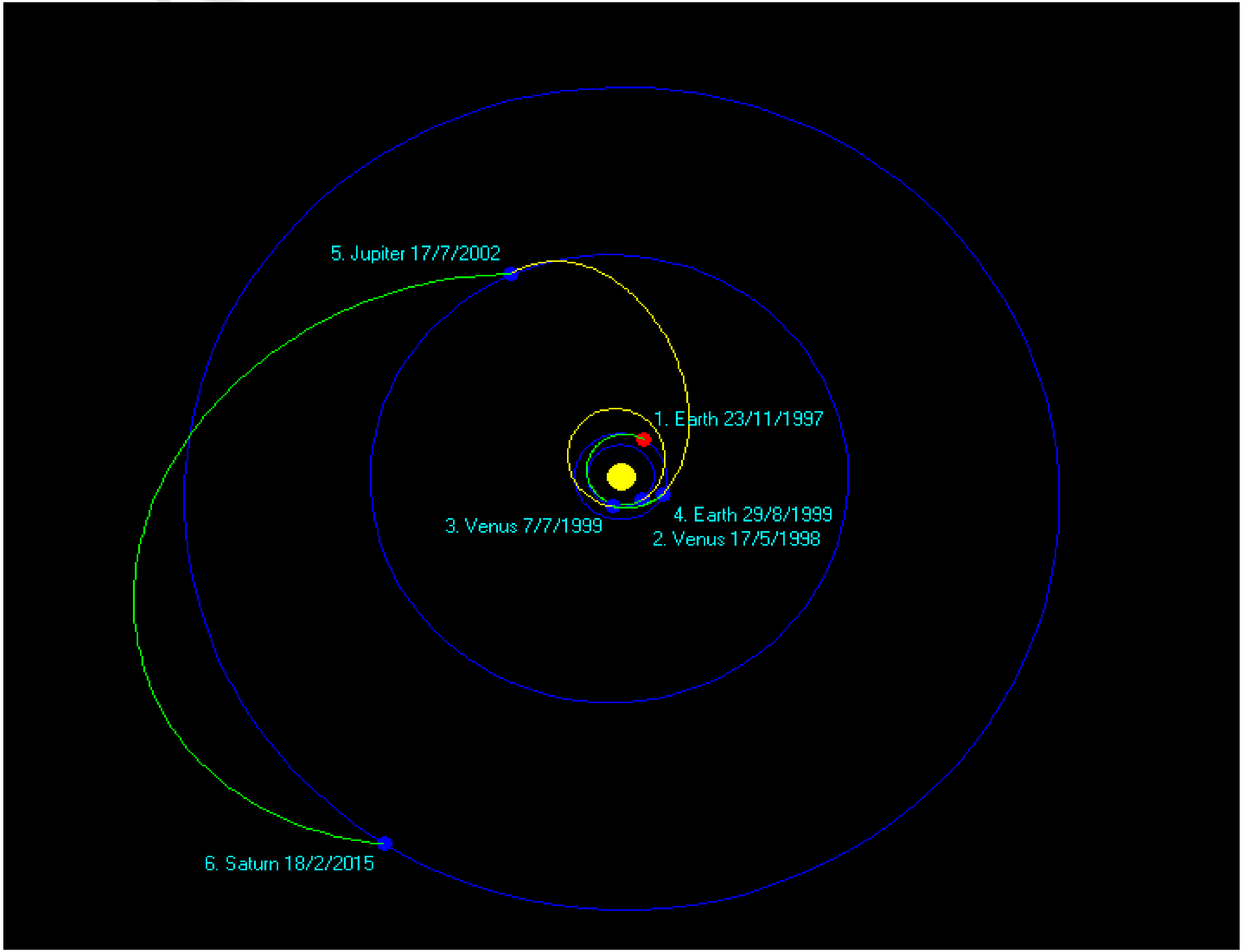








- We apply Differential Evolution to the reduced bounds
- Best solution is 4932.2 m/s
- Launch velocity: 3737m/s
- Probe velocity: 1488 m/s
- A direct transfer requires launch velocity of approx 10000m/s


5. Jupiter 17/7/2002
1. Earth 23/11/1997
4. Earth 29/8/1999
3. Venus 7/7/1999
2. Venus 17/5/1998
6. Saturn 18/2/2015

Can we do the same for the MGADSM problem?