Methods and results of the Eccentric Anomalies when building a Dyson ring

The Eccentric Anomalies

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Outline

Team members

The veterans

- Joris Olympio: GTOCs 4 (bronze medalist), 6, 8, 9 & X
- Carlos Ortega & Romain Serra: GTOCs 9 & X
- Jérémie Labroquère: GTOCs 9 & X
- Ivan Sumelzo: GTOC X

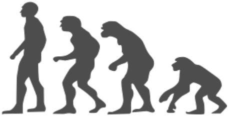
Already on the same team for GTOC X, ranked 9th

The newbies

- Victor Rodriguez
- Noé Charpigny
- Victor Munoz

Best or second best performance for everyone with this edition (rank 6)

Working environment (non-exhaustive)



Outline

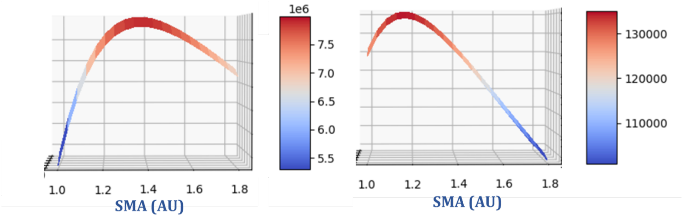
Dyson ring

Analytical approach to find ring location maximizing $f = \sum_i m_f^{(i)}/(12a^2)$

Asteroid mass at ring evaluated thanks to $\Delta t_1 + \Delta t_2$

$\Delta t_1 \longrightarrow \texttt{Edelbaum} = \Delta t_{\Delta a}$, $\Delta t_2 \longrightarrow \texttt{Pollard} = \Delta t_{\Delta e, \Delta i}$

Sensibility of f evaluated for different scenarios (i.e. subset of selected asteroids) within whole available $\{a, \Omega, i\}$ ring domain; such as: all asteroids (left), 300 most massive at arrival (right)



1. Most interesting a in [1.1,1.4] AU, we tried 1.2 & (best) **1.3**
2. Low improvement placing the ring out of ecliptic (hence $i = \Omega = 0$)
3. No investigation of phase, so fixed arbitrarily

Outline

Departures from Earth

Database with up to 5 types of transfers per asteroid (~ 415000)

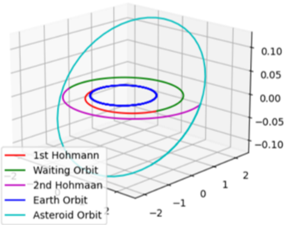
Cheap transfers occurring in the ecliptic plane:

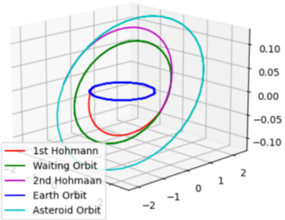
- Dep. at MJD0; 2 Hohmann transfers + intermediate waiting circular orbit; plane correction performed on arrival (asc./desc. node)

Cheap transfers with plane correction at departure thanks to v_∞:

- Like previous strategy but dep. when Earth at node; remaining plane correction performed on arrival

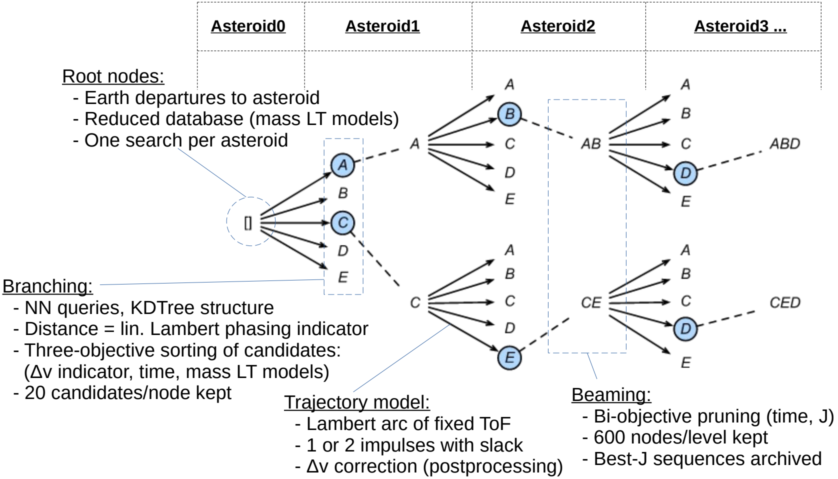
Fast transfer: departing at MJD0; best ΔV out of short Lambert arcs





Asteroid flyby sequences

- First design of flyby sequences ⟶ Beam Search (12k nodes/level)



- Best-J non-overlapping sequences (N = **36-41** asteroids, total 375)

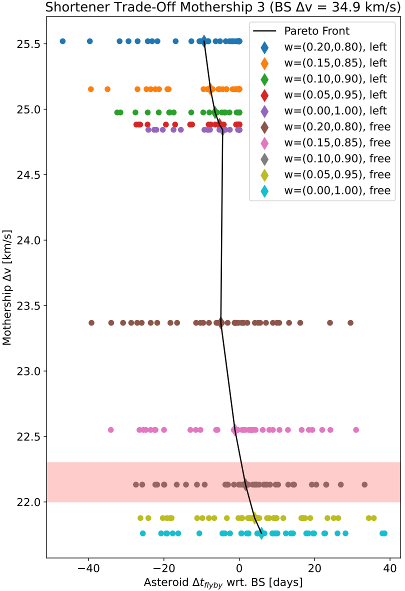
Mothership trajectory (2-impulse model)

Sequence-level optimization after BS:

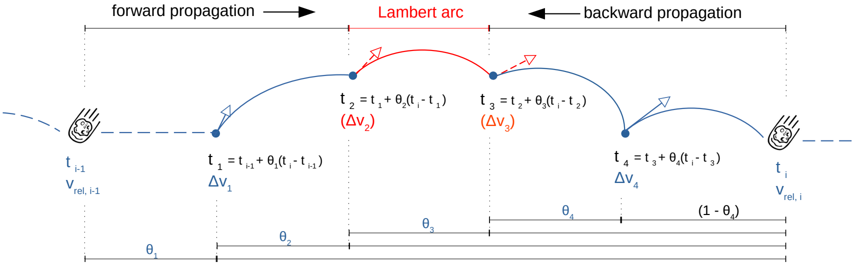
1. **Shortener**:
   - Continuous impulse dates
   - $dim(x) = 2(N-1) \approx 70$
   - Multi-Obj. (avg. t_{flyby}, Δv_{tot})
   - Weights → box-constr. Single-Obj.
   - Differential Evolution + SQP

2. **Refiner**:
   - Re-optimizes Earth departure
   - Includes flyby v_{rel} explicitly
   - $dim(x) = 18 + 5(N-1) \approx 200$
   - Local optimization only (SQP)

- Mode *free/left*: shift flyby dates to past only (allows final tweaks)



Mothership trajectory (4-impulse model)



1. **Transfer optimization** (fixed flyby dates and states)
   - Initialization from best of 0-rev Lambert arc (from ESA's pykep) & fuel-optimal solution under linearized dynamics (via cvxopt's SDP)
   - $dim(x) = 10$, unconstrained $\longrightarrow$ SQP
2. **Sequence-level** *nano-refiner*
   - As *refiner*, includes flyby v_{rel} explicitly (variables + constraints)
   - $dim(x) = 18 + 14(N - 1) \approx 520 \longrightarrow$ **difficult problem** (SQP)

Outline

Fly me to the ring a.k.a. minimum-time optimal control

A mixed pool of traj. (w/ various guess t_0, from all asteroids to all the stations) is generated, later serving as input to the dispatch problem.

Direct approach

Two runs of pykep's improved Sims & Flanagan w/ scipy's SQP:

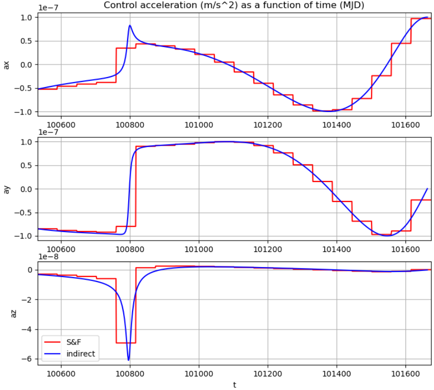
1. Find admissible trajectory w/ free t_0
2. Actually minimize the time-of-flight

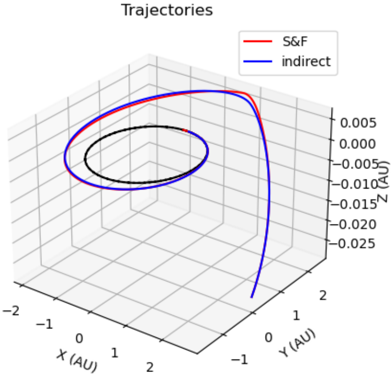
Indirect approach

- Fixed t_0 & state variables as "local" spherical coordinates
- Single shooting with finely-tuned Newton method, first w/o phasing
- Initial guess building on the fact that the adjoint vector is the gradient of the cost-to-go (still w/ analytical formulas)

An alternative indirect method (orbital elements, free dep. & multiple shooting solved w/ Ipopt) was also utilized after the scheduling.

Comparison of ATD's control and transfer for a given t_0

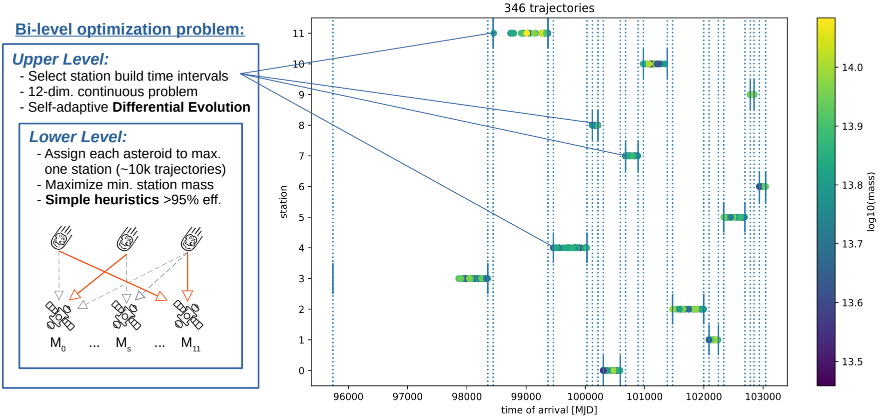




When spanning values of t_0, the indirect one showed better convergence, but was also less flexible and ran slower for programming reasons.
With these hybrid settings we were never able to submit in "mode 1", thus had huge files.

Scheduling

- Which **asteroid** to which **station** and when (from ∼120k trajectories)



- *Tweaks*: remove useless asteroids, detect swaps, random search, etc.
- Our best solution: **375** → **346** asteroids (too many lost?)
- Final asteroid capture set ⟶ reoptimize mothership **flyby sequences**

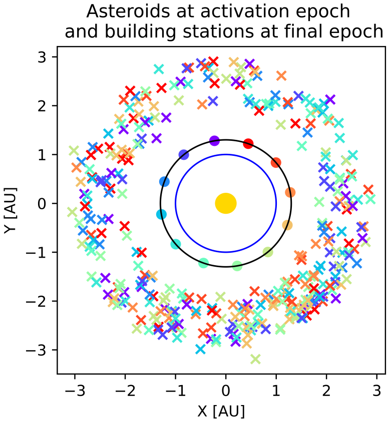
Outline

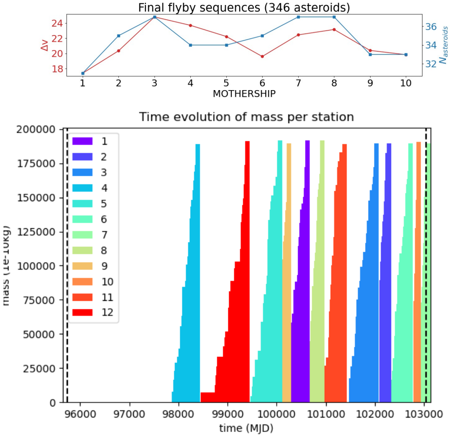
Selected history

Date	Score	Main comment
18/10	4	Basic (v_∞ reachable)
28/10	1817	Dijkstra + Earth dep. DB
29/10	2065	BS + Edelbaum
30/10	4242	BS w/ v_{rel} slack
2/11	4600	*Shortener* (only $\Delta v\downarrow$)
3/11	4768	*Refiner* (only $\Delta v\downarrow$)
4/11	5005	First indirect, "full slack"
7/11	5487	Final settings

Name	Mmin, N	Best Score
TsinghuaLAD&509	1.81364e+15, 388	8443.630600
ACT&Friends	2.0125e+15, 301	6359.724900
theAntipodes	1.27672e+15, 293	5992.298400
UT Austin	1.13283e+15, 235	5885.469300
ASRL	1.10046e+15, 209	5525.388800
The Eccentric Anomalies	1.89224e+15, 346	5487.543400
HIT	1.08546e+15, 250	5208.346300
GHWZZ	1.50229e+15, 294	4794.468600
ASTL-NUAA	1.03068e+15, 213	3735.160200
Team_BIT&ITNS	8.00267e+14, 199	3532.704400

Best solution





$$a = 1.3 \text{ AU} \;\&\; i = \Omega = 0 \text{ deg}$$

Outline

Conclusion

Summary

1. Choice of ring parameters
2. Design of flyby sequences and mothership legs
3. Generation of a pool of min.-time ATD trajectories
4. Scheduling of station windows and individual arrivals
5. Adjustments (on flybys, ATDs, etc.)

Perspectives

- Explore further alternative options for Non-Linear Programming
- Think more ahead to reduce execution time
- Secure additional computational resources

Looking forward to GTOC 12!