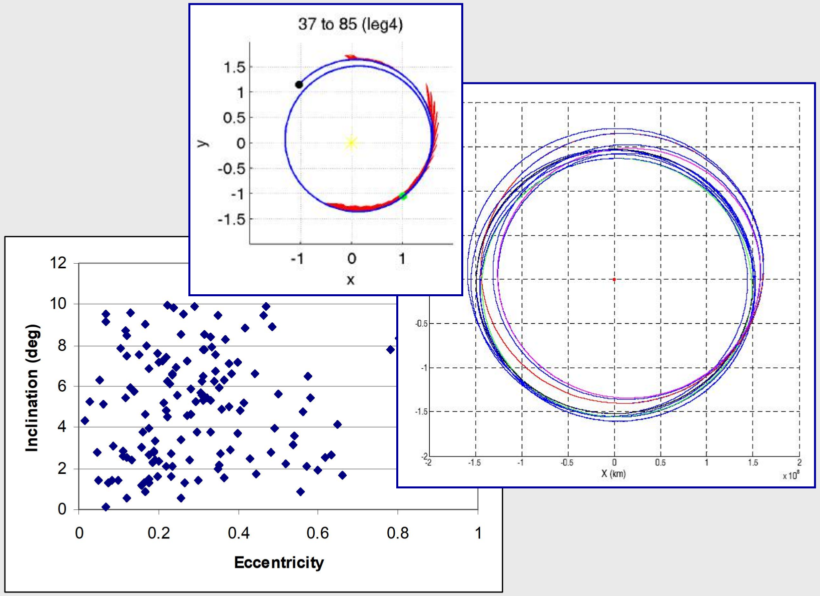
Methods Utilized in Response to the 3rd Annual Global Trajectory Optimization Competition

Team 2: Georgia Institute of Technology

Atlanta, Georgia, USA

Presented by Richard Otero



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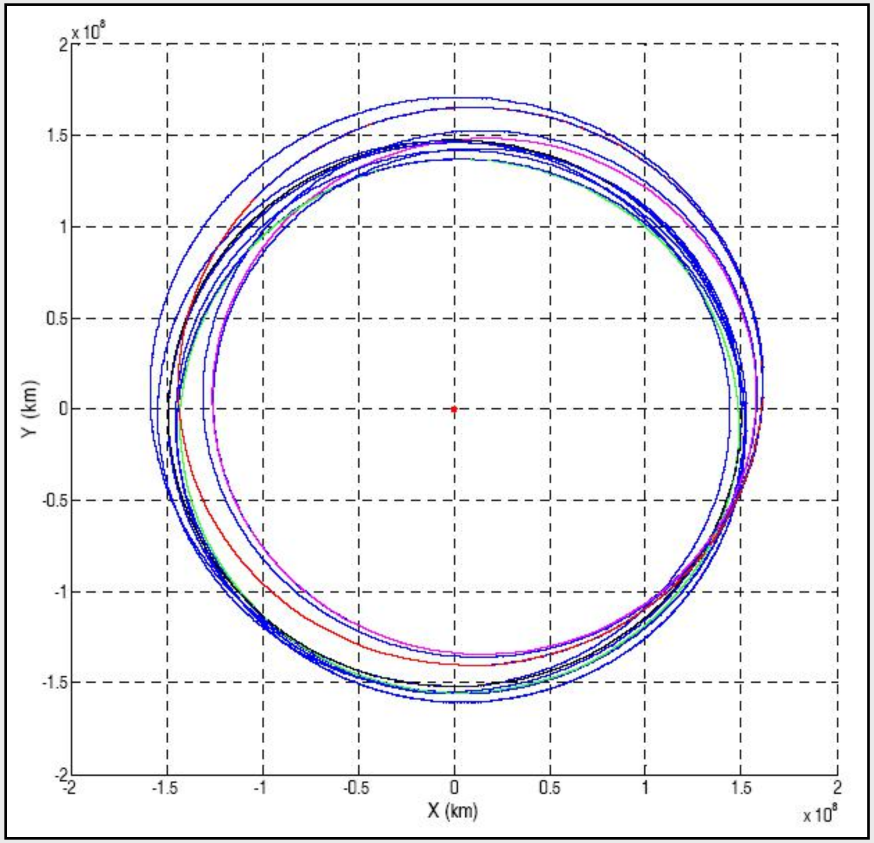
E – 49 – E – 37 – 85 – E – E



Competition Problem

- Objective function for competition: $$J = \frac{m_f}{2000\text{kg}} + 0.2\left(\frac{\min\limits_{j=1,3}\left(\text{stayTime}_j\right)}{10\text{years}}\right)$$
- Final score depends on
  - Maximizing the final mass
  - Maximizing the minimum time spent at any asteroid
- Problem domain
  - 57388 MJD ≤ initial launch ≤ 61041 MJD
  - Minimum stay at asteroid is 60 days
  - The entire trip is to fall within 10 years
  - May use Earth flybys with a min perigee radius of 6871 km
  - Earth orbital elements at epoch provided
  - Gravitational parameters provided
- Constraints must be satisfied
  - Position to within 1000 km
  - Velocity to within 1 m/s

Overview of Solution Approach

Too many low-thrust cases to reasonably compute

2.7 million asteroid combos (not including optional flybys)

Ballistic approximation

Form matrix populated with best multi-rev ballistic ΔV's for each possible leg → Rank full trips using matrix. This assumes perfect phasing.

Few thousand cases

Local low-thrust optimizer

MALTO utilized

Three promising cases

Team developed low-thrust code

Run cases to fidelity required by competition

Final Answer

Modified Initial Design Target

- Objective function for competition: $J = \frac{m_f}{2000\,\text{kg}} + 0.2\left(\frac{\min\limits_{j=1,3}\left(\text{stayTime}_j\right)}{10\text{ years}}\right)$
- Final score depends on
  - Maximizing the final mass
  - Maximizing the minimum time spent at any asteroid

- The minimum time was not a factor to be considered during the initial search
  - Minimum stay time is 60 days
  - If minimum stay time was 1 year this would only lead to a 0.02 improvement to the objective function
  - Team, early on, decided to concentrate on finding minimum fuel solutions

- Modified objective function: $J = \frac{m_f}{2000\text{kg}}$

Ballistic Downselection

- Initially pruned the design space by solving the phase-free multi-revolution ballistic orbit transfer problem
- Enumerated all possible combinations:
  - {Earth - asteroid}
  - {asteroid - asteroid}
  - {asteroid - Earth flyby - asteroid}
- Populate 2-D matrix with the best point to point ΔV
  - Method assumed either no or one flyby for each leg of the flight
  - This method could easily be utilized with other assumptions
- All possible ordered combinations were ranked based on sum of phase-free ΔV costs
  - {Earth - asteroid1 - asteroid2 - asteroid3 - Earth}
  - With and without intermediate flybys
  - Best several hundred combinations were kept

Ballistic Downselection

- Remaining combinations were again evaluated using the ballistic, multi-revolution assumption

- Phasing was now taken into account for each combination
  - Possible dates for launch and arrival at each leg were enumerated using a course time grid
  - Single intermediate Earth flybys were also considered
  - Each solution was again ranked by ballistic ΔV cost
  - ΔV leveraging Earth flybys were prepended and appended to solutions with short flight times
  - Best several thousand solutions were carried forward

Low-Thrust Trajectory Optimization

- MALTO (Mission Analysis Low Thrust Optimization) used as low-thrust trajectory optimization tool
  - Developed at JPL and used by JPL team in 1st GTOC competition
  - Employs a direct method that discretizes the trajectory into a series of impulsive maneuvers
  - SNOPT used as the optimization engine
  - Fortran-based
  - Used to optimize minimum fuel problem
- Automated the creation and running of MALTO cases
  - Generated example cases through GUI to understand and replicate the input file format
  - Wrote several scripts to automatically generate input files and then run each case in MALTO
  - Used GT computer cluster to run thousands of low-thrust cases

Low-Thrust Trajectory Optimization

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- Passed the following information from ballistic downselect as an initial guess into MALTO:
  - Asteroid sequence (with intermediate Earth flybys where applicable)
  - Departure and arrival dates at each body
  - Departure and arrival V-infinity vectors
- Arrival and departure dates set to ±300 days
  - Allowed MALTO optimizer to vary the dates to locate the minimum fuel solution
  - Constraints set on minimum stay time at each asteroid and maximum total flight time
- Field was narrowed to best three cases

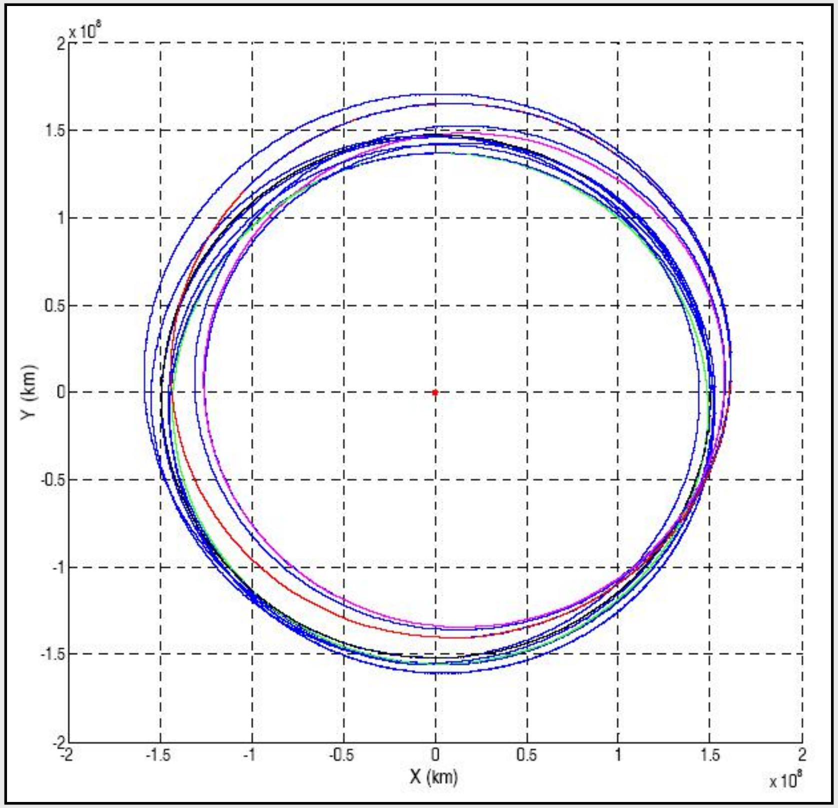
Generating Final Solution

- Our version of MALTO was not able to represent the problem domain exactly
  - Flybys were not allowed for user defined bodies
  - Uncertain how to change without source code access
    - Sun’s gravitational parameter
    - Earth orbital elements at epoch
- The problem domain could be closely represented by the stock body for Earth

- Wrote our own low-thrust code
  - Used MALTO results as initial guesses
  - Refined trajectory for problem domain
  - Refined trajectory to accuracy required by competition

Final Solution

- Best sequence (id numbers): E-49-E-37-85-E-E
- Best sequence (names):
  - Earth
  - 2000 SG344
  - Earth
  - 2004 QA22
  - 2006 BZ147
  - Earth - Earth
- Launch Date: 60996.10 (MJD)
- Launch V_∞ = 0.5 km/s
- Total flight time = 9.998641 years
- Performance Index = 0.863792
- Total thrust duration: various levels of thrust ($0.00000015 \leq T \leq 0.15$ N) for full duration



(spacecraft trajectory in blue)

Trajectory Breakdown

- E-49:
  - Phase-free ballistic pair E-49 was the lowest of all initial leg ΔVs, without using a flyby
  - Known issue regarding prepended flybys

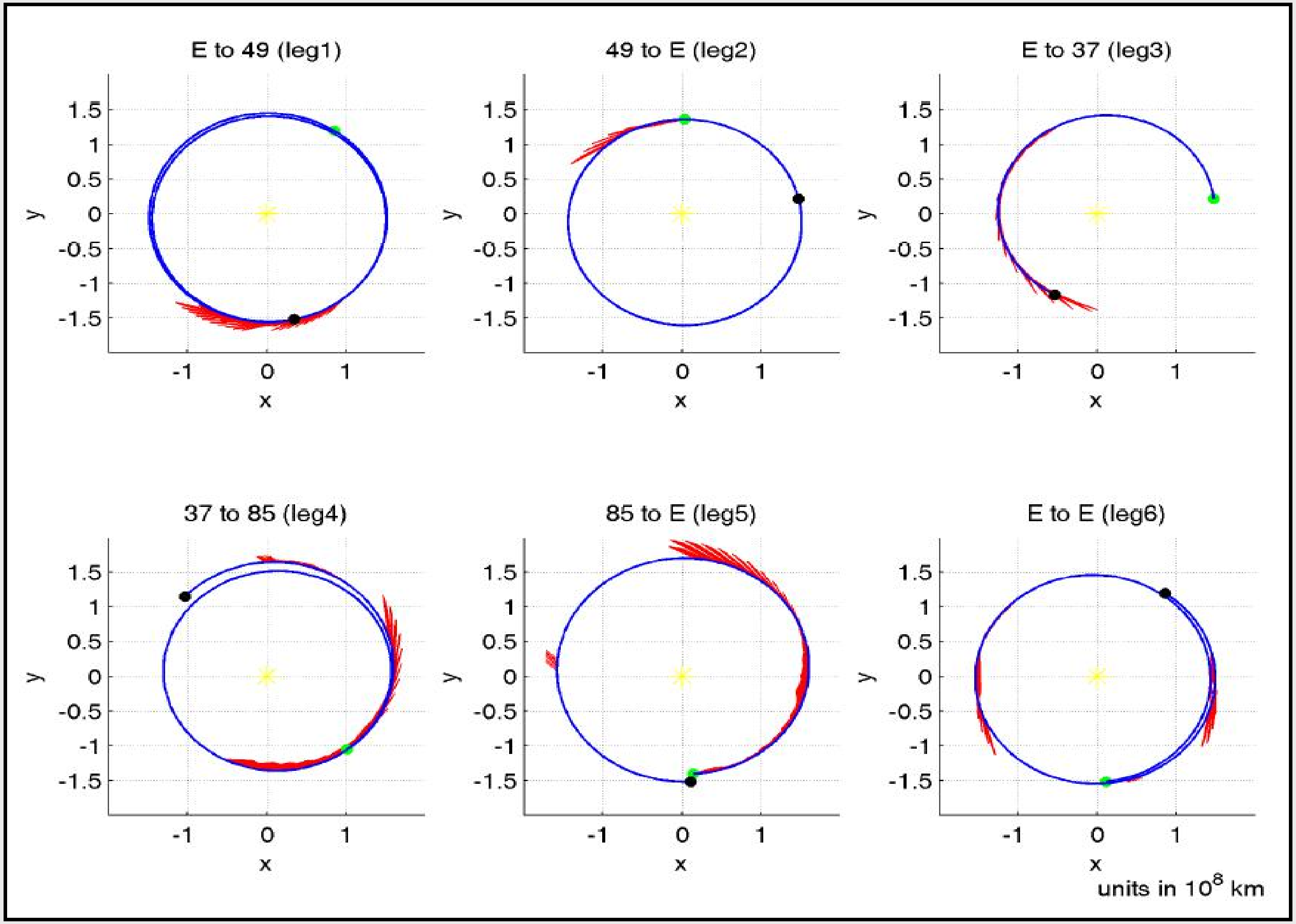
- 49-E-37:
  - Phase-free ballistic combo 49-E-37 ranked 3rd (0.76 km/s) out of ~20,000 possible pairs
  - Best ballistic combo was 0.67 km/s
  - That it appeared in our higher fidelity cases spoke well of the approximation

- 37-85:
  - Phase-free ballistic pair ranked 24th (1.32 km/s) out of ~20,000 without a flyby
  - Best ballistic pair was 0.803 km/s

Trajectory Breakdown

Dep. Body	Arr. Body	Dep. Date (MJD)	Arr. Date (MJD)	Stay Time (days)	Dep. Mass (kg)	Arr. Mass (kg)	Dep. V∞ (km/s)	Arr. V∞ (km/s)	Flyby Periapsis (km)
Earth	49	60996.10	61959.50	165.250	2000	1964.529	0.5	0	N/A
49	Earth	62124.75	62775.94	0	1964.529	1947.182	0	1.996108	10227.48
Earth	37	62775.94	62985.01	60.000	1947.182	1913.354	1.996510	0	N/A
37	85	63045.01	63603.64	132.155	1913.354	1825.984	0	0	N/A
85	Earth	63735.80	64139.13	0	1825.984	1760.557	0	1.300676	51163.16
Earth	Earth	64139.13	64648.10	0	1760.557	1721.014	1.300000	0	N/A

Trajectory Plots



Comments on Solution

- Confident that we had found one of the best possible asteroid sequences based on our domain-spanning pruning procedure
- Recognized that our solution could potentially be improved by adding Earth flybys at the beginning of the trajectory
  - Ran out of time while debugging convergence problem with prepended Earth flybys
  - This step was the difference between finishing third and competing for first place:

GaTech (3rd place):	E-49-E-37-85-E-E
JPL (2nd place):	E-E-49-E-37-85-E-E
CNES (1st place):	E-E-E-49-E-37-85-E-E

Lessons Learned

- Selecting the appropriate approximations were vital
  - Trimming based on orbital elements was not used
  - Ballistic approximation was fast enough to use a straight forward grid search
- Automation
  - Greatly improves the number of cases that can be considered
  - Efforts towards automating tools are often greatly rewarded
- Tool selection vs. tool generation
  - Tools that do not meet your exact needs can still be used for further screening
  - Source code availability offers great flexibility but robust software takes time
  - Tighter refinement of the problem can lower this robustness requirement

Acknowledgements

- Our thanks to the other presenters and to the hosting team
- We also especially wish to thank our team advisor Ryan Russell