Rapid Preliminary Design of Interplanetary Trajectories Using the Evolutionary Mission Trajectory Generator

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Introduction to the General Interplanetary Mission Design Problem

- The interplanetary design problem is composed of both discrete and real-valued decision parameters:
  - Choice of destination(s), number of planetary flybys, identities of flyby planets
  - Launch date, flight time(s), epochs of maneuvers, control history, flyby altitudes, etc.
- For example, for a main-belt asteroid mission, the designer must choose:
  - The optimal asteroid from a set of scientifically interesting bodies provided by the customer
  - Whether or not to perform planetary flybys on the way to the main belt and, if so, at which planets
  - Optimal trajectory from the Earth to the chosen asteroid by way of the chosen flyby planets

Brief History of Automated Interplanetary Trajectory Design

- Gage, Braun, and Kroo, 1994 – autonomous chemical design with variable mission sequence (no deep-space maneuvers)
- Vasile and de Pascale, 2005 – autonomous chemical design for fixed mission sequence
- Vinko and Izzo, 2008 – autonomous chemical design for fixed mission sequence
- Wall and Conway, 2009 – autonomous low-thrust design for fixed mission sequence (no planetary flybys)
- Chilan and Conway, 2009 – autonomous low-thrust and chemical design for fixed mission sequence (no planetary flybys)
- Yam, di Lorenzo, and Izzo, 2011 – autonomous low-thrust design for fixed mission sequence
- Abdelkhalik and Gad, 2011, 2012, and 2013 – autonomous chemical design with variable mission sequence
- Englander, Conway, and Williams, 2012 – autonomous chemical design with variable mission sequence
- Englander (dissertation) 2013 – autonomous low-thrust design with variable mission sequence

Automated Mission Design via Hybrid Optimal Control

- Break the mission design problem into two stages, or “loops”
  - “outer-loop” picks sets of destinations, planetary flybys, sizes the power system, can pick propulsion system – a <u>discrete</u> optimization problem
  - “inner-loop” finds the optimal trajectory for a given candidate outer-loop solution – a <u>real-valued</u> optimization problem
  - For the outer-loop to work, the inner-loop must function autonomously (i.e. no human interaction)

Multi-Objective Hybrid Optimal Control

- The customer (scientist or project manager) most often does not want just one point solution to the mission design problem
- Instead, an exploration of a multi-objective trade space is required
- For a typical main-belt asteroid mission the customer might wish to see the trade-space of:
  - Launch date vs
  - Flight time vs
  - Deliverable mass
  - While varying the destination asteroid, planetary flybys, solar array size, etc
- To address this question we use a multi-objective discrete outer-loop which defines many single objective real-valued inner-loop problems

Mission and Systems Design via Hybrid Optimal Control

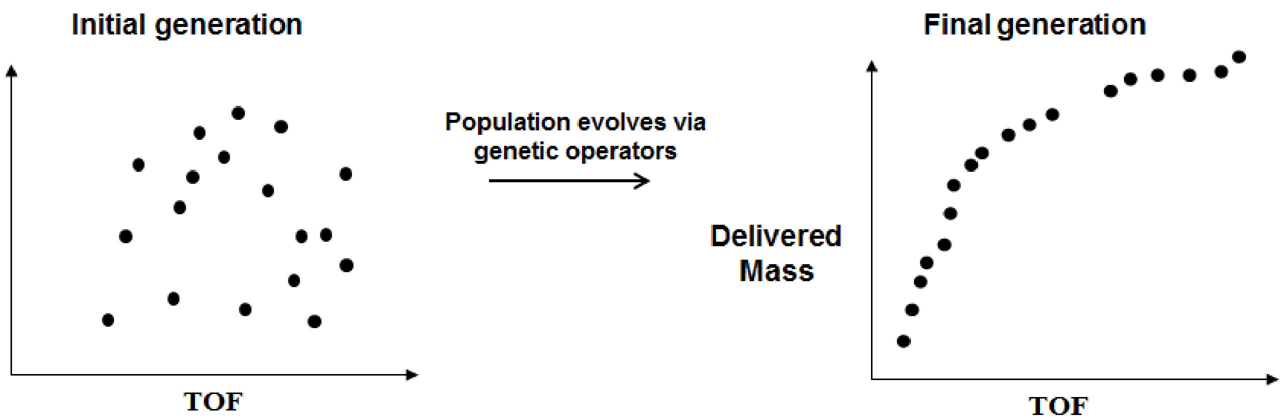
- The interplanetary mission design problem has two types of variables:
  - *Discrete* variables encoding the mission sequence and choice of spacecraft systems (launch vehicle, power, propulsion)
  - *Continuous* variables defining the trajectory
- In *Hybrid Optimal Control*, the problem is divided into two nested loops.
  - The *outer-loop* solves the discrete problem and identifies candidate missions.
  - The continuous *inner-loop* then finds the optimal trajectory for each candidate mission.

Outer-Loop Transcription and Optimization

- The outer-loop finds the non-dominated trade surface between any set of objective functions chosen by the user
- Non-dominated surface means "no point on the surface is superior to any other point on the surface in all of the objective functions"
- The outer-loop solver may choose from a menu of options for each decision variable
- The choices made by the outer-loop solver are used to define trajectory optimization problems to be solved by the inner-loop

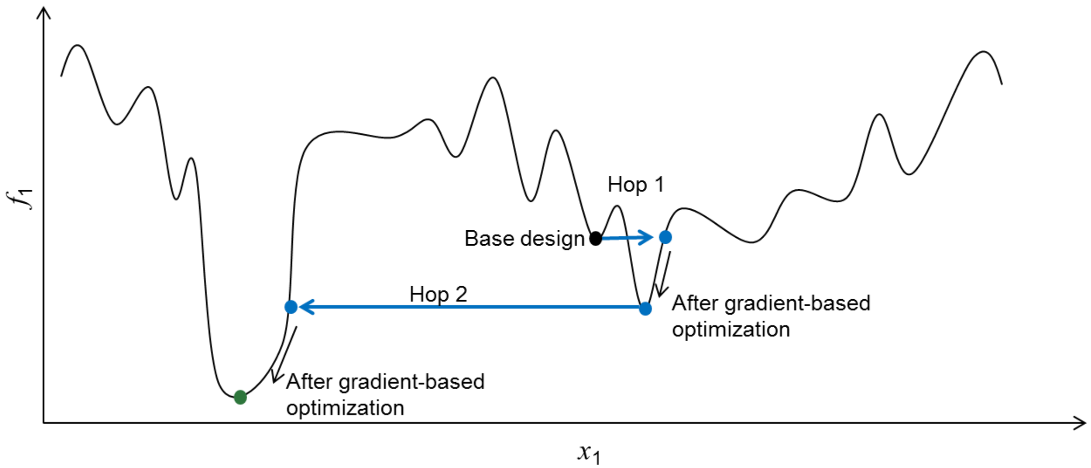
Discrete Optimization of the Mission Sequence and Spacecraft Systems

- EMTG's outer-loop finds the non-dominated set of missions, those which are not strictly better or worse than other missions in the set based on all of the analyst's chosen objective functions
- EMTG uses a version of the Non-Dominated Sorting Genetic Algorithm II (NSGAII) which can evolve to the final non-dominated trade front despite starting from complete randomness. No *a priori* knowledge of the solution is required.

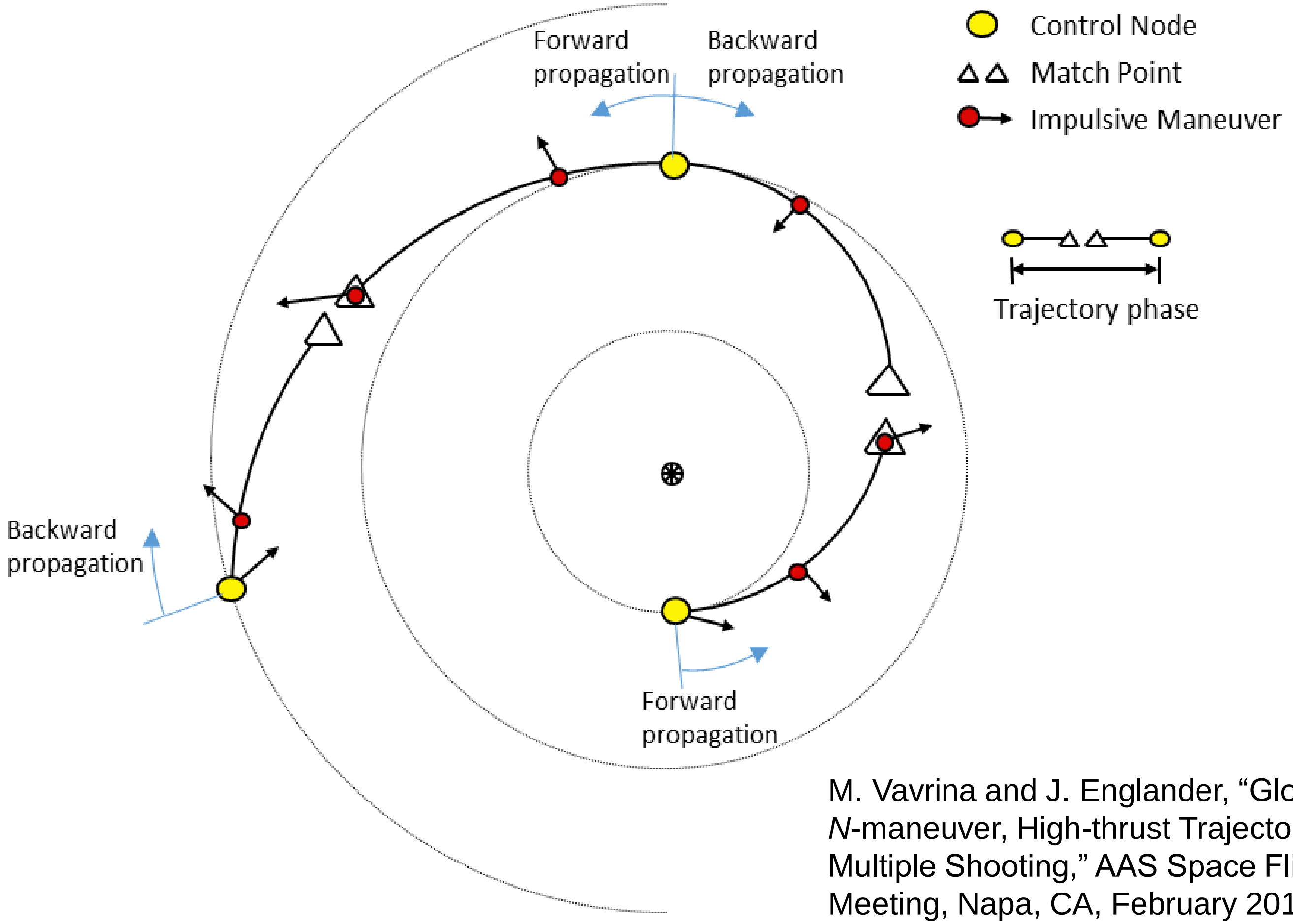


Trajectory Optimization via Monotonic Basin Hopping and Nonlinear Programming

- EMTG’s inner-loop finds the optimal trajectory using a stochastic global search method called Monotonic Basin Hopping (MBH) coupled with a gradient-based local search supplied by the third-party Sparse Nonlinear Optimizer (SNOPT).
- EMTG does not require an initial guess and can find the global optimum autonomously.



Chemical Mission Modeling in EMTG



M. Vavrina and J. Englander, "Global Optimization Of *N*-maneuver, High-thrust Trajectories Using Direct Multiple Shooting," AAS Space Flight Mechanics Meeting, Napa, CA, February 2016.

High-Thrust Example: Whack-a-Rock

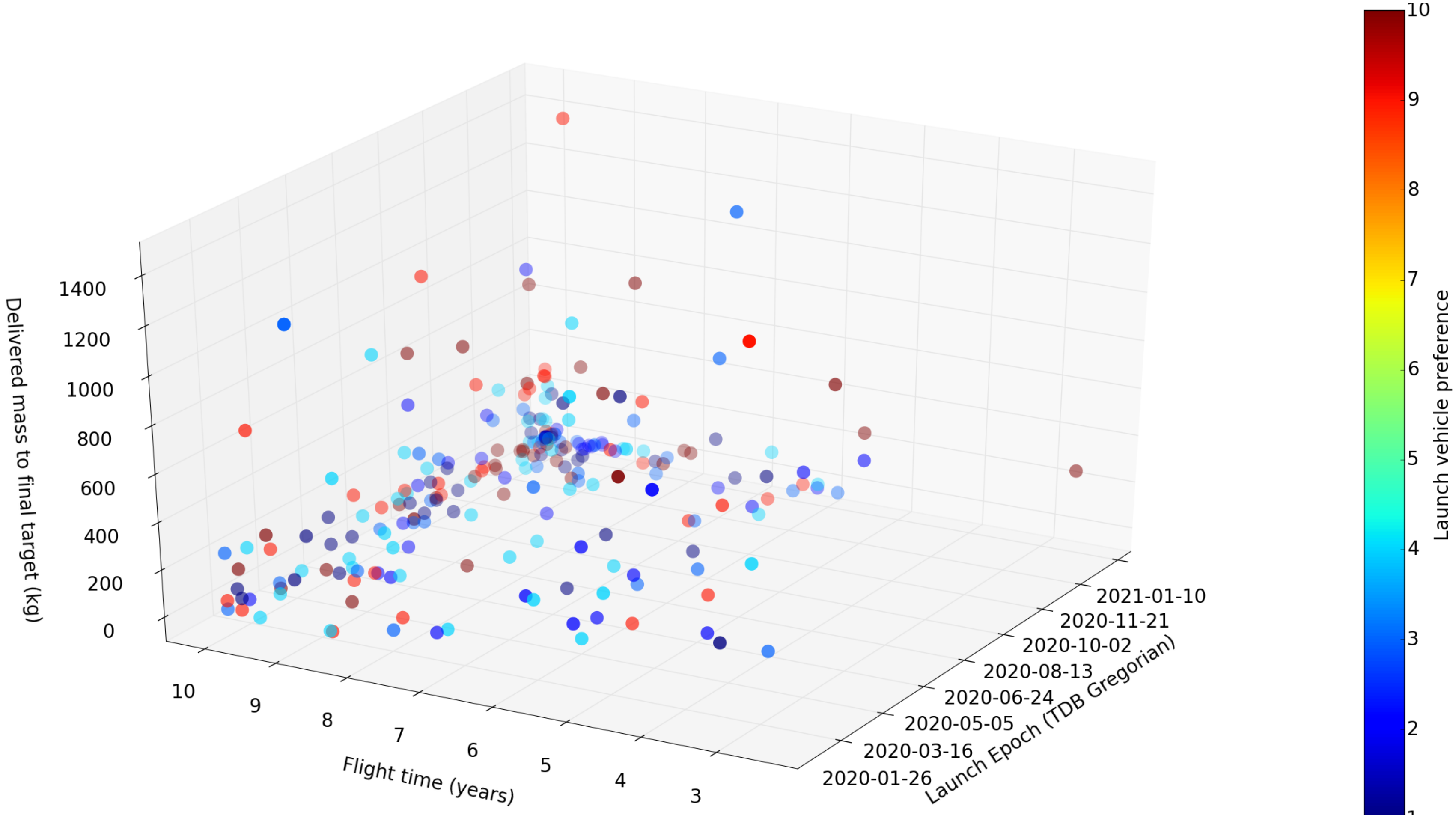
- In the "Whack-a-Rock" problem we design a small bodies mission which delivers a high-speed impactor to a Near Earth Object (NEO) and then returns to rendezvous and perform detailed science some years later.
- All C-type NEOs with diameter of 500m or greater are admissible targets and are considered equally scientifically valuable.
- Planetary flybys can be added as appropriate.
- We want to know what the best C-type NEO is for this mission during the 2020s.

Name	SMA	ECC	INC	RAAN	AOP
2100 Ra-Shalom	0.83	0.44	15.76	170.84	356.04
3671 Dionysus	2.2	0.54	13.55	82.16	204.2
3691 Bede	1.77	0.28	20.36	348.77	234.88
14402 1991DB	1.72	0.4	11.42	158.26	51.32
15817 Lucianotesi	1.32	0.12	13.87	162.52	94.3
16064 Davidharvey	2.85	0.59	4.54	335.61	104.84
65706 1992NA	2.4	0.56	9.71	349.38	8.1
85774 1998UT18	1.4	0.33	13.59	64.71	50.01
136793 1997AQ18	1.15	0.47	17.38	296.3	36.98
141079 2001XS30	1.16	0.83	28.53	251.47	0.87
152563 1992BF	0.91	0.27	7.27	315.57	336.3
152679 1998KU2	2.25	0.55	4.93	205.79	120.28
162173 1999JU3	1.19	0.19	5.88	251.61	211.43
162567 2000RW37	1.25	0.25	13.75	333.34	133.26
175706 1996FG3	1.05	0.35	1.99	299.73	23.99
308635 2005YU55	1.16	0.43	0.34	35.89	273.63
322775 2001HA8	2.39	0.53	11.48	95.89	202.37
370061 2000YO29	1.81	0.69	54.6	262.66	309.32
413123 2001XS1	2.67	0.56	10.93	266.97	164.88
1997 AC11	0.91	0.37	31.64	116.94	141.62
1998 HT31	2.52	0.69	6.8	213.91	80.42
1999 VN6	1.73	0.37	19.48	58.1	43.56
2000 WL10	3.14	0.72	10.24	252.16	115.12
2001 SJ262	2.94	0.58	10.8	210.44	164.93
2002 DH2	2.05	0.54	20.94	345.56	231.79

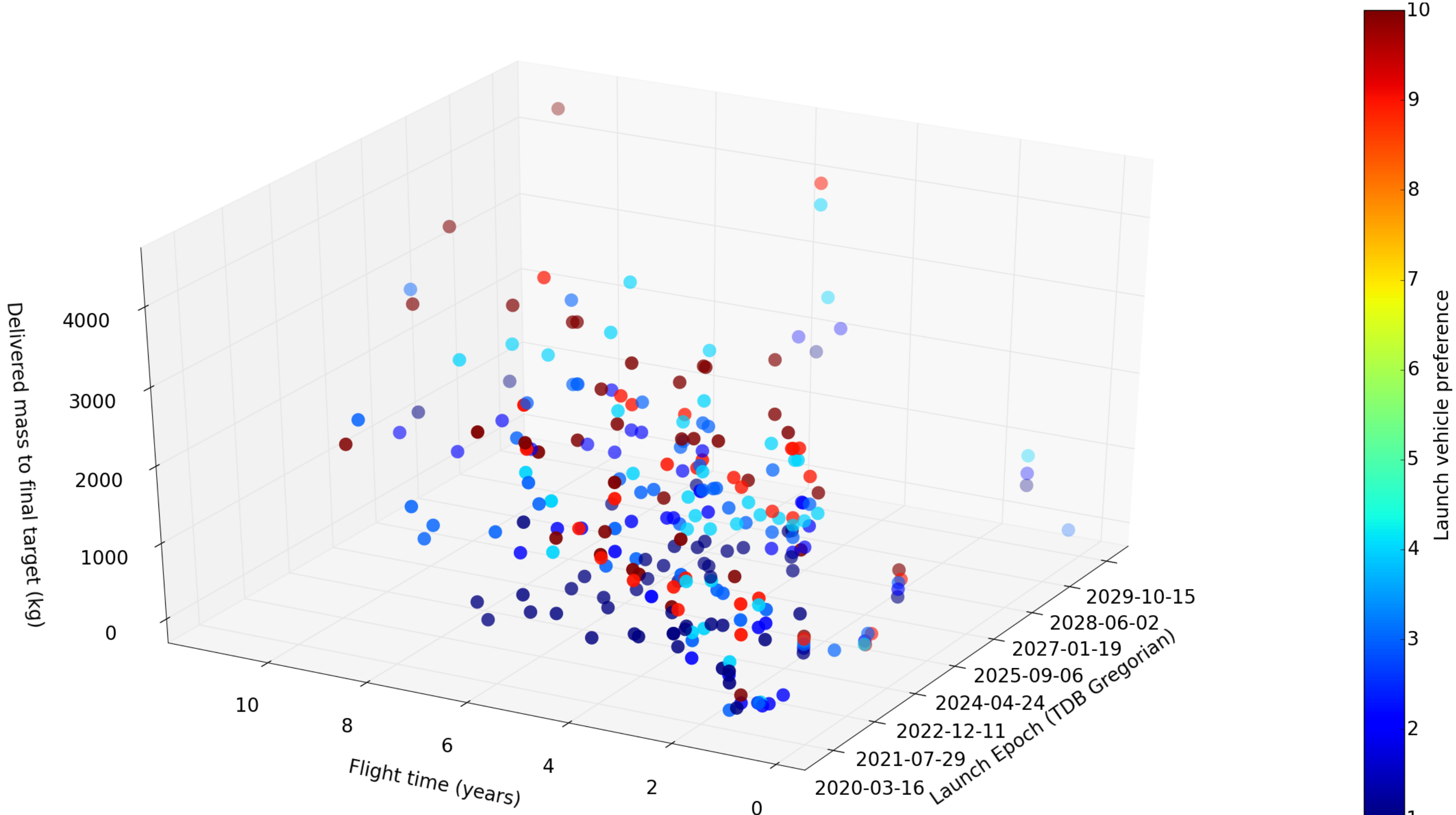
Whack-a-Rock Problem Assumptions

Description	**Value**
Launch year	outer-loop chooses in [2020, 2029]
Flight time	outer-loop chooses in [3, 12] years
Launch vehicle	outer-loop chooses Atlas V 401, 411, 421, 431, 541, or 551
Spacecraft Isp	320 s
Penetrator mass	20 kg
Arrival conditions	
(first Journey)	intercept with v_∞ in [5.0, 10.0] km/s, $\theta_{illumination} \leq 70^\circ$
(second Journey)	rendezvous
Number of flybys allowed	2 in each Journey
Flyby targets considered	Venus, Earth, Mars
Outer-loop objective functions	launch year flight time delivered mass launch vehicle choice
Outer-loop population size	256
Outer-loop mutation rate	0.3
Inner-loop MBH run-time	10 minutes
Inner-loop MBH Pareto α	1.3

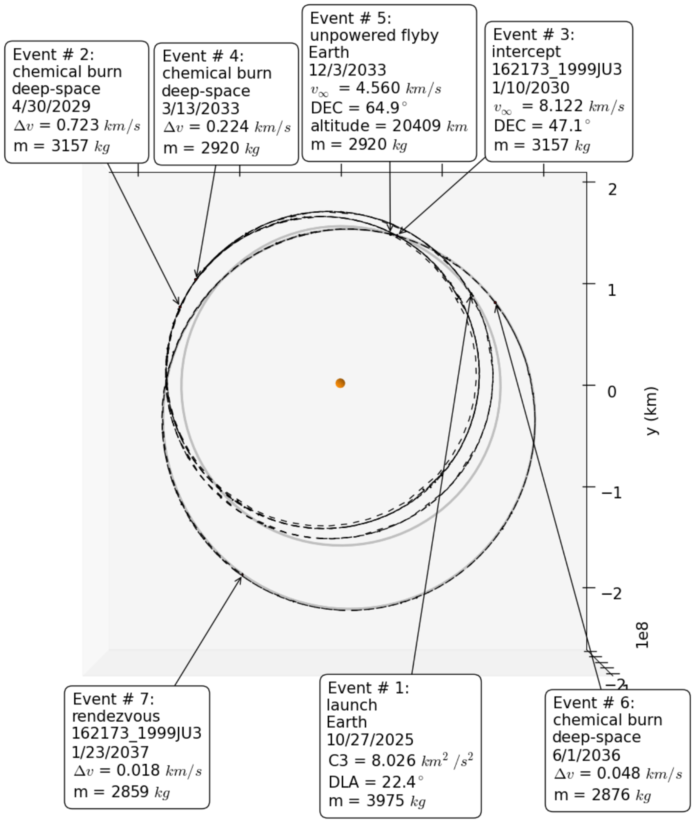
Whack-a-Rock: First Generation Trade Space



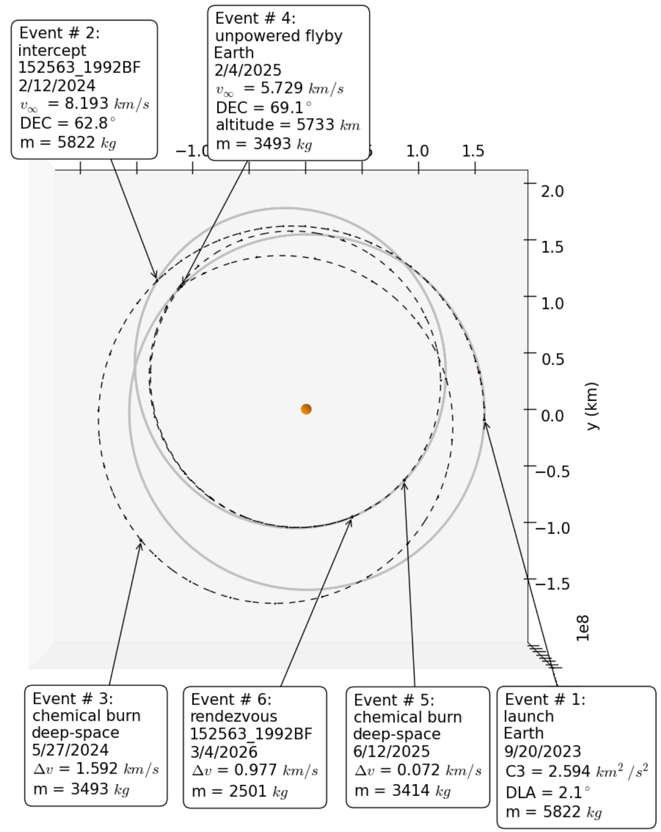
Whack-a-Rock: Final Generation Trade Space



Whack-a-Rock: Example Trajectories



Atlas V 421, 11.25 year flight time



Atlas V 551, 2.45 year flight time

Interlude: What makes Low-Thrust Different?

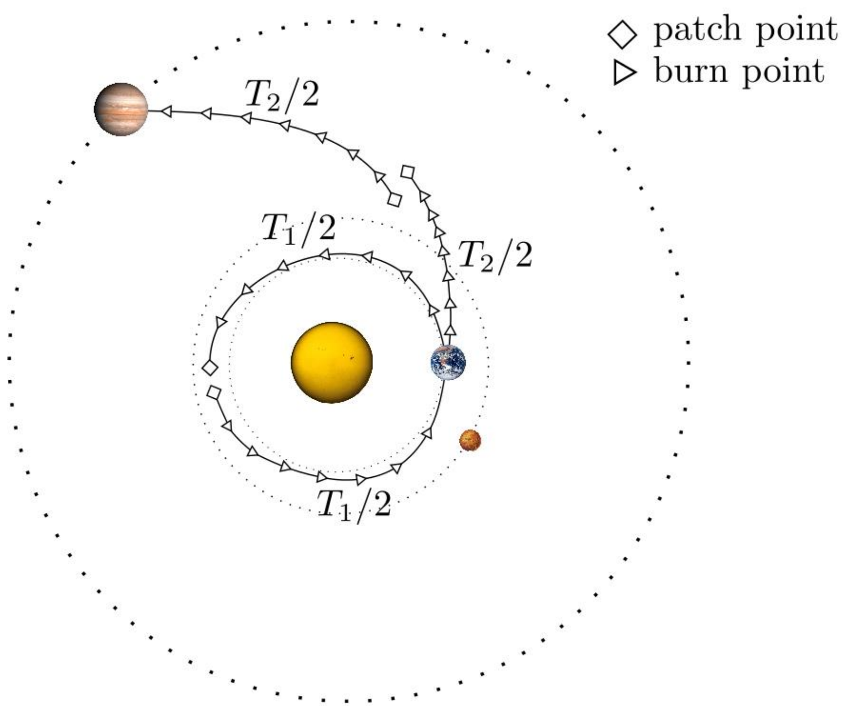
- Low-thrust electric propulsion is characterized by high power requirements but also very high specific impulse (I_{sp}), leading to very good mass fractions
- Low-thrust trajectory design is a very different process from chemical trajectory design
  - Like chemical design, must find the optimal launch date, flight time, and dates of each flyby (if applicable)
  - Unlike chemical design, must find a time-history of thrust control for the entire mission
- ***Low-thrust electric propulsion mission design requires accurate modeling of propulsion and power systems. Every spacecraft design drives a unique trajectory design!***

Traditional Methods of Low-Thrust, Multi-Flyby Trajectory Design

- Several methods of picking the destination and flyby sequence:
  - Grid search over all possible choices of destinations, flyby sequence, propulsion system, power system, etc. (very expensive and often impractical)
  - Intuition-guided manual design of the trajectory (even more expensive, can miss non-intuitive solutions)
- Several methods of designing the trajectory:
  - Local optimization from an initial guess provided by a chemical mission design (but sometimes the optimal chemical trajectory does not resemble the optimal low-thrust trajectory)
  - Local optimization from an initial guess provided by a low-fidelity approximation to the low-thrust model, i.e. shaped-based methods (but sometimes the shape-based method cannot accurately approximate the true trajectory)

Low-Thrust Modeling in EMTG Transcription

- Break mission into phases. Each phase starts and ends at a body.
- Sims-Flanagan Transcription
  - Break phases into time steps
  - Insert a small impulse in the center of each time step, with bounded magnitude
  - Optimizer Chooses:
    - Launch date
      - For each phase:
        - Initial velocity vector
        - Flight time
        - Thrust-impulse vector at each time step
        - Mass at the end of the phase
        - Terminal velocity vector
- Assume two-body force model; propagate by solving Kepler's problem
- Propagate forward and backward from phase endpoints to a "match point"
- Enforce nonlinear state continuity constraints at match point
- Enforce nonlinear velocity magnitude and altitude constraints at flyby



J. Englander and B.Conway, "An Automated Solution of the Low-Thrust Interplanetary Trajectory Problem," AIAA Journal of Guidance, Control, and Dynamics, accepted 2016.

Low-Thrust Modeling in EMTG
Spacecraft and Launch Vehicle Models

- Medium-fidelity mission design requires accurate hardware modeling
- Launch vehicles are modeled using a polynomial fit

$$m_{delivered} = (1 - \sigma_{LV})\left(a_{LV}C_3^5 + b_{LV}C_3^4 + c_{LV}C_3^3 + d_{LV}C_3^2 + e_{LV}C3 + f_{LV}\right)$$

where σ_{LV} is launch vehicle margin and C_3 is hyperbolic excess velocity

- Thrusters are modeled using either a polynomial fit to published thrust and mass flow rate data

$$\dot{m} = a_F P^4 + b_F P^3 + c_F P^2 + d_F P + e_F$$
$$T = a_T P^4 + b_T P^3 + c_T P^2 + d_T P + e_T$$

or, when detailed performance data is unavailable

$$T = \frac{2\,\eta P}{I_{sp} g_0}$$

- Power is modeled by a standard polynomial model

$$\frac{P_0}{r^2}\left(\frac{\gamma_0 + \frac{\gamma_1}{r} + \frac{\gamma_2}{r^2}}{1 + \gamma_3 r + \gamma_4 r^2}\right)(1-\tau)^t$$

where P_0 is the power at beginning of life at 1 AU and τ is the solar array degradation constant

Low-Thrust Example Problem: ARRM

- Asteroid Redirect Robotic Mission: return asteroid boulder or entire asteroid
  - Extensibility option is to return boulder from Deimos
  - Want to understand how return mass & TOF are affected by array size, # of thrusters

→ 4 optimization objectives: max. return mass, min. TOF, min. EOL power, min. # of thrusters (all coupled)

System Design Variables

Design Variable	Integer	Value	Resolution
Launch option	[0, 1]	{Delta IV-H from LV curve, Delta IV-H with LGA}	-
Solar array size	[0, 15]	[25, 95] kW	5 kW
Launch window open epoch	[0, 9]	{8/1/2020, …, 8/1/2030}	1 year
Flight time	[0, 26]	[700, 3300] days	100 days
Engine mode	[0, 2]	{high-Isp, medium-thrust, high-thrust}	-
Number of engines	[0, 7]	[2, 9]	1

207360 possible combinations

Notional Mission Parameters

Description	Value
Launch window	1 year
Wait time at Deimos	[150, 600] days
Min. spacecraft mass with 2 thrusters & 25 kW array	5703.5 kg
Additional dry mass per extra thruster	75 kg
Additional dry mass per kW of array power above 25 kW	12.5 kg
Max. depart. mass if lunar gravity assist ($C_3 \leq 2.0$ km²/s²)	11191 kg
Max. departure mass if direct launch ($C_3 = 0.0$ km²/s²)	10796 kg
Maximum C_3 if direct launch	6 km^2/s^2
Lunar DRO insertion ΔV	75 m/s
Thruster duty cycle	90%
Solar array modeling	$1/r^2$
Spacecraft bus power	2 kW
Propellant margin	6%

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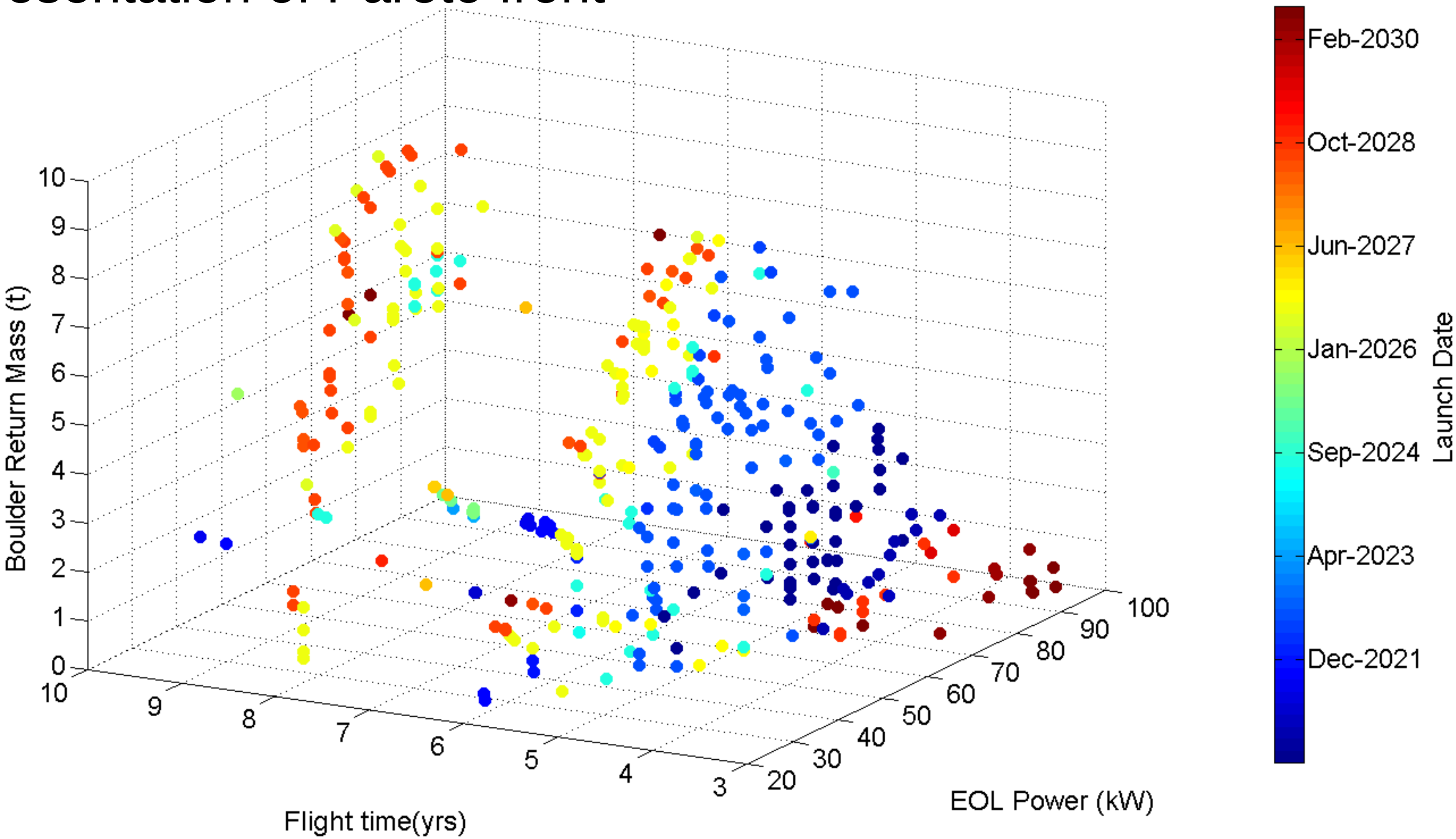
Best Non-Dominated Front

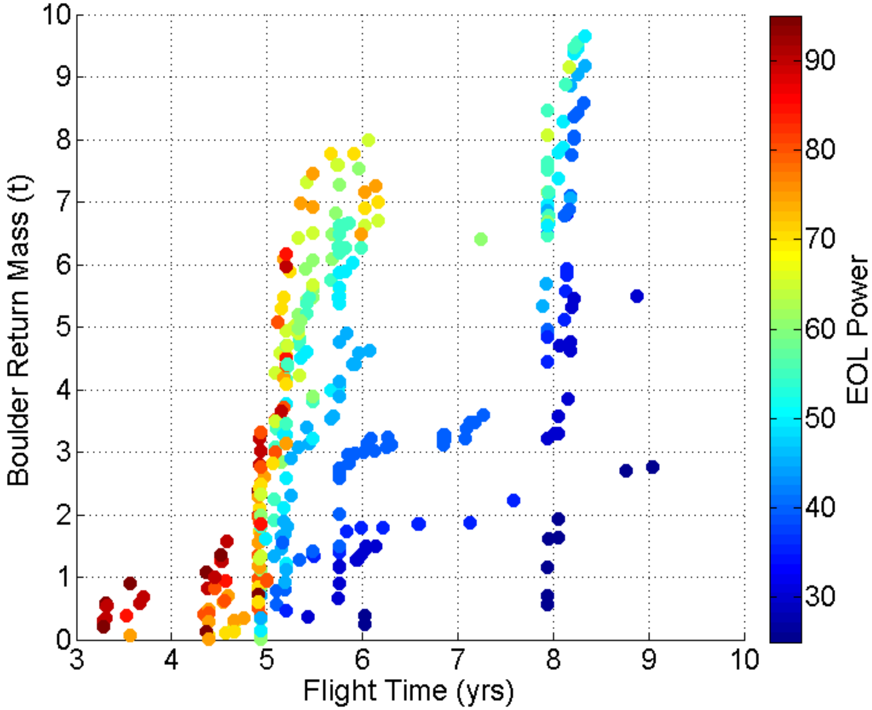
All non-dominated solutions after 56 generations form representation of Pareto front

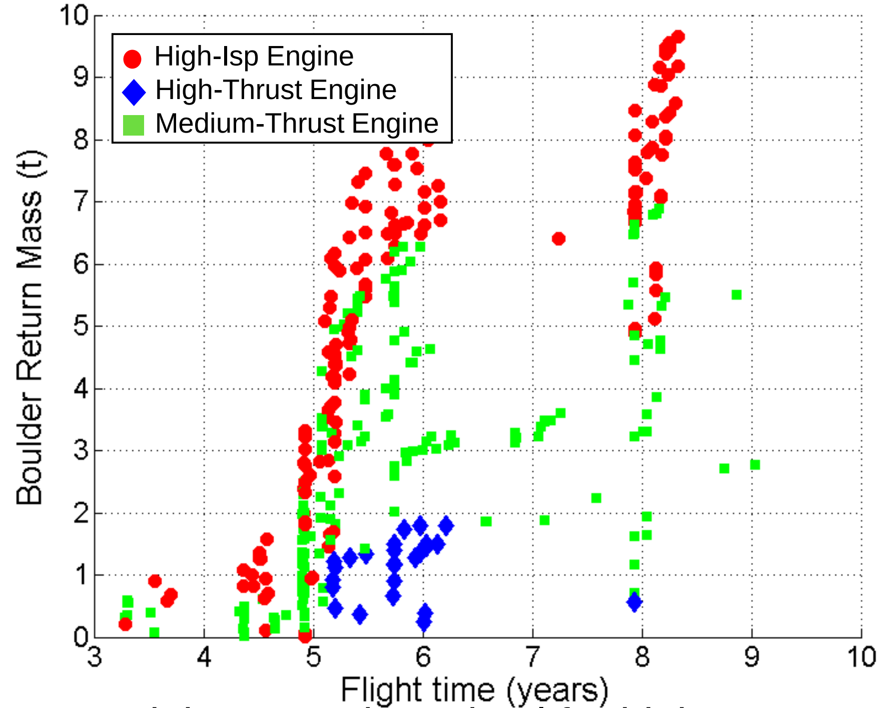


4th objective dimension not shown here (minimize # of thrusters)

Optimal Trade Space

All non-dominated solutions after 56 generations projected in 2D objective space



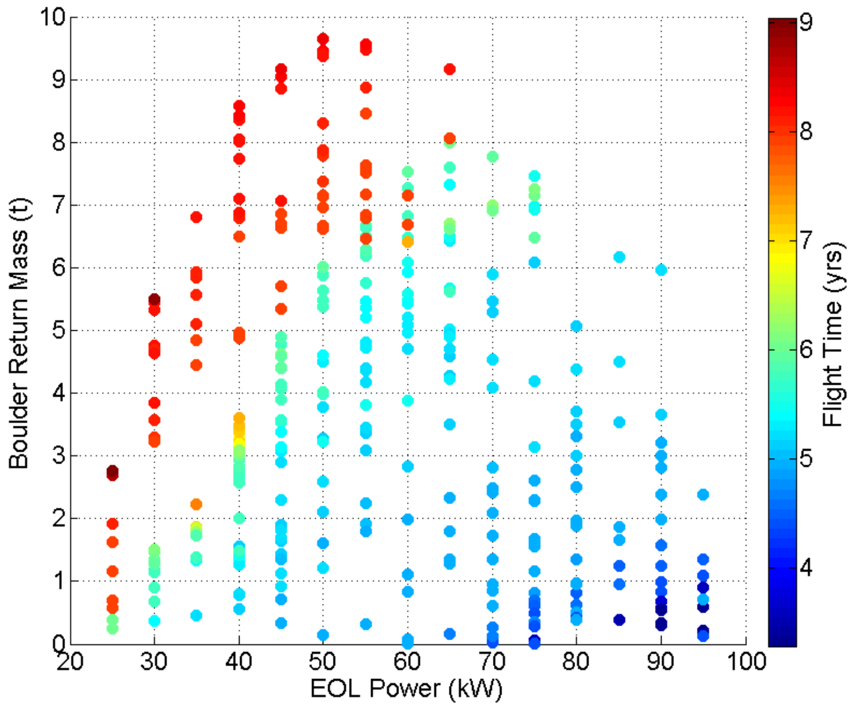


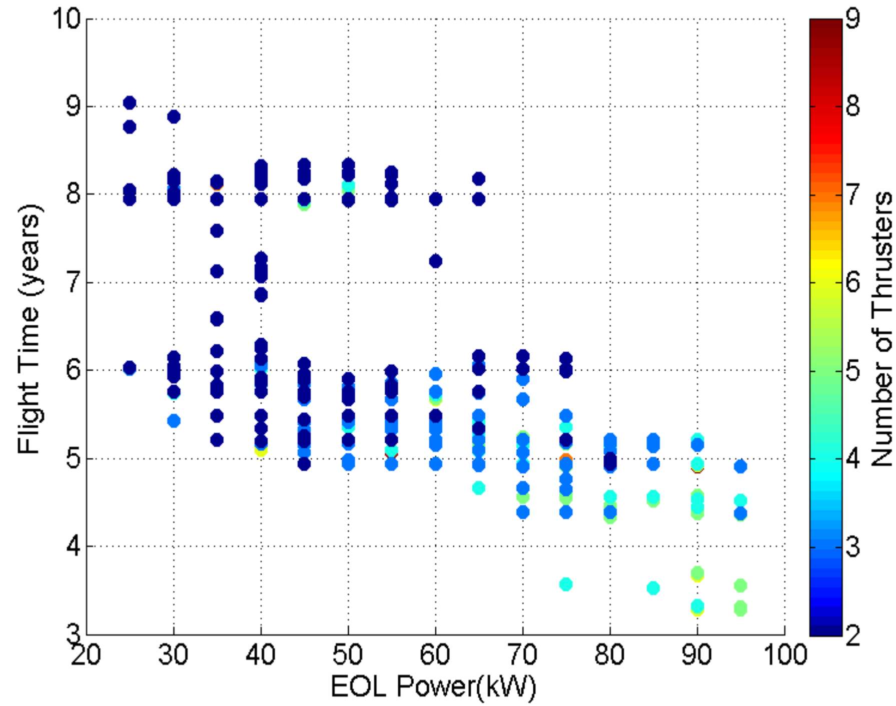
- Sharp increase in return mass up to 6 yr TOF
- 2 yr TOF gap along max. return mass
- Higher power enables short TOF solutions

- High-Isp mode optimal for highest return mass cases
- High-thrust mode optimal for Short TOF, low-power cases

Optimal Trade Space (continued)

All non-dominated solutions after 56 generations projected in 2D objective space





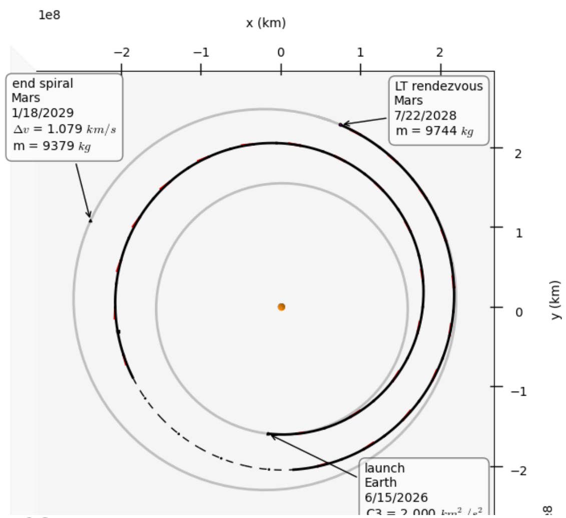
- Increase in array dry mass decreases available propellant
- Shorter TOFs benefit from higher power

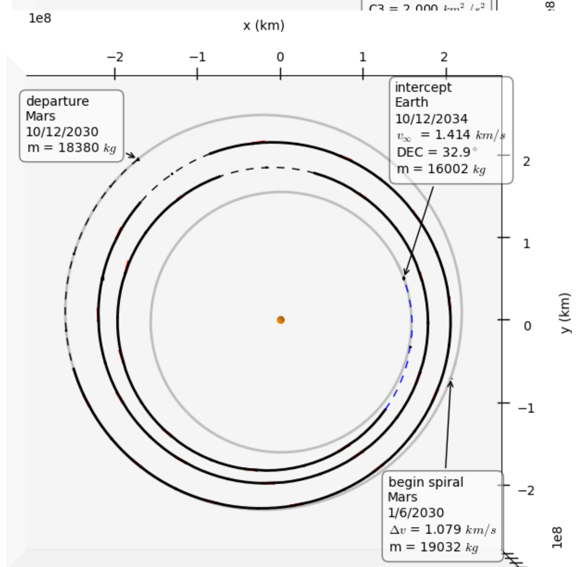
- Most solutions only require 2 or 3 thrusters
- Short-TOF enabled by 4 or 5 thrusters
- Some 6-9 thruster cases hidden in plot

Trajectory Examples

Highest Return Mass Trajectory

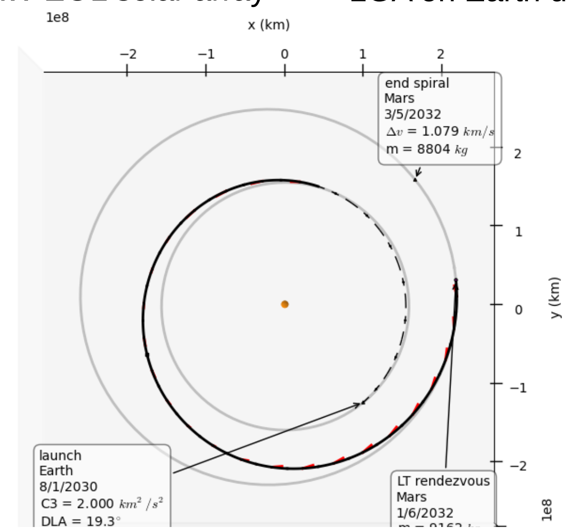
- 9.6 t boulder return
- 8.3 year TOF
- 50 kW EOL solar array
- High-Isp mode thruster
- 2 thruster strings
- LGA on Earth departure

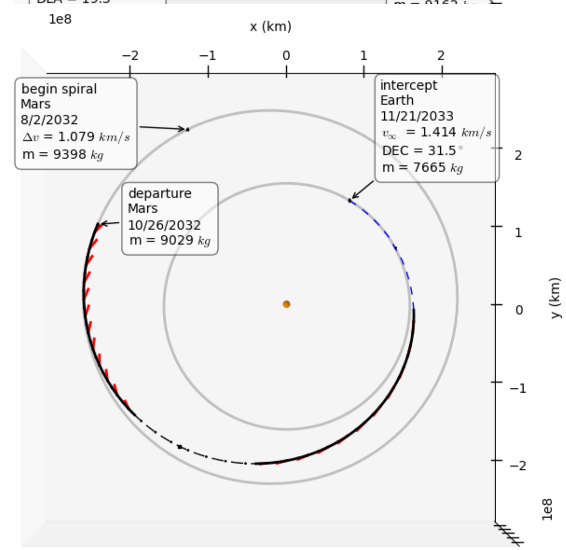




Shortest TOF Trajectory

- 0.6 t boulder return
- 3.3 year TOF
- 95 kW EOL solar array
- Med.-thrust mode thruster
- 5 thruster strings
- LGA on Earth departure





EMTG Design Capabilities

- **Propulsion Types**
  - High-thrust chemical
  - Low-thrust electric
- **Mission Components**
  - Deep-space maneuvers
  - Gravity Assists
  - Asteroid Rendezvous/Flyby
  - Sample Return/Planetary Landing
  - Launch Vehicle selection
- **Spacecraft Systems**
  - Power system sizing
  - Propulsion system sizing
- **Mission Objectives**
  - Maximize science payload
  - Minimize flight time
  - Visit as many diverse bodies as possible
  - Maximize encounter energy (for planetary defense)
- **Operational and Science Constraints**
  - Atmospheric entry
  - Solar distance
  - Any other constraints on final orbit

Conclusion

- Interplanetary mission design problems, whether using high-thrust chemical or low-thrust electric propulsion, may be posed as multi-objective hybrid optimal control problems (HOCP).
- The HOCP may be augmented to include spacecraft hardware parameters such that the trajectory design problem becomes a coupled mission and systems design problem.
- The combination of a multi-objective discrete NSGA-II outer-loop with a MBH+NLP inner-loop is a very powerful way to explore a mission and systems trade space in an efficient, automated manner.
- Mission design mathematics may easily be automated. Communication and understanding cannot be. The method presented here allows analysts to focus their attention on understanding the needs of their customers (scientists) and the capabilities of the spacecraft while leaving the repetitive work to the computer.

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Thank You

EMTG is available open-source at

https://sourceforge.net/projects/emtg/