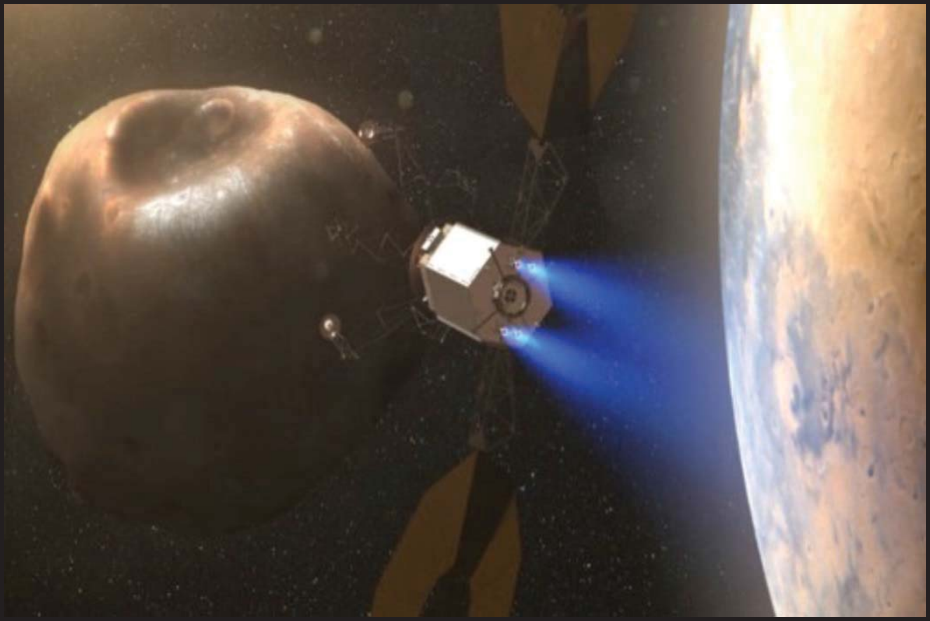
Coupled Low-Thrust Trajectory and Systems Optimization Via Multi-Objective Hybrid Optimal Control



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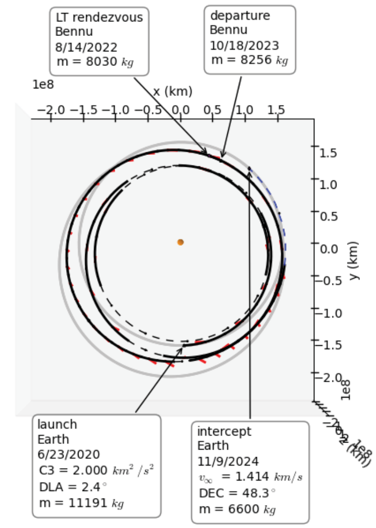
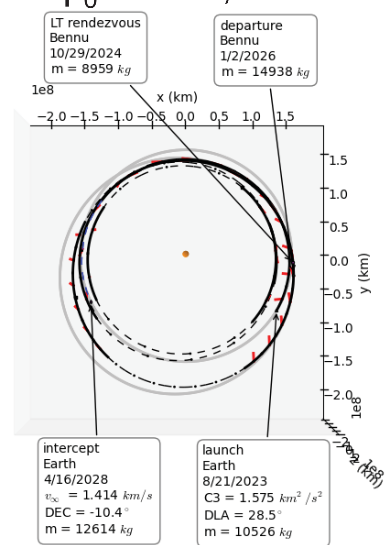
Low-Thrust Systems Design

- Low-thrust trajectory & s/c hardware system are tightly coupled
  - Definition of traj. dependent on propulsion system, LV
  - SEP has variable power & dependent on array size
- Systems design problem
  - Different possible I_{sp}, power levels, number of thrusters, launch vehicle
  - Realistic engine, array models are discrete
  - Hybrid optimal control problem
  - Design space is multimodal, mixed parameter, often expansive
- Traditional approaches to sample trade space
  - Directly vary power & I_{sp} in optimization formulation
  - Simplified models, characteristic solutions
  - Parametric studies, grid searches
- Limitations
  - Trajectory opt. requires initial guess; locally optimal only
  - Only single-objective opt. strategies employed
  - Grid searches intractable
  - Limited fidelity w/out trading realistic hardware models
  - No full mapping of optimal trade space

BOL p_0: 30 kW, 3 thrusters



BOL p_0: 68 kW, 7 thrusters

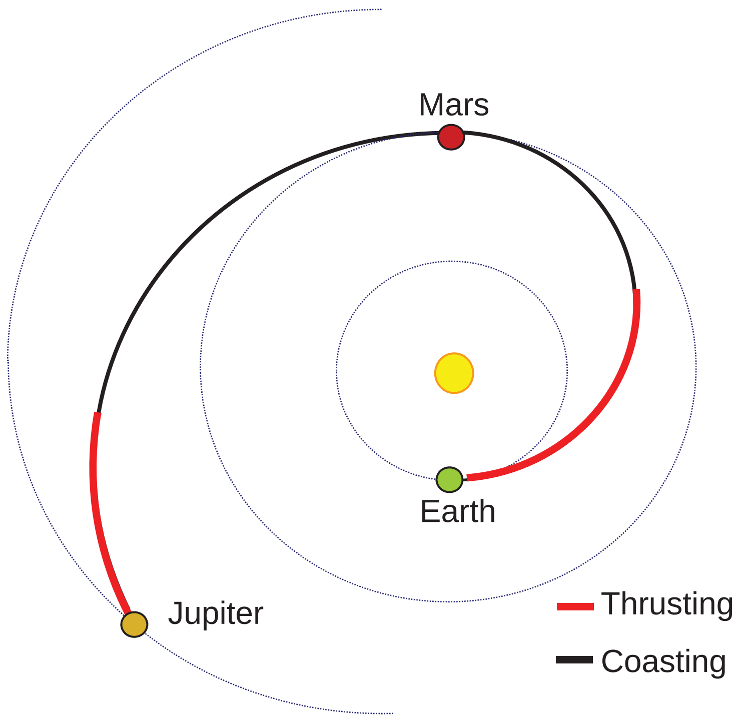


Objective

Solve multi-objective, low-thrust systems optimization problem to fully map optimal systems trade spade

Method should be:

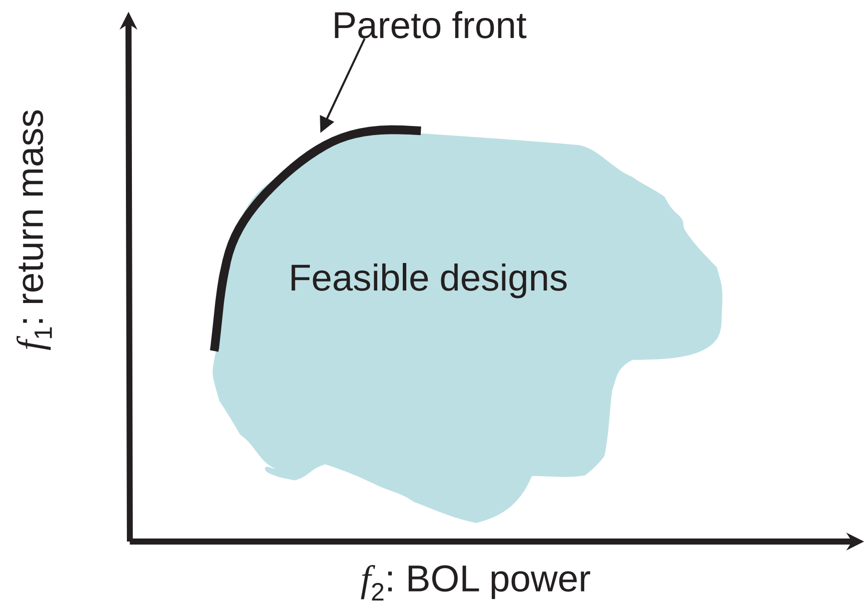
- Capable of **global** trajectory & systems parameter search
- Automated
- Free of user-defined initial guess
- Able to search broad design space
- Medium fidelity for preliminary design purposes
- Efficient



Multi-objective Optimization

- Want to optimize any number of mission design metrics
  – e.g., payload mass, TOF, array size, ref. power, number of thrusters
  – Often coupled & competing
  – Fully map mission trade-offs between optimal solutions

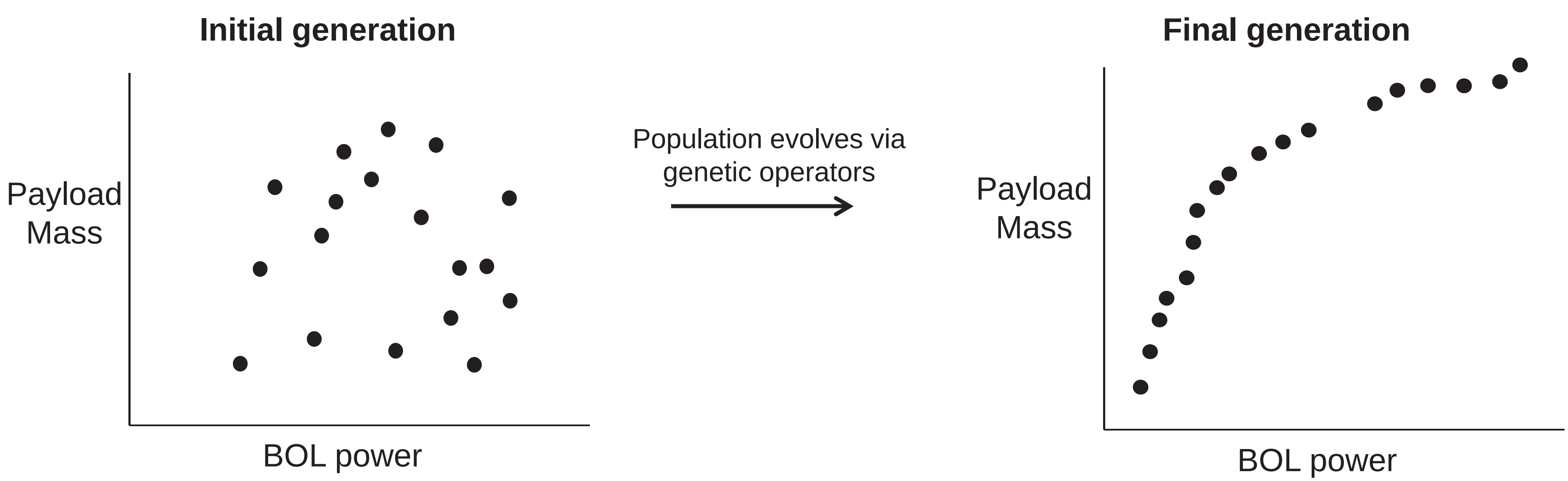
- Optimize multiple objectives simultaneously
  – Entire set of optimal solutions
  – Goal: generate representation of Pareto front
  – Traditionally use repetitions of single objective technique



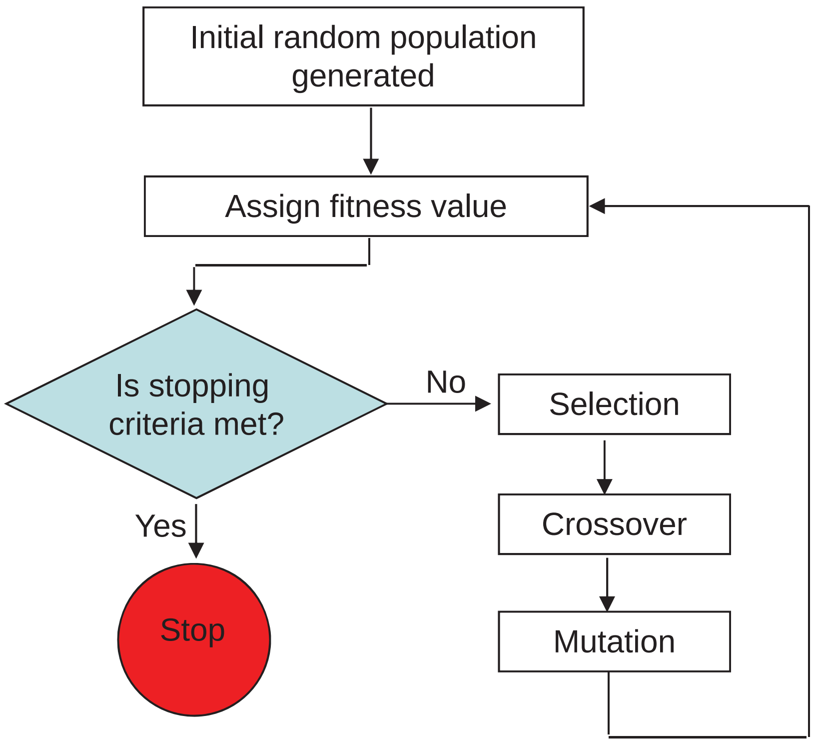
Multi-objective Systems Optimization

Approach: Solve coupled problem simultaneously w/ hybrid optimal control algorithm

- Multi-objective genetic algorithm (GA) as outer loop systems optimizer around direct-method inner loop trajectory optimizer
  - Non-dominated Sorting Genetic Algorithm II (NSGA-II) searches over systems parameters, defining trajectory problem
  - Monotonic basin hopping (MBH) + sequential quadratic programming (SQP) solves trajectory problem



Genetic Algorithm



- Models Darwinian evolution
  - Mimic natural selection & reproduction
- Searches with population of designs
- Globally search design space
- No initial guess required

NSGA-II

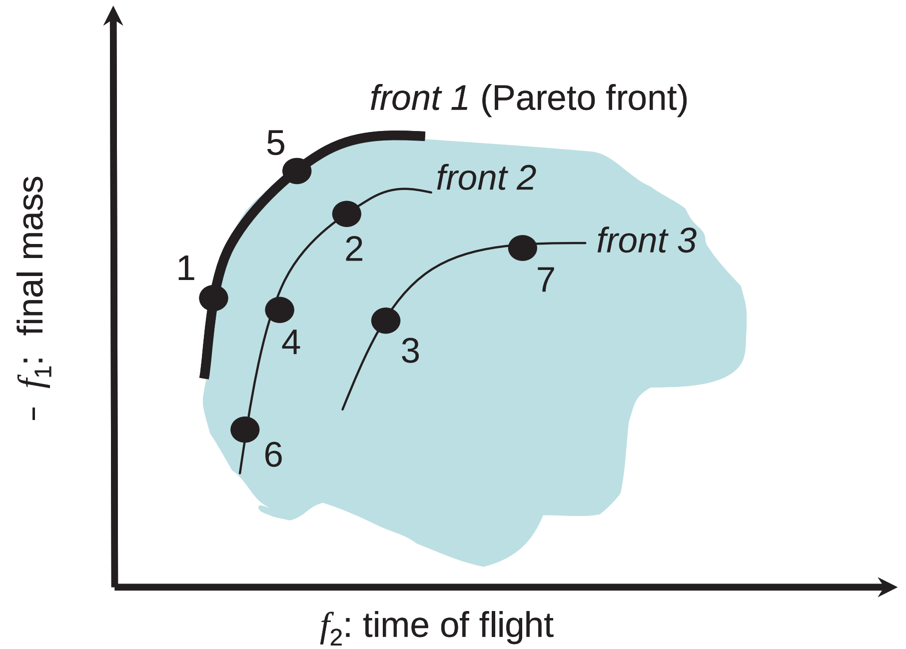
- Develops globally-optimal Pareto solutions using non-dominated sorting
  - Evolves population towards Pareto front

- Fitness assignment based on "nearness" to Pareto front
  - $\mathbf{x}_1$ dominates $\mathbf{x}_2$ if:

$$\forall p : f_p(\mathbf{x}_1) \leq f_p(\mathbf{x}_2) \qquad p = 1,2,\ldots,n_{obj}$$

and

$$\exists p : f_p(\mathbf{x}_1) < f_p(\mathbf{x}_2) \qquad p = 1,2,\ldots,n_{obj}$$

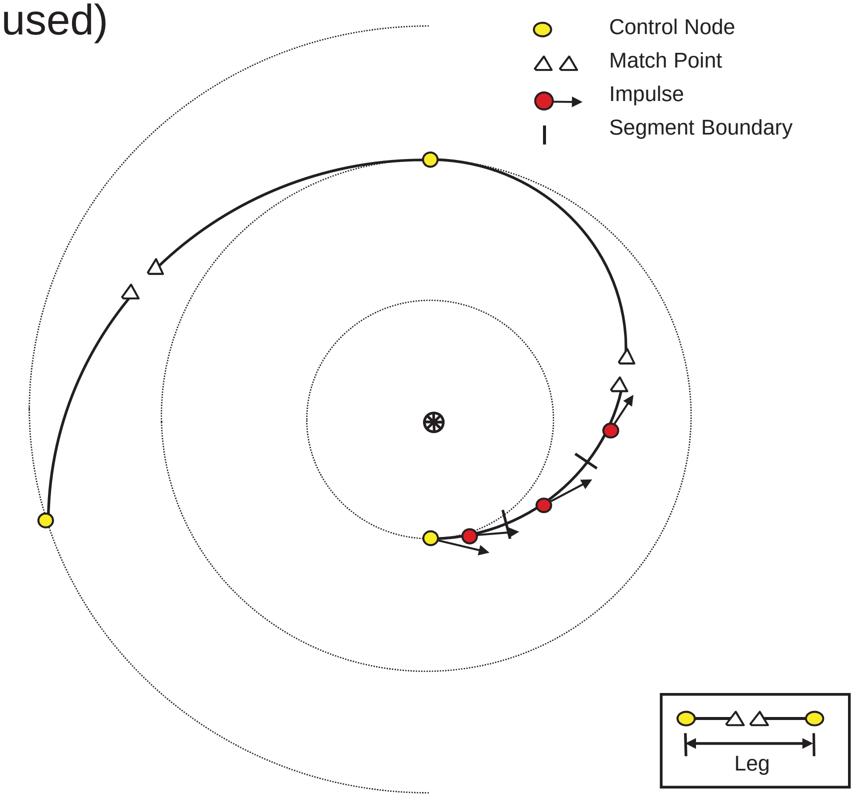


- If neither design dominates other, they are non-dominant
- Non-dominated sorting:
  - Assign fitness based on design's non-dominated front
  - Designs closer to Pareto front → better fitness & more mating opportunities

Low-Thrust Trajectory Optimization

Need automated, robust method that does not require initial guess

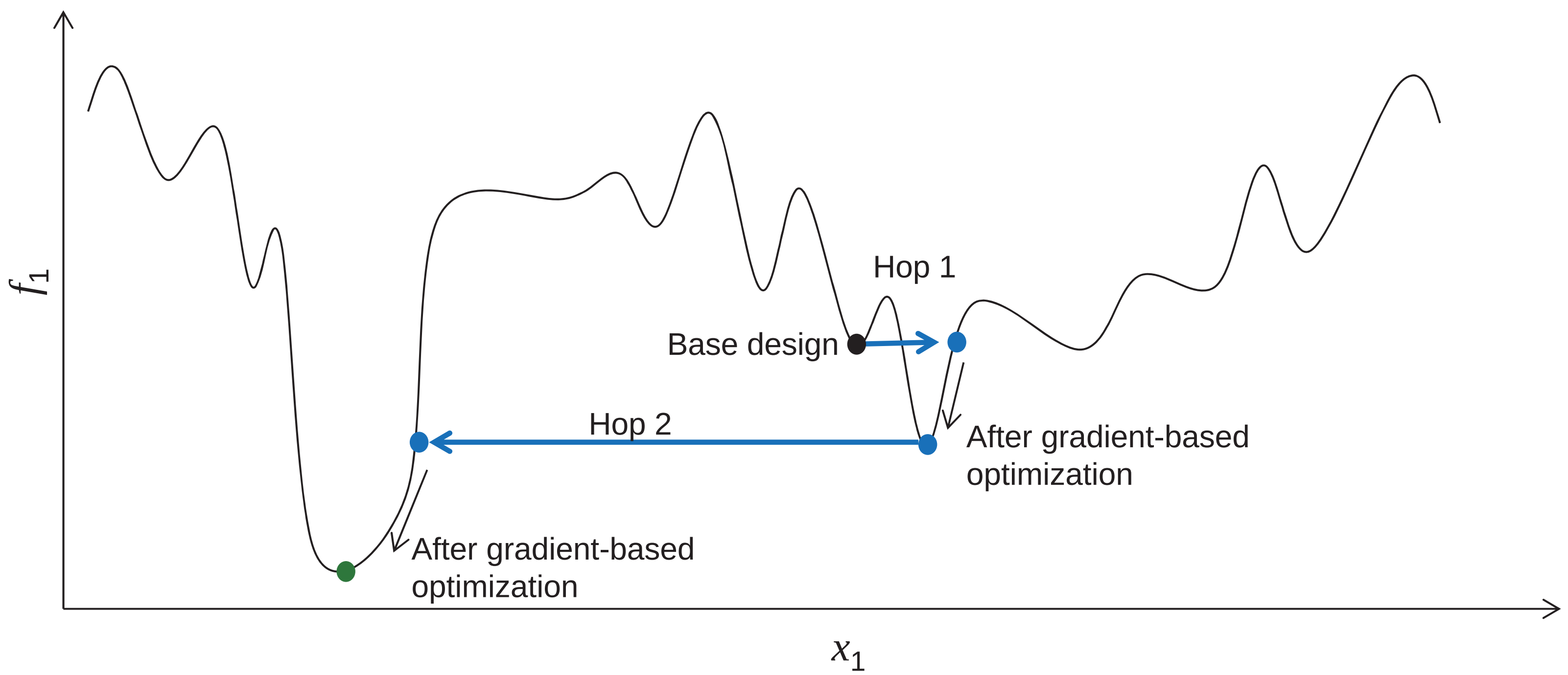
- **Solution**: apply a global-local hybrid algorithm
  - Formulate problem based on Sims & Flanagan transcription
  - Monotonic basin hopping (MBH) drives global search
  - Gradient-based optimizer solves NLP (SNOPT used)
- Robust & efficient formulation
- Continuous thrust approximated
  - Trajectory discretized into segments
  - Impulsive ΔV at segment midpoint
- Efficient constraint handling
  - Gradients guide search
  - Robust & efficient formulation
- Proven approach in EMTG software (Evolutionary Mission Trajectory Generator)



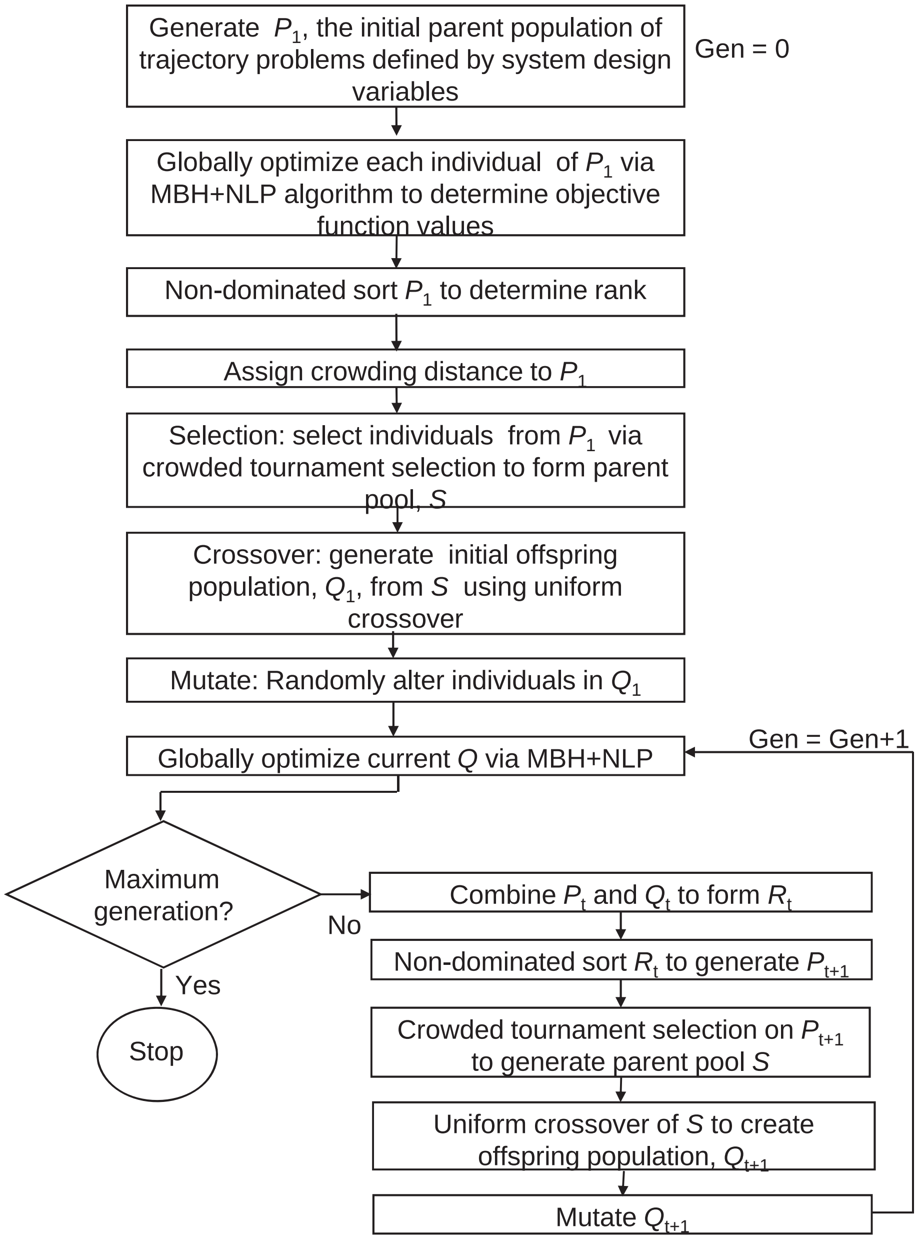
From Sims and Flanagan

Monotonic Basin Hopping + SQP

- Stochastic, global search scheme
- No initial guess required
- Adept at multi-modal problems w/ clustered local minima
- Stochastic “hops” evaluated from base solution
  - Pareto distribution balances exploration & exploitation



Multi-objective Systems Optimization Algorithm



- Synergistic relationship between outer & inner loops
- Generates globally optimal Pareto solutions for mission trade evaluation
- Any number of objectives viable
- Flexible to any unique mission constraints, trajectory constraints enforced in EMTG

Conclusions

- Hybrid optimal control algorithm developed for low-thrust spacecraft systems design
  - Outer loop: NSGA-II solves systems optimization problem
  - Inner loop: MBH+SQP solves trajectory optimzation
- Generates globally optimal Pareto solutions for mission trade evaluation
- Automated
- Any number of objectives viable
- Ability to trade discrete, realistic hardware models
- General applicability to any interplanetary, low-thrust mission
  - Flexible to any unique mission constraints, trajectory constraints enforced in EMTG
- Can make large systems problems computationally tractable

Example Problem: ARRM

- Asteroid Robotic Retrieval 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

  → Multiple objectives: maximize return mass, minimize TOF, minimize BOL power, minimize # of thrusters (all coupled)

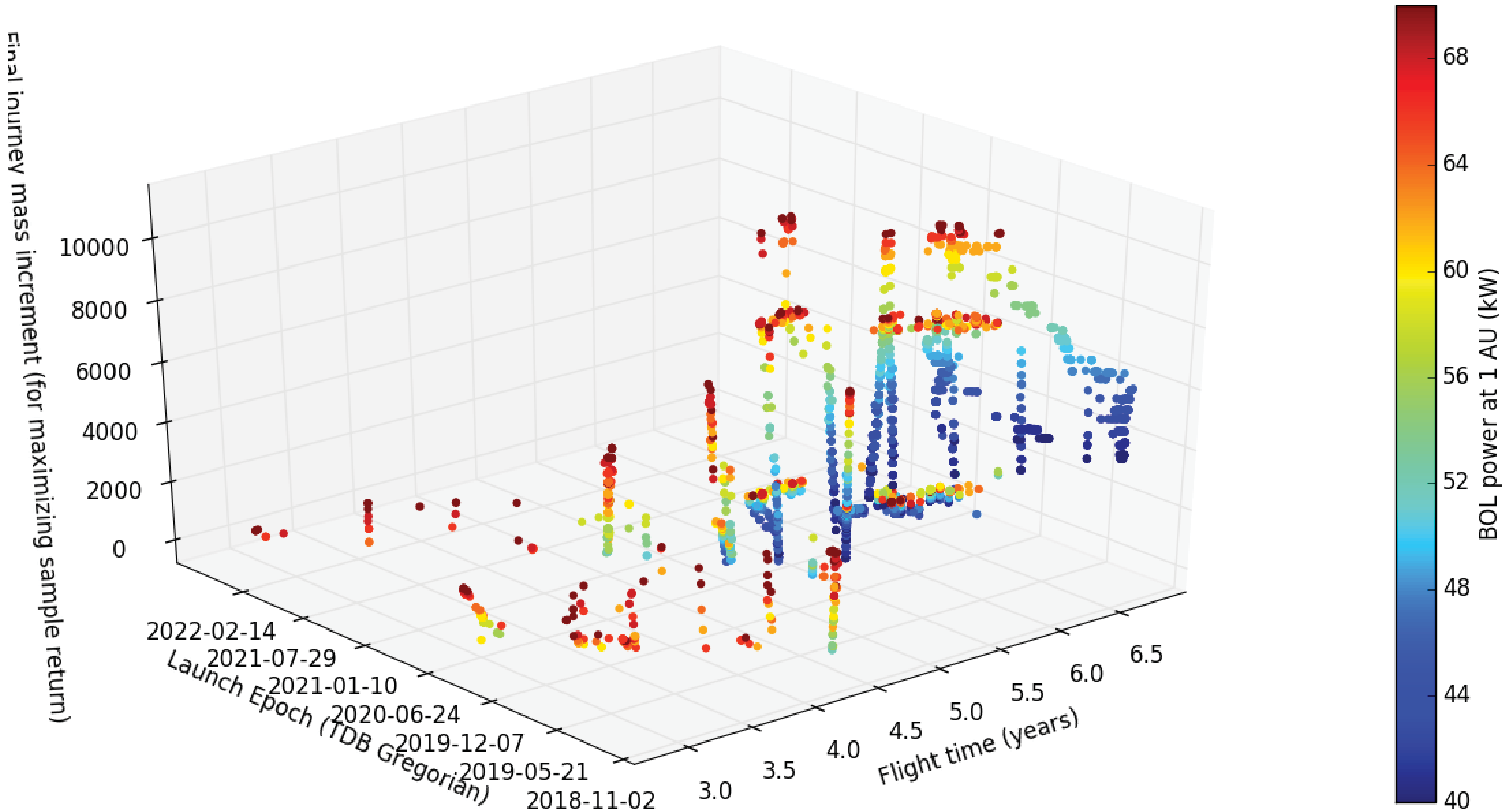
System Design Variables

Design Variable	Integer	Value	Resolution
Launch option	[0, 1]	{Delta IV-H from LV curve, Delta IV-H with LGA}	-
Solar array size	[0, 20]	[30, 70] kW	2 kW
Launch window open epoch	[0, 4]	{2020, …, 2029}	1 year
Flight time	[0, 26]	[700, 3300] days	100 days
Engine type	[0, 2]	{high-Isp, medium-thrust, high-thrust}	-
Number of engines	[0, 5]	[2, 7]	1

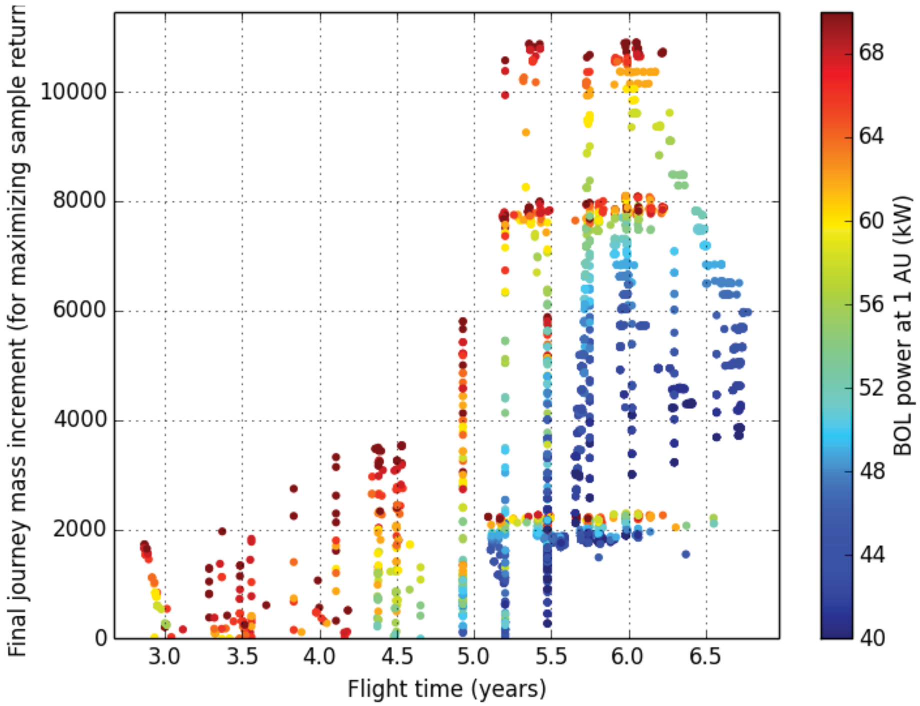
Mission Parameters

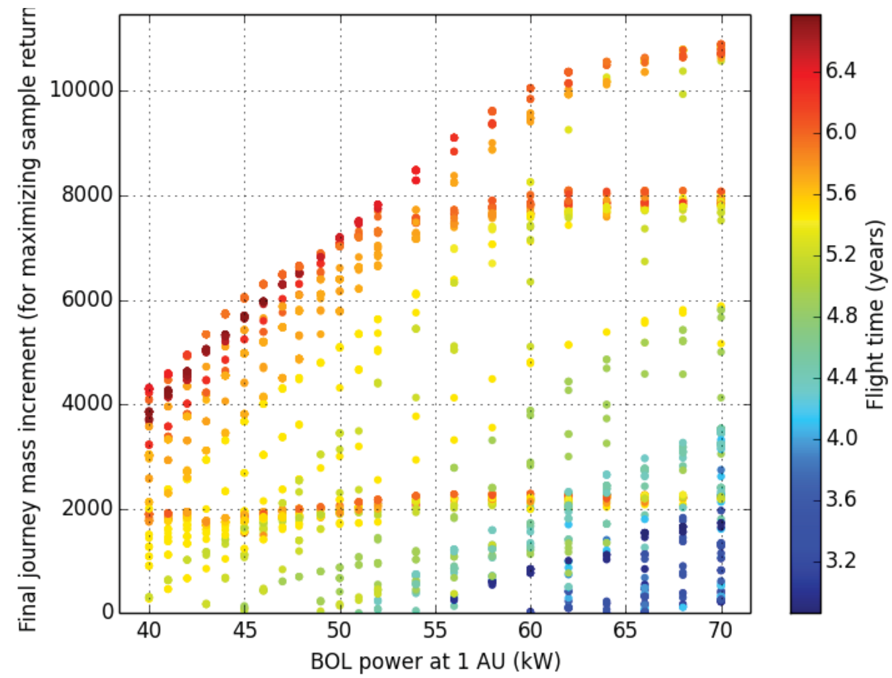
Description	Value
Launch window	1 year
Wait time at Bennu	[430, 700] days
Min. spacecraft mass with 2 thrusters	5991 kg
Additional dry mass per extra thruster	75 kg
Max. depart. mass if lunar gravity assist ($C_3 \leq 2.0$ km^2/s^2)	11191 kg
Max. departure mass if direct launch ($C_3 = 0.0$ km^2/s^2)	10796 kg
Maximum C_3 if direct launch	6 km^2/s^2
Post-mission ΔV, I_{sp}	75 m/s, 3000 s
Thruster duty cycle	90%
Solar array modeling	$1/r^2$
Spacecraft bus power	2 kW
Propellant margin	6%

Pareto-Optimal Solutions



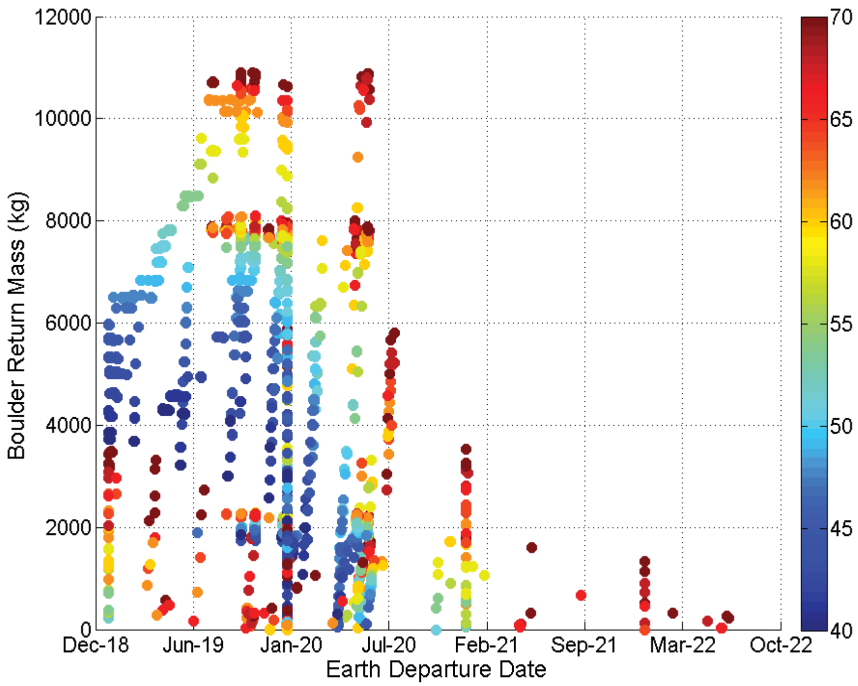
Optimal Trade Space

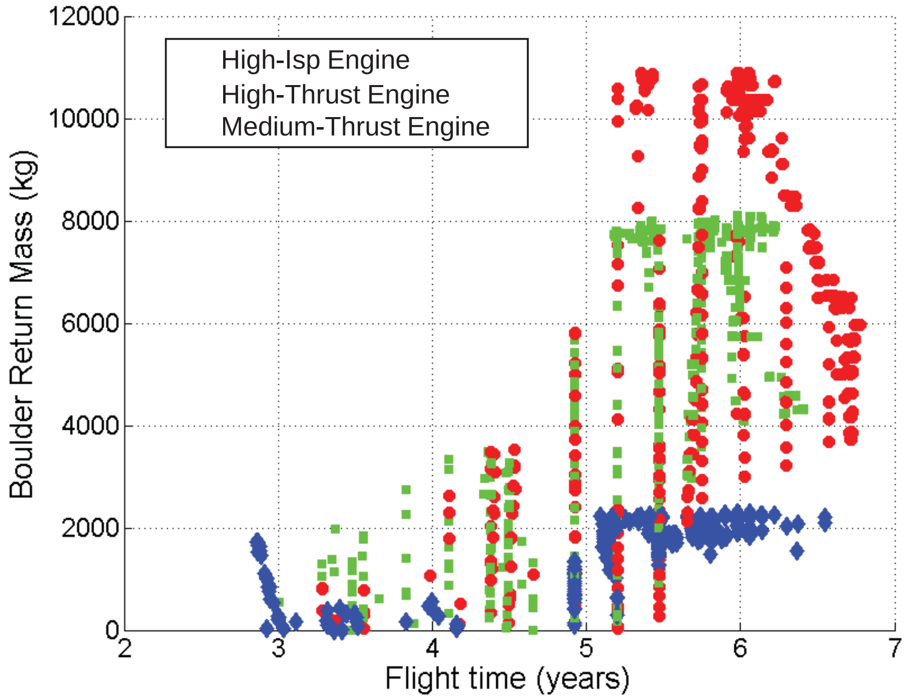




- Sharp increase in maximum return mass w/ increasing power
  - Increase in dry mass for increased power not accounted

Optimal Design Parameters





- Distinct grouping of engine modes based on TOF
  - Return mass plateaus for different engines

Backup

Example: Bennu Large-Mass Sample Return

- Asteroid Robotic Retrieval Mission (ARRM) Option B target

Mission Objective	Return a large boulder from Bennu
Launch Vehicle	
	Delta IV Heavy direct (C3 < 6.0)
	Delta IV Heavy with lunar flyby (C3 2.0)
Power System	
Array power at 1 AU	chosen by optimizer
Cell performance model	$1/r^2$
Spacecraft bus power	2.0 kW
Power margin	0%
Propulsion System	
Thruster	chosen by optimizer (high-Isp , medium thrust, or high-thrust versions of a large Hall thruster)
Number of thrusters	chosen by optimizer (2, 3, 4, 5, 6, 7); dry mass increases by 75 kg for each addtl thruster
Duty cycle	90%
Propellant tank	unconstrained
Mission Sequence	Direct travel to Bennu followed by direct return to C3 2.0 for lunar flyby capture
Inner-Loop Objective Function	Maximize sample return mass
Outer-Loop Objective Functions	Sample return mass
	Solar array size
	Number of thrusters
	Flight time

Bennu Sample Return: Outer-Loop Menu

Power Supply at 1 AU

Code	Array Output
0	30
1	32
2	34
3	36
...	...
20	70

Launch Year

Code	Year
0	2019
1	2020
2	2021
3	2022
4	2023

Flight Time Upper Bound

Code	Days
0	700
1	800
2	900
3	1000
4	1100
5	1200
7	1300
8	1400
9	1500
10	1600
…	
26	3300

Thruster Type

Code	Thruster
0	13 kW Hall (High-Isp)
1	13 kW Hall (medium-thrust)
2	13 kW Hall (High-thrust)

Number of Thrusters

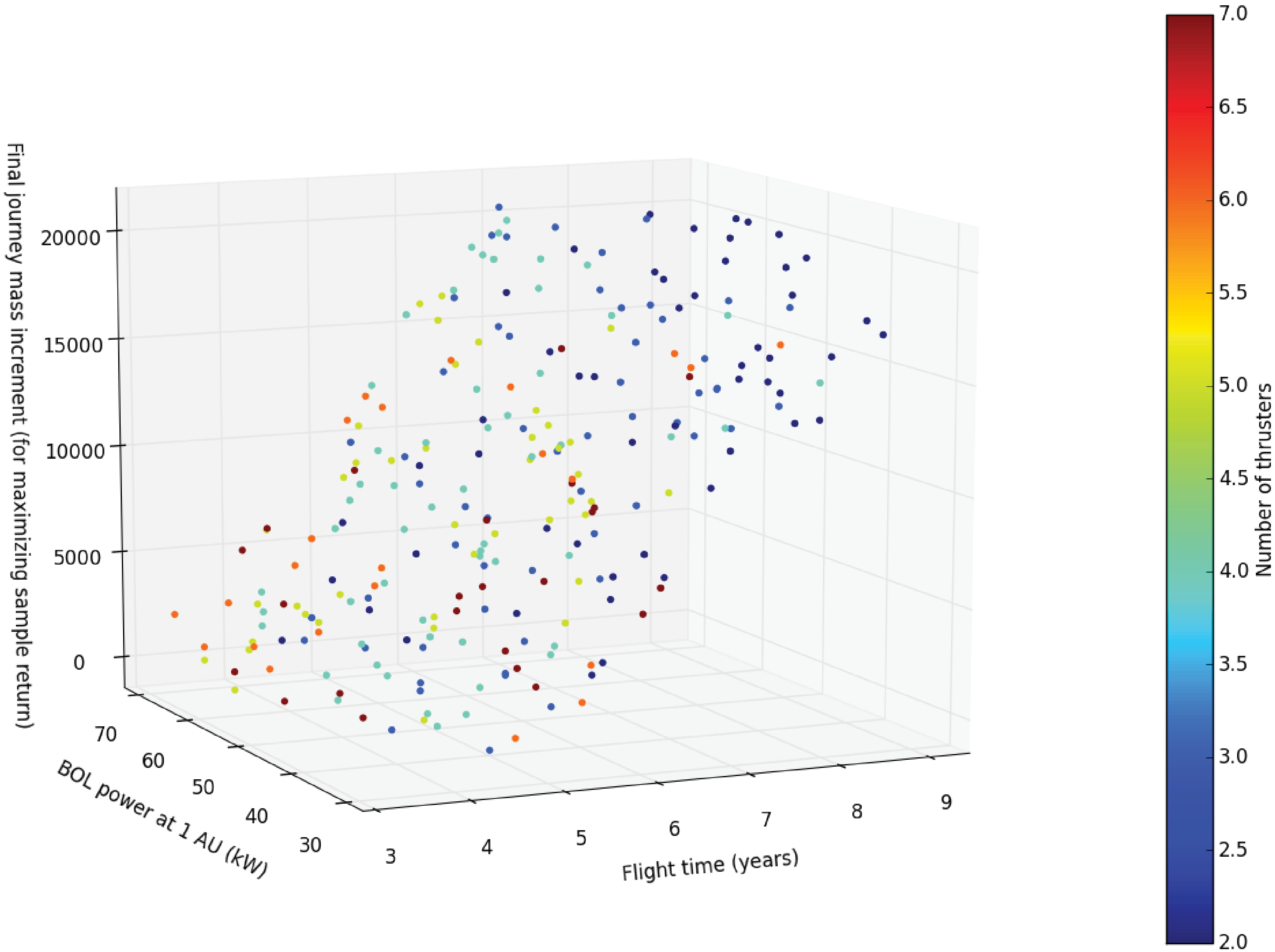
Code	# Thrusters
0	2
1	3
2	4
3	5
4	6
5	7

Earth Departure Type

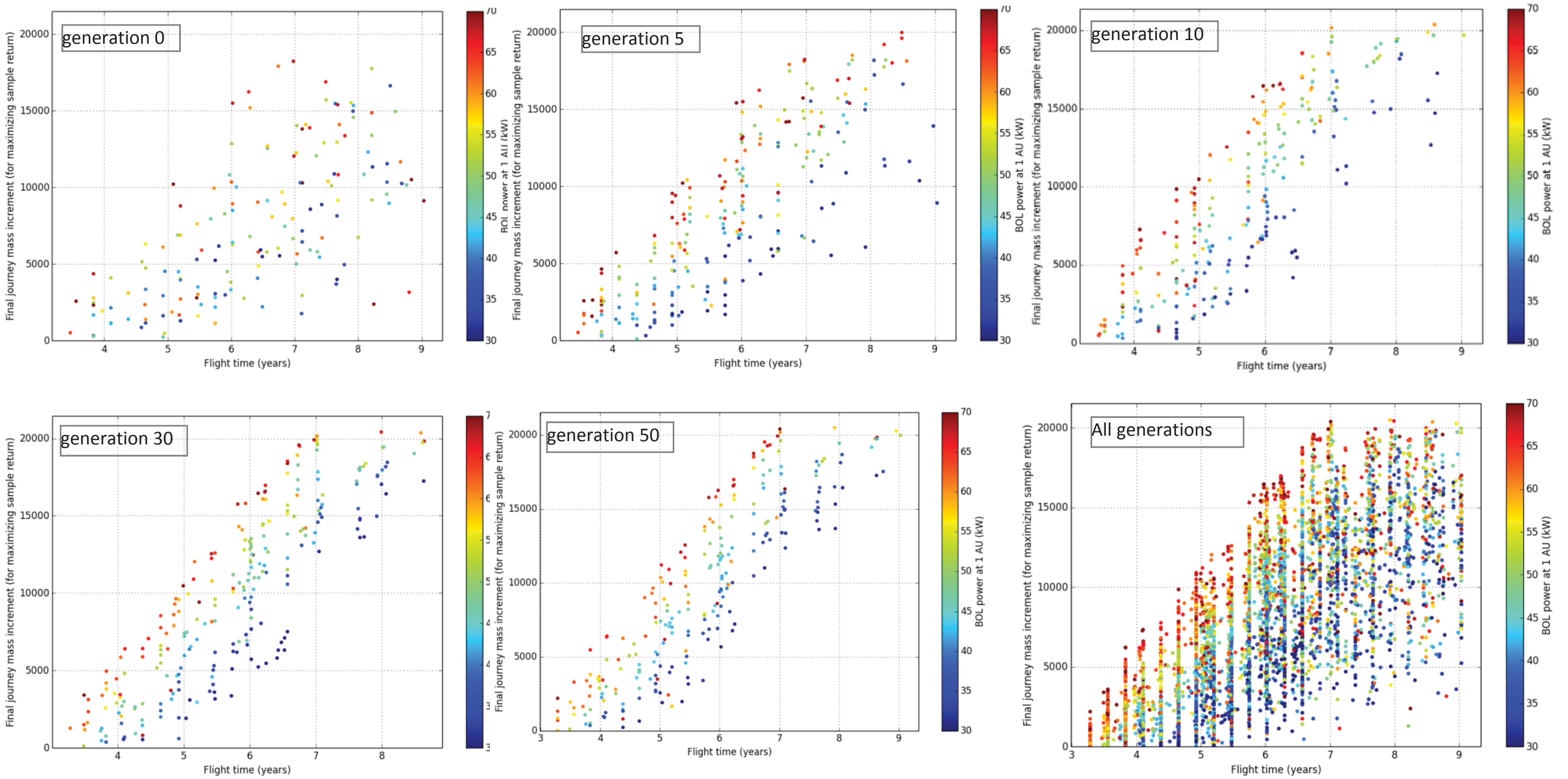
Code	Type
0	Delta IV-H direct
1	Delta IV-H w/ LGA

102,060 possible combinations

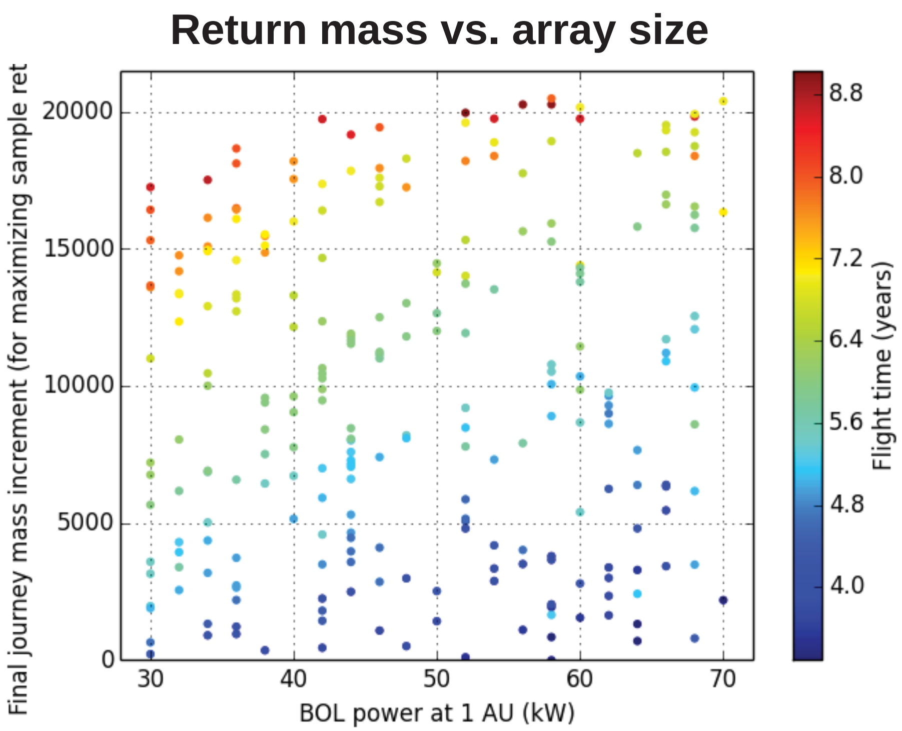
Bennu Sample Return: Final Generation Trade Space

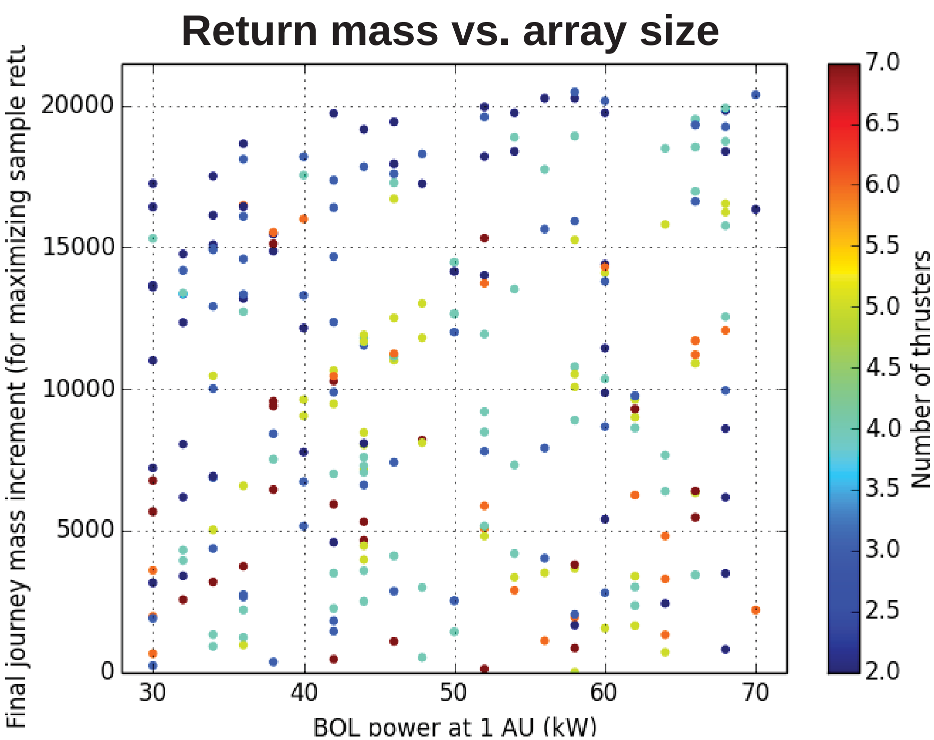


Bennu Sample Return: Evolution of Population



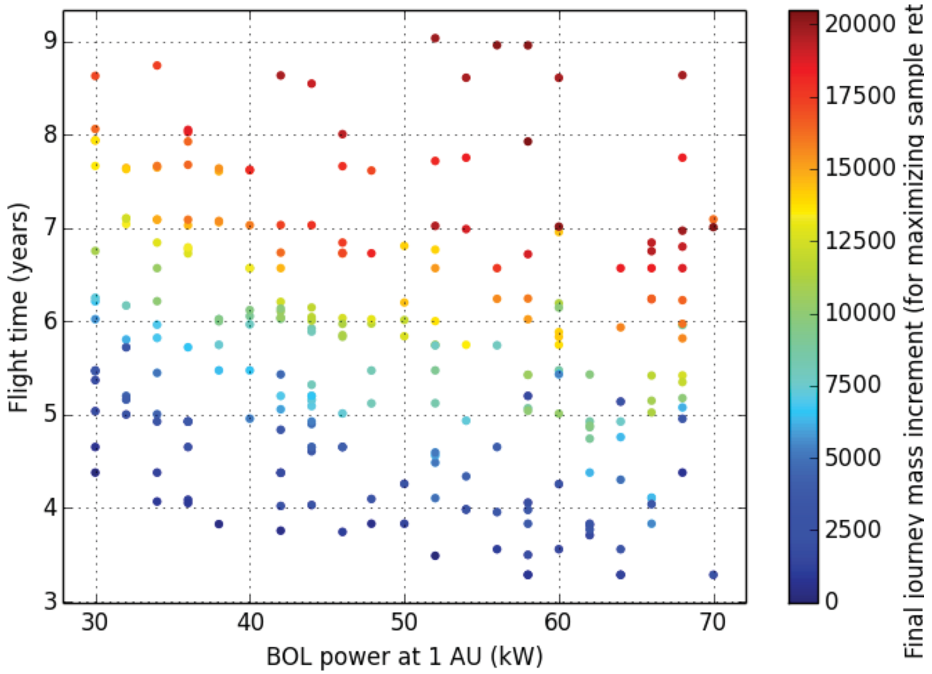
Bennu Sample Return: Objective Space



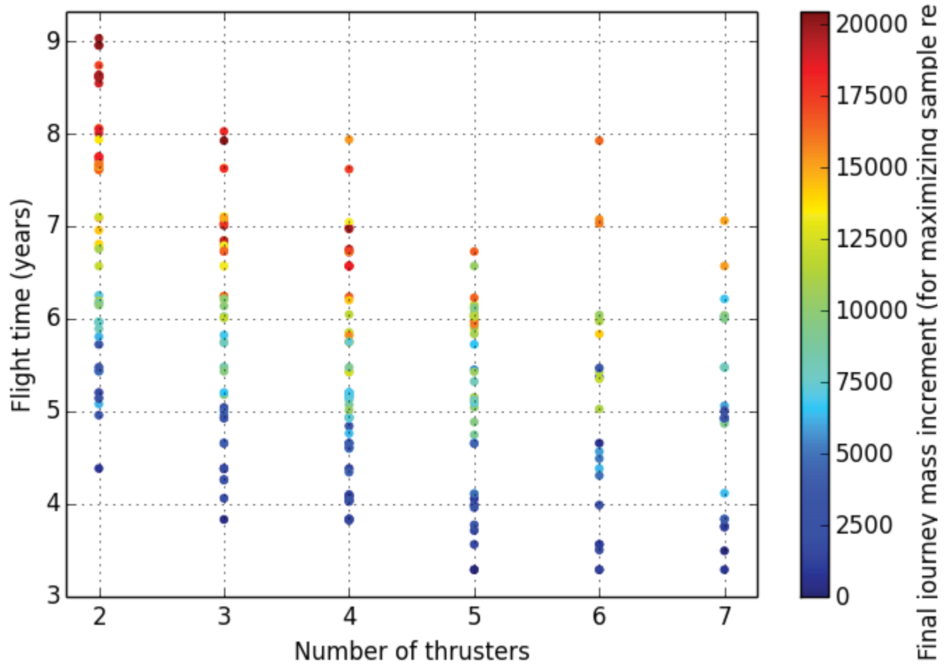


Bennu Sample Return: Objective Space

TOF vs. array size

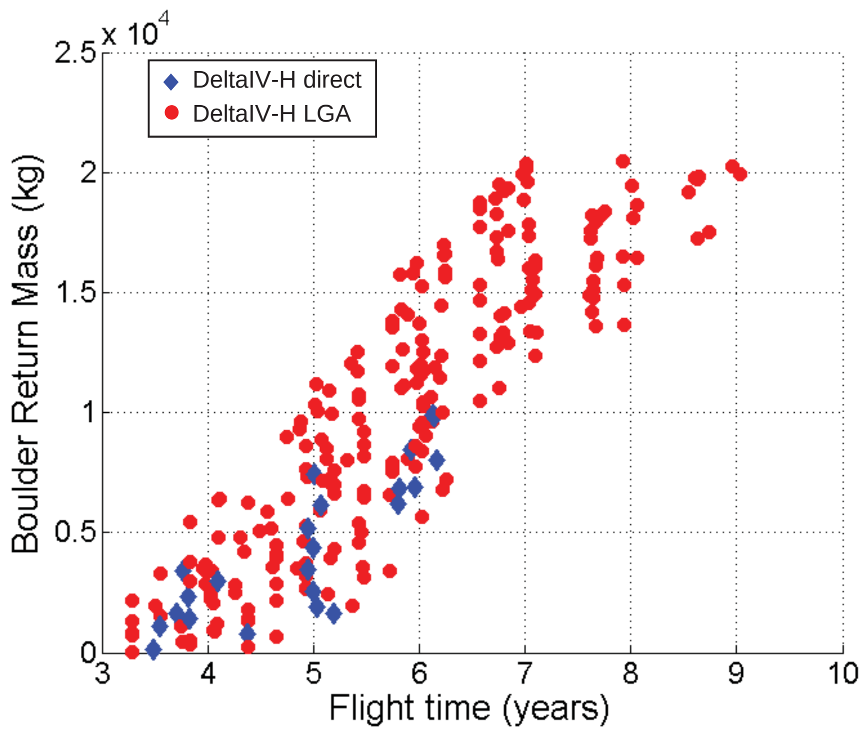


TOF vs. number of thrusters

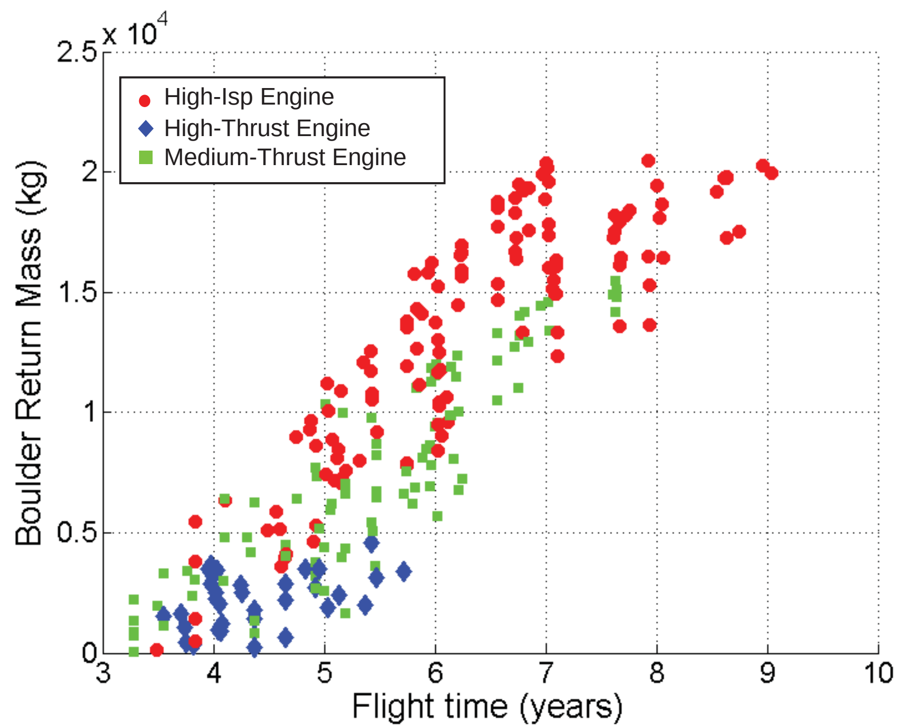


Bennu Sample Return: Optimal Design Variables

Departure Type

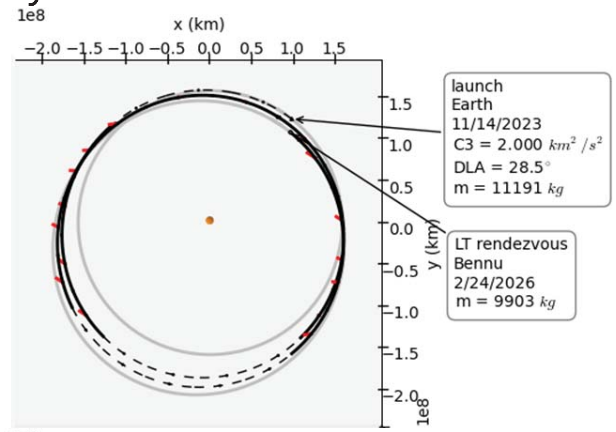


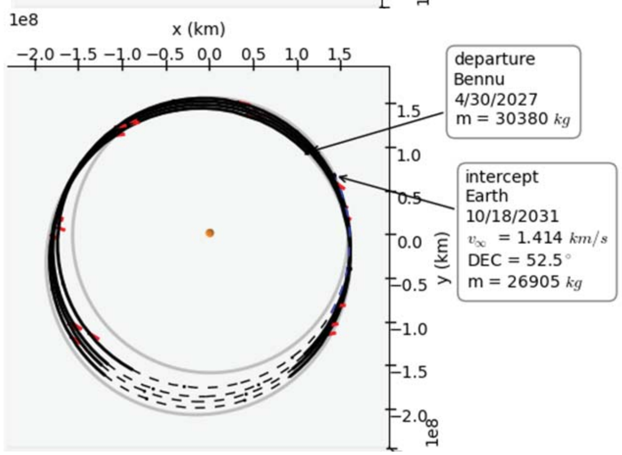
Engine Type



Bennu Sample Return: Two Trajectories

A 8-year mission with a 58 kW solar array returns a 20 ton boulder





A 3.3-year mission with a 70 kW solar array returns a 2.2 ton boulder