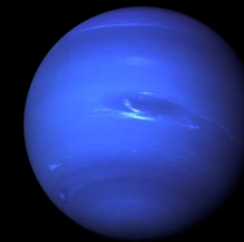
Gravity-Assist Trajectories to the Ice Giants: An Automated Method to Catalog Mass- or Time-Optimal Solutions



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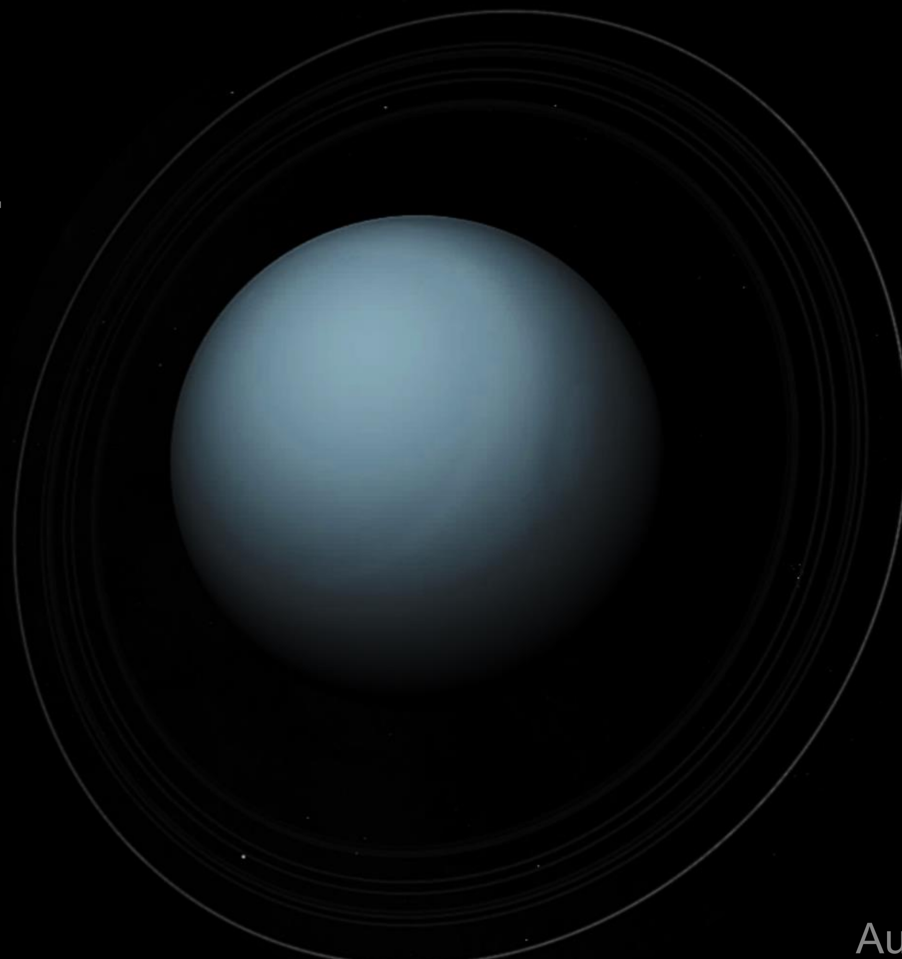
AAS/AIAA Astrodynamics Specialist Conference



NASA Goddard Space Flight Center

August 23, 2017

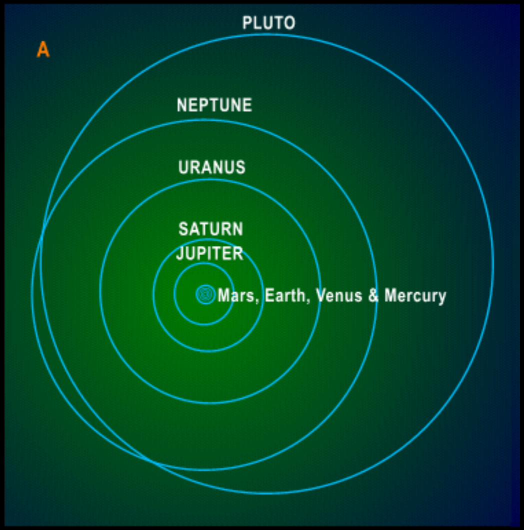
The Ice Giants: Uranus and Neptune

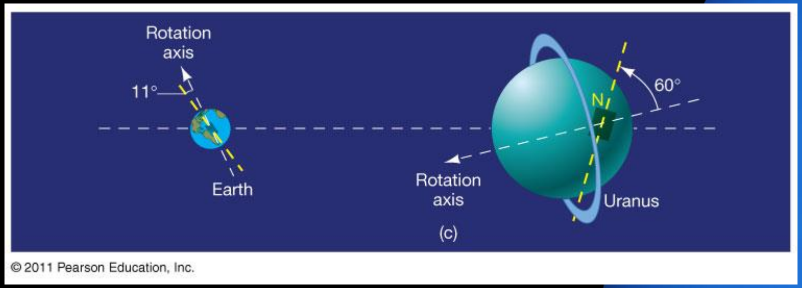
Interest from scientific community:

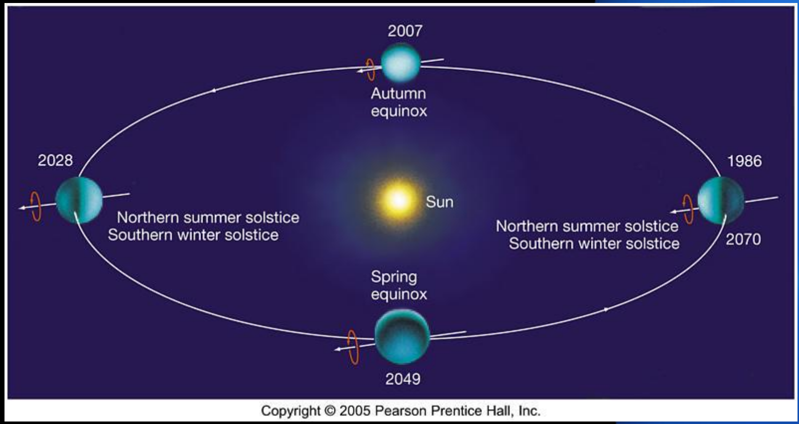
- Ice Giants orbiter is next highest priority flagship mission
- Specified by the "Decadal Survey": a report which drives all NASA science missions

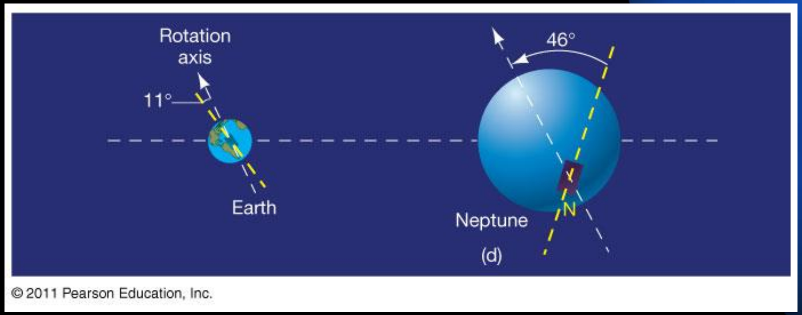
Ice Giants Study:

- Trajectory investigation to survey opportunities for an Ice Giants mission from 2024–2038



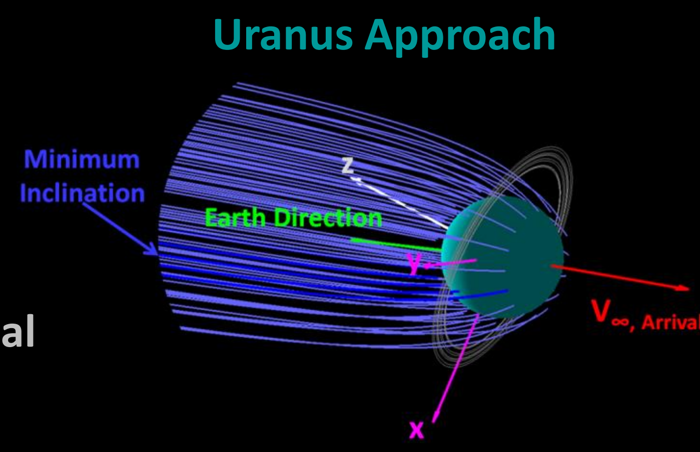


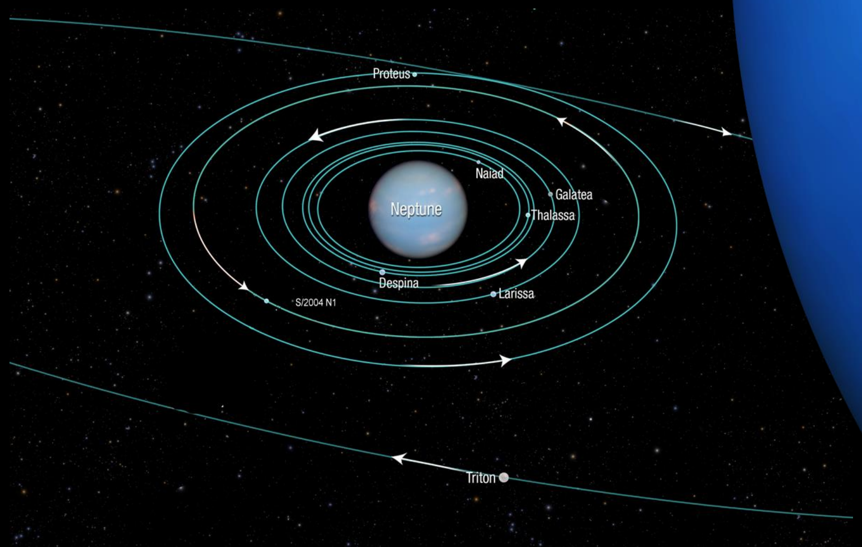




Trajectory Design Challenges

- Difficult to achieve reasonable flight times with adequate delivered mass (Flight + mission should not exceed ~15yrs)
- Uranus:
  - High axial tilt (98 °) makes equatorial orbits a challenge for most arrival dates
- Neptune:
  - It’s really really far away!
  - retrograde s/c capture orbit (to match Triton)—Challenge for atmospheric probes



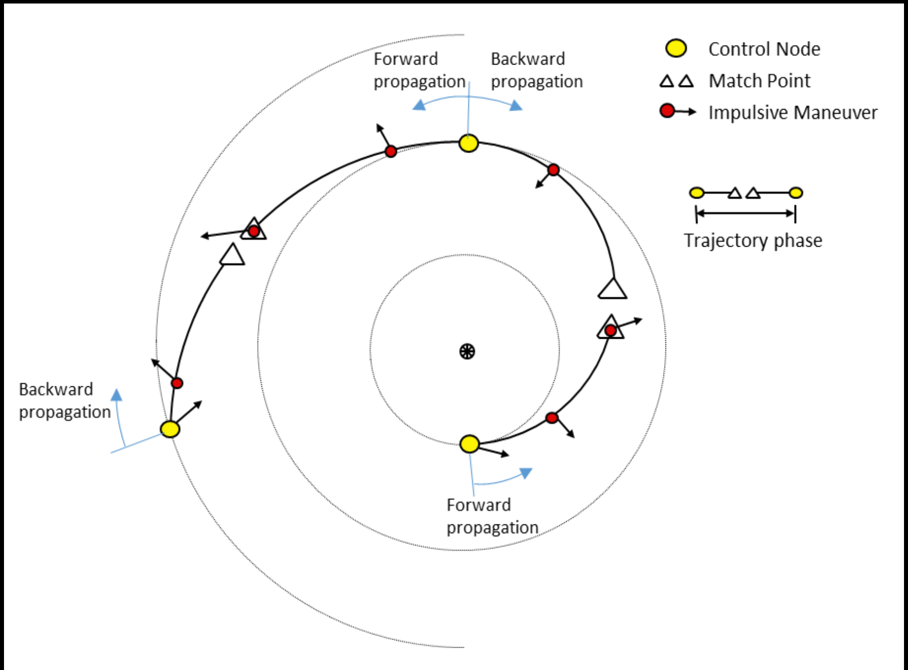


Approach

- Generate library (or catalog) of mass-optimal patched-conic trajectories to the Ice Giants with minimal user involvement after initial setup
- Uses an EMTG wrapper program called PEATSA
- Evolutionary Mission Trajectory Generator (EMTG) is a NASA-GSFC trajectory optimization tool that does not require an initial guess
- Python EMTG Automated Trade-Study Application (PEATSA) is a Python wrapper program for EMTG
  - Iteratively runs a series of EMTG cases
  - Series of EMTG cases are generated by choosing parameters and constraints to step through, e.g. launch date, flyby combination, and maximum flight time
  - After each iteration, PEATSA uses the best solutions in a neighborhood of launch dates to seed neighbors for next iteration
- Results from PEATSA analysis are cataloged and compared to solutions from a grid-search technique (in my PhD thesis)
- Grid search solves Lambert's problem, stepping through launch date and flight time, for specified launch C3 and flyby combination

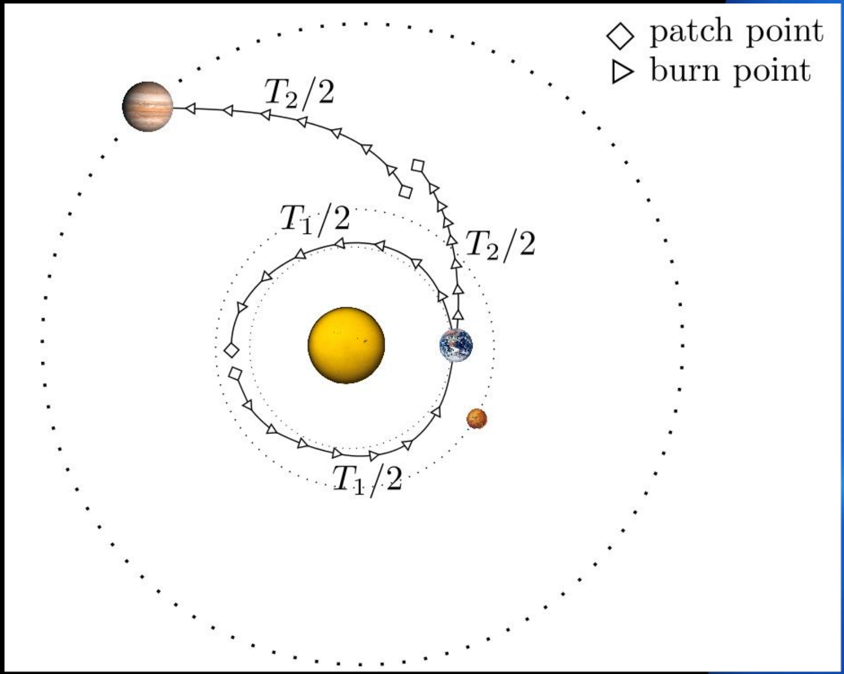
EMTG Transcriptions

Chemical Mission Transcription



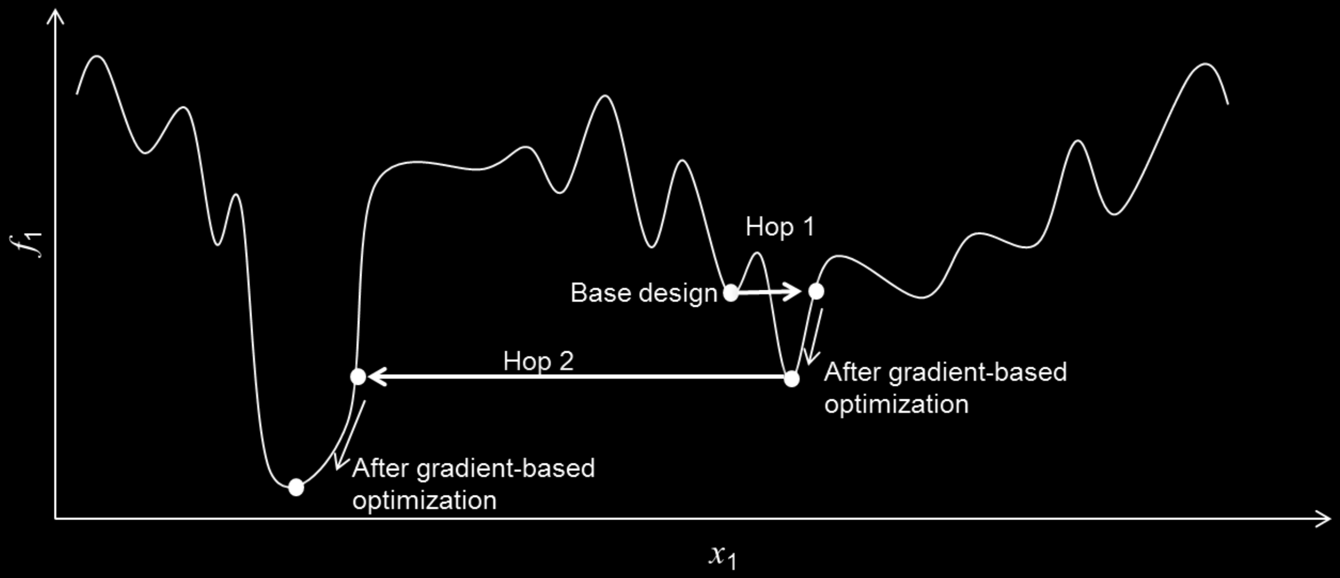
M. Vavrina and J. Englander, “Global Optimization Of *N*-maneuver, High-thrust Trajectories Using Direct Multiple Shooting,” AAS Space Flight Mechanics Meeting, Napa, CA, February 2016.

Low Thrust Mission Transcription



Monotonic Basin Hopping

- EMTG seeks out the global optimum by “hopping” to new solutions, which are then optimized using a gradient-based local search supplied by SNOPT
- The hops are implemented by stochastically choosing the decision variables via a Pareto probability distribution



PEATSA Analysis Details

- Each PEATSA iteration allows MBH to hop for 2 min
- Analysis was run for ~5 weeks using a 64-core server for Uranus trajectories and 60-core server for Neptune

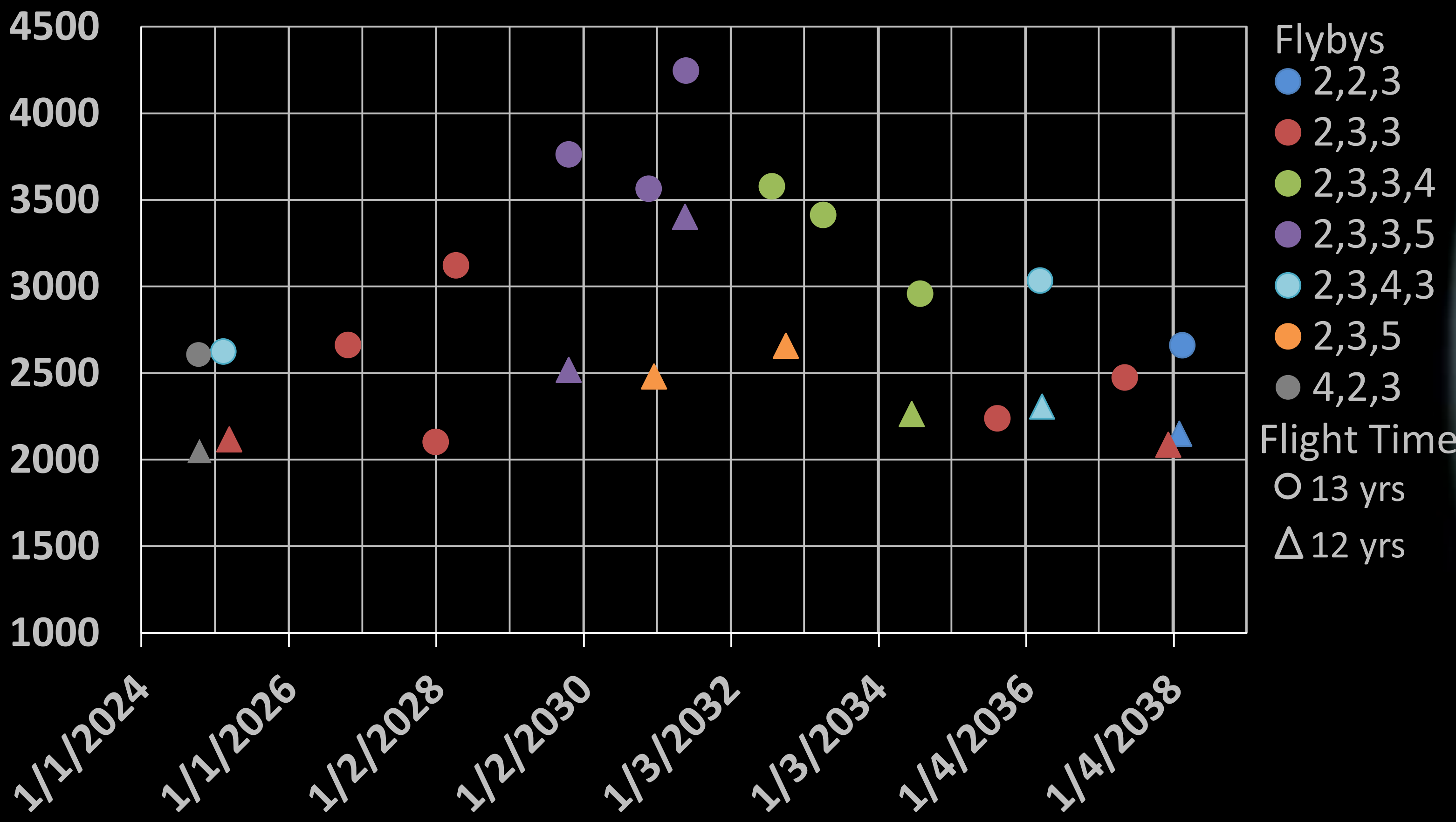
Parameter	Value
Launch Date Range	1-1-2024 to 12-31-2038
Launch Vehicle	Delta IV Heavy
Maximum Flight Times	12 & 13 yrs (Uranus), 14.5 yrs (Neptune)
Capture Orbit Periapsis	3000 km (altitude)
Capture Orbit Period	20 days
Spacecraft I_{sp}	323 s
Propellant Mass Margin	12%
Seed Distance	10 days
EMTG Run Time	2 min

PEATSA Analysis Details

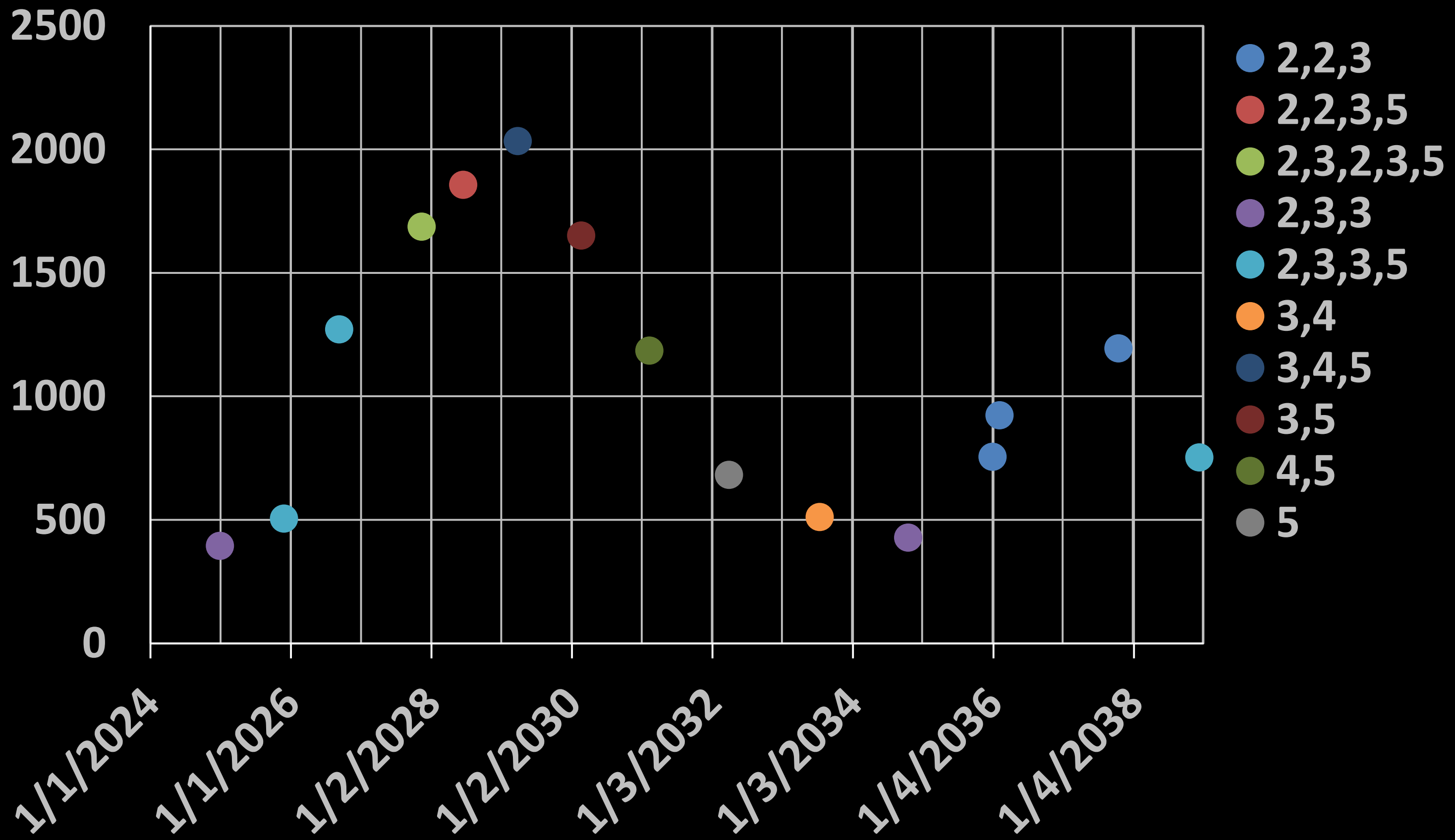
Flyby Combinations Considered

Uranus				Neptune		
0	*2,2,5	*4,3,5	*2,3,2,3,5	0	*2,3,5	2,3,3,6
2	2,2,6	4,3,6	2,3,2,3,6	3	2,3,6	2,3,4,3
3	2,3,2	4,4,2	2,3,3,3,5	4	2,4,2	*2,3,4,5
4	*2,3,3	4,4,3	2,3,3,3,6	*5	2,4,3	2,4,2,5
5	2,3,4	4,4,4	*2,3,3,4,5	6	*3,3,5	4,3,3,5
6	*2,3,5	4,4,5	2,3,3,4,6	2,2	*3,4,5	*2,2,3,3,5
2,2	2,3,6	4,4,6	2,3,4,3,5	2,3	3,4,6	*2,3,2,3,5
2,3	2,4,2	4,5,6	2,3,4,3,6	3,2	3,5,6	*2,3,3,3,5
2,4	2,4,3	*2,2,2,5	2,4,2,3,5	3,3	4,2,3	*2,3,3,4,5
2,5	2,4,4	2,2,2,6	*2,4,3,3,5	*3,4	4,2,5	2,3,4,3,5
2,6	2,4,5	*2,2,3,5	2,4,3,3,6	*3,5	4,2,6	2,4,2,3,5
3,2	2,4,6	*2,2,3,6	4,3,2,3,5	3,6	4,3,3	2,4,3,3,5
3,3	2,5,6	2,2,4,2	4,3,4,3,5	4,3	4,3,4	4,3,2,3,5
*3,4	*3,3,5	2,2,4,5	4,3,4,3,6	4,4	*4,3,5	4,3,4,3,5
*3,5	3,4,5	2,2,4,6		*4,5	4,3,6	
3,6	3,4,6	2,3,3,3		4,6	4,4,3	
4,2	3,5,6	*2,3,3,4		5,6	4,4,4	
4,3	4,2,2	*2,3,3,5		2,2,2	4,4,5	
4,4	*4,2,3	2,3,3,6		*2,2,3	4,4,6	
4,5	4,2,4	*2,3,4,3		2,2,4	4,5,6	
4,6	4,2,5	*2,3,4,5		2,2,5	*2,2,2,5	
5,6	4,2,6	*2,4,2,5		2,2,6	*2,2,3,5	
2,2,2	4,3,2	*4,3,3,5		2,3,2	2,2,4,5	
*2,2,3	*4,3,3	4,3,3,6		*2,3,3	2,3,3,4	
2,2,4	4,3,4	*2,2,3,3,5		2,3,4	*2,3,3,5	

Uranus Trajectory Results



Neptune Trajectory Results



Uranus Trajectory Comparison to Grid-Search

Launch Year	Flyby Sequence		Flight Time, years		Final Mass, kg	
	PEATSA	STOUR	PEATSA	STOUR	PEATSA	STOUR
2024	4,2,3	2,3,3	12.0	13.3	2100	2100
2025	2,3,3	2,3,3,3	12.0	14.4	2100	2000
2026	2,3,3	2,3,3	13.0	12.7	2700	1900
2027	2,3,3	2,2,3,3,5	13.0	13.9	2100	2100
2028	2,3,3	2,3,5	13.0	13.5	3100	2100
2029	2,3,3,5	2,3,3,5	11.9	11.7	2500	2000
2030	2,3,5	2,2,3,5	12.0	12.1	2500	2100
2031	2,3,3,5	2,3,5	12.0	10.9	3400	2100
2032	2,3,5	2,2,5	12.0	13.2	2700	2300
2033	2,3,3,4	2,3,3	13.0	13.4	3400	2000
2034	2,3,3,4	2,2,3	12.0	13.0	2300	2000
2035	2,3,3	2,3,3	13.0	13.1	2200	1800
2036	2,3,4,3	2,2,3	12.0	13.2	2300	2100
2037	2,3,3	2,3,3	12.0	12.6	2100	2000
2038	2,2,3	2,3,3	12.0	12.8	2100	2100

Neptune Trajectory Comparison to Grid-Search

Launch Year	Flyby Sequence		Flight Time, years		Final Mass, kg	
	PEATSA	STOUR	PEATSA	STOUR	PEATSA	STOUR
2026	2,3,3,5	2,3,3,5	14.5	14.8	1300	1300
2027	2,3,2,3,5	2,3,3,5	14.5	14.9	1700	1200
2028	2,2,3,5	2,2,3,5	14.5	14.7	1900	1300
2029	3,4,5	2,3,5	14.5	14.3	2000	1000
2030	3,5	NA	14.5	NA	1700	NA
2031	4,5	4,5	14.5	14.1	1200	1300
2037	2,2,3	NA	14.5	NA	1200	NA

Conclusions

- Iterative, stochastic, optimization techniques of PEATSA were successful in constructing a catalog of attractive solutions with very little involvement by the mission designer after the initial setup
- PEATSA outperformed the grid-search solutions for most launch years considered in this study
- Initiating PEATSA from grid-search solutions found a priori is likely a better approach
  - Provides benefits of MBH global search with optimized solutions
  - Guarantees a certain breadth of the design space is accounted for from grid-search solutions