Trajectory Optimization and Mission Design for Human Space Exploration

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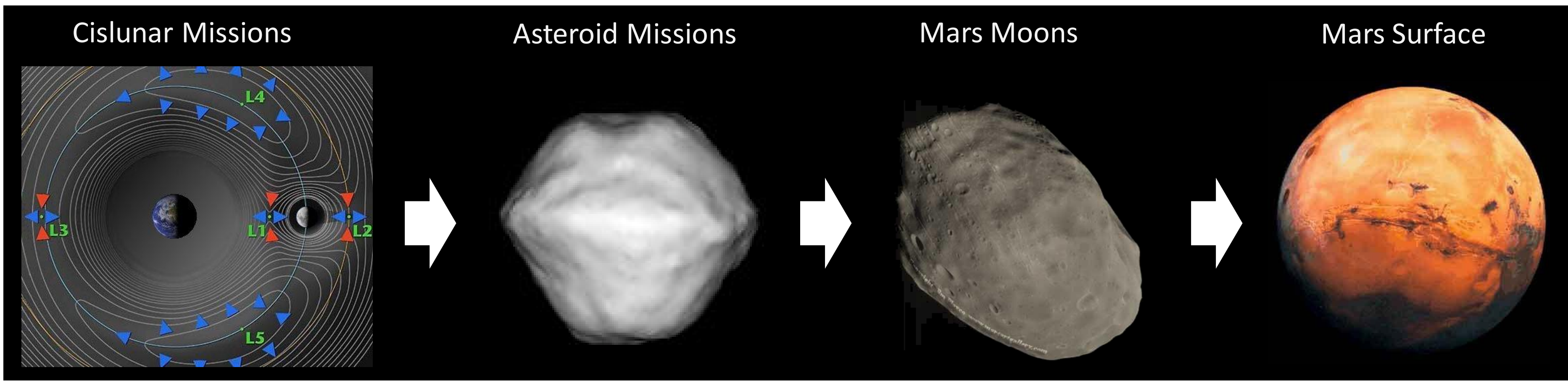
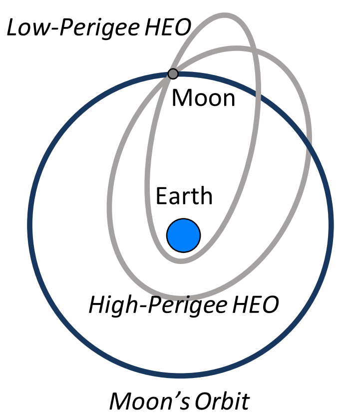
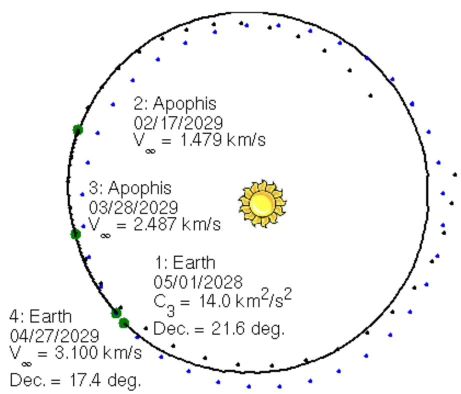
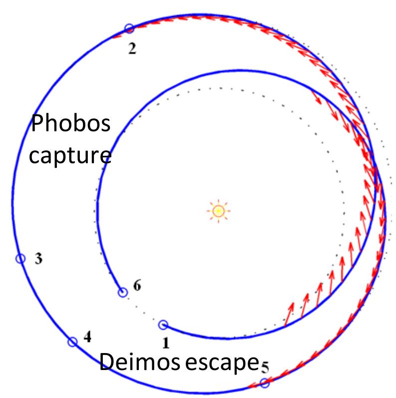
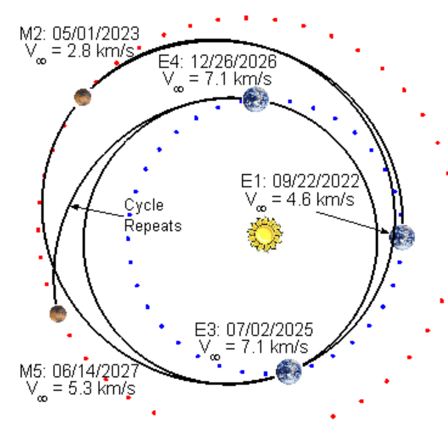






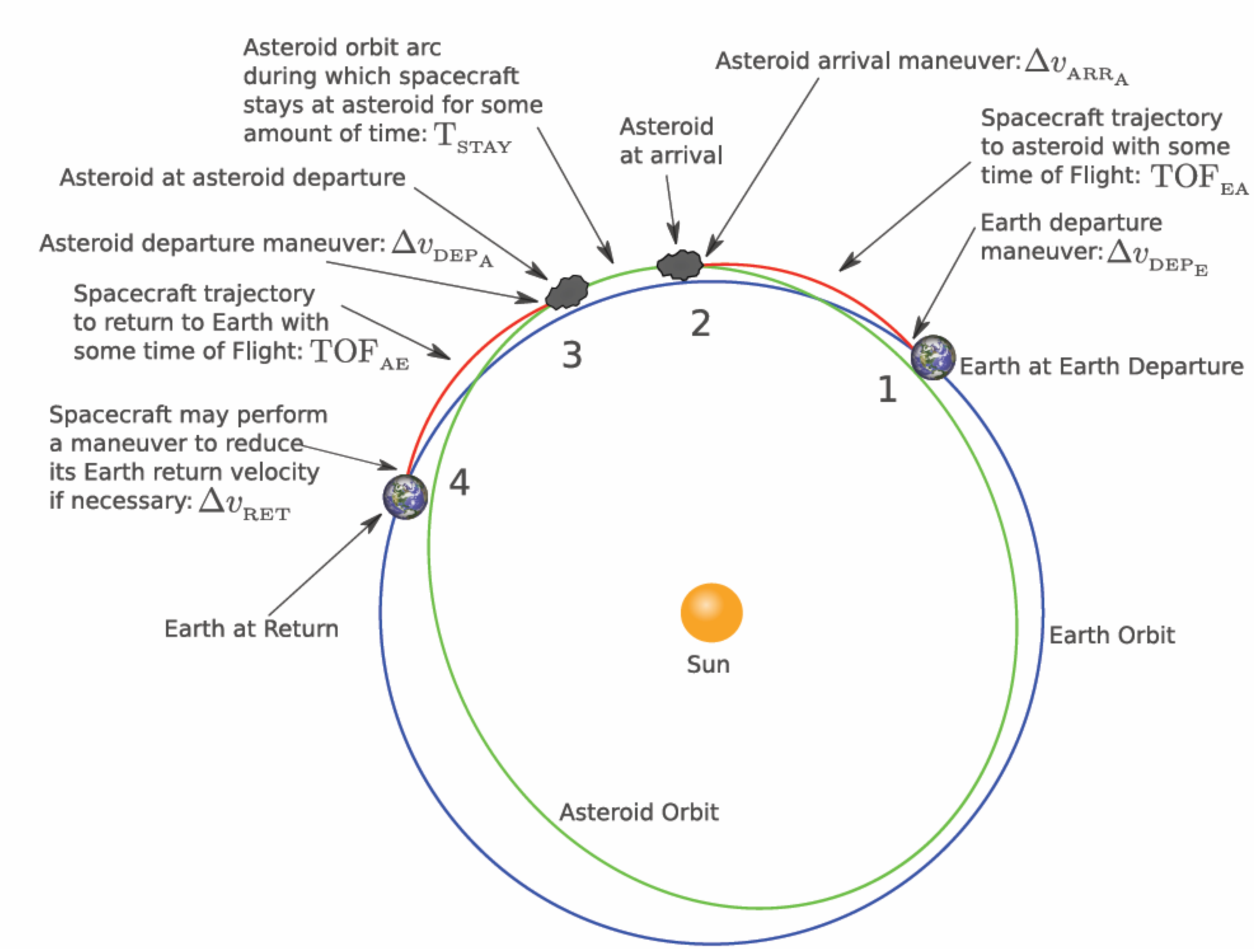




Programmatic Considerations

- Space policy shifts faster than vehicles can be developed
- Design a variety of missions tuned to different exploration objectives
  - Adventure, Science, Technology, Capability
- Identify mission types that repeat regularly and introduce schedule flexibility
  - Mass, Power, Flight time, Target characteristics
- Many potential NEA campaigns emerge that *adapt to an evolving space program*
- Key design driver is to *bridge the gap from cislunar to Mars* exploration capability

Simple Trajectory Model



Note:
Trajectories at target do NOT lend themselves to a simple model. Current rule of thumb is "most objects can be orbited- *after* proper characterization."

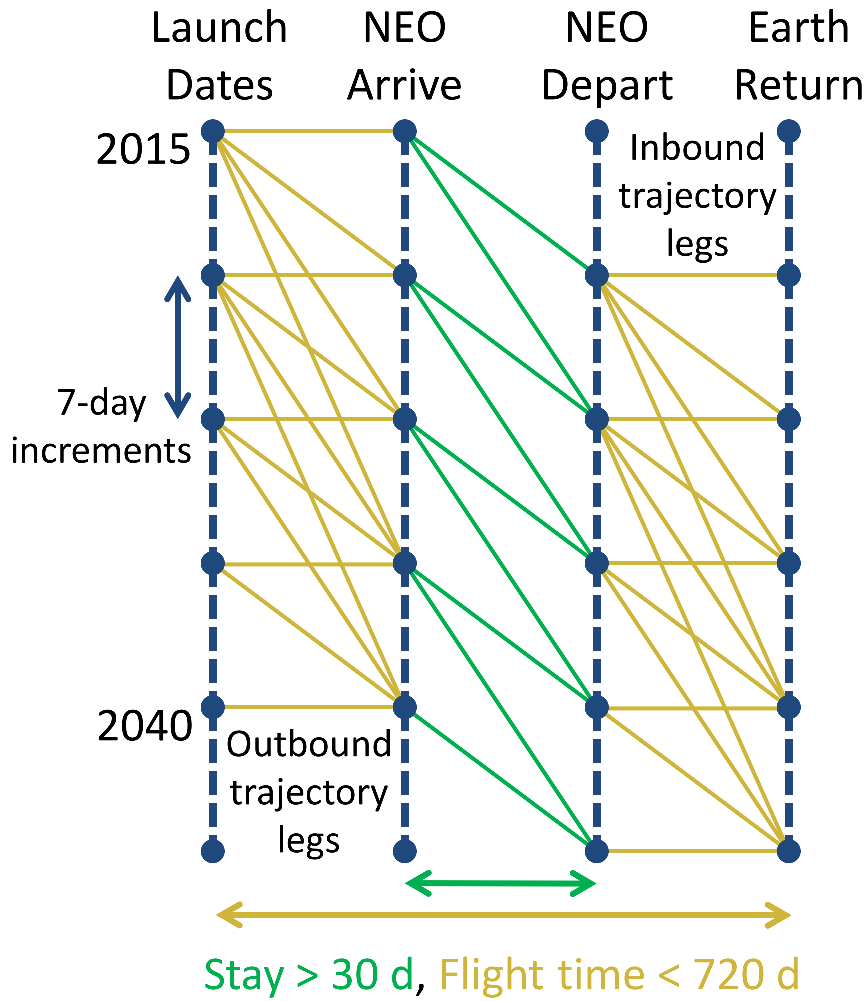
From Barbee et al., "Methodology and Results of the Near-Earth Object (NEO) Human Space Flight (HSF) Accessible Targets Study," Paper AAS 11-444, AAS/AIAA Astrodynamics Specialist Conference, August 2011.

NEO Target Search

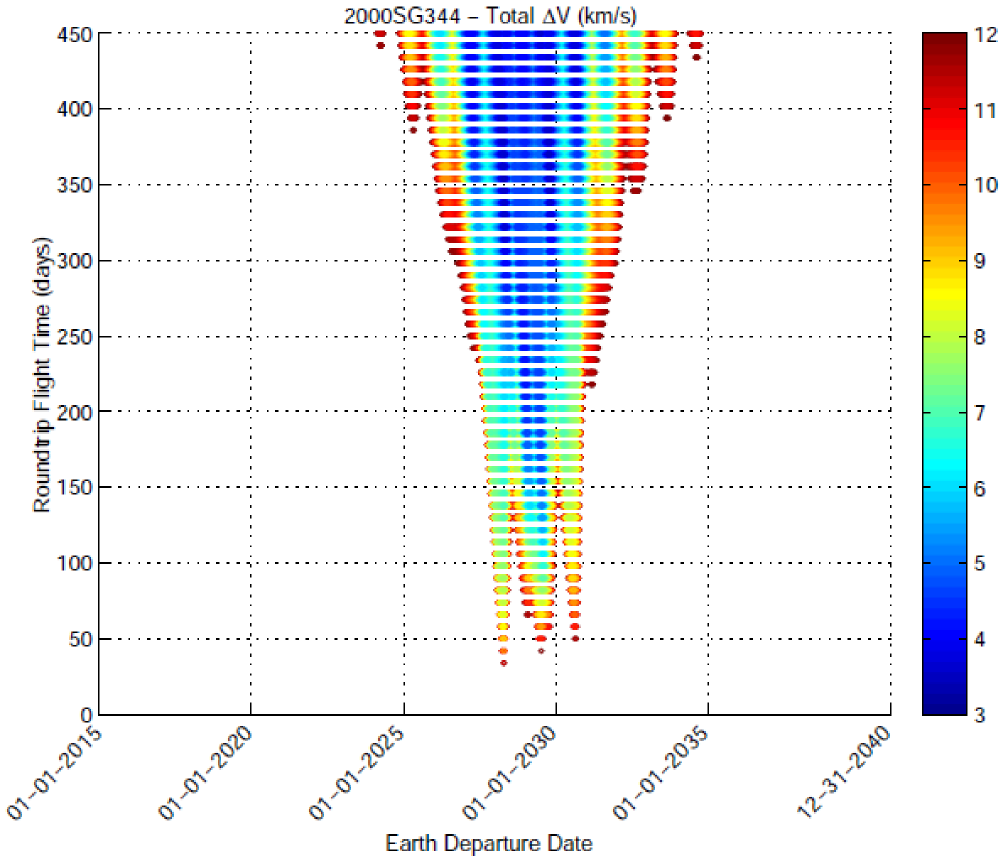
- 2-stage process: Search then Optimize
- Included catalogue of all known NEOs

  7625 objects as of January 22, 2011
- Examined launch dates 2019–2036

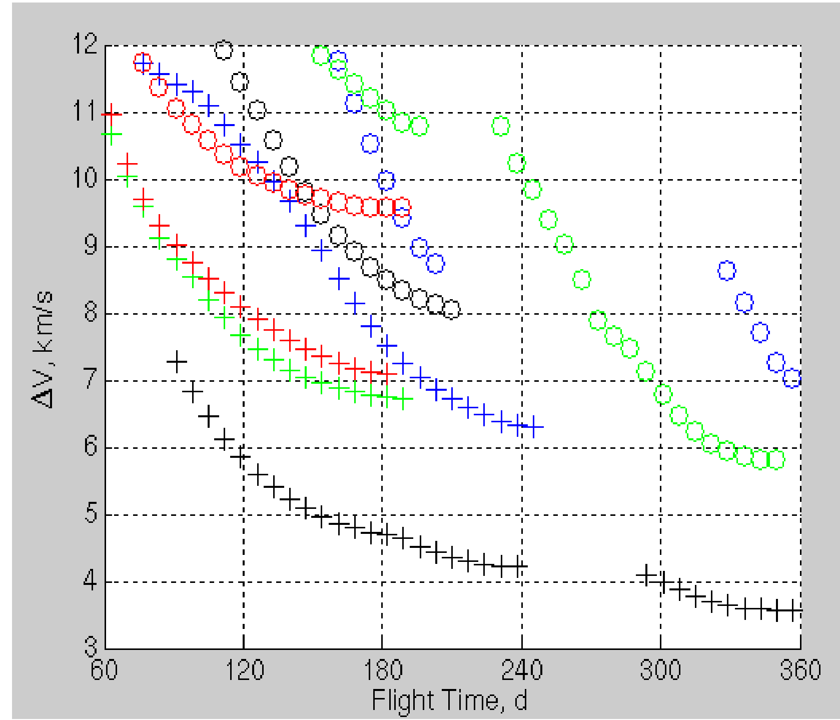
  in 7-day increments, min 30 d stay
- TOF <= 180, 270, 360, 540, 720 d
- Considered ~10^{13} missions
  - "Only" calculate ~2B trajectory legs
  - Filters to ~1400 objects
  - Run time ~1 day on single CPU (0.5 d Lambert fits, 0.5 d combining legs)
- Filter down to ~50k trajectories for optimization

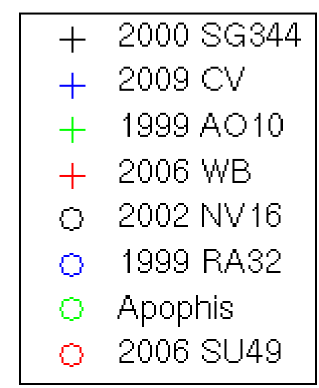


A Few Targets 2024–2029



From Barbee et al. "Methodology and Results of the NHATS"

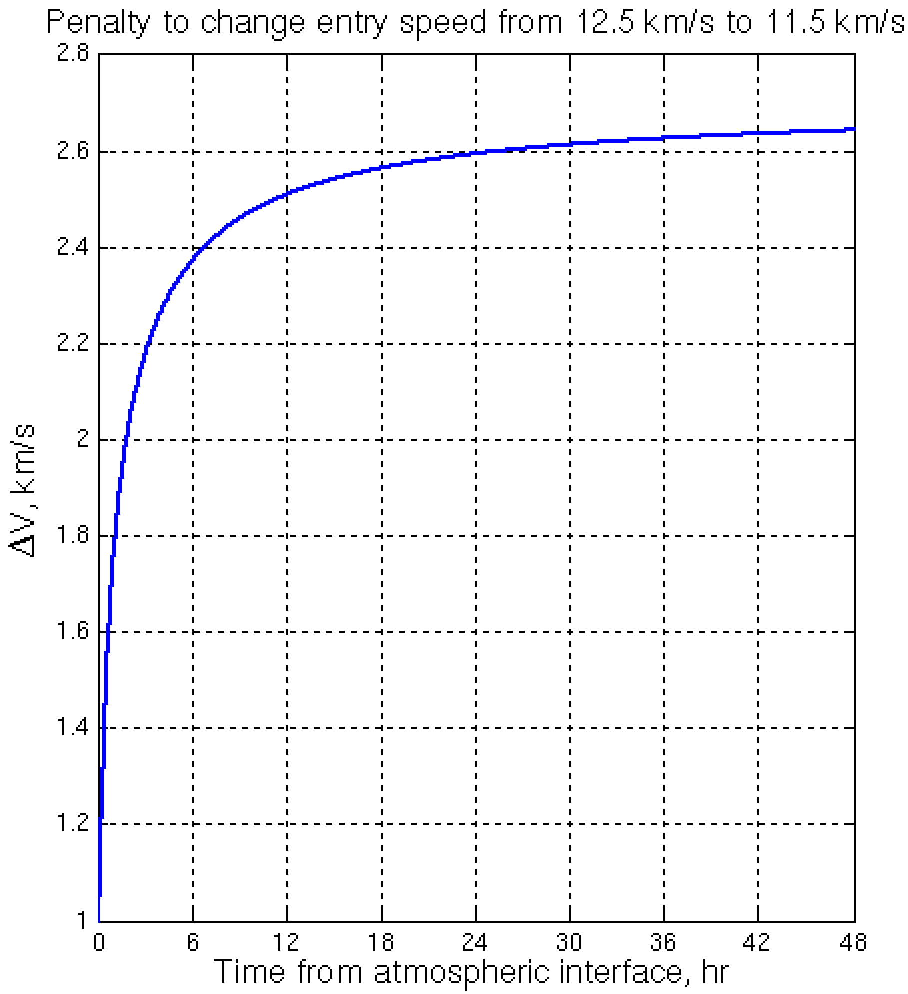




For a big list of individual trajectories see:
"Near-Earth Asteroids Accessible to Human Exploration in 2020–2035"
Can be found by searching "DPS Nathan Strange" in google.

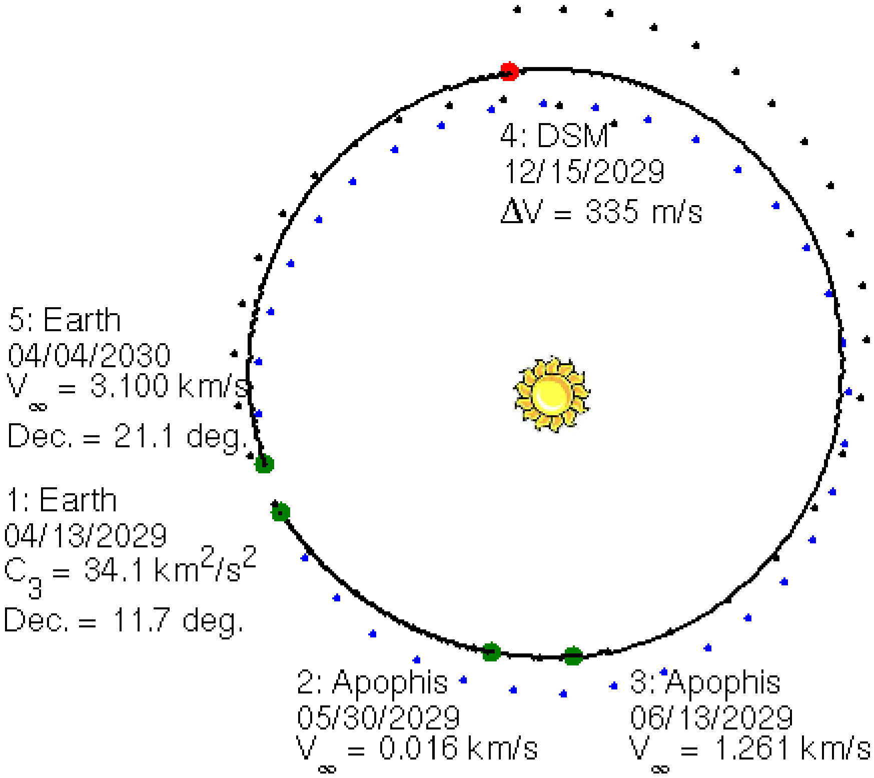
Lowering Entry Velocity

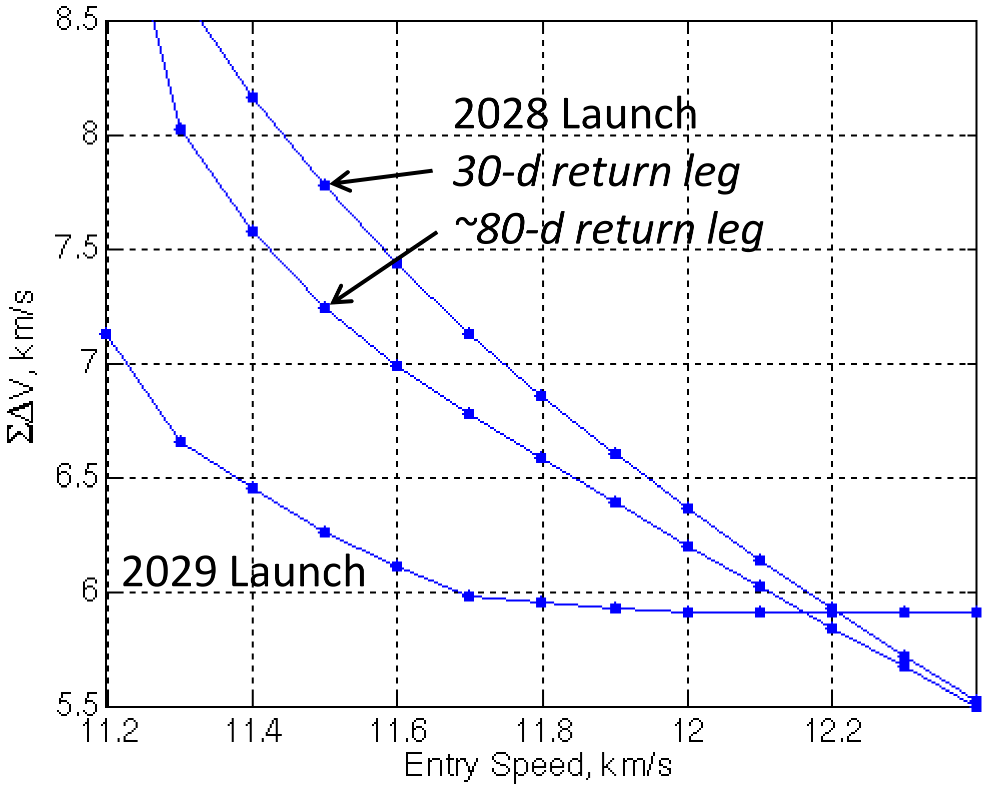
- Very efficient to reduce energy in Earth's gravity well, but efficiency is only available within a few hours of interface (plot on right)
- Orbit determination requires days to ensure proper entry conditions, precluding large maneuvers near interface
- In this case it's usually more efficient to alter the trajectory (i.e. encounter dates) or add deep-space maneuvers (as in 2029 Apophis trajectory) to lower entry speed



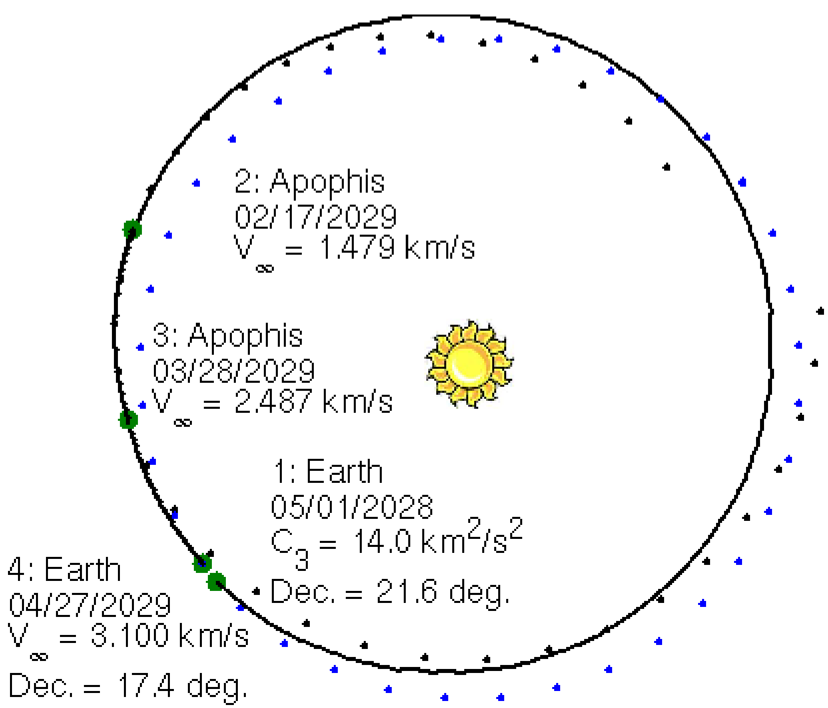
Apophis 2029 Launch

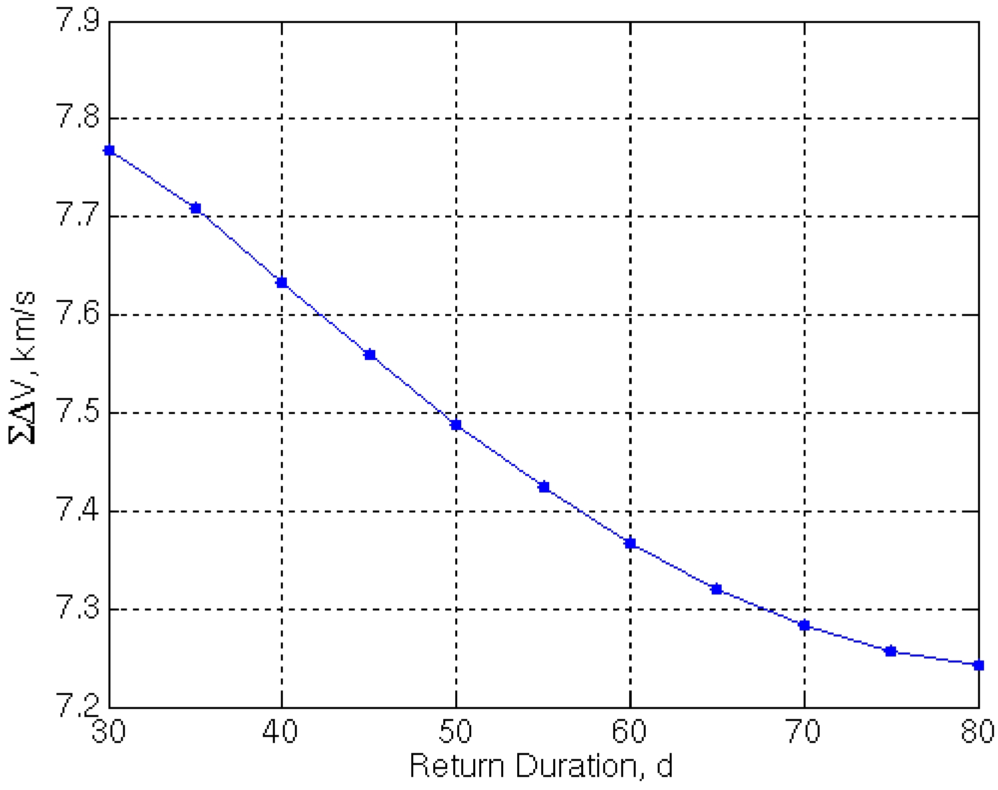
Variable Entry Speed, long return



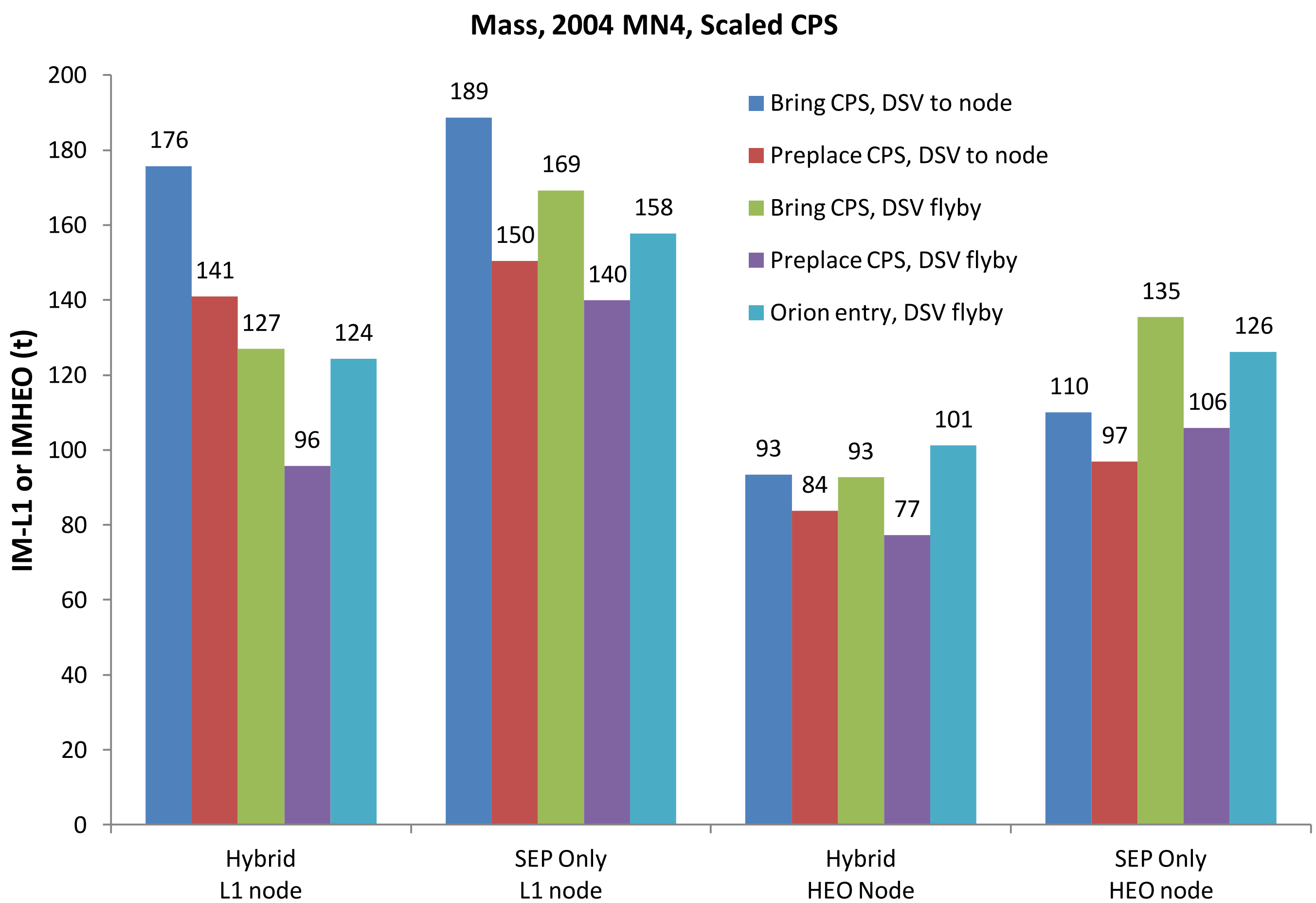


Apophis 2028 Launch
11.5 km/s Entry Speed

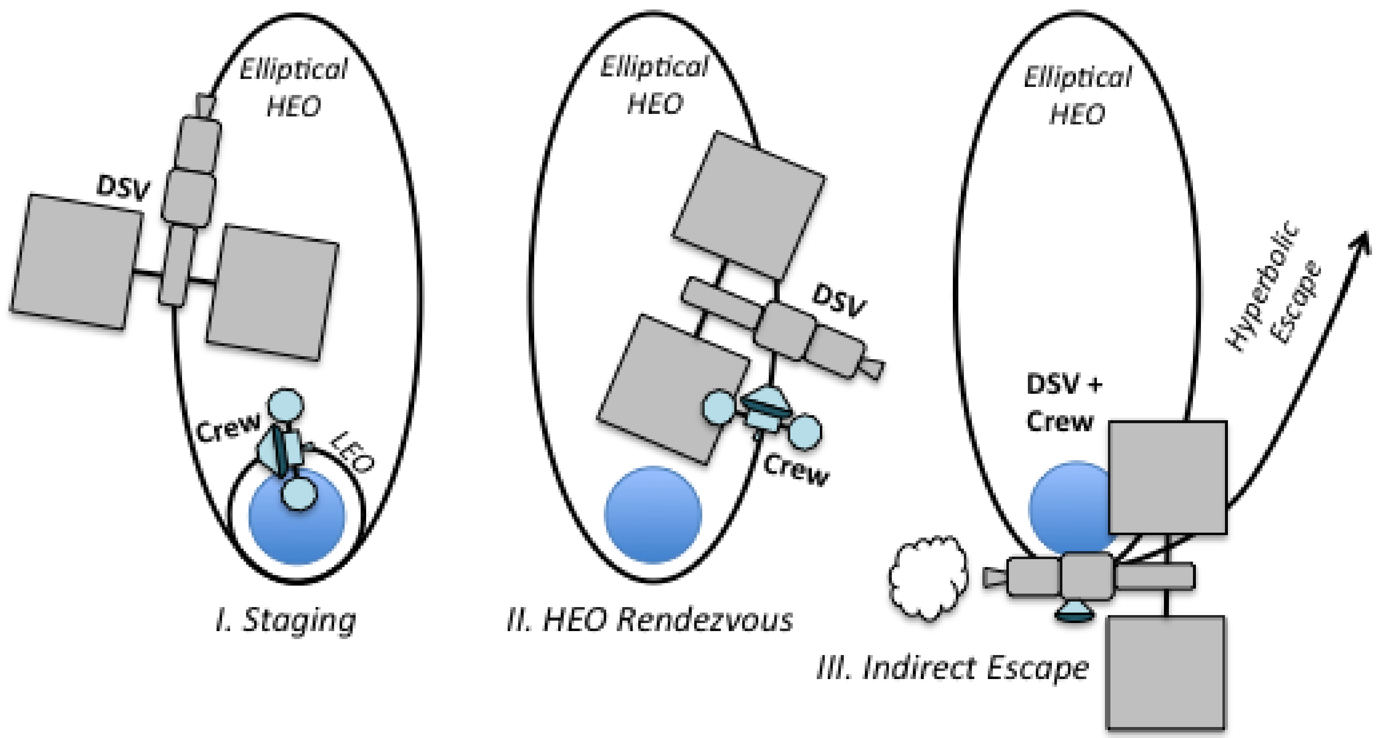




Architecture Trades Galore!



High-Earth Orbit Staging

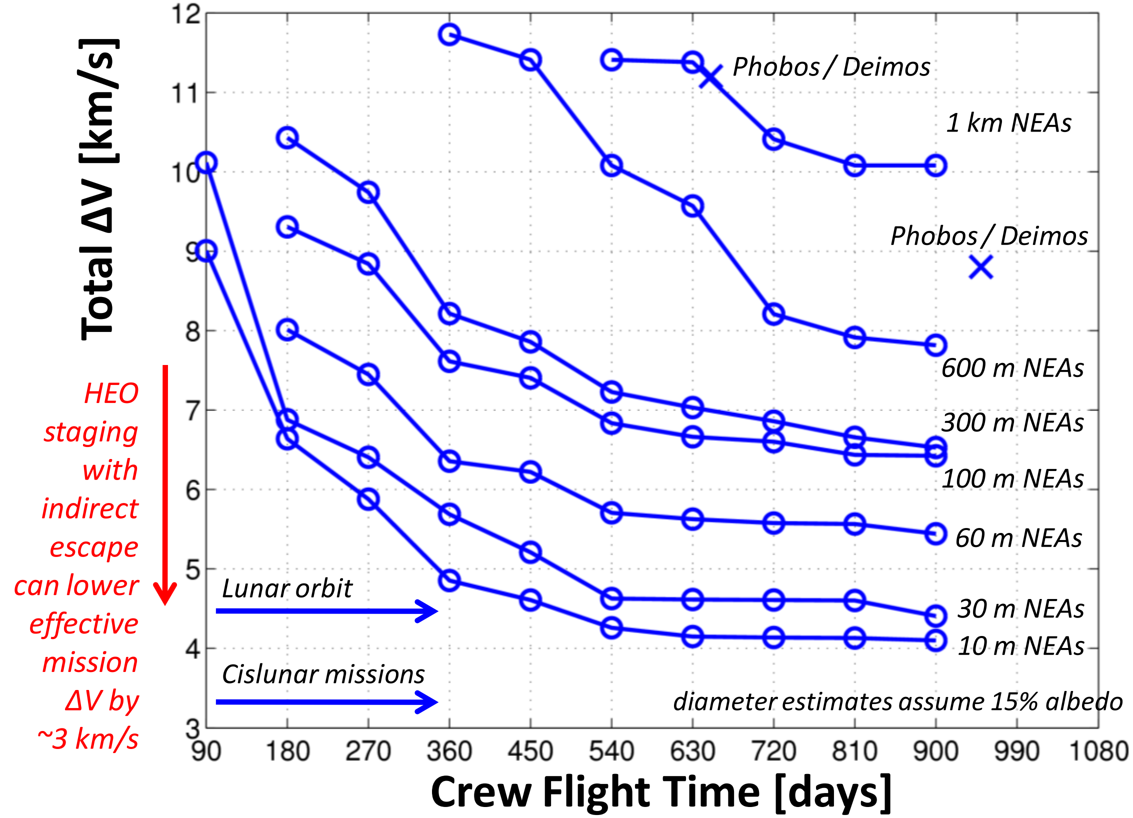


Benefits of HEO Staging Node

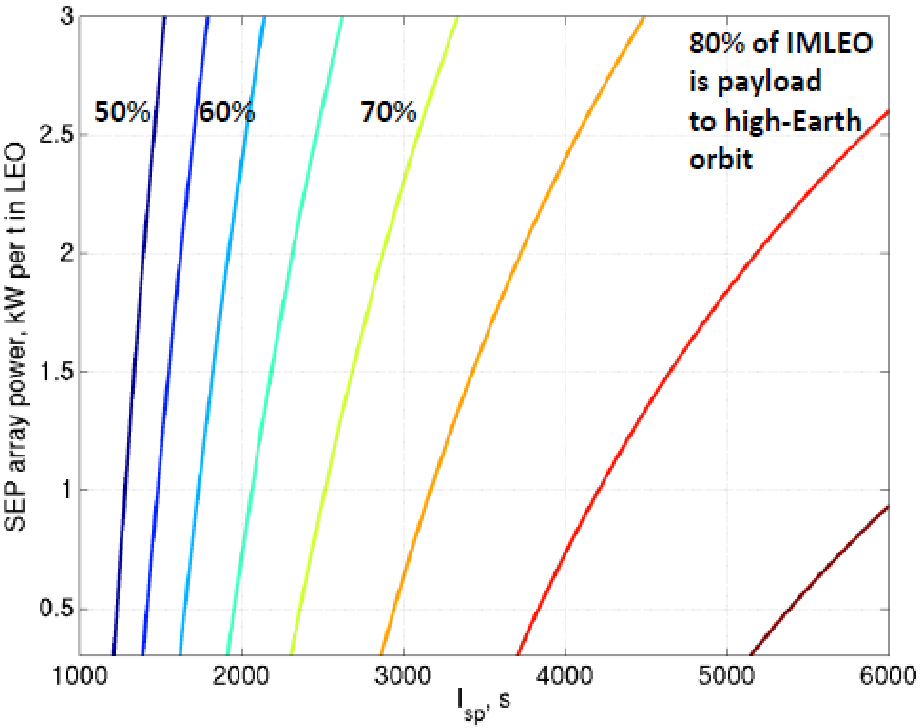
Target Accessibility (CP-Crew)

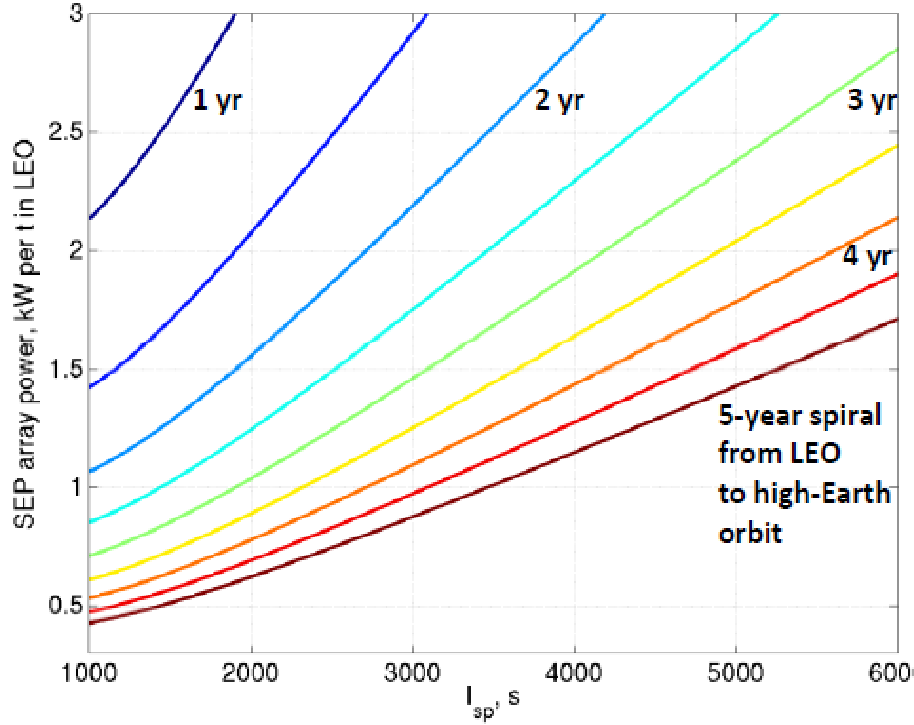
- HEO staging with indirect escape lowers the effective mission ΔV by roughly 3 km/s
- 180-day missions to 10-60 m asteroids are then available every ~2 years with an effective ΔV comparable to lunar missions
- With 1-year missions, the DSV could get to 100 m objects with similar effective ΔV to lunar missions
- Progressively larger objects are accessible as flight time and ΔV capability approach the levels needed for Phobos / Deimos and Mars surface missions

This plot shows the ΔV required to allow at least one mission every Earth-Mars synodic period (2.14 years)



SEP Spiral





Spiral Cheatsheet :

$$\eta_{jet/array} P_{array} = \frac{1}{2}\dot{m}\ gI_{sp}{}^{2}, \frac{m_0}{m_f} = e^{\Delta V / gI_{sp}},\ \Delta V = V_{circ,1} - V_{circ,2}$$

$$m_{propellant} = m_0\left(1 - e^{-\Delta V / gI_{sp}}\right), \dot{m} = \frac{2\eta P_{array}}{gI_{sp}{}^{2}}, Time = m_{prop} / \dot{m}$$

add margin (10–30 %?) for radiation and shadowing

<u>SEP inert mass</u>

30 kg/kW array

15% Xe

<u>Array to Jet efficiency</u>

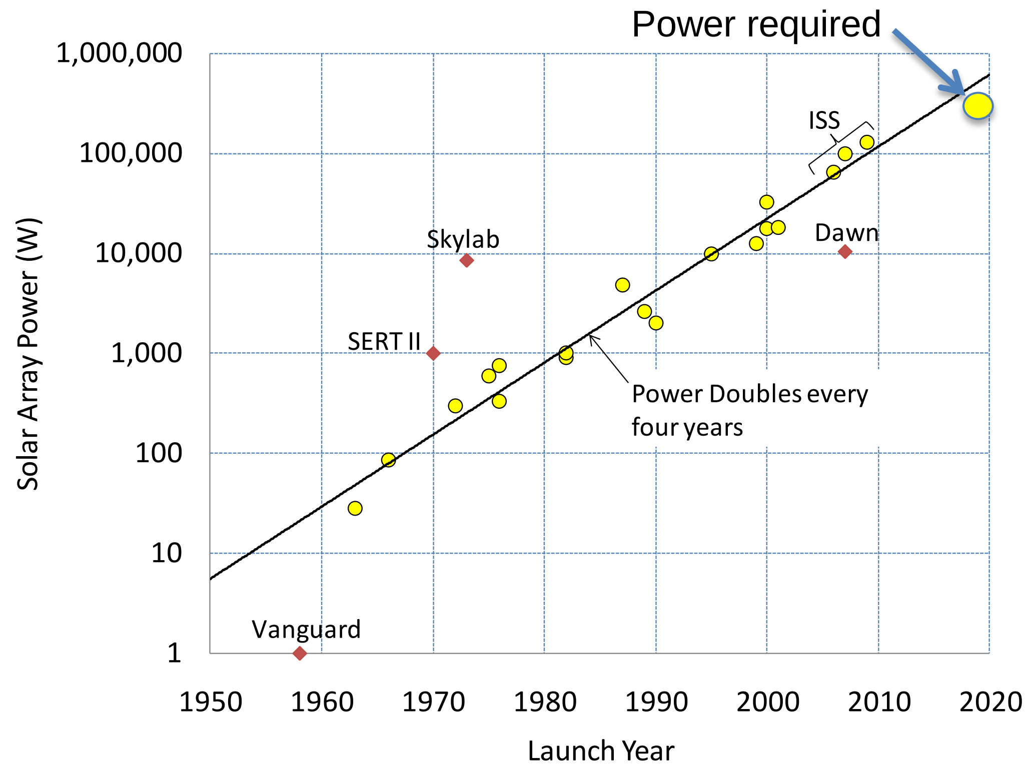
50% @ 1600 s

60% @ 2500 s

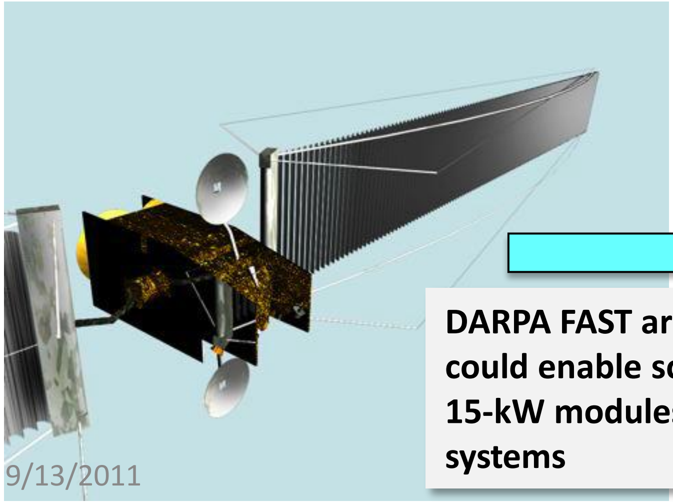
68% @ 6000 s

Solar Power Technology

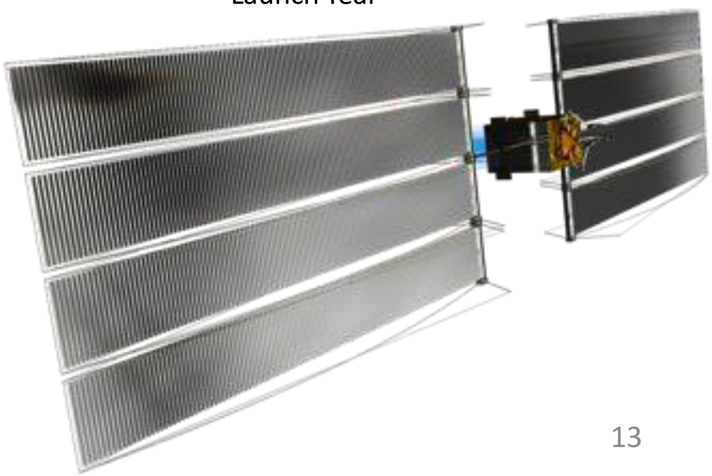
- ISS Power is ~260 kW
- Power levels of 24 kW (BOL) are now routine on commercial communication satellites
- The DARPA FAST solar array is one approach for getting to > 100 kW



Maximum solar power per spacecraft has doubled approximately every 4 years for the last 50 years.

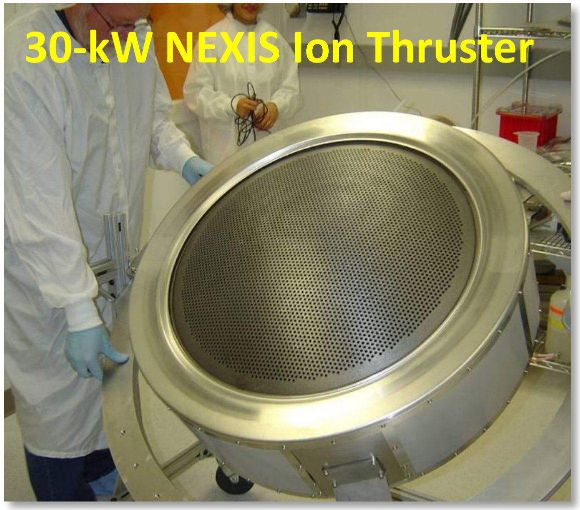


DARPA FAST array modularity could enable scaling from basic 15-kW modules to > 100 kW systems

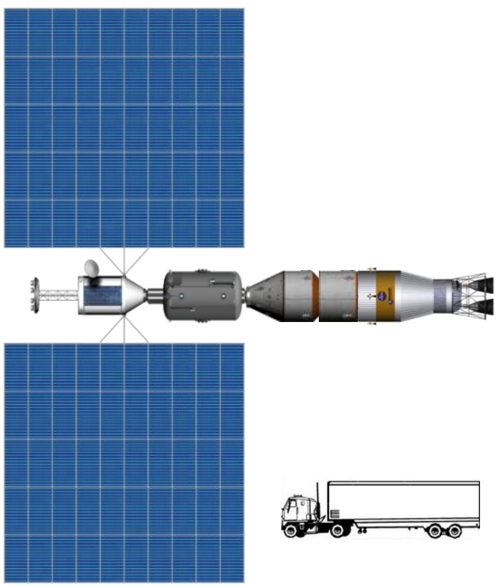


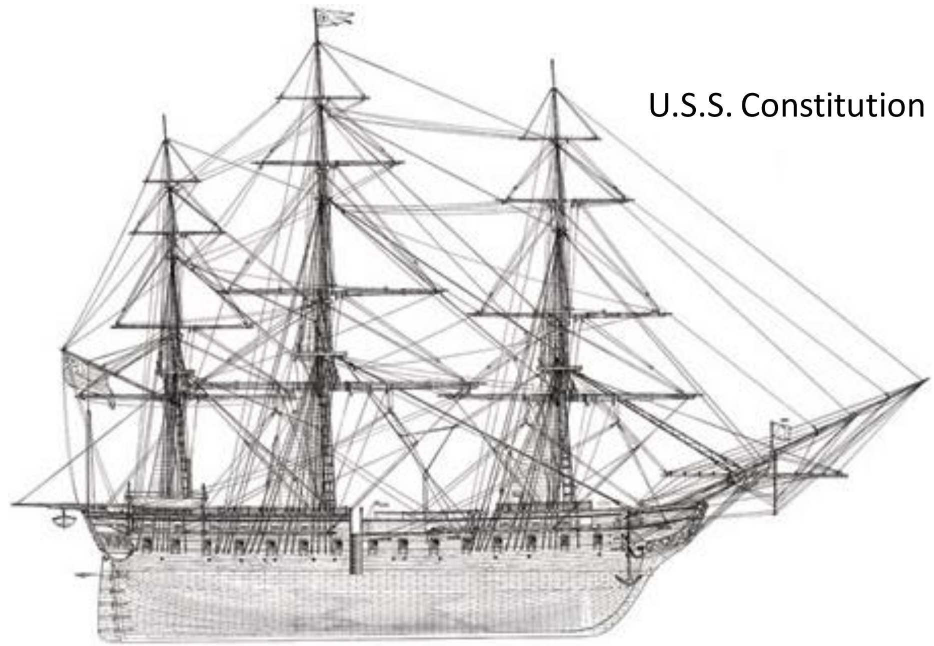
Electric Thruster Technology

- SEP stage would use clusters of thrusters at power levels of 50- to 100-kW each
- Ion and Hall thrusters are very scalable
  - The literature includes descriptions of ion thrusters with power levels from 10 W to 130 kW
  - Hall thrusters have been tested at power levels from 10's of W to 100 kW
- Ion thrusters most useful for spiraling cargo from LEO to HEO
- Hall thrusters provide long-life and high-thrust and are needed for deep space operations
- *A 50-kW, high-Isp, Hall thruster with an extremely long life could now be developed*
  - A 50kW laboratory model Hall thruster has been tested up to 72 kW
  - "Nested Hall" concepts could scale up to over 100 kW per thruster



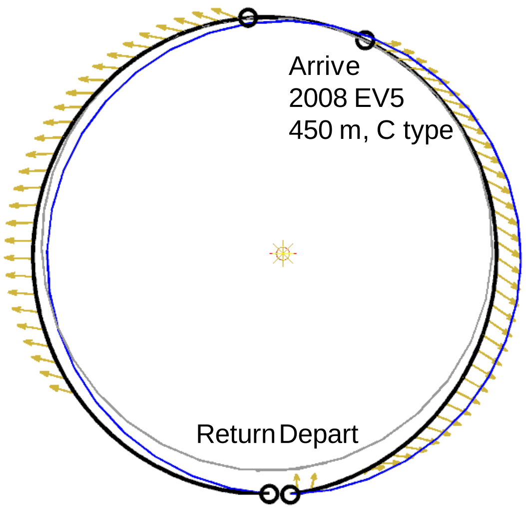
SEP Size Comparison





DSV IMLEO < 150 t, Flight time < 1 yr.

IMLEO = 99.6 t (DSV) + 35.3 t (crew), Power = 131.6 kW

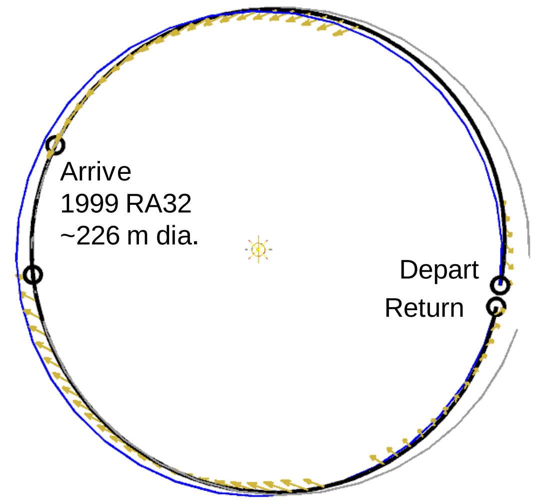


Depart: Earth
6/23/2024
time: 0 d
mass: 61.7 t
C_3: 23.6 km^2/s^2

Arrive: 2008 EV5
11/11/2024
time: 141 d
mass: 54.6 t
stay: 30 d

Return: Earth
6/18/2025
time: **360 days**
mass: 49.0 t
entry: 11.9 km/s

IMLEO = 108.0 t + 35.3 t, Power = 140.4 kW

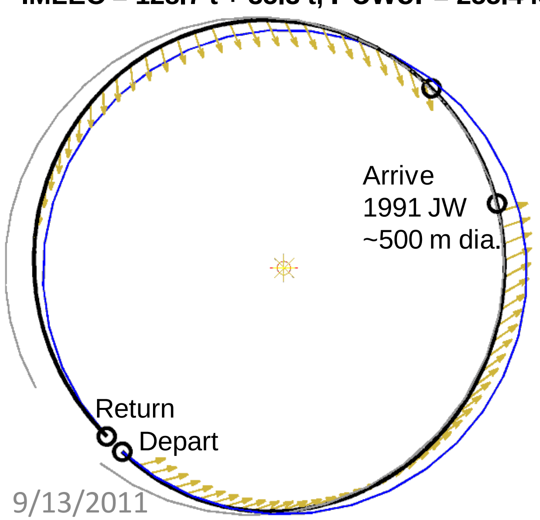


Depart: Earth
9/14/2024
time: 0 d
mass: 62.6 t
C_3: 28.0 km^2/s^2

Arr.: 1999RA32
2/27/2025
time: 166 d
mass: 56.9 t
stay: 30 d

Return: Earth
9/9/2025
time: **360 days**
mass: 49.4 t
entry: 12.0 km/s

IMLEO = 128.7 t + 35.3 t, Power = 255.4 kW

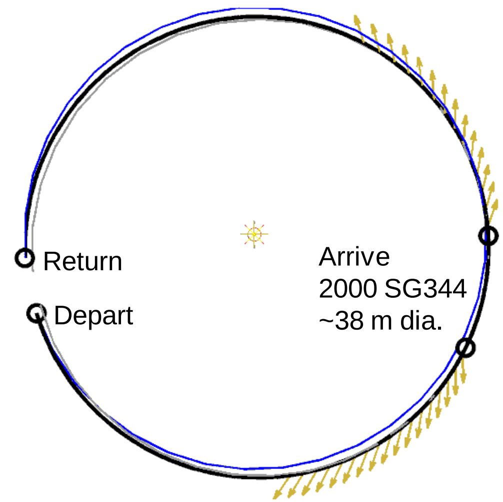


Depart: Earth
5/9/2027
time: 0 d
mass: 78.5 t
C_3: 21.7 km^2/s^2

Arrive: 1991 JW
10/1/2027
time: 144 d
mass: 65.0 t
stay: 30 d

Return: Earth
5/3/2028
time: **360 days**
mass: 54.5 t
entry: 12.0 km/s

IMLEO = 47.8 t + 35.3 t, Power = 36.8 kW



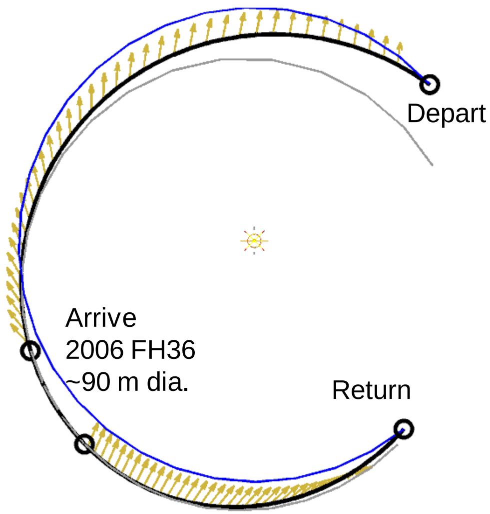
Depart: Earth
4/9/2028
time: 0 d
mass: 46.1 t
C_3: 1.1 km^2/s^2

Arrive: 2000 SG344
9/1/2028
time: 145 d
mass: 45.4 t
stay: 30 d

Return: Earth
3/26/2029
time: **351 days**
mass: 44.5 t
entry: 11.2 km/s

Flight time ≤ 270 d, SEP < 300 kW

IMLEO = 164.8 t (DSV) + 35.3 t (crew), Power = 292.7 kW

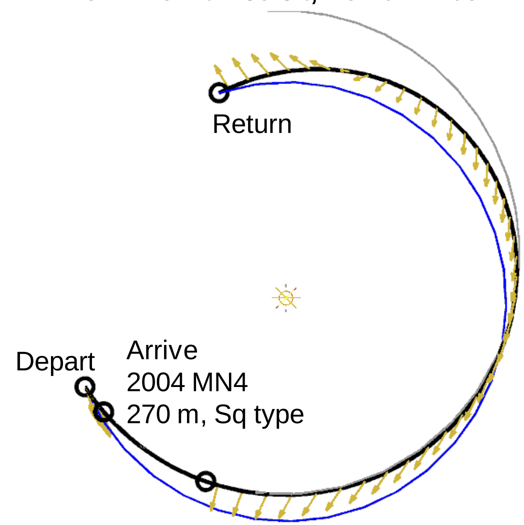


Depart: Earth
11/9/2020
time: 0 d
mass: 76.7 t
C_3: 41.5 km^2/s^2

Arrive: 2006 FH36
3/23/2021
time: 140 d
mass: 60.4 t
stay: 30 d

Return: Earth
7/31/2021
time: **270 days**
mass: 53.6 t
entry: 12.0 km/s

IMLEO = 128.7 t + 35.3 t, Power = 208.4 kW

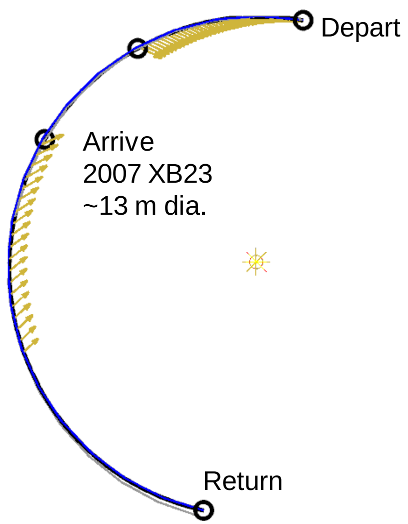


Depart: Earth
4/12/2029
time: 0 d
mass: 67.3 t
C_3: 34.4 km^2/s^2

Arrive: 2004 MN4
4/20/2029
time: 8 d
mass: 66.7 t
stay: 30 d
Return: Earth
1/8/2030
time: **270 days**
mass: 50.2 t
entry: 12.0 km/s

Potential Target Quality Improves with Exploration Capability

IMLEO = 60.9 t (DSV) + 35.3 t (crew), Power = 64.8 kW

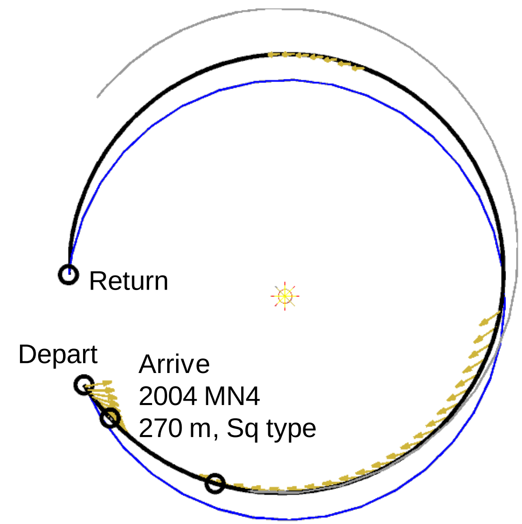


Depart: Earth
12/10/2024
time: 0 d
mass: 43.9 t
C_3: 19.2 km^2/s^2

Arrive: 2007 XB23
1/19/2025
time: 39 d
mass: 43.1 t
stay: 30 d

Return: Earth
6/8/2025
time: **180 days**
mass: 41.9 t
entry: 11.9 km/s

IMLEO = 98.8 t + 35.3 t, Power = 129.8 kW

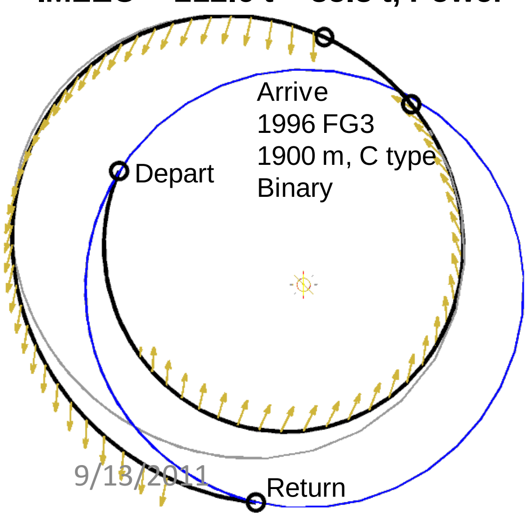


Depart: Earth
4/13/2029
time: 0 d
mass: 54.6 t
C_3: 30.0 km^2/s^2

Arrive: 2004 MN4
4/24/2029
time: 11 d
mass: 54.1 t
stay: 30 d

Return: Earth
3/15/2030
time: **336 days**
mass: 48.1 t
entry: 11.7 km/s

IMLEO = 212.6 t + 35.3 t, Power = 299.7 kW

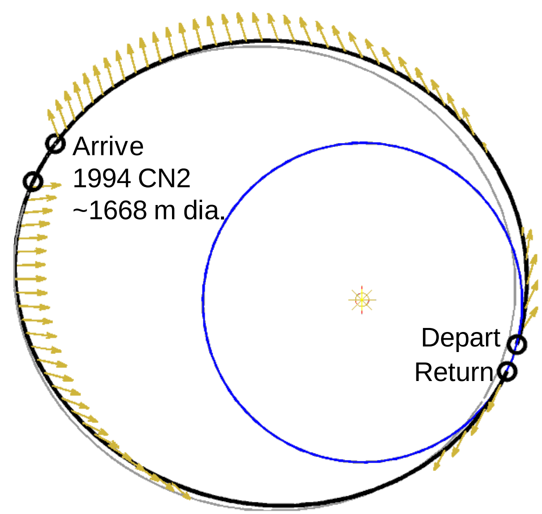


Depart: Earth
2/17/2034
time: 0 d
mass: 103.9 t
C_3: 35.5 km^2/s^2

Arrive: 1996 FG3
8/14/2034
time: 178 d
mass: 78.9 t
stay: 30 d

Return: Earth
6/9/2035
time: **477 days**
mass: 62.9 t
entry: 12.0 km/s

IMLEO = 143.9 t + 35.3 t, Power = 362.6 kW



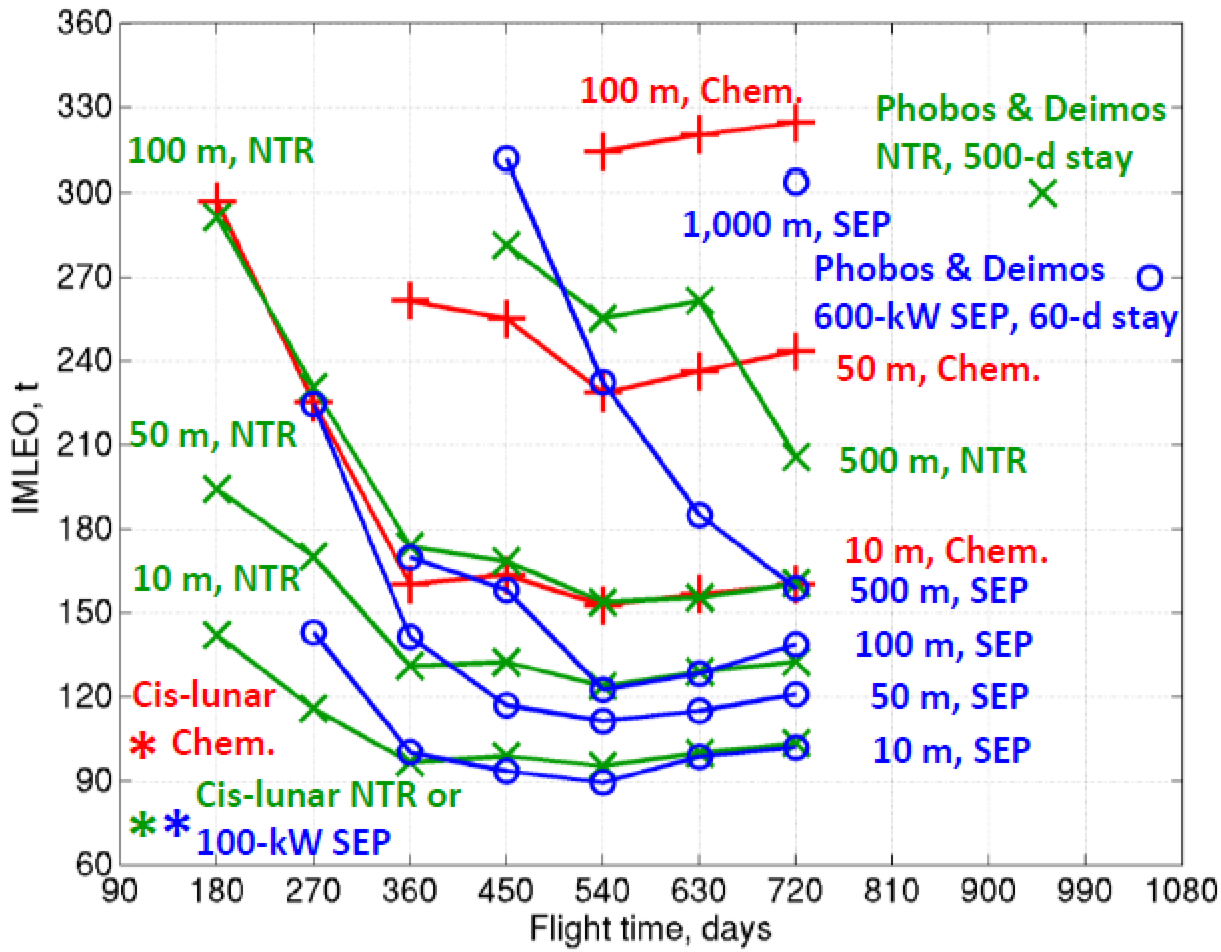
Depart: Earth
9/6/2036
time: 0 d
mass: 92.2 t
C_3: 16.4 km^2/s^2

Arrive: 1994 CN2
7/24/2037
time: 321 d
mass: 76.8 t
stay: 30 d

Return: Earth
8/27/2038
Time: **720 days**
mass: 65.3 t
entry: 12.0 km/s

Exploration Program

one mission every 2.14 years



NEA diameter
For 15% albedo

Here's a Pretty Picture

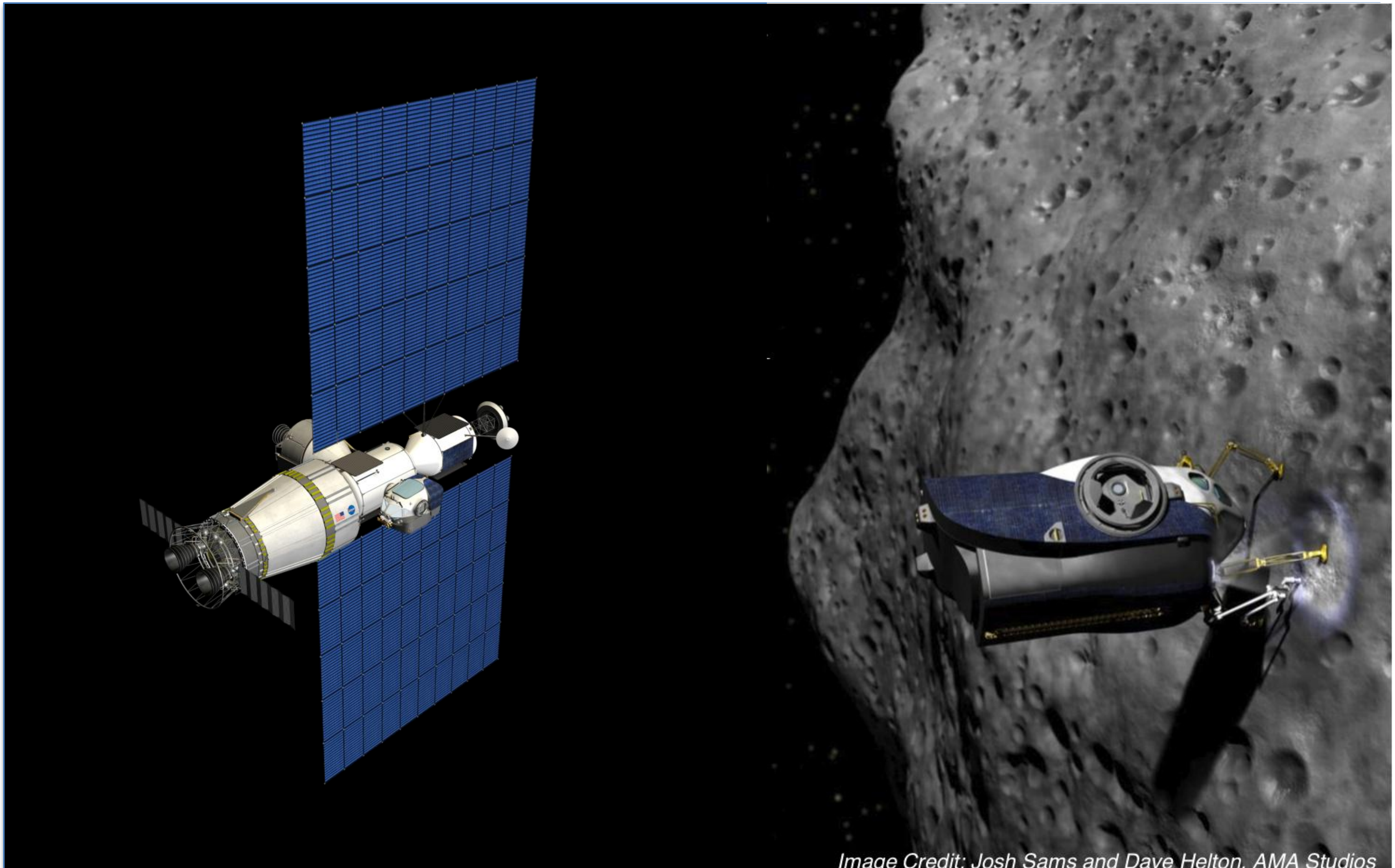


Image Credit: Josh Sams and Dave Helton, AMA Studios