ASEN 6060
ADVANCED ASTRODYNAMICS
Planetary Defense Applications
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Objectives:

- Briefly summarize one interesting ASEN 6060 application: Planetary Defense architecture design

Why Planetary Defense?

- **Near-Earth Objects (NEOs) have risk of impacting large, populated areas** causing <u>environmental, economic, and geopolitical consequences</u>
  - 1908 Tunguska event (12 megatons of TNT)
    - D = 50-60 m
  - 2013 Chelyabinsk event (0.5 megatons of TNT)
    - D = 20 m
  - 2032 - 3% chance of Asteroid YR4 2024 impact
    - D = 40-90 m

Image Credit: Armageddon Movie

- International concern
  - 2005 U.S. Congressional mandate detect, track, catalog, and characterize 90% of NEOs with $D \geq 140$m
  - Recent China planetary defense agency (response from YR4 2024)

Sun-Earth System Challenges

- A massive volume…
  - The Sun-Earth system is over 27 million times more massive than cislunar space
- Observation properties…
  - Objects are difficult for Earth-based systems to detect and track
- Chaotic dynamics…
  - Small changes in the initial state lead to large changes in overall trajectory
- Cost…
  - Planetary defense missions are expensive

Image Credit: https://www.sciencefocus.com/planet-earth/asteroid-impact-change-earths-orbit

Can we build Sun-Earth orbital architectures to effectively support planetary defense missions?

NEO Detection & Tracking

- Let's dive into one of the missions that makes up Planetary defense: NEO Detection & Tracking (D&T)
  - What are fundamental design considerations for a CR3BP, space-based satellite architecture supporting NEO D&T?
  - What orbital characteristics are expected for these satellites?

Detection & Tracking Orbit Characteristics

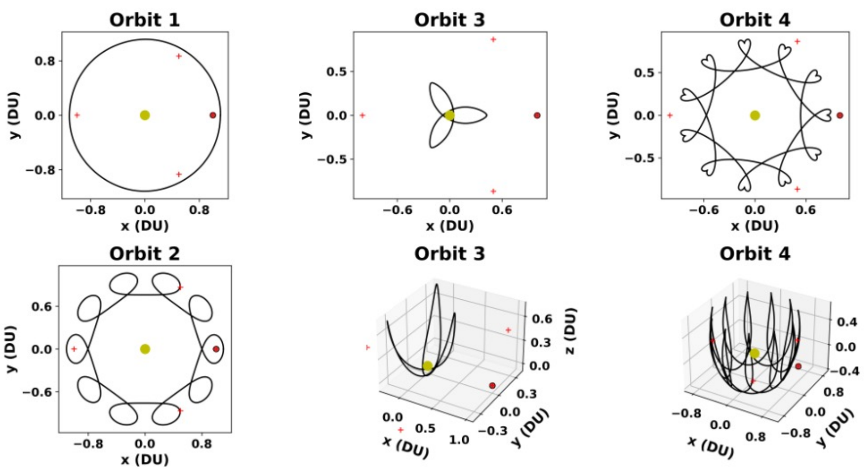


Figure 6: Proposed Sun-Venus Periodic Orbits for NEO D&T

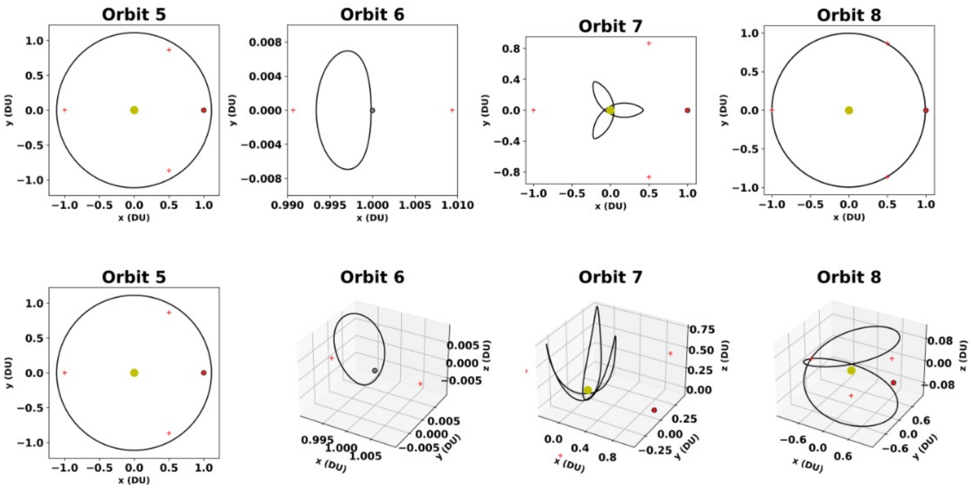


Figure 7: Proposed Sun-Earth Periodic Orbits for NEO D&T

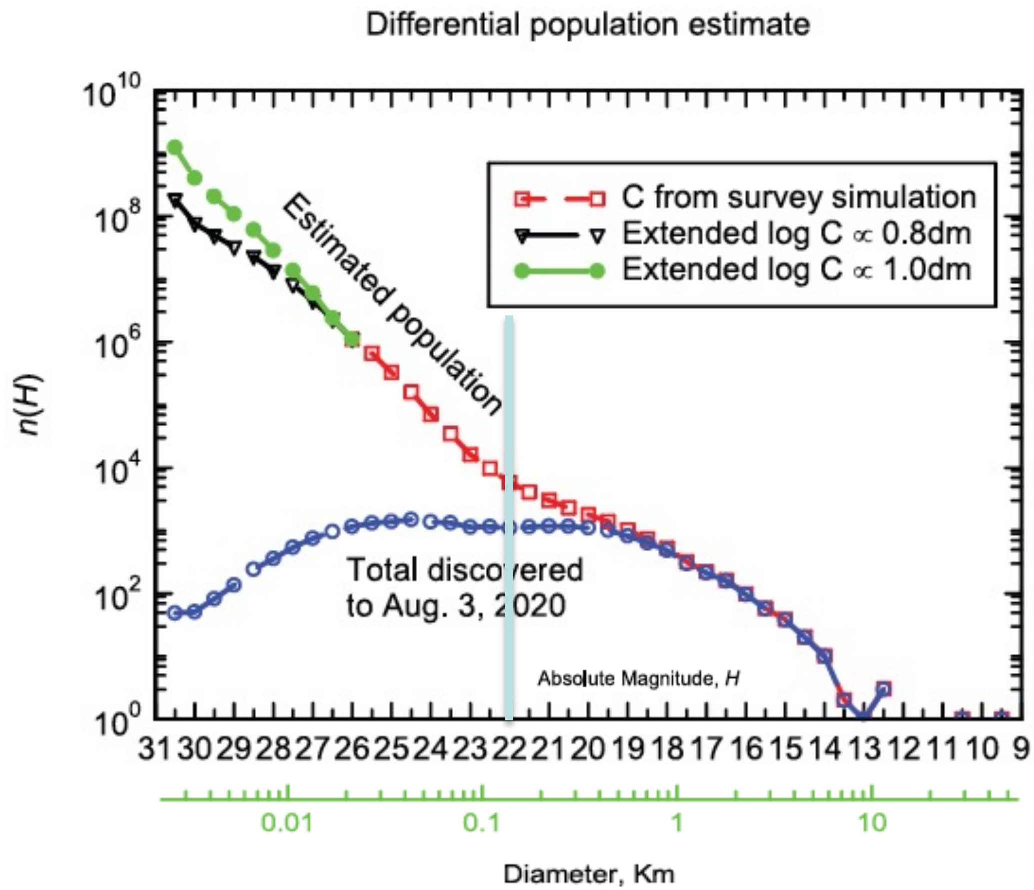
Image Credit: Wilmer, A.P., Bettinger, R.A., Holzinger, M.J. (2025) Strengthening Planetary Defense: Proposed Periodic Orbit and Policy Frameworks. *Space Policy* (under review)

- Low stability indices
  - Reduced need for frequent station-keeping burns
- Complex orbit geometries and/or out-of-plane motion
  - Diversity of observational vantage points
- Minimal risk of impacting other planets
  - Reduced sensitivity to 3rd body perturbations

Motivation

- Insights from previous work
  - Hypothesis - idealized NEO D&T CR3BP orbits have high stability, trajectories that allow for diverse observational vantage points, and/or trajectories that remain close to Earths orbit path
- Gap in discovered vs. estimated NEO population
- Ground-based detection is limited by atmospheric and day-night cycles

- For D>140m (H<22.0)
  - Current completion of ~50%
  - "Brown Act" goal of 90%



Adaptation from Harris and Chodas, 2021

Optical Observations – Sun-Earth CR3BP

- Optical observers in space require illumination from the Sun
  - Observer, space object (SO), and body relative positions inform SO visibility
- Signal-to-Noise Ratio (SNR)
  - Measure of visibility – how clearly a SO stands out against background noise
  - Higher SNR = More visible (brighter)

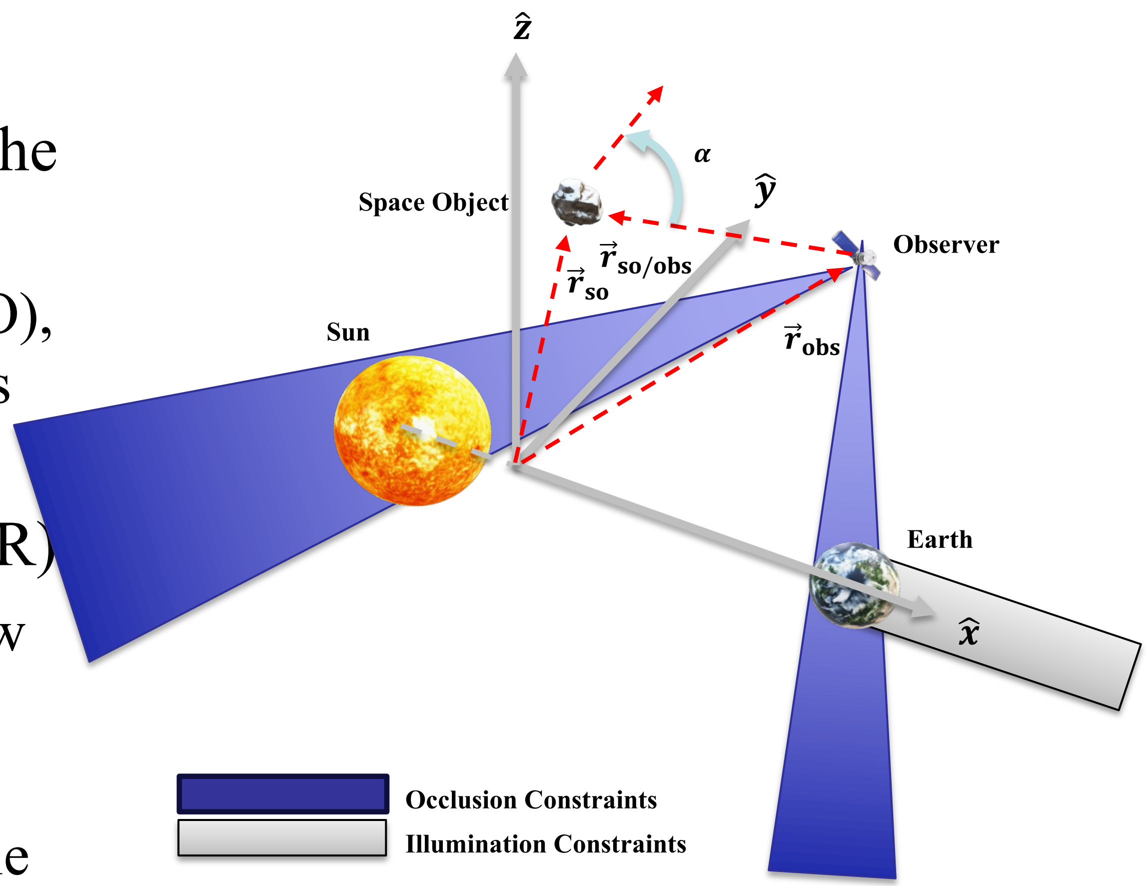


Image Credit: Wilmer, A.P., Klonowski, M., Holzinger, M.J., Bettinger, R.A. (2025) Space Situational Awareness Architecture Design for Planetary Defense using Tree Search Methods. *Journal of Astronautical Sciences* (under review)

SNR Calculations

- Function of <u>target position and physical properties</u>, <u>observer position and measurement capabilities</u>, and <u>solar illumination</u>

$$\boxed{\mathrm{SNR} = \frac{q_{\mathrm{so}}t}{\sqrt{q_{\mathrm{so}}t + m\left(1+\frac{m}{z}\right)\left[q_{\mathrm{p,dark}}t + \frac{\sigma_r^2}{n^2}\right]}}}$$

Photon Flux captured by Optics

$$q_{\mathrm{so}} = \Phi_{\mathrm{so}}\overbrace{\tau_{\mathrm{opt}}\left(\frac{\pi D^2}{4}\right)QE}^{\text{Sensor Properties}}$$

Apparent Visual Magnitude

$$M_v = V(\alpha) + 5\log\left(\left|\vec{r}_{\mathrm{so/obs}}\right|\left[\vec{r}_{\mathrm{so/sun}}\right]\right)$$

Reduced Visual Magnitude

$$V(\alpha) = \overbrace{H}^{\text{Brightness}} - 2.5\log_{10}[(1-\overbrace{G}^{\text{Change in brightness}})\overbrace{\Phi_1(\alpha) + G\Phi_2(\alpha)]}^{\text{Position}}$$

Target Photon Flux Density

$$\Phi_{so} = \Phi_0 \times 10^{-0.4M_v}$$

Solar Phase Angle

$$\alpha = \arccos\left(\frac{\vec{r}_{\mathrm{so/obs}} \cdot \vec{r}_{\mathrm{so/sun}}}{\left|\vec{r}_{\mathrm{so/obs}}\right|\left[\vec{r}_{\mathrm{so/sun}}\right]}\right)$$

Optimization Objectives

Normalized Inverse Cost ($\hat{C}_d$)

$$C_{200mm} = 1$$
$$C_{300mm} = 2.25$$
$$C_{500mm} = 6.25$$

$$C_{total} = C_{200\mathrm{mm}}N_{200\mathrm{mm}} + C_{300\mathrm{mm}}N_{300\mathrm{mm}} + C_{500\mathrm{mm}}N_{500\mathrm{mm}}$$

$$\hat{C}_d = 1 - \frac{C_{\mathrm{total}}}{C_{\mathrm{max}}}$$

Total coverage based on SNR (χ_{SNR})

$$\chi_{\mathrm{SNR},i} = \frac{N_{\mathrm{detections},i}}{N_{\mathrm{steps},i}}$$

$$\chi_{\mathrm{SNR}} = \mathrm{avg}\left(\left[\chi_{\mathrm{snr},1}, \chi_{\mathrm{snr},1}, \dots, \chi_{\mathrm{snr},N_{\mathrm{asteroids}}}\right]\right)$$

Early-warning detection time ($\hat{t}_{w,d}$)

$$\hat{t}_{w,d_i} = \frac{t_{w,d_i}}{t_{sim,i}}$$

$$\hat{t}_{w,d} = avg\left(\left[\hat{t}_{w,d_1}, \hat{t}_{w,d_2}, \dots, \hat{t}_{w,d_{N_{\mathrm{asteroids}}}}\right]\right)$$

$$\mathrm{X} = (\mathrm{Obs}_1, \mathrm{Obs}_2, \dots, \mathrm{Obs}_\mathrm{n}) \rightarrow f(\mathrm{X}) = [\hat{C}_d, \chi_{SNR}, \hat{t}_{w,d}]$$

How do we use these metrics to generate optimal planetary defense architectures?

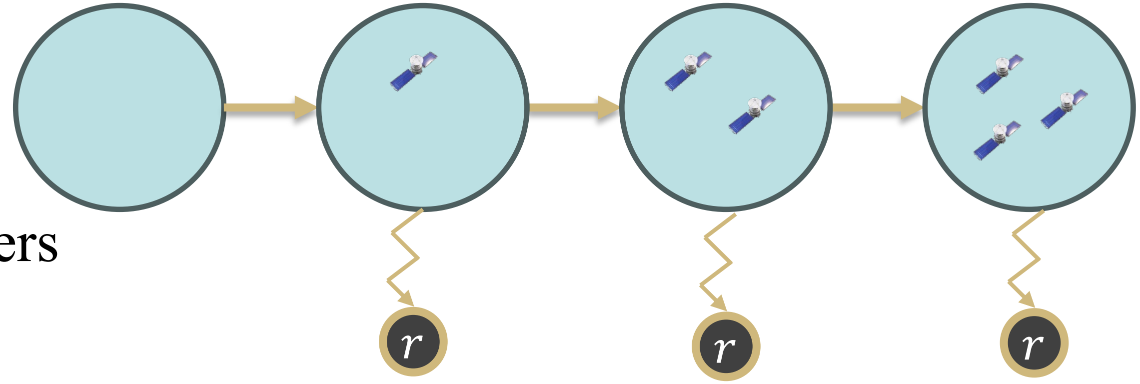
Multi-Objective Optimization Problem

- Solve the MOOPs defined as:

$$\max_{X}\left(\hat{C}_d, \chi_{SNR}\right) \qquad X = (\mathrm{Obs}_1, \mathrm{Obs}_2, \ldots, \mathrm{Obs}_n)$$

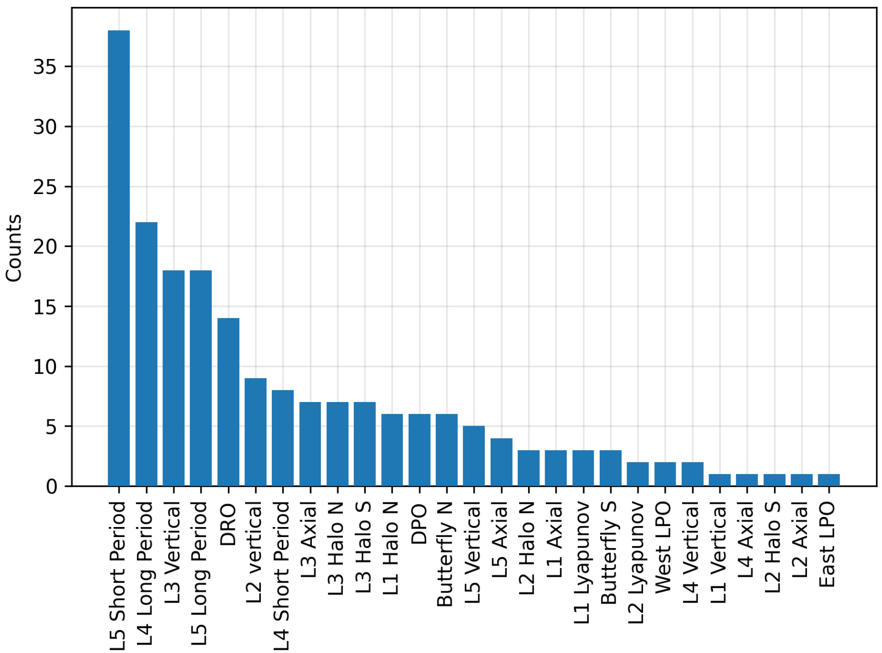
$$\max_{X}\left(\hat{C}_d, \chi_{SNR}, \hat{t}_{w,d}\right)$$

- We may define this as a Markov Decision Process (MDP)
  - State – Planetary defense architecture
  - Actions – Adding observers
  - Rewards – Vector of objective functions



Solving… Pareto-Optimal Architectures

Two-Objective



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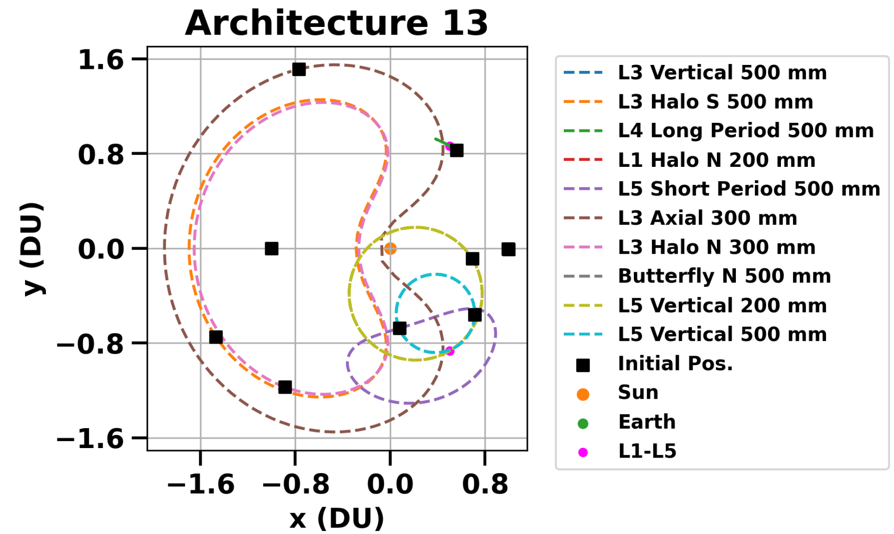
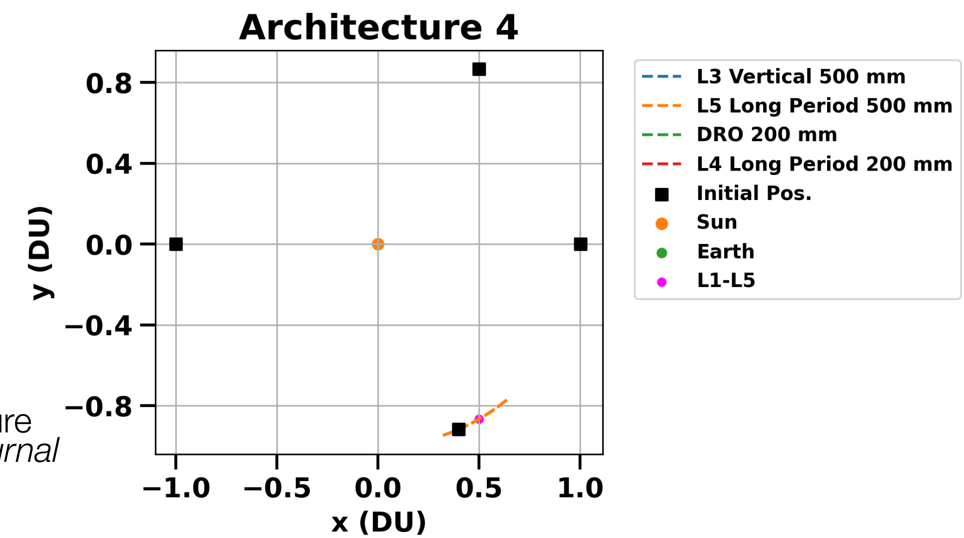
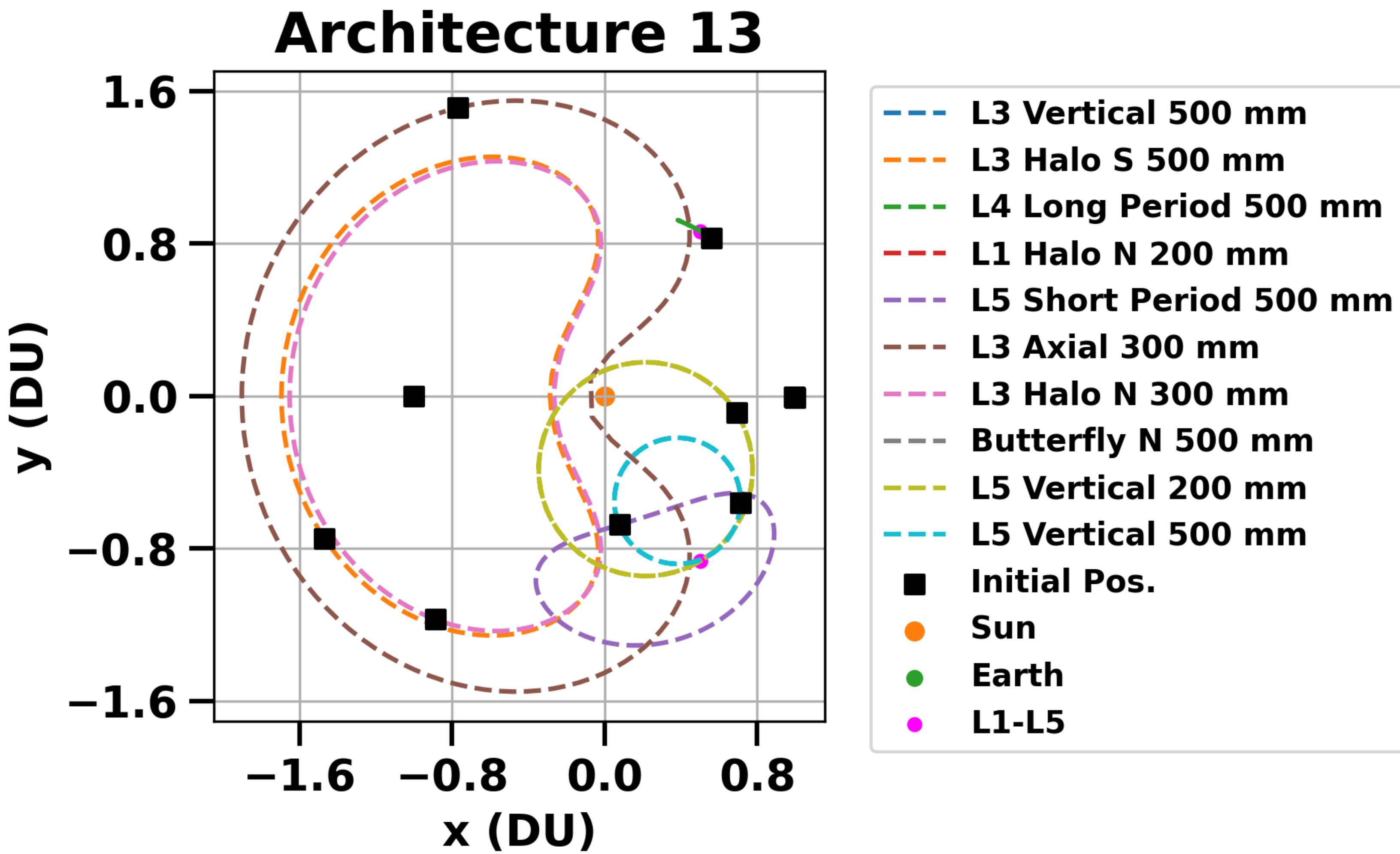
$\chi_{SNR} = 15.50\%$



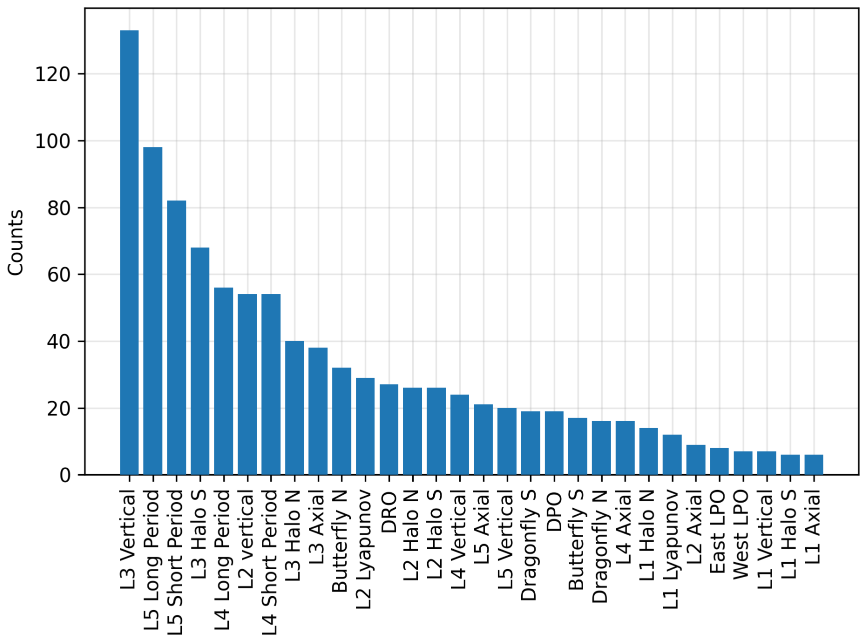


Solving… Pareto-Optimal Architectures

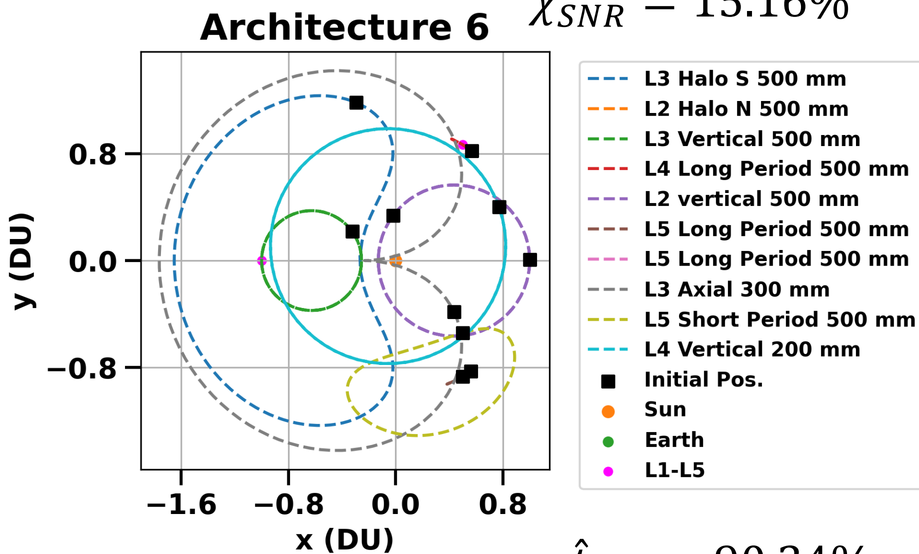


Solving… Pareto-Optimal Architectures

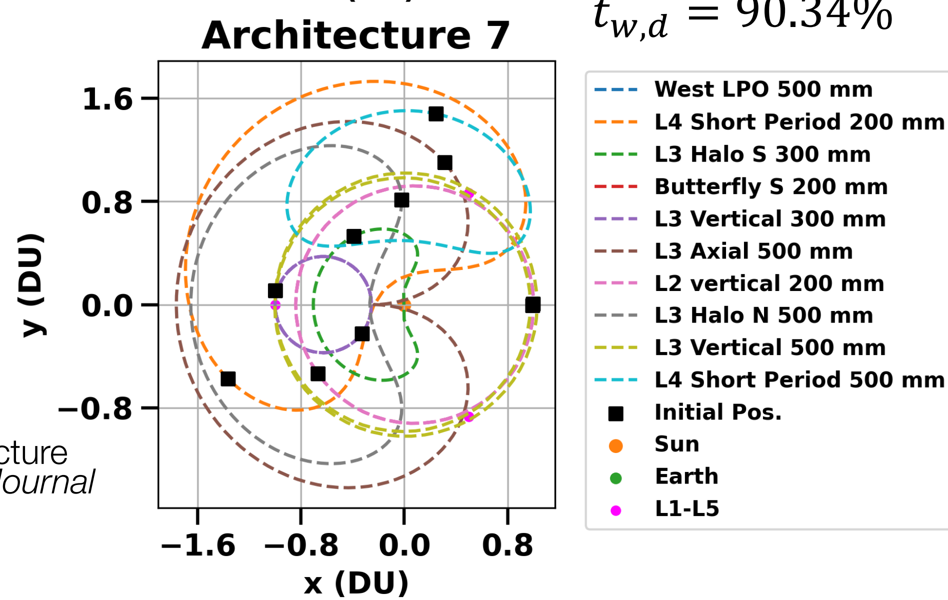
Three-Objective



$\chi_{SNR} = 15.16\%$



$\hat{t}_{w,d} = 90.34\%$



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Ideal Characteristics for NEO D&T

- NEO D&T orbital characteristics:
  - Out-of-plane motion
  - Large trajectory volumes
  - Architectures consist of observers well dispersed throughout system
- The top orbits included within architectures:
  - L4/L5 Short- & Long- period, L3 Vertical, L3 Halo, DRO

Questions?