Orbital Design Tools and Scheduling Techniques for Optimizing Space Science and Exoplanet-Finding Missions

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Dissertation Defense
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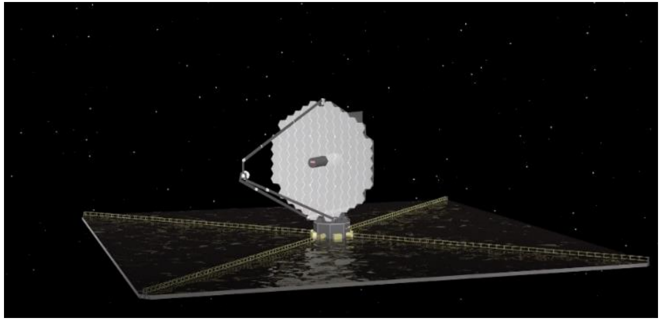
Cornell University (Zoom)

Space Imaging Missions Near L_2

- Space telescope demand and requirements are increasing
  - Advantages to observing from space (L_2)

- Goals of characterizing atmospheres of Earth-like exoplanets!

Roman Space Telescope (~2025)



LUVOIR (proposed)

Costs for Spacecraft Science Missions

Main obstacles are time and fuel costs:

Time

- Instruments deteriorate
- Viewing conditions change with movement of Earth, Sun, Moon, telescope

Fuel

- Limited fuel on-board for maneuvers
- Minimize Δv subject to time constraints

Thesis Contributions

- Develop **Fuel** and **Time** optimal orbital tools and techniques for:

    1. **Delivery of space telescopes to final orbit**

    2. **Efficient maneuvers for space telescope operations or observations**

Publications

Journal Publications

Soto, G., Savransky, D., Garrett, D., Delacroix, C. (2019) "Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules." *Journal of Guidance, Control, and Dynamics*

Soto, G., Savransky, D., Morgan, R., (2020) "Analytical Model for Starshade Formation Flying with Applications to Exoplanet Direct Imaging Observation Scheduling." *Journal of Astronomical Telescopes, Instruments, and Systems – Starshade Special Section* [submitted]

Technical Reports

Morgan, R., Savransky, D., Stark, C., Nielsen, E., Cady, E., Dula, W., Dulz, S., Horning, A., Mamajek, E., Mennesson, B., Newman, P., Plavchan, P., Robinson, T., Ruane, G., Sirbu, D., **Soto, G**., Turmon, M., Turnbull, M. (2019) The Standard Definitions and Evaluation Team Final Report: A Common Comparison of Exoplanet Yield; NASA Jet Propulsion Laboratory

Conference Papers

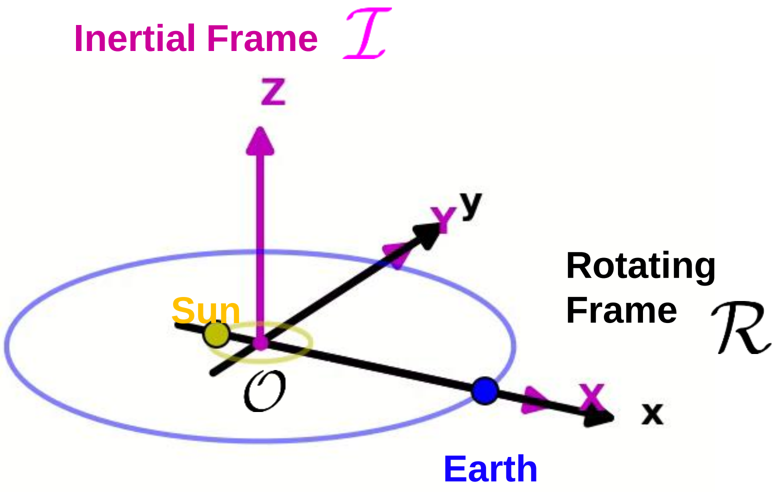
Soto, G., Lloyd, J., Savransky, D., Grogan, K., Sinha, A. (2017) "Optimization of high-inclination orbits using planetary flybys for a zodiacal light-imaging mission." *SPIE Proc. Techniques and Instrumentation for Detection of Exoplanets VIII*

Soto, G., Sinha, A., Savransky, D., Delacroix, C., Garrett, D. (2017) "Starshade orbital maneuver study for WFIRST." *SPIE Proc. Techniques and Instrumentation for Detection of Exoplanets VIII*

Soto, G., Savransky, D., Garrett, D., Delacroix, C. (2018) "Optimal starshade observation scheduling." *SPIE Astronomical Telescopes + Instrumentation*

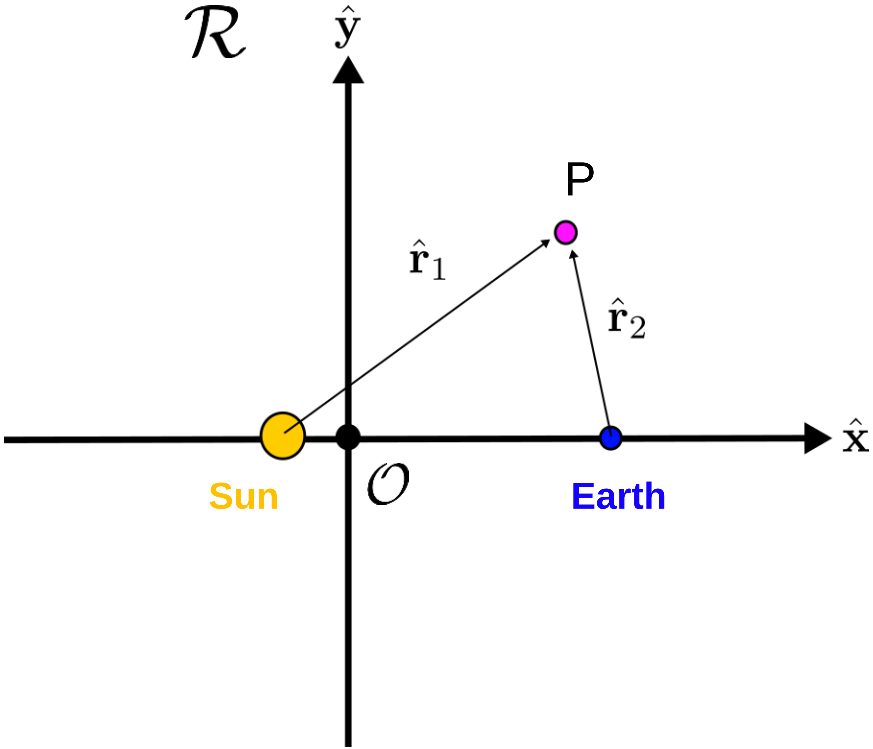
Soto, G., Gustafson, E., Savransky, D., Shapiro, J., Keithly, D. (2019) "Solar Sail Trajectories and Orbit Phasing of Modular Spacecraft for Segmented Telescope Assembly About Sun-Earth L2" *Proceedings of the 2019 AAS/AIAA Astrodynamics Specialists Meeting*; AAS 19-774.

Frame Definitions



- Inertial Frame $\mathcal{I}$
  - Coordinates (X, Y, Z) from $\mathcal{O}$
  - Basis vectors $\hat{\mathbf{X}}, \hat{\mathbf{Y}}, \hat{\mathbf{Z}}$
- Rotating Frame $\mathcal{R}$
  - Coordinates (x, y, z) from $\mathcal{O}$
  - Basis vectors $\hat{\mathbf{x}}, \hat{\mathbf{y}}, \hat{\mathbf{z}}$
- Dynamics in rotating frame are called the Circular Restricted Three Body Problem

Properties of the CR3BP



Equations of Motion

$$\mathbf{f} = {}^{\mathcal{R}}\frac{d}{dt}\begin{bmatrix} \mathbf{r}_{P/\mathcal{O}} \\ {}^{\mathcal{R}}\mathbf{v}_{P/\mathcal{O}} \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ 2\dot{y} + \frac{\partial \Omega}{\partial x} \\ -2\dot{x} + \frac{\partial \Omega}{\partial y} \\ \frac{\partial \Omega}{\partial z} \end{bmatrix}$$

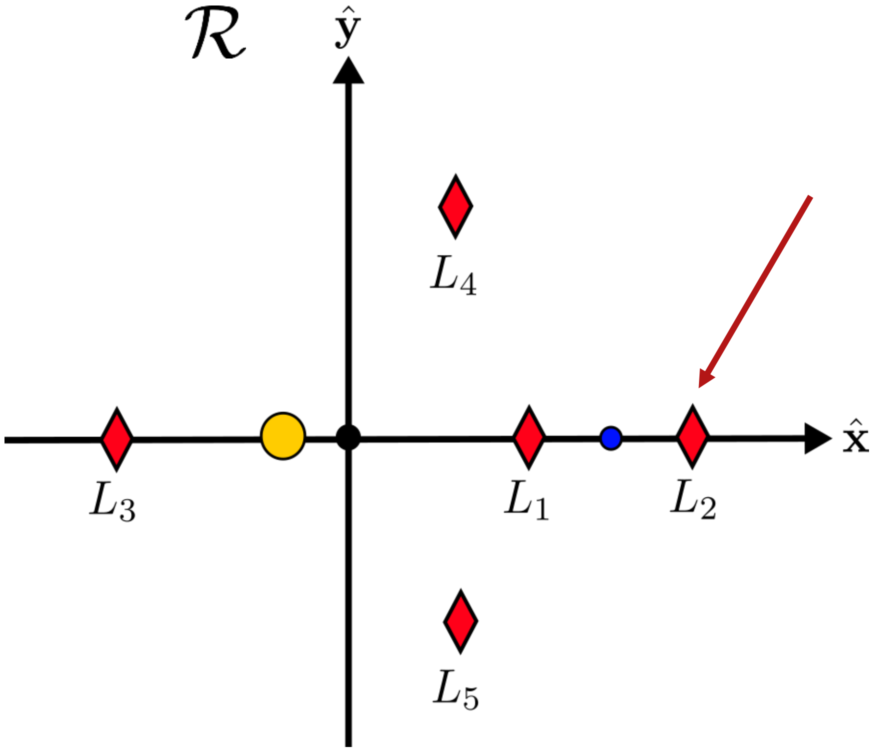
Effective Potential “Energy”

$$\Omega(x,y,z) = \frac{1}{2}(x^2 + y^2) + \frac{1-\mu}{r_1} + \frac{\mu}{r_2},$$
$$r_1 = \sqrt{(\mu - x)^2 + y^2 + z^2},$$
$$r_2 = \sqrt{(1 - \mu - x)^2 + y^2 + z^2}$$

Primary Mass Ratio

$$\mu = \frac{m_2}{m_1 + m_2}$$

Properties of the CR3BP

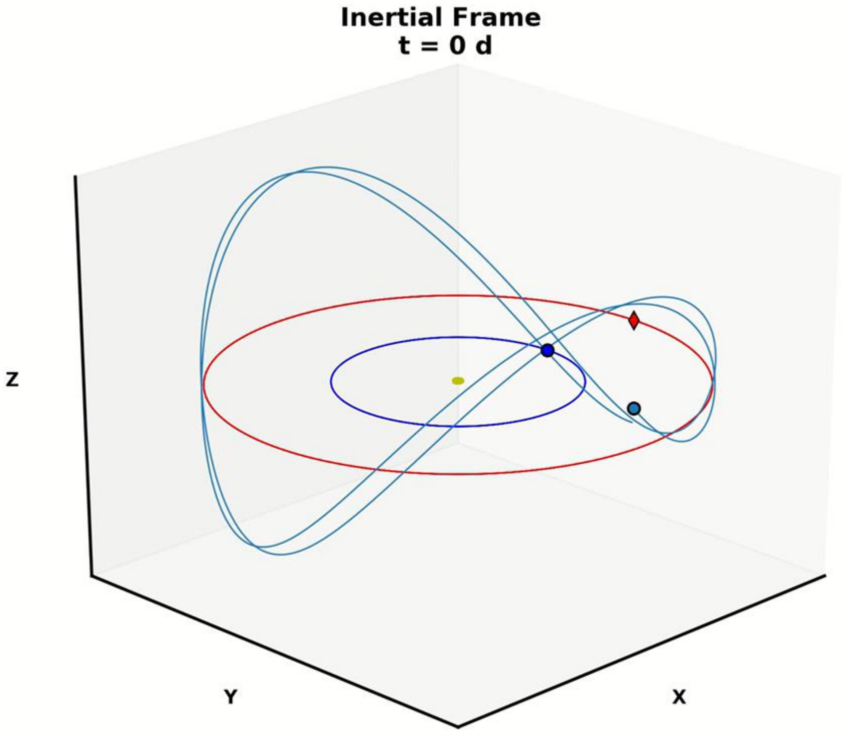


- Jacobi Integral ("Energy" Integral of Motion)

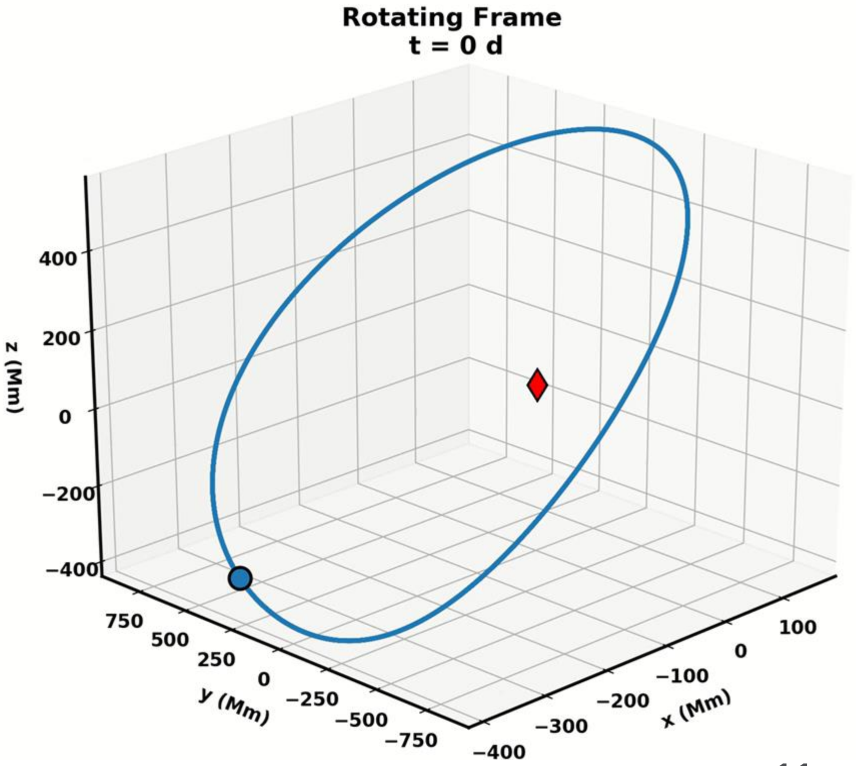
$$C = -(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) + 2\Omega$$

- Five equilibrium (Lagrange) points
  - L_2 is advantageous for observations
- Near Lagrange points, we find:
  - Periodic/Quasi-periodic orbits
  - Invariant energy manifolds

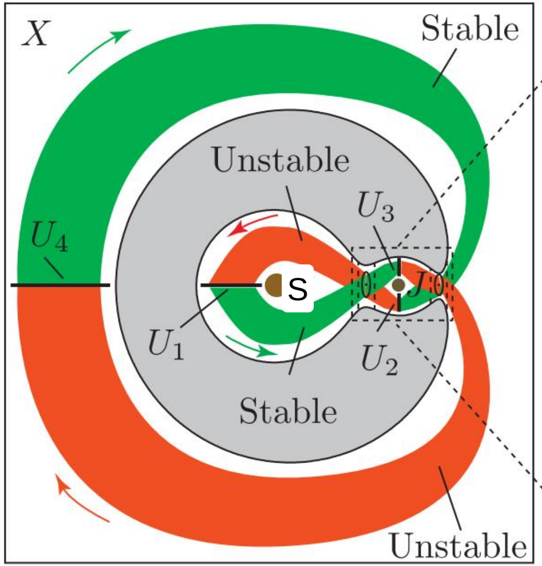
Periodic Orbits in the CR3BP

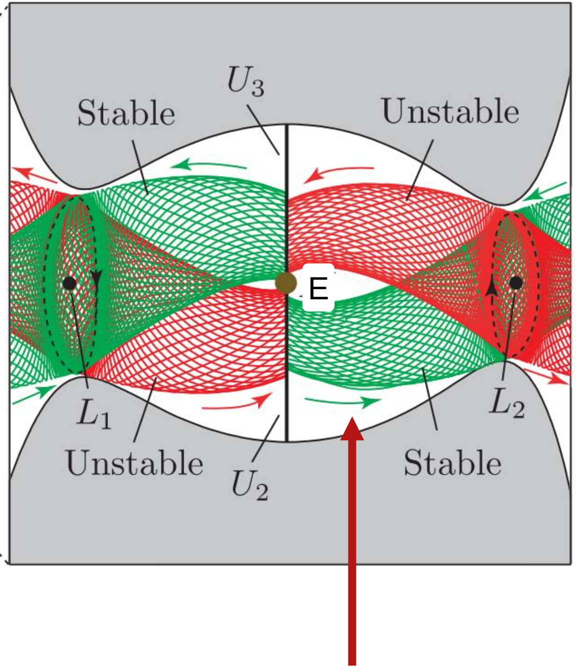


(Not to scale)



Invariant Manifolds





- State transition matrix[1] found for periodic orbit

$$\dot{\mathbf{\Phi}}(t, t_0) = \frac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}} \mathbf{\Phi}(t, t_0)$$

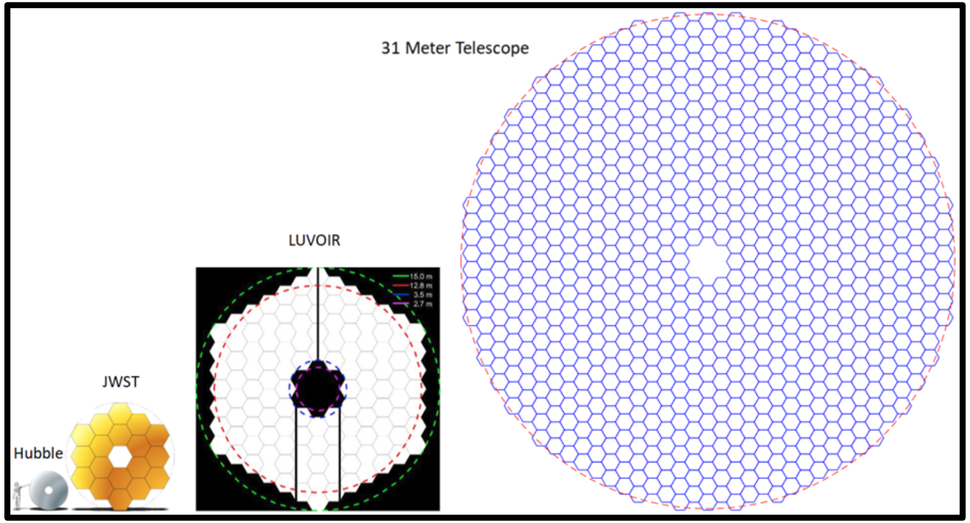
- Monodromy Matrix

$$\mathbf{\Phi}(T, t_0) \begin{cases} \lambda_1 > 1 & \text{Unstable} \\ \lambda_2 = \dfrac{1}{\lambda_1} & \text{Stable} \\ \lambda_3 = \lambda_4 = 1 \\ \lambda_5 = \bar{\lambda}_6 \ , \ |\lambda_5| = 1. \end{cases}$$

[1]W. S. Koon, M. W. Lo, J. E. Marsden, and S. D. Ross, Dynamical Systems, the Three-Body Problem and Space Mission Design (2011)

Motivation

- LUVOIR and future space telescopes require bigger primary mirrors
- Easier to segment the mirrors
  - Manufacturing costs reduced if produced in bulk
- 31m segmented primary mirror would need 840 mirrors[3]



[3]J. Shapiro, D. Keithly, G. Soto, D. Savransky, and E. Gustafson, "Optical design of a modular segmented telescope," Proc. SPIE, Vol. 11116-12, 2019

Ideal Solar Sail Model

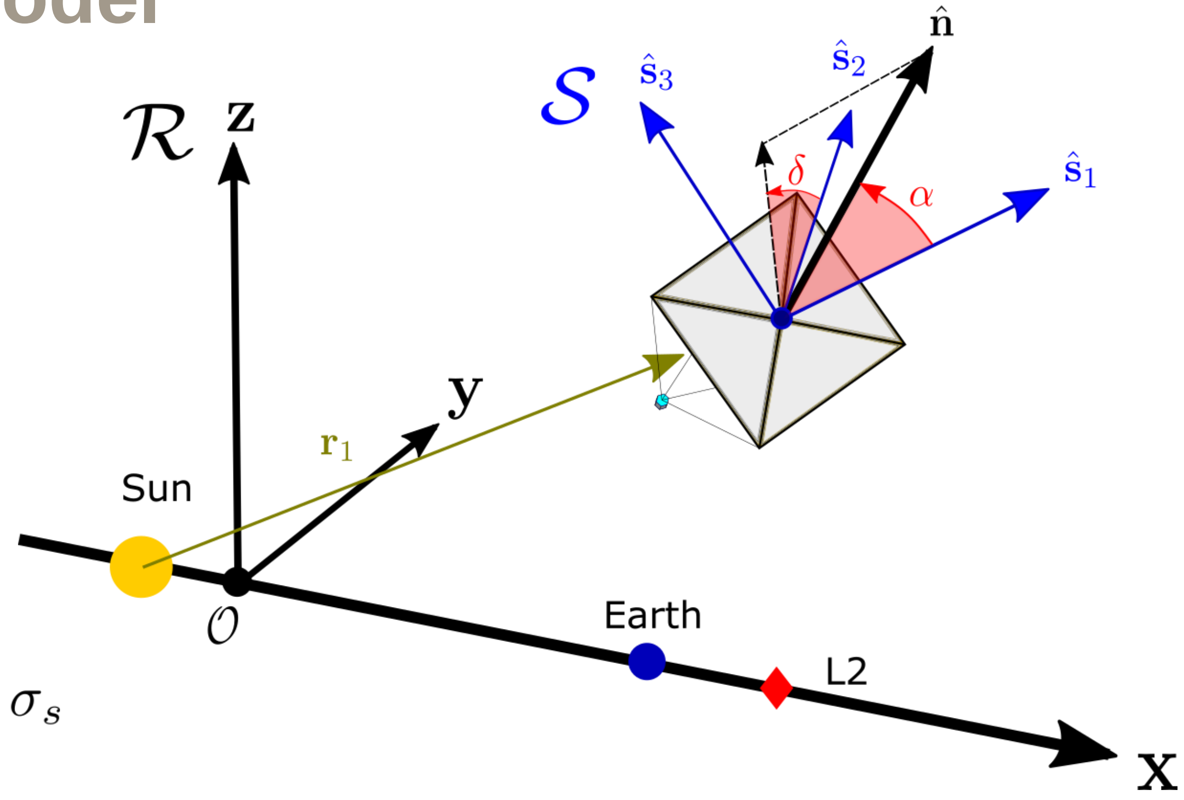
Solar Sail acceleration term[2]

$$\mathbf{a}_S = \beta \frac{1-\mu}{r_1^2} (\hat{\mathbf{r}}_1 \cdot \hat{\mathbf{n}})^2 \hat{\mathbf{n}}$$

Solar Sail performance factor

$$\beta = \frac{L_\odot}{2\pi G M_\odot \sigma} = \frac{\sigma^*}{\sigma}$$

$$\sigma = \frac{m_T}{A_s} = \frac{m_p + m_s}{A_s} = \frac{m_p}{A_s} + \sigma_s$$



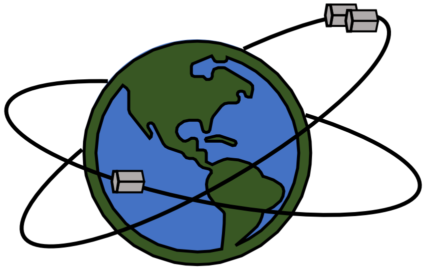
[2]C. McInnes, Solar Sailing: Technology, Dynamics and Mission Applications. Springer-Praxis Books, 1999.

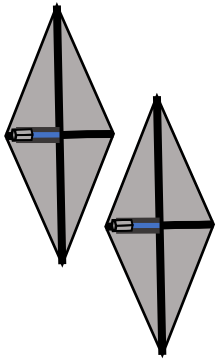
Mission Concept

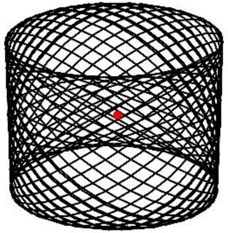
Modular spacecraft start on Earth orbits with mirror as payload.

Solar sails unfurl and propel the mirrors to L2.

Spacecraft are assembled on a Lissajous orbit.

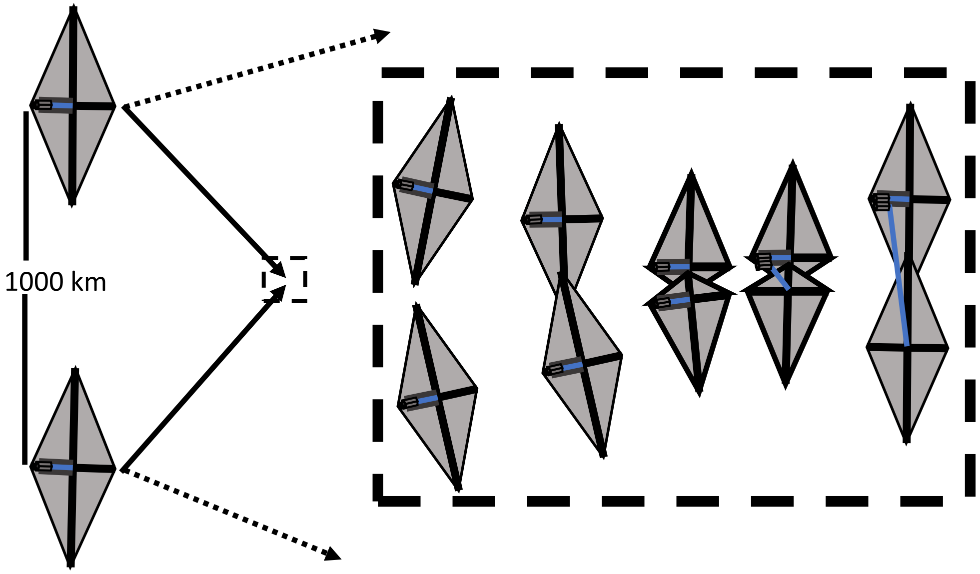


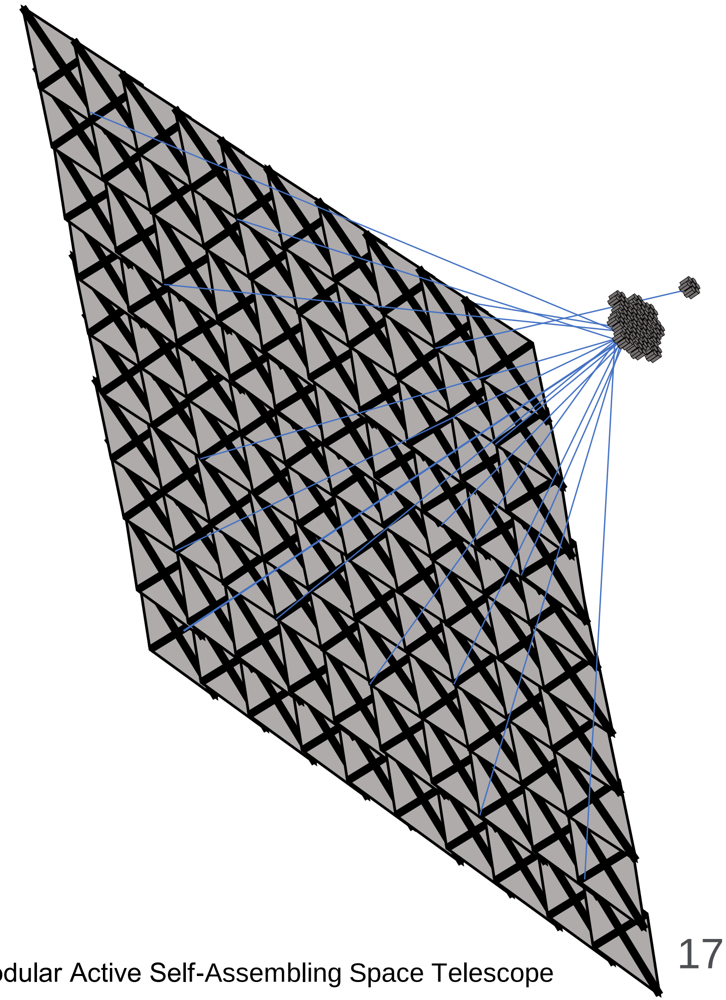




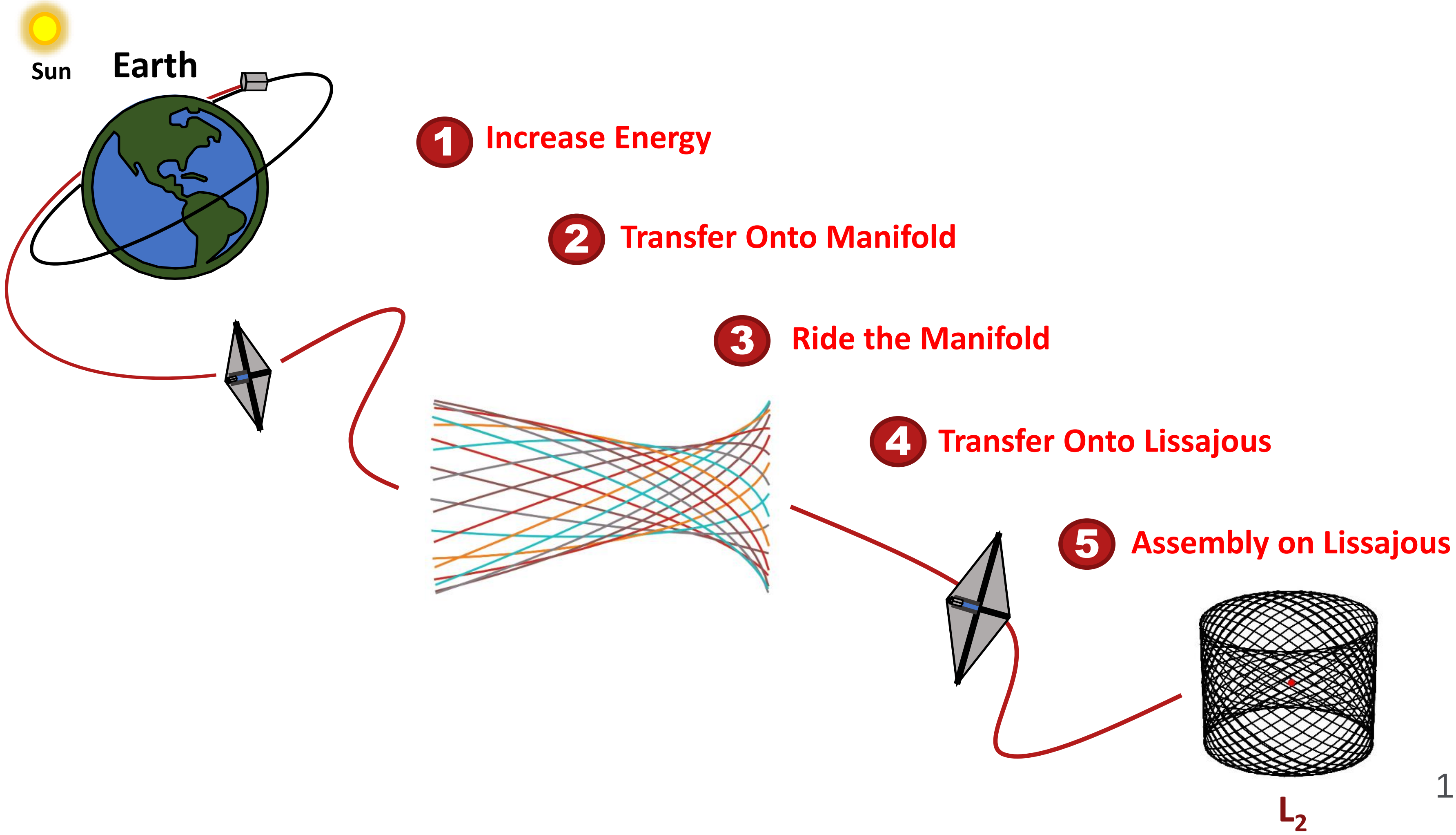
[4]D. Savransky, D. Keithly, J. Shapiro, G. Soto, E. Gustafson, K. Liu, C. Della Santina “Modular Active Self-Assembling Space Telescope Swarms,” NIAC Final Report (2019)

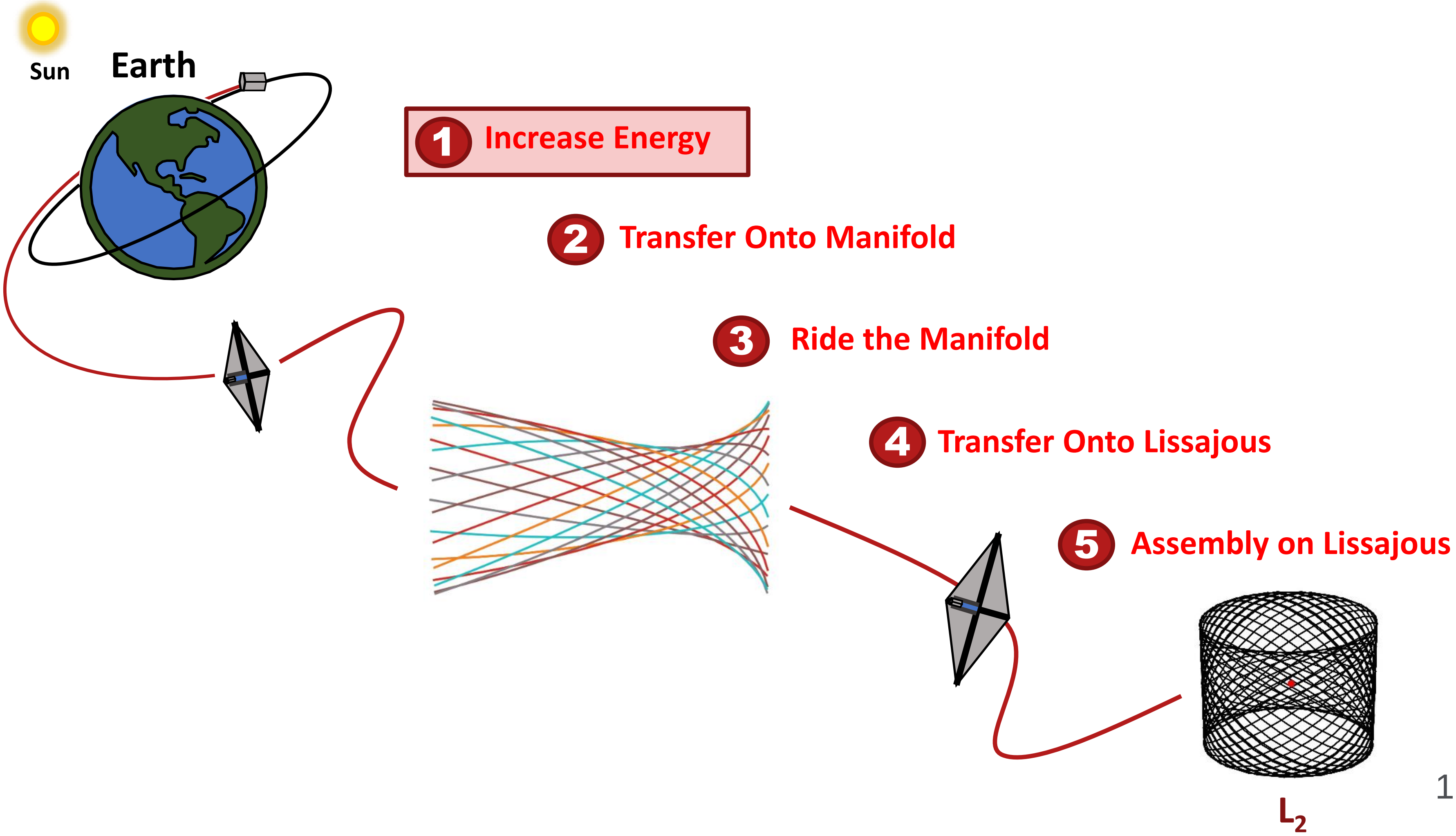
Mission Concept





[4]D. Savransky, D. Keithly, J. Shapiro, G. Soto, E. Gustafson, K. Liu, C. Della Santina “Modular Active Self-Assembling Space Telescope Swarms,” NIAC Final Report (2019)


Sun
Earth
1 Increase Energy
2 Transfer Onto Manifold
3 Ride the Manifold
4 Transfer Onto Lissajous
5 Assembly on Lissajous
L_2


Sun
Earth
1 Increase Energy
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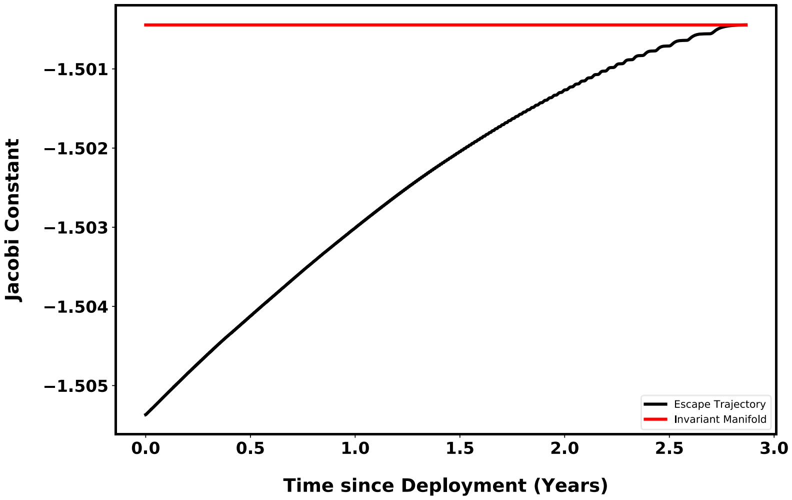
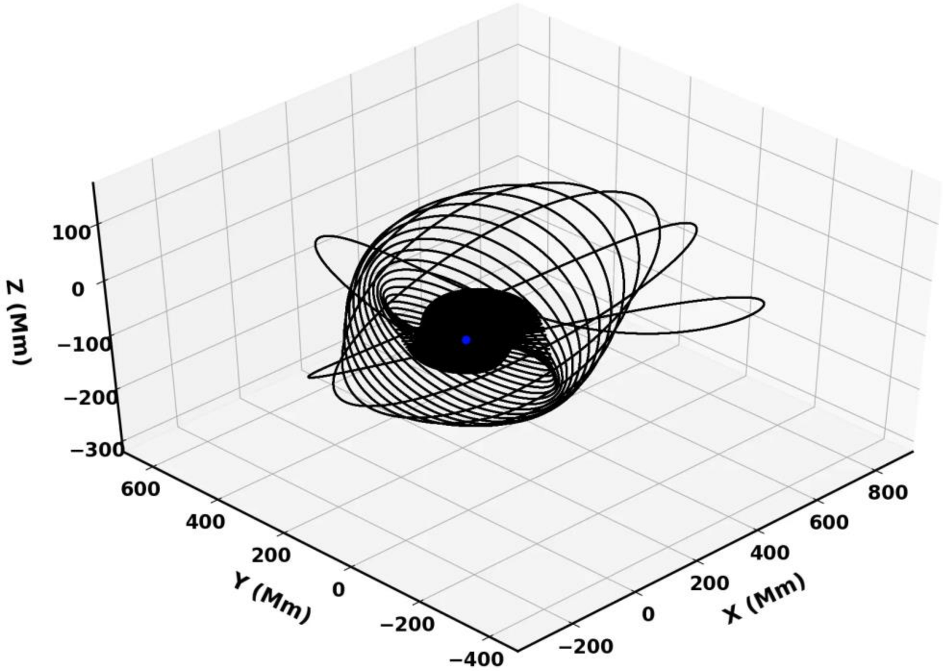
L_2

Earth Escape Trajectories

- Energy maximization control law[5] in rotating frame

$$\max_{\hat{\mathbf{n}}} \ \mathbf{a}_S(\hat{\mathbf{n}}) \cdot {}^{\mathcal{R}}\mathbf{v}$$

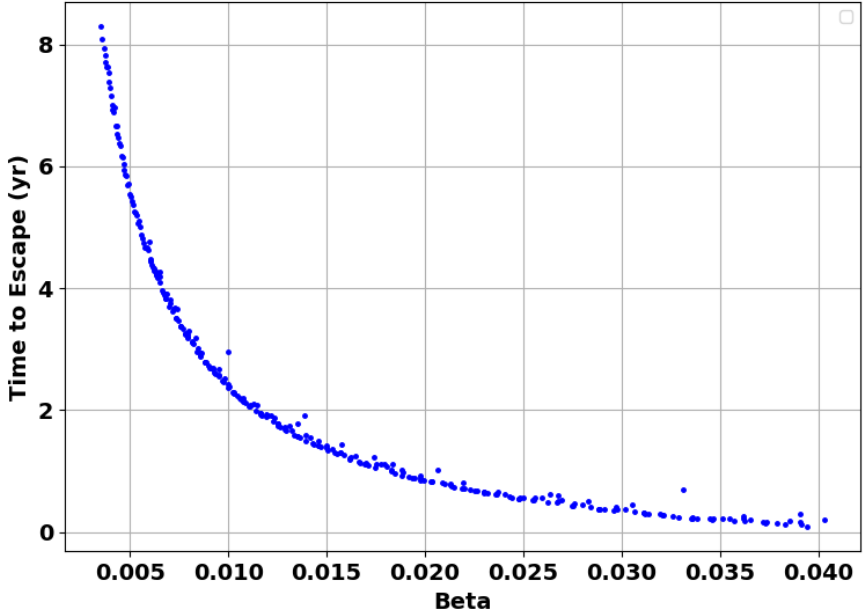


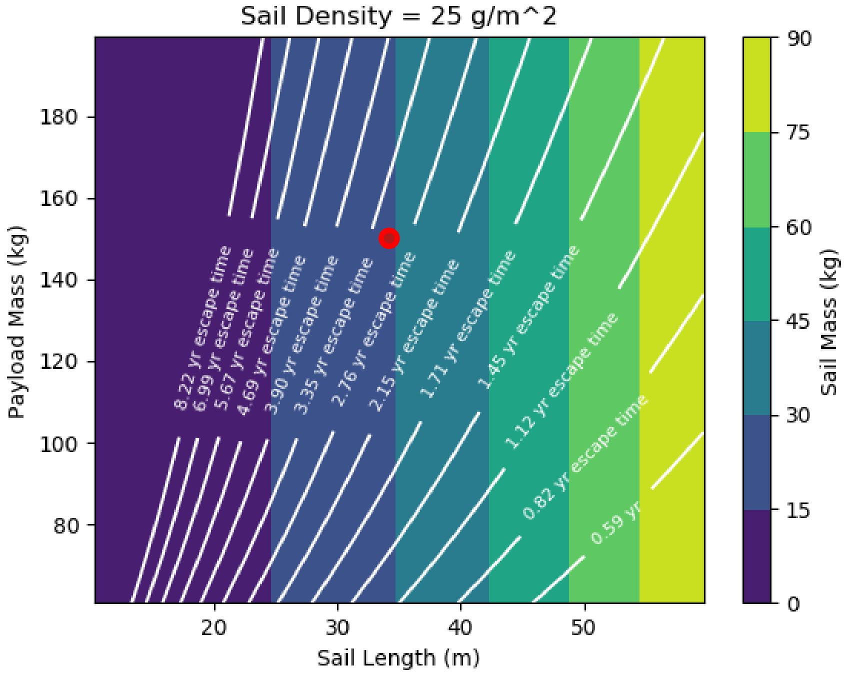


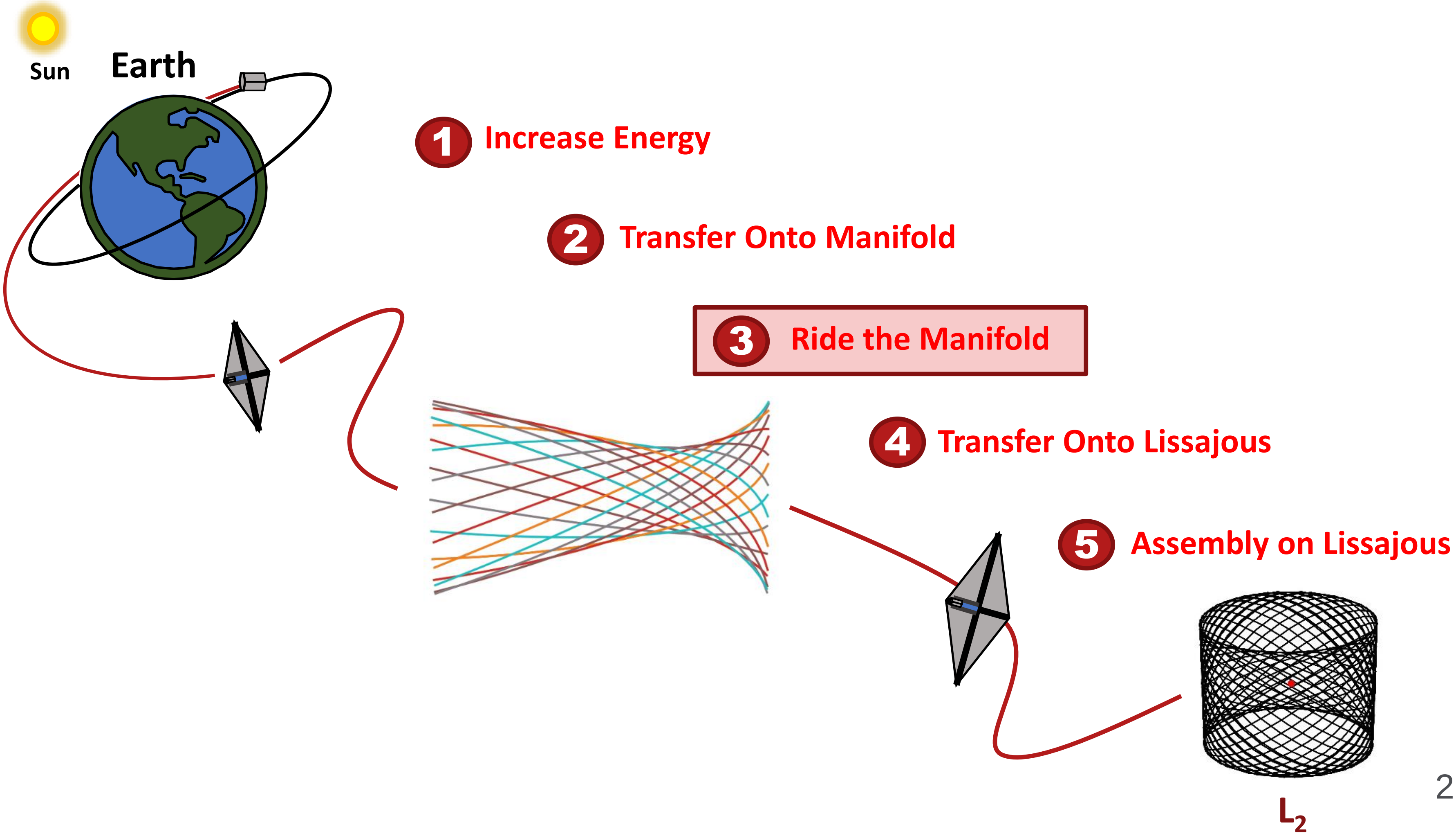
[5]Coverstone, "Technique for Escape from Geosynchronous Transfer Orbit Using a Solar Sail," JGCD, 2003

Designing the Sail

$$\beta = f(m_p, A_s, \sigma_s) = \frac{\sigma^*}{\frac{m_p}{A_s} + \sigma_s}$$



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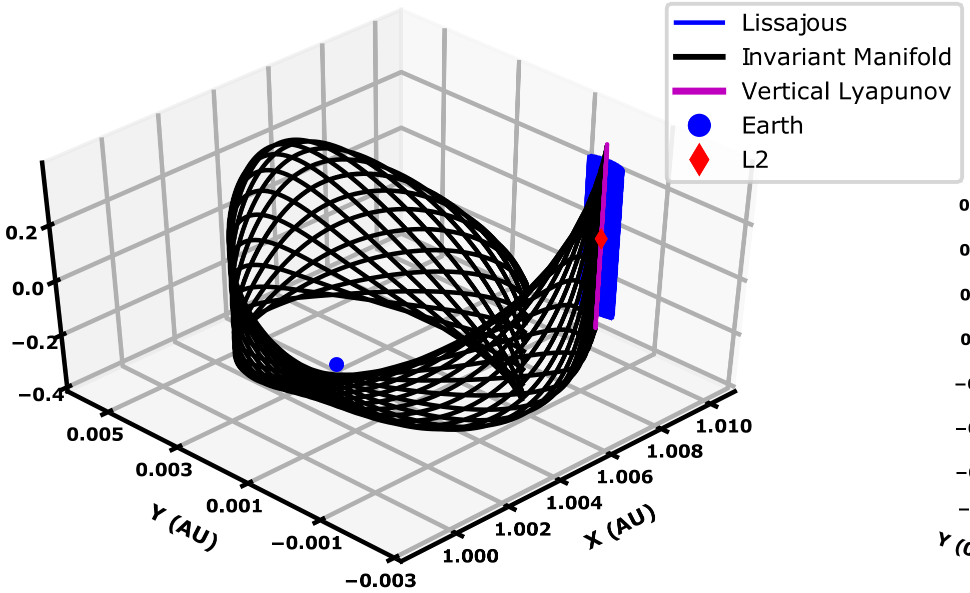
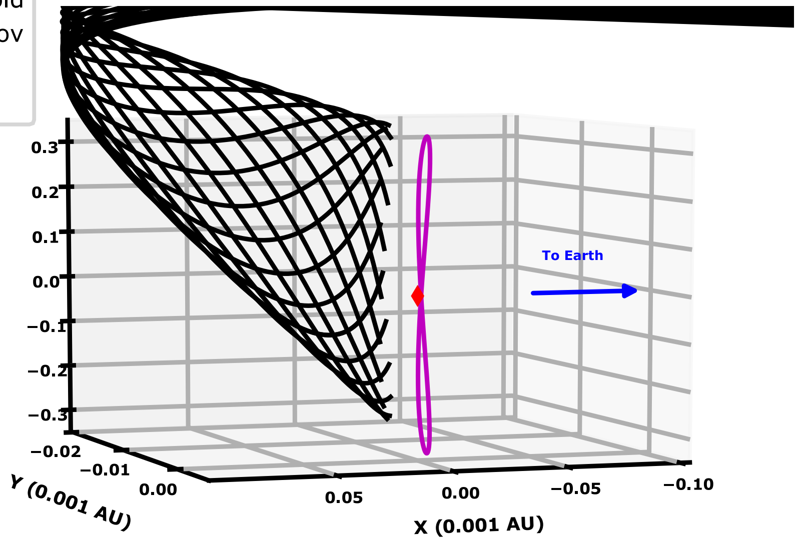
5 Assembly on Lissajous
L_2

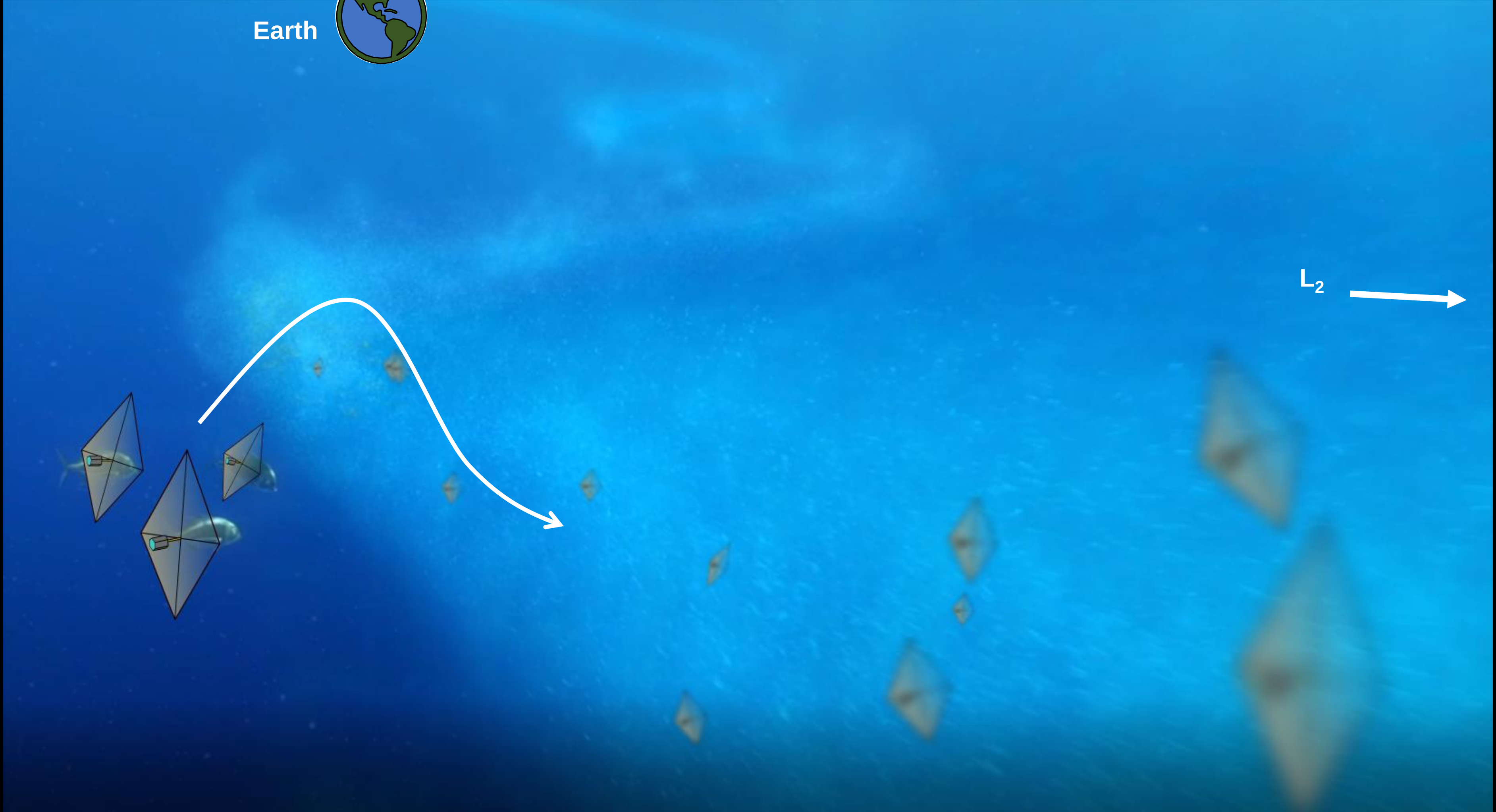
Invariant Manifold Analysis

$$\mathbf{x}_0^{\mathcal{S}}(\mathbf{x}_0^P) = \underline{\mathbf{x}_0^P} + \epsilon \underline{\mathbf{Y}^{\mathcal{S}}(\mathbf{x}_0^P)}$$

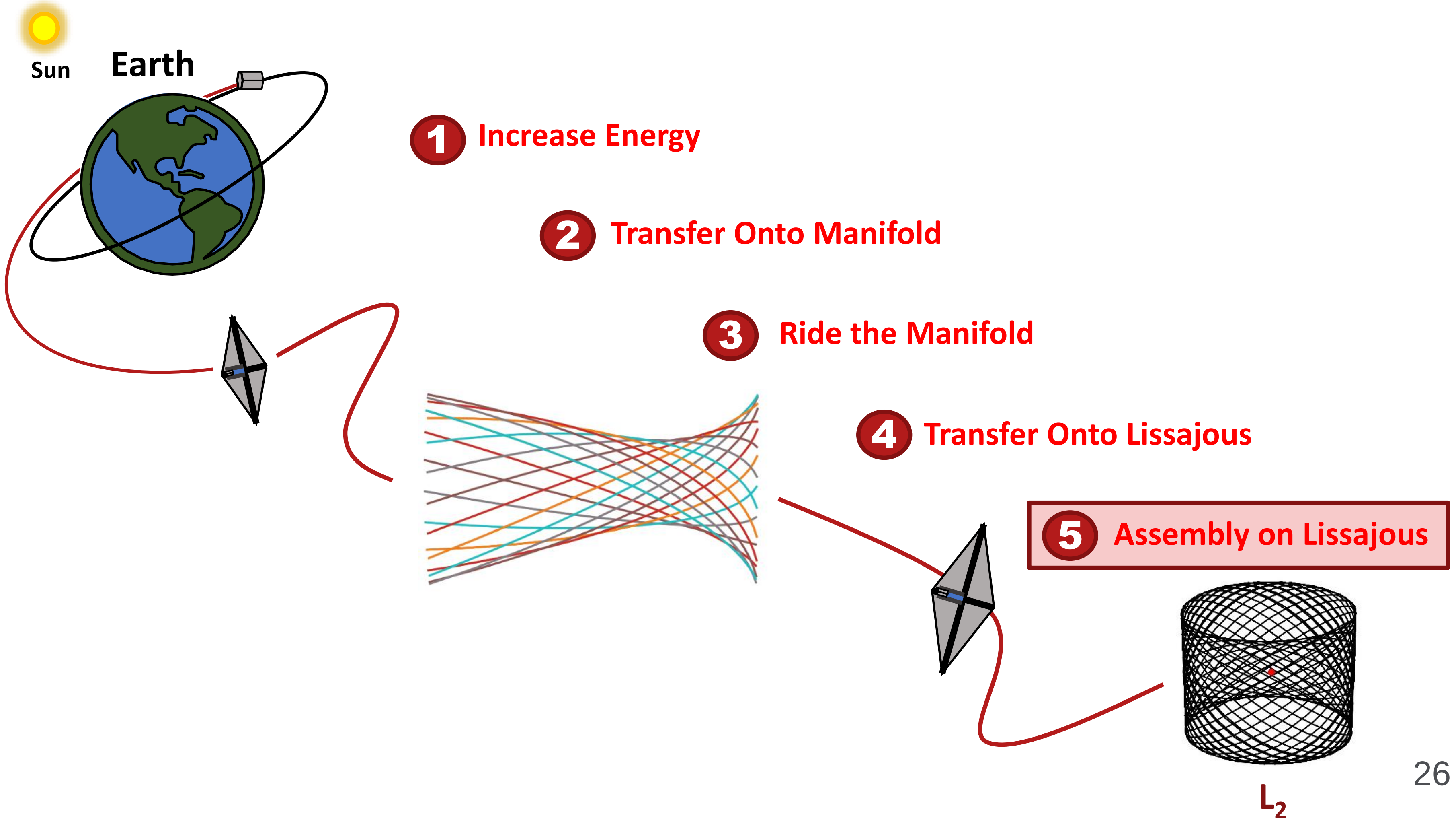




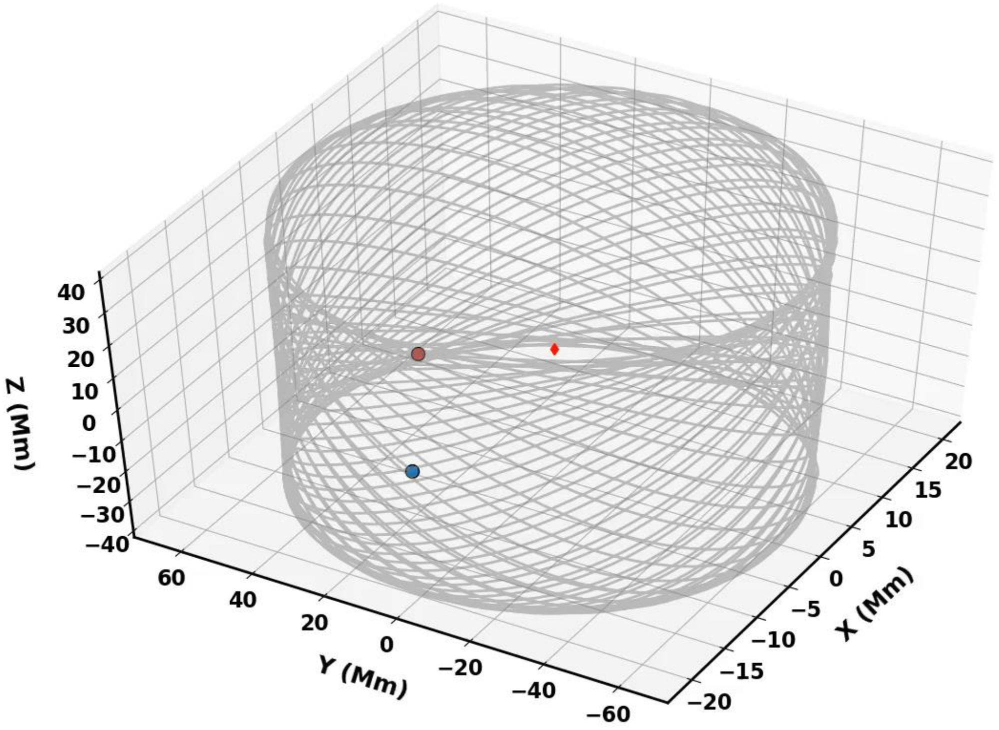
[6]Stanton, “Finding Nemo” *Disney Pixar* (2003)



[6]Stanton, “Finding Nemo” *Disney Pixar* (2003)

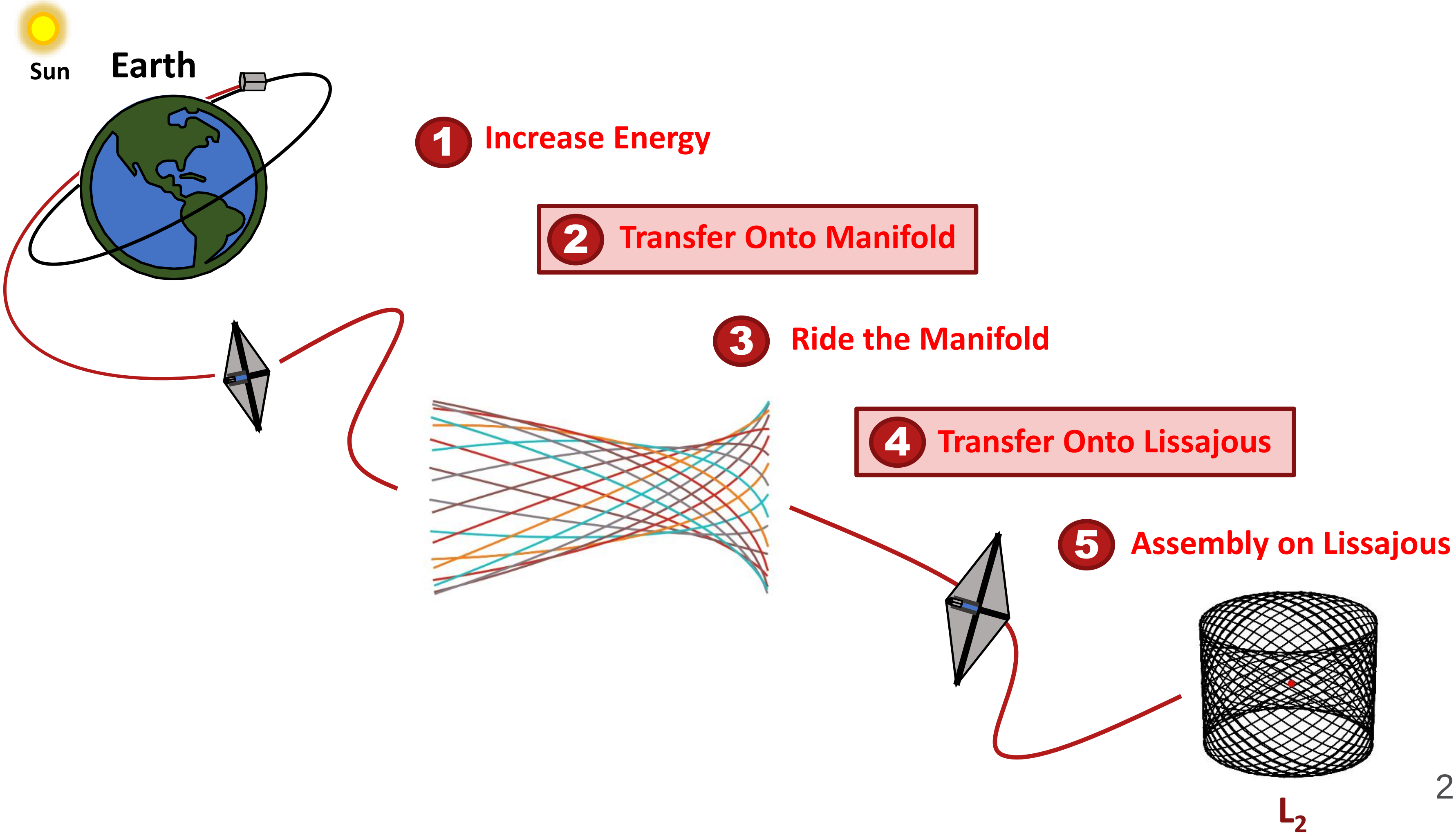

Sun
Earth
1 Increase Energy
2 Transfer Onto Manifold
3 Ride the Manifold
4 Transfer Onto Lissajous
5 Assembly on Lissajous
L_2

Final Orbit - Lissajous



- Found through 2-step differential correction process[2]
- 177-day period, about Sun-Earth L2 ecliptic

[7]K. C. Howell and H. Pernicka, “Numerical Determination of Lissajous Trajectories in the Restricted Three-Body Problem,” Celestial Mechanics, Vol. 41, 1988


Sun
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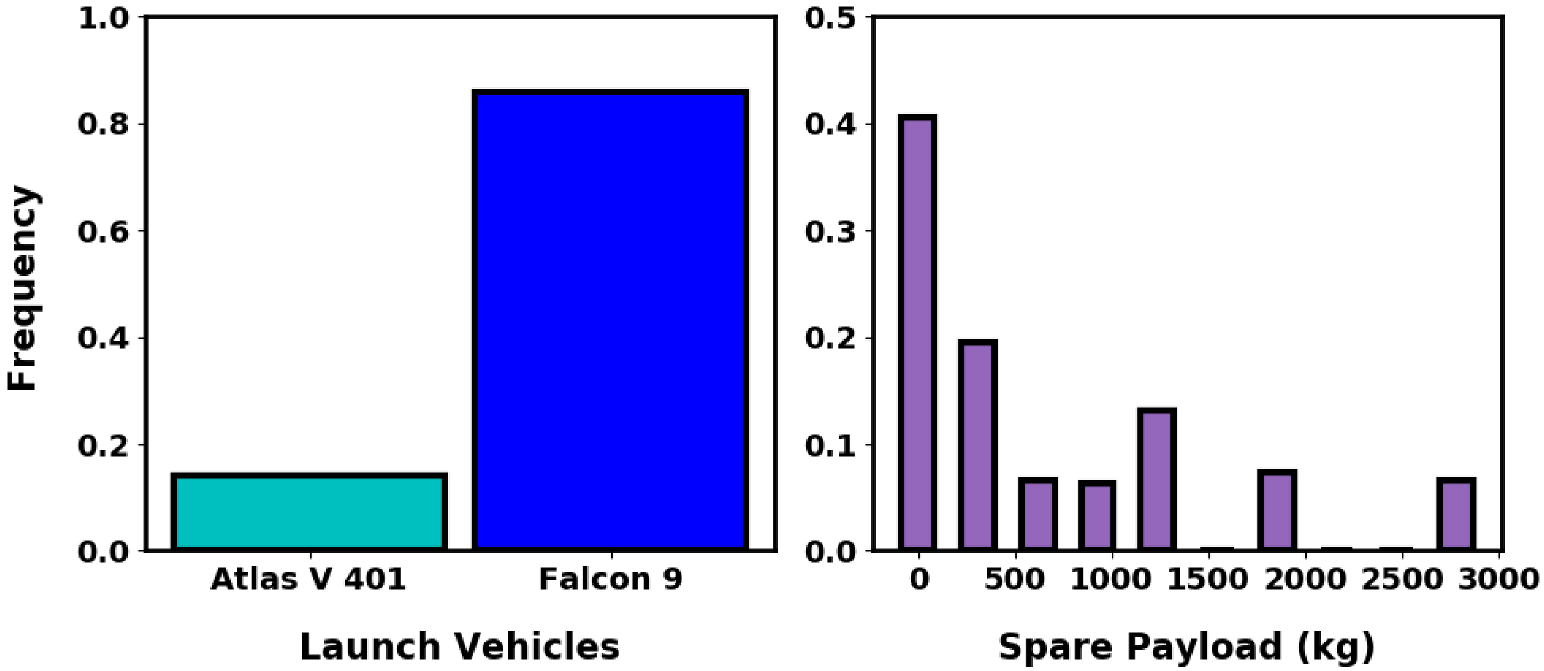
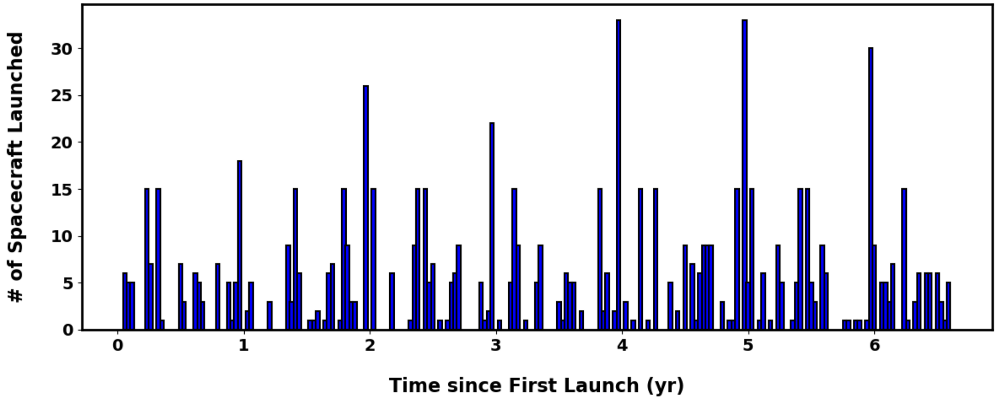
4 Transfer Onto Lissajous
5 Assembly on Lissajous
L2

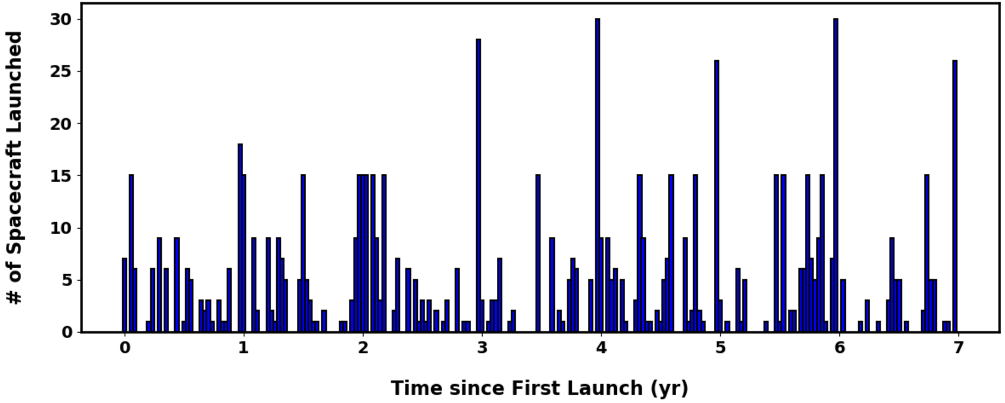
Launch Analysis



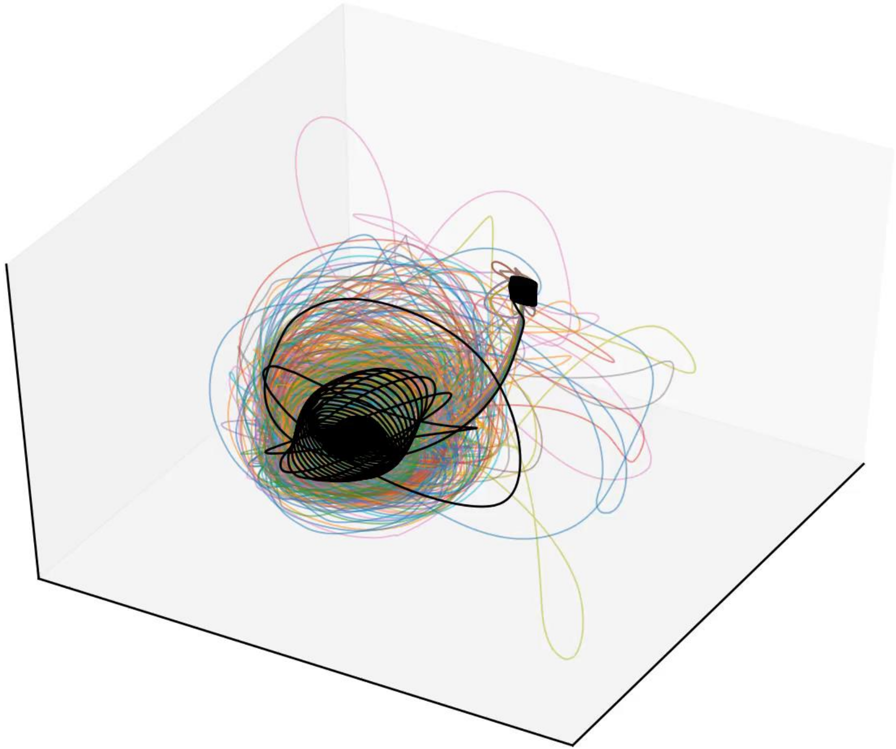
Data taken from Launch Log in: http://www.planet4589.org/space/log/launch.html

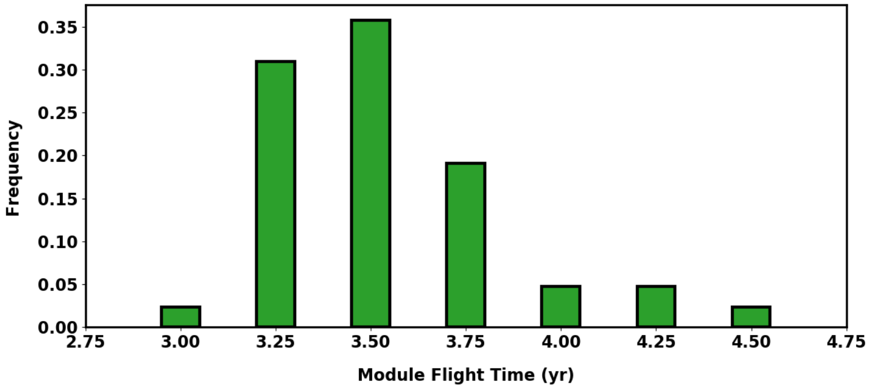
Design Reference Mission





Full Trajectories from Earth to L2





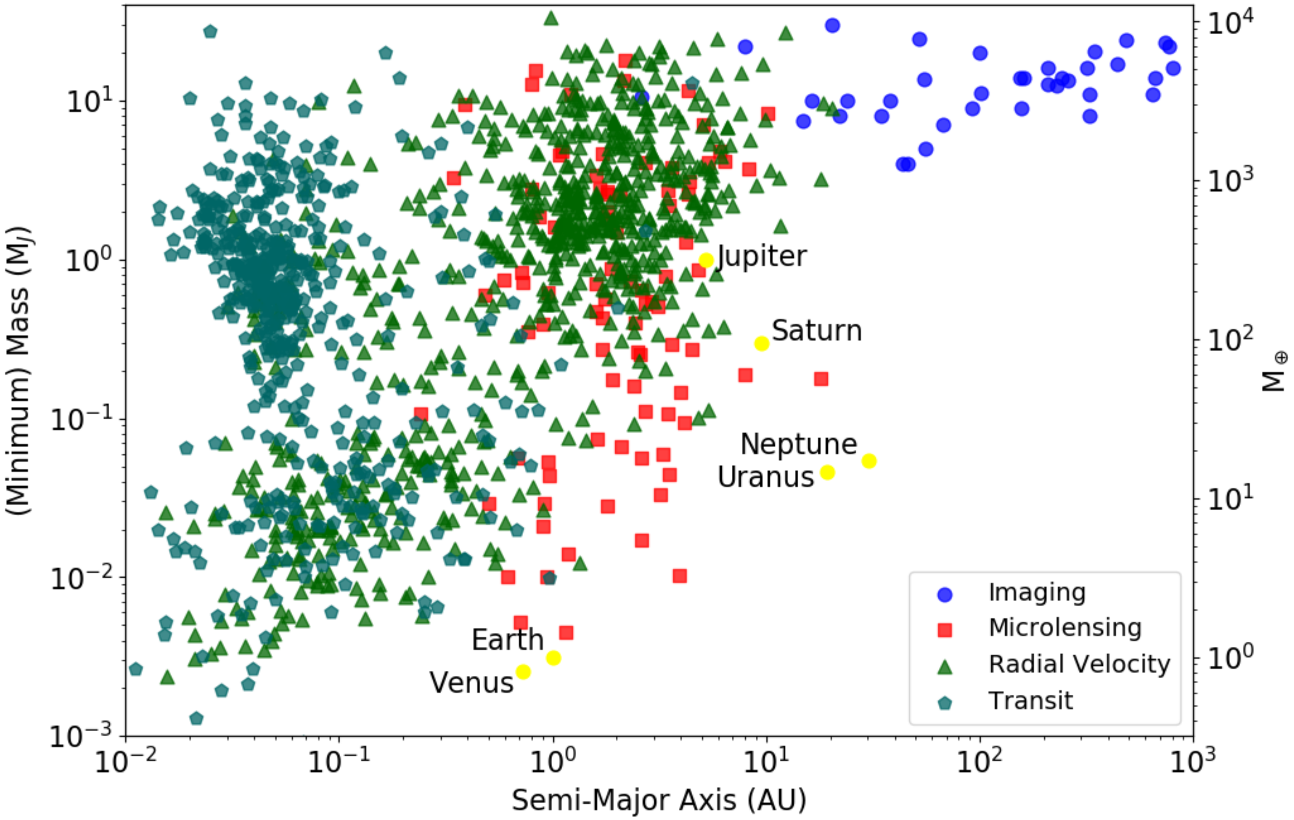
Conclusions

- Simulate future launch schedules using 2016-2018 launch data
  - 840 modules launched within 6-7 years
  - All injected into Lissajous within 11 years
- Developed tools to simulate full mission from Earth to L2 Lissajous orbits
  - Uses standard Python packages including `numpy` and `scipy`
  - Design tools for selecting sail parameters coupled with Earth escape times
- Presented conference paper at the 2019 AAS/AIAA Astrodynamics Specialists Meeting in Portland, ME
  - *Soto, G., Gustafson, E., Savransky, D., Shapiro, J., Keithly, D. (2019) "Solar Sail Trajectories and Orbit Phasing of Modular Spacecraft for Segmented Telescope Assembly About Sun-Earth L2" AAS 19-774*

1. Motivation
2. Dynamics Background
3. Delivering Space Telescopes to L_2
4. **Simulations of Telescope Operations near L_2**
    4.1. Starshade Formation Flying
    4.2. Starshade Slew Maneuvers
    4.3. Observation Scheduling
5. Conclusion

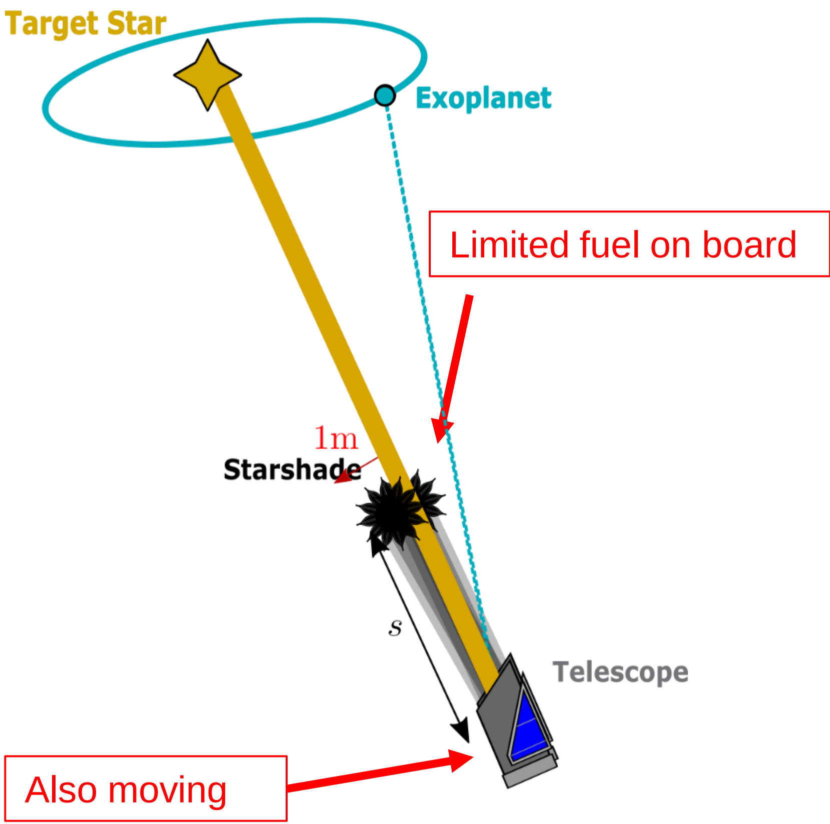
Exoplanets!

Data taken on 07/23/2020 from:
https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=planets

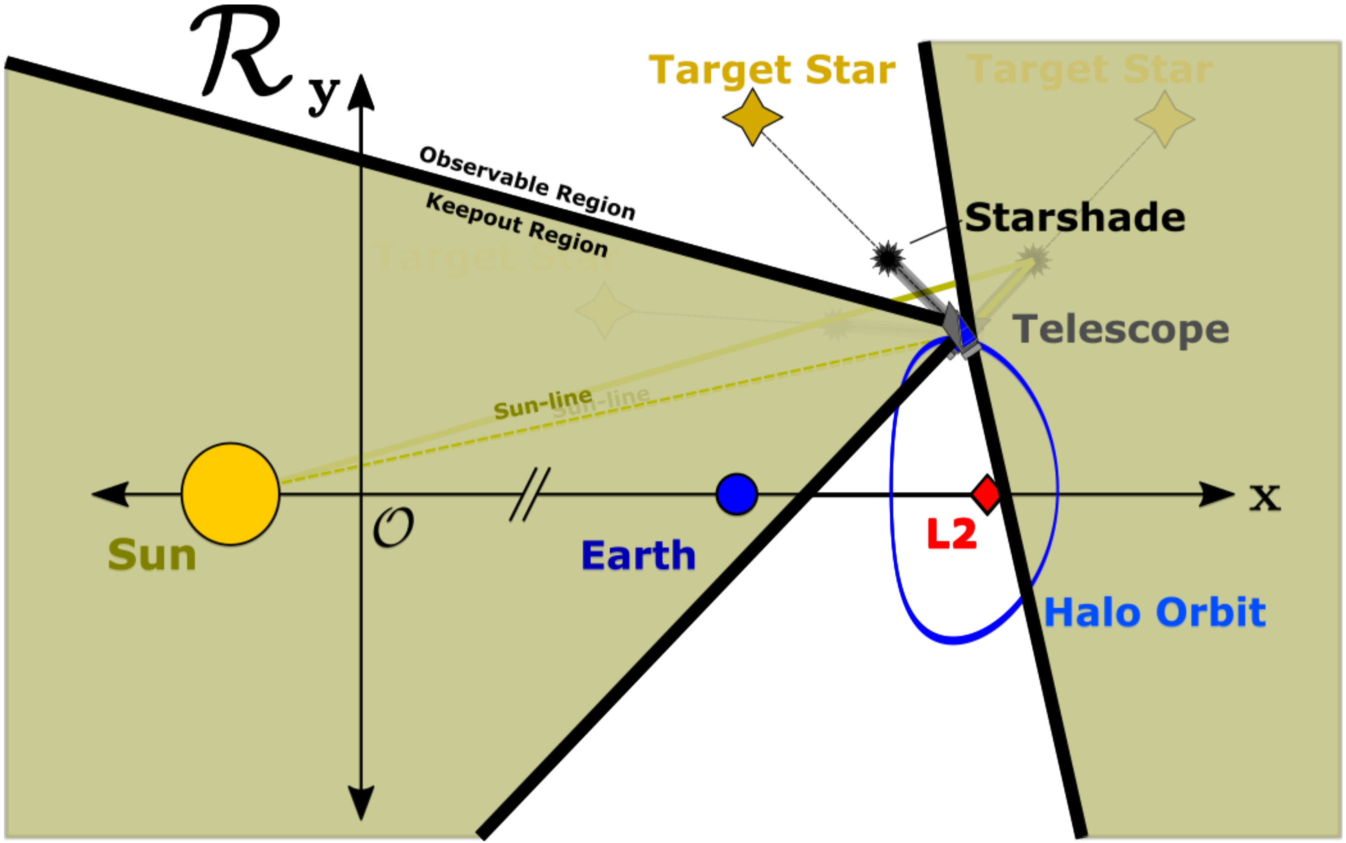


Starshades!

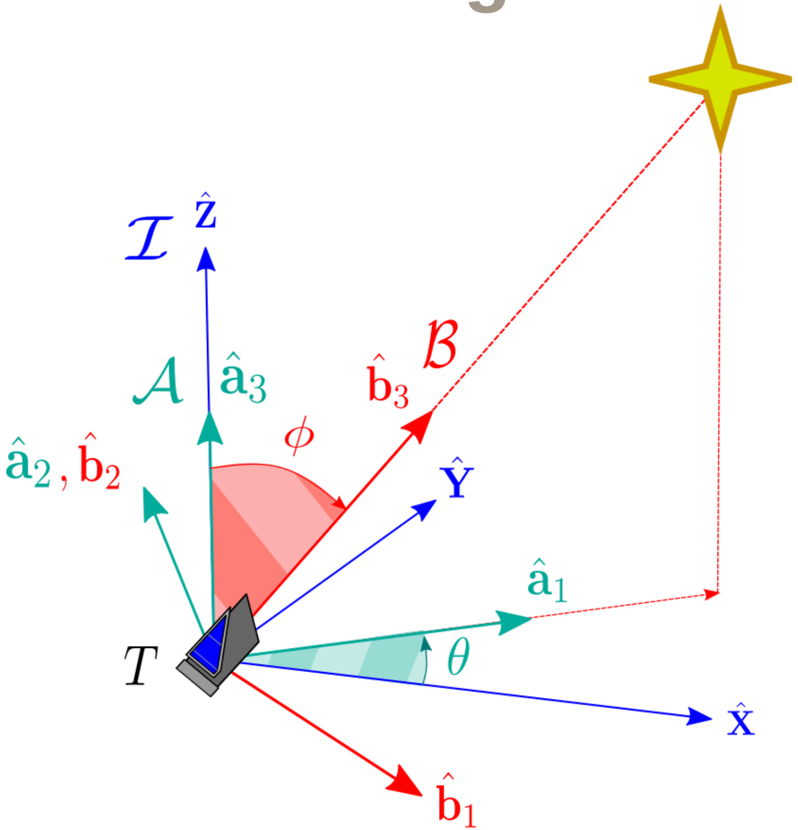
- No starlight enters telescope directly
  - Off-axis exoplanet light collected
- Maintains constant separation distance *s* along target star line of sight (LOS)
- Potential imaging of exoplanets almost *10 billion* times dimmer than their star!
- **Tight tolerance in lateral direction**
  - **Can't move >1m from LOS**
  - **Bad diffraction = No Picture ☹**



Keepout Constraints



Establishing a Line of Sight



- Euler Angles!
  - Frame is centered on the Telescope
  - Rotate by two angles to align with the target star

- Functions of known quantities!

$$\theta = \theta(\lambda, \beta, \varpi, t, \mathbf{r}_{T/\mathcal{O}})$$
$$\phi = \phi(\lambda, \beta, \varpi, t, \mathbf{r}_{T/\mathcal{O}})$$

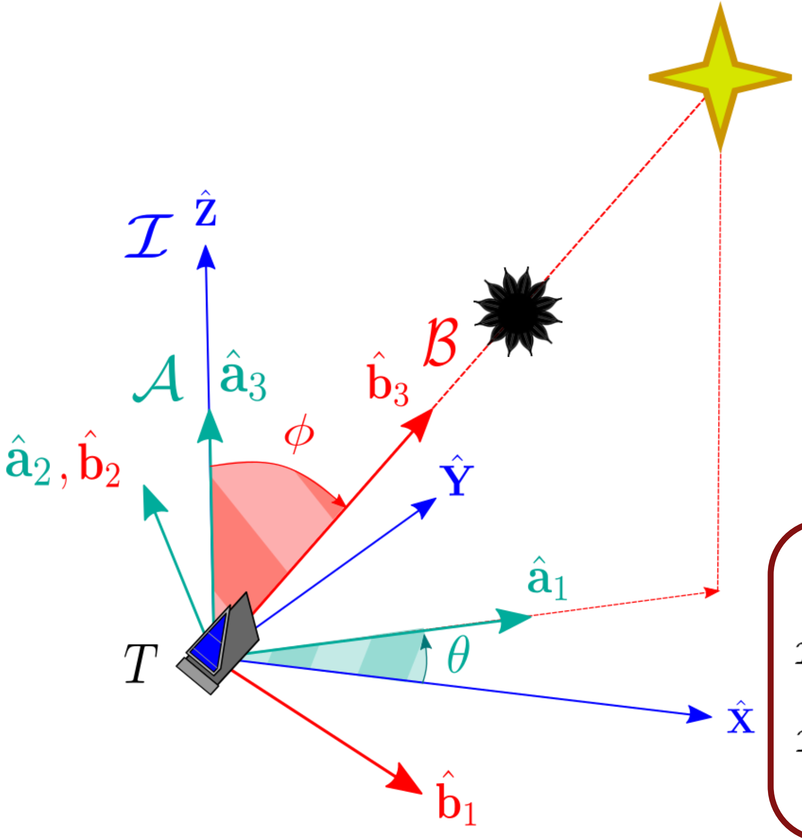
Location of Target Star (Ecliptic Coordinates)

Star Parallax (Measure of Distance)

Time

Position of Telescope (On Halo Orbit, it's Periodic!)

Starshade Kinematics



- Starshade needs to be at constant separation s from telescope

$$[\mathbf{r}_{S/T}]_{\mathcal{B}} = s\hat{\mathbf{b}}_3$$

- Perfect formation flying:
  - Keep up with changing line of sight

$$\mathbf{r}_{S/\mathcal{O}} = \mathbf{r}(s,\theta,\phi,\mathbf{r}_{T/\mathcal{O}})$$

$$^{\mathcal{I}}\mathbf{v}_{S/\mathcal{O}} = \mathbf{v}(s,\theta,\phi,\dot{\theta},\dot{\phi},\mathbf{r}_{T/\mathcal{O}},{}^{\mathcal{I}}\mathbf{v}_{T/\mathcal{O}})$$

$$^{\mathcal{I}}\mathbf{a}_{S/\mathcal{O}} = \mathbf{a}(s,\theta,\phi,\dot{\theta},\dot{\phi},\ddot{\theta},\ddot{\phi},\mathbf{r}_{T/\mathcal{O}},{}^{\mathcal{I}}\mathbf{v}_{T/\mathcal{O}},{}^{\mathcal{I}}\mathbf{a}_{T/\mathcal{O}})$$

Starshade Dynamics

- Forces pull Starshade off nominal track

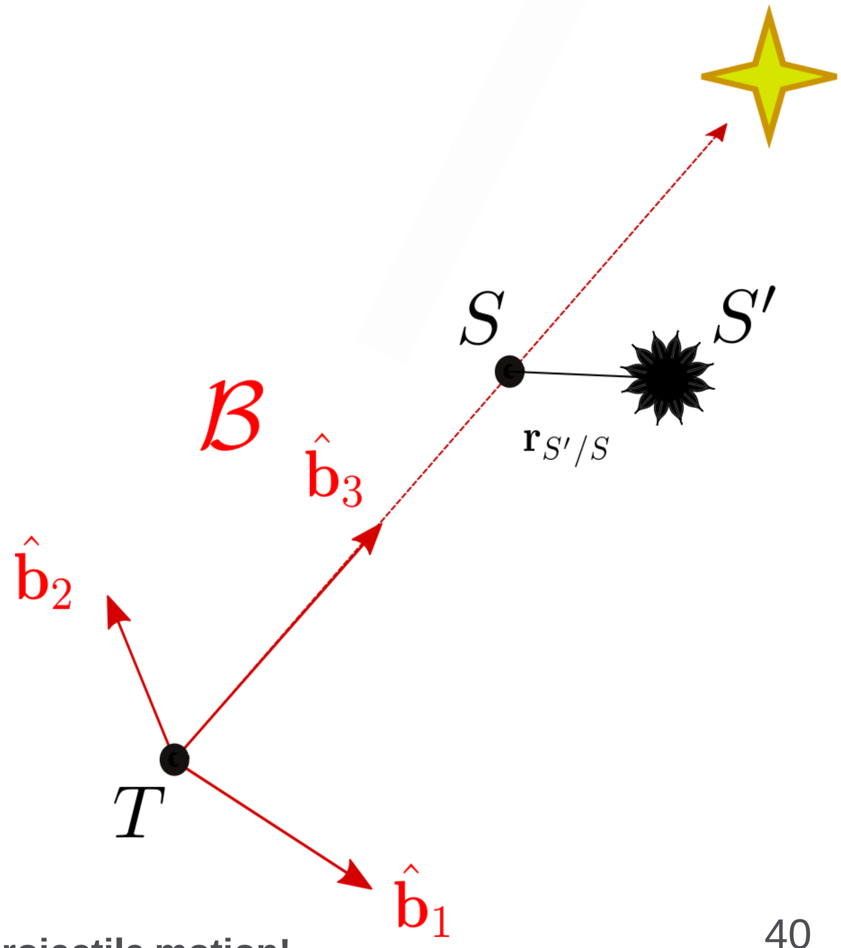
$$ {}^{\mathcal{I}}\frac{d^2}{dt^2}\mathbf{r}_{S'/S} = {}^{\mathcal{I}}\frac{d^2}{dt^2}\mathbf{r}_{S'/\mathcal{O}} - {}^{\mathcal{I}}\frac{d^2}{dt^2}\mathbf{r}_{S/\mathcal{O}} $$

Forces on Starshade due to Sun and Earth

We know this! Perfect formation flying acceleration

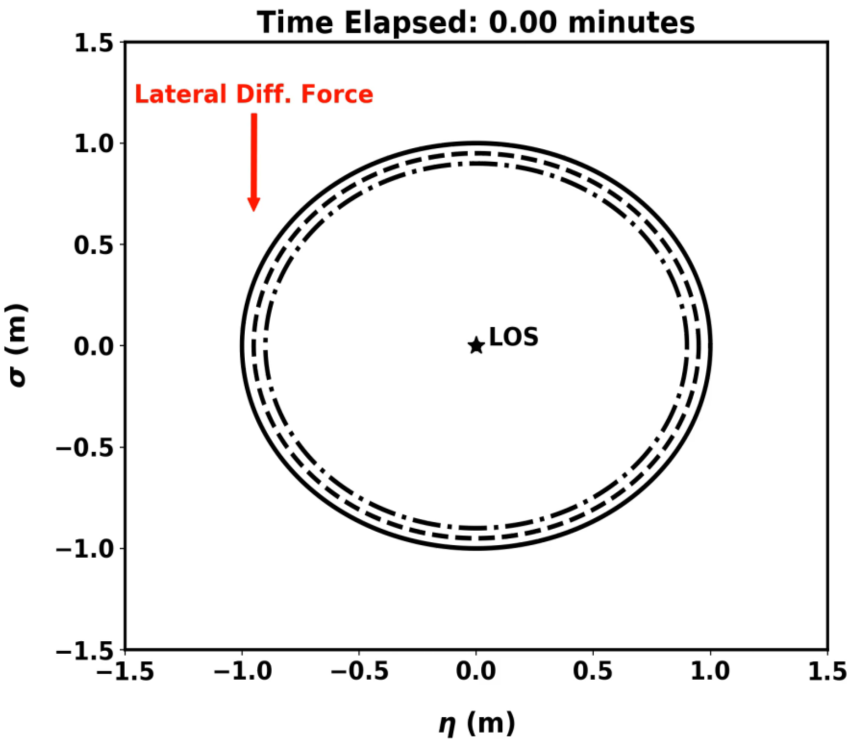
- For short time periods, assume differential forces (RHS) are constant

$$ {}^{\mathcal{I}}\mathbf{a}_{S'/S} = \Delta \boldsymbol{f} $$



Second order differential equation equal to a constant is **projectile motion!**

Deadbanding Simulation



- Maneuvers cause plumes which reflects light
- Long drift time between burns = longer uninterrupted observations

Based on Flinois, T., et al (2020) “Starshade Formation Flying II: Formation Control ” JATIS

Simulation Metrics

- Averaged over a full observation (assume 5 hours)

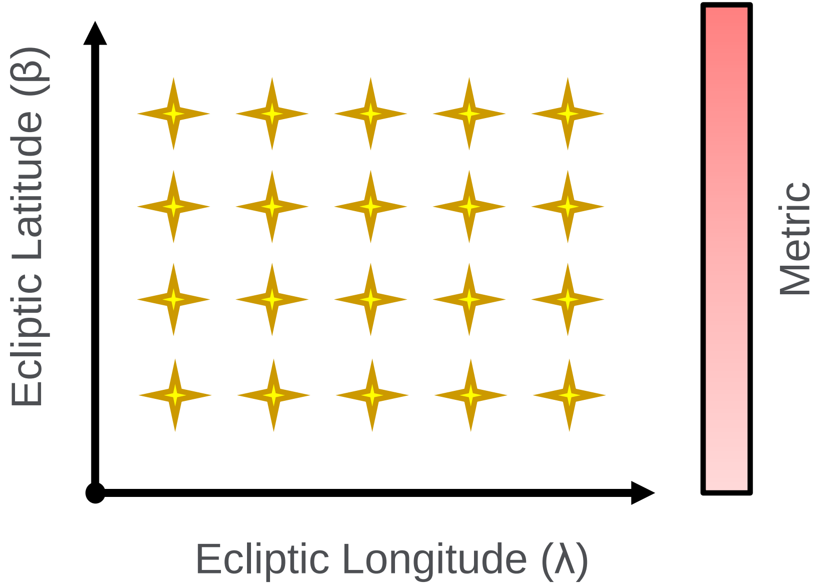
1. Δv — $\langle \Delta v \rangle_{obs}$
2. Δv in Lateral Direction — $\langle \Delta v_L \rangle_{obs}$
3. Number of Thruster Firings — N
4. Drift Time between Firings — $\langle \Delta t_D \rangle_{obs}$
5. Fuel Usage per Day — $\langle \dot{m} \rangle_{obs} = \frac{N \langle \Delta m \rangle_{obs}}{t_{obs}}$
6. Fraction of Observation Time Spent Firing Thruster — $\langle f_P \rangle_{obs} = \frac{N \langle \Delta t_T \rangle_{obs}}{t_{obs}}$

Parameterizing These Metrics

- What parameters affect these metrics?

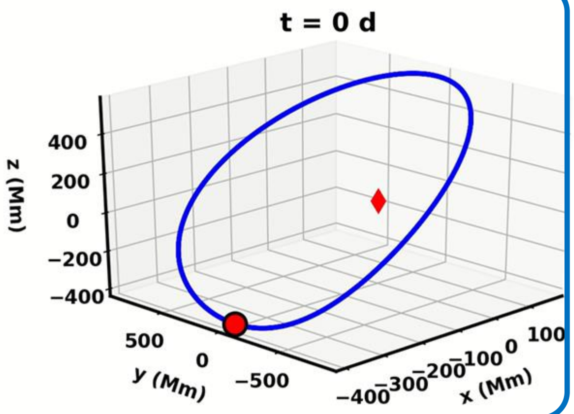
$$M_i = f(\underline{\lambda, \beta}, \underline{t}, \Delta t_P)$$

- These parameters affect the relative location of the Starshade to the Earth, Sun, Moon, etc.
  - Important because we care about **lateral components** to LOS
  - Gravity pulls in different directions and magnitudes depending on location/configuration



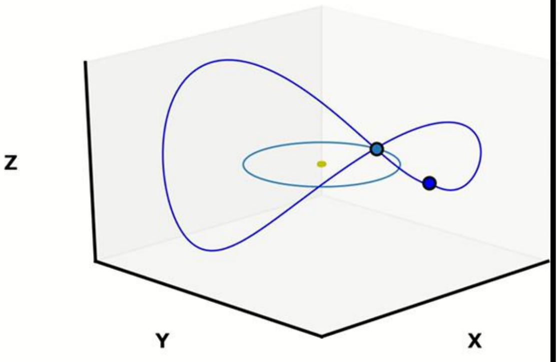
1. Run simulation for every star, plot metrics
2. Repeat (1) over all times *t* --- play as a movie!

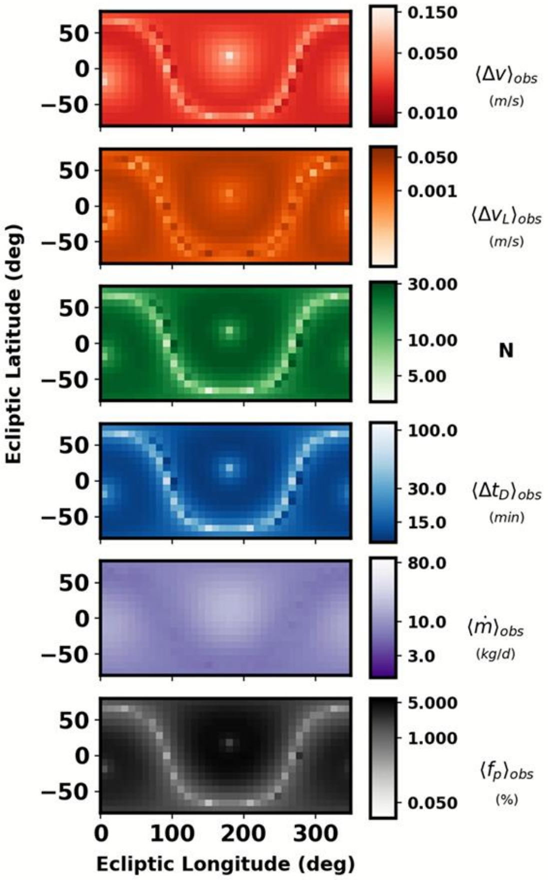
Rotating Frame
(Centered at L2)



Inertial Frame
(Centered at Solar System Barycenter)

[NOT TO SCALE]





Results

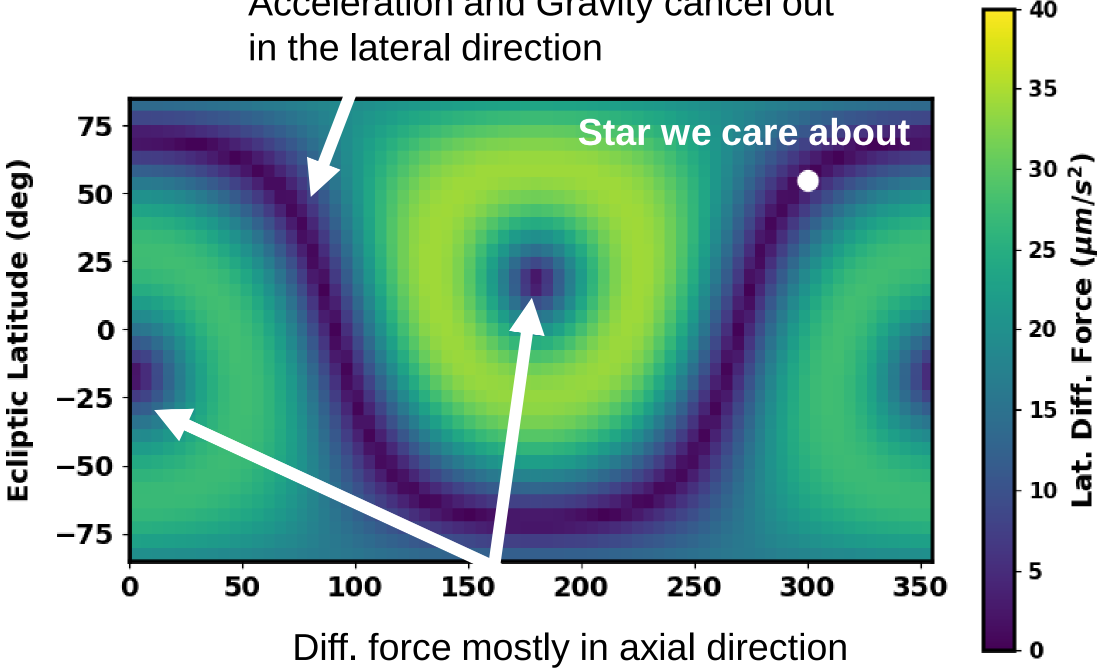
Table 3 Station-keeping simulation case study results with optimal time for observation scheduling using both case 1 (left) and 2 (right) keepout conditions. Stars with one column had the same results for both keepout conditions. We also tabulate the difference in using the optimal versus worst observation times for each metric. The operator $\langle\,\rangle_{obs}$ signifies averages over a 5 hour observation for a given mission time.

	beta Pic	GJ 832	51 Eri		GJ 179		47 UMa	HD 219143
λ (°)	82.54	308.62	67.31		72.44		149.07	23.74
β (°)	-74.42	-32.47	-24.31		-15.93		31.06	54.55
S_I (pc)	19.75	4.97	29.40		12.36		13.80	6.55
t_{opt} (d)	330	200	300	180	300	180	35	135
t_{worst} (d)	270	170	190		190		5	180
Optimal - Worst	Case 1 + 2	Case 1 + 2	Case 1	Case 2	Case 1	Case 2	Case 1 + 2	Case 1 + 2
N	-3	-16	-7	-6	-8	-7	-22	-23
$\langle \Delta t_D \rangle_{obs}$ (min)	+4.08	+18.08	+4.82	+3.91	+6.26	+4.61	+39.70	+42.69
$\langle \Delta v \rangle_{obs}$ (mm/s)	+6.64	+2.07	+1.96	+3.77	+6.34	+4.66	+2.00	+3.14
$\langle \Delta v_L \rangle_{obs}$ (mm/s)	-3.19	-15.14	-5.68	-5.23	-6.91	-6.04	-5.33	-10.86
$\langle \dot{m} \rangle_{obs}$ (kg/d)	+0.92	-5.60	-1.79	-0.81	-0.89	-0.96	-9.50	-10.22
$\langle f_p \rangle_{obs}$ (%)	+0.01	-2.98	-1.22	-0.88	-1.16	-1.01	-4.32	-4.84

Soto, Savransky, Morgan (2020) “Analytical Model for Starshade Formation Flying with Applications to Exoplanet Direct Imaging Observation Scheduling” JATIS [submitted]

What Causes these Patterns?

Acceleration and Gravity cancel out in the lateral direction



Diff. force mostly in axial direction (this is where Sun, Earth, Moon net gravity points)

- Direction and magnitude of differential force:

$$\Delta \boldsymbol{f} = \boldsymbol{f}_{S'} - {}^{\mathcal{I}}\mathbf{a}_{S/\mathcal{O}}$$

Mostly gravity forces ($\boldsymbol{f}_{S'}$)

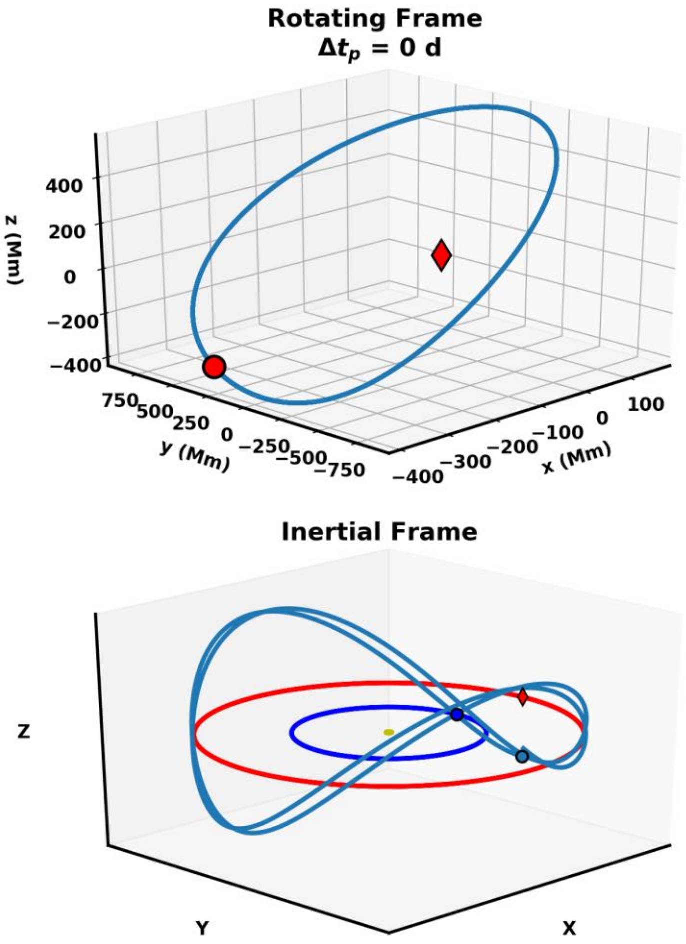
Mostly halo acceleration (${}^{\mathcal{I}}\mathbf{a}_{S/\mathcal{O}}$)

- Depending on Telescope-Star configuration relative to the Earth, Sun, Moon positions:
  - Forces are mostly in the axial direction
  - Forces cancel out

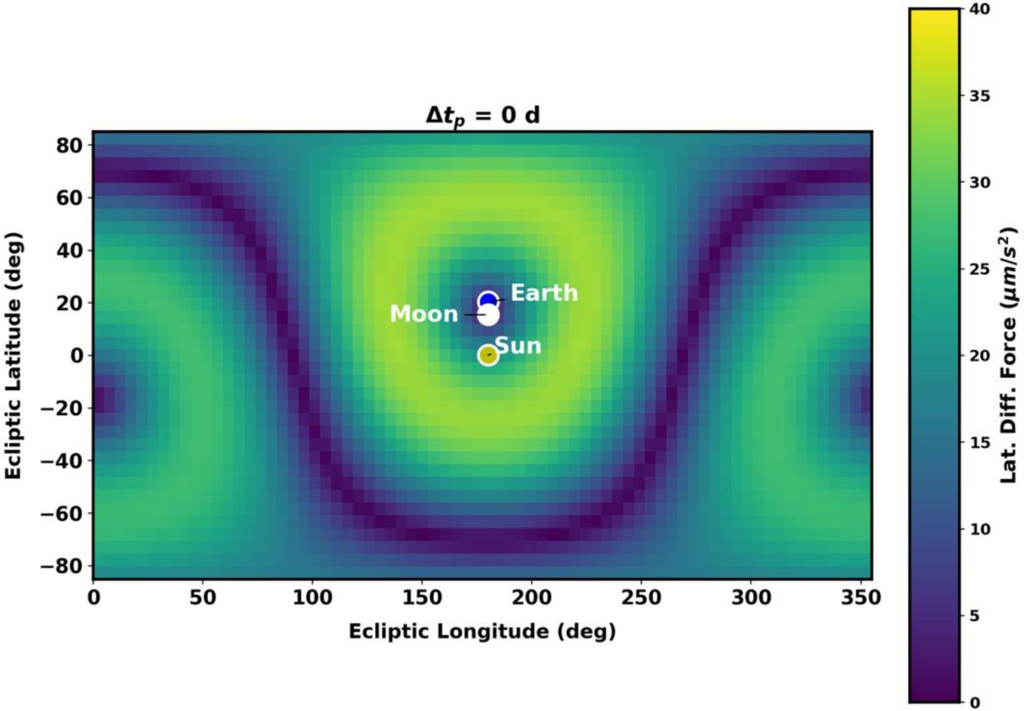
Halo Orbit Phasing

$$M_i = f(\lambda, \beta, t, \underline{\Delta t_P})$$

- CR3BP equations independent of time
  - Inject telescope at different locations of halo orbit at mission start time
- Starting point affects the direction of differential force
  - Selection affects when certain stars see favorable conditions



Halo Orbit Phasing Effects



- Tuning this parameter affects metrics
  - Can use lateral differential force as a proxy

- Hold time constant, animate through orbit phasings

$$M_i = f(\lambda, \beta, t, \Delta t_P)$$

Halo Orbit Phasing Results

Table 4 Station-keeping simulation case study results with optimal halo orbit phasing using both case 1 (left) and 2 (right) keepout conditions. Stars with one column had the same results for both keepout conditions. We also tabulate the difference in using the optimal versus worst halo orbit phasing times for each metric. The operators $\langle\,\rangle_{obs}$ signify averages over a 5 hour observation for a given mission time and $\langle\,\rangle_t$ averages over all mission times.

Average the metrics twice for each phasing:

- Over each observation
- Over future mission times

$$\langle\langle M_i\rangle_{obs}\rangle_t$$

	beta Pic	GJ 832		51 Eri		GJ 179		47 UMa		HD 219143	
$\Delta t_{P,\mathrm{opt}}$ (d)	110	20		130		130		30		150	
$\Delta t_{P,\mathrm{worst}}$ (d)	0	140		0	20	20		120		60	
Optimal - Worst	Case 1 + 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
$\langle N\rangle_t$	-5.23	-6.00	-6.8	-7.44	-8.00	-6.83	-9.33	-10.89	-11.09	-3.31	-5.09
$\langle\langle\Delta t_D\rangle_{obs}\rangle_t$ (min)	+13.23	+13.95	+14.52	+12.66	+12.97	+11.47	+13.27	+20.17	+20.27	+11.55	+14.02
$\langle\langle\Delta v\rangle_{obs}\rangle_t$ (mm/s)	+13.62	-0.98	-0.11	+3.20	+-3.19	-5.82	-2.80	-2.53	-2.42	+5.28	+4.26
$\langle\langle\Delta v_L\rangle_{obs}\rangle_t$ (mm/s)	-0.98	-0.30	-0.89	-3.11	-4.96	-4.27	-6.28	-6.81	-7.02	-1.27	-2.49
$\langle\langle\dot{m}\rangle_{obs}\rangle_t$ (kg/d)	+0.41	-2.98	-2.95	-3.67	-3.84	-4.42	-4.32	-4.47	-4.51	+0.53	-0.59
$\langle\langle f_p\rangle_{obs}\rangle_t$ (%)	-0.25	-1.08	-1.14	-1.36	-1.45	-1.51	-1.76	-1.70	-1.75	+0.20	-0.29

Soto, Savransky, Morgan (2020) “Analytical Model for Starshade Formation Flying with Applications to Exoplanet Direct Imaging Observation Scheduling” JATIS [submitted]

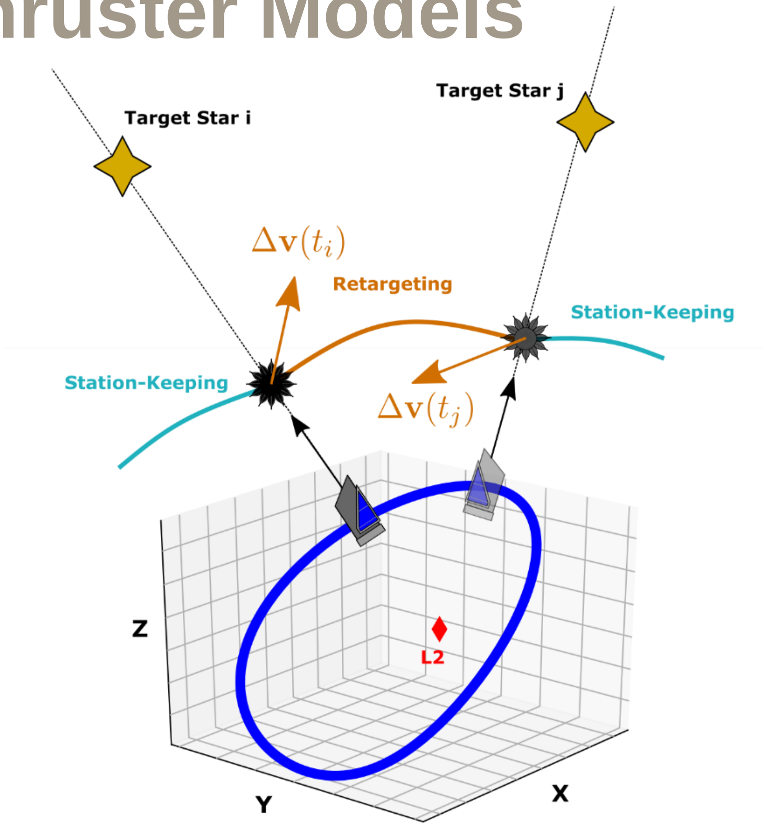
Conclusions

- Analytical model for starshade kinematics and dynamics
- Simulate starshade deadbanding maneuvers within a full end-to-end mission simulator
- Create metrics used for optimizing fuel usage within timing constraints

Soto, Savransky, Morgan (2020) “Analytical Model for Starshade Formation Flying with Applications to Exoplanet Direct Imaging Observation Scheduling” JATIS [submitted]

1. Motivation
2. Dynamics Background
3. Delivering Space Telescopes to L_2
4. Simulations of Telescope Operations near L_2
    4.1. Starshade Formation Flying
    4.2. **Starshade Slew Maneuvers**
    4.3. Observation Scheduling
5. Conclusion

Thruster Models

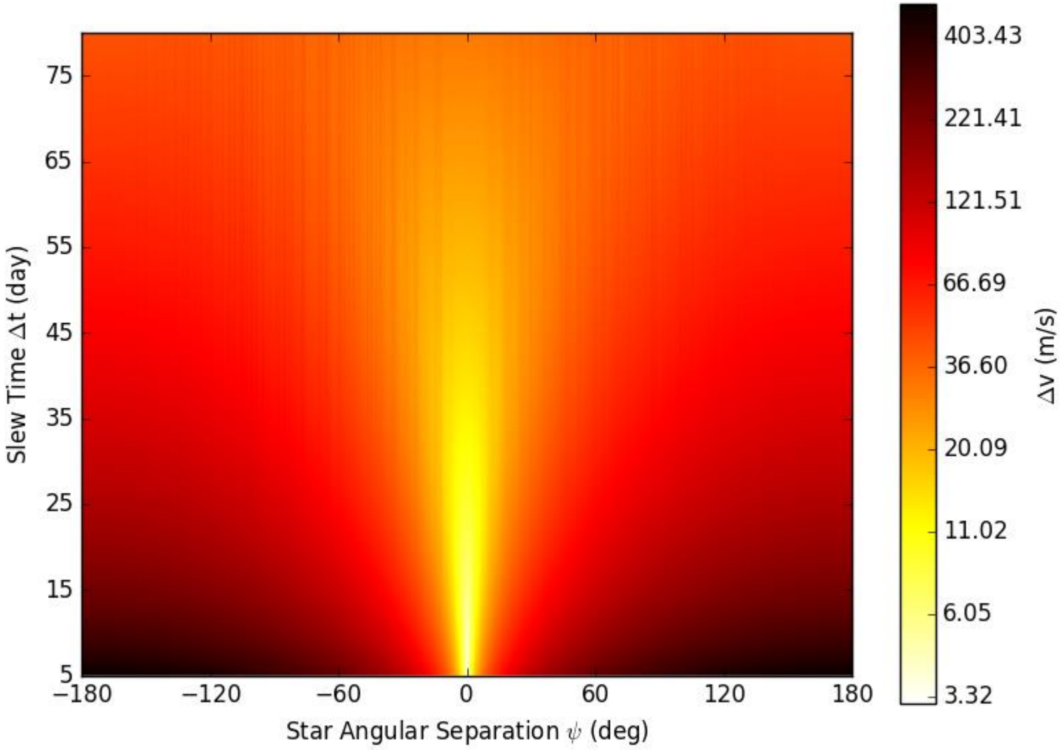


Impulsive Thrust Model

- Chemical Propulsion
- Instantaneous changes in velocity at t_i and t_j
- Solved as boundary value problem (BVP) using collocation algorithm

$$\Delta m = m_0\left(1 - e^{-\frac{\Delta v}{g_0 I_{sp}}}\right)$$

Impulsive Fuel Costs



$$\Delta v = f(i, j, \Delta t, t_0)$$

↓

$$\Delta v = f(\psi, \Delta t)$$

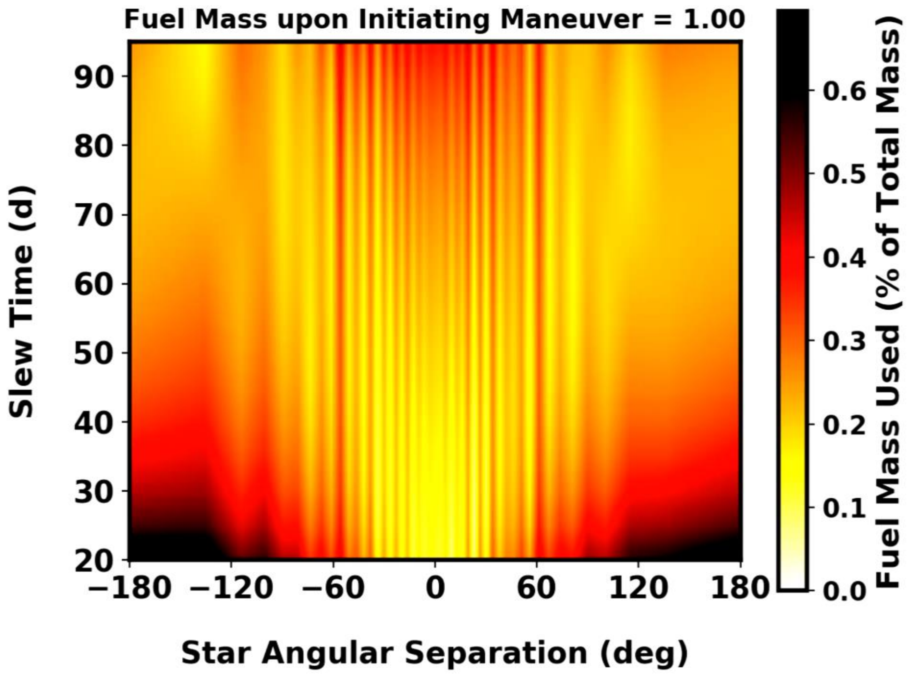
- Before: 12 minutes to compute map at every decision step
- Now: single map generated offline for any target list

Soto et al (2019) “Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules.” *JGCD*

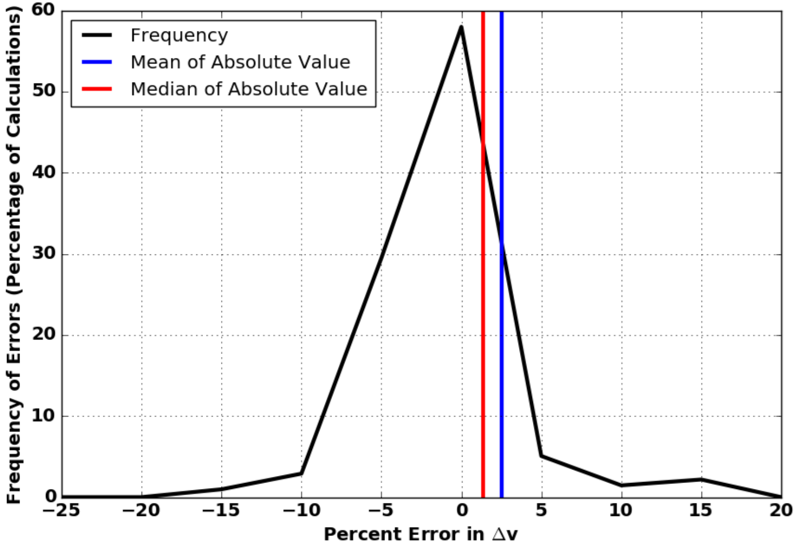
Continuous Thrust Fuel Costs

- Optimal control law to minimize energy
- Fuel cost is directly a function of fuel mass used

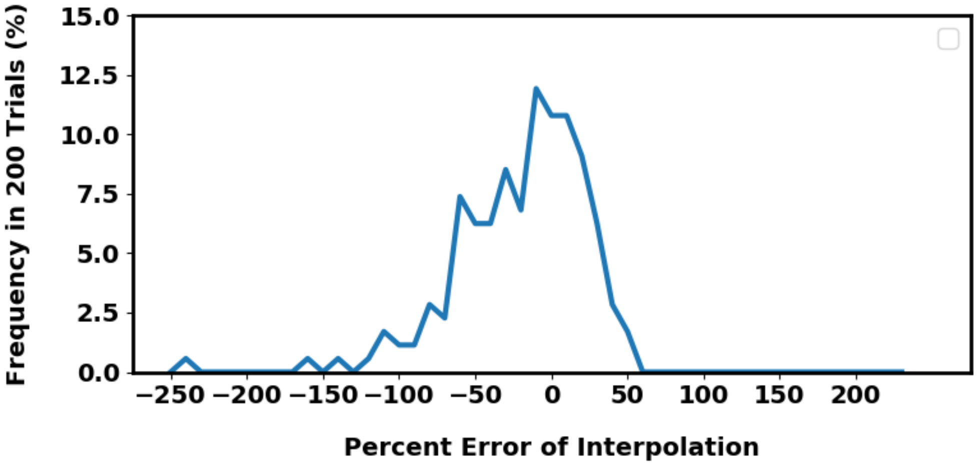
$$\Delta m \approx f(\psi, \Delta t, t_0, m_0)$$



Interpolation Errors



Impulsive Maneuvers



Continuous Thruster Maneuvers

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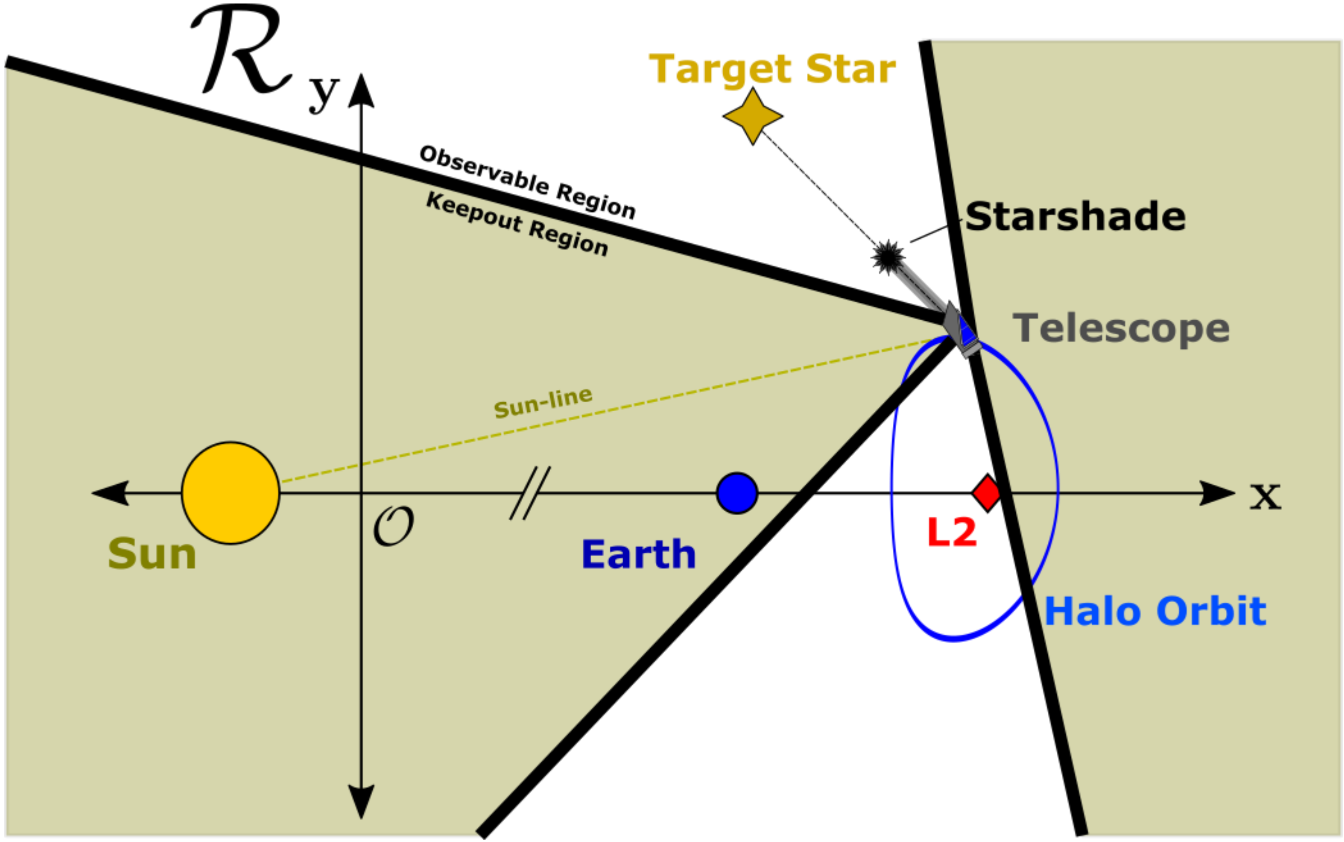
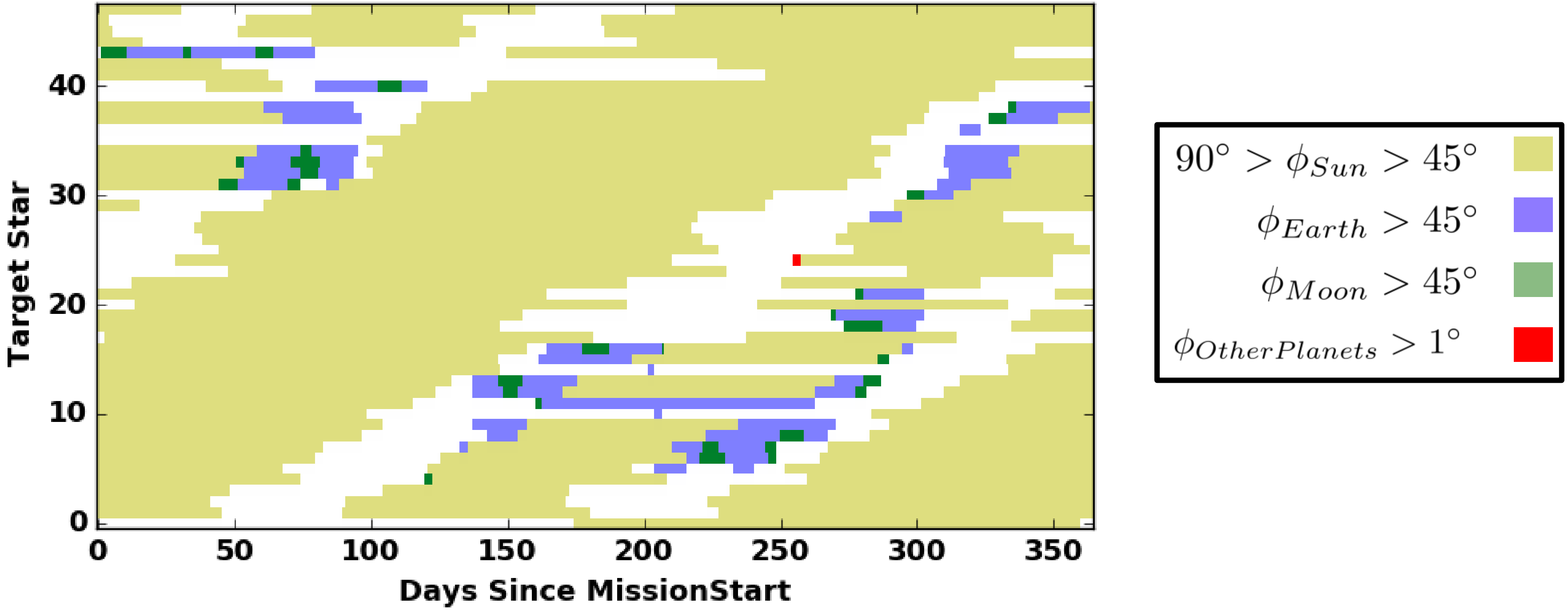
Keepout Constraints



Keepout Constraints



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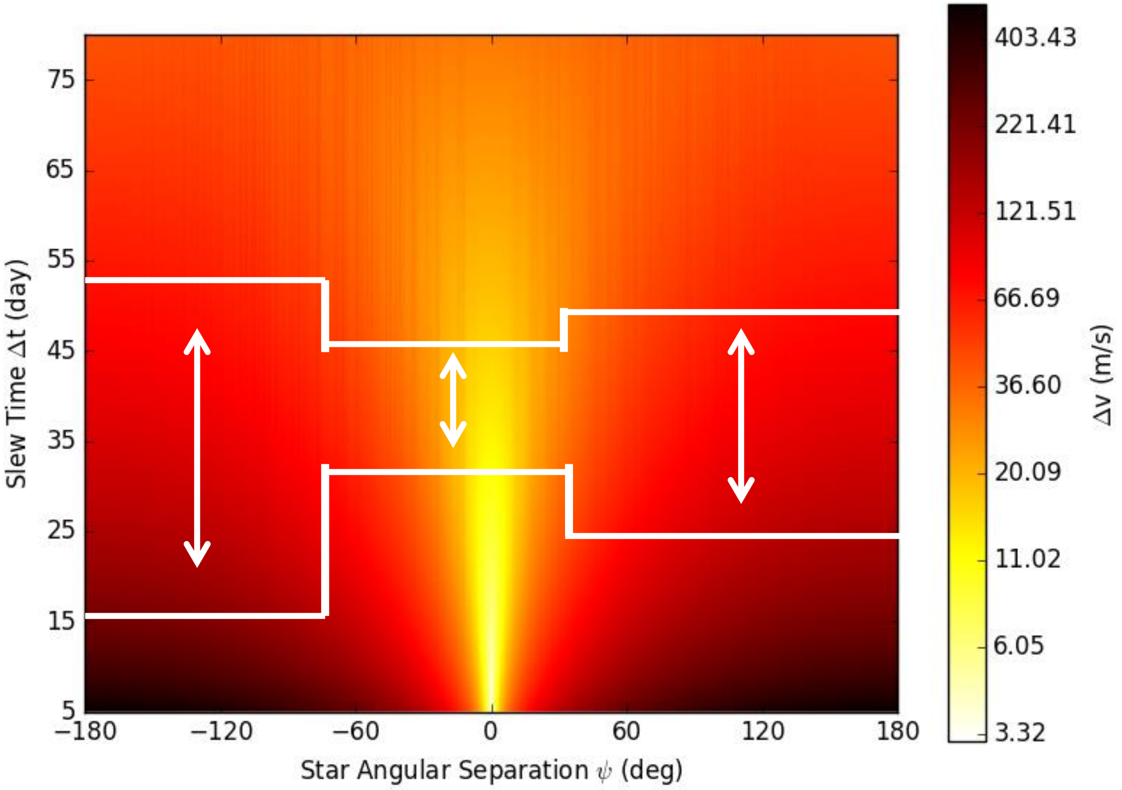
Keepout Constraints



Cost Function

Minimize **fuel use** for all stars *j*

Maximize **completeness** for each star *j*

Prioritize stars that haven't been observed yet

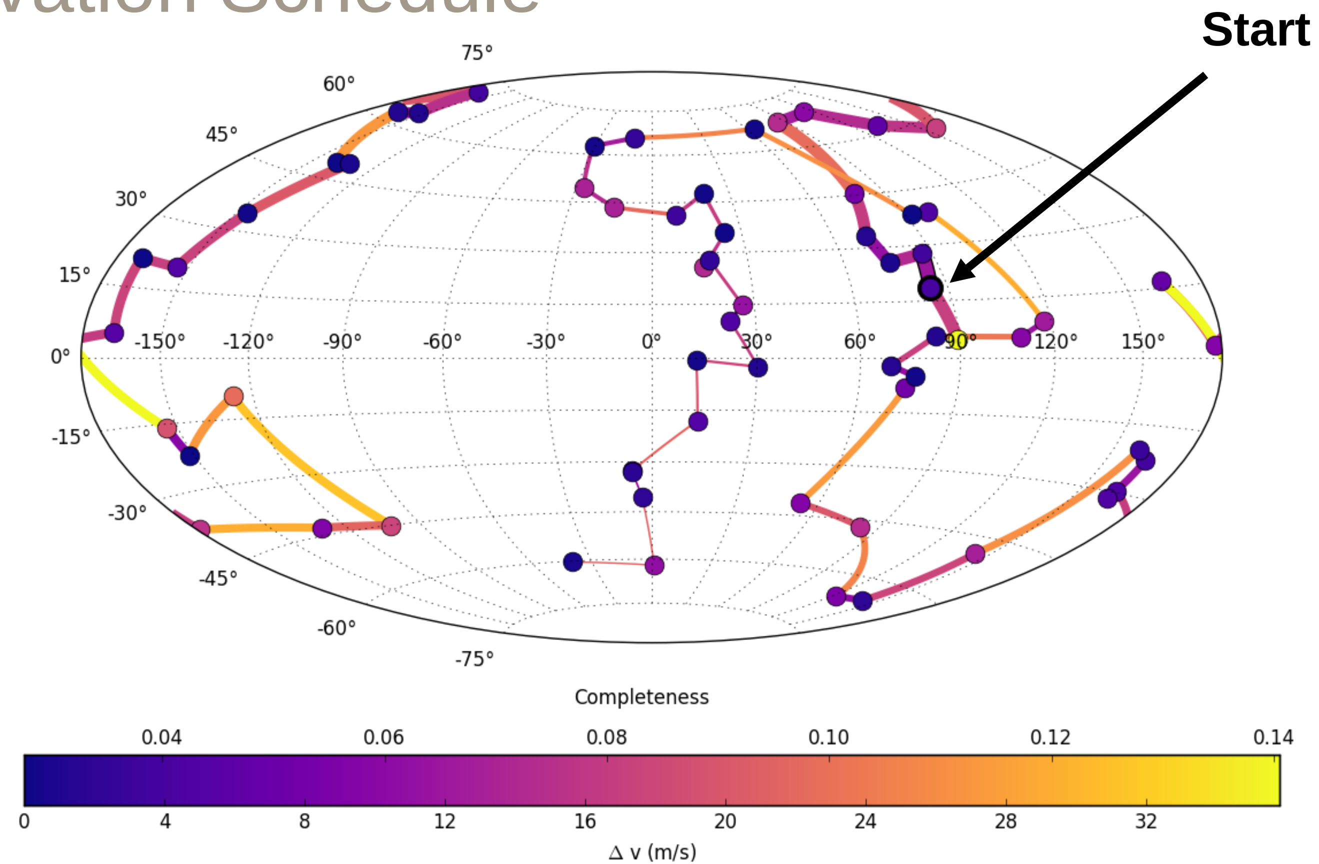
Prioritize stars designated for a revisit

$$\mathbf{c} = c_1 \Delta v_{min} + c_2(1 - C_O) - c_3 f_{unv} + c_4 f_{rev}$$

$$J = \arg\min_j(\mathbf{c})$$

Savransky et al (2010) "Analyzing the Designs of Planet-Finding Missions" *PASP*
Soto et al (2019) "Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules." *JGCD*

Observation Schedule



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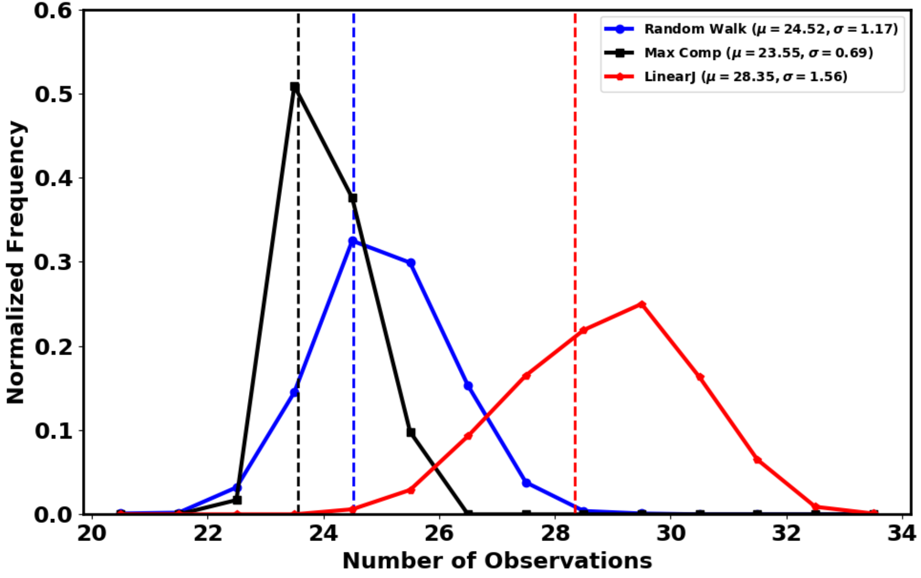
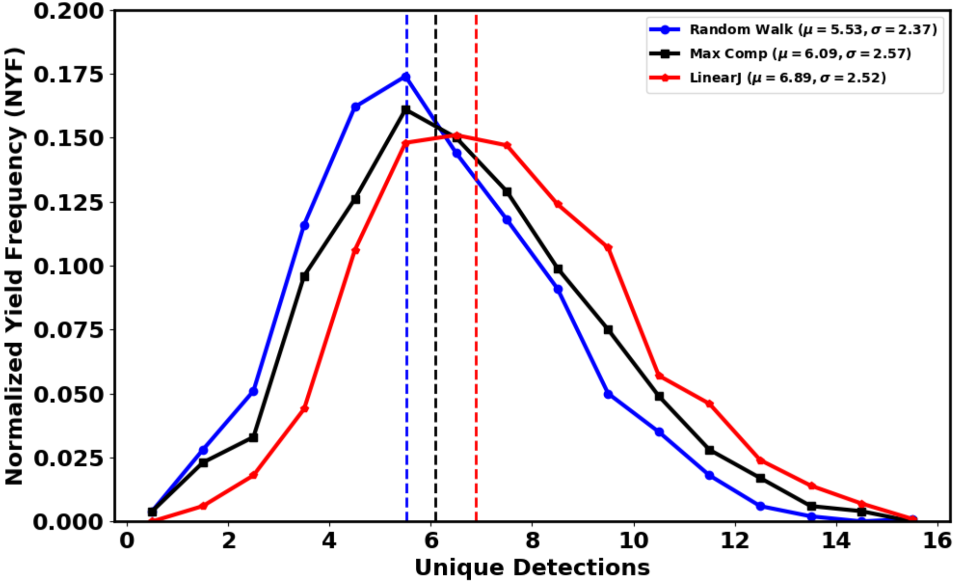
Mission Ensembles





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Minimize Costs under Operation Constraints

Time

- Can assemble 31-meter mirror with 840 segments in under 11 years
- Careful scheduling of observations of targets when configurations are favorable
- Applied keepout constraints for observations, imposed on fuel cost matrix and scheduler

Fuel

- Use solar sails to eliminate fuel costs of mirror segment maneuvers
- Minimize fuel costs of lateral starshade deadbanding maneuvers during an observation
- Explored the parameter space of retargeting maneuver fuel costs in a mission scheduler

Future Work

- Solar sail multiple shooting
  - Add more optimization variables + non-ideal sail parameters
  - Attitude control of fully assembled sailcraft
- Formation flying metrics
  - Parameterization: angle from gravity force to target star
- Starshade low-thrust maneuvers for slews
  - Work on different parameterizations
  - New techniques for achieving minimum fuel case
  - Dynamic scheduling of starshade slews

NASA Innovative Advanced Concepts

NIAC Grant: 80NSSC18K0869 – MODULAR ACTIVE SELF-ASSEMBLING SPACE TELESCOPE SWARMS

NASA Grant: NNG16PJ24C (SIT)

Big thank you to Rhonda Morgan!

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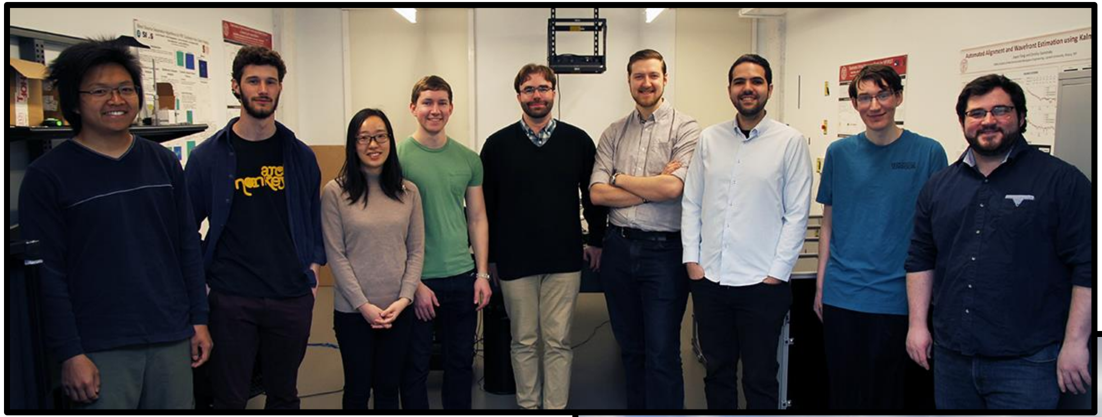
Big Thanks!



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Orbital Design Tools and Scheduling Techniques for Optimizing Space Science and Exoplanet-Finding Missions

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Dissertation Defense
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