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

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A Exam

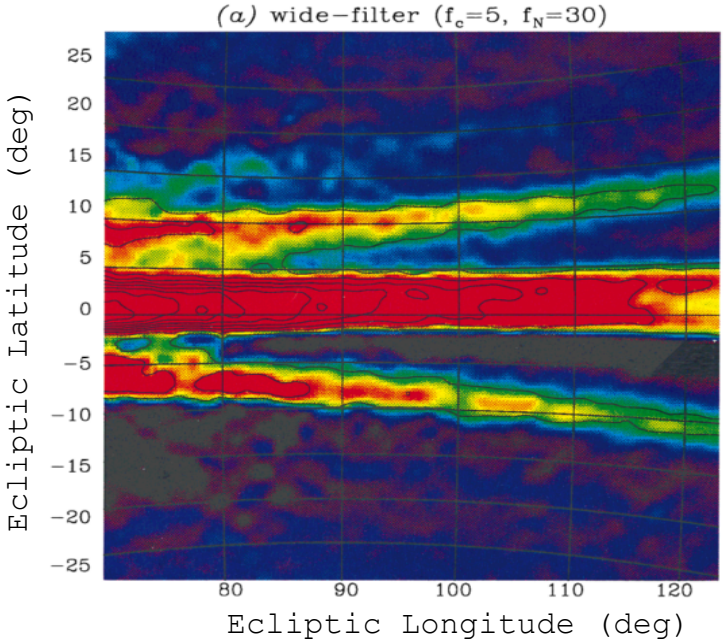
May 7th, 2018

Overview

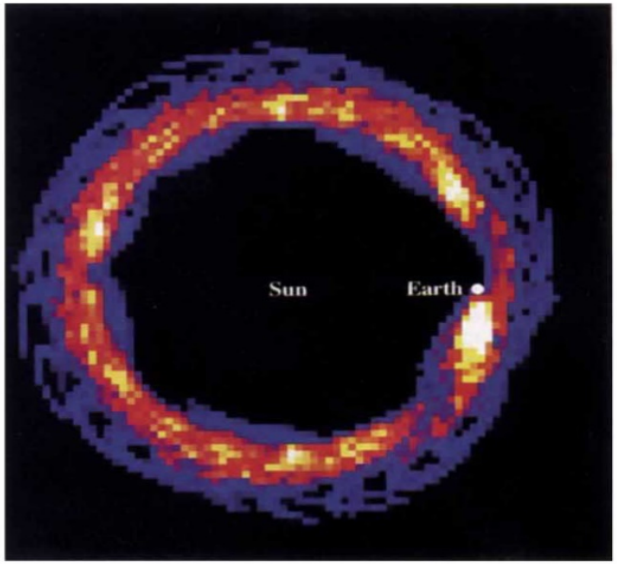
- **Part I**: Trajectory Design for Zodiacal Light Imaging Mission
- **Part II**: Starshade Observation Scheduling
  - Starshade Dynamics
  - Observation Scheduling
- **Part III**: Future Work

Part I: Trajectory Design for a Zodiacal Light Imaging Mission

Motivation

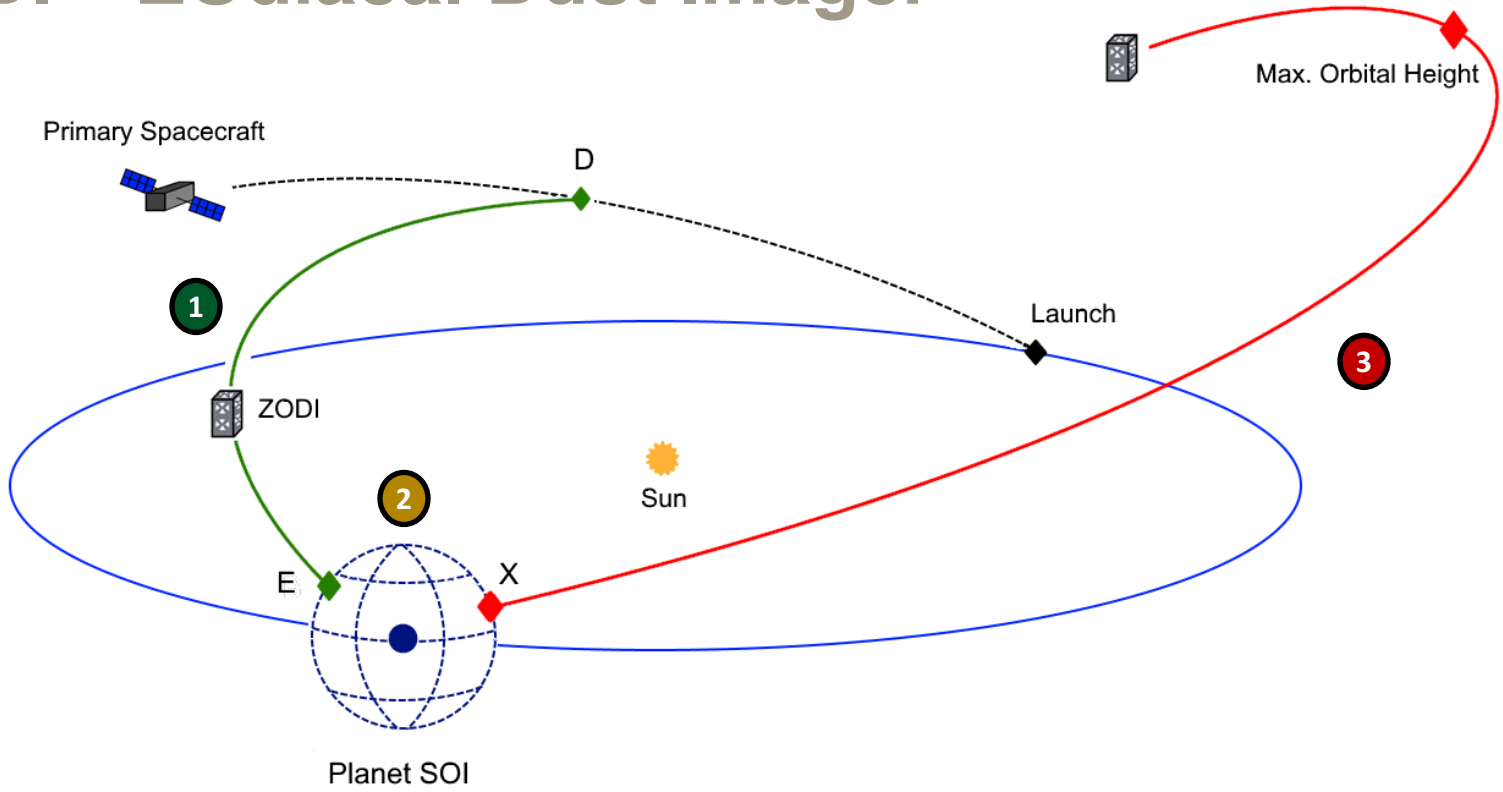


Reach et al, “The Three-Dimensional Structure of the Zodiacal Dust Bands,” *Icarus* 2007



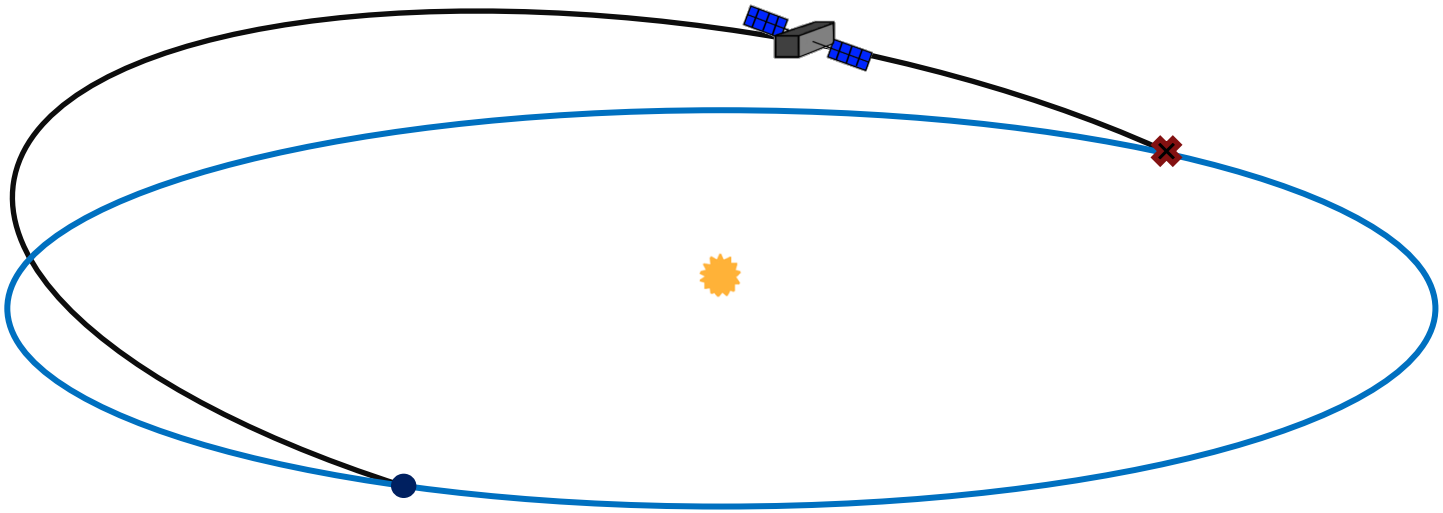
Dermott et al, “A circumsolar ring of asteroidal dust in resonant lock with the Earth,” *Nature* 1994

ZODI – ZOdiacal Dust Imager



Soto et al (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*

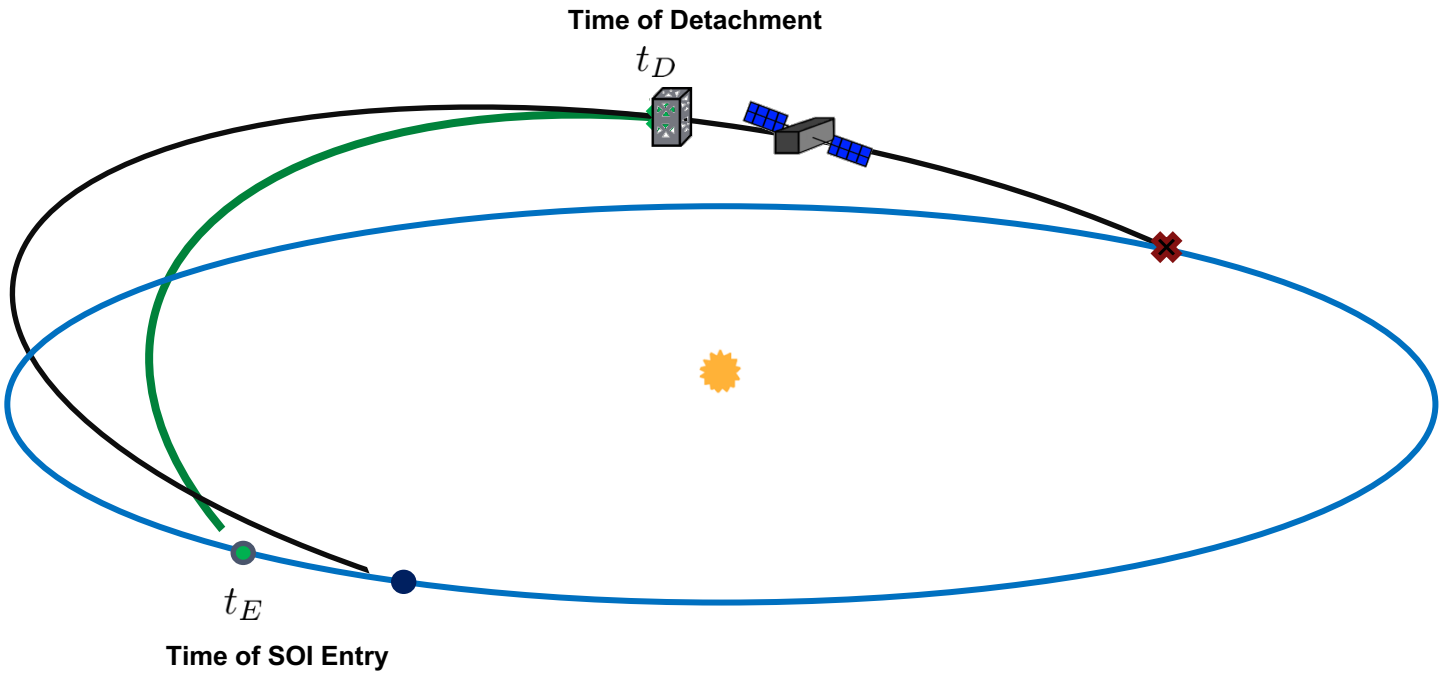
Before Flyby



Before Flyby

Inputs

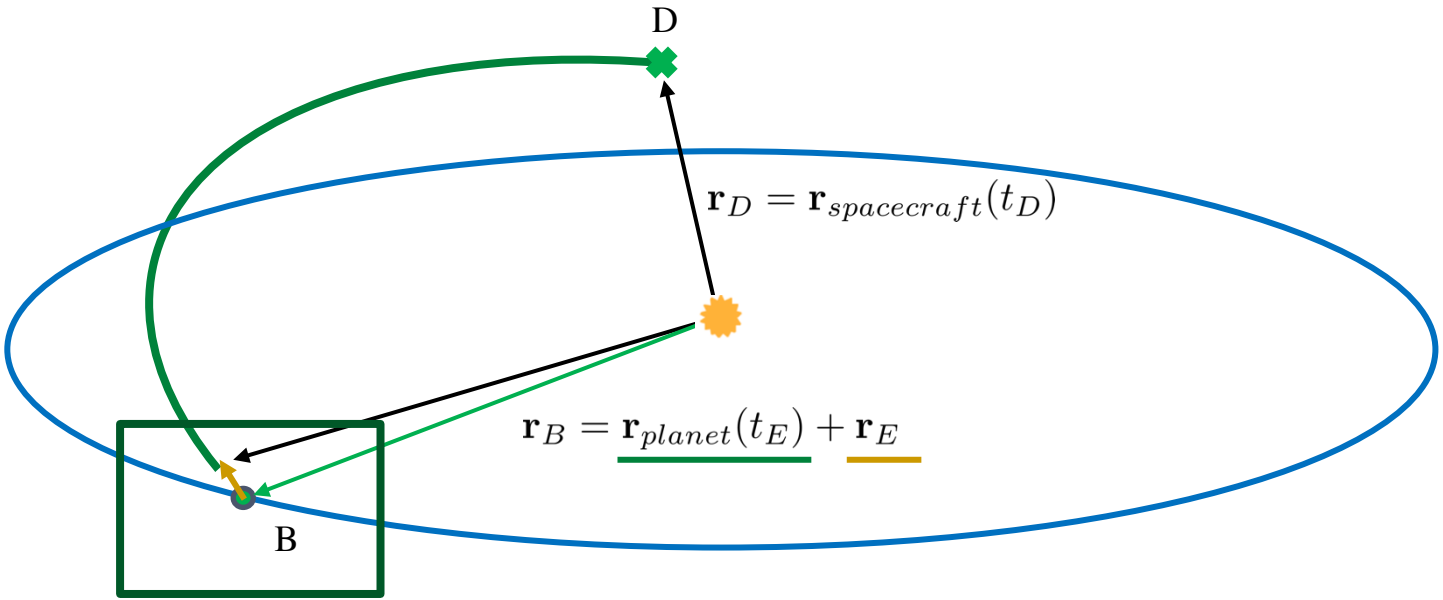
$$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \end{bmatrix}$$



Before Flyby

Inputs

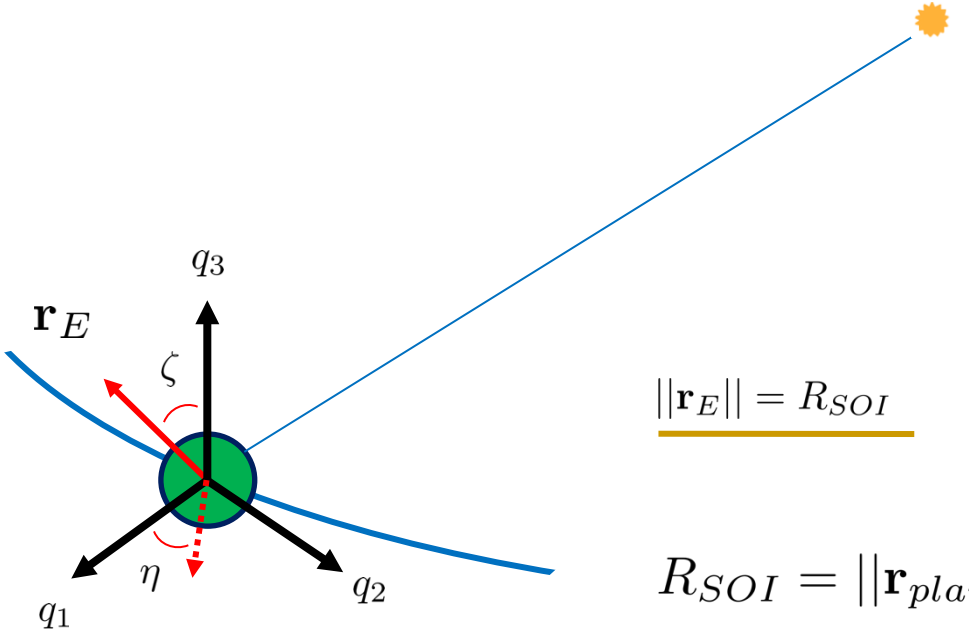
$$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \end{bmatrix}$$



Before Flyby (Planetary Frame)

Inputs

$$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \\ \eta \\ \zeta \end{bmatrix}$$



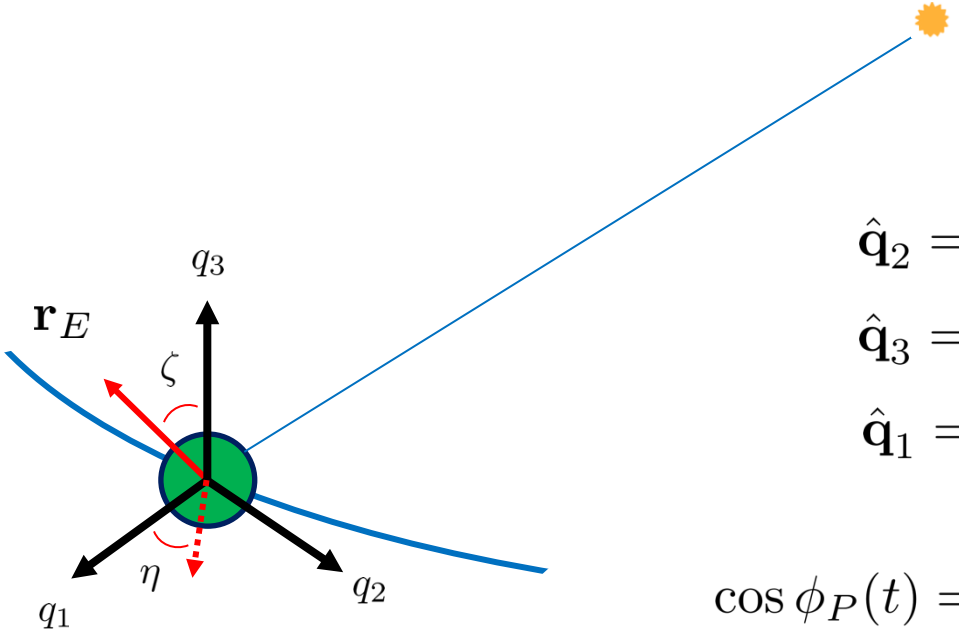
$$||\mathbf{r}_E|| = R_{SOI}$$

$$R_{SOI} = ||\mathbf{r}_{planet}(t_E)|| \left(\frac{\mu_P}{\mu_S}\right)^{0.4}$$

Before Flyby (Planetary Frame)

Inputs

$$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \\ \eta \\ \zeta \end{bmatrix}$$



$$\hat{\mathbf{q}}_2 = \hat{\mathbf{v}}_P(t)$$

$$\hat{\mathbf{q}}_3 = \frac{\hat{\mathbf{r}}_P(t) \times \hat{\mathbf{q}}_2}{\cos\phi_P(t)}$$

$$\hat{\mathbf{q}}_1 = \hat{\mathbf{q}}_2 \times \hat{\mathbf{q}}_3$$

$$\cos\phi_P(t) = \frac{\mathbf{r}_{planet} \times \mathbf{v}_{planet}}{||\mathbf{r}_{planet}||\ ||\mathbf{v}_{planet}||}$$

N. Strange, R. Russell, and B. Buffington, “Mapping the V-Infinity Globe,” *Proc. AAS/AIAA Astrodynamics 2007*

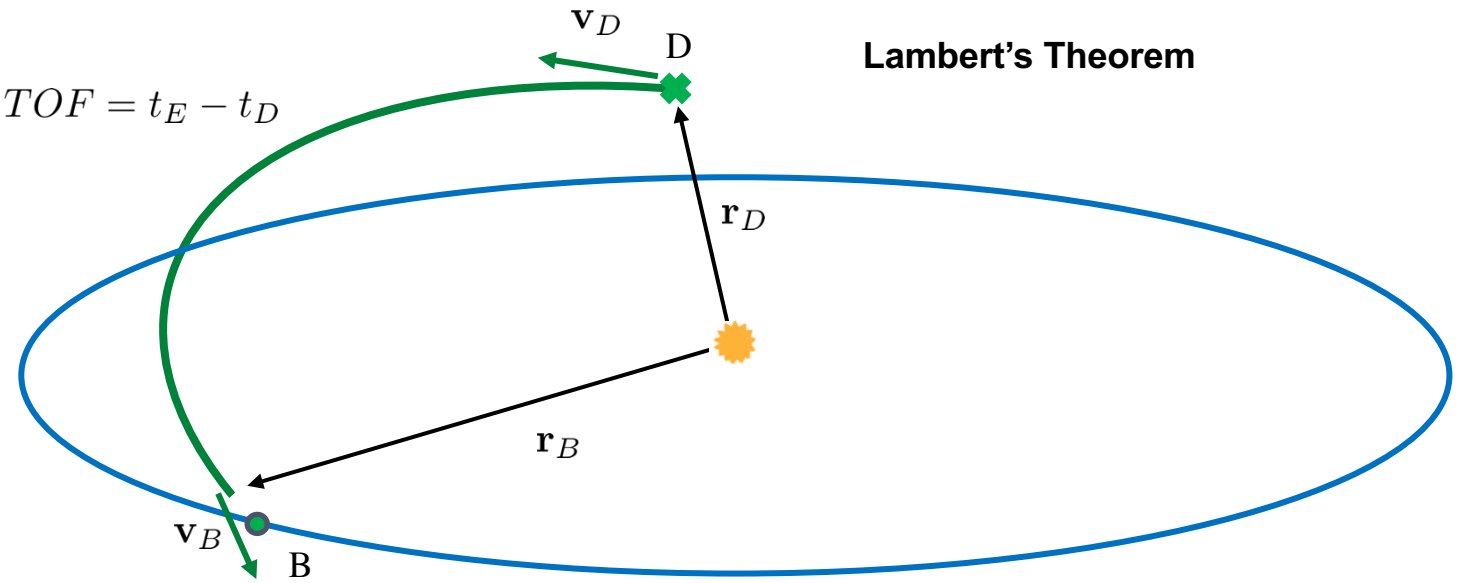
Before Flyby

Inputs

$$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \\ \eta \\ \zeta \end{bmatrix}$$

Lambert's Theorem

$$TOF = t_E - t_D$$



Before Flyby

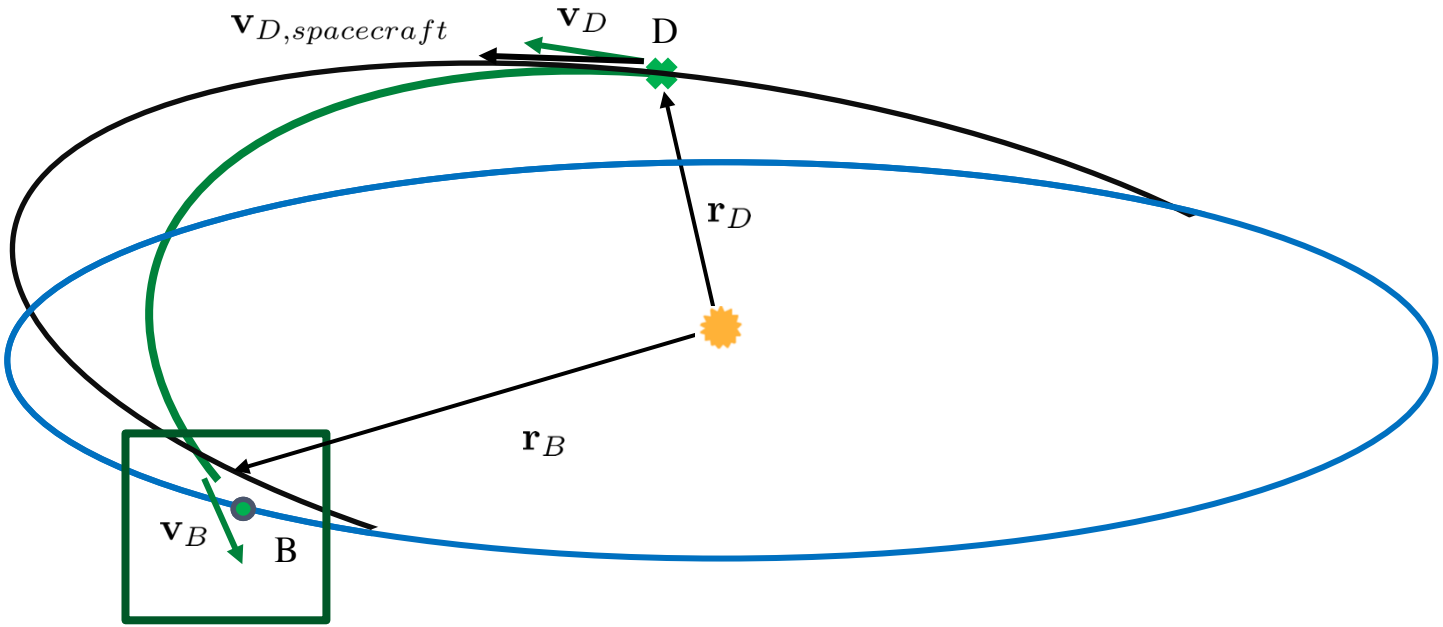
Constraints

$$\Delta v(t_D) < \Delta v_{max}$$

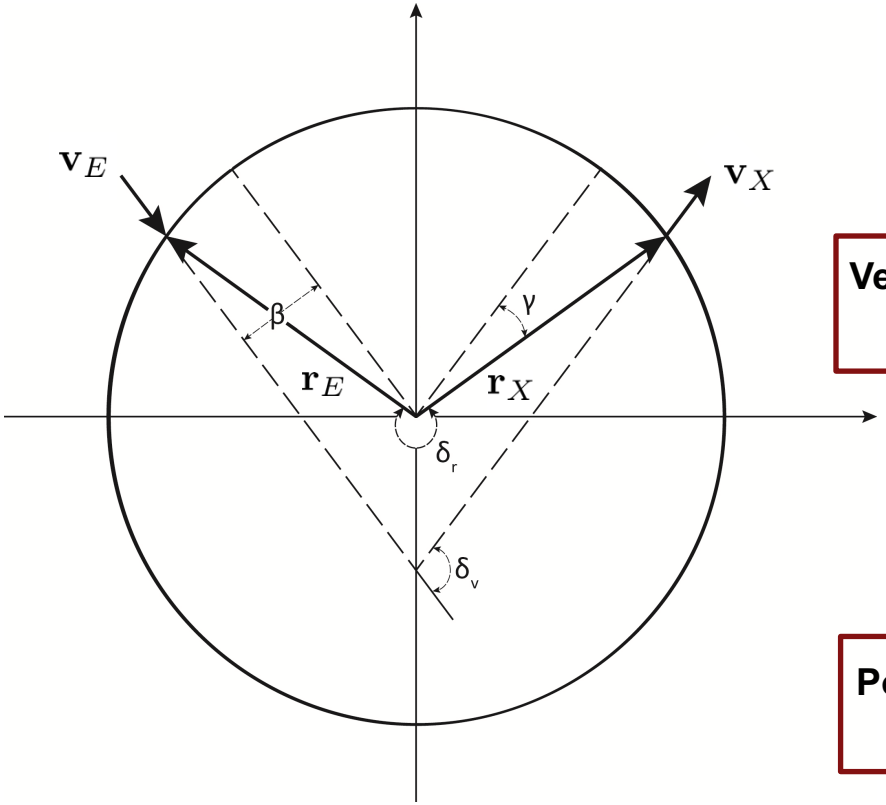
Inputs

$$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \\ \eta \\ \zeta \end{bmatrix}$$

$$\Delta v(t_D) = ||\mathbf{v}_D - \mathbf{v}_{D,spacecraft}||$$



During Flyby



Constraints

$$\Delta v(t_D) < \Delta v_{max}$$

$$\gamma < \gamma_{max}$$

$$r_{per} > R_P + h_{min}$$

Inputs

$$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \\ \eta \\ \zeta \end{bmatrix}$$

Velocity Turning Angle

$$\sin\frac{\delta_v}{2} = \frac{\mu_P}{\mu_P + r_{min} v_\infty^2}$$

$$\sin\gamma = \frac{B}{R_{SOI}} = \frac{||\mathbf{h}_E||}{R_{SOI} v_\infty}$$

$$B = \frac{||\mathbf{r}_E \times \mathbf{v}_E||}{v_E}$$

Position Turning Angle

$$\delta_r = \delta_v - 2\gamma - \pi$$

Labunsky et al (1998) *Multiple Gravity Assist Interplanetary Trajectories* 1st edition

After Flyby

Constraints

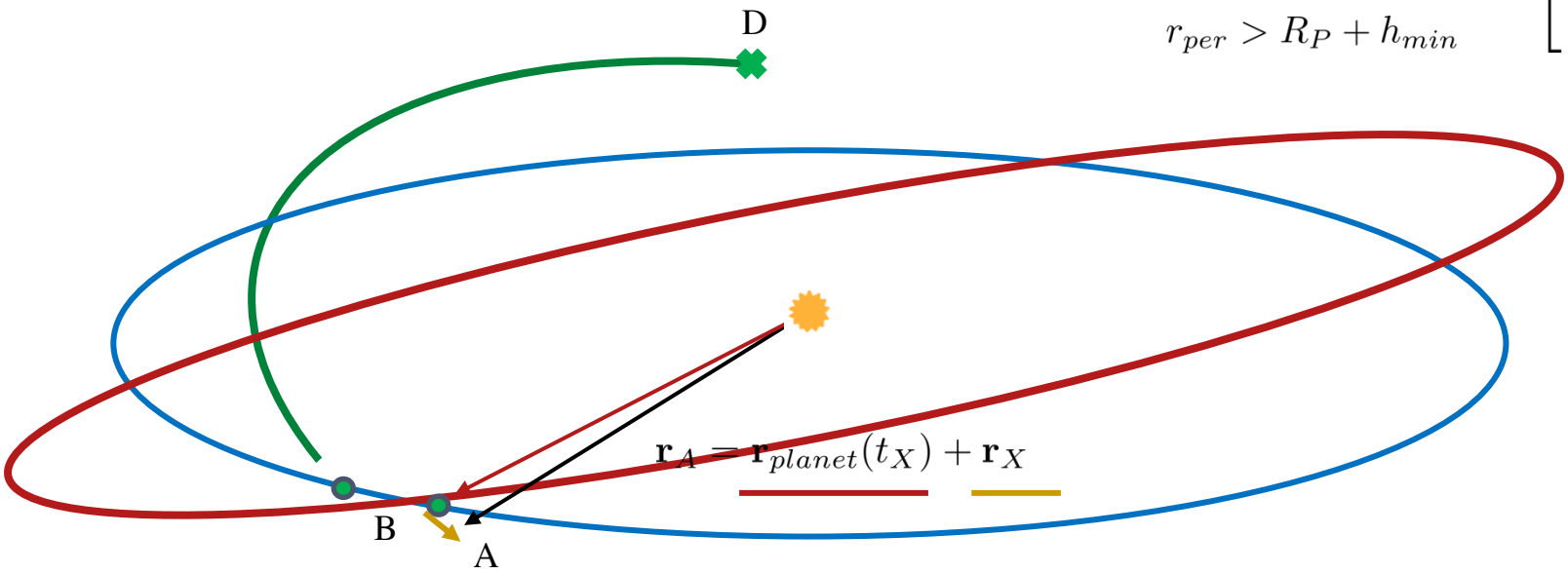
$$\Delta v(t_D) < \Delta v_{max}$$

$$\gamma < \gamma_{max}$$

$$r_{per} > R_P + h_{min}$$

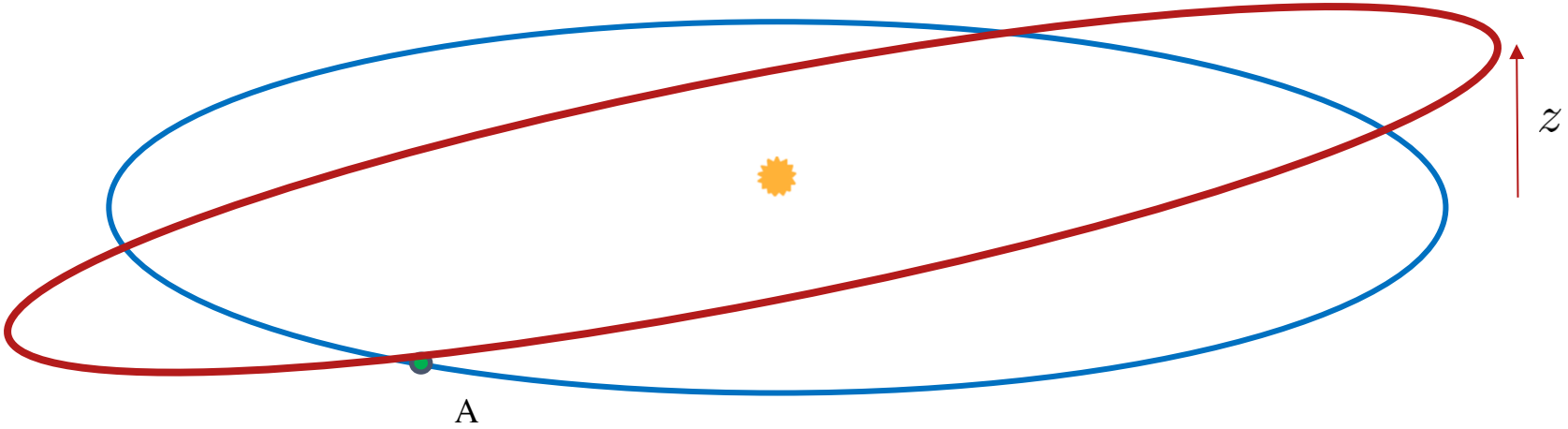
Inputs

$$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \\ \eta \\ \zeta \end{bmatrix}$$



After Flyby

Goal	Constraints	Inputs
$\underset{\mathbf{u}}{\text{maximize}}\ \lvert z \rvert$	$\Delta v(t_D) < \Delta v_{max}$ $\gamma < \gamma_{max}$ $r_{per} > R_P + h_{min}$	$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \\ \eta \\ \zeta \end{bmatrix}$

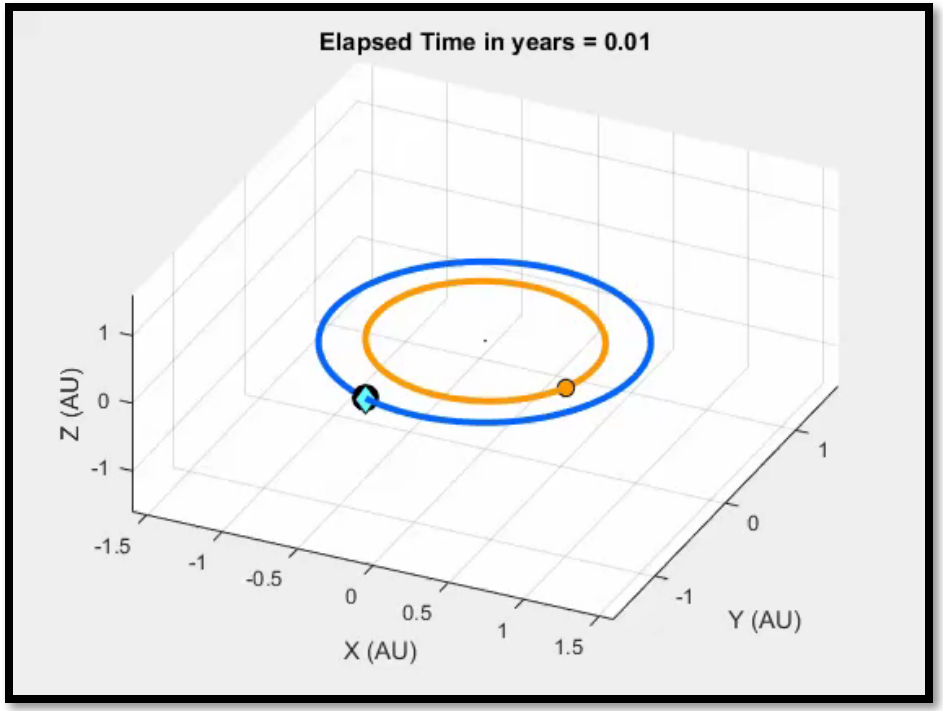


After Flyby

Goal	Constraints	Inputs
$\underset{\mathbf{u}}{\text{maximize}}\ \lvert z \rvert$	$\Delta v(t_D) < \Delta v_{max}$	$\mathbf{u} = \begin{bmatrix} t_D \\ t_E \\ \eta \\ \zeta \end{bmatrix}$
	$\gamma < \gamma_{max}$	
	$r_{per} > R_P + h_{min}$	
	$1.0002 > f_T > 0.9998$	

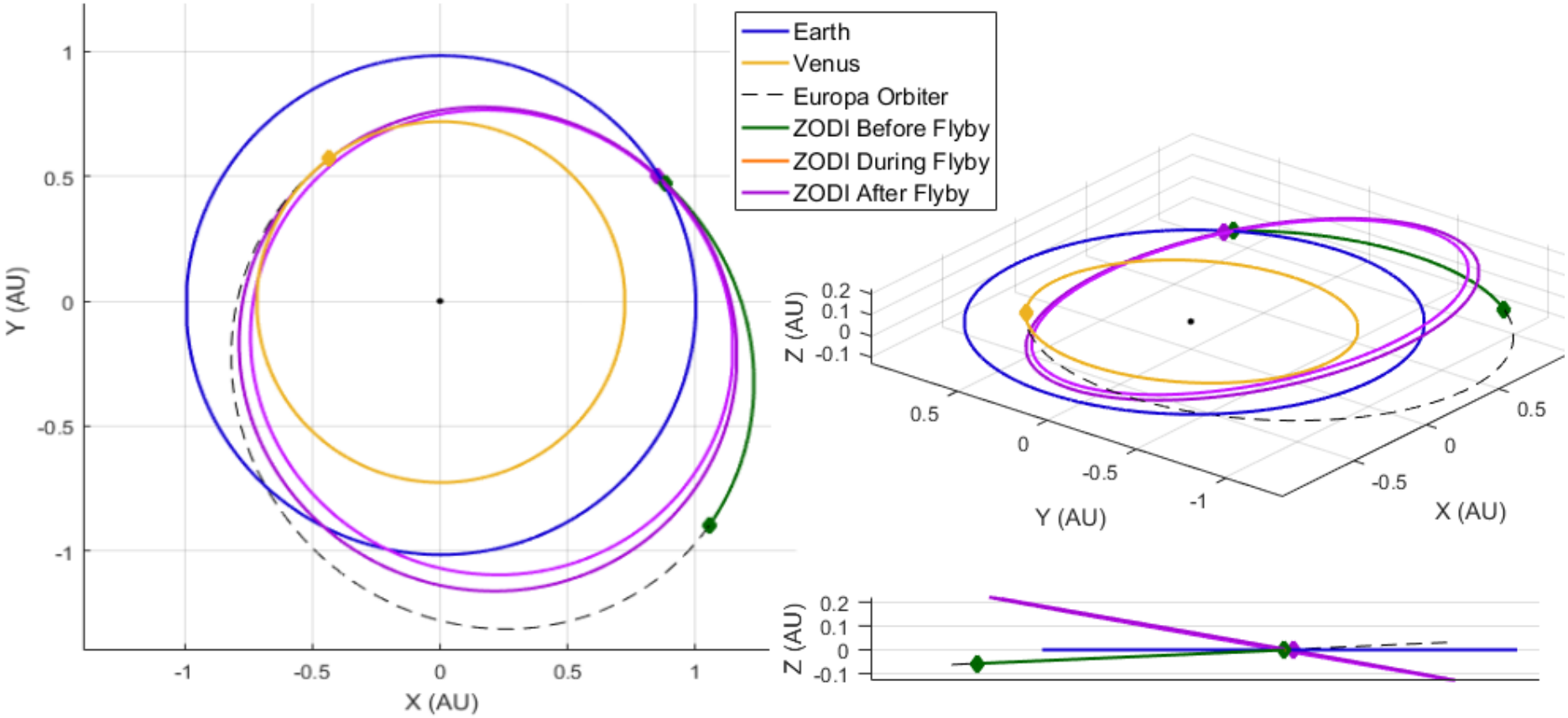
1. Limit Fuel Mass
2. Achieve Proper Field of View
3. Retrieve Data $\quad f_T = \frac{T_A}{T_{Earth}}$

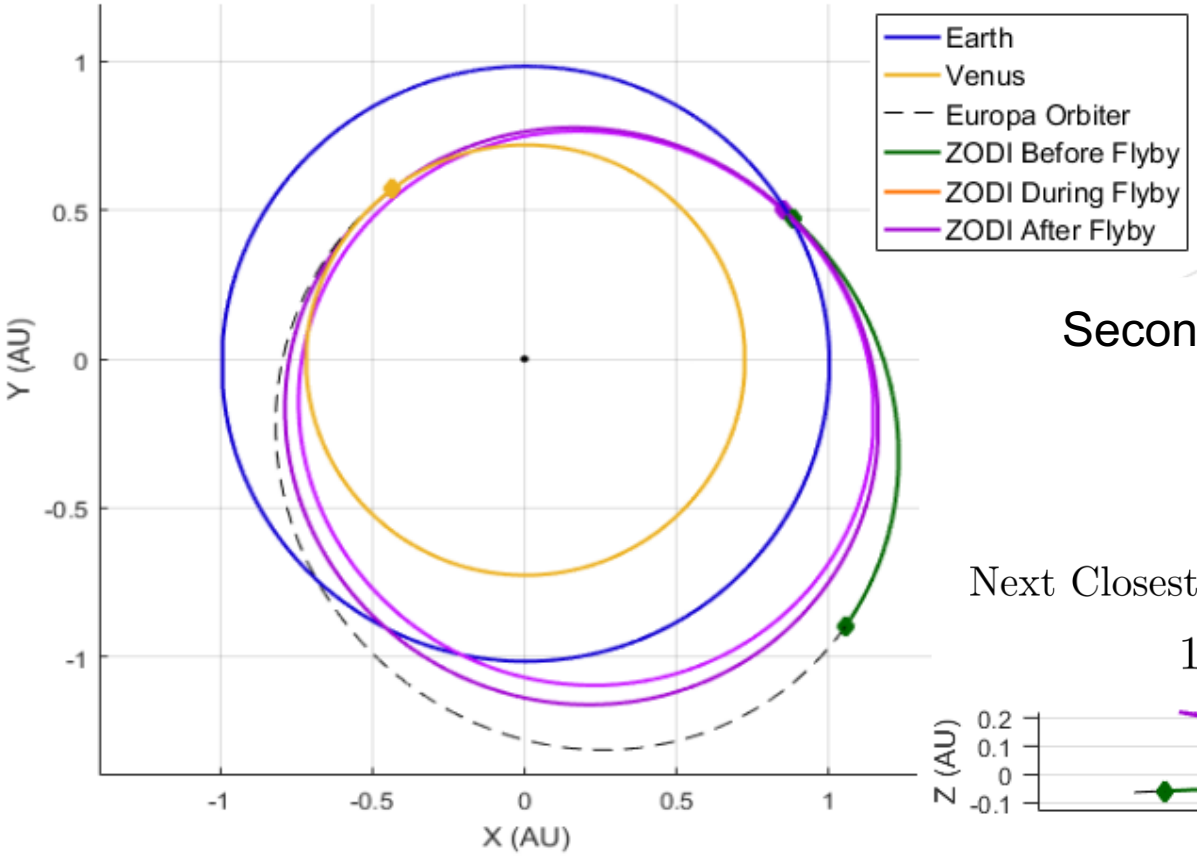
Case Study with Europa Clipper



Launch	May 29, 2022
Earth Flyby 1	May 31, 2023
Venus Flyby 1	Nov 24, 2023
Earth Flyby 2	Oct 21, 2024
Europa Clipper Trajectory	
Venus Orbit	
Earth Orbit	

SPK kernel taken from Acton, C. and is found at https://naif.jpl.nasa.gov/pub/naif/EUROPACLIPPER/


Earth
Venus
Europa Orbiter
ZODI Before Flyby
ZODI During Flyby
ZODI After Flyby
Y (AU)
X (AU)
Z (AU)
Y (AU)
X (AU)
Z (AU)



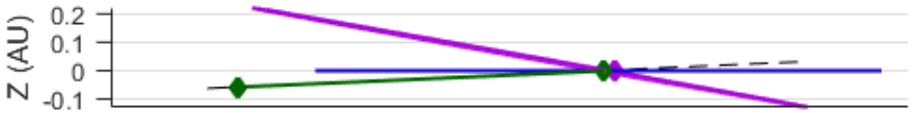
Second Earth Flyby – 10/21/2024

$$z_{max} = 0.2215\text{AU}$$

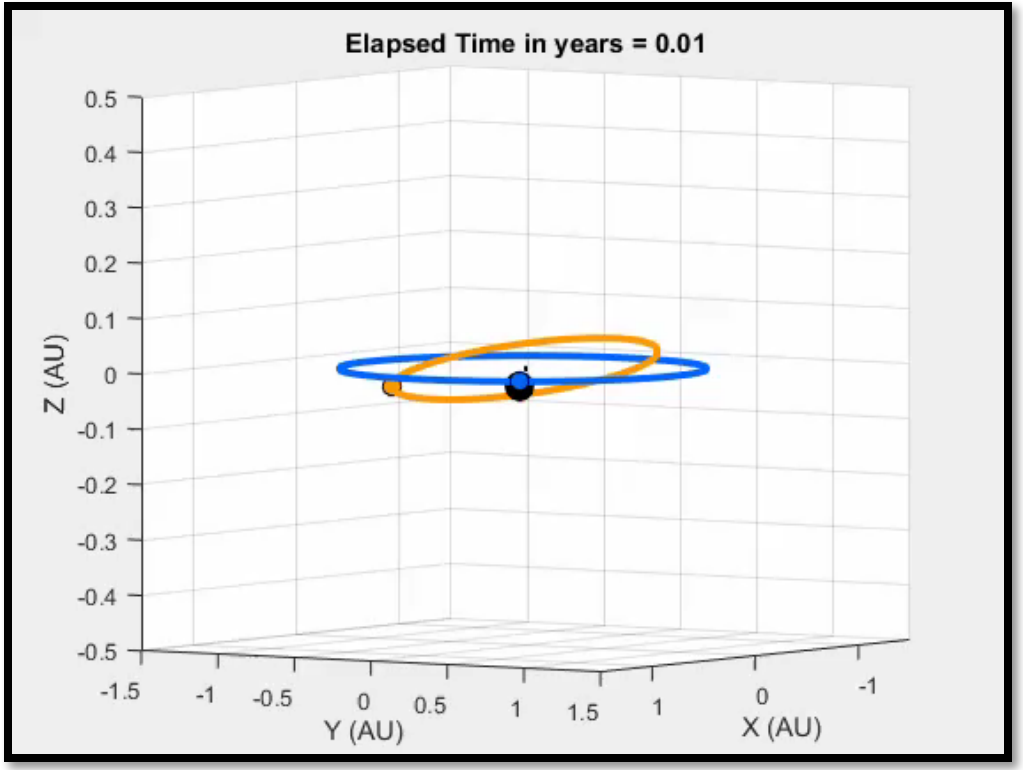
$$\Delta v = 37.21\text{m/s}$$

$$\text{Next Closest Earth Approach} = 2.13 \times 10^5\text{km}$$

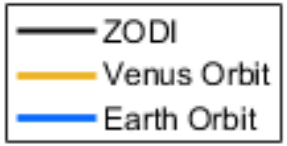
$$10/22/2025, \quad 1\text{yr later}$$



Conclusions



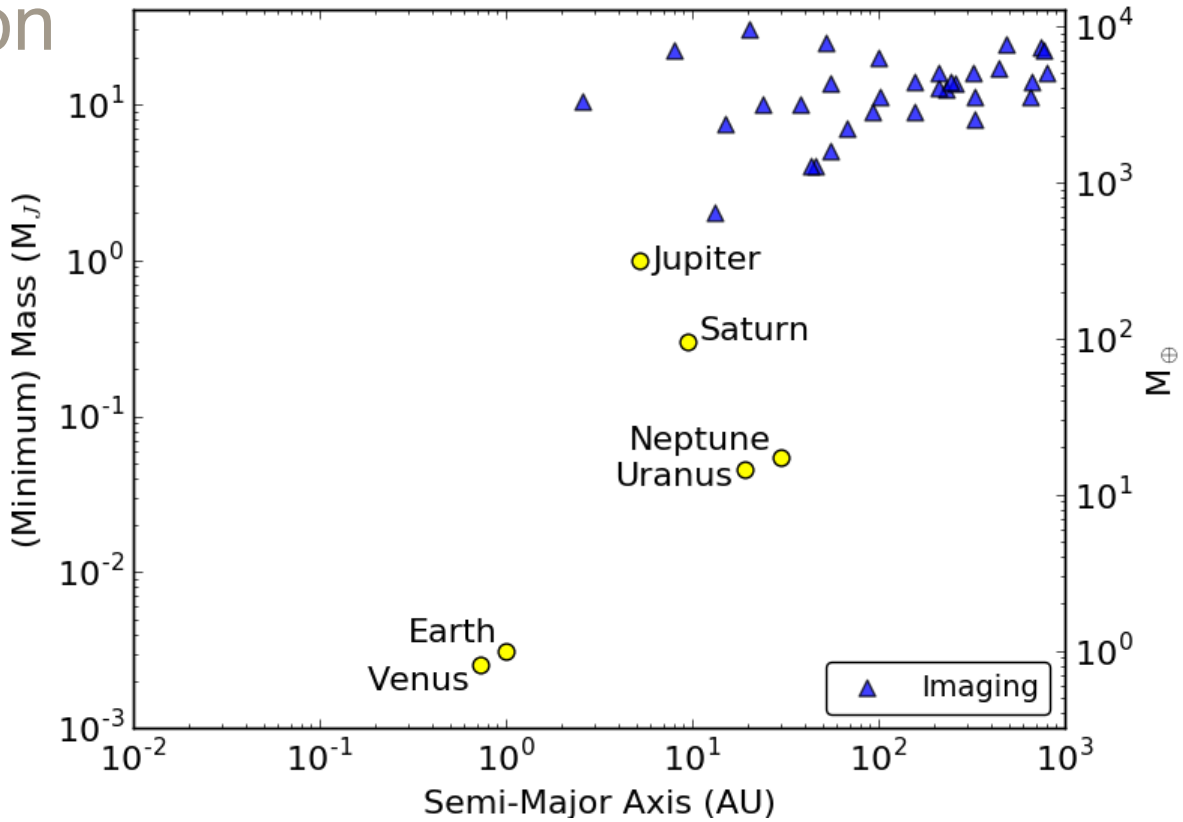
- Developed algorithm for optimizing flyby based on mission requirements
  - Achieves goal: 0.22 AU orbital height
  - Small impulsive correction
- Requires no integration, low computational cost
- Applicable to any payload of opportunity



Part II: Starshade Observation Scheduling for Exoplanet Imaging

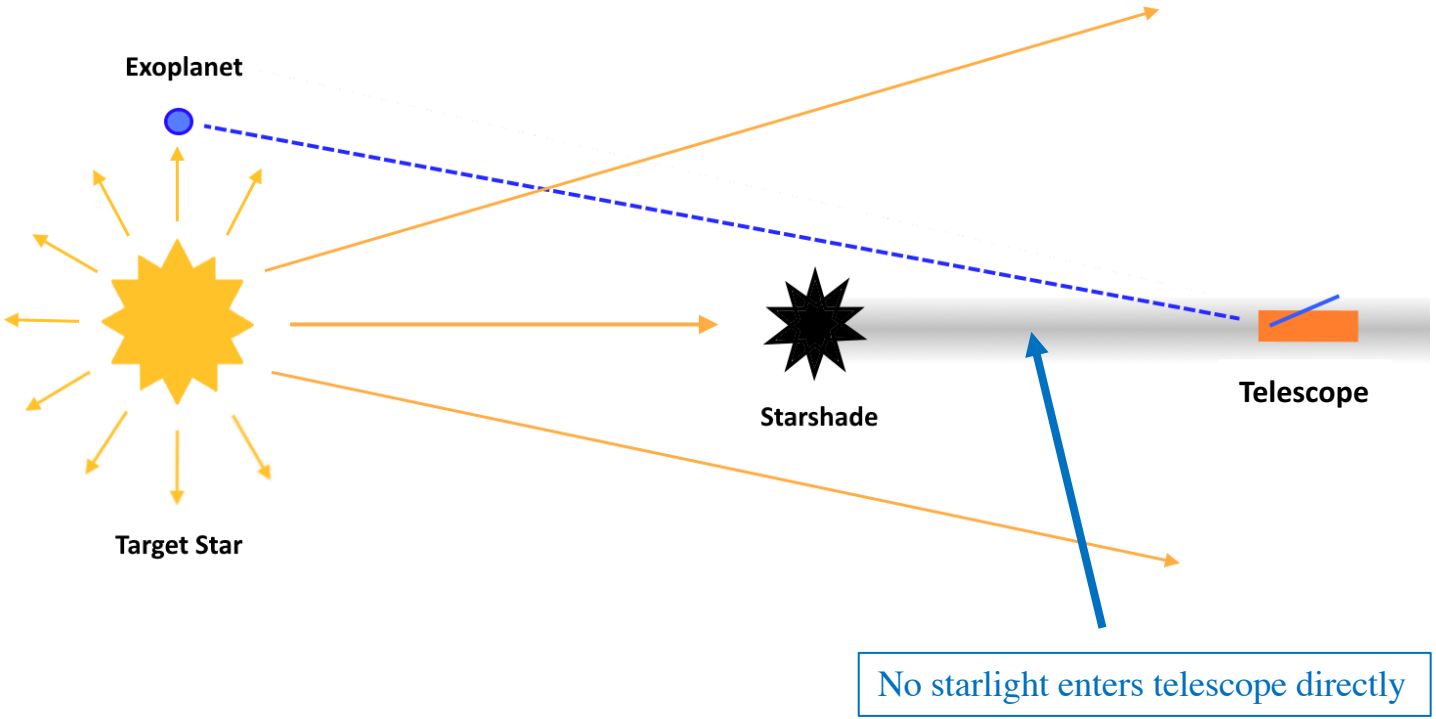
Starshade Dynamics

Motivation

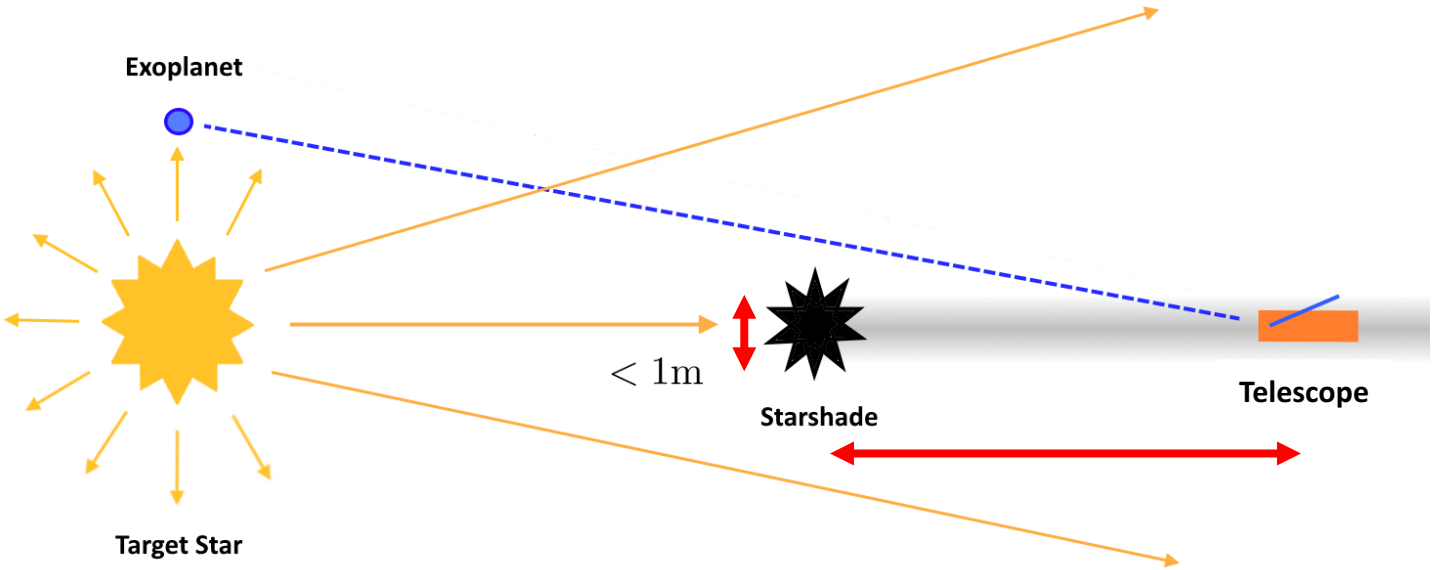


Data taken from NASA Exoplanet Archive found at
http://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=planets

Starshade Configuration



Starshade Configuration

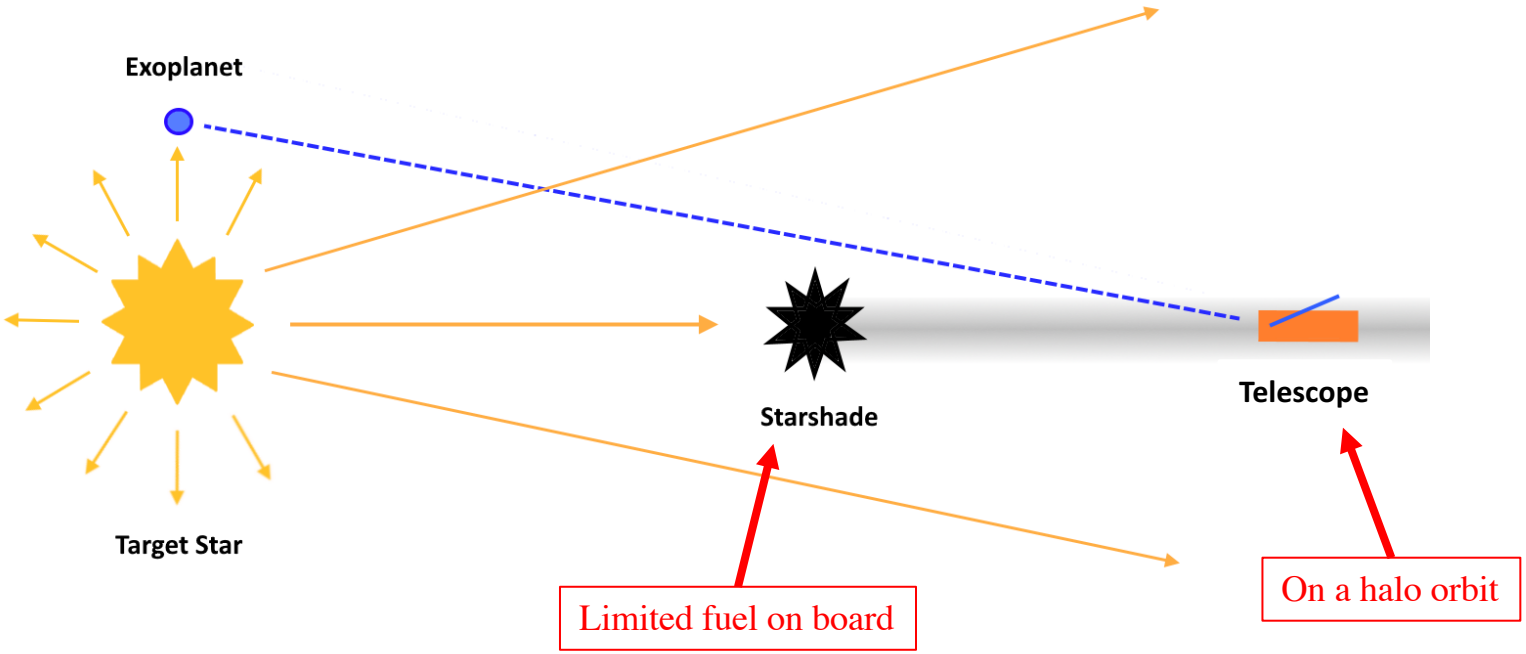


Maintain constant separation during observation

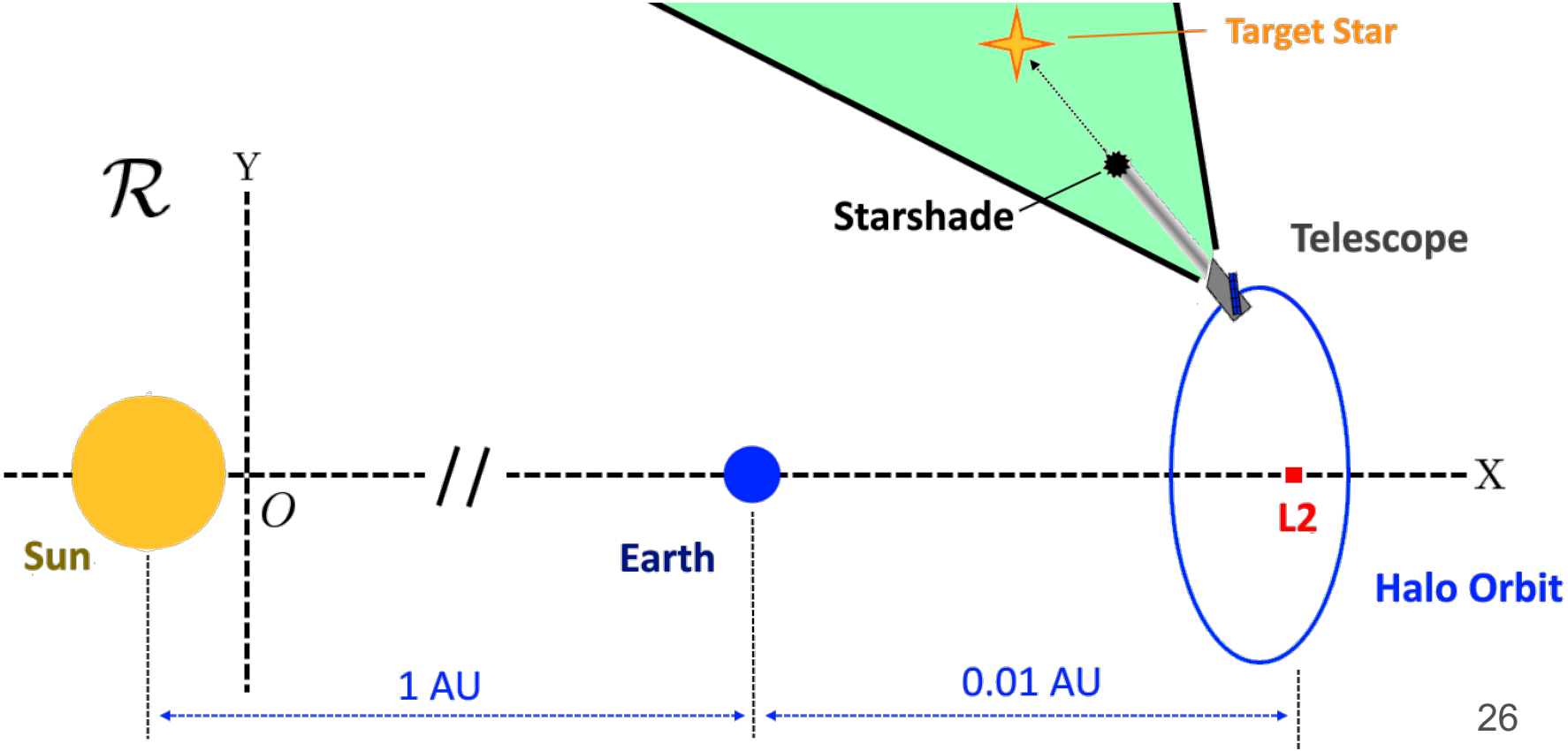
Seager et al (2015) “The Exo-S Probe Class Starshade Mission”

Shaklan et al (2011) "A starshade petal error budget for exo-earth detection and characterization” *SPIE*

Starshade Configuration



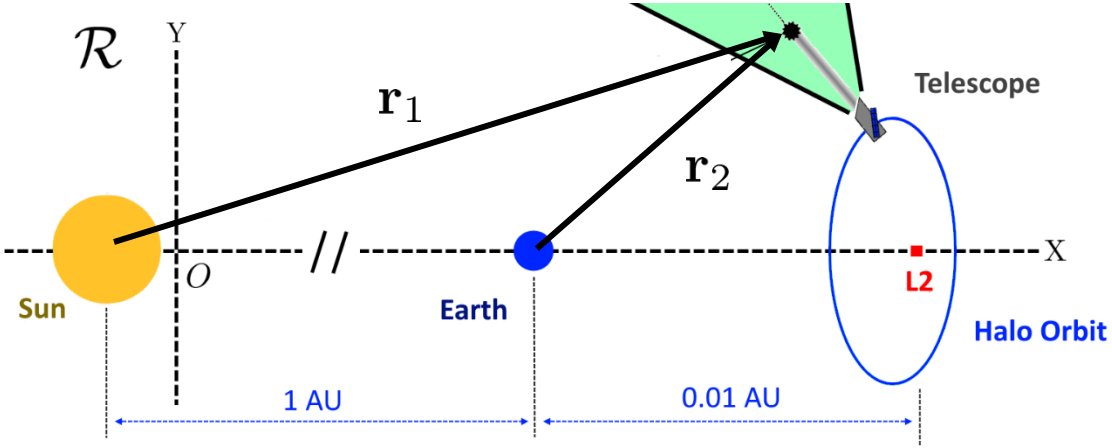
Starshade in the CR3BP Frame



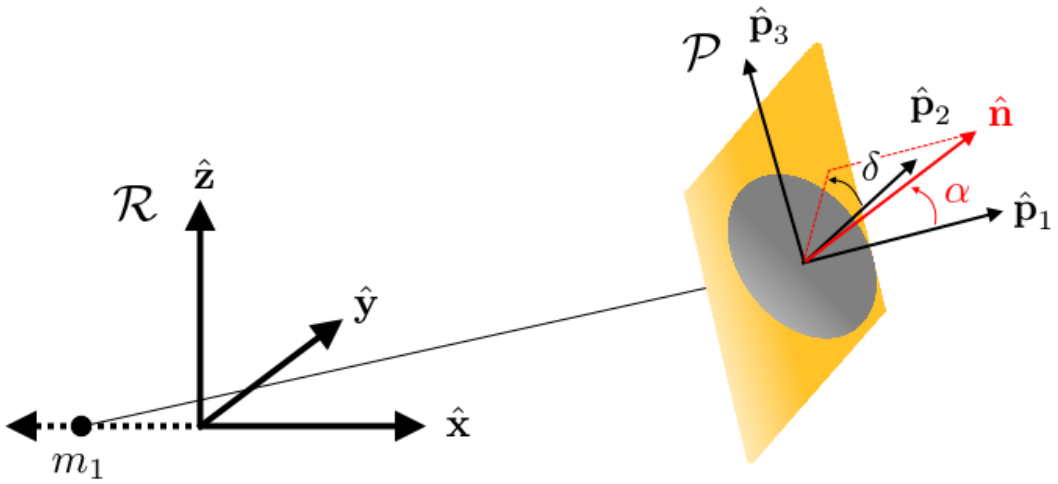
Starshade in the CR3BP Frame

$$\ddot{x} - 2\dot{y} = \frac{\partial \Omega}{\partial x} + \mathbf{f}_{SRP} \cdot \hat{\mathbf{x}}$$
$$\ddot{y} + 2\dot{x} = \frac{\partial \Omega}{\partial y} + \mathbf{f}_{SRP} \cdot \hat{\mathbf{y}}$$
$$\ddot{z} = \frac{\partial \Omega}{\partial z} + \mathbf{f}_{SRP} \cdot \hat{\mathbf{z}}$$

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



Solar Radiation Pressure



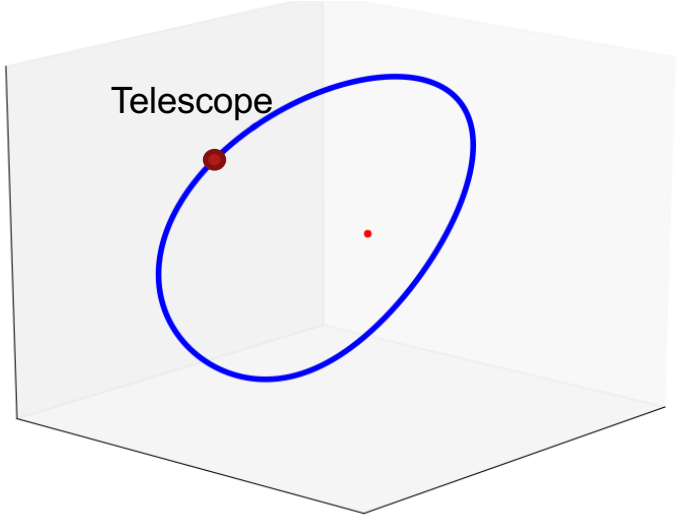
$$\mathbf{f}_{SRP} = 2PA\cos\alpha\left[b_1\hat{\mathbf{p}}_1 + (b_2\cos\alpha + b_3)\hat{\mathbf{n}}\right]$$

$$\hat{\mathbf{n}} = \cos\alpha\hat{\mathbf{p}}_1 + \sin\alpha\cos\delta\hat{\mathbf{p}}_2 + \sin\alpha\sin\delta\hat{\mathbf{p}}_3$$

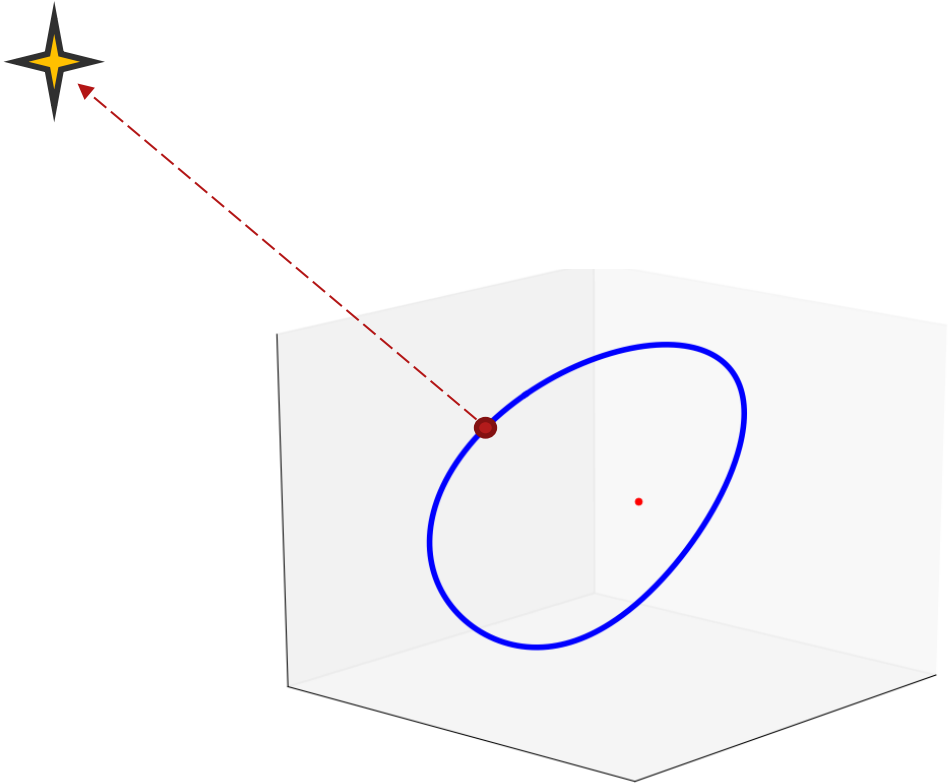
Glassman et al (2011) “Creating optimal observation schedules for a starshade planet-finding mission” *IEEE*
McIness (1999) *Solar Sailing: Technology, Dynamics, and Mission Applications*
Soto et al (2018) “Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules.” *JGCD* (submitted)

Flight Modes

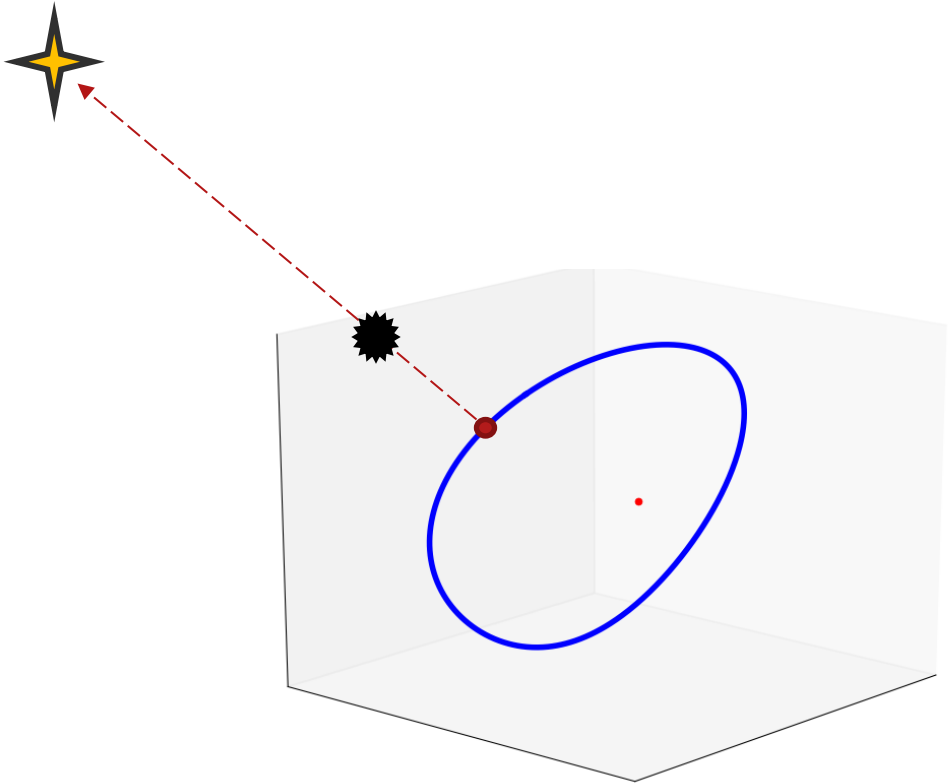
Target Star “A”



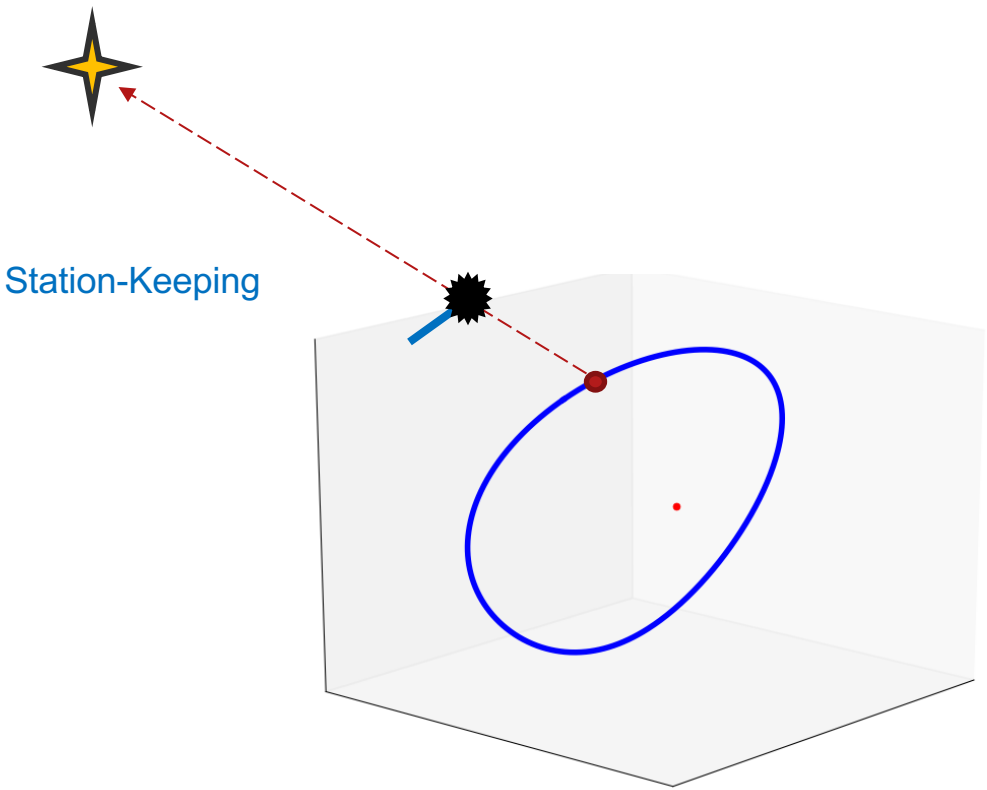
Flight Modes



Flight Modes



Flight Modes

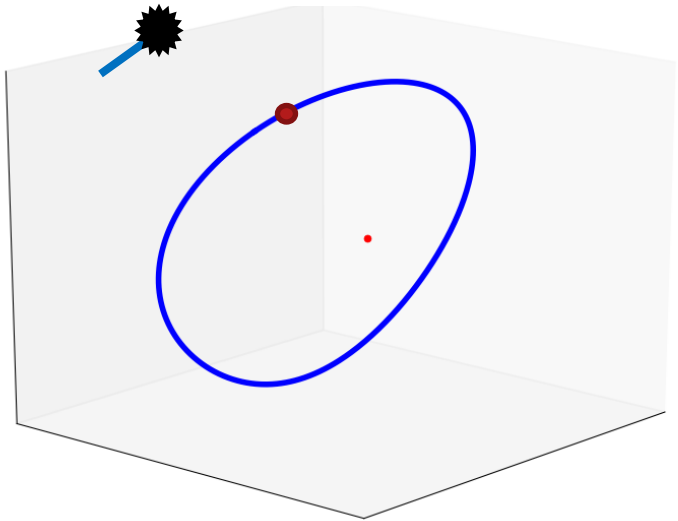


Flight Modes

Target Star “B”

Target Star “A”

Station-Keeping

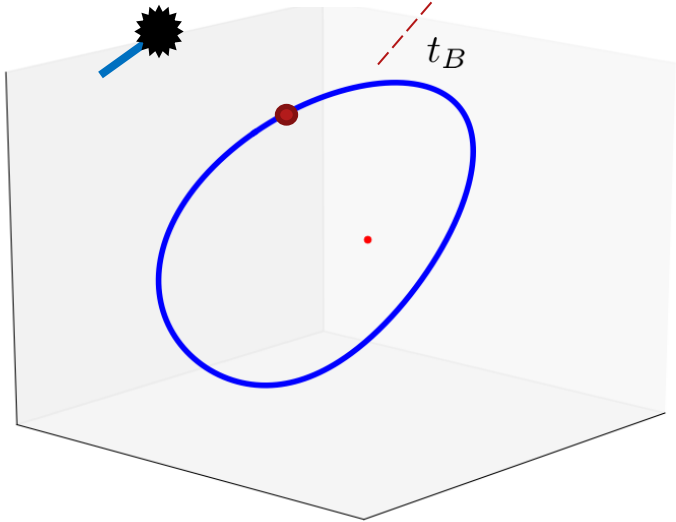


Flight Modes

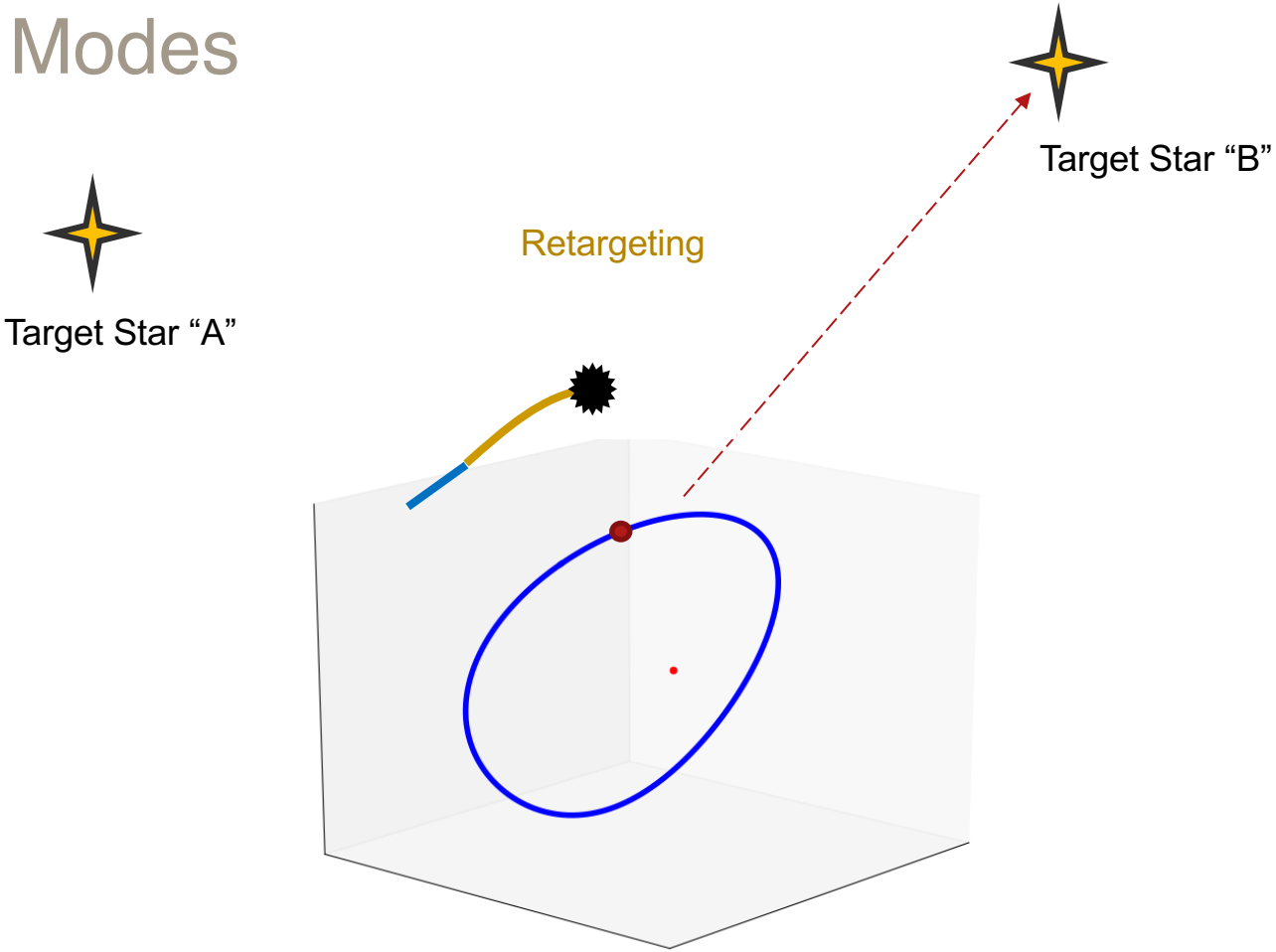
Target Star “A”

Target Star “B”

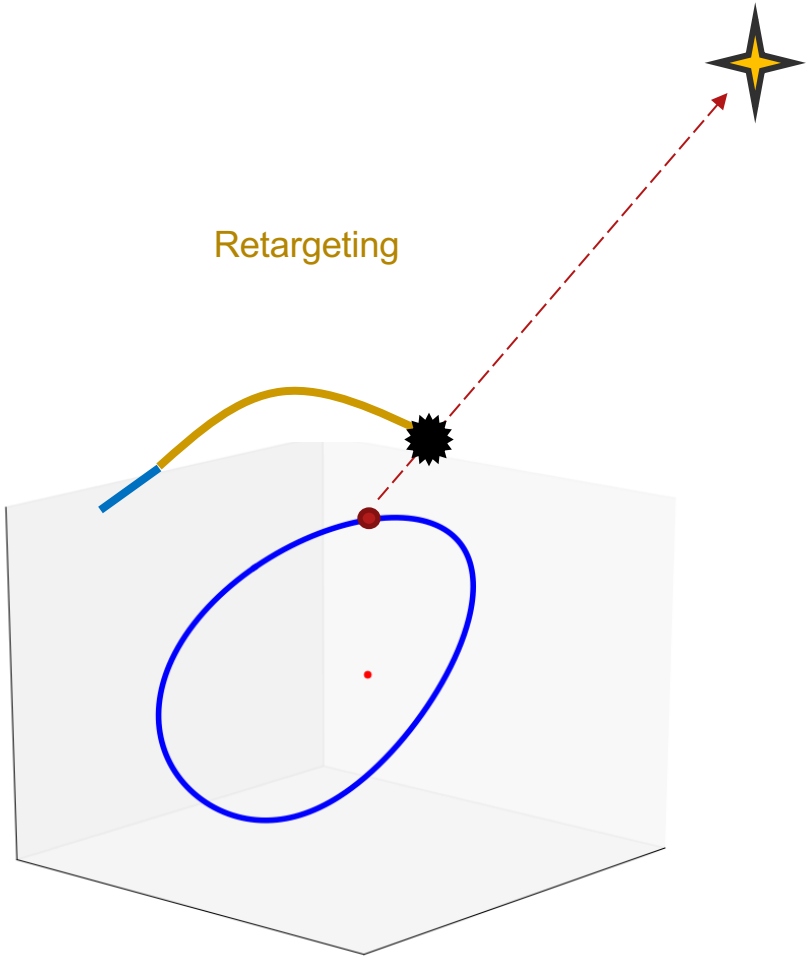
Station-Keeping



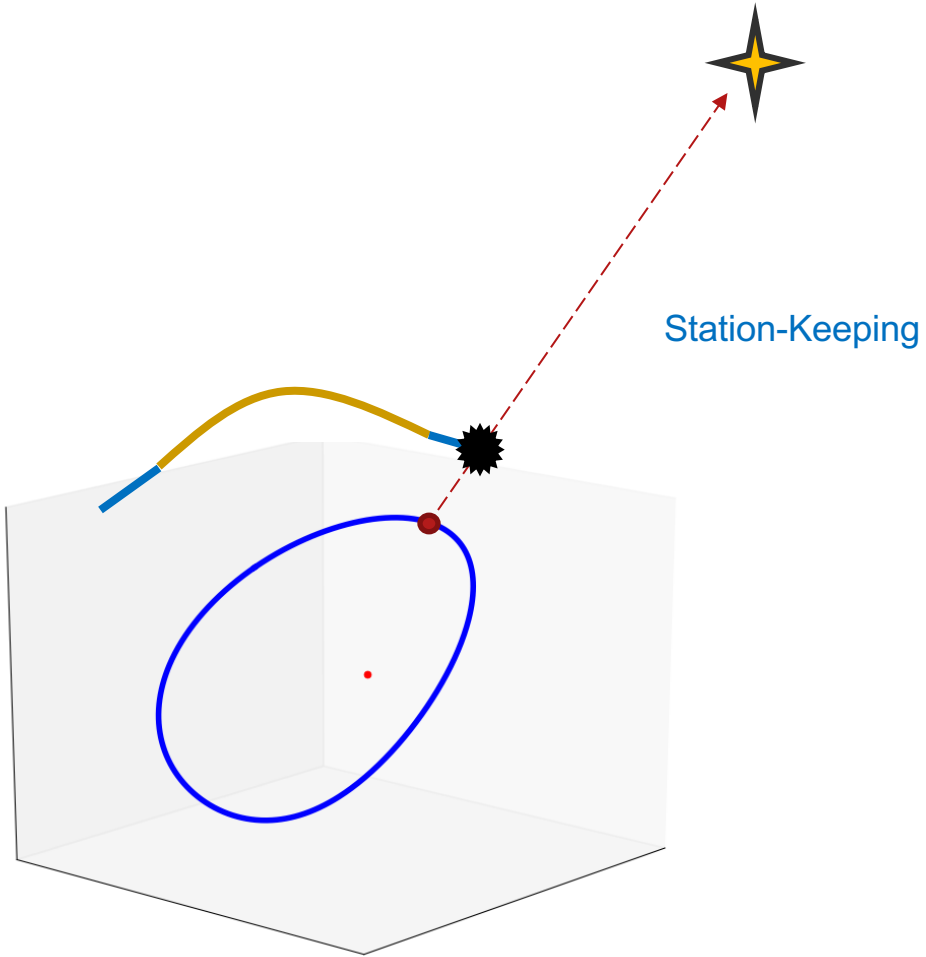
Flight Modes



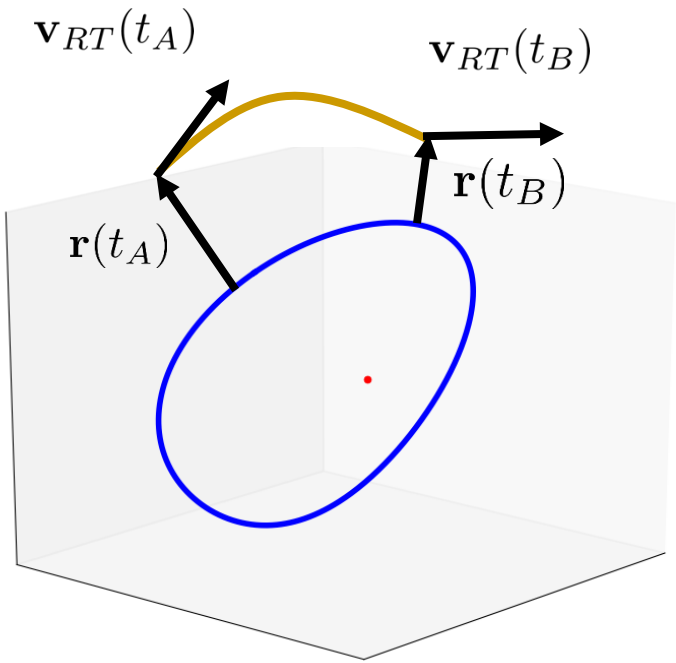
Flight Modes



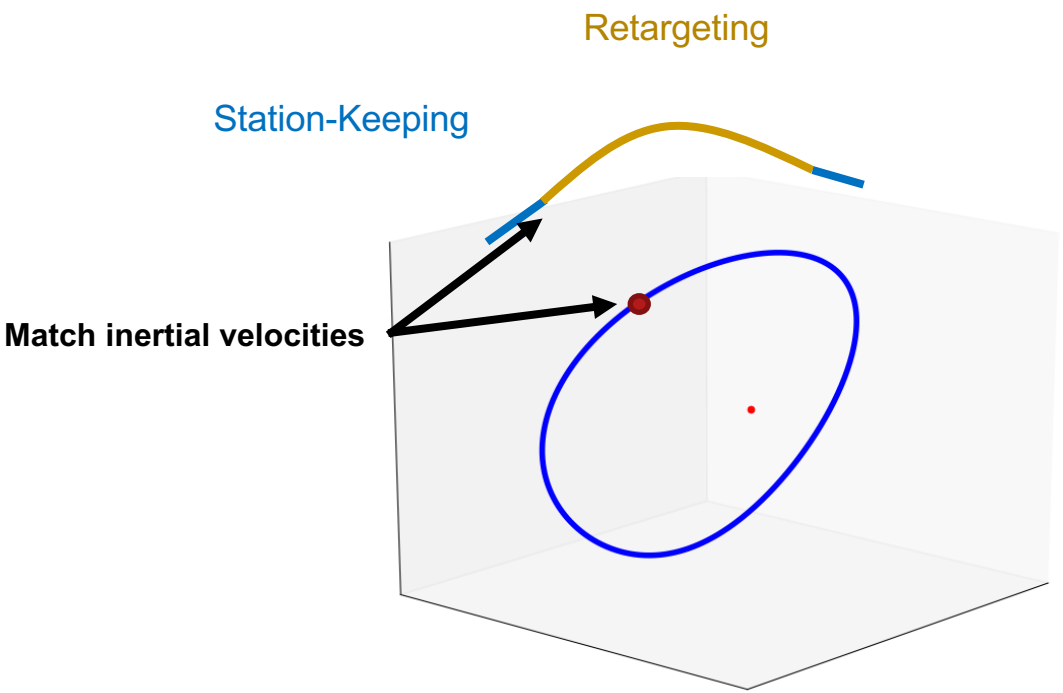
Flight Modes



Retargeting Trajectories



Retargeting Trajectories

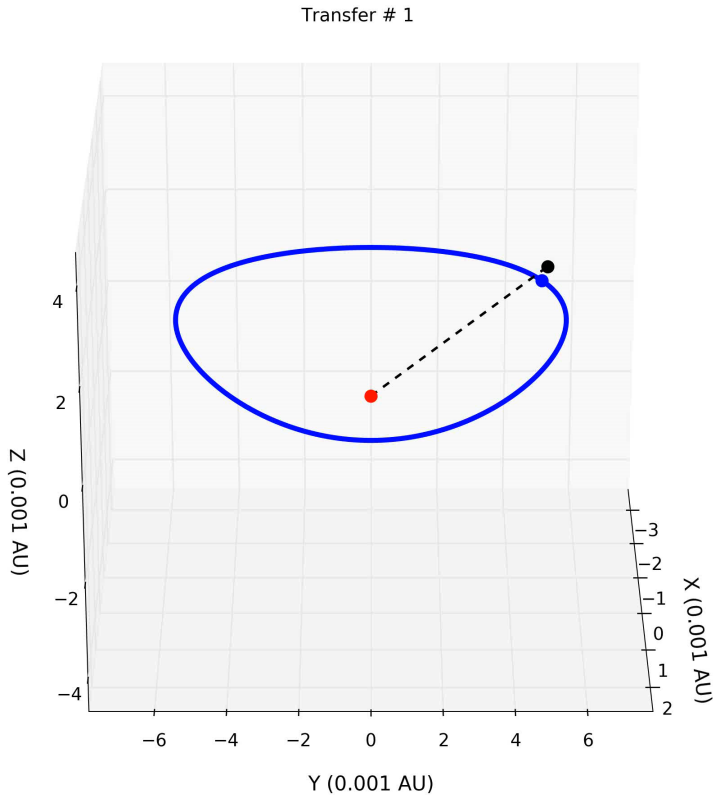


$$\Delta v(t_A) = ||{}^{\mathcal{I}}\mathbf{v}_{RT}(t_A) - {}^{\mathcal{I}}\mathbf{v}_{SK}(t_A)||$$
$$\Delta v(t_B) = ||{}^{\mathcal{I}}\mathbf{v}_{RT}(t_B) - {}^{\mathcal{I}}\mathbf{v}_{SK}(t_B)||$$

Kolemen and Kasdin (2012) “Optimization of an occulter-based extrasolar-planet-imaging mission” *JGCD*

Retargeting Trajectories

Diameter	26 m
IWA	72 mas
Separation Distance	37,242.26 km
Dry Mass	1250 kg
Total Mass	3500 kg
I_{sp}	308 s
Total Δv	2094.33 m/s



Seager et al (2015) “The Exo-S Probe Class Starshade Mission”

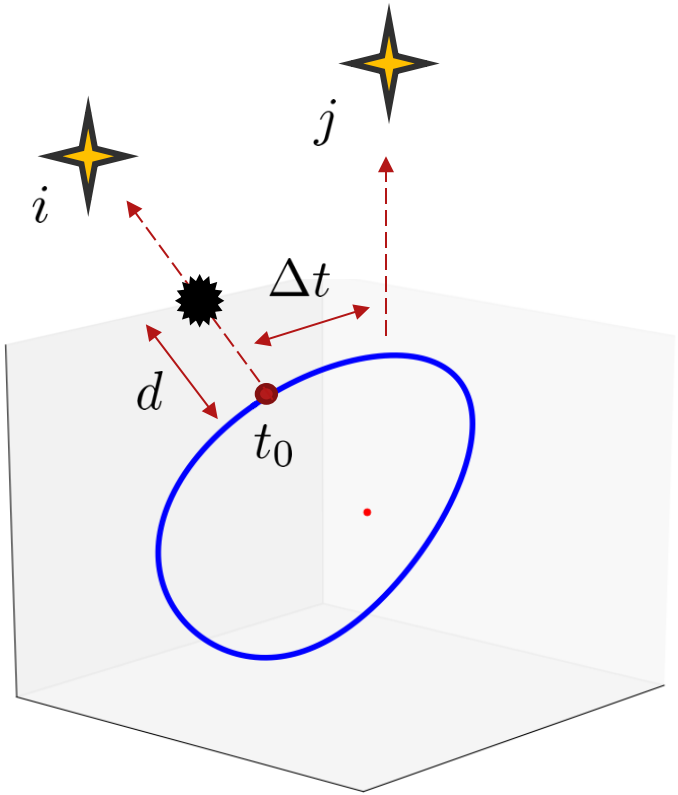
Shaklan et al (2011) "A starshade petal error budget for exo-earth detection and characterization” *SPIE*

Part II: Starshade Observation Scheduling for Exoplanet Imaging

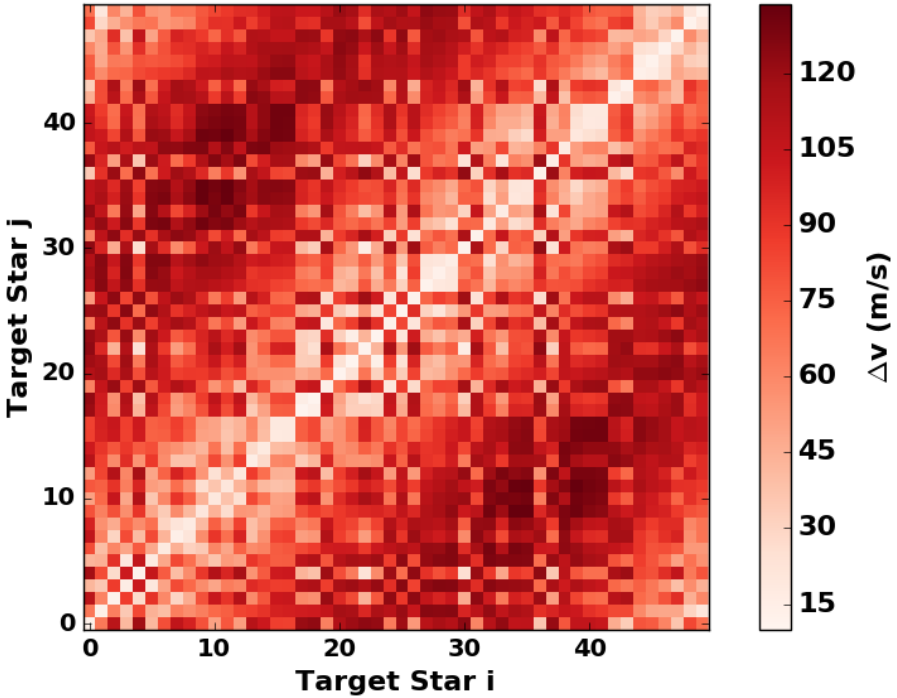
Observation Scheduling

Parameterizing Fuel Costs

$$\Delta v = f(i, j, \Delta t, t_0, \underline{T_{halo}, d})$$



Parameterizing Fuel Costs

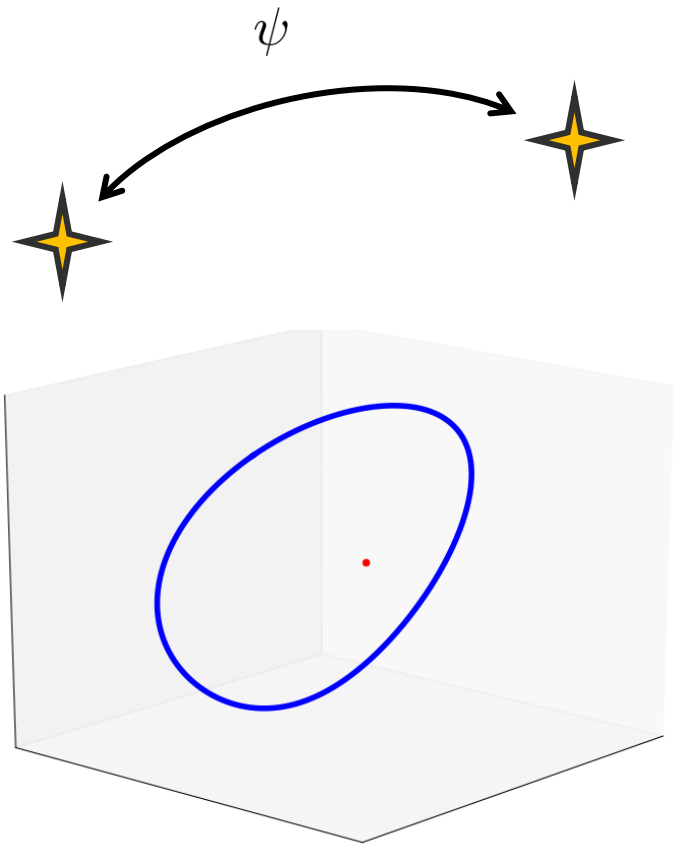


- Stars arranged by ecliptic longitude
- Constant slew time of 20 days
- 3D cost matrix for multiple slew times

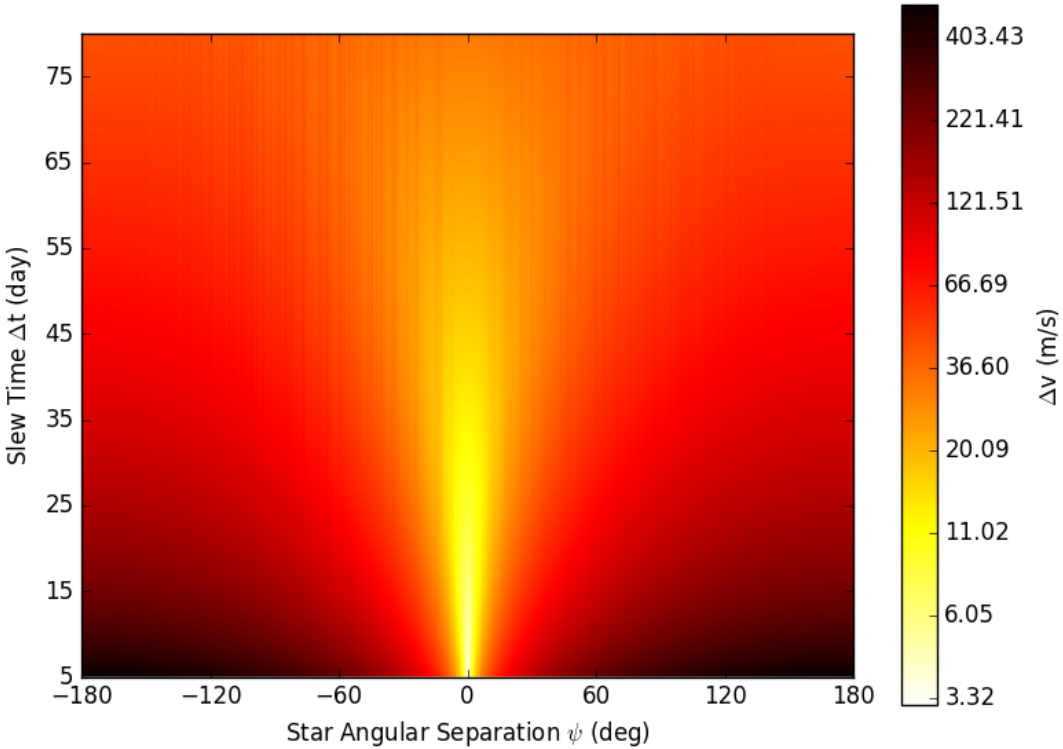
Kolemen and Kasdin (2012) "Optimization of an occulter-based extrasolar-planet-imaging mission" *JGCD*

Soto et al (2018) "Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules." *JGCD* (submitted)

Parameterizing Fuel Costs



Parameterizing Fuel Costs



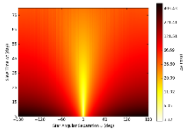
$$\Delta v = f(i, j, \Delta t, t_0)$$

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

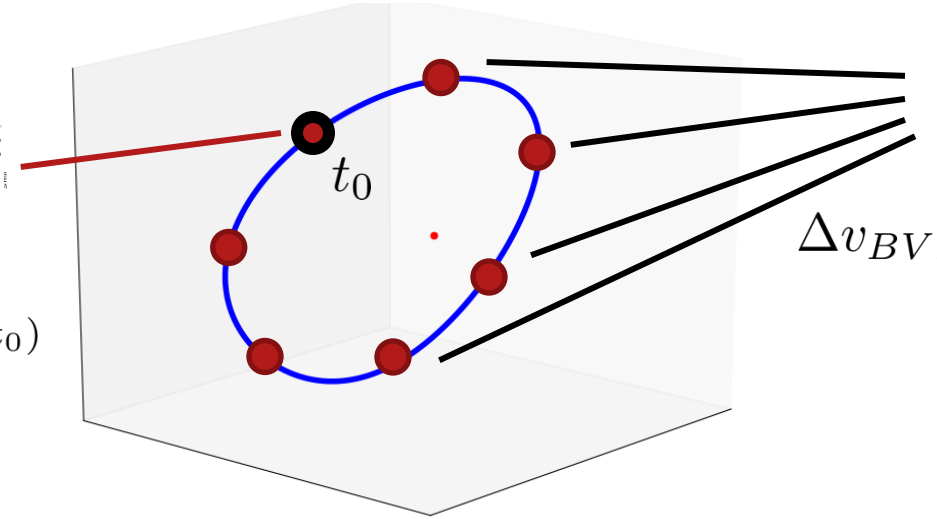
Soto et al (2018) “Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules.” *JGCD* (submitted)

Parameterizing Fuel Costs - Errors

Interpolated Solution



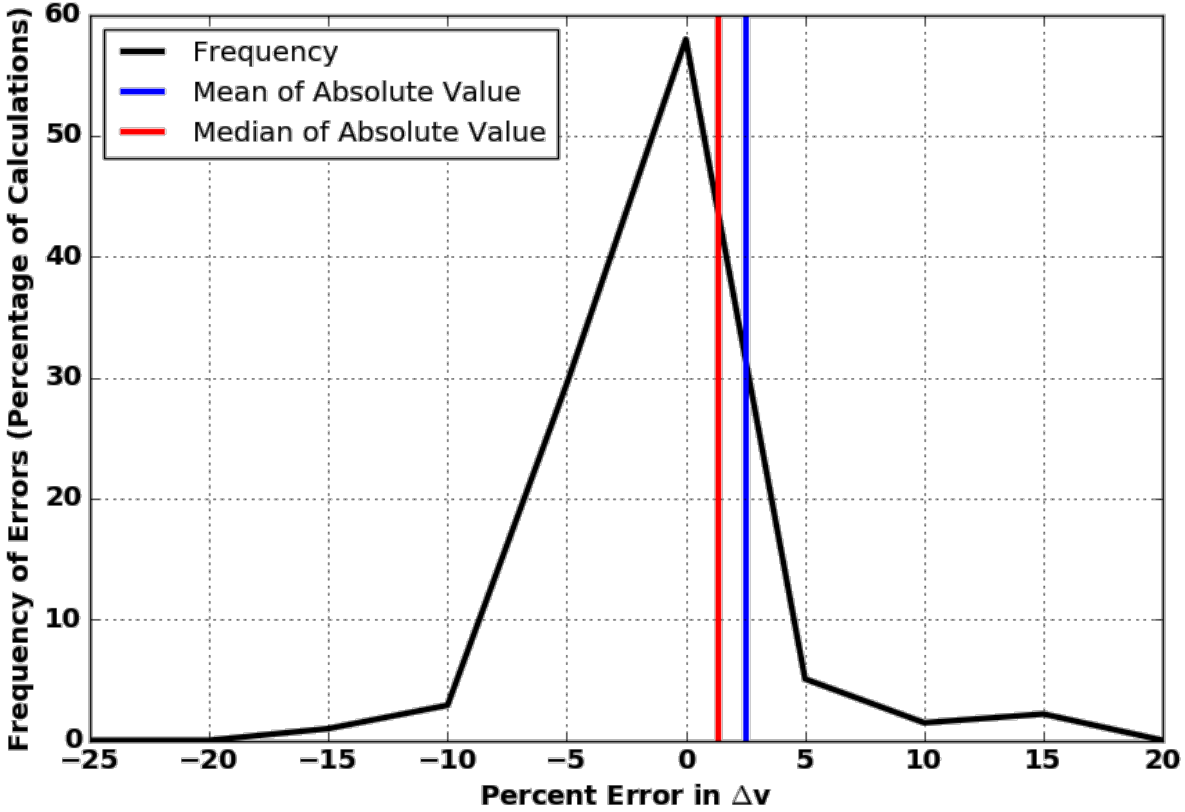
$$\Delta v_{INT} = f(\Delta t)|_{(\psi_0, t_0)}$$



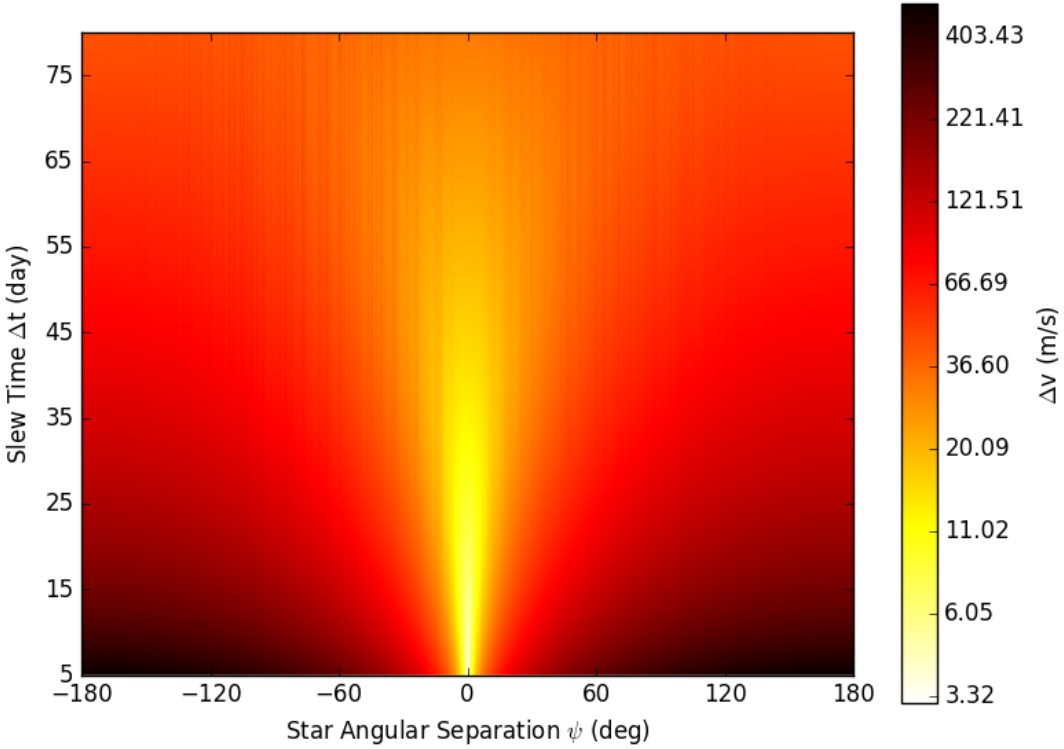
BVP Solution

$$\Delta v_{BVP} = f(\Delta t, t0)|_{\psi_0}$$

Parameterizing Fuel Costs - Errors



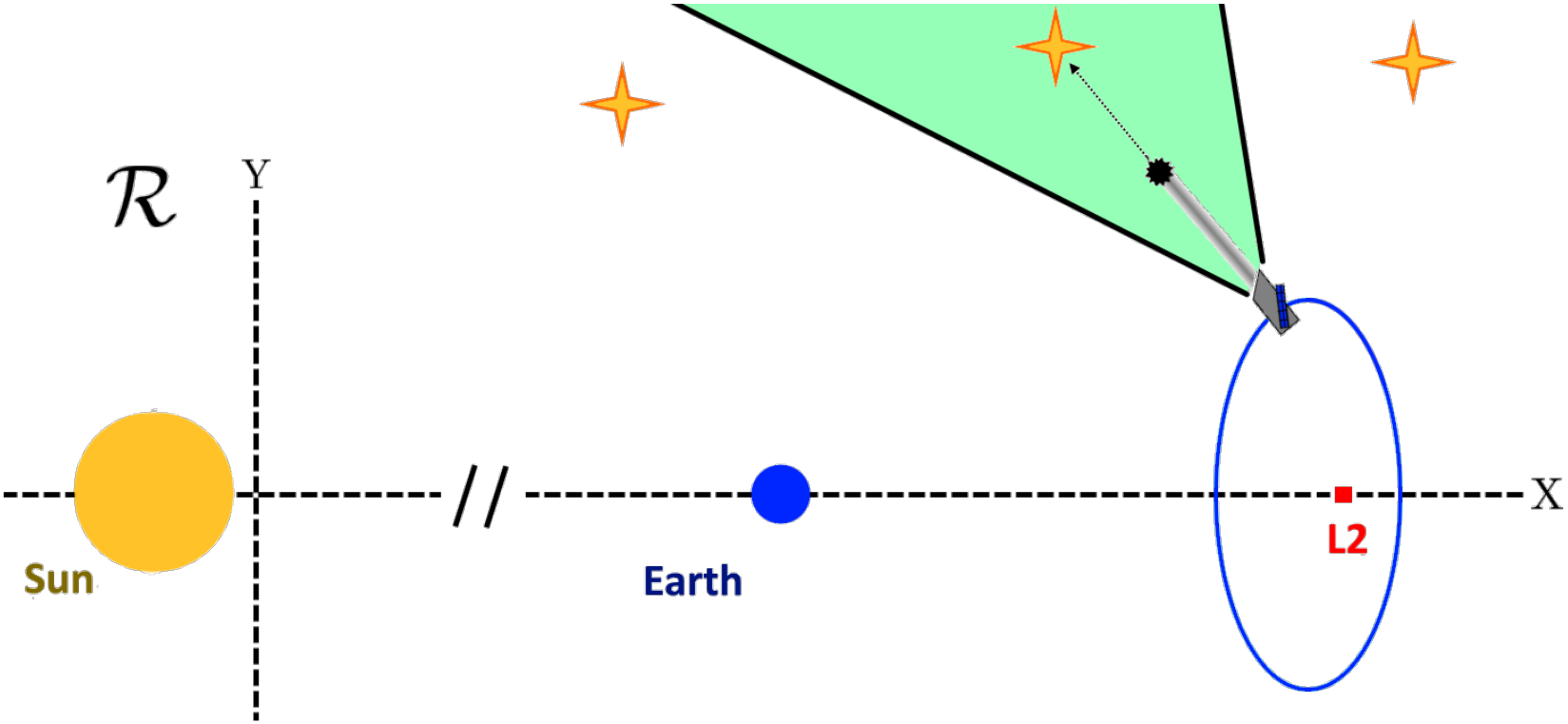
Parameterizing Fuel Costs



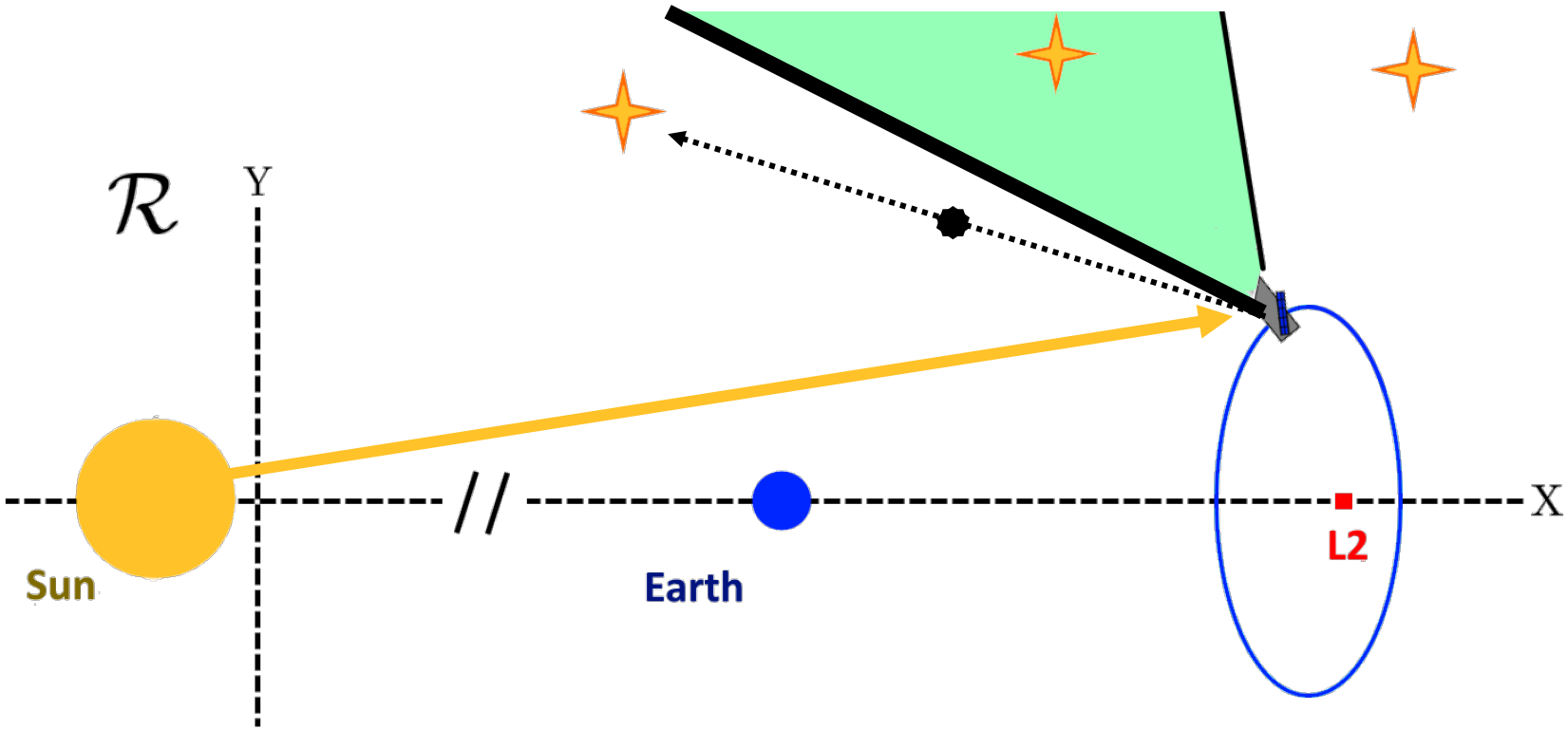
- Assume constant halo and separation distance
- Before: 12 minutes to compute map at every decision step
  - 5 day time step
- Now: single map generated offline for any target list

Soto et al (2018) “Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules.” *JGCD* (submitted)

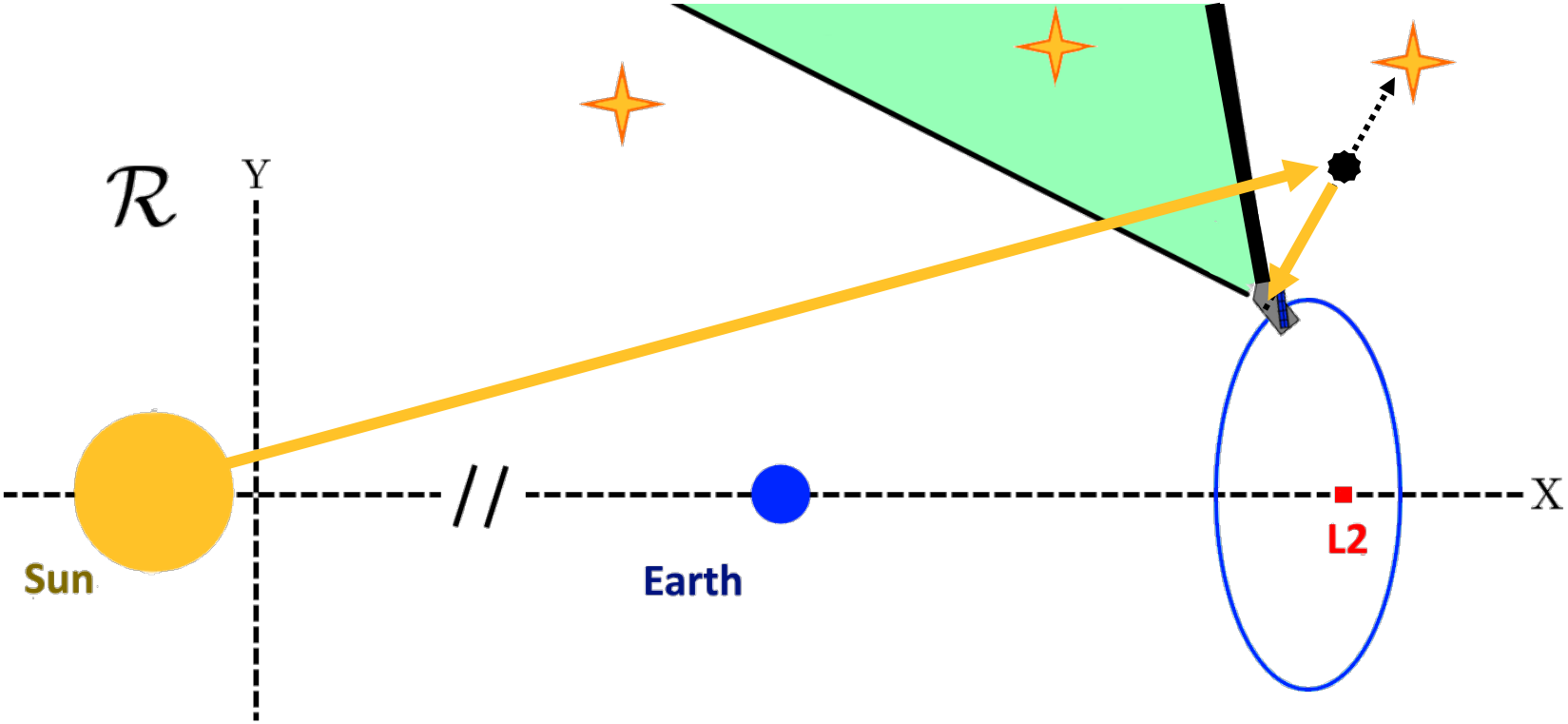
Keepout Constraints



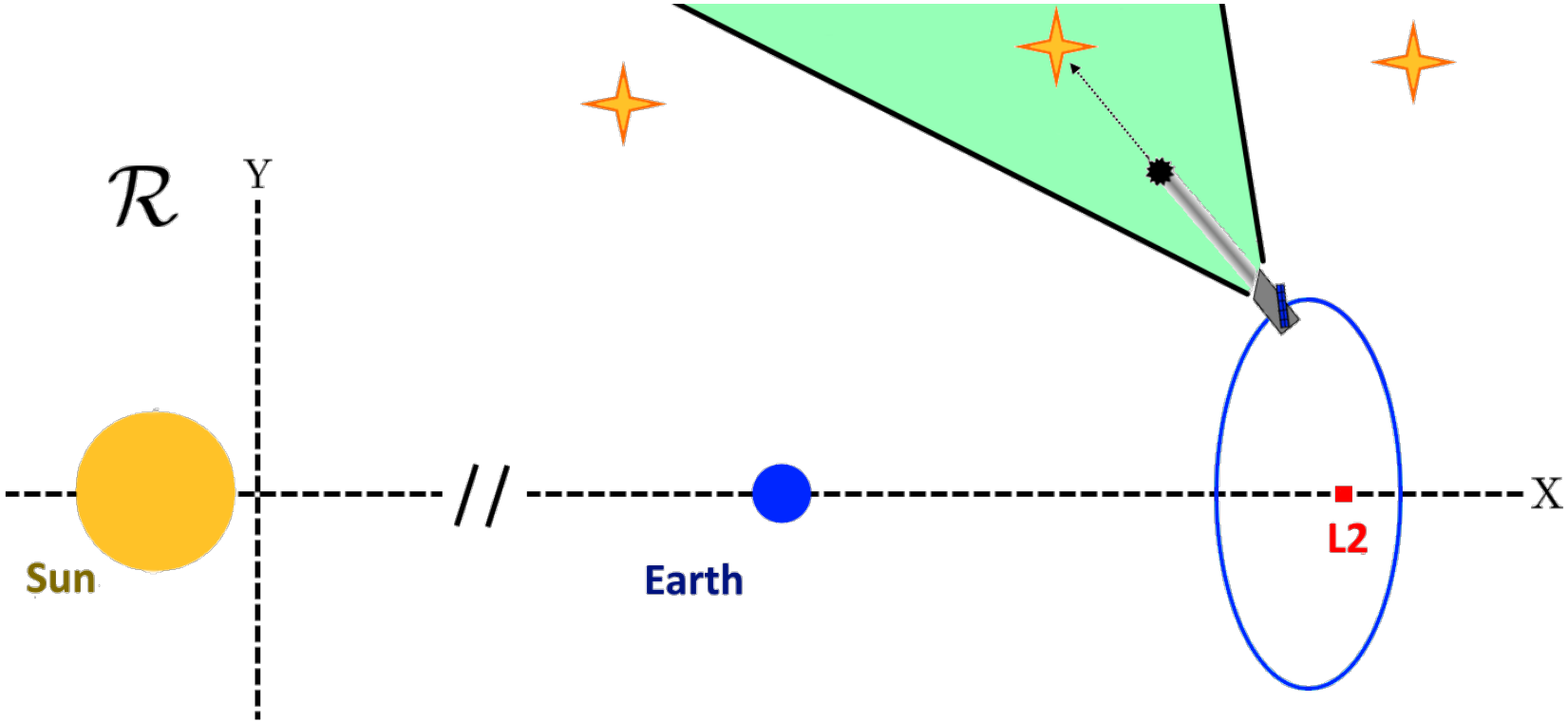
Keepout Constraints



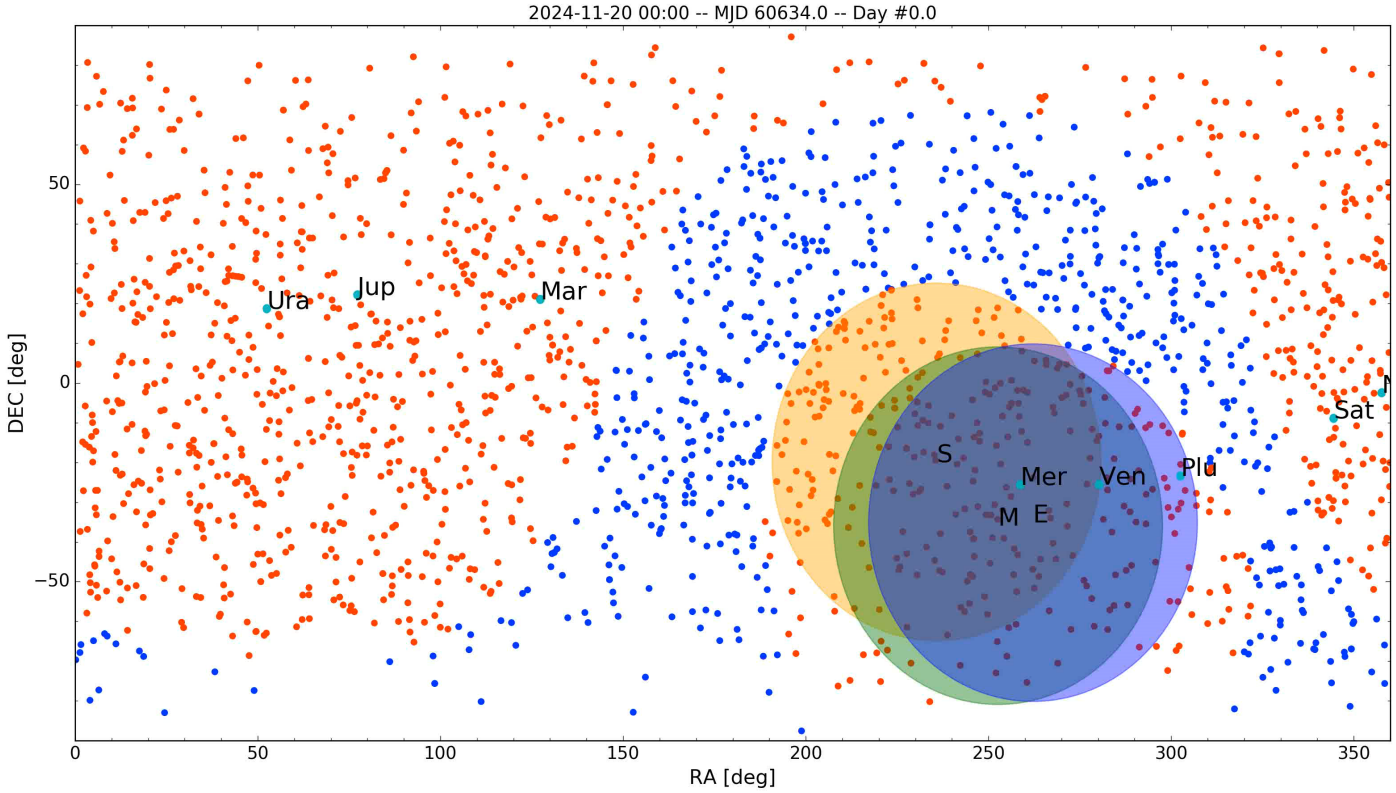
Keepout Constraints



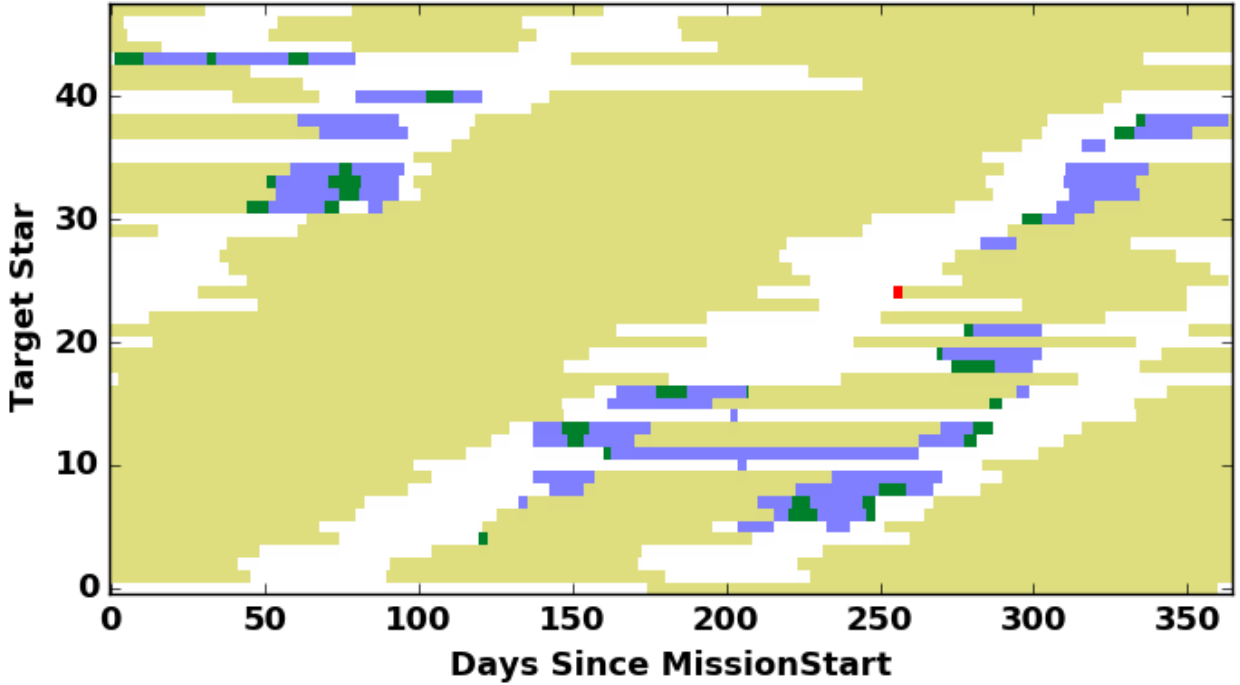
Keepout Constraints



Keepout Constraints



Keepout Constraints



$90° > \phi_{Sun} > 45°$

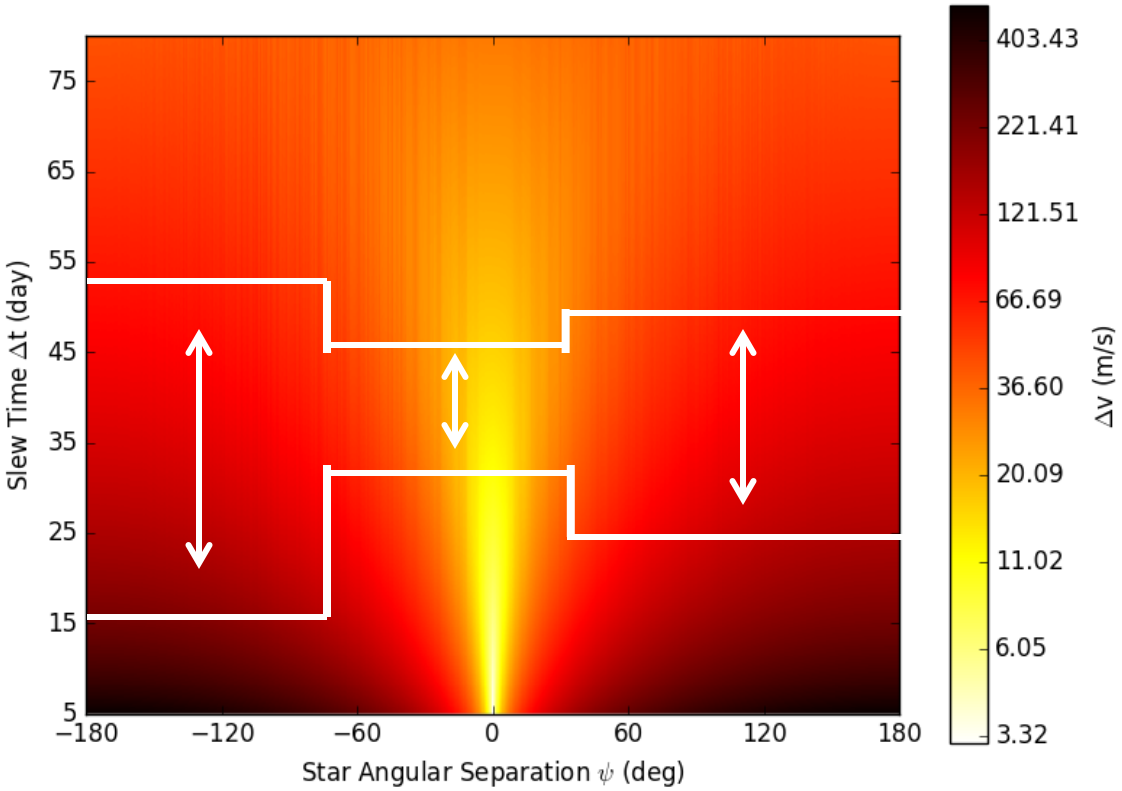
$\phi_{Earth} > 45°$

$\phi_{Moon} > 45°$

$\phi_{OtherPlanets} > 1°$

Soto et al (2018) “Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules.” *JGCD* (submitted)

Keepout Constraints



Cost Function

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

Size $1 \times j$ for stars $j \in \mathbb{T}$

Target List $\mathbb{T} \subset \mathbb{Z}$

$$\boxed{J = \arg\min_{j}(\mathbf{c})}$$

Savransky et al (2010) “Analyzing the Designs of Planet-Finding Missions” *PASP*

Cost Function

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

$$f_{unv}(j) = \begin{cases} 0 & N(j) > 0 \\ \left(\frac{t}{t_F}\right)^2 & N(j) = 0 \end{cases}$$

Number of Observations

$N(j)$

$$f_{rev}(j) = \begin{cases} 0 & j \notin \mathbb{E} \\ 1 & j \in \mathbb{E} \end{cases}$$

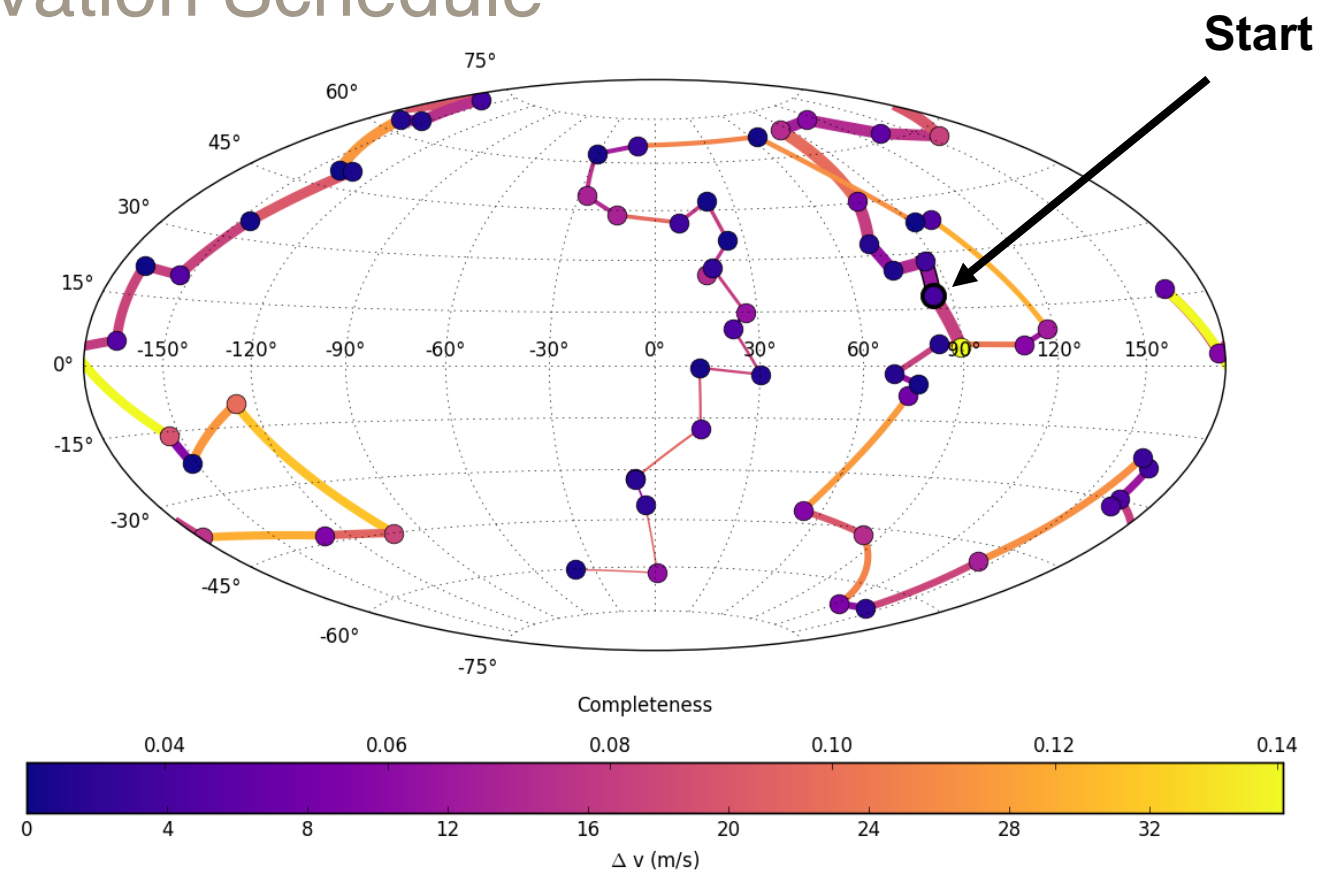
Revisit List

$\mathbb{E} \subset \mathbb{T}$

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

Savransky et al (2010) “Analyzing the Designs of Planet-Finding Missions” *PASP*

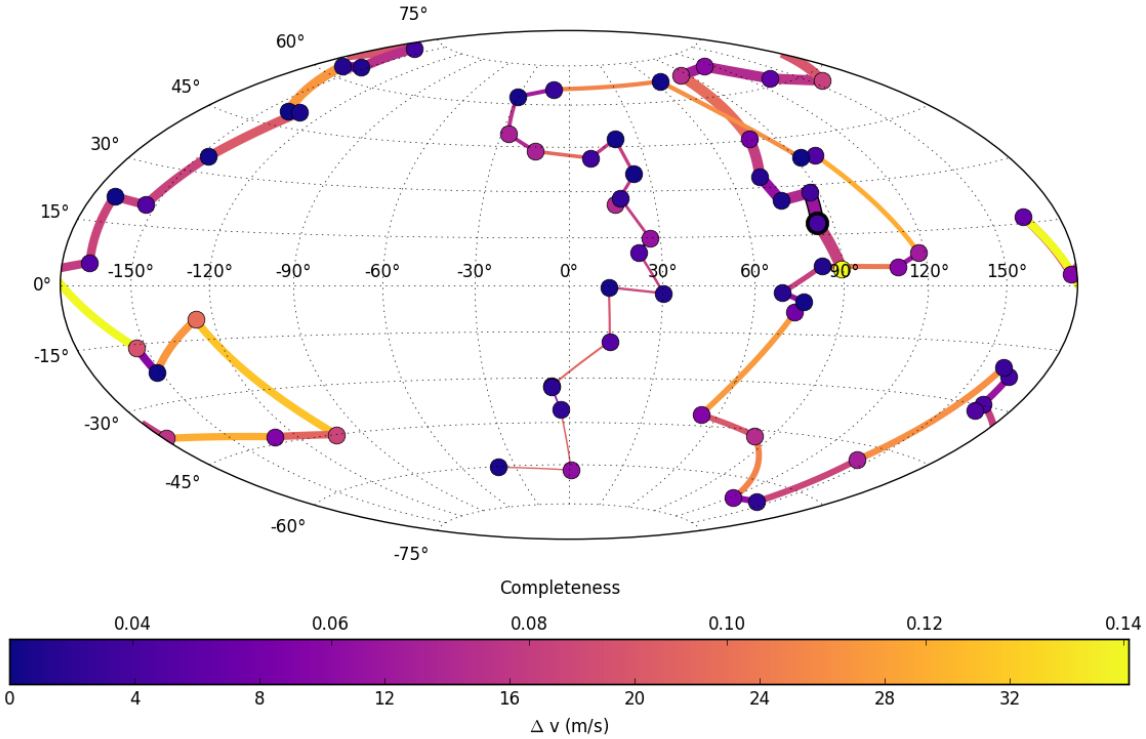
Observation Schedule



Soto et al (2018) “Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules.” *JGCD* (submitted)

Conclusions

- Re-parameterized fuel cost calculation
- Constraints placed on these calculations due to keepout
- Enables faster end-to-end mission simulations



Part III: Future Work

Contributions

Extracurricular Activities

- SGRS Marketing Director 2017
- SiGMA Social Co-Chair 2017-2018

Conference Papers

1. 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*
2. 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*
3. Soto, G., Savransky, D., Garrett, D., Delacroix, C. (2018) "Optimal starshade observation scheduling." *SPIE Astronomical Telescopes + Instrumentation*

Journal Publications

Soto, G., Savransky, D., Garrett, D., Delacroix, C. (2018) "Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules." *Journal of Guidance, Control, and Dynamics* (submitted)

Conference Presentations

1. ERES II – "Optimization of High Inclination Orbits for a Zodiacal Light Imaging Mission" (2016 – *Speaker in Ithaca, NY*)
2. Sibley Graduate Research Symposium – "Starshade Orbital Maneuver Study for WFIRST" (2017 – *Speaker in Ithaca, NY*)
3. 229th AAS – "Starshade Orbital Maneuver Study for WFIRST" (2017 – *Poster in Grapevine, TX*)
4. SPIE Techniques and Instrumentation for Detection of Exoplanets VIII – "Optimization of High-Inclination Orbits Using Planetary Flybys for a Zodiacal Light Imaging Mission" (2017 – *Poster in San Diego, CA*)
5. SPIE Techniques and Instrumentation for Detection of Exoplanets VIII – "Starshade Orbital Maneuver Study for WFIRST" (2017 – *Poster in San Diego, CA*)
6. SiGMA Seminar Series "Starshade Orbital Maneuvers and Observation Scheduling" (2017 - *Speaker in Ithaca, NY*)
7. 231st AAS – "Starshade Observation Scheduling for WFIRST" (2018 - *Poster in Washington, DC*)
8. SPIE Astronomical Telescopes + Instrumentation – "Optimal Starshade Observation Scheduling" (2018 - *Poster in Austin, TX*)

Teaching Assistantships

- MAE 2030 – Dynamics (Spring 2016)
- MAE 2030 – Dynamics (Head TA – Spring 2018)

Coursework

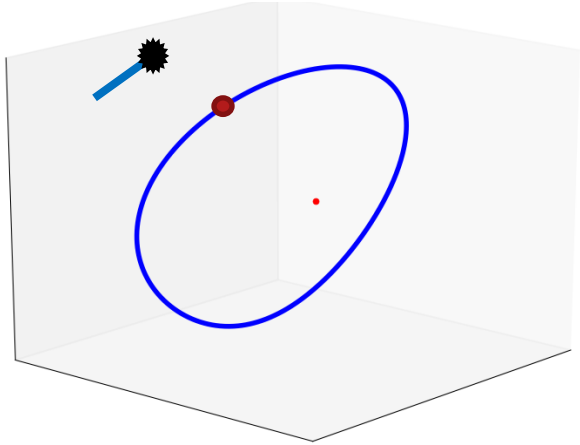
- MAE 5780 – Feedback Control Systems
- MAE 5730 – Intermediate Dynamics & Vibrations
- MAE 5950 – Systems Architecture
- MAE 6060 – Spacecraft Dynamics, Estimation & Control
- MAE 6700 – Advanced Dynamics
- MAE 6780 – Multivariable Control Theory
- ASTRO 6579 – Celestial Mechanics
- ASTRO 7671 – Topics in Planetary Science (Comets)

Future Courses

- ASTRO 7690 – Computational Physics
- ASTRO 6560 – Stellar Structure
- MATH 5790 – Nonlinear Dynamics and Chaos
- MATH 7170 – Applied Dynamical Systems

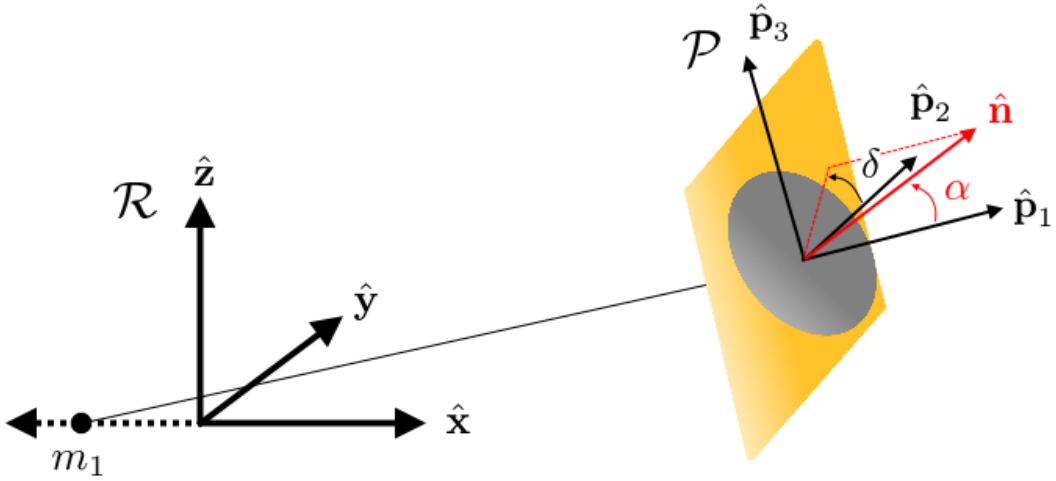
Starshade With Continuous Thrust

- Optimal control problem
  - Develop heuristics for retargeting case
- Extend to starshade station-keeping during observation



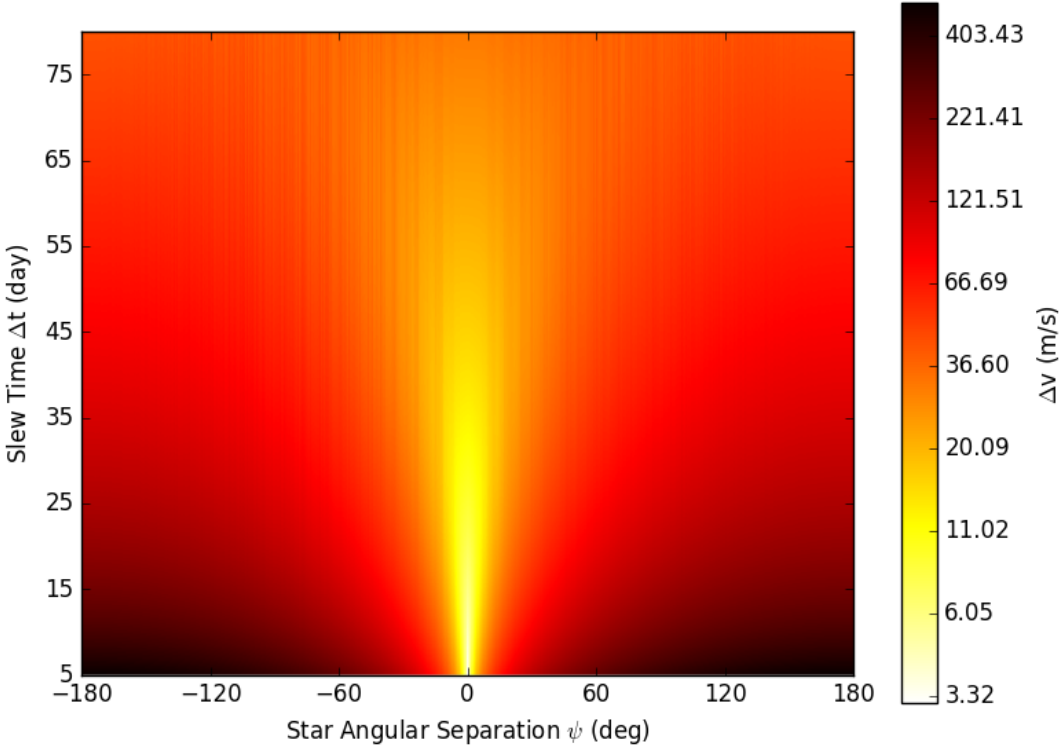
Starshade Attitude

- Starshade attitude dynamics during retargeting
- Configurations due to SRP perturbations



Analytical Approximations

- Richardson Third Order Expansion
  - Nonlinear terms written as Legendre Polynomials
- Study dynamics in Floquet modes
  - Flow equation used to find halo orbits in CR3BP
  - Project motion onto eigenvectors



ZODI Project funded under a Strategic University Research Partnership with JPL

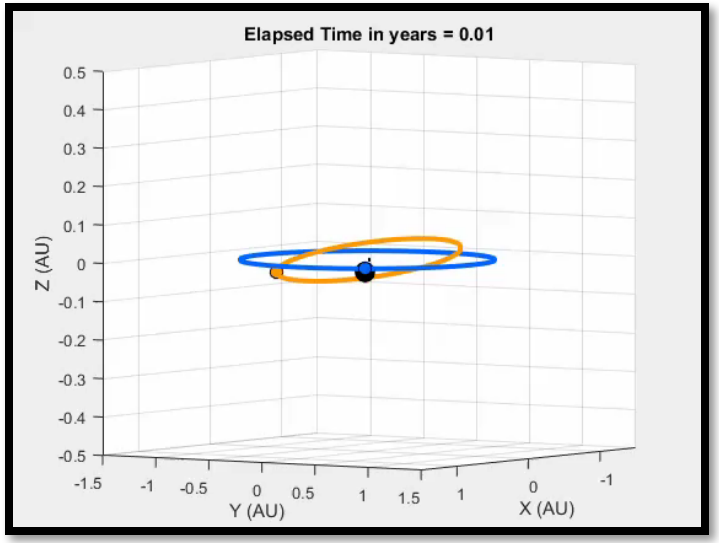
James Lloyd
Dmitry Savransky
Keith Grogan (JPL)

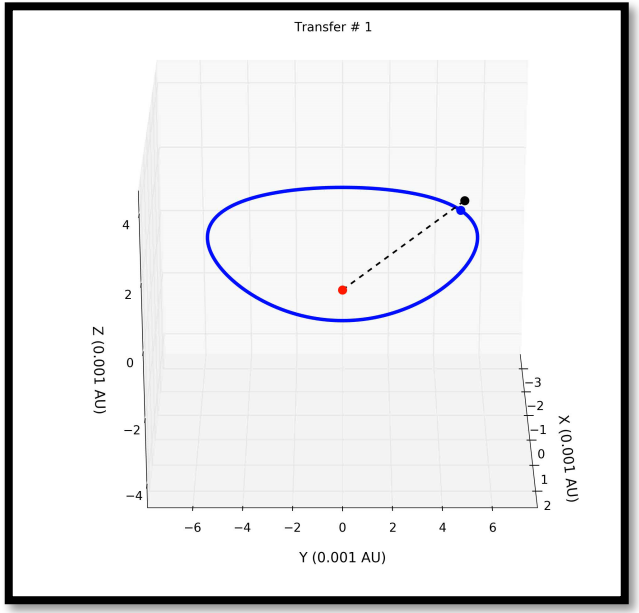
Thanks to SIOSLab Group
Dmitry Savransky
Daniel Garrett
Christian Delacroix
Jacob Shapiro
Dean Keithly
Amlan Sinha

Starshade Project funded under NASA Grant NNG16PJ24C (SIT)

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

Gabriel J. Soto

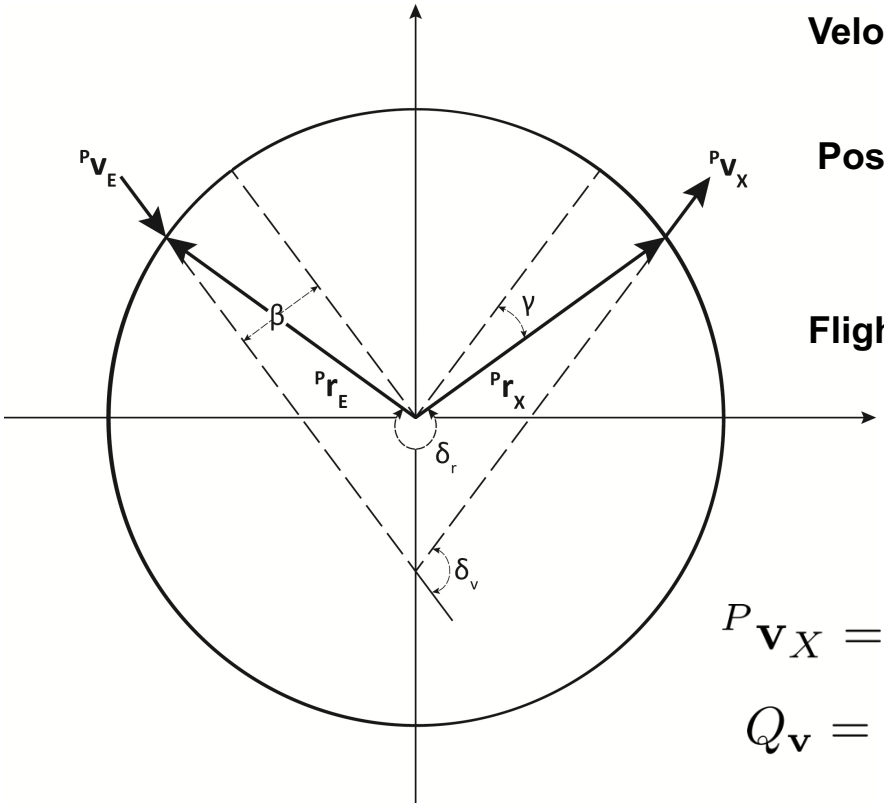




Backup Slides

Flyby State Rotation

$$^{P}\mathbf{h}_E = {}^{P}\mathbf{h} = {}^{P}\mathbf{r}_E \times {}^{P}\mathbf{v}_E$$



Velocity Turning Angle

$$\sin\frac{\delta_v}{2} = \frac{\mu_P}{\mu_P + r_{min} v_\infty^2}$$

Position Turning Angle

$$\delta_r = \delta_v - 2\gamma - \pi$$

Flight Path Angle

$$\sin\gamma = \frac{B}{R_{SOI}} = \frac{||^{P}\mathbf{h}||}{R_{SOI} v_\infty}$$

$$B = \frac{||\vec{r}_E \times \vec{v}_E||}{v_E}$$

$$^{P}\mathbf{v}_X = Q_{\mathbf{v}}\,{}^{P}\mathbf{v}_E \qquad {}^{P}\mathbf{r}_X = Q_{\mathbf{r}}\,{}^{P}\mathbf{r}_E$$

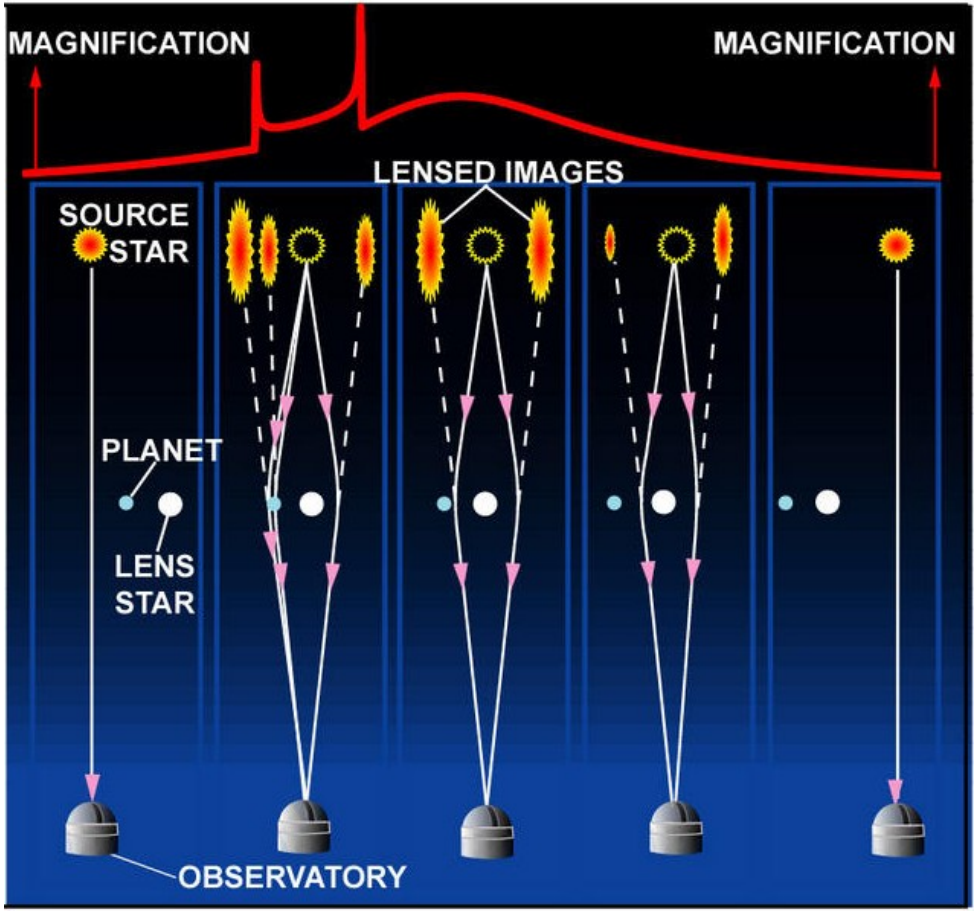
$$Q_{\mathbf{v}} = \exp\left(\left[{}^{P}\hat{\mathbf{h}}\right]_\times \delta_v\right) \qquad Q_{\mathbf{r}} = \exp\left(\left[{}^{P}\hat{\mathbf{h}}\right]_\times \delta_r\right)$$

Second Earth Flyby Results

Primary Spacecraft	Europa Clipper	
Flyby Date	05/29/2023	10/21/2024
Max. Orbital Height	0.1013 AU	0.2215 AU
Increase in Orbital Height	0.0081 AU	0.1283 AU
Δv Burn at Detachment	35.49 m/s	37.21 m/s
Detachment Point D	94.7%	68%
Altitude of Closest Approach	25,142 km	8,371 km
Orbital Period Ratio w.r.t. Earth	1.000	1.000
Date of Next Earth Intercept	05/29/2024	10/22/2025
Next Closest Earth Approach	1.25×10^6 km	2.13×10^5 km

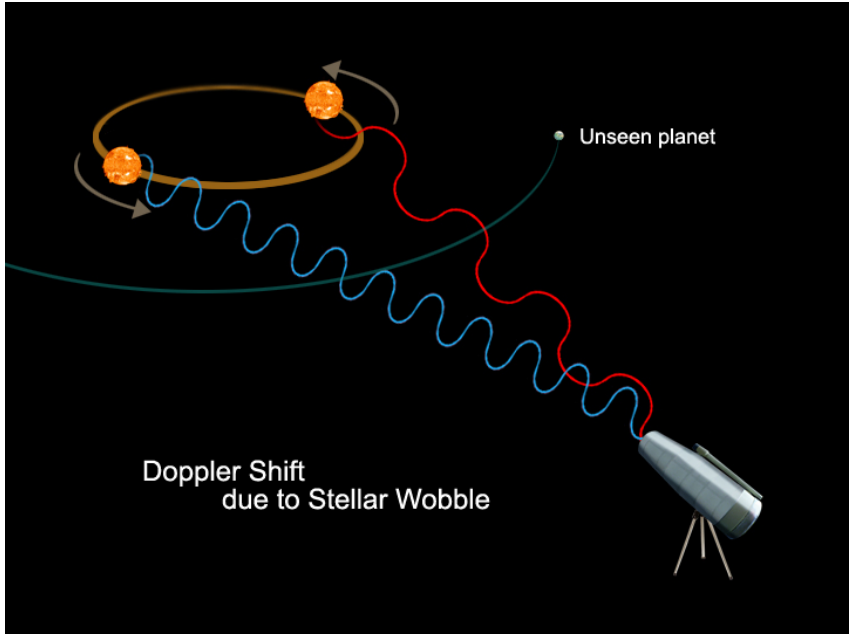
Microlensing

– **Mass & Parallax**



The Planetary Society
http://www.planetary.org/multimedia/space-images/charts/microlensing.html

Radial Velocity/Doppler Spectroscopy

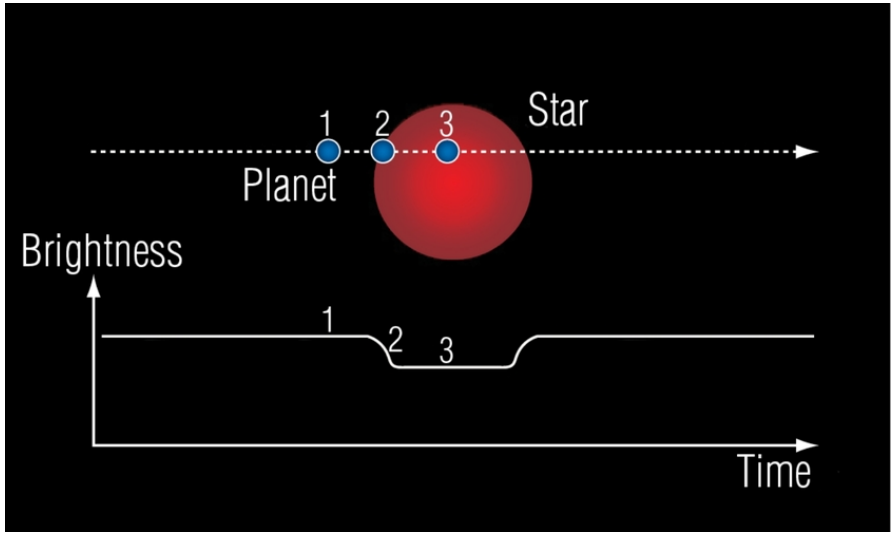


- Doppler shift in radial velocity of the star
  - In the observer line of sight
- **Semi-major Axis** & **Mass**
- Minimum mass = M*sin(i)
- Need high SNR to do doppler spectroscopy as opposed to astrometry

http://earthsky.org/space/how-do-astronomers-discover-exoplanets

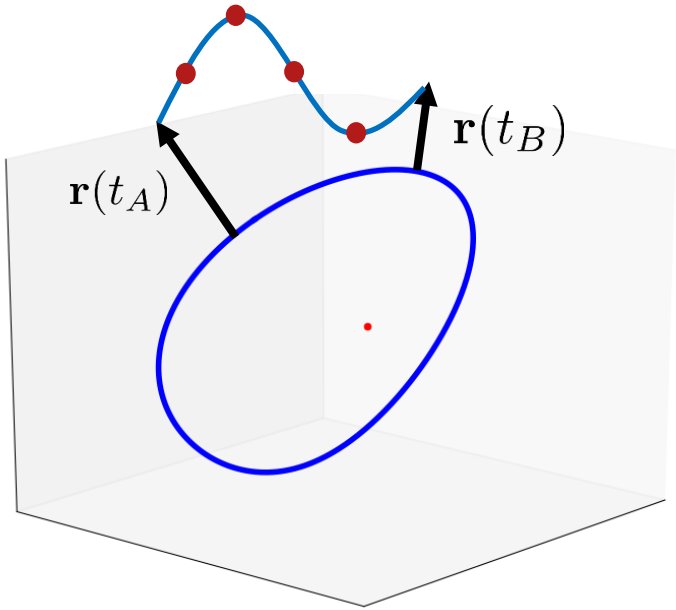
Transit

- Dip in light curve
- **Planet Radius, Atmosphere and Temperature**
  - Length of the dip
  - Stellar spectroscopy
  - Second eclipse – subtract out full planet signal



http://www.planetary.org/explore/space-topics/exoplanets/transit-photometry.html

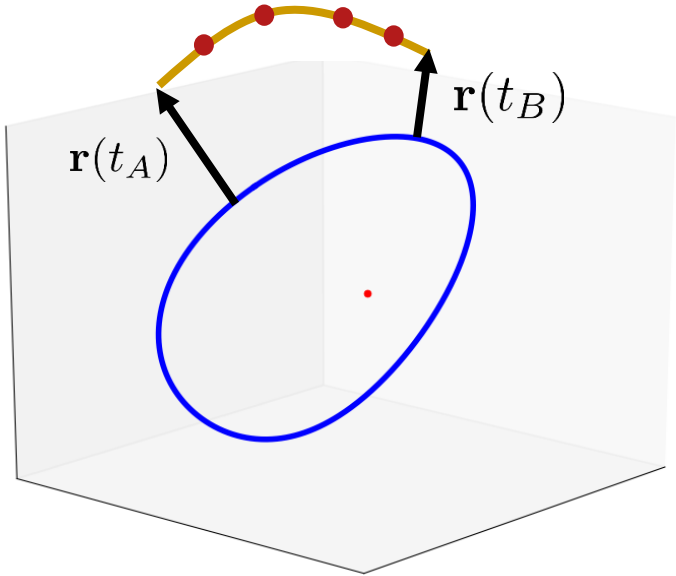
Retargeting Trajectories



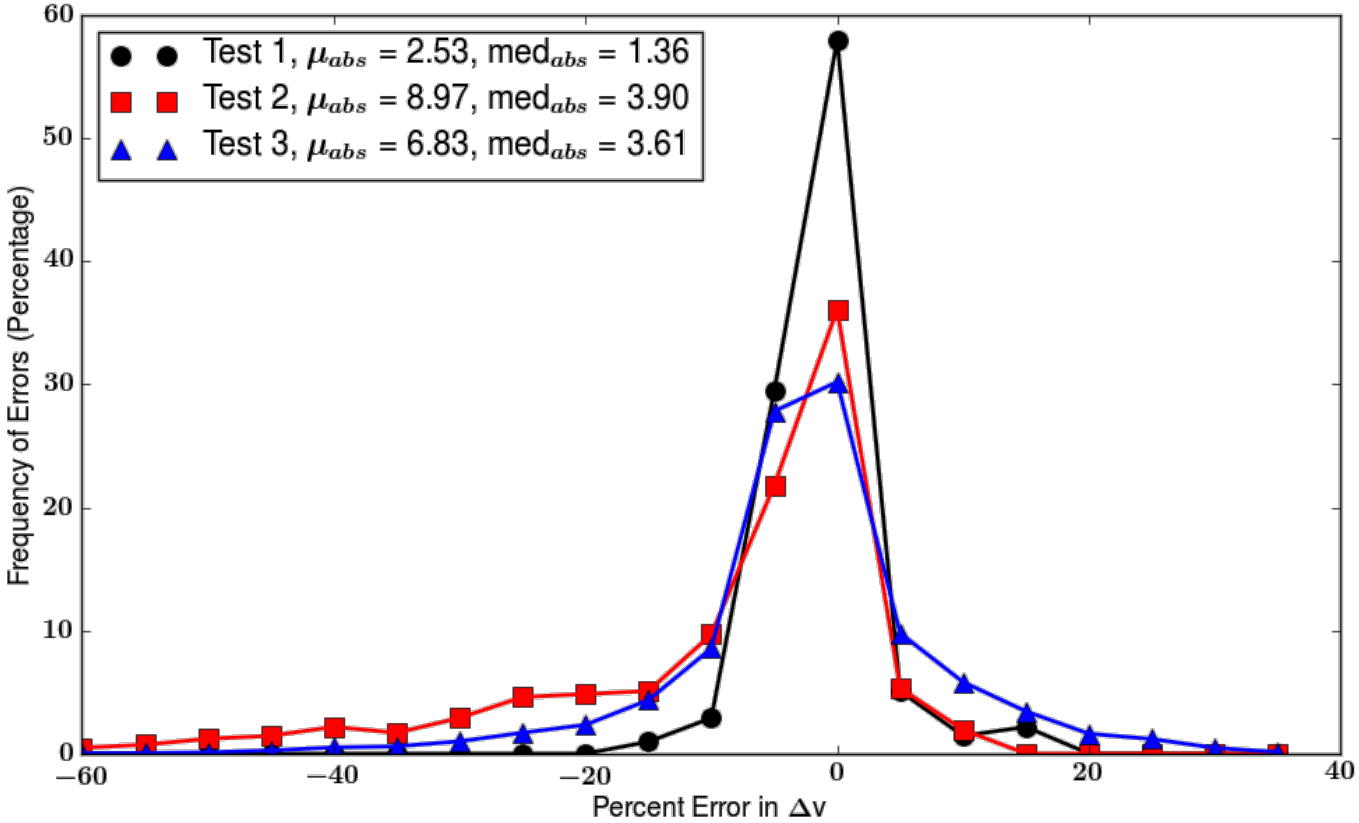
Collocation:

- Cubic polynomial
- Equal at endpoints
- Creates mesh and minimizes residual error

Retargeting Trajectories

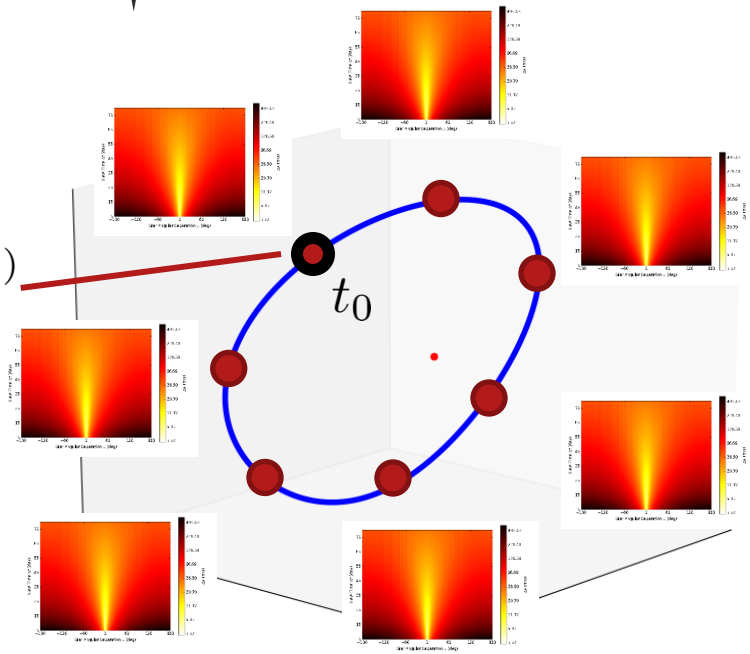


Error Analysis



Parameterizing Fuel Costs - Errors

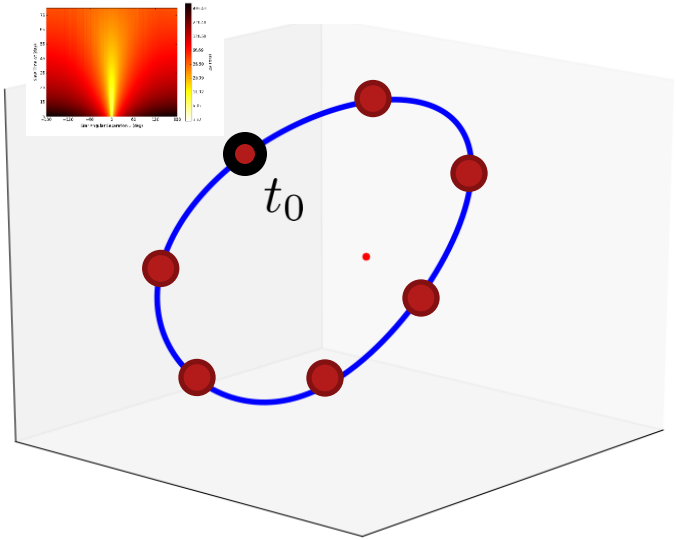
$$\Delta v_{BVP} = f(\Delta t)|_{(\psi_0, t_0)}$$



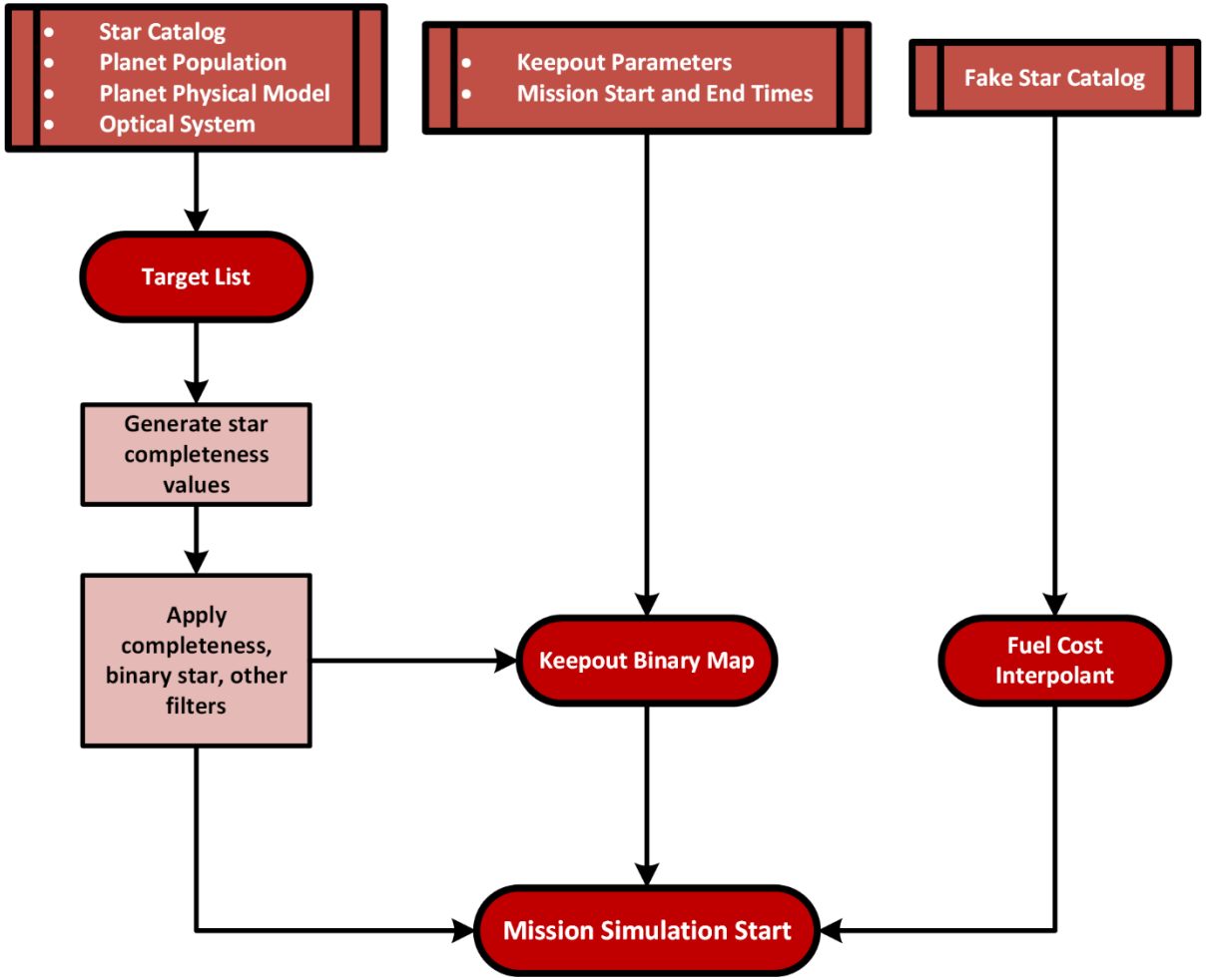
$$\Delta v_{INT} = f(\Delta t, t_0)|_{\psi_0}$$

Parameterizing Fuel Costs - Errors

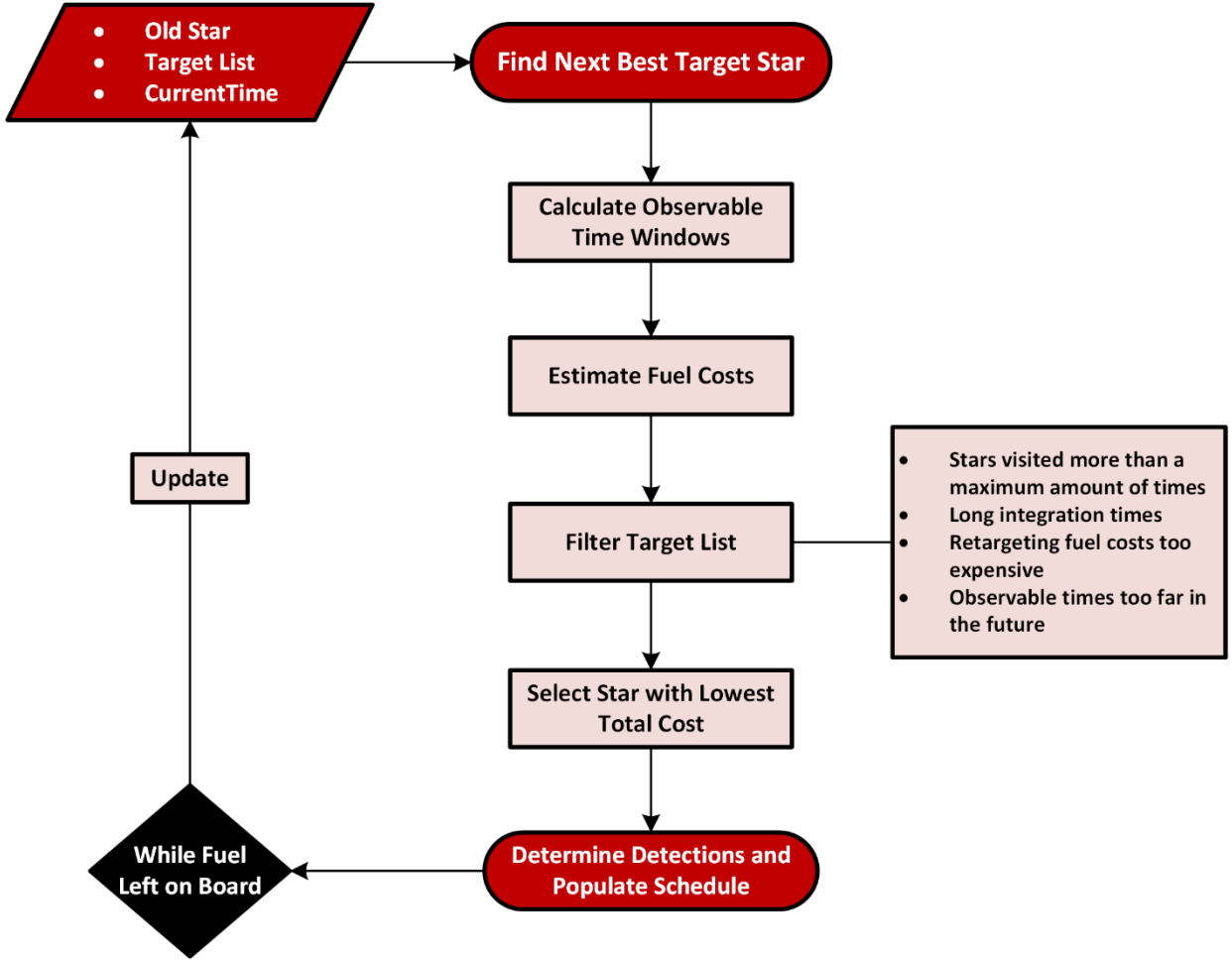
$$\Delta v_{BVP} = f(\psi, \Delta t, t_0)$$
$$\Delta v_{INT} = f(\psi, \Delta t, t_0)$$



Scheduler

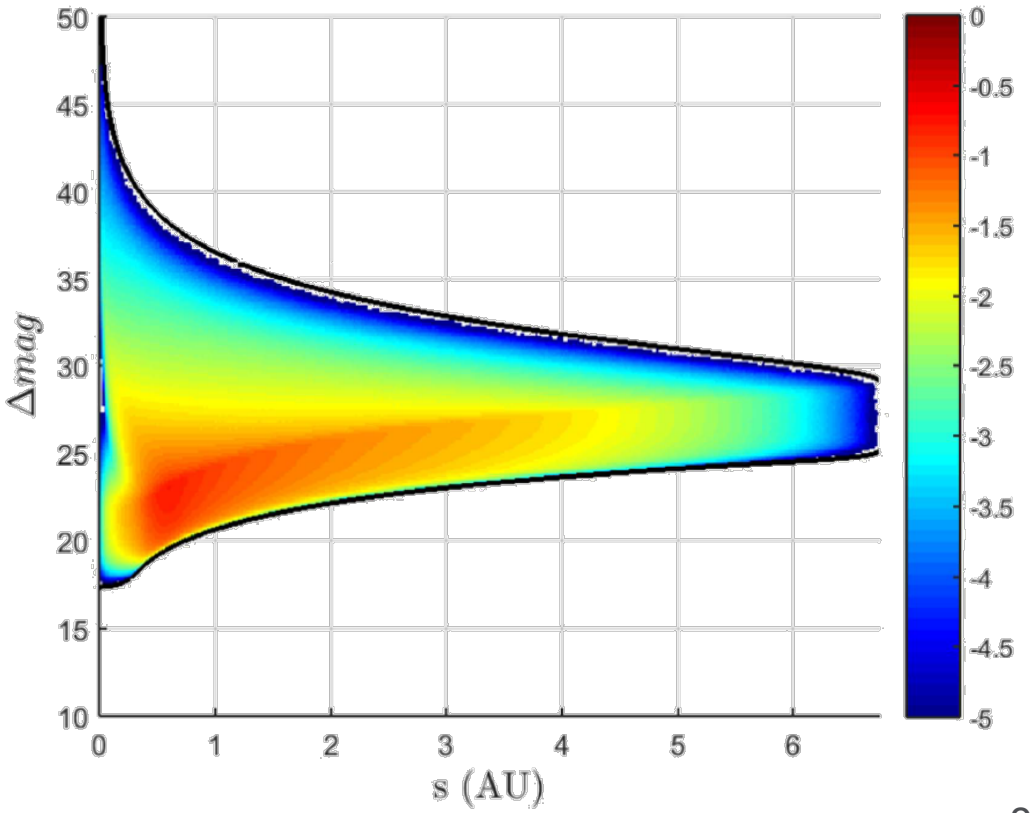

Star Catalog
Planet Population
Planet Physical Model
Optical System
Keepout Parameters
Mission Start and End Times
Fake Star Catalog
Target List
Generate star completeness values
Apply completeness, binary star, other filters
Keepout Binary Map
Fuel Cost Interpolant
Mission Simulation Start

Scheduler


Old Star
Target List
CurrentTime
Find Next Best Target Star
Calculate Observable Time Windows
Estimate Fuel Costs
Filter Target List
Stars visited more than a maximum amount of times
Long integration times
Retargeting fuel costs too expensive
Observable times too far in the future
Select Star with Lowest Total Cost
Determine Detections and Populate Schedule
While Fuel Left on Board
Update

Completeness

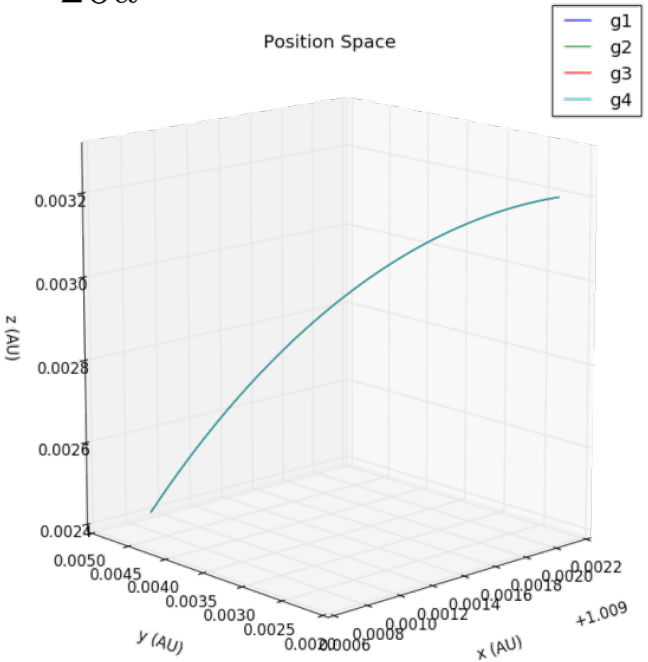
- Joint Probability Density function
  - Star-planet brightness difference
  - Star-planet projected separation
- Based on instrument parameters, integrate over region
- Probability that a planet with assumed parameters is observable near a star

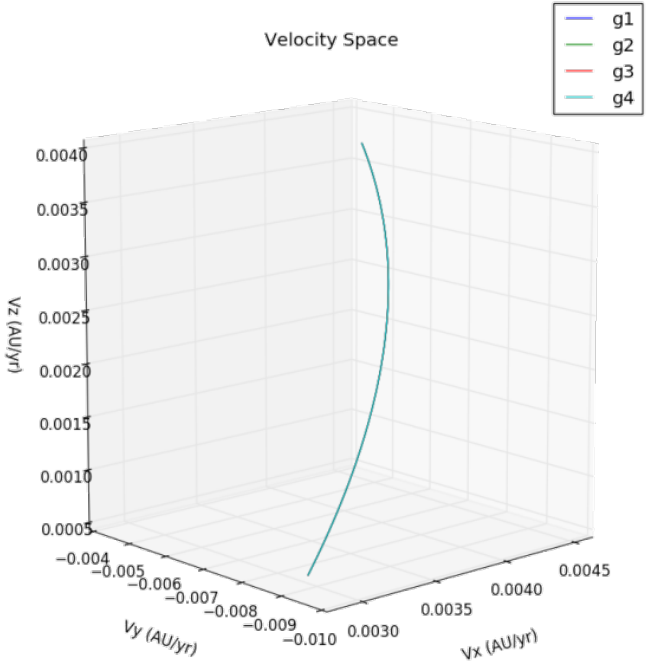


Garrett, D. and Savransky, D. (2016) "Analytical Formulation of the Single-Visit Completeness Joint Probability Density Function"

Uniqueness of BVP Solutions Near L2

$$\Delta t = 20d$$





Uniqueness of BVP Solutions Near L2

$$\Delta t = 270d$$