Fuel Cost Heuristics for Starshade Retargeting Slew Maneuvers (126.04)

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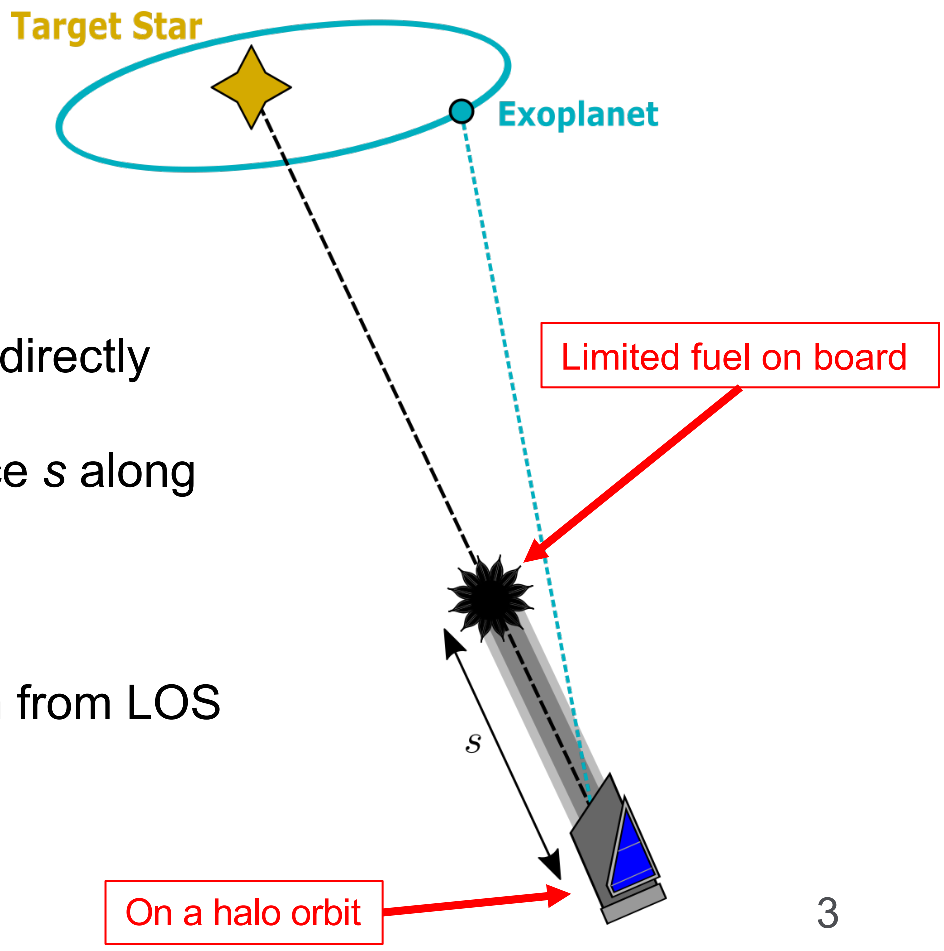
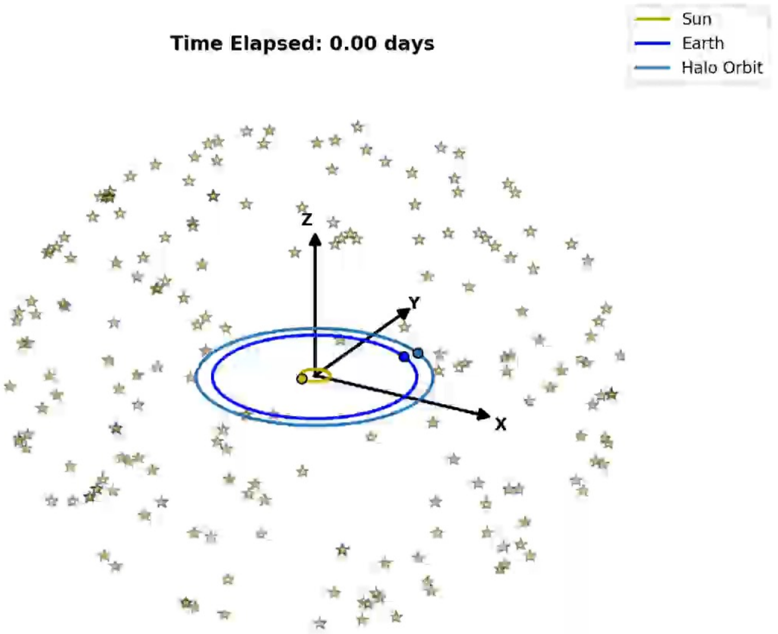
Part I: What is a Starshade and How Do We Model It?

Starshade Configuration

- In-band starlight is suppressed
  - Off-axis exoplanet light collected directly
- Maintains constant separation distance *s* along target star line of sight (LOS)
- Tight tolerance in lateral direction
  - Starlight floods pupil plane if >1m from LOS



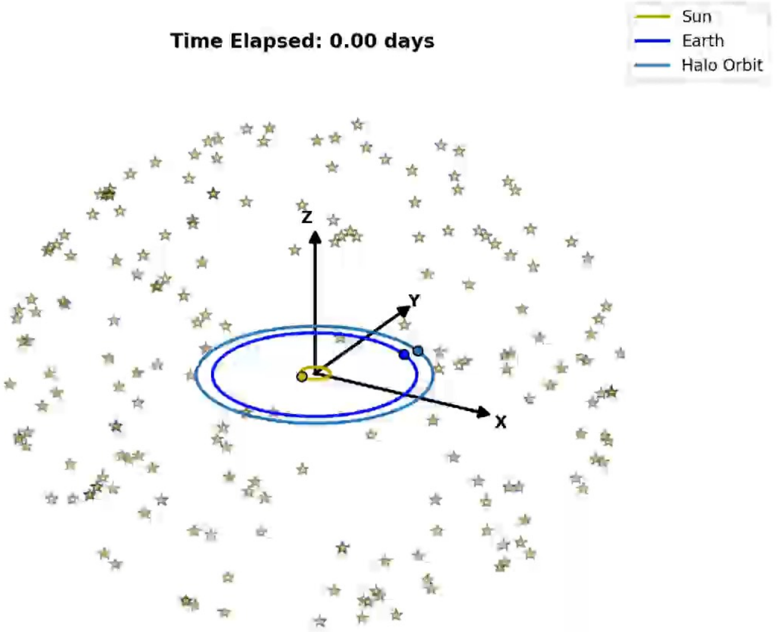
Telescope Orbit (Not Drawn to Scale)



Ecliptic ("Inertial") Frame

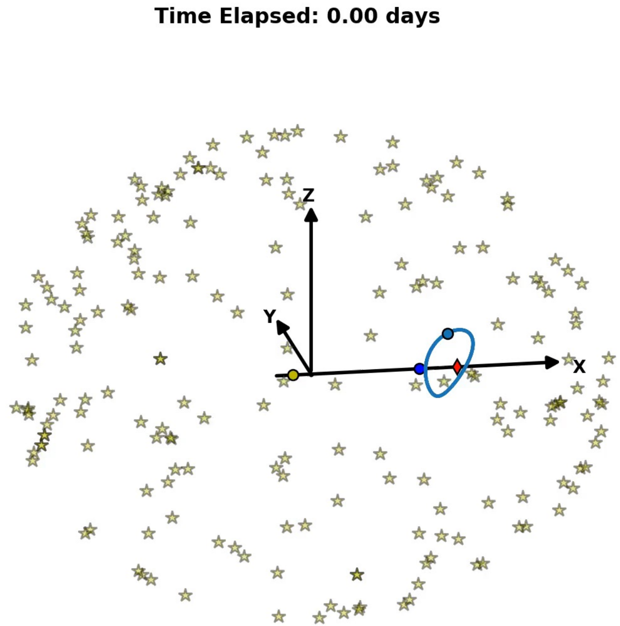
(Rotation only to show structure)

Telescope Orbit (Not Drawn to Scale)



Ecliptic ("Inertial") Frame

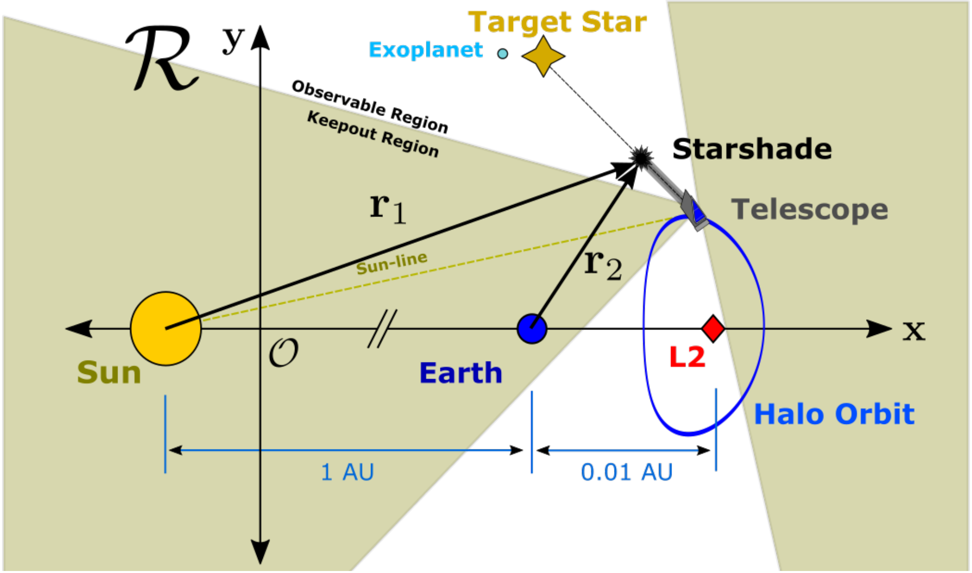
(Rotation only to show structure)



Rotating Frame

(Earth and Sun stationary)

Starshade in the CR3BP Frame



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

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

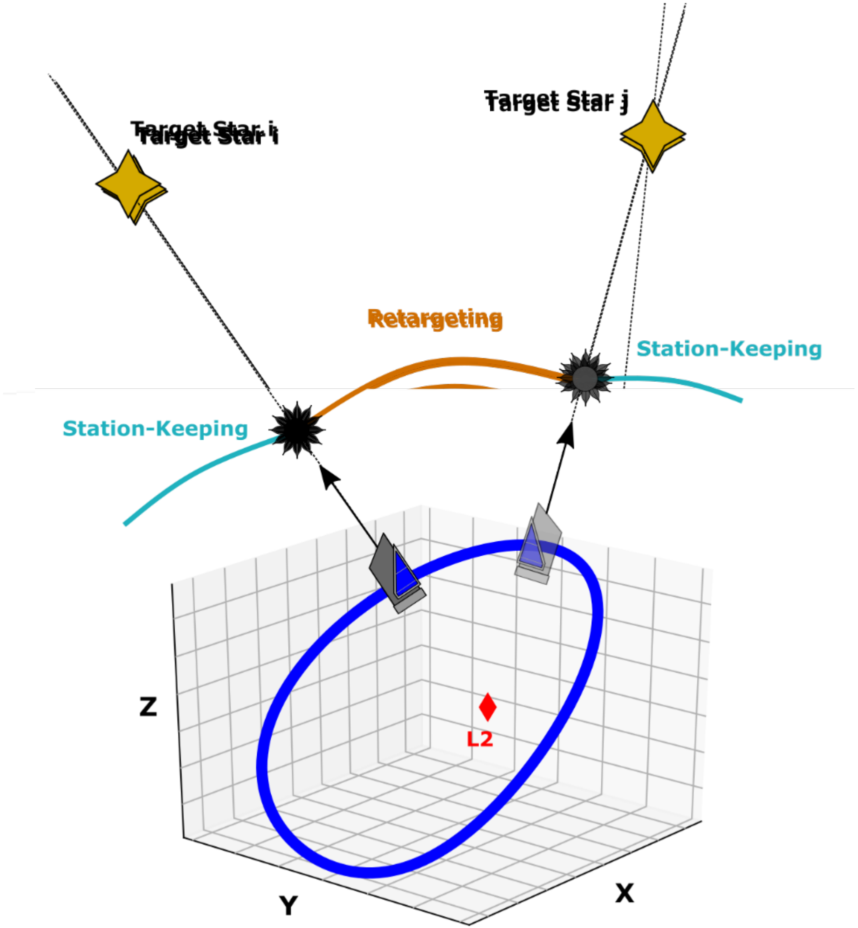
$$\ddot{z} = \frac{\partial \Omega}{\partial z} + \mathbf{f}_{SRP} \cdot \hat{\mathbf{z}}$$

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

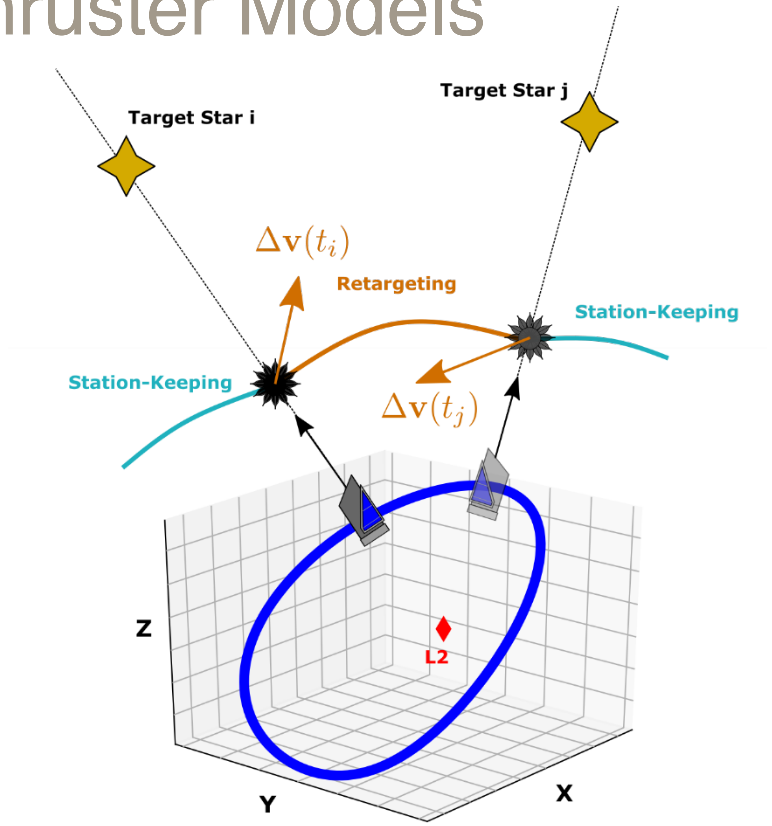
$$r_1 = \sqrt{(\mu - x)^2 + y^2 + z^2},$$

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

Flight Modes



Thruster Models



Impulsive Thrust Model

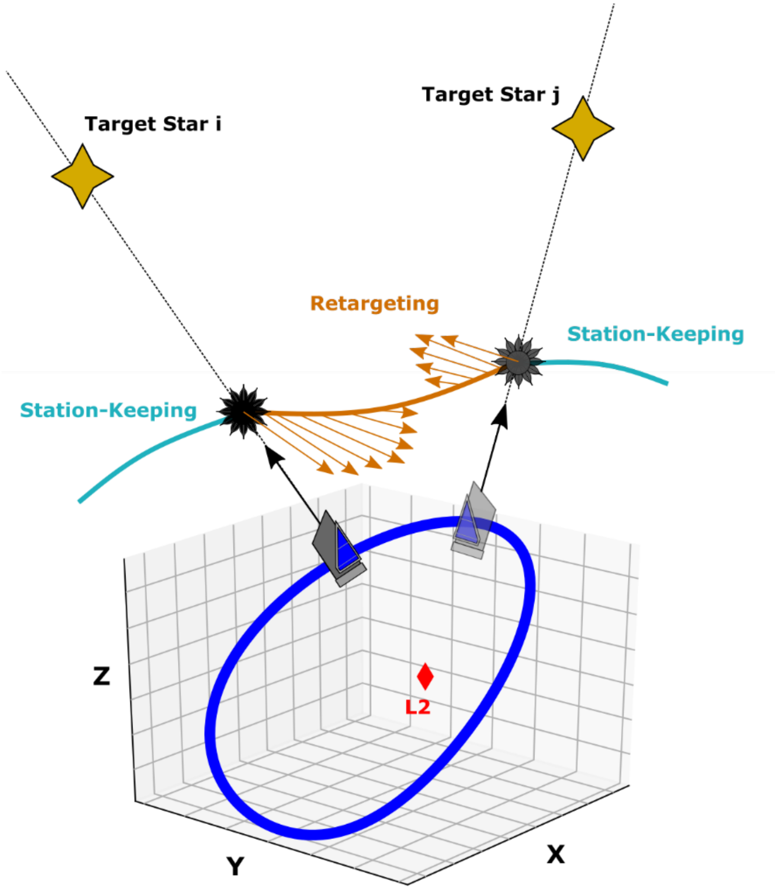
- Chemical Propulsion
- Instantaneous changes in velocity at t_i and t_j
- Solved as boundary value problem (BVP) using collocation algorithm

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

Thruster Models

Continuous Thrust Model

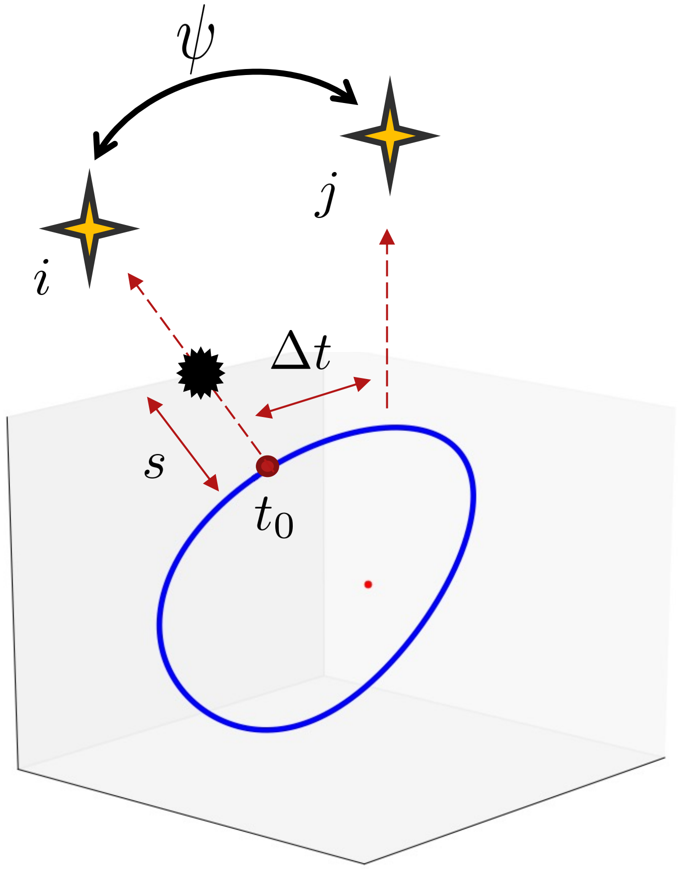
- Solar Electric Propulsion, Ion thruster, etc.
- Thrust can be throttled throughout trajectory
- Must add mass as state variable



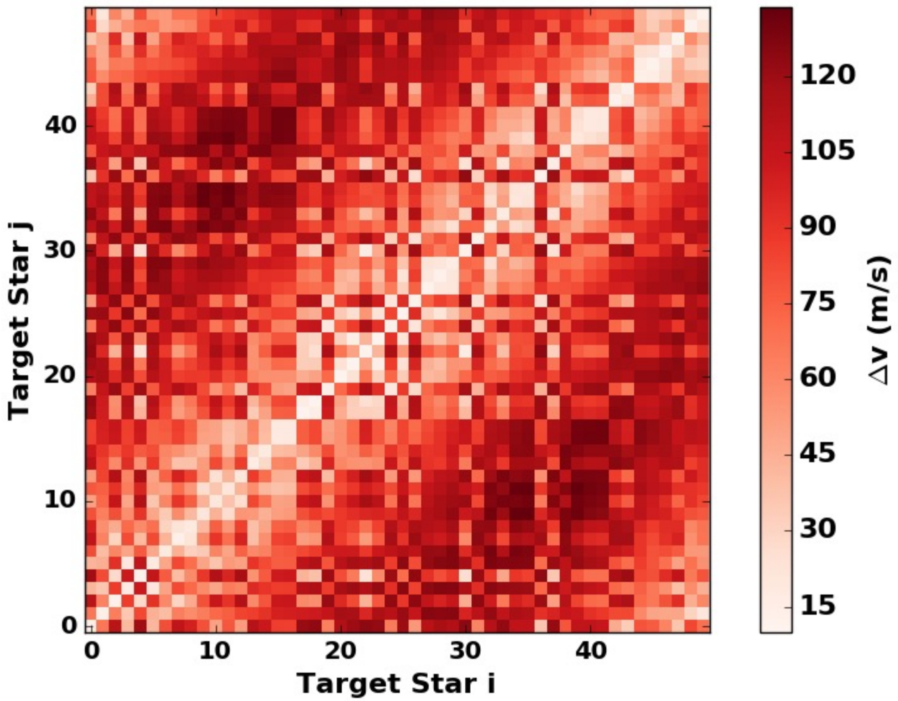
Part II: How Can We Get Quick Fuel Cost Estimates using Starshade Dynamics?

Parameterizing Fuel Costs

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



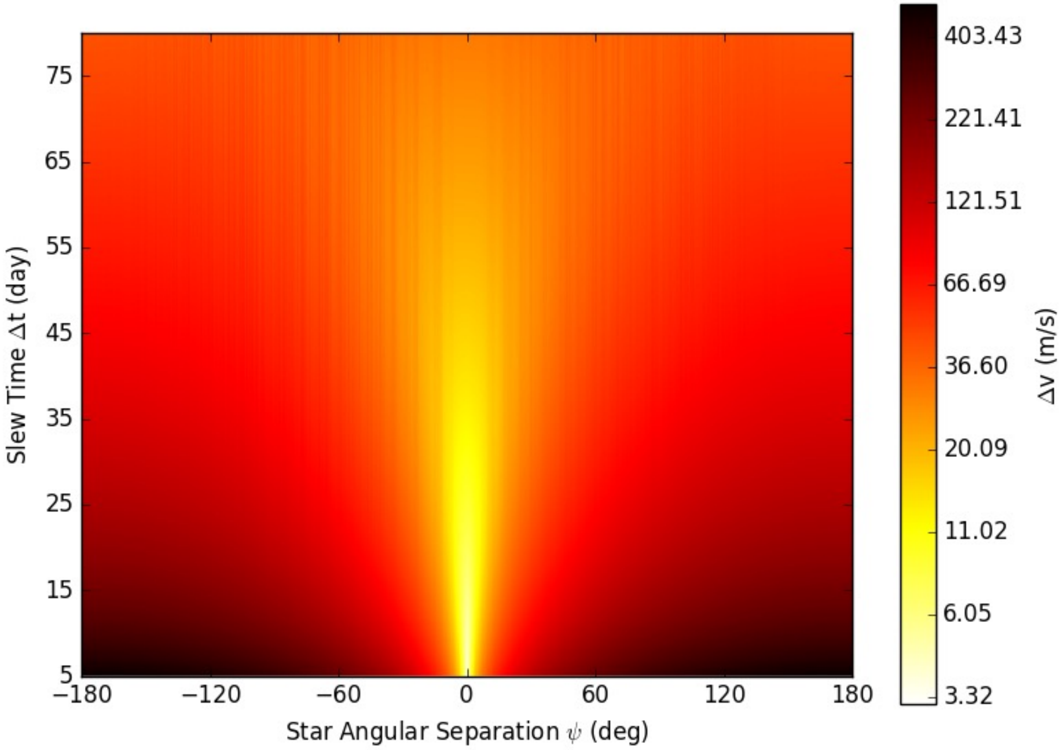
Parameterizing Fuel Costs



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

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

Impulsive Fuel Costs

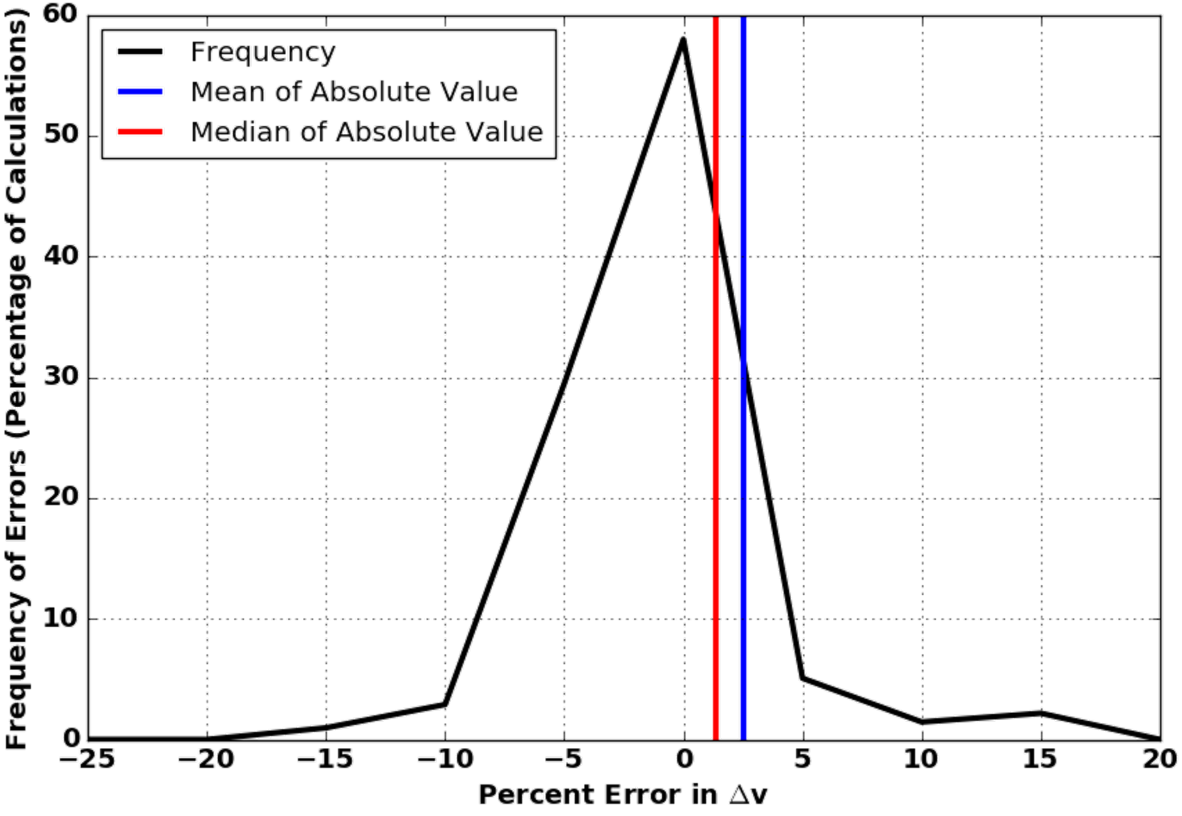


$$\Delta v = f(i, j, \Delta t, t_0)$$

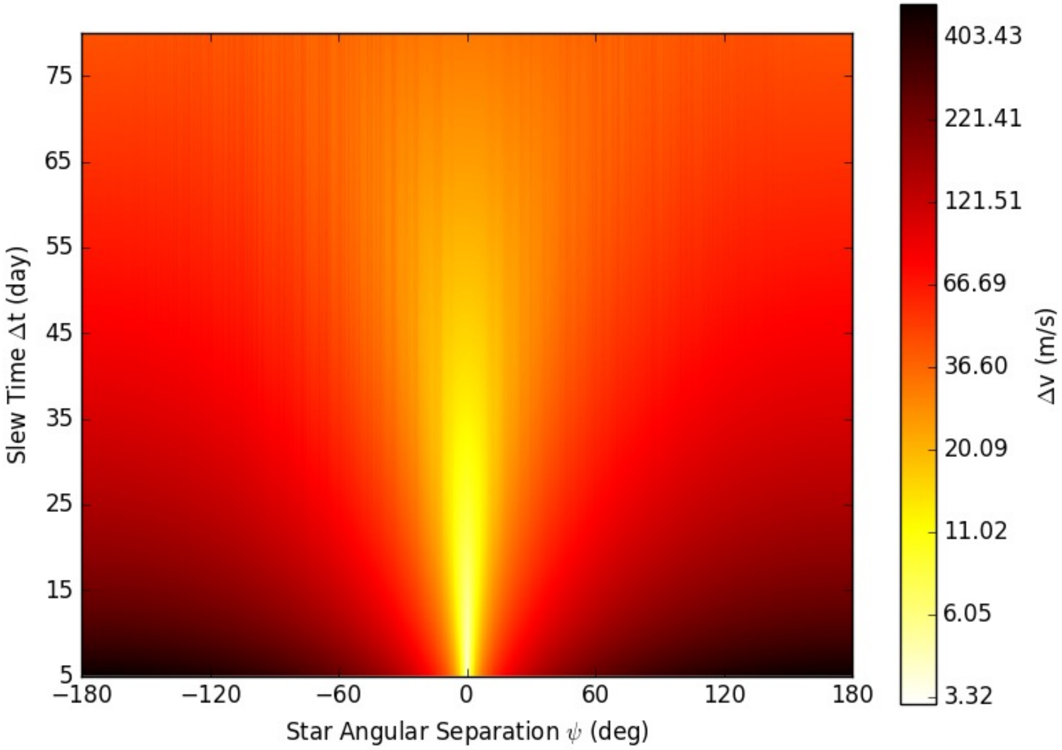
$$\Delta v = f(\psi, \Delta t)$$

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

Parameterizing Fuel Costs - Errors



Impulsive Fuel Costs

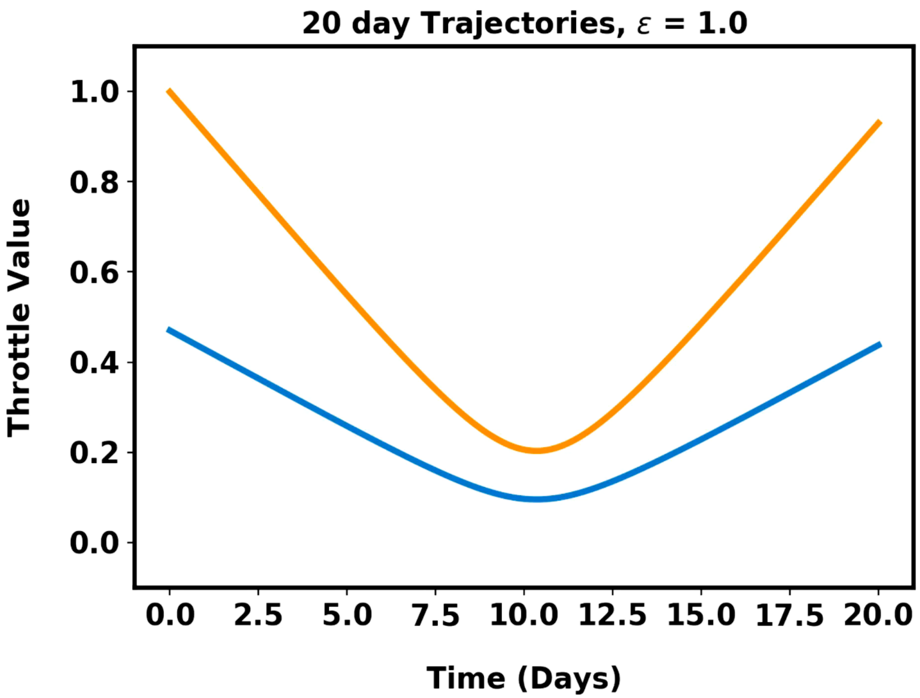


- Assume constant halo and separation distance
- Before: 12 minutes to compute map at every decision step
  - 5 day time step
- Now: single map generated offline for any target list

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

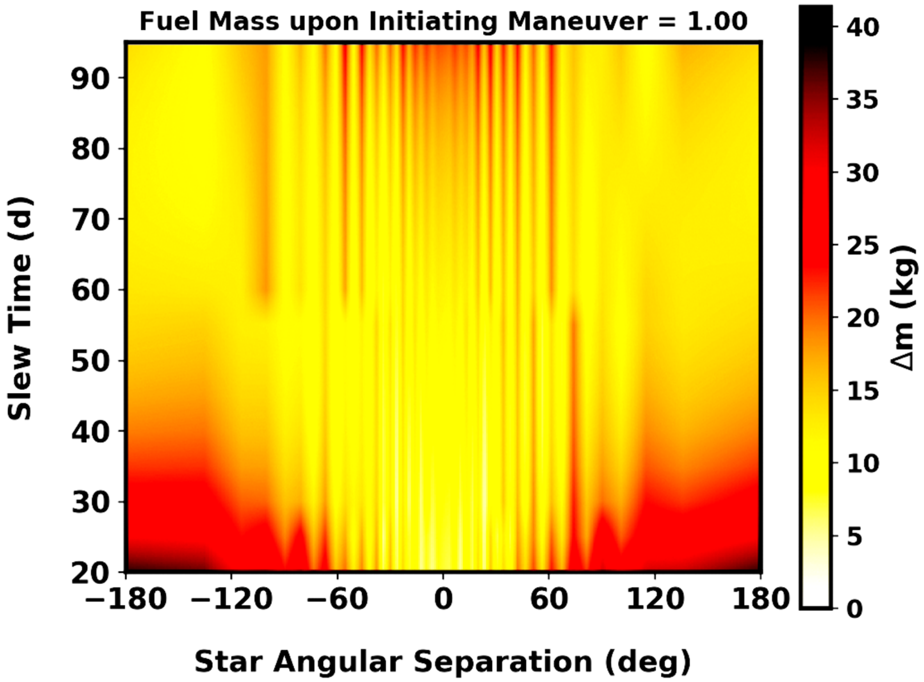
Continuous Thrust Fuel Costs

- Use optimal control
  - Combine dynamics with optimization space
  - Introduce co-states (7 more) for each state – Lagrange multipliers
- Thruster throttle values are a function of states and costates
- Solve BVP with 14 boundary conditions instead of 6
- ε used to vary control law
  - ε=1 is minimum energy
  - ε=0 is minimum fuel



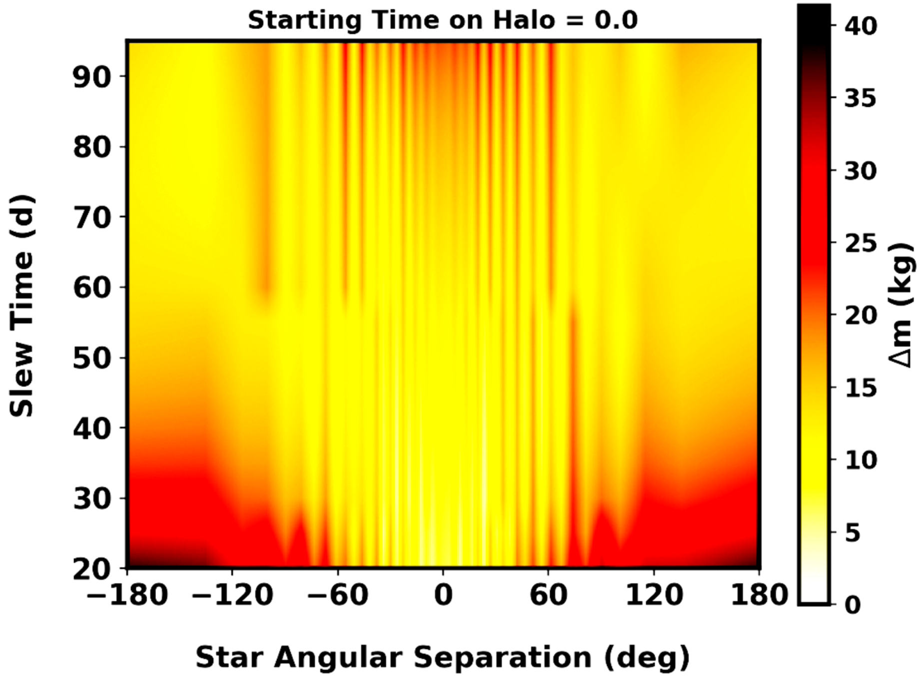
Continuous Thrust Fuel Costs

- Control law minimizes energy
- Fuel cost is directly a function of fuel mass used
- Fuel usage dependent on initial mass at start of maneuver



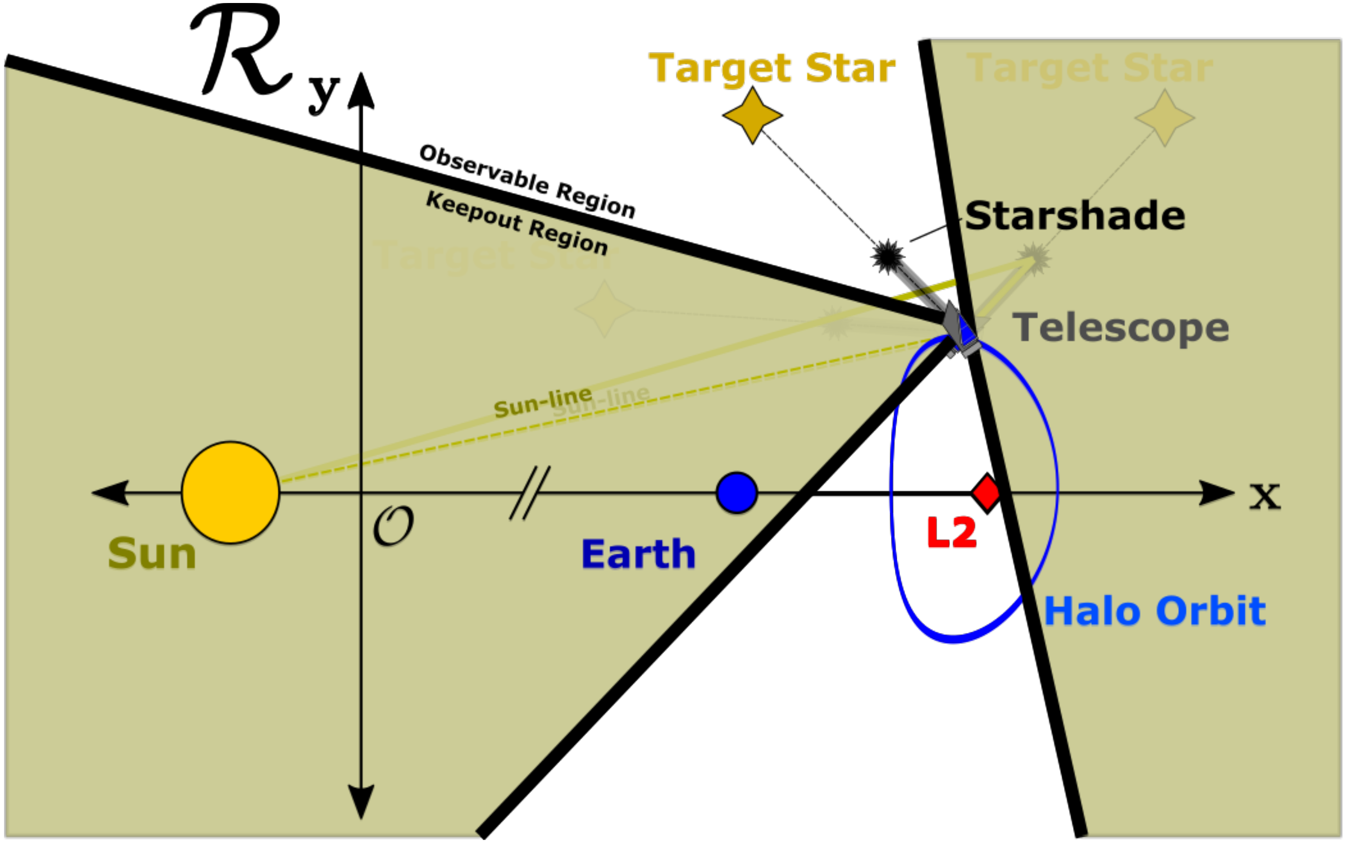
Continuous Thrust Fuel Costs

- Control law minimizes energy
- Fuel cost is directly a function of fuel mass used
- Fuel usage dependent on initial mass at start of maneuver
- More time dependent, too
    - Changes as telescope moves on halo orbit

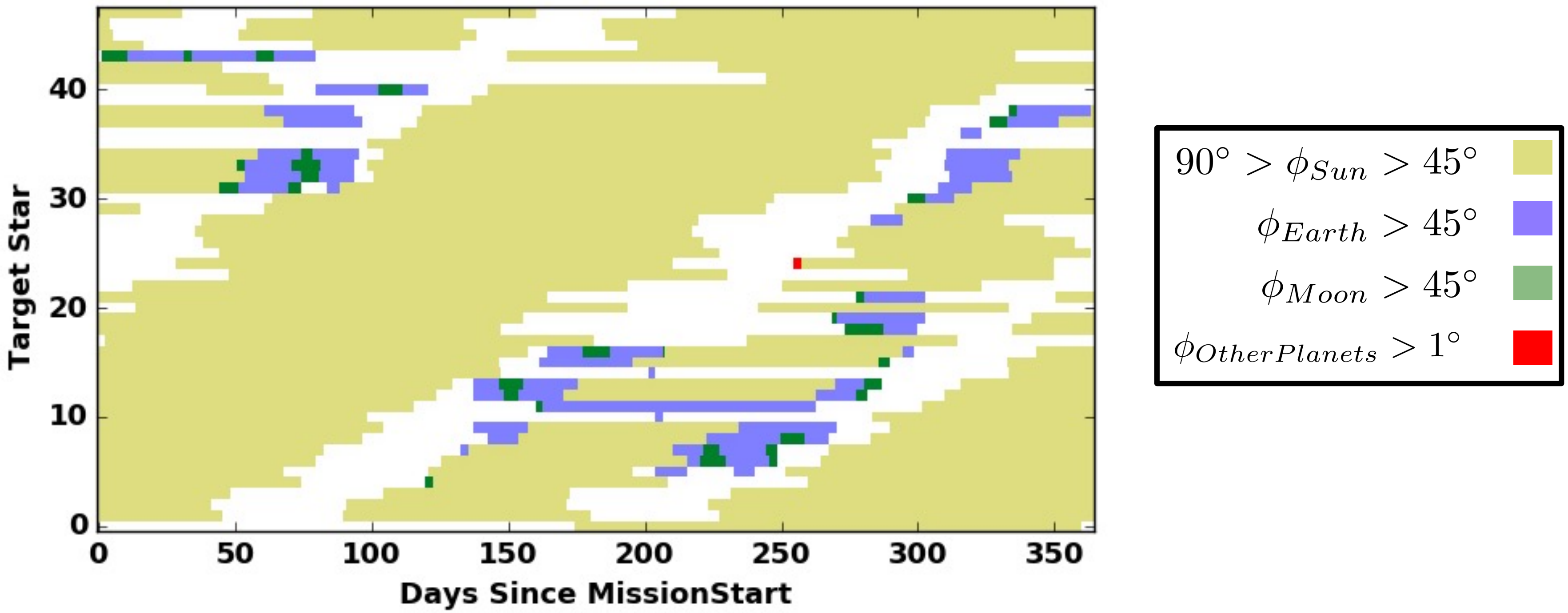


Part III: How Do We Schedule Observations in a Mission Simulator and Impose Realistic Mission Constraints?

Keepout Constraints

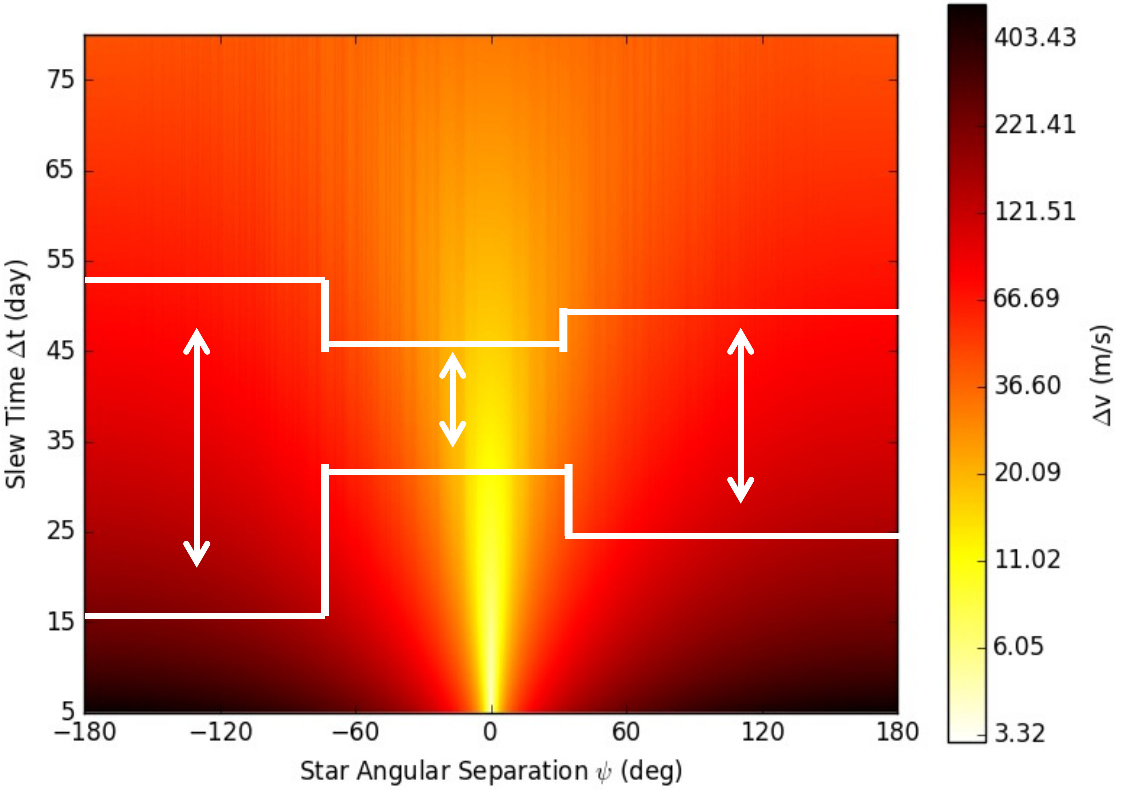


Keepout Constraints



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

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

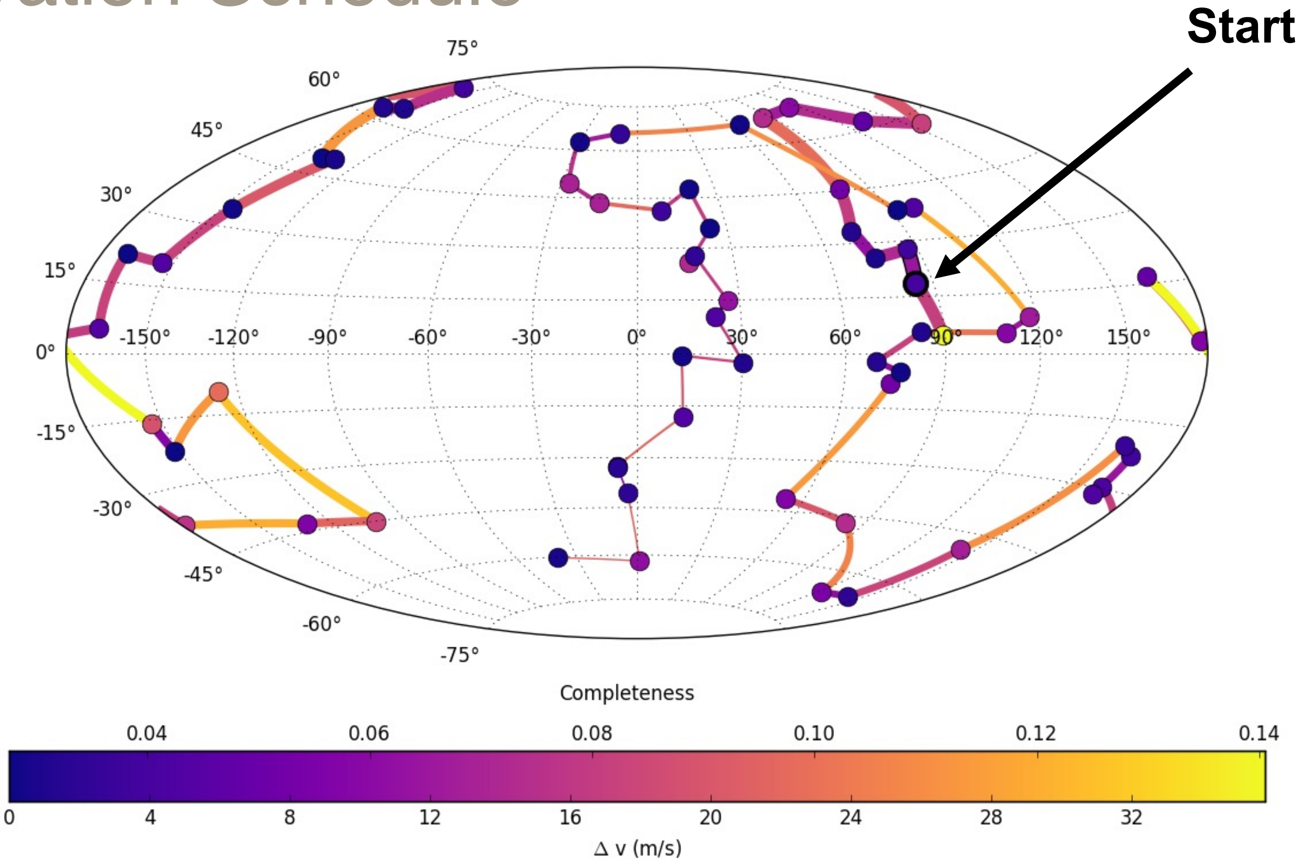
Prioritize stars designated for a revisit

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

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

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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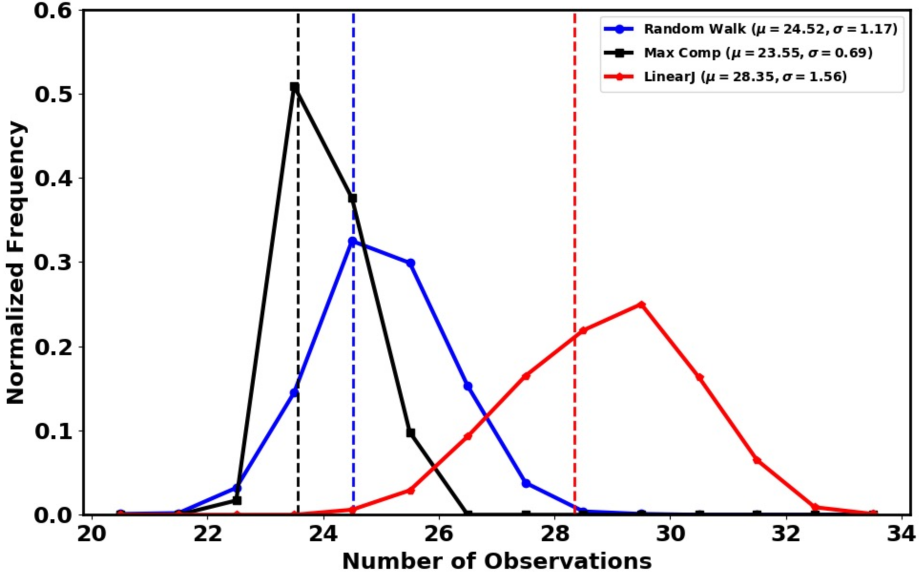
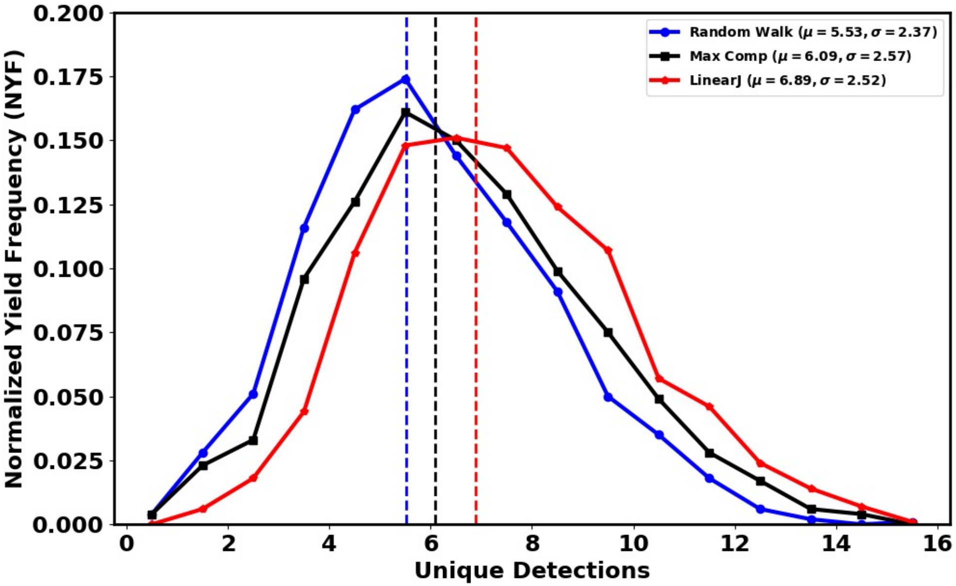
Mission Ensembles





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

Conclusions

- Better parameterization of fuel cost calculation
- Realistic mission constraints placed on these calculations
- Enables faster end-to-end mission simulations
- Near Future:
  - Implement continuous thrust interpolants in EXOSIMS
  - Station-keeping model

EXOSIMS main page:

github.com/dsavransky/EXOSIMS

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- NASA Grant No. NNG16PJ24C (SIT)
- NASA JPL Strategic University Research Partnership RSA No. 1618976

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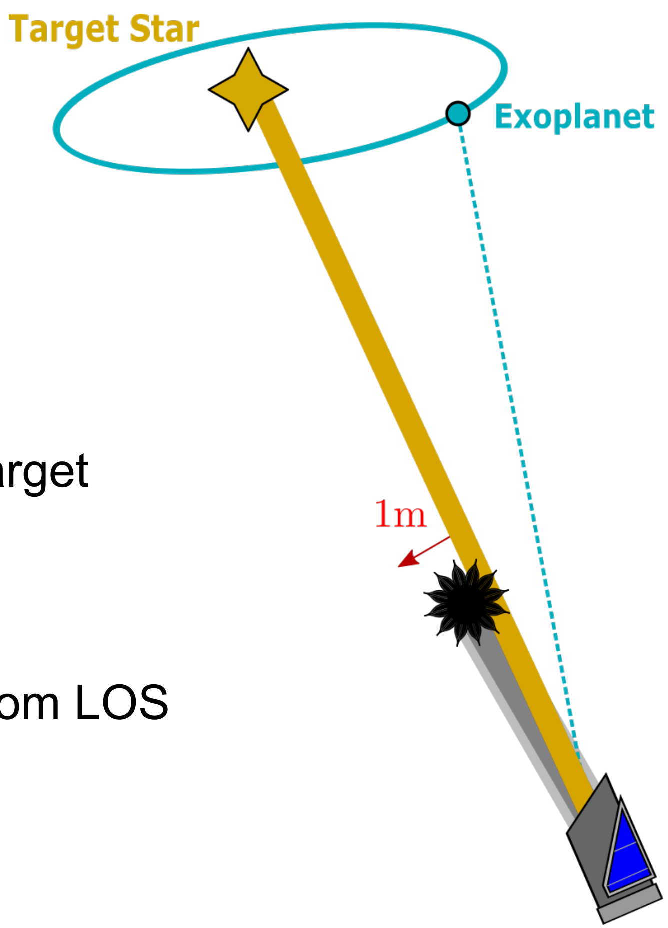
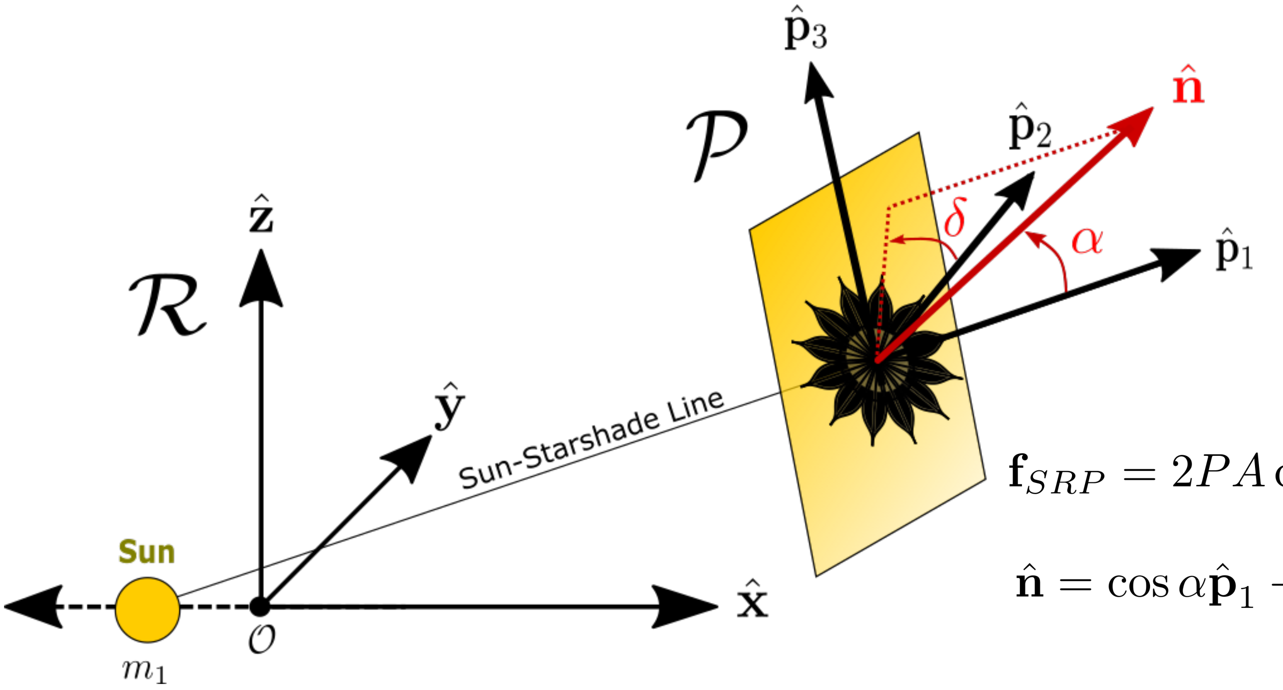
Backup Slides

Starshade Configuration



- No starlight enters telescope directly
  - Off-axis exoplanet light collected
- Maintains constant separation *s* along target star line of sight (LOS)
- Tight tolerance in lateral direction
  - Starlight floods pupil plane if >1m from LOS

Solar Radiation Pressure



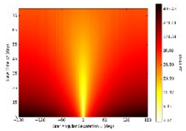
$$\mathbf{f}_{SRP} = 2PA\cos\alpha\left[b_1\hat{\mathbf{p}}_1 + (b_2\cos\alpha + b_3)\hat{\mathbf{n}}\right]$$

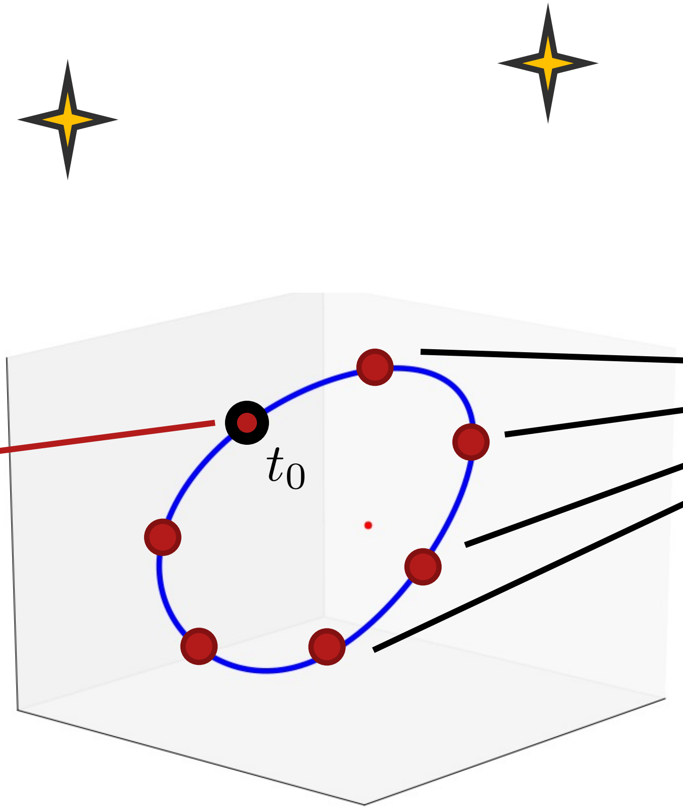
$$\hat{\mathbf{n}} = \cos\alpha\hat{\mathbf{p}}_1 + \sin\alpha\cos\delta\hat{\mathbf{p}}_2 + \sin\alpha\sin\delta\hat{\mathbf{p}}_3$$

Glassman et al (2011) “Creating optimal observation schedules for a starshade planet-finding mission” *IEEE*
McInness (1999) *Solar Sailing: Technology, Dynamics, and Mission Applications*
Soto et al (2019) “Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules.” *JGCD*

Impulsive Fuel Costs - Errors

Interpolated Solution



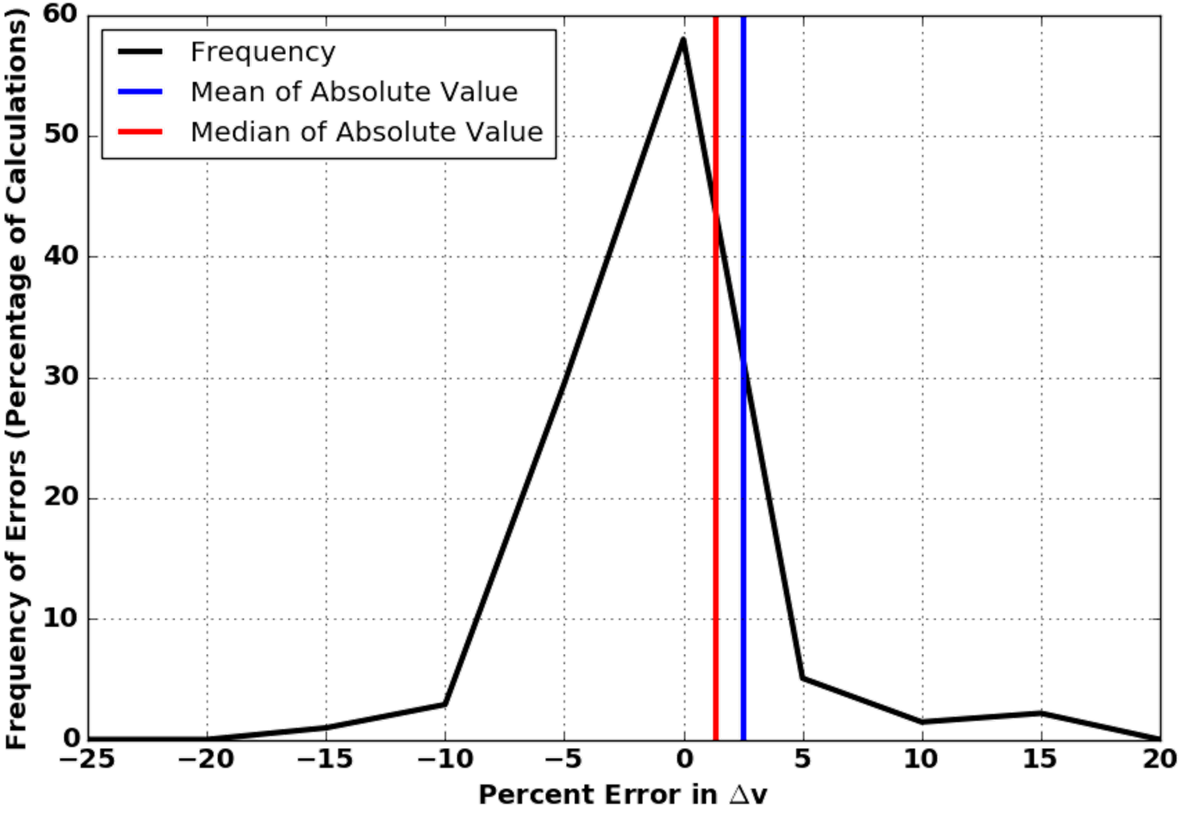


BVP Solution

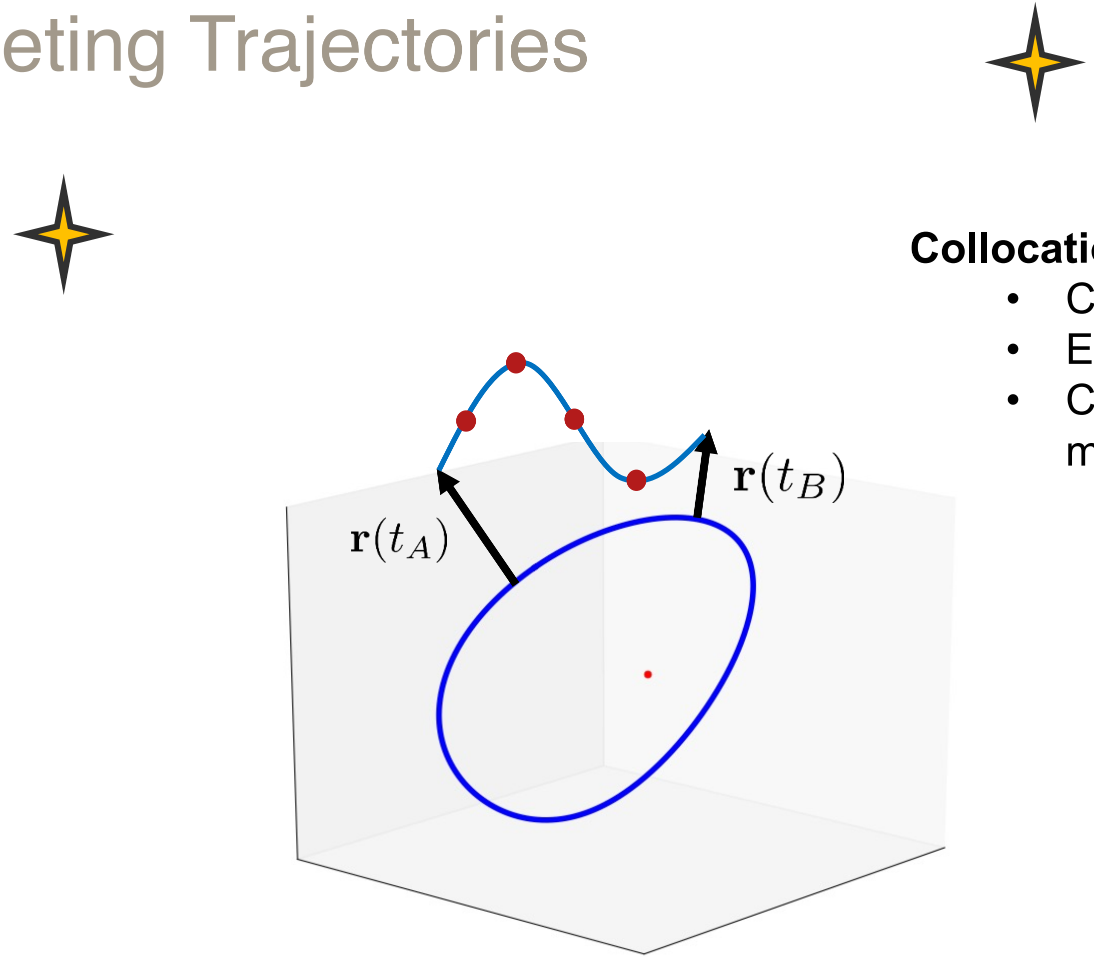
$$\Delta v_{BVP} = f(\Delta t, t0)|_{\psi_0}$$

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

Parameterizing Fuel Costs - Errors



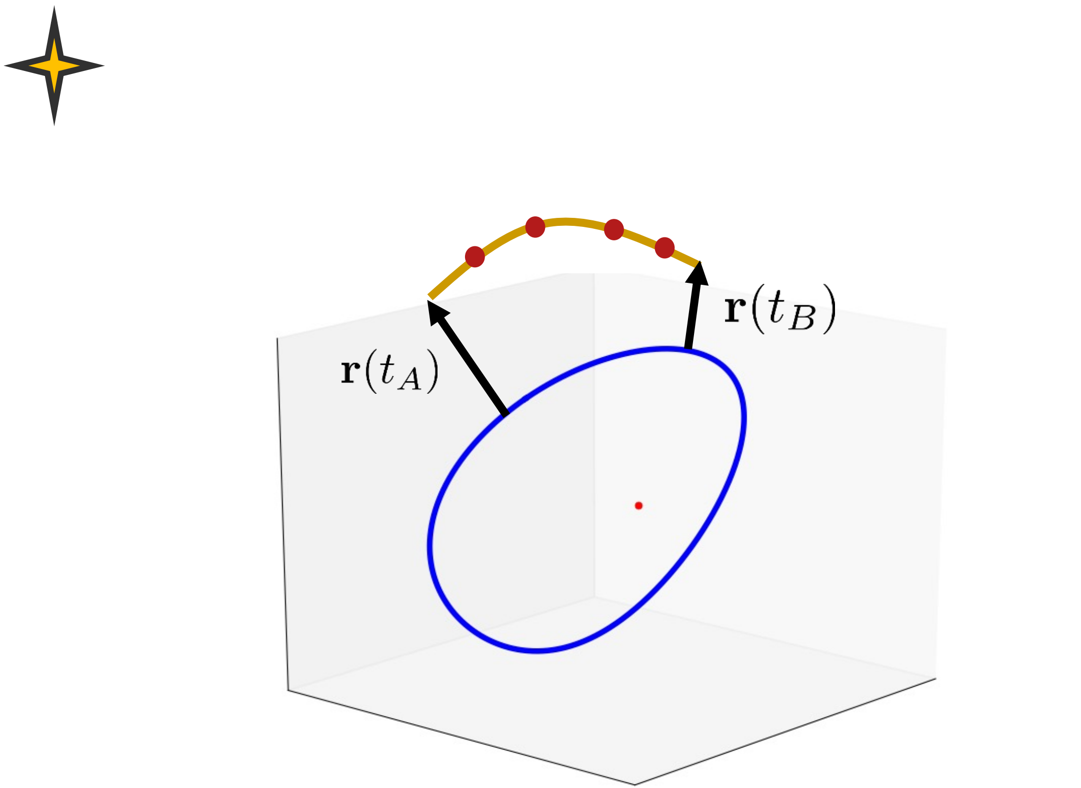
Retargeting Trajectories



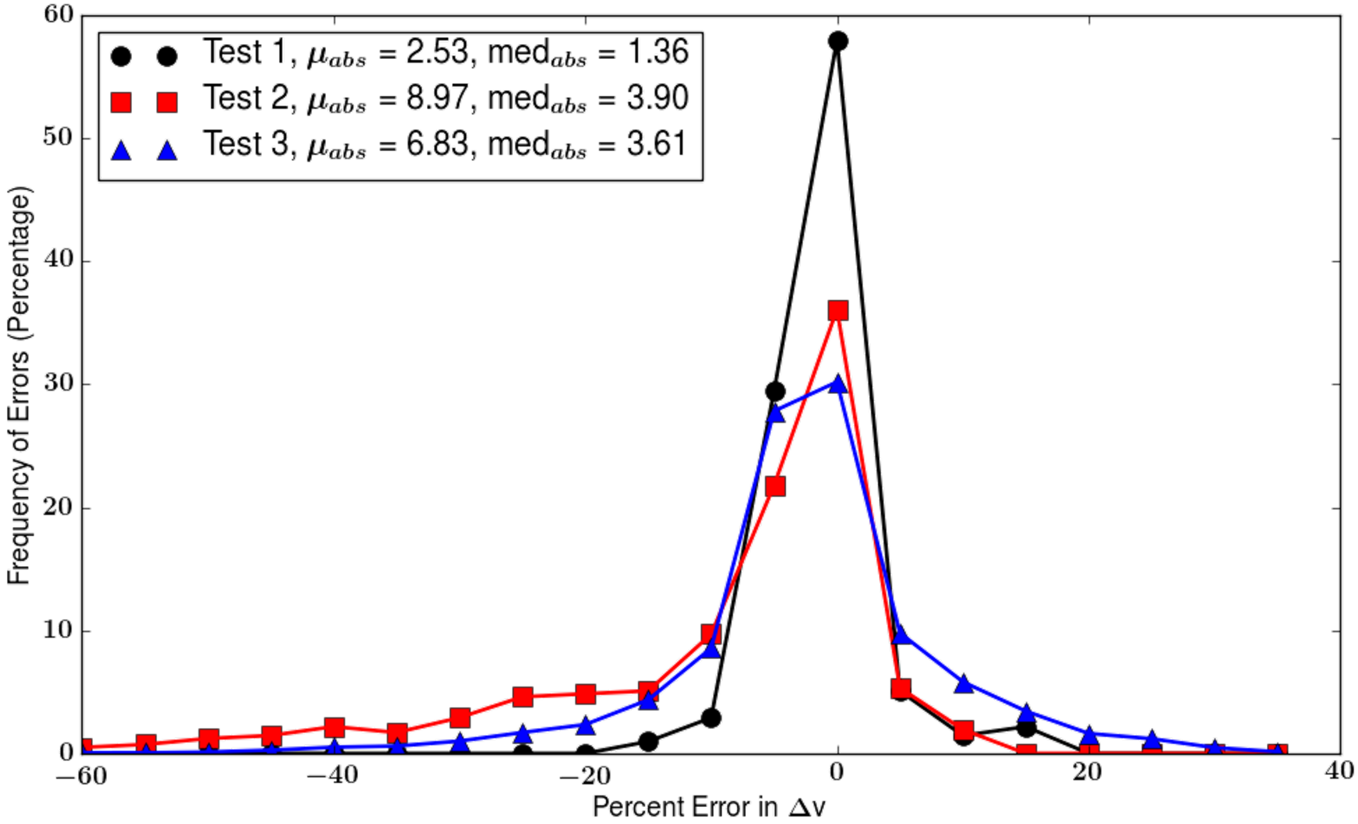
Collocation:

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

Retargeting Trajectories

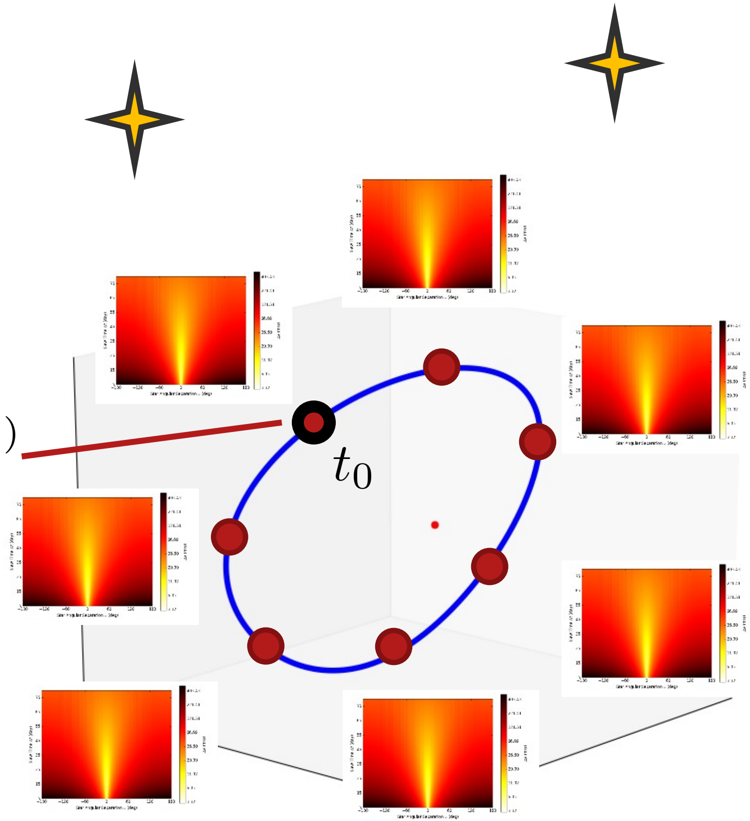


Error Analysis



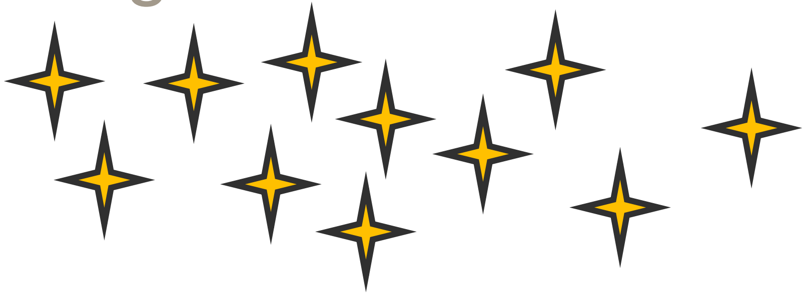
Parameterizing Fuel Costs - Errors

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

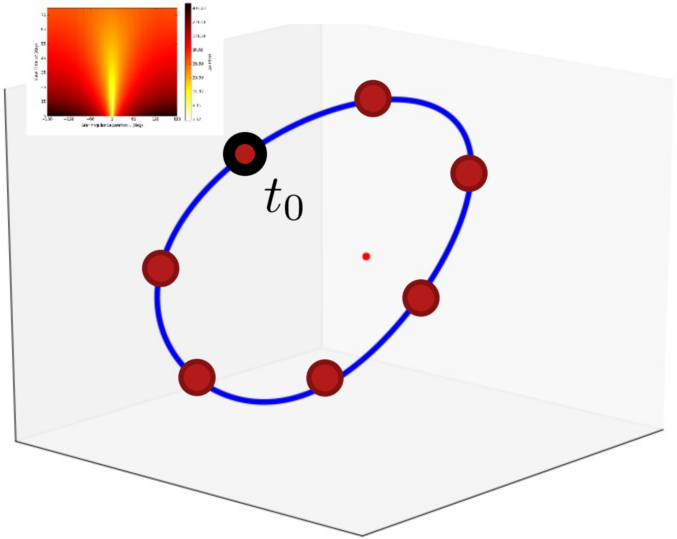


$$\Delta v_{INT} = f(\Delta t, t_0)|_{\psi_0}$$

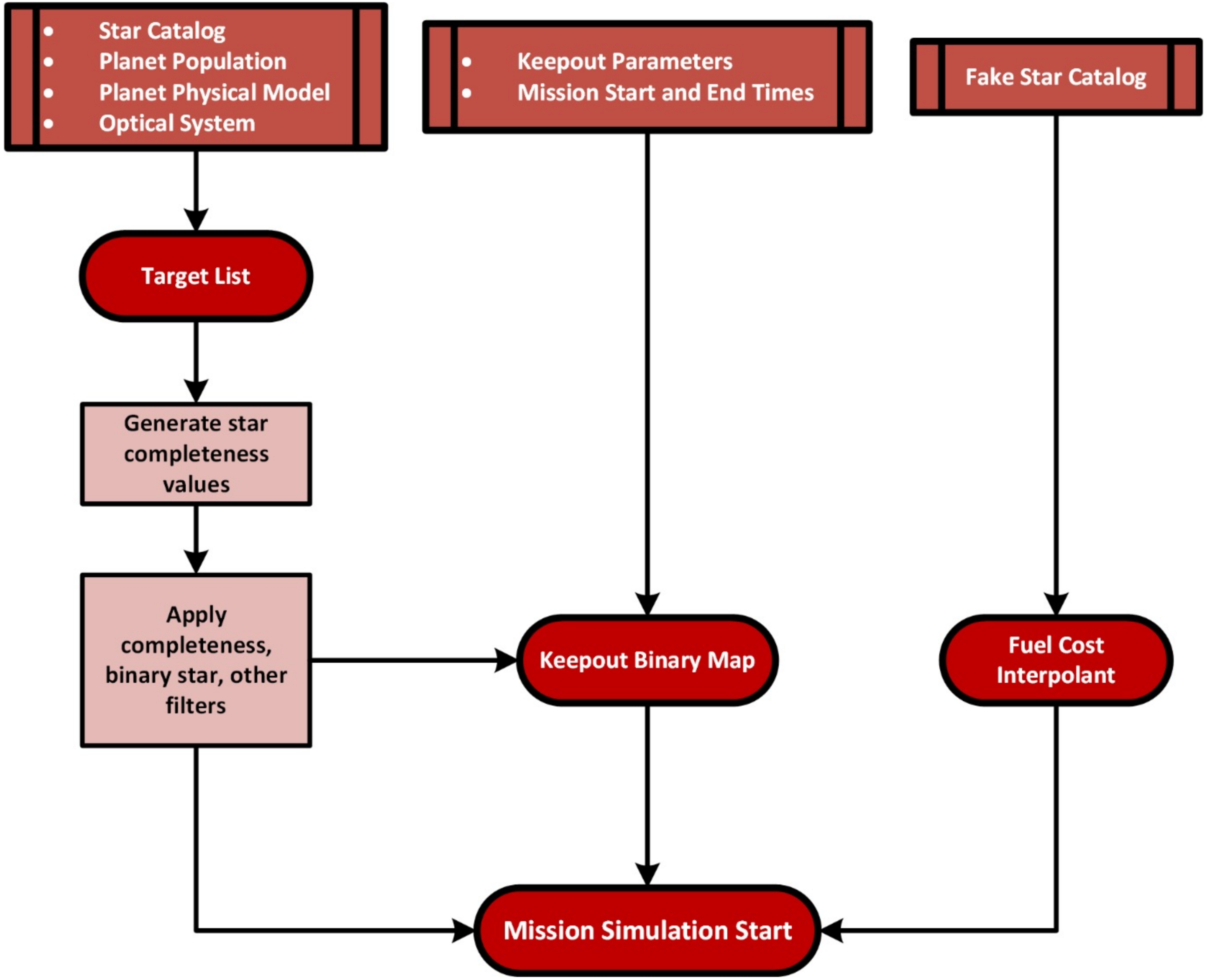
Parameterizing Fuel Costs - Errors



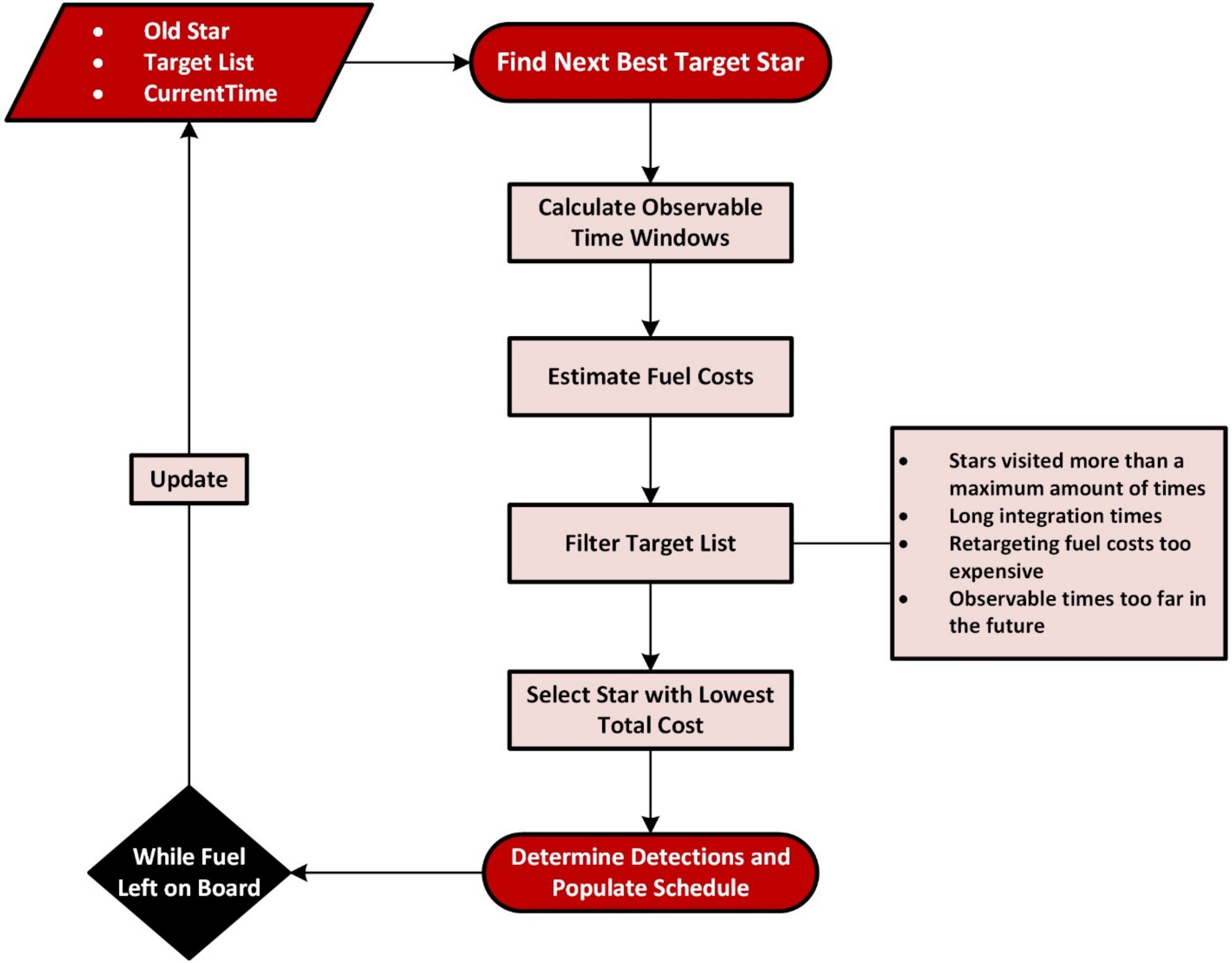
$$\Delta v_{BVP} = f(\psi, \Delta t, t_0)$$
$$\Delta v_{INT} = f(\psi, \Delta t, t_0)$$



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

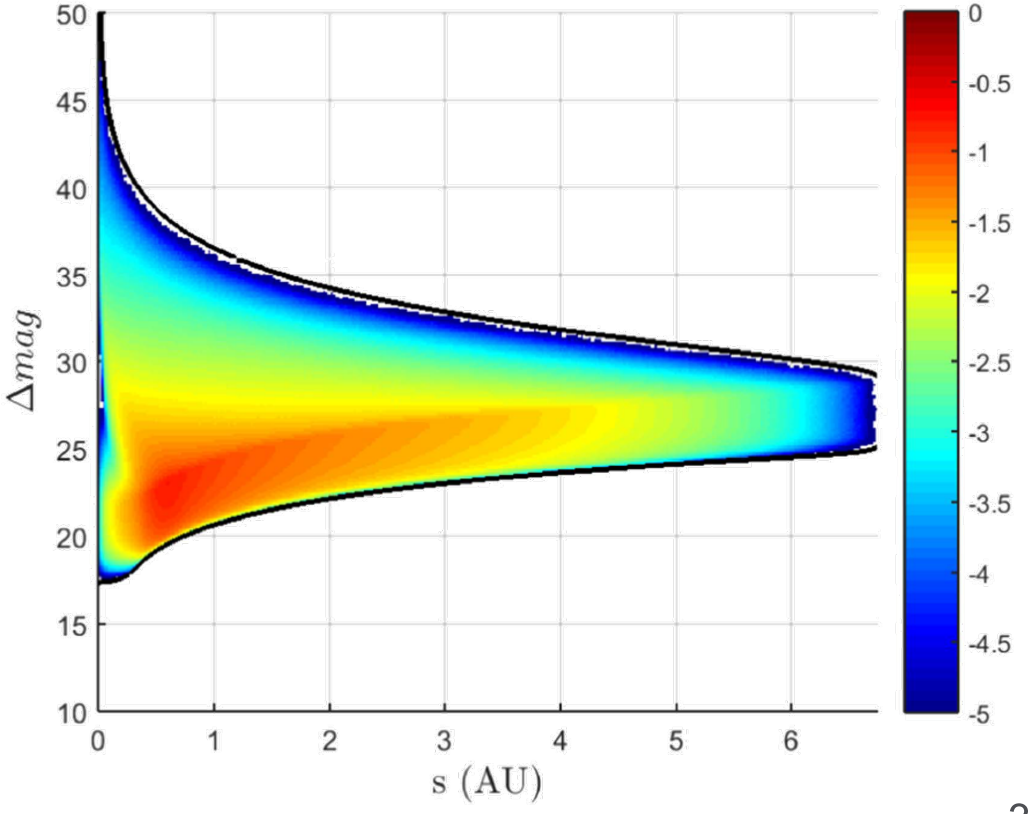
Scheduler



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”