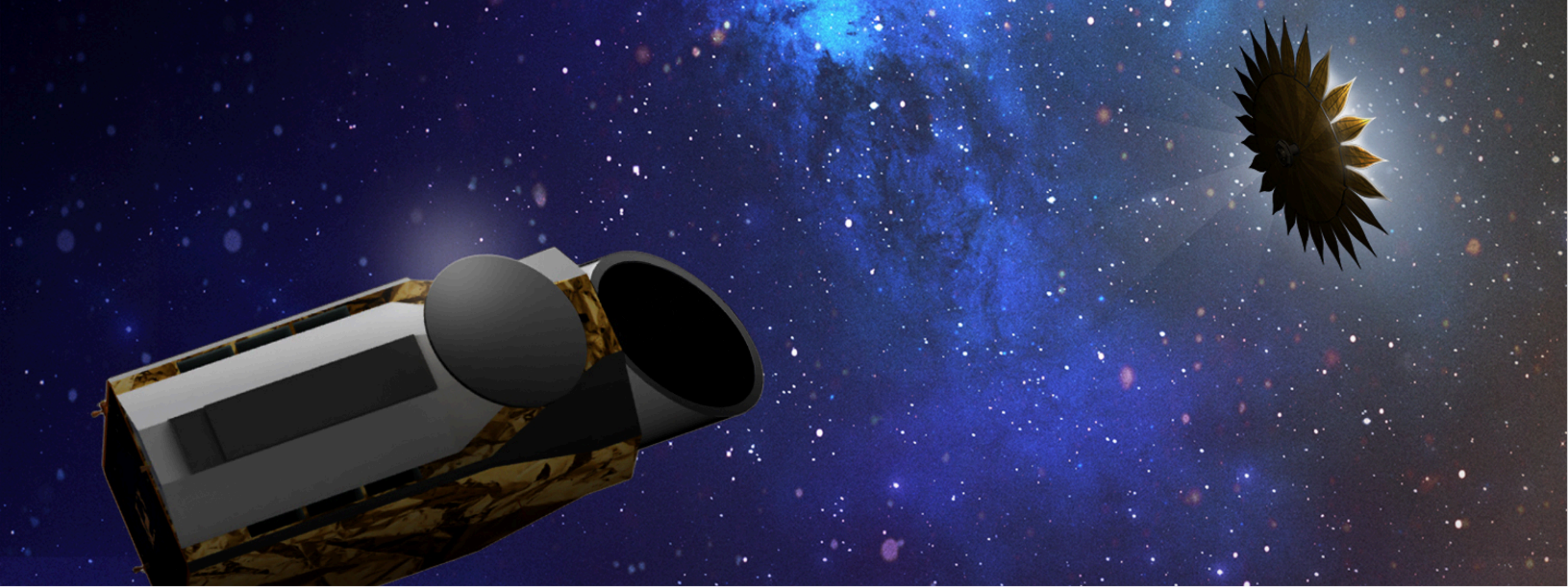


Virtual Research Presentation Conference

Advanced Simulation and Modeling for Direct Imaging Exoplanet Missions

Principal Investigator: Rhonda Morgan (383A)
Co-Is: Dmitry Savransky (Cornell University)
Program: SURP

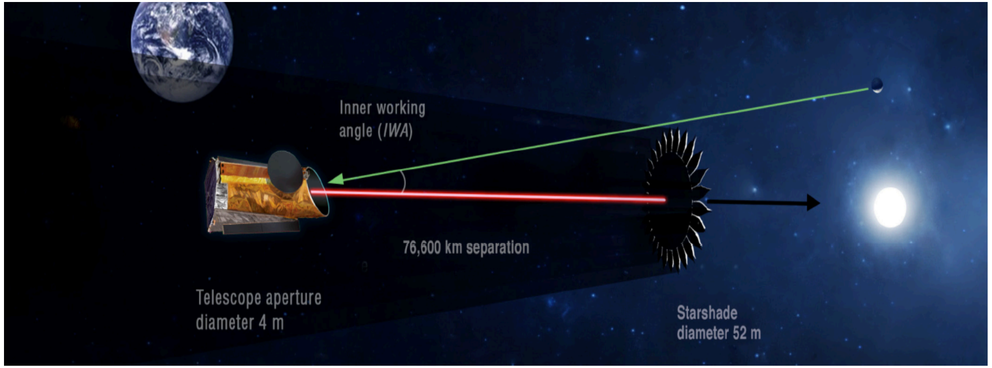
Assigned Presentation: RPC-020

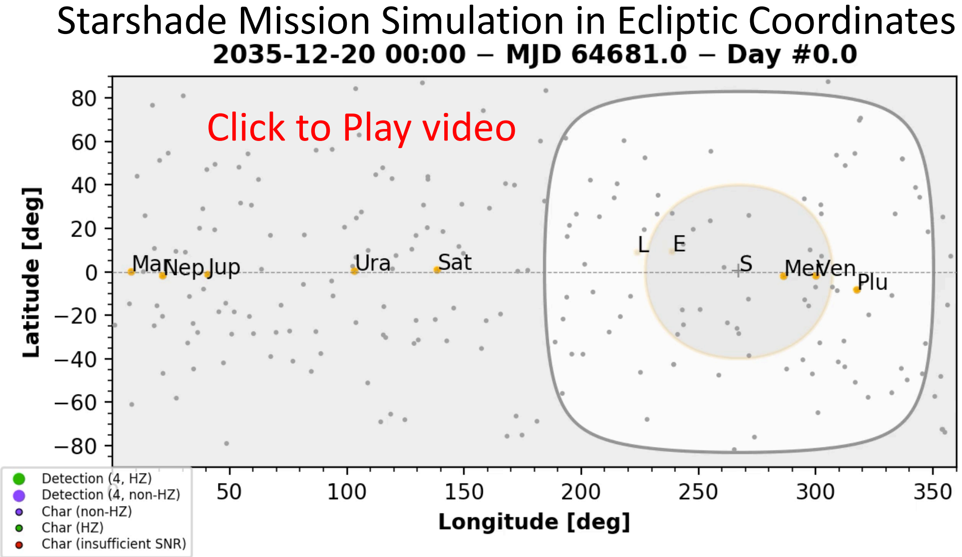
Jet Propulsion Laboratory
California Institute of Technology

Tutorial Introduction

Abstract

We created new capabilities for advancing the state-of-the-art in the simulation, analysis, and planning of direct imaging exoplanet space missions. We focus on creating and implementing scheduling algorithms for starshade-based exoplanet imagers. A starshade is an external occulting spacecraft that flies in formation with a space telescope to enable high contrast imaging. We aim to maximize the science return of a starshade-telescope mission in the presence of real, dynamic mission constraints. We have added orbital dynamics solutions for modelling fuel costs of the starshade. These are associated with two flight modes: (1) station-keeping as the starshade flies in formation with the telescope during an observation and (2) slewing towards a new target at some future time. There are strict constraints to both flight modes. For example, the starshade cannot drift more than 1 meter laterally from the desired line of sight otherwise we can't achieve the desired contrast. We have added both models to the EXOSIMS framework, an open-source software package that simulates full end-to-end missions. The fuel costs can now be used to select observations of promising targets to harbor exoplanets during optimal observing times for fuel usage.





Problem Description

Context and Relevance

- JPL currently engaged in studies for exoplanet missions for the Astrophysics 2020 decadal survey
- NASA goal to *“discover and study planets around other stars and explore whether they could harbor life*”
- JPL leading Starshade to TRL 5 “S5” task for potential starshade rendez-vous with Roman Space Telescope
- More realistic constraints to mission simulations increases confidence in yield results
  - Gauge performance of the starshade before operations
  - Inform mission planning for possible starshades flying with HabEx, LUVOIR, Roman Space Telescope

State-of-the-Art

- EXOSIMS is a full end-to-end mission simulator
  - First to include orbital dynamic solutions as fuel costs
  - First to combine fuel costs with other reward heuristics for target selection and observation scheduling

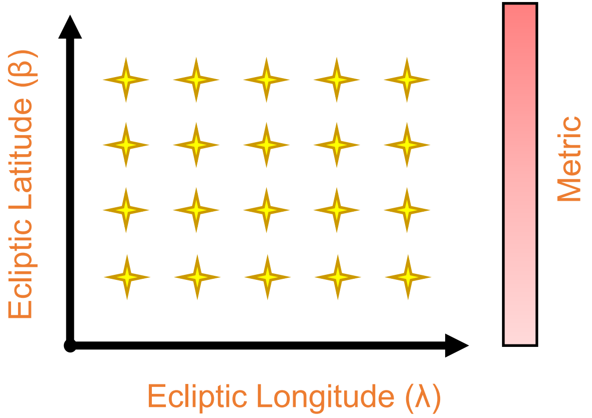
Methodology – Formation Flying

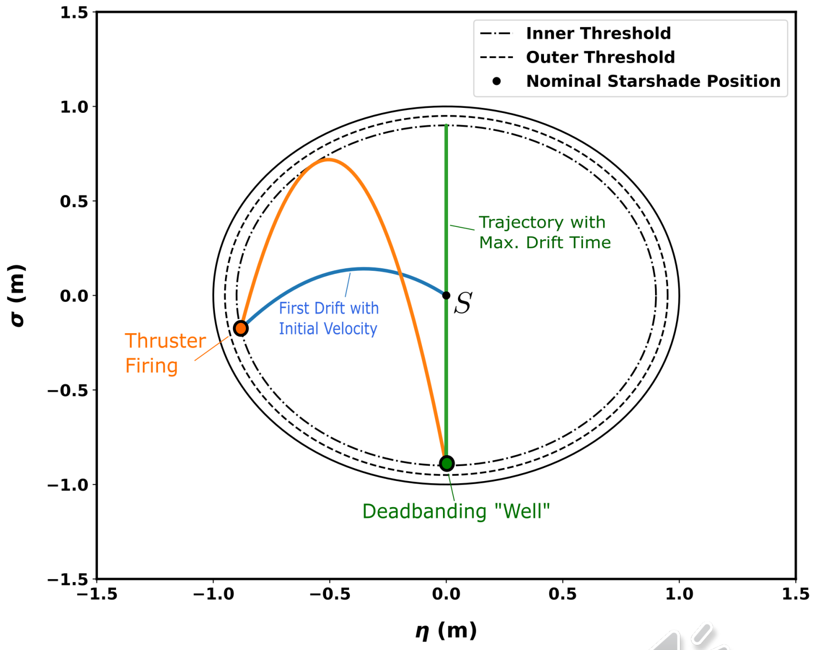
1. Define desired kinematics for perfect formation flight
    - At Sun-Earth L2, separated by 76,000 km from telescope
2. Apply dynamics to starshade to simulate deadbanding maneuvers[1]
    - Increase drift time between burns
3. Collect metrics as a function of star coordinates

   (Δv , N number of thruster firings, Δt_D drift time between burns, etc.)

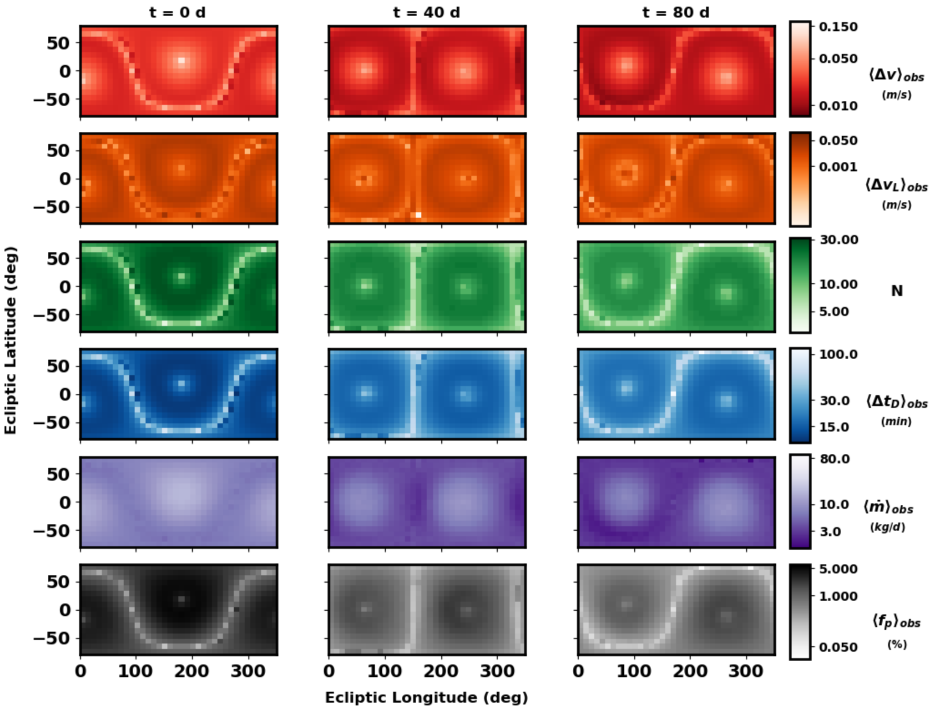
Metrics as a function of:

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





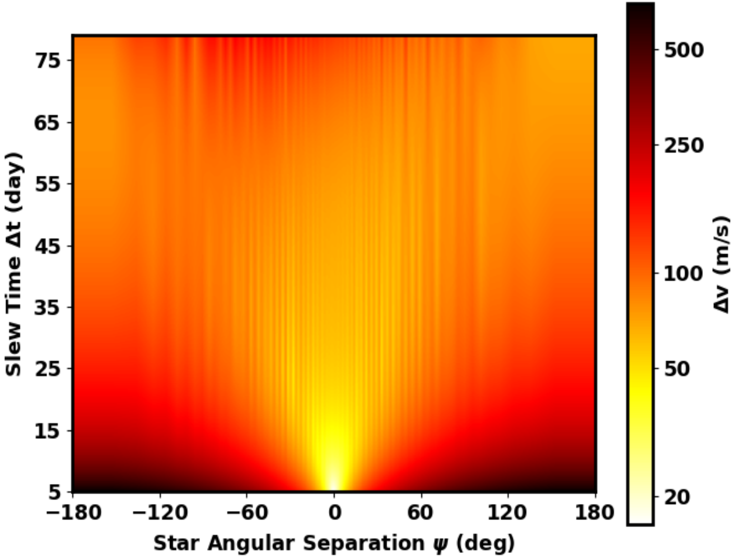
Results – Formation Flying



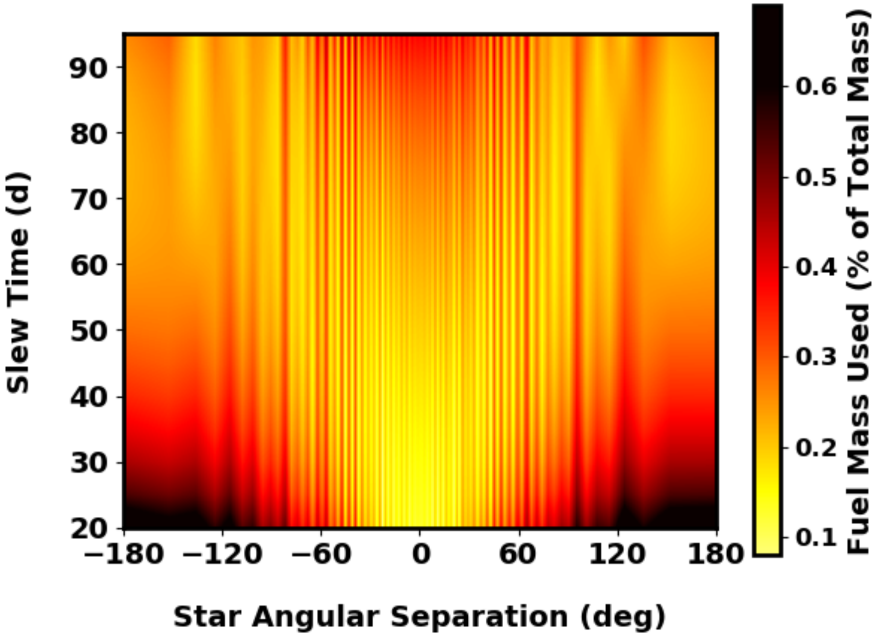
- Costs change as a function of star coordinates *and* mission time
  - Different orientations of the starshade lead to changing magnitudes of lateral forcing
- Selecting optimal time to observe a specific star:
  - Increases average drift times by up to 40 minutes
  - Worst case scenario for drift time is about 10 minutes per burn
  - Decreases fuel by up to 10 kg/day
  - Journal submission under review [B]

Methodology – Slew Maneuvers

1. Solve single trajectories by specifying endpoint stars and flight time
    - Previously conducted for impulsive maneuvers (chemical thruster) [A]
    - Now conducted for continuous maneuvers
2. Use optimal control strategies
    - Minimize control energy
    - Find time history of thruster throttling (given maximum thrust capability)
3. With convergent results, create cost map similar to impulsive costs
    - Parameterize by angular separation from reference star and slew time
    - Impose time constraints on slew time parameter
    - Generate range of possible slew times for observation scheduling
    - Create 2-D interpolant for fast cost calculations during simulations

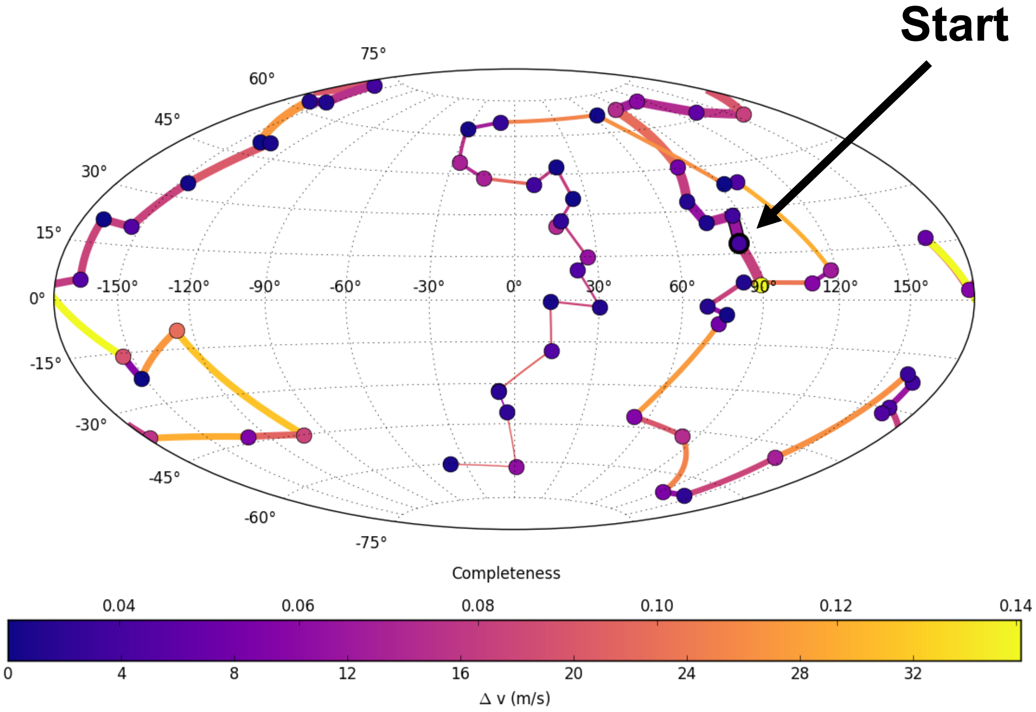


Results – Slew Maneuvers



- Cost matrix uses similar parameterization as impulsive case
  - Directly maps to fuel mass used
  - Fuel costs are *drastically reduced* to fractions of total mass percentage
- More sensitive to location of stars at the endpoints
  - Less continuous along the 2-D parameterization
  - New parameterizations need to be considered for reduced computation times
  - More intricate algorithm needed to produce shorter slew time solutions (if they exist)

Results – Scheduling



- Example of an observation schedule
  - Line colors = Δv (fuel usage)
  - Dot colors = star completeness (probability of detecting an exoplanet with optical instrument)
  - Line thickness decreases over mission lifetime in Figure
- Average of 28 observations in 3 year period, ~7 unique detections
  - Only incorporates impulsive slew maneuver costs
  - Observatory modeled after Roman Space Telescope
  - Formation flying and continuous thrust models will be incorporated in near future

Publications and References

A. Gabriel Soto, Dmitry Savransky, Daniel Garrett, Christian Delacroix, “Parameterizing the Search Space of Starshade Fuel Costs for Optimal Observation Schedules,” *Journal of Guidance, Control, and Dynamics,* **42,** 12 (Dec 2019): pp 2671-2676

B. Gabriel Soto, Dmitry Savransky, Rhonda Morgan, “Analytical Model for Starshade Formation Flying with Applications to Exoplanet Direct Imaging Observation Scheduling,” *Journal of Astronomical Telescopes, Instruments, and Systems* (under review)

1. Thibault Flinois, Daniel Scharf, Carl Seubert, Michael Bottom, Stefan Martin, “Starshade formation flying II: formation control,” *Journal of Astronomical Telescopes, Instruments, and Systems* **6** (Apr 2020): pp. 029001 (1-28)