National Aeronautics and Space Administration

Advanced Simulation and Modeling for Direct Imaging Exoplanet Missions

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Program: FY21 SURP **Strategic Focus Area: Extra-solar planets and star and planetary formation**

Objectives:

The objective of this work was to create new capabilities in the simulation, analysis, and planning of starshade-based direct imaging exoplanet space missions. Our work seeks to maximize the science return of a starshade mission while accounting for realistic, dynamic mission constraints. We have created detailed orbital dynamics simulations for modelling fuel costs of the starshade in both of its two flight modes: (1) the formation flying mode with the telescope during an observation and (2) the slewing flight mode as the starshade re-aligns itself simulations [1] [2]. Fuel costs are combined with other optimization parameters, such as probability of detection and slew time [3] [4]. The mission simulations provide the number of successful exoplanet detections and characterizations. The objectives of this work were to develop a higher fidelity model for fuel usage during impulsive station-keeping maneuvers and continuous thrust transfer slews, then integrate these models into EXOSIMS. Two major objectives for year 3 of this SURP were to:

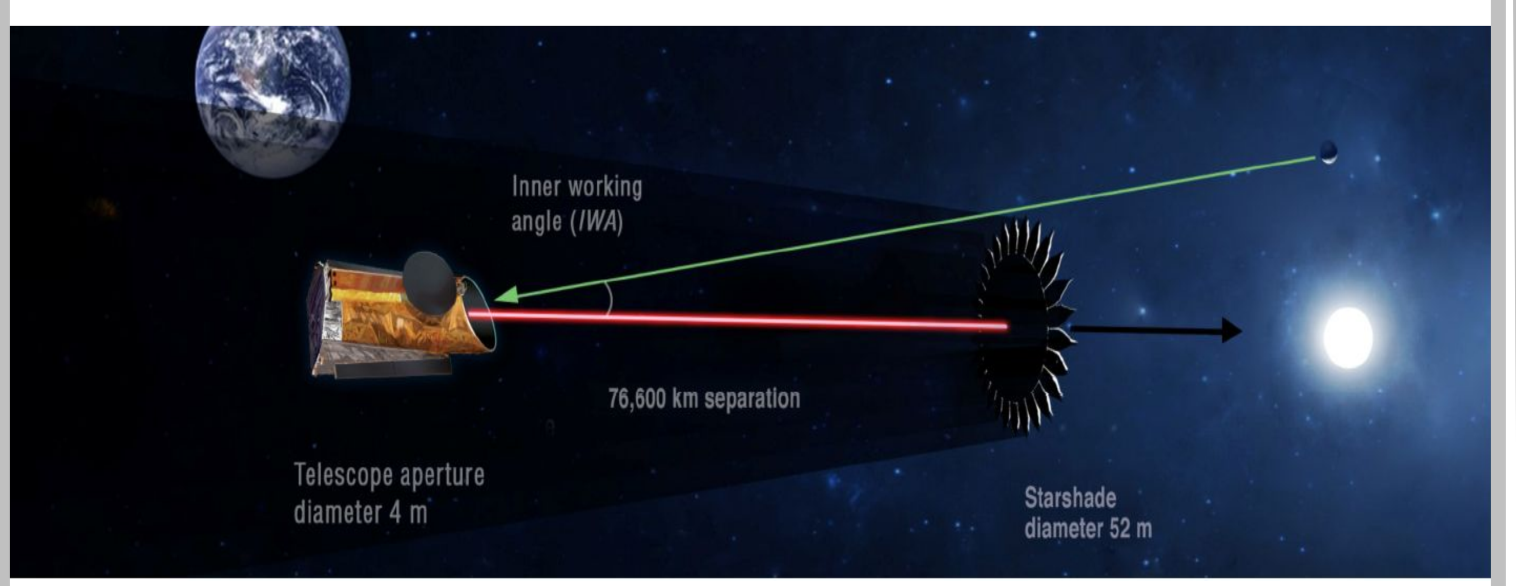
1. Incorporate the higher fidelity fuel usage model in EXOSIMS and run end-to-end design reference mission simulations
2. Improve computation times associated with station-keeping requirements

Benefits to NASA and JPL:

JPL is engaged in studies for exoplanet missions for the decadal survey, and in development of starshade technologies through the S5 Technology project. This work advanced DRM simulation software for evaluating science yields for these exoplanet imaging missions under real fuel and mission time constraints, which was used in the JPL-led HabEx Concept study. The work positions JPL to serve as a leader in the design and analysis of future exoplanet missions.

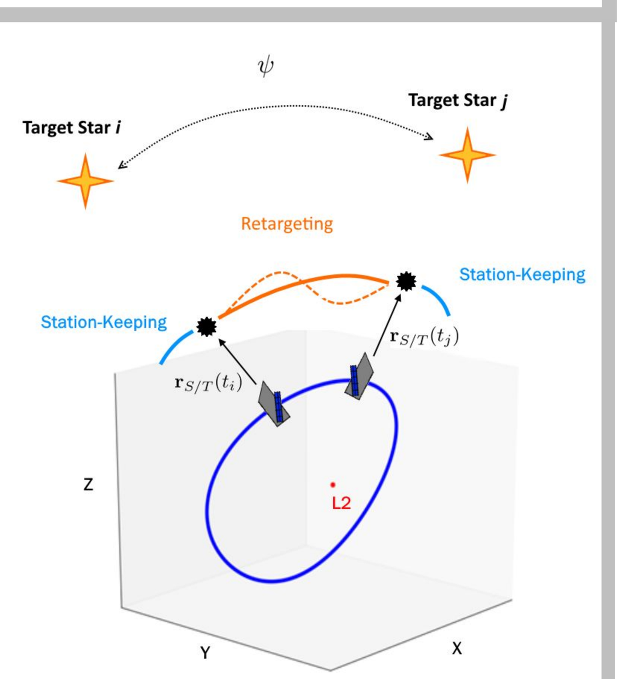
Background:

A starshade is an external occulting spacecraft that flies in formation with a space telescope to enable high contrast imaging. The Habitable Exoplanet Observatory (HabEx) large mission concept is comprised of a 52 m starshade 76,600 km in front of a 4 m diameter telescope.



Starshade Orbital Maneuvers:

- Two starshade flight modes: station-keeping and retargeting (or slewing)
- We analyze fuel costs for retargeting (most costly)
- Starshade is aligned with star *i* at the beginning of maneuver
- Aligned with star *j* at the end of maneuver
- Stars are an angular separation Ψ apart, used for parameterizing fuel costs
- Retargeting maneuvers can be achieved two ways:
  - Impulsive maneuvers through bi-prop chemical burns (instantaneous change in velocity Δv)
  - Low thrust maneuvers through SEP or other continuous thrust engines



Approach and Results:

To the end of improving computation times of station-keeping metrics such as delta-v cost and frequency of maneuvers, we demonstrated that an analytical calculation of differential lateral acceleration between telescope and starshade effectively approximates all station-keeping metrics of interest. Figure 1 compares the delta-v cost calculated with a high fidelity simulation of station-keeping involving numerical integration and event detection against a simple analytical calculation based on differential lateral acceleration, demonstrating differences typically below 1% and on the order of 10% in some edge cases.

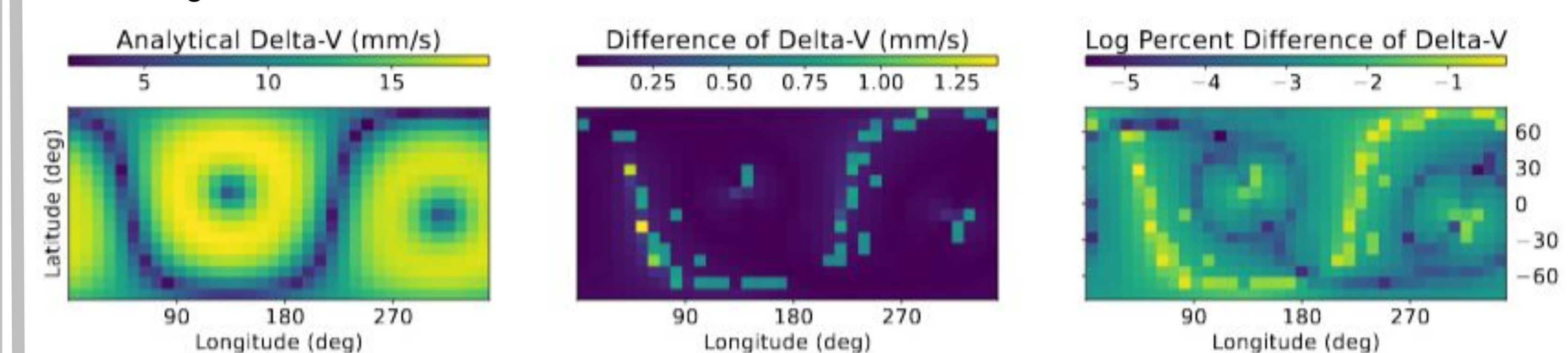


Figure 1: Comparison between numerical and analytical models of the average delta-v to perform a single station-keeping impulse in mm/s during an observation at 340 days from the start of the reference halo orbit.

To improve understanding of trends in station-keeping as a function of telescope position and target star location, we analyzed differential lateral acceleration in the circular restricted three body problem. By projecting station-keeping costs as a function of ecliptic coordinates onto the surface of a sphere in Figure 2, we explain the structure of heat maps from [1]. Minima of differential lateral acceleration lie approximately on a great circle and its two corresponding poles.

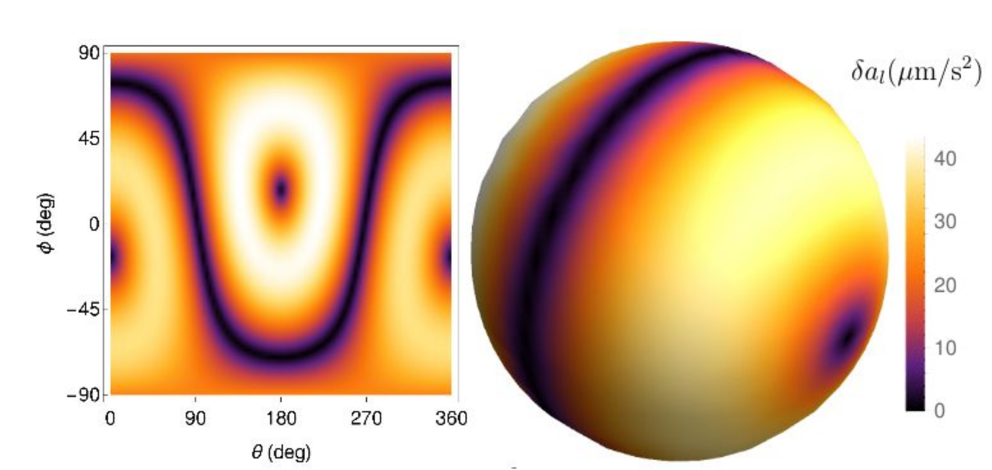


Figure 2: The differential lateral acceleration in micrometers per second squared as a function of target coordinates. The density plot on the left is accompanied by its projection onto the unit sphere on the right.

Given a telescope along a nominal Halo orbit, we plot the location of one pole in Figure 3. We approximate the location of the pole as an eigenvector of the Jacobian matrix of inertial acceleration at the telescope location, and present a closed form analytical expression for its ecliptic coordinates as a function of telescope position. In this manner, all minima of differential lateral acceleration are known by analytical calculation for any telescope position. Future mission designs can leverage this analytical expression for telescope pointing vectors that require the lowest delta-v for station-keeping and fewest interruptions to observations.

By implementing a tiered scheduling system for determining which target to observe next, we minimize the amount of time not spent in an observational mode and fuel used over the course of a mission. Priority is first given to scheduling an observation with the starshade. Coronagraph observations and general science observations, listed in priority, can be scheduled during the starshade's slewing. Targets are filtered out based on integration cutoff time and keep-out regions determined by optical constraints. Final selection from the remaining targets after the filtering process is made using a weighted linear cost function comprised of delta-v cost, potential science yield, amount of existing observations to a given target, and wait time until observation [3]. A variety of instrument ensembles can be used with this scheduling system. The characterization yields for two methods of flying the starshade are shown in Figure 4. Method A, validated in 2019, calculates fuel usage based on the delta-v for a slew [4]. Method B, currently undergoing validation, calculates the cost associated by performing a slew based on the locations of the previous and next targets, the time a slew is initiated, and the amount of time spent slewing as a way to optimize starshade flying. Preliminary results show optimization of the starshade slewing dynamics produces a science yield comparable to Method A when the slew cost function favors conservative fuel use in the cost calculation.

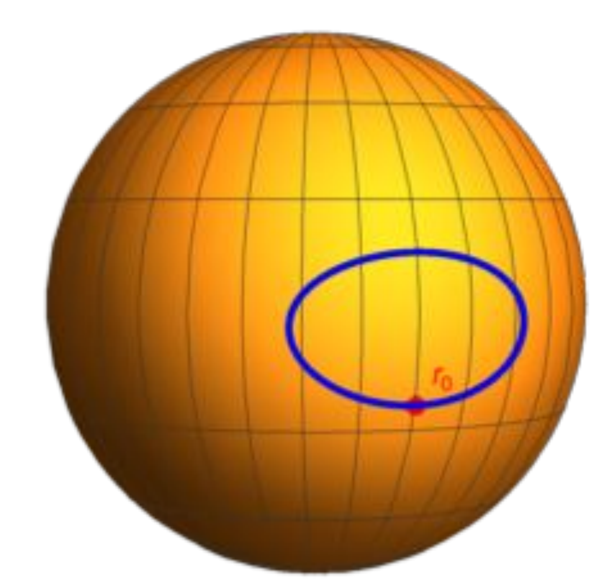


Figure 3: Pole location as the telescope moves along the reference halo orbit trajectory in terms of ecliptic longitude, latitude and location on the unit sphere.

	Method A	Method B
Total Detections	4.59	4.6
Total Characterization Attempts	3.24	3.51
Total Successful Characterizations	3.16	3.15

Figure 4: Science yield comparison between starshade maneuvering methods for characterizations with dual detection coronagraph instruments for detections and characterizations over a five year mission. Values are averaged over 300 trials.

Publications:

[1] Soto, G. (Dec 2020). [Orbital Design Tools and Scheduling Techniques for Optimizing Space Science and Exoplanet-Finding Missions], Dissertation, Cornell University https://hdl.handle.net/1813/103457

[2] Kulik, J., Soto, G. J., & Savransky, D. (2021). Minimal Differential Lateral Acceleration Configurations for Starshade Stationkeeping in Exoplanet Direct Imaging. *arXiv preprint arXiv:2105.05898*.

Citations:

[3] Morgan, R., Savransky, D., Stark, C., &; Nielsen, E. (2019). The Standard Definitions and Evaluation Team Final Report.

[4] Soto, G., Savransky, D., Garrett, D., Delacroix, C., "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

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Links:

EXOSIMS Github Link:

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