National Aeronautics and Space Administration

Advanced Simulation and Modeling for Starshade-based Exoplanet Imaging Missions

Principal Investigator: Rhonda Morgan (JPL 383A)
Co-I: Dmitry Savransky (Cornell University), Graduate student: Gabriel Soto (Cornell University)
Program: SURP

Project Objective:

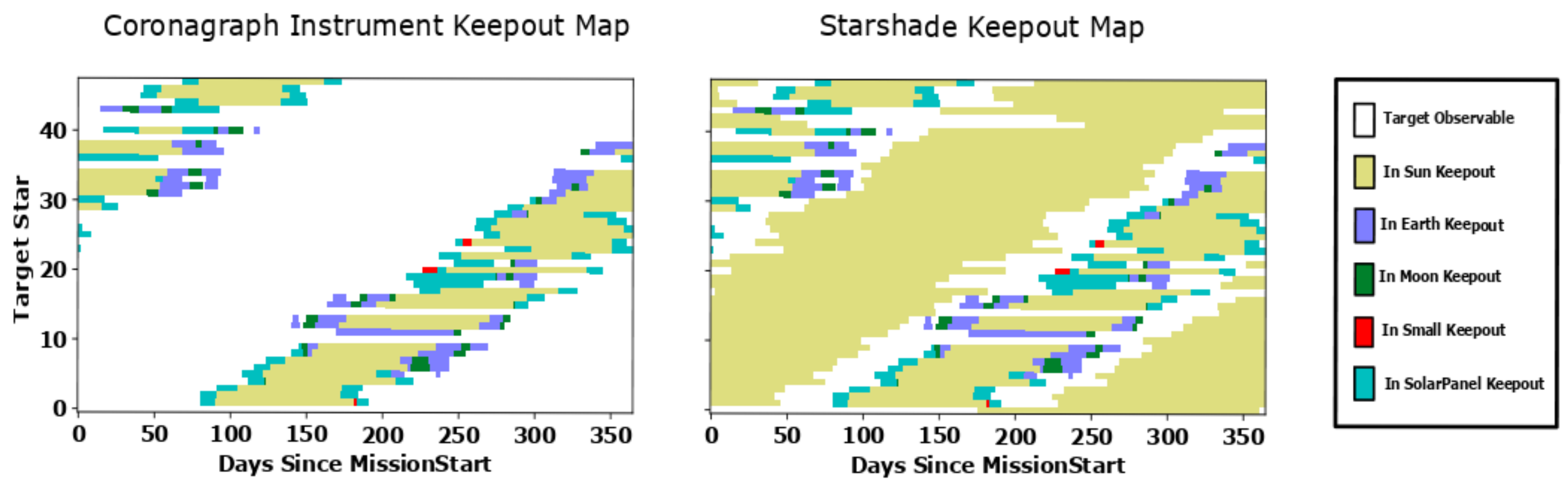
The objective of this work was to add new capabilities that advance the state-of-the-art in the simulation, analysis, and planning of direct imaging exoplanet space missions. Scheduling algorithms were created for starshade-based exoplanet imagers (a formation-flying solution to the problem of high contrast imaging) to maximize science return in the presence of real, dynamic mission constraints. The two major tasks for the design reference mission (DRM) simulation software EXOSIMS were to:

1. Implement efficient slew calculators for starshade spacecraft operating about the Sun-Earth L2 point
2. Integrate variable length starshade slews in the full mission optimization

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.

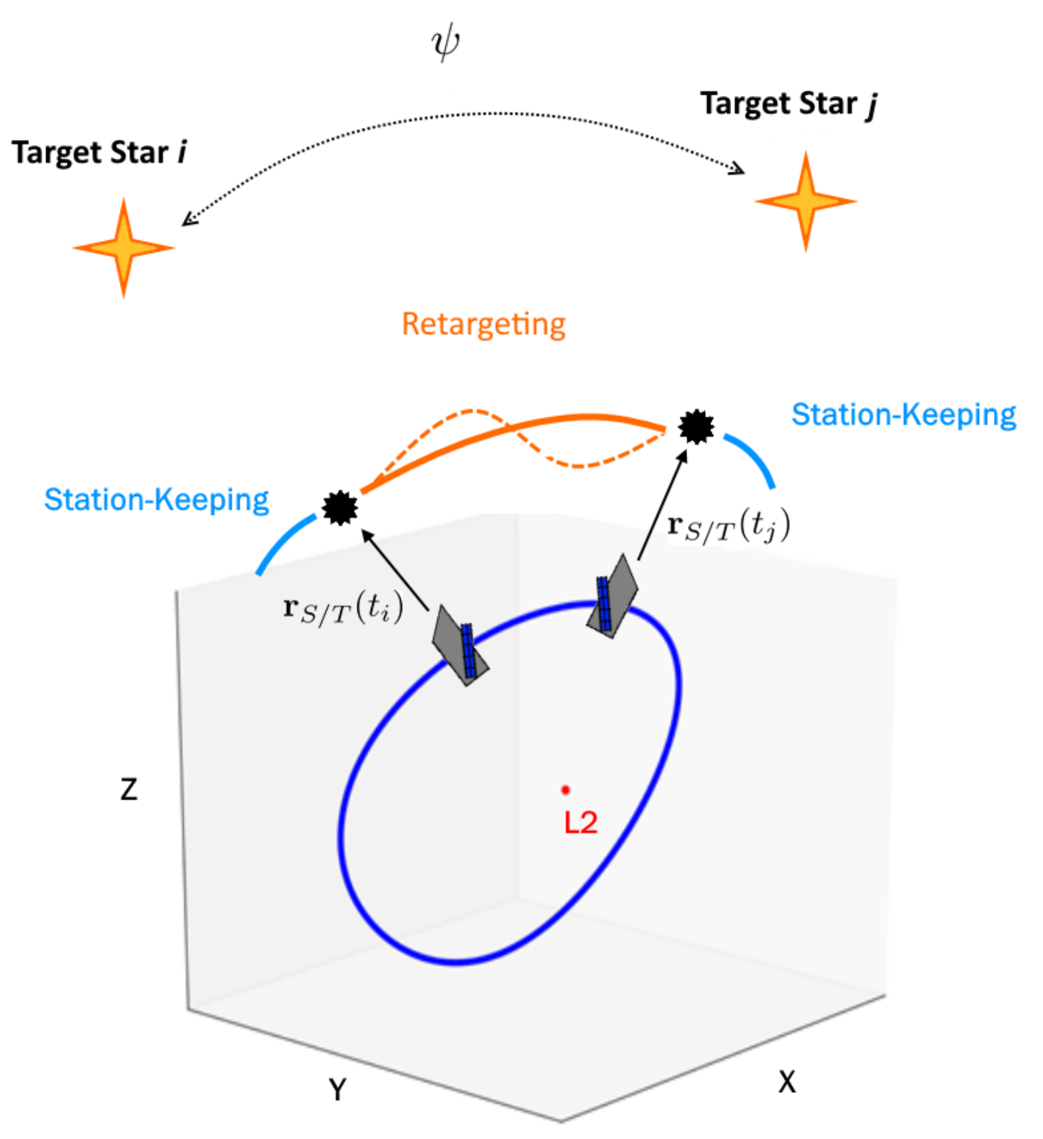
Keepout Angle Constraints



- Motion of bright bodies like Earth, Sun, Moon, etc. prohibit star observations
- Track locations of bright bodies relative to telescope at L2
- Stars within certain angles (45 degrees from Sun, etc.) are in the bright object's keepout and therefore unobservable
- Separate keepout maps used for mission with coronagraph/starshade combination

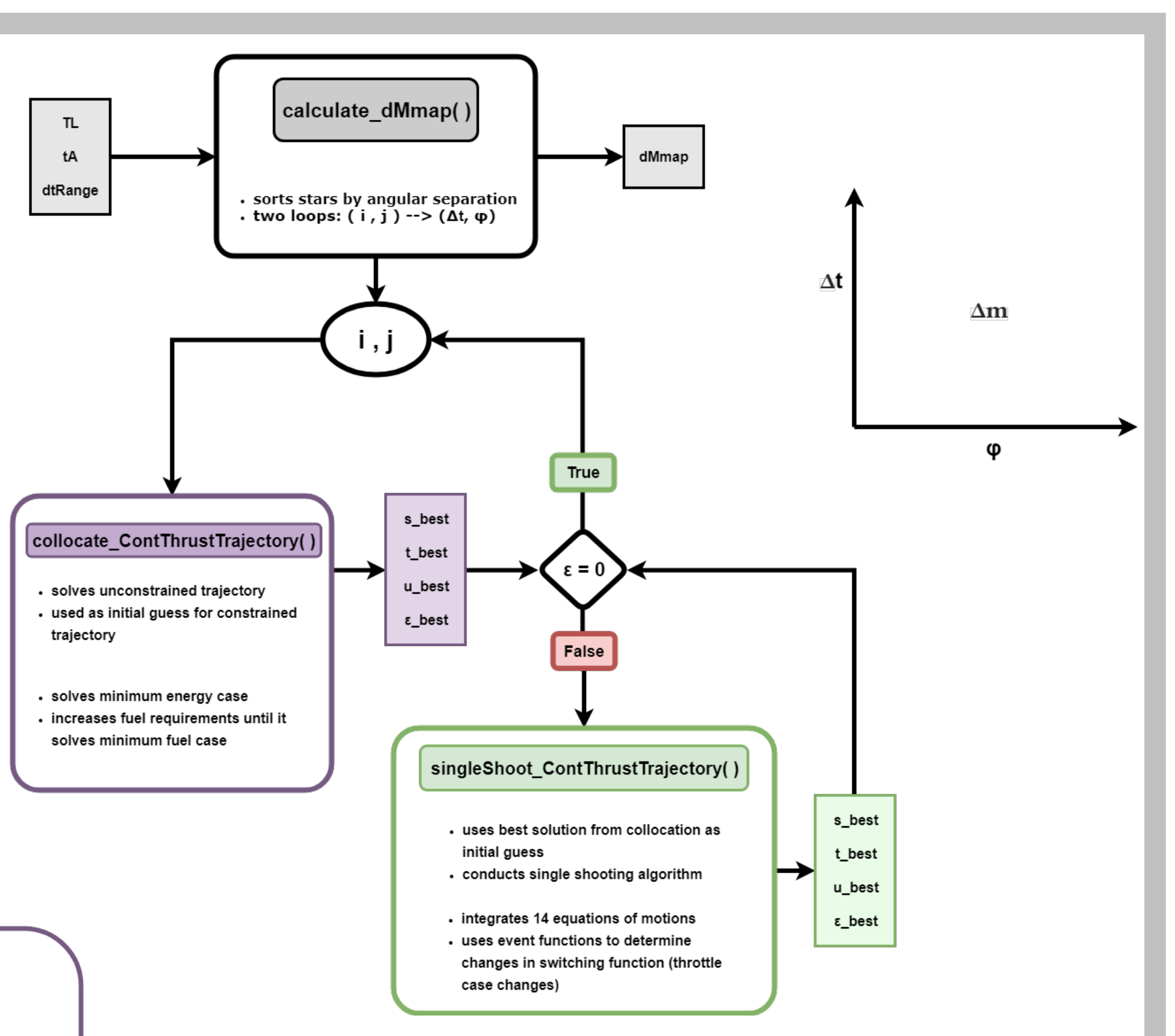
Starshade Orbital Maneuvers

- 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



Continuous Thrust Algorithm

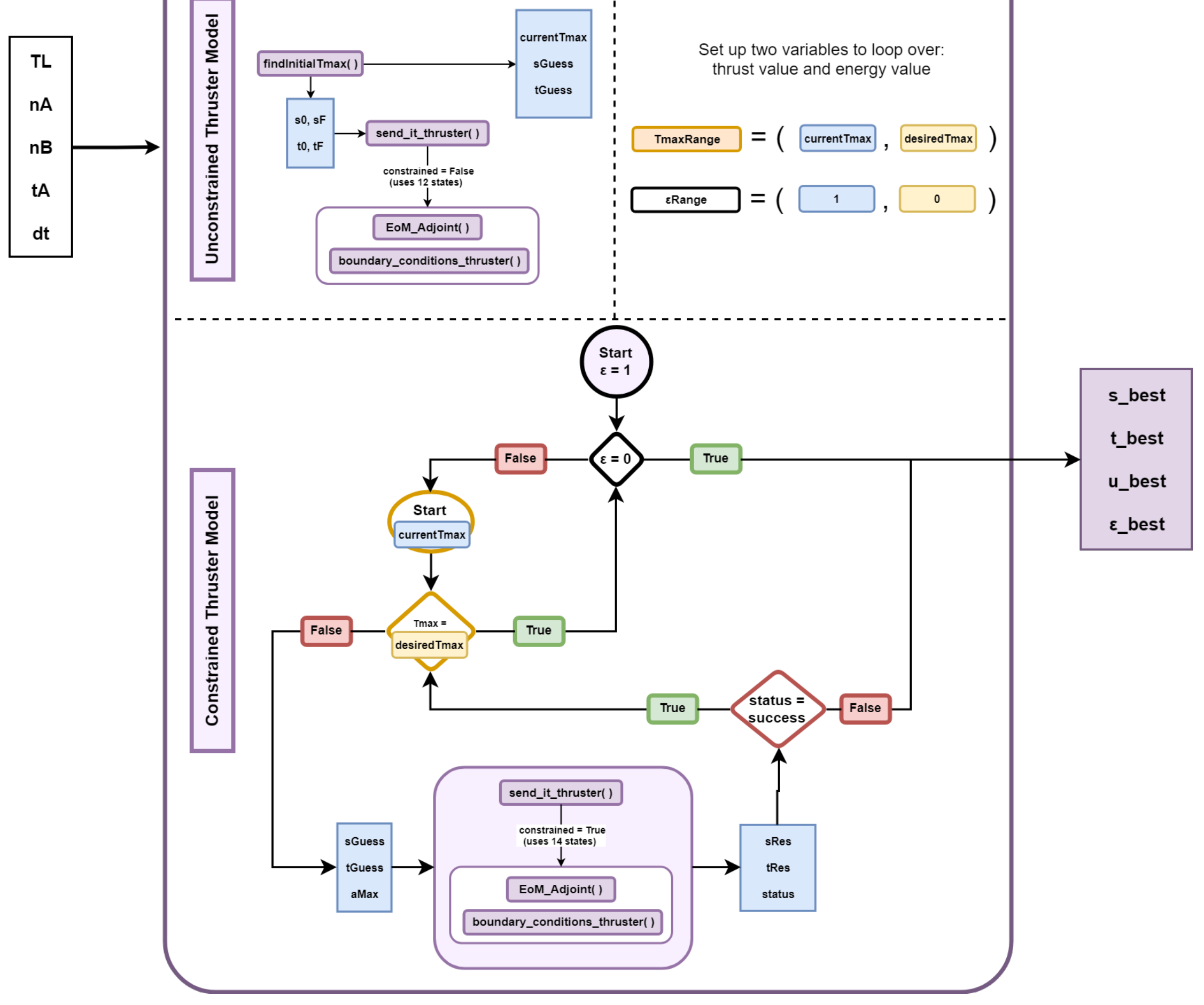
- Objective was to calculate low thrust maneuvers between targets *i* and *j*
- Optimal control theory used to find thruster control laws
- Calculate Δv map for impulsive maneuvers, Δm map for continuous thrust maneuvers
  - Find parameterization that makes cost map continuous, to be interpolated during mission simulations
- All maneuvers solved as boundary value problems using collocation method
  - `solve_bvp` in Python



- sorts stars by angular separation
- two loops: (i , j) --> (Δt, φ)

collocate_ContThrustTrajectory( ):
- solves unconstrained trajectory
- used as initial guess for constrained trajectory
- solves minimum energy case
- increases fuel requirements until it solves minimum fuel case

singleShoot_ContThrustTrajectory( ):
- uses best solution from collocation as initial guess
- conducts single shooting algorithm
- integrates 14 equations of motions
- uses event functions to determine changes in switching function (throttle case changes)



Set up two variables to loop over: thrust value and energy value

TmaxRange = (currentTmax , desiredTmax)

εRange = (1 , 0)

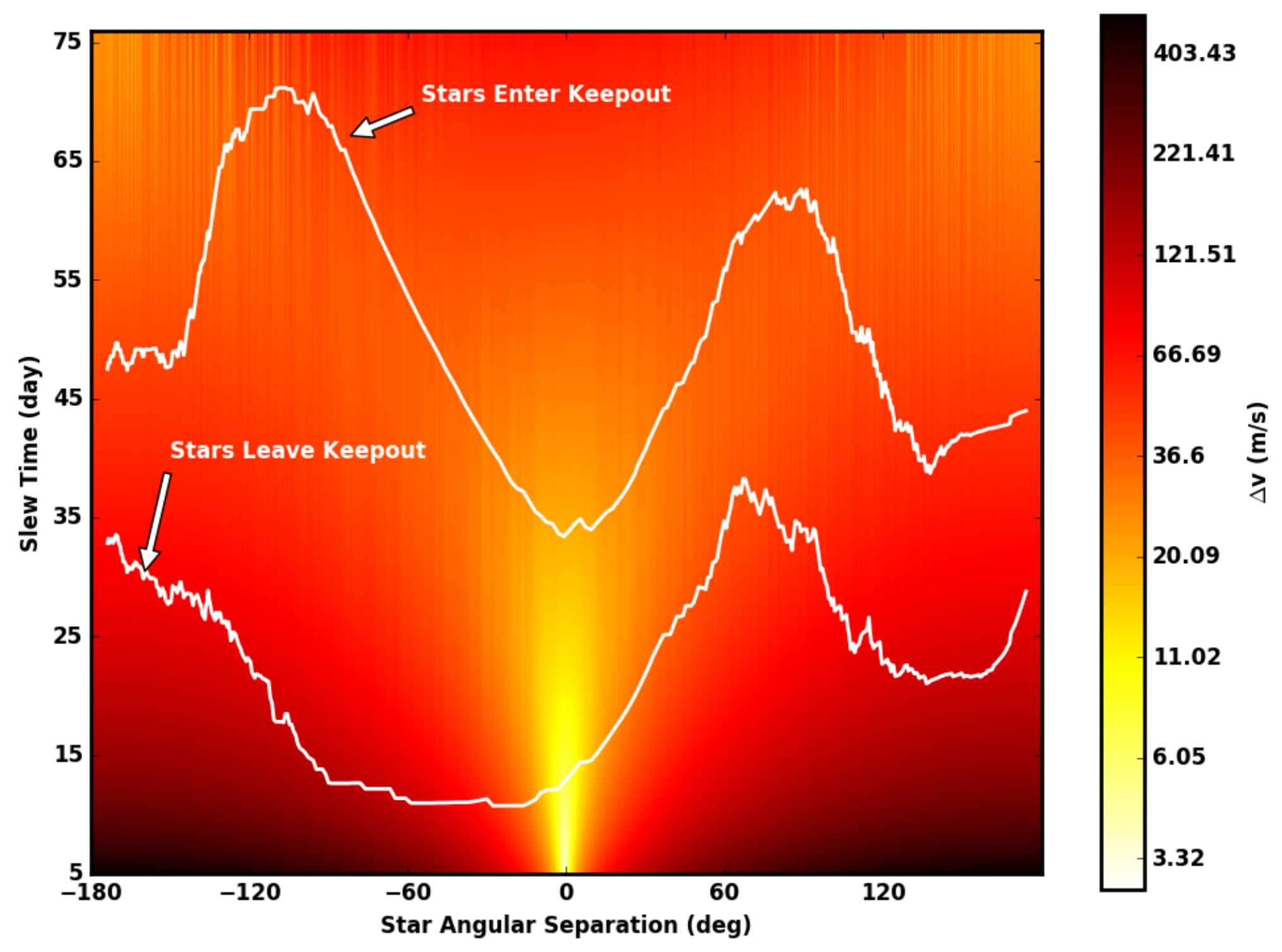
- Good initial guess needed – we use an unconstrained thruster model
  - Control input is unbounded acceleration
- We then constrain the thrust to be equal to maximum thrust under unconstrained conditions
  - Decrease thrust sequentially until we reach desired thrust
- Also solve optimal control problems minimizing cost function:

$$J = \frac{T_{max}}{m}\int_{t_0}^{t_f}[u - \epsilon u(1-u)]dt$$

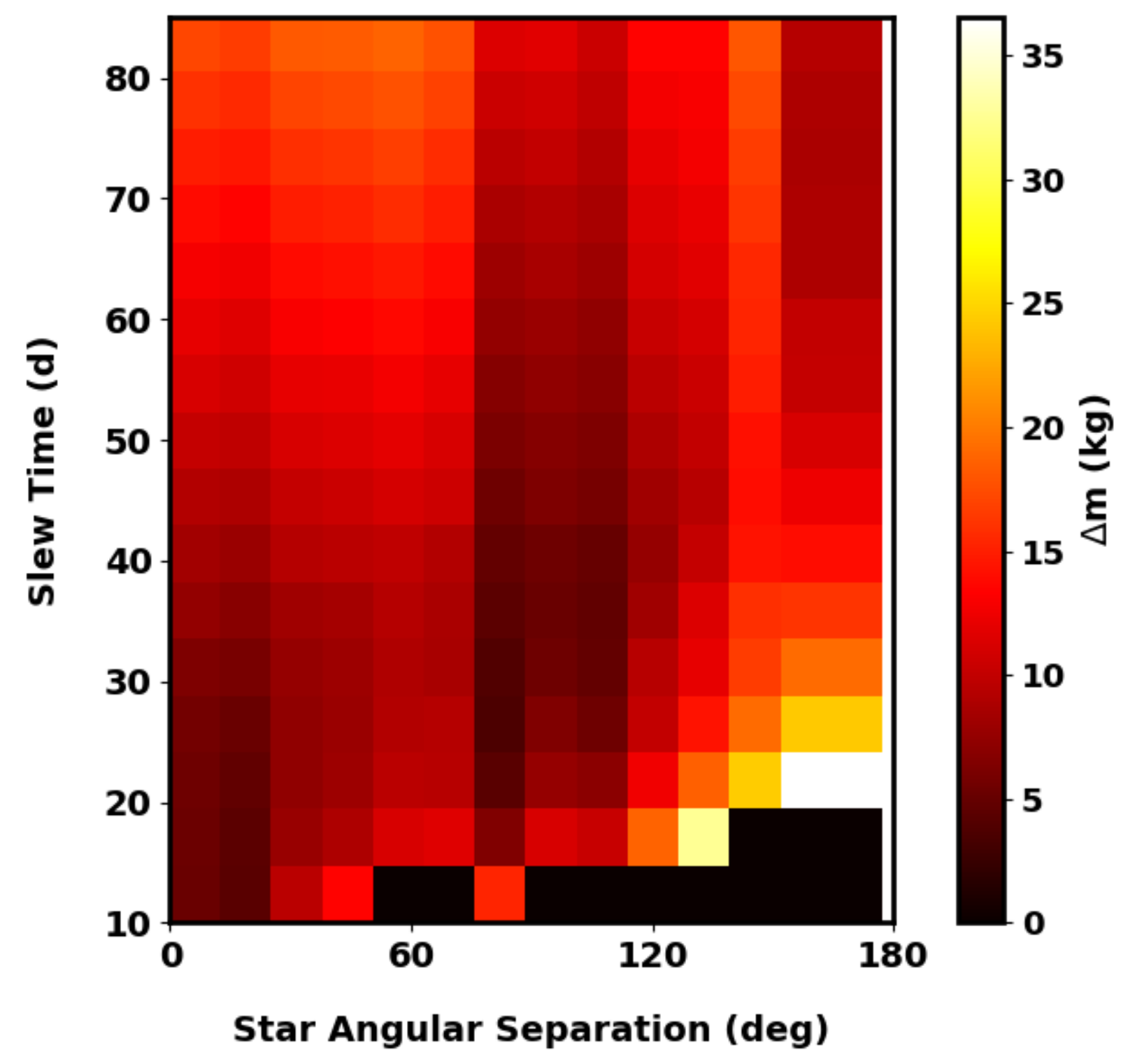
- Solve minimum energy case first (ε = 1) then minimum fuel case (ε = 0)

FY18/19 Results:

- Parameterized fuel costs using slew times (time of flight) and star angular separation from reference star
- Implemented within EXOSIMS, an exoplanet imaging mission open source simulator - https://github.com/dsavransky/EXOSIMS
- Fuel maps are calculated before a mission
  - Costs are found using an interpolant
  - One map used globally
  - Quick heuristic while simulating 1000's of missions
  - Easy to impose time constraints



Δv fuel costs for impulsive maneuver case. Keepout constraints are shown on the slew time axis, to show possible fuel costs at any one time for transfer to a star that is an angle Ψ away.



Δm fuel costs for continuous thrust maneuvers. Results only shown for a subset of angular separation, this is an intermediate product. Still shows continuity exploitable through a 2-D interpolant as before.

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; doi: 10.2514/1.G003747.

Soto, G., Keithly, D., Garrett, D., Delacroix, C., Savransky, D. (2018) "Optimal Starshade Observation Scheduling" Proceedings of the SPIE Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave; doi: 10.1117/12.2311771.

PI Contact Information:

818-393-2321
rhonda.morgan@jpl.nasa.gov

Links:

EXOSIMS Github Link:

Gabriel Soto's Website (Graduate Student):

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

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