A Smoothed Eclipse Model for Solar Electric Propulsion Trajectory Optimization

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Solar electric propulsion (SEP) is the dominant design option for employing low-thrust propulsion on a space mission. Spacecraft solar arrays collect sunlight to power the SEP system but are subject to blackout periods during solar eclipse conditions. Discontinuity in power available to the spacecraft must be accounted for in trajectory optimization, but gradient-based methods require a differentiable power model. This work presents a power model with smoothed eclipse conditions that shows robust performance for example trajectories computed with differential dynamic programming.

Power available to the SEP system depends on the percent of the solar disc that is visible to the spacecraft, named the percent sun, γ. For an inverse square power model,

$$P_a = \gamma \frac{AU^2}{R^2} P_0 \quad , \tag{1}$$

where P_0 is the power available at one astronomical unit (AU) and R is the heliocentric distance. The percent sun is a discontinuous function of the possible eclipse conditions, 100% sunlight and total, partial, or annular eclipse. The smoothed eclipse model removes the hassle of checking eclipse conditions and transitioning between cases by considering a Heaviside step function between 100% sunlight and total eclipse. This approach has seen previous success when applied to the discontinuity in discrete number of thrusters available [1]. The Heaviside step function can be approximated by a logistic function with smooth derivatives that are favorable for gradient-based optimization.

$$f(x) = \frac{1}{1+\exp[-k(x-x^*)]} \tag{2}$$

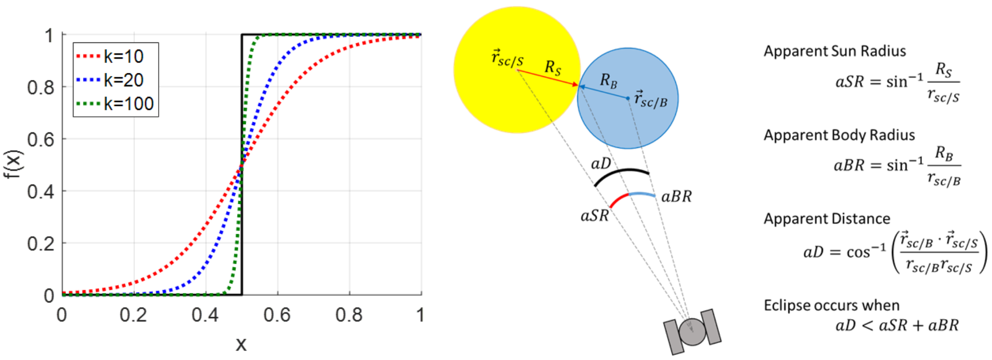

Figure 1: A Heaviside step function approximated by three different logistic curves with a transition at $x^* = 0.5$ and a sketch defining the eclipse transition for the smoothed model.

The transition from 100% sunlight to total eclipse is smoothed across the intersection of the visible solar disc and occulting body, determined by conic geometry [2].

$$\gamma = \frac{1}{1+\exp\{-k[aD-(aSR+aBR)]\}} \tag{3}$$

Equation 3 constitutes the smoothed eclipse model that approximates the SEP power available in a suitable form for trajectory optimization.

References

[1] J. A. Englander, M. A. Vavrina, and D. Hinckley, "Global Optimization of Low-Thrust Interplanetary Trajectories Subject to Operational Constraints," *AAS/AIAA Space Flight Mechanics Meeting*, February, 2016.
[2] O. Montenbruck and E. Gill, 'Satellite Orbits, Models, Methods and Applications', *Springer*, 3rd Edition, 2005.