

OPTIMAL FORMATION DESIGN OF A MINIATURIZED DISTRIBUTED OCCULTER/TELESCOPE IN EARTH ORBIT

Adam W. Koenig⁽¹⁾, Simone D'Amico⁽²⁾, and Bruce Macintosh⁽³⁾

⁽¹⁾⁽²⁾Stanford University, Department of Aeronautics & Astronautics, Space Rendezvous Laboratory, 496 Lomita Mall Stanford, CA 94305, 650-272-9968, damicos@stanford.edu

⁽³⁾Stanford University, Department of Physics, 382 Via Pueblo Mall, Stanford, CA 94305, 650-725-4116, bmacintosh@stanford.edu

Abstract:

The astrophysics community has shown increasing interest in detection and characterization of exoplanets in recent years. Specifically, study of a distributed occulter/telescope (DOT) concept to image earth-like planets has resulted in several mission designs. A DOT uses a dedicated occulter spacecraft to suppress light from a star while a separate, precisely aligned telescope spacecraft images any orbiting planets from the shadow of the occulter. Previous DOT designs operate in visible wavelengths (400-800 nm) with inner working angles of 100 milliarcseconds or less. These missions call for very large spacecraft that must be deployed in deep space, resulting in estimated mission costs in the billions of dollars. Stanford's Space Rendezvous Laboratory is investigating the feasibility of miniaturizing DOTs to allow deployment on micro- or nano-satellites in earth orbit, reducing estimated mission costs by orders of magnitude. Compared to large-scale missions in deep space, miniaturized DOTs in earth orbit are subject to larger relative accelerations. Additionally, smaller telescopes must be used, increasing the required integration time for exoplanet measurements. Considering the limits of current propulsion technologies, it is clear that formations must be designed to minimize the delta-v cost associated with maintaining constant inertial alignment during observations. This paper presents a novel design methodology that minimizes the delta-v cost associated with forced inertial alignment maneuvers by allowing the spacecraft to drift along the observation axis. The presented methodology includes accommodations for earth oblateness J_2 effects and payload operations constraints.

The design strategy first addresses the unconstrained absolute and relative orbit design problems. First, the delta-v cost of a forced inertial alignment maneuver of finite duration is shown to depend on only the location of the target, the absolute orbit elements of the telescope, and the inter-spacecraft separation specified by the occulter optics. To accomplish this, the alignment perturbation component of gravitational relative acceleration is expressed as a function of the inertial position of the telescope and the relative position of the occulter. Next, the pointing vector to an inertial target is expressed in a rotating orbit frame as a function of the telescope absolute orbit elements. This formulation is used to identify orbits that minimize the alignment perturbation over the maneuver duration. With the absolute orbit specified, the relative orbit is selected such that the inertial alignment requirement is satisfied at the start of the maneuver. DOT separation requirements admit a small family of relative orbital element (ROE) sets that precisely align the formation with the target. These families of solutions are subject to the constraint that the uncontrolled evolution of the inter-spacecraft separation must satisfy optical requirements for the duration of the maneuver.

Once the unconstrained design problem is solved, constraints are formulated to address earth oblateness J_2 effects and payload operations constraints. Due to the large integration time required

by a small telescope, orbit precession is significant on the timescale of miniaturized DOT mission lifetimes. Accordingly, the orbit must be selected such that this effect does not severely compromise formation performance during observations. To assess the impact of orbit precession, the target pointing vector and its time derivative are formulated in perifocal coordinates. The relationship between this vector and the required relative motion can be used to identify orbits that minimize deviation from optimal formations over the expected mission lifetime. Preliminary calculations suggest that the light reflected by the occulter from solar illumination and earth albedo may be orders of magnitude larger than the expected signal from an exoplanet. To suppress both of these noise sources, the miniaturized DOT orbit shall be selected such that observations are performed in earth's shadow. This requirement constrains the selection of telescope absolute orbit elements and observation windows. After deriving analytical formulations of these constraints, this work presents a trade study between increased observation duty cycle to shorten mission duration and the costs incurred due to the motion of earth's shadow over long missions. The trade study considers circular orbits of varying semimajor axis and a highly elliptical orbit with sun-synchronous apogee precession.

To validate the proposed design strategy, the devised optimal formations are tested in a high-fidelity simulation environment. These simulations are used to calculate the delta-v cost of the forced motion control segment using a series of observation maneuvers consistent with orbit precession models and eclipse constraints. The number and duration of the observations are selected to achieve the required signal-to-noise ratio for successful detection of a hypothetical exoplanet using a specified telescope model. The numerical propagator accounts for all significant perturbation forces including geopotential harmonics of high order and degree, third body solar and lunar gravity, and non-conservative forces mainly due to solar radiation pressure. For each observation, formation alignment is maintained for a predefined duration using measurements from a shadow sensor model in conjunction with a quasi-continuous, low-thrust actuation system. Measurements and actuator commands include error models consistent with current sensor and thruster technologies. Preliminary results show that miniaturized DOTs in earth orbit can achieve tens of hours of integration time with an observation segment delta-v cost on the order of 100 m/s. The calculated delta-v cost is critically dependent on a large number of estimated factors including telescope aperture diameter, efficiency of the optical chain, detector read noise, parent star brightness, and exozodiacal dust density among others. Nevertheless, these results suggest that achieving sufficient signal-to-noise ratio for exoplanet detection is feasible using newly developed thrusters compatible with nano- or micro-satellites.

Using the presented orbit design methodology may allow miniaturized DOTs to detect and characterize exoplanets at a small fraction of the cost of previous mission proposals. In addition, the proposed mission concept may serve as a technology enabler before significant investments are made in large-scale missions. Besides DOTs, the results of this work will find application in the design of many distributed space systems. Indeed, the proposed orbit selection and observation strategy could enable virtual telescopes and interferometers as key to new astrophysics discoveries.

Keywords: Formation flying, exoplanet, occulter, starshade, maneuver optimization