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Precision formation flying at megameter separations for exoplanet characterization ☆

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ABSTRACT

Starshade missions offer a near-term capability to measure the spectra of Earth-sized exoplanets, searching for possible bio-indicators. To function, a starshade and telescope separated by approximately 50 Mm must align to the meter-level on the line to the target star. From the telescope's perspective, this alignment in turn requires sensing the bearing between target star and starshade to approximately 1 milli-arcsecond (5 nrad). Previously, several fine bearing sensors have been proposed based on pupil images of the starshade's shadow. In this paper, a fine bearing sensor is presented based on measuring in the focal plane the bearing between a laser beacon on the starshade and the diffracted centroid of the target star that "leaks" around the starshade outside the science wavelengths. Coarse and medium bearing sensors are also introduced that allow for autonomous operation. The performance of extended Kalman filters using the bearing sensors is presented, as well as deadbanding performance in science mode.

1. Introduction

NASA is studying the feasibility of a potential Probe-class starshade-based mission called Exo-S for direct imaging and spectral characterization of exoplanets that could be realized within a decade [1]. A starshade is an external occulter that blocks the light of a parent star [2–5] thereby allowing the dimmer light of a planet to be seen by a separate telescope flying in formation with the starshade. With a large enough telescope, a starshade mission enabled by formation flying can measure the spectrum of an Earth-sized exoplanet, searching for bio-indicators like methane and molecular oxygen [6]. This application of formation flying is particularly relevant with recent Kepler-based results showing approximately 22% of Sun-like stars harbor an Earth-sized planet receiving 0.25–4 times the light falling on Earth [7]: exo-Earths could be all around us, simply waiting for us to look.

Previously, several flagship-class starshade mission concepts have been developed in detail [8–11] with others proposed [12,13]. Diffraction calculations for starshades

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show that to achieve inner working angles – IWA, the angular separation from the parent star where sufficient starlight suppression begins – that include habitable zones of the target stars, the telescope must be on the order of tens of megameters from the starshade. Moreover, at these separations, the shadow cast by the starshade that is suitable for science is only meters across. Specifically, at telescope-to-starshade separations of up to approximately 50 Mm, the telescope must fly in formation with the starshade to essentially ± 1 m perpendicular – laterally – to the star-starshade line. Although narrow, the shadow is comparatively long: the axial control requirement on inter-spacecraft distance is hundreds of kilometers.

Even at 50-Mm separation, the norm of the relative acceleration due to the gravity gradient in a heliocentric or L_2 orbit is less than 5e-5 m/s^2 [14], and differential solar pressure is an order of magnitude smaller. While the differential disturbance acceleration affects propellant budgets, controlling to the meter-level with micro-g disturbances is not a technological challenge; centimeter-level control is commonly achieved with similar or larger disturbances during docking in low Earth orbit. For example, a spacecraft on a Vbar approach at 2 cm/s also experiences gravity gradients of 5e-5 m/s^2.

Rather, the principal formation flying challenge for a starshade mission is in sensing the lateral alignment among telescope, starshade, and target star to the submeter level to meet the meter-level requirement for lateral control. It is equivalent to sensing bearing to better than approximately 0.3 m/50 Mm = 6 nrad (1.2 mas), where the sensing requirement is taken as a factor of three tighter than the control requirement. The Hubble Space Telescope Fine Guidance Sensors (FGSs) can sense to the mas-level [15,16]. However, because of the relative scarcity of suitable guide stars ($\sim$0.2 per square arcminute at 15th magnitude), such FGSs require a large field of view plus substantial optics that could significantly increase the cost of a nearer-term mission.

Instead, concepts for an inter-spacecraft fine bearing sensor (FBS) leverage the telescope's large primary mirror aperture and the significant light from the target star that "leaks" around the starshade outside the band of science wavelengths. Hence, the target star itself can function as a guide star. There are then two general categories of FBSs that have been proposed: 1) *pupil-plane FBSs* that process the leaked shadow in the pupil plane [11,17–19] and 2) *focal-plane FBSs* that measure the bearing between the centroid of the diffracted target star and a beacon on the starshade in the focal plane [1]. Measuring the distortion of the target star's point spread function (PSF) has also been proposed [20].

Due to varying system-level and instrument-level impacts, it can be argued there is no single best FBS. To achieve their precision, FBSs necessarily have a limited range of operation. For example, some FBSs must have the telescope, starshade, and star aligned to within meters to function. As a result, coarse and medium levels of bearing sensing are generally needed to move the system to this state. This process is referred to as acquiring lock on the FBS. As a result, FBS approaches cannot be evaluated for a specific mission without also evaluating the combined complexity of all levels of bearing sensing, the autonomy needed to move between them, and impacts to the telescope's instrumentation. In this regard, Refs. [18,21], provide a broader survey of coarse, medium, and precision bearing sensing approaches.

An additional consideration for all levels of sensing is the degree to which a telescope can be tailored to function with a starshade. For example, studies of a starshade for the James Webb Space Telescope had to develop and analyze bearing sensors that would have essentially no impact on the telescope [21].

To initialize a starshade formation, the Deep Space Network (DSN) can provide absolute positions on the order of 100 km for missions to Lagrange points. The coarse level of bearing sensing must be able to acquire lock with this level of uncertainty. For autonomous operations thereafter, a wide field-of-view (FOV), radio-frequency (RF) inter-spacecraft ranging system is generally assumed to provide range to the 100-m level as well as communicating coordination data.

The contribution of this paper is to introduce a focal-plane FBS and corresponding coarse- and medium-bearing sensors that all use active beacons and to show each level's performance through simulations of extended Kalman filters (EKFs). The EKF performances, in turn, demonstrate that autonomous hand-off between sensing levels is possible and are used to demonstrate deadbanding control for Science mode. The new coarse and medium sensors are admittedly variations on previous concepts.

In this paper first the operational modes of a starshade mission are reviewed. Then the existing pupil-plane FBS concepts and their attendant coarse and medium sensor suites are overviewed. Next, the active-beacon sensor suite is introduced. Briefly, the coarse level consists of a standard 2-cm aperture star camera on the telescope measuring the location of a pulsed, 100-W LED array on the starshade. Star trackers commonly output locations of stars that are not identified, providing the bearing to the starshade relative to the background stars. The medium level consists of the telescope simultaneously observing a 20-mW laser beacon on the starshade and the target star. The bearing between the centroids is measured to give a relative bearing. Finally, the fine level – with the starshade occulting the target star – consists of a similar differential centroiding between star and laser beacon, but now with the centroid of the star affected by diffraction. A strategy for addressing this diffraction is presented.

As part of introducing this sensor suite, a high-TRL RF-ranging system simultaneously capable of 10-m precision at 50 Mm and low-bandwidth communication is discussed: the GRAIL S-Band Time Transfer System (TTS) [22]. While it demonstrates a high-TRL system is available, this level of range precision is not needed: simpler ranging systems can be proposed. Then, since the bearing between laser beacon and star-centroid is affected by telescope jitter, this jitter is shown to be controllable even on a "standard" spacecraft bus to the 0.5-mas level. Next, EKF performances are presented for the new sensor suite. Then the complication in the fine level of sensing due to the diffracted target star is addressed: it requires "drifting" from approximately 30-m off alignment to within 2-m of