LightBeam:

Flyby-Like Imaging Without The Flyby

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Figure 1: The *LightBeam* mission concept. *LightBeam* has a central spacecraft node, containing the main guidance and control, power, and communications subsystems, as well as two beam combiners. On two 25 meter manufactured booms are two outboard mirror units, each relaying twin light beams toward the central node. The entire spacecraft system launches within a one meter cube ESPA Grande-class volume.

Abstract: The *LightBeam* spacecraft is a mission concept for an observatory aimed at providing milliarcsecond-class imaging of solar system asteroids, from NEOs to the main belt to Jupiter Trojans. *LightBeam* achieves this goal via innovative in-space manufacturing techniques which enable a long-baseline optical interferometer to be flown in a cost-effective smallsat package.

1 Key Science Goals and Objectives

Significant discoveries have resulted almost universally from high-resolution imaging enabled by spacecraft flybys. The discovery of the first moon of an asteroid, Dactyl, was an unexpected result of the *Galileo* flyby of 243 Ida (Belton & Carlson, 1994). The *New Horizons* flyby of the Pluto system (Stern et al., 2015) provided a wealth of information on the bodies in that system – e.g. the surface compositions (Grundy et al., 2015) and geology (Moore et al., 2015), to name a few. Grundy et al. (2015) credits ‘uniquely high spatial resolution’ as the fundamentally enabling capability for their results. In this white paper we will further motivate the need for, and then briefly present the possibility for, a facility that can provide **flyby-like data, without the flyby**.

The *LightBeam* mission with interferometric imaging of asteroids would:

- Enable 1-2 orders of magnitude increase in the number of objects for which we have spacecraft (*in situ*) or spacecraft-like (e.g. VLT/SPHERE) data; currently those samples combine to a few dozen objects.
- Provide approximately an order of magnitude increase in the angular resolution limit for directly imaged binary systems; the full orbits of every known binary in the inner Solar System could be directly measured.
- Provide new compositional and evolutionary constraints from rotationally resolved color mapping for hundreds of objects, shifting the field away from point source characterization and towards understanding each of these objects as unique geologic worlds.

2 Technical Overview

2.1 State of the art in ground-based optical interferometry

Over the past two decades, substantial progress has been made with astronomical imaging with arrays of telescopes linked in the visible. Currently operational US facilities include the Georgia State University CHARA¹ Array (McAlister et al., 2005; ten Brummelaar et al., 2005), as well as the Navy Precision Optical Interferometer (NPOI; Armstrong et al., 1998, 2013). For the Astro 2020 Decadal Survey, plans have been proposed to expand upon these increasingly sophisticated imaging techniques, with expansions to CHARA (Gies et al., 2019) and NPOI (van Belle et al., 2019) being proposed, as well as long-lead development for new facilities such as the Planet Formation Imager (PFI; Monnier et al., 2019). These ambitious facilities would forge new territory in stellar and planet formation astrophysics enabled by angular resolution at the $\sim$ tens of microarcseconds. However, as ground-based facilities, their capabilities in examining intrinsically faint objects ($m_V > 10$) would be limited. This is due to the limitations of the Earth's turbulent atmosphere, which in the visible levies a requirement that *some* portion of one's interferometer system has to be operating at $\sim$ millisecond exposure times for array phasing.

Simply put: ground-based interferometry is the marquee technique for ultra-high-angular resolution observations of high surface brightness objects (i.e. stars), but for direct observations of low surface brightness objects (i.e. solar system objects), space-based interferometry is required.

It is nonetheless instructive to examine the advances of the field in the last decade or two to see how image reconstruction techniques have advanced, since such techniques can be applied to not just data from existing facilities, but also a putative high-sensitivity space-based facility observing solar system objects.

Single objects. One of the most striking advances during the past decade has been in the arena of stellar surface imaging. Spatially resolved images of stellar shapes and surface features are now routinely achieved by the CHARA Array. Using that facility, Monnier et al. (2007) were able to image the surface of Altair (Figure 2), illustrating (a) its 1.835 ± 0.007 mas equatorial radius, (b) its $24.2 \pm 0.9\%$ shape oblateness (due to rapid rotation), and (c) its pole-to-equator intensity profile (primarily due to gravity darkening). More recent results include a full 3D mapping of the surface of ζ And² and σ Gem (Roettenbacher et al., 2016, 2017), capturing the size and surface features (e.g. starspots) of these objects.

These imaging results are currently obtained utilizing arrays with 4 to 6 apertures, with similarly complex beam combiners. For ground-based interferometric imaging, this is necessary because of the corrupting effects of the Earth's atmosphere. As such, an additional limitation of

Figure 2: Surface imaging of the star Altair from the GSU CHARA Array (Monnier et al., 2007), illustrating the oblate shape of this rapidly rotating star. This rapid rotation alters the surface appearance of the star, with severe gravity darkening overshadowing the stellar limb darkening. Units are in milliarcseconds (mas).

¹Center for High Angular Resolution Astronomy

²See animation online at <https://rmroettenbacher.github.io/Roettenbacher2016-CAPTION.gif>

ground-based observing is that image phase recovery from a single baseline is not possible, and ‘closure phase’ provided by triads of apertures is used instead (Monnier, 2003). For space-based facilities, it is possible to recover absolute imaging phases from a single pair of apertures in an interferometer, resulting in a substantially simpler optical system.

Binary objects. In addition to providing information on the size and morphology of single objects, long-baseline optical interferometry has proven to be particularly powerful in mapping the orbits of binary objects. As an example, using the Palomar Testbed Interferometer (PTI), Boden et al. (2005) were able to map the orbit of the binary star 12 Boo and fit a Keplerian orbit, resulting in $\sim 0.33\%$ mass determinations, as well as a $< 2\%$ distance measurement (Figure 3). These extremely high-precision, dynamic mass determinations are fundamentally constraining for developing robust stellar models.

With the increase in sensitivity expected from a space-based platform, interferometric techniques being brought to bear on single and binary stars could be directly applied to single and binary asteroids.

2.2 Technical Requirements

There are two key driving requirements in assessing a space-based interferometer designed to observe solar system objects.

Sensitivity. Interferometers are often thought of as complex optical systems, and achieving maximum sensitivity is can be an equally complex task. However, at their heart, they are optical systems like ‘conventional’ telescopes, and optimizing the usual parameters such as detector quantum efficiency, optical system efficiency, surface reflectivity apply. Importantly, with a space-based platform, the most enabling parameter – exposure time τ – is no longer limited by the $\sim$ millisecond atmospheric coherence time of the Earth and can be substantially extended. τ is limited only by the spacecraft coherence time – the time over which the spacecraft can maintain a optical conditions for steady interference of light from both input

Figure 3: High-precision mapping the orbit of the binary star 12 Boo (Boden et al., 2005). The orbital solution allows for a full parameterization of the system, including masses of both components, period, masses, and distance.

Figure 4: Over 100 known binary asteroids are resolvable by a modest optical interferometer.

apertures. For a properly designed system, τ can be extended by factors of $1,000\times$ to $1,000,000\times$, resulting in extraordinary gains in sensitivity.

Spatial Resolution. Interferometers achieve ultra-high angular resolutions by virtue of large separations between their input apertures – separations on the order of tens of meters. Historically this has proven difficult to even conceive of how to package such a large structure into a payload fairing – and have it survive launch. However, with creatively applied innovative new technologies – such as additive manufacturing, and in-space robotic assembly – we will demonstrate how an optical system with milliarcsecond (mas) scale angular resolution can be readily flown and operated on a space-based platform.

Derived requirements. For the science goals we will outline in the next section (§3) for a modest yet uniquely capable mission, we have the following baseline technical requirements that build on our overall expectations for

- Sensitivity. For a reasonably sized set of potential targets ($N > 100$ to $1,000$), we expect that a target observing limit of $m_V < 16$ is sufficient.
- Spatial resolution. Matching to our notional set of science targets, at the expected brightness limit, a resolving limit of 2.5 mas will be sufficient. For a system operating in the visible, this requires a baseline of ~ 50 meters.
- Bandpass. For a simple initial demonstration facility, visible light operations is desired to avoid the complexities entailed with longer-wavelength systems. At such wavelengths, optics and detections are much more likely to be commercial-off-the-shelf (COTS).
- Spectral resolution. A modest level of spectral dispersion at $R \sim 10 - 100$ will support both white-light fringe tracking, as well as surface composition characterization of the observed targets. Higher resolution is possible with increases in data volume and detector real estate.
- Coherence time. To provide sufficient sensitivity, the coherence time of the interferometer will need to be on order of $\tau \sim 10$ to $1,000$ seconds. To achieve this, a dual-beam architecture will be pursued, which will allow a bright ($m_V < 7$) off-axis source to be tracked as a phase-reference at high rates (~ 10 to 100 Hz) while a science channel integrates on the on-axis science source. This has been demonstrated with ground-based applications (Sahlmann et al., 2013; Müller et al., 2014) but the limited isoplanatic patch size of the Earth’s atmosphere ($\Delta\theta < 10 - 30''$) limit the availability of bright reference sources. In space the required off-axis pointing to capture a bright reference source all-sky ($\Delta\theta < 1 - 2^\circ$) is possible.
- Target-to-target time. For an efficient survey of primitive bodies, a maximum of one day per object is baselined, translating to hundreds of objects per year.
- Spacecraft mass, volume. Our target is to fit within ESPA Grande-class smallsat rideshare parameters for mass (< 320 kg) and volume (roughly a 1 meter cube).
- Orbit. To enable the full scope of possible targets outlined in §3, an Earth-Sun L1 orbit is desired. Such an orbit enables NEOs to be captured, as well as the more distant solar system objects.

3 Science Goals

Classes of objects. Spatially resolved observations of a large swath of solar system targets are enabled with sensitivity and resolution limits of $m_V < 16$ and $\theta < 2.5$ mas, respectively. From a

Earth-Sun L1 vantage, **Near-Earth Objects** (NEOs) > 10 meters in size with a brightness of $H < 26$ will be resolvable. The JPL Center for NEO Studies (CNEOS) has alerts for objects matching these criteria roughly once per week. Sizes and shapes will be determinable for **Main-Belt Objects** (MBOs) with a size > 10 km and $H < 12.3$ in the main belt. Over 1,000 such objects are known. Finally, **Trojan asteroids** with $H < 9.2$ will be observable with this system; roughly three dozen such objects are known.

3.1 Science enabled on individual objects

As with single stars, spatially resolved observations of asteroids can reveal fundamental parameters for these objects. For the smallest objects, right at the resolution limit (~ 2.5 mas), sizes and shapes can be directly determined. For larger objects, spatially- and spectrally-resolved surface morphology can be mapped over the course of an asteroid's rotational period. Such mapping of crater density, and albedo variation from flybys of objects such as 21 Lutetia (Sierks et al., 2011) and 2867 Steins (Jorda et al., 2012) have been critical diagnostic tools in assessing the geology and dynamic history of such objects. Simple imaging can reveal a wide diversity in these bodies³.

Figure 5: The Additive Manufacturing Facility from Made In Space has been operational aboard the ISS since 2016, and has been used to 3D print test boom sections in zero gee for *Optimast* and *LightBeam*.

3.2 Binary objects

Orbital mapping of asteroid moons can provide constraints on the bulk density of the primary and secondary objects - e.g. Dactyl's orbit provided insights into Ida-Dactyl system and, by association, the Koronis family of asteroids (Belton et al., 1995, 1996). Over 100 known binary asteroids are observable with these sensitivity and resolution limits (Figure 4). Additionally, high-resolution inspection of individual asteroids will reveal previously undetected companions.

4 Technology Drivers

As noted in §2.2, operation from a space-based vantage is necessary to achieve the required levels of sensitivity. A key new technology that further enables space-based interferometry is *in situ* manufacturing. Such an approach allows us to package a large but simple interferometer into an ESPA Grande-class smallsat payload package.

LightBeam is a space-based interferometer mission concept (Figure 1) that has been undergoing development by partners Made In Space and Lowell Observatory, building on their earlier *Optimast* SBIR. *LightBeam* fits compactly into a 1-meter ESPA Grande-class volume for launch and cruise to L1. Upon arrival at L1, two 25 meter metal booms will be manufactured by the spacecraft, extending the outboard mirror units (OMUs) from the central spacecraft node.

³See, for example, <https://www.planetary.org/space-images/asteroids-and-comets-color-2014>.

The OMUs each contain two ~ 150 mm flat mirrors for relaying a primary and secondary science beam towards the central node. At the central node, each beam has a dedicated beam combiner for combining their two OMU beams and forming an image-rich interference pattern. Structurally connecting the OMUs to the central node with manufactured booms has numerous benefits over free-flying interferometry architectures: the OMUs are substantially simpler, with no need for individual propellant subsystems; they are also significantly more fault-tolerant, being unable to drift away. Manufacturing of the booms upon arrival at L1 provides a number of benefits: the physically large booms do not have to be packaged to fit in a payload shroud, nor do they have to be hardened for launch stresses, meaning the required length can be provided in a lightweight manner.

As noted in §2.2, the primary/secondary architecture of the system allows for high-speed tracking of the two OMUs by the primary beam staring at a bright source. Because of that architecture, there is considerable allowance for non-rigidity of the booms; even though the tip deflection may be many tens of cm, tracking of the primary beam allows the secondary science feed to ‘stare’ at the target of interest while tracking at < 25 nm interference tolerances. These structural stability and tracking tolerances, it should be noted, are *significantly* more relaxed (by design!) than the picometer level requirements of the SIM mission concept (Unwin et al., 2008), resulting in a substantially more affordable and less complicated interferometer system.

Figure 6: An optical engineering development unit (OpEDU) and white-light calibration source, demonstrating the one possible architecture for a spacecraft beam combiner.

4.1 Organization, Partnerships, and Current Status

The underlying in-space manufacturing technology supporting *LightBeam* has been undergoing development by Made In Space since 2016. Importantly, Made In Space has had space-based additive manufacturing units in operation on-board the International Space Station since 2014 (Figure 5), already demonstrating zero-gee manufacturing as a flight-proven concept.

More recently, Made In Space and Lowell Observatory have partnered under a NASA Small Business Innovation Research (SBIR) award to develop interferometry concepts based upon space-based manufacturing. The resulting *Optimast* Phase I and Phase II work has been maturing boom manufacturing and beam combining technologies, to reduce risk for a possible flight implementation. A brassboard optical engineering development unit (OpEDU; Figure 6) has been built to demonstrate beam combining and fringe tracking at Lowell, for use in conjunction with a manufactured boom testbed at Made In Space.

Additional developments by Made In Space stand to extend and improve this concept even further. Although the current *Optimast* SBIR work has focused on a polymer-based additive manufacturing approach, newly developed metal-based in-space manufacturing techniques can produce longer, stiffer booms, enabling additional capabilities in angular resolution for

LightBeam. Separately, Made In Space has had its *Archinaut One* mission approved and funded for flight, which will demonstrate polymer-based manufacturing of 10 meter booms supporting roll-out solar panels. The \$73.7M *Archinaut One* is slated for launch in 2022 (Werner, 2020).

4.2 Schedule and Cost Estimates

Building on the risk reduction from the NASA SBIR work on *Optimast*, as well as the experience from development of *Archinaut One*, it has been our intent to size *LightBeam* for the next NASA Small Innovative Missions for Planetary Exploration (SIMPLEx) call for proposals.

4.3 Competing approaches

It is worthwhile to examine other approaches for ultra-high angular resolution collection of data on distant asteroids. The principal advantage of *LightBeam* interferometry is at-will observations of mas-scale objects, which complements or surpasses the alternatives.

- *Light curve analysis*. High-precision time-series photometry can be inverted to solve for the overall shape of various asteroids, but this is generally limited to solutions that converge on triaxial ellipsoid shapes. In particular, concavities of surfaces are difficult to solve for (Kaasalainen & Durech, 2020).
- *Extreme adaptive optics*. Facilities such as VLT/SPHERE have produced striking maps of objects such as 10 Hygeia (Vernazza et al., 2020), but spatial resolutions limits this technique to the largest asteroids, due to the maximum available 8-10 meter aperture sizes.
- *Ground-based occultations*. As noted in Buie (2020), asteroid occultations are a powerful technique for obtaining ‘snapshot’ shilouttes of solar system objects. This technique is significantly increasing in power with improved astrometry from the *Gaia* satellite. However, it still is at the mercy of chance alignment of objects with background stars.
- *Ground-based radar*. Ground-based radar plays an essential role in planetary science and defense (e.g., Taylor et al., 2020) but for detailed surface mapping is limited to cislunar NEOs (Haynes, 2020).
- *ALMA and ngVLA*. These facilities are limited to planetary satellites of Jupiter and Saturn (de Kleer, 2020), and in the case of ALMA, has far less angular resolution (~ 50 mas).

5 Future Potential

An important element of developing this and other interferometer concepts is the extensibility from the modest *LightBeam* implementation to more capable facilities assembled *in situ*. Four to six one-meter-class apertures (i.e. 4 to 6 larger OMUs, all feeding a central node) on ~ 250 meter baselines would provide *New Horizons*-class imaging of objects out to the Kuiper Belt. The most advanced NASA Astrophysics missions envisioned for the next 30 years are all interferometric in nature (Kouveliotou et al., 2014), and Planetary Science can take advantage of this exciting capability as well.

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