Research Campaign: Lunar Optical Astronomical Interferometry

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I. Introduction

Our BPS2023 Science White Paper, "Science Topic: Suitcase Science Case for Astronomical Lunar Optical Interferometry", details the favorable conditions, challenges, and opportunities of operating optical interferometers for astrophysical observations from the lunar surface. These observatories would achieve spatial resolutions one to two orders of magnitude greater then existing space telescopes, while achieving sensitivities four to six orders of magnitude better than current ground-based interferometers. A near-term simple 'suitcase science' demonstration would demonstrate these high-resolution, high-sensitivity techniques and take advantage of the upcoming human return to the lunar surface with NASA's Artemis program. Such a demonstration would also pave the way for more capable facilities, which could provide true snapshot imaging at microarcsecond spatial scales. Overall a research campaign developing lunar surface astronomical interferometers take unique advantages the lunar landscape has for astronomical telescope arrays, and would ultimately have the potential for 'civilization impact'-level science, such as exoplanet surface mapping.

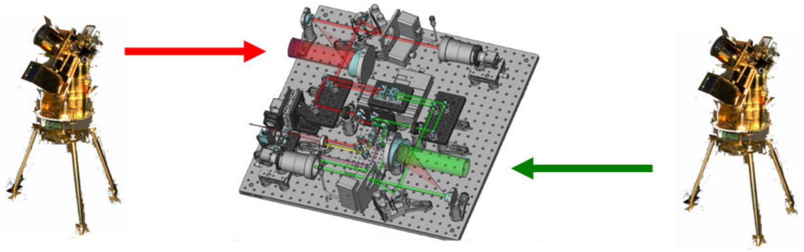

Figure 1. Schematic of two outboard mirror units (OMUs; shown here notionally as Apollo 16 UVC telescopes) and a central beam combiner (CBC; represented here by the Lowell-Redwire optical engineering development unit built for the 'Optimast' space interferometer SBIR study.

II. Initial deployment

An optical interferometer can be distilled down to its most basic elements (Figure 1) - a simple pair of outboard collecting apertures, and a central beam combiner. For the purposes of this White Paper we will concentrate upon a simple architecture that could be deployed in this way on the lunar surface as suitcase science in the form of 'a suitcase and two carry-ons'. This basic architecture allows for simple, direct, rapid demonstration of lunar surface instrument - and, most importantly, also easily scales to significantly more capable facilities to build upon the robust science capability proven by this demonstration.

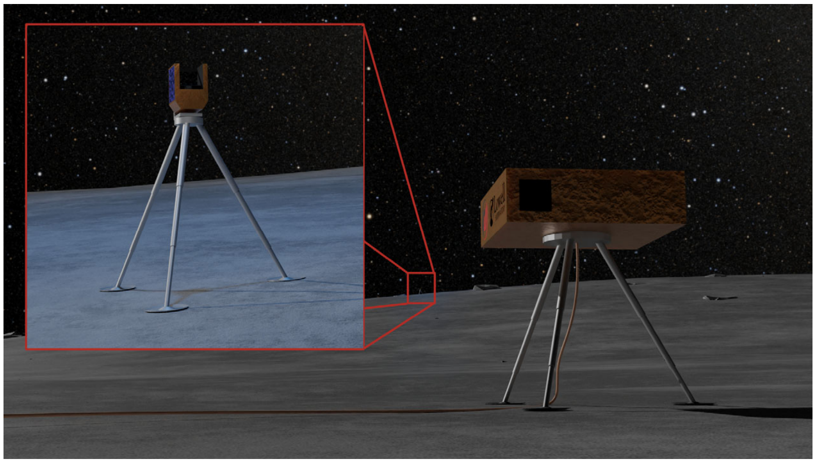

Figure 2. A simple astronomical lunar optical interferometer, showing the central beam combiner in the foreground, and one of the outboard optical mirror units in the 50m in the distance (inset); a second OMU is 50 behind this view.

A two-element demonstration interferometer can be useful for high-resolution parametric characterization of simple objects (eg. angular sizes of Kuiper belt dwarf planets), with a follow-on more capable six- to eight-element interferometer being capable of true imaging (eg. asymmetric outflows from AGN cores).

Such a progression follows a similar evolution in ground-based facilities - for example, on Mount Wilson, the two-element Mark III has been succeeded by the six-element CHARA Array.

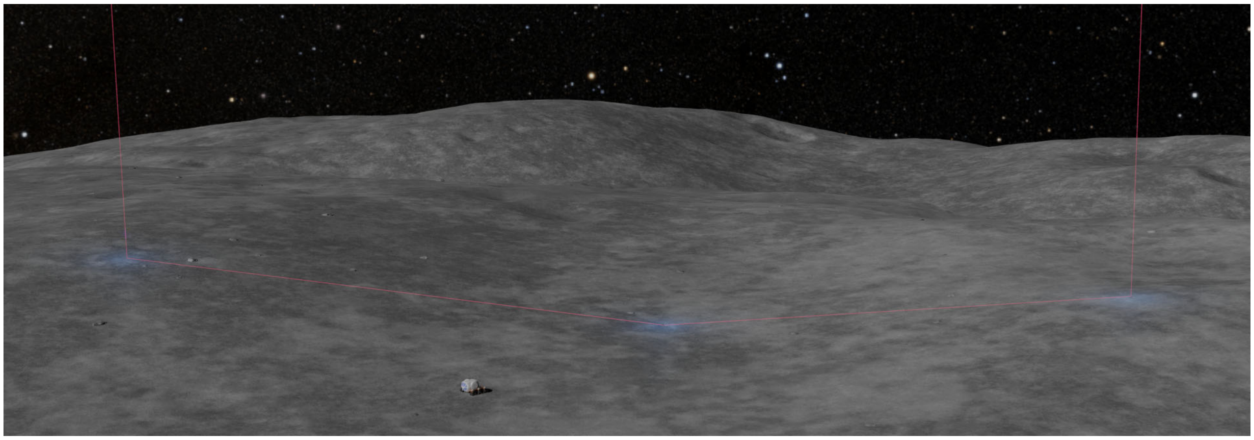

Figure 3. Overhead view of our two-element interferometer, with OMUs (left, right) and CBC (center).

The concept of operations (CONOPS) for the basic two-element astronomical lunar optical interferometer (ALOI) is simple from the astronaut's perspective. The ALOI would consist of 3 packages: a central beam combiner and sensing unit (CBC; the 'suitcase') and 2 outboard optical mirror units (OMUs, the 'carry-ons'; Figure 1 and Figure 2). An astronaut would place the ~50kg CBC on the lunar surface, attach power and telemetry connections; the astronaut would then place a ~20kg OMU 50 meters to the west of the CBC, and an OMU 50 meters to the east. Positional accuracy in both angle and distance to a fine degree is not required, and this could simply be paced off, for a 100 meter baseline. At this point the involvement of the astronaut is complete, and operations of the ALOI would be controlled via a mix of local Command & Data-handling Systems, and remote control from the Earth.

III. Lunar environment

As discussed in our Science Topic White Paper, the lunar environment presents a number of unique challenges and advantages. The maturation of NASA's Artemis lunar program means that serious consideration can be given to astronomical facilities sited on the lunar surface. Given that previous discussion, only a brief recap is covered here.

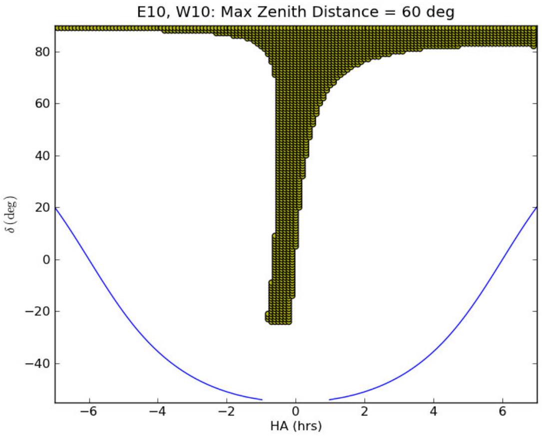

Figure 4. Example sky coverage plot, for the 432 meter east-west baseline of NPOI. Objects in the sky rise in the east and set in the west, traversing the plot from left to right through the strip of sky coverage. An ALOI with an east-west baseline would have similar sky coverage.

Atmosphere. The moon's vacuum environment eliminates the principal roadblock to Earth-based optical interferometry: the turbulent atmosphere, which induces unpredictable, significant pathlength variations at ~10-100λ on ~1-10 millisecond time scales.

Surface Vibrational Environment. Based upon extensive Apollo seismometry, the background vibration environment of the moon's surface is sufficiently quiet for optical interferometry (Lognonné & Johnson 2015).

Lunar Rotation Period. The slow rotation period of the moon - some 28x slower than the Earth - means delay line tracking rates are correspondingly slower; as such, the dynamic range of the delay line servo controller is far less demanding. Secondly, as noted above, the loiter time of targets within a given amount of delay line range is correspondingly longer.

Lunar Day/Night: Power & Thermal. The lunar day/night cycle presents universal challenges for surface equipment providing power and coping with thermal swings. For the latter point, the active control nature of the interferometer actually lends itself to accommodating such challenges.

Dust. Lunar dust is a pernicious problem of the lunar environment. However, given the small size (<200mm) of even the more ambitious unit telescope sizes considered for an optical interferometer, delicate moving parts can be seal away from the outside via optical windows.

Sky Coverage. Interferometry principles are presented briefly in our earlier companion Science Topic White Paper, but of note in this context is the sky coverage for such a deployment. For an optical interferometer, the pathlength from the target to the detector, through both space and the individual interferometer arms that make up a given baseline, has to be equalized to a fraction of a wavelength (typically a minimum of λ/10). An active optical stage called a 'delay line' - usually a mirror on a sliding optical stage - provides a range of possible equalization lengths, and this range translates into areas of the sky that are accessible. For two apertures separated on a 100m baseline along an east-west line, with a relatively modest delay line (~1-5m of differential optical path range), sky coverage is a thin strip along the meridian (Figure 4). While the delay line needs to provide control at a minimum of the λ/10 level (roughly 30 nm for the shortest wavelengths of visible light) during operations, imprecision in the absolute deployment position of the two OMUs merely shifts the sky coverage plot slightly to the left or right. An attractive element of a coverage plot for an east-west baseline is that all targets in the sky pass from east to west, transiting the region of delay line coverage along the meridian. Even if this coverage strip is exceedingly narrow - due to a short delay line - the dwell time of targets in the region of coverage will be long, given the slow rotation period of the moon.

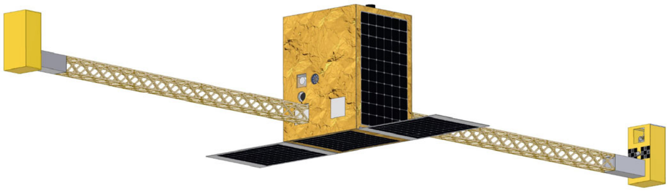

Figure 5. The Redwire Space / Lowell Observatory 'Optimast' concept for a free-flying, structurally connected optical interferometer.

III. Free-Flier Studies. Lowell Observatory and Redwire Space, Inc., have collectively been working on NASA-funded SBIR Phase I and II studies in support of an 'Optimast' free-flying interferometer concept (Figure 5; van Belle et al 2020). The SBIR development efforts have focused on a number of elements, which can broadly be separated into (a) the optical payload, and (b) the bus/supporting structures. Much of the expertise we have developed on the former is directly applicable to a lunar interferometer; for the latter, it is worth noting that the lunar surface is orders of magnitude more stable, and greatly simplifies implementation of an interferometer system.

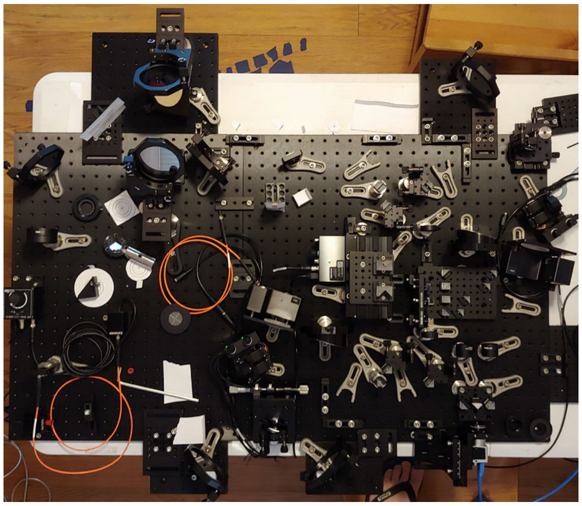

Figure 6. Overhead view of the Optimast optical engineering development unit (opEDU) demonstration beam combiner developed as part of the NASA-funded SBIR 'Optimast' study.

III.1. Relevant Development Work. For the Optimast SBIR work, Lowell Observatory and Redwire developed a prototype representative of essential elements of the Optimast system. This included, an optical Engineering Development Unit (opEDU) of a two-beam interferometer combiner (Figure 6) - analogous to the CBC noted above;

outboard mirror units (OMUs) and OMU tracking systems (Figure 8) - which directly relate to the lunar observatory OMUs described above; and *in-situ* boom manufacturing hardware for the structural connections between the opEDU and the OMUs.

III.1.a. Fringe Tracking. Combination of two or more input beams by an interferometer results in constructive and destructive interference of light, detected photometrically; such flux variations are often referred to as 'fringes'. The Optimast opEDU robustly achieved interferometric combination of beams (Figure 7) despite a COVID- dictated non-optimal location (a plastic picnic table in the first author's spare room at home). This rather 'dirty' (from a vibrational standpoint) non-laboratory environment demonstrates, at least qualitatively, the robustness of the approach taken in the opEDU design. This brassboard combiner, built strictly from COTS parts, measured 0.5 m x 0.5 m x 0.15 m, and massed 50kg. Such a combiner demonstrates the optical payload could be custom flight-built into a very modest 'suitcase' size.

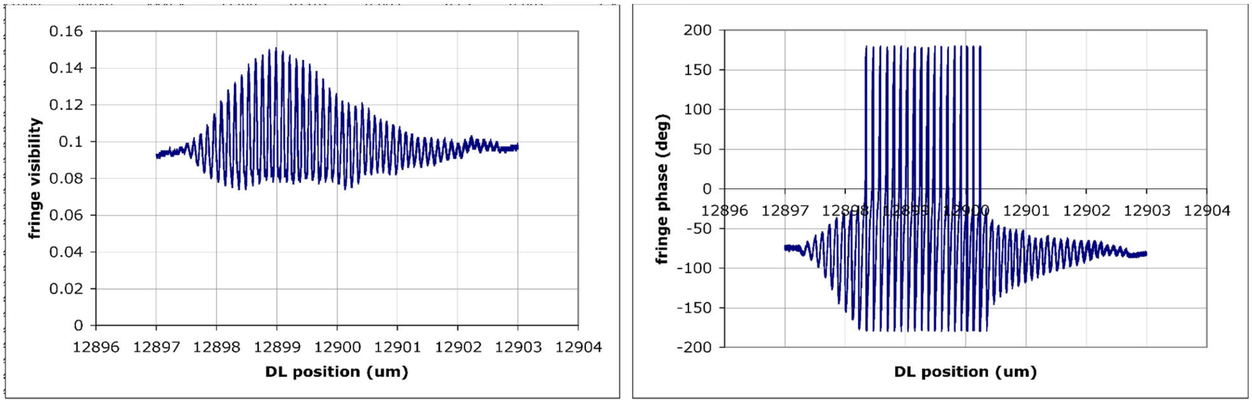

Figure 7. Demonstration of interferometric beam combination with the brassboard opEDU.

III.1.b. OMU Tracking. Associated lab testing at Redwire demonstrated tracking of distant OMUs (Figure 8) as they displaced from a nominal zero position at precision sufficient for beam injection into the prototype central combiner, for displacements far greater (>10s of cm) than expected for any disturbance expected during quiescent operations on the lunar surface. This tracking flexibility would allow for periodic repositioning of the OMUs over the lifetime of the ALOI if different baseline lengths were desired.

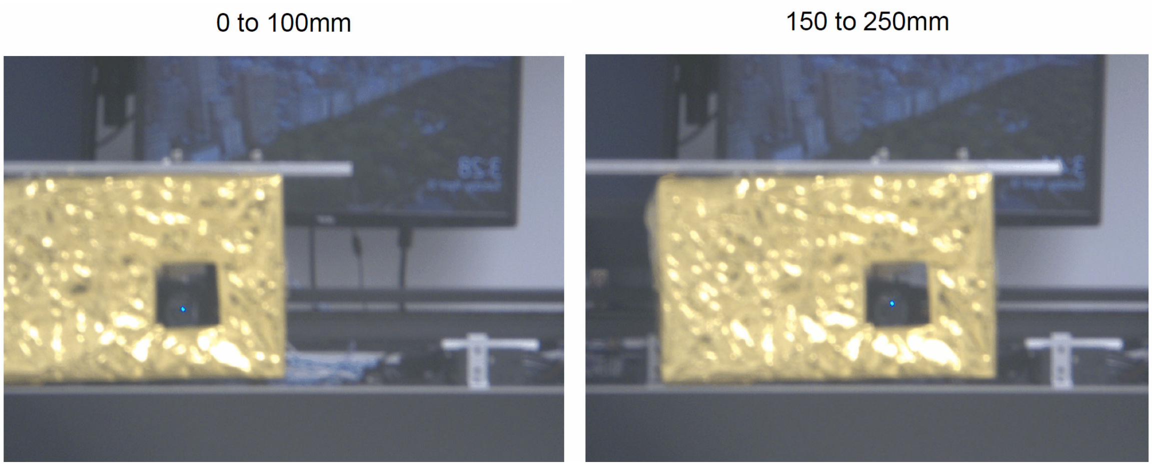

Figure 8. Lab demonstration of tracking an OMU as it displaces and injecting its light (the blue dot) into the opEDU.

III.1.c. Beam Relaying, Surface Manufacturing

There is potential for scattered light contamination when relaying of star light from the two OMUs to the CBC, during lunar daytime operations. However, this presents a further opportunity for technology demonstration - with modest baffling enclosing portions of the light path between the OMUs and the CBC, daytime operations would be enabled. Such baffling would be 1 to 2 meter sections of pipe, which would be manufactured from regolith additive manufacturing. Additional possibilities for enhancing the ALOI infrastructure stem from this capability as well - eg. erecting the OMUs on a structure made of printed regolith girders could also mitigate scattered light.

Redwire Space is the leader in on-orbit manufacturing and has conducted additive manufacturing on materials including polymers and ceramic. One of Redwire's most recent projects is the Redwire Regolith Print (RRP; Figure 9) mission. The RRP is groundbreaking hardware capable of using regolith processed into filament to 3D print parts. Launched in mid-2021, the RRP mission is ongoing but has already produced promising results. The core technology behind RRP was designed for scalability in mind, making it ideal for eventual manufacturing of regolith-based parts for this lunar surface interferometer.

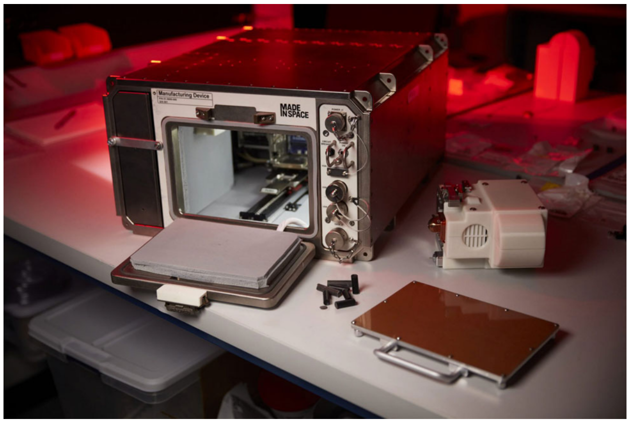

Figure 9. Redwire Space's Regolith Print mission for demonstrating 3D printing with lunar regolith, now flying aboard the ISS.

IV. Future Potential. Previous assessments of optical interferometry from the surface of the moon have been somewhat pessimistic (Bely 1996, Greenaway 1999), and in our estimation, overly conservative. However, it is clear that the prospects for a lunar surface facility are far more appealing given two decades advancement in observatory optomechanical and computer control, and the backdrop of ample surface access via Artemis. What has not changed during this time - and only increased in appeal - is the robustness of using the lunar surface as a solid optical footing for such a facility.

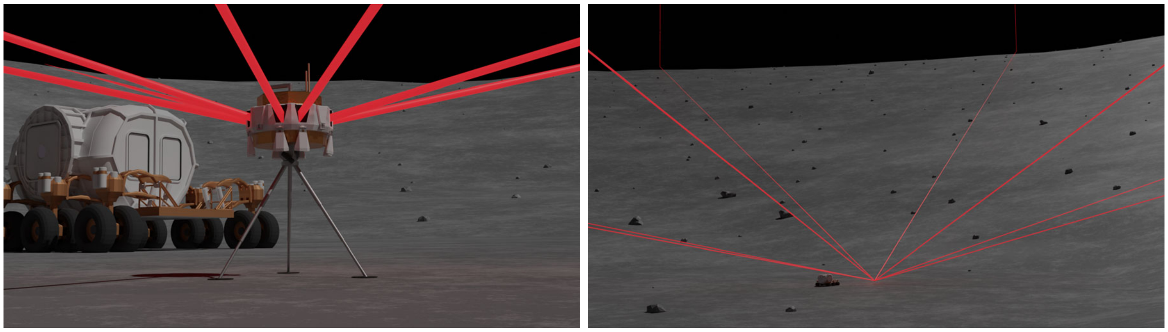

Figure 10. Notional follow-on eight-element astronomical telescope array deployed on the lunar surface.

While we have proposed herein consideration of a simple suitcase science implementation of a lunar optical interferometer, such a facility would lay the foundations for even more capable instruments. Expanding the suitcase implementation simply from 2 to 8 similarly-sized outboard OMUs separated by 100 meters would make an instrument capable of true 'snapshot' imaging at the 600 microarcsecond level (Figure 10). An even more ambitious surface facility that could follow successful demonstration of the technique would have 8 to 16 large OMUs separated by ~10 kilometers and be capable of spatially resolving an Earth-sized object at 10 parsecs into tens of pixels.

V. References

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