Science Topic: Suitcase Science Case for Astronomical Lunar Optical Interferometry
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I. Introduction. The anticipated human return to the lunar surface with NASA's Artemis program presents a significant opportunity to deploy a simple yet capable observatory that uniquely takes advantage of the lunar surface environment. Such an instrument would follow in the footsteps of the Apollo 16 UVC (Ultraviolet Camera/Spectrograph) suitcase science telescope. The instrument would be capable of doing unique science in its own right, and would pave the way for major follow-on lunar observatories. These facilities would have the potential for 'civilization impact'-level science, such as exoplanet surface mapping.

Optical interferometry on the Earth's surface has been under development since the 60s and 70s. Currently there are three major operational facilities worldwide - the GSU CHARA Array on Mt. Wilson, the ESO VLTI on Paranal, and the NPOI array outside Flagstaff, Arizona. All of these facilities feature baselines in the hundred-plus meter class, meter class individual apertures, and operating wavelengths ranging from roughly the visible to near or mid infrared. All of these facilities also share in common the unfortunate characteristic of being severely limited in sensitivity by the Earth's atmosphere, which causes optical paths to fluctuate at the level of tens of microns, on millisecond timescales. Spacecraft-based concepts for optical interferometry have been considered for decades but have yet to be implemented, in part due to challenges in stabilizing one or more free-floating spacecraft buses.

The case for a simple, lunar suitcase science implementation of an optical interferometer is compelling. A portable, 'suitcase plus two carryons' paradigm allows for the deployment on the lunar surface of an easily implemented lunar observatory. Earth-bound facilities have integration times limited to milliseconds. For a lunar interferometer free of that severe limitation, integration times would readily be hundreds of seconds in length, meaning even modest ~100mm unit collection apertures would readily outperform Earth-based ~10-meter apertures.

The lunar surface has major advantages for optical interferometry over ground-based and space-based facility concepts:
- No atmosphere means long integration times & exquisite sensitivity
- A stable optical platform further supports long integration times, as well as simply implemented ultra-long baselines
- Passive mechanical stability of the lunar surface is 3-4 orders of magnitude better than an actively controlled space-based free-flier, greatly simplifying interferometer implementation

II. Basic concepts, II.1 General CONOPs. The expected concept of operations (CONOPs) for an 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 'carryons') consisting simply of one or two steerable flat relay mirrors.
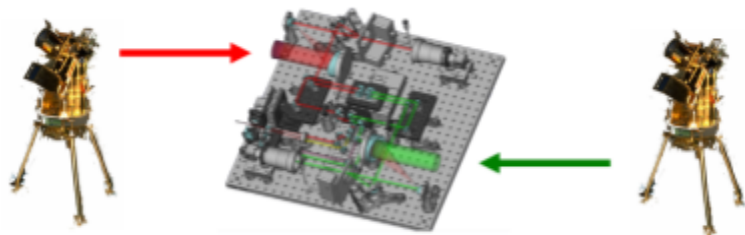

Figure 1. Basic components of a lunar interferometer: twin outboard optical units that relay light to a central beam combiner.

An astronaut would place the ~50kg CBC on the lunar surface, attach power and telemetry connections;
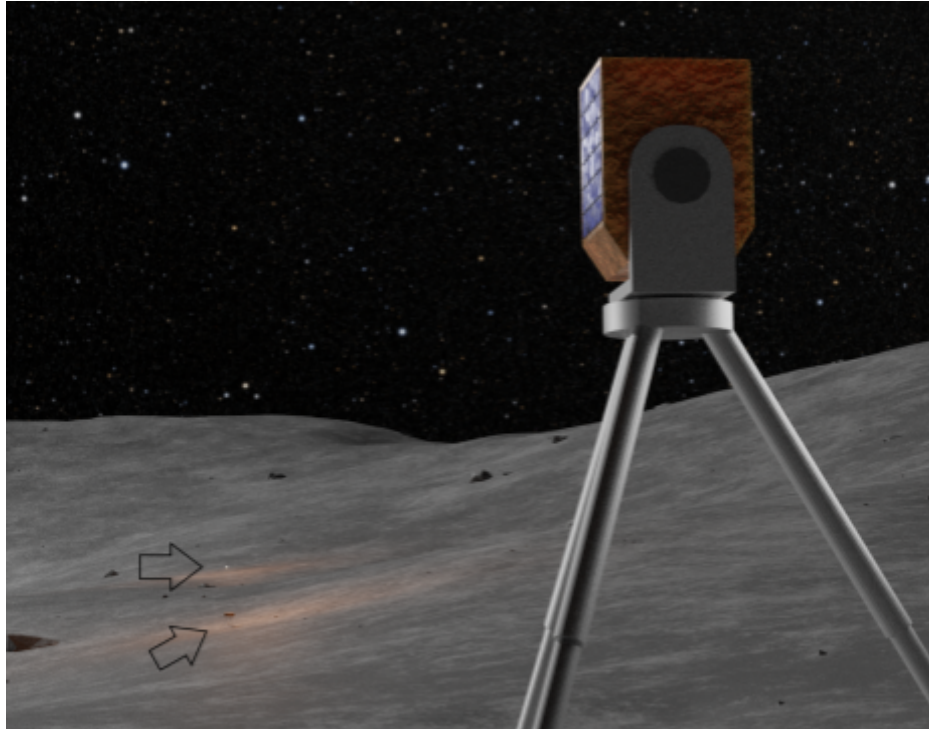
Figure 2. Artist's render of an OMU with the CBC (lower arrow) and opposite OMU (upper arrow) in the distance.

the astronaut would then place a ~20kg OMU 50 meters to the west of the CBC, and an OMU 50 meters to the east. Since gross changes in relative OMU positioning simply turn up in general instrument sky coverage, but don't affect the ability to interferometrically match pathlengths, positional accuracy in both angle and distance between OMUs to a fine degree is not required, and the OMU positions could simply be paced off by the astronaut. 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. This Science Topic White Paper will focus on the advantages of the lunar environment and enabled science cases; a companion Research Campaign White Paper will expand on the technical aspects of implementing a suitcase science lunar interferometer.

II.2. Interferometry principles. An interferometer is a distributed telescope system that, in a typical implementation in the optical, collects light from outboard optics, relays that light to a central beam combiner, and after matching pathlengths to a fraction of a wavelength of light with a 'Delay Line', recombines the beams and senses the resulting interference patterns (Figure 3). Pathlength differences are introduced into the overall optical path by object sky position, relative positions of the OMUs, internal instrument paths (including the deliberate position of the Delay Line), and atmospheric transmission. These pathlength variations can be time-variable, and in the case of the Earth's atmosphere, their rapidity and amplitude are fundamental limitations for ground-based interferometeric facilities which are completely eliminated in a lunar setting.

As described above in the general CONOPs, the basic 'suitcase plus two carryons' (a CBC plus two OMUs) system described takes advantage of the natural lunar environment to
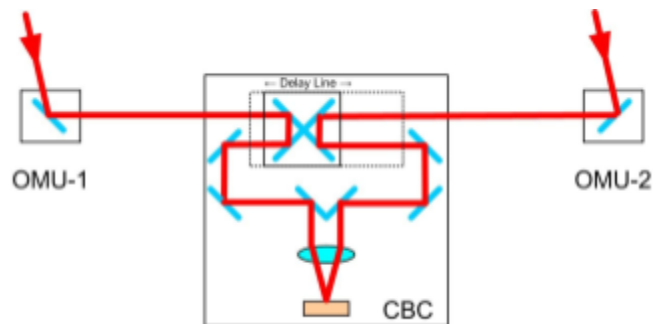

Figure 3. Component sketch of a 'suitcase' (the CBC) plus 'two carryons' (two OMUs) for a lunar interferometer. The OMUs direct light to the CBC, where a Delay Line equalizes the path lengths between the two arms, and then combines the two beams interferometrically.

demonstrate a uniquely capable astronomical observing facility in a remarkably simple package. Such a demonstration would lay the foundation for even more capable lunar observatories to follow. The advantages and challenges of a lunar surface instrument are described below.

As a strawman design reference point, we can postulate a suitcase science interferometer with small (50-100mm) OMU mirror flats separated by 100m, operating at 300-1000nm, with an underlying need for λ/10 control, meaning stability or tracking of disturbances at <30nm. Relative positioning of the OMUs and CBC can be imprecise at the ~1-5 meter level, as long as this stability condition can be met.

III. Lunar environment. The lunar environment presents a number of unique challenges and advantages. Up until recently, surface deployment of an interferometric observing facility had not been considered seriously simply due to the lack of surface access. However, with the Artemis program, this shortcoming is anticipated to be eliminated, prompting consideration of this option for deployment of an ALOI.

III.1. Atmosphere. The trace atmosphere of the moon, in this context, is essentially negligible and can be considered to be a vacuum environment. Contrasting this is the Earth's atmosphere, which for ground-based interferometric facilities, introduces rapidly fluctuating, unequal pathlength variations into the light path followed by separate telescope elements of an array. These pathlengths can be many 10's of microns, on millisecond timescales, and effectively limit ground-based optical interferometry to integration times of that duration: sensitivity is severely limited as a result for these facilities. A lunar interferometer would eliminate this limitation and be capable of integration times 10^6 times longer, meaning that **exceptionally small lunar-based apertures (50-100mm in diameter) can easily outperform the largest ground-based interferometer apertures (8.2m in diameter)**.

A secondary aspect of the lack of a lunar atmosphere is the essentially unlimited sky position ('isoplantic angle') available for tracking of reference objects. With ground-based interferometry, increasing the sensitivity of a secondary science channel has been demonstrated via co-phasing on a nearby bright primary tracking object; however, that application is limited to extremely narrow isoplanatic angles of 10 arcseconds or less. From the lunar surface, if an optical facility has a tracking channel (a second red beam as shown in Figure 2) for active optical path control at the 30nm level, with an acceptance angle of 1-2°, this ensures that a bright star (m_V<6) is available all-sky for co-phasing tracking. Isoplanatic acceptance sky areas available for finding tracking objects are easily >10^6 greater than for Earth-bound facilities and mean active tracking, if needed, is easily achievable.

III.2. Surface Vibrational Environment. As noted above, for interferometric operations at the shortest wavelengths in this notional design demand stability at the 30nm level, achieved through either passive or active means. Overall, the lunar seismic energy is markedly less than the Earth (3 to 7 orders of magnitude lower; Vaniman 1991). Based upon the Apollo lunar seismic experiments, there are two major elements of the lunar vibrational environment worth considering. First, the overall quiescent background vibration level is present at the ~25nm level, which is approaching but not in excess of our stability specification; such a background level can be the dominant (but tolerable) term in the high-frequency error budget of our lunar interferometer. Second, larger amplitude moonquakes appear to occur on ~weekly timescales, introducing displacements on the order of ~mm (Latham et al. 1973), largely associated with the month-long orbit of the Moon about the Earth. Such disturbances would require a small but easily measured level of recalibration of optical path lengths, which could be done remotely. Micrometeorite impacts were detectable by Apollo seismometers at the rate of 70 to 150 per year, down to 100 gm (Latham 1973). The rate per year per km^2 down to the 0.1 gm level appears to be quite low

(eg. less than one such event per year per km^2) which is not a factor in considering the vibration environment for an interferometer facility.

Importantly, with a tracking channel as noted in the previous section, significant disturbances could be tolerated and simply tracked out actively. Such tracking would result in uninterrupted astronomical observations, as well as characterizing lunar seismic data that would complement dedicated seismic data sensors. It is even quite possible that the vibration environment noted above would support elimination of the tracking channel altogether, and that the necessary 30nm stability for 1000-3000 second integration times is possible through simply passive means.

III.3. Lunar Rotation Period. Given that the lunar rotation period is significantly longer than Earth's (28d versus 24h), there are significant benefits for interferometry beam combination. First, for those objects that are in the capture range of the delay line, they have ~28x longer loiter time within a given delay line range. Second, the tracking speed of the delay line is also correspondingly lower. These two effects make delay line tracking significantly easier than for ground-based facilities.

III.4. Environmental Challenges. The lunar environment does present non-negligible challenges for implementation of any lunar optical observatory.

III.4.1. Lunar Day/Night: Power & Thermal. The lunar day-night cycle presents two significant challenges for any surface facility, namely power and thermal. For power, in the context of this specific White Paper we are not presenting a specific solution at the moment, noting only that this is an outstanding challenge in general for surface deployed equipment, and we anticipate such a general demand will mean solutions for that will be forthcoming. For thermal, the temperature extremes present similar challenges; we note that Redwire Space has extensive familiarity with operation of servos and other mechanical components in extreme environments.

III.4.2. Dust. A notable challenge of the lunar surface environment is dust. However, given the modest aperture sizes (50-100mm) of a suitcase-scale interferometer, a straightforward solution would be seal OMUs and the CBC with entry/exit windows. While such a solution would still be susceptible to optical surface contamination, this would only result in minor parasitic sensitivity loss (as seen routinely in operations of
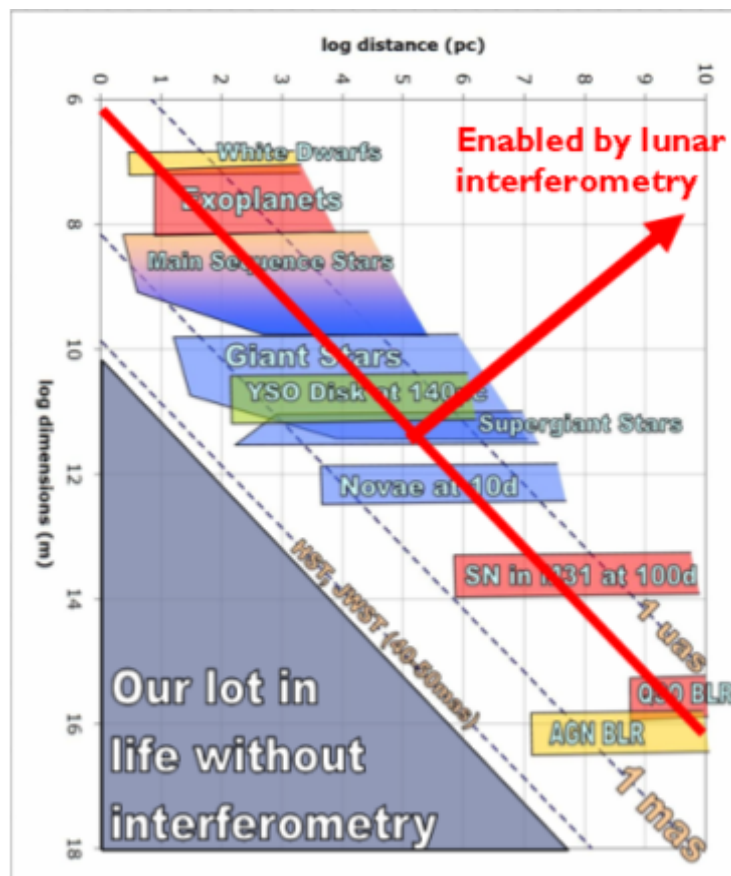

Figure 4. Astrophysical sources as a function of overall dimension versus distance. Most structures require spatial resolution in excess of 1 milliarcsecond (to the upper right); HST and JWST can only reach ~40-50 mas (to the lower left).

ground-based telescopes) and would prevent sensitive actuation servos from being contaminated by the highly abrasive dust.

III.5. Lunar Surface versus a Free-Flier. The lunar surface is inherently much more stable than a free-flier platform. Lowell Observatory and Redwire Space have collectively been working on NASA-funded SBIR Phase I and II studies in support of free-flying interferometer concepts (van Belle et al. 2020, 2021). It is worth noting that the SBIR development efforts have focused on a number of elements, which can broadly be separated into the optical payload, and 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 3-4 orders of magnitude more stable as an optical platform than a free-flying bus, and greatly simplifies implementation of an interferometer system**. A single, structurally connected free flier also suffers from practical limitations on baseline length. We have seen with our SBIR work that implementation of novel concepts such as in situ manufacturing of boom structures can achieve baseline lengths from 10's to 100-plus meters in length, but beyond that there are increasing boom stabilization challenges. Technical solutions for space-based interferometry with independent free fliers have actively been explored for some time (eg. Lay et al 2004), but are complicated and expensive due to coordinated flight of multiple independent spacecraft. Long interferometer baselines are significantly simplified with lunar surface deployment.

IV. Nominal Science Case. Milliarcsecond - and smaller - imaging is the science enabled by optical interferometry with ~100 meter-plus baselines; such a spatial scale is 1 to 2 orders of magnitude finer than possible with HST and JWST. Even though the implementation we have discussed here of a lunar interferometer is quite modest in size, it would be capable of doing unique science. Figure 4 shows broadly that phenomena across the universe begin to reveal themselves spatially at milliarcsecond spatial scales.

We can highlight two areas out of many that will reveal unique insights even with our modest suitcase implementation. First, young stellar objects can have their inner, temperate planet-forming regions characterized. The outer, icy regions of these YSOs have had dramatic imaging by ALMA in recent years, revealing gaps in circumstellar disks being carved by putative protoplanets; imaging with an optical lunar facility inside the central ALMA pixel will reveal if similar such gaps are being carved by terrestrial-sized protoplanets. Second, at megaparsec distances, disk structures encircling the black hole cores of active galactic nuclei can be measured, characterizing the infall of material into these engines that power the hearts of those galaxies.

V. 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 is the robustness of using the lunar surface as a solid optical footing for such a facility.

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. A 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.

VI. References

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