Design Reference Mission for Lunar Telescope Deployment

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Table of Contents

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1. Introduction

The purpose of this document is to define a Design Reference Mission (DRM) for the deployment of a lunar telescope. This DRM will then be used to define, in a separate document, a Design Reference Demonstration (DRD), which will identify a technology demonstration that meets the goals defined by the DRM. This DRD will then be used to guide technology development and evaluate technology effectiveness, as part of the Lunar Telescope Deployment task in the NASA Telerobotics program.

The authors of this document are roboticists, not astronomers or astrophysicists or planetary scientists. Thus, the DRM will be derived from published reports on lunar telescopes.

The proposed work does not currently have a definite mission to serve as program customer and technology driver. Instead, the proposed work fits within a technology push strategy of developing and demonstrating a new capability that will influence the objectives and requirements of future lunar and science missions. Since it is clear that we will someday return to the lunar surface with human bases, resource utilization centers, science instruments and more, the technology push is a sound investment. The Moon is too important a gateway to the solar system to neglect for long.

We select optical interferometry, rather than other telescope concepts, to serve as the focus of this technology push because technically it presents the most challenging problems and because scientifically it promises the greatest potential for revolutionary breakthrough.

2. Lunar Telescope Concepts

A wide variety of lunar telescope concepts have been studied, including radio telescopes on the lunar far-side, a thermal infrared telescope within a permanently shadowed crater at a lunar pole, a 10-km baseline optical/IR imaging interferometer, and a high throughput X-ray telescope [3].

The concept that has received the most attention is an optical/IR imaging interferometer [1][2][4][7]. This concept may represent the largest advance in technology, resolution, and science potential of any of the proposed lunar telescopes.

An optical interferometer gathers light from multiple distributed optical telescopes and combines it to form an interference pattern. The distributed telescopes create a large synthetic aperture equivalent to the distance between the elements, thus providing high angular resolution while using small elements. Optical interferometers equalize the optical path lengths, typically with optical delay lines, so that the fringe patterns from each light-gathering element can be combined properly.

The Moon is particularly well-suited as the location for an optical interferometric array: the vacuum environment improves observation sensitivity and allows observations at all spectral bands; the large, stable, slowly rotating platform offers kilometer-scale viewing baselines; the knowledge of its motion allows for microarcsecond correction of stellar aberration; and the 100 K nighttime temperature passively cools optics, thus permitting high sensitivity.

Two lunar optical interferometer designs have been proposed. The first [1], modeled after the National Radio Astronomy Observatory's Very Large Array in New Mexico, calls for a Y-shaped distribution of elements with 27 four-meter aperture elements distributed with a maximum baseline of 10 km. The second [4], calls for the interferometer elements to be distributed along a non-redundant Cornwell circle with an outer diameter of 10 km.

A number of precursor designs have also been proposed to provide the necessary engineering data for a more informed design study of a future lunar interferometer. McGraw [6] suggested a 1 m lunar transit telescope with few moving parts that would perform a repeated transit survey of strips of the sky. Genet [5] proposed a fully-steerable 1 m class telescope that would perform the first all-sky CCD imaging survey in the far-UV.

3. Mission Concepts Related to Lunar Telescopes

In NASA's Office of Space Science, the Solar System Exploration Division has identified the Origins program as one of its core, long-term program elements. Origins features three so-called second-generation missions:

- The Space Interferometry Mission (SIM), a space-based optical interferometer.
- The Next-Generation Space Telescope (NGST), a 4-meter (or larger) space-based telescope.
- The Planet Finder (PF, previously named Exploration of Neighboring Planetary Systems), a space-based optical interferometer that could be launched around 2005 to search for Earth-like planets around nearby stars.

A third-generation mission would be a Planet Mapper, to map the surfaces of extrasolar planets. In addition, observations with ground-based telescopes will identify stars with planets by indirect means and will be capable of detecting Jupiter-sized planets.

None of these mission concepts require a lunar observatory. However, it is likely that future mission concepts, currently beyond the planning horizon, will seek to capitalize on the many advantages of the lunar location.

4. Mission Scenario

The surface-based segment of a lunar optical interferometer mission, illustrated in Figure 1, can be divided into the following phases.

Deployment Rovers will explore the vicinity of the landing site, gathering information about favorable and unfavorable terrain areas. Based on this reconnaissance data, a deployment pattern will be selected and uplinked. Rovers will carry telescopes to designated locations, with no definite required placement accuracy. However, it is reasonable to expect placement errors no larger than 100 cm.

Metrology A positioning procedure will determine with 10 centimeter accuracy the telescope absolute position and orientation with respect to a central station (which in some scenarios may be a lander). In order to perform interferometry and detect fringes, the accuracy of relative ranging must be measured in nanometers; we explicitly do not include this measurement in the deployment metrology task, and instead include it in the interferometry metrology task.

Calibration The telescopes will point at reference stars and determine the kinematic and dynamic parameters of the motorized mounts. Given a two-stage telescope, it suffices to shoot 5 or more stars and solve the kinematic model. Meanwhile, the central station will point its acquisition

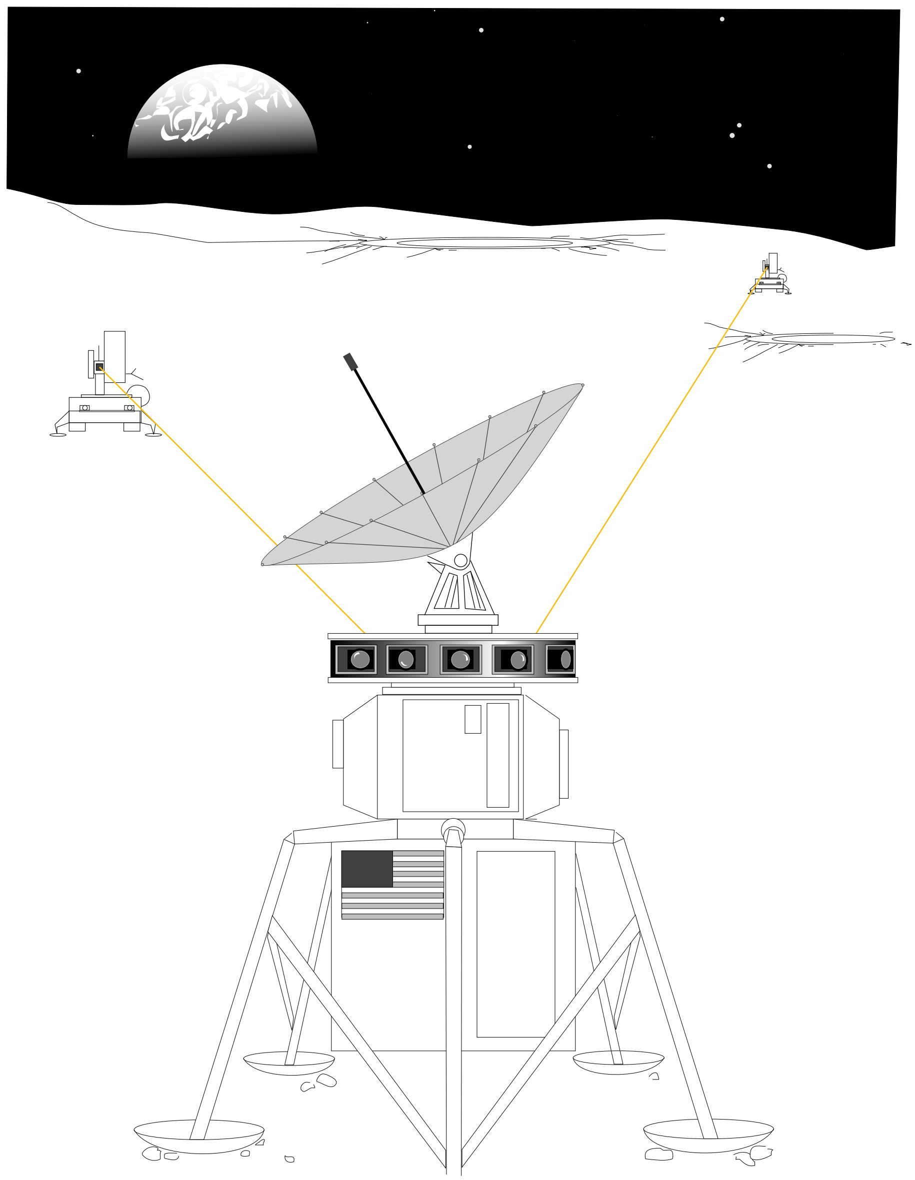

Figure 1 Lunar interferometer concept

cameras at the telescopes and determine the kinematic and dynamic parameters of its motors, as well as a variety of geometric and radiometric camera parameters.

Pointing Each telescope will acquire and track the same star. The light gathered by each unit will be relayed to the central station on the central station.

Phasing At the central station, the optical delay lines will be adjusted to equalize path lengths and produce white light fringes. This data will be recorded and downlinked for analysis and interpretation.

Iterate Repeat the pointing and phasing process for each star of interest.

5. Functional Requirements

5.1 Mobility

5.1.1 Location on Lunar Surface

The location on the lunar surface for deployment of the optical interferometer has not been determined. However, the factors to be considered in the location selection process are reasonably well understood:

- Minimize landing risk. This favors flatter and gentler terrain, such as that found on the lunar mare.
- Minimize deployment risk. Again, this favors more moderate terrain.
- Maximize line of sight. On flat terrain, the visible horizon is several kilometers distant for an observer approximately 1 meter tall. On rough terrain, the visible horizon is likely to lie closer to the observer than in the case of flat terrain. In a crater, the line of sight can be as large as the crater radius.

5.1.2 Terrain

To the extent that the location on the lunar surface has not been determined, it is not possible to state the exact nature of the terrain that the rover will be required to traverse. However, the terrain is expected to be moderate in comparison with the terrain found in the lunar highlands. The CMU Lunar Rover has been designed to be capable of negotiating terrain with the following characteristics: 38 cm high step, 69 cm wide ditch with depth greater than 38 cm, and 25 deg slope (in fully deployed configuration, 23 deg in stowed configuration). Given these rover design specifications, it is unlikely that the moderate terrain will impose any requirements that the rover cannot meet without some maneuvering.

5.2 Deployment

Both Burke [1] and Burns et al. [4] have advocated a baseline distance of 10 km. There does not appear to be any reason not to adopt this same baseline distance for the design reference mission.

5.3 Stellar Imaging and Tracking

5.3.1 Aperture Size

The sensitivity of measurements that are possible with the lunar telescope depends on the amount of light collected by the telescope elements, as well as the integration time of the measurements. The amount of light collected varies with the square of the aperture diameter. Thus, the selection of aperture size will determine how faint an object can be detected by the lunar telescope.

The aperture of the telescope elements in a lunar array will be as large as reasonably possible, with a diameter perhaps as large as 1 meter. The key drivers in the size trade are mass and volume. However, consideration of these factors lies outside the scope of this document.

For our purposes, which concern deployment rather than operation of the interferometric array, it will suffice to use one of the larger amateur units. These are commercially available with typical lead times of a few months. Currently, 30 cm reflector telescopes are the largest common commercial telescopes.

For a 30 cm aperture, the diffraction limit ranges from 0.34 arcsec to 0.84 arcsec for 400 nm (violet) to 1 micron (near infrared) light. This is comparable to or better than current terrestrial seeing conditions, even for large telescopes, without atmospheric correction. For an interferometer with a 1 km baseline, the diffraction limit ranges from 1.0×10^{-4} arcsec at 400 nm to 2.5×10^{-4} arcsec at 1 micron. At 550 nm, the 1 km lunar interferometer could distinguish 2 point sources 1 AU apart at a distance from the Moon of 7200 pc.

5.3.2 Telescope Element Pointing

In order to observe a star, the star must first be found using one of several methods. First, by knowing a rough position estimate of the star, the telescope elements can be pointed in that direction.

Second, a coarse acquisition camera can be used to locate the approximate target area. A field of view of 0.5 deg should be more than suitable. (Note that the Moon subtends an angle of 0.5 deg from Earth.) The image from the coarse acquisition camera must be processed to determine if it is pointing at the correct location. Both the coarse pointing and the coarse acquisition camera can be used together in the pointing process.

5.3.3 Telescope Element Tracking

As the moon rotates about its axis, the telescope elements must track their target, moving to maintain the alignment between their apertures and the imaging target area. The apparent angular velocity of a star is the same as the angular velocity of the moon as it rotates. Since the moon rotates once every 27.3 days, the angular velocity is 0.5 arcsec/sec. Compared with the Earth's angular velocity of 15 arcsec/sec, this is quite slow, but the tracking must still be highly precise for optical interferometry to take place. In addition, each telescope element must track the star simultaneously, at the same rate.

The tracking procedure depends on the type of telescope mounting. An equatorial mounting requires only one motion, tracking the target with a constant slew rate, assuming the target moves with a constant angular velocity. In this case, one axis of the telescope must be precisely aligned with the Moon's rotation axis. A simpler mounting is the alt-az mounting, in which two axes of rotation must be controlled.

For automatically tracking a star, a quadrant detector is often used. Light from a bright tracking star is centered on the quadrant detector, and if the star becomes uncentered, more light falls on one quadrant of the detector than the others, and when this is detected, the telescope is moved so that the alignment is regained.

5.4 Pointing

The requirements of the pointing subsystem are as follows:

1) Point a laser from the base station to the telescope exit aperture, and return the beam to the base station.
2) Point the compressed starlight beam from the telescope at the base station receiver.
3) Direct the starlight beam entering the base station receiver into a sensor suite, while screening out background illumination.

A light beam can be usefully modeled as in Figure 2. In the near field, the beam cross-section shape is dominated by the geometry of the exit aperture; in the far field, diffraction effects dominate, and

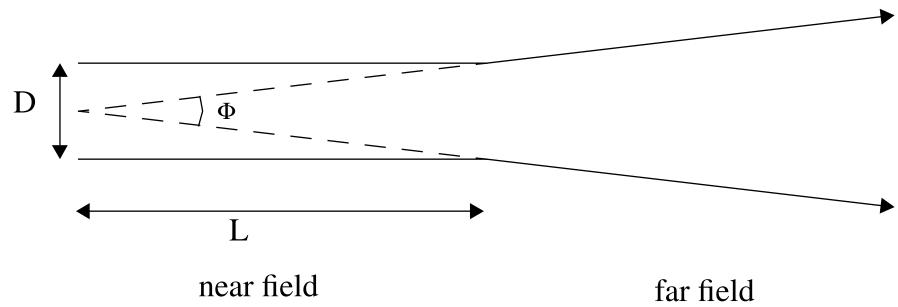

Figure 2 Beam model

the beam propagates in a cone. For a uniformly illuminated circular aperture, the divergence angle (in radians) and beam diameter are related as follows:

$$\phi = 1.2\frac{\lambda}{D}$$

For a typical HeNe laser (692 nm wavelength) with a 10X beam expander/collimator, the divergence is about 30 arcsec, and the diameter is 15 mm, giving a transition distance L of about 100 m. For a visible (400 - 700 nm) light beam 5 cm in diameter, the divergence is at least 2 arcsec and the transition distance extends to about 5 km.

5.4.1 Laser Beam Pointing

The requirement is to illuminate the center of the target (a retro-reflector inside the telescope) with the laser beam. This requires a steering precision of at least

$$\theta = \begin{cases} \phi, \text{ far field} \\ \dfrac{D}{l}, \text{ near field} \end{cases}$$

where l is the distance to the target, and is assumed to be much greater than the target or beam diameters. With the aforementioned laser, this translates to a steering precision requirement of at least 30 arcsec.

To successfully return the beam (that is, illuminate the center of the base station receiver) the retro-reflector must have parallelism of at least half the divergence of the returning beam. For a 2.5 cm diameter fully illuminated retro-reflector operating at 692 nm, the divergence is about 7 arcsec, hence it must have parallelism of at least 3.5 arcsec.

5.4.2 Starlight Beam Pointing

It is essential that starlight losses incurred during transmission from the telescope elements to the base station be minimized. Hence more stringent criteria for successfully pointing are used than for the laser system.

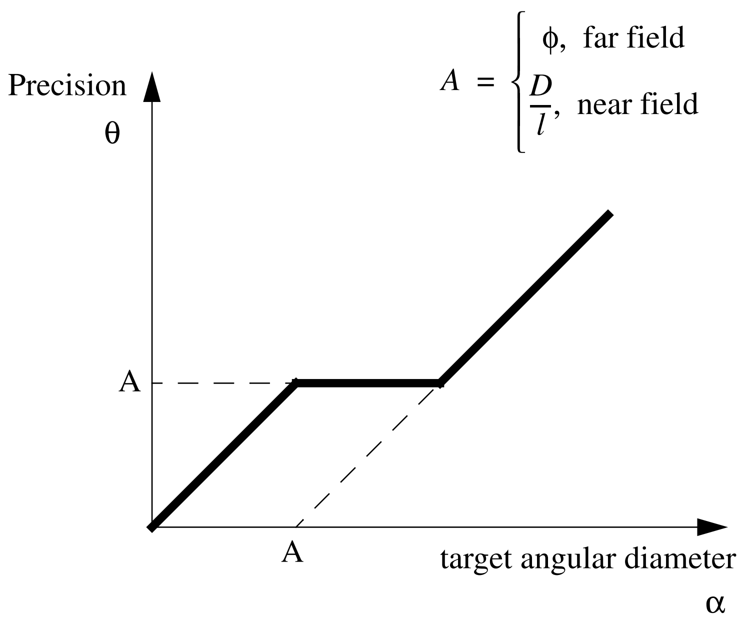

Figure 3 Precision versus target size

Case 1: Target wider than beam.In this case, we require that the entire beam fall upon the target. Let $\alpha = D_T/l$ be the angular diameter of the target as seen from the telescope. Then a beam steering precision of

$$\theta = \begin{cases} \alpha - \phi, \text{ far field} \\ \alpha - \frac{D}{l}, \text{ near field} \end{cases}$$

is required.

Case 2: Target narrower than beam. In this case, we require that the center of the beam lie in the target. Thus $\theta = \alpha$ for both the near and far fields. When the target and beam diameters are comparable we can interpolate between the two extremes as in Figure 3.

Assuming a 5 cm beam diameter and comparable target, a 1 km telescope-base station separation (near field) requires an angular precision of at least 10 arcsec, and a 10 km separation (far field) requires an angular precision of at least 2 arcsec.

It must be emphasized that these are approximate upper limits, and that an operational system may require a larger receiver on the base station and two times better angular precision so as to minimize light loss.

Another consideration in analyzing starlight beam pointing requirements is to set the beam diameter, traveling from the telescope to the central station, to avoid diffraction. This can be expressed in terms of a Rayleigh distance: diffraction effects can be considered negligible when the beam diameter equals or exceeds the square root of the product of the wavelength and the distance. For a 1 km baseline, the diffraction limit occurs for a beam diameter of 2.6 cm. For a 10 km baseline, the diffraction limit occurs for a beam diameter of 8.3 cm.

5.4.3 Base Station Receiver Pointing

At the base station the received light is focused onto a sensor or fiber optic with a given field of view. To minimize signal losses the entire exit aperture of the telescope should lie within the field of view. Yet it should not be so large as to admit excessive background illumination. This dictates that the field of view should be comparable to the angular diameter of the telescope exit aperture. A similar calculation to the far field case above applies, with the field of view replacing the parameter A, and the exit aperture the target.

For a 5 cm exit aperture at a distance of 1 km an approximately 10 arcsec field of view is desirable, and at 10 km a 1 arcsec field of view. This indicates similar angular precisions for the pointing system.

Another approach is to place a field stop in the image plane of the telescope. This will relax the requirements for baffles.

Note that these requirements can be relaxed somewhat by surrounding the exit aperture with a disk of light absorbing material. Then the field of view may be increased without admitting substantially more stray light.

5.5 Metrology

The absolute accuracy required for measuring the distance between the telescope elements and the central station is determined by the method for implementing optical delay lines. We understand, from personal communications with M. Colavita and J. Yu at JPL, that an accuracy of 10 cm is required. These distances must be measured each time the configuration of telescope elements changes.

Again, we distinguish between the absolute ranging accuracy (10 cm) and the relative ranging accuracy (10 nm) required for fringe detection.

5.6 Supervisory Control

In order to minimize mission costs, it is desirable to minimize the scope and complexity of ground operations. In the ideal case, the telescope deployment would proceed with a single uplink command. However, this ideal cannot realistically be achieved using near-future telerobotic technology. In the worst case, the telescope deployment would take place entirely under teleoperation control, in which every robot motion is controlled by a ground-based operator. Such operations would be tedious and expensive.

The supervisory control mode divides the control tasks between remote rover and ground-based operator. In one proven framework, the rover makes tactical decisions about its immediate environment, and the ground based operator makes strategic decisions about larger-scale goals and directions.

Such supervisory control imposes requirements on the communications bandwidth, particularly for the downlink. It also imposes requirements on the types of sensors, computers, memories, and algorithms on-board the rover.

5.7 Summary

Figure 4 summarizes the functional requirements to be achieved by the Design Reference Mission.

Requirement	Value
Maximum height of traversable step obstacle (meters)	38
Maximum width of traversable ditch (meters)	69
Maximum traversable sand slope, deployed configuration (deg)	25
Maximum baseline distance of interferometric array (km)	10
Aperture size expected for terrestrial demonstrations (cm)	30
Angular velocity for star tracking from Moon (arcsec/sec)	0.5
Maximum field of view of coarse acquisition camera (deg)	0.5
Steering precision for laser beam pointing over 1 km (arcsec)	30
Steering precision for laser beam pointing 10 km (arcsec)	30
Steering precision for starlight beam pointing over 1 km (arcsec)	10
Steering precision for starlight beam pointing over 10 km (arcsec)	2
Steering precision for receiver pointing (arcsec)	10
Steering precision for receiver pointing (arcsec)	1
Accuracy of telescope placement at designated location (cm)	100
Accuracy of absolute range measurement (cm)	10
Accuracy of relative range measurement for fringe detection (nm)	10

Figure 4 Summary of selected requirements

6. References

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