

## ASTRONOMY FROM THE MOON: SCIENCE UP ON THE ROCKS?

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**Introduction:** The lunar surface has been assumed (originally [1], and more recently [2, 3, 4]) to be a potent site for astronomical telescopes. Value-based strategic planning by NASA for lunar exploration requires reevaluation of this assumption, however. Following previous policy discussions [5, 6] this white paper is intended to provoke that reevaluation. While the Moon offers astronomical performance unobtainable on the Earth, the importance of the lunar surface relative to sites in free space is not broadly evident. In many respects, siting telescopes on the Moon makes astronomy harder to do, rather than easier. Plans for both technology investment and operations should consider lunar exploration-enabled astronomy to include telescopes that don't actually sit on the Moon, as those may provide the greatest opportunity. Finally, planning what lunar return can do for astronomy should be led by the astronomical community. To a large degree, that hasn't been the case thus far.

**It's About Enabling Science:** As we consider the Moon as a potential site for astronomical instruments, our key decision is the extent to which astronomy is actually enabled by doing so. The question that needs to be asked is not whether it is feasible to put an astronomical facility on the lunar surface, but whether science derives benefit from it being there. We must be guided by what regolith or gravity (which are what the Moon uniquely provides, compared with free-space) actually offer astronomy. While there are many considerations that contribute to the decision, some ground rules apply that are physical and political truisms. The first is that telescopes on the Moon come at the price of telescopes elsewhere. The second is that deployment in a gravity field entails added propulsion requirements and risk. One has to get it down, and get it down softly. As a result, "as long as we're going there anyway" is not a compelling science-enabling justification, in and of itself, to put astronomical instruments on the Moon. Another key question is the extent to which routine accessibility by astronauts based nearby, whether for deployment or frequent maintenance, is critical to the scientific performance of such a facility.

**Stable Platforms in Space:** In addition to the obvious multiwavelength advantage of being in vacuum, one of the early attractions of the Moon as an astronomical platform in space is the large reaction mass. This allows instruments mounted on that surface to be largely dynamically decoupled from astronauts who might be working in close proximity. This was consid-

ered a big advantage in the picture of an operationally hands-on science facility which, as a result of dramatic advances in sensor, communications and remote control technology, is no longer particularly valid. We've learned how to do astronomy remotely, and we do it routinely both on the ground and in space. In the past, it used to be assumed that this large reaction mass offered needed pointing stability for instruments coupled to it. Encouraged by the seismic quietness of the Moon, we were assured that the lunar surface was just as rock steady as the Earth for this purpose, if not a lot better. But as a result of decades of technology development in free-space pointing and tracking, such assurance is now somewhat empty. The decades-old tracking technology on the Hubble Space Telescope provides a platform with a pointing accuracy of several milliarcseconds. It does this continuously in LEO which, with regard to system equilibration, is a particularly unforgiving place. Far more perturbation-benign sites, such as free-space Lagrange points which require only modest stationkeeping, are being targeted for future use. The past twenty years of space astronomy gives us unassailable confidence in pointing telescopes without sinking foundations in concrete.

**Gravity and Flexible Telescopes:** All telescopes are flexible and, for precision optics, slewing and tracking around the gravity vector complicates the operation. While our terrestrial telescopes deal with the effects of gravity using sophisticated active and adaptive optics, as well as the somewhat less sophisticated approach of adding mass to stiffen the structure, both approaches are costly for space. While the gravitational field of the Moon is much smaller than that of the Earth, the price of complexity and landed mass on the lunar surface (facing ~2 km/s delta-V propulsion burden to get it down) is likely to be substantial.

Is gravity good for astronomy? Gravity is useful in keeping dropped tools accessible, and may also offer some dynamical advantages in vibration damping. But these are likely to be secondary. Creative proposals for very large liquid mirror telescopes have been floated [7, 8], and such telescopes depend on lunar gravity to function. The astronomical community must consider the scientific priority of such zenith-pointing telescopes in meeting established goals, however.

A large surface with things held down by gravity can be advantageous in stationkeeping those things, and interferometers using the lunar surface as an optical bench might be helped by it [9]. There are several approaches to interferometer baseline management in

free-space, however. These range from very large, lightweight, deployable trusses (“hard” platform, e.g. SIM, SPIRIT, DLI), to rotationally stiffened tethers that couple telescopes (“soft” platform, e.g. SPECS), to entirely free-flying telescopes that can do formation flying to within the fringe capture tolerance of the beam combiner (e.g. DARWIN, TPF-I, LISA). Free-space radio interferometry is already proven (e.g. VSOP/HALCA). While the other approaches have not yet been proven, they have been studied in detail and considered credible. While interferometry between terrestrial telescopes is well established, there are significant challenges that have to be met in order to duplicate that on the surface of the Moon.

The astronomical community needs to consider a strategic approach to space interferometry very carefully. On the one hand, the lunar surface may provide an opportunity to duplicate successful terrestrial interferometers. On the other hand, technology investment in large stiff trusses, tether systems, and formation flying may provide astronomers with opportunities to eventually do much better in free-space – with all-sky visibility, flexible baseline reconfiguration, UV-plane filling, and much larger baselines than can be conveniently accommodated by lunar landforms.

**The Dirt on Dust:** The pervasiveness of lunar dust, its clinginess, abrasiveness and propulsion on ballistic trajectories by everything that moves has been understood for many years [10]. The Apollo astronauts were beset by problems with it. In addition to operations-driven dust transport (including dust kicked up by ascent and descent stages), transport by natural mechanisms has been suggested, and invoked to explain “horizon glow” and “streamers” observed by Apollo astronauts, Surveyor, and Clementine. Although the precipitation rate of these dust grains has not been directly measured, recent electrostatic levitation models [11] provide targets for future dust-detection experiments. It should be noted that the performance of the three decade old lunar laser retroreflectors has not been followed carefully. Their location in full sunlight may, in the context of dust levitation by photoionization, regularly “clean” them in ways that a shielded telescope would not. The dust situation deserves serious study, as it bears on all lunar exploration. While creative strategies for dust mitigation have been proposed, the impact of lunar dust on mechanical interfaces and seals as well as optics –in terms of emissivity, absorptivity, and scattering for short wavelength applications, must be viewed with considerable concern.

To the extent that an astronomical instrument benefits from astronauts based nearby who can interact

with it, that this interaction will only exacerbate dust contamination.

**Exploration and Astronomy:** It should be clear for future strategic planning efforts that while certain astronomical applications (e.g. far side quiet-zone radio astronomy and particle astrophysics which can both benefit from the large mass of lunar regolith), may be enabled by lunar siting, Exploration architecture (heavy lift, CEV) can be used to deploy and service large optics in free-space. That is, lunar return can enable astronomy that is not based on the lunar surface. This will be addressed in other contributions, but it should be understood that in terms of field-of-view, thermal control, contamination mitigation, optical alignment, and power availability, astronomical telescopes in free-space, ideally at Earth-Sun Lagrange points, have enormous advantages over those on the lunar surface. While lunar based telescopes might be frequently visited for servicing and upgrade by nearby astronaut residents, observatory access has been carried out for almost two decades in free space. The low delta-V needed to transport facilities back from the scientifically optimal Earth-Sun L2 locale to the more convenient Earth-Moon L1 makes such telescopes easily accessible to CEV-based crews. Advanced robotics developed as a part of Exploration are likely to be of great value as well. Such robotic technology, which could play a major role in surface operations, will complement human efforts on telescopes in free space.

In the interest of maximizing return on investment our nation is making in Exploration architecture, the agency should encourage and expand efforts that are now being made to at least identify options for future free-space, as well as lunar based, observatories. Ideally, these options could be developed at a level that could shed light for the next NRC Astronomy and Astrophysics Decadal Survey, which is an established procedure for assessing value of astronomy programs with large costs. The astronomy community should be fully engaged in these Exploration-based efforts, exercising true leadership to navigate through decisions about where and whether telescopes ought to be built.

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