

Build astronomical observatories on the Moon?

Technological challenges, expense, and the problem of dust are among the issues to confront in any discussion of astronomy performed away from Earth. Two scientists debate the relative merits of Moon-based telescopes compared with ones in free space.

Paul D. Lowman Jr: YES

Paul Lowman Jr is a geophysicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Daniel F. Lester: NOT SO FAST

Dan Lester is a research scientist at the University of Texas at Austin.

Astronomy is today in a golden age, one that began approximately in the early 1990s with the launch of the *Hubble Space Telescope*. The *HST* and its counterparts, such as the *Spitzer Space Telescope*, have produced stunning images. Earth-based astronomy at optical, IR, and submillimeter wavelengths has achieved comparable progress. The most striking advance has occurred in interferometry—especially optical interferometry, which produces spatial resolutions previously unimaginable in single-aperture telescopes. The twin Keck telescopes on Hawaii's Mauna Kea, for example, are now referred to as the Keck Interferometer. Other Earth-based instruments and techniques have likewise made enormous progress with, for example, the discovery of dozens of extrasolar planets.

Given those achievements, Dan Lester and others have reasonably asked if there is any reason to reopen the once-popular topic of observatories on the Moon. My answer is yes. To organize my reasons, I suggest here a hypothetical lunar-astronomy program, termed the Grimaldi Robotic Observatory (GRO)—an acronym recycled from the now-completed Compton Gamma Ray Observatory.

The program would be the emplacement of a family of small (one-meter-diameter) robotic telescopes in the Grimaldi Basin, perhaps accompanied by submillimeter dishes, mission constraints permitting. The Grimaldi Basin ("Grimaldi" henceforth) is a lava-filled, multi-ring impact crater located on the left-hand side of the Moon at 5° S latitude as seen from Earth. It is easily visible with binoculars during a full or last-quarter moon.

What does Grimaldi offer as an observatory site? First, its near-equatorial location would give access to almost the entire celestial sphere over a 28-day period. The Earth hangs low over the eastern horizon, in continuous line of sight for uninterrupted data transmission, but blocks almost none of the sky. Grimaldi's location would also make centimeter-wavelength radio astronomy possible, as long as the radio telescopes are not pointed directly at Earth. The popular view that radio astronomy is possible only from the lunar far side applies only to low frequencies, at which auroral interference is demonstrably a problem.

The advantages of the GRO site are shared with those of some other lunar limb locations, so let's now widen the

I offer what I would call the value proposition for astronomical measurements from the lunar surface. NASA's new directions prompt such a discussion as a part of space-science strategic planning. The surface of the Moon was recognized long ago as offering conditions—vacuum, in particular—that allow astronomical telescopes to perform vastly better than they could on Earth. The absence of an obscuring atmosphere offers a truly panchromatic perspective on the universe, compared with telescopes on even the highest terrestrial mountaintops. Enthusiasm for telescopes on the Moon peaked in the wake of the Apollo program, which convinced scientists that, if cost was no object, it was possible to put people and big things there. With the new Vision for Space Exploration—the national call to return humans to the Moon by the end of the next decade—many look ahead to such emplacements as being routine.

The belief that telescopes on the lunar surface are enabling to astronomy has come to be somewhat reflexive, based on what one can consider an engineering perspective. The Moon certainly offers a place to set things down in vacuum. One can dig holes and pour concrete. One can tie things down so they don't fall over. For telescopes that need to be very cold, one can put them in a permanently shadowed crater to keep sunlight off them. People stationed on the Moon can walk over to a telescope and tweak it. Much work has been devoted to whether telescopes can, in fact, be built on the lunar surface. The creative engineering expended offers some confidence that they can.

But then there's the science question: Can we get science of higher quality by putting telescopes on the Moon rather than in other places? In general, I believe the answer to that question is no, and astronomy should not be a strategic driver for planning lunar-surface operations.

Experience gained over 40 years has left us no lack of places to put telescopes in space. We have a large flotilla in Earth orbit and several telescopes in heliocentric orbit. Future major telescope facilities are almost all intended to be located at Earth-Sun Lagrange points. We can't dig holes and pour concrete at those places, but we don't need to. Free-space stabilization, telescope tracking, and flight operations are done with proven technology, much of which is off-the-shelf. Although low Earth orbit is a thermally challenging place—

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discussion: What does the Moon offer that is not already achieved with Earth- or space-based telescopes?

The most obvious advantage of a lunar observatory site is one shared with many space-based instruments, a continuously visible sky with an unlimited spectral window. But what the Moon offers uniquely is a surface—or more precisely, a solid surface.

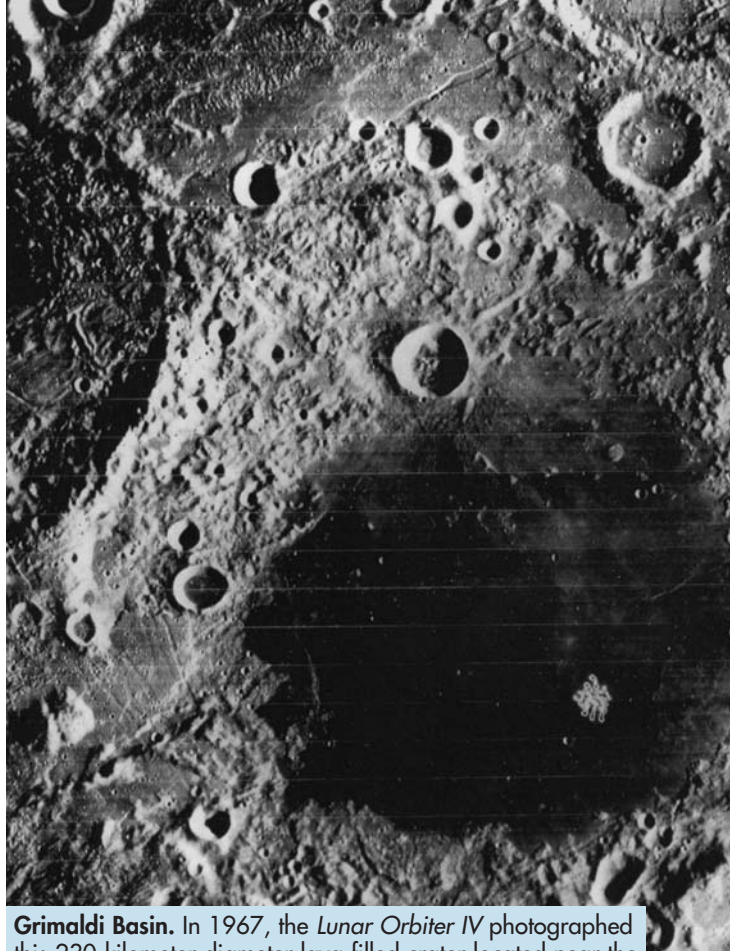
For decades astronomers have recognized the Moon as an ideal site for optical and submillimeter interferometry. Recently, however, some have proposed plausible concepts for space-borne interferometry, such as the free-flying *Terrestrial Planet Finder* and the rigid-beam *Space Interferometry Mission*. These concepts face formidable technological challenges, such as keeping the distance between telescopes constant to within a fraction of a wavelength of visible light. Earth-based interferometry has overcome that problem through fiber-optic links. Seven of the Mauna Kea telescopes, for example, are now joined by fiber optics in the OHANA (Optical Hawaiian Array for Nanoradian Astronomy) network. Baselines of up to 800 meters separate those telescopes; that's far longer than even the most ambitious space-borne interferometers. Lunar telescopes could similarly be linked to form kilometer-length interferometric networks.

The second advantage of a Moon-based observatory is that it would offer far more observing time than any Earth-based one not located at the poles. The term "time allocation" will be familiar to anyone proposing to use a large telescope. Any Earth-based telescope with access to most of the sky, such as the Keck or the paired Gemini North and Gemini South instruments, can provide at most 12 hours observing time per day. Typically, it is much less. A Moon-based telescope located in Grimaldi, however, could provide up to 14 days of continuous observing time. Furthermore, the observation time would be subject only to instrumental malfunctions; other observational constraints, such as cloud cover, humidity, and air mass, would be nonexistent, given the Moon's black sky.

The question of observing time, or telescope time, is more complex, though, as space-based instruments at Lagrange points can also provide almost unlimited access to any point in the sky for as long as desired. Even the *HST*, in low Earth orbit, provides spectacular deep-sky images by combining those from many orbits of observation. But telescopes on the Moon can provide more observing time than any Earth-based ones, other factors being equal, and almost as much as those provided by Lagrange-point telescopes.

To illustrate the issue of observing time, here's a bit of over-simplified arithmetic. A telescope on Mauna Kea can operate for no more than 12 hours a night. That adds up to 336 hours of observing time for a 28-day month, given perfect observing conditions. A similar telescope at the GRO would provide 672 hours of total observing time for the entire sky. The 14-day lunar rotation period would cut that down to 336 hours for any one celestial object. But the total observing time from the GRO would be much more than twice as great as that from Mauna Kea because of weather and other observing-condition constraints. The great increase in potential observing time would enormously expand opportunities not only for professional astronomers, but also for students and amateurs. Small amounts of time for such non-professionals have occasionally been provided on the *HST*, but the GRO would make much more time available.

The surface environment of the proposed GRO is a familiar and technologically benign one. The problems of operating on the lunar surface—the presence of lunar dust, in



Grimaldi Basin. In 1967, the *Lunar Orbiter IV* photographed this 230-kilometer-diameter lava-filled crater located near the Moon's equator. The reflectivity difference between the basin's lava and the Moon's surface accounts for Grimaldi's black appearance. The white feature in the crater is a photo-processing flaw. (Photo from the *Digital Lunar Orbiter Photographic Atlas of the Moon*, http://www.lpi.usra.edu/resources/lunar_orbiter/.)

particular—during the Apollo missions are well known. The 14-day lunar night of the GRO site is another problem. However, I can also cite the record of American and Soviet lunar landing missions, robotic and manned, of which there were dozens. Of the US's seven Surveyor missions in the 1960s, five were successful; the two failures were caused by in-flight problems, not landing ones. (The Surveyor television systems, incidentally, carried out many rudimentary astronomical observations, producing images of the solar corona, the zodiacal light, and Earth-based lasers.) For many months in the 1970s the USSR operated two robotic rovers, the Lunokhods, and even had successful robotic sample-return missions—two achievements the US has yet to match for the Moon.

The Apollo missions have been well described in the literature, though it should not be forgotten that *Apollo 16* astronauts successfully emplaced and operated George Caruthers's UV camera, the first true lunar telescope. Less well described are the Apollo Lunar Surface Experiment Packages, complex geophysical instrument arrays left behind on the Moon. Nuclear powered, the ALSEPs operated for years until turned off for budgetary reasons. One ALSEP component, the lunar laser retroreflector arrays, is still operational in that Earth-based observatories in the US and France are still receiving usable reflections.

The presence of dust was a major problem for all Apollo missions that followed the two-hour *Apollo 11* lunar-surface

excursion. The lunar regolith is composed largely of angular agglutinate fragments formed by billions of years of meteoritic impact. This regolith can only form from particles in the absence of atmosphere; it is significantly different from volcanic ash. As the Apollo astronauts found out, lunar dust quickly saturates space-suit fabrics and abrades surfaces.

However, robotic missions did not encounter those problems. Moreover, the lunar dust obviously has not obscured the lunar retroreflectors—unprotected optical surfaces—even after three decades. More informative is the experience from the *Apollo 12* mission, in which astronauts Charles “Pete” Conrad Jr and Alan Bean retrieved components from the *Surveyor 3* spacecraft that had been on the Moon for 31 months. On exhaustive study back on Earth, components such as the *Surveyor* TV camera were found to be essentially functional. Some dust had been deposited from the *Surveyor 3* and *Apollo 12* descents, but researchers concluded that “‘lunar transport’ was relatively insignificant, if evident at all.” (See NASA Special Publication 284, *Analysis of Surveyor 3 Material and Photographs Returned by Apollo 12*, 1972, page 28.) For manned missions the lunar-dust problem should not be minimized. But for robotic programs such as the GRO, it is demonstrably one that can be planned for and overcome.

The GRO would be located on the mare material, basaltic regolith that fills the Grimaldi Basin. Now-historic lunar missions, Ranger and Surveyor in particular, found that such a location would be a familiar environment. US Geological Survey scientists, in particular the late Eugene Shoemaker and his colleagues, found that the population of small craters and the size distribution of particles are essentially identical on all mare surfaces. This means that the lunar regolith was formed by a steady-state process that reflects billions of years of meteoritic bombardment. To put it simplistically, when you’ve seen one mare site, you’ve seen them all. So I do not hesitate to say that a robotic mission to Grimaldi could be scheduled with no precursor missions at all.

Moon-based astronomy has been dismissed in recent years because of the perceived cost. This misconception, I have found, comes from the assumption that astronomy from the Moon requires astronomers on the Moon. I plead guilty to promoting this mistaken assumption with my fictional account of a human observatory complex with dozens of people living in a biosphere-like structure (*Sky and Telescope*, September 1992). The GRO outlined here is, I hope, a much more realistic concept. It could operate much like the Mauna Kea instruments, which are manned by a few hardy astronomers while most of the staff sits comfortably in Hilo or Waimea with no need for supplemental oxygen. With 21st-century robotic technology, even the few hardy astronomers would stay on Earth.

Costs of a lunar robotic observatory are hard to estimate. Based on cost estimates for two multipurpose robotic lunar missions proposed in the 1990s by the University of Hawaii and the University of Wisconsin, each under a cap of \$150 million, I estimate that three robotic lunar missions carrying only astronomy-related payloads could be flown even now for about \$300 million. Furthermore, once landed, lunar telescopes could be turned off should budget cuts require it, and then easily reactivated later; they will not go anywhere. By comparison, the cost for new Earth-based instruments is several hundred million dollars, and the *James Webb Space Telescope* costs are estimated to be \$4 billion. So cost comparisons should not be used to argue against Moon-based robotic astronomy.

In summary, astronomy from the Moon appears to be a concept whose time has come again, and one that deserves a careful second look.

Further reading

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spacecraft there pass quickly through Earth’s shadow—the 30-year-old technology on the *Hubble Space Telescope (HST)* provides continuous tracking

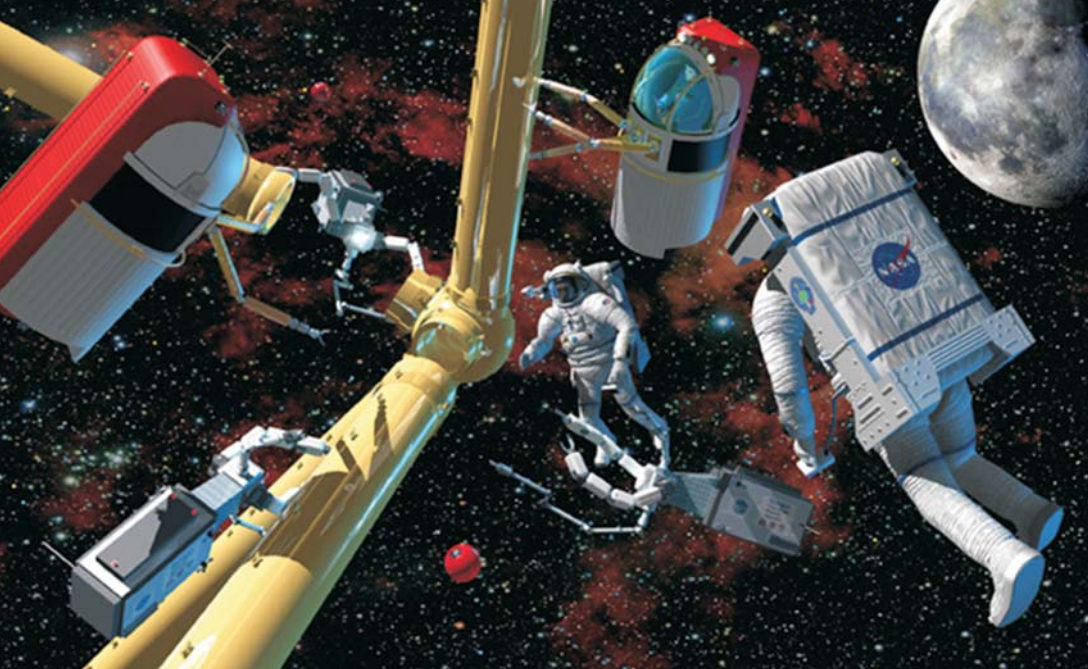
to within 2 milliarcseconds, an accuracy superior to that achieved on the ground. Residual torques and forces at more distant places in space are vastly lower.

Astronomers have touted the Moon’s seismic quietness as an advantage for telescope pointing, but it doesn’t come close to that of free space. For sky-background-limited IR telescopes, which must be cold, the quasi-stable second Earth–Sun Lagrange point (Earth–Sun L2, about 4 lunar distances beyond Earth) is a remarkable place and advantageous compared with lunar polar craters. With Earth, the Moon, and the Sun all in roughly the same direction, lightweight and easily deployable shields at L2 provide passive cooling to temperatures of a few tens of kelvin. The *James Webb Space Telescope (JWST)*, now under construction and destined for Earth–Sun L2, will operate in this way below 40 K. Moreover, facilities there have abundant solar power and continuous line-of-sight communication with Earth.

Moon-based astronomy used to be a broadly compelling idea, advanced by visionaries and strategic thinkers such as the late Harlan Smith, with whom I had the privilege to work closely. But it is precisely because our technology has advanced so dramatically that Moon-based astronomy is no longer that compelling.

Dust may be a major limiting factor for lunar-surface operations because it poses a daunting challenge to the performance of precision optical, electrical, and mechanical systems. The razor-sharp lunar grains are highly abrasive and adhere electrostatically. Apollo astronauts were surprised at the dust’s clinginess and the difficulty of keeping anything clean. Dust can be expected to cause problems on all mechanical interfaces, especially seals and bearings. Our astronauts struggled with those problems after just a day on the lunar surface. Although it was originally assumed that meteoritic impacts would distribute dust gradually and sporadically, the situation is more perilous. Lunar-surface operations, such as ascent and descent propulsion, surface transport, and the excavation of dust, rock, and grit, would disperse grains on broad ballistic trajectories.

Even undisturbed, the natural lunar environment harbors a tenuous atmosphere of submicron dust that is lofted electrostatically as a result of photoelectric charging from UV light. The grain density in these “dust fountains” is not yet well known, but the phenomenon is not subtle. Apollo command-module astronauts saw with their own eyes the



For the largest space telescopes that we envision, in-space operations by both humans and robots may enable a leap in astronomical capability. In this artist's rendering, humans and robots assemble trusses for such a space telescope at an Earth–Moon Lagrange point, L1. The telescope might subsequently be deployed to an operations site at another location, Earth–Sun L2. Such in-space activities have more potential for astronomical discovery beyond the Moon than do lunar-surface activities. (Image courtesy of John Frasanito and Associates.)

scattered sunlight from dust plumes at heights well above their orbital altitude. Even primitive cameras on the Surveyor and Lunokhod landers detected what was termed horizon glow from the levitated dust, as did the *Clementine* orbiter later. Deposited on optics, the dust would compromise the imaging performance and increase the emissivity of telescopes looking for extrasolar planets. That emissivity would add background noise to thermal IR measurements. No such pollutant is found in free space.

Some people counter that we're going to the Moon anyway. We're going to have people based there, and we can use them! But this is not a humans-versus-robots issue. With due respect to critics, many scientists and engineers believe that human spaceflight may actually offer some important opportunities for astronomy, and it would be premature to dismiss those opportunities outright. The continuing astonishing performance of the *HST* has depended, for example, on maintenance and upgrades from astronaut visits. As we look ahead to very large space telescopes that cannot fit in a single launch vehicle, "some assembly required"—perhaps by gloved human hands or by sophisticated robots—is likely to become a common theme. Given almost two decades of servicing missions to the *HST*, the engineering successes of the continuously occupied International Space Station, and the fact that astronauts must travel through free space to reach the Moon in the first place, it is surprising that accessibility by humans is often cited as an advantage somehow unique to the lunar surface.

Placing telescopes near lunar bases is particularly risky, even beyond the problem of dust contamination. Permanently shadowed lunar polar craters have been proposed as homes for passively cooled IR telescopes, but any large-scale development will depend on resources that are found there. For example, discovering water-ice deposits would drive lunar polar development strongly. And such deposits would be found in the same permanently shadowed craters used to host telescopes. Mining activity would not only kick up debris, but likely boil off significant amounts of condensed gases, for which a nearby passively cooled telescope becomes a cold trap.

Free-space telescopes offer advantages over lunar-based ones in design and deployment. Although lunar gravity is only a sixth of that on Earth, pointable telescopes on the Moon will still have to contend with gravitational deformation and the resulting optical misalignment. To be sufficiently

stiff, surface telescopes must therefore always be heavier than free-space telescopes. Furthermore, lunar gravity requires substantial propulsion for spacecraft to land softly. That adds significant cost and risk. Moreover, although the lunar surface is seismically quiet, it is not particularly flat, and surface irregularities would complicate deployment and alignment of precision optical systems. The management of an in-space assembly depot, in contrast, would require careful navigation and special tools, but the zero-gravity environment would offer telescope builders some convenience in manipulating massive parts.

Given that a free-space environment can, in those many respects, offer higher performance than the lunar surface for astronomical instruments, how can we make best use of human perception, intelligence, and dexterity there? For astronomical telescopes operating in a low Earth orbit, the *HST* exemplifies one scenario. The crew exploration vehicle—a key component of the Vision for Space Exploration architecture—will have straightforward access to such an orbit, much like the space shuttle. For assembly and deployment of very large telescopes, however, especially those destined for the Lagrange points, a low Earth orbit is not a particularly useful venue. The residual atmosphere there imposes a drag on large lightweight systems.

Humans could, in principle, travel to the Earth–Sun Lagrange points to assemble, deploy, or service telescopes, but such travel might be more appropriate for a Mars-faring program than a Moon-faring one. Orbital dynamics offers some useful tricks, however. The Earth–Moon L1 point, about 84% of the way from Earth to the Moon, is energetically close to the attractive Earth–Sun Lagrange points. A minuscule change in velocity of several tens of meters per second—basically just a swift kick—connects them. Consequently, only a small amount of propulsive power would be needed to move large facilities between an Earth–Sun Lagrange point and the Earth–Moon L1 point, where telescopes could be assembled and serviced. Earth–Moon L1 would be a waypoint for Moon-bound ships and thus easily accessible to missions developed to support lunar-surface operations.

This vision of future in-space operations is one in which the architecture required to return humans to the Moon can be modestly augmented to achieve priority goals in free space. The architecture includes not only the astronaut-supporting crew exploration vehicles, but heavy

lift launchers and sophisticated space robots. A team of scientists and engineers is currently assessing options and concepts for harnessing such capabilities.

A basic tenet here is that the surface of the Moon is valuable for what it truly enables, and should not be used for what can be done better in free space. What the Moon offers is rocks, grit, and gravity. None of those are widely useful for astronomy.

Nevertheless, gravity can perhaps serve certain niches. Roger Angel of the University of Arizona has proposed a novel rotating liquid-mirror telescope with a large light-collecting aperture. It needs gravity to shape the liquid mirror into a light-focusing parabola. To the extent that a zenith-pointing space telescope is a high priority for astronomers, and to the extent that such a telescope can be built and operated more easily on the Moon than a similarly large one in free space, the concept is worth considering.

The Moon's rocks and grit can similarly be exploited for astronomical observations. Continuously shielded, the far side of the Moon offers electromagnetically quiet sites that could host a sensitive radio telescope. To assess the idea's utility, astronomers must weigh the tradeoffs among advanced shielding, interference rejection, and facilities constructed much farther from Earth. For optically linked telescope systems, the lunar surface has been promoted as a stiff optical bench for a large-baseline interferometer. To the extent that formation-flying spacecraft, which would allow much more baseline flexibility and better thermal control, cannot serve this need, the concept should be considered. Design studies of formation flying for the *Terrestrial Planet Finder*, *Life Finder*, and, in the nearer term, *Laser Interferometer Space Antenna* mission concepts, however, make astronomers optimistic that precision fringe tracking for such large-baseline free-space interferometry is achievable. Finally, researchers have proposed ideas for cosmic-particle detection using energy deposition in the lunar regolith.

In a destination-driven space program—from the Moon to Mars, for example—it is tempting to consider opportunities that are limited to the destinations themselves, with an observing site defined as something with rocks, grit, and gravity. But that limits our options. To the degree that lunar exploration is a national priority and accordingly requires an investment in mission architecture, astronomers should look for opportunities in that architecture as well as in the destination. Many of us in astronomy believe that within that architecture, opportunities can be better found in free space than on the lunar surface.

Further reading

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Lowman replies to Lester

I agree with much of Dan Lester's article, and share his respect for the late Harlan Smith, with whom Mike Mumma and I worked to organize our 1990 "Astrophysics from the Moon" meeting. I offer the following reply.

First, Lester greatly overstates the lunar-dust problem. The Apollo instrument complexes operated for years with little if any problem from dust. Indeed, the laser retroreflectors left there are still reflective. The instrument complexes included a dust-detector experiment on *Apollos 11, 12, 14, and 15* to measure possible accumulation from the lunar module liftoff. The accumulation proved much lower than expected. The *Surveyor 3* TV camera, returned after 31 months on the Moon, showed some dust deposited by the module, but investigators concluded that natural dust transport was "relatively insignificant, if evident at all." The long survival of natural lunar albedo features, such as the 100-million-year-old Tycho ray system, bears out the same conclusion.

Second, Lester barely mentions the long-advocated use of the Moon for interferometry. Optical and submillimeter interferometry is the leading edge of Earth-based astronomy, with 800-meter fiber-optic baselines that link seven telescopes on Mauna Kea. Space-based interferometry, in contrast, is years from being demonstrated, and the free-flying *Terrestrial Planet Finder* has been deleted from NASA plans. The rigid-beam *Space Interferometry Mission* will have only a 9-meter baseline using two 0.3-meter telescopes.

In summary, I think telescopes on the Moon are still not only feasible but potentially valuable.

Lester replies to Lowman

The Moon can serve as an interferometric optical bench, as Paul Lowman argues in his essay, but free space allows astronomers to build a large synthetic aperture for interferometry using just a few maneuverable spacecraft. Maneuverability is hard on the Moon, where redeploying precision instruments entails moving heavy parts over irregular surfaces. Radio interferometry is well established in space, and kilometer-scale (or shorter) wavelength implementations using fringe trackers and perhaps tethers are considered achievable.

To argue that a lunar observatory gives more observing time is a red herring. Lowman estimates slightly more observing time from a Moon-based telescope than from its Earth-based counterpart. However, because the cost of the former is orders of magnitude greater than the latter, the cost per observing hour on the Moon is vastly higher than it would be on Earth. A hundred terrestrial telescopes provide more access value. Moreover, observatories on any surface offer less access to the sky than those in free space.

Lowman's comparison of tiny lunar telescopes to the National Research Council's priority *James Webb Space Telescope* and the largest terrestrial telescopes is misleading. An "aperture in a suitcase" is less expensive than telescopes measuring meters in diameter. However, it's much less productive and has many more challenges—among them bimonthly thermal shocks, the expense of landing fragile systems, and pervasive lunar dust—than one based in space. Comparably capable lunar telescopes are likely to be much more expensive than those designed to operate in free space anyway.

The golden age of astronomy we now enjoy was born by precisely those technologies that obviate the need to place telescopes on the Moon. ■