

Introduction: A variety of different types of lunar observatories have been proposed over the years and a long list of potential advantages/disadvantages over terrestrial sites has been compiled [1, 2, 3, 4]. Regardless of the type of observatory being considered, one of the most important first steps will be a thorough site survey of the proposed lunar location. Small spacecraft equipped with high resolution cameras, such as the Descent-Panoramic Camera used on the SMART-1 mission conducted by the European Space Agency, can provide some of the information required. However, the level of information required to select the optimal site for a lunar observatory requires a dedicated small spacecraft that can evaluate the site in significant detail, providing input to enable a precision landing and a determination of the dust effects at this location.

Here we offer thoughts which arise from potential gaps in planning and from the more in-depth understanding of lunar and interstellar dust obtained over the past decade. First, the notion of a site survey in the context of lunar exploration is now expanded from that of traditional site surveys for astronomy. In 1990 at the Astrophysics of the Moon conference in Annapolis, studies focused on the astrophysics one could do from the Moon, and so the site selection and environment issues were aimed towards the particular astronomical question and type of astronomy being considered. Today, we are driven to the Moon primarily to explore. Here we need to know more than the physical conditions at the site where astronomy might be done, because we are investigating the lunar surface for other non-astronomical opportunities as well. For instance, the radio-quiet environment of the lunar far side is speculated as a real advantage for astronomy at radio wavelengths, and therefore a focus on the far side of the Moon is necessary to address the degree of quietness for radio telescopes. However, other issues will need to be addressed in terms of how to get from one point to another on the lunar surface if humans and machines are to establish a long-term presence, and so we might design a small satellite mission to sample the radio quiet environment while at the same time investigating some other component of the lunar far side that will be necessary for human bases.

Lunar Observatories: There is vigorous and ongoing debate within the scientific community over the advantages and disadvantages of conducting astronomical research from the Moon [1, 2, 3, 4]. The absence of a substantial lunar atmosphere has long tanta-

lized astronomers, particularly at optical wavelengths. However, the extent to which lunar dust may scatter light at optical and ultraviolet wavelengths, or introduce added thermal effects at infrared wavelengths, remains unknown. The ultimate answer(s) on the conditions and suitability of the lunar surface for astronomical purposes will not be known until we go there with the express purpose of investigating this question. In this sense, the Moon is no different than the South Pole or the high Atacama plains. Before investing substantial resources in building and operating astronomical instruments, it behooves us to assess the quality of the site and to understand the technical challenges in building and commissioning astronomical instruments on the Moon.

“Peaks of eternal light” in the lunar polar regions are gaining increased scrutiny as potential sites for human outposts. These mountaintops, surrounded by permanently shadowed craters, are bathed in permanent solar illumination. These locations thereby offer an ideal mix of constant solar energy on the peaks and potential water ice in the deep craters. From an astronomical perspective, the poles offer a zenith view fixed on the sky along the (lunar) spin axis. Thus, a zenith (or transit) telescope design makes it possible to consider larger apertures with fewer structural movements. Such a telescope would provide very deep integrations, with no telescope steering, for high sensitivity studies of the distant universe.

Furthermore, small (0.5 – 1 m) telescopes are well within the capability of the larger of our small lander proposals (a few tens of kilograms) for small satellite missions. Small 0.5 - 1.0 m telescopes and other components—which would serve as the evolutionary building blocks for a more powerful lunar observatory—could be suitably delivered via small landers carrying a few tens of kilograms each. Conducting science with small satellites requires one to embrace a mission philosophy of rapid development timescales and the potential use of commercial-off-the-shelf technologies. Such schedule compression and use of heritage makes it possible, with modest funds, to implement a series of low-cost small satellite launches as often as every six months. Thus small spacecraft missions using existing capabilities could serve the build-up of such an observatory as a first step after a successful site survey. A thorough study of the Moon will require a coordinated remote and on-site sensing program (and perhaps sample return activities). A notional concept for a lander with a <10 kg payload would determine the sky brightness at optical and infrared

wavelengths, determine the dust environment through deployment of a liquid test cell, incorporate fish-eye visible-light cameras, and a radiatively cooled mid-infrared zenith camera. NASA's Ames Research Center, in cooperation with NASA's Goddard Space Flight Center, is formulating a series of low-cost lunar orbiters and landed probes that will facilitate lunar exploration and development.

While geo-ranging laser data using retro-reflectors emplaced by the Apollo astronauts suggest that the mirrors have not been severely compromised by dust accumulation, other indicators suggest the accumulation could be seriously detrimental (e.g., the Lunakhod solar panels), and in any case the relevance of the data near the poles is unknown. Given what we now understand about extraterrestrial dust samples from a variety of sample return missions, it is clear there is much to learn about the size, shape and composition of lunar dust and that it may vary with location. The relative "stickiness" of the dust should be evaluated to assess the interaction with construction materials of different types. Small satellites can play a vital and cost-effective role in conducting site surveys of possible telescope sites, especially near the lunar poles which seem to provide added advantages (such as peaks of eternal light near well sheltered and possibly ice-containing craters). In particular, some of the experiments described earlier in this paper could lay the foundation for researching the effects of levitated dust on telescope optics and mechanical systems, as well as data to assess the site quality for astronomical background sensitivity.

Lunar Transit Search: The Moon can serve as an ideal location to base a long-lasting extrasolar planet transit search system. Without the extinction and scintillation effects of an atmosphere, we can achieve shot-noise limited photometric precision, allowing a small (~10 cm) lens to detect Earth-sized planets around 7th magnitude stars. In addition, the lack of scattered light from an atmosphere removes the observing constraints caused by the day-night cycle on the Earth. A photometer with a 30 degree field-of-view can observe the same stars continuously without any tracking system for two days per lunar month looking at zero degrees latitude and 3.2 days per month looking at 45° latitude. Over the course of the month, the photometer at 45° will cover 20% of the whole sky, or about 7,500 square degrees, in which there are around 5,000 stars brighter than 7th magnitude. The photometer looking at zero degrees latitude covers nearly 40% of the sky, but has the added complication of avoiding the Sun. If pointed towards the lunar pole, 1000 square degrees of sky could be observed, most of it continuously, allowing for the detection of planets that are smaller and/or in longer-period orbits than possible for pointings at

lower latitudes. Thus, cutting edge science could be accomplished regardless of what latitude on the lunar surface was selected for this test station. A simple, robust system could be built with no moving parts, simple optics, and a single CCD camera. The data recording and transmission requirements could be minimized with on-board image compression and analysis.

Such a photometer would also be an excellent way to measure dust accumulation. A reflective object, e.g., a white vertical stick, could be located in the field-of-view in order to monitor the changing reflectance as a function of altitude as dust accumulates on the pole. Dust accumulation on the lens would also be measurable through the dimming of the ensemble of stars with time.

Conclusions: The Moon could offer great astronomical science opportunities. Lessons learned from other remote sites, such as Antarctica, suggest beginning with site surveys and then small remotely operated facilities before mounting major initiatives. Small robotic spacecraft, both in orbit around the Moon and on the surface, offer exciting and affordable near-term opportunities to begin. In general, soft lander automated observatories are much cheaper than large scale observatories that require human operation and set-up. Free flyers appear to be even more affordable-unless substantial infrastructure is already in place for non-astronomical purposes.

The infrastructure established for lunar surface activities will open new gateways to astronomy by virtue of the creation of new capabilities such as the heavy life launch vehicle that might be used to deploy a 50 m telescope in free space. The extensive communication/navigation satellite system necessary for a safe and effective human presence will also enable data transfer and in-situ measurements to be conducted robotically.

Whatever steps taken in the roadmap we follow as we explore the Moon, we would do well to follow the admonition given by Harlan Smith in 1990 with regard to lunar astronomy: to follow an "evolutionary" rather than "revolutionary" approach. In his words, "establishing one or more great lunar observatories, but outfitting them at the beginning with, and continuing indefinitely with the addition and use of small and low cost telescopes each dedicated to a specific function, virtually all of them operated from the earth, while building up over several decades to ever larger and more powerful instruments."

References: [1] Burke, B.F. (1990). *Science* 250, 1365. [2] Mumma, M.J. and Smith, H.J. (1990) *Astrophysics from the Moon*. AIP Conf. Proc. 207. [3] Lowman Jr., P.D. (2000). *Mercury* 29, 31. [4] Lester, D.F. et al. (2004) *Space Policy* 20, 99.