COST CONSIDERATIONS FOR ASTRONOMY AT A LUNAR BASE. E. Friedman, D. Ebbets, S. Kilston, Ball Aerospace & Technologies Corp., PO Box 1062, RA4, Boulder, CO, 80306-1062 efriedma@ball.com

Introduction: The Vision for Space Exploration includes a lunar component that may result in frequent landings and the establishment of infrastructure at one or more sites. Lunar bases could be used as scientific stations with astronomical telescopes being some of their clients. In this paper we use our knowledge of space systems to suggest services that could be provided at a lunar base that could lower the direct cost of the scientific payload. We think that transportation costs are a major factor, so an important aspect of the cost trade may be how the costs of departure from Earth, landing on the moon, and deployment to the operational site are accounted for.

Free-space vs a lunar base: In many cases observations could be made either from the surface of the moon or from an observatory in free space, and justification will be needed for the selected approach. Technologies for operating astronomical observatories in free space have become mature, and the availability of Earth orbit or heliocentric orbit adds flexibility and performance benefits. The lunar exploration architecture may provide access to another venue. While the moon will not be ideal for all astronomical applications, it will be acceptable for many, and may be preferable for some. Table 1 summarizes our initial assessment of the relative merits of free-space and the lunar surface.

Science Performance vs. Location

LEO = Low-Earth Orbit
HEO = High-Earth Orbit
SO = Solar Orbit

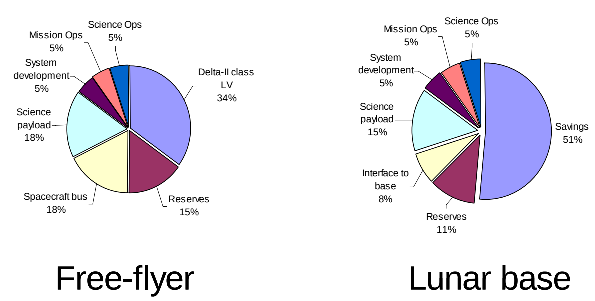
	Space			Moon			
	LEO	HEO	SO	Mid-Lat	Polar	Dark	Far Side
Sun–Earth & space weather	3	2	1	2	3	2	3
Extrasolar planets, imaging	3	3	1	3	3	1	3
Extrasolar planets, interferometry	3	3	1	3	3	1	3
Earth imaging (& weather, climate)	1	1	1	1	2	3	3
Solar imaging	2	1	1	2	1	NA	2
Planet imaging & spectroscopy	1	1	1	1	2	3	2
General optical astrophysics	1	1	1	2	1	1	2
Non-imaging spectroscopy	1	1	1	1	1	1	2
Astrometry	1	1	1	3	3	2	3
Particle / cosmic ray physics	2	1	1	1	1	1	1
Gravity wave science	3	3	1	3	3	3	3
Submillimeter-wave imaging	3	3	1	2	2	2	1

1-ideal location **2**-possible, somewhat limited **3**- possible, highly limited

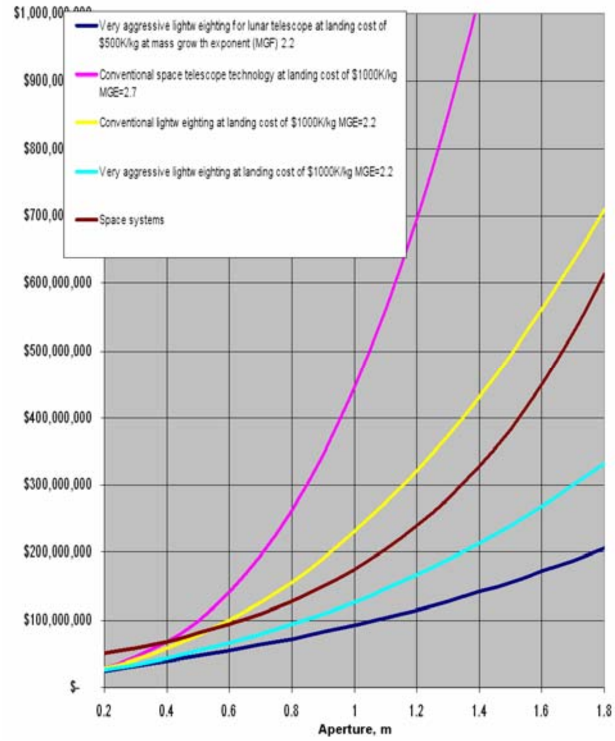
Cost Elements: Would a space observatory designed to enable a particular scientific investigation be less expensive to implement as a free-flyer or at an established lunar base? Many of the costs of a space observatory will apply either way. For simplicity we will assume that the science instruments, including optics, detectors and software are equivalent, and that the scientific productivity of the space and lunar telescopes would be about the same. Costs of design, development, integration and testing, operations, data management and science team support will be similar. Both approaches will require some structure, thermal control, electrical power, stray-light baffling, radiation protection, communications with the earth etc. A free-flyer may incur higher costs for propulsion, navigation, station-keeping, and possibly more requirements on reliability and redundancy. An observatory at a lunar base will incur costs for site preparation, survival of landing loads, surface transportation, a stiffer gravity-bearing structure, dust mitigation, astronaut safety, and provisions for future augmentations or repairs.

Figure 1 shows notional distributions of costs for a medium size astronomy mission, comparable to a MIDEX explorer with a total cost near $200M. The launch vehicle and spacecraft bus account for roughly half of the mission cost. If the accounting were such that payloads could be delivered to the lunar base with significantly lower launch costs charged to the science budget, and if the utilities such as power and communications were made available for less than the cost of the bus, then the apparent cost of an instrument at a lunar base could be lower than a free-flyer with similar scientific capabilities. Of course, these costs will still exist and will need to be accounted for somewhere.

Notional costs for a small observatory



The value of lightweight optical systems: Landing a payload on the moon is expensive. Costs in the range of $500K to $1M per kilogram are often discussed. The mass of an optical system is a steep function of aperture size, scaling as a power of the diameter with an exponent often near 2.7. Large, i.e massive systems will be very costly to emplace on the moon, and may be less expensive to implement as free-flyers. However, if the landing costs continue to scale with mass down to small systems, there may be a regime in which the lunar option is competitive, or even cheaper. Figure 2 shows an attempt to compare costs for modest aperture telescopes in free space and at a lunar base. For telescopes with steep scaling of mass vs aperture, and for the higher range of transportation costs the lunar option is more expensive for any size telescope. For aggressive light-weighting technologies (where the mass scaling factor is 2.2 rather than 2.7) and significantly reduced transportation costs the lunar case may be less expensive than a free-flyer even for 2m apertures. For intermediate cases, assuming a mass relation somewhat more favorable than that possible today, and



transportation costs near the lower end of the range, costs may be comparable for telescopes near 1 m aperture diameter. If more careful analysis supports this impression, we may conclude that small astronomical missions, with SMEX or even MIDEX-class telescopes, may be cost-effective to place at a lunar base. To achieve this result, investments must be made to finance technology developments that enable lower mass systems, management of dust and its effects, lower transportation costs, and lower costs of basic utilities. Successful implementation would give the lunar base option a greater cost advantage, and may push the break-even point to larger aperture telescopes. It is also true that some of the technologies will be developed to accommodate other lunar bases, particularly those associated with human outposts. Thus, the cost of technology development specifically for enabling telescope science may be lower than would be the case if the human bases were not also present.

Conclusions: 1. The moon provides a favorable location for many, but not all, types of investigations of interest to space astronomy. The choice between free-flyer and lunar base will need to be made judiciously for each mission. 2. Spacecraft utilities comprise roughly 20% of a mission cost. A lunar base might provide services to a number of payloads with a common installation. Electrical power, communications with Earth, centralized data management, some aspects of thermal control, maintenance and repair services are examples. 3. If the expense of developing the infrastructure is borne entirely by the science community, there will be large costs and much time invested before any science return, not a favorable situation. If establishment of facilities is paid for as part of the larger exploration initiative, or if the costs to science are amortized fairly over many missions, the return on investment might be worthwhile. 4. Transportation costs are a significant factor. The launch vehicle for a space mission is often 1/5 to 1/3 of the total cost. Additional costs for landing and surface operations may make a lunar base unfavorable if all costs are charged to science. 5. Launch and landing costs scale with mass. Lightweight technologies will be advantageous, perhaps essential, for enabling a lunar telescope enterprise. 6. Mass scales with aperture. Large-aperture telescopes may be cheaper in free space. Small systems may be cost-effective on the moon. A careful analysis using relevant scaling factors and cost models will be needed to locate the break-even point with confidence. 7. A significant aspect of the cost trades for free space vs lunar base appears to be related to accounting practices and policies, rather than to technical or scientific issues. When science, exploration and other activities in space are sharing national assets, who pays for what? 8. As an extension of the prior point, creation and operation of telescopes on the moon may be found to be valuable if the measures of merit are expanded from simple economics and science return; the exploitation of the persistent presence of humans and their support systems could be seen as valuable in itself as it may lead to new capabilities and skills that are seen to be valuable in the general exploration enterprise.