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# Multi-Use Lunar Telescopes

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## Philosophical and Political Underpinnings

A fundamental characteristic of human nature is to explore. In ancient times, an intrepid individual was able to satisfy his or her need for exploration in a fairly inexpensive and direct manner. The oceans were a vast open frontier – new continents lay beyond, waiting to be discovered, explored, and developed. As the centuries have passed, however, earthly frontiers, save for the ocean depths, have now been explored quite completely. The greatest frontier left to us lies above. However, exploring this new frontier requires more than the far-sighted vision and the daring of a single individual. The frontier is space, of course, and its exploration must be achieved by mankind as a whole. Any nation that intends to take the lead in this exploration must bear in mind that it is the collective body of its citizenry that forms the bulwark of that exploration. Not only will they pay for such exploration, but they must be made an integral part of this great endeavor.

In the United States of America, NASA is the clearly identifiable agency that carries the standard for the dream of exploration. In these days, the early 1990s, as we once again look towards the moon, it is important to help the public maintain focus on the relevance of our exploration goals. One of these goals is found in the oldest of the sciences – astronomy. The average man can still buy a telescope and look to the heavens and, in fact, people do so by the hundreds of thousands. No science has such a large following as astronomy. Astronomy is also the science that many youngsters first get excited about as they try to understand their place in space and time.

Therefore, as we contemplate returning to the moon, one of the most important things we can do, from the standpoint of science, society, and the politics of this endeavor, is to place astronomical telescopes on the moon that are inexpensive and accessible to both research astronomers and members of the population at large – particularly young students. This vanguard of our aggressive return to the moon would provide early and outstanding scientific returns.

We believe it is possible to create actual public involvement in science. This can be done with small robotic telescopes in the earliest phases of our return to the moon. Inherent in the design of these telescopes would be simplicity at every possible stage. The optical technology would be straightforward and historically proven. The telescopes themselves, and there would be many more than just one, would each be dedicated to a single, well defined, and achievable mission, *i.e.* would have a dedicated instrument.

One of the great advantages of small, deployable, lunar telescopes is that they can go from a concept to working systems on the lunar surface in much less than a decade. A number of such telescopes could be made highly accessible to individual researchers in the astronomical community. The format for this use could be made highly streamlined with a minimum of overhead. Individual observers, with approved programs, would be able to access the lunar telescope that met their requirements directly from their home institution via computer networks such as Internet, or through a simple modem and telephone connection. Unlike

telescopes operating in low earth orbit, the operation of multi-use lunar telescopes should not require an extensive infrastructure. It should be no more difficult for future astronomers to remotely operate lunar-based telescopes than it is for present-day astronomers to operate existing earth-based robotic telescopes. Some research programs might require extensive, on-line interaction between the astronomer and the lunar telescope (*i.e.* real-time operation); other programs might only need to uplink a "pointing list" of targets.

In calling these Lunar telescopes "multi-use" we actually have two aspects in mind. First, the same basic telescope (and supporting electronics, *etc.*) will be able to be used with a wide variety of instrument payloads – one instrument with each payload. Thus it will not be necessary to design, develop, and test a number of different telescopes. Second, we are proposing multi-use in the sense that the telescopes would be used for both research and education.

Since, under the multi-use lunar telescope concept, each telescope will have a dedicated function (photometry, imagery, *etc.*), the prospective user groups for each telescope should be fairly well-defined. Telescope time could be allocated by a Telescope Allocation Committee made up of a rotating subset of telescope users. A Principal Astronomer (PA), who would also be an astronomer/user, could serve as the primary point-of-contact between NASA and the user community. But, paramount at the outset, should be the minimization of bureaucratic overhead.

One great advantage of the multi-use lunar telescope concept is its ability to accommodate observing programs that require extended intervals of observing time – not always possible from low earth orbit. Long term programs could and should be encouraged. A large number of observers may be accommodated by using automated scheduling and prioritization with uplink of the pointing sequence being made daily.

The multi-use telescopes should be viewed not only as being a collection of telescopes with multiple dedicated purposes, but they should also be viewed as serving multiple user types. We have already mentioned the most obvious group of users – professional astronomers employing the telescopes to push out the frontiers of knowledge in their particular branch of astronomy, using capabilities which do not exist on the ground. But the application of these systems may be considerably extended beyond this with significant overall benefits.

The United States will maintain its leadership in science and technology only if there is a new generation of well-trained scientific minds prepared to take the place of their elders. If we place telescopes on the moon and do a hundred worthwhile scientific projects in the next few decades, but fail to educate the next generation of young minds to carry them forward, then we will have been remiss. In this regard the multi-use lunar telescope concept may be readily employed in several ways.

First, graduate students may be allowed, under the guidance of their major professors, to conduct research using these systems. It would be perfectly sensible for an astronomy graduate student to attack some interesting problem using a combination of ground-based and lunar-based telescopes. This, however, is an obvious use of such telescopes – to educate

the next generation of astronomers. But what of other gifted students – perhaps those who show some promise in the sciences – but are only at the undergraduate level? It would seem to make sense to set aside some fraction of time on lunar telescopes or even to provide for the establishment of a dedicated system for undergraduate education; this resource would be available to students from every state of the union. Projects could be developed and proposed, and regional and state-wide conventions and symposia could be held for the students to present their proposals. Judges, made up of a group of astronomical professionals, could select projects from every state. The students would then be allowed to carry out their research under the guidance of a professional astronomer. Not only would the student experience a great educational gain, but the prestige and honor of being selected could be highly motivational.

In addition to use by graduate and undergraduate students a limited amount of guided access could be provided for high school students – perhaps even in conjunction with the undergraduate program. Not only would this be of value to the students involved, it would clearly demonstrate a national commitment to science education. Not every state currently has a heavy involvement in the space program; however, there isn't a congressional district in the country that doesn't have a high school, college, or university in it. The average citizen-voter may find it a lot easier to be sympathetic to the goals of the space program if the high school kid who mows his grass was selected to make observations of a distant galaxy using a telescope on the moon in her senior year.

The multi-use lunar telescope concept, if kept simple, would be inexpensive enough for concerns smaller than the federal government to take on the expense of establishing one on their own. Several states might get together and fund a telescope for their universities – even an individual state. For any state, or consortium willing to fund the building of a telescope, NASA could provide the launch service.

In summary, the multi-use lunar telescope concept:

- is a good way to do inexpensive, high-return astronomy from the moon within a decade;
- is a good way to learn how to do astronomy in the lunar environment on a scale such that our mistakes will not cost too much;
- is a good way to put astronomical research from the moon directly in the hands of the astronomical community with rapid return of results;
- is a great tool for education;
- is a potentially great motivator of today's students;
- is a way of involving the whole nation in the space program in a fashion that helps them feel that it is *their* program.





## Multi-Use Lunar Telescopes

The objective of multi-use lunar telescopes is to reduce the initial and operational costs of space telescopes to the point where a fair number of telescopes (a dozen or so) would be affordable. The basic approach is to have a common telescope, control system, and power and communications subsystems that can be used with a wide variety of instrument payloads, such as imaging CCD cameras, photometers, spectrographs, *etc.* By having such a multi-use (and multi-user) telescope (a common practice for earth-based telescopes), development costs can be shared across many telescopes, and the telescopes can be produced in economical batches.

As mentioned earlier, users would themselves directly operate the telescopes from their home institutions on earth. This is already being done with earth-based fully automatic telescopes. For instance, the Fairborn Observatory and the Smithsonian Institution operate seven fully automatic telescopes at an automatic observatory on Mt. Hopkins in southern Arizona. The approximately four dozen institutions that use these telescopes operate them via modem or computer network. Only two persons, working part time, are required to care for the equipment and handle the miscellaneous paperwork. One of the users on each telescope is designated the principal astronomer (PA). The PA is responsible for resolving any scheduling conflicts that the automated scheduling cannot handle, for assuring the smooth flow of observational requests and results, and for monitoring the quality of the results. The same general approach could be taken to the operation of telescopes on the moon.

The moon provides a solid and highly stable platform for the telescopes to operate from, obviating the need for an expensive space stabilization system. These multi-use lunar telescopes could be placed on the moon either by a soft lander, such as the proposed Common Lunar Lander, Artemis, or taken as part of the cargo manifest to a manned lunar outpost. If taken to the moon by a soft lander, we have assumed that power and communications would have to be a part of the multi-use lunar telescope, while if taken to a manned lunar outpost, power and communications could be provided from the outpost. This would, presumably, lower the cost per telescope.

The Common Lunar Lander, Artemis, is a concept developed by Stephen Bailey, Alan Binder, and others at the Johnson Space Center. A conference on Artemis was held in July, 1991, and a summary is available from Stephen Bailey.

We have assumed that the most constraining size and weight requirements would be the case where a single telescope and attendant power and communications capabilities along with a lunar lander were carried by a Delta II launch vehicle. This vehicle provides a payload capability (after allowing for the lunar lander) that in size is about 90 inches in diameter and 137 inches in height (assuming the telescope were pointed straight up at launch), and in weight is about 440 lbs. (200 KG). As will be suggested, we believe that a 1-meter class aperture telescope may be accommodated within these constraints, and a 0.8-meter (32-inch) telescope almost certainly could be.

## Scientific Requirement

From a scientific perspective, what is proposed is a 1-meter or smaller multi-use lunar telescope, along with attendant control and, in some cases, power and communications, that would accept a wide range of astronomical instruments. With the appropriate instrumentation modules, we envision such telescopes being used for the following purposes.

General purpose imaging and area photometry in the UV, optical, and near IR. This could be done with the same CCD camera on the same telescope, although separate cameras might want to be considered for widely different spectral regions. With diffraction-limited optics and absence of an atmosphere, such a system would compare very favorably with the current HST, would be much more accessible for use (as there would be more of them) and, at some lunar locations, would provide continuous coverage for months on end if desired.

High precision aperture photometry in the UV, optical, and near IR regions of the spectrum (again perhaps with the same instrument module on the same telescope or, more likely, with different detectors for different spectral regions). Such high-precision photometry could reveal fine details (at the sub milli-magnitude level) of microvariability in stars, active galactic nuclei, quasars, *etc.* Such high-precision photometry could also be used to detect earth-sized planets transiting other stars.

UV spectroscopy similar to the IUE, but with a much larger aperture and modern instrumentation. This would not only significantly increase the limiting magnitude (and hence access an order of magnitude more objects), but it would improve temporal resolution and, with its greater capacity, serve an even larger number of users.

Narrow field-of-view imaging of planets, the sun, and other solar system objects. The secondary mirror for this system would be different than in the other systems to provide a much longer effective focal length. These objects could be frequently monitored at very high resolution.

While many other applications are possible (such as polarimetry, *etc.*), we mention just one of these other applications as a matter of interest and variety. This is IR imaging and area photometry, including the far IR. In this region of the spectrum it is not only necessary to cool the detector and filters, but also the entire telescope. If one of the multi-use lunar telescopes were soft landed in a lunar crater near one of the moon's poles, it has been suggested that the entire telescope would cool to about 40 Kelvin, making it suitable for many IR applications without the need for the sort of helium-filled jacket that was required for IRAS (and which eventually ran out of the helium coolant).

## Multiple Instruments

Single telescopes can, of course, be equipped with multiple instruments. The HST, for instance, is equipped with five different instruments. However, if one has a number of multi-use telescopes in operation, it may be more effective to equip each one with a single instrument, making each telescope dedicated to a single (but widely utilized) form of astronomical observation. If one has only a single telescope, such as the HST, then it makes sense to equip it with many instruments. However, if one has many telescopes available, then it would be more efficient and considerably lower in cost to equip each one of them with only one instrument.

A case can be made, however, for equipping each telescope with a light-weight CCD camera that could be used not only for general imaging and area photometry in the UV, optical and near IR, but also for orientation of the telescope, identification of objects in crowded fields, *etc.* This would have the added advantage that should the main instrument (such as a photometer or spectrograph) fail, then the telescope could still be operated in an imaging or area photometry mode (both always in great demand). We believe this case to be fairly compelling, so each telescope would have, as part of the standard configuration, a CCD camera with appropriate filters, *etc.* In the cases where the main instrument were also a CCD camera, we presume that this camera would have a different, probably wider field-of-view.

## Lunar Locations

A primary location for operation would be a manned lunar outpost or a location very near such an outpost. Even in the case of soft-landed telescopes prior to manned re-occupation of the moon, strong arguments can be made for placing telescopes at or very near the eventual outpost location.

Major earth-based telescopes are typically utilized for 50 years (or perhaps even longer) before they are considered obsolete. Achieving such a long life requires, of course, that failed modules be replaced, but more importantly that instruments be upgraded as technology advances and astronomical research requirements change.

The main portions of the telescope (optics, mount, mechanical drives, *etc.*) might last longer than a (human) lifetime (although the effects of the lunar environment may make such components have a different life on the moon than we are used to here on earth). By making control electronics, computers, and instruments modular appendages to the main telescope, they can be replaced, leaving the main telescope intact. Considering the cost of even "low cost" lunar telescopes, utilizing them over long life times has much to commend it.

As human occupancy on the moon matures, one might expect at least occasional human presence at more than one location on the moon, and it would make sense to concentrate telescopes at these locations. As astronomy itself will, in the long run, be an important reason for human presence on the moon (a lunar "growth industry"), it would also be appropriate to consider which locations are most favorable from a purely astronomical viewpoint.

If we assume that telescopes are initially placed at the first lunar outpost location, and further assume that this is near the moon's equator and near the midline as the moon faces the earth, then it might make sense to eventually establish two outpost sub-stations also near the lunar equator but on the backside of the moon, each about 120 degrees in longitude from the nearside outpost. This would provide continuous coverage of objects as they pass from a telescope at one outpost to another as the moon rotates. In making many types of astronomical observations, there are considerable advantages to be gained if objects can be observed more frequently than the once-a-month period allowed by the lunar cycle. Many astronomical changes of interest occur on time periods of hours or days, and the ability to sample observations at these intervals adds much to the science that can be accomplished. Some types of observations, such as "stellar seismology," require continuous observations that go on unbroken for many weeks or even months.

One of the disadvantages of a minimal multi-telescope network for obtaining continuous or frequently sampled observations is that should any one of the telescopes on the network fail, then a sizable gap can be introduced that essentially ruins the continuous nature of the results. This problem can be overcome, however, by having overlapping or redundant coverage. Furthermore, one must maintain calibration between the participating telescopes (instruments) in the network.

Another approach to obtaining continuous or frequently sampled observations is to locate a telescope at or near one of the moon's poles. In these locations, the sky just wheels around in essentially a great circle. What is paid for this advantage is, of course, loss of complete sky coverage - one can now only look at about half of the celestial sphere, but one can look at it essentially all the time. A special case is a location very close (essentially at) the poles (and in a continuously shadowed crater), and this is an advantageous location where one requires a "cold" telescope for IR observations. For other situations, however, a location down from the poles 10 to 15 degrees or so may be advantageous.

By moving down a few degrees from the poles, one can be assured of having sunlight (for power purposes) during half of the lunar cycle. The moon is tilted from the orbital plane about the sun by just a few degrees (unlike the earth which has a large 23 degree tilt). To be assured of sunlight, one has to move far enough south to not have the sun blocked by local mountains on the horizon, *etc.* While providing full power when it is up, the sun would always be close to the horizon during the day, making observations away from the sun possible in almost the entire available sky (and minimizing problems of scattered light in the telescope to be discussed later).

If one is located on the nearside of the moon and desires direct communications with earth, then one has to go further away from the poles than just a couple of degrees, or the earth will, during the 17 year earth-moon cycle, dip below the horizon. By going about 15 degrees away from the poles on the midline of the moon facing the earth, one can be assured of both continuous power during the lunar day, and continuous communications with the earth. If one is off the midline, then one might have to go further yet from the poles.

It might be noted that while the earth will always be visible, it will also always be fairly low in the sky, not too far above the horizon, and thus observations away from the earth will be possible for most of the sky at all times. With the earth always low in the sky, scattered light problems from earth shine might also be reduced.

Another advantage of moving down somewhat from the poles is that a strip of sky at the celestial equator would be visible by telescopes near both the northern and southern lunar poles. This simplifies calibration of instruments at these two locations, as they can both use the same set of equatorial calibration objects.

The arguments given above for near polar locations can also be applied to locations on the farside of the moon. The advantage of the farside is that one does not have to contend with earthshine reflecting through baffles and onto detectors. Thus one might be able to observe fainter objects than would be otherwise possible. The disadvantage is that direct communications with the earth would not be possible, necessitating relayed communications via a lunar satellite or a satellite parked at a Lagrange point.

It might be noted that it is not known yet whether radiation-induced noise in detectors or earthshine bouncing off multiple baffles will be more limiting when it comes to long integrations trying to go to the faintest possible limits. There have been discussions of using stacked CCD arrays (for instance) as coincidence detectors to reduce the effects of unwanted radiation effects during long exposures.

## Optics and Optical Assembly

We considered HexTek gas-fusion optical blanks (manufactured by a firm in Tucson) as an example of what could be done, weight-wise, for a 1-meter telescope. With current manufacturing techniques, HexTek can produce a 1-meter mirror blank that weighs 200 lbs. With some (but not extensive) efforts, they could produce a mirror blank that weighed 150 lbs. HexTek uses a Pyrex-type material.

While very low-expansion materials could be used for the optics, the temperature range over which they have low "expansion" is somewhat limited. The late Harlan Smith pointed out that there might be some merit to "living with" the day-night thermal cycle and simply refocusing after each transition.

In keeping with the philosophy of building many systems, keeping optical prices modest may have some merit, and Pyrex-type materials certainly are not expensive. Harlan also suggested that fused silica is known to keep its optical shape over a wide temperature range, and therefore should be given consideration. An alternative to living with the wide temperature swings in the optics is to work at reducing the swing via environmental control – perhaps with appropriate “shutters”, *etc.* Whatever approach is taken, there should be no sacrifice in optical performance. Diffraction-limited performance would be expected at all wavelengths (except perhaps the UV).

The approach being taken to focusing in changing temperature environments by the Lunar Transit Telescope is to have an assembly between the primary mirror and instrument at prime focus that is designed to have, overall, essentially a zero expansion coefficient. This approach is worth considering. Another, more traditional approach would be to have a focus mechanism, such as a linear stepper motor, move a secondary mirror (or move the instrument payload if at prime focus). Some limited tilt adjustment of the secondary might also be worth considering. After going to all the trouble and expense to place a telescope on the moon, we must be assured that optical performance will be superb. If this requires controllable adjustments, so be it.

## Dust Covers, Baffles, and Tube Rotation

For soft-landed telescopes, the payload shroud will presumably be ejected in earth orbit, and this will leave the telescope out in the open when landing occurs. Dust kicked up during the powered landing (or by other near-by landings) must not be allowed to contaminate the optics. Thus the optics need to be enclosed by a tube with a dust cover. If there were never to be any later nearby landings, then the dust cover could be opened or ejected one time. However, if later landings or nearby human activities were expected that could contaminate the optics with dust, then it might be appropriate to be able to command the dust cover shut. If so, some redundancy would be called for here, as it would be a shame to have an otherwise functional telescope with a dust cover that couldn't be opened.

It might be briefly noted that there is some possible advantage to leaving the telescope on a lunar lander from the viewpoint of getting the telescope above the surface of the moon somewhat. There have been reports of dust levitation near the surface during the day-night transition periods.

Interior baffling to reduce stray light must be given very careful consideration, as this will probably limit how faint the system can observe during the lunar day. It might also be noted that optics with a high surface polish produce less stray light. Furthermore, avoiding dust on the optics (as above) reduces stray light.

Another strategy for reducing stray light is the use of a sunshade (and perhaps an earth shade). The end of the optical tube (extending out beyond the secondary mirror (or prime

focus instruments) can be cut at an angle, and the entire optical tube, optics, instruments, *etc.*, rotated as a unit to place the high side of the cut towards the sun (or earth). This then places the entire opening from the tube to the sky in the shade. Rotation of the entire assembly can serve other purposes as well.

In a non-equatorial mount (which is likely to be the case), the tube can be slowly rotated to counter field rotation in long exposures. Failure to do this can, for long exposures, smear the image via field rotation. As previously discussed in the context of optics, one should not do anything to degrade optical performance, and this includes the effects of field rotation. The ability to take very long exposures (to the limit imposed by stray light or background radiation on the detector) is vital for space telescopes. One of the many potential advantages of a steerable (controllable) telescope over a transit telescope is that the objects being investigated can be kept exactly positioned on the detector for long periods of time, allowing fainter objects to be observed than might be possible with non-tracking systems.

Rotation of the optical assembly can also be used to position an instrument to some preferred orientation.

There are other, more exotic approaches that might be considered to reducing stray light from the sun or earth. For systems located near (but not at) the moon's poles, the sun and earth would always be near the horizon on one side of the telescope (the side towards the moon's equator). A large "pop up" shade could cover this portion of the sky at all times except when observations of this (small fractional) of the sky were desired. To reduce scattered light from the ground around the telescope it has been suggested (with slight humor perhaps) that carbon black could be sprayed over the moon's surface for a few hundred meters all around the telescope.

## Type of Mount

We have primarily considered three types of mounts. These are: (1) equatorial; (2) alt-alt; and (3) alt-az. Each of these will be discussed below.

The primary advantage of an equatorial mount (when properly physically aligned) is that the field does not rotate during long exposures. The main disadvantage of an equatorial mount is that its primary axes must be aligned to be parallel to the moon's axes of rotation. A secondary disadvantage is that the "tilt" of an equatorial mount would depend on the moon's latitude where it was placed. This can mean, for instance, that a mount near the moon's equator would be very different than one near the poles.

For soft-landed systems, the requirement for equatorial alignment would suggest that the soft lander would have to orient itself on landing to within a few degrees of some prescribed orientation. Furthermore, after landing, observations would have to be made, and the results from these then used to physically adjust the altitude and azimuth of the mount, albeit over

some limited range and, presumably just a single time (or perhaps a few times early on to allow for some fine tuning). Once positioned such adjustments would no longer be required. At the Lunar Outpost (or other manned or occasionally manned sites) the astronauts could be called on to make telescope alignment adjustments but, other things being equal, it would be best not to add to their busy work schedule out on the lunar surface. While not totally eliminating equatorial mounts from consideration, we consider such requirements to be a severe handicap.

It might be noted, before leaving the subject of equatorial mounts, that at the equator, an alt-alt mount (if oriented north-south and leveled) is an equatorial mount. Similarly, at the poles (if leveled) an alt-az mount is an equatorial mount.

An alt-alt mount (assumed not-equatorial) suffers from field rotation, so would probably need a third axis, perhaps as discussed above in terms of rotating the entire optical/instrument assembly. On the other hand, it can be placed in any orientation, and need not be completely level. Thus it could just be soft-landed with random orientation. Observations could then be made to figure out the orientation and the pointing equations could then use this information to properly point the telescope from then on.

The alt-alt mount, unless it is heavily counterbalanced, has two "blind spots" (similar to "gimbal lock") at two opposite locations on the horizon. As one rarely wants to look at the horizon, however, these are good locations for these blind spots.

An alt-alt mount, however, is bulkier than the alt-az mount to be discussed below. Furthermore this bulkiness is in a horizontal direction, and thus is not a good form factor for sitting on top of a lunar lander in a shroud on a launch vehicle. This is a serious handicap that, while not totally eliminating such a mount from consideration, makes it seem somewhat unattractive to us.

Finally, there is the alt-az mount. As with all non-equatorial mounts, it suffers from field rotation. It has a single blind spot near the zenith (straight overhead). This is a true disadvantage, although (except at or very near the moon's poles) one can usually catch objects that transit this blind spot either before or after the blind spot (as the moon rotates). Typically the blind spot is just a degree or so in diameter, a very small percentage of the total sky available, although the size of the blind spot is dependent on the available slew rates, the moon's rotation rate, and the location of the telescope.

The alt-az mount may be placed in any orientation, needs only to be very roughly level (off 10 degrees or so should not hurt), can be placed at any latitude, and nicely matches the form factor available for launch. At this point in time we favor the alt-az mount type.



## Planning and Scheduling

A lunar telescope will be an extremely valuable resource, and requests for time on the telescope will greatly overwhelm the number of observing slots that are available. Telescope observing time will be a precious commodity that must be carefully apportioned among members of the scientific community. The management infrastructure that supports the day-to-day operation of a set of lunar telescopes must be able to allocate telescope time in an efficient, flexible, and safe manner.

Efficiency is important since we want to make maximum use of the telescope resource. Of course, efficiency is a goal both for the use of the telescope and the process by which the resource allocation is actually carried out. Efficiency in the first sense affects how much of the telescope's time is spent making useful observations; efficiency in the second sense affects how much of the scientists' time is spent wading through the bureaucracy that surrounds the telescope. We need a system for allocating telescope observing time that is efficient in both senses.

Flexibility of scheduling is also extremely important. Different users will have different scientific goals and strategies for achieving those goals. A telescope scheduling system must cater for a wide variety of observational requests. For instance, a scientist might simply require luminosity data on a particular clean eclipsing binary at a precise moment. Such an observing goal is easily translated into a request for telescope observing time, and can be directly and competitively scheduled with other such requests. However, another scientist might want to find flare stars, and might decide that the best way to do this is to iteratively scan a set of stars, comparing luminosity values with preset norms, detecting deviations, and locking on to and observing any star exhibiting a significant deviation. Such a scientific goal is not easily translated into a specific observation request at a specific moment in time. The scientist in this case must be allowed to write a procedural observing strategy for the telescope, and the procedure must be run on the telescope for a given interval of time. The point here is simply that different scientific goals engender different sorts of telescope requests, and a telescope scheduling system must be flexible enough to accommodate a wide variety of request types.

Safety is also an important consideration in telescope scheduling. Safety relates to the way that a particular telescope is used; essentially, a schedule must operate the telescope without breaking it. For example, it is clearly unsafe to point sensitive telescope instruments at extremely bright objects, and it is also typically unsafe to drive mechanical linkages through their limits of motion. All safety constraints for a given telescope must be articulated in advance, and all observational schedules must be formulated so as to respect these constraints. This is particularly important when local telescope control is surrendered to an astronomer's procedural observing strategy (as in the flare star example).

Initial deployment of telescopes on the moon is obviously a reasonably expensive venture, so we seek to minimize the recurrent operational costs by using automation whenever appro-

priate. Current technology provides for a reasonable level of automated scheduling (see, for instance, Johnston, 1989; Collinot, Le Page, and Pinoteau, 1988), and there is a significant amount of on-going research dedicated to extending this functionality in various ways. In particular, there are now some systems that provide a combination of scheduling and planning (Currie and Tate, 1991; Drummond, and Bresina, 1990). The key idea here is that a scheduler can only sequence a given set of observations, while a combined planner-scheduler can reason about alternative observations that might be made in order to satisfy a given scientific goal. There is little doubt that planning and scheduling the operations of lunar-based telescopes will offer significant new challenges for planning and scheduling systems, but it seems clear that existing levels of automation promise to address a significant part of the problem.

Telescope planning and scheduling automation can reside in computers remotely on Earth, or local to the telescope, on the moon itself. As we discuss below, the telescope will have limited power, so a large computer at the telescope is probably out of the question. This earth-moon automation split imposes certain interesting limits on the amount and nature of the computation that can be done at the telescope. For instance, it might not be possible to install extremely sophisticated scheduling software at the telescope itself. Instead, it might be necessary to do all planning and scheduling using earth-based computers, and to use the local telescope computer only as an "execution engine" to carry out individual observations and monitor results. Errors of execution requiring significant replanning might necessitate further computation on Earth. Of course, the details of the earth-moon automation split depend on the sort of computational horsepower available at the telescope, and this in turn depends on the amount of electrical power available. In theory, we would like to place as much of the automation as possible at the telescope, to allow maximally flexible modes of telescope operation and control. In practice, however, the amount of automation we can actually place at the telescope will depend on the available electrical power.

Perhaps the key point to be made with respect to scheduling and command is that the approach we are advocating is much simpler than most space telescope approaches (such as the HST's), and is similar to the operation of current automatic telescopes on earth (at Mt. Hopkins and elsewhere). In this approach, each telescope has a single, dedicated instrument. One astronomer, the Principal Astronomer (PA) is responsible for the overall scheduling and use of the telescope, and is also responsible for initial data reduction, monitoring quality, *etc.* Since all the astronomers using a given telescope are all using the same (single) instrument, their observations will tend to be similar, and thus scheduling, quality control, and initial data reduction all are greatly simplified compared to multiple-instrument telescopes. This approach has worked out very well on earth, and PAs have been able to handle the scheduling, quality control, and initial data reduction for an entire telescope as a part time job.

## Power Strategy

Lunar telescopes should operate day and night (and especially at night!). We have rejected any notion of having telescopes that would operate only during the lunar day when relatively large amounts of power would be available from solar cells. The exception to this, of course, are any telescopes devoted primarily to observing the sun itself.

A potential advantage to lunar telescopes will be their ability to observe very faint objects (even with modest aperture telescopes). To sacrifice this advantage by operating only in the daytime when, almost certainly, stray light will hurt the faint limit, would be sad indeed. Design consequences follow from this decision, however.

If power were provided by a radioisotope thermal generator (RTG), then power could be the same day and night. This might be a necessity for a system located in a permanently shadowed crater near the pole, as discussed earlier.

An alternative approach is solar cells and batteries. Batteries are heavy, but we are willing to accept this penalty in order to achieve our other goals, even if it results in a somewhat smaller aperture telescope. The use of batteries (and their weight penalty) places a very high premium on achieving low power consumption, especially at night.

To some extent, power consumption can be reduced at night by scheduling faint objects for night time observation (when they are best made anyway), as this reduces telescope movement, communications, and computations. Movement lengths can also be reduced via appropriate scheduling (*i.e.* not running back and forth across the sky).

Low power environmental control can be optimized for night time efficiency. For instance, electronics could be packaged in insulated containers such that naturally consumed power will keep them at the proper temperature. During the day, when much greater power is available, active cooling might be considered.

How low power consumption might be achieved during the night remains to be determined, but it is our hope that, on the average, it can be brought down to just a few watts. We have set, as a goal, a total system weight (including telescope, control, solar cells, batteries, communications, *etc.*, but not including any lunar lander) of less than 200 KG. We are assuming, at this point, that almost 100 lbs. would be devoted to an RTG or to solar cells and batteries, suggesting the importance we attach to night time operation.

## Communications

We are assuming that communications will consist of three somewhat separate areas. These are the command uplink, the science and engineering downlink, and the earth network.

The command uplink would be a low-bandwidth, low baud rate channel for sending commands to the telescope (objects to be observed, *etc.*). As the telescope itself will be quite

intelligent, these commands can be at a fairly high level and thus brief. We assume that it will only be necessary on infrequent, perhaps prescheduled intervals to uplink commands.

The downlink would send both scientific observations and engineering (housekeeping) data. Again we assume that the downlink would operate only on occasion, again perhaps at prescheduled times.

As controllable telescopes are capable of very precise pointing, consideration should be given, for the main downlink, to using these capabilities to reduce power consumption. Specifically, a highly directional, high frequency (perhaps Ka band) antenna might be fastened to the telescope itself. When it was time for a prescheduled communications to take place, the telescope would stop regular observations, and not only point to the earth, but point to a very specific place on earth.

An extension of this idea is the realization that, at optical frequencies, a telescope is, of course, a very highly directional antenna in its own right. At a prescheduled time, the telescope would stop its normal observations, point at and track a highly specific location on earth (where a larger optical telescope would also momentarily stop its normal astronomical observations). A simple detector selector would move to communications (transmit), and a very low-power optical diode laser would dump the information to earth. The detector selector might then go to the communications receive port and new instructions might be uploaded from earth.

JPL is considering something similar for very deep space communications (Jupiter and well beyond), where the spacecraft would be equipped with about an 8-inch telescope. If this would work, imagine how much easier it would be with a 1-meter class telescope on the very nearby moon!

Whatever type of downlink is used, there is a tradeoff between the amount of data stored and how frequently data needs to be sent to earth (and to some extent how many earth stations there needs to be). For instance, at one extreme, one might store up data for a full earth day and downlink only once a day. This would allow the use of a single earth station, but would require storage of large amounts of data, at least in the case of imaging systems. At the other extreme, one might insist on not storing any data at all, and downloading data as, for instance, it was clocked off a CCD chip. This latter extreme, however, would require continuous communications.

## Lunar Lander Requirements

We envision a 0.8–1.0-meter telescope system, complete with power, communications, *etc.*, weighing a bit less than 200 KG. For most locations, the landing accuracy requirements would be very modest – perhaps measured in miles.

The landing orientation, at least in some configurations we are considering, could be entirely arbitrary. Furthermore, the system would need to be only approximately level - perhaps within 10 degrees or so.

Landing G forces would, hopefully, not greatly exceed launch G forces (if they did this would increase system weight somewhat or result in a slightly smaller aperture).

We would prefer that the system be permanently mounted on the lander and stay on the lander after landing.

## Earth-Based Precursors

We strongly recommend that a fair number of remotely located, earth-based precursors be utilized in "routine" astronomical observations by a wide cross section of researchers and students for at least a couple of years before somewhat similar systems are placed on the moon. This will assure that all the bugs have been worked out of the systems, that the user interfaces are made as friendly as possible, that direct operation by users without intermediaries is practical, and that the systems are highly reliable.

The remote location or locations chosen for the earth-based precursors could be better than any current location occupied by telescopes here on earth. Harlan Smith, before his untimely death, pointed out that there is a 20,000 foot elevation mountaintop in northern Chile where it almost never rains (about once every 10 years), where it is unusually cloud free (perhaps the most cloud free location on earth), and where there is a good road to within 400 feet of the summit (the highest road on earth). This location looks like the moon. Astronomical observations made from this inhospitable and remote site might be the of the highest possible quality anywhere on the earth.

There have also been discussions of an 18,000 foot elevation plateau not far from the south pole. Long, continuous observations from this location would be possible, and it certainly qualifies as being one of the most remote and inhospitable places on the earth, perhaps more inhospitable than the moon itself.

By operating a number of precursor lunar telescopes at very remote and inhospitable locations on earth, considerable confidence can be developed in the operation of such systems while, at the same time, making higher-quality observations that are possible from any current location on earth.

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