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Paper Session II-C - Feasibility of Astronomical Observatories on the Moon

Max E. Nein
.NASA, George C. Marshall Space Flight Center

John D. Hilchey
.NASA, George C. Marshall Space Flight Center

FEASIBILITY OF ASTRONOMICAL OBSERVATORIES ON THE MOON

Max E. Nein and John D. Hilchey*
NASA, George C. Marshall Space Flight Center
Alabama 35812, USA

The Program Development Directorate of the Marshall Space Flight Center (MSFC), NASA, has conducted conceptual studies of an evolutionary family of UV/Visible/IR optical telescopes to be based on the lunar surface. Included are: (1) the 16-m aperture Large Lunar Telescope (LLT); (2) the 4-m aperture precursor Lunar Cluster Telescope Experiment (LCTE); and (3) the 1-m Lunar Ultraviolet Telescope Experiment (LUTE) proposed by John McGraw of the University of New Mexico. Development and emplacement of these advanced astronomical facilities would parallel the buildup of an initial lunar exploration site, an early Lunar Outpost, and a permanent Lunar Base. The Directorate, in conjunction with astronomers of various institutions, has examined the feasibility of constructing such telescopes and has assessed technology, subsystem, system, transportation, operations, and logistics requirements for their development and emplacement. Influences of the lunar environment and site selection on telescope design and operation were also evaluated.

In the next century our return to the Moon for scientific exploration and as the "waypoint" for travel to Mars will become a reality. Because of the advantages of astronomical observations from the Moon, scientists and engineers have been developing concepts for lunar telescopes which can be constructed in conjunction with the build-up of a lunar base.

Although NASA is not currently involved in an active lunar program, future plans will have to involve revisits to our nearest "planet". Two factors indicate that planning for lunar-based science should continue so that feasible designs and plans for the next generation of astronomical tools will be in hand when the return to the Moon does begin. First, design lifetimes of space-based telescopes are relatively limited, ranging from a few months for the Apollo Telescope Mount (ATM) to two decades for the HST. Second, experience indicates (Fig.1) that as much as 20 years may be required to bring a major space-based astronomy facility from scientific concept to full operation. This realistic figure includes feasibility and advanced technology work, as well as effects of budget constraints, consequent redesigns and transportation problems.

The Moon can be the ultimate "mountain top" on which the science community emplaces a "Next Generation Space Telescope" capable of at least one order of magnitude improvement over HST in resolution and sensitivity. The superb observational opportunities from the Moon [1,2,3]

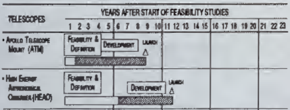

Fig. 1. Development duration for space telescopes.

* John Hilchey NASA MSFC (retired)

outweigh most adverse factors. The only significant concerns would be availability and cost of transportation and crew support for construction and maintenance of large instruments.

In order to maintain the scientific momentum achieved with the Great Observatory program and assure scientific continuity, space development institutions such as NASA and ESA, with the support of the science community, should begin long-range planning for a lunar-based astronomy program. MSFC began this process five years ago identifying the system requirements for lunar-based telescopes. Designs and plans were developed both for the near future and for the long-range goal of a full scale observatory to be erected and operated on the Moon early in the next century. Results of these studies are detailed in the series of NASA reports summarized below.

APPROACH

Four in-house conceptual design studies were conducted by the MSFC Lunar Telescope Working Group between early 1990 and the present to define the Large Lunar Telescope (LLT), the Lunar Cluster Telescope Experiment (LCTE), the Lunar Transit Telescope (LTT), and the Lunar Ultraviolet Telescope Experiment (LUTE) [4].

First the 16-m LLT was designed as a lunar-based Next Generation Space Telescope (NGST), a giant step to support cutting-edge science in the 21st century. The study showed that, given large budget and mission priority, a full scale LLT could be deployed to the Moon in less than 25 years. It would satisfy science goals and mission requirements identified for NGST-class instruments [5,6,7] and could be developed with rational extensions of advanced technologies, new materials, and evolving system design approaches. However, before committing to a full-scale LLT, intermediate scale instruments would be needed to:

- characterize the lunar environment and environmental impacts on telescope elements;
- evaluate and evolve suitable materials and technologies;
- assess subsystem and systems design approaches;
- test telescope deployment and construction methods; and
- gain experience in operations and maintenance.

The Working Group investigated smaller systems to serve as logical steps toward the long-range goal. The 4-m LCTE was detailed both as an instrument to extend the frontiers of astrophysics and as a major lunar telescope testbed which could be deployed within 15 years. However, development of the LLT and the LCTE would necessarily be deferred until major new transport became available, e.g., the Lunar Transfer Vehicle (LTV) and the Lunar Excursion Vehicle (LEV).

"Precursor" telescopes could be landed on the Moon to begin scientific observations before men return to its surface. The 2-m LTT proposed by John McGraw [8,9], was examined in engineering detail. LTT would serve as an excellent astronomical outpost and testbed, but realistic estimates of LTT's mass exceeded the capacity of any planned lander.

The LUTE, a 1-m aperture LTT derivative, was proposed by McGraw [10] as a feasible early precursor system. Detailed engineering and programmatic studies conducted by the MSFC LUTE Task Team showed that LUTE would be a promising first step in using the Moon as a scientific base [11].

Each study developed details of the design challenges imposed by science and mission requirements, environment/telescope interactions, site selection, and subsystem choices and sizing, based on the tradeoff patterns described in other publications [12,13]. Based on these results, detailed conceptual designs, transportation options, mission profiles, costs, and schedules were developed and documented.

LARGE LUNAR TELESCOPE (LLT)

The LLT is visualized as a 16-m Ultraviolet/Visible/Infrared imaging, optical telescope; a Reference Design Concept is given in Figure 2, and its characteristics are listed in Table 1. This National/International investment can be the "flagship" astronomical research instrument of a Lunar Observatory during the first half of the 21st century [14]. The LLT Project should be rooted in the accumulated experience in lunar-based science, technology, design, engineering, operations, and management acquired with testbeds and precursor telescopes during the early 2000s. It would be uniquely able to combine unprecedented aperture with hours-long integration times, in a superb "seeing" environment. The melding of these factors would ensure that the LLT could produce observations of a very high sensitivity and resolution across the spectrum, giving us an unprecedented grasp of the universe.

A 16-m segmented mirror would form the primary of the 3-mirror, 4-reflection system. Eighteen 4-m hexagonal clusters, each composed of 61 0.5-m hexagonal segments, comprise this primary. Its spherical figure, chosen to simplify primary manufacturing, maintenance, and replacement, would be maintained by active correction of all 1098 segments. A tripod would support the 3.2-m secondary 15 m forward of the primary. A 3.2-m active tertiary would replace the central cluster of the primary. The fourth reflection of the light beam (the second reflection by the secondary) would pass it through a Coude' system behind the tertiary to the external instrument chamber, whatever the LLT's orientation.

Subsystem trades show that power and communication support could best be supplied by a Lunar Base, if it is less than ~ 10 km distant, and at the LLT if much more than 10. A

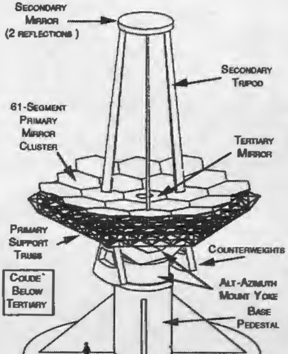

Fig. 2. LLT Reference Design Concept

Tab. 1. Summary of LCTE and LLT Characteristics.

CHARACTERISTICS	LCTE	LLT
PERFORMANCE		
• APERTURE	4-m CLASS	16-m CLASS
• TYPE	Alt-Azimuth	Alt-Azimuth
• FOCAL RATIO	f/21	f/16
• SPECTRAL RANGE	0.1 - 10 μ	0.1 - 10 μ
• RESOLUTION	80 μRADS AT 0,25 μ	60 μRADS AT 0,25 μ
	1 μRADS AT 3 μ	1 μRADS AT 3 μ
• LIMITING MAG.	(~ V) 26	(~ V) 27
• FIELD OF VIEW	UV: 20 ARCSEC	UV: 20 ARCSEC
	Vis/IR: 2 ARCMIN	Vis/IR: 2 ARCMIN
PROPERTIES		
• MASS	6,900 kg	24,000 kg
• DIMENSIONS (D x H)	5.0 x 6.4 m	17 x 32 m
• POWER AVAIL.	2,500 W	5,600 W
• DATA RATE (RAW)	0.4 Mbps	2.5 Mbps
MISSION		
• DATE	2006	2012
• DURATION	15 YRS	35 YRS

subsurface instrument chamber, shielding instruments from cosmic radiation, would house a UV/Vis Imager, an IR Imager, a UV/Vis Faint Object Spectrograph, a Medium Resolution IR Spectrometer, and a Wide-field Camera. A major shelter could protect the LLT from excess thermal loading, dust, micrometeoroids and ejecta.

Two shuttle launches would transport the LLT, foundation, and telescope base to Earth orbit. The LLT would be flown to lunar orbit by LTV, then to the surface by LEV. A major, trade will be needed to identify a site distant enough from the Base to avoid operations interference, but near enough for Base crews to construct, maintain, and upgrade the LLT.

The LLT would gather scientific data with the initial single primary mirror cluster plus the secondary and tertiary mirrors. It would evolve the full science capability by incremental additions of mirror clusters, to develop the required diffraction limited imaging capabilities.

The enormous capabilities of the Large Lunar Telescope would open up new frontiers of astronomy and astrophysics, clarifying many of the most significant problems in the physical sciences. For example, structures of all known galaxies would be resolved down to a level now achieved only in the nearest ones. Exercising an immense outreach to the most distant regions of the universe, LLT could survey immense populations of objects never before recorded. Ultimately, it could accomplish one of the most challenging, exciting researches humans can undertake: to image planets circling neighboring stars and, perhaps, to identify Earth-type planets showing the spectrographic signature of life.

LUNAR CLUSTER TELESCOPE EXPERIMENT (LCTE)

The LCTE is defined as a scientific, technological, engineering, and managerial precursor of the LLT. It could be deployed several years prior to the LLT as the large-scale, long-duration "testbed" for science operations, technologies, system designs, and engineering/construction capabilities needed as the foundation of a full scale lunar observatory program. The simplified system requirements of earlier lunar instruments needed only modest technology advances to gain early operational experience. In contrast the LCTE would include and test many prototype LLT elements.

LCTE would be a 4-meter-class UV/Visual/IR, imaging telescope to be deployed autonomously to the Moon. A Reference Design Concept is shown in Figure 3, and its characteristics are summarized in Table 1, from the MSFC report [15]. The LCTE would be launched direct to the lunar surface by a Heavy Lift Launch Vehicle (HLLV). A LEV might land the telescope and also serve as a temporary base until crews are available to transfer it to a sturdier one. The LCTE should be placed near sites planned for the Lunar Outpost or Base, to enable easy surface crew access for system maintenance and evaluation of technology and testbed results. Open areas such as Oceanus Procellarum, or Crater Grimaldi could be preferable to the rough terrain northeast of Mare Orientale suggested elsewhere [16].

The LCTE would be capable of diffraction limited imaging through the 0.1 - 10 μm range and observing 25 % of the celestial sphere. Designed to provide a 70-100 K background, with instruments at 4 K, LCTE could be the first instrument to exploit the Moon's IR viewing opportunities.

LUNAR TRANSIT TELESCOPE (LTT)

The LTT would be a 2 m-class, optical telescope, capable of imaging in the Ultraviolet, the Visible, and the Infrared. It would be deployed and operated on the Moon without crew support. The Reference Design Concept shown in Figure 4 and its characteristics summarized in Table 2 are provided from a detailed MSFC report [8].

Three-mirror, 3-reflection optics are proposed, including a 2-m primary, a 0.95-m secondary, and a 0.49-m tertiary; any need for adaptive optics remains to be resolved. The focal plane instrument would be a 5-bandpass array of CCDs with anti-coincidence counting to minimize cosmic ray "noise." Telescope structures and optics could be scaled up

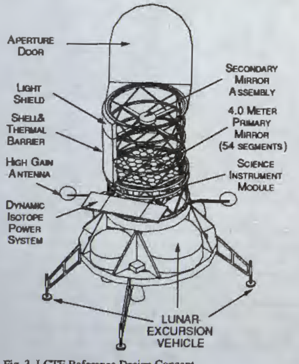

Fig. 3. LCTE Reference Design Concept.

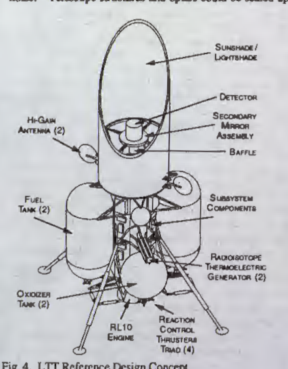

Fig. 4. LTT Reference Design Concept.

Tab. 2. Summary of LUTE and LTT Characteristics.

CHARACTERISTICS	LUTE	LTT
PERFORMANCE		
• APERTURE	1-m CLASS	2-m CLASS
• FOCAL RATIO	f/3	f/4
• SPECTRAL RANGE	0.1 - 0.35 μ	0.1 - 2.2 μ
• BAND PASSES	3	5
• RESOLUTION	< 0.5 ARC SEC	0.1 ARC SEC
• LIMITING MAG. (~ V)	26	27
• FIELD OF VIEW	1.4°	2°
• COVERAGE (PER MO.)	~ 300 DEG²	~ 600 DEG²
PROPERTIES		
• MASS	472 kg	3000 kg
• DIMENSIONS (D x H)	1.1 x 2.7 m	2.1 x 5.3 m
• POWER AVAIL.(RTG)	600 W	350 W
• DATA RATE (RAW)	3 MBPS	31 MBPS
MISSION		
• DATE	1999	2002
• TYPE	UV SURVEY	UV/VIS/IR SURVEY
• DURATION	2 YRS	2 YRS

from those of a 1-m aperture precursor telescope which has been studied as a pathfinder system for early return to the Moon, potentially launched in conjunction with other exploratory systems deployed from lunar roving vehicles.. Two RTGs would provide up to 600 W of power day and night. Passive thermal control techniques, where feasible, would control temperatures in the optical system and the focal plane instrument. Linear actuators might be used for initial pointing and alignment. The communications subsystem would compress 31 Mbps of raw data to 3 Mbps for transmission to NASA's Deep Space Network. A Titan IV-class launch would be needed to deploy the LTT to the Crisium-Berosus region [8,9] or to the more benign thermal environment of 65° N. [18].

The Lunar Sky Survey would be significantly enhanced by the LTT with its expanded spectral range, increased resolution, and broadened sky coverage. For example, it will be able to: identify brown dwarves out to 4 kpc; detail galactic kinematics; resolve extended sources, e.g., "IR cirrus;" evaluate variations in Active Galactic Nuclei; and clarify galaxy cluster morphology and evolution to redshifts greater than 3.

LUNAR ULTRAVIOLET TELESCOPE EXPERIMENT (LUTE)

The LUTE has been identified as a strong candidate to be the first astronomy payload to be operated from the surface of the Moon. First proposed by McGraw [10] in 1992, the LUTE concept was the subject of an intensive, two-year feasibility and conceptual design study by the LUTE Task Team of the Marshall Space Flight Center. The results of these studies have been reported elsewhere [19,20,21].

LUTE is proposed as a 1-meter aperture, lunar-based telescope designed to produce a unique celestial survey in the Ultraviolet portion of the spectrum [10]. After being placed on the Moon by an autonomous lander, this non-tracking, "transit-type" instrument, would point continuously at a scientifically important area on the lunar sky. During the Moon's monthly rotation, over a two-year lifetime, LUTE would digitally image the celestial objects on a continuous strip across the lunar sky and relay the data continuously to Earth for scientific and educational use. Science operations have recently been described in detail [10,22]. LUTE would also monitor and forward detailed data on the lunar environment as well as its own engineering health and performance.

The Reference Design Concept shown in Figure 5 was developed in the iterative process of analysis, tradeoff, and design described in detail elsewhere [19]. The characteristics and performance of the telescope which resulted from that approach are summarized in Table 2. This f/3 telescope, with its wide (1.4°) field of view, would have compact, light weight optics. A two-dimensional mosaic of Charge Coupled Devices (CCDs) would serve as a wide-field detector, while a second CCD mosaic will enable anti-coincidence counting methods to mitigate cosmic ray background "noise". The LUTE UV survey could image more than 300 square degrees of the sky in a year's time to an equivalent visual magnitude of 27, and with a resolution of 0.5 arcsec or better. The spectral range of the survey could extend from 1000 to 3500 Å in three bandpasses, each about 800 Å wide.

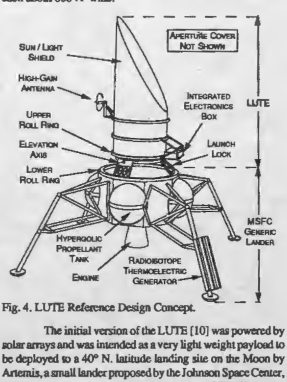

Fig. 4. LUTE Reference Design Concept.

The initial version of the LUTE [10] was powered by solar arrays and was intended as a very light weight payload to be deployed to a 40° N. latitude landing site on the Moon by Artemis, a small lander proposed by the Johnson Space Center. Intensive engineering analyses showed that LUTE, limited to photovoltaic power and passive thermal control, could not operate properly at a latitude of 40° N. It could not maintain required optical system temperatures, and Artemis mass limitations prevented carrying sufficient batteries to support full day-night operations.

A landing site at 66.5° N. x 24.2° W. was evaluated [18] to assess the improvement possible through reducing the thermal loading on the LUTE and accepting the limitations to daytime operations only. Thermal responses improved, but the latitude increase required a sunshield and pointing subsystem redesign to aim LUTE back to the required celestial latitude, 40° N., and adding significant mass to the design.

A Radioisotopic Thermoelectric Generator (RTG) was incorporated in the final evolution of the LUTE concept.

This addition made feasible the application of active thermal control measures to the optical system and the electronics elements of the telescope which could be harmed by lunar night cold-soak. Inclusion of the RTG can provide the basis for a successful LUTE design in spite of any programmatic difficulties encountered in RTG acquisition.

The design approach for the LUTE system emphasized simplicity of mechanisms and subsystems in order to minimize the likelihood of malfunction and to assure the highest probability of mission success.

TELESCOPE LANDING SITES

Site selection for the power-limited precursor instruments will be dominated by a need to minimize thermal loading by landing at high latitude (Fig. 6) [18,19]. Detailed thermal/engineering analyses show they should be located at least 65° North to avoid overheating. The same would likely be true for the LTT, proposed for Crater Berosus, at 34° North or for central Mare Crisium at ~18° North.

LCTE and LLT would not be thus limited. Their advanced electrical power systems could support active thermal control of the telescope and its focal plane detectors. Site selection trades for the crew-supported LCTE and LLT will be influenced more by the need for easy surface access for the servicing crews. Thus, the LCTE and LLT could be located near the western limb (cartographic convention) to minimize Earthlight interference with observations and ensure crew access, e.g., western Oceanus Procellarum, or Craters Grimaldi, or Hevelius. These sites for the large astronomical systems would enable a far simpler, more reliable deployment, operations, maintenance, and logistical plan than would the difficult locations proposed elsewhere, such as the broken ground northeast of Mare Orientale [16] or atop the central peak of Riccioli crater [17]

Fig. 8. Landing Site Options for Lunar-based Telescopes

TELESCOPE CONSTRUCTION ON THE MOON

Assembly of a large lunar telescope such as LLT will be executed by astronauts and telerobotic machines. Three major construction phase have been identified. Site preparation, (Phase 1) includes the excavation, debris removal and placement of a construction hut. Telescope construction (Phase 2) begins with the unloading of the LEV cargo, the connection of power supply, setting up of communication equipment and the orientation and leveling of the LEV/telescope pedestal assembly. It concludes with construction of the primary truss structure, secondary mirror support assembly and secondary mirror, and, finally, with primary mirror assembly from the preassembled mirror clusters. Instrumentation placement (Phase 3) includes placement of the instrument chamber containing preinstalled instruments, covering of the instrument chamber with regolith, initial telescope check out, site clean up and transportation of the construction equipment back to Base.

Using task outlines for the various assembly procedures a productivity and duration time line for the telescope construction was generated. Assembly times of the telescope have been estimated to be 1400 hrs, based on astronaut task assessments [14]. This estimate is probably very optimistic, but indicates that assembly of a 16-m telescope is a very labor intensive task requiring dedication of considerable astronaut crew-time and equipment.

ENABLING TECHNOLOGIES

Technology availability will be a dominant factor in the development of lunar observatories. Inclusion of the appropriate technologies could be critical to assure the required scientific performance, simplify fabrication, enhance schedules, and significantly reduce costs.

Some non-critical development needs can be met with design solutions based on current technologies, materials and hardware. An example would be the pointing and alignment system. Likewise the communications and data handling system could be derived from hardware now available, such as, omnidirectional and parabolic high-gain antennas, data compression systems, and standard electronics.

A third example, the telescope protection system, might also be developed using current materials and design approaches. The light/sun shields and the aperture cover are the vital elements of this subsystem which protect the optical bench assembly from light, thermal radiation, micrometeoroids; secondary ejecta, and dust.

In contrast, a number of emerging technologies will be crucial in evolving the capabilities required of the telescopes if their performance is to measure up to the system requirements imposed by the science needs and the aspects of the lunar environment which will be faced in long-term operations on the Moon's surface.

Optical System. Although many unmanned and six manned spacecraft have landed and explored the harsh lunar environment, attaining and maintaining the desired optical performance of high resolution telescopes during many lunar day-night cycles remains a major problem in the design of these systems. It is therefore imperative to concentrate research tasks on some of the critical systems engineering problems, which are anticipated, but lack acceptable solutions.

The optical bench assembly, the heart of any telescope, comprises several elements [2]:

- mirrors and their baffles;
- the focal plane CCD mosaic;

- the metering system which:
  - supports, e.g., the forward metering ring, spider, and mirror assemblies, etc.;
  - and maintains the proper relationships among optical elements;
- the baseplate, which integrates all optical, structural, protective and pointing elements with, e.g., the lander.

Several of these require key technology advancements, especially in the areas of: mirror materials, adaptive optics, optical coatings, detector capabilities and thermal control.

Mirror Materials. The optical system with its passive thermal control, has to withstand large temperature swings in the range of 90 - 375 K. The optical performance of various mirror materials and their degradation during thermal cycling is of primary importance to the feasibility of a lunar telescope. Historically space optical systems have been operated at the manufacturing temperature or at a constant temperature for which the optical prescription has been biased during manufacture. In the case of lunar telescopes this is not possible because of the continuously changing temperatures during the lunar cycle (primarily in the day time portion). Therefore suitable mirror materials which combine the requirements for light weight, thermal stability, and optical performance over a wide range of temperature variations must be evaluated.

Candidate materials such as beryllium, silicon carbide, and Ultra Low Expansion glass (ULE) exhibit desirable characteristics. However, many questions remain regarding their performance under the extreme temperature cycles to be encountered on the Moon.. Such areas as thermo-structurally optimized design shapes, non-linearity of material properties, adhesion of substrate coatings and optical coatings, must be investigated and verified experimentally to enable the selection of the right combination.

Adaptive Optics. While a 1-m aperture telescope may not require an adaptive optics system, larger telescopes must have the ability to adjust the distortions caused by temperature gradients in the mirrors. Telescopes with apertures larger than approximately 3 meters must be assembled on the Moon from segments and will depend on adaptive optical systems.

It is therefore imperative that the technologies for active and adaptive optics currently under development for earth and space-based systems be extended for the thermal and structural requirements imposed by the lunar environment.

Typical requirements in these areas of technology include:

- an actuated, deformable primary mirror that will maintain an optical surface within 100 Å in a lunar thermal environment;
- a lightweight secondary mirror actuation system that does not increase the obscuration ratio of the telescope;
- active metering structures that will accommodate large thermal gradients

During the design process it will also be essential to have an advanced, integrated, multi-body dynamics analysis program. It should have the capability of dynamically modeling the thermal loads on an interconnected set of structures using temperature-dependent material properties, and it should interface with software for control-system development, and optical analysis.

Optical Coatings. In order to assure acceptable performance for extended periods of time in the lunar environment one must investigate the durability and optical performance of high reflectance coatings for the 1000-10,000 Å band, both as freshly applied ("new") and after exposure to a simulated lunar environment of temperature, vacuum, dust, potential contaminates and galactic and solar proton radiation.

Detectors. The focal plane detectors currently envisioned are based on a CCD mosaic array. Pixel size, currently larger or equal to 7.5 µm, should be reduced to 5µm if feasible. Although tremendous advances in detector technology have been made in recent years, there is a continuous requirement to explore the capability to produce large area CCD detectors with very small pixels for science applications. These detectors must be either fabricated directly on a spherical substrate or must be sufficiently thinned that they could be "stretched" to conform to a spherical surface, matching the detector to any image field curvature in the planned telescopes.

Technology developments of this type are very expensive and the drivers for such developments do not exist in the commercial fields; as a result advances in many key technologies have depended on defense objectives. Because of the decline of these demands advanced development of detectors for science instruments has become one of the critical enabling technologies.

Thermal Control. The extreme temperature variations of a lunar day/night cycle coupled with the absence of electrical power during the lunar night as dictated when using a solar array power system requires avionics components and system to operate well beyond the qualification limits. This creates unknown engineering risk in the development of avionics systems. To understand and quantify this engineering risk, an applied technology and development program is needed to explore techniques for design, packaging and thermal control of electrical and electronic avionics systems. For instance, a technology effort is needed to investigate a common and integrated packaging concept that will integrate all thermal sensitive circuits and components with a passive thermal control technique. The ultimate goal is to manage and store the waste operational heat of the avionics system during lunar day operation and utilize this stored heat to maintain an acceptable storage temperature during lunar night when the avionics are not operating.

Electrical Power System. Historically electrical power for space-based orbiting telescopes has been provided by photovoltaic arrays. During the short, up to 90 minute, "night time" of the orbital path sufficient electrical energy can be stored in batteries, which are recharged during the sun lit portion of the orbit. However, lunar-based experiments requiring electrical power cannot depend on photovoltaic arrays and batteries, if they must operate during the night portion of the lunar cycle. While the 14 earth-day long lunar day is ideal for deriving power from solar arrays-except in the shadow of deep craters or regions near the poles -the mass and volume of electrical batteries to store the energy for night time operation is prohibitive. Therefore the only reasonable energy source for night time operation at relatively low (300 W) power level is an RTG. Use of RTG's has some additional benefits. The large amount of thermal energy produced by an RTG as a by-product of the radioactive decay process can be utilized to maintain operating temperatures of components and systems.

However, there are also problems associated with the use of RTG's, not the least of which are the potential radiation effects on sensitive detectors. The use of RTG's requires thermal control from the time the generator is installed. Thermal waste heat is continuously produced and thus the location of the RTG on the telescope must be carefully selected and cannot easily be changed during the development phase of the telescope because of the complex thermal interactions with the optical system. Thermal modeling and means of transmitting thermal energy to components and subsystems, where the thermal load can be of benefit must be assessed. Technology efforts are needed to assess and experimentally verify detector performance in the presence of an RTG. Recently the use of RTG's is no longer tolerated, except for deep space probes, because of the potential hazardous environmental problems associated with a launch failure.

SUMMARY

Conceptual designs and programmatic studies show that sophisticated telescopes can be emplaced and be operating on the Moon within a few years of project approval. Development of large, advanced systems such as the LCTE and the LLT must await the emergence of new technologies for large active optics, and the advent of routine astronaut lunar surface operations including the construction techniques and hardware needed in observatory site preparation and in telescope erection.

Although the Moon's environment poses some difficult technical issues for the telescope designers no unsurmountable problems have surfaced in our studies. For the next generation space telescopes the Moon offers advantages which overshadow the environmental, construction and maintenance and longevity issues experienced with earth orbital locations of large telescopes.

The MSFC studies provide a first-generation model of a logical build up sequence for the establishment of a permanent Lunar Astronomical Observatory to be associated with, and supported by, the permanent Lunar Scientific Base. The initial step would deploy a small automated transit telescope, the 1-m LUTE. Uprated versions of the LUTE, including mobile systems [23], would follow over the next decade or so. By CY2008 technology development and designs for the LCTE could be complete, with development and deployment to occur by 2012 or shortly thereafter. The experience base required for successful development, deployment, operation, and logistics support of the LLT should be accumulated by 2016-18. Development of the LLT could begin by 2020, followed by deployment at the approximately the quarter-century mark.

It is entirely possible that, beginning with modest feasible precursor telescopes, a generation of astronomers and astrophysicists can choose the Moon as their next "mountain top" from which to reach out to see and understand our beginnings and our future.

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