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REQUIRED TECHNOLOGIES FOR A LUNAR OPTICAL UV-IR SYNTHESIS ARRAY

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Abstract

A Lunar Optical UV-IR Synthesis Array (LOUISA) proposed to take advantage of the characteristics of the lunar environment requires appropriate advances in technology. These technologies are in the areas of contamination/interference control, test and evaluation, manufacturing, construction, autonomous operations and maintenance, power and heating/cooling, stable precision structures, optics, parabolic antennas, and communications/control. LOUISA needs to be engineered to operate for long periods with minimal intervention by humans or robots. What is essential for LOUSIA operation is enforcement of a systems engineering approach that makes compatible all lunar operations associated with habitation, resource development, and science.

Introduction

LOUISA (figure 1) is one of several types of astronomical observatories that have been proposed to take advantage of the unique nature of the lunar environment. Other observatories include the Very Low Frequency Array (VLFA) for radio astronomy (Douglas and Smith 1985), and the Moon-Earth Radio Interferometer (MERI) (Burns 1985, 1988). With each proposed telescope, there are a myriad of engineering issues to be resolved.

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Advanced Technologies and Critical Engineering Issues

A major difficulty in determining what the critical engineering issues are for LOUISA is that systems for LOUISA are in their early planning stages. Examples of some of the technology development considerations to be addressed for LOUISA are shown in Table 1. The identification of critical engineering issues is somewhat arbitrary predicated on judgment as to observatory design and types of materials and technologies to be used. There will be many significant components such as foundations and supporting structures (which will have stringent requirements for stiffness and thermal stability), thermal control systems, power, communications and control, and data processing and transmission (Johnson 1988).

Table 1. Examples of Technology Development Considerations for LOUISA

LOUISA

- Requirements
- System definition and specifications
- Site selection and characterization
- Control capability (stringent requirements limiting differential settlements, tide compensation)
- Lunar surface layout requires locating and modifying a suitable site
- Dynamic response of lunar soil to movement of telescopes
- Preservation, cleaning, and renewal of optical surfaces and coatings

General Technology Needs

- Automation, telepresence, and robotics for construction, operations, and maintenance
- Human factors considerations (man-in-the-loop) and realistic artificial intelligence interaction
- Stiff, stable, light-weight structures from modern composite metal matrix or other selected materials transported from Earth or made on the moon
- Data gathering, storage, processing and transmission
- Thermal control, cryocoolers, heat dissipation and heaters as appropriate
- Power sources to serve lunar outpost requirements
- Potential applications of superconductivity
- Mobility on the surface (robots/human)
- Earth to Moon and return transportation
- Test and evaluation of system
- Self-organizing failure characteristics prediction/detection and remote correction

Each of these significant components suggests a set of critical engineerng issues which can be addressed from the point of view of required technologies to make LOUISA perform in an acceptable way. Table 2 lists the significant new technologies discussed in this paper which will be required for LOUISA.

Table 2. Technologies for LOUISA

Contamination/Interference Control
Test and Evaluation
Construction
Power and Cooling/Heating
Stable Precision Structures
Optical Systems
Parabolic Antennas
Shielding
Communications and Control

Manufacturing:
    Terrestrial
    In-space
    Lunar

Autonomous/Semi-autonomous:
    Deployable
    Operations
    Maintenance

Contamination/Interference Issues

One of the challenges facing telescope designers and operators is coping with natural and operations-induced sources of contamination and interference (Table 3) on the Moon. Sources of contaminants and interferometers will have implications for all aspects of the lunar astronomical observatory performance (Tables 4 and 5).

Particulates and gases deposited on surfaces can significantly alter optical and thermal properties of surfaces and degrade performance. They can defeat the important attributes of delicate coatings and scatter light, create assembly and erection problems (particulates), and lead to problems in electronics. This paper first looks at some contamination and interference control technologies needed and then deals with selected other technologies for lunar observatories.

Table 3. Some Contamination and Interference Sources and Implications

Fine-grained particulates from the lunar surface - stick to surfaces

Meteoroid impacts - loft debris; cause surface pitting

Gases - stick to surfaces
- Natural
- Induced by operations
  - rocket plumes
  - outgassing from excavations/fill in soil and mining/manufacturing
  - outgassing from suited workers

Radio frequency - interference problem for radio astronomy/communication

Ground shock/vibrations both natural and operations induced - problem for optical interferometers/other instruments

Other:
- Reactor radiation
- Waste heat from power sources

Table 4: Instrument Contamination and Interference and Possible Countermeasures for LOUISA

Possible Contamination/Interference	Possible Countermeasures
Gasses "sticking" to optical surfaces and changing optical properties	Reduction of effluents at source. Technology to purge and renew surfaces
Fine-grained particulates from lunar regolith adhering to optical surfaces and other surfaces	Dust mitigation technologies (reduce operations generating gases); clean-up technologies
Radio frequency interference with broad-band data transmission/reception	Frequency allocation and transmitter standards
Ground shock/vibrations interfering with nanometer precision alignments	Alignment sensing/adjustment in real time; shock/vibration isolation at telescope; shock suppression at origin; keep-out zones

Table 5. Some Recommended Contamination Technology Programs for Lunar Surface Astronomy

Contamination effects research
- Determination of effects
- Development of acceptable standards

Modeling of the mechanisms of contamination

Critical diagnostics/measurements program for lunar surface contamination
- Material/structural samples deployed to lunar surface and data collected
- Verification/comparison of model and cleaning techniques

Development of contamination prevention and cleaning techniques

Telescopes on the Moon may tend to be surrounded by transient atmospheres resulting from staffed and unstaffed operations in the vicinity (Fernini et al. 1990). That there will be a transient gas cloud is evident from the work of investigators (T.H. Morgan, personal communication) interpreting measurements from atmospheric detection instruments on the Apollo Lunar Surface Experiments Package (ALSEP). Under a worst-case scenario, the "cloud" of transient atmosphere could degrade astronomical observations. The cloud density will be dependent on relative rates of contaminant generation and removal. Removal is by collisions with solar wind protons, diverging orbits of particles, expansion into space, decomposition and evaporation, and entrapment or sticking in the lunar soil or regolith.

Particulate and gaseous deposits on critical surfaces of astronomical instruments on the lunar surface may occur as a result of both natural and man-made environments. Deployment and emplacement will involve vehicles and perhaps suited construction workers outgassing water and other byproducts of metabolism and suit functions.

Required power and communication units may be sources of unwanted heat, radiation, and radio frequency interference. Surface operations for emplacement of observatories may involve excavation, compaction, trenching, and fill operations which will accelerate and disperse particulates and liberate gases.

Contamination and Interference Control Technologies

Contamination control is a prime area of concern for virtually any telescope installation. Contamination control technologies required for telescopes to be based on the Moon include protection of precision surfaces and parts through the life cycle including manufacturing, assembly, test and checkout, transportation, landing, erection and deployment, and lunar surface operations and maintenance. Safe techniques to remove contaminants at any stage in this life cycle are needed. Obviously, means to detect and establish the nature of contaminants are required so that the severity of the contamination problems can be monitored and appropriate countermeasures can be taken.

Particular attention is needed to ascertain the implications of long-term lunar surface operations for accumulation on surfaces of contaminants such as fine-grained particulates, products of outgassing of materials, and propulsion products.

There are needs for investigations to improve our understanding of optical and thermal control coatings, their behavior, and interactions with contaminants and radiation environments on the lunar surface. The processes of contamination and contamination removal can be modeled to assist in predictions of the severity of problems developing as a result of various operational scenarios. To develop useful models will require an improved understanding of the physics of surface deposition and better characterization of the lunar environments, both natural and operations-induced. The longer-term goal will be to develop techniques for surface cleaning and coating restoration in situ on the lunar surface.

Johnson, Taylor, and Wetzel (1989) discuss environmental effects on astronomical observatories. They relate to experience with recovered Surveyor III, Solar Max, and other parts exposed to the lunar and orbital environments. The results they present are instructive in formulating future contamination control technologies.

Test and Evaluation Technologies

A methodology and facilities and resources are needed to assure that systems concepts for a lunar astronomical observatory can and will be modeled and tested adequately at various stages of conceptualization, research, development, fabrication, and preparation for launch. The goal is to avoid unpleasant surprises after arrival on the lunar surface. Questions to be resolved by a test and evaluation process relate to the operational effectiveness and suitability of the observatory systems. Effectiveness questions for test and evaluation are those tied in with performance such as pointing and tracking accuracy and precision, resolution, and image quality. Suitability questions relate to reliability, maintainability, and supportability of the telescope operational systems on the lunar surface. All of the suitability questions are or enormous importance when the logistics line of support is from the Moon to the Earth.

Early involvement of test and evaluation methodologies will start at the telescope system concept level to make adaption possible to assure testability. Ground-based simulators will be needed to verify interoperability and autonomy of telescopes. Systems for calibration of telescope systems are an important aspect for the prelaunch modeling, test, and evaluation process.

Manufacturing Technologies

Two types of manufacturing capabilities should be pursued to support lunar-based astronomical observatories. One set of capabilities will be on Earth and the other eventually on the Moon. Terrestrial manufacturing of telescopes will be aimed at producing very lightweight, reliable, and packageable components of observatories for shipment to and deployment on the Moon. One example will be composites manufacturing which requires technology development for coatings, joints, fabrication techniques, and complex fixtures for support of steerable dishes and mirrors for radio astronomy and optical astronomy. Parts should be produced so that they are interchangeable where possible (e.g., the struts supporting mirrors and dishes). Optics and electronics suitable for long-term use at a lunar observatory require special care in manufacturing to avoid faults and impurities that lead to subsequent degradation and failure.

In the area of manufacturing, the prime technology issue is producibility. Required for lunar optical array are capabilities to manufacture, assemble, inspect, test, and maintain high quality at reasonable cost. This technology issue becomes of greater importance as more components are required as in the case of an optical array. Ultimately, some components may be manufactured from lunar materials on the Moon--requiring a whole new set of manufacturing technologies.

Construction Technologies

Mobility and transportation with minimal environmental impact are key elements in the deployment of the observatory and its components on the lunar surface. Transportation of components to the lunar surface will, for example, require safe and secure packaging to preserve the integrity and cleanliness of delicate optical and other elements. Deployment and erection sequences must be carefully preplanned so that components match up in spite of temperature variations from component to component and with time. Technologies for deployment should minimize the needs for intervention by construction Workers in space suits. Teleoperated cranes may serve as backup for automated off-loading of components from arriving payload packages. Ways will be needed to prevent the accumulation of fine-grained particulates from the lunar regolith on mating surfaces of contiguous elements of the observatory. Confidence in deployment and erection technologies will be critical in determining the future success of the observatory.

The emplacement of the LOUISA observatory on the Moon will require the capability to maneuver vehicles in remotely controlled (teleoperated) or preprogrammed operational modes. A variety of terrains will be encountered including small and large craters, boulder fields, hills, and valleys.

Autonomous Operations and Maintenance Technologies

Autonomous operation and maintenance of telescope systems on the Moon is a goal that will be difficult to achieve because of the unpredictability of the problems that will be encountered. Allowance should be made for teleoperation and maintenance workers in space suits if unanticipated difficulties arise. Prelaunch test and evaluation efforts on Earth will focus on various aspects of teleoperated operation and maintenance to predict and resolve difficulties before arrival at the Moon.

The vehicle associated with the LOUISA should be able to operate in several different modes as needs dictate change from manual operation to local teleoperation or to remote teleoperation, or perhaps to autonomous operation and hybrid modes. Technical issues with the vehicle design relate to vehicle size and mass, load carrying capacity and range, communications and control, number of wheels (or tracks), manipulator capabilities, power, and methods of coping with the environment (e.g., the soil, rock, and terrain; vacuum; meteoroid impact; radiation; extremes of temperature; and diurnal cycles of solar radiation). The robotic vehicle system that supports the construction of the LOUISA will be required to support all phases of the effort including transport, layout of the system according to the predetermined plan, emplacement of a central station, and performance of maintenance and repair tasks. The vehicle must have flexibility to meet and cope with unanticipated difficulties such as breakage, unusual terrain, soil variability, and layout adjustments.

The prime power source for the lunar astronomical observatory and associated facilities will be either solar or nuclear or a combination. Solar arrays appear to be suitable if backed by sufficient energy storage capacity (batteries or regenerative fuel cells) to continue operations during the lunar night. There is a strong need for development of regenerative or rechargeable power storage devices, both large and small, for use with solar energy devices to furnish power during the 14 Earth-day lunar night. One option for the next generation battery is a Na/S battery being developed at the Aero Propulsion Laboratory at Wright-Patterson Air Force Base, Ohio (Sovie 1988). Radioisotope thermoelectric generators are also possible power sources although they are inefficient and generate relatively large amounts of heat. Focal plane arrays for optical telescopes on the Moon will need to be cooled. Much technology development is required for cryocoolers to fill this need. One option is the development of an integrated radioisotope-fueled dynamic power generator and cryocooler to cool the focal plane arrays.

Stable Precision Structures Technologies

Technology is required for large, stable, precision structures to support observatory components on the Moon. Geometrically precise structures using advanced materials such as metal matrix composites are needed. These structures can be designed to have the required very low coefficients of thermal expansion.

The supporting structures for optical telescopes on the Moon need attention to isolation from disturbance, structures and controls interaction, and testing issues as portrayed in Table 6.

In operation, LOUISA will involve sequences of structures that are precisely aligned with tracking to high precision. Technologies will be required to measure very accurately and to make adjustments if needed (Table 7).

Optical Systems Technology Drivers

There are many technology drivers for these optics. They include optical coatings that resist delamination, optics that are stress-free after manufacture, and refractive materials that do not darken or develop color centers. Refractive materials should have low scatter. Adaptive optics will be important for lunar optical telescope applications. Actuator and controls development and power and thermal control for adaptive optics should be pursued.

For mirrors on the lunar surface, active cleaning and contamination control techniques will be needed. Polishing techniques need to be improved; renewable coatings may be required. Materials used for telescopes need to be thermally stable. The appropriate degree of coating hardness against the ultraviolet and X-ray environments of the lunar surface will be needed. The telescope optics will require the necessary vibration isolation.

Table 6. Issues Relating to Large Structures to Support Optics on the Moon

Disturbance Issues

- What are the critical disturbances?
    - Natural - seismic shock, thermal
    - Operations induced - ground shock, vibrations
- What mitigation technologies are applicable?
- How can disturbances be characterized and mitigation approaches formulated?

Structures Issues

- What approaches can be taken to build lightweight, high-stiffness structures optimized for the lunar 1/6 g and extreme thermal environments?
    - Structural parameters - how ascertained?
    - Improved models (computational)
    - Test and instrumentation challenges
    - Optimization
    - Assembly/erection/inspection

Control Issues (for orienting mirrors)

- Control - structure interactions
- Transients and damping in structures optimized for 1/6 g
- Experiments and tests of control mechanics

Testing Issues

- Ground testing on Earth vs. on Moon
- Scaling of terrestrial structures tests to larger structures at 1/6g
- Measurements/instrumentation for terrestrial/lunar use

Table 7. Technology Development for LOUISA

- Surface accuracies
- Precise demountable segments
- Stable frameworks
- Easily transportable pieces
- Disassemble/reassemble without loss of accuracy
- Means for adjustments
- Mounts with pointing accuracies
- Foundations in lunar regolith

Communication and Control Technologies

There are many requirements on the communication system for the lunar astronomical observatory. Communication satellites in lunar orbit may be needed. At a possible observatory site on the far side of the Moon, communication antennas will be needed for uplink and downlink which are high-gain, lightweight, and have low power consumption. Frequency and bandwidth selection for communications must be compatible with radio astronomy and other operations.

Conclusion

The LOUISA observatory needs to be engineered with technologies that make it possible to perform well for long periods of time with minimal intervention by humans or robots. Better astronomy can be done if contamination and interference (gases, particulates, ground shock, and extraneous RF radiation) resulting from nearby operations can be kept to very low levels by limiting the need for nearby operations. An obvious need is to strive for facilities compatibility in lunar surface operations at various sites by controlling and reducing functions (e.g., proximity of mining operations or rocket launch pads to optical astronomy facilities) that lead to undesirable consequences. This need for compatibility implies the enforcement of a broad-based systems engineering discipline to all lunar engineering, construction, and operations.

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Figure Caption

Figure 1: Artist concept of 21st Century Lunar Optical UV-IR Synthesis Array (LOUISA). Outer circle of 33 telescopes is a 10 km in diameter; inner circle is 500 m. From the Moon, LOUISA could distinguish (resolve) a dime at the distance of the Earth. Anticipated resolving power is 4,000 to 10,000 times greater than Hubble Space Telescope.

NOTE: For clarity, the individual telescopes are shown larger than they would actually appear on the Moon.

PART V

REPORTS FROM THE WORKING GROUPS

The following three reports represent efforts on the part of our working groups to (1) review the relative merits of Earth-orbit versus Moon-based interferometers, (2) describe the very exciting science to be performed with LOUISA, and (3) produce a strawman design for the array configuration, optics, metrology, control systems, and power. These reports are the results of nearly two days of brainstorming, using the talents of some of the leading experts in both science and engineering. They are intended to represent a starting point from which future, more indepth studies may begin.

WORKING GROUPS

Science

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Space/Moon Tradeoffs

(Chair: D. Nash)

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