REQUIRED TECHNOLOGIES FOR LUNAR ASTRONOMICAL OBSERVATORIES

N93-17453

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Each of the major new observatories 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. Telescopes for the lunar surface need to be engineered to operate for long periods with minimal intervention by humans or robots. What is essential for lunar observatory operation is enforcement of a systems engineering approach that makes compatible all lunar operations associated with habitation, resource development, and science.

INTRODUCTION

Several types of astronomical observatories have been proposed to take advantage of the unique nature of the lunar environment. These observatories include the Very Low Frequency Array (VLFA) for radio astronomy (*Douglas and Smith,* 1985), the Moon-Earth Radio Interferometer (MERI) (*Burns,* 1985, 1988), and the Optical Interferometer (*Burke,* 1985, 1990). Examples of some of the technology development considerations to be addressed for each of these observatory types are shown in Table 1. With each proposed telescope, there are myriad engineering issues to be resolved (*Burns et al.,* 1990).

ADVANCED TECHNOLOGIES AND CRITICAL ENGINEERING ISSUES

A major difficulty in determining what the critical engineering issues are for these three astronomical observatories on the Moon is that these systems are in their early planning stages and point designs are in the future. 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).

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

CONTAMINATION/INTERFERENCE ISSUE

One of the challenges facing telescope designers and operators is coping with natural and operations-induced sources of contamination/interference (Table 3) on the Moon. Sources of

TABLE 1. Examples of technology development considerations for observatory options.

MERI - Parabolic Dish Radio Antenna
- System definition and specifications
- Site selection and characterization
- Thermal strain rates at sunrise and sunset
- Sun shield
- Foundation excavation and placement
- Foundation dynamics
- Breakdown into transportable packages with semiautomated erectability
- Shielding for electronics and other vital operations

VLF Radio Telescope - Dipoles on Surface over a Large Area
- System definition and specifications
- Site selection and characterization
- Capability to traverse large area and place dipoles
- Erection and shielding of a control facility

Optical Interferometer
- System definition and specifications
- Site selection and characterization
- Control capability (stringent requirements limiting differential settlements, tide compensation)
- Rails several kilometers long laid out on lunar surface require 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 for all Three Options
- 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 and materials either transported from Earth or made on the Moon
- Data gathering, storage, processing, and transmission (e.g., with a communications satellite orbiting the Moon)
- 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
- Self-organizing failure characteristic prediction

TABLE 2. Technologies for lunar observatories.

Contamination/Interference Control	Manufacturing:
Test and Evaluation	Terrestrial
Construction	In space
Power and Cooling/Heating	Lunar
Stable Precision Structures	
Optical Systems	Autonomous/Semiautonomous:
Parabolic Antennas	Deployment
Shielding	Operations
Communications and Control	Maintenance

TABLE 3. Some contamination/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

contaminants and interference 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/interference control technologies needed and then deals with selected other technologies for lunar observatories.

Telescopes on the Moon may tend to be surrounded by transient atmospheres resulting from manned and unmanned operations in the vicinity (*Burns et al.,* 1991). That there will be a transient gas cloud is evident from the work of investigators (T. H. Morgan, personal communication, 1988) 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 by-products of metabolism and suit functions.

TABLE 4. Instrument contamination/interference and possible countermeasures.

Instrument	Possible Contamination/Interference	Possible Countermeasures
VLFA and MERI	Radio frequency interference VLFA—1 MHz to 50 MHz MERI—GHz regime	Preservation/allocation of radio frequencies
	Gases from rocket plumes, manufacturing, construction, excavation, etc. creating denser transient atmosphere and ionosphere	Control and use of "clean" technologies
	Fine-grained particulates from lunar soil clinging to surfaces. Particular concern with MERI relative to erection/operation of steerable dish	Control of gas and dust mitigationtechnology
	Ground shock/vibrations related to pointing and tracking of steerable dish for MERI	Use of "quiet" operations technologies nearby; define keep-out zones
Optical Interferometer	Gases "sticking" to optical surfaces and changing optical properties	Reduction of effluent 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 dust-disturbing operations); 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 to results of data collection

Development of contamination prevention and cleaning techniques

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 that will accelerate and disperse particulates and liberate gases.

CONTAMINATION/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 manufacture, assembly, test and checkout, transportation, landing, erection/deployment, and lunar surface operations/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 et al. (1991), in this volume, discuss environmental effects on astronomical observatories that relate to experience with recovered Surveyor 3, 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, 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 concepualization, 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 system. 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 the suitability questions are of enormous importance when the logistics line of support is from the Moon to the Earth (*Johnson and Leonard,* 1988).

Early involvement of test and evaluation methodologies will start at the telescope system concept level to make adaptation 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 that 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 and radio telescope dishes 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 interferometers. 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 spacesuits. 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 an observatory on the Moon will require the capability to maneuver vehicles over many-kilometer distances in remotely controlled (teleoperated) or preprogrammed operational modes. The VLFA observatory will depend for deployment on the capability to emplace dipoles over surface areas extending to 20 or more kilometers in diameter (*Burns et al.,* 1989). 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 farside of 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 spacesuits 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 VLFA 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 how the vehicle copes 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 VLFA on the lunar surface will be required to support all phases of the effort including transport of large reels of cable, laying out the cable according to the predetermined plan, emplacing a central station, and performing maintenance and repair tasks. The vehicle must have flexibility to meet unanticipated needs such as coping with cable 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. Power requirements will probably be much less than 100 kW for VLFA. Solar arrays appear to be suitable for the VLFA 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/rechargeable power storage devices both large and small for use with solar energy devices to furnish power during the 14-Earth-days 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 also are 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 large optical telescopes and steerable dish radio telescopes on the Moon need attention to isolation from disturbance, structures and controls interaction, and testing issues as portrayed in Table 6.

Some types of observatories on the Moon will involve very large structures or sequences of structures that must be precisely aligned and that must be movable and must track to high precision (e.g., to milliarcseconds). Technologies will be required to measure surface accuracies of millimeter and submillimeter radio astronomy parabolic dishes to 5-10 μm and to make adjustments if needed (Table 7).

TABLE 6. Issues relating to large structures to support optics and steerable radio telescope dishes 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?

Structure Issues
- What approaches can be taken to build light-weight, high-stiffness structures optimized for the lunar ⅙ *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 and radio telescope dishes)
- Control—structure interactions
- Transients and damping in structures optimized for ⅙ *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 ⅙ *g*
- Measurements/instrumentation for terrestrial/lunar use

TABLE 7. Technology development for millimeter and submillimeter astronomy.

- Surface accuracies—10 μm rms or less
- Precise demountable panels
- Stable frameworks
- Easily transportable pieces
- Disassemble/reassemble without loss of accuracy
- Means for adjustments
- Mounts with pointing accuracies better than 6-10 arcsec; tracking of 1-2 arcsec or better
- Foundations in lunar regolith

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. As always, the telescope optics will require the necessary vibration isolation.

PARABOLIC ANTENNA TECHNOLOGIES

Conventional techniques of maintaining the shape of steerable parabolic antennas rely on the use of low expansivity materials and the maintenace of isothermal conditions. As antenna size increases, the conventional approach becomes more difficult, and new materials and designs (*Akgul et al.,* 1990) for assembling, testing, deploying, and stabilizing structues with low natural frequencies (0.01 Hz) will be needed. Over system lifetimes, acceptable performance may depend upon the ability to control antenna shape by means of adaptive mechnical or electronic compensation.

Material systems should be developed to function as protective shields for antenna structures (and mirrors) against the worst extremes of the lunar thermal environment and the micrometeoroid environment.

COMMUNICATION AND CONTROL TECHNOLOGIES

There are many requirements on the communication system for the lunar astronomical observatory. Communication satellites in lunar orbit are needed. At the observatory site on the farside of the Moon, communication antennas will be needed for uplink and downlink that are high-gain, lightweight, and have low power consumption. Frequency and bandwidth selection for communications must be compatible with radio astronomy operations. Figure 1 illustrates the growing interference problem noted at the Very Large Array (VLA) west of Socorro, New Mexico.

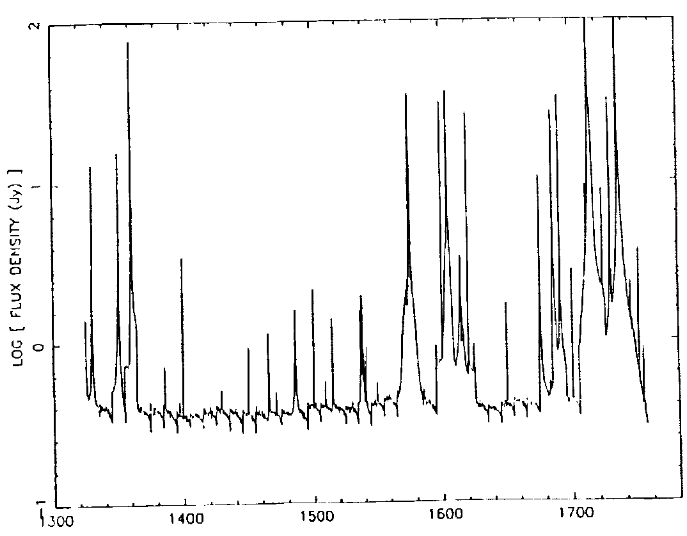

Fig. 1. Radio frequency interference is an increasing problem at the Very Large Array (VLA) west of Socorro, New Mexico, even though the frequency ranges of particular interest are protected by international agreement. The spikes of the man-made interference noted on the figure are of such magnitude to overwhelm signals from radio frequency sources in space. Technology advances should be focused on preventing such interference (from any man-made source) at radio astronomy sites on the farside of the Moon.

CONCLUSION

The need for all the observatories under consideration and for all extraterrestrial facilities is to engineer them 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.

Acknowledgments. The support of BDM International, Inc., the University of New Mexico, and the National Aeronautics and Space Administration (Grant NAG 9-245) Johnson Space Center in the preparation of this paper is acknowledged. We thank T. H. Morgan for perceptive comments on the paper. The authors are grateful for the advice and support of J. Burns, N. Duric, J. Taylor, W. Mendell, M. Duke, and B. Roberts. Appreciation is expressed to J. K. Helmick for preparation of the manuscript.

REFERENCES

Akgul F., Gerstle W., and Johnson S. (1990) Computer-aided structural design of a lunar radio telescope. In *Engineering, Construction and Operations in Space II* (S. W. Johnson and J. P. Wetzel, eds.), pp. 697-706. American Society of Civil Engineers, New York.

Burke B. F. (1985) Astronomical interferometry on the Moon. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 281-291. Lunar and Planetary Institute, Houston.

Burke B. F. (1990) Astrophysics from the Moon. *Science, 250,* 1365-1370.

Burns J. O. (1985) A Moon-Earth radio interferometer. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 293-300. Lunar and Planetary Institute, Houston.

Burns J. O. (1988) 21st century astronomical observatories on the Moon. In *Engineering, Construction, and Operation in Space* (S. W. Johnson and J. P. Wetzel, eds.), pp. 1083-1094. American Society of Civil Engineers, New York.

Burns J. O., Dunic N., Johnson S., and Taylor G. J., eds. (1989) *A Lunar Far-side Very Low Frequency Array.* NASA CP-3039. 78 pp.

Burns J. O., Duric N., Taylor G. J., and Johnson S. W. (1990) Astronomical observations on the Moon. *Sci. Am., 262,* 42-49.

Burns J. O., Fernini I., Sulkanen M., Duric N., Taylor, J. and Johnson S. (1992) Artificially generated atmosphere near a lunar base. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Douglas J. N. and Smith H. J. (1985) A very low frequency radio astronomy observatory on the Moon. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 301-306. Lunar and Planetary Institute, Houston.

Johnson S. W. (1988) Engineering for a 21st century lunar observatory. *J. Aerosp. Eng., 1,* 35-51.

Johnson S. W. and Leonard R. S. (1988) Engineering test support for construction in space. *J. Aerosp. Eng., 1,* 206-218.

Johnson S. W., Taylor G. J., and Wetzel J. P. (1992) Environmental effects on lunar astronomical observatories. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Sovie R. J. (1988) Power systems for production, construction, life support and operations in space. In *Engineering, Construction, and Operations in Space* (S. W. Johnson and J. P. Wetzel, eds.), pp. 928-939. American Society of Civil Engineers, New York.