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ENVIRONMENTAL EFFECTS ON AN OPTICAL-UV-IR SYNTHESIS ARRAY

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Abstract

The Moon offers a stable platform with excellent seeing conditions for the Lunar Optical-UV-IR Synthesis Array (LOUISA). Some troublesome aspects of the lunar environment will need to be overcome to realize the full potential of the Moon as an observatory site. Mitigation of negative effects of vacuum, thermal radiation, dust, and micrometeorite impact is feasible with careful engineering and operational planning. Shields against impact, dust, and solar radiation need to be developed. Means of restoring degraded surfaces are probably essential for optical and thermal control surfaces deployed in long-lifetime lunar facilities. Precursor missions should be planned to validate and enhance the understanding of the lunar environment (e.g., dust behavior without and with human presence) and to determine environmental effects on surfaces and components. Precursor missions should generate data useful in establishing keepout zones around observatory facilities where rocket launches and landings, mining, and vehicular traffic could be detrimental to observatory operation.

Introduction

The Moon's environment makes it an excellent place for a Lunar Optical-UV-IR Synthesis Array (LOUISA) (Burns and Mendell 1988). Some of the environmental factors that make the Moon a useful platform for astronomy, however, are not benign and will require special efforts to mitigate their effects. This paper reviews degradation of the components and systems, summarizes results of studies of Surveyor III components exposed to the lunar environment, and presents a preliminary assessment of ways to diminish the damaging effects of the space environment. In the previous paper in this volume, G. Jeffrey Taylor discusses the lunar environment and its effect on optical astronomy. That paper discusses the tenuous atmosphere, the extremes of radiation, micrometeorite flux, dust, and other aspects of the environment. That discussion will not be repeated here and the reader is referred to Taylor's paper.

Degradation of Materials and Systems

The Surveyor III spacecraft landed on the Moon on April 20, 1967. Apollo 12 astronauts Conrad and Bean subsequently visited Surveyor III on the lunar surface in 1969. They retrieved components which they returned to Earth.

Investigations of Surveyor components. Surveyor III components were studied on Earth after these parts had been exposed to the lunar environment for 31 months (roughly 32 lunar days) from April 20, 1967, until November 20, 1969. The following parts were studied (Nickle 1971; Carroll et al. 1972):

(1) the television camera, which included optics, electronics, cables, and support struts;

(2) the scoop portion of the soil mechanics surface sampler device (which contained more than six grams of lunar soil);

(3) a section of polished aluminum tube 19.7 cm long; and

(4) a section of cabling and painted aluminum tube.

These parts were analyzed for surface changes and characteristics (e.g., adherence of soil particles, sputtering, and UV-induced degradation of thermal control coatings), micrometeorite impacts, radiation damage, particle tracks, and naturally induced radioactivity.

Although the Surveyor III was on the lunar surface for 31 months, it was operated for only two weeks. It experienced 30 1/2 months exposure in a dormant or nonoperating state. Involved were 1500 resistors, capacitors, diodes, and transistors in the camera returned to Earth. Tests after recovery verified the integrity of most parts after 31months on the Moon (Carroll et al. 1972). A few components failed apparently because of thermal cycling to very low temperatures (e.g., a tantalum capacitor) and as a result of thermal strain (e.g., glass envelopes). Some failures caused a cascade of failures. For example, a failure of the circuit that drove the shuttle was caused by the failure of a transistor that had been degraded in a preflight test; this caused failure of a shuttle solenoid, which in turn caused evaporation of a photoconductor in the vidicon as a result of the shuttle being open (Carroll and Blair 1972).

Solar radiation and effects. The maximum time of exposure of solar radiation during the time the retrieved parts were on the lunar surface is theoretically 10,686 hrs. Shadowing effects limited actual exposure times to considerably less than the theoretical maximum. It was, for example, estimated that the clear optical fiber on the camera had a total exposure of only 4180 h, but that the scoop arm, which had been left fully extended at maximum elevation in 1967 at the Surveyor mission termination, had a total exposure of 9078 h.

As the evaluation of Surveyor III parts was in progress, the tan color of the originally white joint faded due to photobleaching. Photobleaching of induced optical damage can also occur. Therefore, hardware must be sampled and returned carefully to avoid or account for subsequent alteration in the terrestrial laboratory environment (Carroll and Blair, 1972). Although some environment-induced failures occurred, it is clear from the superb results obtained by most experiments of the Apollo Lunar Surface Experiments Packages (ALSEP), that it will be possible to produce systems that will function through many lunations.

Degradation of thermal control coatings. Coatings exposed to the space environment exhibit radiation-induced darkening that increases with time. After 31 months on the Moon, inorganic coatings originally white were tan in appearance. This discoloration was observed to be in a pattern consistent with the amount of irradiation received (Carroll and Blair 1971). Overall discoloration patterns were the result of several effects attributable to solar radiation (e.g., in the ultraviolet), lunar dust, and products of organic outgassing from spacecraft parts (Carroll and Blair 1971). Dust and irradiation played the key roles in altering the appearance (and usefulness) of the surface coatings.

The blue color of the scoop faded to a whitish blue. The surfaces painted with inorganic white degraded from a solar absorptance of 0.2 to 0.38 up to 0.74, depending on orientation. Polished aluminum tubes rose in absorptance from 0.15 to 0.26 (on a "clean" or relatively dust-free surface) to 0.75 where dust was present (Anderson et al. 1971).

The greatest changes in reflectance were for shorter (0.6 to 1.0 μm) as opposed to longer wavelengths (up through 2.0 or 2.4 μm). Both solar radiation and dust were instrumental in decreasing reflectance.

Dust presence. It was estimated that the upper portion of the clear filter, which was positioned over the Surveyor camera lens by remote command at the close of the Surveyor III mission, had 25 percent of its surface area covered by particulate material. This fine-grained lunar soil had a median grain size of 0.8 µm and ranged up to 15 µm in size (Nickle 1971). Dust on the Surveyor mirror was thought to have caused a marked loss of contrast in relayed pictures during the performance of the Surveyor mission (Carroll and Blair 1971). "Lunar material, even in small quantities, can have a significant effect on temperature control and optical performance of hardware on the lunar surface" (Carroll and Blair 1972). Even 10^{-5} to 10^{-4} grams per cm^2 of lunar fines can increase absorbed solar thermal energy for a reflective thermal-control surface by a factor as large as 2 or 3 (Carroll and Blair, 1972). On the other hand, there are no reports of degradation of the laser reflectors left by three Apollo missions.

Sources of dust. There was dust on the returned Surveyor III television camera attributable to one or more of five sources (Carroll and Blair 1971):

(1) the disturbance of the soil during the Surveyor III landing, accentuated by the vernier descent engines that continued thrusting during two rebounds from the lunar surface;

(2) disturbance mechanisms operating on the Moon (e.g., meteoroid impact and electrostatic charging);

(3) Apollo 12 lunar module approach and landing;

(4) operation of the scoop on the Moon; and

(5) retrieval and return to Earth by Apollo 12 astronauts.

The Surveyor III and lunar module (LM) landings were probably the most significant sources of the dust found on the camera. The LM descent engineer, which disturbed the dusty surface over the last 1000 ft of its ground track before landing 155 m away, was probably the most significant dust source. Dust was accelerated by the LM rocket plume to velocities in excess of 100 m/s. This accelerated dust literally sandblasted the Surveyor III and removed much discolored paint (Cour-Palais et. al 1972).

Erosion surfaces in the lunar environment. Three processes may be considered in evaluating erosional effects on parts exposed to the lunar environment (Barber et al. 1971):

(1) sputtering of individual atoms by the solar wind (mainly hydrogen);

(2) damage from solar flare heavy nuclei (e.g., Fe); and

(3) micrometeorite impact.

Estimated erosion rates per year from these effects are very small (e.g., 0.4A for sputtering, 0.1 to 0.4A for heavy nuclei, and 1 to 2A for micrometeorite impacts). Micrometeorite impact is probably the most significant mechanism of the three for degradation of telescope optical surfaces, although the effects of sputtering on optical coatings over several years require a restorative capability or replacement.

Results of examinations for micrometeoroid impacts. The television camera shroud, the camera's optical filters, and a piece of aluminum tube were scanned for possible craters resulting from micrometeorite impacts. Magnifications in the range of 25X to 40X and greater were used over substantial portions of the surfaces of these objects as the search for impact craters proceeded (Cour-Palais 1971; Brownlee et al. 1971).

No hypervelocity impact craters were identified in the original studies on the 0.2 m^2 of the shroud or on the optical filters. Five craters ranging in diameter from 130 to 300 μm were noted as having a possible hypervelocity impact origin. The many other craters found were thought to have originated as a result of impact of low velocity debris accelerated by the lunar module descent engine plume. However, continued study of the Surveyor materials and of impact pits on lunar rocks led to a reevaluation of the original Surveyor data (Cour-Palais 1974), which indicated that most of the craters on the returned material were hypervelocity impact pits. Nevertheless, damage from low velocity impact was still substantial.

Buvinger (1971) performed an investigation by electron replication microscopy of two sections of the unpainted aluminum tubing. Erosion damage apparently resulted from impact of soil particles during landing maneuvers. Some pits in the approximately 1 mm range had some characteristics of hypervelocity impacts. Solar-wind sputtering apparently had little effect on the tube and damage by particle impact was apparently by lower velocity particles and limited to a depth no greater than 2 mm.

Mitigation of Degradation

As Carroll et al. (1972) noted, "The need to protect optical elements from dust contamination was obvious during Surveyor III lunar operations in 1967 and was confirmed during analysis of returned hardware. All other optical performance information gained from post-mortem analysis is secondary to this conclusion."

LOUISA design and operation can mitigate and compensate for the potentially detrimental effects of solar radiation, dust accumulation, surface erosion, changes in thermal control coatings, and micrometeorite impacts. We outline below some ideas for blunting the hazardous effects of the lunar environment.

Dust mitigation. Rocket landing and ascent operations can be performed at locations sufficiently far removed from observatory sites to prevent dust erosion and accumulation on optics, antenna, and thermal control surfaces. Shielding against dust driven by rocket plumes may be useful. How great the required keep-out distances or shielding heights against accelerated dust must be depends on the rocket engine and plumes. Keep-out distances may be in excess of 1000 ft based on the extent of LM descent engine sand blasting effects, dust disturbance, and deposition on Surveyor III components.

Harrison "Jack" Schmitt (personal communication, 1988) suggested using optics provided with lens caps that could be remotely controlled to cover and protect optical surfaces before permitting construction and repair teams to approach observatories on the Moon. He noted that the lunar dust is difficult to avoid in astronaut and vehicular traffic on the Moon.

Preserving thermal control surfaces. Some telescope components and other base facilities will be dependent for temperature control on use of thermal control coatings designed to have appropriate values of absorptance and reflectance. If these coatings degrade--as was noted in the case of Surveyor III coatings--temperatures of critical components will deviate from specified values and diminish or negate observatory performance. Protecting coatings by use of layers that intercept UV radiation may help. More stable coatings applied under conditions avoiding contamination may also help.

Use of shields. Shields against micrometeorite impact, dust particles, and solar radiation can be devised to reduce the probability of impact, contamination, or interference by stray light rays. Shields can reduce the probability of impact on optics by reducing the portion of the sky from which impacting particles can originate. Appropriate baffles can prevent the shield from directing stray or scattered light on mirrors or other optics.

Restoration. According to Watson et al. (1988), equipment for restoring coatings on telescope mirrors and thermal control surfaces has been developed and tested on orbit by the USSR. These metal coating operations were performed in space after extensive experimentation in ground-based laboratories to overcome technical difficulties associated with heating, vaporization, and deposition of aluminum. In 1975, cosmonauts Gubarev and Grecho were reported to have recoated the mirror of a solar telescope on the Salyut spacecraft in 1979, 1980, and 1984. Details have not been made available, but results were reported as excellent. These coating-technology experiments suggest that the capability to restore optical and thermal control surfaces degraded by exposure to the space environment may be available for astronomical observatories on the Moon.

It has also been suggested that large mirrors for space use be composed of numerous replaceable segments so that if impact or abrasion causes damage, only the degraded portion need be replaced. Also, mirror surface coatings should be selected that are compatible with cleaning processes and reduce electric charge effects (Bouquet et al. 1988).

Laboratory investigations. Laboratory studies have played and continue to play an important role in estimating the degradation likely when components of space systems are exposed to the space environment. The thermal-vacuum test (Flanagan 1986) will be an essential step in the development and preflight preparations for any observatory components to be deployed on the lunar surface. The systems will be subjected to vacuum and thermal cycling comparable to that found on the Moon to assure that they are capable of operating under very cold and very hot conditions and can accommodate large temperature gradients.

Vacuum chambers with thermal cycling can also include solar simulation which provides an approximation of the solar spectrum. Micrometeorite protection systems can be designed based on available laboratory data (e.g., from light gas guns and Van de Graff Generators) and data gathered from recovered components (e.g., the Long Duration Exposure Facility (LDEF) and , Solar Max).

Precursor missions. Plans to return to the Moon should include visits to at least one Apollo landing site to ascertain the degradation and changes in selected Apollo materials and components. Six Apollo landings were made between 1969 and 1972, and a wide range of equipment was left on the surface, including the descent stages of the LM, Lunar Roving Vehicles (LRV), and the ALSEPs. Items to be studied include thermal blankets, optics, retroreflectors (for laser ranging), batteries and motors (e.g., on the LRV), communications equipment such as parabolic dishes, various pieces of tankage, and test equipment.

These parts can be studied to ascertain the degradation caused by long-term exposure to micormeteorite bombardment, solar and cosmic radiation, thermal cycling, and vacuum. Areas for study are suggested by the previous experience with Surveyor hardware (Scott and Zuckerman 1971). To be determined are dust and radiation darkening of surfaces, particle impact effects (both primary and secondary), and the effects of long-term thermal cycling in vacuum.

The goals of the visit and study will be to improve the technology for design, fabrication, and test of future lunar astronomical observatories (Johnson 1988), enhance our understanding of processes that occur on the Moon and of the rates at which they operate, and to check the validity of accepted design approaches. Figure 1 demonstrates a generic representation of our need to better understand lunar environmental degradation (Johnson and Wetzel 1988). As shown in the figure, we possess a very limited amount of experience with lunar surface degradation. We must gather additional information about degradation and its effects over a long period of time. For example, revisiting and studying the materials and equipment from the Apollo sites will allow us to acquire information about lunar degradation in the 30-yr time range.

Examination of Apollo materials will be extremely valuable, but will leave many questions unanswered. Additional experiments will be required to fully understand micrometeorite impacts (both primary and secondary), dust levitation, and assorted operational disturbances.

Apollo materials will shed light on the present flux of micrometeorites and shrewd collection of surfaces shielded from direct impact will provide crucial information about the flux of and damage done by secondary projectiles. Nevertheless, an array of micrometeorite detectors, either passive or active, ought to be deployed on the lunar surface to obtain information on fluxes, masses, velocities, and directions of impacting particles. A device of this sort was emplaced during the Apollo 17 mission (Berg et al. 1973). Furthermore, instruments like this will be developed for use on the Space Station. In addition to supplementing data that will be obtained from study of surfaces of the Apollo spacecraft and instruments, the new generation of lunar surface micrometeorite detectors will provide up-to-date data and a basis for comparison with detectors in low Earth orbit (LEO). This will help establish the natural flux in LEO, a critical parameter to know if we are to accurately monitor the growth of manmade debris in LEO.

As noted earlier, Criswell (1972) suggested that a brightening at the horizon in Surveyor photographs taken shortly after sunset was caused by electrostatic effects. The idea is that electrons are removed by the photoelectric effect when sunlight strikes the surface. This results in a charge imbalance with the uncharged surroundings, causing small grains to be lifted off the ground. It seems prudent to determine the extent to which this process operates and assess whether it will interfere with lunar surface operations. It might, for example, cause micron-sized dust grains to be deposited on telescope mirrors, thereby degrading astronomical observations. An active detector designed to measure that flux and size distribution of low-velocity dust grains could provide the necessary information.

It will also be necessary to monitor disturbances caused by lunar base operations. This includes dust raised by rockets landing and taking off, vehicles moving, and astronauts walking. For example, if astronauts are needed to service telescopes, one must know how much dust could be transferred from their space suits onto a mirror. Perhaps this could be measured by having astornauts approach a low-velocity dust detector. If significant dust were measured, other means of servicing telescopes would have to be devised. Disturbance by the transportation system could also be monitored by an array of dust detectors.

Summary and Conclusions

Although the Moon is an excellent place for astronomy, special efforts will be required to mitigate or compensate for detrimental effects of the lunar environment on LOUISA components. The most troublesome characteristics of the lunar environment are the vacuum (which leads to outgassing), solar and cosmic radiation, micrometeroite impacts, the surface temperature regime, and the ubiquitous dust particles.

Valuable information on degradation of parts and systems in the lunar environment was obtained by retrieval to Earth and careful analysis of Surveyor III components. These components had been on the Moon nearly 32 lunar days from April 1967 to November 1969. Most parts retained their integrity, but a few failed (e.g., because of thermal cycling). Degradation of coatings also occurred, primarily because of ultraviolet radiation and the static and dynamic effects of dust particles on optical and thermal-control surfaces. The dust can cause scattering of light and loss of contrast in optical trains.

Several approaches can be taken to mitigate the negative effects of the lunar environment on astronomical observatory components. First, an effort is needed to better understand and model the degradation mechanisms. This effort should be addressed early in precursor missions to the Moon. Second, operational rules will be necessary to confine activities that generate dust and rocket plumes to zones outside those where astronomical observatories are being used. When it is necessary to approach the observatory sites with vehicles and construction or maintenance teams, precautionary shielding should be activated to protect optics and reduce deposition on thermal-control surfaces. Processes will eventually be needed to clean and restore dusty and impact-damaged surfaces. Fortunately, the lunar environment, although dusty, lacks the hazards in LEO associated with atomic oxygen and orbiting debris, such as chips of paint, from previous missions.

Although the lunar thermal regime offers a severe test of observatory components, careful engineering can control degradation, and the number of cycles to be endured (about one per month) is much fewer than cycles encountered in LEO (about 480 per month). The environment on the lunar surface is conducive to the use of shields and baffles against micrometeorite impact, dust particles, and solar radiation. Experiments in terrestrial laboratories and precursor missions to the Moon are needed to assist in predicting degradation and in reducing its ravaging effects on future lunar astronomical observatories. Restoration processes should be developed to enhance the longevity of observatory components on the Moon. The technology of degradation mitigation that will be developed will apply not only to astronomical observatories, but also to a wide range of lunar base elements. It is prudent to initiate studies of lunar environmental effects early so that beneficial results can be implemented early in the planning of all lunar base facilities.

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Precursor missions

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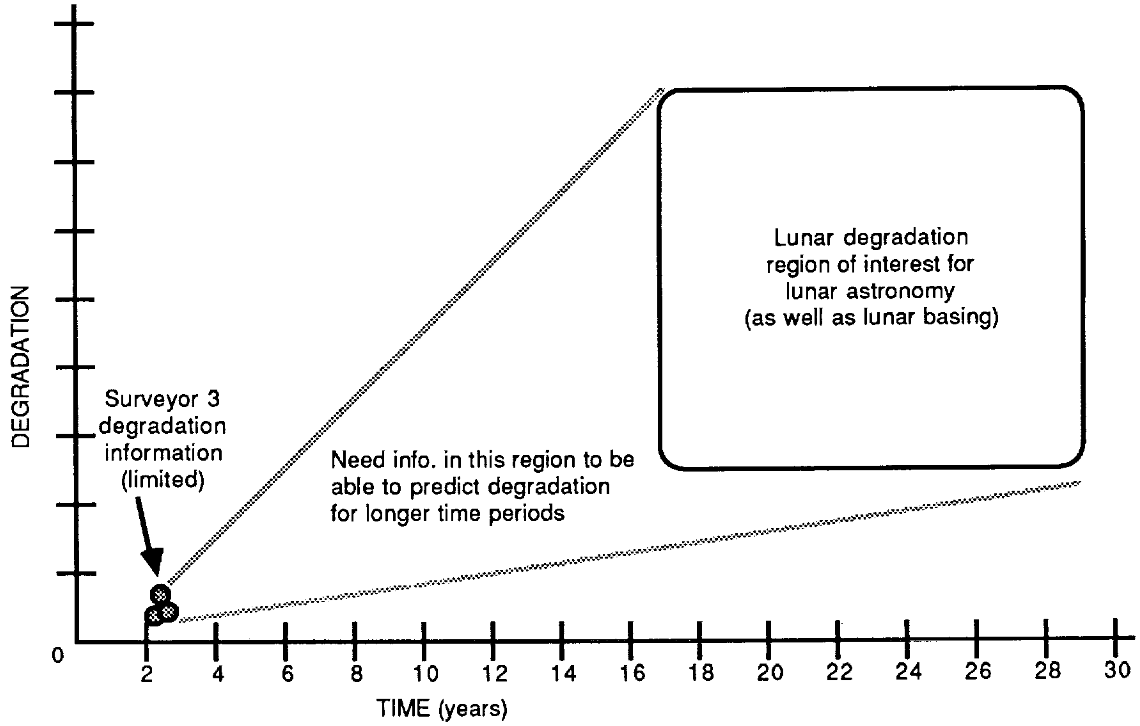

Figure 1. Schematic representation of the information needed to investigate degradation on the lunar surface over a long period of time.