

THE LUNAR ORBITAL PROSPECTOR

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The establishment of lunar bases will not end the need for remote sensing of the lunar surface by orbiting platforms. Human and robotic surface exploration will necessarily be limited to some proximate distance from the support base. Near real-time, high-resolution, global characterization of the lunar surface by orbiting sensing systems will continue to be essential to the understanding of the Moon's geophysical structure and the location of exploitable minerals and deposits of raw materials. The Lunar Orbital Prospector (LOP) is an orbiting sensing platform capable of supporting a variety of modular sensing packages. Serviced by a lunar-based shuttle, the LOP will permit the exchange of instrument packages to meet evolving mission needs. The ability to recover, modify, and rotate sensing packages allows their reuse in varying combinations. Combining this flexibility with robust orbit modification capabilities and near real-time telemetry links provides considerable system responsiveness. Maintenance and modification of the LOP orbit are accomplished through use of an onboard propulsion system that burns lunar-supplied oxygen and aluminum. The relatively low performance of such a system is more than compensated for by the elimination of the need for Earth-supplied propellants. The LOP concept envisions a continuous expansion of capability through the incorporation of new instrument technologies and the addition of platforms.

INTRODUCTION

Human and robotic exploration of the Moon during the last two decades has greatly increased our knowledge of the Moon's geophysical and geochemical nature. The Ranger, Surveyor, Lunar Orbiter, Luna, and Apollo missions returned vast amounts of data by means of orbit-based photography, remote sensing, and lunar surface samples. Notwithstanding these efforts, coverage of the Moon by remote sensing remains woefully inadequate. Data from the Ranger and Surveyor missions were limited to a few isolated sites, and the Lunar Orbiter missions provided only photographic information. Although the Apollo command modules carried remote-sensing instruments, their data were obtained only at low latitudes.

One of the primary reasons for establishing a manned lunar presence is the possibility of exploiting the Moon's resources. In addition to a known abundance of lunar oxygen and various metals, undiscovered resources, possibly large deposits of lunar ores, probably exist in permanently shadowed polar craters (Watson *et al.*, 1961), and early lunar volcanic activity may have provided a mechanism for forming large ore and mineral deposits near the lunar surface (Vaniman and Heiken, 1985). Given the known resource potential of only a few explored lunar sites (high concentrations of oxygen, titanium, and aluminum were found in many Apollo surface samples), the existence of large deposits of these and other yet undiscovered lunar ores seems highly likely.

Although a manned presence is required for the recovery of lunar resources, a global search for these resources requires highly advanced remote-sensing satellites.

A remote-sensing orbital mission, such as the planned Lunar Geoscience Observer (LGO), is a necessary precursor to the development of a manned lunar base. The need for a mission of this nature, however, does not end with the establishment of the base. Several of the most fundamental geophysical and geochemical questions, such as the composition, structure, and thermal state of the interior, can be adequately addressed only by long-term observation and electromagnetic sounding of the lunar

surface (Hood *et al.*, 1985). A long-term remote-sensing mission, in conjunction with a manned lunar base, can expand the LGO's geophysical and geochemical database and serve as the "eyes and ears" of the manned base by searching for lunar transient events and by monitoring humans' impact on the lunar environment. The LGO provides a great start, but its limited lifetime and its inability to evolve to meet changing mission requirements prevent its meeting long-term needs.

THE LUNAR ORBITAL PROSPECTOR

The Lunar Orbital Prospector (LOP) is a lunar-based, orbiting platform whose primary mission is to prospect the Moon in support of early lunar colonization and exploitation. Using the LGO mission as a baseline, the LOP mission is designed to support the next generation of lunar exploration in conjunction with a manned base.

The primary purposes of the LOP are to map the Moon's chemical and mineralogical composition and to conduct lunar science studies from orbit. Data returned from onboard passive and active sensors will identify mineral and chemical species and allow examination of surface and subsurface geological structures. Through careful processing and examination of sensed information, lunar resource distribution on a global scale can be determined.

Perhaps the LOP's most important characteristic, and its primary improvement over the LGO, is its highly modular design. Remote-sensing instrument packages can be exchanged or upgraded to fulfill many different mission requirements. Subsystems that support the science instruments, e.g., power and communications, can also be upgraded as needs dictate. This modularity also permits the refurbishing and reuse of sensing packages.

MISSION DESCRIPTION

The LOP mission is divided into three primary phases: transport from Earth to low lunar orbit (LLO), operation in lunar orbit, and platform servicing in lunar orbit. Transport of the LOP from Earth

can be accomplished by a vehicle with a 1000-kg translunar payload capability. This is within the range of the Titan 34D with an upper stage or a space shuttle/upper stage combination. The upper stage provides the initial translunar insertion burn, and the platform's onboard propulsion system provides midcourse corrections and lunar orbit insertion burns.

After delivery to LLO, normal orbital operation commences. The initial orbit is baselined to be a 100-km, near-polar orbit to permit global viewing of the lunar surface. The initial remote-sensing package is projected to be an updated version of the LGO instrument suite. The basic objectives of the initial mission are to conduct a global survey of the Moon, calibrate instruments, and gain experience with the spacecraft.

Since the platform can mount various remote-sensing instruments, many types of follow-on missions can be contemplated. Conceivably, these will be more ambitious and complicated. When such missions are desired, a lunar-based servicing vehicle provides a means for changing instrument systems and spacecraft subsystems. This operation is illustrated in Fig. 1. The LOP propulsion module can also be replaced by a refueled version, thus renewing the platform's ability to change orbits. This ability to service the platform in lunar orbit allows a great deal of mission

flexibility in support of new exploration and science needs, and is vital to the utility and usability of the LOP.

The general configuration of the LOP is driven by three major requirements: overall system modularity and expandability, on-board propulsion, and a preferential nadir-pointing instrument platform. The system configuration is shown in Fig. 2.

The overall configuration objective is to allow the system to grow and adapt to new and different science and exploration needs. The base structure provides 24 mounting ports on the sides of the spacecraft to support power, communications, attitude control, and minor instrument subsystems. The ports provide the necessary power and communications utilities to support these subsystems. The propulsion module is located on the anti-nadir end of the LOP; the primary remote-sensing instruments are mounted opposite the propulsion module in the preferential nadir-pointing direction. This latter position gives the instruments required nadir viewing while providing unrestricted expansion away from undesired spacecraft thermal and magnetic interference.

Communications are provided by four phased-array, medium-gain antennae mounted on the sides of the spacecraft. These antennae are electronically steered to track relay satellites located

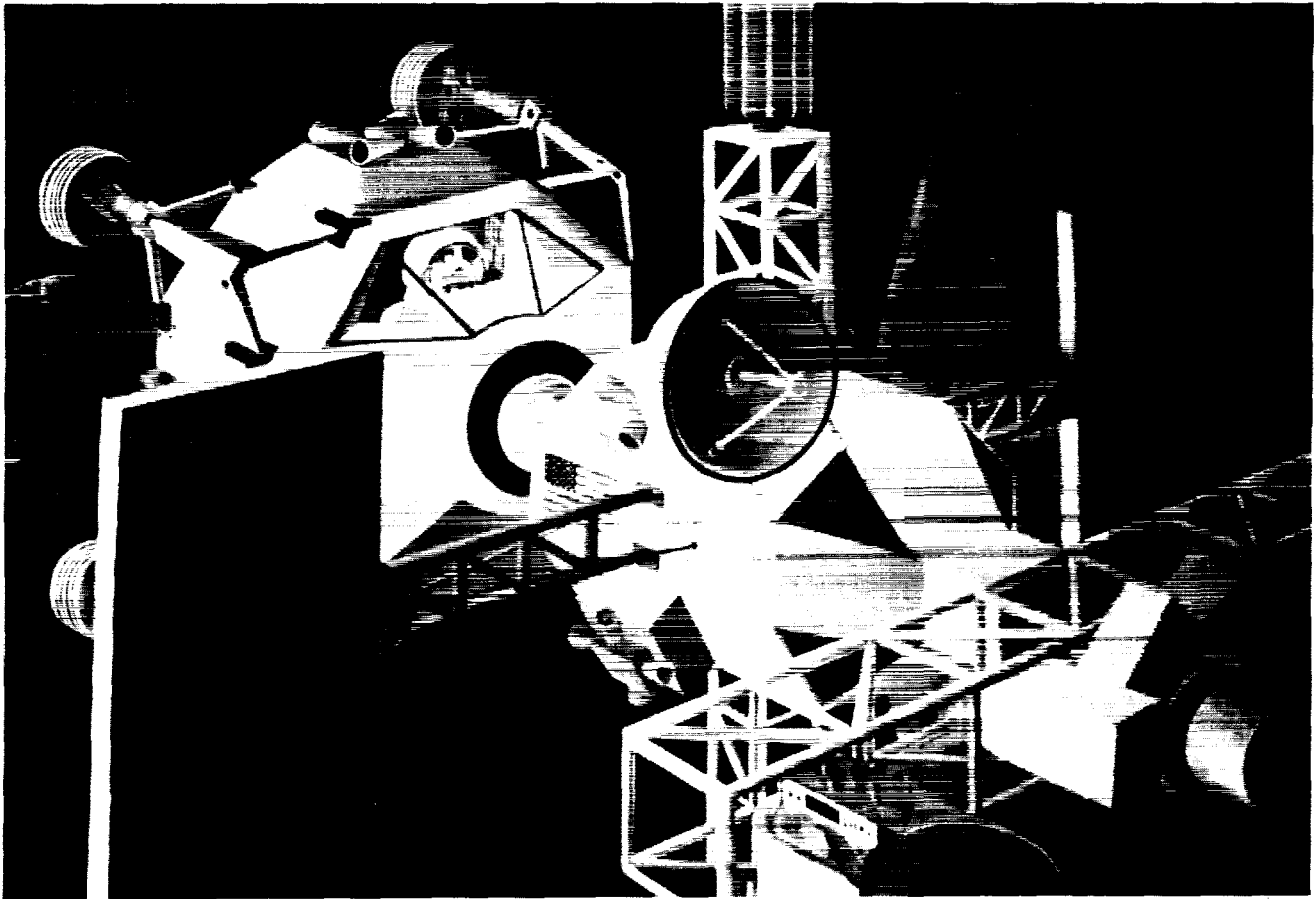


Fig. 1. To accomplish on-orbit servicing, the LOP relies on the use of a lunar based servicing vehicle. This illustration shows the servicing vehicle docking on the LOP's antinadir end. Any vehicle capable of on-orbit satellite servicing can perform this function; this eliminates the need for a specialized vehicle to perform this function.

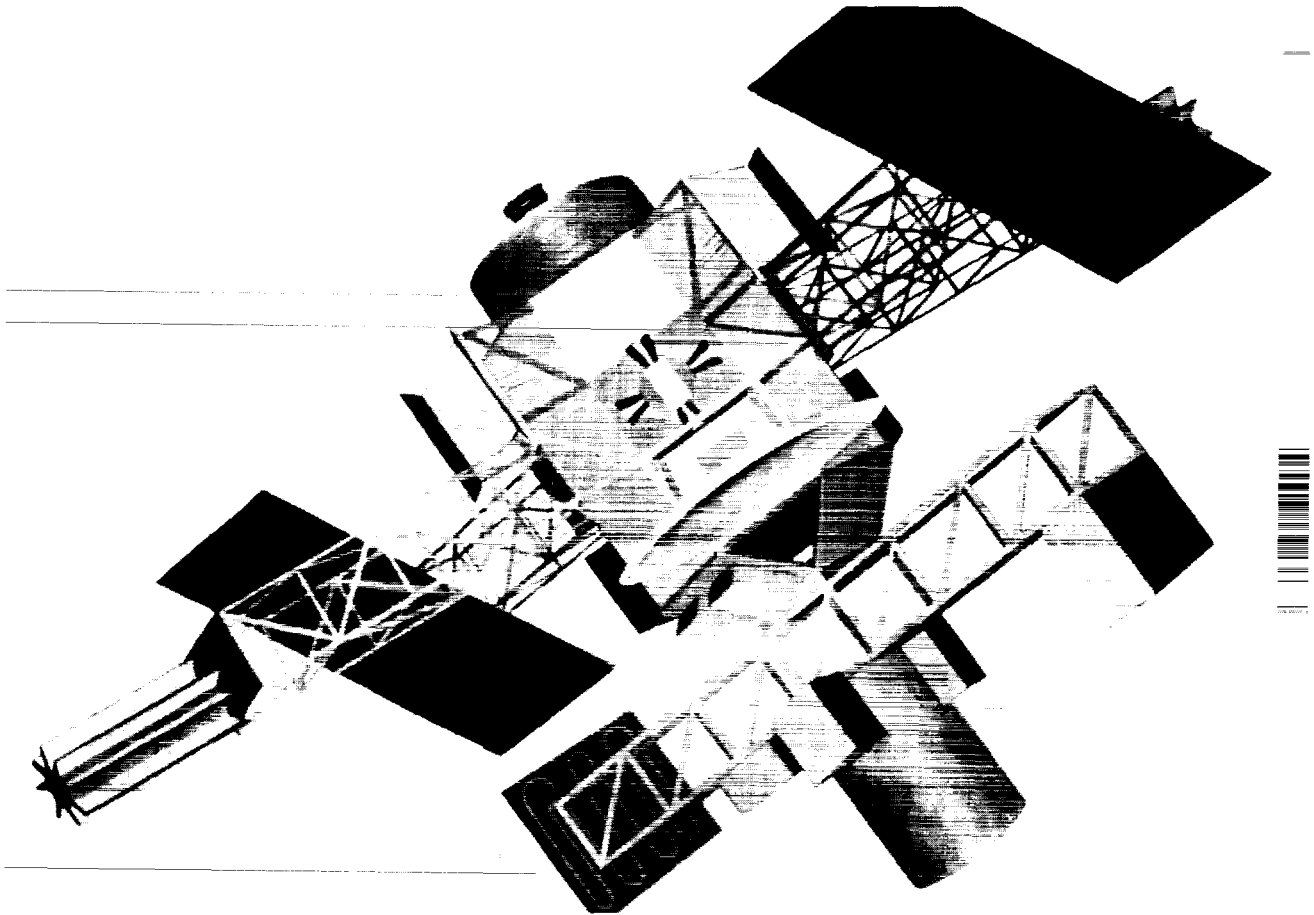


Fig. 2. The LOP consists of three major systems: the primary structure, the propulsion module, and the remote-sensing instrument package. The primary structure houses the propulsion module on its antinadir end. The remote-sensing instruments are mounted on the lower portion of the satellite in the nadir direction.

at LaGrange points L1 and L2. The relay satellites and their locations allow constant data transmission to either the lunar base or Earth. Present estimates indicate that a data rate of 10^9 bps will be attainable. If this rate is achieved, real-time transmission of a $1024 \times 1024 \times 8$ -pixel image can be performed without data compression or storage.

The spacecraft is expected to pitch continuously to maintain nadir pointing, and yaw as required to position solar panels normal to incident sunlight. Attitude control is maintained by a bias momentum system consisting of four bias momentum wheels, hydrazine control thrusters, and pitch and roll attitude sensors. Analysis estimates that the average pitch pointing accuracy will be approximately ± 2 mrad. In the event of attitude control failure, the satellite is gravity-gradient stabilized.

The following sections will further amplify the unique characteristics of LOP remote-sensing packages, subsystems, orbital strategies, and mission considerations. The remote-sensing discussion will focus upon instrument systems that are not included within the capabilities of the currently envisioned LGO. Readers interested in the LGO instrument suite are referred to "Contributions of a Lunar Geoscience Observer" (*LGO Science Workshop*, 1986). The use of a propulsion system designed to use lunar-derived propellants is also emphasized.

REMOTE-SENSING INSTRUMENTS

Two sensor systems are discussed: the Remote Raman Spectrometer (RRS) and the Radar Subsurface Mapper (RSM). Neither of these instruments can be flown on the LGO due to size and mass constraints and the priority of other sensor payloads. However, both the RRS and the RSM can greatly enhance our understanding of the Moon.

REMOTE RAMAN SPECTROSCOPY

The RRS is an active remote-sensing instrument; it uses a laser to stimulate raman emissions at the lunar surface, which are received by an onboard detector system. This instrument is more sensitive than the LGO's present instruments and it yields much higher spatial resolution. It is expected to detect more mineral and chemical species.

The primary advantages of using raman spectroscopy in lunar remote sensing over traditional methods such as reflectance and gamma-ray spectroscopy are (1) the raman spectra of most substances are less ambiguous than corresponding reflectance spectra; (2) the obtainable spatial resolution is better; (3) smaller

concentrations of mineral and chemical species can be detected; (4) an estimate of concentrations is obtainable; and (5) raman spectroscopy can be used to study additional features of the molecule beyond composition and volumetric concentration.

Raman scattering has been used extensively in laboratory applications to study molecular and crystal structures of substances. Raman spectroscopy has also been applied to the analysis of extraterrestrial materials such as the Apollo Moon rocks (Karr, 1975). The application of raman spectroscopy to remote sensing has been very limited, however. This is due mostly to the very weak nature of raman scattering; the raman spectra intensity is approximately six orders of magnitude smaller than the incident light intensity. The return of raman scattering is also further weakened by the presence of an atmosphere that scatters the returning signal. Despite this, some atmospheric pollution studies have been performed using remote raman spectroscopy and have met with limited success (Freeman, 1974).

Recent advances in laser, detector, and filter technology will allow the raman scattering principle to be more successfully applied to remote-sensing applications. This is particularly true on the Moon, where the lack of an atmosphere and its cold surface temperatures are favorable environmental conditions.

Principles of Raman Spectroscopy

Incident light can interact with a substance by either absorption or scattering. This interaction can be thought of as photons colliding with molecules. Absorption occurs when a molecule completely absorbs the photon's energy and no photons are re-emitted. Scattering occurs when a molecule absorbs a photon's energy and re-emits photons at the same or different energy. When there is no change in photon energy, this is known as rayleigh scattering. When photons are re-emitted at a different energy, this is known as raman scattering. The change in the photon's energy gives rise to a change in its wavelength and frequency.

The distinguishing characteristic of the raman effect is the shift in frequency that occurs between the exciting light energy and the re-emitted light energy. This frequency difference, called the raman shift, is directly characteristic of the molecule and is independent of the incident light frequency. Figure 3 illustrates laboratory raman spectra of two lunar materials. The high intensity spikes represent raman lines characteristic of the lunar materials. These lines are shifted from the incident laser frequency, and they correspond to photons that are reflected back at energies different than the laser light.

Raman scattering can be further understood by examining the energy changes that take place in the molecule. When raman scattering occurs, some of the molecules in the substance return to a different energy level than they had before the collision with the photons. Since the molecules have either gained or lost net energy during the collision, the photons will be emitted with a corresponding loss or gain in energy. The molecular energy transition $E_2 - E_1$ can be related to the photon's energy change by

$$E_2 - E_1 = -h\delta\nu \quad (1)$$

where h is Planck's constant, and $\delta\nu$ is the photon's shift in frequency. Molecules that pass to a lower energy state scatter photons at a higher frequency; this gives rise to what is known as antistokes lines. Molecules that change to a higher energy state give rise to a decreased photon frequency called a stokes line.

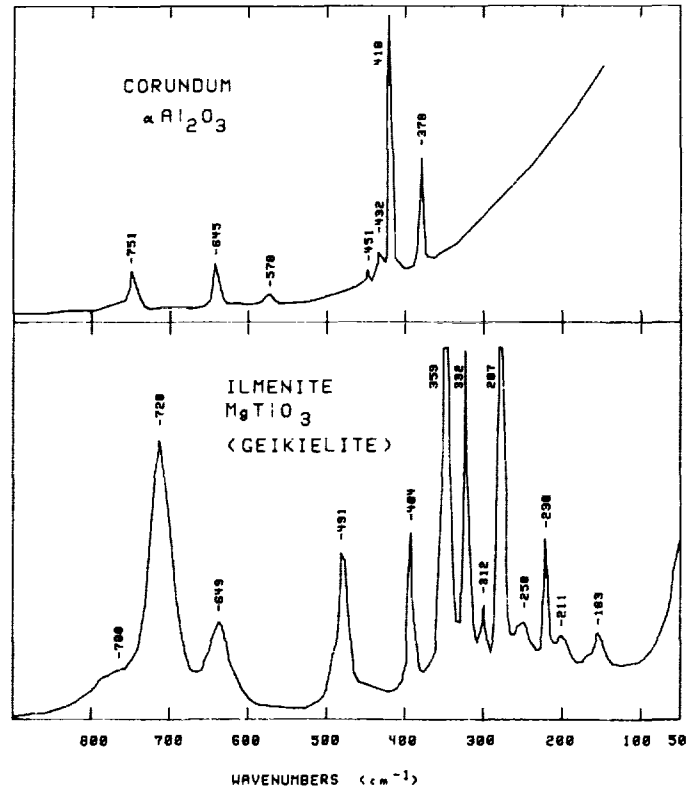


Fig. 3. The raman spectra of two lunar materials, corundum and ilmenite, are shown. The high-intensity spikes represent characteristic raman lines. The exact location of these lines is determined by the individual substances. The data are from Karr (1975).

The stokes and antistokes lines are, in most cases, mirror images of each other and contain the same information. For substances at cold temperatures, however, the stokes lines are more intense than the antistokes lines. It is for this reason that stokes lines are most often studied.

The net change in molecular energy is a quantum effect and is a function of the polarizability of the molecule. The molecular energy transitions that occur in raman scattering are discrete; the photon frequency shifts are accordingly discrete. Stokes and antistokes lines are thus directly characteristic of the molecule responsible for the scattering and can be used to identify the substance.

Since the raman effect is, in principle, an emission phenomenon, raman line intensities are proportional to elemental concentrations. This is a valuable attribute that will enable the determination of concentrations of mineral and chemical species.

Instrumentation

The RRS configuration is shown in Fig. 4. A laser is used to stimulate raman emissions at the lunar surface, and the returning energy is focused on a spectrally sensitive detector array. A filter is required to remove the laser frequency from the returning signal to avoid overwhelming the low intensity raman spectra.

The primary difficulty with using raman scattering as a remote-sensing method is the low intensity of the returned signal. Roughly 10^{-6} of the incident laser energy is returned as raman scattering; this is due to a very small fraction of the substance's molecular population that will alter energy states.

The ability of the detector system to read weak raman signals is an important consideration. Figure 5 plots the returned signal intensity at the spacecraft for differing altitudes and laser outputs. Raman emissions are considered to be diffuse at the lunar surface, and the returning signal is diminished by $1/\text{altitude}^2$. Present estimates indicate that a combination of a 10-W laser, an imaging spectrometer similar to that being developed for HIRIS, and a 157-mm telescope objective will permit the detection of raman spectra at altitudes up to 50 km.

The wavelength of the laser is an important quality. If one chooses the proper excitation frequency, many instrument problems can be avoided. The intensity of the raman effect is proportional to the fourth power of the exciting frequency, thus lasers of a higher frequency will improve the detectability of returning raman spectra. The frequency of the laser, however, is limited by problems with mineral fluorescence. Lasers of higher frequencies, such as ultraviolet, are likely to cause fluorescence at the sample and this will interfere with detecting the raman spectra. A krypton laser, whose frequency is in the visible wavelength region, is an appropriate compromise. This laser uses available technology and is of a high enough frequency to maximize the raman intensity but low enough to avoid problems with mineral fluorescence.

Using a visible wavelength laser requires the use of a visible wavelength imaging spectrometer. The use of visible wavelengths has two important benefits: (1) cryogenic instrument cooling is not required and (2) highly sensitive detectors are being developed for this wavelength region. The use of visible wavelengths, however, imposes constraints on the times when remote sensing can be performed. The RRS is limited to sensing on the dark side of the Moon where visible light pollution is not sufficient to interfere with the raman spectra.

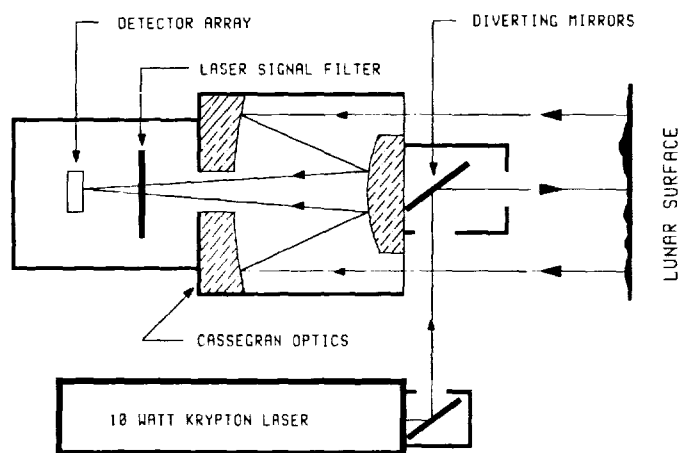


Fig. 4. The Remote Raman Spectrometer configuration. A laser is directed at the lunar surface and returning raman spectra are focused on an imaging array. The laser signal is removed by a mask filter.

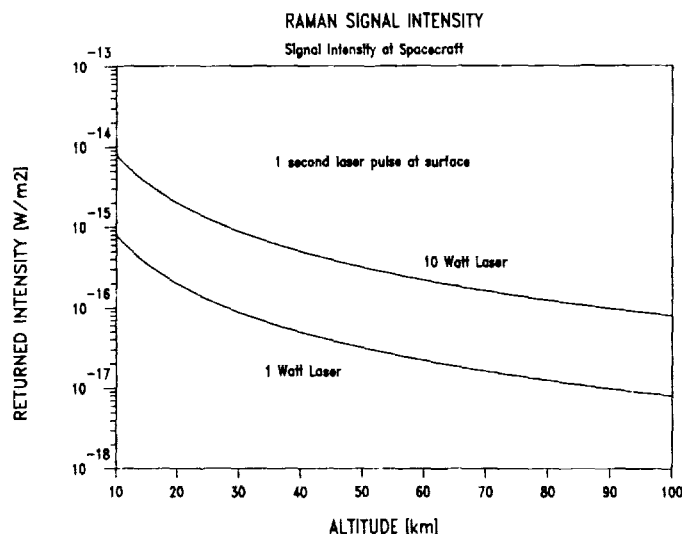


Fig. 5. Raman signal intensity at the spacecraft vs. altitude and laser power.

Spatial Resolution

The spatial resolution of the RRS is determined primarily by the size of the laser footprint on the lunar surface. The laser footprint at a 50-km orbital altitude is estimated to be 30 m in diameter; this corresponds to the surface resolution if the instrument is slewed to compensate for orbital velocity. If less resolution is desired, the slewing can be impeded. The laser pulse time and the orbital velocity will then combine to form an elongated footprint that will decrease the net surface resolution. The ability to alter spatial resolution enables either high-resolution site-specific coverage or lower-resolution coverage of larger regions.

RADAR SUBSURFACE MAPPER

In order to fully understand the subsurface attributes of the Moon, an orbital-based instrument capable of examining this region is needed. With such an instrument, subsurface layers can be traced and mapped; this will enable a better understanding of the local geology and will help locate lunar ores that might exist under the surface of the Moon.

The absence of moisture in the Moon's outer layers indicates that radio frequency electromagnetic energy will penetrate much deeper than is possible on the Earth. The use of radar signals pulsed at the lunar surface can explore the subsurface at depths of at least tens of meters (Barrington, 1986). Radar sounders carried by Apollo 17 penetrated as much as 1.5 km below the lunar surface and mapped subsurface layering in the Mare Serenitatis region (Peeples et al., 1978).

This simple technique pulses radar energy at the lunar surface and detects the returned signals. A short pulse of electromagnetic energy is propagated into the lunar subsurface and is reflected by geologic interfaces. The ability of the radar signal to propagate is dependent on the electrical properties of the subsurface; in order for radar reflection to occur, an electrical property discontinuity must exist across the geologic interface.

Radar sounding can be used for both surface imaging and subsurface profiling. Profiling is accomplished by maintaining a time reference between the radar transmission and the returned signals; a longer time between the radar pulse and its return is associated with greater depths. A composite from different depths constitutes a full subsurface profile. Imaging is accomplished by recording the diffuse radar backscattering at the surface. The combination of imaging and depth profiling will be highly useful for the interpretation of surface geology.

Instrumentation

The RSM consists of three primary elements: a Coherent Synthetic Aperture Radar (CSAR) that contains the transmitting and receiving elements, and two separate antennae for imaging and profiling. For imaging and shallow profiling, an operating frequency of 150 Mhz is used; for deep profiling (10 m-1 km), an operating frequency of 15 MHz is used.

ORBITS

The Moon's low mass (about one eightieth that of the Earth) and lack of an atmosphere make it a very attractive body for remote-sensing orbiters. Low-energy orbits associated with the low lunar mass require substantially less propellant for orbit maintenance and alteration than comparable Earth orbits. The lack of atmospheric drag permits orbital altitudes that are limited only by topography and lunar gravitational perturbations.

Orbit/Instrument Synergy

The platform's ability to change orbital parameters is important to achieving desired mission versatility. Optimization of the relationship between surface coverage and instrument resolution requires a variety of orbits. Variation of orbital altitude, eccentricity, and inclination will permit tailoring to meet specific mission needs and instrument requirements. Several classes of orbital coverage are considered: global surface coverage at moderate to high resolution, and site-specific coverage at very high resolution. The parameters of the lunar orbit (inclination, eccentricity, and altitude) will dictate the type of surface coverage and resolution that can be realized.

Orbital inclination strongly influences the quality of regional surface coverage. Figure 6 illustrates the effect of various orbital inclinations on local coverage. In general, viewing is most complete at the lunar latitudes equal to and less than the orbit inclination angle. Viewing of the entire lunar surface is offered only by polar orbits, but this advantage is offset by sparse coverage at low-latitude regions where successive orbital tracks are far apart. Reducing orbital inclination from 90° improves the coverage at low latitudes and equatorial regions, but this completely eliminates polar coverage. Low-inclination orbits are consequently best suited to high-resolution, site-specific coverage of low-latitude regions; polar orbits are best suited to lower-resolution global coverage, and high-resolution coverage of the polar regions.

Orbital altitude strongly influences instrument resolution. In general, high altitudes decrease optical resolution and increase instrument dwell time, while low altitudes increase resolution and decrease dwell time. The higher orbital velocities associated with low-altitude orbits decrease the amount of time available for instruments to sense the surface; however, for reasonably small altitude differences, dwell time is not a significant factor since

lunar orbits exhibit relatively small changes in orbital velocity with changes in orbital altitude. Thus, orbit altitude selection is primarily a function of required instrument resolution, viewing needs, and concerns for orbital stability.

Orbital Stability

Mission objectives require orbits stable enough to permit orbital maintenance with a reasonable amount of maneuvering but low enough for good instrument resolution. The Moon's gravity field directly affects the stability of lunar orbits, depending on their altitude and inclination. Experience from earlier lunar flights and known lunar gravitational harmonics indicates that polar orbital inclinations and low-altitude orbits are unstable. Precise polar orbits exhibit a rise in eccentricity leading to periapsis (closest approach to the surface) lowering and eventual collision with the lunar surface. This phenomenon is shown in Fig. 7 (Chesley et al., 1988). The inability to precisely assess the effects of known large

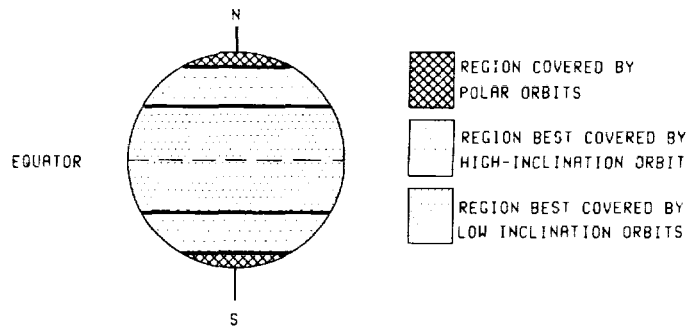


Fig. 6. Orbit inclination vs. optimum regional coverage.

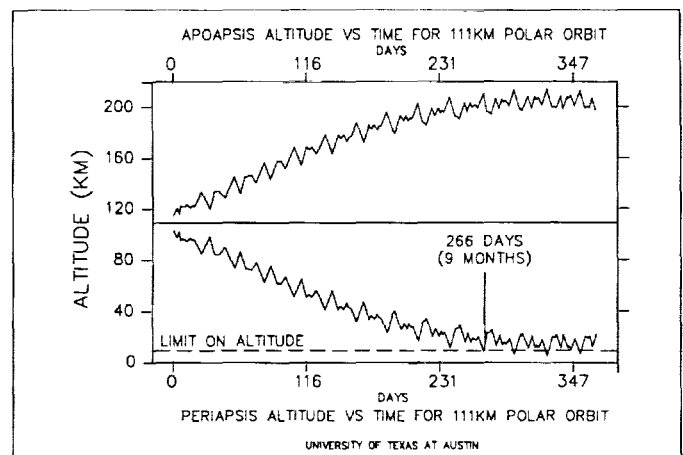


Fig. 7. Results from a numerical simulation of the effects of lunar gravitational perturbations on orbital stability. Data are from Chesley et al. (1988). The upper curve represents the altitude of orbit apoapsis and the lower curve represent the orbital periapsis altitude. The results indicate that a polar orbit will experience a rapid rise in eccentricity, and the result will be the spacecraft impacting the lunar surface after 266 days.

lunar gravitational anomalies on the stability of low-altitude orbits leaves a degree of uncertainty in prediction models. Numerical simulations of lunar orbits, based on low-order spherical harmonics, suggest a pattern of rising eccentricity on polar orbits (Chesley et al., 1988) and on oscillating eccentricity on equatorial orbits (Bond and Mulcihy, 1988). Present estimates of orbit lifetime (before surface collision) for a 100-km polar orbit are approximately 9 months.

The net effect of orbital instabilities is to increase propellant usage for orbital maintenance. General avoidance of very low altitudes and certain inclinations can partially negate stability problems. Estimates of lunar gravity harmonics indicate that stable near-polar orbits may be available. These slightly eccentric, so-called "frozen" orbits (Burke, 1976) have their periapses fixed near the Moon's south pole and may remain stable for up to two years (Upboff, 1976).

Orbital Strategies

Several surface-coverage strategies are made possible through variation of the orbital altitude (e.g., large regions at low resolution, small regions at high resolution, and global coverage at moderate to high resolution). Global coverage at moderate resolution can be achieved through the use of a 100-km near-polar orbit such as that planned with the LGO mission. Higher altitudes reduce the resolution obtained but increase the instruments' field of view, thus allowing the equatorial regions to be more adequately viewed. Complete surface coverage from a polar orbit can be obtained in 27 days.

A highly elliptical orbit with a low periapsis over the region of interest gives a high-resolution sensing opportunity without the stability problems associated with low circular orbits. Since a small fraction of the orbit is spent at low altitudes, the net effect is to provide a low-altitude sensing opportunity while maintaining a higher average orbital altitude. The drawback to this method is the small region of coverage that accumulates under the periapsis. The highly eccentric orbit is also capable of giving low-resolution, large regional coverage on the apoapsis (maximum distance from the surface) side with a smaller required velocity change than is associated with an equivalent transfer to a high circular orbit. The elliptical orbit offers a variety of surface-coverage opportunities through the proper choices of periapsis latitude and orbit eccentricity.

A possibility exists for high-resolution global coverage by using a highly eccentric orbit and periodically shifting the latitude of periapsis. Figure 8 illustrates this concept. Since the orbital precession is small, the orbit can be considered to be fixed in space while the Moon rotates under it. By rotating the orbit's line of apsides (the line connecting the orbit's periapsis and its apoapsis) at appropriate intervals, the entire lunar surface can be viewed from a low altitude without severe orbital stability problems.

Required Velocity Changes

Orbital plane changes are most efficiently accomplished at the apoapsis where the orbital velocity and, thus, the required velocity change are lowest. Figure 9 displays the velocity changes required to achieve inclination changes for orbits of varying apoapses. Figure 10, in turn, displays the propellant mass required to achieve a given velocity change. The designed platform propellant capacity will enable a maximum velocity increment of 1.5 km/sec. From

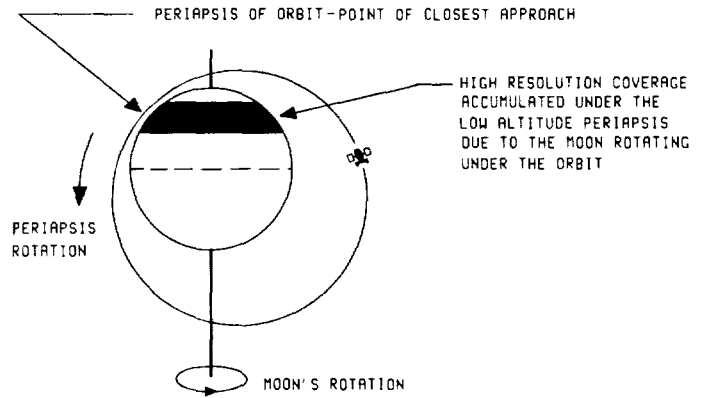


Fig. 8. High-resolution coverage of large regions can be accomplished by periodically rotating the latitude of periapsis. This will yield an orbit more stable than an equivalent low-altitude circular orbit.

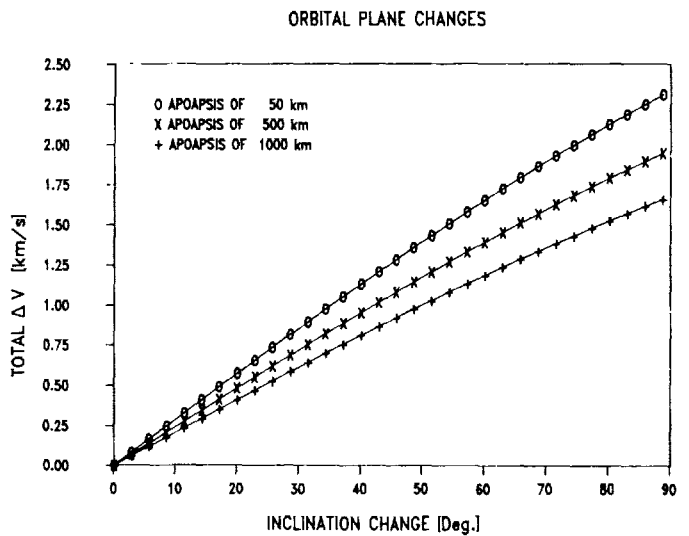


Fig. 9. Delta V requirements for orbit inclination changes.

Fig. 9 it is seen that this capacity allows orbital changes exceeding 50° for most orbits with changes of 90° possible for highly elliptical or high-altitude orbits.

Velocity changes required for coplanar orbit changes are shown in Fig. 11. The calculations assume an initial 25-km circular orbit with minimum energy transfer to the final circular or elliptical configuration. As shown, transfer from a 25-km circular orbit to a 1000-km circular orbit requires a relatively small 320-m/sec velocity increment, and transfer to an eccentric orbit with a 100-km apoapsis requires a velocity increment of only 180 m/sec. From Fig. 10 it is seen that these velocity changes translate into propellant burns of approximately 100 kg and 55 kg, 100 kg and 40 kg, respectively. With such small maneuvering requirements, many platform orbital changes and adjustments are possible in one mission.

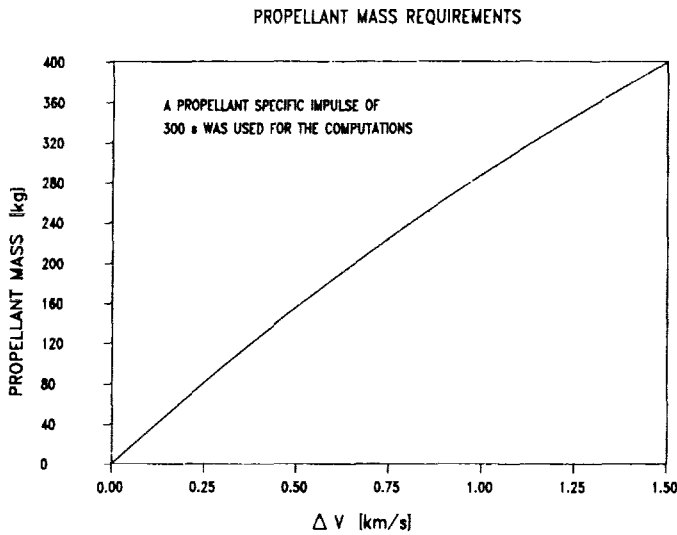


Fig. 10. Propellant mass requirements vs. ΔV .

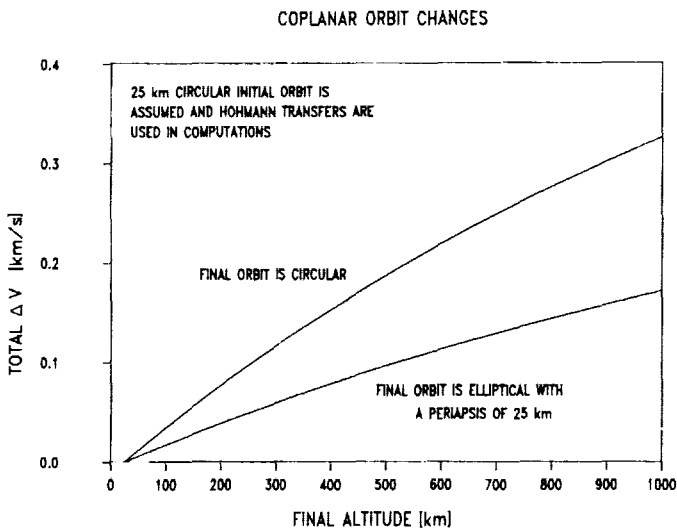


Fig. 11. Delta V requirements for coplanar orbit maneuvers.

Rotation of the line of apsides can be accomplished in two ways. The first method involves a three-step maneuver that first circularizes the eccentric orbit at the apoapsis, then proceeds to the new line of apsides, and finally reduces the velocity to acquire the new periapsis. The second method causes periapses rotation by rotating the velocity vector at apoapsis, then correcting the eccentricity. The comparative efficiency of the two methods depends upon the magnitude of the desired rotation. In general, the first method would seem most efficient since it requires the same propellant expenditure regardless of the rotation magnitude.

PROPULSION

The versatility allowed by the LOP orbit-changing capability requires considerable propellant usage. This usage represents one of the principle expenses associated with platform operation. Pro-

pellant costs can be substantially reduced by using lunar-derived fuels that do not require costly transport out of the Earth's gravity well. Use of lunar-derived fuels also helps to minimize Earth support requirements.

Lunar Propellant Sources

Lunar minerals that show the most promise for lunar propellant production are olivine [(Mg,Fe)₂SiO₄], pyroxene (a family of silicates rich in Ca, Fe, and Mg), and ilmenite (FeTiO₃). Olivine and pyroxene occur in concentrations up to 60% and ilmenite in concentrations up to 20% (Williams and Jadwick, 1980). These minerals are particularly promising for oxygen production. Selected elemental concentrations from Apollo samples are shown in Table 1.

Inasmuch as oxygen is abundant on the Moon, this element is an obvious choice for a bipropellant oxidizer. Extraction from lunar minerals by chemical and thermal processes is already planned for lunar colonization activities. The critical constituent of a lunar-derived propellant, then, is the fuel. Hydrogen is an excellent fuel when used with oxygen, but its lunar concentrations are extremely small. Other lunar-derived fuel possibilities include, but are not limited to, silane (SiH₄), AlCa, Al, AlCaMg, Ca, and lunar soil.

Silane has been theorized to perform well but has never been used (Rosenberg, 1986). Its primary advantages are its lunar-derived silicon, its high specific impulse (360/sec), its thermal stability for regenerative cooling, and its high boiling temperature. Silane production from lunar materials, however, would be quite slow due to its reliance on MgO in the production process (Rosenberg, 1985).

A comparison of lunar-derived propellants normalized to the aluminum/liquid oxygen (LOX) combination is shown in Table 2. The high performance offered by liquid H₂/O₂ is really unavailable due to its extremely low availability on the Moon. Silane performs well, but its long production time plus its reliance upon terrestrially supplied hydrochloric acid in the production process

TABLE 1. Elemental concentrations of Apollo samples.

Element	Concentration (wt%)	
	Mare	Highlands
Oxygen	41.7	44.6
Silicon	21.2	21.0
Aluminum	6.9	13.3
Calcium	7.8	10.7
Magnesium	5.8	4.5
Hydrogen	54 ppm	56 ppm

Data are from Williams and Jadwick (1980).

TABLE 2. A comparison of lunar-derived propellants with quantities normalized to 1 for Al/LOX.

	Al/LOX	LH ₂ /LOX	LSiH ₄ /LOX
Oxidizer Mass	1	0.70	0.77
Oxidizer Volume	1	0.70	0.78
Fuel Mass	1	0.78	1.12
Fuel Volume	1	29.84	4.47
Production Time	1	10.86	9.57

negate its performance advantage. Aluminum and oxygen thus show the most promise for lunar-derived propellants (*Utah State University*, 1988). Powdered aluminum, when used in combination with an Earth-based binder and lunar-derived oxygen, can provide up to 300 sec of specific impulse (*Streetman*, 1978).

Thruster Design

The thruster is a hybrid design using solid Al and LOX. A refillable oxygen tank is mounted in the center of the spacecraft where it is insulated and shaded to minimize boil-off. The solid fuel portion of the thruster mounts on the antinadir end of the LOP. The solid fuel, casing, injector, and nozzle are replaced with a refueled version on orbit. The nozzle and combustion chamber are regeneratively cooled for reusability.

CONCLUSIONS

Man's return to the Moon will be characterized by a commitment to a permanent presence designed to exploit a body rich in natural resources, to find answers to a host of intriguing scientific questions, and to establish a base for further exploration of the solar system. The early orbital exploration mission of the LGO will most certainly be followed by longer-term, more versatile orbiting systems that operate in a synergistic manner with human exploration efforts. The LOP provides a preliminary example of such a system. Designed-in modularity and orbital mobility allow flexible operation adaptable to many instrument/mission combinations. Provision for the replacement of instrument clusters and subsystem modules permits expansion to incorporate new technologies and evolution to extend mission capabilities. The LOP thus projects a broad range of long-term operational possibilities for continued lunar exploration well into the twenty-first century.

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