TECHNIQUES AND RESULTS OF REMOTE SENSING OF THE MOON

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ABSTRACT

Remote sensing techniques played a major role in advancing our knowledge of the Moon. Earth-based tools such as imaging telescopes and multi-spectral and radar sensors were employed in addition to photographic cameras and geophysical and geochemical instruments that collected data from spacecraft in lunar orbit. Interpretation of the remotely-sensed data has involved a highly successful interdisciplinary approach. Samples and supporting data collected from the Apollo and Luna landing sites were essential to the calibration of the remotely-sensed data. The latter were fundamental to the extrapolation of knowledge gained from the landing sites to larger parts of the Moon.

I. INTRODUCTION

The exploration of the Moon undoubtedly started with the naked eye at the dawn of history, when mankind hunted in the wilderness and settled the earliest farms (reference 1). Our knowledge of the Moon took a quantum jump when Galileo Galilei trained his telescope toward it. Since then, generations of researchers have followed suit, utilizing successively more complex instruments (reference 2). The most significant quantum jump in the knowledge of our only natural satellite came with the advent of the space age (reference 3), when the Moon became the object of efforts of the most intensive scientific research programs of all time.

Lunar exploration has involved a highly successful interdisciplinary approach to solving a number of scientific problems. It has required the interactions of astronomers to classify surface features; cartographers to map interesting areas; geologists to unravel the history of the lunar crust; geochemists to decipher its chemical makeup; geophysicists to establish its structure; physicists to study the environment; and mathematicians to work with engineers on optimizing the delivery of exploration tools (reference 4).

This paper summarizes the methods and techniques used in remote sensing of the Moon. It also gives the salient results and their meaning. The utilization of remote sensing techniques in the study of the Moon helps greatly in our understanding of the nature and evolution of its surface. The process serves as a model of global studies of planetary bodies in the solar system.

II. EARTH-BASED REMOTE SENSING

A. Telescopic Observations

Much of our basic knowledge regarding the lunar surface was derived from observations using telescopes. It all started with Galileo Galilei who first used a crude telescope to observe the Moon in 1609. He observed and began
mapping the mountains, plains and craters. He was the first to call the bright highlands terra (the lands) and the dark regions maria (seas). And thus began the often tumultuous history of classifying and naming the features of the Moon (reference 3). Galileo became caught up in conflict with the Church, but his work resulted in the publication in 1647 of a map of the Moon that is accurate by modern standards. He was the first man to show the lunar regions that are intermittently revealed by lunar librations. He recognized the bright halo around the crater Copernicus and the dark one around Tycho. In addition, he also recognized slight variations in the brightness of the lunar maria.

The building of increasingly sophisticated telescopes shifted lunar observations from studies of the Moon's appearance and its motions to investigations of the nature and origin of its surface features. Telescopic photographs of the Moon's near side were followed by photometric studies of the lunar albedo, which showed that reflectance values vary from as low as 6% for the darkest maria to up to 22% for the brightest terrae. The first method to be employed in differentiating the lunar surface units was based on this fact that different parts of the surface have different albedo values as measured at full Moon. Brightness curves were constructed as a function of lunar phase (reference 6). In addition to diffusing sunlight, the Moon's surface also polarizes the light. The Moon was analyzed as a function of phase, and some differences of lunar materials were revealed (reference 7).

Today, even with the largest telescope on Earth, it is impossible to distinguish features on the Moon with dimensions less than 500 m. The immense distance between the Earth and the Moon has hampered detailed investigations, even when telescopes are flown on airplanes at altitudes of 12 km to make observations in infrared wavelengths unhindered by atmospheric absorption.

B. Other Earth-based Studies

Although visual observations and photography of the lunar surface provided the basic data, specialized information came from remote sensing using segments of electromagnetic spectrum other than visible light (figure 1). Studying the Moon by photographing it with ultraviolet and infrared filters was successful. For example, by combining a positive transparency of a near-infrared photograph with an ultraviolet negative, a composite was produced that differentiated redder and bluer areas within the lunar maria (figure 2). The differences were interpreted to be due to the presence of several types of volcanic flows (reference 8).

In the spectral region of 0.3 to 3.0 μm, absorption bands appear in the reflection spectrum of many iron-bearing minerals. Absorptions arise from the molecular vibrations, electronic transitions in ions such as those of iron and titanium, and the exchange of electrons between adjacent ions in the crystals. These absorptions are diagnostic of mineral composition. For the Moon the reflection spectra between 0.3 and 1.1 μm were found to be particularly useful. The absorption features in this range were analyzed using theoretical compositions and later calibrated by laboratory analyses of lunar surface materials (reference 9). To emphasize subtle differences between the various lunar surface units, such spectra were divided by the reflectance of one region in Mare Serenitatis to produce relative reflectance spectra (figure 3).

Another spectral range that was used to study the Moon's surface is the sunlight that is absorbed and later emitted by radiation, the thermal infrared.
Because such sources of radiation are easier to define during darkness, in the absence of reflected energy, 10 to 12 μm images of the entire Earth-facing lunar hemisphere were obtained during a total eclipse (reference 10). The eclipse provided the additional benefit of a standard energy background for the entire lunar disc. The patches that were not cooling as rapidly as the surrounding areas stood out as bright or "hot" spots. It was immediately obvious that these hot spots corresponded to the relatively young and fresh-appearing craters (reference 11).

Additionally, radar astronomy was born in 1946 when radio signals were sent from the Earth and bounced off the lunar surface. In early radar studies, beam resolution was poor, and observations of the entire disc were averaged together. This aggregate approach resulted in prophetically interpreting the back-scattering data to signify a surface repolith composed of an equal volume mixture of fine-grained material and fragments of rock. In more recent studies, radar beam resolution has been improved to encompass areas of two kilometers or less (see, for example, figure 4). Such studies gave us a measure of the surface roughness in the various lunar surface units. They further provided a method of measuring topographic variations in unmapped areas (reference 12).

In Earth-based remote sensing, instrumental elegance far outstripped understanding of physical behavior. The potential remained exciting but largely unrealized (reference 11).

III. ORBITAL REMOTE SENSING

A. Unmanned Spacecraft

To get closer to the Moon, both the Soviet Union and the United States sent remote sensing instruments on board several types of spacecraft. First among these were the lunar "flyby" missions which were the least expensive. Because such spacecraft spent less than a few hours near the Moon and observed only a small area, the amount of information these missions sent back to Earth was limited. Still, this information was richer in detail than Earth-bound data and increased our knowledge manyfold. For example, the Luna 3 photograph of the Moon's far side showed it to be very different from the familiar Earth-facing hemisphere; the dark maria are very rare on the far side (figure 5). The Luna 3 was one of several successful Soviet missions to the Moon.

Other successful Soviet flights were made by Zond spacecraft, which were flyby and circumlunar missions that photographed the Moon, particularly the far side and west limb. Their objectives and schedule indicate that these missions were to be forerunners of a never-realized manned lunar project. The Zond program consisted of five successful missions. Zond 5 through 8 returned to Earth and were recovered. Because the Zond spacecraft did not achieve a lunar orbit, but only passed by or circled once around the Moon, the number of photographs brought back was limited. About 44 in all were published in the United States as prints or in atlases. Some reveal the Moon in excellent detail, e.g., the photographs of the far side crater Atken.

Another type of a relatively simple mission was the one in which the probe headed on a collision course with the Moon. In the last part of its 500,000-km voyage, before impacting the lunar surface, the probe transmitted images before meeting its violent fate. The Ranger spacecraft are the example of these missions. The Ranger project is a good reminder that the United States space effort has not always run so smoothly. The first six6 Rangers all malfunctioned in some aspect of their mission. However, the ultimate goal of the project, which was to photograph the Moon at resolutions vastly better than those obtained by Earth-based telescopes, was achieved on Rangers 7, 8, and 9.

These Rangers were built to take and transmit thousands of close-up photo-
graphs shortly before lunar impact (e.g., Ranger 7 provided 4,300 frames in about 17 minutes). They carried 6 cameras: four narrow-angle "P" cameras that provided only partial coverage, and two wide-angle "F" cameras that provided full coverage. The signals were transmitted to the tracking station at Goldstone, California, where they were recorded on film and magnetic tape. The best resolution achieved in these photographs was 0.3 m in the last frames from Ranger 9. The Ranger missions were labeled "hard landers" as opposed to "soft landers," which slowly descended to the surface and started investigating it up close.

The Surveyor missions did this well. Seven attempts at a soft landing were made, five were successful. Four landing sites were in the relatively smooth and level maria, the best bet for a safe landing. On the last mission, planners decided to risk the hazards of rough terrain to satisfy scientists’ desire for some knowledge about the as yet unexplored highlands.

The Surveyor cameras provided over 86,000 photographs of the lunar terrain at resolutions up to 1 mm. In addition to the cameras, Surveyors carried several experiments to test the chemical and physical properties of the soil and rocks at the landing sites. For example, the alpha-scattering experiment was a device that gave off alpha particles, which were scattered and absorbed by the lunar surface. It then measured the reflected particles, which contained the signatures of elements present. The results showed that the lunar maria were similar in composition to terrestrial (basaltic) rocks. Highland composition was found to be lower in iron than the maria. A scoop was used to test the physical properties of the soil; trenches were dug and impact tests were performed. The scoop proved to be a very versatile tool; it was even used on Surveyor 7 to dislodge a stubborn piece of equipment.

When we consider the overall knowledge of the lunar surface features, the most important of all missions were the orbital photographic ones. The Lunar Orbiter spacecraft probably provided us with the most significant data. The program consisted of five missions (reference 13). They were placed in both equatorial and near-polar orbits. Naturally, the closer the craft came to the poles, the more its orbital coverage. Their primary purpose was to scout out landing sites for the earlier lunar landings. In the process the Lunar Orbiter missions taught us much about the surface geology of the Moon. Most of the landing site work was completed on the first three missions, allowing the last two to be more science-oriented. Lunar Orbiter IV photographed the entire near side (Figure 6), while Lunar Orbiter V was targeted to specific areas of interest and completed medium-resolution coverage of the lunar far side.

The photographic system had 2 cameras, which provided a medium-resolution frame and a nested high-resolution frame, (the best resolution for the first three missions was 1 m; for mission IV, 80 m; and for mission V, 4 m). The film was processed and scanned on the spacecraft; this scanning process produced the distinctive banding of Orbiter photography (reference 13). The images were then transmitted to ground stations as electrical signals. In addition to the surface photographs, the Lunar Orbiters also gave us information about the Moon’s gravitational field, and carried micrometeoroid and radiation detectors.

B. Apollo Missions

In addition to the collection of rock and soil samples from the landing sites, the Apollo astronauts conducted numerous experiments while orbiting the Moon and on the lunar surface. Surveys from orbit included photography from the command module windows and by sophisticated cameras mounted on a special bay in the service modules of Apollo missions 15, 16 and 17 (reference 14). These camera systems included a Fairchild 76 mm metric camera and a 500 mm f/6.3 panoramic camera. From these systems ortho photographs of approximately 15% of the lunar surface have been made at 1:250,000 scale and of selected
areas at 1:50,000 and 1:10,000 scale. It is interesting to note that these maps of the Moon are better than those available for many areas of the Earth. Fifteen other experiments, conducted mainly on the last three missions, obtained geochemical and geophysical data pertaining to overflow parts of the Moon (about 20% of the surface area).

Data from the X-ray and \(\gamma\)-ray spectrometers (carried on Apollo missions 15 and 16) were confirmed and calibrated by the chemical "patterns" detected by studying the returned lunar samples. The X-ray sensor measured the characteristic fluorescence signatures of aluminum, silicon, and magnesium that were excited by impinging solar radiation in the top 20 microns of the Moon's surface. The Al/Si intensity profiles clearly show low Al/Si values over the lunar maria, and higher values over terra materials, especially on the lunar far side (figure 7). Intermediate Al/Si values usually correspond with boundaries between the basaltic mare units and the anorthositic highlands. A reverse correlation generally exists in Mg/Si ratios, where mare units show a higher value than the highlands. The X-ray data were also found to be useful in studies of smaller scale features such as: (1) basin rings which exhibit compositional differences from the surrounding terrain; (2) ejecta around impact craters which may have excavated subsurface layers of different composition; and (3) compositional differences related to ridges in the lunar maria (reference 15).

The \(\gamma\)-ray spectrometer measured concentrations of natural radioactive emissions from the lunar surface. The highest counts, which correspond roughly to about 10 ppm thorium, are confined to the western near side of the Moon, particularly in and around the Imbrium basin. The latter is the largest of the impact basins on the lunar near side and, therefore, may have penetrated through originally radioactive parts of the crust. A high resolution spot in the vicinity of the crater Van de Graaff on the far side is also within a very old and large basin, even larger than Imbrium. The localization of the highly radioactive rocks supports the deduction that they cannot represent average lunar surface materials. A technique of deconvoluting orbital \(\gamma\)-ray data was recently explored to improve the spatial resolution (reference 16). Results showed the generally diminishing thorium levels extending outward from the Imbrium basin. This reinforced the hypothesis that the terrae contain a premare layer of volcanically-derived and relatively radioactive material.

Details of the broad-scale lunar topographic relief were first provided by laser altimeter measurements made on Apollo missions 15, 16 and 17. The altimeter, which was part of the metric camera system, measured precise altitudes of the orbiting command service module above the surface (reference 17). Measurements were made at points spaced every 1.0 to 1.5 degrees, or every 30 to 45 km on the surface. Agreements between measurements on the three missions emphasize the accuracy of the profiles. The laser altimeter data indicated a 2 to 3 km offset toward the Earth of the Moon's center of mass from its center of figure. This was ascribed to a variable thickness of a low-density terra crust, thinner on the near side than on the far side. Thus, the maria may be concentrated on the near side because the mare basalts could more easily penetrate the thinner crust. Similarly, local thinning of the crust by basins, and particularly by craters superimposed on basins, may explain the observed distribution of maria on the far side (figure 5).

Another method of generating elevation profiles of the lunar surface was provided by the lunar sounder (reference 18). The sounder, which was carried on Apollo 17 consisted of a three-frequency coherent radar (5 megahertz, 15 MHz, and 150 MHz). Continuous surface profiles were optically recorded and showed excellent details of the outer skin of the Moon. The 5 MHz radar data were used to generate profiles with an estimated absolute accuracy of 150 m and an estimated relative accuracy of 5 m over mare surfaces. These radar profiles (figure 6) were compared with the Apollo 17 laser altimeter measurements. Although the two types of data were not acquired simultaneously, they
agree within 150 m over mare surfaces. The sounder also supplied some information on subsurface layering of the Moon.

From laser altimeter and radar sounder profiles as well as photogeologic data, it became clear that the impacts that formed the lunar multi-ringed circular basins resulted in an enormous loss of mass from the impact sites. These basins display large positive gravity anomalies or mascons (reference 19). Gravity measurements, which were made only on the nearside and limb regions (figure 9), indicate positive gravity anomalies in excess of 200 milligals in such areas as mare Oceanus and mare Smythii. Both mascons are located where other data suggest probably thick inner fill of circular basins. Relatively thin mare fill within basins and in basin troughs and other lowlands does not show any mascons (figure 9).

IV. CONCLUSION

The exploration of the Moon has involved a highly successful interdisciplinary approach. Remote sensing techniques, both earth-based and lunar orbital, have played a major role in gradually increasing our knowledge of the nature and evolution of the lunar surface.

Telescopic observations and photogeology provided the basic data. These data were enhanced by multispectral studies in the visible, infrared and radar spectral ranges. However, Earth-based remote sensing was not sufficient to answer major questions on the physical nature, chemical characteristics, and geologic evolution of lunar surface materials. Remote-sensing from orbit coupled with the return of samples from the Moon provided the necessary confirmation and calibration of the data.

Orbital remote sensing of the Moon began with imaging systems that provided the necessary data for photogeologic interpretations. This was followed by the acquisition of geochemical and geophysical data that allowed the extrapolation of knowledge gained from the detailed studies of spacecraft landing sites to larger areas of the Moon, particularly its equatorial region.

From data gathered during the past two decades, we are now able to specify the gaps in our knowledge of the Moon and the best ways and means of filling them. However, the available data do not provide the means for testing all of the hypotheses regarding the origin of the Moon and the nature of its polar regions. What the lunar scientific community requires is a better understanding of areas outside of the Apollo coverage. Plans have been discussed for a "Lunar Polar Orbiter" to be placed in lunar polar orbit for an extended period of time to relay remote sensing data on the whole Moon. Sensors aboard such a mission might transmit multispectral, stereo images to map specific regions and to distinguish rock composition including the concentration of critical elements. This would extend our present small envelope of data coverage to the rest of the Moon's surface.

Gathering data in this way can be considered a resource survey. In this context the Lunar Polar Orbiter would be to the Moon what Landsat is to the Earth. This becomes important if we consider the possibility of utilizing lunar materials in future space endeavors. The Lunar Polar Orbiter would allow resource evaluation of the lunar materials. These resources may include metals that might be extracted from the lunar soil, such as titanium, and water that is possibly frozen as ice in the permanently shadowed polar regions.

The proposed Lunar Polar Orbiter could also be looked at as a precursor to future missions to the inner solar system, particularly to Mars and Mercury. The mission would utilize a spacecraft that might be modified to fit the needs of planetary exploration. In this respect, additional lunar data will augment our knowledge of all the terrestrial planets and provide a basis for comparative planetology.
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Figure 1. Left, the electromagnetic spectrum with black areas representing regions where the atmosphere blocks the radiation; Right, schematic representation of certain types of energy received on Earth for remote sensing of the Moon (see reference 11).

Figure 2. Color difference photograph of the Moon produced by merging a 6,100Å image minus a 3,700Å image. Red areas appear light-colored and dark areas signify bluer regions on the lunar surface. (Courtesy of E. A. Whitaker Lunar and Planetary Laboratory, University of Arizona).
Figure 3. Relative reflectance spectra for a variety of lunar areas. The measured reflectance spectra were divided by the spectrum of an area in Mare Serenitatis, to bring out subtle differences (reference 9).

Figure 4. Depolarized 70 cm radar image (left) and corresponding contours (right) of the region of Lunar Aeronautical Chart (LAC) 39. The bright spot near left edge is the relatively young crater Aristarchus (courtesy of T. Thompson, Jet Propulsion Laboratory).
Figure 5. Distribution map of mare material on the lunar surface on an equal area projection. Note that the maria tend to concentrate within large circular basins (reference 14).
Figure 6. Photographic coverage of Lunar Orbiter missions I, II and III (A), mission IV (B), and mission V (C). Coverage in the northern and southern polar regions is not shown; major parts of these regions were photographed by Lunar Orbiter mission IV (reference 13).
Figure 7. Aluminum/silicon concentration ratios as detected by the X-ray experiment on Apollo missions 15 and 16. Higher values for aluminum show over highland areas and lower values over the maria. Magnesium concentrations show a converse relationship, i.e., higher values over the maria and lower magnesium concentrations in the terrae. (Courtesy of I. Adler, University of Maryland).

Figure 8. Radial plots of lunar sounding radar profiles about the center of mass (A), the center of figures (B) and the center of maria (C). (Reference 20).

Figure 9. Gravity anomalies on the lunar near side and limb regions. Mascons (circular areas) have mass excesses of 800 Kg/m². (Reference 19).