Experimental Photogrammetry of Lunar Images

GEOL OGICAL SURVEY PROFESSIONAL PAPER 1046-D

Prepared on behalf of the
National Aeronautics and Space Administration

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Experimental Photogrammetry of Lunar Images

By SHERMAN S. C. WU and H. J. MOORE

APOLLO 15–17 ORBITAL INVESTIGATIONS

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An experimental photogrammetric study, using
Apollo orbital photographs for geologic
studies of the Moon and the exploration of
the Moon and other planetary bodies
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EXPERIMENTAL PHOTOGRAMMETRY OF LUNAR IMAGES

By SHERMAN S. C. WU and H. J. MOORE

ABSTRACT
High-quality cameras capable of making reliable measurements and topographic maps were carried aboard the orbital Command and Service Modules during Apollo missions 14, 15, 16, and 17. In addition to providing selenodetic control and topographic maps with scale factors of 1:10,000, 1:50,000, and 1:250,000, photographs taken by these cameras can be used to obtain quantitative data for specialized scientific studies such as: (1) the relation between stereophotogrammetric measurements and illumination conditions; (2) measurement of structural deformations; (3) crater geometry and lunar landforms; (4) morphological properties of lunar flows; and (5) fine-scale lunar surface roughness.

Experimental photogrammetric studies have produced results applicable to the exploration of the Moon and other planetary bodies. Optimum illumination conditions for lunar stereophotogrammetric studies include sun elevation angles near 90°. Lower sun elevation angles result in excessive shadows, and much higher angles result in loss of scene contrast. For any given scene, local slope and albedo affect stereophotogrammetric measurements. Lunar results may be applied to other planetary bodies devoid of thick atmospheres.

Topographic maps prepared from vertical Apoll 15–17 mapping camera photographs can be prepared with contour intervals as small as 50 m depending on map scale, local roughness, illumination, and other conditions. Oblique photographs taken by the mapping camera can be used to prepare topographic maps with contour intervals of 50 m or larger. Panoramic camera photographs taken by Apol 15–17 can be used to prepare topographic maps of fine-scale features with false-line intervals near 5 m under ideal conditions.

For scientific purposes, the small- and large-scale topographic maps can be used to determine subtle structural deformations of the lunar surface. Certain geologic features and shapes of small lunar landforms can be portrayed at a fine scale with an accuracy never before possible.

The geometry of lunar craters—the most ubiquitous lunar landforms—has been determined using profiles and topographic maps prepared from Apollo 15–17 photographs with high accuracy. These profiles and maps required a revision of equations describing lunar craters.

Profiles of lunar volcanic and impact melt flows using the stereophotogrammetric method established the thicknesses and widths of the flows. When combined with theory and with lunar topographic maps to establish the gradient of the flow, it has been shown that the materials of mare flows had a yield strength about the same as basalt lava in Hawaii and that material of the flow of impact melt north of the crater Kea had a yield strength larger than the mare flow. Additionally, structural tills of the mare after the mare flow formed were negligible, but some local warping occurred.

Stereophotogrammetric measurements on the high-resolution panoramic camera photographs of Apollo 15–17 and the lunar topographic camera photographs of Apollo 14 have been used to determine lunar surface roughness and slope-probability distributions at scale lengths of 17 to 25 m and larger. These data form a basis for comparison of the Apollo 14–16 bistatic radar method of determining lunar surface roughness and slope-probability distributions at comparable scale lengths. The photogrammetric and radar methods agree on four major points: (1) lunar mare are smoother than lunar uplands; (2) the magnitude of the algebraic standard deviations of slope-probability distributions for lunar mare are comparable for both methods; (3) mare appear rougher at small scale lengths than at large scale lengths; and (4) slope-probability distributions are typically similar in shape, but they vary and may be Gaussian and complex.

Although the potential use of Apollo photographs in special scientific studies has not been fully realized, existing studies employing the photographs and maps prepared from them have been profitable. Achievement of required memoranda for special scientific studies requires close coordination between the photogrammetrist and the user.

INTRODUCTION
In a substantial improvement over all previous Apollo lunar missions, the Command and Service Modules of the Apollo 15, 16, and 17 missions carried camera equipment capable of obtaining high-quality topographic and selenodetic data for the Moon from orbit. Equipment on each spacecraft included a mapping camera, a stellar camera, a laser altimeter, and a high-resolution panoramic camera. Accurate topographic measurements of the lunar surface in support of quantitative geologic studies can be made using the photographs returned to Earth by these later Apollo missions. Apollo 14 carried a lunar topographic camera (Hycom) in orbit from which quantitative topographic data could be obtained. Previous missions, as well as Apollo 14–17, carried Hasselblad cameras. Stereoscopic Hasselblad photographs of the lunar surface taken from orbit by the Apollo 11, 12, and 14 missions provided improved topographic data of selected features and were used in prelanding studies of the Apollo 16 landing site (Descartes).

This paper is one of four separately bound chapters summarizing Apollo 15–17 orbital investigations: (1) "Stratigraphy of the Lunar Nearside" (Chapter
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A. Wilhelms, 1980, "Lunar Remote Sensing and Measurements" (Chapter B, Moore and others, 1980), "Geometric Interpretation of Lunar Craters" (Chapter C, Pike). The lunar topographic mapping projects on board the Apollo 14 Command Module (Dietrich, 1971) was used to obtain data on fine-scale lunar topography (Moore and others, 1975, 1976, 1980). Apollo missions 15, 16, and 17 carried the sophisticated mapping camera system in orbit (Dietrich and Clanton, 1972a, 1972b; McEwen and Clanton, 1973). In the mapping camera system, a 3-inch stellar camera was mounted at a 98° angle to the axis of a 3-inch mapping camera, and a laser altimeter capable of measuring slant range within 2 m was aligned with the mapping camera system. This system has been used for establishing a seismologic control network as well as topographic mapping (Doyle and others, 1976; Cannell and Ross, 1976; Kopal and Carder, 1974). A panoramic camera, carried on Apollo missions 15-17, obtained high-resolution stereophotographs that are useful for detailed studies. The cameras and photographs used to collect data in this report are discussed briefly below and listed in table 1.

LUNAR TOPOGRAPHIC CAMERA

The lunar topographic camera (45.5-cm focal length) (also called the Hycon camera) was carried aboard the orbiting Command Module of Apollo 14 to obtain high-resolution topographic data of the Apollo 16 landing site and the Apollo 14 landing site. A camera malfunction prevented acquisition of these data and resulted in the recovery of only 183 frames from a nominal altitude of approximately 18 km extending from the east rim of the crater Theophilus to a point northwest of the crater Kant (1E-83 and Head, 1971). At a nominal spacecraft altitude of 20 km, each photograph has a 11.43 x 11.43 cm format, covers an area about 5.0 km on an edge. Photocell is about 1:44,000. Stereoscopic coverage corresponds to a ground resolution of 0.06 km (72 mm X 72 mm). The data are at a scale of 1:60,000, producing a base-height ratio of 0.095. Use of alternate pictures gives a base-height ratio near 0.19.

Photography taken with this camera had the highest resolution of all the Apollo missions flown previously, but higher resolutions were achieved by later missions. Resolution achieved by the lunar topographic camera are 62 optical pairs per millimeter at a tricolor contrast of 0.5 with 3400 type film, which corresponds to a ground resolution of 0.7 mm H. W. Radin, memorandum for Bellcomm Inc., August 30, 1971). The high resolution required image motion compensation, which was accomplished by rocking the camera in the direction of flight. Calibration of the camera using stellar methods yields a calibrated focal length of 450.672 ± 0.013 mm. A maximum radial distortion of 26 μm occurs at a radial distance of 72 mm from the center, which is less than 10 μm within a distance of 40 mm for a standard format (Malhotra, 1970). Tangential distortions are 1.2 and 0.4 μm at distances of 72 and 40 mm, respectively.

MAPPING CAMERAS

Mapping cameras (7.62-cm focal length) (also called metric or terrain cameras) were carried in the scientific instrument modules of the orbiter spacecraft in Apollo 15, 16, and 17. Among the scientific objectives of the cameras were the development of a consistent set of coordinates of control points on the lunar surface with an accuracy of 10 to 15 m (Light, 1972) and the preparation of topographic maps (for example, Defense Mapping Agency, 1974a). Photographic coverage of the Moon by these cameras is extensive but constrained by the sparse network of orbital altitudes and illumination conditions of the Moon during the missions (Aeronautical Chart and Information Center, 1971; Defense Mapping Agency, 1972a). Importantly, some coverage was taken at oblique angles by rolling the spacecraft camera, and others at nominal spacecraft altitude of 110 km, each photograph, which has an 11.43 x 11.43 cm format, covers a area about 105 km on an edge. Photocell is about 1:1400. Stereoscopic coverage was obtained by overlapping consecutive frames 78 percent, producing base-height ratios near 0.35. Use of alternate frames increases the base-height ratio to 0.66. Resolution of the cameras was 200 lines/mm at 1.00 to 1 contrast with film type 5460 at a scale of 1:60,000, the field of view of the ground is near 15 to 20 m at nominal altitude (National Space Science Data Center, 1972, 1973, 1974). Lens distortions are nominal less than 50 μm (Light, 1972) and can be removed from the image by controlling use of images of 8 fiducial marks and a square array of 122 reserve marks engraved on the glass with a 72 μm laser. Standard plate measurements (National Space Science Data Center, 1972). Calibration data for each camera are listed below.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Calibration data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 15</td>
<td>73.936 ± 0.003</td>
</tr>
<tr>
<td>Apollo 16</td>
<td>73.936 ± 0.003</td>
</tr>
<tr>
<td>Apollo 17</td>
<td>73.942 ± 0.003</td>
</tr>
</tbody>
</table>

PANORAMIC CAMERA

The panoramic camera (60.96-cm focal length) is the highest resolution optical system aboard the Apollo and combines high resolution with overlapping convergent photographs so that fine-scale measurements and detailed topographic maps may be made from photographs taken by the camera. In contrast with the
A. Wilhelms, 1980). (2) " Lunar Remote Sensing and Measurements" (Chapter B, Moore and others, 1980), (3) " Geometric Interpretation of Lunar Craters" (Chapter C, Piler). The lunar topographic mapping on board the Apollo 14 Command Module (Dietrich, 1971) was used to obtain data on fine-scale lunar roughness (Moore and others, 1975, 1976, 1980). Apollo missions 15, 16, and 17 carried the sophisticated mapping camera system in orbit (Dietrich and Clanton, 1972a, 1972b; McEwen and Clanton, 1973). In the mapping camera system, a 3-inch stellar camera was mounted at a 96° angle to the axis of a 3-inch mapping camera, and a laser altimeter capable of measuring slant range within 2 m was aligned with the mapping camera. This system has been used for establishing a seafloor control network as well as topographic mapping (Doyne and others, 1976; Cannell and Ross, 1976; Kopal and Carder, 1974). A panoramic camera, carried on Apollo missions 15-17, obtained high-resolution stereoscopic photographs that are useful for detailed studies. The cameras and photographs used to collect data in this report are discussed briefly below and listed in table 1.

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Photography taken with this camera had the highest resolution of all the Apollo missions flown previously, but higher resolutions were achieved by later missions. Resolutions achieved by the lunar topographic camera are 62 optical pairs per millimeter at a tribar contrast of 2:1 with 3400 type film, which correspond to a ground resolution of 0.7 m H.W. Rabinowitz, a memorandum for Bellcomm Inc., August 31, 1970). The high resolution required image motion compensation, which was accomplished by rocking the camera in the direction of flight. Calibration of the camera using stellar methods yields a calibrated focal length of 455.672 ± 0.013 mm. A maximum radial distortion of 0.026 mm occurs at a radial distance of 72 meters, with the maximum value of 10 μm within a distance of 40 mm for a standard format (Malhotra, 1970). Tangential distortions are 1.2 and 0.4 μm at distances of 72 and 30 mm, respectively.

MAPPING CAMERA

Mapping camera (7.62-cm focal length) (also called metric or terrain cameras) were carried in the scientific instrument modules of the orbiter spacecraft in Apollos 15, 16, and 17. Among the scientific objectives of the cameras were the development of the U.S. photogrammetric control of control points on the lunar surface with an accuracy of 10 to 15 m (Light, 1972) and the preparation of topographic maps (for example, Defense Mapping Agency, 1974a). Photographic coverage of the Moon by these cameras is extensive but constrained by the image-rotation and illumination conditions of the Moon during the missions. Aeronautical Chart and Information Center, 1971; Defense Mapping Agency, 1972, 1973a). Importantly, some coverage was taken at oblique angles by rolling the spacecraft, which significantly reduces the spacecraft altitude of 110 km, each photograph, which has an 11.43 x 11.43 cm format, covers a area about 105 km on an edge. Photoplate is about 1:14,000. Stereoscopic coverage was obtained over lapping consecutive frames 78 percent, producing a base-height ratio near 0.35. Use of alternate frames increases the base-height ratio to 0.66.

Resolution of the cameras was 200 lines/mm at 1.000 to 1 contrast with film type 5400. Photoplate format is 8 x 10 in., the field of view is 45 x 45 degrees, with 100 percent overlap. Photographic coverage is high-resolution stereoscopic coverage of a strip approximately 250 km wide, centered on the ground track.

Table 1.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Frames</th>
<th>Film size and type</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar Topographic Camera</td>
<td>45.5-cm focal length</td>
<td>74 by 74&quot; field of view</td>
<td>Used to obtain high-resolution photographic coverage of lunar surface near candidate landing sites.</td>
</tr>
<tr>
<td>127 mm, type SO 349 high-definition aerial film, Asf 6</td>
<td>1400 Panatomic-X black-and-white film, ASA 80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Camera | Frames | Film size and type | Remarks |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapping Camera</td>
<td>Electric controls in CSM</td>
<td>280 by 550 mm</td>
<td>10 mm field of view, 8 by 8 frames, 4 fiducial marks, and the camera serial number recorded on each frame with auxiliary data of time, altitude, shutter speed, and forward and reverse markers.</td>
</tr>
<tr>
<td>472 m of 127-mm film type 3400 Panatomic-X, ASA 80</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Panoramic Camera | Electric controls in CSM | 80 by 150 mm | 100 mm field of view, fiducial marks printed along both edges, B & G time code printed on back edge, black blocks frame number, time, mission data, V, V, and camera-pointing attitude. |
| 1981.2 m of 127-mm film EK | 114 by 114 mm images were taken looking forward 12.5° then 12.5° forward and 12.5° backward for stereo. |
| EK | 3414. |

Command and Service Module

EXPEDIENT PHOTOGRAMMETRY OF LUNAR IMAGES

D3

To obtain used high-resolution photographic coverage of lunar surface near candidate landing sites. Operating difficulties prevented scheduled convergent stereo photography of the Lunar Module near the landing sites of the Apollo 16 landing site. When the camera gook exposure, it was on one of the impact points of the Apollo 16 Lander skid stage.
other Apollo cameras, the Iké optical bar panoramic camera is a fixed focal-length direct-scanning camera producing cylindrical camera geometry. Scanning is accomplished mechanically with the scanning slit and center field of the lens perpendicuad to the image plane, as shown in Fig. 3. Use of the center field of the lens permits projection of the sharpest possible image onto the film. Photographic coverage of the Moon is extensive but constrained by the spacecraft orbits and illumination conditions of the Moon (Draper and Informaton Center, 1971; Defense Mapping Agency, 1972, 1973a). The frame format is 11.43 x 11.43 cm. Because of the cylindrical camera geometry, highest resolution is achieved along the ground track traced by the camera optical axis with minimum distance from the surface. At the nominal spacecraft altitude and 12.5° tilt in the direction of flight, the 11.43-cm film width corresponds to about 21 km along the ground track. Coverage in the cross-track direction is about 350 km wide. Resolution decreases and coverage increases in the cross-track direction as tilts due to scanning in- crease symmetrically about the ground track. Photo- scale along the track is near 1:18,000 for the nominal altitude. Stereoscopic coverage was obtained by alter- nately tilting the camera 12.5° forward along the track and 12.5° aftward along the track at 5-second intervals so that overlaps were 90 percent (National Space Data Center, 1972, 1973, 1974). Base-height ratios for nominal altitudes were near 0.44, producing strong stereo-model geometry.

Resolution of the camera is 135 lines/mm at a con- trast ratio of 0.180 lines/mm with medium-contrast targets, and 150 lines/mm with low-contrast targets (Iké Corp., 1967). Line-pair resolutions correspond to ground resolutions of 3.0, 2.0, and 2.5 m respectively at the center of the scan. Because of scanning, cylindrical geometry, and convergent stereopairs, distortions are complicated and more difficult to correct than those of frame cameras, and stereo-models are difficult. For these reasons, specially designed equipment such as the AS-11A stereolocater (Ottico Meccanica Italiana, 1966) was required for mapping purposes. Some measurement data such as profiling may be obtained with little or no error in directions parallel to the ground track using the APC photometer (Ottico Meccanica Italiana, 1966). The panoramic cameras used during each of the Apollo missions were completely calibrated (Iké Corp., 1967), and calibrated focal lengths were listed.

Some of the panoramic camera photographs of the Apollo 17 mission were taken in the area of the lunar crater Euler. We obtained without rocking the camera to produce the 25.0° convergence angle. For this photogra- phy a 90° overlap of consecutive frames was obtained, giving base-to-height ratios less than or close to 0.1. Here stereomodel geometry is weak, and mensura- tion is substantially poorer than for the nominal panoramic photographs.

METHODS AND PROCEDURES

PHOTOMETRIC EQUIPMENT AND MATERIALS

Photometric equipment used in the mensura- tion and topographic mapping in this report were the APC (Ottico Meccanica Italiana, 1966) and the AS-11A (Ottico Meccanica Italiana, 1964) analytical stereolocaters. Both photogrs are controlled by com- puters. The photors are very flexible in accommodating a wide range of photographic geometries, principal dis- tances, and base-height ratios, and lens distortion and lunar curvature can be corrected by the computers. Topographic maps prepared from panoramic camera photographs require the AS-11A photometer, but the APC can be used with panoramic camera photographs for profiles parallel to and measured near the ground track. Cross-track profiles from panoramic camera photographs prepared using the APC are curved because of the cylindrical geometry described above. Both photors have a least significant reading capability of 1 μm, and repeated measurements have a precision near ±2 μm. When combined with the scale- height ratios of the camera photographs, this precision translates to ±7.5-10 m for a variety of mapping camera photographs (Wu, 1976). Small base-height ratios for each camera are listed in table 5.

In the studies, second-generation master positive transparencies prepared from the original negative were used in the photors. These transparent positives are the best quality reproductions available in the original format size and provide photographs with minimal loss of the original resolution. Probable errors in elevation measurements are interpreted in terms of nominal photographic resolution (Gardner, 1932) in table 2.

CONTROL AND LEVELING

Because the sidereal control points were not available at the time of part of the photometric processing, being modelled as the photographic photographs were oriented and leveled using soapbub data and existing small-scale topographic maps. For setting up models of panoramic camera photographs, control information was obtained from stereomodels of

mapping photographs covering the same area. In the case of the lunar topographic camera photographs, model orientation information was sometimes obtained from Lunar Orbiter pictures and data (National Space Data Center, 1969). In some cases, where the geology of a local area was of interest and where no information was available, such techniques as assum- ing a more narrow to be level or the rim of a large crater to be level were used.

METHODS OF MEASUREMENTS

For map compilation or profile plotting, after a stereomodel is obtained, regular photometric procedures are followed to plot measurements. However, for the support of terrain analysis, specifically for the study of slope-probability distributions of the lunar surface, which will be described in detail in this report, statistical profiles are measured in a model along linear traverses using a constant horizontal distance between consecutive points. Each profile contains at least 500 points. At each point three to five readings were taken. A sample area was chosen that is repre- sentative of a surface geologic unit. The slope- probability statistics then provide a quantifier for that type surface or that geologic unit.

PRECISION OF MEASUREMENT

The level of detail that can be achieved in preparing profiles and topographic maps from Apollo stereophotographs depends on the standard error in elevation measurement (σ), which is the product of photographic scale or its reciprocal-scale factor (S), the height-base ratio (HB), and the standard error of parallax measurement (σ_r) (Doyle, 1963; Light, 1972). Scale factors and height-base ratios using Apollo pho- tographs with suitable scanners are generally ideal to very good. The standard error of parallax measure- ment is related to a number of factors such as lens distortions, photographic quality, scene contrast, and the person who measures parallax. Scene contrast is re- lated to surface roughness or patterns and illumination conditions. The wide variety of illumination conditions of Apollo photography combined with the reflective properties of the lunar surface offered an opportunity to discover the relation between illumination and the standard error in measurement. Extensive studies using mapping camera photographs have been made relating standard error in measurements with variable illumination conditions and, to some extent, with slopes (Wu, 1976). Data on standard errors in meas- urement for the lunar topographic camera and panoramic camera photographs are limited, but some results are reported here (see also Wu and others, 1973).

MAPPING CAMERA PHOTOGRAPHY

Standard errors in measurement for Apollo mapping camera photographs correlate strongly with the illu- mination conditions (Wu, 1976). When sun elevation angles are less than about 10°, measurement errors on rug- ular parts of the Moon are covered by shadow. This condition precludes measurements in deep shadows, and standard errors in diffuse shadows tend to be large. Photograms taken with sun elevation angles larger than 30° show increasing average standard errors in measurements because scene contrast is reduced by the luminal values in target sunlight or shadow (Wildy, 1972).

Regression fits were made to the data in the form

\[ Y = a + \beta X + \gamma X^2. \]

Where Y is the standard error in measurement, X is sun elevation angle, and a, \( \beta \), and \( \gamma \) are coefficients listed in table 3, the regression curves are displayed in Fig. 13. The combined mensurations. The regressions, exclusive of Apollo 16, show

<table>
<thead>
<tr>
<th>Mission</th>
<th>Lunar Date</th>
<th>Camera</th>
<th>Calibration Distal Length</th>
<th>Apollo 15</th>
<th>Apollo 16</th>
<th>Apollo 17</th>
<th>Apollo 16-17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 16</td>
<td>N-45</td>
<td>003</td>
<td>609.752 ± 0.025</td>
<td>0.007</td>
<td>0.0086</td>
<td>0.0045</td>
<td>0.0045</td>
</tr>
<tr>
<td>Apollo 17</td>
<td>N-45</td>
<td>003</td>
<td>609.524 ± 0.025</td>
<td>0.0045</td>
<td>0.007</td>
<td>0.0056</td>
<td>0.0056</td>
</tr>
</tbody>
</table>

When statistically determined, the standard error in elevation measurement is denoted \( \sigma \).
other Apollo cameras, the Ike optical bar panoramic camera is a fixed focal-length direct-scan camera producing cylindrical camera geometry. Scanning is accomplished mechanically with the scanning slit and center field of the lens as a unit. Use of the center field of the lens permits projection of the sharpest possible image onto the film. Photographic coverage of the Moon is extensive but constrained by the spacecraft orbits and illumination conditions of the Moon during the missions (Aeronautical Chart and Information Center, 1971; Defense, Mapping Agency, 1972, 1973a). The frame format is 11.43 × 11.43 cm. Because of the cylindrical camera geometry, highest resolution is achieved along the ground track traced by the camera optical axis with minimum distance to the surface. At the nominal spacecraft altitude and 12.5° tilt in the direction of flight, the 11.43-cm film width corresponds to about 21 km along the ground track. Coverage in the cross-track direction is about 350 km wide. Resolution decreases and coverage increases in the cross-track direction as tills due to scanning in increase symmetrically about the ground track. Photo scale along the track is near 1:185,000 for the nominal altitude. Stereoscopic coverage was obtained by alternatingly tilting the camera 12.5° forward along the track and 12.5° aftward along the track at 5-second intervals so that overlaps were 90 to 100 percent (National Space Science Data Center, 1972, 1973, 1974). Base-height ratios for nominal conditions were near 0.44, producing strong stereo-model geometry.

Resolution of the camera is 135 lines/mm at a contrast ratio of 2:1, 180 lines/mm with medium-contrast targets, and 150 lines/mm with low-contrast targets (Ike Corp., 1967). Line-pair resolutions correspond to ground resolutions of 3.0, 2.0, and 2.5 m respectively at the center of the scan. Because of scanning, cylindrical geometry, and convergent stereopairs, distortions are complicated and more difficult to correct than those of frame cameras, and stereomodels are difficult. For these reasons, specially designed equipment such as the AS-11A stereolocator (Ortico Meccanica Italiana, 1966) was required for mapping purposes. Some measurement data such as profiling may be obtained with little or no error in directions parallel to the ground track using the APC plotter (Ortico Meccanica Italiana, 1966). The panoramic cameras used during each of the Apollo missions were completely calibrated (Ike Corp., 1967), and calibrated focal lengths were listed.

Some of the panoramic camera photographs of the Apollo 17 missions were taken in the area of the lunar crater Euler. Apollo 16 astronauts returned to this area without roving the camera to produce the 25°0 convergence angle. For this photography a 10 ppr opaque overlay of consecutive frames was obtained, giving base-to-height ratios less than or close to 0.1. Here stereomodel geometry is weak, and measurement is substantially poorer than for the nominal panoramic photographs.

### METHODS AND PROCEDURES

#### EQUIPMENT AND MATERIALS

Photogrammetric equipment used in the measurement and topographic mapping in this report were the APC (Ortico Meccanica Italiana, 1966) and the AS-11A (Ortico Meccanica Italiana, 1964) analytical stereolocators. Both photograms are controlled by computers. The photograms are very flexible in accommodating a wide range of photographic geometries, principal distances, and base-height ratios, and lens distortion and lunar curvature can be corrected by the computers. Photographic maps prepared from panoramic camera photographs require the AS-11A plotter, but the APC can be used with panoramic camera photographs for profiles parallel to and measured near the ground track. Cross-track profiles from panoramic camera photographs prepared using the APC are curved because of the cylindrical geometry described above. Both photograms have a least significant reading capability of 1 μm, and repeated measurements have a precision near ±2 μm. When combined with the scale height/height ratios of the Apollo panoramic photographs, this precision translates to ±0.5-10 m for a variety of mapping camera photographs (Wu, 1976). Base and height measurements for each camera are listed in table 3.

In the studies, second-generation master positive transparencies prepared from the original negative were used in the photograms. These transparent positives are the best quality reproductions available for original format size and provide photographs with minimal loss of the original resolution. Probable errors in elevation measurements are interpreted in terms of nominal panoramic photograph resolution (Gardner, 1932) in table 2.

### CONTROL AND LEVELING

Because the selenodetic control points were not available at the time of part of the photogrammetric processing, scenes of panoramic camera photographs were oriented and leveled using support data and existing small-scale topographic maps. For setting up models of panoramic camera photographs, control information was obtained from stereomodels of mapping photographs covering the same area. In the case of the lunar topographic camera photographs, model orientation information was sometimes obtained from Lunar Orbiter pictures and data (National Space Science Data Center, 1969). In some cases, where the geology of a local area was of interest and where no information was available, such techniques as assuming a mirror surface to be level or the rim of a large crater to be level were used.

### METHODS OF MEASUREMENTS

For map compilation or profile plotting, after a stereomodel is obtained, regular photogrammetric procedures are followed to plot measurements. However, for the support of terrain analysis, specifically for the study of slope-probability distributions of the lunar surface, which will be described in detail in this report, statistical profiles are measured in a model along linear traverses using a constant horizontal distance between consecutive points. Each profile contains at least 500 points. At each point three to five readings were taken. A sample area was chosen that is representative of a surface geologic unit. The slope-probability statistics then provide a quantifier for that type of surface or that geologic unit.

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\[ Y = a + \beta X + \gamma X^2 \]

Where \( Y \) is the standard error in measurement, \( X \) is sun elevation angle, and \( a, \beta, \) and \( \gamma \) are coefficients listed in table 3. Note that \( a \) is the standard error in measurement for each measured point.
a tendency for the minimum standard error in elevation measurement to occur near a sun elevation angle of 30° (fig. 1). Similar results are obtained when local slope is taken into account (fig. 1). Results in detail are described in an investigation on illumination and measurement precision for lunar photography (Wu, 1976). Although these studies clearly show that sun elevation angles near 30° are optimal for stereophotogrammetry, the effects of the photometric function, surface albedo, and height-base ratio have not been carefully studied.

**PANORAMIC AND LUNAR TOPOGRAPHIC CAMERA PHOTOGRAPHY**

As part of the measurements for surface roughness and slope-probability distributions at the fine scale, average standard errors in measurement were computed for 500 to 1,000 points on lunar topographic and panoramic camera photographs. Standard errors in elevation measurements \( \delta_z \) for each point were estimated from the readings. Averages of the standard error in measurement, tabulated below, represent an estimate for those photographs.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Average of standard error ( \delta_z ) in m</th>
<th>Number of standard errors in average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar topographic</td>
<td>0.7 ± 0.4 m</td>
<td>9</td>
</tr>
<tr>
<td>Panoramic</td>
<td>2.9 ± 2.2 m</td>
<td>15</td>
</tr>
</tbody>
</table>

**TOPOGRAPHIC MAPS**

Apollo mapping and panoramic camera photographs provide accurate data on the morphology of lunar craters and other features with subtle relief. Topographic mapping of the Moon at 1:250,000 scale with mapping camera photographs has been extensive (Kinsler, 1975). Contour intervals of 100 m are standard for these maps, and in some cases supplementary contours with a 50-m interval are given (see for example Defense Mapping Agency, 1975). Scales and contour intervals of maps prepared from panoramic camera photographs vary depending on the features portrayed. The largest scale maps are 1:10,000 with a 10-m contour interval and 5-m supplementary contours (see for example Defense Mapping Agency, 1974d). These contour intervals are entirely consistent with the capabilities of the cameras and the quality of the photographs. Acceptable contour intervals are three or more times the standard error in elevation (0.7 m) and fall within or close to the combined errors of resolution, instrument errors, and errors measured experimentally.

Some experimental topographic maps were prepared by the U.S. Geological Survey to test the capability of the photography and to obtain scientific data on a timely basis and with sufficient detail. Purposes of the maps included support of the bistatic-radar studies, dimensions of craters, and miscellaneous geologic studies. Table 4 summarizes the maps prepared and their use. Although not considered in detail here, two maps prepared from Apollo 12 Hasselblad photographs are included in the table.

**VERTICAL MAPPING CAMERA PHOTOGRAPHY**

A topographic contour map of the scablands region north of the Aristarchus Plateau was compiled from vertical mapping camera photographs (fig. 2). The photographs were taken under a number of favorable conditions such as (1) vertical optic axes, (2) a large base-height ratio (0.4), and (3) good sun illumination conditions (sun elevation angle of 12°). In addition, horizontal and vertical control was available from the

**FIGURE 1** Regression curves determined from standard error in elevation measurement \( \delta_z \) and local sun elevation angles (dashed lines); standard error in measurement and local sun elevation angles corrected for surface tilt (solid lines): (A) Apollo 15, (B) Apollo 16, (C) Apollo 17, and (D) combined data.

**FIGURE 2** Vertical Apollo 15 mapping camera photograph 2483 of scablands region north of Aristarchus plateau. Photograph is one of a stereoscopic pair used to make topographic map in plate 1.
a tendency for the minimum standard error in elevation measurement to occur near a sun elevation angle of 30° (fig. 1). Similar results are obtained when local slope is taken into account (fig. 1). Results in detail are described in an investigation on illumination and measurement precision for lunar photography (Wu, 1976).

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<table>
<thead>
<tr>
<th>Camera</th>
<th>Average of standard error of observations (σz)</th>
<th>Number of standard errors of observations</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.7 ± 0.4 m</td>
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**TABLE 4.—Experimental topographic maps prepared in support of Photogeology Apollo 15-17 (NASA Experiment 8-222)**

<table>
<thead>
<tr>
<th>Map name</th>
<th>Scale</th>
<th>Location</th>
<th>Photography used</th>
<th>Plotter used</th>
<th>Mag map scale</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hasselblad</td>
<td>1/250,000</td>
<td>2° W, 65° S</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Support bistatic-radar experiments, study of topographic lunar structures.</td>
</tr>
<tr>
<td>Lasberg</td>
<td>182° W, 6° S</td>
<td>1,086,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Support bistatic-radar experiments, study of topographic lunar structures.</td>
</tr>
<tr>
<td>Scablands north of Aristarchus plateau</td>
<td>50° W, 60° N</td>
<td>1,106,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Geologic study of Aristarchus region.</td>
</tr>
<tr>
<td>De</td>
<td>50° W, 60° N</td>
<td>1,106,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Geologic study of Aristarchus region.</td>
</tr>
<tr>
<td>Alphonsus</td>
<td>6° W, 12° S</td>
<td>1,250,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Demonstration of use of oblique mapping camera photographs in preparation of topographic maps.</td>
</tr>
<tr>
<td>Southeast Kraig area</td>
<td>49° W, 6° S</td>
<td>1,040,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Study of morphology of moderately rough surface.</td>
</tr>
<tr>
<td>Moon-floor surface of Aristarchus plateau</td>
<td>50° W, 60° N</td>
<td>1,150,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Study of morphology of lunar surface.</td>
</tr>
<tr>
<td>North of Daphnis</td>
<td>34° W, 70° N</td>
<td>1,350,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Study of morphology of lunar surface.</td>
</tr>
<tr>
<td>Durand crater in crater Athabasca</td>
<td>16° W, 17° S</td>
<td>1,110,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Study of morphology of lunar surface.</td>
</tr>
<tr>
<td>Lava-flooded bright terrain map</td>
<td>30° W, 60° N</td>
<td>1,250,800</td>
<td>Apollo 10-17</td>
<td>Apollo 10-17</td>
<td>1:250,000</td>
<td>Study of morphologic variation of lunar surface.</td>
</tr>
</tbody>
</table>
OBlique mapping camera photography

An experiment has demonstrated that valuable topographic data can be obtained from high oblique photographs (Wu and others, 1972). As shown in figure 3, the crater Alphonsus was covered by Apollo 16 mapping camera photographs 2477 and 2478. The high tilt (40°) of these photographs was enough to include the horizon. A topographic form-line map was compiled from this model in the APC plotter (fig. 4). In spite of the large tilt angles, this model has a 0.35 base-height ratio. The average standard error of repeatability of elevation measurements within the mapped area was near 11 m. Thus it is possible to attain a contour interval of 50 m. Because the photographic support data for the Apollo 16 photographs were not available at the time this test was made, the model was scaled using Lunar Orbiter support data (LOTV H-108) and leveled assuming that the floor of Alphonsus was level.

Panoramic camera photography

Very detailed topographic information of subtle landforms and small craters can be obtained from the panoramic camera photographs. Several experimental topographic maps were compiled of geologically significant features on the lunar surface. Some of these topographic maps are described in the following sections. All of the model geometries from which these maps were compiled are similar in that they all have a 25° convergent angle, which gives a strong base-height ratio of 0.44, and they all have from 90 to 100 percent overlap. The model scales range from 1:150,000 to

Figure 3.—Apollo 16 mapping camera photograph 2477 is one of the photographs used in compiling the topographic map shown in figure 4. Outline shows location of boundaries of map in figure 4.
1: 250,000-scale maps "Nielsen" and "Freud" (Defense Mapping Agency, 1974, f). For these reasons it was a good model to use to determine the smallest contour interval that could be obtained with this type of photograph. As shown in plate 1, a 50-m contour interval can be obtained from the Apollo mapping camera photographs. This map, combined with one prepared from panoramic camera photographs, was used to detect warping of the lunar surface that occurred after the formation of the rilles. Figure 2 is one of the mapping camera photographs used in compiling the topographic map in plate 1.

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One experimental topographic map of an area southeast of Krieger was compiled from Apollo 15 panoramic photographs (pl. 2). This map demonstrates that a scale as large as 1:10,000 with a 5-m form-line interval can be obtained from a model of panoramic photography.

To obtain control information to orient this model, a

FIGURE 3. — Apollo 16 mapping camera photograph 2477 is one of the photographs used in compiling the topographic map shown in figure 4. Outline shows location of boundaries of map in figure 4.

FIGURE 4. — Contour map of Alphonsus compiled from oblique Apollo 16 mapping camera photographs 2477 (see fig. 3) and 2478. Map prepared under NASA contract T5874A.
model from Apollo 15 mapping camera photographs (numbers 2478 and 2479) was set up on the AFC analytical plotter. The scaling information for this mapping camera model was obtained from the photographic support data, and the leveling was accomplished by selecting elevations from Lunar Topographic Orthophotomaps LTO 39A1, Kreiger (Defense Mapping Agency, 1973b). Secondary craters portrayed on this map were produced by Aristarchus some 150 km south and form part of the data set on lunar crater geometry (Pike, 1974, 1980). Secondary crater diameters, depths, rim heights, circularity, and ejecta symmetry can be measured on the map.

Another topographic map (pl. 3) illustrates that subtle features such as lunar domes can be accurately portrayed using panoramic camera photographs. The dome has a mere 60 m of relief and is seen with vivid clarity on low-altitude photographs. On the 1:250,000-scale Lunar Topographic Orthophotomap (LTO), Kreiger (Defense Mapping Agency, 1973b), only one contour is present around the dome because of the 50-m contour interval. Thus, subtle features barely detectable in topographic maps prepared from mapping camera photographs can only be portrayed in detail by stereophotogrammetry from panoramic camera photographs.

A topographic map of the Delisle-Diplanitsus area compiled on the AS-11A plotter is included on the area covered by LTO Delisle (Defense Mapping Agency, 1974a) (pl. 4). Dimensions of small craters derived from this map represent the best data in the sample on very small lunar craters used in establishing the geometry of lunar craters (Pike, 1974). The nature and amount of filling of Rima Brahms (the sinuous rille that transects the map) by ejecta from two larger craters to the north and south (Delsile and Diplanitsus) can be measured. Some data on the morphology of ejecta blankets can be obtained from this map.

**CRATER GEOMETRY**

Profiles of craters were very important in the early phases of studies employing Apollo mapping camera photographs when carefully controlled maps prepared with them were not yet available. Profile data along with geological stratigraphic relations resolved the controversy of the origin of the previously enigmatic crater Linné (fig. 5), which turned out to be an ordinary albeit very fresh impact crater (Pike, 1973a, 1980). Topographic analyses of 25 farside craters (Table 5) 1.6 to 2.7 km across showed that the craters do not differ in shape from nearside craters and their shapes were more consistent with an impact origin than a volcanic origin (Pike, 1973a, 1980). It was also shown that shapes of farside craters measured with stereophotogrammetry were more consistent with lunar nearside craters than those measured using photogrammetry. Because carefully controlled maps were not available for these early studies, orientations of stereomodels were arrived at using photogrammetry. For craters with superimposed on maria, surrounding surfaces were assumed to be level, for large craters, their flat floors were taken as level, and for smaller craters, Lunar Orbiter data were used (National Space Science Data Center, 1969). Stereophotogrammetric profiles prepared by the U.S. Geological Survey and measurements obtained from Lunar Topographic Orthophotomaps (for example Defense Mapping Agency, 1974a) prepared from Apollo mapping and panoramic photographs have resulted in a revision of depth-diameter relations of lunar craters (Pike, 1974) and have revealed discrepancies of some pre-Apollo data (Pike, 1972).

**LUNAR FLOWS**

Detailed profiles of a flow lobe (figs. 6 and 7) in Mare Imbrirum were a necessary part of a study of the rheological properties of the flow and tectonic deformation in the general area (Moore and Schauber, 1975). In this study it was shown that the yield strength of the lunar flow was comparable to measured values of molten lava in Hawaii and that little or no post-flow deformation had occurred, although there was evidence for local warping. Both carefully controlled maps and high-resolution Apollo panoramic camera stereophotographs were prepared for the study. Relief of the flows is 7–20 m, comparable to the standard error of elevation measurement of the mapping camera photographs. In contrast, panoramic camera photographs have a standard error of measurement near 1.0 m (Wu and others, 1973). Profiles were measured using the AFC stereolplotter because the detailed profiles were very nearly parallel to the ground track. Cross-
model of Apollo 15 mapping camera photographs (numbers 2478 and 2479) was set up on the AFC analytical plotter. The scaling information for this mapping camera model was obtained from the photographic support data, and the leveling was accomplished by selecting elevations from Lunar Topographic Orthophotomaps LTO 39A1, Kreiger (Defense Mapping Agency, 1973b). Secondary craters portrayed on this map were produced by Aristarchus some 150 km south and form part of the data set on lunar crater geometry (Pike, 1974, 1980). Secondary crater diameters, depths, rim heights, circularity, and ejecta symmetry can be measured on the map. Another topographic map (pl. 3) illustrates that subtle features such as lunar domes can be accurately portrayed using panoramic camera photographs. The dome has a mere 60 m of relief and is seen with vivid clarity on low-angle photographs. On the 1:250,000-scale Lunar Topographic Orthophotomaps (LTO) Krieg (Defense Mapping Agency, 1973b), only one contour is present around the dome because of the 50-m contour interval. Thus, subtle features barely detectable in topographic maps prepared from mapping camera photographs can only be portrayed in detail by stereophotogrammetry from panoramic camera photographs. A topographic map of the Delisle-Diophantus area compiled on the AS-11A plotter is included on the area covered by LTO Delisle (Defense Mapping Agency, 1974a) (pl. 4). Dimensions of small craters derived from this map represent the best data in the sample on very small lunar craters used in establishing the geometry of lunar craters (Pike, 1974). The nature and amount of filling of Rima Brahms (the sinuous rille that transects the map) by ejecta from two larger craters to the north and south (Delisle and Diophantus) can be measured. Some data on the morphology of ejecta blankets can be obtained from this map.

**PROFILES**

Some topical studies of the Moon require carefully and specially prepared profiles in order to achieve the objectives of the study, and close coordination between the user and photogrammeters is required. Pioneering efforts were conducted with Apollo 10 Hasselblad photographs to compare profiles derived with photogrammetric and photometric techniques (Lucchita, 1971), to study mass wasting (Pike, 1971b), and to demonstrate the photogrammetric method for lunar research (Wu, 1969, 1971). Subsequently, photographs taken with the photogrammetric quality cameras of Apollo 15, 16, and 17 were used to make profiles for specific studies. Two such examples are the quantitative studies of crater dimensions and lunar flows.

**CRATER GEOMETRY**

Profiles of craters were very important in the early phases of studies employing Apollo mapping camera photographs when carefully controlled maps prepared with them were not yet available. Profile data along with geologic interpretations revealed the controversy of the origin of the previously enigmatic crater Linné (fig. 5), which turned out to be an ordinary albeit very fresh impact crater (Pike, 1973b, 1980). Topographic analyses of 25 farside craters (Table 5) 1.6 to 2.7 km across showed that the craters do not differ in shape from nearside craters and their shapes were more consistent with an impact origin than a volcanic origin (Pike, 1973a, 1980). It was also shown that shapes of farside craters measured with stereophotogrammetry were more consistent with lunar nearside craters than those measured using photogrammetry. Because carefully controlled maps were not available for these early studies, orientations of stereomodels were accomplished in a variety of ways: (1) For craters superposed on maria, surrounding surface features were assumed to be level, (2) for large craters, their flat floors were taken as level, and (3) for small craters, Lunar Orbiter data were used (National Space Science Data Center, 1969). Stereophotogrammetric profiles prepared by the U.S. Geological Survey and measurements obtained from Lunar Topographic Orthophotomaps (for example Defense Mapping Agency, 1974a) prepared from Apollo mapping and panoramic photographs have resulted in a revision of depth-diameter relations of lunar craters (Pike, 1974) and have revealed discrepancies of some pre-Apollo data (Pike, 1972).

**LUNAR FLOWS**

Detailed profiles of a flow lobe (figs. 6 and 7) in Mare Imbricum were a necessary part of a study of the rheological properties of the flow and tectonic deformation in the general area (Moore and Schaber, 1972). In this study it was shown that the yield strength of the lunar flow was comparable to measured values of molten lava in Hawaii and that little or no post-flow relaxation had occurred, although there was evidence for local warping. Both carefully controlled maps and high-resolution Apollo panoramic camera stereophotographs were required for the study. Relief of the flows is 7-20 m, comparable to the standard error of elevation measurement of the mapping camera photographs. In contrast, panoramic camera photographs have a standard error of measurement near 1.0 m (Wu and others, 1973). Profiles were measured using the AFC stereolplotter because the denser profiles were very nearly parallel to the ground track. Cross-
track profiles showed the curvature expected from camera geometry and were not used. Approximate leveling was achieved using an existing base map (Defense Mapping Agency, 1974b). The profiles appear to be tilted a large amount (fig. 7) because of the large vertical exaggeration, but tilts are in reality very small, less than 0.4° in every case. In an independently measured profile (not shown in fig. 7) along C–C’, the tilt was in the opposite direction. Thickness estimates remained the same. Because of the artificial tilts and obvious curvature in the cross-track profiles, gradients in the direction of flow for the rheological and tectonic study were obtained from a map at a scale of 1 : 250,000 prepared from mapping camera photographs (Defense Mapping Agency, 1974b). The 100-m contour interval of the map was much too large for estimating the thickness of the flow.

Profiles of a flow lobe in the basin just north of the crater King (fig. 8) were also analyzed in conjunction with a quality 1 : 250,000-scale map (Defense Mapping Agency, 1974c) to study the rheology of flows in the lunar highlands (Moore and Schaber, 1975). Yield strengths for this highland flow were much larger than those of the Imbrium volcanic flow and consistent with a higher silica content of the highland flow. Additionally, topographic data showed that frictional sliding could not account for the movement of the flow mass.

LUNAR SURFACE ROUGHNESS

The Apollo orbital missions provided two independent methods of estimating surface roughness: radar and photogrammetry. Command and Service Modules of Apollo 14, 15, and 16 conducted bistatic-radar experiments which resulted in estimates of surface roughness from areas 10 to 20 km across along the gound tracks (Howard and Tyler, 1971). Slope-probability distributions are also obtained at two wavelengths by summing the echoes over 2° intervals (Parker and Tyler, 1973). Roughness and slope-probability distributions measured on positive transparencies of stereoscopic photographs taken by the lunar topographic, mapping, and panoramic cameras provide a basis for comparison of the radar and photogrammetric methods. Earlier studies compared the results of the Explorer 35 bistatic-radar experiment with 220-cm wavelength radio transmissions (Tyler and Simpson, 1970) and photographometric studies on Earth-based photographs (Tyler and others, 1971). Preliminary studies of lunar surface roughness using stereophotogrammetry began during Apollo 10 and employed Hae.
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hand calculations and machine-calculated algorithms (Tyler and Howard, 1973). These two estimates are not necessarily equal (Moore and others, 1976, p. 46).

Slope-probability distributions were determined by analysis of the doppler shift of the echo spectra (Parker and Tyler, 1973) summed over 2° of lunar longitude and limited to slope angles less than 20°. Algebraic standard deviations estimated from the slope-probability distributions are normally larger than hand- and machine-calculated rms slopes (Moore and others, 1976, p. 5, 1980). The scale length sampled by the radar is a function of the wavelength of the transmitted signal and surface roughness characteristics (Tyler, 1976). The mean horizontal distance of the scale length for the radar from empirical determinations is about 100 to 300 radio wavelengths (Tyler and others, 1971; Moore and others, 1976).

**PHOTOMETRIC METHOD**

In the stereophotogrammetric method, slope-probability distributions are obtained using stereoscopic pairs of lunar topographic, metric, and panoramic camera positive transparencies in the A/PC plotter. Stereopairs were leveled and scaled from auxiliary data derived from orbital support data (National Space Science Data Center, 1972, 1973, 1974). Three elevation measurements are averaged for each of a number of points separated by a fixed horizontal distance along a linear traverse. The fixed horizontal interval will be referred to as slope length (L). In the following discussion, it is roughly equivalent to the scale length of the radar. Use of a fixed horizontal interval is compatible with previous terrain analysis procedures (Pike, 1971a, Rowan and others, 1971, Pike and Rosema, 1975). Repeated elevation measurements are used to estimate the standard error of measurement (\(S_e\)), which can substantially affect results under certain circumstances. More than 400 slope reads are determined for each slope-probability distribution. Two statistical descriptors commonly used are mean absolute slope angle (\(X\)) and algebraic standard deviation (\(\sigma\)). Mean absolute slope is the average of all values of absolute slope angle. Algebraic standard deviations are estimated from the cumulative absolute slope-probability distributions and taken as the slope angle corresponding to a cumulative fraction of 0.52 (+0.3174) when slope angles are near 25°. For large slope lengths, mean absolute slopes and algebraic standard deviations are calculated by the U.S. Geological Survey's terrain analysis computer program.

**READING ERROR PROBLEM**

As an initial test case, slope-probability distributions for Mare Fecunditatis and the Censorinus Highlands were measured using the stereophotogrammetric method and Apollo 16 mapping camera photographs (Wu and Moore, 1972) at a slope length of 200 m. Estimated algebraic standard deviations from the distributions were compared with rms slopes from the Explorer 35 bistatic-radar experiment (Tyler and Simpson, 1970) for which a scale length between 230 m and 660 m should be expected. The results showed that the roughness determined by the photogrammetric method was higher than the radar method by a significant factor of 1.5 but that both methods found the highland area rougher than the maria by a factor of 2.5 (see table below). This difference prompted an investigation of the effect of reading error on stereophotogrammetrically determined slope-probability distributions (Moore and Wu, 1973).

### Table

<table>
<thead>
<tr>
<th>Location</th>
<th>Radar slope length</th>
<th>Photogrammetry slope length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Censorinus Highlands</td>
<td>5</td>
<td>9.1</td>
</tr>
<tr>
<td>Mare Fecunditatis</td>
<td>2.4</td>
<td>3.8</td>
</tr>
</tbody>
</table>

In the photogrammetric method, a fictitious roughness of sensible magnitude can be introduced (Moore and Wu, 1973). Repeated elevation measurements are normally distributed about the true value under ideal conditions that include a large sample size. These normally distributed elevation errors introduce "noise" in...
hand calculations and machine-calculated algorithms (Tyler and Howard, 1973). These two estimates are not necessarily equal (Moore and others, 1976, p. 46).

Slope-probability distributions were determined by analysis of the doppler shift of the echo spectra (Parker and Tyler, 1973) summed over 2° of lunar longitude and limited to slope angles less than 20°. Algebraic standard deviations estimated from the slope-probability distributions are normally larger than hand- and machine-calculated rms slopes (Moore and others, 1976, p. 80, 1980). The scale length sampled by the radar is a function of the wavelength of the transmitted signal and surface roughness characteristics (Tyler, 1976). The mean horizontal distance of the scale length for the radar from empirical determinations is about 100 to 300 radio wavelengths (Tyler and others, 1971; Moore and others, 1976).

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BISTATIC-RADAR METHOD

In the Apollo radar experiments, radio signals with wavelengths of 15 cm and 116 cm transmitted by the orbiting spacecraft were reflected from the lunar surface and their echoes received on Earth (Tyler and Howard, 1973). The echoes were broadened in doppler according to the roughness of the reflecting area or

self-blade photographs (Pike, 1971a). Such studies continued through Apollo 17 using the newer photographs (Wu and Moore, 1972; Moore and Tyler, 1973; Moore and Wu, 1973). Slope-probability distributions measured with the radar and photogrammetry were compared for the first time after Apollo 17 (Moore and Tyler, 1973). As a result of these studies, certain aspects of the slope-probability distributions were found to be similar and others different (Moore and others, 1980).

READING ERROR PROBLEM

As an initial test case, slope-probability distributions for Mare Fecunditatis and the Censorinus Highlands were measured using the stereophotogrammetric method and Apollo 16 mapping camera photographs (Wu and Moore, 1972) at a slope length of 500 m. Estimated algebraic standard deviations from the distributions were compared with rms slopes from the Explorer 35 bistatic-radar experiment (Tyler and Simpson, 1970) for which a scale length between 230 m and 660 m should be expected. The results showed that the roughness determined by the photogrammetric method was higher than the radar method by a significant factor of 1.5 but that both methods found the highland area rougher than the maria by a factor of 2.5 (see table below). This difference prompted an investigation of the effect of reading error on stereophotogrammetrically determined slope-probability distributions (Moore and Wu, 1973).
the resulting slope probability distribution making the surface appear rougher than it actually is. The general effect is illustrated in Figure 9A (Moore and Tyler, 1973). Reading errors may produce more pronounced or less pronounced effects on slope-probability distributions depending on the ratio of the slope length and the standard error of elevation differences, $\Delta L/E$. For small slope lengths and large standard errors of elevation differences, changes are pronounced, whereas for very large lengths and small errors changes are trivial (Fig. 10). Application of the general analyses to the Censurinus Highlands and Mare Fecunditatis for reading errors near 10 m and slope-lengths near 500 m places the ratio of $\Delta L/E$ near 50, and so the differences between the radar and photogrammetry (1° and 3') are too large to be accounted for by reading error. Most mare surfaces have algebraic standard deviations of 3' to 5' depending on slope length. Thus, slope lengths employed for traverses were guided by reading error. Individual slope-probability distributions at the smallest slope lengths were corrected using the practical method outlined in Moore and Wu (1973). Table 6 summarizes the results of slope-probability distributions and their correction, and general agreement in the forms of the distributions (Figs. 10, 11, and 12). Perhaps the most important finding by

RESULTS OF COMPARISON

The radar and photogrammetry methods generally agree on four major points: (1) Maria are smoother than uplands, (2) the magnitude of the algebraic standard deviations derived from the two methods are comparable for the maria, (3) maria appear rougher at small scale lengths than at large scale lengths, and (4) slope-probability distributions are typically semilogarithmic, but they vary and may be gaussian or complex. They disagree on two major points: (1) The roughness of the upland surfaces may appear smaller to the radar at small scale lengths than at large scale lengths, whereas the photogrammetric method shows a larger roughness at a small scale length than at a large scale length, and (2) the magnitude of the radar roughness of the uplands at the small scale length (13-cm wavelength) is low compared to the roughness measured by photogrammetry. Although these results have been discussed previously (Moore and others, 1975, 1976, 1980; Moore and Tyler, 1973), several examples are discussed below.

Comparison of slope-probability distributions of typical maria and the uplands of the Kan Plateau determined by photogrammetry and the radar illustrate the agreement in relative roughness, magnitude of the roughness (algebraic standard deviation), and general agreement in the forms of the distributions (Figs. 10, 11, and 12). Perhaps the most important finding by

Figure 10—Effect of photogrammetric reading error on statistical descriptions of slope-probability distribution as a function of slope length $\Delta L/E$, standard deviation of elevation difference $E$, and surface roughness $A$. Mean absolute slopes of apparent slope-probability distributions as a function of standard error of slopes resulting from elevation readings for logarithmic or linear slope-probability distributions. Mean absolute slopes for the logarithmic slope-probability distributions are indicated near right ordinate as slope angles. Solid lines indicate apparent mean absolute slopes for various ratios of slope length and standard deviation of elevation differences for adjacent points $\Delta L/E$. Standard deviations of apparent slope-probability distributions as a function of standard error of slope resulting from elevation readings for normal or gaussian hypothetic slope-probability distributions. Algebraic standard deviations for the hypothetical slope-probability distributions are indicated near right ordinate as slope angles. Solid lines indicate apparent algebraic standard deviations for various values of the ratio of slope length and standard deviation of elevation differences for adjacent points $\Delta L/E$.
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**FIGURE 10—Effect of photogrammetric reading error on statistical descriptions of slope-probability distributions as a function of slope length ($\Delta L_x$), standard deviation of elevation difference ($\sigma_{gr}$), and surface roughness. $A$, Mean absolute slope of apparent slope-probability distributions as a function of standard error of slopes resulting from elevation reading errors for semilogarithmic semilogarithmic slope-probability distributions. $B$, Mean absolute slopes for the hypothetical slope-probability distributions are indicated near right ordinate as slope angles. Solid lines indicate apparent mean absolute slopes for various ratios of slope length and standard deviation of elevation differences for adjacent points ($\Delta L_x$, $\sigma_{gr}$). $C$, Distribution of apparent slope-probability distributions as a function of standard error of slopes resulting from elevation reading errors for normal or gaussian hypothetical slope-probability distributions. Aligned standard deviations for the distribution of apparent slope-probability distributions are indicated near right ordinate as slope angles. Solid lines indicate apparent mean absolute slopes for various standard errors of elevations (10.2) and the standard error of the mean elevation is equal to the standard error of measurement ($\sigma_{gr}$) divided by the square root of the number of measurements in the sample 10.2.**
Table 6.—Statistical parameters of slope-probability distributions using Apollo photographic and astrographic methods.

<table>
<thead>
<tr>
<th>Location</th>
<th>Slope Angle, Degrees</th>
<th>Frequency</th>
<th>Cumulative Probability</th>
</tr>
</thead>
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<td>A</td>
<td>0-10</td>
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</tr>
<tr>
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</tr>
<tr>
<td>C</td>
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<td>30</td>
<td>0.3</td>
</tr>
<tr>
<td>D</td>
<td>30-40</td>
<td>40</td>
<td>0.4</td>
</tr>
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</table>

Figure 1.—Slope-probability distributions of lunar cratered plains measured by photogrammetry and radar. Distributions found by both methods are very nearly semilogarithmic and estimated algebraic standard deviations are nearly equal. Radar results courtesy of G. L. Tyler, Stanford University.
Table 11-17 ORBITAL INVESTIGATIONS

<table>
<thead>
<tr>
<th>Photograph</th>
<th>Slope Angle, Degrees</th>
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<tr>
<td>A</td>
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</tr>
<tr>
<td>C</td>
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<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>D</td>
<td>0.4</td>
<td>0.04</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Figure 11.—Slope-probability distributions of lunar cratered plains measured by photogrammetry and radar. Distributions found by both methods are very nearly semilogarithmic and estimated algebraic standard deviations are nearly equal. Radar results courtesy of G. L. Tyler, Stanford University.
both methods is the widespread occurrence of semi-logarithmic distributions for cratered mare and upland plains (Moore and others, 1975, 1976, 1980). Such distributions had previously been recognized for cratered lunar plains at smaller scale lengths and found to characterize cratered plains produced by experimental impacts (Moore and others, 1974, and unpublished data). Both methods find distributions different from semilogarithmic in some uplands. These may approach a gaussian distribution or be complex with several modes (fig. 12). Slope length dependence on roughness as measured by the algebraic standard deviation for single photogrammetric traverses is illustrated in figure 13 (see also table 6), where it may be seen that roughness increases with decreasing slope length (scale length). For the radar, the magnitude of algebraic standard deviation estimated from the distributions may be smaller for the shorter wavelength radar echoes (smaller scale length) than for the large wavelength ones (Moore and others, 1975, p. 88). Root-mean-square slopes of uplands measured by the radar are commonly larger at the large wavelength than at the small wavelength (Moore and others, 1975, 1976). Differences between roughness estimates based on radar and photogrammetry are significant for some uplands such as the Kant Plateau (fig. 12), where photogrammetry estimated the algebraic standard deviation to be 11° and the radar method obtained 7.4° for the smaller scale lengths. In some uplands such as near Vitruvius the two methods agree (Moore and others, 1976, p. 85).

Unresolved problems remain for both methods. In some lunar areas such as the Censorinus Highlands and the south flank of Crisium, the scale length of roughness may exceed the "spot-size" of the radar and the length of the photogrammetric traverses. In these areas as well as the Kant Plateau, many slopes exceed 20° and are not measured by the radar. Although photogrammetry measures slopes greater than 20° along the traverse, very steep slopes are avoided in the selection of a sampling area. These factors may account for the difference in roughness for the Censorinus Highlands measured with the mapping camera and that measured with panoramic camera in the Censorinus Highlands near Capella (table 6). Despite these unresolved problems, current comparisons between the radar and photogrammetry have yielded encouraging results, particularly for the cratered plains, and recognition of the complexity of some upland areas.

CONCLUSION

Apollo orbital photography progressed from unsophisticated systems with valuable but limited measurement capabilities to a sophisticated system with high-quality measurement capabilities. The sophisticated mapping camera system has provided the ingredients for lunar selenodetic control and topographic mapping at scales of 1:10,000 to 1:250,000. The metric quality of the photographs obtained with the Apollo 14 lunar topographic camera and Apollo 15–17 mapping cameras and panoramic cameras have been profitably used to achieve experimental and scientific objectives. Stereophotogrammetric measurements have been found to be most accurate at sun illumination angles of about 30°. The fine-scale morphology of lunar landforms and structural deformation of the lunar surface can be quantified using topographic maps prepared from the photographs. Equations describing the geometry of lunar craters have been revised because of the topographic maps and profiles prepared from the photographs. Rheological properties of some lunar lava flows have been determined using theory and measurements made from the photographs. Data on lunar surface roughness measured by
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Data on lunar surface roughness measured by
stereophotogrammetry form a basis for comparison with results obtained independently by the bistatic-radar experiments.

Full use of the metric quality photographs for some scientific purposes has not been realized. Close coordination between the operator and investigator is required for the purpose. Among the investigations that are incomplete are:

1. A careful study relating stereophotogrammetric measurement with local slopes, the photometric function, and surface albedo.
2. Collection of additional data on crater geometry at the fine scale.
3. Measurements of additional lunar flows.
4. Collection of additional data on lunar surface roughness using a random sampling grid covering a large area comparable to that of the bistatic-radar work.

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1974b, Lunar topographic orthophotograph, La Hvie: LTO 40 A4 (250), scale 1:250,000.

1974c, Lunar topographic orthophotograph, Katchalsky: LTO 65 DZ (250), scale 1:250,000.

1974d, Lunar topographic map, INA: 41 C35 (100), scale 1:10,000.

1974e, Lunar topographic orthophotograph, Nielsen (2nd ed.): LTO 3882, scale 1:250,000.

1974f, Lunar topographic orthophotograph, Freud (2nd ed.): LTO 3883, scale 1:250,000.

