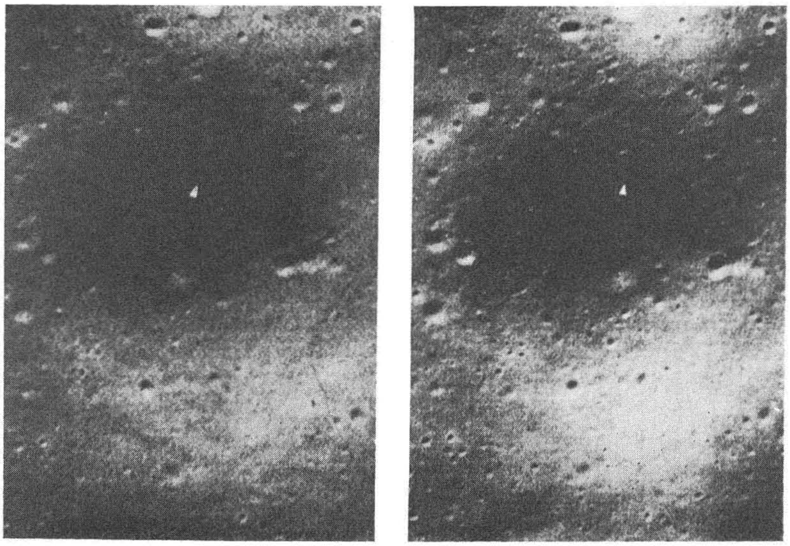

FIG. 1. The Surveyor III Crater.

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# Mapping the Surveyor III Crater

## Large-scale maps may be produced from Lunar Oribiter photographs

*(Abstract on next page)*

### INRODUCTION

SURVEYOR III spacecraft was launched on April 17, 1967 toward the moon on a mission to explore possible Apollo landing sites. On April 19 the Surveyor landed on the moon's Ocean of Storms and almost immediately began transmitting television pictures back to Earth. When the lunar day ended on May 3, over 6,300 photographs had been received from Surveyor III by the Jet Propulsion Laboratory.*

When the spacecraft landed, it came to rest on the inside slope of crater giving it a 12.4° tilt from the local vertical (Figure 1). Because of the inclination of the camera, lunar features were viewed more clearly than would have been possible on flat terrain.

This crater, then, became an object of intense interest to the scientific community, especially to astrogeologists who had the unique opportunity of observing high quality pictures of the interior of a lunar crater for the first time.

Because of this unusual characteristic, the National Aeronautics and Space Administration (NASA) requested that the Department of Defense prepare two maps of the crater and surrounding areas. The request was for a photo mosaic at 1:2,000 scale with 10-meter contours and a shaded relief map with contours at the smallest interval possible. Astrogeologists will use these maps as a base to delineate features found on Surveyor III photography. These maps were made at AMS (later named TOPOCOM) using high-resolution

† Presented at the Annual Convention of the American Society of Photogrammetry in Washington, D. C., March 1968 under the title "Mapping Surveyor III's Landing Area."

* Surveyor III crater became the landing sight for Apollo 12 and two of its Astronauts on November 18, 1969.—*Reviewers*

convergent photographs which had been taken by NASA's Lunar Orbiter III spacecraft prior to the Surveyor III landing.

## Photograph Assembly

Lunar Orbiter III had photographed the Surveyor III landing area with its 24-inch focal-length camera. Each photograph was exposed as a full frame with a camera format of 2.165 inches by 8.622 inches. The film was processed on board the spacecraft and electronically transmitted to earth in segments 0.10 inch by 2.165 inch in size. As the signals were received on earth they were recorded on magnetic tape. From these tapes permanent 35-mm film records of the images were made. The 35-mm film records of each segment are called *framelets* and are 7.2× enlargements of the original spacecraft segments.

AMS received the 35-mm framelets from NASA. They were then trimmed and reassembled into complete frames using a precision cutting instrument developed by AMS.

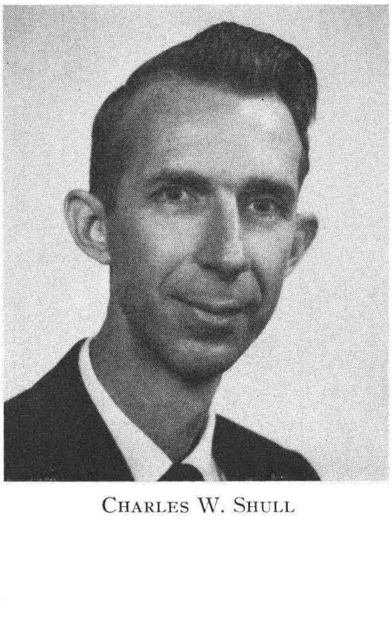
In the transmission, however, were erratic fluctuations which caused non-linear distortions within the framelets and even greater distortions between framelets. For triangulation, corrections were made to the measured image coordinates by the preprocessor program described in the next section. No method is available which will remove these transmission distortions from the reassembled photographs.

Abstract: *Two lunar orbiter high-resolution convergent photographs were used to produce a 1:2,000 scale controlled photo mosaic and a 1:500 scale shaded relief map. A control net from previously triangulated Lunar Orbiter medium resolution photography was used to control the two high resolution photographs. The map area was triangulated by a block process to establish a large number of pass points. These pass points controlled the AS-11A analytical plotter upon which the 1:2,000 scale manuscript was compiled. The use of high resolution photography can give relative accuracies which are great improvements over medium resolution photographs.*

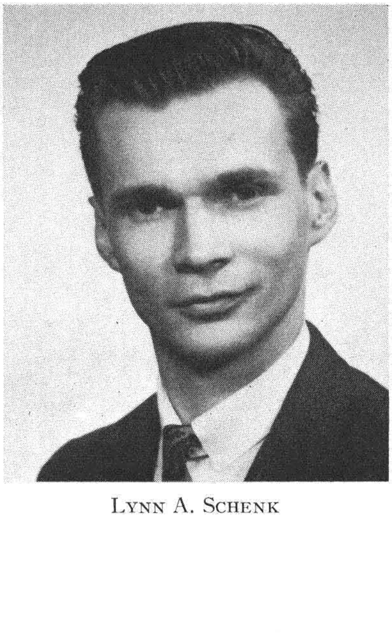
## Mapping the Crater

Two high-resolution photographs, H137 and H154, cover the Surveyor III landing site. These photographs were taken on two different passes of the same Lunar Orbiter mission. Photograph H154 has $-2°$ of $x$-tilt and photograph H137 has 37.°6 of $x$-tilt. Thus it was possible to construct a convergent stereo model of the crater area (Figure 2).

It was evident that this was an unusual model. As the two frames were exposed from different passes over the site, the rotation of the moon during the interval between exposures resulted in the $BY$-distance being greater than $BX$ ($BX$: 11.6 km, $BY$: 40.6 km). Hence the vertical displacement was



Charles W. Shull



Lynn A. Schenk

determined from $y$-parallax. What actually existed was a two-photograph block. The Surveyor landed in Lunar Orbiter Site I P-7. However, insufficient control points were in the Surveyor III area to permit compilation on photogrammetric instruments. Therefore, a control network had to be established.

Several conventional approaches were considered. One logical approach for a two-photograph model would be an intersection. However, previous tests had shown a possible discrepancy of five km in camera positions for different missions. Also a displacement of 100-to-300 meters in position and 800 meters in elevation occurred between adjacent passes of the same mission. The control had been established from Mission I, and this photography was from two different passes of Mission III. This left much uncertainty about the relationship between Mission III camera parameters and control from Mission I. Clearly some other means of establishing control had to be used.

As mentioned earlier, the Surveyor III crater fell within the area previously photographed by the Lunar Orbiter I medium-resolution camera. This area, Lunar Orbiter Site I P-7, had been triangulated by AMS using analytical programs. These programs performed a simultaneous adjustment of a strip of lunar satellite photography treating orbital elements, camera attitude, recorded exposure time, ground control coordinates, and plate measurements as weighted observations. These parameters were weighted according to their known standard errors given for the particular mission. The mathematical model for the short-arc triangulation can be represented in functional form as follows:

Collinearity equation:

$$\begin{bmatrix} x \\ y \end{bmatrix} = F[(x_p, y_p, c), (X^c, Y^c, Z^c, \omega, \phi, \kappa), (X, Y, Z)]$$

where

$$\begin{bmatrix} X^c \\ Y^c \\ \dot{Z}^c \end{bmatrix} = \Phi(X_0, Y_0, Z_0, \dot{X}, \dot{Y}, \dot{Z}, t).$$

Then, by substitution

$$\begin{bmatrix} x \\ y \end{bmatrix} = G\ [(x, y, z), (\omega, \phi, \kappa, t),$$

$$(X_0, Y_0, Z_0, \dot{X}, \dot{Y}, \dot{Z}), (X, Y, Z)]$$

An auxiliary program computed ground coordinates for an unlimited number of image points based on the adjusted camera parameters as determined in the triangulation program. Both programs generate statistical evaluations for all computed values.

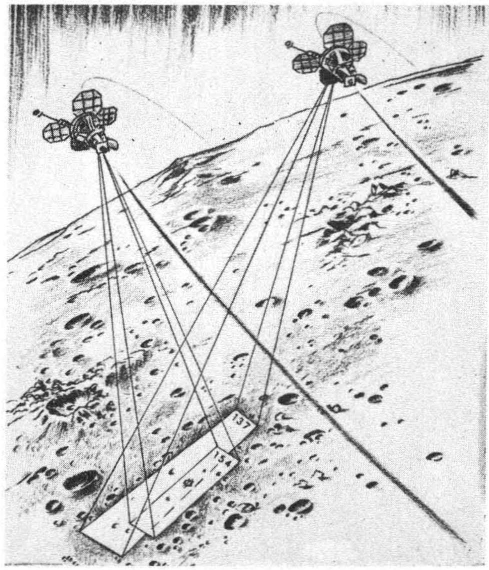


FIG. 2. Lunar Orbiter Coverage of Surveyor III.

Six control points from the Site I P-7 reduction fell near the Surveyor III landing area. These six control points were identified and marked on the high-resolution photographs at a scale of 1:22,000 using a Wild PUG modified with Bausch and Lomb Zoom 70 adjustable lenses. The Zoom 70 made it possible to mark the points even though there were significant changes in scale across the photographs resulting from the tilt.

Sixty-four pass points were marked and measured in and around the crater area, with 45 of these points within the crater itself. The coordinates of these points were measured on a Mann Comparator and automatically recorded on punched cards in the desired format for preprocessing. In the preprocessing program, analytical techniques apply corrections to the image measurements to remove distortions and unify the coordinates into one system (Figure 3). The photographs have both a calibrated sawtooth system, which serve as fiducials, and a preprinted reseau.

Using a six- or eight-parameter projective transformation, the preprocessing program first transformed all image measurements for each framelet into the calibrated reseau system. The resulting values were then transformed again, this time into the calibrated sawtooth fiducial system. This process is repeated for all framelets, resulting in a uni-

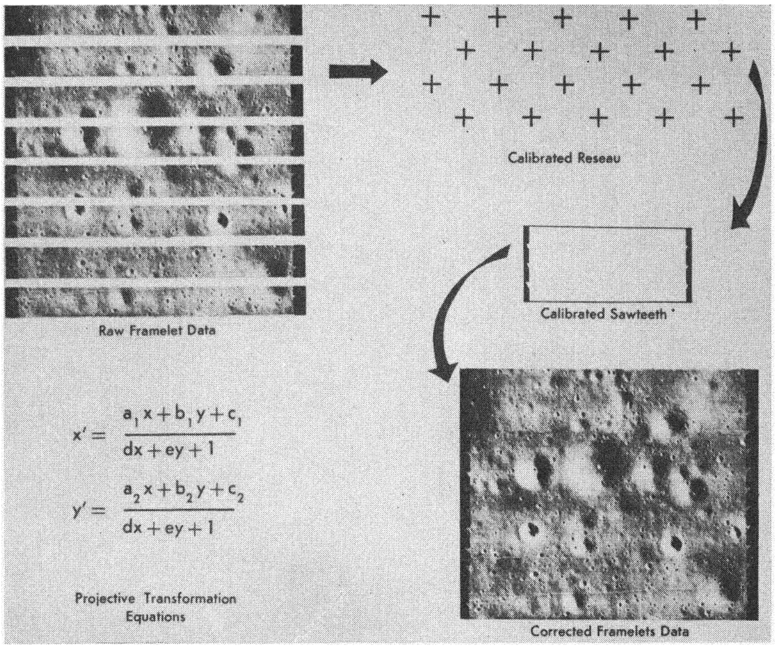



FIG. 3. Lunar Orbiter Preprocessing.

fied system of image measurements referenced to the principal point of the photograph. Finally, these coordinates were corrected for lens distortion, and a punched cart output was generated. These cards were used in the triangulation program.

## Triangulation

As previously stated, the existing situation was treated as a two-photo block. An attempt was made to adjust to all six control points, but the control from Lunar Orbiter I had standard errors of 238 meters horizontally and 518 meters vertically. Obviously a precise solution of this net was unlikely. Four of these six control points were consistent with each other in position and elevation. These four points were used to tie the map area to Site I P-7.

In the triangulation program, the camera parameters were weighted to their one-sigma level. This allowed the spacecraft position to adjust. Both cameras adjusted in the same direction by nearly the same distance thus orienting the model to the Lunar Orbiter site. The shifts in longitude and $y$-tilt were somewhat greater than expected. There are no indications as to whether this is due to control discrepancy or uncertainty in the orbit.

Pass points were forced to intersect in the object space with image coordinates weighted to 20 micrometers. The plate residuals were well within these limits in the vicinity of the crater where there were 45 pass points. However, residuals became quite large, often over 50 micrometers, as the distance of the points from the crater increased. No pass point with a residual greater than 50 micrometers was retained in the solution, but the relationship between the location of these points and the residuals is an indication that the removal of all distortions is incomplete. There is no reason to believe that these points were marked and measured less accurately than those within the crater.

After eight iterations, the program converged to within 30 seconds in longitude, 10 seconds in latitude, and 500 meters in elevation with respect to control established from Site I P-7. Camera parameters converged to within 10 mintues of arc. The use of different combinations of the six control points shifted the positions of the 64 pass points on the lunar surface, but they always remained consistent with each other. Thus, although there is a circular probable error of 47.6 meters in position relative to Site I P-7, there is a very close agreement within the points themselves. This internal consistency is the essence of the task because the primary interest is the relationship of these points to each other.

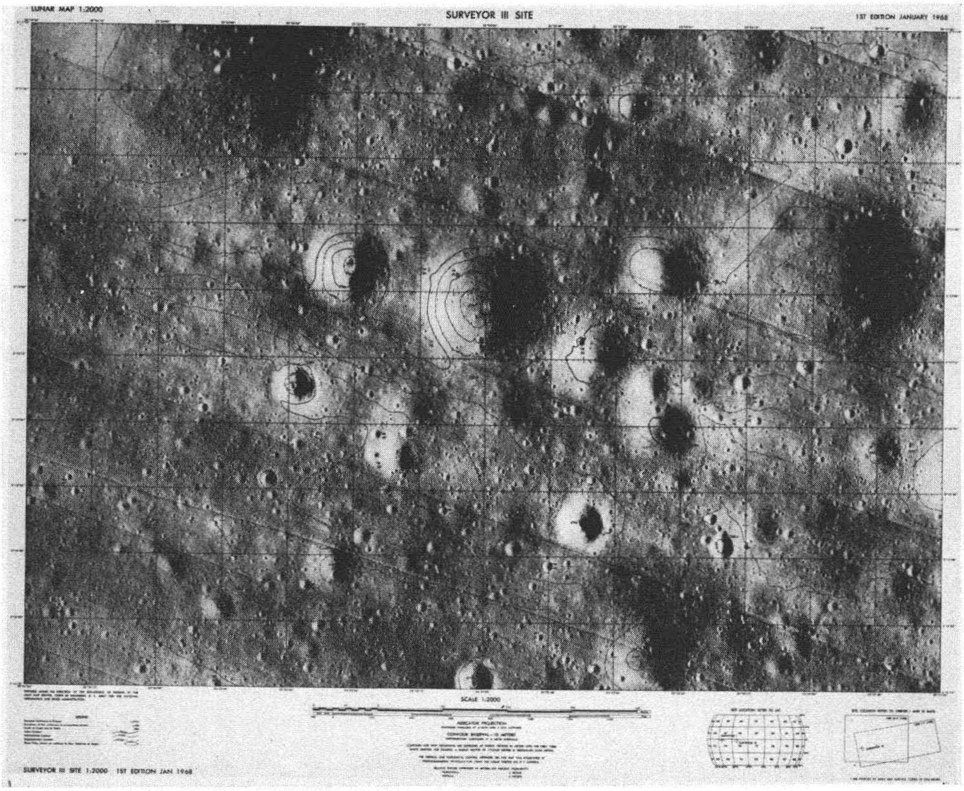



FIG. 4. 1:2,000-Scale Map.

## CONTROL ACCURACY

With respect to Site I P-7, the four control points had a standard deviation of 367.18 meters in elevation. Standard deviations for latitude and longitude were 2.8 seconds and 8.3 seconds respectively (23.45 meters and 69.73 meters). The pass points were very consistent with themselves in their relative positions on the model. The standard deviation, as determined from the program error propagation was 1.6 meters in latitude, 1.4 meters in longitude and 3.6 meters in elevation.

## COMPILATION

The map was compiled on the AS-11A analytical plotter. The plates were viewed in the instrument at a scale of 1:13,000. Plate H137 was rectified to plate H154 and the instrument was cleared of parallax manually.

The model was compiled one framelet at a time. Each framelet was scaled and leveled to the computed pass points within the framelet. Because the framelet in which the crater fell had the most control, and was the point of greatest interest, it was compiled first. The outer framelets were then held sequentially to this. This meant that areas previously compiled were used to constrain the entire mapping area to the crater framelet. The outer framelets were then adjusted and scaled by additional control points.

It would seem that 64 control points would be sufficient to control a model. But 70 percent of these points were within the crater. Thus, the entire model was held tightly to the crater area. The nonlinear distortions in the photographic models made it necessary to relevel the model to the pass points from time to time. For this purpose, the control along the northern edge was less than desirable.

The manuscript was compiled at a scale of 1:2,000 with two-meter contours. From this manuscript, a 1:2,000 controlled photomosaic with 10-meter contours was produced. The 1:2,000 scale manuscript was enlarged to the scale of 1:500 with additional features added from a large-scale enlargement of the photographs. The enlarged manuscript was made into a 1:500-scale shaded relief map with two meter contours (Figures 4 and

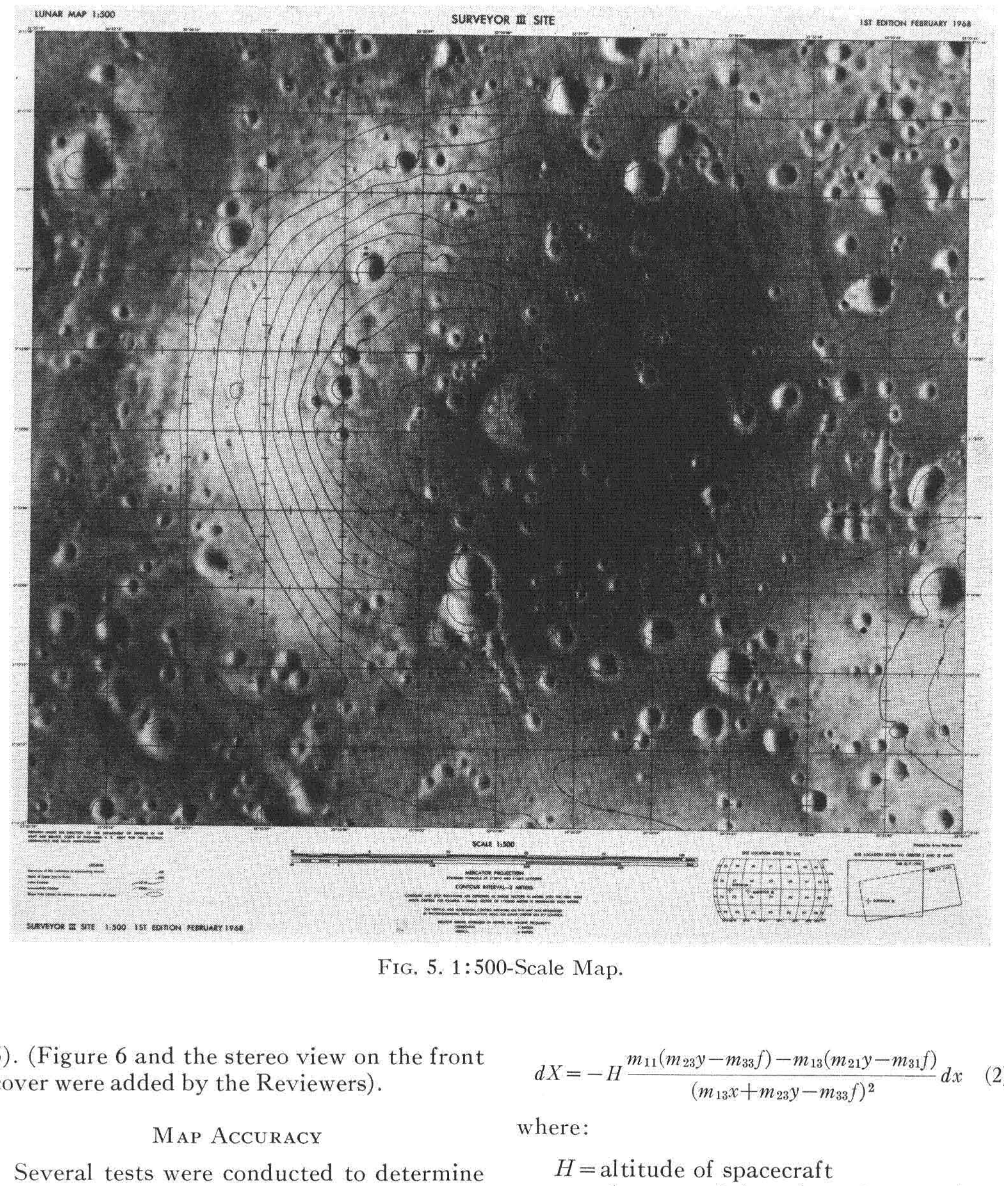



FIG. 5. 1:500-Scale Map.

5). (Figure 6 and the stereo view on the front cover were added by the Reviewers).

## Map Accuracy

Several tests were conducted to determine the accuracy of the compilation. The first step was to find the possible topographic accuracy that may be obtained from the photographs. To determine the possible elevation accuracy, the formula

$$d_h = \frac{H}{B}(dX_2 - dX_1) \tag{1}$$

was used, where $(dX_2 - dX_1)$ is the error in the ground $X$-parallax and $d_h$ is the corresponding error increment in elevation. To compute $dX_1$ and $dX_2$ for non-vertical photography, the collinearity equation was differentiated, giving the equation

$$dX = -H\frac{m_{11}(m_{23}y - m_{33}f) - m_{13}(m_{21}y - m_{31}f)}{(m_{13}x + m_{23}y - m_{33}f)^2}dx \tag{2}$$

where:

$H$ = altitude of spacecraft
$m_{ij}$ = elements of the orientation matrix
$x,y$ = image coordinates
$f$ = focal length
$dx$ = differential error of image x-measurement.

Using the well-known law of error propagation, Equation 2 may be written in terms of standard deviations as:

$$\sigma_X = H\frac{m_{11}(m_{23}y - m_{33}f) - m_{13}(m_{21}y - m_{31}f)}{(m_{13}x + m_{23}y - m_{33}f)^2}\sigma_x \tag{3}$$

where $\sigma_x$ is the standard deviation of one image coordinate measurement and $\sigma_X$ the

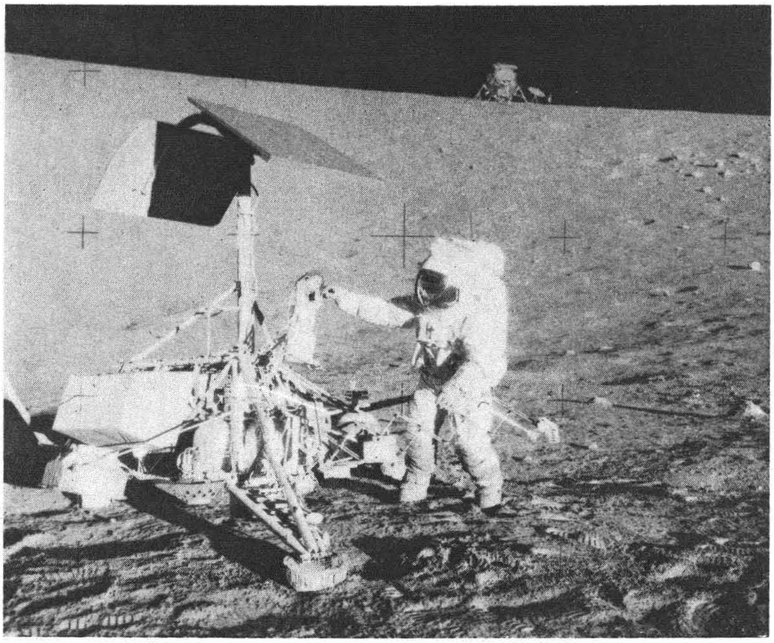


FIG. 6. This unusual photograph, taken during the second Apollo 12 extravehicular activity on November 18, 1969, shows two U.S. spacecraft on the surface of the moon. The Apollo 12 Lunar Module is in the background and the unmanned Surveyor III spacecraft is in the foreground. The Apollo 12 LM, with Astronauts Charles Conrad, Jr., and Alan L. Bean aboard, landed about 600 feet from Surveyor III in the Ocean of Storms. The television camera and several other pieces were taken from Surveyor III and brought back to earth for scientific examination. Here, one of the Apollo 12 crewmen examines the Surveyor's TV camera prior to detaching it. Astronaut Richard F. Gordon, Jr., remained with the Apollo 12 Command and service Modules in lunar orbit while Conrad and Bean descended in the LM to explore the Moon. Surveyor III soft-landed on the Moon on April 19, 1967. (Photo by NASA).

corresponding standard deviation in object space.

Similarly, equation 1 may be rewritten as:

$$\sigma_h = \frac{H}{B} \sqrt{(\sigma x_1^2 + \sigma x_2^2)} \qquad (4)$$

where $\sigma_h$ is the standard error in elevation.

With the assumption that $\sigma_{x_1} = \sigma_{x_2} = 20$ microns, Equation 3 is evaluated and substituted in Equation 4 giving an estimation of the accuracy obtainable from these non-symmetrically, convergent, high-resolution photographs. The value obtained was found to be $\sigma_h = 2.7$ meters, which is the standard deviation of the height observation for a point on the model.

During compilation, readings were taken to determine the repeatability of the AS-11A. The operator read each point in sequence until 15 points had been read. He then made the circuit again, and again, until all 15 points had been read five times. The results for elevations are shown in Table 1. These points were selected over the entire model to include areas of varying contrast. This is reflected in the table of variances. Variance was determined for the entire model ($n = 75$) by the formula

$$s^2 = [\Sigma(\bar{h} - \bar{h}^2)]/(n - 1) \qquad (5)$$

TABLE 1. TABLE OF VARIANCES FOR 15 POINTS EACH OBSERVED 5 TIMES

| *Point No.* | *Range of h (m)* | *Variance $s^2$ ($m^2$)* | *Standard Deviation s(m)* |
|---|---|---|---|
| 4 | 4.81 | 3.28 | 1.81 |
| 17 | 6.86 | 7.57 | 2.75 |
| 29 | 2.49 | 1.17 | 1.08 |
| 35 | 1.27 | 0.23 | 0.48 |
| 40 | 3.19 | 2.28 | 1.51 |
| 42 | 2.04 | 1.39 | 1.18 |
| 44 | 0.64 | 0.20 | 0.45 |
| 45 | 7.74 | 12.01 | 3.46 |
| 47 | 1.19 | 0.23 | 0.48 |
| 50 | 3.37 | 1.55 | 1.24 |
| 51 | 3.23 | 2.42 | 1.55 |
| 52 | 3.52 | 2.90 | 1.70 |
| 55 | 4.09 | 2.34 | 1.53 |
| 57 | 1.71 | 0.51 | 0.71 |
| 58 | 7.65 | 9.57 | 3.09 |

TABLE 2. VARIANCES AND STANDARD DEVIATIONS FOR HORIZONTAL AND VERTICAL COORDINATES

| | |
|---|---|
| $\sigma_X^2 = 0.409$ m$^2$ | $\sigma_X = 0.639$ m |
| $\sigma_Y^2 = 7.122$ m$^2$ | $\sigma_Y = 2.668$ m |
| $\sigma_h^2 = 2.598$ m$^2$ | $\sigma_h = 1.611$ m |

where

$$\bar{h} = (\Sigma h)/n. \quad (6)$$

Tables for horizontal positions were also computed. The results for the model are given in Table 2. These results show that it is possible to compile contours within a two-meter interval. Clearly this test is more stringent than the requirement for plotting contours that does not require ability to recover an image.

## CONCLUSION

This project indicates that Lunar Orbiter high-resolution convergent photography may be used for triangulation and mapping purposes, at least on a single-model basis and in relatively small areas. Use of this photography can give relative accuracies which are greatly improved over those obtained solely from medium-resolution photographs. However, due to the nature of the overlap, medium-resolution photography is still required to establish a control network to which these convergent models may be related.

## ACKNOWLEDGEMENT

Many elements within the U. S. Army Topographic Command assisted in producing these maps. Although it would be impossible to mention by name the numerous technicians who contributed to this project, particular acknowledgement should be given to Mr. Warren Saffel, for marking and measuring the plates; Messrs. Steve Smore and Billy Love, who did a major part of the compilation; Messrs. Irving Cohen, James Wannan, and George Beere for cartographic editing; and Mr. Maurice Curtis who did the relief shading on the large-scale crater map.

## BIBLIOGRAPHY

Army Topographic Command (formerly Army Map Service), *Pre-Orbiter Investigation*, Washington, D. C.: July 1967.

Barry, B. Austin, *Engineering Measurements*. New York, N. Y.: John Wiley & Son's Inc. 1964.

Doyle, Frederick J., "The Absolute Accuracy of Photogrammetry." *Photogrammetric Engineering*. June 1963: Vol. XXIX p. 105.

Jet Propulsion Laboratory, "Surveyor III Mission Report," *Technical Report* 32-1177, Part 1, 1967.

Miller, Irwin and Freund, John E. *Probability and Statistics for Engineers*. Englewood Cliffs, N. J.: Prentice-Hall, Inc. 1965.

## Coming ISP Symposiums

Comm. I—Columbus, Ohio, U.S.A.; May 25–28, 1970.
Comm. II—Munich, Germany; Sept. 16–19, 1970.
Comm. III—London, England; Aug. 9–13, 1971.
Comm. IV—I.T.C., Delft, The Netherlands; Sept. 8–10, 1970.
Comm. V.—Paris, France; Sept. 21–23, 1970. To be followed by a joint meeting of the Council and the Commission Presidents, Sept. 24–26.
Comm. VI—Bratislava, Czechoslovakia; Sept. 1–3, 1970.
Comm. VII—Dresden, East Germany; Sept. 10–16, 1970.

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