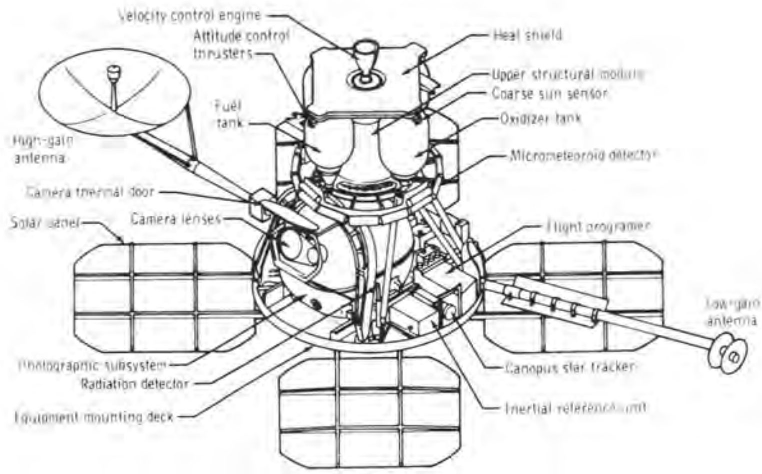

FIG. 1. The Lunar Orbiter system.

PAUL E. NORMAN
NASA Manned Spacecraft Center
Houston, Texas 77058

Out-of-this-World Photogrammetry

The program demonstrates the potential of surveying and mapping from space, particularly for establishing control and for small-scale mapping.

(*Abstract on next page*)

INTRODUCTION

IN A SHORT TIME, American astronauts will set foot on the lunar surface. This feat represents a tremendous technological accomplishment in which extensive surveying and mapping play a key role. The organization which has the responsibility for providing the cartographic support for much of the NASA space program, including the lunar-landing missions, is the Mapping Sciences Laboratory, NASA Manned Spacecraft Center, Houston, Texas. In carrying out its duties, the Mapping Sciences Laboratory determines requirements, carries out the planning, monitors production, and performs research investigations pertinent to its sphere of responsibility. While the Mapping Sciences Laboratory does a limited amount of data reduction, the bulk of the actual production is conducted by the Department of Defense (DOD) mapping agencies, notably the U. S. Army Map Service and the Aeronautical Chart and Information Center. The Mapping Sciences Laboratory is also assisted in its photogrammetric work by an onsite contractor.

It is not surprising that photogrammetry plays a key role in the NASA lunar surveying and mapping activities. This is, of course, partly a result of the remoteness of the subject to be measured and partly a result of the ever-increasing role of photogrammetry in modern surveying and mapping techniques. Although some aspects of these activities have been documented,[1,2,3] recent developments have significant importance to the science of photogrammetry. This paper summarizes the NASA lunar surveying and mapping activities with particular emphasis on the generation of control by analytical photogrammetric methods.

REQUIREMENTS

The current requirements for lunar surveying and mapping are dictated by the operational needs of the Apollo manned lunar-landing missions and by the future needs of subsequent lunar exploration and scientific investigations. The Apollo lunar-landing missions need information about the topography of the lunar-landing sites and their approach corridors, as well as positions of selected features on the lunar surface. The knowledge of the topography is necessary for the selection of sites which are free from hazards and which conform to constraints imposed by the descent and landing phases. The most obvious topographic constraint is that the landing site must be flat enough to insure that the lunar-landing vehicle will remain in an upright position when landing. As the legs of this vehicle are only seven meters apart and provide less than one meter of effective ground clearance, the topographic constraint on the landing site is severe. However, the landing site is not the only operational requirement that has topographic limitations. The navigation system uses radar to measure ground clearances and to update the position of the landing vehicle during the descent phase. Severe terrain variations will have adverse effects on this phase; therefore, restrictions have been placed on the maximum allowable depth of craters in the approach path.

ABSTRACT: *The Apollo manned lunar landings require information about the topography of landing sites as well as the position of lunar features for navigation. These data were obtained by photogrammetric data reduction based on imagery and control data obtained by means of a photographic satellite, Lunar Orbiter. The specific techniques involved were those that employed analytical photogrammetry and camera-position and attitude data for control. This work demonstrates the potential of surveying and mapping from space, as well as containing several aspects significant to photogrammetry.*

The coordinates of the selected features are required for navigation. First, the coordinates of the landing sites are required. Because these landing sites are featureless, and as they nevertheless require sightings from the spacecraft, a series of reference points is used. The coordinates of these reference points, called *landing-site landmarks*, must be obtained, as well as a tie between them and the landing site. There is also another series of features whose coordinates must be determined. These features are navigation landmarks which serve as a backup capability for orbit determination and navigation. No specific accuracy specification has been placed on these position data. However, the Mapping Sciences Laboratory is endeavoring to establish the landmark positions with an absolute accuracy of one kilometer. The ties between the landing-site landmarks and the landing site can be obtained, it is thought, with an error of less than 100 meters as the distances involved are less than 30 kilometers. In addition to the coordinates for the previously mentioned feature points, estimates of their accuracy must also be furnished.

The future requirements are even more stringent than those needed for the Apollo missions. A NASA committee studied this question in August 1967 and concluded that a control net with an accuracy of 10 meters would be needed.[4] As the Mapping Sciences Laboratory is currently engaged in establishing control accurate to one kilometer, future requirements are indeed more stringent.

DATA REDUCTION

In considering the surveying and mapping problems posed by the previously mentioned requirements, photogrammetry seems to be an obvious choice. In considering the matter further, two distinct avenues of approach seem to be available. The first possibility would be to use earth-acquired photography and control, whereas the second possibility would be to place a satellite in lunar orbit for the acquisition of photography and control data. Both of these avenues of approach have been used in the NASA lunar surveying and mapping activities, although greater use is currently being made of the latter approach. The earth-based method hinges on the acquisition of photography by means of astronomical telescopes. By using individual photographs or by exploiting the difference in position and movement of the earth and the moon, stereophotography can be obtained.

The earth-based approach has been used for a number of years by astronomers and was used by NASA for its initial lunar control net.[5] The results of the earth-based method have been used extensively for small-scale lunar maps, but are not being used widely for the requirements covered by this paper. In the first place, the scale of the photography

(1:20,000,000) and the geometry are factors which limit the accuracy of the earth-based approach. Another disadvantage is that the resultant coordinates are in a *center-of-figure* system rather than the *center-of-mass* system required for the Apollo missions.

The use of satellite-acquired imagery and control basically consists of placing a photographic satellite in lunar orbit and tracking the satellite so that not only the desired photography is obtained but also the required position and attitude needed for control. The advantage of this approach is that the scale of the photography is larger, and external geometry is greatly improved. Furthermore, the resultant data are in a coordinate system the origin of which is the center of mass of the moon. There are also disadvantages. For example, the biases in the tracking data are difficult to ascertain. Another problem is that, unless the spacecraft is brought back to earth, the acquired imagery must be transmitted by electronic means. This introduces the possibility of severe distortions in the internal geometry of the photography. Nevertheless, the satellite-based system has formed the basis for much of the surveying and mapping support of the NASA Lunar Exploration Program.

Data reduction for the Apollo missions

The requirements for the Apollo missions have been stated previously as consisting primarily of the acquisition of information regarding the topography of candidate landing sites and of position data for navigation The topographic information is being obtained by first mapping the landing site and the approach path during the descent phase. From these topographic maps, profiles can be obtained which provide the specific information required. The highly detailed height information required for the actual landing site proved to be beyond the photogrammetric capability of the acquired photography, so that information is being obtained by photometry.[6,7] The required position information consists of the selenographic coordinates of points in an area bounded by ±20° latitude and ±50° longitude. It was considered that these data could be obtained best by aerial triangulation of a block of photographs.

The basic photogrammetric materials which are being used in the data reduction for the Apollo missions were provided by the photographic satellite, Lunar Orbiter. The Lunar Orbiter system was used for five lunar photographic missions from August 1966 to August 1967 (Figure 1). The system provided photography ranging in scale from 1:80,000 to 1:34,000,000 and coverage which varied from selected photographs taken from a near-equatorial orbit to extensive coverage taken from a near-polar orbit. In addition to the photography, data were acquired concerning the position and attitude of the photographs.

The nature of the Lunar Orbiter System has been explained in detail by Kosofsky

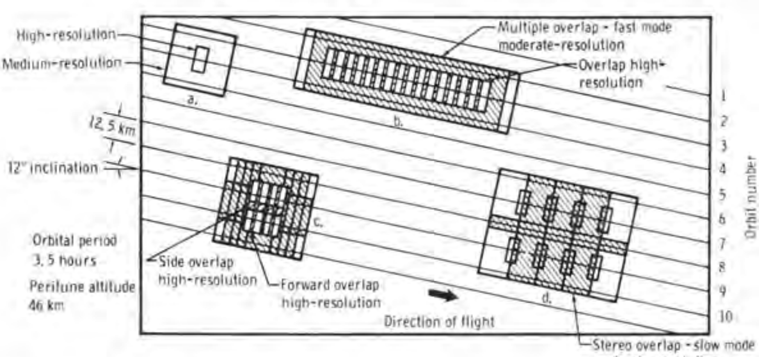

FIG. 2. The different modes of operation. (*a*) Single exposure at the 46-km. altitude; high-resolution coverage is 16.6 by 4.15 km, moderate-resolution is 37.4 by 31.6 km. (*b*) Design mission target site coverage—16 consecutive exposures during one orbital pass over the target site. The interval between exposures (approx. 2.2 sec) is timed to provide 5 percent overlap of the high-resolution frames, with approximately 87 percent overlap on the moderate-resolution frames. (*c*) Eight typical frames from a site-examination type mission—contiguous high-resolution coverage is provided by rapid exposure rate as in (*b*) to give high-resolution forward overlap, and by photographing on consecutive orbits (9 and 10) to give high-resolution side overlap. (*d*) Eight typical exposures from a site-searching type mission—stereo, moderate-resolution coverage is provided by increasing the time interval between exposures (appox. 8.8 sec.) to obtain 50 percent moderate-resolution forward overlap, and by photographing on alternate orbits (7 and 9) to obtain moderate-resolution side overlap.

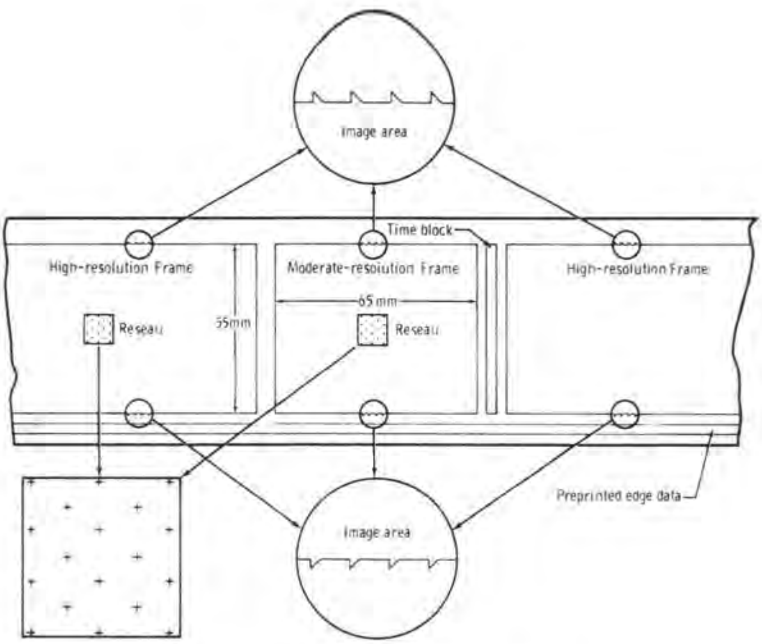

FIG. 3. The fiducial mark system.

1966[8]; therefore, only a summary will be presented here. The photographic system consisted of two cameras: one with a 610-mm lens and the other with an 80-mm lens. The resultant formats, restricted in one direction by the use of 70-mm film, were 55×219 mm. for the 610-mm. camera and 55×65 mm. for the 80-mm. camera. Both cameras were fired simultaneously with provisions being allowed for single photographs or for series of 4, 8, or 16 consecutive photographs. The sequencing rate for the consecutive photographic series was either the *slow mode* which produced 50 percent forward lap for the moderate-resolution photographs (80-mm. lens), or the *fast mode* which produced contiguous high-resolution photographic (610-mm. lens) coverage and 87 percent forward overlap for the moderate-resolution photographs (Figure 2).

The body of each camera contained a series of *V*-shaped fiducial marks along two sides (Figure 3). Edge data were also preexposed on the film. Also of considerable assistance was the addition of a reseau preexposed on the film used for the last four missions (Figure 3). The exposed film was developed on board the spacecraft by the Kodak Bimat process and then electronically scanned and transmitted back to earth.

As shown in Figure 4, the scanning process breaks up the photographs into strips, or *framelets*, as they are called. The result is 27 or 28 framelets for a moderate-resolution photograph and about three times that number for the high-resolution photograph. The transmitted electrical video signal was received on earth and simultaneously recorded and fed into reconstruction equipment to reconvert the signal to photographic images. This reconversion placed the individual framelets on 35-mm. film at a scale 7.5 times the original negative. An unfortunate consequence of the transmission and reconstruction processes is the introduction of large distortions.

Of the five Lunar Orbiter missions, four were flown to photograph selected areas; and one, Mission IV, was flown to obtain general coverage. The first three missions were flown in an elliptical near-equatorial orbit at a perilune altitude of about 50 kilometers. The resultant scales of the photography at perilune were approximately 1:80,000 for the high-resolution photography, and 1:625,000 for the moderate-resolution photography. Mission IV was flown in an elliptical near-polar orbit, with a 2,700-kilometer perilune altitude which resulted in scales of the photography of approximately 1:4,400,000 and 1:34,000,000.

Finally, Mission V was flown in an elliptical near-polar orbit at about 100 kilometers; consequently, the scales of the photography at perilune are roughly double those of the first

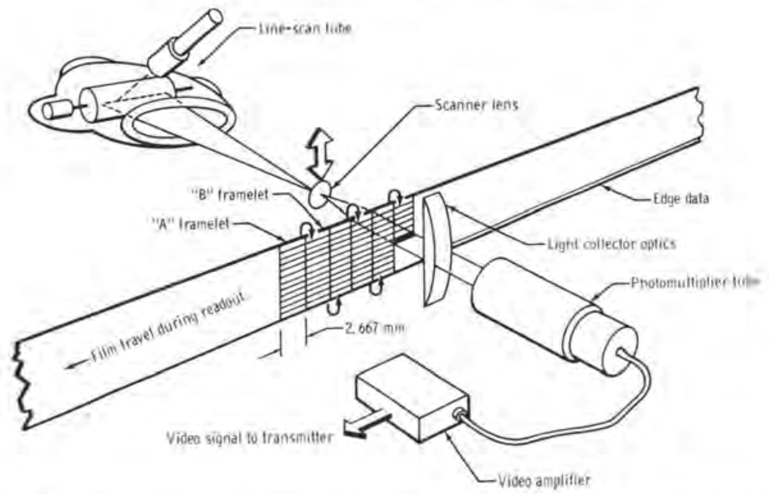

FIG. 4. The scanning process separates the photographs into strips, or framelets.

three missions. The photography was flown usually in the *fast mode* and usually in sequences of either four or eight photographs. In many cases, the same area was photographed from successive orbits and, in some cases, from multiple missions as well. This has resulted in a number of overlapping passes. Figure 5 shows representative coverage in the Apollo Zone, an area bounded by $\pm 5°$ latitude and $\pm 45°$ longitude, and Figure 6 shows overlapping passes at one site.

In addition to the photography, data regarding spacecraft position, attitude, altitude, velocity, and so forth were obtained for the time of each photograph. These data, called *photographic support data*, provide the camera position and attitude required to control the photography. Also furnished was information regarding the accuracy of the position and attitude data.

The photogrammetric data reduction of the Lunar Orbiter photography presented several unique problems, the nature of which made the use of analytical methods virtually mandatory. One of the most obvious problems was that the framelets must be joined together to form the equivalent of the original full-frame photograph. For this aim, the pre-

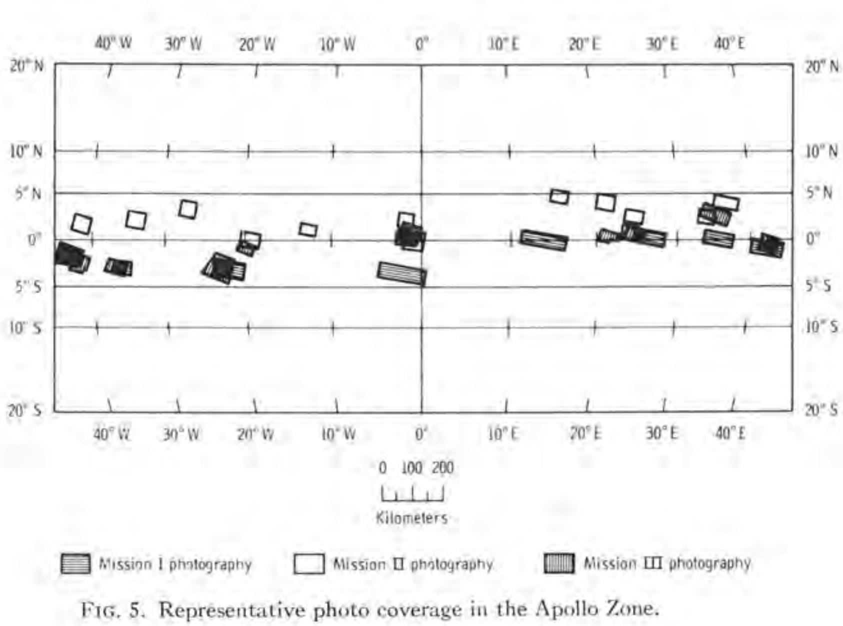

FIG. 5. Representative photo coverage in the Apollo Zone.

exposed reseau has been found, with one exception, to provide a satisfactory full-frame reference system. The exception, of course, was the Mission I photography, the film of which did not have the reseau, and the data reduction of which will not be discussed here. The preexposed reseau also proved invaluable in correcting distortions introduced by the processes used to scan and transmit the images back to earth.

The procedure adopted was to carry out the comparator measurements on the individual framelets, including in these measurements both the reseau crosses and any fiducial marks contained in the framelet. Measurements were then corrected to the calibrated reseau values to give the full-frame system. However, because the reseau is preexposed, the coordinates are now in an arbitrary system. The tie to the original photographic system is accomplished by a transformation of the arbitrary system based on calibrated fiducial-mark values obtained during the camera calibration.

Another problem was the use of the photographic support data to control the photography. The photographic support data proved to have an accuracy less than that which would be required normally to control photography of this nature. The matter was complicated further by the discovery that the photographs would not achieve a purely relative solution among themselves. Therefore, a solution was forced to constrain to the photographic support data through weights derived from their estimates of accuracy. The determination of these accuracy estimates proved to be a difficult task, but recent investigations indicate that, for the most part, the camera attitude data have a standard error of about 10 minutes and that camera position data have a relative standard error from 100 to 200 meters.

For the actual triangulations, two analytical photogrammetric methods are being employed. In the work being done at the Mapping Sciences Laboratory, a modified version of the Multiple Station Analytical Triangulation (MUSAT) Program is being used. Further triangulations are being carried out by the U. S. Army Map Service and the Aeronautical Chart and Information Center where the tendency has been to use methods developed by Duane Brown Associates (DBA)*. The methods are similar in that both use direct simultaneous solutions for the adjusted position and attitude of all photographs. Once this position and attitude have been determined, the coordinates of the desired points are computed. Both methods will work with either strips or blocks; however, they do require a large computer, that is, the Univac 1108 or the IBM 7094. The DBA method differs from the modified MUSAT method in that it incorporates orbit constraints. Both methods have proved to work very well and seem to produce similar results. For further information regarding the MUSAT method, see references 9 and 10, and for the DBA method, see references 11 to 13.

* Recently renamed dba Systems, Inc.

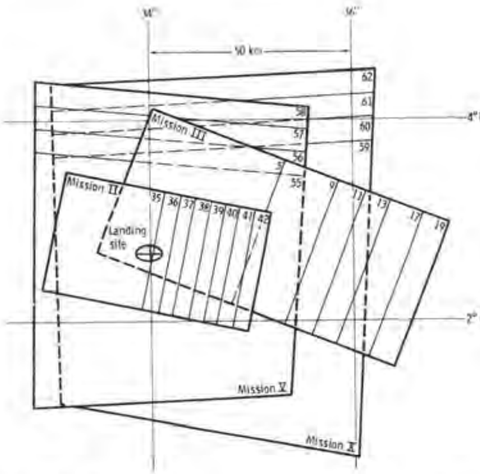

FIG. 6. Overlapping passes at one of the sites.

The first triangulations of the Lunar Orbiter photography were carried out to provide control for the topographic mapping of potential landing sites. Initial screening and preliminary mapping reduced the number of sites to eight (set *B*) (Figure 7). Then these eight sites were mapped at a scale of 1:100,000 with a contour interval of 100 meters. As previously mentioned, these sites were covered in some instances by a single photographic pass, while in other instances, by multiple photographic passes. These passes generally consisted of eight photographs, yet there are cases where they consist of either four or 16 photographs. As the high-resolution photography does not afford sufficient forward overlap, the triangulation was restricted to the moderate-resolution photography.

The initial work primarily involved photography from Lunar Orbiter missions II and III; therefore, the scale of the photography was 1:625,000. Many pass points were selected because the framelet situation causes many problems for the compilation phase. Generally speaking, more than 1,000 points

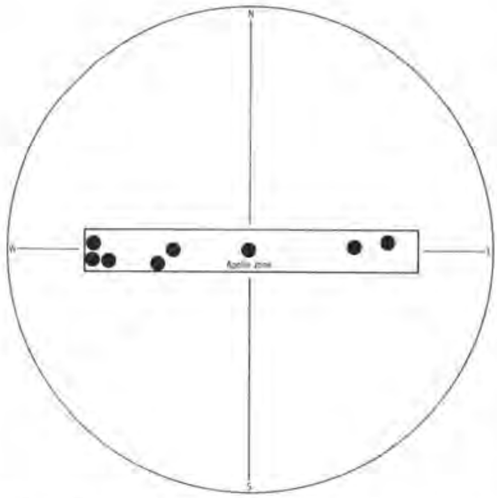

FIG. 7. These eight sites were mapped at 1:100,000 with a contour interval of 100 meters.

were selected for an eight-photograph pass. The results from these triangulations were both encouraging and discouraging. Under the circumstances, the passes seemed to triangulate quite well. The plate residuals were in the range of 15 to 25 microns, and the triangulated coordinates seemed to have relative accuracies in the range of 50 to 100 meters over distances up to 40 to 45 kilometers. However, the coordinates of points common to overlapping photographic passes, either from adjacent orbits in the same mission or from different missions, showed biases of 1,000 meters or more.

These biases probably are due to lack of knowledge about the lunar potential. Furthermore, the absolute accuracy of the photographic support data was not known; thus, the triangulations were in a virtually unknown datum. Another discouraging discovery was that ties to the previously established earth-based control showed an incompatibility between the two systems. This is not surprising because the Lunar Orbiter data are based on a center-of-mass system, whereas the earth-based control has its origin at the geometrical center of the moon.

The biases between passes, the inconsistencies between earth-based control, and the lack of absolute accuracy information did not severely affect the acquisition of the topographic information. The sites were simply mapped and the profiles were obtained relative to the landing site. However, the position data needed for navigation purposes required absolute coordinates and estimates of absolute error, that is, relative to the center of mass of the moon. Furthermore, some desired points had coordinates falling only on the coverage from Lunar Orbiter Mission IV.

With these problems in mind, two more triangulation projects were initiated. The DOD mapping agencies were asked to triangulate additional overlapping photographic passes at the five possible landing sites (designated set *C*) for the first lunar landing. These data will provide additional information on the biases in the photographic support data and will assist in the absolute accuracy estimates.

The second project initiated was the triangulation of a block of mission IV high-resolution photography. In acquiring the Mission IV photography, the spacecraft was rotated 90° so that the long dimension of the high-resolution photographs was downtrack in the polar orbit. This resulted in strips of high-resolution photography flown at a perilune altitude of 2,700 kilometers with a forward overlap of about 20 percent and a side overlap of about 10 percent. The resultant scale of the photography was approximately 1:4,400,000. The Mapping Sciences Laboratory undertook the triangulation of a block of 40 of these photographs with full awareness of the dangers to be encountered. In choosing the pass points for this block, ties were made to several hundred earth-based control points and to the additional Mission II, III, and V triangulations being carried out by the DOD mapping agencies. Figure 8 shows a scheme of this Mission IV triangulation. Preliminary results indicate that this work will be successful. In fact, the ties to the Mission II, III, and V triangulations look so promising that

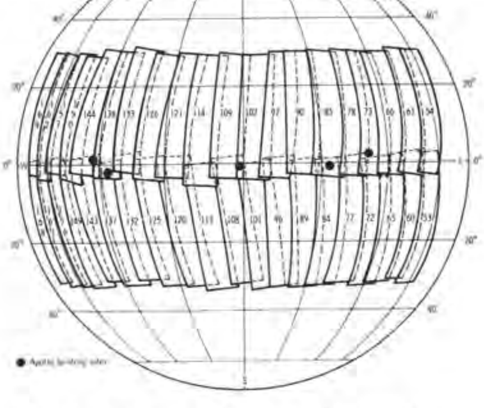

FIG. 8. A scheme of Mission IV triangulation.

consideration is being given to including these ties in the final adjustment.

Once the mission IV triangulation is completed, it will provide the feature positions required for navigation. It is hoped that the DOD triangulations of the five selected sites, along with the ties to the Mission IV triangulation, will provide information on biases contained in the photographic support data and allow for accuracy estimates. Work is also in progress on topographic mapping of sites of scientific interest which will be used for lunar landings after the first Apollo landings.

As indicated in this report, the Lunar Orbiter missions have provided the basic materials and data to enable the topographic mapping and to acquire the position data required for the first lunar landings. However, the Mapping Sciences Laboratory is constantly striving to improve the available data. Several manned missions involving no lunar landing are scheduled to go into lunar orbit prior to the actual lunar-landing missions. These lunar-orbit missions offer the possibility of acquiring additional photography as well as improved information regarding the lunar potential. Also, plans are being made to improve the internal geometry of the Lunar Orbiter imagery.

As previously mentioned, the transmission of the photographic imagery to earth is accomplished by converting the image density to electric video signals. The receiving stations on earth record these signals on magnetic tape. Investigations have shown that analog signal can be digitized, processed numerically to remove distortions and framelet edges, and then reconverted to photographic imagery. Investigations are currently underway to determine the feasibility of applying these principles to reestablish the Lunar Orbiter photographs on a full-frame system.

FUTURE DATA-REDUCTION PLANS

Mention was previously made of the need for a lunar control net with an accuracy of 10 meters. Such accuracy, of course, requires a new photographic mission, new hardware, and the development of new technology. The Mapping Sciences Laboratory is currently initiating the planning phase for this work.

CONCLUDING REMARKS

The following discussion concerns the facets of the NASA lunar surveying and mapping activities that have a special significance to the field of photogrammetry. First, the program apparently demonstrates the potential of surveying and mapping from space, particularly for establishing control and for small-scale mapping. Another important point is the complete dependence on auxiliary data. The photogrammetric community seems to be reluctant to make widespread use of auxiliary data, probably because of lack of accuracy. However, the Mapping Sciences Laboratory was forced to use the auxiliary data, and this use will continue to grow, particularly with space-acquired photography.

Aside from the obvious advantage of eliminating the problem of where and how to establish ground control, the use of auxiliary data has other advantages. For example, if a constraint to camera attitude and position is used, a propagation of errors does not occur. This is, of course, nothing new because photogrammetrists have been aware of this for years. However, what has not been quite so obvious is that the use of auxiliary data could put forward overlap in a new light, particularly for strip triangulations. Once the propagation of errors is controlled, the number of photographs is less important. In the lunar case, using a large forward overlap is advantageous in order to increase the number of intersecting rays and thus improve the relative accuracy of the point determination. Such a concept may possibly have other applications.

Another significant point of the program is the wealth of lunar data that are now available. The ties to earth-based control should assist in the evaluation of lunar data and may add information concerning the difference between the center of figure and the center of mass of the moon. The data that are available now and in the future should also furnish valuable information about the size and shape of the moon. It should also be mentioned that NASA is quite willing to make this lunar data available to the scientific community for further scientific investigations.

ACKNOWLEDGMENT

The author expresses his appreciation to the various organizations, particularly the Department of Defense mapping agencies, for their valuable and often unrecognized assistance in this work.

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Errata

Manual of Photogrammetry, Third Edition

In the previous errata (April 1969, page 365) for the *Manual of Photogrammetry*, Third Edition, this Editor failed to show correctly all the errors in paragraph 4 as indicated by Professor Wolf:

4. Page 64, in the lower right-hand corner, (a) the closing parenthesis was omitted from the end of the sixth line from the bottom, (b) a division sign was omitted in the fifth line from the bottom which should read $\tan\alpha = -\tan\phi/\sin\omega$, and (c) in some copies of the Manual the letter kappa and a closing parenthesis, κ), are omitted at the end of the last line.

The following three corrections were submitted by Mr. James B. Case, Raytheon/Autometric, Alexandria, Virginia.

1. Vol. 1, Chapter 4. On the indicated lines of the following pages, change lightface italic M, intended to represent the orientation matrix, to boldface $\mathbf{M}$:

Page 187, left-hand column: in equation 4.22, in the sixth line under this equation, and in equation 4.23.

Page 189: in equation 4.37.

Page 191, left-hand column: last line; right-hand column: in equations 4.60 and 4.61, and in text lines 4, 7, 11, 25, 26, 29, and last line.

Page 192, left-hand column: in equation 4.62, and text lines 4 and 7.

Page 193, left-hand column: lines 2 and 4, and equations 4.70.

2. Page 190, Vol. 1, Chapter 4. Left-hand column, equation 4.48: lower right-hand element of the matrix should be σ_B instead of σ_K.

3. Page 946, Vol. 2, Chapter 19. Right-hand column, line 11 under 19.4 Map Compilation From Terrestrial Photography should read: and at low cost, *and with equipment and personnel readily available, when aerial photography is employed. Thus, virtually all national mapping programs utilize aerial photography exclusively. On the other hand,* when very small areas. . . .

This is the third errata note for the *Manual*, the first one was published in the December 1968 issue on page 1216.