SELENODETIC CONTROL DERIVED FROM APOLLO METRIC PHOTOGRAPHY *

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Abstract. The data reduction of the metric photography from the Apollo missions is progressing in an orderly fashion within the Defense Mapping Agency (DMA). The data from all three Apollo missions is ultimately to be utilized for development of a lunar control network covering approximately 20% of the lunar surface. In this paper, the status of the data reduction from the Apollo 15 mission is summarized. More specifically, the evaluation of system parameters, proposed control generation plan, and the anticipated characteristics of the network are discussed.

1. Introduction

The data acquisition and reduction of the Metric Camera System photography from Apollo 15 and 16 missions is currently being performed within the Defense Mapping Agency (DMA). The assignment of work on Apollo 15 materials was made in October 1971 to the DMA Aerospace Center (DMAAC). Recently a similar assignment has begun at the DMA Topographic Center (DMATC) with the photographic materials from Apollo 16. The ultimate aim of the National Aeronautics and Space Administration (NASA) in making the above assignments to DMA is to incorporate the Metric Camera System photography from Apollo missions 15, 16, and 17 into one mathematic solution which would compute the coordinates of selected lunar surface features with respect to the center of mass of the Moon. This system of coordinates, called the Apollo Control Network, would cover approximately 20% of the lunar surface and would be used as a basis for studies of selenodesy.

The Apollo 15 data reduction assignment is due to be completed in April 1973. The objectives of the Apollo 15 assignment are (1) to produce various types of precise measurement data, and (2) to combine reduced measurement data with other supporting information to compute the coordinates of surface features by employing the fundamental principles of analytical photogrammetric triangulation. This paper will discuss the status of the Apollo 15 Control Network reduction. The triangulation method, the available data, the evaluation of data, and the anticipated characteristics of the computed network of coordinates will be stated in the following pages.

2. Photogrammetric Method

The data included in the conventional mathematical model of analytical photo-

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grammetric triangulation are the position of camera at each exposure time, the orientation of the camera at each exposure time, measurements of the photo images of lunar surface features (each feature measured on two or more photographs) and, if available, lunar surface features, the coordinates of which have known values. The mathematical model can, of course, be expanded to take advantage of data provided by other system components such as precise exposure time or altimeter observations. Least-squares estimation techniques are employed to compute the best estimates of the above parameters. Statistical variance-covariance estimates may be applied to each of the modeled data types.

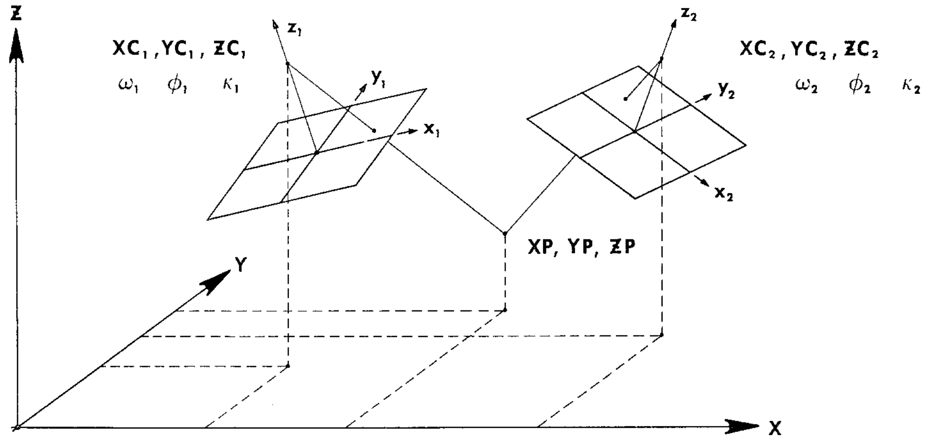

Fig. 1. Geometric relation of two photographs as used in analytical photogrammetry.

Analytical photogrammetric techniques are used in practice primarily to intensify the number of known coordinates in an area. Surface positions may be computed if the position and orientation of the camera are known for each photograph on which images were measured. The assurance associated with the computed surface position will naturally depend on the accuracies of the position and orientation elements as well as the accuracy of image measurements. Figure 1 shows a schematic of the geometry of the mathematical model for analytical triangulation of a pair of photographs. Additional photographs may be included in the solution in an analogous manner.

3. Metric Camera System

The Metric Camera System consists of a mapping camera which records the lunar surface, a stellar camera which simultaneously photographs a star field, and a laser altimeter and precise relative timing equipment. The mapping camera has a 76 mm focal length with a 115 mm photograph format. Reseau marks with a spacing of 10 mm are recorded on every photograph in order to compensate for film deformation. This camera has the capability to compensate for forward motion and to automatically

TABLE I

Metric system camera characteristics

Type	Mapping camera	Stellar camera
Lens and aperture	76 mm, *F*/4.5 (fixed)	76 mm, *F*/2.8 (fixed)
Format	115 mm × 115 mm	32 mm diam with 25 mm flats
Exposure time	0.067 to 0.004 s	1.5 s (fixed)
Exposure control	Automatic between lens shutter	
Forward motion compensation	12.1 to 16.1 mrad s^{-1}	
Resolution	90 lines mm^{-1} AWAR, 2:1 contrast target, EK 3404 film	80 lines mm^{-1} AWAR, 1000:1 contrast target, EK 3400 film
Distortion	± 50 μm radial, 5 μm maximum tangential	± 10 μm radial, 5 μm maximum tangential
Overlap	78% (nominal), 67%, or 58%. Adjustable only prior to installation in spacecraft	

set the shutter interval based on sensor information of lunar surface brightness. Under optimum conditions, the resolution of the camera will be $90 l\,\mathrm{mm}^{-1}$. The stellar camera has a 76 mm focal length and a photographic format of 32 mm by 25 mm. This camera has a 5 mm reseau grid for film deformation compensation. Pre-mission calibration provides the relationship between the mapping and stellar cameras. The laser altimeter gives an observation of the spacecraft altitude with an accuracy of 2 m at a precisely defined time with respect to the photographic sequence. This observation along with its time is recorded on the corresponding mapping camera exposure. Table I gives more information concerning the mapping and stellar cameras. Detailed descriptions of the Metric Camera System may be obtained from NASA [2].

4. Data Sources

Input data for the analytical photogrammetric triangulation is obtained from the Metric Camera System as well as independent computations from NASA.

The position of the camera at the time of each exposure is obtained from the Photo Support Data furnished by NASA [6]. The camera positions are computed by NASA with the Houston Operations Predictor/Estimator (HOPE) computer program [5] utilizing Doppler Tracking Data from the mission along with the appropriate timing data for the photographic revolutions. The Photo Support Data also gives a variety of information about the Metric Camera System at the time of each exposure. The positional data is directly input to the analytical triangulation computer program.

The orientation of the camera system at the time of each exposure is computed at DMAAC using the stellar photography associated with mapping camera exposures and pre-mission calibration data. The procedure is to measure the photographic images of stars recorded on the stellar photograph. By utilizing the star images and

TABLE II

Mapping camera photographs used in Apollo 15 reduction

Revolution	Exposures[a]	Total number
4	76–102	14
15	106–160	28
16	288, 292–424	68
22	464–598	68
27	876–1010	68
33	1022–1112, 1113, 1115, 1116–1156	69
38	1564, 1565, 1566–1664, 1665, 1666–1702	72
44	1712–1744, 1745, 1746–1804, 1805, 1808–1848	70
50	1852–1924, 1925, 1926, 1927, 1928–1940, 1941, 1942, 1943, 1944, 1945	52
60	1950–2032, 2033, 2034–2086	70
62	2094–2202	55
63	2210–2348	70
70	2358–2484, 2485, 2486, 2487, 2488, 2489, 2490	70
72	2626–2740	58

[a] Even numbered exposures unless otherwise indicated.

their corresponding star catalog positions, the precise orientation of the stellar camera may be computed. With this information the orientation of the mapping camera may be calculated by means of the premission calibration determination of the angular relationship of the stellar and mapping cameras. Standard errors from the stellar reductions for the three angles which define the orientation of mapping camera with respect to the inertial reference frame are generally no greater than 20″.

Precision measurements of lunar surface features on the mapping camera photography have also been made at DMAAC. Image coordinates have been measured on alternate photographs from each of the fourteen revolutions during which near vertical photography was acquired. The average number of image points measured on each photograph is 30. Also measured is the photographic image of the spot on the lunar surface corresponding to the laser altimeter observation locations. These image coordinates will be included in the triangulation solution and in this way the coordinates of the location where the laser energy impinged on lunar surface will be computed. Analysis has shown the accuracy of the image measurements on the mapping camera photography to be in the 5 to 10 μm range. Table II gives a listing of the numbers of the mapping camera photographs used in the Apollo 15 reduction.

5. Apollo 15 Control Network Reduction

Figure 2 shows the position of the fourteen orbital revolutions where near vertical photography was collected during the Apollo 15 mission. Figure 3 depicts the limits of the mapping camera near vertical coverage of the lunar surface. These limits are also the boundary of the Apollo 15 Control Network. The block of photographs

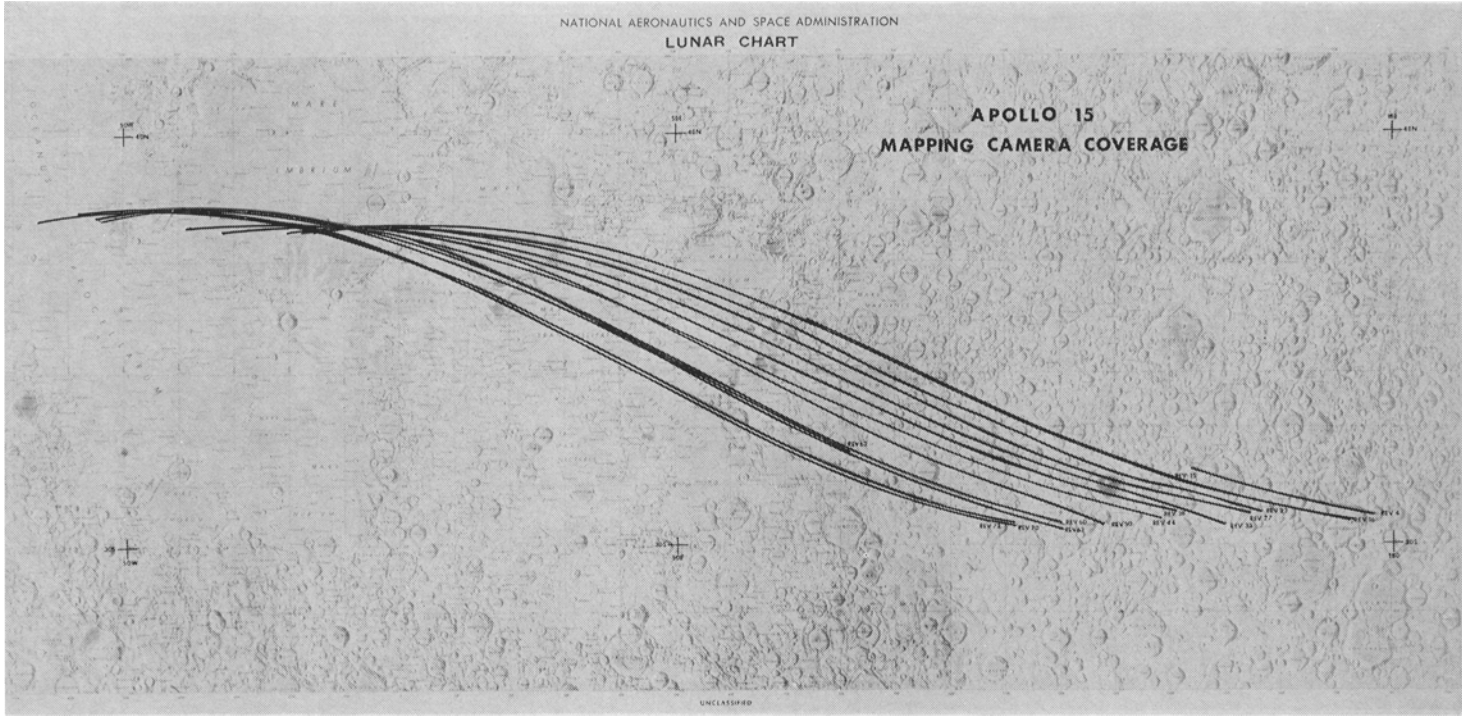

Fig. 2. Ground track positions of revolutions with near vertical mapping camera photography.

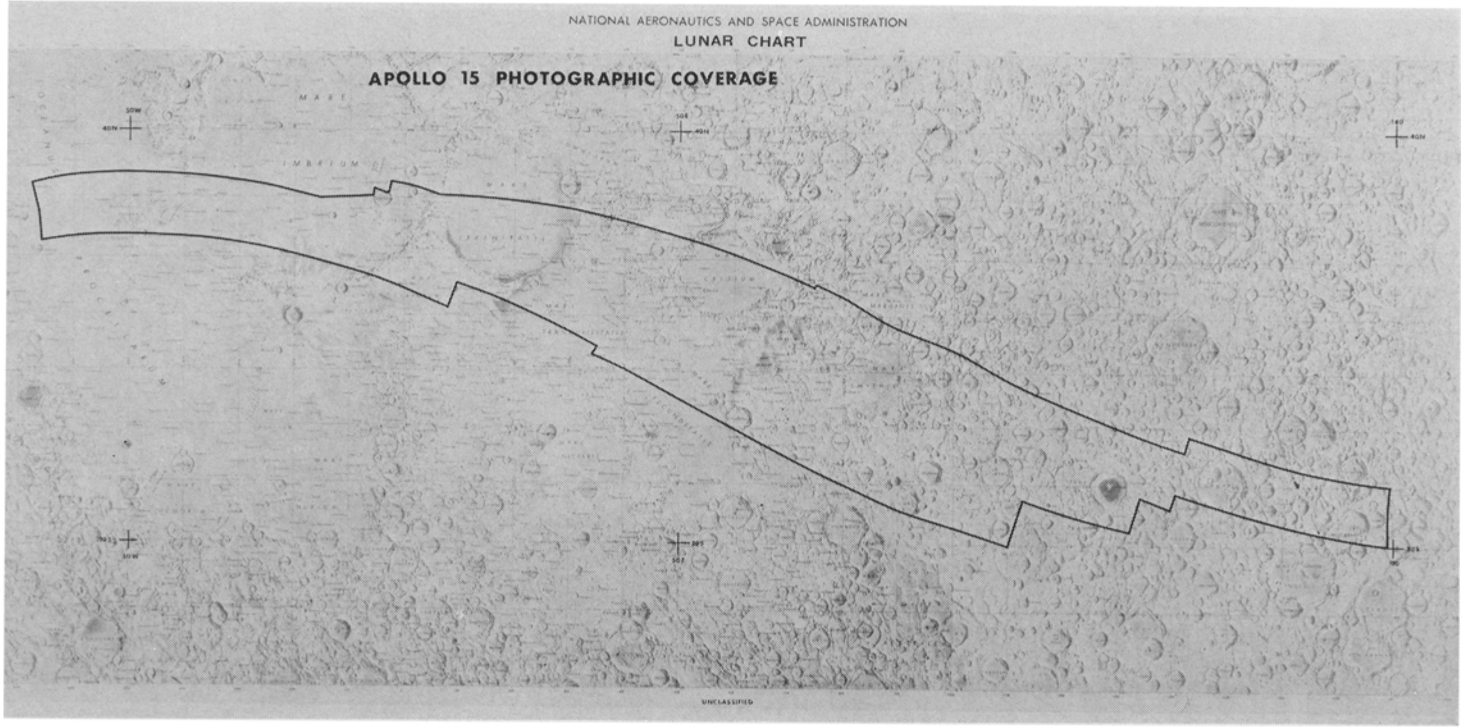

Fig. 3. Limits of metric camera system coverage.

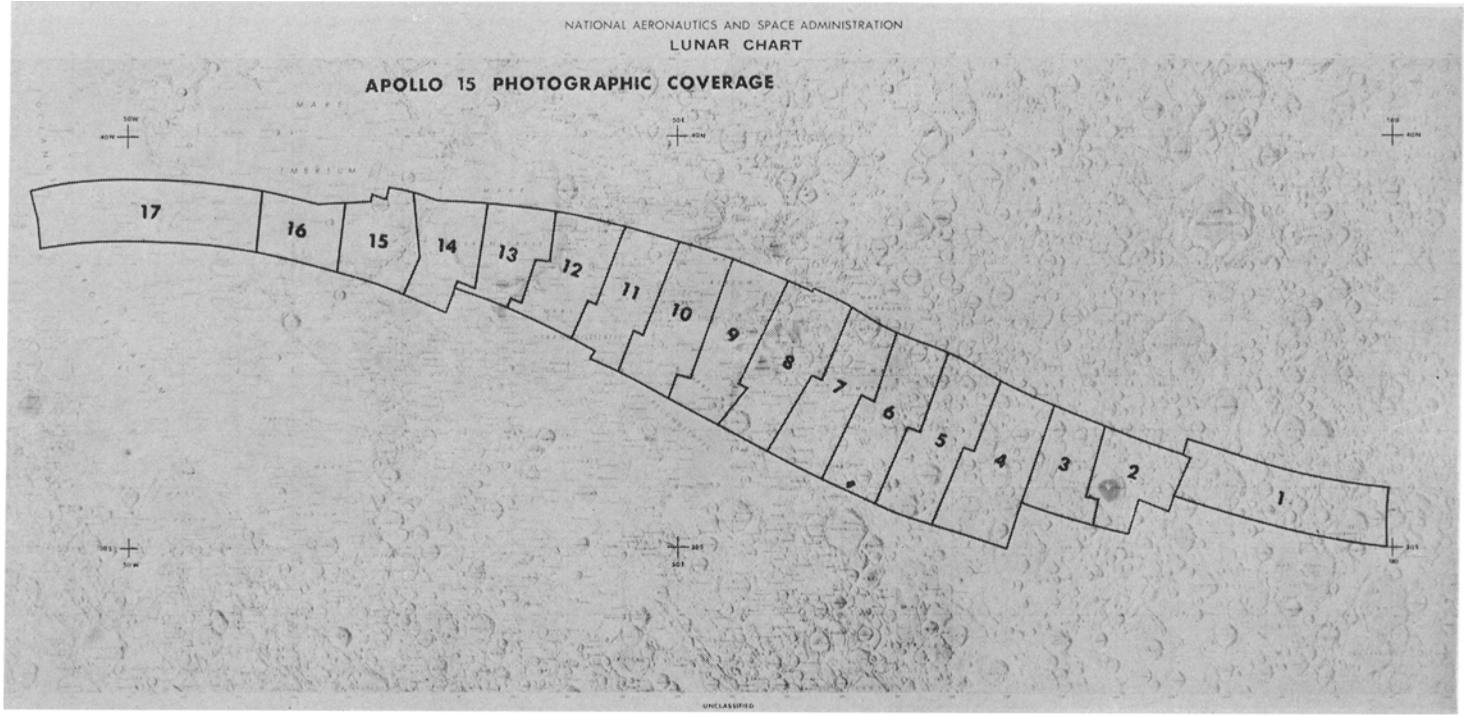

Fig. 4. Sub-block configuration from metric camera coverage.

covering the lunar surface has been divided into seventeen sub-blocks for ease of project management and implementation of strict quality control procedures. The limits of each of the sub-blocks are shown in Figure 4. Image measurements and stellar orientations were validated by relative analytical solutions for the photographs in each of the individual sub-blocks. The images of selected lunar surface features have been measured on all the mapping camera photographs listed in Table II. The total number of exposures on which images of features have been measured is 832. The stellar orientation reductions corresponding to each of the mapping camera exposures have also been completed.

Strip triangulation solutions are being performed for the sequence of photographs from each revolution (see Table II). It is seen that these solutions contain measurements from a minimum of fourteen photographs to a maximum of 70 photographs. Analysis of these solutions indicates that for local areas surface positions may be computed with standard deviations of 20–40 m relative to the coordinate system established by the ephemeris positions and orientations of that revolution. Also, as the number of photographs included in the solutions were increased, inconsistencies between data types were encountered; that is, the initial position, orientation, and image coordinates would not satisfy the geometric configuration required in the analytical strip triangulation solution. It was found that the geometric conditions of the solutions could be satisfied by allowing the ephemeris camera positions to change from the values presented in Photo Support Data. The changes to position were usually represented as azimuthal changes to the orbital track and in some cases amounted to 2000 m at the ends of the photographic revolutions. The magnitude of the positional changes varies with each revolution and is time dependent; that is, the earlier revolutions exhibit the largest changes. Also, the positions on the far side of the Moon, where no tracking data was available, tend to be less reliable than those on the front side. Figures 5 and 6 show the changes in the camera positions from the Photo Support Data required in the strip triangulation solution. The changes are shown for solutions with data from sub-blocks 1 through 6.

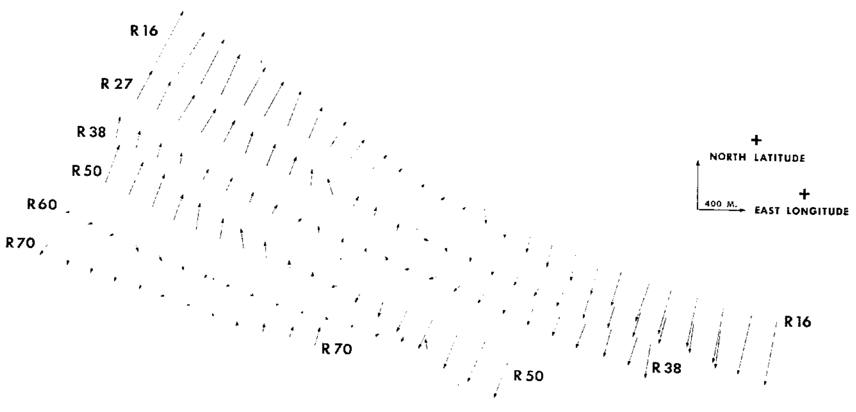

Fig. 5. Changes in photo support data camera positions (latitude and longitude) after strip solutions.

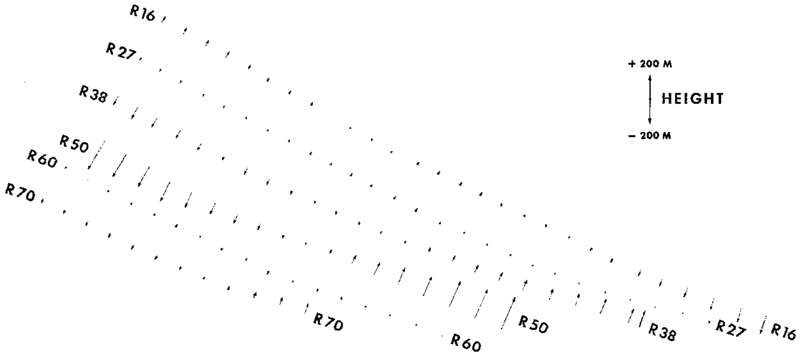

Fig. 6. Changes in photo support data camera positions (height) after strip solutions.

NASA was aware of these problems and was advised of the discrepancies which have been found in the analytical triangulation solutions. They are confident that significant improvements can be realized in the Photo Support Data positions by employing advanced orbit reduction mathematical techniques. Test cases to demonstrate the improvements are currently in work at NASA and DMAAC.

A method of detecting biases between orbits is to constrain the orbital data of each revolution and derive the position of the same lunar feature. This is effected by computing the coordinates of lunar surface features which have been imaged on the photography of two or more adjacent revolutions. A comparison of the derived coordinates will reflect the amount of inconsistency between the orbital positions from these revolutions. This procedure has revealed that an average inter-orbit bias of 600 m exists between the revolutions compared. NASA expects that these differences also can be minimized with the mathematical methods referenced above. Table III shows a comparison between orbitally derived positions with data from sub-blocks 4 and 11. Strip 27 derived selenographic positions were considered to be

TABLE III

Mean differences between coordinates derived from various strip solutions with those from standard solution of strip 27

Sub-block	Strip number	Mean differences		
		Latitude	Longitude	Height
4	16	−171 m	−129 m	+143 m
4	22	−731	+ 84	−127
4	33	+223	+160	−235
4	38	−343	+ 72	+276
11	16	−472	+ 31	+ 58
11	22	−530	+ 75	− 39
11	33	+409	− 16	− 99
11	38	− 19	+ 47	+ 79

the standard. The corresponding positions of the same surface features derived from other strip solutions were compared to strip 27 positions and the mean differences were computed. These values are found in Table III. Although the longitude and height are improved in the sub-block 11 comparisons, the latitude still shows significant biases. These differences correspond primarily to an orbital cross-track discrepancy.

The altimeter observations, although not used directly as an input parameter in the analytical triangulation solutions, offer additional information on the correctness of the triangulation solution. The altimeter distances yield an independent check on the camera orientation and distance between camera positions. The analysis consists of computing the distance from the camera position to the lunar surface feature corresponding to the point where the laser energy struck the surface. The adjusted camera position and surface coordinates are computed in the triangulation solution. This distance is then compared to the actual altimeter observation recorded in the Photo Support Data. For well-defined features on the photographs the differences are generally less than 20 m. In some cases where the altimeter feature is not recognizable, differences of 100 m may be found. Unfortunately, the laser altimeter malfunctioned during the Apollo 15 mission and therefore data is available for only 275 of the total 832 photographs.

Also of importance to the Apollo Control Network development are the selenodetic investigations which are currently in work or may be initiated by NASA in the near future. Included are the laser ranging experiments, interferometry positioning investigations, and sub-satellite studies of the lunar gravitation field. Each of these will provide a unique contribution to the Lunar Control Network under development.

6. Conclusion

With the work which has been accomplished and that scheduled for completion in the near future, one would have to be optimistic concerning the development of the Apollo 15 Lunar Control Network by April. Utilizing the Metric System photography and photogrammetric techniques, it is reasonable to expect that the strips of photography which have been processed and analyzed will be combined in a block triangulation solution yielding a coordinated and consistent set of lunar surface positions. This solution will rely on the geometric aspects of the photogrammetric conditions and the best orbital parameters available at this time. The density of the network will be the coordinates of one lunar surface feature for each 900 square kilometers. The control network will cover approximately 10% of the lunar surface. Subsequently, it is expected that the Apollo 15 network will be refined with information from the Apollo 16 and 17 missions, computations of new positional ephemerides, and improved parameters from advanced selenodetic investigations.

References

[1] *Apollo 15 Initial Metric System Evaluation Report*, Aeronautical Chart and Information Center March 1972.

[2] *Apollo 15 Sim Bay Photographic Equipment and Mission Summary*, National Aeronautics and Space Administration – Manned Spacecraft Center, August 1971.

[3] Final Technical Report, *Computer Program for Utilization of Stellar Photography for Determining the Attitude of a Terrain Camera in a Local Lunar Coordinate System*, Raytheon Company, March 1971.

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[5] TRW Note No. 70-FMT-792A, *Houston Operations Predictor/Estimator (HOPE) Engineering Manual*, TRW Systems Group, June 1970.

[6] TRW Note No. 71-FMT-870, *Apollo Photograph Evaluation Program Manual*, TRW Systems Group, January 1971.