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Final Report

**THE ANALYTICAL AEROTRIANGULATION
OF THE APOLLO 10 HASSELBLAD
PHOTOGRAPHY**

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ABSTRACT

A strip of 75 80mm focal length Hasselblad photographs of the far side of the Moon, acquired during Revolution 23 of the APOLLO 10 Mission, was simultaneously adjusted using a modified version of the SURBAT (Simultaneous Unlimited Rigorous Block Analytical Triangulation) Program.

The external information available for defining the scale, position, and orientation of the strip consisted of the following.

- Spacecraft position and velocity at 10 second intervals.
- Camera orientation angles derived from the spacecraft attitude determination system.
- Two control points located near the 12th and the 110th photographs of the strip.

Exposure times were not recorded. It was known only that the exposures were made at a constant time interval with an intervalometer.

Considerable difficulty was experienced in attempting the simultaneous adjustment of the entire strip because of the marginal quality of the external data and the lack of metric fidelity of the camera. One aspect of these difficulties was the inconsistency of the trajectory data and the photogrammetric solution. It was not possible to ascertain whether these inconsistencies arose from errors in the orbital and timing data or from instability of the interior orientation of the camera. A simultaneous adjustment was achieved only by overconstraining the orbital and derived timing data and by introducing artificial control points.

These aspects led to the recommendation that further extensive analytical aerotriangulation with APOLLO 8 and 10 Hasselblad photography was unwarranted. With regard to the APOLLO 14 Hasselblad photography, several short substrip adjustments are recommended to test if the introduction of the focal plane reseau improves the

SECTION I

DESCRIPTION OF ADJUSTMENT TECHNIQUES

The analytical cerotriangulation of a strip of 75 overlapping photographs of the far side of the Moon is described in this document. These photographs are part of a longer strip of about 105 photographs acquired during the APOLLO 10 mission (see Figure 1.1). The basic photographic parameters are as follows.

- focal length: 80mm
- attitude: pitch, 25° ; roll, 0° ; azimuth, 270°
- format: 70mm
- altitude: 100km
- forward overlap: 60% approximately

The following external metric information was available and furnished by MSC for use in the adjustment.

- Two ground control points (see Figure 1.1) established by manual sightings with the spacecraft sextant.
- Orbital ephemeris data comprised of spacecraft position and velocity every 10 seconds in the GET (Ground Elapsed Time) system.
- The exposures were made at nominally equal time intervals with an intervalometer. Neither the magnitude of the time interval nor the GET of any exposure was known.
- Camera orientation angles derived from the spacecraft attitude determination system. The orientation angles were also referenced to the GET system and furnished at 10 second intervals.

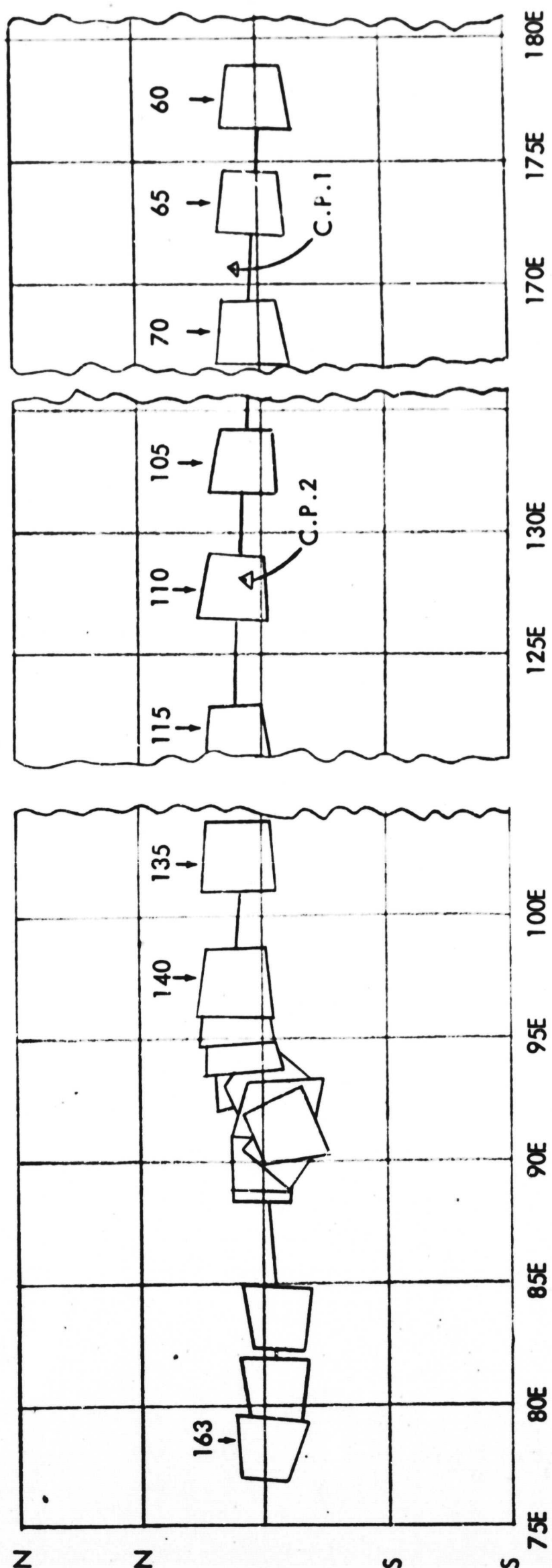


FIGURE 1.1. Sketch of Portion of APOLLO 10 Hasselblad Photographic Coverage

The virtual absence of ground control made the utilization of the orbital data mandatory. It would thus appear that the LO-SAT (Lunar Orbiter Strip Analytical Triangulation) Program (developed by DBA Systems, Inc.) would be the ideal vehicle for adjusting the APOLLO 10 photographs. However a prohibitive amount of computer time would have been required if LO-SAT was used since the present version of the program was not designed to adjust long strips of photography. For this reason it was felt that the most feasible approach would be to modify the SURBAT (Simultaneous Unlimited Rigorous Block Analytical Triangulation) Program (Reference 1) to permit utilization of the orbital and timing data. This approach provided valuable insights into the characteristics of the data and suggested more powerful methods for reducing such data in the future.

In addition to the APOLLO 10 photos an attempt was made to tie two strips of APOLLO 8 photography to the APOLLO 10 strip. This attempt was not successful. The problems encountered are discussed in this document with recommendations for adjusting Hasselblad photographs in the future.

1.1 Utilization of Orbital, Timing, and Control Point Data

The two ground control points in the APOLLO 10 strip were established by visual sightings using the on-board sextant of the spacecraft. Thus the control point positions inherited the errors of the spacecraft positions in addition to the errors in sextant attitude, pointing, etc. Thus the errors in the control point positions were probably no less and probably greater than the errors in the spacecraft positions. For this reason it was decided that the orbital elements, associated with the strip, would remain fixed and serve as the datum for the adjustment. This would essentially define the exposure station positions in the radial and cross-track directions relative to the orbit. The positions of the exposure stations along the orbit are defined by the times of exposures of the photographs. However it was known only that the photographs were exposed at a nominally constant time interval by an intervalometer. It was necessary to determine the exposure time interval, Δt , and the epoch of the strip, t_0 .

Since the orbit was nearly circular and equatorial, changes in exposure times were directly proportional (very nearly) to changes in the selenographic longitudes of the control points. Thus the control point longitudes could be used to define the positions of the exposure stations along the orbit. This was done by adjusting Δt and t_n so that the aerotriangulated longitudes of the control points would conform with the longitudes determined from the sextant sightings. The adjusted values of Δt and t_n were then used to compute the exposure times in the GET system.

1.1.1 Incorporation of Orbital Constraints in the SURBAT Program

The SURBAT Program is a block analytical aerotriangulation program developed by DBA Systems, Inc. for RADC (Rome Air Development Center). The program rigorously performs a least squares adjustment of photo coordinate measurements and computes the adjusted elements of exterior orientation and the ground coordinates of the passpoints. The program has no provision for incorporating orbital constraints. On the other hand SURBAT utilizes the Method of Recursive Partitioning (Reference 2) which makes feasible the simultaneous solution of large blocks and long strips of photographs. The LO-SAT and LO-BAT Programs (also developed for RADC by DBA) rigorously incorporate orbital constraints in the adjustment by substituting the six orbital elements and exposure times for the exposure station positions. Thus instead of 3 positional coordinates for each photograph one has simply the exposure times and the six orbital elements for all the photos in a strip. LO-SAT and LO-BAT however were not designed to adjust large blocks of photography efficiently. The techniques used in the present version of the programs for the formation and solution of the normal equations would make the adjustment of the APOLLO 8 and 10 photography prohibitively time consuming. Revision of the programs, however, to make them more efficient was considered beyond the scope of the effort. The approach adopted which was consistent with the requirements of computational efficiency, utilization of the orbital constraints, and reasonable re-programming effort, was to modify SURBAT.

The orbital data furnished by MSC consisted of the position and velocity of the Command Service Module (CSM) at 10 second time intervals in a variety of coordinate systems. Thus if the exposure times of the photographs were

known the positions of photographs could be easily obtained by interpolation in the orbital data. The coordinate system chosen for utilization with the strip adjustment was Moon fixed selenocentric. That is the position of the spacecraft was given in a Cartesian coordinate system, fixed in the Moon with X-Y axes coincident with the lunar equator. This simplified the revisions required to SURBAT since the internal strip adjustment is performed in a Moon fixed system.

Since, as noted earlier, it was decided to accept the orbit as the datum for the adjustment, the question arose whether the photographs should be constrained to conform exactly with the orbit and be permitted to adjust only along the orbit corresponding to corrections in time or if some provision be made for cross-track and radial adjustment. The latter approach was adopted since the uncertainties of the orbit and the lack of metric fidelity of the camera might lead to inconsistencies between the positions of the exposure stations given by the orbital data and as determined by the photogrammetric solution. The uncertainties in the orbit arise from (a) the extrapolation of the ephemeris for the APOLLO 10 photographs from near side tracking data; and (b) the uncertainties of the far side lunar gravity field. With regard to the camera there is no platen to define the focal plane nor a fiducial system to define the position of the principal point precisely. Thus the possibility existed that the interior orientation would change from frame to frame. If the calibrated values of the interior orientation were held fixed in the aerotriangulation but the actual values of x_p , y_p , and c did indeed change during the mission, the result would be a variation in the position of the exposure stations. If tight cross-flight and radial constraints were exercised under these circumstances the photogrammetric solution would be inconsistent with the orbital data. The result would be an increase in the residuals of the photo coordinate measurements relative to a solution where the above constraints were relaxed. In fact considerable experimentation was required to arrive at a set of constraints which allowed for a stable solution and at the same time was reasonably consistent with the photo coordinate measurement data.

It was apparent, for the reasons given above, that the modifications

to SURBAT be such as to permit the exposure station positions to be constrained to lie precisely on the orbit or permitted to adjust in the cross track and radial directions. This was done as follows. A computer program was written to compute the components of the three principal unit vectors at any point, at time t , along the orbit. The principal unit vectors are an orthogonal triad comprised of the tangent, principal normal, and bi-normal vectors. Thus the tangent vector corresponds to the in-track, the principal normal to the radial, and bi-normal to cross-track components of the position of a point in the orbit. Let us denote a Cartesian coordinate coincident with the orthogonal triad by (U, V, W) . If (X, Y, Z) is the Moon fixed coordinate system its relation to (U, V, W) may be expressed as:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = A \begin{bmatrix} U \\ V \\ W \end{bmatrix},$$

where A is a 3×3 orthogonal matrix. The basic version of SURBAT accepts exposure station constraints in either an (X, Y, Z) system or a latitude, longitude, height system. The basic revision to SURBAT consisted of permitting the constraints to be input in terms of (U, V, W) . Thus if the a priori standard deviations of the exposure station positions in the (U, V, W) system were σ_U , σ_V , and σ_W the covariance matrix in the (X, Y, Z) system is:

$$\text{cov}(X, Y, Z) = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{XY} & \sigma_Y^2 & \sigma_{YZ} \\ \sigma_{XZ} & \sigma_{YZ} & \sigma_Z^2 \end{bmatrix} = A \begin{bmatrix} \sigma_U^2 & 0 & 0 \\ 0 & \sigma_V^2 & 0 \\ 0 & 0 & \sigma_W^2 \end{bmatrix} A^T.$$

This procedure permits constraining the exposure stations to conform precisely to the orbit by inputting very small values for σ_V and σ_W . σ_U , the constraint in the in-track direction, is of course directly related to the time. The capability to input different values for σ_U permits, in effect, different constraints to be imposed on the derived values of the exposure times. Determination of adequate values for the in-track

constraint was one of the most difficult problems encountered in the reduction of the data. This is because the scale of the APOLLO 10 strip is essentially defined by the exposure time intervals derived from the intervalometer data. The ground calibration performed by MSC indicated that under controlled conditions the time interval was constant to ± 0.01 second. Since the nominal time interval between photographs was 20 seconds a precision of ± 0.01 second of the intervalometer would provide scale information precise to $1/2,000$, a precision of ± 0.02 second would provide scale to $1/1,000$, and a precision of ± 0.05 second would provide scale to only $1/400$. Scale constraints of the order of $1/1,000$ are not nearly adequate for a stable solution of a long strip of photographs. However the results of the reductions, to be presented in detail in the next section, indicated that deviations of several tenths of a second from constancy may be present in the intervalometer. However these variations might be caused instead by variations in the recovery the x-coordinate of the principal point. It is impossible from the photogrammetric solution alone to differentiate between these possible error sources since both cause a shift in camera position along the orbit. If in-track constraints corresponding to time interval accuracies of several tenths of a second were exercised it would have been impossible to achieve a stable solution since the resulting normal equations would have been too ill-conditioned to converge without additional sources of external information such as ground control points. Thus a compromise of sorts was reached whereby in-track constraints were used corresponding to a time interval accuracy of ± 0.02 second. This was done with the realization that while such a constraint exceeded the accuracy of the timing data it permitted a determinate simultaneous adjustment of the strip.

1.1.2 Determination of the Exposure Time Interval and Epoch

If we let the exposure time t_n of the n th photograph be the epoch, the exposure time of the i th photograph is:

$$t_i = t_n + (i-n) \Delta t,$$

where Δt is the exposure time interval assumed to be truly constant. t_n and Δt were unknown. The two sources of external information which could contribute to the

determination of t_n and Δt were the angular orientation data referenced to the GET system and the ground control data. The technique based upon the angular orientation data, described in the next paragraph, did not prove successful. The method adopted consisted of choosing t_n and Δt such that the adjusted longitudes of the control points were in conformity with the values furnished by MSC. Two photo substrips covering each control point were selected such that the nadir of the center photo of each strip was nearest the corresponding control point. The computational sequence was begun by computing t_i from initial approximations of Δt and t_n . The positions of the exposure stations were obtained by interpolation in the orbital ephemeris using the t_i as arguments. These positions were used as initial approximations in the substrip adjustments with the orbital positions constrained as follows.

	<u>Cross-Track</u>	<u>In-Track</u>	<u>Radial</u>
Center photos	1	0.1 m	5
Other photos	1	50	5

Let λ'_1, λ'_2 be the longitudes of the control points resulting from the adjustment and λ_1 and λ_2 the given longitudes. The shift in time for the center photograph of each substrip was then computed corresponding to the shifts of $\Delta\lambda_1 = \lambda'_1 - \lambda_1$ and $\Delta\lambda_2 = \lambda'_2 - \lambda_2$. Using the new exposure times new values of t_n and Δt were computed. Then new values of t_i were computed and a new set of exposure station positions interpolated in the orbital data.

The above process was repeated until $\Delta\lambda_1$ and $\Delta\lambda_2$ were less than one arc second. Thus an epoch and average exposure interval were computed which were consistent with control point longitudes. The corresponding exposure times as computed from $t_i = t_n + (i-n)\Delta t$ were used to interpolate in the orbital data to obtain exposure station positions for the simultaneous adjustment of the entire strip.

1.2 Utilization of Attitude Data

The attitude of the APOLLO 10 spacecraft was continuously determined by the

spacecraft attitude system. The relative orientation angles between the camera and the spacecraft attitude reference were approximately known permitting the absolute orientation angles of the camera to be approximately computed. The absolute orientation angles are probably in error systematically by several degrees due to the error in the relative orientation angles. For purposes of the APOLLO 10 strip adjustment external information is required only for the camera roll angle since the orbital constraints determine camera pitch and azimuth. Since the strip is essentially indeterminate in roll and since no other information was available the camera roll angles furnished by MSC were constrained ± 10 minutes of arc. This constraint did not seem to introduce any inconsistencies in the adjustment though the possibility exists that the roll angles are systematically in error by a degree or more.

In addition to using the camera roll angle to orient the strip an attempt was made to exploit the variations in camera attitude to determine the exposure time interval and epoch of the strip. This approach was based on the cyclic variations of the camera orientation angles derived from the spacecraft attitude data illustrated in Figure 1.2. While there might be a systematic error in the camera orientation angles due to the uncertainty of the orientation of the camera relative to the spacecraft attitude system, the orientation angles derived from the spacecraft attitude system should, it was thought, accurately represent the variations in the camera attitude. Thus if the camera orientation angles were determined independently by the analytical aerotriangulation adjustment and then cross correlated with the corresponding spacecraft attitude system angles, a time shift and time scale could be derived for the strip. In attempting to apply this approach it was found that the spacecraft attitude system seemed to have errors of about one degree. This meant that the data was not nearly of sufficient accuracy to permit application of the method. The reductions performed in connection with this approach provided, however, a valuable evaluation of the spacecraft attitude system which is reported in detail in the next section.

1.3 In-Flight Calibration of the Camera

The calibration data furnished by MSC for the APOLLO 10 Hasselblad camera

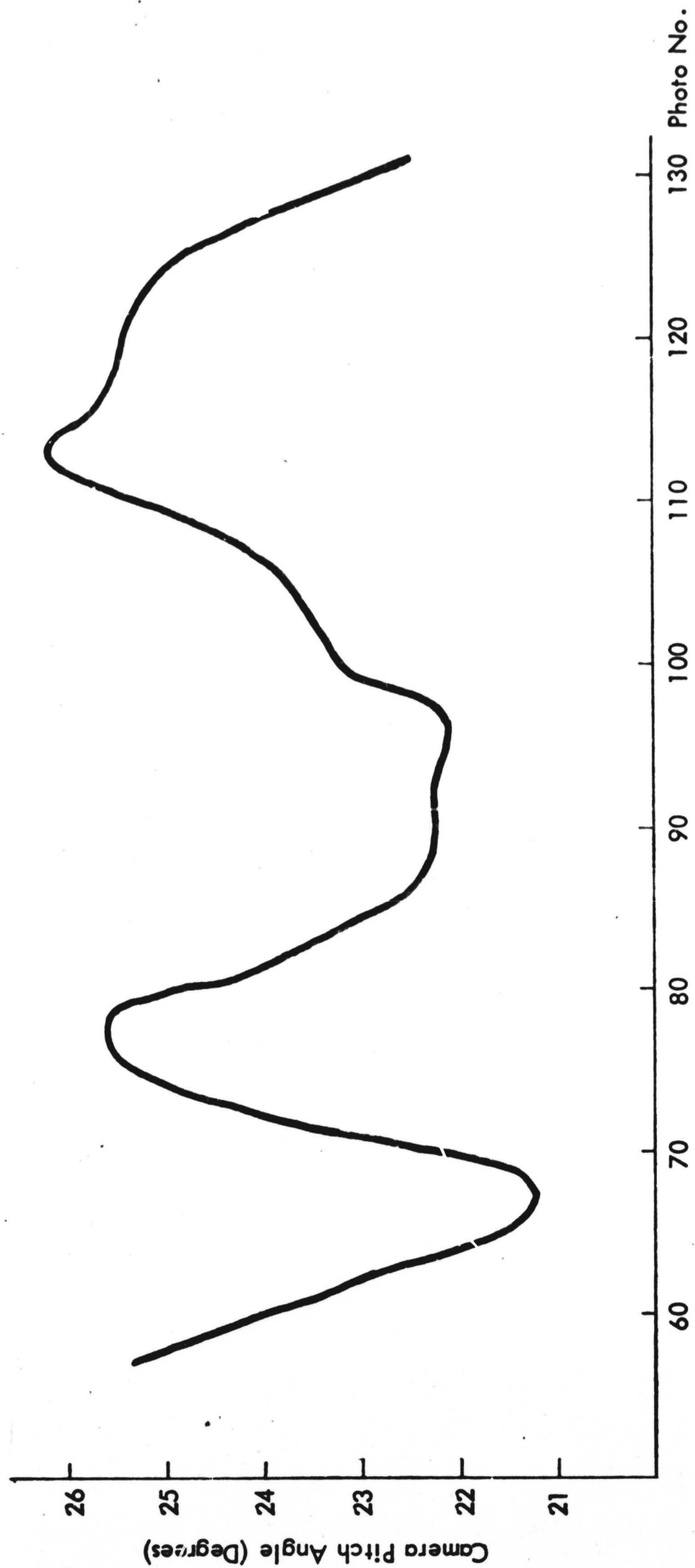


FIGURE 1.2. Variation of Local Vertical Camera Pitch.

consisted of three single frame reductions of stellar exposures. The results of two calibrations with Magazine O and one calibration with Magazine R are given below.

	<u>Magazine O</u> <u>Exposure 1</u>	<u>Magazine O</u> <u>Exposure 2</u>	<u>Magazine R</u> <u>Exposure 2</u>
x_p (mm)	-0.193 ± 0.013	-0.195	0.018
y_p (mm)	0.116 ± 0.013	-0.234	-0.331
c (mm)	80.545 ± 0.015	80.633 ± 0.009	-80.705 ± 0.014
K_1	0.8900×10^{-5}	0.1032×10^{-4}	0.1095×10^{-4}
K_2	-0.3498×10^{-9}	-0.7402×10^{-9}	-0.1127×10^{-8}
K_3	0.2766×10^{-12}	0.5831×10^{-13}	0.2988×10^{-12}
J_1	0.1880×10^{-4}	0.4450×10^{-5}	0.9919×10^{-5}
J_2	-0.8388×10^{-8}	0.2958×10^{-8}	-0.2720×10^{-8}
Φ (deg)	0.6302	1.427	2.21

Plots of the symmetric radial distortion curve and the decentering profile are given in Figure 1.3.

We first note the large discrepancy in the values of y_p as determined from Exposures 1 and 2 of Magazine O. This discrepancy should not be surprising since the Hasselblad cameras lack a fiducial system. The intersection of the corners of the format was used by MSC to define the center of the format. The format edges were fuzzy on two sides and defined by rollers on the other two sides. The rollers could easily move several tenths of a millimeter from exposure to exposure, thus changing the position of the center of the frame.

The interior orientation values obtained with Magazine O are not comparable with those obtained with Magazine R since the position of the frame edges and the focal plane could be quite different for different magazines. The lens distortions however may be compared for the three calibrations summarized above. These are in reasonable agreement, as may be seen from the curves of Figure 1.3. The lens distortion calibration

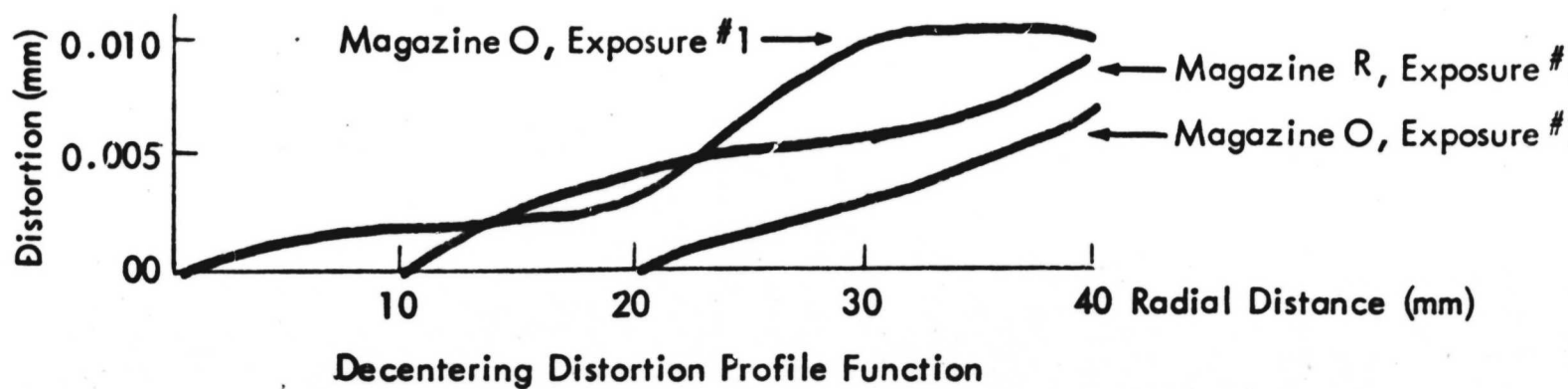
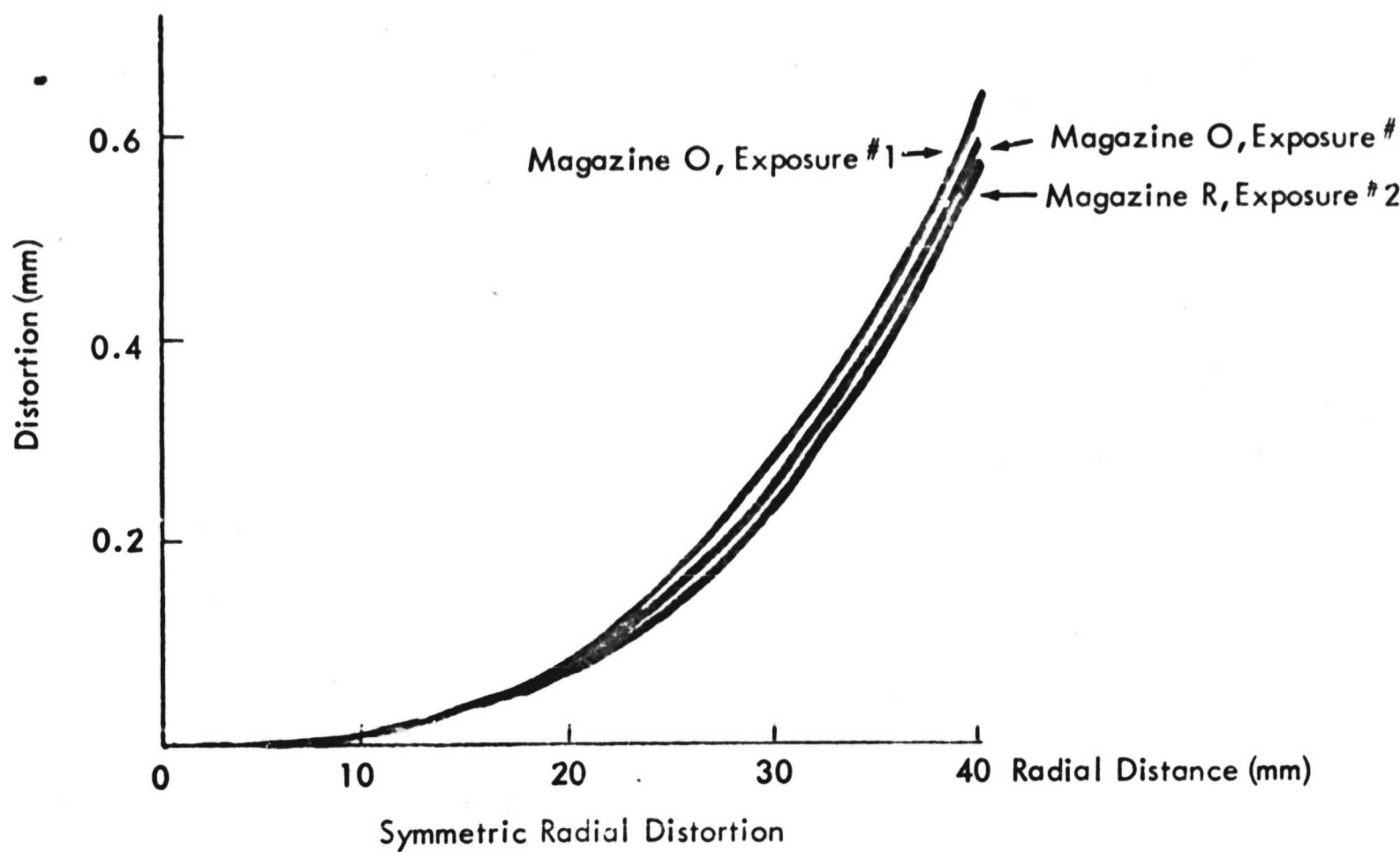


FIGURE 1.3. Plots of Lens Distortion Functions for Three MSC Calibrations of the APOLLO 1080mm Hasselblad Camera.

however is overparameterized for a relatively narrow field camera such as the 80mm Hasselblad. Rather than solving for the full compliment of coefficients, i.e., K_1, K_2, K_3, J_1, J_2 , and Φ , it would have been preferable to solve only for K_1, J_1 , and Φ since these parameters are sufficient to model the lens distortion of the Hasselblad cameras. Such overparameterization often leads to unstable and unreliable results. Because of the overparameterization and because of the desirability of attempting to reconcile the discrepancy in y_p , a request was made by DBA for either the original stellar photographs or the photo coordinate measurements. The intent was to recalibrate the camera using the simultaneous multi-frame technique and validate the above results. However since neither the photographs nor the measurements were available an attempt was made to recalibrate the camera using five in-flight photographs of the lunar surface. The reduction was based upon in-flight calibration techniques developed by DBA (Reference 3) for calibrating aerial cameras in their operational environment. The original in-flight calibration procedure consisted of flying the camera over a precise targeted test range while the aircraft was being tracked, with ballistic camera or electronic DME, in order to precisely determine exposure station positions. This procedure has since been generalized in the calibration of DBA's close range photogrammetric cameras. It was found that by taking a series of highly convergent photographs of a target array, where the coordinates of the target array are completely unknown, it is possible to precisely recover both lens distortion and interior orientation on a basis of a relative orientation solution alone. The lunar photography was not highly convergent and hence no attempt was made to recover the interior orientation. However it was felt that a one parameter model of radial distortion might be determinable from a relative orientation solution of five photographs. This was not the case however because the field angle of the Hasselblad cameras was too narrow to permit even the radial distortion to be recovered in this fashion. Some additional information was required in the form of relative camera altitudes or a sprinkling of vertical control points in object space. Vertical control points of course were not available but relative camera heights were available from the orbital data. In order to determine whether a recalibration

constraining the camera altitude was worthwhile a strip triangulation of the five photographs used in the in-flight calibration was performed using the ground calibration values and constraining the camera altitudes to conform with the orbital values. This was compared with a solution where the altitudes were free to adjust. There was no significant difference in the magnitude of the photo coordinate residuals and the corresponding mean error. This implied that no significant changes would result from a redetermination of the lens distortion parameters.

While the configuration of the APOLLO 10 strip did not allow the extraction of significant camera calibration data the concept of an in-flight calibration under the proper circumstances has great merit. These considerations are discussed in Section III where specific procedures for implementing such a calibration are recommended.

SECTION II

SUMMARY AND EVALUATION OF FINAL RESULTS

The final adjustment of the APOLLO 10 photographs consisted of a simultaneous analytical aerotriangulation of photos 57 to 131. The number of photos triangulated was less than originally planned because the uncertainties in the data gave rise to greater difficulties than were originally anticipated. The various problems encountered and our success and failure in solving them are described in the following paragraphs.

2.1 Evaluation of the Timing Information

As noted in the previous section one of the most difficult problems encountered was the evaluation of the timing information. This information consisted simply of the fact that the photos were exposed at a nominally constant but unknown time interval by an intervalometer. Of course the time interval was not exactly constant but subject to random and possibly systematic fluctuations. Thus the exposure times may be expressed as:

$$(1) \quad t_1; t_2 = t_1 + \Delta t_1; \dots; t_i = t_{i-1} + \Delta t_{i-1}; \dots; t_n = t_{n-1} + \Delta t_{n-1}.$$

The t_i are the exposure times and the Δt_i are the exposure time intervals. An evaluation, on the ground, of the fluctuations of the Δt_i was made by MSC in November of 1968. The results are reproduced in Figure 2.1 where it is readily apparent that after the first few intervals the time intervals are constant to 0.01 or 0.02 second. Such constancy was not to be expected during the lunar photographic operation because it was anticipated that there would be greater fluctuations in the voltage levels which control the intervalometer. In order to test the variations in Δt_i and thus determine the permissible constraints to be used for the in-track component of the exposure station positions a series of 21 photo substrip adjustments were performed. The adjustments consisted of holding the position of the center photo fixed and constraining the radial and cross-track components of the

<u>5 Volts DC</u>	<u>7 Volts DC</u>
20.53	19.85
19.82	19.27
19.77	19.24
19.75	19.23
19.74	19.22
19.73	19.22
19.73	19.22
19.72	19.22
19.72	19.22
19.72	19.22
19.71	19.22
19.71	19.22
19.71	19.22
19.71	19.22
19.71	19.22

FIGURE 2.1. MSC Test of Intervalometer Times

positions of the other photographs to ± 50 meters and ± 1 meter respectively. Four adjustments were performed with in-track constraints (σ_u) of 150, 75, 15, and 5 meters respectively. These distance constraints are equivalent to time constraints of 0.1, .05, 0.01 and 0.003 second respectively. The objective was to determine at what point the mean error of the adjustment would increase as σ_u was decreased. The results are as follows.

<u>Case</u>	<u>Equivalent Time Constraint (seconds)</u>	<u>In-Track Constraint (meters)</u>	<u>Mean Error (μm)</u>
1	0.1	150	8.2
2	0.05	75	8.7
3	0.01	15	9.6
4	0.003	5	9.6

It is apparent that a change from a 0.1 second constraint to a 0.05 second constraint increases the mean error of the adjustment from 8.2 to 8.7 μm . This is significant and indicates that the standard deviation of the exposure times is of the order of 0.1 second.

The time intervals corresponding to the adjusted exposure station positions are plotted in Figure 2.2 for Case 1 where the exposure stations positions are essentially free to adjust in the in-track direction. The time intervals shown in Figure 2.2 for this case may be construed as resulting from a purely photogrammetric determination of the in-track distances between exposure stations.

As noted earlier the variations in the apparent time interval may be due to variations in the recovery of the x-coordinate of the principal point rather than variations in the intervalometer or a combination of both. It is impossible to differentiate between the two affects on the basis of the photogrammetric adjustment alone. However the problem still remains of the proper constraint to use for the in-track component of the exposure station positions. On the basis of the above results a value for σ_u less than ± 150 meters (corresponding to a time variation of ± 0.1 second) seems to be inconsistent with the photogrammetric results. However,

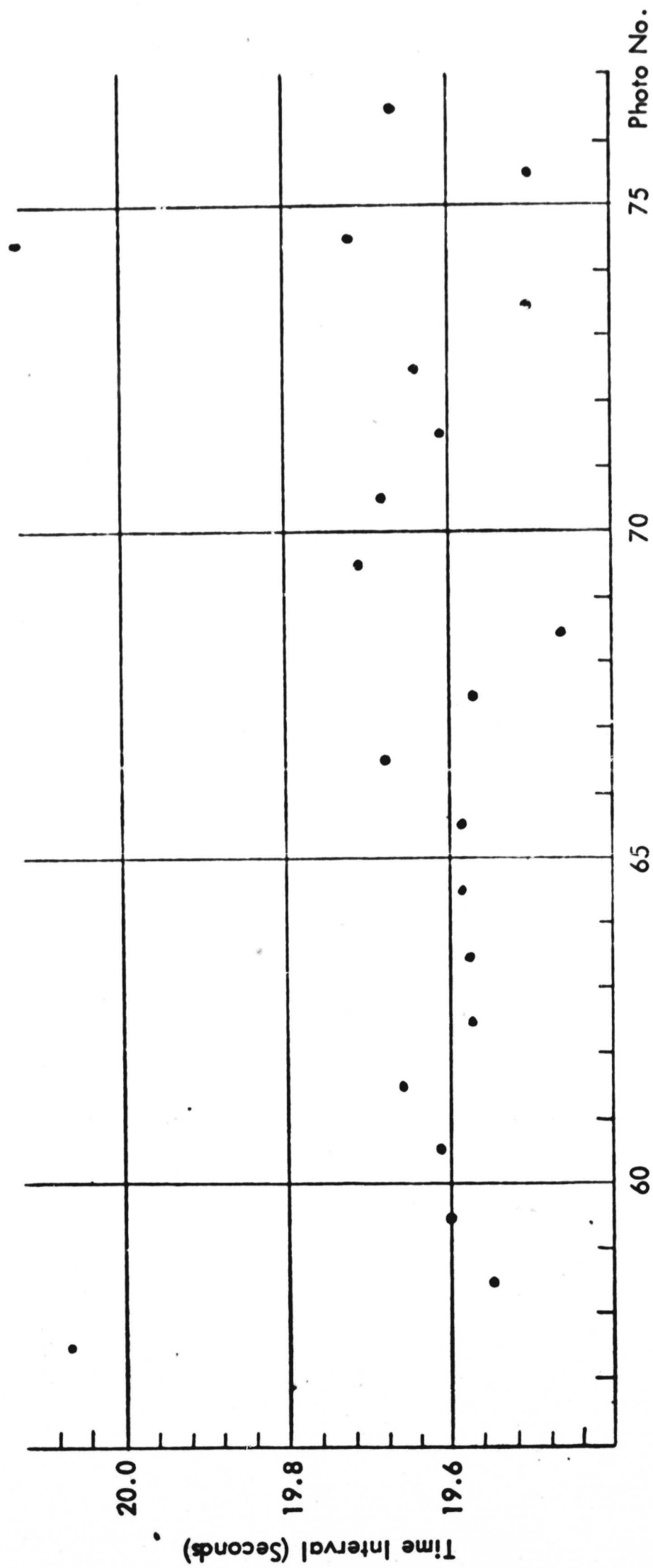


FIGURE 2.2. Exposure Time Intervals Resulting from 21 Photo Substrip Adjustment With In-Track Component of Exposure Station Position. Constrained ± 150 Meters.

constraint of 150 meters results in scale information precise to only 1/200. This is completely inadequate to achieve a stable solution for the strip triangulation of the 75 Hasselblad photographs. Thus in implementing the triangulation for the entire strip a compromise was reached between the requirements for determinacy and what seemed to be the true errors in the data defining the in-track distances. A constraint of ± 0.02 seconds was used after considerable experimentation. The results of the adjustment are detailed in paragraph 2.3 below.

It may be noted by some that the t_i as defined in equation (1) are not statistically independent. Rather they form an autoregressive sequence and to treat the t_i as statistically independent is not strictly correct. However if the correlation structure of the t_i were rigorously taken into account, (as described for example in Reference 4) and incorporated in the normal equations, the narrow bandwidth of the normal equations matrix would have been destroyed and made the efficient solution of the normal equations impossible. Thus it was felt that, since it was necessary, in any case, to overconstrain the in-track components of the positions of the exposure stations to achieve stability, treating the t_i (or equivalently the in-track components) as independent was practical and justified.

2.2 Evaluation of Ephemeris Data

The techniques of interpolating in the orbital ephemeris to obtain exposure station positions in a Moon fixed system and then constraining the exposure station positions in the adjustment to conform to the orbit in terms of cross-track and radial constraints were described in the previous section.

The problem of reconciling possible inconsistencies between the orbital data and the photogrammetric solution has already been touched on in paragraph 1.1. It was pointed out that both the orbital information and the photogrammetric solution determine the relative positions of the exposure stations and that these may not be consistent because of the uncertainties in the ephemeris and the lack of metric fidelity of the Hasselblad cameras. Thus variations in principal distance would result in

inconsistencies with the orbital values of the radial component of the exposure station position while variations in the recovery of the x-coordinate of the principal point (x_p) would result in inconsistencies with the orbital values of the in-track component of the exposure station positions.

It was found that there was almost no inconsistency between y_p and the cross-track component (W) making it possible to constrain W to ± 1 meter. However because of the relatively narrow field of the camera, inconsistencies, if they did indeed exist, could have been compensated by the roll angle.

The last set of tests consisted of varying the constraint of the radial component, V , in a series of twenty photo substrip adjustments. The results are as follows.

<u>Case</u>	<u>Constraint on Radial Component of Exposure Station Position</u>	<u>Mean Error of Adjustment</u>
1	50 meters	8.2 μm
2	25	8.4
3	5	8.6
4	1	8.7

Thus if σ_u is less than 50 meters a small but significant change in the mean error results. The change in principal distance, c , corresponding to a change in altitude H , is given by $\delta c = \frac{c}{H} \delta H$. The values of δc corresponding to the values of σ_v in above table, for $c = 80\text{mm}$ and $H = 100\text{km}$ are 40, 20, 4, and $0.8\mu\text{m}$ respectively. Since the Hasselblad camera does not have a platten, it would not be surprising if the variations in camera altitude plotted in Figure 2.3 for Case 1 arose from variation in principal distance. However here again it is not possible to definitely assert whether the altitude deviation arises from ephemeris errors or changes in principal distance. We are inclined to the view that variations in principal distance are the cause since it seems unlikely that ephemeris errors, even those caused by unknown Mascons, would result in such random deviations over such relatively short distances as those illustrated in Figure 2.3 for Case 1.

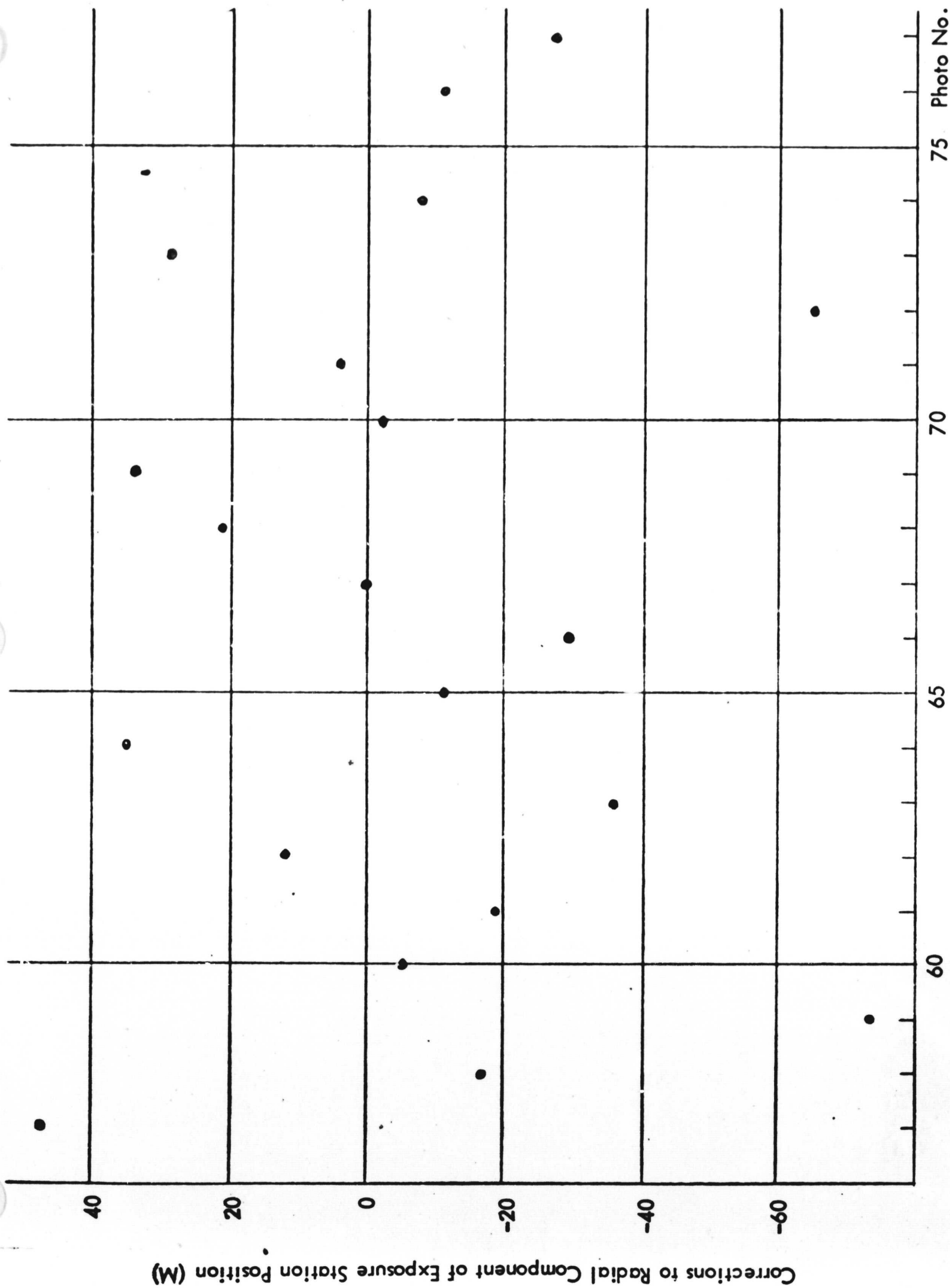


FIGURE 2.3. Corrections to Radial Components of Exposure Station Positions Resulting from 21 Photo Substrip Adjustment
Where the Radial Component was Constrained to ± 50 Meters.

2.3 Utilization and Evaluation of Attitude Data

The camera angular orientation data furnished by MSC were derived from the spacecraft attitude determination system. For purposes of discussing the utilization of this data in the strip adjustment and its evaluation let us adopt the following notation:

Φ_j, Ω_j, A_j = spacecraft pitch, roll, and azimuth at time t_j as determined by the spacecraft attitude determination system;

$\varphi'_j, \omega'_j, \alpha'_j$ = camera orientation angles as derived from the spacecraft attitude Φ_j, Ω_j, A_j ;

$\varphi_j, \omega_j, \alpha_j$ = camera orientation angles as determined from the strip triangulation.

$\varphi'_j, \omega'_j, \alpha'_j$ were derived by MSC from Φ_j, Ω_j, A_j by estimating the orientation of the camera relative to the frame of reference of the spacecraft attitude determination system. Denoting the relative orientation angles by $\Delta\varphi_j, \Delta\omega_j, \Delta\alpha_j$ we have then:

$$\varphi'_j = \Phi_j + \Delta\varphi_j, \quad \omega'_j = \Omega_j + \Delta\omega_j, \quad \alpha'_j = A_j + \Delta\alpha_j.$$

$\Delta\varphi_j, \Delta\omega_j, \Delta\alpha_j$ are probably in error by several degrees since no effort was made, so far as is known, to calibrate these parameters.

φ'_j, ω'_j , and α'_j were furnished at 10 second intervals. Using the exposure times, t_j , (as determined by the method described in paragraph 1.1) as an argument, the orientation angles corresponding to the particular photographs were obtained by interpolation. The interpolated values of φ'_j and α'_j were used as initial approximations in the strip adjustment and were constrained to only ± 5 degrees since the orbital data was sufficient to define the pitch and azimuth of the photographs. ω'_j on the other hand was constrained to ± 10 arc minutes. This was done, despite the realization that ω'_j was probably in error by a degree or more, because there was no other information to define the roll angles of the photos in the strip.

Since, as stated above, the camera pitch and azimuth angles could be determined independently from the strip adjustment, a comparison of φ_j and φ'_j , and α_j and α'_j would permit an evaluation of the spacecraft attitude data for photogrammetric purposes. This

comparison is made in Figures 2.4 and 2.5 for pitch and azimuth respectively. It is apparent that there are differences up to two degrees between the two sets of values. Furthermore these differences are neither systematic or smooth as may be seen in Figures 2.6 and 2.7 where $\delta\varphi_1 = \varphi_1 - \varphi'_1$ and $\delta\alpha_1 = \alpha_1 - \alpha'_1$ are plotted. The standard errors of the φ_1 as determined by the aerotriangulation are about ± 2 arc minutes. Thus the variations in the discrepancies for the pitch angle illustrated in Figure 2.6 may be considered to reliably represent the actual situation. However the standard errors of some of the α_1 as determined from the aerotriangulation are as much as ± 40 arc minutes. This is because the relatively narrow field, combined with the 25° pitch angle, resulted in a relatively weak determination azimuths of the photographs. Thus a portion of the discrepancies plotted in Figure 2.7 may be due to errors in α_1 . However based upon the results with the pitch angles it is felt that the spacecraft attitude system does not provide data suitable for use in photogrammetric reductions unless there is no other source of data to define one or more of the angles as was the case with the roll angle. ω'_1 and ω_1 are compared in Figures 2.8 and $\delta\omega_1 = \omega_1 - \omega'_1$ is plotted in Figure 2.9.

2.4 Results of Strip Adjustment

The analytical aerotriangulation consisted of simultaneously adjusting Hasselblad Photos 57 to 131 of Magazine O. Orbital constraints were incorporated in the adjustment by constraining the exposure stations to conform as close to the orbit as required for a stable solution and still not introduce any significant contradictions into the photogrammetric solution. Considerable experimentation was required to arrive at a set of constraints consistent with this criterion. The results of some of the tests were summarized in the previous paragraphs. The exposure station constraints that were used in the final adjustment were as follows for all photos except Photo 95.

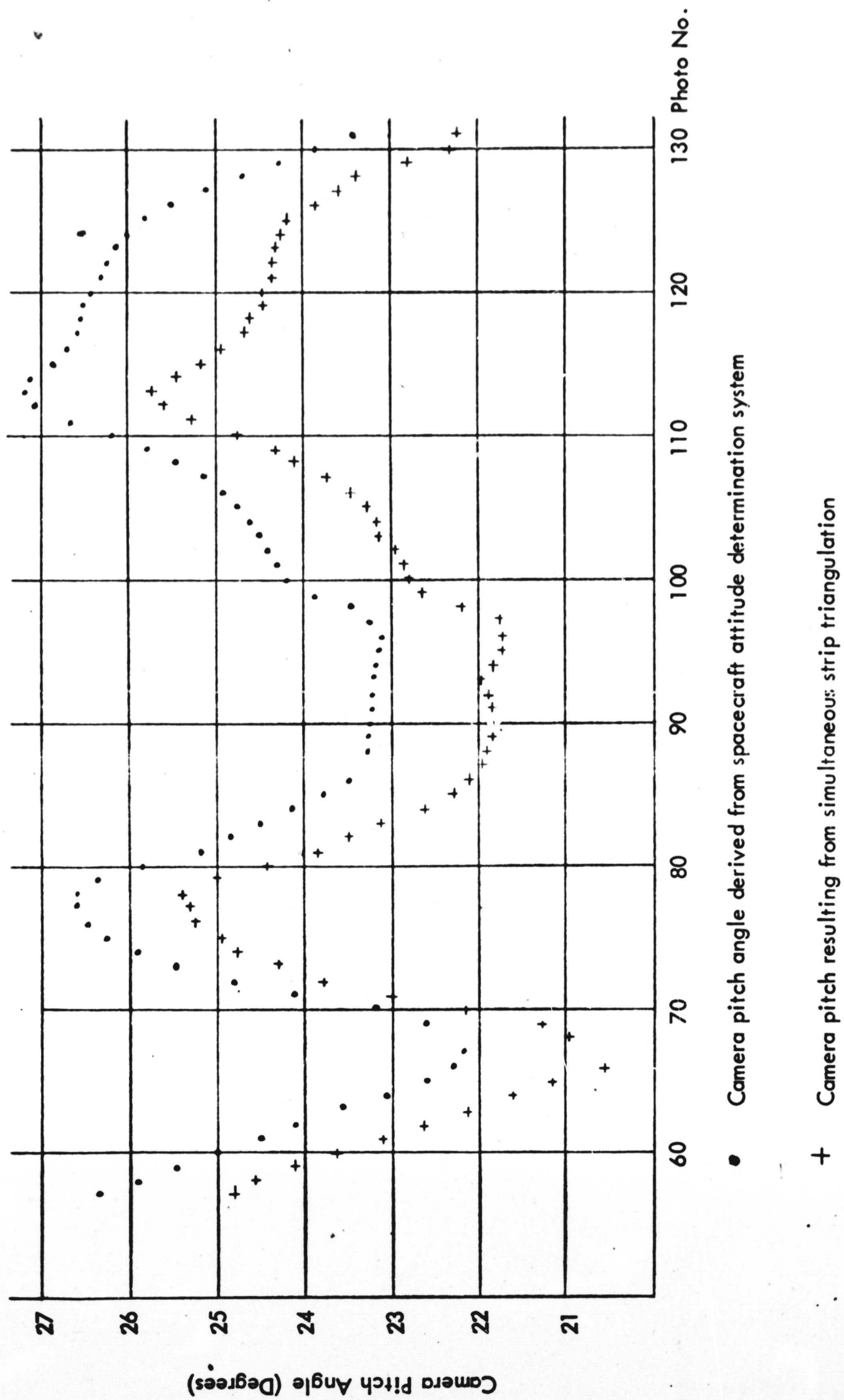


FIGURE 2.4. Comparison of Camera Pitch Angle Determination.

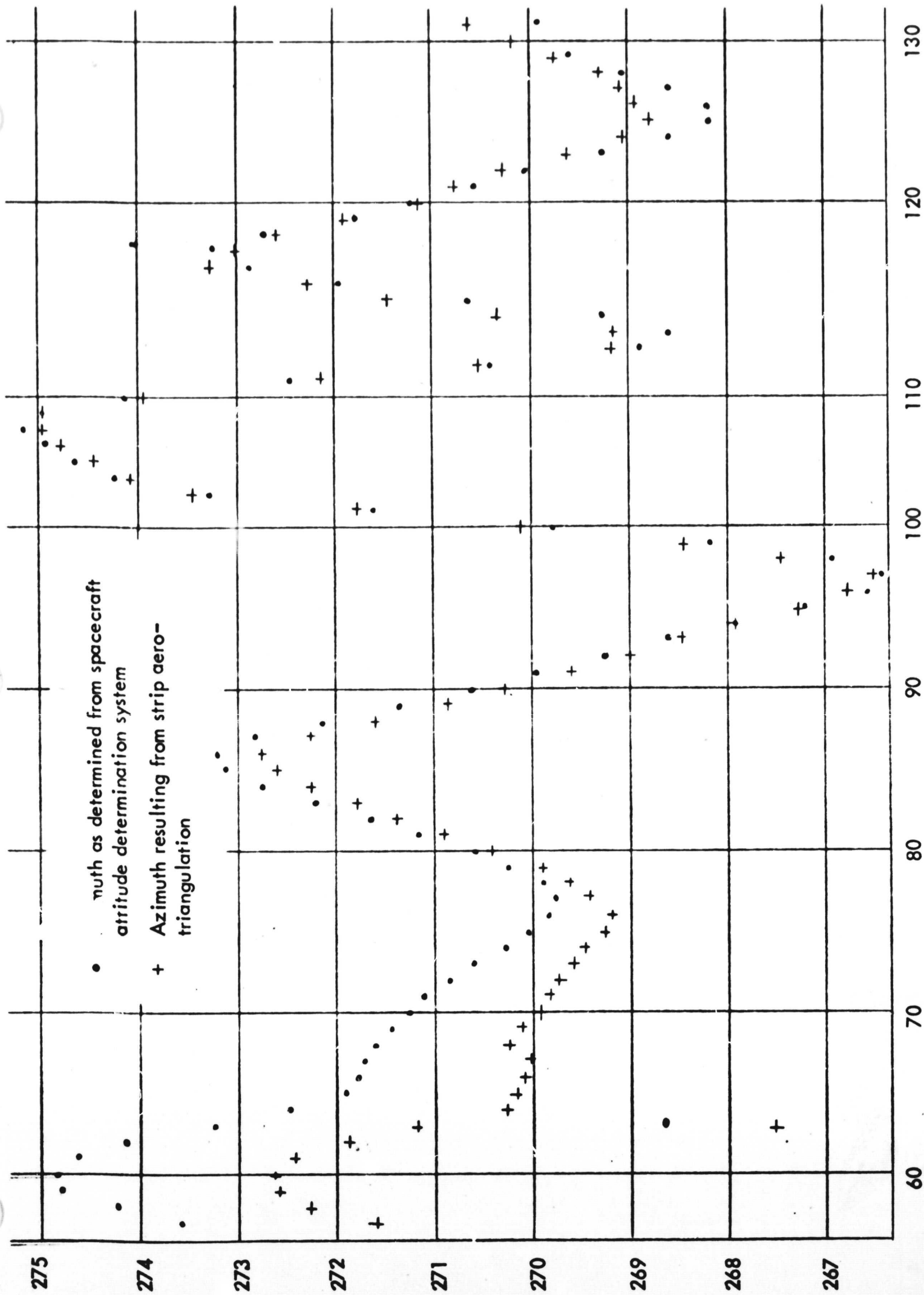


Photo No.

FIGURE 2.5. Comparison of Camera Azimuth Determination.

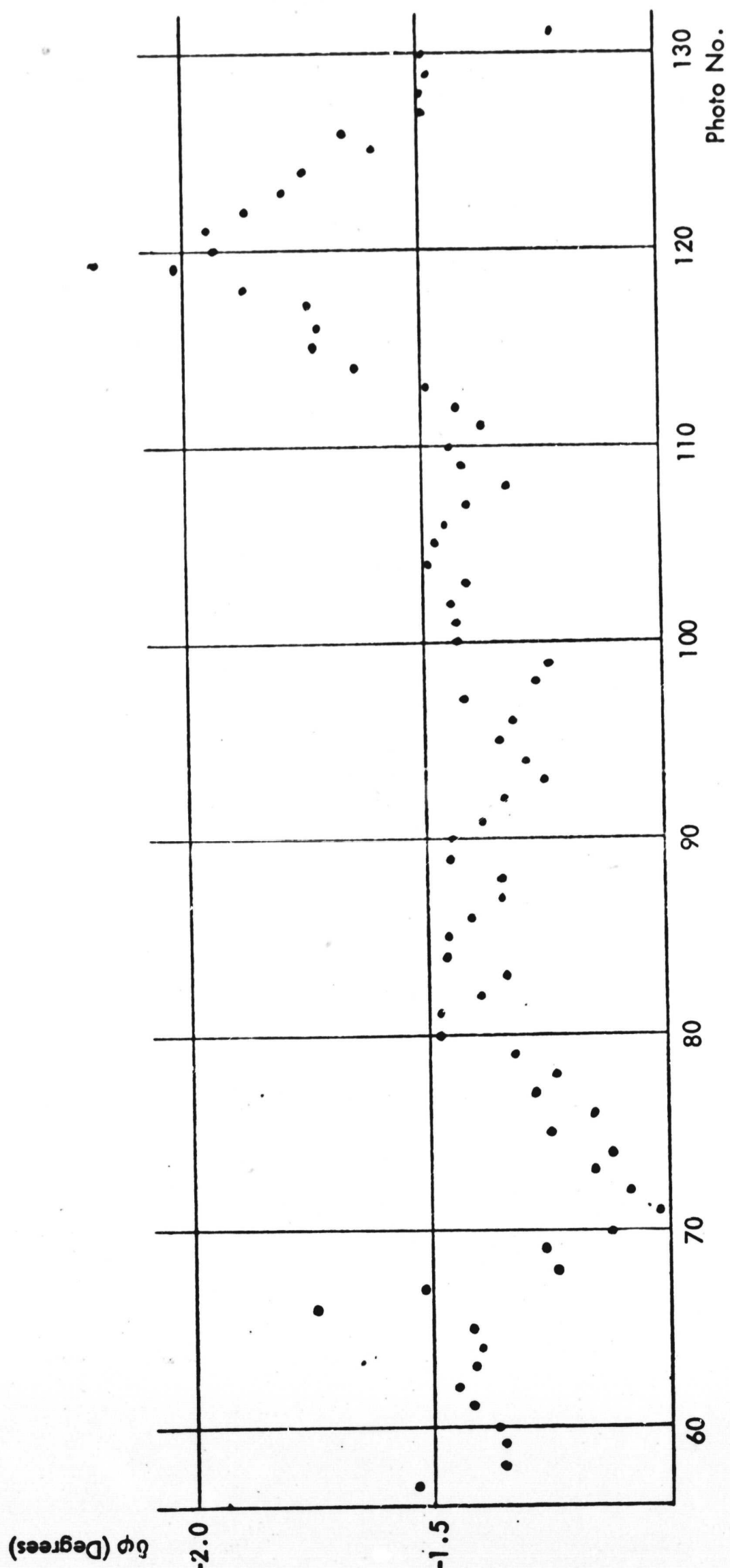


FIGURE 2.6. Corrections to Input Values of Camera Pitch Angles Resulting from Strip Aerotriangulation.

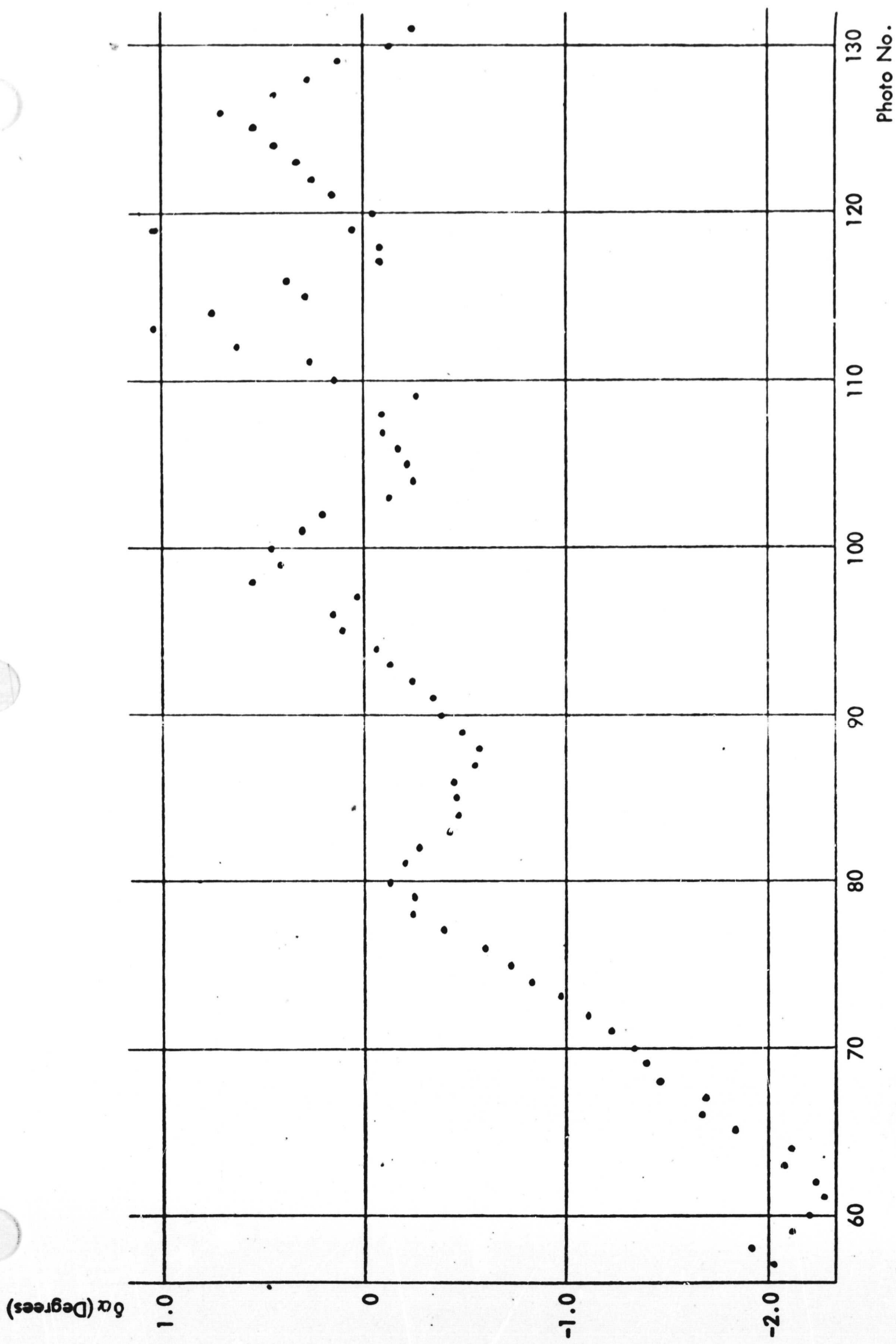


FIGURE 2.7. Corrections to Initial Values of Camera Azimuth Resulting from Strip Aerotriangulation.

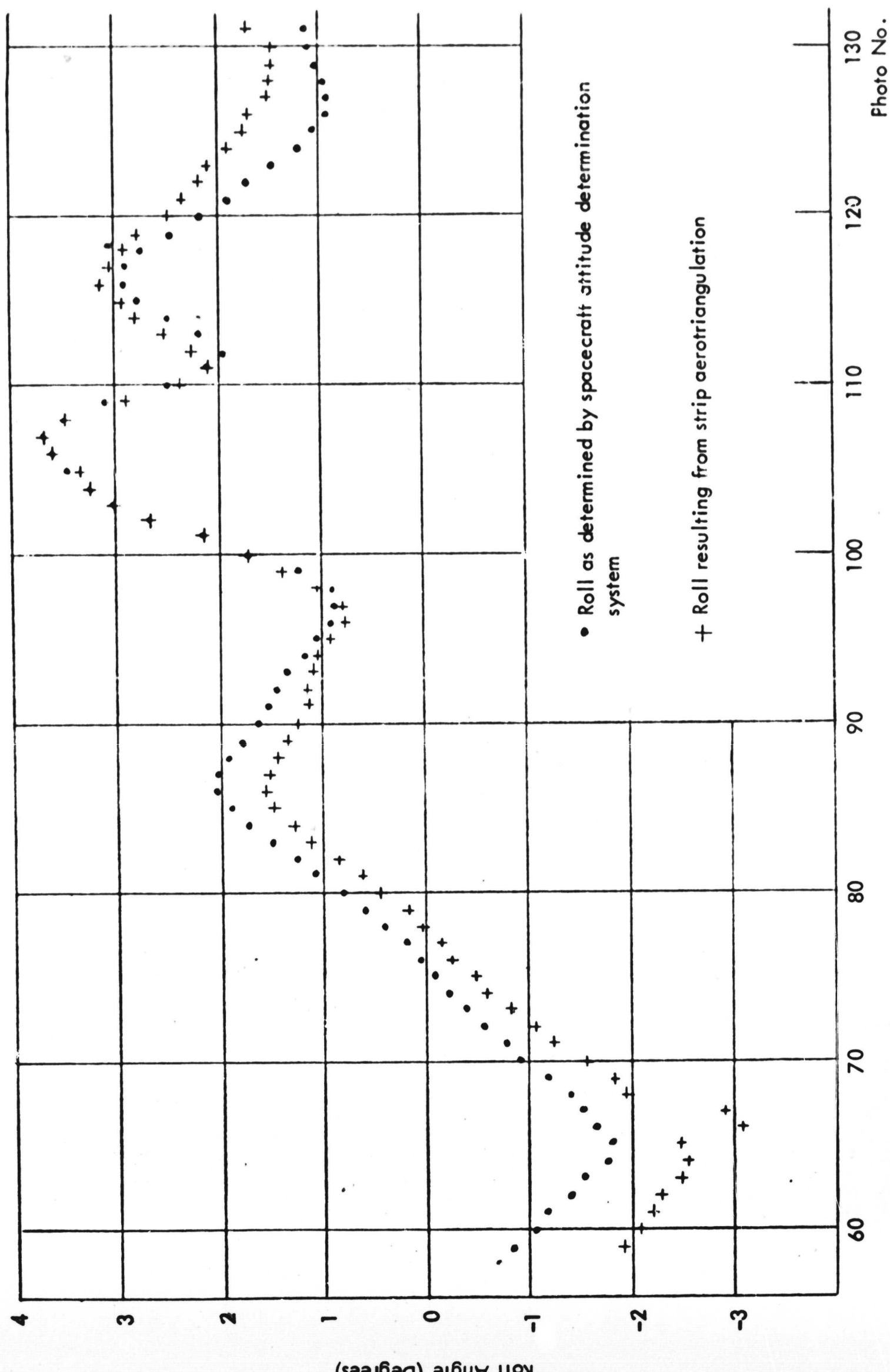


FIGURE 2.8. Comparison of Determination of Camera Roll Angles

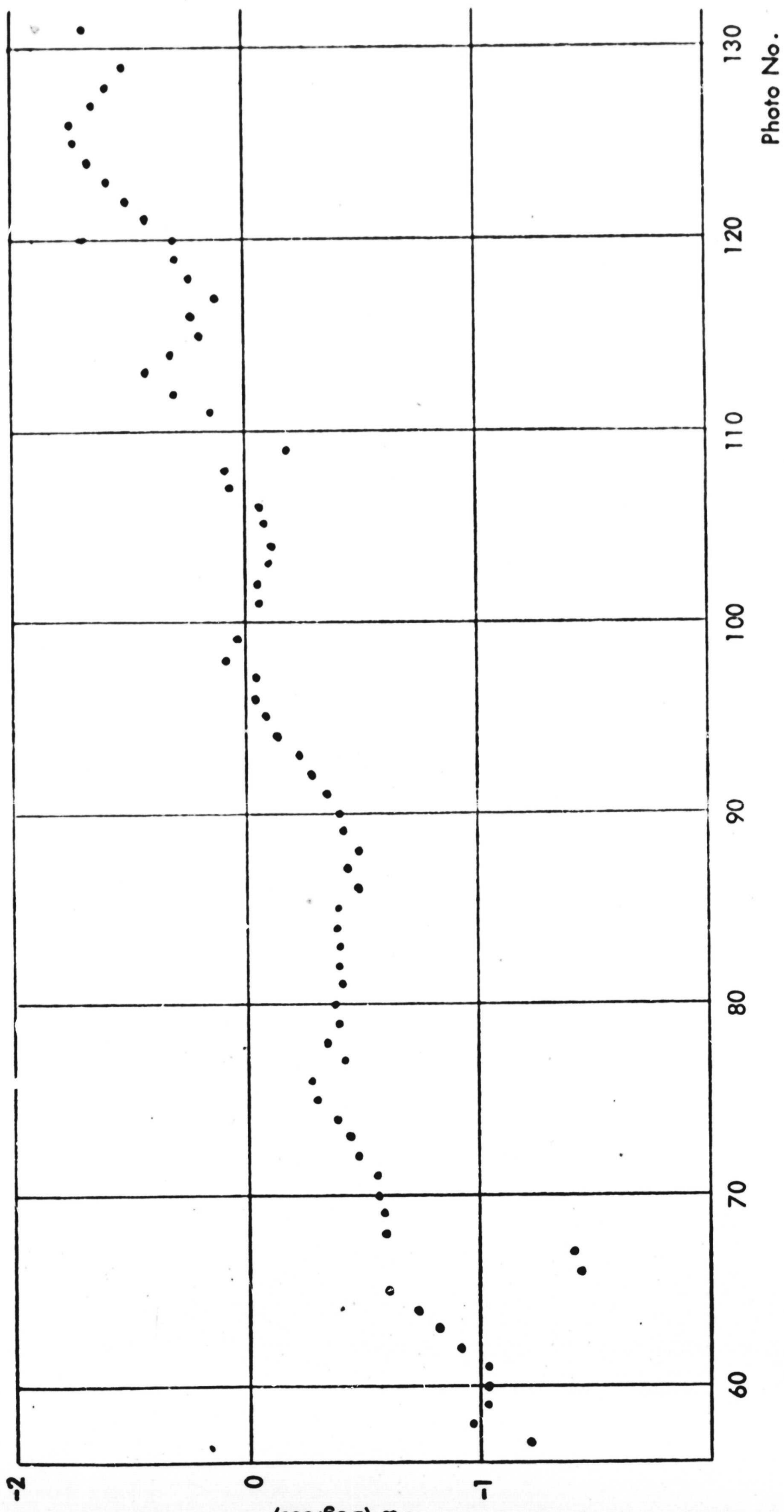


FIGURE 2.9. Corrections to Initial Values of Camera Roll Angle Resulting from Strip Aerotriangulation.

<u>Constraint</u>	<u>Value</u>
Cross-Track	1 meter
In-Track	30
Radial	10

For Photo 95, the center photo of the strip, in-track component was constrained to 0.1 meter. This was equivalent to defining an epoch for the adjustment. The constraints on the initial approximations of the orientation angles were $\sigma_{\varphi} = \sigma_{\alpha} = \pm 5$ degrees, $\sigma_{\omega} = \pm 10$ minutes. Essentially the orbital information, the timing information derived from the intervalometer, and the roll angles were the only external information available to control the strip. A series of attempts were made (after adjusting the photographs on a substrip basis to detect and delete erroneous measurements and experiment with constraints) to adjust the 75 photo strip using the positional and angular constraints given above. The normal equations were too ill-conditioned to permit the solution to converge. Ill-conditioning of the normal equations arises in strip and block adjustments when there is too little external information such as ground control or exterior orientation data. As the normal equations become more ill-conditioned the accuracy of the solution deteriorates until complete divergence results. For the results of a systematic test on the effect of decreasing the level of ground control in a strip adjustment see Reference 2. In the case of the APOLLO 10 strip adjustment the orbit, timing, and roll angle information were inadequate for a strip of 75 photographs. It was possible however to adjust 26 photos simultaneously, i.e. 84 to 109. Then using the results of this adjustment a pair of points at either end of the strip were selected (see Figure 2.10a) and treated as control points in the adjustment of Photographs 78 through 120. The process was repeated as illustrated in Figure 2.10 until the entire 75 photo strip was adjusted simultaneously. This procedure was merely an expedient to permit the entire strip to be adjusted simultaneously. Thus the values of the standard errors of the adjusted parameters, computed at the end of the adjustment, are far too optimistic since the error propagation computation is based upon the presence of ten additional ground points whose coordinates do not really represent additional information. The optimism in the error propagation is primarily in the in-flight direction because it was in this direction that the solutions tended to diverge.

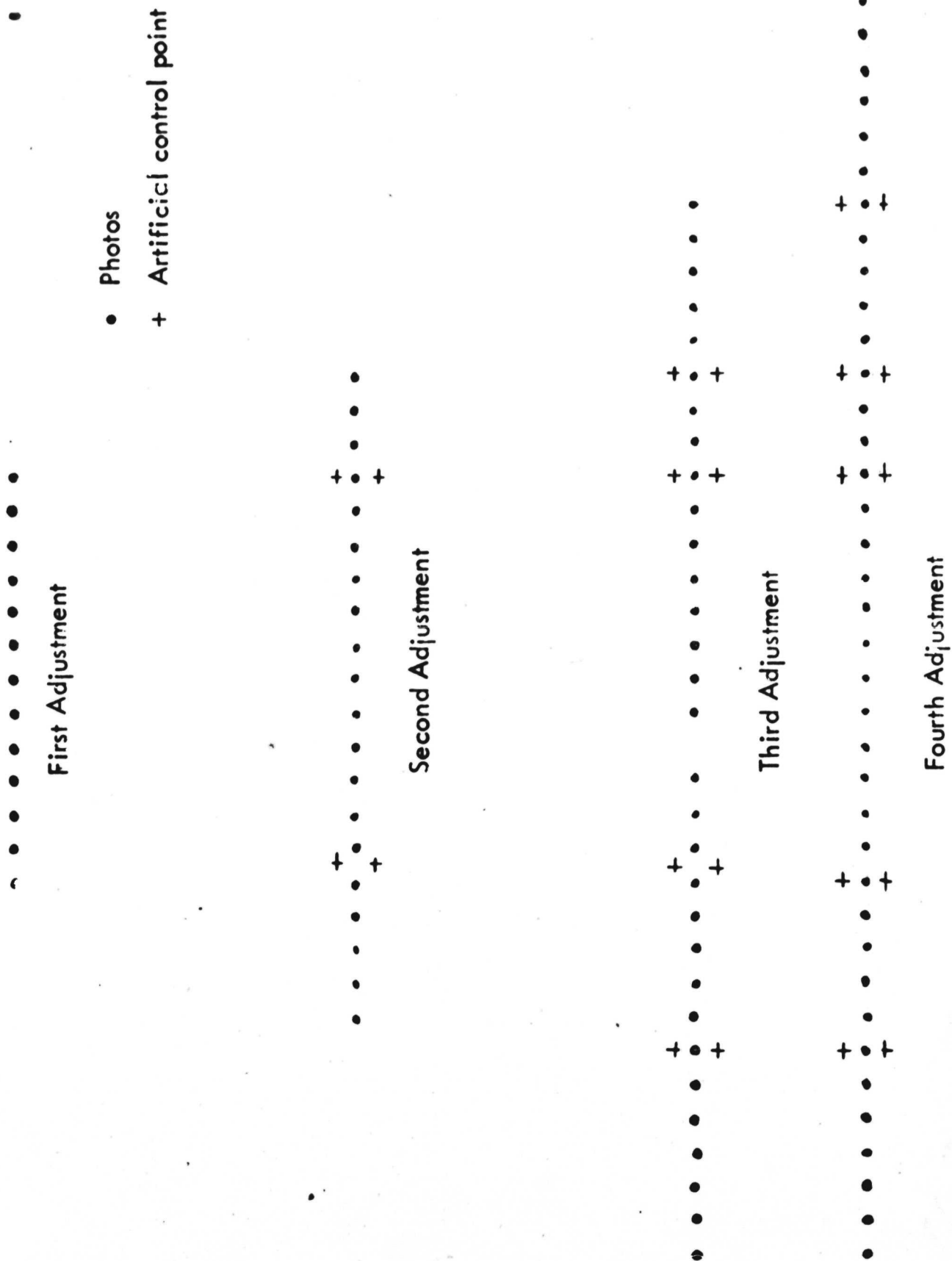


FIGURE 2.10. Successive Adjustments with Artificial Control Point

The computed standard errors of the adjusted exterior orientation elements of every fifth photograph of the adjustment is given in Figure 2.11. The standard error of the adjusted coordinates of selected passpoints is given in Figure 2.12.

The mean error of the plate measurements of the adjustment using the procedures described above was $18.4 \mu\text{m}$. The reasons for this rather large value are twofold.

a) The photographs at the west end of the strip (110 = 131) were near the subsolar point and overexposed. The poor imagery resulting from the overexposure caused a deterioration in point transfer and resulted in mean errors of $25 \mu\text{m}$ for the substrip adjustments. This is in contrast to the results at the end of the strip near the terminator where mean errors between 7 and $10 \mu\text{m}$ were typical.

b) The exposure station positions, derived from the orbital data, and used as initial values in the strip adjustment were over-constrained (especially the in-track component) in order to permit a simultaneous adjustment. Over-constraining the parameters introduced inconsistencies in the solution which resulted in an increase in the mean error of the result.

The two control points described earlier were not held fixed in the adjustment. Instead the exposure times were adjusted to make the adjusted longitudes agree as closely as possible with the furnished values of the longitude. The latitudes and heights were allowed to adjust. A comparison of the results is as follows.

		<u>Furnished by MSC</u>	<u>Computed By Strip Adjustment</u>	<u>Difference</u>
C.P.1	{ lat.	0° 50' 41".64	0° 54' 16".47	3' 34".84
	{ long.	170° 08' 19".32	170° 08' 23".13	3".82
	{ elv.(m)	967	793	-174
C.P.2	{ lat.	0° 34' 54".84	0° 34' 29".69	-25".15
	{ long.	127° 57' 13".32	127° 57' 1".97	-11".35
	{ elv.(m)	4230	4265	35

The large discrepancy in the latitude of about 1.8km for C.P.1 may be caused by either or a combination of the following.

	<u>Photos</u>	<u>$\sigma_{\omega}(\text{sec})$</u>	<u>$\sigma_{\phi}(\text{sec})$</u>	<u>$\sigma_{\alpha}(\text{sec})$</u>	<u>$\sigma_{\kappa}(\text{m})$</u>	<u>$\sigma_{\lambda}(\text{m})$</u>	<u>$\sigma_{\mu}(\text{m})$</u>
1	57	1517	133	2513	2	51	18
6	60	1093	121	1954	2	47	17
9	65	465	105	998	2	46	17
14	70	112	82	230	2	41	17
19	75	416	91	843	2	47	17
24	80	288	88	639	2	45	17
29	85	302	80	848	2	45	17
34	90	638	113	2083	2	48	17
39	95	517	94	2043	2	0.2	17
44	100	304	114	1349	2	48	17
49	105	58	92	199	2	49	17
54	110	98	108	349	2	49	17
59	115	64	119	266	2	49	17
64	120	43	93	162	2	45	17
69	125	85	127	578	2	49	17
74	130	134	339	911	2	50	17
75	131	160	543	1026	2	54	18

FIGURE 2.11. Standard Errors of Adjusted Elements of Exterior Orientation of Selected Photographs.

- a) An error in determination of the position of the point with the spacecraft sextant due to errors in sighting or in spacecraft position while sighting.
- b) An error in the roll angles, of about one degree, for the photos of the portion of the strip in proximity to C.P.1.
- c) An error in the cross-track component of the orbit of the strip.

The agreement in elevation is surprisingly good and simply corroborates the spacecraft altitude and the C.P. elevation. Nothing can be deduced from the longitude values since these were arbitrarily made to agree as closely as possible. It is difficult to draw any conclusions about the quality of the control points from the sparse data available.

The computed photographic exposure times and computed time intervals are tabulated in Figures 2.13 and 2.14. The times were computed by interpolating in the table of exposure station positions (latitude, longitude, and altitude) versus time using the adjusted longitudes of the exposure stations as arguments.

The results of the entire adjustment printed out in the standard SURBAT format have been furnished MSC. This printout includes the following for each photograph: initial approximations, total corrections and, adjusted values of the exterior orientation parameters; the a priori standard deviations of the initial values; and the unweighted and weighted residuals of the photo coordinate measurements. The photographic data is followed by a listing of the adjusted passpoint ground coordinates. Finally the standard errors of the adjusted elements of exterior orientation and the adjusted passpoint ground coordinates are given. The standard errors are rigorously computed from the inverse of the normal equations matrix.

APOLLO TEN EXPOSURE TIMES

PHOTO NUMBER	ELAPSED TIME FROM L/B. DAYS HOURS MINS SECS	PHOTO NUMBER	ELAPSED TIME FROM L/B. DAYS HOURS MINS SECS	PHOTO NUMBER	ELAPSED TIME FROM L/B. DAYS HOURS MINS SECS	PHOTO NUMBER	ELAPSED TIME FROM L/B. DAYS HOURS MINS SECS
57	4 23 41 41.459	82	4 23 49 51.916	107	4 23 58 2.292		
58	4 23 42 1.212	83	4 23 50 11.556	108	4 23 58 21.904		
59	4 23 42 20.800	84	4 23 50 31.147	109	4 23 58 41.587		
60	4 23 42 40.377	85	4 23 50 50.755	110	4 23 59 1.195		
61	4 23 43 .018	86	4 23 51 10.372	111	4 23 59 20.813		
62	4 23 43 19.610	87	4 23 51 30.027	112	4 23 59 40.359		
63	4 23 43 39.234	88	4 23 51 49.601	113	5 0 0 .031		
64	4 23 43 58.819	89	4 23 52 9.174	114	5 0 0 19.605		
65	4 23 44 18.447	90	4 23 52 28.826	115	5 0 0 39.187		
66	4 23 44 38.101	91	4 23 52 48.434	116	5 0 0 58.849		
67	4 23 44 57.706	92	4 23 53 8.081	117	5 0 1 18.427		
68	4 23 45 17.265	93	4 23 53 27.729	118	5 0 1 38.051		
69	4 23 45 36.916	94	4 23 53 47.305	119	5 0 1 57.620		
70	4 23 45 56.548	95	4 23 54 6.911	120	5 0 2 17.092		
71	4 23 46 16.149	96	4 23 54 26.554	121	5 0 2 36.766		
72	4 23 46 35.807	97	4 23 54 46.110	122	5 0 2 56.385		
73	4 23 46 55.354	98	4 23 55 5.755	123	5 0 3 16.065		
74	4 23 47 15.028	99	4 23 55 25.399	124	5 0 3 35.724		
75	4 23 47 34.573	100	4 23 55 44.978	125	5 0 3 55.316		
76	4 23 47 54.223	101	4 23 56 4.577	126	5 0 4 14.973		
77	4 23 48 13.859	102	4 23 56 24.222	127	5 0 4 34.617		
78	4 23 48 33.438	103	4 23 56 43.869	128	5 0 4 54.258		
79	4 23 48 53.099	104	4 23 57 3.429	129	5 0 5 13.845		
80	4 23 49 12.657	105	4 23 57 23.051	130	5 0 5 33.437		
81	4 23 49 32.290	106	4 23 57 42.659	131	5 0 5 53.049		

FIGURE 2.13. Adjusted Exposure Times in GET System.

APOLLO TEN		TIME BETWEEN EXPOSURES			
PHOTO NUMBERS	ELAPSED TIME IN SECS.	PHOTO NUMBERS	ELAPSED TIME IN SECS.	PHOTO NUMBERS	ELAPSED TIME IN SECS.
58- 57	19.753	83- 82	19.640	108-107	19.612
59- 58	19.588	84- 83	19.591	109-108	19.684
60- 59	19.577	85- 84	19.608	110-109	19.608
61- 60	19.642	86- 85	19.616	111-110	19.618
62- 61	19.591	87- 86	19.655	112-111	19.545
63- 62	19.624	88- 87	19.575	113-112	19.672
64- 63	19.586	89- 88	19.572	114-113	19.574
65- 64	19.628	90- 89	19.653	115-114	19.583
66- 65	19.654	91- 90	19.608	116-115	19.662
67- 66	19.605	92- 91	19.647	117-116	19.577
68- 67	19.559	93- 92	19.648	118-117	19.624
69- 68	19.651	94- 93	19.576	119-118	19.569
70- 69	19.631	95- 94	19.606	120-119	19.472
71- 70	19.601	96- 95	19.643	121-120	19.674
72- 71	19.658	97- 96	19.556	122-121	19.619
73- 72	19.546	98- 97	19.644	123-122	19.680
74- 73	19.674	99- 98	19.644	124-123	19.659
75- 74	19.545	100- 99	19.579	125-124	19.591
76- 75	19.650	101-100	19.599	126-125	19.657
77- 76	19.636	102-101	19.645	127-126	19.644
78- 77	19.580	103-102	19.647	128-127	19.641
79- 78	19.661	104-103	19.560	129-128	19.588
80- 79	19.558	105-104	19.622	130-129	19.591
81- 80	19.633	106-105	19.608	131-130	19.612
82- 81	19.626	107-106	19.633		

FIGURE 2.14. Adjusted Exposure Time Intervals.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

It should be apparent to most readers of this report that almost all of the difficulties encountered in the adjustment arose because of the marginal character of the Hasselblad camera for photogrammetric purposes. If a similar adjustment had been performed with a wide angle metric camera equipped with a synchronous stellar orientation camera and with a system for precise timing (at least ± 1 ms) of the midpoint of exposures, a strong, reliable result would have been achieved with little if any of the many qualifications and uncertainties associated with the present adjustment. NASA is of course planning such a system for APOLLO 15 and after. However it is our understanding that the near rather than the far side of the Moon will be illuminated on most if not all of the APOLLO Missions carrying the metric camera. Thus the Hasselblad photographs obtained on APOLLO 8, 10, and 12 may remain the most extensive relatively large scale coverage of the far side of the Moon for some time to come. Under this assumption the question is then, in light of the experience with the APOLLO 10 strip adjustment, is it worthwhile to aerotriangulate any more Hasselblad photographs? Our recommendations are as follows.

a) No further extensive aerotriangulation seems warranted with either the APOLLO 8 or 10 Hasselblad photographs. The lack of adequate timing and camera attitude data and the uncertainty of the recoverability of the interior orientation of the photographs makes the results of the triangulation too doubtful for the effort that would be required for a solution.

b) The APOLLO 14 Hasselblad cameras will be equipped with a glass, near focal plane reseau. In addition the exposure times will be determined to $\pm 1^\circ$ msec. Under these circumstances an aerotriangulation of the photography should yield useful results. It is recommended, however, that prior to any extensive aerotriangulation a

a series of tests such as those described in paragraph 2.1 be performed with a ten to fifteen photo substrip. Such a test would reveal the consistency of the timing data and the consistency of the calibrated values of the interior orientation. If the results of the tests indicate that exposure time errors are of the order of 1° msec and the interior orientation elements did not vary by more than 10 or $20\mu\text{m}$ then a complete aerotriangulation of the photos would be justified.

c) Any future aerotriangulation with the Hasselblad photography should be performed using the LO-BAT program where the orbital constraints are rigorously incorporated in terms of the orbital elements as constrained unknowns. This is especially recommended when two or more strips are adjusted simultaneously. LO-BAT permits the discrepancies in the initial orbital values to adjust to accommodate the photogrammetric conditions. As was noted earlier the present version of LO-BAT is not designed to efficiently reduce long strips of photographs. The extended version of LO-BAT presently under development will be much more efficient and for single strips will solve the normal equations by Recursive Partitioning. However for blocks of two or more strips the program still orders the photographs down each strip. This is highly inefficient for blocks with long strips. The program should be revised to automatically renumber the photographs, when required, across the strips and thus generate a normal equations matrix with minimal bandwidth.

d) An in-flight calibration of the cameras would be highly desirable. The in-flight calibration attempted under the present project with the APOLLO 10 Hasselblad camera was not successful because insufficient external information was exercised. This deficiency could be easily overcome using the extended LO-SAT program which will have the capability of solving for camera calibration parameters while exercising orbital constraints. Using vertical photography in this fashion will permit a re-determination of the lens distortion. If a series of convergent photographs is acquired, as illustrated in Figure 3.1, the principal distance and x-coordinate of the principal point can also be determined. Such a procedure is highly recommended for APOLLO 14 and would permit determination of the effect of the window and the gravity free environment on the calibration parameters.

constraints. Using vertical photography in this fashion will permit a re-determination of the lens distortion. If a series of convergent photographs is acquired, as illustrated in Figure 3.1, the principal distance and x-coordinate of the principal point can also be determined. Such a procedure is highly recommended for APOLLO 14 and would permit determination of the effect of the window and the gravity free environment on the calibration parameters.

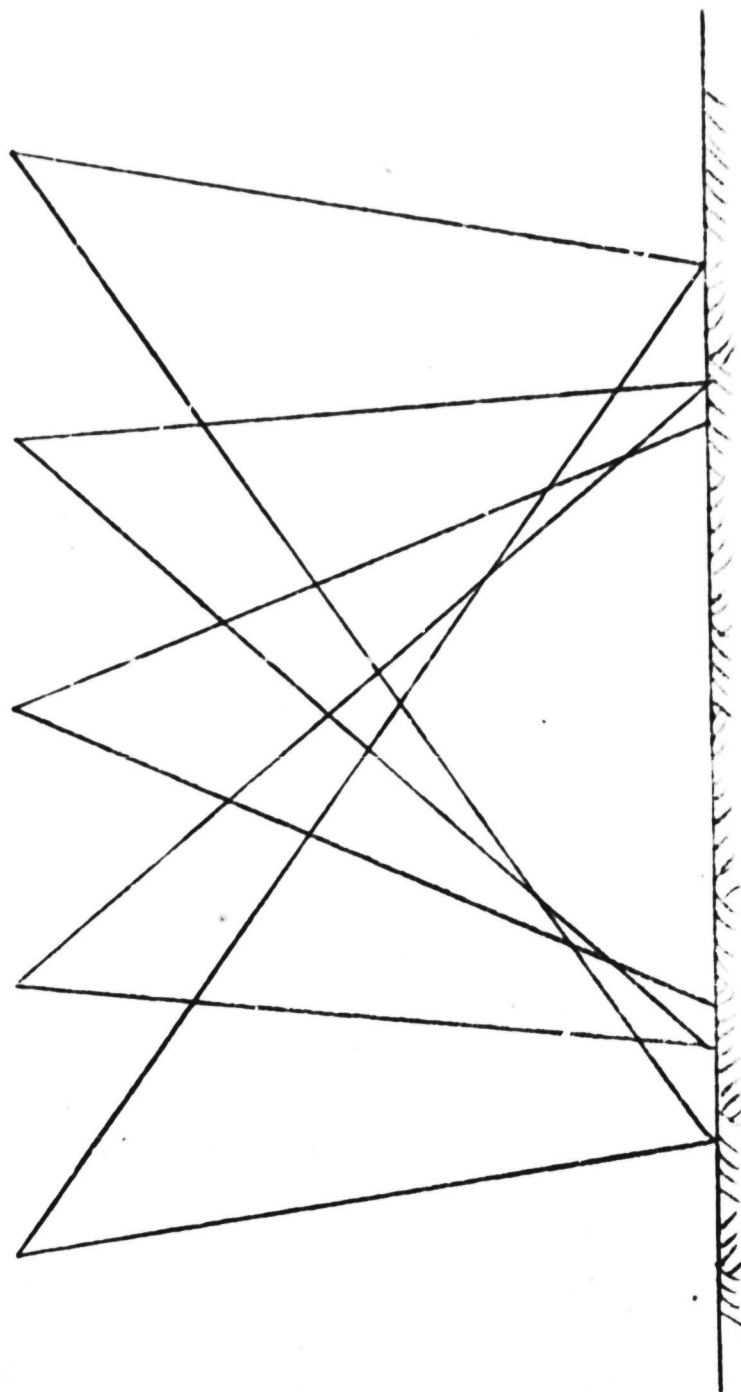


FIGURE 3.1. Ideal Convergent Photographic Configuration for In-Flight Self-Calibration of Camera.

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