Potential of Large Format Camera Photography

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ABSTRACT: This error propagation study explores the potential of large format camera (LFC) photography for photogrammetric control extension. The study is based on a series of error propagation analyses in photogrammetric triangulation of a block of 22 LFC photographs. The photographs, which have an approximate scale of 1:755,000, were taken during the October 1984 NASA shuttle mission STS–41G. Several present and future systems of data acquisition and reduction were studied. The General Integrated ANalytical Triangulation (GIANT) program was used for error propagation and block triangulation computations. The most accurate triangulation results are achievable when a system, such as the Global Positioning System (GPS), is used together with ground control in LFC photography block triangulation. Average standard deviations of coordinates of triangulated ground points can be as low as ±2.9 m in planimetry and ±5.7 m in elevation. LFC attitude information from the stellar camera array (SCA) is also useful in conjunction with GPS for areas where the ground control is not available for use in a block triangulation.

FROM THE VIEWPOINT of improved precision, resolution, area coverage, and other terrain mapping considerations, a working group within the National Aeronautical and Space Administration (NASA) recommended in 1965 the development of a large format camera with 30-cm focal length and a pair of stellar cameras for Apollo Applications Flights (Doyle, 1985). It was not until the late 1970s that Itek Corporation was given a contract to design and construct for NASA a large format camera and the attitude reference system (ARS), composed of two stellar camera arrays (SCA).

The LFC and ARS were a part of the Orbiter camera payload system deployed on space shuttle sortie missions in low Earth orbit aboard the space transportation system Orbiter vehicle. The LFC is used for making very high resolution images of the Earth's surface with great geometric fidelity. The SCA takes simultaneous photographs of two star fields at the instant of the midpoint of exposure of each LFC terrain photograph, in order to determine the precise pointing attitude of the LFC with reference to the inertial geocentric coordinate system. A precise relationship of the LFC optical axis to the two SCA optical axes is obtained by executing an inflight stellar calibration sequence of exposures.

The LFC/ARS camera system was carried into space 5 October 1984 on shuttle mission STS–41G. The orbit inclination was 57 degrees and the shuttle operated at nominal altitudes of 352, 272, and 222 km. A total of 2160 frames was exposed (Doyle, 1985).

A description of some of the LFC parameters follows:

- fully metric lens (focal length of 30.5 cm and fixed aperture of *f*/6.0);
- high resolution system with an area weighted average resolution (AWAR) of 80 line pairs per millimetre on high resolution aerial film at a constrast ratio of 2:1 (AWAR = 125 at 1,000:1 contrast);
- automatic exposure control from 1/250 to 1/30 seconds;
- rotary (between the lens) shutter;
- forward motion compensation, 0.01 to 0.045 rad/sec;
- maximum lens distortion of 20 micrometres;
- format 23 by 46 cm (longer dimension in the flight direction);
- cycling for forward overlap of 10, 60, 70, or 80 percent;
- twelve illuminated fiducials;
- backlighted 5- by 5-cm reseau grid (total of 45 reseaus);
- vacuum film flattening;
- minimum cycle time 4.3 seconds between exposures;
- film capacity of 4,000 ft, or 2,400 frames, of 9- by 18-inch photographs;
- weight of the camera system – 506 pounds (plus fully loaded magazine weight); and
- physical size of the camera – 50 by 35 by 20 inches (height, length, and width, respectively).

Compared to a typical 6-inch focal length, 9- by 9-inch format aerial mapping camera flown at the same altitude, the LFC has several advantages. First, the larger scale (double) and consequent higher resolution will enable more precise measurements because of clearer image detail and better point identification. Second, the reseau will promote higher accuracy. However, there are other considerations which must be kept in mind. First, the triangulation solution will be weaker in the cross-flight (shorter photo dimension) direction than in the along-flight (longer photo dimension) direction. Second, compared to the NOS-owned, specially constructed Wild RC-10G camera which has reseau spacing of a 1- by 1-cm grid, the LFC has reseau spacing of a 5– by 5–cm grid. This LFC reseau pattern is relatively less effective for film distortion removal.

PHOTOGRAMMETRIC CONTROL EXTENSION

One of the most promising areas in which LFC could be used is photogeodesy, or photogrammetric control extension. Table 1 lists several projects in photogrammetric control extension (Fritz, 1985), giving the normalized system precision and photo accuracy. Special attention may be given to the Casa Grande, New Mexico, 1978, and the Ada County, Idaho, 1981, projects, using the Wild RC-10G (reseau) camera, in which the most accurate results were obtained. The normalized system precisions in the two projects were reported to be 516,159* and 641,025 or photographic accuracies of 1.9 and 1.5 micrometres, respectively. The normalized system precision is defined as (scale number)/(ground accuracy in metres).

Photogeodesy projects of such high accuracies – less than 2 micrometres at photo scale and between 4 to 5 cm in the ground positions – were possible because of the well established implementation features. Some of these features involved

- optimization of the geometry of the block of photographs by providing cross flights, two-thirds forward and side overlaps, and well defined or targeted pass points and ground control points spaced at regular intervals throughout the entire project;
- determination of radial and decentering lens distortion and other camera calibration parameters using the highest degree of accuracy by means of the most precise camera calibration system available;
- calibration of comparator and grid (reseau) plate; and

*The project adhered to the following concept (Fritz 1985): ". . .one must strive to remove all systematic errors *a priori* before resorting to the application of 'self calibration' parameters into an adjustment process . . . ."

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TABLE 1. PHOTOGRAMMETRIC CONTROL EXTENSION PROJECTS

Project	Camera	Altitude (m)	Scale Factor (sf)*	Number of Photos	Forward/ Side Overlap (%)	Ground Accuracy (m)	Normalized System Precision sf/m	Photo Accuracy m/sf (μm)
Salt Lake,[1] Utah, 1964	RC-7 (glass plates)	850	8,400	9	66/66	033	254,545	3.9
Anchorage, Alaska. 1965	RC-8 (8 fiducials)	900	6,000	39	66/50-80	028	214,286	4.6
Parsons, Kansas. 1967	RC-9 (4 fiducials)	6,100	70,000	180	60/60	646	108,359	9.2
Tucumcan,[3] New Mexico. 1969	RC-9 (4 fiducials)	5,200	60,000	150	60/60	640	93,750	10.6
Rockville, Maryland. 1971	RC-8 (8 fiducials)	1,600	10,000	30	60/60	076	131,579	7.6
Casa Grande,[3] New Mexico 1978	RC-10G (Reseau)	3,600	24,000	306	66/66 CF	046	516,159	1.9
Tallahassee, Florida, 1980	RC-10G (Reseau)	2,400	15,800	146	66/66 CF	042	376,190	2.6
Ada County,[4] Idaho. 1981	RC-10G (Reseau)	3,800	25,000	434	66/66 CF	039	641,025	1.5

*sf = 1/Photographic scale

[1]Woodcock and Lampton. 1964
[2]Eichert & Eller. 1969
[3]Slama. 1978
[4]Lucas. 1984; Perry. 1984

CF = crossflights

- corrections for all known systematic errors in the data reduction process, including radial and decentering lens distortion, film deformation, and atmospheric refraction.

ERROR PROPAGATION STUDIES

To determine the potential of the LFC photography for photogrammetric control extension, a photogrammetric block triangulation of 22 LFC frames from NASA shuttle mission STS-41G was performed for several present and future systems of data acquisition and reduction (Table 2).

Figure 1 shows the layout of the 22 LFC frames block with 80 percent forward overlap over the states of Montana, South Dakota, and Nebraska, covering an overall length along the strip of about 600 miles and a width across three strips of about 200 miles. Each LFC photograph covers approximately 200 by 100 miles at an average photo scale of 1:755,000.

Figure 2 shows the location of ground control points selected for error propagation studies in the block triangulation. Figure 3 shows the location of pass points as selected for the triangulation of the 22 LFC frame block. Generally, in the case of 80 percent forward overlap LFC photographs, each photograph has

TABLE 2. LFC SYSTEMS FOR BLOCK TRIANGULATION

	CONSTRAINTS (STD. DEV.)											
	PLATE COORDS.		GROUND CONTROL			CAMERA POSITION			CAMERA ATTITUDE			
SYSTEMS	σ_x	σ_y	$\sigma_{LONG.}$	$\sigma_{LAT.}$	$\sigma_{ELEV.}$	$\sigma_{LONG.}$	$\sigma_{LAT.}$	$\sigma_{ELEV.}$	σ_ω	σ_ϕ	σ_κ	REMARKS
1. (LFC) + (GPS)	YES	YES		NONE		YES	YES	YES	NO	NO	NO	FOR "NO" CONSTRAINT
2. (LFC) + (GC)	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO	USED VERY LARGE
3. (LFC) + (GPS) + (SC)	YES	YES		NONE		YES	YES	YES	YES	YES	YES	VALUES OF STD. DEV.
4. (LFC) + (GPS) + (GC)	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	

LFC - LARGE FORMAT CAMERA
GPS - GEODETIC POSITIONING SYSTEM (CAMERA POSITION CONSTRAINTS)
SC - STELLAR CAMERA (CAMERA ATTITUDE CONSTRAINTS)
GC - GROUND CONTROL (CONFIGURATION-FIG. 2)

ASSUMPTIONS:
1. FORWARD OVERLAP = 80%
2. PLATE COORDS. MEASUREMENT PRECISION
$\sigma_x = \sigma_y = \pm 3$ MICROMETRES
3. GROUND CONTROL (GC) WHEN USED WITH (GPS) & (SC)
CONFIGURATION - FIG. 3
$\sigma_{LONG} = \sigma_{LAT.} = \sigma_{ELEV.} = \pm 0.1$m.
4. STELLAR CAMERA (SC) WHEN USED WITH (GPS):
$\sigma_\omega = \sigma_\phi = \sigma_\kappa = \pm 10$ sec. of arc.

σ_x, σ_y = STD. DEV. of MEASUREMENT OF PLATE COORDS - x, y.
$\sigma_{LONG.}$ = STD. DEV. LONGITUDE
$\sigma_{LAT.}$ = STD. DEV. LATITUDE
$\sigma_{ELEV.}$ = STD. DEV. ELEVATION
σ_ω = STD. DEV. ROLL
σ_ϕ = STD. DEV. PITCH
σ_κ = STD. DEV. YAW

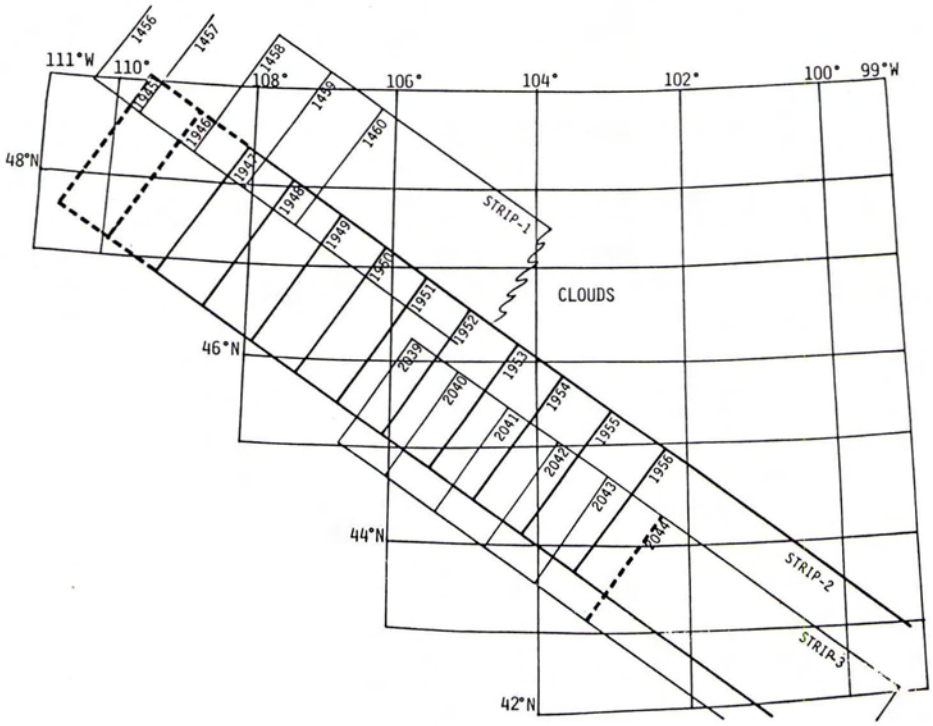

FIG. 1. LFC frame layout

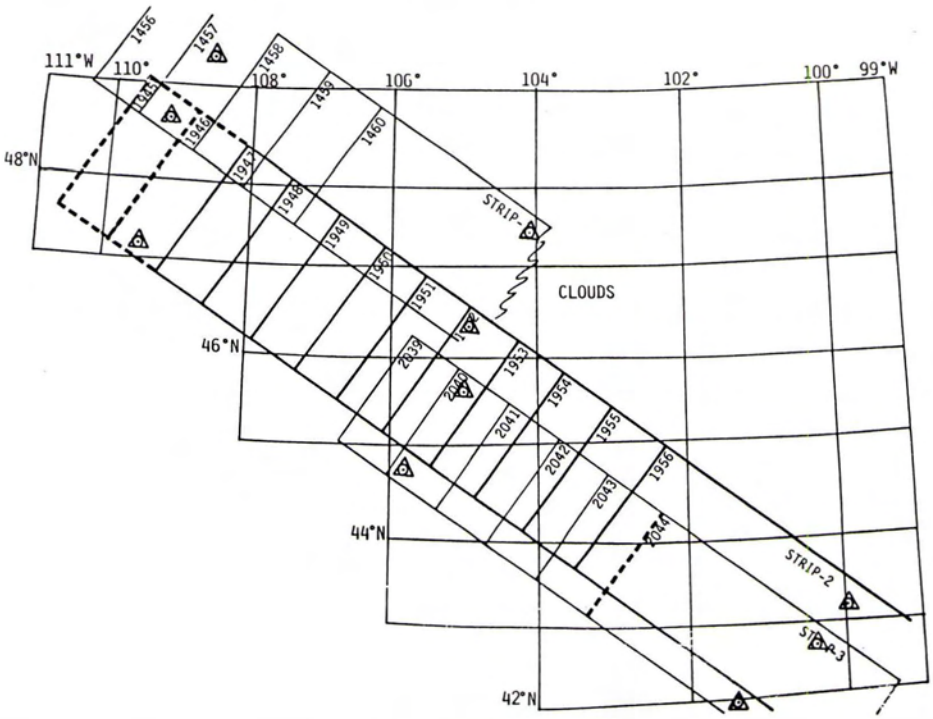

FIG. 2. Minimum ground control

at least 15 pass points, in addition to ground control points. Pass points in one strip only, and not common to other strips, will appear in two to five photographs. Pass points common to two strips will appear in four to ten photographs.

NOS stellar calibration data for the LFC was available and used in this study. The calibration is a comprehensive determination of camera constants (Fritz and Schmid, 1974).

The following data files were input to the GIANT program for executing error propagation analysis (Elassal, 1976):

CAMERA - Camera parameters

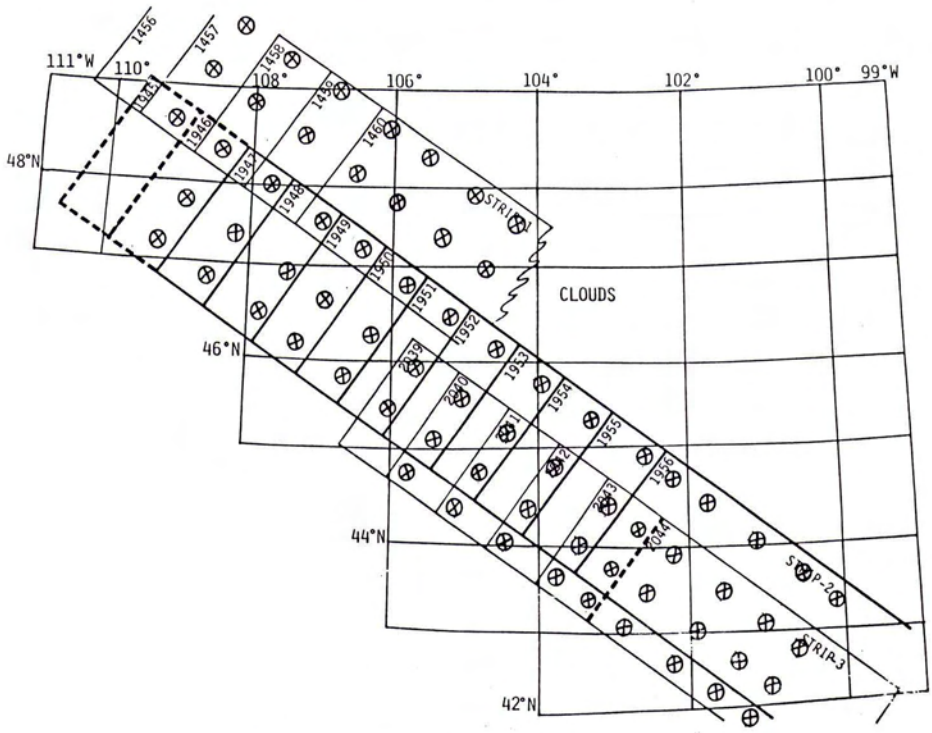

FIG. 3. Pass point locations for a block triangulation

FRAMES - Camera station parameters-position and attitude- and their standard deviations for all frames

GROUND - Positional coordinates and their standard deviations for all ground control points in the block

IMAGES - Image plate coordinates of all ground and pass points, and standard deviations of their measurement for all plates

The image plate coordinates were obtained from comparator measurements of all 12 fiducials and image points in each of the LFC photographs by means of the National Ocean Service Analytical Plotter (NOSAP). Camera station positions were approximated from the layout of the project on a map sheet showing the center of the photographs. Camera attitude was assumed for the normal (vertical) case of photography and the direction of flight. In Figure 2, minimum control was obtained from the initial block triangulation solution with NOSAP measurement data and existing ground control. Also, in order to approximate a system, constraints (standard deviations) were applied to various parameters (Table 2).

SOME PRELIMINARY INVESTIGATIONS

To investigate the potential of the LFC for photogrammetric control extension or triangulation, four present and future systems (Table 2) were identified and evaluated for optimal results. Preliminary investigations were undertaken to determine the effect on the error of determination of aerotriangulated ground points due to the factors common to all the systems. These factors are (1) errors in plate coordinate measurements (2) 80 percent versus 60 percent forward overlap and (3) errors in camera attitude determination.

Study cases for error propagation were set up for demonstrating the effect of each of the above factors by using proper parameter constraints in the solution of a block triangulation. In Figures 4, 5, and 6, the error curves show the effects in ground point positioning as a function of perturbations of the photo measurements, camera attitude, and forward overlap. respectively.

Figure 4, curve 1, shows the effect of the precision of plate coordinate measurements on the accuracy of determination of the triangulated ground points. The precision of the plate coordinate measurements was varied in the solution from ± 3 to ± 10 micrometres. All other factors, such as ground control distribution with an assumed accuracy of ± 0.1 m in ground coordinates and 80 percent forward overlap LFC photography, were kept the same for all the study cases. The variation of the accuracy of plate coordinate determination from ± 3 to ± 10 micrometres would represent a practical precision range of the measurement and data reduction systems used by various photogrammetric agencies.

As expected, the results for the determination of the triangulated points improve significantly with higher accuracy of plate coordinate measurements. In the systems study discussed in the next section, the accuracy of plate coordinate measurements is taken to be ± 3 micrometres.

Figure 5, curve 2, shows the effect of the precision of the LFC attitude angles, as determined by the stellar camera, on the determination of the triangulated ground points. The precision with which the attitude angles are determined depends on the number and distribution of the stars on the stellar photography, the number and orientation of stellar cameras relative to the LFC camera, and other factors. The precision values of an LFC attitude angle determination in the error propagation studies were considered to be ± 1, ± 3, ± 10, ± 20, and ± 30 seconds of arc. The most likely range of precision values at the present time can be expected to be from ± 5 to ± 15 seconds of arc. In the systems study, ± 10 seconds of arc is considered as the precision of LFC attitude angles.

Figure 6, curves 3 and 4, shows the effect of 80 percent and 60 percent forward overlap LFC photography, respectively, on the accuracy of determination of the triangulated ground points. Clearly, the 80 percent forward overlap gives better results.

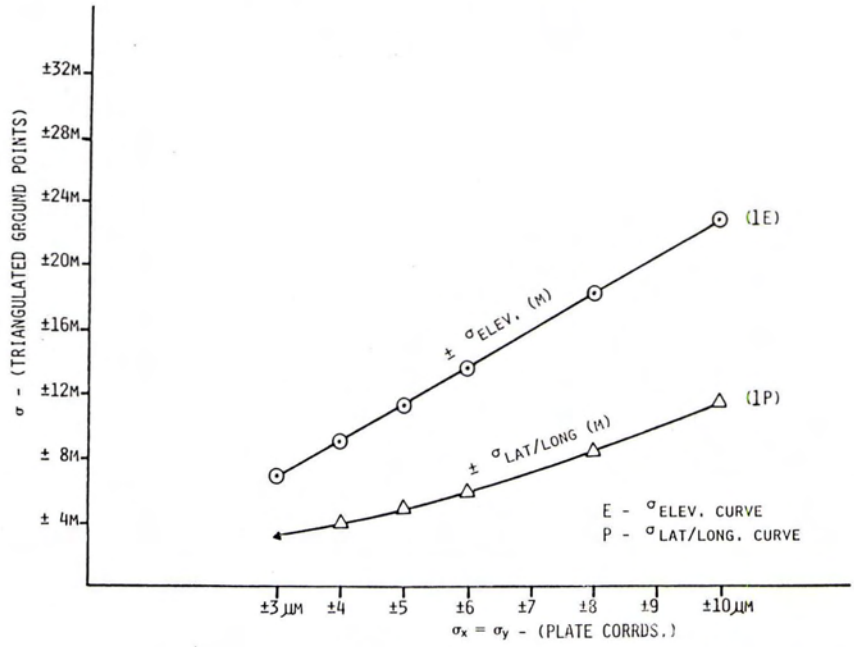

FIG. 4. Effect of plate coordinate measurements on triangulation

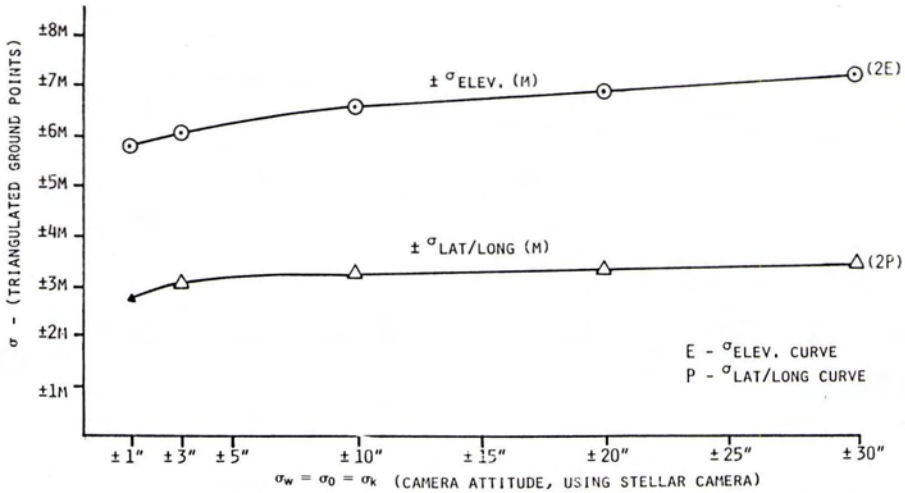

FIG. 5. Effect of constraints on camera attitude (stellar camera) on triangulation

Eighty percent forward overlap LFC photography is considered in the systems study that follows.

SYSTEMS STUDY

Figure 7, curves 4 through 7, shows the potential of each of the LFC photography systems considered for photogrammetric control extension. Results of error propagation from the GIANT program block triangulation were plotted for each of the cases studied for a system. Average standard deviations of latitude, longitude, and elevation were averaged over all the triangulated ground points for each of the cases studied. The results obtained for each of the LFC systems are plotted as error curves and are explained below.

LFC SYSTEM WITH GPS-TYPE CONSTRAINTS FOR CAMERA POSITION

Curves 4P and 4E (Figures 6 and 7) are the error curves generated for the system. These errors are plotted as average standard deviations of triangulated ground points, due to the variations in the accuracy of camera station coordinates. The system study covers the range of accuracies for the camera station coordinates which GPS is expected to produce. Considering absolute datum, GPS may be considered operational somewhere at the higher end of the accuracy range (up to ±20 m). However, in the local coordinate system, GPS may be considered operational at the lower end of the accuracy range (±1 to ±2 m). The camera position determination to ±0.1 m is included only for a theoretical consideration of future systems. With a ±2 m constraint on the camera position, the standard deviations of

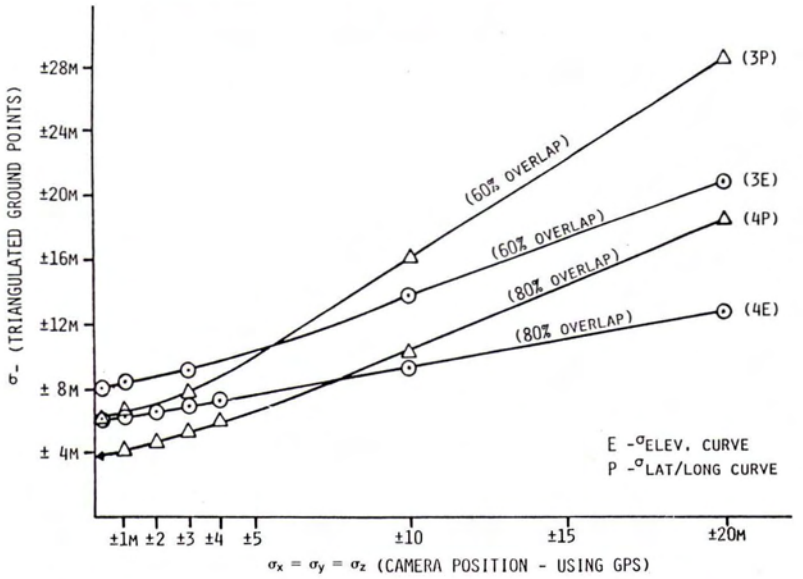

FIG. 6. Effect of 80 percent versus 60 percent longitudinal overlap on triangulation

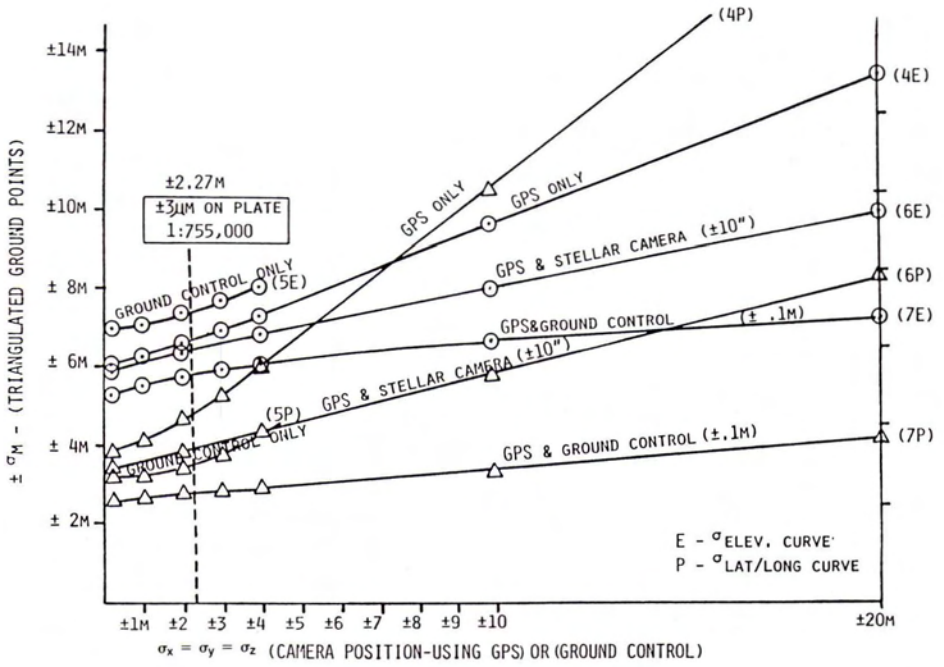

FIG. 7. Error analysis of triangulation systems

triangulated ground points is ±4.7 m in planimetry and ±6.6 m in elevation. This corresponds to ±6.2 and ±8.7 micrometres, respectively, at the photo scale.

LFC System with Ground Control

Curves 5P and 5E (figure 7) show the error trends in the accuracy of determination of triangulated ground points caused by variations in the accuracies of the ground control points (Figure 2) used in the block triangulation. In the decimetre range of accuracies of ground control, the accuracies of triangulated ground points are ±3.2 m in planimetry and ±7.0 m in elevation, which correspond to ±4 and ±9 micrometres, respectively, at photo scale. In the study cases, the range of the ground control accuracies are considered from a decimetre to ±4 m, to allow for all possible cases, including the ones in which the ground control is obtained from maps or other approximate means.

The error curves 5P and 5E show that, at the level of accuracy of ±2.3 m in the coordinates of ground control, equivalent to ±3 micrometres at photo scale, the accuracy of triangulated points is about ±3.4 m in planimetry and ±7.3 m in elevation. These values correspond to the ±4.5 and ±9.7 micrometres, respectively, at the photo scale. The significance of accuracy at ±3 micrometres at photo scale is that it represents the threshold value for the measurement accuracy of plate coordinates.

Therefore, under the conditions of the project, the best possible accuracy of triangulated points is as stated above.

LFC System with Constraints on Camera Position (GPS-Type System and Camera Attitude (SCA of the Attitude Reference System)

Curves 6P and 6E (Figure 7) show the error trends in accuracy of determination of triangulated ground points caused by variation in accuracy of the camera position (using a GPS-type system) and assuming a known accuracy (±10 seconds of arc) of camera attitude angles. The error trends show much better results than the case study in which only the camera position was constrained.

Compared to the block triangulation case with ground control (curves 5P and 5E), this case (curves 6P and 6E) is more accurate for elevation determination and about the same for planimetry. Given a camera position constraint of ±2 m, using a GPS type system and ±10 seconds of arc camera attitude from a stellar camera, the achievable accuracies are ±3.8 m in planimetry and ±6.3 m in elevation, which correspond to ±5.1 and ±8.4 micrometres, respectively, at photo scale.

LFC System with Constraints on Camera Position from a GPS-Type System and Ground Control (±0.1 m)

Curves 7P and 7E (Figure 7) show the error trends in accuracy of determination of triangulated ground points caused by variation in accuracy of the camera position, using a GPS-type system and given ground control (Figure 2) with an accuracy of ±0.1m. This system gives the most accurate results compared to the rest of the systems studied. Note that there is only a slight variation in the accuracy of triangulated ground points: ±3.5 m to ±4.7 m in planimetry and ±5.5 m to ±6.7 m in elevation, corresponding to a considerable variation in the accuracy of the camera position (GPS-type constraint) from ±1.0 m to 20.0 m. This indicates that the use of the ground control points (±0.1 m) minimizes the effect of variation in the GPS-type constraints. Overall, this system has a great potential for mapping purposes. For example, when the LFC position coordinates are known with a standard deviation of ±2.0 m, and the ground control coordinates are known with a standard deviation of better than ±1.0 m, the accuracy of triangulated ground points is ±2.9 m in planimetry and ±5.7 m in elevation. This corresponds to photo accuracies of ±3.8 and ±7.6 micrometres, respectively, or normalized system accuracies of ±1 m at a photo scale of 1:264,000 for planimetry and ±1 m at the photo scale of 1:136,000 for elevation.

NOS PRODUCTION LINE AEROTRIANGULATION RESULTS

The initial investigations of error propagation studies for the present and proposed future LFC photography systems were followed by the NOS production line aerotriangulation (Fritz and Malhotra, 1987). The error propagation study that most closely approximated the actual LFC flight parameters and solution constraints predicted average standard deviations of coordinates for triangulated points of ±5.5 m in planimetry and ±12.3 m in elevation at an average photoscale of 1:755,000. The corresponding production line aerotriangulation results produced standard deviations of ±6 m in planimetry and ±16 m in elevation. The accuracy checks on five ground control points not included in the adjustment gave standard errors of ±8.5 m in planimetry and ±15.8 m in elevation.

CONCLUSIONS

The following are some of the important findings from the error propagation study of present and future LFC photography systems which may be used in block triangulation for ground control extension:

- Plate coordinates must be measured as precisely as possible and refined to the fullest extent. All the fiducials and available reseau must be used.
- New technological advances, e.g., GPS, should be used to constrain camera position in the block triangulation solution. These GPS-type constraints provide an array of control points located at each of the camera stations.
- Whenever possible, more accurate triangulation can be provided by using available ground control along with GPS-type camera position constraints (Figure 7, curve 7) rather than ground control only.
- In the absence of ground control, the camera attitude (SCA-type) constraints should be used with the camera position (GPA-type) constraints in the block triangulation (Figure 7, curve 6).
- From among all the LFC systems studied, the LFC system with camera position (GPS-type) constraints and a few ground control points of decimetre precision gives the most accurate triangulation results (Figure 7, curve 7).

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REFERENCES

Doyle, F. J., 1985. Large format camera photography of Massachusetts, *Photogrammetric Engineering and Remote Sensing,* Vol. 51, No. 2, pp. 200–206.

Elassal, A. A., 1976. *General Integrated ANalytical Triangulation Program (GIANT),* U.S. Geological Survey Report No. W5346.

Fritz, L. W., 1985. Photogeodesy, *Vermessung Photogrammetrie Kulturtechnik,* September, special issue, pp. 306–309.

Fritz, L. W., and H. H. Schmid, 1974. Stellar calibration of orbigon lens, *Photogrammetric Engineering,* Vol. 40, No. 1, pp. 101–115.

Fritz, L. W., and R. C. Malhotra, 1987. Block aerotriangulation capabilities for large format camera photography. International Scientific Colloguium on Space Photography, International Society of Photogrammetry and Remote Sensing, Liepzig, GDR, 4–6 Sept. 13 p. (preprint).

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