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HIGH PRECISION ANALYTICAL PHOTOGRAMMETRY USING A SPECIAL RESEAU GEODETIC LENS CONE

By

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BACKGROUND

In view of the rapid developments in numerical photogrammetry over the last decade it seems only logical that serious consideration should be given to the use of the aerial photograph in geodesy. At first glance, most photogrammetrists might argue that, in reality, photogrammetry has been used to determine geodetic positions in support of stereomapping as early as the 1940's. Initially, there were the template methods, followed by extension of control using various analog devices. Finally, with the aid of the digital computer, came the so-called analytical approach. In most cases, the systems were designed to provide coordinates having sufficient accuracy to support the stereocompilation of topographic data using instruments of lower order. The main point is, the resulting coordinates were of such low order, in the eyes of the geodesist, that they were never taken seriously. That is, they were seldom maintained in any sort of data base and were very rarely recorded on the ground with permanent markers. Geodetic applications of photogrammetry imply that the accuracy of the resulting coordinates will be consistent with those that can be obtained using ground instruments and methods, and further, the point on the ground will be recoverable by reference to some sort of permanent marker. Nobody has ever denied the fact that photogrammetry could produce coordinates having millimeter accuracy. This has been demonstrated many times through the use of close range techniques. What was questioned, however, was the error propagation associated with the extension of many photographs in a block and the resultant economies of processing the abundance of data.

In the fall of 1971, Duane Brown (1971) presented a paper at the Semi-Annual Convention of the American Society of Photogrammetry (ASP) in which he discussed the potential use of analytical triangulation in place of ground surveying. In that paper he concluded that photogrammetry was "economically competitive with ground surveying in many applications calling for geodetic accuracies consistent with first and second order standards." This statement was based on a comprehensive analysis of time and costs of both systems, coupled with variations in geometry of the photogrammetric problem with their associated error propagations.

Again in the spring of 1973, at the ASP annual meeting, Duane Brown (1973) presented a paper on aerotriangulation as a supplement to ground surveying. Using an analysis of photogrammetric projects carried out in the past, he showed that "Photogrammetric densification . . . can cut overall project costs to as little as one third . . . without compromising accuracies." Finally, at the XIII Congress of The International Society for Photogrammetry, Duane Brown (1976) reported the results of a pilot project conducted for the city of Atlanta and the Department of Transportation of the state of Georgia. There he showed results that proved some of his earlier estimates both from a standpoint of cost and accuracy.

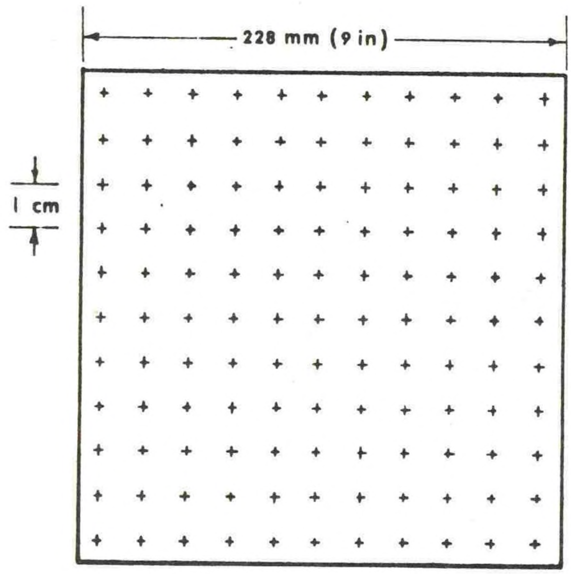
Meanwhile, at the National Ocean Survey (NOS), Dr. Hellmut Schmid recognized the need to pursue greater precision in the acquisition and reduction of analytical photogrammetric data. Before retiring as Director of the Geodetic Laboratory, he contracted with WILD, Ltd., for the purchase in 1974 of a special geodetic lens cone. This resulted in a NOS cooperative project between the Geodetic Laboratory and the Coastal Mapping Division to investigate the potential of a high precision numerical photogrammetric triangulation system for geodetic control densification. A general description of that project, coupled with a discussion of some partial results, is the subject of this paper.

PROJECT PHILOSOPHY

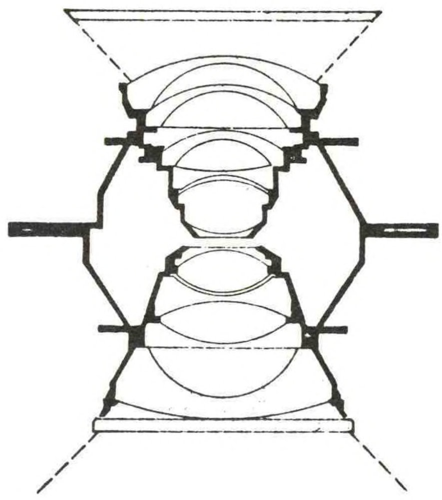
When one analyzes the results of numerical extension, it becomes readily apparent that systematic errors are the major causes of inaccuracies in the interpolation process. Recognizing this, Brown (1974) suggested two avenues of approach open for the improvement of accuracies. One is the exercise of the process of "self calibration," and the other is the application of more accurate and more comprehensive corrections prior to adjustment. At NOS we have chosen the second approach as our primary effort with the reservation that "self calibration" would be applied when and if the system warrants it.

For control of the sensor, a special WILD Universal Aviogon II lens cone was procured, having a maximum aperture of f/4, a 15-cm focal length, and a projected reseau array in the focal plane. The cone is compatible with our present WILD RC-10 camera and therefore blends well with our present system. The most important feature of the lens is that it is designed for optimal resolution at a narrow band of the visible spectrum. This can provide several advantages to the system not normally available to regular mapping. First, since the aberrations are minimized for a particular wavelength, images of targets reflecting that color will be presented with the sharpest definition. Second, errors introduced into the system through the variation of lens distortions with color will be minimized by having all targets imaged by the same wavelength. Thus, the lens can provide a tool whereby transient systematic errors of pointing in the mensuration phase will be reduced by improved definition, and persistent systematic errors due to unmodeled lens distortion will be reduced by calibration to a narrow band of light.

The projected reseau pattern in the focal plane of the new lens cone will control one error source in photogrammetry that is a major contributor to the limitation in accuracy. That error source is the unpredictable deformations that take place in aerial film after the exposure. Without a reseau, the only means of providing stability was through the use of glass plates as a transport for the photographic emulsion.



Projected Reseau



Universal Aviogon II Lens Cone with reseau f/4, f=15 cm (6 in)

Figure 1.

Obviously, glass is not only expensive but, in addition, presents problems in logistics and storage. The reseau does not prevent the film from changing dimension but, when precisely calibrated, does provide a means of predicting the changes that have taken place by measuring their relative positions during the mensuration phase.

Upon receipt of the cone in late July 1974, several studies were initiated. First, an investigation of emulsion, target size and color, aperture, shutter speed, and filters was conducted to obtain optimum image definition at various flying altitudes. Second, the cone underwent a complete stellar calibration, using techniques developed for the worldwide satellite triangulation program. The stellar calibration allows the determination of various internal perturbations of the lens that are not readily available from standard laboratory bench techniques. Finally, the cone was flown over a geodetic test field to further evaluate the internal geometry (coupled with atmospheric effects) in an operational environment.

The introduction of a reseau into the system carries with it the added burden of increased office mensuration. To compensate, NOS installed a Mann Automatic Stellar Comparator that is computer controlled to drive to any preselected position and has density centroid correlation circuitry for centering on symmetrical images such as reseau crosses or round ground targets.

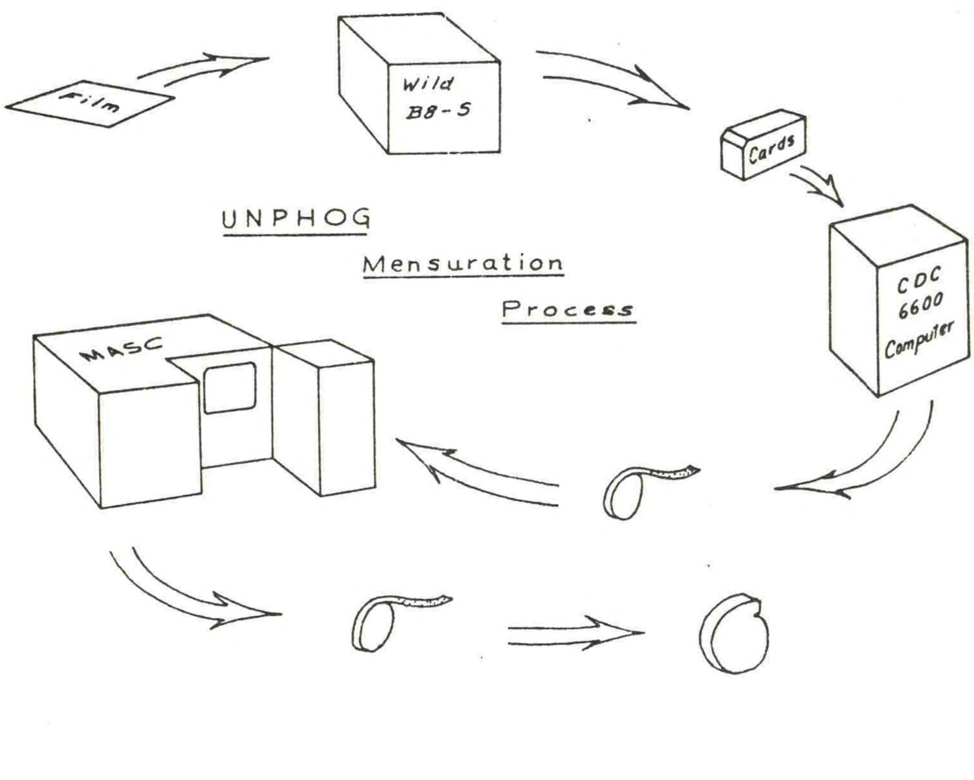


Figure 2.

The measurement scheme is depicted graphically in Figure 2. First, several key reseau crosses and all control point images are digitized using the output of the tri-axis locator on the WILD B-8S. These values, along with their identifiers, are processed in a computer to generate a punch paper tape for input to the automatic comparator. That is, after an initial orientation, the stage is automatically driven to each control point image and then sequentially to the surrounding reseau markers. Thus, the operator is left free to concentrate on final pointing only and is not burdened with locating the target or the typing in of identifiers. Also, because of the ease of measurement, the operator was asked to provide five pointings at each image, resulting in about 250 measurements per photograph. Using this method, one operator was able to measure thirteen photographs in one eight-hour shift, or roughly 3,250 pointings per day.

Although NOS presently has a new operational block triangulation program that is capable of adjusting the data, an effort is currently underway to introduce modifications for special geodetic applications. Namely, the solution is being expanded to allow for transient systematic changes to the camera. Brown and others have shown that an introduction of additional parameters into a standard block adjustment as a flexible "after treatment" or "self calibration" is effective in the reduction of systematic biases and improves the accuracy of the final coordinates. Foremost, however, will be a concerted effort to identify and initially remove the systematic errors. The block will also be modified to allow for constraints in the ground control normally encountered in geodesy, such as azimuths between points and geodetic distances. Ultimately, I would hope that the calibration and control of the internal geometry of our camera would be adequate to support the investigation of external sensors such as APR, positioning devices, etc.

A major software effort will be required to provide compatibility with the geodetic data bank presently under development at the National Geodetic Survey (NGS). The uniqueness of the NGS data bank is that the system must be capable of not only providing the user with coordinates of a particular station, but these coordinates will be accompanied by distances and azimuths to all other visible stations surrounding the point. More importantly, the statistics of these data must be available to the user. In the past the photogrammetrist has been mainly interested in those parameters of the solution that described the camera (both interior and exterior orientation), as usually a limited number of ground points have been available to be carried in the solution. This led to a scheme whereby the ground points are eliminated from the normal equations, and the solution is iterated on a reduced system of air stations only. Additionally, the photogrammetrist has been satisfied in the past to propagate the variances and covariances of the three coordinates associated with the individual ground points only. The added requirements of the geodesist will require a new look at the solution logic.

THE CASA GRANDE TEST

The Casa Grande, Arizona, test range was selected as the site for the precision analysis phase of the project. The range is about 16 miles on a side, with geodetic monuments spaced throughout at one-mile intervals. Each test point was premarked on the ground with a 30-inch plastic disk precisely centered over the monument. To provide contrast with the blaze orange marker, the disk was surrounded with an 8-foot-square tar paper background.

CASA GRANDE TEST RANGE — ARIZONA

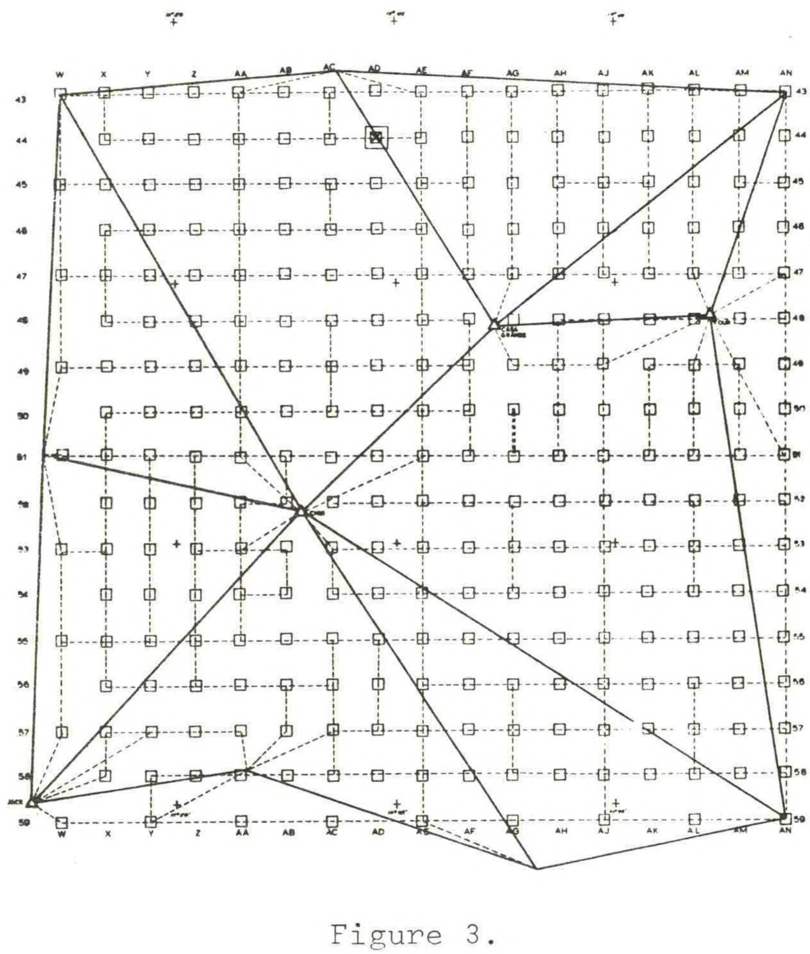


Figure 3.

To guarantee a minimum pattern of nine control points per photograph, the flight altitude above terrain was set at 12,000 feet, resulting in the image size of 50-60 μ meter.

Early numerical simulations had shown the importance of geometry to the final adjusted positions. Specifically, adjustments of fictitious data indicated that one could hope for a mean error of about 2 1/2 cm for each ground coordinate (horizontal), with 24,000 scale photography and measurement precision of about 3 μ meters. The fictitious data were generated in such a fashion that each ground point was "seen" by at least nine photographs. This can be accomplished two ways--by flying the area with photography having two-thirds overlap in both the forward and side direction, or by flying orthogonal coverage with two-thirds forward and one-third side overlap. To provide data for comparison, both were executed over the test range. That is, two-thirds forward and side overlap coverage was flown in the north-south direction, and two-thirds forward with one-third side overlap photography was flown from east to west.

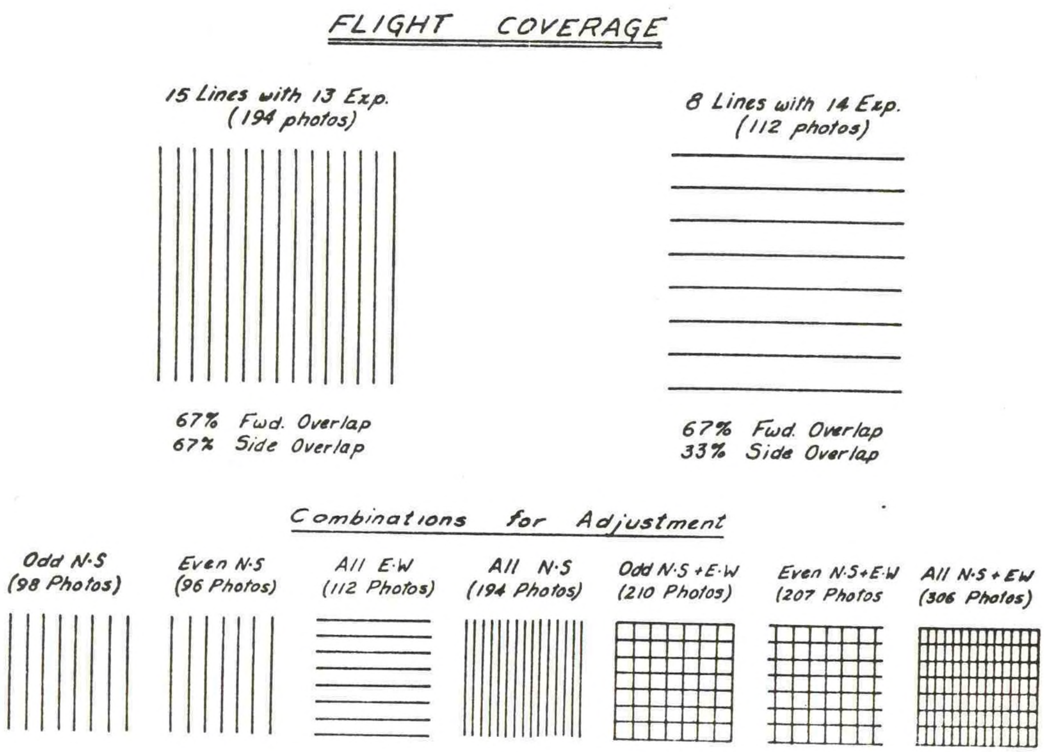


Figure 4.

The resulting coverage afforded seven different combinations for adjustment, as shown in Figure 4. The first three are considered standard type coverages, whereas the last four are special in that each ground point position is determined from at least nine directions.

A preliminary analysis of the precision for each photograph could be carried out since the test range contained geodetic positions for all targeted points. That is, measurements for each photograph were first adjusted for comparator errors, lens distortion, and dimensional change. The dimensional change was computed from a least squares fit of the measured versus the calibrated coordinates of the four reseau markers surrounding each image.

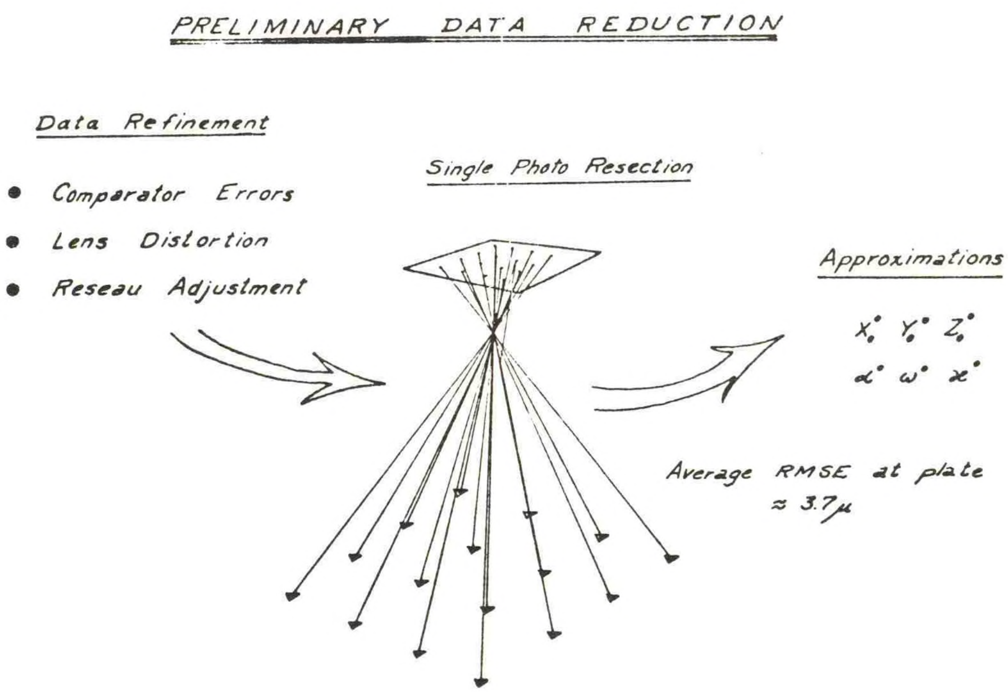


Figure 5.

These refined coordinates,* in turn, were used along with the given ground positions to compute a single photo resection which yielded approximations to the air-station position and angular orientation of the camera. More importantly, the x and y residuals of the image coordinates (when holding the ground positions to absolute) provided some statistical evidence of the inherent system precision. An average root mean square error of about 3.7 micrometers was computed from the intersection of all 306 photographs. This was an encouraging preliminary result.

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*Note: Corrections for atmospheric refraction were made iteratively as part of the single photo resection.

Having assembled the data into eight different blocks as shown in Figure 4, consideration was given to the basic control configuration. First, based on the results of error propagation studies of strips of photography by Schmid (1961) and Hallert (1958), a separation of seven airbases (eight photographs) was found to be optimum. (Hallert showed five airbases to be optimum.) As test case A then, horizontal and vertical points were placed at each corner of the area, plus half way between, with one vertical only point in the center of the figure. The mean errors of these coordinates were given as .1 mm, or absolutely known. For case B, the ground values were relaxed to 7.6 mm.

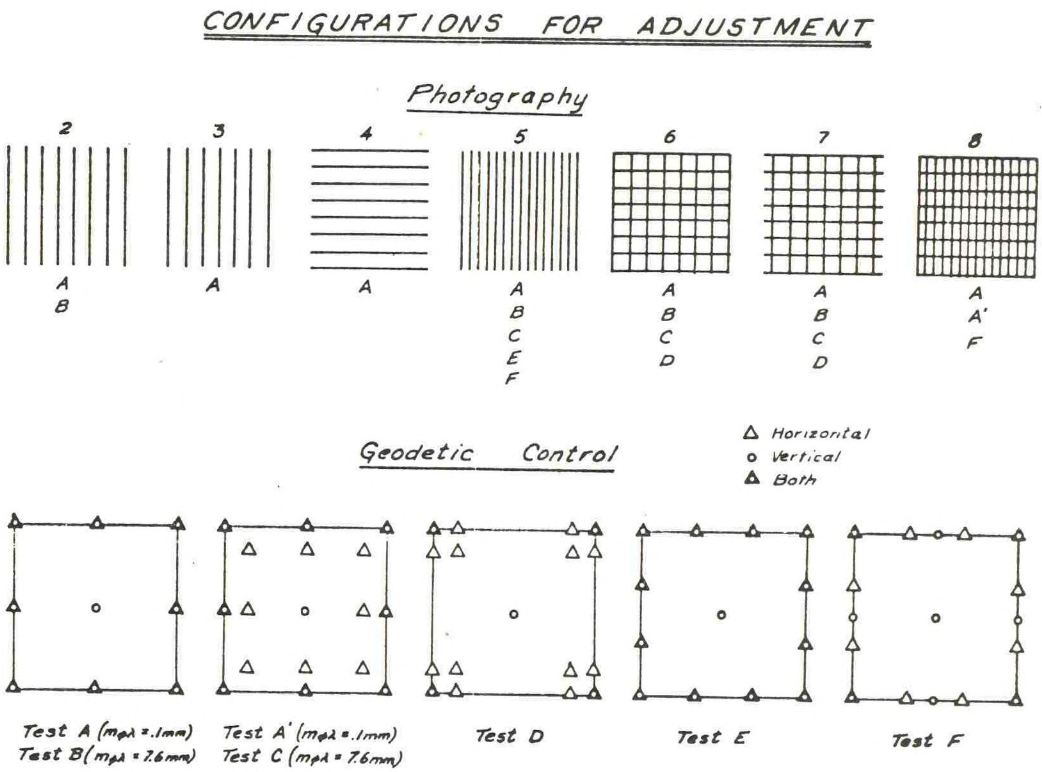


Figure 6.

Recognizing the weakness of interpolating to a single point, test cases A and C were set up to include a second horizontal control point at each location. Test case D is an extension of this concept to four points for interpolation, with an increase in the number of base distances. Finally, cases E and F introduce a reduction, with control spaced at about five airbases.

Figure 7 is a table of results of each of the cases computed. That is, the rows represent the configuration of photography, and the columns represent the control placement. In each case the upper two figures are the pooled standard errors

ADJUSTMENT RESULTS

Photo Configuration	Control Configuration: A	B	A'	C	D	E	F
2 4' 30"	.120 .129 .119 .092	.120 .129 .119 .092		m_ϕ Pooled m_λ Pooled RMSD ϕ RMSD λ			
3 3' 36"	.109 .117 .144 .148						
4 5' 50"	.099 .096 .111 .149						
5 17' 9"	.056 .057 .079 .068	.056 .057 .079 .068		.050 .051 .066 .056		.051 .051 .058 .056	.051 .051 .055 .052
6 30' 32"	.058 .058 .055 .078	.058 .058 .055 .078		.053 .052 .049 .056	.068 .068 .057 .072		
7 29' 35"	.057 .060 .059 .072	.057 .060 .059 .072		.051 .052 .056 .059	.068 .070 .108 .078		
8 88' 43"	.045 .045 .047 .063		.041 .041 .046 .047				.040 .040 .042 .049

Figure 7.

in latitude and longitude (meters). In other words, the standard deviation in latitude and longitude for each with-held point from the error propagation was squared, summed, divided by the number, and the square root of the result taken. These numbers can be looked upon as representing the statistical significance of the computed ground positions, relative to the geometry and noise level of the observed data. The lower two figures are the root mean square difference between the geodetic and photogrammetric positions. The slight rise between the upper and lower pair indicates the presence of a remaining systematic bias in the photogrammetric model or in the geodetic control.

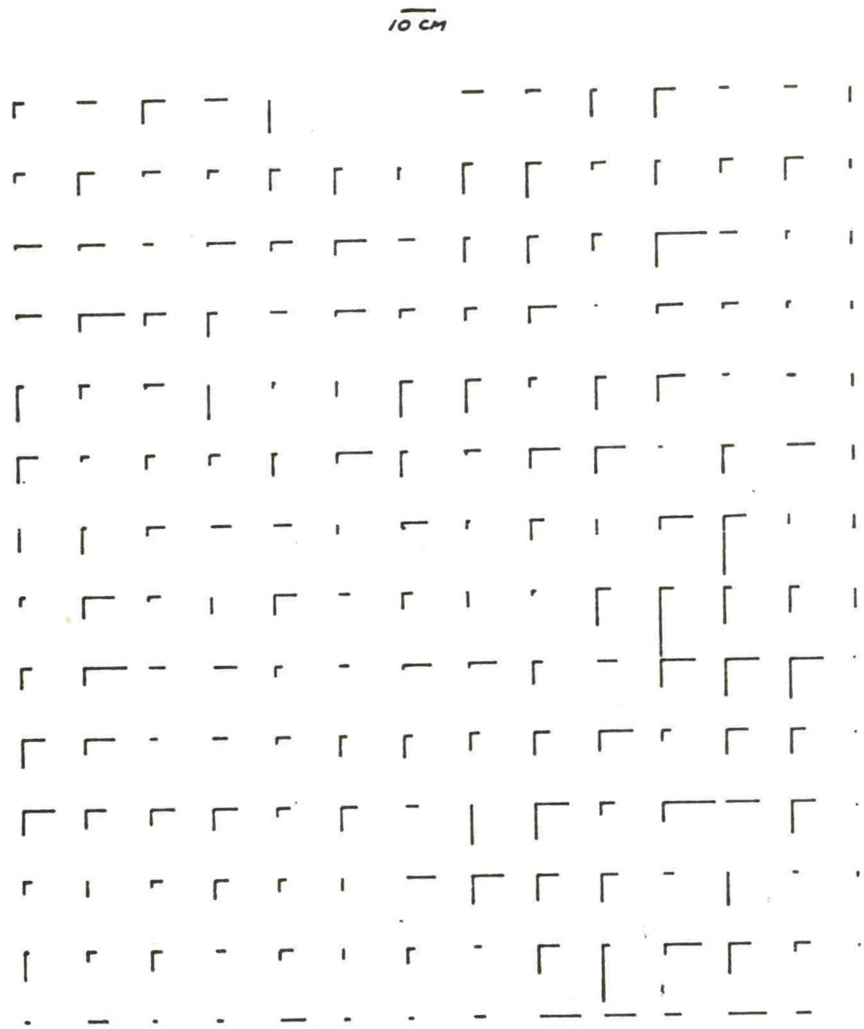
As a further analysis of the data, run 7C was looked at from a standpoint of differences in distance between adjacent points. A chord distance was computed from the given geodetic positions and compared to the same pair as determined photogrammetrically. The resulting vectors are shown in Figure 8. Since there is a high correlation between adjacent points in a photogrammetric adjustment, it was reasoned that the geometric mean of RMS difference in position of latitude and longitude should agree closely with the expected RMS difference in distance between the points. This was borne out in the comparison, as evidenced in Figure 8 by the values .057 m versus .059 m. From this result, it was decided that the geometric mean provides a reasonable single figure to describe the precision of a system, whereby one might make comparisons with other results.

By way of comparison, a search was made of the results presented to the XIII Congress of the International Society for Photogrammetry in Helsinki in 1976. These data are tabulated as the second six projects in Figure 9. The first entry is a result presented by NOS in 1969, and is included for contrast and to emphasize the increase in precision over the last decade. The last seven entries are the results of this test as keyed to Figure 7. A single asterisk indicates a reseau equipped camera, and a double asterisk shows those systems which applied "after treatment." All columns are self-explanatory, with the exception of columns six and eight. The values in column six are the geometric means of the RMS differences (meters) in latitude and longitude. Column eight is then the scale factor divided by the value in column six. This number might be likened to a normalized measure of precision of the system. That is, given a scale factor of photography, this number when applied as a divisor will produce the expected accuracy of the resulting ground control in meters. In this way, one can hope to compare results from projects with varying focal lengths and flight altitudes.

DIFFERENCES IN DISTANCE

Geodesy minus Photogrammetry

1 Mile Spacing



From Adjustment: $RMSD\varphi = .056 m$ $RMSD\lambda = .059 m$

Geometric Mean = .057 m

RMS Difference in Distance = .059 m

(Run 7C)

Figure 8.

COMPARATIVE RESULTS

Parameters

Project	Camera	Altitude (m)	Scale Factor	Number of Photos	$m_{\varphi\lambda}$	Forward /Side Overlap	$Sf/m_{\varphi\lambda}$
NOS	RC-9	6,100	70,000	180	.640	60/60	109,375
South Australia[1]	*RMK AR	2,000	12,700	48	.049	60/60	258,164
Alborg 1973[2]	C=15 cm	1,500	10,000	53	.041	65-70/25-70	243,902
Atlanta DBA[3]	*RMK 8.5/23	1,494	17,500	28	.073	60/60	** 239,726
Hordorf FGR[4]	RC 10 15/23 RMK A 30/23		6,000	868	.025	60/60 CF	** 240,000
Rheimback[5]	RMK A 15/23	1,690	11,000	69	.041	60/20 CF	** 268,292
Konigshugel[6]	RMK A 15/23	1,155	7,600		.037	60/39	** 202,829
UNPHOG 2	*RC 10 G	3,600	24,000	98	.105	66/33	229,374
UNPHOG 3	RC 10 G	3,600	24,000	96	.146	66/33	164,398
UNPHOG 4	RC 10 G	3,600	24,000	112	.129	66/33	186,619
UNPHOG 5	RC 10 G	3,600	24,000	194	.053	66/66	448,774
UNPHOG 6	RC 10 G	3,600	24,000	210	.052	66/33 CF	462,910
UNPHOG 7	RC 10 G	3,600	24,000	207	.057	66/33 CF	417,533
UNPHOG 8	RC 10 G	3,600	24,000	306	.046	66/66 CF	516,159

Figure 8.

In summary one might conclude from the results that the accuracy potential of analytic aerotriangulation, coupled with the sophisticated block adjustment technique, can be exploited for many applications, especially for mapping, cadastral and engineering purposes. Generally, resources are not available for densifying uncontrolled areas in the United States in any brief span of years using classical geodetic methods. Geodetic control must be accomplished with utmost care and is relatively slow and costly, thus making it necessary to assign priority to those areas where accurate geodetic control of a high order is needed most. The importance of the photogrammetric system lies in the fact that control, having sufficient accuracy for mapping and many engineering and cadastral applications especially, can be established rapidly and profusely and at relatively low cost.

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