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Autor: Fritz, L.W.

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dann korrekt zu $m = \hat{\sigma}_0^2/n$ und ergibt, dass M streng in K und die Wirkung von t_1 und t_2 zerlegt werden kann. Da t_1 und t_2 Datumsparameter sind, über die frei verfügt werden darf, kann M hier einfach durch $K = mK' = (\hat{\sigma}_0^2/n)I$ ersetzt werden.

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Adresse des Verfassers:
Prof. Dr.-Ing. Heinrich Ebner
Lehrstuhl für Photogrammetrie
Technische Universität München
Arcisstrasse 21, D-8000 München 2

Photogeodesy

L. W. Fritz

Photogrammetry is the science of obtaining precise measurements from photography. It provides non-contact measurement capabilities that permit significant economies for land survey when compared with traditional field methods. It further provides the advantages of a photographic data base in that all measurements may be reobserved; a photographic record of all ground point locations is permanently recorded; and, with the assist of a modern analytical stereoplotter equipped with zoom magnification capability, any new ground object may be rapidly positioned by stereomeasurement of new photography in conjunction with an existing photographic data base.

Photogeodesy for the densification of geodetic control networks is the most significant land survey capability developed in the past decade.

Photogeodesy is geodetic control densification using analytical photogrammetric block adjustment techniques. In the United States the recognized need for a national multipurpose cadastre has generated the requirement for densification of the National Geodetic Horizontal Control Network (NCR, 1980). Photogeodesy in most cases is the most economical means to provide this densification.

The constraints of photogrammetric survey with its "flying theodolite" are similar to those on a geodetic survey in that strength of figure, line-of-sight, and atmospheric refraction must be accounted for with rigor to obtain optimal accuracy.

Photogeodesy has been developed at the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration to an operational capability. To reach this state there have been many projects conducted at NOS*, each successively advancing the capability through added refinements in technique and/or instrumentation. Some of the characteristics of these efforts and the results obtained are summarized in the Table. The most noteworthy results are obviously demonstrated by the Casa Grande, New Mexico, and Ada County, Idaho, projects.

The achievement of accuracies less than 2 µm on the photograph, equivalent to 4 to 5 centimeter accuracies for ground positions within the block from 1:25,000 scale photography, is to a large account due to the influence of Dr. Hellmut Schmid from his tenure as Director of the NOS Geodetic Research and Development Laboratory. The Worldwide Satellite Triangulation Program which he directed is the prime example of his drive to continually improve photogrammetric accuracies. His insistence on the isolation of systematic errors and the implementation of means for their removal continues to pervade the NOS photogrammetric research environment to this day. This philosophy includes maintenance of a state of statistical rigor in all mensuration activities. It has instilled the concept that one must strive to remove all systematic errors "a priori" before resorting to the application of "self calibration" parameters into an adjustment process.

Development of the Worldwide Satellite Triangulation Program (Schmid, 1974) provided many of the tools and techniques required to develop photogeodesy to its present state. Camera calibration by the stellar method was employed on every exposure made for that program. It now serves as the basic, as well as most accurate, procedure for the determination of radial and decentering lens distortion and the other camera constants of cameras used for photogeodesy (Fritz & Schmid, 1974). Other studies on the determination of atmospheric refraction, comparator calibration, grid plate (reseau) calibration, film distortion, error propagation, and most significantly adjustment techniques for large systems of simultaneous equations, have also been influential on the development of photogeodesy at NOS.

In 1974 Chester Slama was requested to design, develop, and implement a block aerial triangulation project to enable NOS to densify portions of its National Horizontal Geodetic Network. This Ultraprecise Numerical Photogrammetric Geodesy (UNPHOG) project recognized the strengths and pitfalls of the earlier NOS photogeodesy efforts and a photogrammetric research team was formed to address them. Although no single individual can be credited with the total design or development of any single aspect of the photogeodesy process, the following is a summary of the general team effort conducted under the most capable technical direction of Chester Slama. Emil Homick developed the block adjustment program; Mort Keller, Bill Golder, and the author designed and tested the ground targets; Les Perry and Bill Golder designed the field procedures; the author designed the calibration and office procedures; and Chester Slama designed all planning procedures, analysis phases of the adjustments, as well as the following optimal geometry for photogeodesy.

The basic requirement for optimization of geometry is two-thirds forward and side overlap of the photography. The key design point is that geometric strength of figure is ideally provided by assuring that every passpoint and control point is targetted and appears on a minimum of nine photographs that overlap by approximately 66 percent. This means that ground targets or well defined points must be spaced at regular intervals throughout the entire project area and that every photograph contain a minimum of nine imaged

* NOS is the former U. S. Coast and Geodetic Survey.

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
Tucumcari,[2] 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	145	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 & Lampton, 1964
[2] Eichert & Eller, 1969
[3] Slama, 1978
[4] Lucas, 1984; Perry, 1984

CF = crossflights

ground targets. To insure this geometry, the flight altitude must be designed so that exactly 16 ground targets are imaged on perfectly-centered photographs. (See figure)

Other basic design requirements and characteristics of NOS photogeodesy projects include the use of:

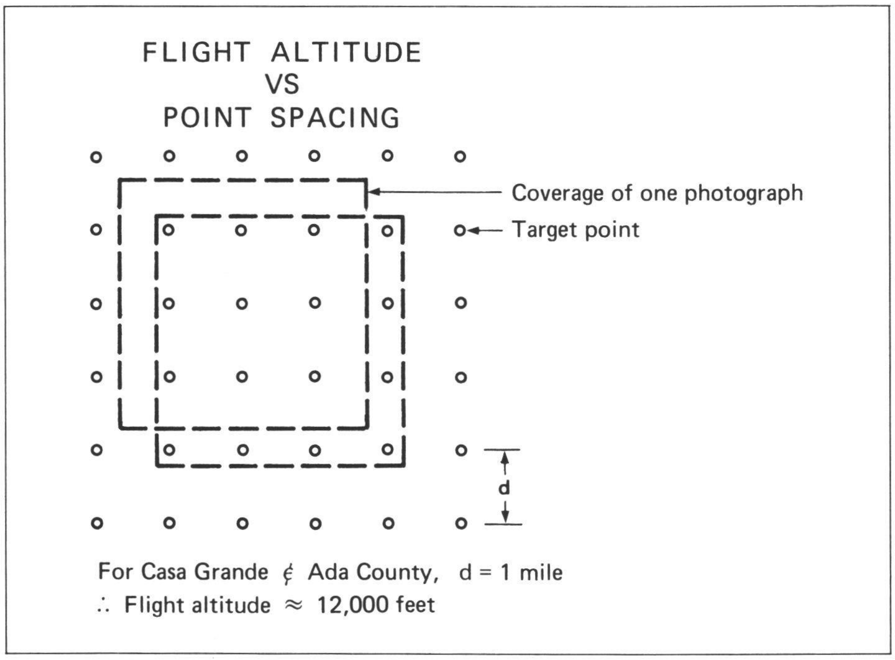
Metric Camera – wide angle; 2 cm or closer spaced reseau calibrated to <1 µm; full stellar calibration of lens cone parameters to <1 µm; plane of best focus optimized for color (wavelength) of ground targets;

Film – black-and-white original negatives used for measurement;

Targets – precisely circular with 1. 0–1.2 cm hole cut precisely in center; fluorescent; placed on a black matte background; sized to produce 40–80 µm images;

Metric Comparator – fully calibrated to provide accuracy ≦1 µm; environmentally controlled at film plane to ±1 °F and ±5 percent relative humidity; automatic prepositioning control; digital input-output;

Digitizer – backlighted; digital output; ≦0.1 mm resolution.



Planning and Field Processes

It is desirable for a block adjustment simulation to be performed during the project planning stage to determine geodetic control requirements. This adjustment will provide "a priori" estimates of the ground point accuracies to be anticipated given the geometry of the control and project configuration. The development of the Global Positioning System (GPS) promises to be a perfect complement to photogeodetic surveying. Precise GPS relative positioning can be used to establish any additional horizontal and vertical control that may be needed around the periphery of the block.

Targets must be precisely centered and secured over the ground monuments of all geodetic control, offset control, or points to be positioned. Care must be taken to observe proper overhead target clearance to permit imaging by the full camera field angle. Target offsets from control monuments must be very accurately determined. No precision is required for the placement of passpoint* targets which are not needed for monumentation but are needed for photogrammetric geometry. Simulations and projects (Brown, 1977; Slama, 1978) have shown that multiple ground targets at the geodetic control

* A passpoint is a point used to transfer geometry between adjacent photographs but is not of interest for ground location. For example, currently photogeodesy projects require placement of a single row of targets around their periphery to maintain photogrammetric geometric strength only.

point sites should produce marginal accuracy improvements in the block adjustment results by virtue of statistical redundancy. As the targets are being placed, their positions are marked on U.S. Geological Survey (USGS) quadrangle maps.
Aerial black-and-white photography is obtained at one to two stops under exposure to accentuate the high energy (fluorescent) target images. A secondary set of color photography is flown at approximately three times the scale of the black and white photographs for the purpose of positive office identification of each target. Obviously, it is preferable to take both sets of photography in a narrow timeframe (2 days or less) to detect damage or movement of targets. Also, each target must be checked and noted for centration upon prompt removal after completion of the photographic flights.

Office Processes

The original film (negatives) is indexed, carefully cut into single frames and bagged in clear plastic ziplock envelopes for cleanliness. Since it is original, delicate film, extreme care is used to prevent dimples or other crease marks which can negate the use of standard film distortion removal algorithms. The approximate nadir of each photograph is marked on the same USGS quadrangle maps that were used in the field. The target locations, photograph nadirs with nominal flight height, and projection lattice on the quadrangle map are then digitized with unique identifiers and transformed to geocentric coordinates. This process produces approximate ground coordinate and camera station position data bases that will be successively updated during the project.
On each of the photographs selected for measurement, three to five widely spaced target images and three specific reseau images are digitized. This is done on a backlighted digitizer table with each negative photograph still sealed in its clear envelope. A single-photo resection is computed for each photograph using the sampling of its digitized targets and the corresponding ground and nadir positions from the digitized quadrangles. Approximate positions and unique identifiers for all the other targets can then be generated, as can all reseau locations on each photograph, from the three specific digitized reseaus. A computer program has been prepared by Les Perry to perform these computations and to simultaneously generate on tape an optimal measurement path for the automated prepositioning capability that is available on the NOS laser comparator. The attractiveness of this technique is that the comparator operator *never* needs to provide a point identifier for reseau or target image during measurement and the most efficient measurement route has been automatically predetermined. In other words, the operator's response is isolated to concentration on pointing only, thus adding to the precision of measurement.
Photograph measurement is performed on the NOS Laser Mann Automatic Stellar Comparator (LMASC) using input paper tapes containing all measurement positions generated by the single-photo resection program. The LMASC photostage is transported by precision lead screws but measures with a Hewlett-Packard interferometric laser system designed, constructed, and installed at NOS. It is calibrated to provide measurements 0.7 µm or better accuracy. The operator can place two 23 x 23 cm photographs on the 25 x 50 cm photostage, load the input preposition tape, manually locate and measure two specified reseau marks and then make target and reseau pointings, with the comparator slewing automatically from point to point. The optimized measurement path takes the operator to each approximate ground target position and to its *nearest* six reseau marks. The operator makes multiple (five is standard) pointings on each target and on each reseau. Return to automatic slew control is initiated by depressing a foot pedal.
This semiautomated measurement process is so efficient that with two operators working four hours each per day, an average of over 2,650 pointings per day has been maintained for periods of over two months (including instrument down times). To illustrate, the Casa Grande project required measurement of 306 photographs and the Ada County project 434 photographs. An average photograph contains 12.5 ground targets (Note: nine minimum to sixteen optimum for geometric strength). Each target and its six reseau are measured five times. Thus, an average of 440 pointings per photograph, with an average of six photographs measured per day are produced, providing approximately 135,000 measurements for Casa Grande and 200,000 measurements for Ada County. These measurements are best equated to a geodetic triangulation scheme that employs an airborne wide-angle theodolite that has the capability to determine simultaneously azimuths to all points in its field of view.

Data Reduction

The digital output of the LMASC is processed through edit, coordinate refinement and strip/block adjustment programs. The edit phase is an interactive computer terminal process whereby obvious blunders and any desired data cleanup or rearrangement may be conducted. The coordinate refinement program computes the mean of multiple pointings; applies non-linear comparator calibration correction; performs a general affine linear transformation (six parameter) of each target point using a least squares fit of the six surrounding reseau points to their corresponding calibrated coordinate positions; prints residuals and statistics of the fit and then deletes all reseau points; applies lens distortion corrections from the stellar calibration; and then computes a single-photo resection using the digitized quadrangle positions. The affine transformation removes film distortion and linear comparator errors and then transforms all target points into the calibrated coordinate system of the camera. The use of the six nearest reseau provides sufficient redundancy to detect and remove reseau measurement blunders that are not normally detectable with four equally spaced reseau. The resection of the refined target points provides updated camera station parameters for each photograph.
Thus, for each photograph, the coordinate refinement program uses and then deletes the reseau points, produces refined coordinates of target points in the camera (photograph) coordinate system and provides target coordinates and updated camera station parameters in a geocentric coordinate system.
These refined photograph coordinates, updated camera station parameters and target coordinates are input to a photogrammetric block adjustment to produce accurate ground coordinates for each target point. Normal procedure is to process each strip of photography through the block adjustment program to detect blunders or weaknesses in geometry which can be improved by additional measurements, as well as to improve the approximation of the camera station exterior orientations for the full block adjustment runs. The original block adjustment program was written for processing on the CDC 6600 computer and subsequently has been converted to the UNIVAC 1100/80 computer. The block program is designed to handle 900 photographs (30 x 30) but can be readily modified to handle more or less. It automatically orders the photographs by row or column and performs internal checks for data and ordering consistency. The solution is performed by elimination of the ground points (targets), solving for the camera stations, and then for the ground points. Full statistical analyses

are provided including individual variances and covariances for all ground points and camera stations. A subsequent block adjustment program has been written by James Lucas (Lucas, 1984), that proceeds by elimination of the camera stations and solving for the ground points. This approach is more amenable computationally to determine the distance, azimuth, and elevation difference with corresponding variances and covariances for all intervisible ground points that are located within a moderate distance of each other to satisfy geodetic survey requirements.

Any targets or passpoints that have been overlooked, or rejected during coordinate refinement or block adjustment, may be recovered. Only the required point and its six nearest reseau need be measured manually, processed through the coordinate refinement program, merged with the other photograph points and reprocessed through the block adjustment. This relatively short process not only helps maintain block geometry and data set integrity, but also can be used to add new points for which precise coordinates are desired.

Results and Comments

The results presented in the Table of the Casa Grande and Ada County projects demonstrate the power of this photogrammetric process. Each of those projects was designed for U.S. section corners set at one mile spacing which in turn dictated the project photoscales. The only other design constraint of the process is a nominal spacing of geodetic control every five to seven air bases around the periphery of the project area.

Although the above describes a very efficient process, there are several improvements that we hope to achieve. Automatic pointing using a solid state detector array on the comparator, coupled with a high speed on-line parallel processor, can eliminate the need for manual operator pointings on all targetted and reseau images. The use of a backlighted reseau such as the NOS design (Perry, 1978) that was used for the NASA-ITEK Large Format Camera and is currently being fabricated at NOS for a Wild RC-10 camera will enable more optimal photograph processing. That is, photographic exposure can be optimized for both backlighted reseau and ground target images, since both are high energy light sources, whereas the current combination of shadow (projected) reseau with high energy ground targets limits the latitude of photograph exposure and development. The addition of bordering techniques and self calibration modeling to the block adjustment programs can enhance the output products. And finally, it can be foreseen that in the not too distant future new digital stereocorrelation devices used in conjunction with high resolution metric camera systems, employing forward motion compensation, will eliminate the need for artificial ground targets to be placed in passpoint locations, thus eliminating significant field efforts.

Summary

The attainment of accuracies better than two micrometers, as demonstrated in the 1978 Casa Grande project and repeated in the Ada County project, can be routinely achieved if proper care is taken "a priori" to eliminate all known sources of systematic error. The pursuit and achievement of such high accuracies can be attributed to the influence of Dr. Hellmut Schmid on the photogrammetric research efforts at NOS. The photogeodesy process described is dependent on the strength of geometric design coupled with redundant observations and measurements, and powerful adjustment routines. Its use to densify basic control while at the same time providing a photographic control data base will meet many of the initial and future needs of a national multipurpose cadastre program.

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Adresse des Verfassers:
Lawrence W. Fritz
NOAA, National Ocean Survey
6001 Executive Blvd., N/CG 233
Rockville, Maryland 20852, USA

Adaptive kleinste Quadrate Korrelation und geometrische Zusatzinformationen

A. Grün

Vorwort

Es ist das Bestreben nach Verfeinerung der photogrammetrischen Verfahren zur Punktbestimmung, welches sich als das Hauptelement aus dem beruflichen Lebenswerk Hellmut Schmids herauskristallisiert. Methoden zur Punktbestimmung und deren Verbesserung stehen auch heute noch im Zentrum wissenschaftlichen Interesses in der Photogrammetrie. Zum Aspekt der Verfeinerung der Schätzmodelle kommt in letzter Zeit zunehmend das Problem der Automatisierung der Aufnahme- und vor allem der Auswerteprozesse. Der automatischen Korrelation, oder etwas allgemeiner, der Methode des ‹Image Matching› kommt dabei eine entscheidende Bedeutung zu. Image Matching ist eine Grundfunktion der Photogrammetrie. Fast alle anderen Arbeiten bauen auf ihr auf, und ihr Ergebnis ist bestimmend für die Qualität des Ge-

Institut für Geodäsie und Photogrammetrie
ETH-Hönggerberg, CH-8093 Zürich
Separata Nr. 93