*The Historical Development of Analytical Photogrammetry**

FREDERICK J. DOYLE,
*The Autometric Corporation,
Washington, D. C.*

ABSTRACT: *The development of analytical photogrammetry started long before photography was invented, with geometrical studies of the laws of perspective and projective geometry. Application to aerial photography was initiated by S. Finsterwalder in papers published around 1900. Von Gruber analyzed the problems in depth, but because of the burdensome calculations, abandoned them in favor of the analogue instrumental approach. In the United States, Earl Church was the leading proponent of analytical photogrammetry from 1930 to 1950. The arrival of high-speed computers and the work of Hellmut Schmid and Duane Brown, directed primarily to ballistic photogrammetry have brought analytical methods to a practical procedure.*

"PERSPECTIVE is nothing else than the seeing of an object behind a sheet of glass, smooth and quite transparent, on the surface of which all the things may be marked that are behind this glass. All things transmit their images to the eye by pyramidal lines, and these pyramids are cut by the said glass. The nearer to the eye these are intersected, the smaller the image of their cause will appear."

If, in this quotation, the sheet of glass is replaced by a piece of film, and the eye is replaced by a lens, one finds a good description of a photograph. And what is its source? —the notebooks of the universal mind, Leonardo da Vinci, written about 1480. Leonardo continues to discuss the appearance of points, lines, angles, surfaces, and volumes on the picture plane. Other painters, notably Leone Alberti, Piero della Francesca, and Albrecht Dürer published studies of graphical perspective at about the same time.

The artists' theorems raised questions of momentous interest to professional mathematicians who developed a geometry of great power and generality to answer them. Its name is projective geometry and it is the fundamental basis for photogrammetry. It treats the geometrical properties which are common to all projections and to all sections of projections of a given object.

The first man to supply this insight was a self-educated architect and engineer, Gerard Desargues, who worked during the first half of the seventeenth century. However, his work and that of his contemporary, Blaise Pascal, were lost and not rediscovered until about 1800. In the meantime, most of their discoveries were remade independently by nineteenth century geometers.

The problem of space resection was first attacked in 1759 by J. H. Lambert (1), who discussed the geometrical properties of a perspective image and the procedure for finding the point in space from which the picture was made. In 1883, two Germans, R. Sturm and Guido Hauck (2) established the relation between projective geometry and photogrammetry.

However, the real foundations of analytical photogrammetry were established by Sebastian Finsterwalder in a series of papers published around the turn of the century. In 1899 he treated the photogrammetric resection of single and double points in space (3), and noted the existence of a critical cylinder for single-point resection. The principles of topographic mapping from aerial photographs were demonstrated by Finsterwalder in 1900 (4), and in 1903 he published one of the most important early papers in photogrammetry (5). This work contains the principles of modern double-image photogrammetry, including the methods of relative and absolute orientation. The analytical condition that rays must intersect is written in vector terminology, and for the case of redundant

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pairs of rays, the condition is introduced that the sum of the squares of the vectors between corresponding rays shall be a minimum. A second paper from 1903 (6) treated in detail the single-point resection in space and gave a practical example. Vector terminology was again employed in the analysis. Finsterwalder summed up his analytical investigations in a final paper in 1932 (7). There is little doubt that if Finsterwalder had possessed modern capabilities for extensive computation, the course of aerial photogrammetry might have been quite different.

Another early pioneer was Carl Pulfrich of the Zeiss works in Jena. In 1901, in a lecture before the 73rd Conference of Natural Scientists and Physicians in Hamburg, he announced the development of the first stereocomparator designed for the precise measurement of photographic image coordinates. This instrument was originally employed for the measurement of terrestrial photographs with the corresponding simple computations. Through the course of natural development, the stereocomparator evolved into Von Orel's stereoautograph for terrestrial photographs and, with the help of R. Hugershoff into the Aerokartograph for aerial photographs. In this way the pattern of instrumental photogrammetry was established and lasted until after World War II.

However Pulfrich was involved in the first application of analytical photogrammetry to a practical mapping problem (8).[1] In 1920 the Netherlands government contracted with Luftbild G.M.B.H. in Berlin, supported by Zeiss and the firm of Ilvo, for mapping several islands and a stretch of the coast line of Holland. Hugershoff applied the pyramid method using oblique photographs (9), and Luftbild applied a method derived by T. Fischer (10). The results were unsatisfactory with errors in scale up to 10 percent and in azimuth up to 7 degrees. The amount of ground control which was provided would be considered inadequate even by today's standards. Nevertheless these poor results and the introduction of the Aerokartograph in 1926 militated against any further practical application of analytical triangulation for mapping for almost thirty years.

The preceding does not mean, however, that investigations ceased. Otto Von Gruber in 1924 had another look at space resection (11). He participated in the Vacation Course in Photogrammetry at Jena and in 1930 published the lectures. These were almost immediately translated into English and fortunately are still available in reprint (12). In Chapter II, Von Gruber discussed single-point resection in space. He gives a bibliography of 28 entries on this subject, the earliest dating to 1841. However he concludes, "The calculation of resection in space, either by the direct or the differential method, is merely waste of time and is of minor practical importance." What would he say if he could be aware of current developments in analytical photogrammetry?

Von Gruber's most important contribution is the differential formulas of the projective relations between planes. These have been applied by Hallert (13) and others to investigate the propagation of errors in photogrammetry. Von Gruber's attention was diverted to the instrumental approach and he was directly responsible for the development of the Zeiss Stereoplanigraph.

In 1930, the scene shifts from Germany to the United States. Up at Syracuse University Earl Church, assistant professor of applied mathematics, operating under a Guggenheim grant for the promotion of aeronautics, began the publication of a series of bulletins on analytical photogrammetry. In the first paper, published in March 1930, he attacked again the old problem of space resection of a single photograph. However, Professor Church introduced an innovation by separating the problem into two stages: first, the determination of the air station coordinates, and second, the solution for the orientation angles. The first solution, utilizing an approximate position for the air station, and iterative approach, has remained virtually unchanged to this day, and is probably the single most used computation in analytical photogrammetry. For the orientation angles, Church used the now familiar tilt, swing, and azimuth. This choice was undoubtedly unfortunate since the swing and azimuth are indeterminate for a vertical photograph. Nevertheless Professor Church never employed any of the other angle combinations.

The first six bulletins, of which the last appeared in November 1933, were bound in a book (14) which if available today would serve as the best possible introduction to analytical photogrammetry. It includes the computation of rectification data as a basis

[1] AUTHOR'S NOTE—I am indebted to Prof. W. Schermerhorn, Dean of the International Training Centre for Aerial Survey, in Delft, for this information and reference.

for triangulation using stereocomparator measurements, the use of photogoniometer observations, and the extension of control using the four point per stereo model procedure.

A problem which interested Professor Church was what he called the determination of scale data; that is, sufficient information to compute the dimensions of objects on the photographs without reference to their absolute positions in space (15). He also turned his attention to the computation of settings for a rectifier (16).

In Bulletin No. 15 (17), Professor Church codified his derivations in the direction cosine notation. It is easy nowadays to criticize this notation as cumbersome. It uses nine long equations to represent a coordinate rotation which is now expressed in one three-letter equation in matrix notation. Nevertheless, it was extremely valuable in organizing and systematizing the work, and it guided the person operating the desk calculator through the computations with the least chance of error.

Bulletin 19 (18) was the last of the series. In it Professor Church recapitulated most of his earlier work, but now expressed in the new direction cosine terminology. He considered it his *magnum opus.*

Professor Church served as a consultant to the Mapping and Charting Research Laboratory at Ohio State University. There his work was taken up, and the first really practical applications of space resection were made. W. O. Byrd in 1951 published a technical paper (19) which represents the definitive statement of Church's work. Those fortunate enough to have a copy own one of the priceless documents in the history of the development of analytical photogrammetry in the United States.

Apart from the notation, two criticisms can be made of Professor Church's work. The first is that all of his solutions were explicit; that is, no consideration was given to the use of redundant ground control or photo images. This is certainly excusable in view of the fact that he had to perform all of his calculations on a desk computer. But it meant that a single error in identification, measurement, recording, or computing could invalidate everything that followed. The second criticism is that he never applied an error analysis to his solutions. As a consequence some of his procedures, notably the extension of control using elevations of pass-points, turned out to be geometrically weak when applied to real photography. Nevertheless, Professor Church directly or indirectly inspired most of the analytical photogrammetrists now working in the United States.

Much of the early work in photogrammetry in the United States came from a group of men working for the Tennessee Valley Authority. One of these was Ralph O. Anderson. Discouraged by the lengthy computations in Earl Church's solutions, Anderson proposed a scheme in which photo orientations would be found semigraphically, while the main scheme of control extension would be determined analytically (20). It never competed with instrumental bridging.

In the years 1950 and 1951, Everett Merritt, working at the Naval Photographic Interpretation Center in Washington, D. C., developed a series of analytical solutions for camera calibration, space resection, interior and exterior orientation, relative and absolute orientation of stereo pairs, and finally analytical control extension (21). Although the two never met, Merritt's work shows the strong influence of Church both in approach and in notation. It is, however, more complete in the variety of approaches and in the number of problems attacked. In 1958 Merritt collected his works in a published book (22) which is the only complete exposition of analytical photogrammetry that is generally available.

Dr. Hellmut Schmid came to the United States from Germany after World War II, and became director of the Ballistic Measurements Laboratory of Ballistic Research Laboratories at Aberdeen, Maryland. In a series of important publications (23, 24, 25, 26) he developed the principles of modern multi-station analytical photogrammetry. Although his investigations were directed initially to the ballistic camera operations in which several cameras may observe an event simultaneously, the application of these procedures to control extension by strips and blocks of aerial photography followed immediately. The principal features of Schmid's work are a rigorously correct least squares solution, the simultaneous solution of any number of photographs, and a complete study of error propagation. He is the first photogrammetrist to plan his solutions in anticipation of the use of high-speed electronic computers. Although his early reports were written in vector notation, he later introduced the matrix notation which is now considered almost a standard for analytical treatises.

Credit for the first operational system of analytical triangulation goes to the British. Faced with the problem of providing control for the 1:2500 resurvey of Britain, the Ordnance Survey in 1947 first tried analytical radial triangulation. This was abandoned in favor of spacial triangulation using measurements made on reseau photography with the Cambridge Stereocomparator. The procedure was first described in March 1951 by Brigadier (then Colonel) H. A. L. Shewell at the Commonwealth Survey Officer's Conference, and published in the *Photogrammetric Record* (27) in 1953. The only part of the system that is truly photogrammetric is the relative orientation of one photograph with respect to another. Subsequent transformations connect the individual stereograms together and fit them to ground control. The relative orientation formulation was published by Professor E. H. Thompson in 1959 (28). Its principal feature is the complete elimination of trigonometric functions with a consequent ease and speed of computer implementation. The complete system was described by D. W. G. Arthur in 1955 (29), and the changes since that time, which are primarily in the computer implementation, were published by the same author in 1959 (30).

While serving as a consultant to the Mapping and Charting Research Laboratory at Ohio State University, Dr. Paul Herget in 1956 developed a system of analytical control extension (31). Like Finsterwalder 53 years earlier (and of whom he was certainly unaware) Herget used vector notation and minimized the perpendicular distances between pairs of corresponding rays in order to achieve a solution. He employed an ingenious device whereby ground-control equations took the same form as relative orientation equations. Although Herget originally proposed simultaneous solution of an entire strip, the eventual implementation of his system at Ohio State developed a cantilever strip photo by photo (32).

The Herget method was taken over by Cornell University and, under contract to Engineer Research and Development Laboratories at Fort Belvoir, developed into a method capable of simultaneous solution of a block of photographs and utilizing either ground point or exposure station control (33).

The same method was also adopted by the U. S. Geological Survey and developed into what is called the "Direct Geodetic Restraint Method." The principles of this method, which permits the use of partially known ground-control points, were described by Hugh F. Dodge (34), and the formulation was published by the Geological Survey in 1959 (35).

In 1953, another formulation for analytical aerotriangulation was developed by G. H. Schut at the National Research Council in Canada. This was published in *Photogrammetria* in 1956 (36). Schut uses the condition of coplanarity of conjugate image rays. He recognizes the theoretical superiority of a simultaneous block solution, but because of computer limitations, discards it in favor of a cantilever strip extension. As in the Ordnance Survey method, Schut computes the relative orientation of each stereogram separately with subsequent connection into a strip and final adjustment of the strip coordinates to ground control.

Schut performed another valuable service to analytical photogrammetrists. In two papers (37, 38) in *Photogrammetria* he analyzed the existing methods of triangulation, reduced them to a common notation, and classified them according to three criteria:

a. Triangulation procedure
   (1) relative orientation with subsequent scaling
   (2) relative orientation with simultaneous scaling
   (3) simultaneous solution of all photographs
b. Type of condition equations
   (1) coplanarity of conjugate image rays (which is equivalent to colinearity of object, image, and lens node)
   (2) zero Y-parallax
   (3) zero distance between conjugate rays
c. Method of solving condition equations

For a comprehensive grasp of the various methods of analytical photogrammetry, these two papers are without equal.

In recent years, Duane Brown, a protege of Hellmut Schmid, working at the Air Force Missile Test Center in Florida, has made major contributions to the theory of photogrammetric triangulation and error analysis.

In 1957, Brown published the procedures employed at the Missile Test Center for orientation and triangulation of ballistic camera data (39). In this paper he demonstrated the use of the intersection conditions of stereophotogrammetry to reinforce the relative orientation of several photographs. An appendix to this report contains a formalized treatment of error propagation and relates it to the least squares adjustment. This serves as a basis for evaluating the accuracy and the significance of all photogrammetric computations.

In Report No. 43 (40) the necessary modifications are made to apply the theory to the case of aerotriangulation. The major contributions of this report are the method of treating all interior and exterior orientation parameters as either known or unknown, and the demonstration of the fact that carrying the ground coordinates of all observed points as unknowns in the solution does not increase the rank of the matrix to be inverted. The solution of the normal equations is achieved by partitioning to separate the orientation elements and the ground points.

In Report No. 46 (41), Brown described the application of his theories to the problem of geodetic triangulation using missile-borne flares. The results of an actual experiment in determining the coordinates of Bermuda are described in Report No. 54 (42). More important from the development point of view is the theory presented in the appendix of this report. Whereas previously it had been necessary to treat ground-control points and air station parameters as either completely known or completely unknown, this appendix demonstrates the method of introducing them with appropriate weights. Thus it is possible to include observed auxiliary data in an analytical aerotriangulation in a completely satisfactory fashion.

A final contribution to the theory of analytical photogrammetry was made by James B. Case. In an important paper (43) he showed how a substitution of parameters may greatly reduce the rank of the normal equation matrix, while at the same time decreasing the error accumulation by constraining the parameters to a known function. This treatment may be expected to be particularly valuable in the reduction of photographs obtained from a vehicle in ballistic trajectory or orbit.

The Geodesy, Intelligence, and Mapping Research and Development Agency (GIMRADA) at Fort Belvoir has conducted tests with both fictitious and real photography using an analytical triangulation procedure which is based on the Herget system with additional condition equations by Hugh Dodge, and a method of weighting developed by Miller at Massachusetts Institute of Technology (44). Strips of photography with subsequent adjustment to control were run on the IBM 650 and the Recomp II computer, with results which were appreciably better than obtained by instrumental triangulation of the same photography. Simultaneous solutions of blocks of as many as 30 photographs were computed on the IBM 704 in 50 minutes with acceptable accuracy.

This discussion of the development of analytical photogrammetry would not be complete without mention of the first system to become operational in a U. S. mapping organization. Credit for this achievement goes to G. C. Tewinkel and the U. S. Coast and Geodetic Survey (45). Their method is based upon the formulation of Schmid. The reduction of theory to practice with all the attendant problems of measurement, data handling, and scheduling is a formidable task, and the Coast Survey is to be congratulated on their accomplishment.

Analytical photogrammetrists have always justified their efforts on the basis that they should be able to achieve more accurate results in less time than the instrumental approach. It is gratifying to note that the Coast Survey states this to be a fact.

Any historical survey such as this must necessarily reflect the interests and the contacts of the compiler. For this reason the emphasis has been on the development of theory rather than practice or instrumentation. It must also necessarily be incomplete. This paper contains fifty references, and in its preparation almost four times that number have been consulted. The attempt has been made to include those papers that trace the main stream in the development of analytical methods with particular reference to the United States. This means that important methods developed in France (46), Italy (47, 48), Austria (49), Japan (50) and Russia (51) have been omitted. Apology is made for these and other omissions, and for any errors in interpretation of the contents of those papers which are discussed.

Analytical photogrammetry seems to be on the verge of a tremendous expansion in application, as witnessed by the fact that since 1955, five new stereocomparators have been placed on the market. It is therefore appropriate at this time to pay homage to those who have contributed step by step to its development.

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