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Analytical Stereoplotter Development

The device has evolved from an idea of Mr. Helava in 1957 to an automated version and an electronic orthophoto and hypsoline printer.

ANALYTICAL STEREOPLOTTER REVIEW

BASIC PRINCIPLES

THE ANALYTICAL Stereoplotter concept was introduced by Mr. U. V. Helava on August 30, 1957, at National Research Council (NRC), Ottawa, Canada, during an International Photogrammetric Conference. Mr. Helava's paper entitled, "New Principle for Photogrammetric Plotters" and a companion paper by Mr. W. J. M. Moore, entitled, "Considerations in the Design of an Electronic Computer for a Photogrammetric Plotting Instrument," describes in detail the basic functional organization of an Analytical Stereoplotter. Mr. Helava's description of the Analytical Plotter concept is: "The photographs are not projected using conventional optical or mechanical projection. Rather, a position is computed in which an image point appears as if an ideal central projection had taken place. In addition, deviations from the ideal case, such as those caused by lens distortions, are also derived."

This basic functional operation of the Analytical Stereoplotter as described by Mr. Helava is still being employed in the current stereoplotter systems. It is interesting to note that the Analytical Stereoplotter operation is somewhat of a reverse operation as compared to conventional analytical photogrammetric procedures. That is, the analytical stereoplotter operator selects a desired model position and then the electronic system computes the resultant photographic position. Whereas, in analytical photogrammetric procedures, the operator selects the photographic position and then the electronic system computes the resultant model position.

* Presented at the Semi-Annual Convention of the American Society of Photogrammetry, Los Angles, Calif., September 1966. Prof. Lanckton is presently teaching photogrammetry at the College of Forestry, Syracuse, N. Y.

With this analytical stereoplotter operational concept, the operator selects the *desired* model position via the hand and footwheel motions. The electronic system accepts this model data and adjusts the imagery with respect to the index marks for the operator to see the *actual* position of the floating mark. These image adjustments are based on known perspective, lens distortions, and other sys-

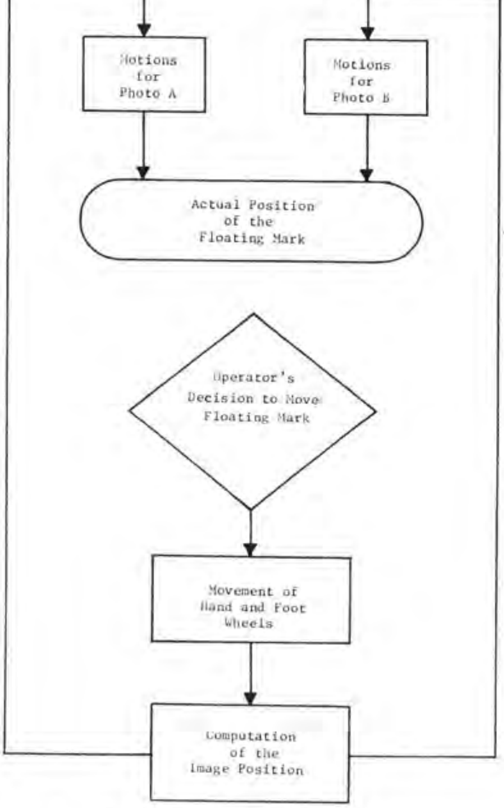

FIG. 1. Information flow diagram for the Analytical Stereoplotter

tematic conditions. Thus, the operator is able to compare the actual position of the floating mark as referenced to his perception of the stereoscopic model. This comparison can then be used for determining the direction in which the floating mark is to be moved for a new measurement. (Figure 1)

The reason for using this particular feedback loop, i.e., measuring, computing, image adjustment and operator viewing sequence, is to provide for a means of establishing an optimum man-machine interface. With this particular instrumental configuration, the man maintains control over the machine by visually sensing the differences between the desired and the actual model position of the floating mark. However, to implement this interface successfully, the differences between the desired and actual position of the floating mark must not be visually apparent to the operator. That is, the electronic system must be designed to sense the model position, compute and position the two images at a rate higher than the visual response rate of the operator.

A generally accepted visual response rate of the human eye is about 30 cycles per second. This, if the electronic system completes a cycle (sense, compute and position) at a rate greater than 30 times per second, the operator will not be aware of his controlling function within the feedback loop. That is, the operator is not conscious of his sensing and correction of the differences between the desired and actual model position of the floating mark. In the present analytical stereoplotter the electronic system completes a cycle every 1/100 of a second.

The major problem in actually implementing this concept is to compute all of the necessary mathematics involved in solving the photogrammetric problem (especially the projective equations). Mr. Helava recognized this problem in his original paper, and he discussed the advantages and disadvantages of digital and electrical analog computational systems, including the use of such analogies as mechanical, hydraulic and electronic. For an experimental system Mr. Helava decided on an electrical analog system as the most practical approach. Mr. Helava then developed the necessary photogrammetric mathematics in a form such that they were amenable for the analog electronics. The magnitude of this problem can be appreciated by noting that considerable portions of Mr. Helava's paper is devoted to describing these mathematics.

ABSTRACT: *About a decade ago, Mr. U. Helava began organizing in his mind the Analytical Stereoplotter concept. In 1957 Mr. Helava introduced this concept at the International Photogrammetric Conference on Analytical Aerotriangulation at the National Research Council at Ottawa, Canada, in a paper entitled, "New Principle for Photogrammetric Plotters." Since that first introduction by Mr. Helava many technological advances have been taken in photogrammetry and other allied sciences, especially those required to implement an Analytical Plotter. It is the purpose of this paper to elaborate on the unique characteristics of the Analytical Stereoplotter and to review its development from its original concept to the present AS-11B System. From this review it is hoped that an understanding of the basic principles employed in the Analytical Stereoplotter may be appreciated, and the influence of these principles on the current trends in photogrammetric instrumentation may be realized. With this knowledge one can then begin to postulate the future of the science of photogrammetry and its potential influence on other technologies. Included in this paper is a complete bibliography of published and unpublished papers, whose technical content is related to the Analytical Stereoplotter.*

ANALYTICAL STEREOPLOTTER DESIGN

Somewhat simultaneously two independent groups were stimulated by Mr. Helava's unique analytical stereoplotter concept. Umberto Nistri and his technical staff at Ottico Meccanica Italiana (OMI) of Rome, Italy, recognized the potential of Mr. Helava's concept and initiated a program to gain licensing rights from NRC to develop an analytical stereoplotter. Also, at about the same time, the U. S. Air Force initiated a development program to improve their charting capability at the Aeronautical Chart and Information Center. Included in this program was the development of a stereoscopic plotter based upon the Helava concept. In June of 1960, the Rome Air Development Center (RADC) contracted with the Bendix Research

FIG. 2. The first Analytical Stereoplotter AP-1.

Laboratories of Southfield, Michigan, and OMI for the development of an analytical stereoplotter.

The original analytical stereoplotter design (Figure 1), as proposed by the BENDIX-OMI team, consisted of the stereoviewer-coordinatorgraph interfaced with an incremental digital processing unit. This particular incremental system employed a magnetostrictive device as a memory, organized to use a digital differential analyzer computation technique. This system was able to handle the photogrammetric problem efficiently for two primary reasons:

(1) The delay line memory (Figure 2) offers the unique capability of being a natural recirculatory memory for about 3,000 bits every one hundredth of a second.

(2) The digital differential analyzer computing technique (commonly employed in servo controlled devices) is a simple technique to program and is very accurate in solving mathematically continuous functions.

The stereoscopic viewer proposed by the BENDIX-OMI team was a unique departure from conventional stereoplotter image translation systems. The viewer was designed to be constructed with a very light weight but stable metal. The image translation was accomplished by moving the photo carriage on one axis and a direct optical viewing system and illumination source on the orthogonal axis. This particular translation system is ideally suited for servo control, for automation, and for adaptation of other improved measuring systems.

During the next few months after the award of a contract there were several critical decisions made in the development of the analytical stereoplotter computer. Perhaps the most important of these was the incorporation of a programmable system in lieu of a fixed programmed system. This decision also initiated serious consideration for integrating a modified general purpose digital computation capability with the digital differential computation technique.

ANALYTICAL STEREOPLOTTER DEVELOPMENTS

The design considerations resulting from the short study period evolved into the first prototype analytical stereoplotter, the AP/1. The AP/1 is a rather limited system as compared to the present analytical stereoplotter systems, and can be described as a manual analytical stereoplotter for near vertical frame photography. With the AP/1, interior, relative and absolute orientation require off-line calculations and the system could only accommodate frame photography with a range of focal lengths from 1 inch to 50 inches and with a spatial orientation limitation of $\pm 9°$ for Kappa, Phi and Omega. The AP/1 exhibited a photogrammetric capability far more versatile than any of the conventional optical-mechanical projection stereoplotters because, for the first time in any stereoplotter, the AP/1 system could be programmed to correct for such variable distortions as earth curvature, atmospheric refraction, film shrinkage and lens distortions.

Soon after fabrication and checkout in August 1961, the AP/1 system underwent extensive testing and evaluation by both Air Force and contractor personnel. This test and evaluation resulted in establishment of requirements for an operational analytical stereoplotter. In September of 1962 the first operational analytical stereoplotter was installed at the Aeronautical Chart and Information Center, in St. Louis, Missouri. This first operational analytical stereoplotter was given the designation of AP-2. However, when its measuring system was improved from 10 to 5 microns it was given a new designation of AS-11A. (The nomenclature was intended to have been the AS-II/A meaning Analytical Stereoplotter Number *Two*/A. However, as a result of a typographical error, the Roman Numeral number *two* became *eleven*). The AP/2 or the AS-11A was reported on in great detail during the Second International Photogrammetric Conference at the National Research Council in Ottawa, Canada, by the following series of papers:

(1) "Analysis of Mechanical-Optical Design," Parenti, Dr. G.
(2) "Analytical Plotter," Helava, U.
(3) "General Concept of the Analytical Stereoplotter," Lesser, B.
(4) "Operational Use of the AP/2 at ACIC," Mahoney, Dr. W.

FIG. 3. The production model of the Analytical Stereoplotter AS-11A.

Since September, 1962, the AS-11/A has been performing extremely well and the two prototype AP/2's have been modified with a 5-micron measuring system so that they can now be considered to be AS-11A's. (Figure 3)

AUTOMATION OF THE ANALYTICAL STEREO-PLOTTER

In March of 1963, the Air Force set aside an AS-11/A for automation. The basic instrumental philosophy employed in the automation of the analytical stereoplotter was to design an automated system such that it would aid and assist the basic manual operation, and would not destroy or disturb the very successful manual system.

In June 1963, a contract for a design study to automate the analytical stereoplotter was awarded to the same BENDIX-OMI team that developed the analytical stereoplotter. Then in December 1963, the BENDIX-OMI team began work on fabricating the automated analytical stereoplotter.

The automation of the AS-11A (Figure 3) required development of a photographic image scanning system to convert the image density information into electrical information. The resultant electrical information from the two stereophotographs is processed in an electronic system called a correlator. The correlator processes the electrical stereo information in such a manner that it can measure the amount of cross correlation (total misalignment of two homologous images) and the X-parallax, Y-parallax, X-slope, and Y-slope existing within that image area being scanned. These five types of image data are accepted by the analytical stereoplotter's digital computer via the Digital Differential Analyzer.

The five separate types of stereo data are processed, using any one of several programmed plotting strategies. The selection of a plotting strategy to be used depends on the characteristics of both the terrain and the photography. Involved in the strategy selection are considerations of tradeoffs between speed and accuracy. This programmable system in conjunction with the basic analytical stereoplotter feed back system (i.e., man-machine interface) is the key in the automation of a stereoscopic plotting system.

The basic Analytical Stereoplotter concept of incorporating a means of sensing the differences between the *desired* and *actual* model position provides the digital system with information, measured by the image correlator, for numerically evaluating a plotting strategy. When the system is in the automated mode of operation, the programmed plotting strategy is to adapt itself according to the quality of the image being examined and according to the amount of relief contained in the image area. This adaptability of the automated system is the major reason for its success. The entire concept can be best understood by sequencing through the image correlator-digital operation and analytical stereoplotter feedback loop and examining the numerical evaluation and the logic employed in the digital system. (Figure 4)

For the purpose of describing this continu-

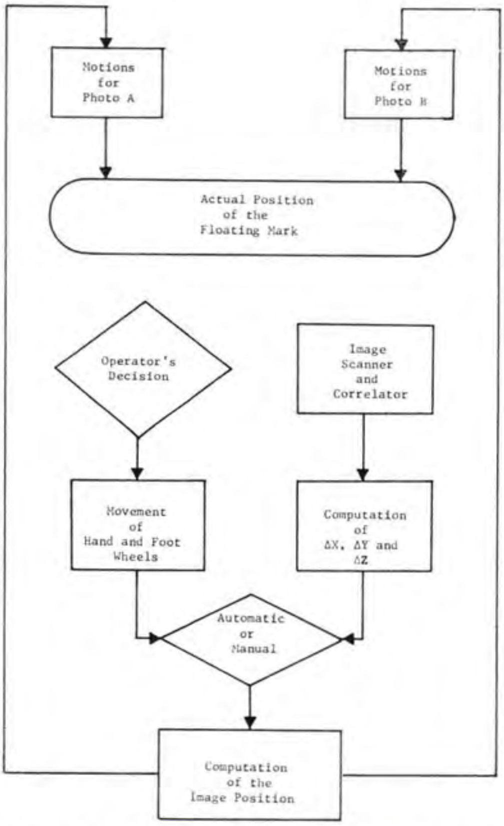

FIG. 4. Information flow diagram for the Automated Analytical Stereoplotter

ous cycle, it is best to begin with the digital system incrementing the model coordinates under program control (dX, dY and dZ). The analytical stereoplotter goes through its normal computing sequence and positions the two stereophotographs. The correlation system in the meantime has scanned the image area about the floating mark and measured the cross correlation and the amount of X-parallax, Y-parallax, X-slope and Y-slope contained in the image area. These five values are incremented into the computer where the following calculations are performed for contouring (dZ is zero):

$$-V \sin B - W \cos B = \frac{dX_m}{dt}$$

$$V \cdot \cos B - W \cdot \sin B = \frac{dY_m}{dt}$$

$\tan^{-1}\left[(S_y)/S_x)\right]$ = Terrain Slope Angle or the angle B

S_y = Y-slope

S_x = X-slope

$F_2(\overline{C})F_3(P_x^2)$ = Plotting Velocity or V

$K_{12}P_x(1/S_m)$ = Correction for X Parallax or W

$\frac{1}{\sqrt{S_y^2 + S_x^2}}$ = Slope magnitude or S_m

P_x = X-Parallax

$\overline{C}$ = Average Correlation Quality

F_2, F_3 and K_{12} are pre-determined contants of the plotting strategy.

From these equations it is evident that the actual motion of the floating mark (both direction and velocity) dX_m and dY_m are functions of

(1) Degree of Image Correlation,
(2) Magnitude of the Terrain Slope,
(3) Amount of X-parallax,

FIG. 5. The first Automated Analytical Stereoplotter AS-11B.

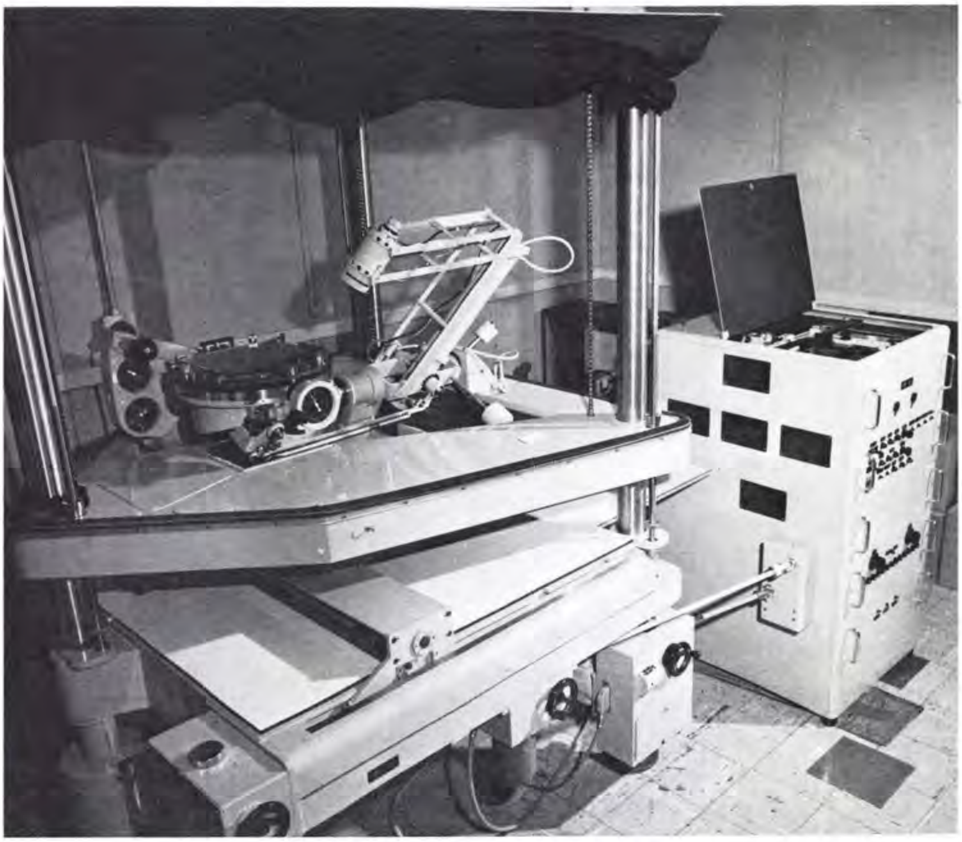

FIG. 6. The Gigas-Zeiss orthophoto printer and reading unit.

in addition to being constrained by the various predetermined constants. Therefore, every 10 milliseconds the automated Analytical Stereoplotter can adapt itself to the type of image characteristics being stereoscopically reduced. It should be noted that this machine decision-making procedure can always be altered or changed by reprogramming the computer system.

The automation of the Analytical Stereoplotter (Figure 5) has been given the detailed description of the entire system and its organization was reported by Mr. F. A. Scarano in a paper entitled, "Automated Analytical Stereoplotter (AS-11/B)" and presented at the Semi-Annual Meeting of the American Society of Photogrammetry held in September 1965 at Dayton, Ohio.

CURRENT ANALYTICAL STEREOPLOTTER SYSTEMS

The versatility of the Analytical Stereoplotter is well illustrated by its integration with the following equipments:

(1) The Gigas-Ziess Orthoprojector with the reading and storage units (Figure 6). The actual interface is with the storage unit (SG-1) in a similar manner that the unit is interfaced with the C-8 Stereoplanigraph. This type of system organization permits the off-line production of high quality orthophotos and drop line contours on the Orthoprojector and Reading Unit (LG-1).

(2) A Magnetic Tape Recording Unit for recording model coordinates at a fixed interval of time (Figure 7). Therefore, model coordinates can be recorded at a minimum of 2.5 microns when the floating mark is moved at a rate less than 0.25 mm per second, to a maximum of 100 microns when the floating mark is moved at its maximum rate. These recording rates are for rote-recording of terrain data. The Analytical Stereoplotter can be programmed to record data based upon any desirable criteria such as the rate of change of any one of the three coordinate values. (Figure 8)

(3) An electronic orthophoto and hypsocline printer to operate simultaneously with the AS-11/B in the Automatic Profile Mode (Figure 6). This system can produce an orthophoto using a profile width from 0.5 mm to 5 mm. in increments of 5 microns. The hypsocline output is similar to a standard contour chart except that the width of the actual contour line varies as a function of the slope of the terrain through which it is passing. This particular graphic presentation is unique in the representation of terrain data in graphic form and appears to have several po-

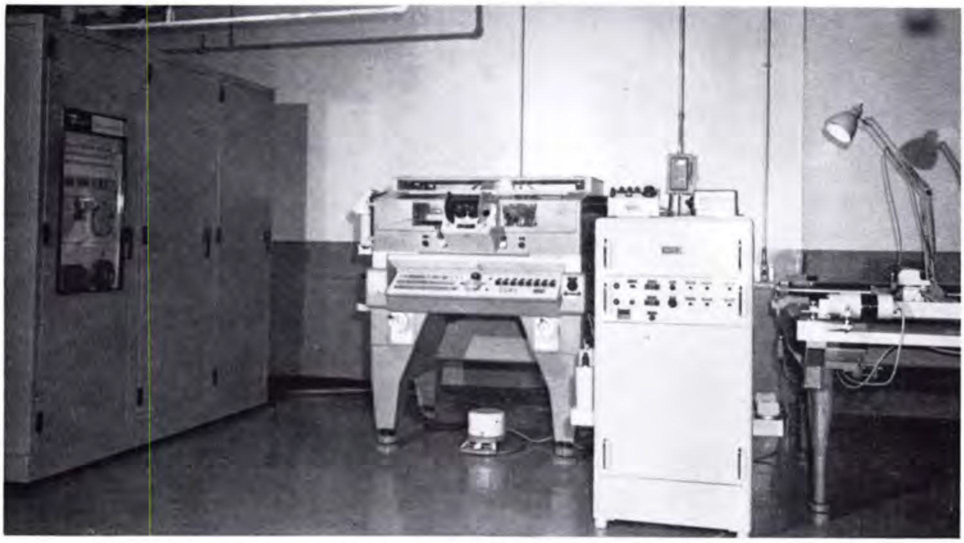

FIG. 7. An AS-11A with a Gigas-Zeiss storage unit.

tential applications. This system and its organization will be reported on by Mr. J. Edmond in a paper entitled, "The Analytical Stereoplotter and Orthophoto Printer."

FUTURE ANALYTICAL STEREOPLOTTER SYSTEMS

The next Analytical Stereoplotter will most probably employ the same basic feedback concept as formulated by Mr. Helava. The reason being that the feedback concept is ideally suited for both manual and automatic operation. However, the equipment for implementing this concept will undoubtedly be different. The present Analytical Stereoplotter magnetostrictive delay lines will probably be replaced by either a digital shift register or possibly a thin-film or a coated wire memory. The present digital differential analyzer computing technique will probably be replaced by conventional arithmetic digital processors operating in parallel with a few channels operating in a fixed mode. These hardware changes are premissed on the following technological advances that will permit the practical manufacture of special purpose systems:

(1) Advanced Integrated Circuit Technology will reduce the cost, size and power requirements for shift registers and arithmetic processor and will increase their operating speed.

(2) Advanced Thin Film Memory Concept will become a practical reality.

An obvious limiting component in the present Analytical Stereoplotter is mechanical motions of both the Viewing Unit and the Coordinatograph. This is especially true in operating in an Automatic Mode. In fact this limitation has already been encountered with

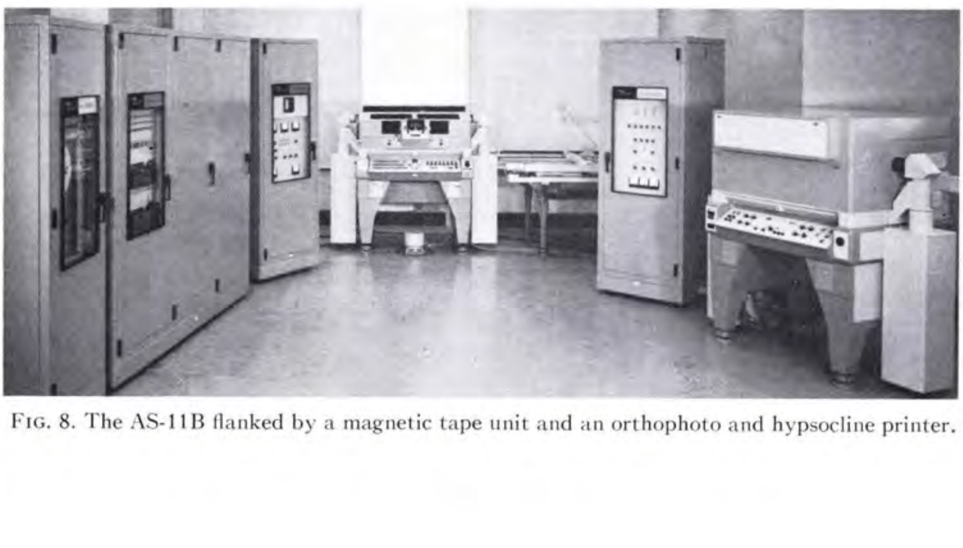

FIG. 8. The AS-11B flanked by a magnetic tape unit and an orthophoto and hypsocline printer.

the AS-11B when plotting an ideal image and terrain areas.

Mr. Helava recognized this limitation in his paper "A Fast Automatic Plotter" (PHOTOGRAMMETRIC ENGINEERING, January, 1966) and suggests several types of image transducing systems with inertial free (or nearly so) image translation systems. However, for these systems to be practically implemented the state-of-the-art must be advanced in many areas.

An alternative to the pure Analytical Stereoplotter, using the precise and accurate digital computation system, is a Hybrid Stereoplotter. The Hybrid Stereoplotter System employs a combination of analog and digital computation system to solve the photogrammetric problem. In particular, the Hybrid Stereoplotter System would employ a fixed programmed analog system to solve the projective equations and a programmable digital system to solve the variable systematic effects, such as lens distortion, film shrinkage, atmospheric refraction, earth curvature, etc. Of course, this stereoplotter concept would not have the degree of flexibility or versatility as is enjoyed with the AS-11/A and AS-11/B systems.

One of several possible configurations of a Hybrid Stereoplotter is presently being developed by RADC. This particular plotter employs a Kelsh Plotter to solve the parallax equations and a special platen containing a digitally controlled Z-, X- and Y-correction system for removing model distortions. The Z-correction is applied to the platen height independent of the Model Z-measuring system and the X- and Y-corrections are applied to the pencil-holding mechanisms independent of the floating mark. The correction system is under control of a digital computer which can be programmed to perform absolute orientation, to remove model distortions, and to calibrate the basic stereoplotter.

The basic concept of the Hybrid Stereoplotter will be reported on at a later date and the Hybrid Plotter will be described in great detail.

CONCLUSIONS

This paper attempted to describe the system principles of the Analytical Stereoplotter introduced by Mr. Helava in 1957. From these basic principles the AP-1, AP-2, AS-11A and the AS-11B Analytical Stereoplotters evolved. This successful evolution was the result of a unique feedback system and an equally unique type of instrumentation. That is, a magnetostrictive delay line organized as a digital differential analyzer integrated with a general purpose digital processor.

Except for the influence of integrated circuit technology the pure digital analytical stereoplotter will probably remain unchanged. However, the recent development of a Hybrid Stereoplotter may become competitive in manual compilation.

Automated compilation with ideal image and terrain is already being inhibited by the image translation systems. This fact, will soon force the photogrammetrist to develop a better system concept; a few which have been suggested by Mr. Helava in his paper, "A Fast Automatic Plotter."

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