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Computer Simulation of Automatic Stereoplotters

This may be useful in predicting the performance of systems under various circumstances, and to designers in predicting what would result from many types of system changes.

ABSTRACT: *The performance of an automatic stereoplotter depends on many photograph and stereoplotter characteristics, and upon the complex interactions between these characteristics. To explore and exploit the instrument potential, it is useful to employ mathematical simulation. A computer simulation has thus been prepared of the AS-11B automated analytical stereoplotter. For the simulation, the static and dynamic characteristics of each subsystem are mathematically represented. The characteristics of the input photography are also represented mathematically. The individual subsystem models are interconnected to simulate operation of the system. This simulation can be used to determine the performance boundaries of the system, to establish its applicability to specific charting assignments, and to evaluate potential design improvements.*

INTRODUCTION

THE AS-11B AUTOMATED analytical stereoplotter* automatically produces contour and profile charts from stereo photos. The performance of this instrument, in terms of both speed and accuracy, depends on the characteristics of the input photography, orientation procedures, and stereoplotter components. The interactions between these many characteristics are extremely complex, and it is therefore difficult to predict system performance for any given set of conditions, to say nothing of the case of changing conditions.

To explore and exploit the full potential of the AS-11B system, or other automated stereoplotters, it is useful to employ a mathematical model. Although performance data can be obtained from actual operation of the system, it is difficult (if not impossbile) to control the many variables as required to evaluate specific aspects of performance. Experimental evaluation is furthermore an expensive and time-consuming task, and during this time the instrument cannot be used for its intended purpose. The development of a mathematical model and the use of it in simulation of the actual system, using a general-purpose digital computer, offers a powerful tool for methodical evaluation of system capabilities and limitations.

The simulation process brings with it some valuable by-products. One of them is a better and deeper understanding of the fundamental characteristics of all the parts and processes that make up a functioning automatic stereoplotter; successful, explicit mathematical description of an ill-understood process is impossible. Another by-product is a better understanding of all existing auto-

* The AS-11B automated analytical stereoplotter has been described in a number of papers, including "Automation Modules for the AS-11A Plotter" by A. E. Whiteside and J. E. Bybee, PHOTOGRAMMETRIC ENGINEERING, April 1969. The simulation of this system was done by Bendix Research Laboratories, Southfield, Michigan, for Rome Air Development Center, U.S. Air Force, under Contract AF 30(602)-3862. The present article is essentially the same as that published under the same title in the *Bendix Technical Journal*, Vol. 1, No. 2, Summer 1968.

mated stereoplotters, as all such instruments use similar principles, differing in implementation only. The differences in implementation, however, can be rather crucial to the performance of the system; this can be demonstrated using the simulation without actually building a system. Similarly, deficiencies and troubles in an automatic system can be simulated. This is expected to provide valuable basic information for designing standard tests for automated stereoplotters.

The simulation of the AS-11B automated analytical stereoplotter can be used for the following purposes:

- To establish the accuracy and performance boundaries of the current system.
- To determine the applicability of the system to specific charting assignments.
- To define the system growth potential associated with potential design improvements, and to establish reasonable objectives to realize this potential.

These points are briefly discussed below.

The simulation can be used to determine the plotting speed and accuracy performance of the system with a wide variety of photographs. It can also be used to evaluate the performance of the system with the particular photography applicable to a specific charting assignment. Use of the simulation permits prediction of system performance without requiring availability of such photographs; use of photographs not yet available or only theoretically possible can be simulated.

Use of the simulation also facilitates comparisons between different kinds of photographs. The effect of an important difference between two types of photographs can be determined by keeping all other possible variable factors constant in two subsequent simulations. By analyzing in detail the differences obtained, the effect of the factor varied can be determined precisely. The computer simulation also facilitates the determination of system accuracy since the error in every analyzed point can be readily determined; evaluation of accuracy for the actual system requires a considerable amount of accurate control data which is seldom available.

The simulation can be used to determine the effect of potential design improvements upon the performance of the system. Evaluation of the results arising from design changes is usually easier by simulation than by actually changing the system. Furthermore, changes which are not immediately technically feasible can be simulated to determine whether significant improvements would result; a change showing significant improvement indicates an area where technical development might be attempted. Various degrees of that change can then be simulated to determine the optimum degree of change for use as the objective of system redesign or technique development.

The AS-11B system is capable of both manual or automatic plotting, and stereo model orientation can be performed in various ways. Although mathematical models could be developed for any mode of operation, models for automatic plotting and semiautomatic orientation are of prime interest. The following two sections describe the models developed for these operations. Then the next section describes a special model developed to assist correlator simulation. Subsequent sections describe variable parameters and give details of the simulation programs.

In each mathematical model, the static and dynamic characteristics of each subsystem are mathematically represented in modular form. The characteristics of the input photography are also represented mathematically. The individual subsystem models are interconnected and operated together in direct analogy to the operation of the actual system. This approach assures that basic interactions between the various subsystems are represented. Also, output data is provided which can be compared on a detailed basis to actual system operation. Changes to equipment subsystems can be readily represented by appropriately changing the corresponding subsystem models.

Automatic Plotting Model

The automatic plotting mathematical model permits simulation of the system, in the time domain, as automatic plotting takes place. The organization of the mathematical model sections concerned with the simulation of automatic plotting is presented in block diagram form in Figure 1. The basic operations of the viewer, scanner, and correlator in representing and detecting errors in parallax and terrain slope are described in mathematical models within the blocks labeled model-point calculations, point-parallax and slope error calculations, and viewer dynamics. The photomodel geometry and terrain model blocks provide inputs for these calculations. The remainder of the correlation system is represented by the video correlator block (with the image characteristics as inputs) and by the scan generator.

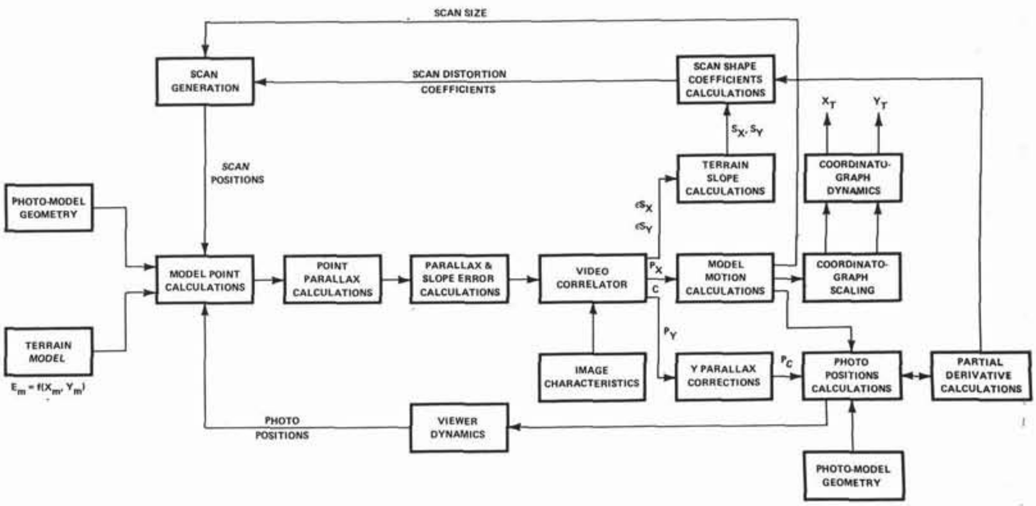

FIG. 1. Plotting simulation organization.

The calculations concerning scan shaping coefficients, terrain slope components, model motions, Y-parallax corrections, photo positions, coordinatograph scaling, and partial derivatives all represent simulations of the functions performed by the AS-11B computer.

Continuing with Figure 1, the simulation programs automatically place initial conditions on the pertinent variables and mathematical models of the system for the specified conditions of any simulation run. After initialization, the mathematical model of the model motion calculations, including the round-off and propagation characteristics of the computer, determines the model-point coordinates of the scan center, the scan size, and the coordinatograph coordinates. The model-point coordinates are then transformed to photo positions in accordance with the mathematical model and operating characteristics of the photo-position calculations. This transformation uses the photo-model geometry (which may differ from that used as input to the correlation process by virtue of the orientation simulation) and the Y-parallax correction which modifies this geometry as a function of sensed Y-parallax.

The photo positions computed are modified by the viewer dynamics to determine the true photo positions of the scan centers. The viewer dynamics are defined by second-order servo response characteristics, random servo noise sources, gear backlash characteristics, random positional errors arising from the effects of lead screws and ways and, finally, for the X-viewer carriage response, a second-order mathematical response characteristic. Deflection of the scan pattern for viewer servo error is also represented.

The scan size, as determined by the model calculations, is used by the mathematical model of the scan generator to determine, in model coordinates, 12 points about the scan center which may be used to determine existent parallax and slope error components within the scan pattern. These 12 model points are transformed to corresponding photograph positions about the scan center using the current values of the scan shaping coefficients. In the model point calculations, the 12 pairs of photo scan positions are combined with the previously computed photo positions of the scan center to determine the actual locations of the points on each photograph.

The model point calculations use the given photo-model geometry to perform transformations of the photo points, thus determining the coordinates of the 12 scan points in model space. Each of the 12 photo point pairs is used with the photo geometry to define a pair of rays in model space. Each pair of rays represents an attempt by the system to scan conjugate points on the two photographs. Using the given terrain model, the model point calculations determine the piercing point of each ray with the terrain surface in model coordinates. Iterative techniques are used to solve the system of simultaneous equations represented by the ray, atmospheric refraction, earth curvature correction, and the terrain model.

The point-parallax calculations determine the existent parallax components at each of the twelve points of concern by taking signed differences in the X_m and in the Y_m coordinates of each pair of terrain piercing points. The parallax and slope error calculations use the point-parallax components computed for the 12 scan points. The parallax components at the proper four model points are used to determine the existent X- and Y-parallaxes within the scan pattern. The existent slope error components are determined using the X-parallax components at the other eight model points.

The video correlator and image characteristics modify the existent parallax and slope error components in keeping with the characteristics of the correlation process and the photograph images. In addition, the correlation signal is derived as a function of these characteristics and of the parallaxes and slope errors. A relatively large number of correlator and image characteristic parameters are associated with this section of the simulation model to allow a wide range of video correlator and image characteristics to be investigated.

In closing the simulation loop, the outputs of the video correlator serve as inputs to the model motion calculations and other computer functions as shown in Figure 1. Each of the simulated computer functions utilizes the same mathematical models as are used in the corresponding functions of the physical equipment. In addition, cycle times, round-offs, and function limiting are simulated to the degree necessary to realistically characterize the operation of the AS-11B computer and its program.

The closed loop operation of the simulation model as described in the preceding paragraphs is repeated for each increment of time. Time increments are used which correspond to the computer program cycle time, namely 0.01 second.

Orientation Procedures Model

The plotting accuracy obtainable in a stereoplotter depends on the quality of the stereomodel orientation. The orientation quality is an input to the automatic plotting mathematical model discussed in the previous section. The orientation quality depends on the orientation procedures used and on the photograph position and measurement errors in the points used for orientation.

The functional organization of the mathematical model sections used to simulate relative and absolute orientation procedures is presented in the block diagram of Figure 2. First, photo error grids are calculated to represent random photograph image displacements.

Each photo is divided into a grid of squares two centimeters on a side. For each grid inter-

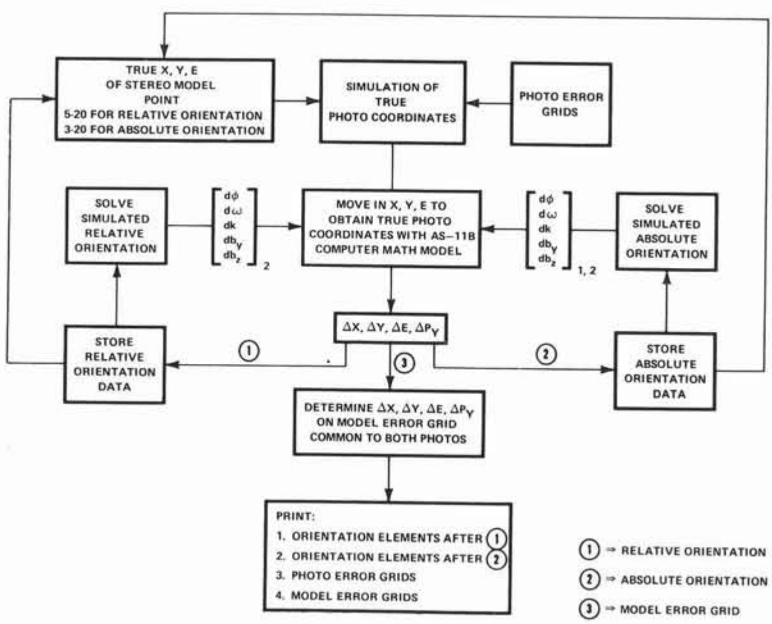

Fig. 2. Organization of simulation of orientation procedures.

section, the applicable *rms* errors σ_x' and σ_y' are computed from the x, y coordinates, the photo geometry, and the known correlated error causes. Next, a random number is drawn from a normal distribution and scaled by σ_x' to represent the X-error, Δx, at the grid point. A similar procedure for y gives a value of Δy. This procedure is repeated for each grid intersection of each photo and the results are stored as two tables of Δx, Δy, versus x, y.

The procedures for handling relative orientation parallax points and absolute orientation control points are similar in concept and will be discussed together. In both instances, a given model point is transformed to corresponding true photo coordinates using an exact model-to-photo transformation and precise corrections, including the photo error grid data. The same model point is then transformed to photo coordinates using the model-to-photo transformation of the AS-11B computer. In general, the photo coordinates obtained from the AS-11B computer will differ slightly from those obtained from the exact transformation and it is necessary to modify the model point coordinates of the AS-11B computer to attain correspondence of photo coordinate outputs. The model point inputs to the AS-11B computer are modified by means of partial fractions and the loop is iterated until the photo coordinate outputs agree to within one round-off interval of the AS-11B computer.

After the requisite convergence of photo coordinates for a point, the pertinent data is stored and the entire process is repeated for a new model point. The relative orientation simulation may have from 5 to 20 model points, whereas the absolute orientation simulation may have from 3 to 20 model points.

After convergence of photo coordinates for all of the model points of interest during the relative orientation simulation, modified orientation elements for photograph two are determined by means of a least-squares solution of the observation equations. These modified orientation elements are then used in the absolute orientation simulation. After convergence of all absolute orientation points, the orientation elements of both photographs are modified to scale and level the model in accordance with the standard techniques of the AS-11B system.

On completion of the simulation of relative and absolute orientation an error grid is calculated over the model area. This error grid represents model errors in model coordinates and is common to both photographs. These model errors are determined as signed differences of model coordinates after convergence of photo coordinates between the exact model-to-photo transformation and the actual model-to-photo transformation of the AS-11B computer using the final orientation elements. It should be noted that the orientation elements of the exact transformation remain unchanged during the simulation, whereas the elements used in the AS-11B computer transformation change after relative orientation and again after absolute orientation.

Special Correlator Model

For determining the validity of the mathematical model for the entire system, it is useful to verify the simulation in segments by a comparison with the response of the actual system. This is especially important for the correlator section of the automated stereoplotter system, for which it is particularly difficult to develop adequate mathematical models. The general difficulty in validating the correlator mathematical model is in separating scanner and correlator effects from photographic image characteristics, which are also complex and difficult to model mathematically with high precision. One way to do this is to use test photographs having carefully controlled (or measured) image characteristics. The image characteristics must be relatively simple for adequate mathematical representation. A set of test plates suitable for this purpose was prepared for the Air Force by Gurley Engineering Instruments of Troy, New York. These test plates have bar targets ranging from 10 to 150 line pairs per millimeter. Each bar target is printed with nine different background densities and nine different contrast ratios.

To aid in validating the mathematical model of the correlation section of the system, a mathematical model of the correlator response to the Gurley test targets has been prepared. This mathematical model includes a representation of the test target image characteristics and a corresponding representation of the video correlator. The image characteristics of bar targets with arbitrary spatial frequency, density, and contrast ratio are modeled and supplied to the video correlator. The video correlator X-parallax error and correlation quality outputs are modeled for arbitrary scan size and actual X-parallax error. Other features of the video correlator model are similar to the video correlator section of the automatic plotting mathematical model discussed in a previous section.

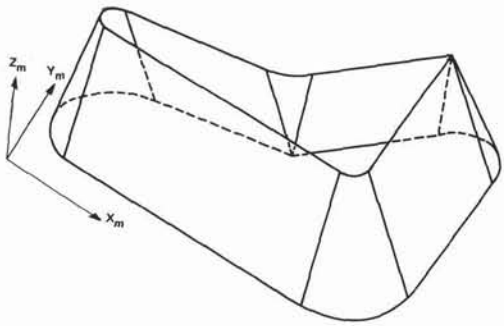

FIG. 3. Terrain model-contouring, perspective view.

VARIABLE PARAMETERS

Variable parameters are used in the simulation programs to represent the characteristics of the photographs and the automated plotter system. A large number of such parameters are included in the current simulation programs; the total is in excess of 370 parameters. The following paragraphs describe briefly the function and ranges of major variable parameters used in the simulation.

For the photographs, the orientation elements and the focal length for each photograph are parameters. The various constants associated with earth curvature, atmospheric refraction, relative vehicle motion (panoramic photography), lens distortion, and film shrinkage are also parameters. The true photo-to-model geometry used in the calculation of parallax at discrete points and the system model-to-photo geometry used in calculating photo positions may be different.

The contouring terrain model is shown in perspective view in Figure 3. Basically, this model consists of four right circular cones, one of which is inverted, joined by four tangent planes. Parameters specify the cone radii and the slopes of the plane and conic surfaces. The profiling model consists of a series of parallel cylinders joined by tangent planes. The sizes of the cylinders, the inclination angles of the connecting planes, and the rotation of the entire surface are defined by variable parameters.

For the photograph image detail, parameters are provided for the spatial frequency range of the imagery, film emulsion characteristics, average photo density, and image noise. For the scanner and correlator, parameters are provided for CRT spot size, lens aperture and point spread, frequency range of the video amplifier, correlator offsets, correlator output noise, correlator smoothing times, measurement channel gains, and maximum scan size.

Optical, mechanical, and electrical system characteristics are represented by a variety of parameters. The four viewer and three coordinatograph servo positioning subsystems are each represented by parameters for servo dynamic response, electrical servo noise, gear backlash, lead screw and ways errors, and mechanical dynamic response.

For the computer and its programs, parameters are provided for program gains and constants, computation delays, function range limits, and change rate limits. Computation round-off errors are not presently represented by parameters but correct values are programmed and could be changed if desired. Certain simulation initial conditions, modes, and desired outputs are parameters.

For the orientation procedure simulation, the 5-to-20 model point locations for relative orientation, and the 3-to-20 point locations for absolute orientation, are also parameters. In addition, the characteristics of each of the error components used to generate the photo error grids are parameters for each photograph.

SIMULATION PROGRAMS

The mathematical models for the simulation of the AS-11B are programmed in Fortran IV for the GE 635/645 general-purpose digital computer. These programs provide for the input of specified values for the various parameters previously discussed.

For automatic plotting, the computer programs permit simulation of plotting and evaluation of system performance. For the latter purpose, the simulation programs are arranged to compute plotting speed and error at each plotted point. Various error statistics may also be computed such as average, root-mean-square, and average magnitude. The plotting simulation programs may be exercised in any combination of the following modes:

* Plotting mode—contouring or profiling.
* Correlation mode—ideal, that is unity transfer function for the video correlation and image characteristics, or normal, that is use of the video correlator and image characteristics to determine parallax and slope error components.
* Simulation mode—dynamic, dynamic-*rms*, or static.

The plotting modes provide the basic flexibility of the physical system in automatic plotting. The correlation modes allow the user to determine idealized and/or actual system responses to a variety of simulations.

The simulation modes allow the user to exercise the plotting model dynamically or statically. In the dynamic mode, the program simulates the action of the AS-11B in automatic plotting with printouts of errors in pertinent variables occurring each k time increments. Each printout reflects the conditions at a point in time and space. In the dynamic-*rms* mode, the program again simulates the action of the AS-11B in automatic plotting with printouts occurring every k time increments. In this instance, however, certain printouts reflect *rms* and mean values based on the last k time increments. The remaining printouts again pertain to points in time and space. The static mode of simulation produces no plotting motion and corresponds to automatic point height measurement system operation. Printouts in this case are identical with those of the dynamic-*rms* mode.

The plotting simulation printouts include time, model coordinates, coordinatograph coordinates, plotting velocity, direction of terrain slope for contouring, terrain slope components, correlation quality, parallax and slope errors, and elevation error. For the dynamic-*rms* and static simulation modes, printouts of plotting velocity and slope error components are mean values based on the last k time increments. The printouts of elevation error and parallax error components are *rms* values based on the last k time increments.

For orientation procedures, the programs simulate orientation operations and determine errors in the oriented model. To represent errors, the simulation programs are arranged to compute an error grid of model errors, as previously discussed. Other outputs from this orientation procedure simulation include the photo error grids and the AS-11B computer orientation elements after relative orientation and after absolute orientation.

For the correlator section, the programs simulate correlator operation with bar test targets and determine the correlator outputs. The correlation quality and X-parallax error outputs from the correlator are computed and printed out for desired X-parallax errors, scan size, and bar target frequency, density, and contrast.

Conclusions

Comparative tests of simulation runs against AS-11B automated stereoplotter runs show that the simulation exhibits characteristics very similar to those of the actual system. The simulation shows variation of system response for different kinds of photography quite similar to the differences observed when using the actual system. Certain dynamic plotting characteristics of the AS-11B system are also exhibited by the simulation. The present work demonstrates that an adequate computer simulation of this particular automated stereoplotter is possible. Furthermore, the simulation of the AS-11B has produced more fundamental understanding of the problems involved; many of the results of this work are applicable to any automated system using scanning and correlation.

It is expected that simulation of automated stereoplotter systems in general will prove to be useful to the users in predicting the performance of the systems under various circumstances, and to the designers in predicting the performance that would result from many types of systems changes. In addition, the simulation approach can lead to fundamentally sound and practically efficient methods for testing sophisticated automatic stereoplotting systems.

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Articles for Next Month

R. C. Aldrich, Space photos for land use and forestry.
J. R. Anderson, Land-use classification schemes.
A. H. Gerbermann et al, Color & color-IR films for soil identification.
D. T. Lindgren, Dwelling unit estimation with color-IR photos.
A.-M. Martin, Archaeological sites—soils and climate.
D. G. Orr and *J. R. Quick*, Construction materials in delta areas.
R. D. Rudd, Macro land-use mapping with simulated space photos.