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Why Analytical Plotters?

The ease of operation, accuracy, and versatility of the analytical plotter are sufficient reasons.

ABSTRACT: *The presentation of analytical stereoplotters by six manufacturers during the ISP Congress in Helsinki in 1976 represented a breakthrough in the development of plotting equipment.*

The author analyzes the general process of scientific progress and of photogrammetry which is integrated in this overall evolution. The progress assured by this evolution is discussed.

Access to projective spaces in infinite numbers on the basis of exposures free of parametric constraints is especially analysed.

The accuracy of analytical plotting is pointed out in the very process of making the spatial model. The system's economy is achieved by automating orientation and exploitation routines.

The possibility of carrying out three types of plotting—graphical, digital, and orthophotographic—on the basis of the same modules as those of an analytical plotter, is noted particularly that the storage of simultaneously acquired data in the exposure and space planes permits the surest and most elegant solution in orthophotography.

If analytical plotters are no more costly than first-order analog plotters, their qualities of precision and productivity and the possibilities of new applications open, quite significantly, a new era in photogrammetry.

INTRODUCTION

THE UNIVERSAL STEREOPLOTTING INSTRUMENT, in principle analog, which is capable of satisfying all the requirements of a survey is a myth which has been abandoned in our day. Preference has gone to a variety of analog instruments adapted in shape and accuracy to specifically defined functions: aerotriangulation, first- or second-order plotting, small-scale plotting, plotting terrestrial pairs of views, etc., more or less facilitated by coordinate recorders or ancillary systems adapted to these functions.

Suddenly, the 1976 Helsinki Congress demonstrated that this line of thought had been abruptly interrupted by the appearance of analytical systems of photogrammetry which had become effectively operational.

When one is aware of the sum of effort and the volume of investments which such a creation requires, the idea of merely having followed fashion for commercial reasons must be excluded. And when one remarks that this has been achieved by six manufacturers, one is quite justified in making an exhaustive analysis of the implicit and explicit, intuitive and deductive reasons for this event. This is the purpose of this paper.

As a matter of fact, this evolution corresponds to the traditional development of progress in all scientific and technical realms, as well as in philosophic thinking. Initially simple, universal systems satisfy thinking and requirements. Next they are complicated by the successive adjunctions whose single fields of application are more and more limited, thus becoming complex assemblies or groups which, through these very complications, create an impasse in the pursuit of progress. Then comes a breakthrough which, by questioning fundamental principles, provokes the appearance of a new, simple,

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universal system. Through its generalization, it encompasses the possibilities of all the previous systems and, in addition, opens new horizons whose perspective is so vast that man cannot as yet see their limits. History shows that, in spite of the bitterness of those who stood by former principles, enlightened minds of the period accept new systems without reservations. It is these latter which alone prevail for future development.

Indeed it is this scientific and technical progress which has just occurred in photogrammetry, in accordance with the general process of the evolution of sciences. An extraordinary arsenal of analog photogrammetric means which, in spite of highly perfected equipment, has reached the limits of human possibilities, is replaced by analytical stereoplotting. It relies on computer technology and servo-electronics, the progress of which are in constant development and which constitute the most profound technical and economical revolution of our time.

It is a fact that it is computer technology which increases tenfold the possiblities in almost all fields of the human mind by freeing it from servile tasks and enabling it to devote itself to the irreplaceable "why?" Paradoxically, perhaps, this liberation lightens the load of training men for tasks which were conventional until now, rendering them available for new actions.

One must hasten to recognize what has just occurred in photogrammetry, in order to preserve possibilities of acting in the future.

In general, the analytical stereoplotter permits the performing of three-dimensional plotting of *projective spaces in infinite number.*

Through the play of software alone, i.e., without acquiring and installing new equipment, it is possible to obtain views, plans, elevations, sections, and perspectives, oriented in space according to any position whatsoever, from digitizations of single points in the "photogrammetric model."

It is the computer which has the prime function of controlling the elements of the analytical stereoplotter and which assures, in addition, all mathematical transformations of the object being examined. Consequently, it slaves peripherals used to create the desired expression. This may be a new digital expression or the image on a conversational graphical cathode ray tube (CRT) of the terminal, or, quite simply, the real-time drawing on the automated coordinatograph table of the stereoplotter.

Access to these new projective spaces opens new possibilities not only in the cartographic field, but also in industrial, architectural, and town planning applications.

To be able to use whatever photogrammetric exposure taken under the most varied conditions, to plot the projection in any plane whatsoever, or to create all possible basic data files with accuracy, reliability, and an economy of production never before achieved. These are some of the aspects of analytical photogrammetry.

Relative Orientation on an Analytical Plotter

It is a well-known *leitmotiv* that the only real problem with an analog plotting instrument is that of relative orientation, rather than that of absolute orientation. The whole question of accuracy lies in this operation, whether for aerotriangulation or for any form of plotting. This problem disappears entirely in analytical photogrammetry, since it is solved by the computer with an accuracy two or three times greater than that of analog plotters and in a matter of seconds by using as great a number of points as one wishes. Figure 1 outlines the steps in relative orientation.

It is interesting to recall the material and human operations which allow one to obtain this result. First let us discuss relative orientation. Then we will examine the setting routine, including the extraordinary internal orientation possibilities.

Having roughly oriented the exposures in their plane through rotation so that stereoscopic viewing is comfortable, the operator plots, frame by frame, the corresponding image points and records their coordinates within the proper system of each exposure. These recordings are controlled by simple pressure on the knob situated on the console (e.g., when using the Matra TRASTER 77), which assures storing the values read off the optical scales at plus or minus a half-micrometer. The operation is performed on at least the six traditional relative orientation points, but may include more (up to 40 on the TRASTER). The computer then intervenes with the usual mathematical algorithms, imposing the coplanarity of rays corresponding to the same points. (see Figure 1) The resolution of this group of equations permits an initial definition of the relative orientation parameters. For the superabundant pairs of points, the computer specifies the space coordinates of the mid-points of minimum vectors joining the corre-

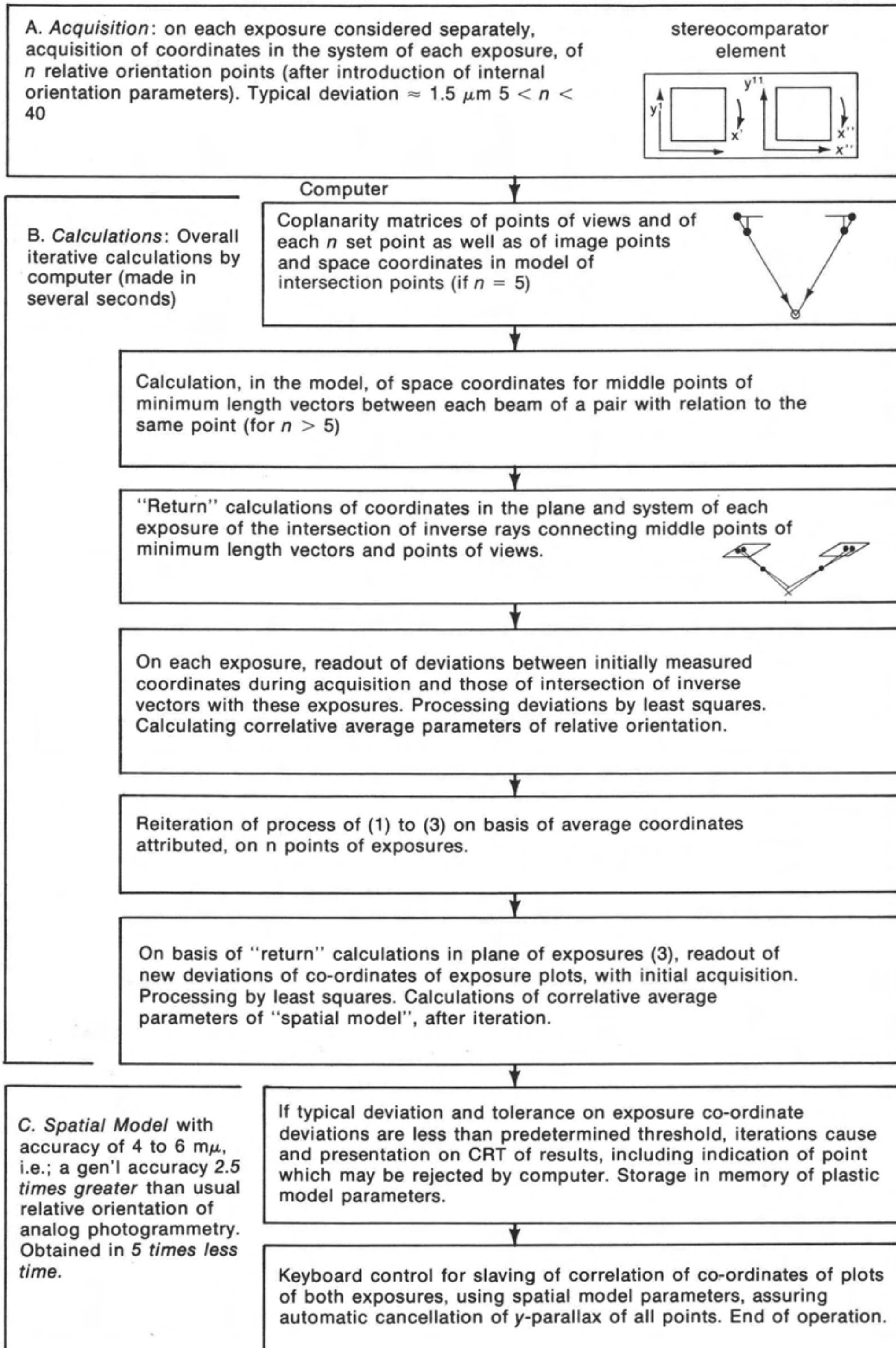


FIG. 1. Diagram of relative orientation on analytical stereoplotters.

sponding rays and then calculates the correlative coordinates of the aimed-at point of each exposure, for all points used for relative orientation. The comparison of these "return coordinates" with those initially measured in the exposures, shows residuals which are dealt with by least squares. This optimizing permits a better definition of orientation parameters. An iteration may then ensue.

Naturally, the operator has no need to concern himself with the computer's work. He merely gives the start order to the console. In a few seconds he sees the results of its operation appear on the console's cathode ray tube: residuals for each point, typical residuals (in micrometers), and, if necessary, points which have been rejected because of aberrations.

The absence of a need to simulate space by mechanical or optical means with their imperfections, and the formal logic of the process described, permit the integral preservation of the accuracy potential of the photogrammetric exposures being processed. This is the fundamental reason for the great superiority of analytical processing over analog restitution. Today, analytical results are two to three times more accurate than analog results, but tomorrow the gap will be even wider, when the homogeniety of photographic media and the fidelity of emulsions and optics will have progressed even further. As a matter of fact, it is the photograph itself which at present sets the limit to accuracy obtained in forming this veritable spatial image.

Interior, Relative, and Absolute Orientation

Having described the fundamental principle of model shaping, let us now see how it is introduced into the overall data-processed orientation routines. It should be pointed out, however, that the operator receives all successive operating instruction "spelled out" on the console's conversational tube. Any eventual erroneous action is immediately signalled. The result is "intellectual comfort" for the operator, a factor which should not be underestimated. Figure 2 outlines the steps in orientation.

Let us consider once again the beginning of the orientation and plotting phases, using, as an example, the TRASTER.

Interior Orientation

The exposures having been set up on their carriers and roughly oriented to permit easy stereoscopic viewing, the operator must introduce via the keyboard the geometric characteristics of each exposure (which may be different for each image), that is, the focal distance, the characteristics of symmetrical distortion, the calibration of the cone, accompanied by monocular pointings on the four fiducial marks of each image, and, finally, the flight altitude, linked, as we know, to the earth's curvature and atmospheric refraction. These represent the overall parameters designated as "internal orientation." This may be refined even more, however, by the creation of software designed specifically for non-symmetrical lens distortion or for passing exposure rays through several media with different indexes of refraction.

Relative Orientation

Once this operation has been completed, the conversational tube invites the operator to proceed with relative orientation and the shaping of the spatial model, as described in detail above. We should like to point out that, henceforth, we shall designate by "relative orientation" the first part of the operation which defines the initial parameters, and by "spatial model or image" the final determination which results from "return" compensation by least squares. The important fact is that, at the end of this phase, the functioning of the servo system is assured automatically to conjugate x and y motion of each exposure in its plane with the XYZ space position of the point under consideration in the model. This signifies that all y-parallaxes have been cancelled in the model and that, with the reservation of Z altitude adjustment in the model, the two corresponding images fall under the floating mark. The operator need no longer shift his floating mark in X, Y, Z, as both exposures are being slaved in this travel by the computer.

Absolute Orientation

It is at this point that instructions appear on the console's conversational tube, inviting the operator to carry out absolute orientation. Naturally, this phase can be dispensed with if an operation of aerotriangulation via independent models is performed. In this case, the tie points of the aerotriangulation are recorded in the spatial model, while the relative orientation parameters are preserved in computer storage so that they may be used later during the plotting of details without performing a new calculating operation.

To carry out absolute orientation, the operator sets on known points in the model after having introduced into the keyboard the known values of the XYZ ground coordi-

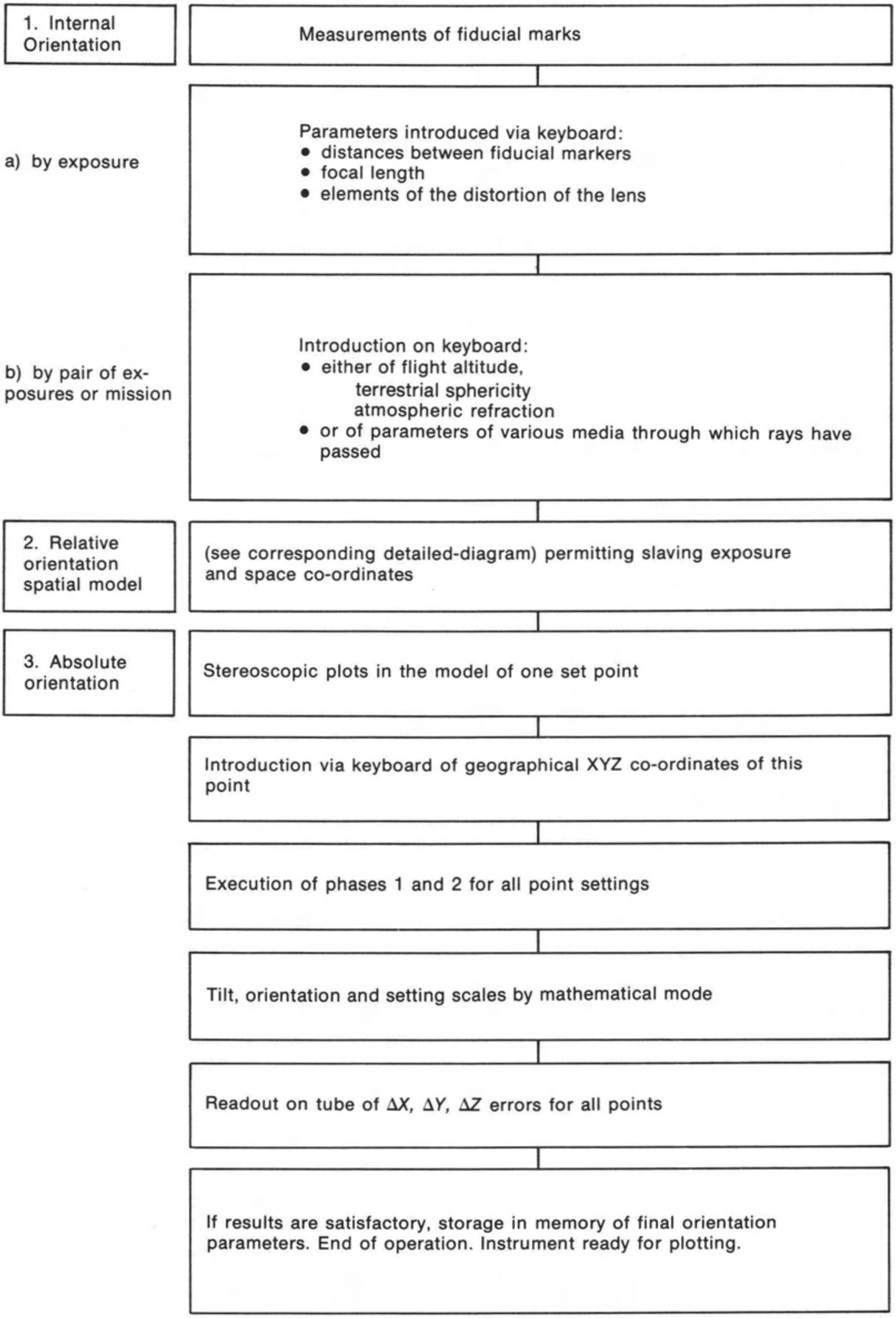


FIG. 2. Diagram of phases of analytical orientation.

nates of these points. The arrangement and number of these absolute orientation points may be arbitrary in analytical plotting. These points may result from previous aerotriangulation or from topometric measurements made on the ground. In the former case, this presumes that the pair of exposures had been placed in the instrument for the aerotriangulation measurements and that they must be replaced therein for the eventual plotting. In the case of TRASTER, for example, the fact of placing the exposures once again in any position whatsoever does not oblige one to recreate the spatial model, since the parameters of the initial model are stored in memory; it is then sufficient to measure two diagonal fiducial marks monocularly for each exposure. The initial accuracy of the orientation is reestablished in a 30-second operation. The conversational tube indicates the residuals in absolute orientation, in *XYZ*, on the initially known points. The plotting itself may then begin. Less than 12 minutes has been required since the beginning of the operation.

Note that the presence of a computer in the circuit utilized for achieving absolute orientation offers exceptional possibilities for adaptation to a previous cartographic back-up. This is a typical problem in updating drawings and maps. One may use a Helmert transformation or any anamorphic solution, or one of affinity, as one wishes.

Applications

Until now, stereoplotting could not be conceived without respecting the formal constraints of compatibility with equipment used for taking the photos. Most of these constraints are abolished by analytical photogrammetry.

Let us mention, first of all, those servitudes related to focal lengths and to the formats of photogrammetric cameras. The international standardization which has resulted from such constraints, however satisfying it may be in certain aspects, has been terribly restrictive for users. One striking example of this has been the difficulty of adapting to super wide angle lenses.

In addition, the appearance of short focal length, metric cameras raises endless problems of adaptation. Even worse, the developing of certain methods of taking photographs in space lead to using lightweight non-metric cameras where mechanical and optical solutions of photogrammetric problems clash. Only the analytical method can make the best of these photos, for example, thanks to calculated corrections of the laws of deformation of the photos taken.

This, therefore, opens a vast field of applications, both in measurements from space and those of "near" fields such as industry, architecture, and medicine.

The plotting of shallow coastal beds, especially, becomes possible thanks to software that accounts for the passing of light rays through air and water.

Not only have analytical stereoplotters lifted the veil covering the myth of learned orientation techniques of models, now outdated, but they have disclosed new possibilities in the very exploitation of details of the pair of exposures.

With the simple means of a unique analytical instrument, one disposes of synthesis possibilities never before achieved between the various phases of photogrammetric production, as well as between the various means of expression of plotting.

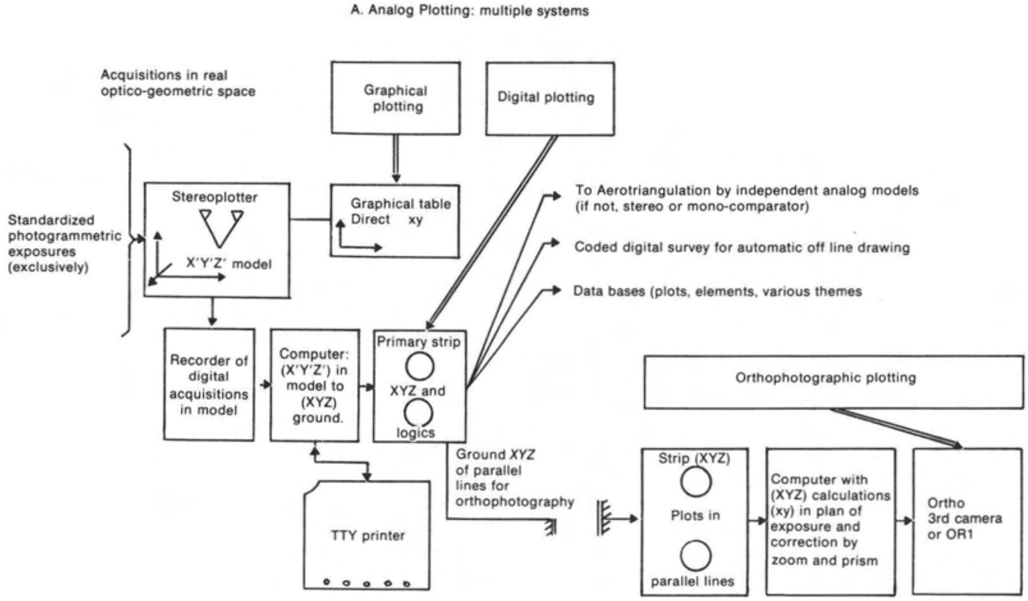
In an analytical plotter (the TRASTER, for example), the scales measuring travel are read to plus or minus a half-micrometer. This quite obviously permits the best triangulation procedure. One might even devise a means for transferring the photographic images of the aerotriangulation points without markings which alter the exposures themselves. This is also true for transfers between strips. In addition, the transfer of points from pair to pair on the same strip is performed by basic mathematical inversion, the coordinates of the points on the same exposure remaining in the same system of coordinates.

But there is even more: by so doing, one has not only acquired stereoscopically the coordinates in the plane of each exposure, as with any stereocomparator but, in addition, one has practically collected in "real time" all the definitive relative orientation parameters of the spatial model, of use for later plotting.

True, during the acquisition performed in aerotriangulation, one could collect the exposure coordinates of detail points if they were not too numerous, but the results would have been a greater amount of time spent by the computer in "off-line" calculations during aerotriangulation compensation. The possibility of instant resetting of pairs of exposures in the analytical procedure permits rejecting this eventuality.

Plotting

The plotting of details, strictly speaking, may be expressed in the three customary forms: graphical, digital, and orthophotographic. Figure 3 shows these forms for both analog plotters and analytical plotters. Practically, the choice between these forms is



B. Analytical Plotting (for example: TRASTER)

UNIQUE plotter unit, compact and undissociable, assuring simultaneously or independently:

- automatic, ultra-fast mathematical orientations or reorientations
- acquisition of mathematical spaces defined in real time (*X'Y'*, *x"y"* of exposures and ground *XYZ*).
- real-time graphical drawing on coordinatograph table controlled by computer. *GRAPHICAL PLOTTING*
- determining ground *XYZ*s for analytical aerotriangulation, for numerical survey, for automatic drawing and the bases of data *DIGITAL PLOTTING*
- orthophotography by arranging the plotter's internal system: *ORTHOPHOTOGRAPHIC PLOTTING*

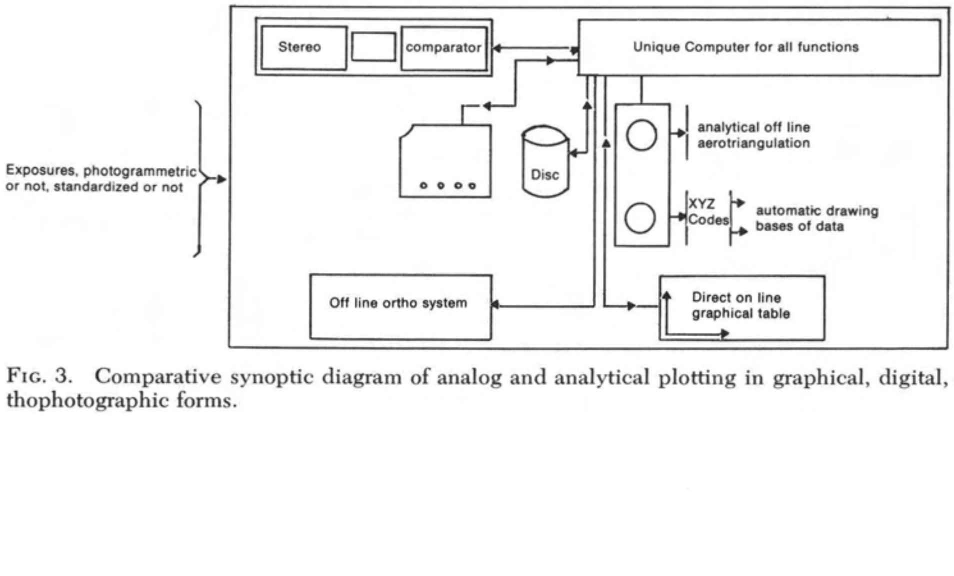


FIG. 3. Comparative synoptic diagram of analog and analytical plotting in graphical, digital, and orthophotographic forms.

often made as a function of the available equipment, but an analytical plotter is capable of supplying all three types of results. The expression which one wishes to give to plotting thus becomes more convenient and flexible. This is not the least of the advantages offered by analytical stereoplotters.

GRAPHICAL PLOTTING

Graphical plotting is performed in a plane of reference programmed by direct slaving of the coordinatograph table to the computer, on the basis of calculated space coordinates. This includes, evidently, all aids required for drawing elementary programmed objects, which have today become available items on various types of equipment.

It is important to emphasize that in analytics the only cause of inaccuracy which remains for a plot is the stereoscopic plotting itself, which provokes *xy* errors on each exposure, but that all the succeeding transformations and corrections are mathematical. There is thus total elimination of all instrument errors, as well as mechanical and optical, so closely linked to customary analog plotting. This permits accepting a much more important difference of scales between the aerial exposure and the plotted drawing. This represents considerable savings in performing the ground control survey as well as the aerotriangulation.

Plot errors, which are fundamental in analytics, are lessened through considerable enlarging of the image of the exposures used for setting the plot (on TRASTER, image enlargement reaches 25X).

DIGITAL PLOTTING

Graphic plotting may be accompanied by digital plotting by simply connecting addressable or sequential magnetic storage units to the computer. In this case, simultaneous graphic drawing on the coordinatograph table is used to check digital recordings, unless it is preferred that this check be carried out off-line; for example, by using an interactive graphic conversational console linked to the computer. In any event, this digital plotting is organized and programmed in the computer by setting the format of the recording of points and the logical coding of mutual junctions. The way is then open to complete automatic drawing in deferred time and to creating data processing files.

Digital plotting may be carried out in profiles, either in *X* or in *Y* (equidistant spacing of lines), in order to collect the information required for driving off-line orthophotographic instruments (third camera system, for example). In this case, the recordings may be triggered automatically at equal intervals and/or manually on characteristic ground points. The recording of a point then includes the *XYZ* coordinates of the ground point and the *xy* coordinates of the conjugate image points on each exposure.

ORTHOPHOTOGRAPHY

Analytical stereoplotters permit organizing and carrying out rigorous orthophotography with lateral rectifying of plotted strips in the most rational manner. It is well known, in fact, that the most recent orthophotographic systems assure transverse rectifying of scanning strips via fragmentary optical projection of the initial exposure, the enlargement being controlled by zoom optics and the orientation of the fragment of the image by a prism. These servo operations require knowledge of both the orthogonal ground coordinates of the corresponding points of contiguous initial scanning strips, and those of the image points in the plane of the orthophotographic exposure.

However, all this information has been recorded in the analytical stereoplotter and is preserved in storage, as opposed to that which occurs with acquisition carried out on an analog instrument, which gives only the *XYZ* ground coordinates, excluding the exposure coordinates, which must then be calculated "by return" in the pilot computer of the orthophotographic third camera. It must be admitted that this is a great advantage of analytical plotting over analog plotting insofar as orthophotographic production is concerned.

Even more, however, an analytical instrument includes, as an integral part of the unit, all the constituent elements of an orthophotographic third camera, i.e.: the basic flight exposure to be orthophotographed with its system of coordinates; *xy* and *XYZ* information of each point in storage issuing from the initial scan; and the medium of the orthophotograph itself, which may be made in various ways.

Thus, an analytical stereoplotter may constitute of itself an autonomous orthophotographic third camera if it is merely complemented by the following additional system: Software, an optical system servoed by the computer for its zoom and its rotation prism, and a cassette containing the sensitized surface, animated by the existing movements in ground *X* and *Y*. This solution even eliminates all problems of setting the projected exposure, already known and recorded.

We should add, finally, that if scanning takes place along X, one can introduce by means of software the function of artificial variation of x-parallax, because of Z altitude, which assures the anamorphosis of one of the two projected exposures forming the pair, in order to achieve the stereomate required for stereo-orthophotography.

It need not be emphasized that the accuracy of such a system is very great, as compared to that usually practiced in orthophotography.

Scanning performed prior to this orthophotography may also supply data required for the "digitial terrain model" and for the ultimate drawing, simultaneous or not, of corresponding contour lines.

Conclusions

This summary review of possibilities is far from being exhaustive of the reasons for analytical stereoplotting. It demonstrates in an obvious manner, however, that this principle succeeds in achieving a synthesis, never achieved before, of all possibilities of expression on a plotter and this on a unique item of equipment: aerotriangulation, graphical plotting, digital plotting, and integral orthophotographic plotting, in all possible manners.

Today, the analytical plotter is the most highly developed approach to reasonable automation which can be achieved in all its forms. It is the method which will probably permit the most efficient technological liaison between traditional photogrammetry and multispectral remote sensing of all sorts.

If the investment which the analytical plotter requires does not exceed that of analog stereoplotting, savings achieved due to its use will assure its commercial success. In addition, the infinite variety of technical advantages which it offers opens unexplored fields of application.

Finally, thanks to the simplicity of its design, analytical plotting becomes accessible to technicians in other disciplines which, until now, remained aloof from it.

Announcement and Call for Papers

International Symposium on the Problems of the Accuracy Improvement of Photogrammetric Constructions

Moscow, USSR
July 31—August 5, 1978

Sponsored by Commission III, Mathematical Analysis of Data, of the International Society for Photogrammetry.

Topics to be covered by the Symposium include:

- Analytical methods in photogrammetry, on-line analytical triangulation, methods of adjustment and their accuracy, utilization of auxiliary data, application and experimental results;
- Determination and compensation of systematic errors;
- Digital terrain model, contour interpolation, digital mapping, and solution of other tasks;
- Geometry of remote sensing;
- Processing of single and multiple images, different applications;
- Photogrammetric methods in planet investigations; and
- Expected developments.

If you wish to present a paper at the Symposium, please supply an abstract of 200 words, the title of the paper, and the names and addresses of authors to the address below by December 1, 1977. Further information regarding the Symposium may be obtained from:

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