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Evaluation of Analytical Plotters for the Commercial Mapping Firm

A method to quantitatively evaluate analytical plotters is presented.

ABSTRACT: *Aspects of analytical plotter evaluation are discussed. Both technical and nontechnical considerations are described with respect to their impact upon commercial photogrammetric mapping firms. A numerical technique is presented for uniform prepurchase accuracy evaluation as well as postpurchase acceptance testing.*

INTRODUCTION

THE PURPOSE of this paper is to examine the selection criteria faced by any commercial mapping firm when confronted with the purchase of a mapping instrument. There are quantitative (accuracy, resolution, etc.) as well as qualitative (reliability, computer compatibility, etc.) considerations that must be honestly evaluated in order to justify the expenditures of the large sums of capital involved (Fritz, 1980). These considerations are not uniform, and will have a different level of importance for every mapping concern. None of the purchase considerations are surprising, yet we at MARKHURD have been asked by many organizations (government, academic, and private industry) what we believe to be the requirements for an analytical plotter. Thus, an article on the subject will serve a useful purpose for those who contemplate equipment acquisition.

In the following paragraphs, I will try to show the areas which we at MARKHURD (specifically, a nongovernment and nonacademic environment) have found to be important to us in the investigation of analytical plotters. The possibility is quite distinct that similar examination by other firms could lead to the purchase of a mapping instrument other than an analytical plotter, or to no purchase at all. Finally, I will describe a numerical technique that we have found to be quite useful in evaluating all types of photogrammetric equipment.

MAPPING COMMUNITY REQUIREMENTS

The first step in the evaluation of analytical plotters is to honestly examine the needs of one's own company, a process that inherently takes time away from production. In the short run, taking personnel away from production is detrimental to a firm's ability to pay wages, taxes, and overhead, but in the long run, the proper selection of equipment will pay off in terms of greater production and far fewer headaches. Often we take the time to evaluate the plotters themselves and to listen to the propaganda of the vendors, but without a final objective determined from one's own needs, the comparison of one analytical plotter against another is meaningless and a waste of everybody's time, the vendor's included. And most vendors are smart enough and gracious enough to try to sell the correct instrument for the correct job, if the commercial photogrammetrist really knows what he or she needs.

The advantages of analytical plotters are substantial, and if applicable to any particular firm, can offer many advantages over traditional analog plotters (Konecny, 1980). Flying heights may be slightly increased for a given contour interval, and set-up time for interior and exterior (relative and absolute) orientation will be faster and more accurate. On the other hand, contour and/or plan detail compilation will probably not be much faster than with analog equipment. Quality control may be enforced by means of analysis of the residuals from the orientation procedures, but operator blunder will still be a problem. Aerotriangulation, profile scanning, digital terrain modeling, all are areas in which analytical plotters excel, some more so than others. Thus, to rank analytical plotters in some order of preference, the photogrammetrist must know which features are the most important for his or her requirements.

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Analytical Plotter Criteria

The following are those areas which, in our opinion, should be considered. Some criteria may not be applicable to some firms. Similarly, there are probably criteria which could be added if required.

- *Computer Compatibility.* Computer compatibility is only important if a firm has an in-house computer (or external time-sharing system) that the analytical plotter's computer will be linked to for purposes of software development, data editing, or data manipulation. If that is the case, computer communication is normally simplified if computers manufactured by the same company using the same or compatible operating systems are utilized. This advantage of similar computers will be reduced after familiarization takes place and the computers, even if different, are eventually linked.
- *Software Documentation.* The documentation should be complete, including application module source codes. If no in-house programming is required, then simple instructions to operate the system should suffice. The instructions must be complete and understandable to the plotter operator, not just the manufacturer. If in-house programming is expected, then accessible subroutines, including functional descriptions and required parameters, must be documented. Without these documented subroutines, any in-house programming will be futile. Even so, in-house software development requires a significant investment of time and resources.
- *Hardware Documentation.* Instructions for simple preventive maintenance should be provided, as well as some type of diagnostic guide. Wiring diagrams are not vital, but are helpful.
- *Operating System.* If simultaneous program development (such as FORTRAN compilation) and normal mapping are required, then a multiuser operating system and sufficient disk storage must be provided.
- *Accuracy.* Accuracy is the degree of conformity or closeness of a measurement to its "true" value (Mikhail, 1976, 1981). Uncorrected systematic errors (or bias), as well as any random error, are thus included in the computation of accuracy. One procedure to estimate bias is to average the residuals for 25 or more grid points. We believe that the bias should be close to the least count of the system. If the bias is close to the least count, the standard deviation may be used as the measure of accuracy. Another measure of accuracy is the root mean square error calculated from discrepancies at withheld grid points.
- *Precision.* Precision has been defined (Mikhail, 1976, 1981) as the degree of conformity among a set of observations of the same quantity. As mentioned above, precision is the same as accuracy, when there is no bias present. In my opinion, however, it is important that the proper variable be analyzed. Analytical plotters create maps as engineering documents, with a horizontal displacement as part of the specifications. Because this displacement is not separated into x and y components, neither should the plotter precision be divided into separate x and y components. Thus, the variable we compute is the error vector $(\Delta x^2 + \Delta y^2)^{1/2}$ for 25 or more points measured on a grid plate. A method to compute this standard deviation σ_0 will be presented at the end of this paper. Unfortunately, there seems to be no standard procedure for manufacturers of analytical plotters to compute their estimates of accuracy or precision, thus leading to much confusion.
- *Reliability of the Manufacturer.* The computer, electro-optical, and software systems should be considered as separate items. Customer support is difficult to quantify, but past history and common sense should provide the appropriate guidelines.
- *Reliability of the Equipment.* The standard technique for determining equipment reliability is to measure the "mean time between failures" (MTBF). The MTBF is different for the computer than for the electro-optical system. A standard unit for MTBF could be days.
- *Maintenance.* Generally, the computer and the electro-optical system have different schedules and requirements, and will be an additional annual cost. Close proximity of the manufacturer to the customer also might be important. Many times maintainability is referred to as the "mean time to repair" (MTTR). Units for MTTR would be the same as MTBF.
- *Availability of the Equipment.* Comparative availability of an analytical plotter for production may be computed using the equation

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \quad (1)$$

where MTBF and MTTR are defined as described above. Because "A" may be computed separately for each component, the overall system availability is the product of all the components. Thus, if two components each had an availability of 0.9, then the system would have an availability of 0.81. As with precision, at the present time availability is not a standard item provided by the manufacturers.

- *Cost.* This should include maintenance, software, updates, financing fees, installation and delivery, training, all required peripherals and computer links, etc. The possibility of hidden costs arising is quite likely whenever purchasing any instrument this complex.
- *Peripherals.* Not all pen plotters, CRT's, tape drives, disk drives, etc., are compatible with every computer/plotter operating system. Some configurations might require special drivers to account for different word lengths, "handshake" codes, etc. Any configuration utilizing different manufacturers should be discussed with each manufacturer.
- *Training.* The training should be complete for each area: hardware maintenance, operating system and program development, and operation of mapping functions.
- *Operator Friendliness.* Operator friendliness is a nebulous term, but becomes very real when trying to set up a stereo model and compile a map. Many times an experienced compiler will have valuable comments when allowed to test a particular analytical plotter.

- *Available Functions*. These are sometimes helpful options:
  - binocular left or right viewing
  - zoom optics
  - variable dot color
  - variable dot size
  - variable dot shape
  - free-hand cursor
  - profile throttle
  - position locator screen
  - X, Y, Z coordinate display
  - audio feedback
- *Resolution*. The optical train should be tested at a standard magnification (such as 10×) against the standard Air Force resolution bar target.
- *Field of View*. This should be measured on a diapositive at a standard magnification (such as 10×).
- *Appropriate Hardware Design*. These are a few features which generally increase the precision and reliability (and cost) of an analytical plotter.
  - linear encoders for measurement separate from the positioning device (as opposed to a screw with shaft encoders for positioning and measurement) (Jaksic, 1980).
  - distributed processing, i.e., a microprocessor for real-time functions and separate minicomputers for time consuming calculations.
  - stationary optical train (only the carriages move).
  - independent carriage movement (left carriage is independent from the right carriage).

RATING METHOD

A common and straight-forward method for rating all the previously listed functions is the weighted average. Any item may be *weighted* according to its relative importance, say from 0 to 10, as well as *rated* from 0 to 10. The following equation may be easily calculated using a hand calculator:

$$\text{Avg.} = \Sigma(W \times R)/\Sigma(W) \qquad (2)$$

where Σ = summation,
W = weight 0 to 10, and
R = rating 0 to 10.

When plotters are ranked against each other, the instrument with the highest average would be considered the best. If the weights for all items are the same, then a weighted average simply becomes the arithmetic means of ratings.

When required, any criterion may be subdivided into subcategories at the discretion of the investigator, and that weighted average from the subcategories can then be used as a single term in the overall weighted average (McKenzie and Makarovic, 1980; Makarovic, 1980).

METHOD TO COMPUTE THE STANDARD DEVIATION

A method to evaluate analytical plotters in a uniform manner both prior to purchase the after delivery is to employ the three-parameter transformation. This procedure, solving only for the x and y shifts and a rotation, is used rather than a more complex method in order not to disguise the plotter inaccuracies within the residuals. A precision grid plate with known coordinates and access to a small mini or microcomputer are required to perform this procedure. The program to compute the transformation can be written in as few as 300 lines of FORTRAN code.

The basic equation is

$$\begin{aligned} X_2 &= X_1 \cos\beta + Y_1 \sin\beta + \Delta X \\ Y_2 &= X_1 \sin\beta + Y_1 \cos\beta + \Delta Y \end{aligned} \qquad (3)$$

where X_1, Y_1 are the coordinates as recorded by the analytical plotter and
X_2, Y_2 are the known coordinates of the grid plate (Note: the coordinates of X_1, Y_1, X_2, Y_2 must be recorded in the same units, because there is no parameter for scale);
β is the rotation angle between the two coordinate systems; and
ΔX, ΔY are the shifts between the systems.

Using the least-squares process (Mikhail, 1976):

$$\mathbf{v} + \mathbf{B\Delta} = \mathbf{f} \qquad (4)$$

$$\mathbf{B} = \begin{bmatrix} (-X_1 \sin\beta + Y_1 \cos\beta) & 1 & 0 \\ (-X_1 \cos\beta - Y_1 \sin\beta) & 0 & 1 \end{bmatrix}$$

$$\mathbf{f} = \begin{bmatrix} X_2 - X_1 \cos\beta - Y_1 \sin\beta - \Delta X \\ Y_2 + X_1 \sin\beta - Y_1 \cos\beta - \Delta Y \end{bmatrix}$$

$$\mathbf{\Delta} = \mathbf{N}^{-1}\mathbf{T} \qquad (5)$$

where $\mathbf{N} = \Sigma\mathbf{B}^T\mathbf{B}$, (6)

$\mathbf{T} = \Sigma\mathbf{B}^T\mathbf{f}$, and (7)

Σ is summation over the number of points used.

Because the basic transformation equations are nonlinear, delta ($\mathbf{\Delta}$) is the *correction* vector to the last estimate of ΔX, ΔY, and β. The solution must be iterated until delta is very small (normally less than the least count of the coordinate's units). Four or five iterations will probably be required.

Once the solution has converged, the residuals may be computed, and then the standard deviation. That is;

$\mathbf{v} = \mathbf{f} - \mathbf{B}\,\mathbf{\Delta}$ where $\mathbf{f}$, $\mathbf{B}$, and $\mathbf{\Delta}$ are those from the last iteration (8)

$$\sigma_0 = (\mathbf{v}^T\mathbf{v}/r)^{1/2} \qquad (9)$$

where $r = 2n-3$ (n is the number of grid points).

σ_0 is then the unbiased estimate of the reference standard deviation, which is the value that should be less than or equal to the repeatability (or precision) value as stated in the analytical plotter manufacturer's specifications.

Conclusion

Analytical plotters are expensive, complex electro-optical systems which hold great promise for the photogrammetric industry. Selection of the suitable type of instrument is possible, based on qualitative and quantitative considerations. The selection of an analytical plotter will remain, however, a difficult and very important decision for any commercial mapping company. It is hoped that the thoughts expressed in this paper will help others in the plotter analysis and selection process.

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