Evaluating Dynamic Performance of an Analytical Plotter

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ABSTRACT: The accuracy evaluation of plotting at an analytical plotter related to its dynamic mode (as against its static mode) is discussed. This study is concentrated on the evaluation of plotting with regard to various plotting directions, speeds, and configurations, as well as locations on the plotting table.

An IBM-PC Microcomputer connected to the Wild BC-1 (analytical plotter) table is used to input the necessary parameters for figures to be plotted. Each figure is plotted in various dynamic modes. Subsequently, specific test points on the plotted figures are repeatedly measured at a precision coordinatograph. The measured coordinates of the test points are compared with their true (theoretically correct) coordinates. The differences between the measured and the true coordinates are considered in analyzing the dynamic performance of the plotter.

The test results show that dynamic plotting errors may be significant in certain cases. One should either avoid or correct for such dynamic distortions in order to achieve better accuracy in plotting or in deriving mensural data.

INTRODUCTION

THE EVALUATION OF THE STATIC PERFORMANCE of an analytical plotter is generally well known. Such evaluations are normally concentrated on three of the major components of an analytical plotter: the stereoviewing system, the control computer (including software), and the interfaces. Existing publications in photogrammetry indicate a remarkable lack of studies on the dynamic behavior of the plotting table attached to an analytical plotter and its dynamic behavior. Ghosh (1982) observed at a specific analytical plotter system that the dynamic mode of operation may result in an accuracy 11.5 times lower than that in the static mode. As analytical plotters become further utilized in modern photogrammetry, their dynamic performances deserve to be appreciated more and more.

In extracting quantitative data in photogrammetry, one is concerned about the assessment of their quality. This assessment, in practice, is often made by considering certain properties related (1) to the statistical behavior of the observed and extracted data and (2) to the nature of the measuring system they refer to. While the former bears upon certain theoretical concepts, the latter pertains to the physical reality. In dealing with mensural data, they both are equally important and need some elaboration. Furthermore, such quality considerations are necessary both in designing and in evaluating the measuring process.

The quality or the degree of perfection in a measurement is expressed in terms of accuracy (defined in Webster's dictionary as "The degree of conformity of a measure to a standard or a true value"). The accuracy requirements for a measuring process are regulated partly by experience, partly by conference (i.e., discussions and exchange of ideas with various persons from various fields associated with the system), and partly by analyses. However, the observations, i.e., the outcome of a measuring process, are assessed in terms of "accuracy" and "precision." These two terms are confusing to the uninitiated. It will therefore be pertinent to elaborate them.

Without going deeper into theoretical statistical connotations, it can be said that "accuracy" indicates the degree of closeness of the observations to the "true" value or the "input." "Precision", on the other hand, indicates the degree of closeness of the observations to their average value, i.e., the degree of agreement or uniformity among a set of observations of the same random variable.

The relationship of precision to the corresponding mean (or average value) is almost parallel to that of accuracy to the true value. That is to say, the difference between accuracy and precision implies the possible presence of systematic error or bias. Both the terms are applied to multidimensional distribution of the observations. However, accuracy refers to the true value regardless of the precision of the measuring process.

When observations are repeated, the understanding is that several trials are better than one. One takes the average. The average of the readings is not the value that corresponds to the input. However, in spite of a variety of individual indications, the average result is useful. The differences of the individual values from the mean help one to calculate the "standard deviation" of the observations. The standard deviation would indicate the precision. The outputs can be related to the input by accuracy in view of the degree of probability or other considerations. To specify accuracy completely, one must specify both a range of values within which one expects the output to lie and the probability that this will occur.

Such plotting errors are influenced by both external and internal sources.

External Sources like ambient temperature, humidity, external vibrations, fluctuating electric currents, etc. Their effects are generally indeterminable. However, the effects are minimized if such external sources stay constant during the operations and the instrument is calibrated under such "working conditions."

Internal Sources

- Elastic deformations due to friction between parts, elasticity of materials, flexibility of rails, etc.
- Back-lash due to gimbal suspensions, ball bearings, etc. Changing speeds and directions affect such back-lash errors.
- Temporal or time related hysteresis.
- Vibrations and resonances within the instrument itself, and so on.

In practice, it is impossible to isolate every source, find the effect, and eliminate or account for their error contributions. Furthermore, it is the total effect that counts. Therefore, the best experimental procedure would be to study the "response function," i.e., to expose the instrument to certain specific inputs (which would be independent of the system) to be followed by the corresponding outputs (data) and analyze their differences.

One can relate accuracy directly to the input (without the probability consideration) only when the true value is known. In the mensuration process such knowledge can be provided by using "standards" or control data which can be assumed to

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be correct (i.e., errorless). However, if the true value can be provided through rigorous mathematical modeling by using a computer at the analytical plotter, one can talk about the true errors, the "input" control data being errorless. The present studies must be viewed in the above perspectives.

ERROR STUDIES

The present study addresses various tests performed with regard to the (dynamic) plotting errors at the plotting table (Wild AVIOTAB TA10) attached to one Wild BC-1 Analytical Plotter in the Photogrammetry Laboratories of Laval University.

The devices involved in these tests are an IBM-PC Microcomputer, a Wild AVIOTAB TA10 Digital Plotting Table, and a Haag-Streit Coordinatograph (model 1096).

Each test consists of the following procedures:

(1) Input into a connected IBM-PC the necessary mathematical models for some standard figures to be plotted at the TA10 plotting table.
(2) At the TA10 plotting table, plot (without interruption) the figures, in each of which around 30 critical (test) points are subsequently marked with the help of the computer. These points were selected in view of their (a) equable distribution and (b) locations where plotting direction would change.
(3) Measure the coordinates of the test points on plotted figures at the coordinatograph. Quadruplicate measurements are made at each point to obtain enhanced pointing precision as well as to eliminate blunders and effects of instrumental backlash.
(4) Compare the measured coordinates of the test points with the computer input coordinates (the true values) of the same points and obtain the differences between the measured and the true coordinates.
(5) Analyze the coordinate differences obtained in step (4) to evaluate the dynamic performance in plotting.

In order to obtain a complete picture, the dynamic plotting errors are studied with regard to

- Different directions of plotting (at the table),
- Different locations on the table,
- Different shapes (configurations) of figures, and
- Different plotting speeds.

WITH REGARD TO DIFFERENT PLOTTING DIRECTIONS

With the conjecture that magnitudes and directions of the plotting errors may be related to the direction of plotting, two sets of standard figures were tested. The first set (Figure 1) consists of four concentric circles, the outermost circle having 16-cm diameter. The other circles have their diameters 20 percent less than the preceeding. The second set (Figure 2) comprises four concentric squares, the outermost being 20-cm square. The other squares are similarly designed to have their size reduced successively by 20 percent. The direction of plotting was always in a clockwise sense. The plotting started in each case at the point nearest the origin of the coordinate system.

The figures were measured at the coordinatograph and the coordinate differences are obtained in the procedure as described. The coordinate differences are vectorially represented in Figures 1 and 2.

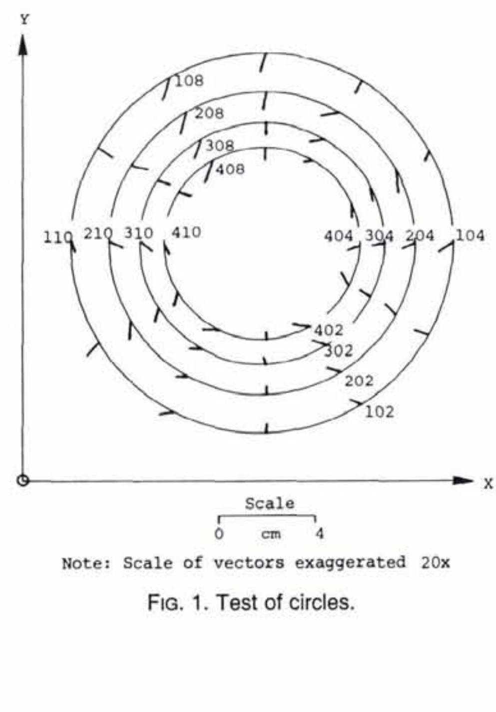
It would be apparent from Figures 1 and 2, that at the beginning the error dX ($dX = X_{measur.} - X_{true}$) is positive. However, as the plotting advances in the X positive direction, dX becomes negative with its magnitude increasing with the distance of plotting.

Similar plotting errors occur in the Y direction when the plotting moves toward the positive Y direction. It is also found that the error in the Y direction is larger than that in the X direction. It means that $|dY|_{max} > |dX|_{max}$ when the figure has the same X, Y dimensions. Representative values on typical sections of the circles and squares are presented in Tables 1 and 2.

Furthermore, considering the value 0.02 mm as the resolution capacity, as claimed by the manufacturer (Wild Heerbrugg, undated), one would note that most of the dynamic plotting errors can be significant.

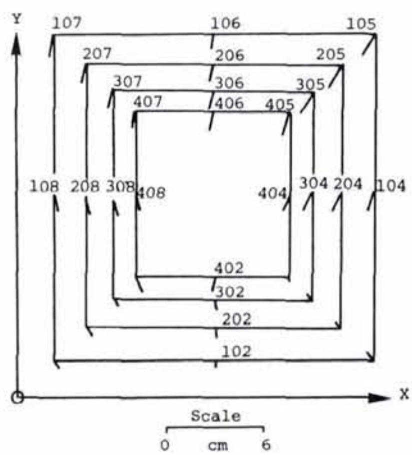
WITH REGARD TO DIFFERENT LOCATIONS

In order to study the distortions on plotting in different areas of the plotting table, the same figures (Figures 1 and 2) are plotted at five different areas on the plotting table. These five areas are lower left quarter (LL), lower right quarter (LR), upper



Note: Scale of vectors exaggerated 20x

FIG. 1. Test of circles.



Note: Scale of vectors exaggerated 20x

FIG. 2. Test of squares.

TABLE 1. dX,dY ON TWO TYPICAL SECTIONS (CIRCLES)

Pt. No.	110	210	310	410	404	304	204	104
dX	0.02	0.05	0.02	0.01	−0.08	−0.12	−0.09	−0.16
dY	−0.08	−0.08	−0.09	−0.05	−0.08	−0.08	−0.09	−0.10
Pt. No.	102	202	302	402	408	308	208	108
dX	−0.09	−0.20	−0.19	−0.19	−0.12	−0.10	−0.10	−0.03
dY	0.06	0.04	−0.01	−0.05	−0.24	−0.25	−0.26	−0.21

Note: See Figure 1 for point locations. All the units in this table are mm.

TABLE 2. dX, dY ON TWO TYPICAL SECTIONS (Squares)

Pt. No.	107	207	307	407	405	305	205	105
dX	0.01	−0.01	0.02	0.01	−0.06	−0.05	−0.12	−0.09
dY	−0.23	−0.24	−0.20	−0.21	−0.22	−0.22	−0.25	−0.24
Pt. No.	102	202	302	402	406	306	206	106
dX	0.02	0.01	0.02	0.01	0.01	−0.01	−0.03	−0.04
dY	−0.05	−0.07	−0.07	−0.09	−0.23	−0.22	−0.22	−0.24

Note: See Figure 2 for point locations. All the units in this table are mm.

left quarter (UL), upper right quarter (UR), and the central area (CEN).

The plotted figures in each area are evaluated by comparing the standard deviations σ_x, σ_y, and σ_{xy} (in X, in Y, and the circular error, respectively (Ghosh; 1988); i.e.,

$$\sigma_x^2 = \sum (dX_i)^2/n, \qquad \sigma_y^2 = \sum (dY_i)^2/n \tag{1a}$$

$$\sigma_{xy}^2 = (\sigma_x^2 + \sigma_y^2)/2 \tag{1b}$$

where dX_i, dY_i are the plotting errors at test point i on the plotted figure and n is the number of test points.

The standard deviations related to the plotted figures on each area are shown in Table 3. One would note that both the circles and the squares have smaller plotting errors at the lower areas (*LL* and *LR*) of the plotting table.

It may be mentioned that the results (Table 3) are based on the two specific types of figures. More tests are, however, needed to make a general conclusion as to which area is the best for which type of plotting.

TABLE 3. PLOTTING ERRORS IN DIFFERENT AREAS (VALUES IN MM)

		LL	LR	UL	UR	CEN
circles	σ_x	0.08	0.08	0.08	0.13	0.10
	σ_y	0.09	0.08	0.11	0.18	0.17
	σ_{xy}	0.09	0.08	0.10	0.16	0.14
squares	σ_x	0.03	0.03	0.04	0.03	0.04
	σ_y	0.07	0.09	0.12	0.11	0.12
	σ_{xy}	0.06	0.07	0.09	0.08	0.09

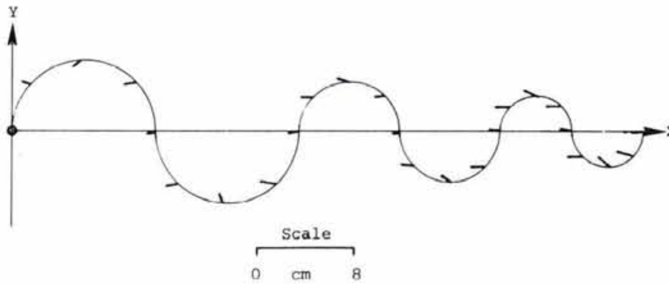


FIG. 3. Test of semi-circle wave pattern in the *X* direction.

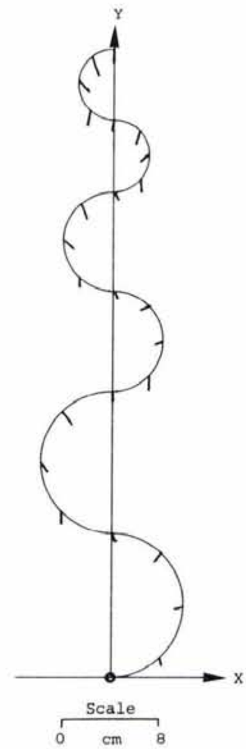


FIG. 4. Test of semi-circle wave pattern in the *Y* direction.

WITH REGARD TO DIFFERENT CONFIGURATIONS

Three different types of figures - circles, squares, and semi-circular decreasing wave patterns - were tested and compared in order to study if different configurations of figures suffer differently under the same plotting conditions.

The circles and squares are the same as those in Figures 1 and 2. The semi-circular wave patterns in the *X* and *Y* directions are shown in Figures 3 and 4, respectively.

By comparing Figures 1 and 2 with Figure 3 and also Figure 3 with Figure 4, the following observations are made:

- In a symmetric closed figure with the same dimensions in both the *X* and *Y* directions, (circles and squares), the *dX* and *dY* plotting errors are not significantly different from each other. This conclusion is based on a t-test for the *dX* and *dY*.
- If the figure is clearly extended along one direction, then the plotting errors are larger in this direction than in other directions (Figures 3 and 4). It seems that the error propagates almost linearly proportional to the extension of the figure.

WITH REGARD TO DIFFERENT PLOTTING SPEEDS

The effects of plotting speeds on plotting accuracy were studied by using the same three figures, concentric circles and squares as well as semi-circular wave patterns. Each type of figure was plotted at four different plotting speeds: 296 mm/sec, 200 mm/sec, 96 mm/sec, and 8 mm/sec. The standard deviations σ_x, σ_y, and σ_{xy}, are used to evaluate the effect of the plotting speeds on the plotting errors (Table 4).

Table 4, however, does not show the sporadic high magnitude errors we have experienced with the extremely high plotting speeds. These are as high as 0.3 mm even with an extremely stable plotting base.

The following observations are made with regard to plotting speeds:

- The slower the plotting speed, the better is the plotting accuracy, the limit obviously being the static mode. That is, very high plotting speeds usually yield low plotting accuracies.
- There is an efficiency trade-off between plotting accuracy and plotting speed. This may be due to the loss of precision response of the plotting instrument. Therefore, one should avoid using very high plotting speeds (such as 296 mm/sec), at least to avoid sporadic errors.
- Although by using a very low plotting speed, one can improve

TABLE 4. RESULTS OF DIFFERENT PLOTTING SPEEDS (VALUES IN MM)

		296mm/sec	200mm/sec	96mm/sec	8mm/sec
circles	σ_x	0.10	0.09	0.08	0.06
	σ_y	0.11	0.09	0.07	0.08
	σ_{xy}	0.10	0.09	0.08	0.07
squares	σ_x	0.04	0.06	0.05	0.02
	σ_x	0.12	0.09	0.08	0.06
	σ_{xy}	0.09	0.08	0.07	0.05
semi-circular wave patterns	σ_x	0.05	0.06	0.04	0.04
	σ_y	0.11	0.08	0.09	0.08
	σ_{xy}	0.09	0.07	0.07	0.06

the plotting accuracy, it may take an unusually long time to plot a specific figure, which may not be economical. One can see from Table 4 that the accuracies from the speed of 96 mm/sec is not much worse than the accuracies from the speed of 8 mm/sec. Thus, for example, by using the speed of 96 mm/sec instead of 8 mm/sec, one can save a lot of working time by slightly compromising the plotting accuracy.

CONCLUSIONS AND RECOMMENDATIONS

Through these tests, it is found that dynamic plotting errors may at times be significant. Dynamic errors should never be ignored in practice if high plotting accuracy is desired. The test results are summarized in the following:

- Dynamic plotting errors are higher in magnitude in the Y direction than in the X direction of the particular plotter.
- For best plotting accuracy at the specific TA10 digital plotting table, it is better to use the lower areas (LL and LR) of the plotting table.
- The shape of the figure to be plotted contributes significantly to the expected plotting error - in terms of both magnitude and direction. This may be very significant in plotting irregular lines (like contours).
- Very high plotting speeds do not contribute highly towards plotting accuracy. On the other hand, very low plotting speeds are time consuming and thus not always economical. Thus, a compromise plotting speed should be found for cost-effective plotting at a plotter.
- The above facts are based only on the specific tests on one Wild AVIOTAB TA10 digital plotting table. This case must be taken as an example for the working concepts.

It may be noted that all our studies refer to the use of extremely stable base materials (glass or stable myler) for plotting and subsequent measurements without any delay. With paper as the base material for plotting, errors on the order of more than a millimetre have been noted, as would be expected. Furthermore, one cannot completely ignore the human contributions to such errors, varying from operator to operator.

The following are recommended for further studies in these regards:

- Study by changing dimensions of the test figures and see whether larger figures may suffer from larger dynamic plotting errors.
- More tests at numerous instruments are recommended to substantiate or refute our conclusions.
- The causes of such detected dynamic plotting errors at the plotting table would have to be found in order to improve on the applications of analytical plotters.

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