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TESTING PROCEDURES FOR ANALYTICAL PLOTTERS

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ABSTRACT

Performance and acceptance tests of equipment are procedures for quality control that are essential in any evaluation process. The wide variety of analytical plotters on the market today, and their basic differences from analog plotters, requires that we institute a new look at these procedures. This paper addresses many of the test procedures that should be applied and the underlying philosophy of these performance tests for analytical plotters. Included is, what should be tested, why it should be tested, and how it can be tested. The approaches suggested are pragmatic in that they are addressed to the needs of the majority of analytical plotter users and are therefore designed to quantify performance. Practical simplified tests are proposed that will enable a typical user to verify that a particular analytical plotter is suitable for his needs or, to provide a means for him to ascertain that his specifications for an analytical plotter have been met. An example from an actual analytical plotter acceptance test is presented.

INTRODUCTION

Working Group II-1 of Commission II, ISP has devoted considerable effort since the 1976 Helsinki Congress XIII in developing a System for Evaluation of Analytical Plotters. One of the subtasks of the Working Group is the development of testing procedures for analytical plotters. Specifically, the test procedures chosen to be addressed are for accuracy, time-efficiency, different system-components, operational modes, phases of operation, and for the reliability of components in different operational modes. This report covers only a few of these objectives.

Testing procedures are quite useful for users to evaluate the suitability of an AP before purchase, and are needed as a quality control after purchase. The tests proposed by an ISP Working Group should be simplified and pragmatic so as to address the widest variety of analytical plotters. Certain analytical plotters will require additional tests for those components that are unique to a particular brand of manufacture. A set of practical tests to evaluate similar areas of analytical plotters has been developed that emphasizes quantifiable properties and avoids time-consuming, all-encompassing tests.

TEST CONDITIONS

There are three primary instances when test procedures are required. Tests are required; (1) to make a preliminary evaluation of a variety of analytical plotters before purchase, (2) to test the acceptability of a specific analytical plotter during purchase, and (3) for periodic quality control after purchase. Recommended steps to pursue in each of these instances are presented here.

1. It is essential that the user prepare technical specifications for, or outline the performance required of, the analytical plotter. The prospective buyer can then take the following steps:

(a) Evaluate and rank available analytical plotters using checklists such as those proposed by McKenzie and Makarovic (1980) and by Jaksic (1980). The user can make much of this preliminary evaluation from technical data and specifications supplied by the manufacturer.

(b) Set up stereomodels with imagery the user typically uses to demonstrate the suitability of the available software. This test also will show the types of input data needed (lens distortion, fiducial coordinates, etc.) that may differ from normal operations, especially if the user has only analog hardware.

(c) Perform specific hardware tests using resolution targets, glass scales, grids, etc., on those components of the analytical plotter that are most critical to the user's needs. Hardware tests also should be made on those components that are most suspect to be deficient in meeting the user's needs.

2. For the new owner of an analytical plotter a series of testing procedural steps are required as acceptance testing to ensure that the contractor has adhered to the specifications:

(a) Inspect each hardware component of the analytical plotter for completeness, quality of materials and workmanship, and adherence to key dimensions.

(b) Check the software to ensure complete documentation; that all disks, tapes, etc., have been delivered; and to verify that training in maintenance software and operation has been performed satisfactorily.

(c) Perform specific hardware tests for accuracy, precision, optical train quality, stability, and plotting.

(d) Use typical imagery to test for potential bugs in the delivery applications software routines and to ensure that all servo systems are properly functioning and will provide smooth, continuous stereoscopic viewing throughout the entire stereo model area.

3. For the long-term owner of an analytical plotter, testing procedures are required as quality control measures to detect changes in state, such as the need for maintenance, and for early detection of deterioration and malfunctions. These testing procedures should be scheduled periodically and should be standardized and complete. These steps are diagnostic and are quantifiable rather than subjective:

(a) Run specific hardware tests.

(b) Run controller diagnostic tests.

(c) Maintain records of the quantified results and statistics.

Test procedures chosen for the three above instances must be carefully selected. The objective of a test is to determine a statistic that is representative of the expected performance of an instrument and that is reliable when used under similar operating conditions. Therefore, an "a priori" knowledge of what tolerances and performance specifications are desired is necessary to make the tests truly meaningful. Another criteria for choosing the test to be performed is time. Research environments often have considerably more time (and interest) in determining instrument performance, whereas in production environments quality control tests are usually considered a nuisance and of lower priority than the production work at hand. Therefore, the standardized test procedures must be concise and meaningful. In addition, the procedures must be properly documented and should be complemented by a standard procedure for evaluation.

BASIC HARDWARE TESTS

The author recommends the following tests he used with the National Ocean Survey Analytical Plotter (NOSAP)--a special, state-of-the-art analytical plotter developed to perform all conceivable tasks desired in an analytical plotter (Fritz,1978). These tests represent a selection of tests that have been useful in performing acceptance tests on NOSAP and are not the only way such tests can be made. Although hardware tests will assist in evaluating the accuracy, precision, stability, and optical train quality of the stereoviewer, tests for evaluating plotting hardware peripheral to the stereoviewer are not presented. All of the tests outlined here involve only one photostage and tests such as those for parallelism of dual optical trains are not given. The tests of typical imagery, however, will provide indications of the effectiveness of stereoviewing.

ACCURACY, PRECISION, AND STABILITY

Accuracy, precision, and stability are quality and performance factors that determine the effectiveness of photogrammetric work on analytical plotters. They are often considered of limited importance for "lower order" analytical plotters that are designed for approximate feature extractions. However, it has been demonstrated that one of the great advantages of an analytical plotter is its capability for rapid stereomodel recovery when one wishes to reset photography. To effectively accomplish this requires the measurement of a minimum of fiducial marks. Thus, it must be noted that since the reset model is highly dependent on the accuracy of the pointing on the fiducial marks, all contributing factors to pointing errors will cause the reset model to suffer from significant disturbing parallaxes. Therefore, the need for high accuracy should not be discounted.

Each stage of the analytical plotter may be considered a monocomparator stage. The x, y coordinates encoded from each of the analytical plotter stages are the primary indicators of the ultimate accuracy that can be expected in any output measurements. It should be noted that an analytical plotter is more dynamic in its performance than a monocomparator, in that it is continually checking and upgrading its stage positions (and optics), even during measurement, whereas a monocomparator is static during measurement. Thus, analytical plotters designed for precise work must be stable so that mechanical misalinements can be removed by calibration parameters that represent systematic performance of the hardware. A complete comparator calibration of each stage using precision grid plates is one comprehensive test that is rapid, convenient, and reliable for checking accuracy, precision, and stability.

Several manufacturers have built into their analytical plotter stages tick marks or other means for on-line calibration. Each of these calibrations must stand on its own; but for independent, more complete calibration of the stages, the author recommends the following method (Fritz, 1973):

Grid Plate

A square reseau or grid plate containing 25 symmetrically-spaced reseau or point images is required. The plate must be stable, microflat, optically clear and at least 1/4 inch thick. Each of the 25 images should be identical in shape and easy to point on with a measuring mark. The side dimension of the grid plate should be approximately 200-215 mm for standard stage formats of 250 mm. This will enable the grid to be rotated 11.3^{o} from the stage axes. Calibrated coordinates for each grid point are not required for determination of the parameters that describe the linear systematic errors of the analytical plotter stage. However, calibrated grid coordinates are necessary to determine many of the nonlinear parameters.

Measurement

Redundant, repetitive measurements (pointings) on all 25 grid points should be performed such that the mean pointing on each of the grid points is of equal quality to the mean pointing on any other grid point. (This allows for equal weighting for all grid point means.) The grid plate is then rotated 90^0 and redundant measurements on all 25 points are repeated. Similarly, the plate is measured in the 180^0 and 270^0 positions so that a complete set of measurements in four placements of the grid plate on the same stage location is made. Additional four placement measurements of the grid plate are required for large format stages.

Data Reduction

All of the measurements are processed through a grand least squares adjustment that determines parameters for differential scalers (Sx, Sy), nonorthogonality (α), rotations (θ_i), and translations (Tx_i, Ty_i). The adjustment assumes the grid plate coordinates to be known and adjusts the four measurements sets (i = 1-4) while allowing for each set one rotation (θ_i), and two translations (Tx_i, Ty_i) and, for all, a common nonorthogonality angle (α), scaler x (Sx), and scaler y (Sy). The observation equations for this adjustment are in the form of:

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} + \begin{bmatrix} e \\ f \end{bmatrix} - \begin{bmatrix} x \\ y \end{bmatrix}$$

or

$$\boldsymbol{v} = \boldsymbol{A}\boldsymbol{X} + \boldsymbol{T} - \boldsymbol{x}.$$

where:

$$\boldsymbol{X} = \begin{bmatrix} X \\ Y \end{bmatrix} = \text{orthogonal (grid) system}$$

$$\boldsymbol{x} = \begin{bmatrix} x \\ y \end{bmatrix} = \text{nonorthogonal (comparator) system}$$

$$\boldsymbol{v} = v_x, v_y = \text{residual errors}$$

$$\boldsymbol{A} = a, b, c, d, e, f = \text{parameters}.$$

It has been shown that an exact, linear, noniterative solution for the stage calibration, with residuals given in the measurement system, does exist. Furthermore, the physically identifiable comparator calibration parameters defined in the comparator coordinate system can be explicitly derived as:

$$Sx = \frac{(c^2 + d^2)^{1/2}}{(ad - bc)}$$

$$Sy = \frac{(a^2 + b^2)^{1/2}}{(ad - bc)}$$

$$\alpha = \tan^{-1}\left(\frac{-ac - bd}{ad - bc}\right).$$

These parameters define the systematic linear errors that should be removed from all stage measurements.

Most of the nonlinear systematic errors that may be present in an analytical plotter can be determined from the same four sets of measurements only if the grid plate has been precisely calibrated. Since the grid plate was rotated approximately 11.3^{o} on the stage, the projection of the 25 grid points onto each measurement axis provides an even spacing for data sampling. Normally, the following 4th degree polyomials are more than sufficient to describe the independent nonlinear errors along the stage axes.

$$lx+v_x=Ax^4+By^4+Cx^3+Dy^3+Ex^2+Fy^2+Gx+Hy+J$$

$$ly+v_y=A'x^4+B'y^4+C'x^3+D'y^3+E'x^2+F'y^2+G'x+H'y+J'$$

$$-l+v=Ax.$$

Where: $l=lx,\ ly=$ residuals after linear calibration adjustment (previously denoted as $v_x,\ v_y$).

$v=v_x,\ v_y=$ residuals after the least squares nonlinear calibration adjustment.

$x=A-J,\ A'-J'=$ unknown linear coefficients of the polynomial.

$A=x,\ y=$ comparator measurements after correction for systematic linear errors.

Calibration Analysis

The standard error of a single observation of unit weight from each of the linear and nonlinear adjustments is the statistic that represents the accuracy of a stage of the analytical plotter. The precision of measurements from a stage can be determined from a statistical analysis of the redundant pointings on each of the 25 gridpoints, e.g., the standard deviation of a single pointing observation and the standard deviation of a mean pointing observation. It is appropriate here to note that it is futile to attempt to isolate backlash components either through measurement techniques or by statistical analyses. An analytical plotter positions its stages from encoder or other digital inputs and its final approach direction is determined by the closed servo loop and is thus unpredictable. However, the total pointing precision statistic will include the influence of backlash as well as any other instabilities and random setting errors.

For large format stages an overlapping or adjacent grid placement technique is used to cover the entire measurement area. In this case, the square grid plate must be measured in the four 90^{o} rotation sets for each area of the stage. Simultaneous reduction of all placements will produce a single set of parameters that physically describes the systematic errors of the stage.

COMPARATOR NUMBER 17 CALIBRATION
OPERATOR NUMBER 1
DATE OF MEASUREMENT
GRID AND CASE NUMBER 773
CALIBRATION SUMMARY

ANALYSIS OF VARIANCE

X	Y		
2.301	2.796	2.561	= ROOT MEAN SQUARE ERROR OF A SINGLE OBSERVATION OF UNIT WEIGHT BEFORE CALIBRATION
1.108	1.097	1.103	= STANDARD ERROR OF A SINGLE OBSERVATION OF UNIT WEIGHT AFTER LINEAR ADJUSTMENT
0.890	0.869	0.879	= STANDARD ERROR OF A SINGLE OBSERVATION OF UNIT WEIGHT AFTER LINEAR AND NON-LINEAR ADJUSTMENTS
0.617	0.607	0.612	= STANDARD ERROR OF MEAN POINTING MEASUREMENTS
		0.220	= A PRIORI STANDARD ERROR OF MASTER GRID 773
		0.132	= COMPUTED UNBIASED STANDARD ERROR OF MASTER GRID 773
		2.311	= STANDARD ERROR OF SYSTEMATIC LINEAR ERRORS
		0.665	= STANDARD ERROR OF SYSTEMATIC NON-LINEAR ERRORS
		0.592	= STANDARD ERROR OF RANDOM (IRREGULAR) COMPARATOR ERRORS

ADJUSTED COMPARATOR CALIBRATION PARAMETERS FROM THE SIMULTANEOUS SOLUTION OF 8 CASES

LINEAR PARAMETERS

	PARAMETER VALUE	SIGMA
SCALER X =	0.9999862E+00	0.11029807E-05
SCALER Y =	0.9999741E+00	0.11029709E-05
NON-ORTHOG. ANGLE ALPHA =	0° 0' 9".830	0° 0' 0".3217
SCALER RATIO SX/SY =	0.1000012E+01	

VARIANCE-COVARIANCE MATRIX

SCALER X	SCALER Y	ALPHA
0.12165665E-11	0.72059774E-20	0.13252143E-15
	0.12165449E-11	0.13251236E-15
		0.24332253E-11

SCALERS IN MICRONS/METER

SCALER X =	-13.8283	1.1030
SCALER Y =	-25.8684	1.1030
SX/SY =	12.0401	

NON-LINEAR PARAMETERS

NON-LINEAR CORRECTION COEFFICIENTS FOR X

A	B	C	D	E	F	G	H	J
-0.2117961E-01	-0.1271758E-02	-0.1747051E-03	0.9278875E-05	0.1886816E-03	0.5310517E-04	0.2736659E-05	0.8674509E-07	-0.1687531E-06

NON-LINEAR CORRECTION COEFFICIENTS FOR Y

A	B	C	D	E	F	G	H	J
0.1666035E-01	-0.6816204E-03	-0.3367289E-03	0.8032993E-04	-0.1078274E-03	0.2949555E-04	0.1825535E-05	-0.2524643E-05	-0.3428897E-06

Calibration Summary From 9 x 18" Right Stage of NOSAP
FIGURE 1

It must be emphasized that calibration of a large format stage should be made only with a square grid plate. The use of non-square grid plates can contribute significant grid coordinate biases that will invalidate the physical significance of the stage calibration. Furthermore, the calibration of any format comparator is dependent on the collection of measurements from the four 90° placements of the grid plate on the same area of a comparator stage to minimize the influence of grid plate coordinate errors.

Stage slew speed tests may be performed to provide an indication of not only how fast the stage can travel from point A to B but also how stable the stereoviewer system performs during dynamic operations. These tests should be performed axially and diagonally. High slew speeds are desirable for many perfunctory stereoviewer operations such as fiducial measurement or between scale transfer point locations. An easy method to test slew operations is to observe deviations of the measuring mark from a straight grid plate line while clocking its traverse time.

The above comparator calibration technique will take less than 4 hours to perform per stage. It provides statistics, such as those shown in figure 1, that represent stage accuracy after correction for linear systematic errors and after correction for nonlinear systematic errors, plus the error components from pointing precision and from the grid plate coordinates. Thus, this one test can provide quantifiable indicators of the analytical plotter accuracy and precision and its results can infer an indication of the system stability.

Optical Train Quality

The optical train is the major hardware variant among designs of analytical plotters. Unlike the stages whose dynamic functions create wear and can alter performance with time, most basic optical train characteristics are inherently stable and need not be checked periodically. The optical train characteristics that may warrant testing include resolving power, field of view, stage focus, viewing illumination, viewing magnification, zoom magnification, optical alinement, viewing rotation, measurement mark size, and distortions of the field of view. Most of these characteristics will be tested only prior to purchase or during acceptance testing. Optical alinement and stage focus, however, may need to be checked periodically, as they are the indicators of system performance that will most seriously affect accuracy.

The following presents some suggested techniques for testing the performance of some of these optical train characteristics. These tests can be all performed in one-half day.

- Resolving power can be quantified directly in line pairs per millimeter by reading a set of resolution targets placed in several locations on the stage. A crossed array of five resolution targets that simultaneously cover the field of view is preferred so that resolution throughout the field of view can be checked.

- The diameter of the field of view can be quantified by reading the length of the viewable portion of a linear scale that has been placed on the stage.

- Stage focus may be performed in conjunction with the resolution tests. The prime focus requirement is that imagery placed on any portion of the photostage be in clear focus at only one setting of the viewing focus adjustment.

- Viewing illumination can be quantified by placing a sensitive light meter, preferably a spot meter, in front of the exit pupil or viewing screen. Care must be taken to mask off other light sources from the meter's field.

- Absolute magnification can be quantified by the comparison of a small grid pattern of known dimensions placed on the stage with an identical grid pattern placed immediately behind the eyepiece or on the viewing screen. A count of the grid squares on the stage that can be enclosed in a single eyepiece grid square provides the enlargement factor. Similar procedures can be used to check zoom magnification performance.

- To test optical alinement requires the placement of a circular target in the center of the exit pupil of the viewing optics. The diameter of the circular target is defined by the allowable tolerance specified. The alinement test requires that the measurement mark be maintained within the confines of the circular target under all conditions of stage location, optical rotation, zoom or steps of magnification, viewing focus adjustments, and allowable temperature ranges.

Further, more elaborate tests will be necessary for the more complex analytical plotter stereoviewers. For example, all Dove prisms are not perfectly symmetrical and can change resolution with the angle of rotation of the view. For those analytical plotters that allow for a continuous range of optical rotation and zoom magnification, a set of special tests and standards must be prepared to allow for evaluation of their dynamic performance. For the NOSAP evaluation, an overlapping pair of artifically generated, high oblique views of a grid pattern were prepared on a precision flatbed plotter. Stereotesting of this model consists of moving to various grid intersections and comparing the known angular convergence and known enlargement ratio with those computed in the generation of the pattern. Criteria for the test is that the observed discrepancies must be within the specified tolerances.

TEST GUIDELINES AND SUMMARY

In selecting those tests that will demonstrate system performance, the task of how to evaluate the results must be carefully considered. For those tests that may be quantified, it is recommended that results be kept in tabular form or plotted on a control chart so that a running record of instrument performance can be maintained. A careful determination of what magnitude of change is statistically significant will enable the user to use the table as a quality control. Significant change indicates the need for certain maintenance to be performed. Value will also be obtained from the tabular record in that it documents any deterioration with time that in turn can assist management in long-term plans for repair and replacements.

It should be noted that before starting any component testing that the operator be familiar with all aspects of operating the analytical plotter.

This paper has addressed only a few of the objectives of Working Group II-1. As the user community expands, a series of additional test procedures for analytical plotters will evolve. The collection, evaluation, and dissemination of a complete generalized set of testing procedures is a logical extension of Working Group II-1's efforts.

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