CAPABILITY STUDIES OF DENSITOMETERS AND DENSITOMETRY

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Abstract: Since densitometric data is used in **SPC**, Statistical Process Control, it is essential to know the capability of densitometery as a measurement process. Also, knowing the inherent variability and stability of process components can lead to improved data by optimizing operating and control procedures. Studies of commercial densitomers are used to illustrate the process of resolving components of system variability. Identical experiments can be applied to colorimeters and spectrophotometers since they are closely related instruments. The examples illustrated do not represent an endorsement or condemnation of the instruments by either PSI ASSOCIATES or the ANSI Subcommittee IT2-28. One fact, however, is clear all densitometers are not created equal.

Measurement as a Process

Measurement of any kind is not a single action but a process. The measurement process is shown in the schematic diagram of Figure 1. Virtually all measurement is made by comparison and involves a procedure whereby the operator judges the equality of end points, selection of samples, or perhaps the

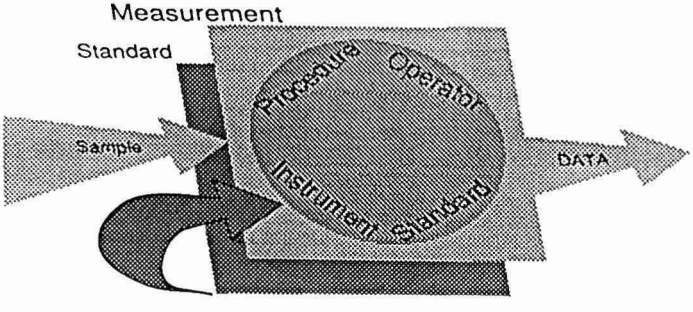

Figure 1. Measurement as a Process

existence of a state of equilibrium. The instrument, or device, used for measurement is based on some assumption of physical fact and some method of calibration. On the left of the schematic the sample is presented to the process

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and measurement data leaves the process at the right. The process elements must include the instrument, operator, procedure and standards. These are shown in a cyclic configuration because they are of equal importance but may not have equal bearing on the precision and accuracy of the data. Each element in the measurement process contributes variability, sometimes referred to as measurement error, to data values output from the process. When a measurement process is tested to determine its accuracy and precision, a confidence level may be defined that produces a statement such as: 95% of the measurements lie within 5% of the accepted value. By devising experiments to evaluate individual components of the process, or even sub sets of the individual components, analytical information is obtained to aid in changing the process to provide optimum overall performance. Note that the values and physical materials used to establish standards for the measurement process are the product of a similar process which also has inherent variability. It is an aim of the standards community to keep the variability of standard reference materials to less than 10% of the variability of the measurement process. This long standing rule of thumb is also verified by system analysis using the techniques of information theory. In the real world of measurements, the standards metrology meets this 10% rule of thumb. The physical materials used as transfer standards are often deficient.

Precision & Accuracy
Short Range & Long Range

Whenever a process such as densitometric measurement is repeated, the results will vary from one measurement to the next. It is a fact of nature that events or actions influenced by their environment will not be exactly replicated. When the

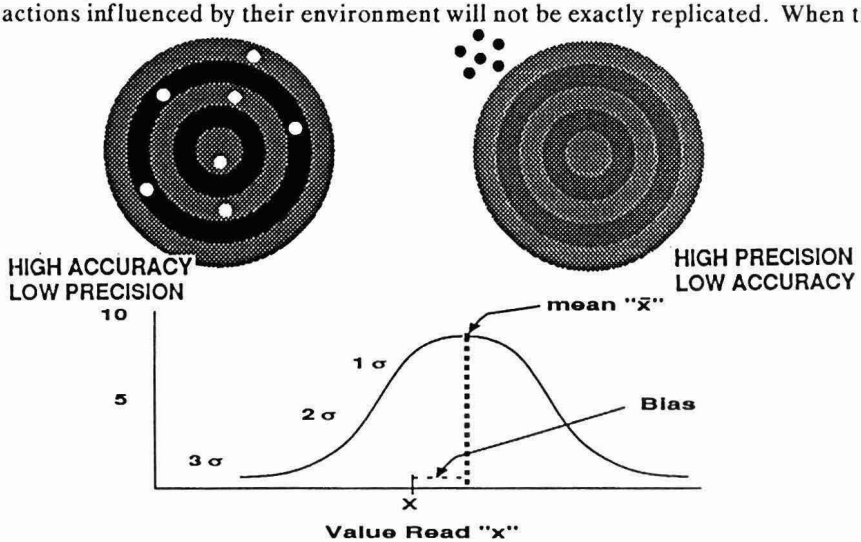

Figure 2. Accuracy & Precision -- Mean & Sigma

variation is random in nature, the result of the process will vary according to statistical principles described by a bell shaped, or Gaussian, distribution. In fact, plotting the frequency of occurrence of output values is one test for random processes. If the resulting histogram is bell shaped and symmetrical, the process behaves as if variability were random. One may think of the distribution of data being similar to shots on a target as shown in Figure 2. The peak value of the bell shaped curve is the mean value and the spread is described by a standard deviation written as σ. The departure of the mean value from the accepted value is the accuracy of the measurement; the spread of the distribution of many replications is the precision of the measurement. If you must be the target of a person with a gun, hope that the marksman has high accuracy and low precision because his efforts to compensate for error will increase the spread where if he has high precision and low accuracy each correction will bring the shot closer to the target.

In the statistical process control environment, precision is more important than accuracy within any process or limited manufacturing operation. Accuracy is needed when the control information is to be shared outside the process or local operation. A firm understanding of the capability (accuracy and precision) of a measurement system is the starting point for good statistical process control. When the values of the accuracy and precision, the bias and σ, are determined over a few hour period of measurement, the values represent the short range stability and variability of the measurement process. When these same values are determined for a longer period, a month or so, they are long range values. Both are important parts of the capability study.

Determining Precision & Accuracy

The precision and accuracy of the densitometry measurement system may be determined by obtaining a set of at least twenty readings of a single bar chart over a period of a few hours. Note that this method determines the capability of the total system of densitometry — the instrument, the operator and a unique interaction of the densitometer's reading field with the uniformity of a single sample. A complete description of the experiment is given in the booklet Introduction to Densitometry (Graphic Communications Association, 1989).

1) The densitometer should be calibrated and checked in using the normal production procedures.

2) Without readjusting the densitometer take three readings of the same bar chart, or similar test target, each hour for twenty hours. It is equally valid to take the twenty sets of readings spaced over several days. Each time read the bar chart in the same sequence and record the data.

3) The X-bar/R chart supplied by GCA provides a handy form for analysis of the data, although a person already familiar with spread sheets on a personal computer would find the electronic method faster and easier. Perform the X-bar/R analysis for each target -- white, black, cyan, magenta and yellow. The values of σ obtained for each target and color measured provide an

indication of the total standard deviation, σ_T, at each measurement level. It is not unreasonable that σ's associated with the white measurement be smaller than σ's for black or the major color densities because the signal to noise ratio is higher at low densities. Consider σ's within $\pm 5\%$ of the σ value to be essentially the same.

At this point the σ's indicate the current capability of the measurement system. If these can be resolved into the contribution of each independent variable, the system or procedure may be modified to increase precision.

Resolving the Components of Variability

Variability of processes that are independent can be described by the standard error σ. When two independently variable processes (σ_1 and σ_s) act in concert, their combined standard error, σ_T is described by the Pythagorean addition:

$$\sigma_T = \sqrt{\sigma_1^2 + \sigma_s^2} \quad \text{or} \quad \sigma_T^2 = \sigma_1^2 + s_s^2$$

One component of variability, σ_1, may be removed from the overall, σ_T, and the residue computed by simple algebra.

$$\sigma_1^2 = \sigma_T^2 / \sigma_1^2$$

All that is required is to devise an experiment that determines the standard error for only one component of the system. Further experiments can resolve the residue and by repeating the process the individual components can be removed one by one. Some caution is required in the design of the experiment because the computations will only resolve independent components of variation. Thus if dependent components are derived, the computed and actual variability will differ.

Instrument Variability

The first independent component of measurement variation is the ability of the densitometer to repeat measurements of an invariant sample. Since the densitometer's response may vary across the reading aperture and the sample being read may have a reflectance that varies from point to point across this aperture, it is essential that the reading aperture and sample be fixed together so there is no movement. Ceramic tiles made for densitometer set up have the advantage of having reflectance that is virtually independent of the environment. They are not really uniform in reflectance from point to point and have some sub surface reflectance. These factors both make it imperative that the sample and densitometer be immobilized. The densitometer's photometry alone may be tested by measurement of all four color densities at regular intervals. This test should be done for both the white and a dark or black sample. The variability will usually be greater for dark samples than for the white sample because the signal level from a dark sample is reduced and the noise remains constant.

Most modern commercial densitometers actuate the measurement by lowering the reading head. If the stability testing is done with an operator moving the head the resulting standard deviation, σ_r, includes the variation of the measurement triggering as well as the variation of the lamp-photocell-signal processing system. For densitometers with a bidirectional RS232 computer connection, the head may be left in the down position and the reading triggered by computer command. Experimentalists may make a parallel connection between a switched interface card and the lamp switch as shown in Figure 3. Computer initiation of the reading isolates the photometric stability and permits

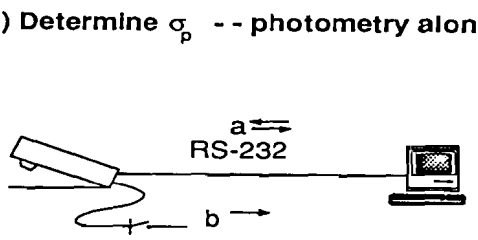

Figure 3. Reading Initiated by Computer Command

collection of data taken over extended time periods in an unattended manner. The computer may also be programmed to compute X-bar and σ for each of the four color densities. The sample may be read every 15 sec for days on end. By partitioning the data in segments of five hours, the change in X-bar may be recorded. This represents a drift in the zeroing of the photometer. If the values from this test are plotted on a "clothes line" control chart, the variation contributing to the σ values are scattered about the central line and the drift is shown as a steady trend upward or downward. The standard deviation and drift for two commercial densitometers is shown below. All densitometers are not equal!

All of the following values are one σ.

	Computer trigger	Manual trigger
Very Good -- Brand 1	σ_V = 0.0009	σ_V = 0.0014
	σ_R = 0.0008	σ_R = 0.0016
	σ_G = 0.0009	σ_G = 0.0021
	σ_B = 0.0011	σ_B = 0.0025

The drift was about 0.001 per 100 hours on both conditions.

Not So Good -- Brand 2	σ_V = 0.008	σ_V = 0.009
	σ_R = 0.007	σ_R = 0.008
	σ_G = 0.011	σ_G = 0.014
	σ_B = 0.018	σ_B = 0.020

The drift was about 0.029 per 100 hours on both conditions.

This test extended over 200 hours. The computer triggered measurements every 15 seconds. The manual trigger was spaced about 20 minutes or so during working hours as the spirit and other assignments moved the operator.

When this test was repeated for a dark sample, Density = 1.6, the drift was essentially the same as it was for white but the dark standard deviation was greater than that for white.

$$\sigma_{1.6} \approx 5\sigma_{0.1}$$

At this point one might wonder if densitometer readings are improved by rezeroing the instrument with each set of bar charts.

The Reading Variability

Analysis of data from the preceeding test produced values for the standard deviation introduced by the photometric system of the densitometer. It also produced information about the short and long term stability of the photometric system. Production measurements can never get better than this.

The ink on paper samples are not totally uniform from point to point and neither is the reading sensitivity of most portable densitometers. The standard deviation contributed by the process of carefully positioning the densitometer on the sample can be determined by a test like the previous X-bar/R test. Because we know the drift and long range standard deviations for the instrument alone, sample readings of 60 or so can be taken in a relatively short period of time. The variable here is the change of density with positioning.

Select solid ink patches on a bar chart that appears to be uniformly printed. Mark sets of reference lines centering on each target. These will be used to aid in positioning the densitometer. Without resetting the calibration, measure the targets, repeatedly moving the densitometer from target to target each reading cycle. Determine the reading standard deviation values, σ_R, for each target. Repeat the test with different operators because this standard deviation is technique sensitive. Study the deviations obtained by the different operators to find the best technique of reading. The standard deviation for positioning, σ_P, is obtained by removing the value of σ_I obtained in the previous section from σ_R by the pythagorean equation.

The standard deviation for reading, σ_R, is probably smaller than the overall standard deviation, σ_T, because of other environmental factors not yet considered. The standard deviation, σ_R, represents the best condition of reading real ink on paper targets with this densitometer since it includes the morphology of response and target.

Other Positioning Considerations

Since both the instrument and operator caused random variation has been accounted for in the preceding tests, a new set of experiments will measure the instantaneous systematic positioning errors.

1) Response uniformity and the sample uniformity may be measured by taking a series of readings centered on the target with the densitometer rotated in equal angular increments until the full 360° of rotation have been spanned. The spread in these density values represent the non uniformity of the target as seen by the densitometer under test. If the target were completely uniform, the variation of response across the measurement aperture would not matter; and similarly, if the response were uniform across the measurement aperture the non uniformity of the target would not be noticed. The spread in these density readings is not a random variable and thus is not properly defined with a σ value. Try this experiment with a number of color bar charts and find a typical spread. This density spread is an uncertainty or "fuzziness" applied to the mean density values not the σ's.

2) The 45°-0° geometry has been chosen for densitometric measurements and is becoming more frequently used for colorimetry because it is the least sensitive to surface variations. The 45°-0° geometry provides measurements that correlate to visual perception of density or reflectance better than the sphere geometry in complete collection mode or even in the specular excluded mode. Figure 4 shows a 45° - 0° geometry meeting the definition of ANSI PH2.17 as sharply focussed for both illumination and collection There

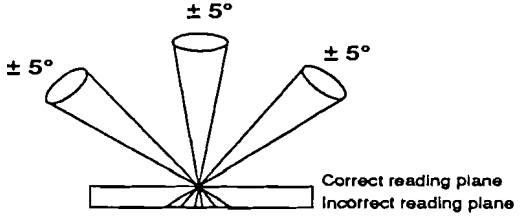

Figure 4. The 45° - 0° Geometry is Sharply Focussed

is little depth of field and small changes in the "Z-axis," up and down position, create variation in readings. As shown in Figure 5 read the target on a hard flat surface next shim one side of the reading shoe and finally shim

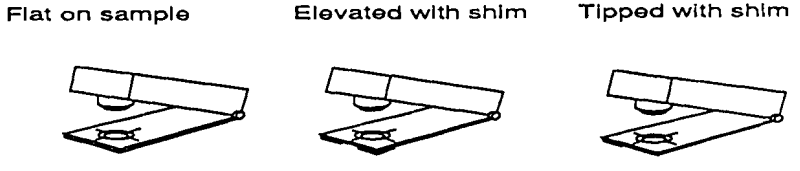

Figure 5. Shims as a Test for Z-axis Sensitivity

both sides of the shoe with a business card. Try this on densitometers of different design or manufacture. The sensitivity to positioning is an indication of conformance to ANSI standards. This experiment should make the user critical of measurement procedure and not of the densitometer. Measurements made on a soft yielding stack of paper are subject to larger errors than those made with a single sheet on a hard surface. These tests of

sample position sensitivity are performed to help the user develop measurement techniques that reduce errors caused by the operating procedure.

The Effect of Ambient Conditions

Light measuring instruments are often dependent on the ambient conditions of temperature, light level and supply voltage. Many modern densitometers are battery operated and are independent of supply voltage. Sensitivity to ambient conditions is easily tested by repeating the head-down sample fixed computer activated experiment. Readings are taken about every 10 seconds for 30 minutes. Performance is characterized by the values of X-bar and σ. The new ambient condition is introduced and the effect on X-bar and σ noted.

1) For sensitivity to ambient light, the 30 minute multiple reading test is performed using a target with density over 1.3. Operate the first test with the room darkened and repeat the test with bright light flooding the area occupied by the densitometer. Of the instruments tested, none showed a variation of σ with light level. The best densitometer for this attribute showed a shift of X-bar of -0.001 with a change of ambient light from <1 lux to 50 lux. The poorest instrument shifted 0.016 for these light levels.

2) For sensitivity to ambient temperature, the 30 minute multiple reading test is performed using both a near white target and a target of density over 1.3. The two tests are made because it is necessary to determine both the change of signal and change of gain with temperature. Operate the first test and determine X-bar and σ for light and dark targets at room temperature. Place the densitometer in a black lined box heated with a 25 watt lamp. The lamp should be baffled so that the densitometer is not directly illuminated. Place a thermometer in the box and repeat both light and dark target tests with with temperature at equilibrium. Of the instruments tested, none showed a significant variation of σ with temperature. The best densitometer for this attribute showed a shift of X-bar of -0.002 per 10°F. and no real shift in the gain, measured by the difference between the high and low densities at each temperature condition. The poorest instrument shifted 0.01 in level but not in gain.

Calibration, Standardization and Control

The variability of reading that has been determined in these tests will also be present when the densitometer is being calibrated or set by reading a standard. Two densitometers calibrated to the same set of physical reference standards will agree within 1σ 68% of the time and within 2σ 95% of the time. Since standards generating is also a process, the value of σ_T must be expanded to include the σ values for the standards process when the densitometers are calibrated to different physical standards . The standard deviations for the standards generating process are usually about ¼ of densitometric errors. The largest error is that of sample morphology, this is included in the densitometer's standard deviation. Matching instruments closer than the 68% confidence level indicated by the 1σ values, requires that multiple reading techniques be used.

A common mistake in establishing densitometric procedures is the frequent re-zeroing of the instrument. Having studied the long range σ and drift for the photometric measurements and the σ associated with manual reading an operator can draw a control chart. The reference zero target should be read before each set of measurements and if the value lies within the control limits, the instrument should not be reset. In the ideal case, if the check of the reference zero is out of tolerance for three successive retests, the correction should be made for ½ of the indicated value. The automatic calibration procedures built into many densitometers make this procedure difficult. However, at the very least, only recalibrate the zero reference value when several repeated checks indicate an out of tolerance condition.

Summary

The total standard deviation of the densitometric process, σ_T, as determined by manual operation of the instrument making repeat measurements of a single target provides a figure of merit for interpreting data in a Statistical Process Control operation. This value should be derived for each local densitometer, or for enough densitometers of the same model that it is reasonable to use the average values as representative of the family of instruments.

Exact or typical values for the components of this standard deviation may be derived for each densitometer and may serve as a guide to better understanding of the source of measurement variability. These data are a guide to specifying a better procedure for control and measurement. Typical components of variability are:

Photometer alone	$\sigma_P = 0.002$
Manual trigger	$\sigma_M = 0.004$
Environment	$\sigma_E = 0.003$
Reading Sample	$\sigma_R = 0.015$

The densitometric hardware contributes less variation to the data than the sample, operating techniques and control procedue.

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