SPEED-INVARIANT, ON-PRESS COLOR QUALITY MEASUREMENT

M. L. Simpson, R. F. Bliss, D. E. McMillan, R. N. Nodine, and J. S. Goddard*

Abstract: Color measurement is an important aspect of quality control for graphic printing press operation. Normally, measurements of color quality are performed by sampling the product off-line, in which case feedback to press operators is not available in a timely manner. On-press measurement of color quality provides timely feedback to the press operators; however, maintaining the accuracy of the measurement in a dynamic setting is not trivial. In this paper, a colorimeter measurement system using commercially available equipment is described for making reliable, on-press color measurements. The system was demonstrated on a web test bed running loops of printed graphic images. Examples of commercially printed graphic material include product labels, packaging, and stamps. Resulting color measurements were shown to be highly sensitive to variations in color-content while maintaining invariance to web speeds as high as 500 ft/min.

Subject terms: colorimetry, on-process measurements, printed graphic images

1. INTRODUCTION

The purpose of color measurement is to provide a quantitative evaluation of the phenomenon of color as perceived by human vision [1]. Standards for these measurements have been set by the Commission Internationale de l'Eclairage (CIE) in 1931 based on a series of experiments in which trained observers were asked to adjust the proportions of red, blue, and green light in one field to match a specific color in a second field. These proportions were found to be unique for each color and were then transformed into the standard X,Y, and Z tristimulus values by the CIE [2]. Therefore, color measurement systems are designed to provide XYZ tristimulus values as an output and must have a standard reference to achieve traceability to the 1931 CIE observer tristimulus values. The two color measurement systems now being used by the graphics printing industry are the spectrophotometer and the colorimeter. A third measurement system that is used in color evaluation in the printing industry, but is not traceable to the 1931 curves, is the densitometer [3].

Colorimeters are perhaps the most common color measurement system used by the graphics printing industry. The standard references used by colorimeters to obtain 1931 CIE tristimulus values are the illumination source and the filter/photodetector spectral response. The illumination source is typically Standard Illuminant C and the filter/photodetector combination is designed to replicate the standard X,Y, and Z curves [4]. Therefore the outputs of the photodetectors yield the tristimulus values directly. Variations in static colorimeter measurements (off-line) are due to differences in the filter/photodetector spectral response and that of the 1931 standard observer as well as variations in the intensity of the illumination source. Illumination variations can be differences between the source and the standard illuminant and/or spatial changes in light intensity across the measurement field. Dynamic

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colorimeter errors (those incurred while measuring a moving web) are also present when sampling complex images such as product labels and stamps. Dynamic errors are linked to at least three factors: 1) nonuniform sampling of image color-content by the three photodetectors/filters, 2) sampling different portions of the printed image(s) as the web moves, and 3) including miscellaneous web features such as color bars or sheet breaks in the measurement.

Previous on-press color quality measurements have reduced the sources of dynamic error in colorimeters by using a large aperture and long measurement integration times [5]. These systems have been demonstrated as valuable quality control tools; however, the dynamic error sources were eliminated at the expense of sensitivity and resolution. In the present paper, a colorimeter measurement system is described which addresses the on-press errors described above and provides reliable, high resolution, image color-content measurements on a moving web transport system. The system was developed with commercially available hardware. The system design as well as experimental data taken from loops of printed graphic material on a web test bed are described.

2. ON-PRESS ERRORS IN COLORIMETERS

The potential sources of dynamic error discussed above come from geometric limitations of the colorimeter design and from web synchronization problems. Geometric limitations result in the color measurement system being sensitive to lateral web movements. The failure to synchronize the measurement to the moving web results in errors from web artifacts such as sheet breaks and color bars. Problems also occur when the printed images on the web are not identical as is the case with numerous types of stamps. In those cases, non-synchronized sampling of the web also results in the inclusion of different images in the measurement. In the following paragraphs, these sources of errors are discussed in detail.

2.2 Geometric Limitations

A typical colorimeter system is diagrammed in Figure 1. The colorimeter consists of a pair of calibrated illumination lamps, a front aperture, an incoherent fiber bundle, four filters (Xa, Xb, Y, and Z), and four photodetectors. The product to be measured is placed at a fixed distance below the front aperture and illuminated symmetrically via the pair of lamps. The resulting image is then transmitted through appropriate lenses to the incoherent fiber bundle. The fiber bundle, then randomizes the color-content of the image, divides the randomized image into four equal samples, and transmits the samples to the individual filter/photodetector units.

One source of error from the geometric configuration of the colorimeter is due to the front aperture. The aperture acts like a field stop to the colorimeter optics and thus limits the field of view seen by the photodetectors. Due to the physical position of the lamps in the colorimeter probe head, the aperture can also restrict the image illumination and can cause areas of different intensities within the measurement field, as depicted in Figure 2. This effect tends to deemphasize peripheral regions of the printed image and emphasize central regions. For a highly restrictive aperture, the result would be a thin, highly illuminated strip down the

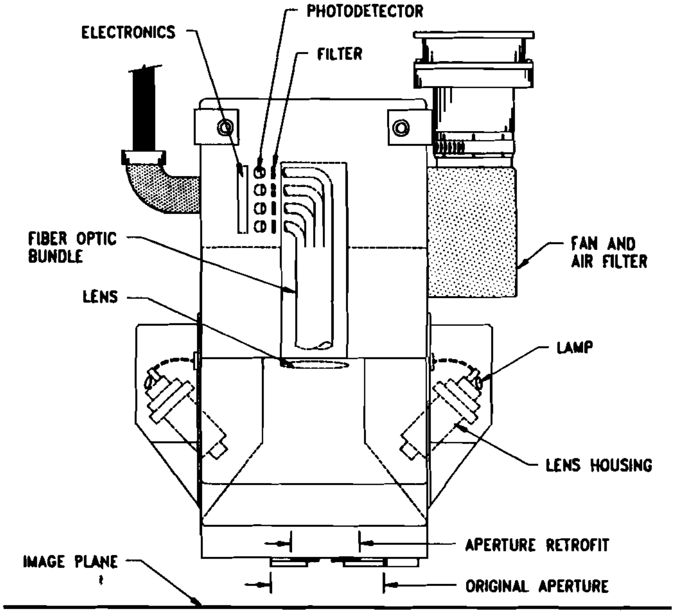


Fig.1 - Colorimeter Probe Head

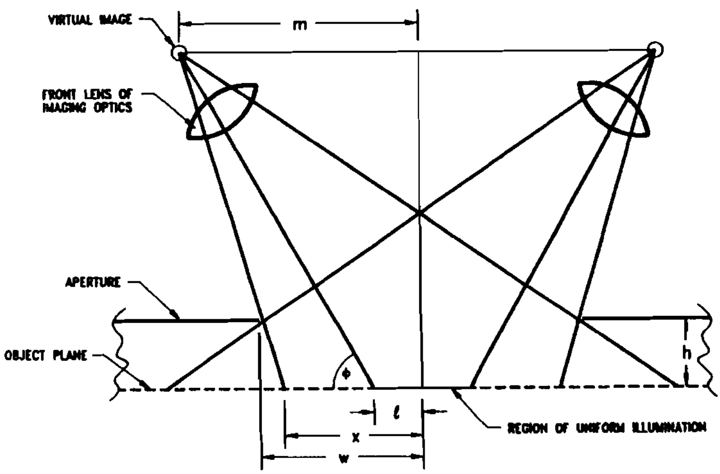


Fig.2 - Geometry of Colorimeter Optics

center of the image which would dominate the color-content measurement. Any lateral web movements will then cause different portions of the image to be emphasized in the color measurement, resulting in variations in the readings. Thus one consequence of the aperture effect is an increased sensitivity to lateral web motion. This effect can be observed by varying the height of the aperture (offset) above the image while recording the output of the colorimeter for a given image translation under the aperture.

A second source of error caused by geometric limitations in the colorimeter is the incoherent fiber optic bundle. Ideally, the incoherent fiber bundle is randomized so that each filter/photodetector combination sees the same image color-content. In commercially-available colorimeters, though, the fiber bundle is not ideally randomized. The result is that each of the filter/photodetector units is sensitive to different regions of the measurement field. As long as the same image position is maintained with respect to the aperture of the colorimeter, color difference comparisons can be made between sequential images. However, if the image is rotated or translated (lateral web movements), variations in the color readings will result. This effect can be demonstrated by using an image which is a uniform color square, smaller in size than the aperture, on a uniform background of a second color. Large variations in the colorimeter outputs are observed as the smaller square is translated within the confines of the aperture.

2.2 Web Synchronization

Another important aspect for controlling error sources in dynamic web measurements is the synchronization of the measurement to the movement of the web. Most standard, off-the-shelf colorimeters average individual readings over a fixed integration time. The output of the colorimeter is then the average XYZ reading for that period of time. In some commercial colorimeters, the integration time can be altered (software), however, there are only a finite number of integration times available to the user, and the integration time is normally fixed during operation. The use of a fixed integration time for on-press color quality measurements on a web of complex images can result in two types of errors; 1) inclusion of different images or portions of images in the measurement and 2) inclusion of miscellaneous web artifacts (ie. color bars or sheet breaks) in the measurement. One partial solution is to use a short integration time which is synchronized with the web such that web artifacts are not included in the measurement. This solution works for the situation where the web transport speed is always constant, however if the web transport speed varies, different images or portions of images are again presented to the colorimeter. The sensitivity of the measurement to web transport speed for the synchronized, fixed integration time is very noticeable for webs of highly diverse images.

3.0 ON-PRESS COLORIMETER MEASUREMENT SYSTEM DESIGN

In designing a speed-invariant, on-press colorimeter system for web inspection, the single most important design criterion is to present the colorimeter with the same image(s) every measurement. This requires two things: 1) customization of the aperture of the colorimeter for the product to be inspected and 2) synchronization of the integration time of the colorimeter with fixed regions of the web. In this section, details of the on-press colorimeter measurement system design are presented.

3.1 Customized Aperture

Several shapes, including circular and rectangular, and several sizes of apertures are available in commercially-manufactured colorimeter systems. If a generic front aperture is used, however, variations in the colorimeter outputs occur from translations of the image under the aperture since different images or portions of images are included in the measurement. This effect can be seen in Figure 3a where a circular aperture is used to inspect multiple rectangular images. As the images are translated (web direction) the colorimeter sensors "see" different images. If the aperture is large compared to the size of a single image on the web, this effect is minimized; however, the sensitivity of the colorimeter to color-content variations in a single column of images is then reduced. An alternative is to customize the front aperture of the colorimeter such that it is the same size as an image or an integral number of images on the web. With a customized aperture, the colorimeter sensors are restricted to the same image region regardless of the position of the images under the colorimeter probe head since the fiber optic bundle, interfacing the image to the sensors, is designed to randomize the color-content over the whole image field. The customized aperture is depicted in Figure 3b. The front aperture of a standard, off-the-shelf colorimeter is easily adapted to various product image sizes by retrofitting a second aperture, smaller than the original front aperture, on the face of the colorimeter probe head as shown in Figure 1.

One problem encountered with using a second aperture is the spatial variations of light intensity incurred in the measurement field as discussed in the previous section and as depicted in Figure 2. Two things can be done to make the light intensity over the measurement field more uniform: 1) correcting the width of the second aperture from geometric considerations and 2) reducing the offset between the aperture face and the measurement surface. Geometric corrections are performed by making the second aperture slightly larger than the image (or integral number of images) so that the illumination over the actual image is uniform. From Figure 2, an expression for the angle between the lamp normal and the measurement plane, ϕ, can be derived from the color probe offset, h; the distance, l, from the lamp normal/measurement-plane intersection and the measurement field center line; the distance, m, from the lamp to a normal from the center of the measurement field; the width, x, of the uniform illumination; and the width, w, of the aperture. This expression is:

$$w = x + \frac{h(m-x)}{(\tan\phi)(m-l)} \quad . \tag{1}$$

In practice, one can easily measure h, l, w, and x from the illumination field and probe head offset; however, m and ϕ are not easily obtained. An alternate approach for obtaining these parameters is to make two apertures of different size and measure the resulting w and x parameters in the illumination field for given offsets, l and h, thus generating two equations and two unknowns (m and ϕ). Once m and ϕ are known, the required aperture width, 2w, to produce a uniform illumination field of width, 2x, can be calculated.

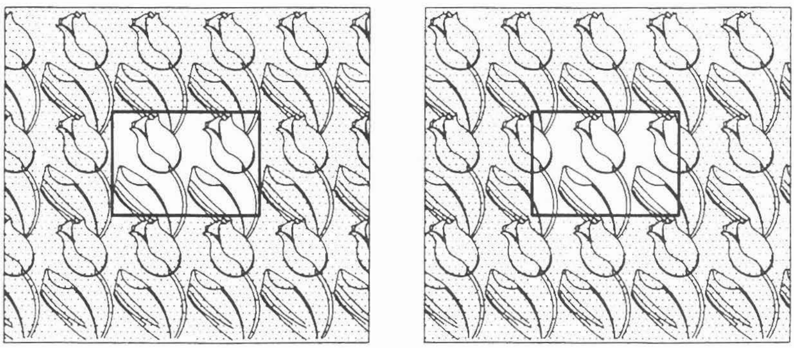
A second correction to the non-uniform illumination caused by the presence of the additional aperture is the adjustment of the offset, h, between the face of the aperture and the measurement plane. The smaller this distance, the smaller the fringe area of nonuniform

Fig. 3a.

POSITION 1: GENERIC APERTURE

POSITION 2: GENERIC APERTURE

Fig. 3b.



POSITION 1: CUSTOMIZED APERTURE

POSITION 2: CUSTOMIZED APERTURE

Fig.3 - Generic vs. Customized Colorimeter Aperture

illumination, (w-x), and the better the second aperture performs as a field stop to the imaging optics. The recommended offset range for commercially-available colorimeters is typically from 0.75 to 0.25-in. Since there is little out-of-plane motion of webs in graphic printing processes, the offset should be adjusted to the minimum recommended distance (0.25-in.) for best performance. These effects (sensitivity of colorimeter measurement to aperture width and offset) were verified in a series of tests in which both aperture width and offset were varied for given image translations. Minimum variations in the colorimeter readings for both lateral and web direction motion were obtained with a corrected, customized aperture and a 0.25-in. offset.

3.2 Synchronized Measurements

The second issue that must be addressed before speed-invariant color content measurements can be made on a moving web of printed material is synchronizing the measurement to the movement of the web. More specifically, since graphic printing processes have an image repeat length due to the physical nature of the printing cylinder, one would like to make measurements on the same images every repeat length. Thus the colorimeter would average readings only when the images of interest were under the colorimeter probe head. In this way, miscellaneous artifacts such as the appearance of color bars between repeat lengths or the appearance of sheet breaks, do not compromise the color-content measurement. Also, for the case of complex multiple-images, even though the images are different in the direction of web travel, the color-content measurement is always made on the same combination of images. Thus consistent color-content information is presented to the operator for quality control of the printing process, independent of web velocity.

To implement color-content measurements, synchronized to the web, two items are required: 1) a synchronization signal from the web and 2) a colorimeter with gated integration times. The synchronization signal can be obtained using inputs from an optical mark sensor positioned over the web and from an encoder wheel. The mark sensor operates in the photo-reflective mode to detect the occurrence of color registration marks in the selvage area of the web. The spacing between a unique pair of marks on the web is detected each repeat length. The encoder wheel pulses, generated every 5-mils, are then used to locate a specific region within the repeat length after the occurrence of the signal from the mark sensor due to the unique spacing. The synchronization system, termed the "ticker", has been implemented using "look-up" tables so that multiple, aperiodic pulses can be generated each repeat length. This implementation provides flexibility to examine the color content of any region(s) of the web within each repeat length.

Two types of colorimeter software packages are available in commercial systems, one with fixed, preset integration times and the second with variable, gated integration times. The latter package must be used if speed-invariant, color quality measurements are to made on moving webs of printed graphic images. In addition, the colorimeter must provide the hardware to process the gating signal from the ticker and thus gate the color measurement. Once the ticker and the gated measurement capability are established, one final item must be addressed. Logistics of mounting the colorimeter and the ticker on the press usually dictate a physical separation of the two sensors. A fixed delay in the ticker signal must therefore be added to compensate for this separation and guarantee the synchronization of the colorimeter measurement to specific regions on the web.

4.0 EXPERIMENTAL RESULTS AND MEASUREMENTS

The colorimeter system, modified for synchronized sampling and retrofitted with a second aperture, was mounted on a web test bed at the Oak Ridge National Laboratory (ORNL) for testing. The web test bed is designed to operate in both a roll-to-roll mode and a loop mode up to 1200-ft/min. In the roll-to-roll mode, a single 200-lb roll of printed material can be unwound and fed past an inspection station and then rewound into a second roll. In the loop mode, a continuous loop of printed material (approximately 100-ft in length) can be fed past the inspection station. A loop of printed graphic images was used in these tests to examine the sensitivity of the customized colorimeter system to web velocity and to examine the repeatability of the resulting color measurement. The results of these tests are presented in this section.

The repeatability of the modified colorimeter system was tested by positioning the colorimeter probe head over a column of images and making both synchronized and unsynchronized color quality measurements at a fixed web velocity of 300-ft/min. The unsynchronized measurements were implemented by using a fixed integration time of 30-ms and a measurement repetition rate not linked to the movement of the web. Synchronized measurements were made by integrating the color content signals from the colorimeter over a single image repeat length. The color scale used in the tests was the Hunter LAB scale [6]. The results of the tests are plotted in Figures 4 and 5. A repeatable pattern in L,a, and b color space is generated with the synchronized measurement as the loop of images passes the sensor (the loop splice is indicated by the large repetitive negative spike in the L curve of Figure 4). As expected, the unsynchronized measurements (Figure 5) had no repeating pattern. Note also that the average values of the color readings were substantially different between the synchronized and unsynchronized measurements. The average value of the synchronized dynamic measurements accurately reflected LAB values obtained with the colorimeter positioned over single images while the web movement was stopped (static LAB readings varied spatially over the loop as depicted in Figure 4).

The sensitivity of the modified colorimeter system to variations in web speed was tested by again positioning the color probe head over a single column of images, but this time the web velocity was varied from 50 to 500-ft/min. In the test, approximately one hundred readings were taken at each of the speeds 50, 150, 300, 500-ft/min and the L, a, and b values from the one hundred readings are plotted in Figures 6 and 7 for both the synchronized and the unsynchronized cases respectively. In the figures, the first and second quartiles of the data set at each speed are shown as a rectangle. The median value of the data is represented by the line drawn within the rectangle and the bars represent the range of the data set. Statistical outliers (outside the range of the data set within a certain percentile) are plotted separately. For the synchronized data set plotted in Figure 6, the first and second quartiles, the median values, and the range of the data are very consistent with speed. The variations in the data are thus a result of actual color content variations on the web. As mentioned above, these L, a, and b values accurately reflect static measurements (web stopped). The outliers in Figure 6 are a result of the loop splice overlapping images.

The asynchronous data sets plotted in Figure 7, however, demonstrate a dramatic change in the first and second quartiles as well as the range as a function of speed. The large variance in the asynchronous data sets at low speeds (much larger than the synchronous case)

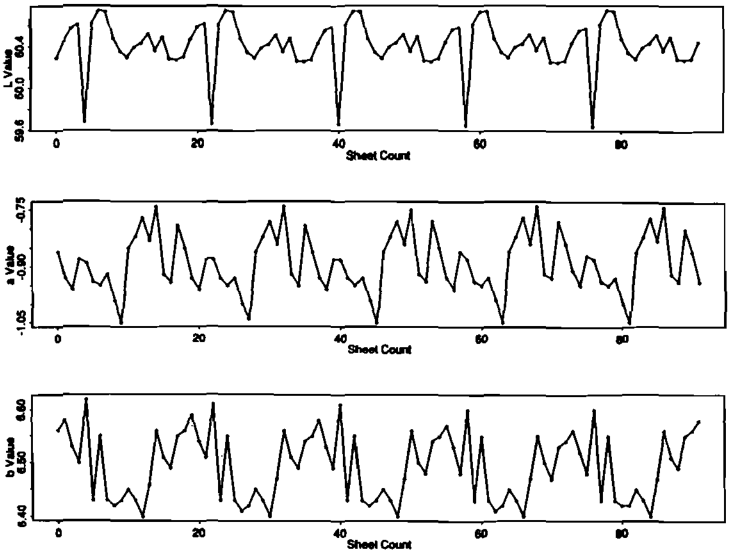


Figure 4: Synchronous Colorimeter Readings (300 ft/min)

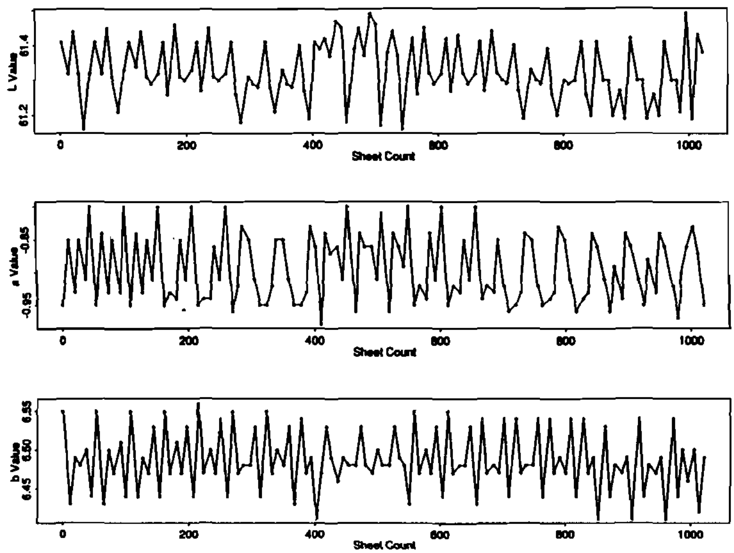


Figure 5: Asynchronous Colorimeter Readings (300 ft/min)

is a result of the inclusion of color bars, sheet breaks, loop splices and other miscellaneous web artifacts in the measurement. At higher speeds, more of the web is sampled during the measurement due to the fixed integration time, thus the variance in the data is diminished. The variance in the data sets for the asynchronous measurement is thus highly dependent on the integration time of the colorimeter and the web velocity, masking the effect of actual color content variations in the web. Also, inaccuracies in the color measurement are introduced by the inclusion of web artifacts. This effect is particularly obvious in the median L values shown in Figures 6 and 7.

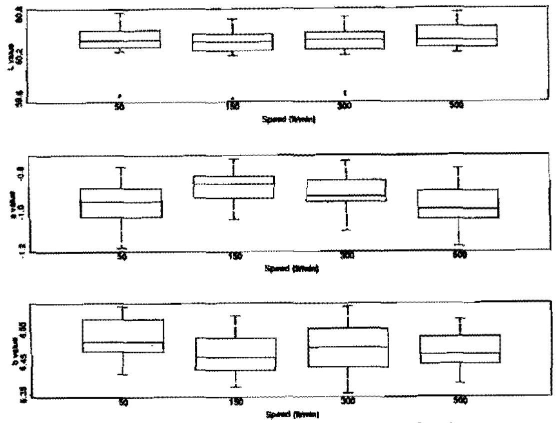


Figure 6: Synchronized Colorimeter Readings vs. Speed

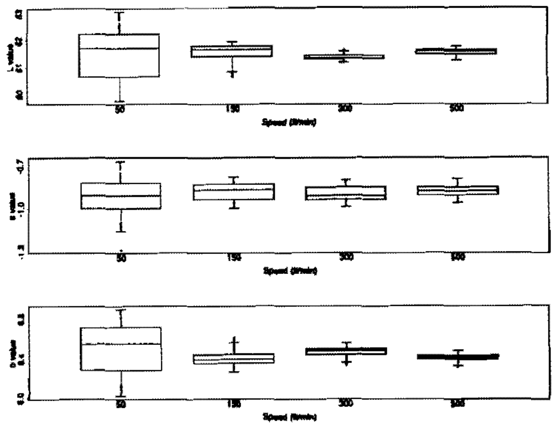


Figure 7: Asynchronized Colorimeter Readings vs. Speed

5.0 CONCLUSIONS

This paper describes various static and dynamic errors encountered while using a commercially-available colorimeter system to make color quality measurements on a moving web of printed graphic material. Design methodologies for reducing the errors were then discussed. These methodologies were implemented in a commercial colorimeter system and the modified colorimeter was tested using a loop of printed graphic images running on a web test bed at speeds to 500-ft/min. The design criteria used in modifying the colorimeter system was to present the colorimeter sensors with the same image(s) every measurement. This criteria required customizing the aperture of the colorimeter probe head and synchronizing the color content measurement to fixed regions of the web. Ensuing tests performed with the modified colorimeter system showed that the colorimeter output accurately measured color content variations on the web, regardless of the speed of the web transport system. Tests made using a fixed integration measurement time, not synchronized with the web (standard operating mode for most off-the-shelf colorimeters) showed dramatic changes in the variance of the data sets with speed, masking the effect of the actual color content variations in the web and introducing inaccuracies in the resulting measurement. Current efforts in the measurement of color quality, on-press, at ORNL are concentrating on the use of the modified colorimeter as a scanning system to obtain full-web color content information.

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