Spectrophotometer inter-instrument agreement on the color measured from reference and printed samples

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Abstract

There are many different color measurement instruments that are used within a printing industry. As with all instruments, there have been trends in their application and design as they have evolved over time. Currently there is a move towards the use of spectrophotometry from densitometry, as the de-facto measurement method. This is being pushed specifically by the application of ISO standards, and print specifications such as ISO 12647 and G7™. This paper addresses the issue in the communication of color data between different users where different instruments are used.

Earlier work carried out and presented at TAGA [1] showed that when using densitometry there good agreement between the instruments was when measuring standard reference tiles. However, there was a difference in the measured data between instruments when considering actual printed product.

This study evaluated the impact of the different instruments in the industry which has an increased focus on color tolerance levels in the printing environment. The investigation evaluated color measurement repeatability of hand held instruments from a number of different suppliers with different illuminants and filters.

The substrates measured as part of this study were reference standards, unprinted substrates, proof products, and actual printed material. The printed material evaluated included digital, lithographic (coated and uncoated), rotogravure and flexographic. The differences in the CIE L*a*b* color data measured are reported upon.

PIA/GATF
Printing Industries of America / Graphic Arts Technical Foundation

Introduction

Since the invention of four-color process printing there has been a need for standards or guidelines for controlling the process. Over the recent years, several approaches have been adopted to include those based on specific market segments such as newsprint (SNAP™) [2], general commercial (ISO 12647) [3] (GRACoL G7™) [4] and heat-set publication (SWOP™) [5]. All of these approaches have moved away from densitometric control as its primary method to take on more advanced and color accurate spectrophotometric techniques. As the industry moves to these new methods of color control, instrument manufacturers are developing new instruments that meet the user's needs as far as interface, data reporting, and cost expectations.

The objectives of this investigation was to evaluate the spectrophotometers marketed for the graphic arts industry, specifically pre-press and print production, and determine how well these instruments agree when measuring standard reference materials, as well as printed samples produced using various printing methods. By facilitating a project assessing measurement agreement we aim to provide a full understanding of the capabilities of the instrumentation and how the print condition (paper, ink, and process) impacts the capabilities of the instruments.

Experimental Procedure

The setup of each instrument used in this study was carried out in a similar manner. The first task was to ensure the instrument was functioning correctly. This was achieved by measuring the calibration plaque and verifying that the numbers specified were achieved.

Once interfacing was completed, the instrument configuration was verified. All of the measurements taken in this study were taken at D_{50} illuminate at a 2° observer angle. In terms of aperture, several of the instruments came pre-configured with a fixed aperture ranging in size from 3.0 mm to 4.5 mm. Of the instruments with multiple apertures, the aperture closest to 4.0 mm was selected.

Several different samples were measured that included a standard reference target and printed samples. The standard reference materials included a current Lab-Ref, which is composed of 12 different color patches. Printed samples measured included lithographic offset, flexographic, gravure, and digital printing on coated paper, uncoated paper, and plastic. A lithographic offset sample with aqueous overprint coating was also included to evaluate the impact on the instruments measurements.

The process of measuring the samples was standardized and followed proper techniques in accordance with CGATS 5 - "Spectral measurement and colorimetric computation for graphic arts images + Supplement 1 to CGATS.5-2003." [5] In following this method all measurements were taken on a flat, hard surface upon a GCA backstop, which is a black plastic with the appropriate amount of reflectance.

On each sample, the primary printing colors were measured (black, cyan, magenta, and yellow) as well as the overprint colors (red, green, and blue). Paper white was also measured for each sample. If a coating was printed over the paper, paper white values included the overprint coating. Each sample was measured a minimum of three times.

By measuring the color of the substrate, the impact of optical brightening agents on the instrument readings could be analyzed. It was also deemed important to document the ability of the instrument to measure through a film of overprint coating accurately.

The three data points were used to not only validate that the first measurement was taken correctly, but also to assess the instrument's repeatability. For the comparison of instruments, an average of the three data points was used. In the case where a high deviation greater than $1\Delta E_{ab}$ was documented within these readings, the measurement process was repeated with the appropriate instrument and print sample combination.

Once all of the instruments were used to measure a sample, the median was generated from that data set to be used as the point of comparison. By using the median instead of the average, the potential for a single point to skew the results was minimized. The median was produced for each of the three axis per color and substrate. By separating the axis, a true center-point was developed limiting the potential for one instrument to skew the results. There was however the impact on the optically brightened substrates on the median as the instruments containing UV-cut filters and those without had significantly different b* values. This in turn was believed to have set the median point between the two different groups of instruments.

The comparison process of the instruments followed the same protocol throughout this investigation. For the comparison process the 1976 ΔE_{ab} equation was used. Several other equations are available for calculating ΔE, but none of them have been agreed upon by the industry to provide a better description of color differences.

Tolerances for the ΔE_{ab} values will be discussed in this paper based on the expectations of PIA/GATF and industry accepted norms, which was determined to be a $1\Delta E_{ab}$ or less.

Instruments

A total of eight instruments were used in this study from four different suppliers, Table 1. Each of the instruments was classified as a spectrophotometer, but had the capabilities of providing densitometric measurements as well. The measurement technology driving the instruments varied by supplier and represents a broad range of options.

Instrument	Geometry	Aperture	Spectral Range	Measure Interval	Agreement	Engine
X-Rite SpectroEye	45/0°	4.5mm round	380-730nm	10nm	0.30ΔE_{ab}	Holographic diffraction grating
X-Rite EyeOne	45/0°	4.5mm round	380-730nm	10nm	0.40DE*94	Holographic diffraction grating
X-Rite 530	45/0°	3.4mm round	400-700nm	12nm	0.40ΔE_{cmc}	DRS Spectral
X-Rite 939	0/45°	4mm round	400-700nm	10nm	0.15ΔE_{ab}	DRS Spectral
X-RITE CA22	45/0°	4mm round	400-700nm	20nm	<0.50ΔE_{ab}	DRS Spectral
Techkon SpectroDens	0/45°	3mm round	400-700nm	10nm	0.01D/0.03 ΔE_{ab}	Spectral Remission (filtered)
Beta Industries BetaColor 2000	45/0°	3.3mm round	400-700nm	20nm	na	Photodiode
IHARA S900	0/45°	3 mm round	400-700nm	20nm	<0.5ΔE_{ab}	Photodiode

Table 1: Instrument specifications

Beta Industries submitted to the study the BetaColor 2000. The BetaColor 2000 was the only instrument in the study that used LED illumination with a photodiode detector. The spectral range of the instrument is 400-700nm in 20nm intervals.

Ihara's spectrophotometer solution was the S900. This instrument measures in 20nm intervals, but converts to 10nm intervals for output. This is a filtered based instrument that uses a photodiode receiver.

The Techkon SpectroDens instrument was based on a filtration type engine. This instrument measures from 400-700nm in 10nm intervals and had the smallest aperture of all instruments submitted at 3.0mm.

X-Rite Corporation submitted five instruments. These were the 530 (UV-cut), 939, CA22, EyeOne (UV-cut), and SpectroEye. The 530, 939, and CA22 have filter based engine technologies driving the measurements and were capable of a spectral range of 300-700nm. The EyeOne and SpectroEye are based on the former GretagMacbeth engine technology that measures using diffraction grating and captures data from 380-730nm.

The most distinctive difference between instruments was the graphical user interface (GUI). The instrument interface allows the user to navigate through the options and displays the data. Each instrument was shown to display the measurements differently.

All but two instruments had a display on the instrument itself. These two instruments were the X-Rite CA22 and X-Rite EyeOne, and they required a computer and special software to setup and display the measurements. All of the other instruments did come with interfacing software, which allowed the instrument to be tethered to a computer so the data could be input directly into a spreadsheet, but these instruments were fully capable of working independently of a computer as well.

Results and discussion

The results of this investigation will be discussed in terms of the substrate. First to be discussed will be the agreement of the instruments on the standard reference materials. The Lab-Ref will be the primary focus as this is a commonly available standard measurement target used to check spectrophotometers used in a printing environment.

Following the results from the standard reference materials, the results from the printed samples without overprint coatings will be discussed. These findings will include print samples produced using lithographic offset, flexographic, and gravure printing methods. A lithographic offset sample with an aqueous overprint coating will also be discussed. This sample was included to determine if measuring through a clear film would have an impact on the instruments ability to measure the underlying color.

Results of Lab-Ref Measurements

Measuring the twelve patches of the Lab-Ref with the X-Rite SpectroEye produced measurements that were close to the median for the majority of the colors, Figure 1. Only two of the twelve patches (yellow and green) exceeded $1\Delta E_{ab}$, but were under $2\Delta E_{ab}$. Most closely measured to the median were black and gray, which were under $0.5\Delta E_{ab}$.

The X-Rite EyeOne (i1) measurements produced four patches that were greater than the tolerance of $1\Delta E_{ab}$. These colors were magenta, red, green, and blue. All of these colors however did not exceed $1.5\Delta E_{ab}$. Black, cyan, gray, and brown were the most accurately measured in comparison to the median as these colors were less than $0.5\Delta E_{ab}$ from the median.

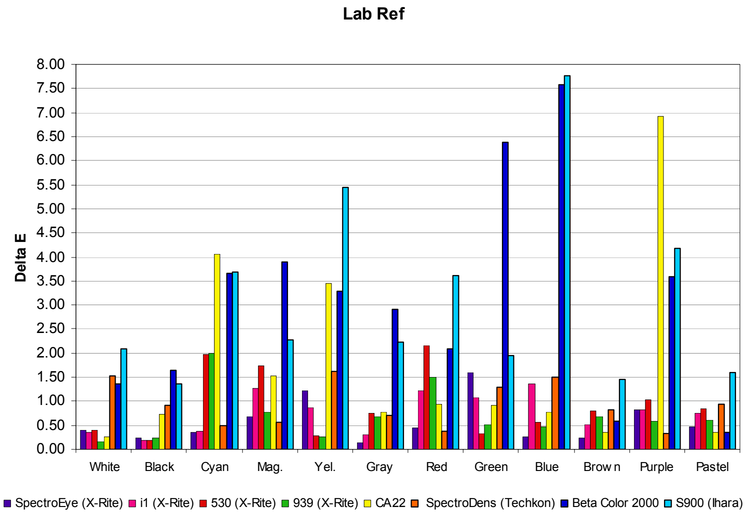

Figure 1: Lab-Ref by instrument and color

X-Rite's 530 also produced values greater than $1\Delta E_{ab}$ for four of the patches measured. These colors were cyan, magenta, red, and purple. Two of the colors, cyan and red, were greater than $2\Delta E_{ab}$ from the median. The colors closest to the median were black, yellow, and green, which were less than $0.5\Delta\ E_{ab}$ from the median.

The X-Rite 939 was the only other instrument, to measure ten of the twelve colors within the $1\Delta E_{ab}$ tolerance. With this instrument, cyan and red were the colors to exceed the tolerance as both colors were greater than $2\Delta E_{ab}$ from the median.

Measuring with the X-Rite CA22 showed three colors to measure in excess of $3\Delta E_{ab}$. These colors were cyan, yellow, and purple, with purple producing the highest ΔE_{ab} of $7\Delta E_{ab}$. The patches closest to the median were brown and pastel. Both of these colors were less than $0.5\Delta E_{ab}$ from the median.

With the Techkon SpectroDens, four of the twelve colors including the white, yellow, green and blue were greater than $1\Delta E_{ab}$ from the median, but less than $2\Delta E_{ab}$. The closest colors to the median were cyan, red, and purple all of which were under $0.5\Delta E_{ab}$.

Beta Screens Beta Color 2000 was only capable of measuring two colors, brown and pastel, within $1\Delta E_{ab}$. Black and the substrate were between $1\Delta E_{ab}$ and $2\Delta E_{ab}$, while the remaining eight patches were greater than $2\Delta E_{ab}$. The maximum ΔE_{ab} documented with this instrument was blue at greater than $7\Delta E_{ab}$.

The Ihara S900 showed large deviations from the median. With this instrument, not one color was within $1\Delta E_{ab}$ of the median. Four of the colors were measured below $2\Delta E_{ab}$, which were black, green, brown, and pastel. The remaining eight colors exceeded $2\Delta E_{ab}$ with three colors exceeding $4\Delta E_{ab}$.

The Lab-Ref target itself has stated values determined by an unknown instrument. When the measurements taken from this study were compared to the stated values on the Lab-Ref, the results in terms of ΔE_{ab} from the target (median or stated) were similar. This confirms that the instruments closest to the median were also in line with the stated values on the Lab-Ref. It is also possible that one of the instruments used in the study was the instrument used to produce the stated values.

When measuring the Lab-Ref with the eight instruments, the problematic color for the instruments was cyan. This color variation was $2\Delta E_{ab}$ from the median for five of the eight instruments. The colors closet to the median for the majority of instruments were black and white as more than half of the instruments measured these colors within $0.5\Delta E_{ab}$.

Offset on gloss coated paper

Printing on an optically brightened 80lb gloss coated paper was shown to produce high ΔE_{ab} values when compared to the results from the standard reference materials. This was shown in previous work [3].

When measured with the X-Rite SpectroEye the white, magenta, and green patch data exceeded the tolerance of $1\Delta E_{ab}$, Figure 2. Magenta had the highest ΔE_{ab} from the median of $1.7\Delta E_{ab}$. Green was the closest to the tolerance, but measured just over $1\Delta E_{ab}$.

The paper measurements taken on this sample produced relatively high ΔE_{ab} for all of the instruments. This occurred because median value was defined at a point between the instruments with and without UV-cut filters. Thee instruments with UV-cut filters were shown to have b* values that were significantly more neutral than the instruments without UV-cut filters, which measured the paper color as a blue shade. This in turn shifted the b* axis to a more centralized value. It did not however significantly effect the L* or a* values as these axises were shown to be impacted far less by difference between instruments.

It was also shown when measuring white, that instruments without UV-cut filters either identified the optically brightened paper as a blue shaded paper or reacted as if they had a UV-cut filter producing a measurement close to neutral gray. Those without UV-cut filters, which measured the paper as a neutral color, were believed to have some type of correction built into the instrument.

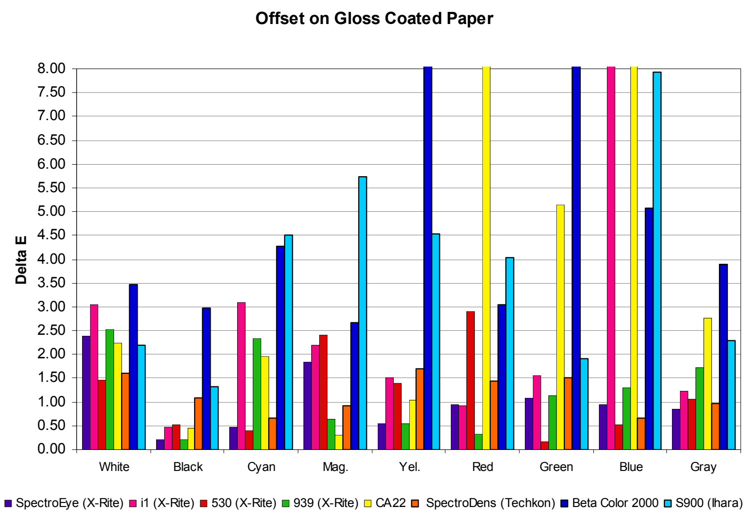

Figure 2: Offset on gloss coated paper by instrument and color

The X-Rite EyeOne, which had a UV-cut filter, had a greater than $1\Delta E_{ab}$ for seven of the nine color patches. The only colors within tolerance were black and red. Black was closest to the median value as this color was less than $0.5\Delta E_{ab}$ from the median.

With the X-Rite 530, five of the nine colors were greater than the accepted tolerance. The colors within tolerance were black, cyan, yellow, green, and blue. The colors closest to the median were cyan, green, and blue at less than $0.5\Delta E_{ab}$.

Measurements taken with the X-Rite 939 produced five measurements that exceeded the tolerance of $1\Delta E_{ab}$. These colors were white, cyan, green, blue, and gray. Black, magenta, yellow, and red were closest to the median with a less than $0.5\Delta E_{ab}$.

Measurements with the X-Rite CA22 showed that only the black, magenta, and yellow were below the tolerance of $1\Delta E_{ab}$. The other colors had relatively high ΔE_{ab} values with the highest values generated from the three overprint colors (red, green, and blue), which were greater than $5\Delta E_{ab}$.

The Techkon SpectroDens produced CIELab values close to the median for the cyan, magenta, blue and gray. Each of these colors was less than $1\Delta E_{ab}$ from the median. The remaining colors were greater than $1\Delta E_{ab}$ but were under $2\Delta E_{ab}$.

All nine patches measured with the Beta Industries BetaColor 2000 were greater than $2\Delta E_{ab}$. The closest color to the median was magenta at $2.7\Delta E_{ab}$. Cyan, yellow, green, and blue were the colors with the highest ΔE_{ab}, all of which were greater than $4\Delta E_{ab}$.

The Ihara S900 was closest to the median when measuring black and green. These two colors were less than $2\Delta E_{ab}$ from the median. All of the remaining colors were greater than $2\Delta E_{ab}$ with the highest value generated when magenta and blue, which were greater than $5\Delta E_{ab}$.

The color to be considered problematic when measuring this sample was white as all eight instruments were unable to measure this color within $1.5\Delta E_{ab}$ of the median. The high ΔE_{ab} values from the median were again caused by the b* differences between those instruments with and without UV-cut filters. Better agreement was shown with other colors on this sample as the inks blocked the optical brighteners from becoming excited producing a measurement difference. The color showing the best agreement amongst the instruments was black, which was measured at less than $0.5\Delta E_{ab}$ for five of the eight instruments.

Large ΔE_{ab} values were also produced between instruments when measuring specific colors for all of the print samples measured in this study, Figure 3. When measuring each of the samples certain colors were problematic for some of the instruments. This lead to very high ΔE_{ab} values from the median for specific instruments.

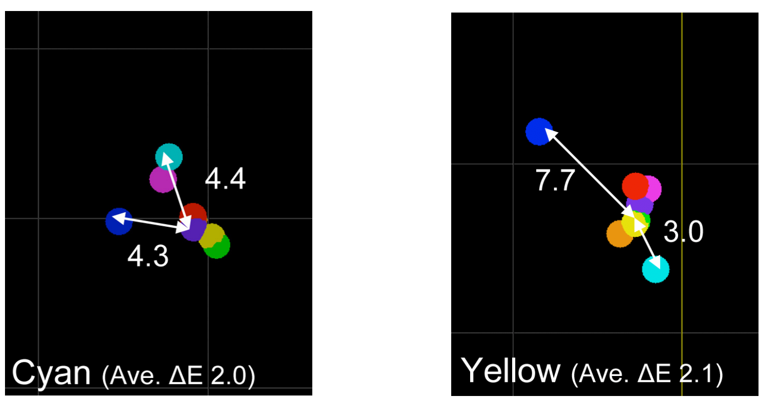

Figure 3: ΔE_{ab} of instruments measuring offset sample

ΔE_{ab} values twice that of those documented from the median were recorded when two instruments were at apposing sides of the median. Figure 3 shows this to have occurred with the offset print sample when measuring the magenta. This sample to shows a single instrument to be $7.7\Delta E_{ab}$ from the median, but as much as $10\Delta E_{ab}$ from another instrument.

Gravure printing on plastic

A sample of gravure printing on a white opaque plastic was included in this study so the impact of gravure ink colorants on a non-traditional substrate could be evaluated. The non-optically brightened substrate was also considered important for evaluating this sample as the optically brightened substrates with other printing methods have been shown to significantly impact the measured results as high ΔE_{ab} were produced.

The X-Rite SpectroEye was able to measure the white, black, and blue at less than $0.5\Delta E_{ab}$ from the median, Figure 4. Just above this value, but below $1\Delta E_{ab}$ were colors cyan, yellow, red, and gray. Only two colors, magenta and green, exceeded $1\Delta E_{ab}$, however both of these colors remained under $1.5\Delta E_{ab}$.

Measurements taken with the X-Rite EyeOne showed the white, black, red, blue, and gray to be under $1\Delta E_{ab}$. Those colors greater than $1\Delta E_{ab}$ were the cyan, magenta, yellow and green, all of which were under $2\Delta E_{ab}$ from the median.

Those colors under $1\Delta E_{ab}$ when measured with the X-Rite 530 included white, black, green, blue, and gray. Of these five colors, black and gray were under $0.5\Delta E_{ab}$. The other colors measured were cyan, magenta, yellow, and red, and these were greater than $1\Delta E_{ab}$ but were under $2\Delta E_{ab}$.

The only color to exceed the tolerance of $1\Delta E_{ab}$ when measured with the X-Rite 939 was cyan. This color was approximately $1.6\Delta E_{ab}$ from the median. The colors closet to the median with this instrument included white, black, magenta, yellow, red, and gray, all of which were less than $0.5\Delta E_{ab}$ from the median. Green and blue produced values greater than $0.5\Delta E_{ab}$ but were under $1\Delta E_{ab}$.

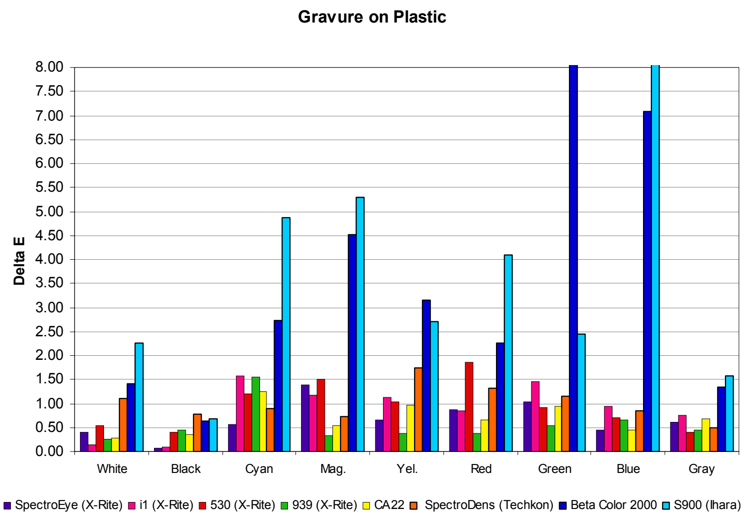

Figure 4: Gravure sample by instrument and color

Measurements taken with the X-Rite CA22 were similar to those taken with the X-Rite 939 in that only cyan exceeded the tolerance of $1\Delta E_{ab}$ but was under $1.5\Delta E_{ab}$. The colors closest to the median (under $0.5\Delta E_{ab}$) included white, black, and blue. The remaining colors were greater than $0.5\Delta E_{ab}$, but within the accepted tolerance.

Values from the Techkon SpectroDens were furthest from the median when measuring white, yellow, red, and green. These colors exceeded the tolerance of less than $1\Delta E_{ab}$, however, were under $2\Delta E_{ab}$. Colors closest to the median when measured with this instrument included black, cyan, magenta, blue, and gray. These colors were less than $1\Delta E_{ab}$ from the median.

The Beta Industries BetaColor 2000 measured all colors except for black at greater than $1\Delta E_{ab}$. The highest values were recorded on magenta, green, and blue. These colors were greater than $4\Delta E_{ab}$. Black was the only color within tolerance and was approximately $0.7\Delta E_{ab}$ from the median.

The Ihara S900 was similar to the Beta Industries BetaColor 2000 with only black within tolerance of less than $1\Delta E_{ab}$. The other colors were classified as out of tolerance and were greater than $2\Delta E_{ab}$ from the median, except for gray, which was approximately $1.6\Delta E_{ab}$ from the median.

When measuring the gravure sample, the most problematic color for the instruments was cyan as six of the eight instruments measured this color to be greater than $1\Delta E_{ab}$ form the median. Black, blue, and gray showed the best agreement as these colors were measured by at least six of the eight at less than $1\Delta E_{ab}$.

Flexographic printing on non-OB plastic

The flexographic print sample used for this study was printed on the same substrate as the gravure print sample. This will allow for a direct comparison of colorants between printing methods.

With the X-Rite SpectroEye, cyan and magenta were the only colors to measure greater than $1\Delta E_{ab}$ from the median, Figure 5. These colors were approximately $1.3\Delta E_{ab}$ away from the median values. The colors closest to the median were white, black, red, and blue, these colors were within $0.5\Delta E_{ab}$ from the median.

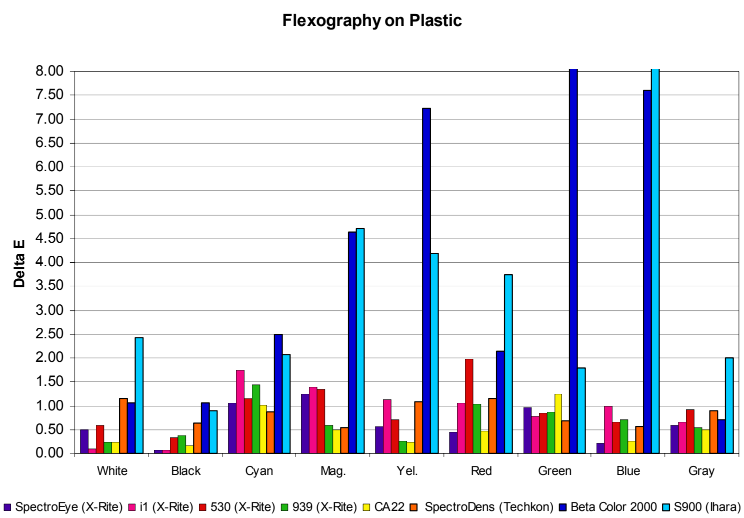

Figure 5: Flexography sample by instrument and color

The colors less than $1\Delta E_{ab}$ from the median when measured with the X-Rite EyeOne were white, black, green, blue, and gray. These colors were under $1\Delta E_{ab}$ with white and black within $0.5\Delta E_{ab}$. The colors producing the highest ΔE_{ab} values were cyan, magenta, yellow, and red. These were the colors that had ΔE_{ab} values higher than the $1\Delta E_{ab}$ tolerance. Though these colors exceeded the tolerance, they all produced value of less than $2\Delta E_{ab}$.

When measured with the X-Rite 530, the colors within tolerance were white, black, yellow, green, blue, and gray. The colors greater than the tolerance of $1\Delta E_{ab}$ were cyan, magenta, and red. Of the colors out of tolerance, red had the highest value of $2\Delta E_{ab}$. Cyan and magenta were below $2\Delta E_{ab}$.

The X-Rite 939 measured the majority of colors within the tolerance of $1\Delta E_{ab}$, except for cyan. The ΔE_{ab} value from the cyan was slightly higher than the tolerance at approximately $1.4\Delta E_{ab}$. When measured with the X-Rite 939, the colors closest to the median were the white, black, red, and blue, all of which were within $0.5\Delta E_{ab}$.

Low ΔE_{ab} values (less than $1\Delta E_{ab}$) were documented with X-Rite CA22 for all colors except for the green, which was above the tolerance of $1\Delta E_{ab}$ by approximately $0.3\Delta E_{ab}$. With the X-Rite CA22, white, black, magenta, yellow, red, and blue were within $0.5\Delta E_{ab}$.

Measurements with the Techkon SpectroDens were close to the median when measuring black, cyan, green, blue, and gray. These colors were under $1\Delta E_{ab}$. White, yellow and red had values greater than $1\Delta E_{ab}$ but less than $1.5\Delta E_{ab}$ from the median on this sample.

The Beta Industries BetaColor 2000 measured gray within the accepted tolerance. Colors moderately higher than the tolerance were white, black, cyan, and red. These four colors were within $2.5\Delta E_{ab}$ from the median. The colors considered to be well above the tolerance were magenta, yellow, green, and blue, these colors were greater than $4.5\Delta E_{ab}$ from the median.

The color closest to the median when measured with the Ihara S900 was black at approximately $0.8\Delta E_{ab}$. Colors above the tolerance but below $2.5\Delta E_{ab}$ included white, cyan, green, and gray. The remaining colors (magenta, yellow, red and blue) were greater than $3.5\Delta E_{ab}$.

When compared to the Gravure sample, the flexographic sample had similar ΔE_{ab} values, which provides evidence that the different gravure and flexographic colors did not have a significant impact on the instruments and that the non-optically brightened substrate also minimized the high ΔE_{ab} values produced by the instruments when compared to the offset sample, which was produced on a paper with high optical brightener content.

The most problematic colors when measuring the flexographic sample were cyan, magenta and red, which were slightly greater than $1\Delta E_{ab}$ from the median for the majority of instruments. The colors showing good agreement amongst the instruments were black and white, which were less than $1\Delta E_{ab}$ for at least five of the eight instruments.

Offset printing with aqueous coating

The assessment of the sample with an aqueous coating by instrument showed the X-Rite SpectroEye to be under $1\Delta E_{ab}$ when measuring the black, cyan, yellow, green, blue and gray colors, Figure 6. The colors to exceed the tolerance of

$1\Delta E_{ab}$ were white, magenta, and red which were approximately $1.5\Delta E_{ab}$ from the median.

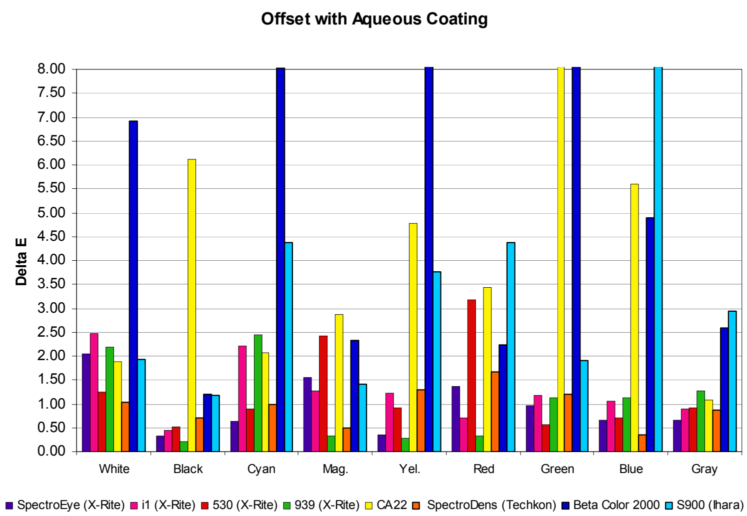

Figure 6: Aqueous coated sample by instrument and color

The X-Rite EyeOne was closest to the median when measuring black and gray. Other colors, including magenta, yellow, red, green, and blue were slightly above the tolerance, but below $1.5\Delta E_{ab}$. The colors producing high ΔE_{ab} in comparison to the median were white and cyan, which were greater than $2\Delta E_{ab}$.

When measured with the X-Rite 530 the black, cyan, yellow, green, blue, and gray were under the tolerance of $1\Delta E_{ab}$ from the median. The other three colors, white, magenta, and red, were greater than $1\Delta E_{ab}$ with the color furthest from the median being red, which was slightly higher than $3\Delta E_{ab}$.

Colors measured within tolerance using the X-Rite 939 included black, magenta, yellow, and red. The green, blue, and gray were slightly greater than the tolerance but less than $1.3\Delta E_{ab}$. White and cyan produced the highest ΔE_{ab} values with this instrument and they were between $2\Delta E_{ab}$ and $2.5\Delta E_{ab}$.

It was shown that when measured with the X-Rite CA22, none of the colors with aqueous coating were within $1\Delta E_{ab}$ of the median. Those closest to the median were white and gray; these were less than $2\Delta E_{ab}$ from the median. The remaining colors were all greater than $2.5\Delta E_{ab}$ from the median with black, magenta, green, and blue all greater than $4.5\Delta E_{ab}$.

The Techkon SpectroDens produced measurements close to the median when measuring black, cyan, magenta, blue, and gray. Other colors to include white, yellow, red, and green were above the set tolerance of $1\Delta E_{ab}$ but were less than $1.5\Delta E_{ab}$.

When measured with the Beta Industries BetaColor 2000, none of the colors were measured within the $1\Delta E_{ab}$ tolerance. The lowest ΔE_{ab} values were produced when measuring black and magenta, which were less than $2.5\Delta E_{ab}$. The remaining colors were greater than $2.5\Delta E_{ab}$ with the highest values produced when measuring white, cyan, yellow, and green, all of which exceeded $6.5\Delta E_{ab}$.

The Ihara S900 also produced values greater than $1\Delta E_{ab}$ for all nine colors. The colors closest to the median were white, black, magenta, and green, which were greater than $1\Delta E_{ab}$, but less than $2\Delta E_{ab}$. Cyan, yellow, red, blue, and gray were all greater than $2.5\Delta E_{ab}$, with cyan, red, and blue exceeding $4\Delta E_{ab}$.

Problematic colors for the instruments measuring this sample were white, cyan, and magenta, all of which produced ΔE_{ab} values greater than $1\Delta E_{ab}$ with at least six of the instruments. Black was the only color to produce ΔE_{ab} values of less than $1\Delta E_{ab}$ for at least five instruments.

Substrate Comparison

In addition to measuring the primary and secondary colors, the base substrate was also measured and analyzed. The reason was to investigate the impact of UV-cut filters found within certain spectrophotometers in terms of measuring white and how optical brighteners in papers influence the different spectrophotometers.

The UV-cut filters by design minimize the impact of optical brightening agents commonly found in paper. This is done by filtering out the UV content found in the 300-420nm range of the spectrum of light. By filtering out the UV content, the substrate measurements produce a more neutral result.

Those instruments without a UV-cut filter produce values that are considered blue when measuring substrates containing optical brightening agents. The blue shade is a natural product of the optical brightener which when measured, is stimulated by the light source of the instrument.

As stated earlier in this report, two of the instruments had UV-cut filters (X-Rite 530 and X-Rite EyeOne) and the remainder did not. These two instruments on the non-optically brightened substrates (Lab-Ref, gravure on plastic and ceramic tile) showed to have excellent agreement with other instruments that were proven to be within the accepted tolerance, Figure 7.

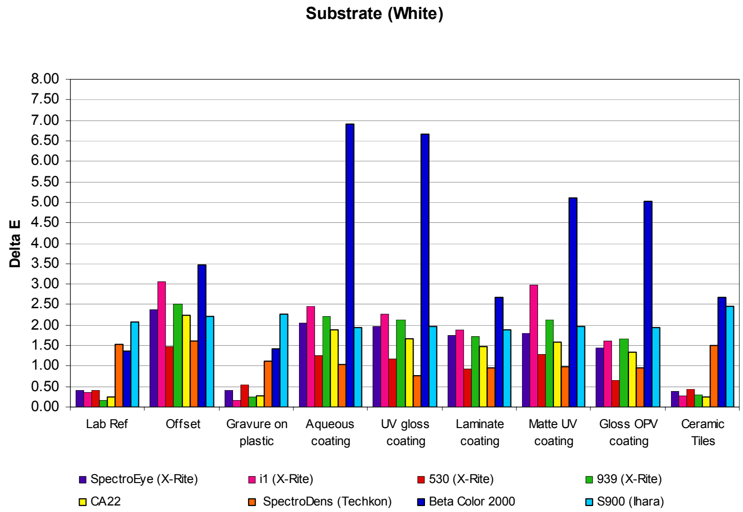

Figure 7: Substrate sample by instrument and color

When assessing the instruments individually on the non-optically brightened substrates, measurements taken from the Lab-Ref produced ΔE_{ab} of less than $0.5\Delta E_{ab}$ when measured with the X-Rite SpectroEye, X-Rite EyeOne, X-Rite 530, X-Rite 939, and X-Rite CA22. The Techkon SpectroDens, Beta Industries BetaColor 2000 and Ihara S900 instruments did not have good agreement as these instruments produced a ΔE_{ab} of greater than $1.5\Delta E_{ab}$ from the median.

The Beta Industries BetaColor 2000 and Ihara S900 were shown to not agree when measuring the samples as well. The Techkon SpectroDens had poor agreement on the white, but measured a majority of the colors on the various substrates within the tolerance of $1\Delta E_{ab}$ from the median, Figure 9.

The gravure sample measurement of the substrate was extremely similar to the Lab-Ref. Again the Techkon SpectroDens, Beta Industries BetaColor 2000, and Ihara S900 produced ΔE_{ab} greater than $1\Delta E_{ab}$. The X-Rite 530 on this sample was slightly greater than $0.5\Delta E_{ab}$ as the remaining instruments were less than $0.5\Delta E_{ab}$ from the median.

When the instruments were used to measure the optically brightened samples, each individual instrument measured the various samples consistently. The results of the measurements show each of the instruments to measure paper white consistently as the same paper was used for several of the various print conditions in this investigation. However, when the measurements from the different instruments were compared to one another, the results showed the instruments not to agree, Figure 8. The measurements of the paper white were inconsistent when comparing the two instruments with UV-cut filter as one instrument produced a more neutral measurement than the other. Those instruments without UV-cut filters were also inconsistent as these six instruments produced measurements that were anywhere from a blue shade to a green shade in color spanning a maximum ΔE_{ab} of $6\Delta E_{ab}$.

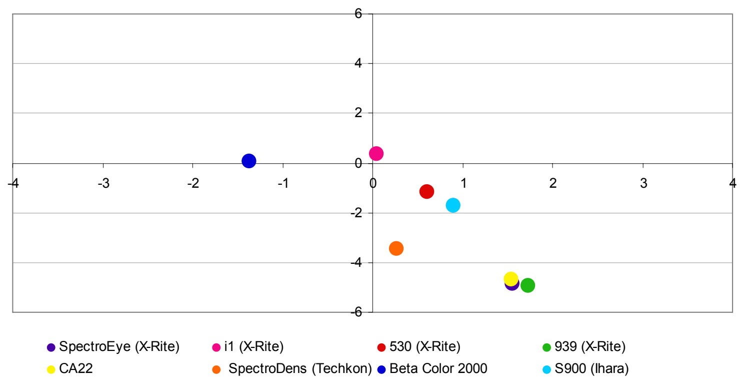

Figure 8: a,b, plot of optically brightened substrate

With an aqueous overprint coating, the impact of the optical brightening agents could be detected in the measurements, but not at the same magnitude. The ability to detect the optical brightened agents through the overprint coatings was confirmed with a black light as the printed samples with overprint coatings fluoresced under the black light, but not as well as the sample without overprint coating.

When the optically brightened samples were measured with the eight instruments, it was determined that the offset sample without overprint coating produced the highest ΔE_{ab} paper white values of greater than $2\Delta E_{ab}$ for six of the eight instruments. The X-Rite 530 and Techkon SpectroDens were the only two instruments below $2\Delta E_{ab}$ at approximately $1.5\Delta E_{ab}$. These results provide evidence that the impact of the optical brightening is greater on an uncoated print and that the overprint coatings minimize the impact of the optical brightening agents.

Also observed was that the two instruments with UV-cut filters did not measure the same. These two instruments were approximately $1.7\Delta E_{ab}$ apart. The results show the X-Rite EyeOne to produce a measurement that was more neutral in color, whereas the X-Rite 530 produced a measurement that was slightly blue. This confirms the different measurement technologies and methods of performing the UV-cut are not the same and that measurement differences can be expected between the different instruments.

When analyzing the white of the print samples with the aqueous overprint coating, the results show the ΔE_{ab} values to be greater than $1\Delta E_{ab}$ for the majority of the instruments, which is $1\Delta E_{ab}$ less than the majority of the instruments measuring the sample without overprint coating. This was again influenced by the optical brightening agent as the samples without optical brightening produced white point measurements of less than $0.5\Delta E_{ab}$ from the median.

When comparing the optical brightened samples to the non - optical brightened samples, the majority of the instruments were closer to the median when measuring the non - optical brightened sample. The only exception to this result was the Techkon SpectroDens, which on the non - optical brightened substrates produced high ΔE_{ab} values and on the optically brightened samples produced some of the lowest ΔE_{ab} values.

The low ΔE_{ab} values of the Techkon SpectroDens measuring the white, optically brightened sample was produced for the fact that this instrument measured the white between that of the instruments with UV-cut filters and those without. This instrument did not measure the paper white as blue shaded or neutral, but at a point in between. The instruments to include the X-Rite SpectroEye, X-Rite 939, and X-Rite CA22 produced values that reflect typical measurements of an OB paper taken without a UV-cut filter. The IHARA S900 produced a slightly more neutral measurement but was still considered to measure the white as a blue shade.

For an unexplained reason the Beta Industries BetaColor 2000 measured all of the optical brightened papers not as a blue or neutral shade, but as a green shade. The reason for this occurrence could not be identified.

Discussion and Conclusions

Throughout this study the primary focus was on instrument agreement and not defining one instrument to be better than another. The goal in facilitating this project was to provide technical information to consider when taking measurements with these instruments.

This study was not a blind evaluation of random instruments, but an evaluation of instruments supplied specifically for the project by each manufacturer. The only requirements for these instruments to be included in the study were that they were 0/45 geometry instruments, capable of reporting the readings in CIELab, and were marketed to the pre-press and / or the print production industry.

Prior to measuring any of the samples in this evaluation, each instrument was calibrated to its own calibration tile and was connected to a computer via proprietary software provided by each of the suppliers with the instruments.

When measuring the standard reference material with the eight instruments the results show that all eight instruments did not measure all twelve colors the same. In many cases the difference between any two instruments was documented to be greater than $1\Delta E_{ab}$. Problematic colors on the Lab-Ref for the instruments were instrument specific. It was shown that all instruments had problematic colors, meaning that each instrument was unable to measure all colors within $1\Delta E_{ab}$ of the median.

The measurements of the samples produced from different printing processes produced the same results as those documented on the standard reference materials. It was also shown that colorant differences of these samples did not have a significant impact on the various instruments' ability to measure the colors. There were however, differences as to which instruments measured the different colors within close proximity of the median.

Those colors to produce extremely high ΔE_{ab} values regardless of instrument were generally recorded on the substrates containing optical brightener and were generally blue in shade. This is due to the optical brightening agents in papers negatively impacting the measuring capabilities of certain instruments.

When measuring samples with various types of overprint coatings, the average ΔE_{ab} was lower than the sample produced on the same paper without any form of overprint coating. This provides evidence that even though overprint coatings do not totally block out the influence of optical brightening agents in paper it does however reduce its impact. This was not only documented when measuring paper white, but the blue shaded colors as well.

Measurements of the substrates with and without optical brighteners and overprint coatings showed that substrates without optical brighteners have better agreement of all instruments regardless of having a UV-cut filter or not. UV-cut filters in this study were shown to function as intended by minimizing the impact of the optical brightening agents on the measurements. Even though only two of the instruments had UV-cut filters, these two instruments were shown to respond differently when measuring paper white. The UV-cut techniques amongst the suppliers does not function the same. The results of this study also showed that certain instruments that did not have UV-cut filters to our knowledge respond as if they did.

Importantly identified in this investigation is that when communicating color, one must supply as much information as possible about the instrumentation and sample being measured. It was also learned while performing this investigation that settings within the instruments must also be checked and validated against measurement standards and guidelines. Not all of the instruments submitted conformed out of the box to standard measurement practices. This will require an understanding of the instrument and how to navigate through the options.

The investigation can be summarized as

- Significant color differences between instruments when measuring the same samples.
- The measurements were more consistent with the standard reference samples.
- Large influence of optical brighteners on the white measurement inter-instrument agreement.
- UV cut filters made optically brightened measurements more appear neutral, though there was not consistency in the measurements.
- The largest color differences from the median were instrument dependant and not color specific.

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