STANDARD REFERENCE MATERIALS FOR DENSITOMETRY
An Update on Standards and Standardization in Optical Radiation Measurements

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Abstract: In 1985, Franc Grum of the Munsell Color Lab at Rochester Institute of Technology, Milton Pearson of the RIT Research Corporation, and Norman Scharpf of the Graphic Communications Association co-authored a TAGA paper on standards and standardization in optical radiation measurements. Since that time, a successful Standard Reference Material (SRM) has been developed for graphic arts densitometry. This paper describes the SRM, the method of certification tracing density values to fundamental standards, and results of laboratory and field testing. The industry impact of using the SRM to bring groups of densitometers into agreement and the future plans for development of standards are discussed.

Prologue to the Grum-Pearson-Scharpf Paper

Until quite recently, new and improved densitometers were typically designed in part using an evolutionary cloning process. The reading agreement with accepted measurement systems was obtained using the same, or equivalent, components. New features were often limited to those that did not conflict with current accepted measurements. This was almost a commercial fact of life; purchasers of new densitometers wanted the latest technology but at the same time required that this new instrument match older models already in service. These conflicting demands are frustrating to the densitometer designer, who is in the position of being expected to initiate great improvements without changing anything.

When the light source and the photo-receiver remain constant in the development of a new densitometer, the color filter serves as the major component determining spectral response. As a result, spectral response and the selection of the color filter set were used interchangeably. In 1948, a densitometer spectral response for photographic materials was standardized by defining components, including a

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filter set called Status A. Qualitative data describing densitometer response were reported[1]. The original aim for the design of Status A was to provide approximately equal red, green, and blue readings from a neutral sample of Eastman Kodak's cut-sheet Kodachrome Film. New photographic products implied new responses, and by 1951, some twelve filter sets, or status conditions, existed. Only two survived when the Kodak Electronic Densitometer Model 31A became the de facto standard for color density. Thus, though each filter set had a rational origin, today they are considered arbitrary.

In 1973, all spectral and electrical characteristics of the 31A densitometer were documented spectrally by Macbeth Corporation and Eastman Kodak and used as a basis for the design of new instruments[2]. This work served as the basis for specifying response functions for different marketplaces and was the foundation for ANSI[3] and later ISO documentary standards. A modern generation of densitometers manufactured since 1982 and based on these standards has reduced instrument variability and improved data exchange. The spectral products specified in ANSI PH2.18 provided a documentary definition of color density and in fact are a densitometric analog to CIE $\bar{x}$, $\bar{y}$, $\bar{z}$ responses. Having these values as an accepted documentary standard has given the graphic arts industry the ability to develop a standard reference material for reflection densitometers. The Grum-Pearson-Scharpf TAGA paper[4] proposed this concept, subsequently realized in the development of T-Ref™.

Description of T-Ref

The documentary standard for status density makes possible a number of different standard reference materials to test and calibrate densitometers. For example, analytical standard references have been designed and used by densitometer manufacturers. These analytical references are sensitive, special-purpose references to test a single element of response.

A standard reference for overall performance testing is said to be functional if it emulates routine use of the densitometer. The design aim of the T-Ref™, shown in Figure 1, provides such a functional standard. The T-Ref™ is printed with spectrally evaluated SWOP inks on a coated paper stock that has a shade representative of that typically used. Targets are sized to match the alignment apertures of commercial densitometers. Each target is centered at the intersection of reference cross lines that also match with the densitometer's alignment shoe. Though a range of densities could be used, the inks are printed to densities similar to those used for production printing. There are five targets: paper white to check the reference zero, black to test the photometry, and three colors--cyan, magenta, and yellow--to test spectral response. The back side of the card is printed with a black ink backing behind the target area in agreement with standard practice.

The printed reference card is laminated using a heat-sealed process and 1.5mil clear, durable, moisture-resistant film. The laminates are sealed film-to-film at all edges to prevent intrusion of air and moisture. Investigation of the laminating process included a study of the effect of laminate thickness on the difference between spectrophotometer and densitometer data, an important consideration because the small scale of densitometer geometry makes the densitometer more sensitive to laminate thickness than the comparatively larger scale geometry of the spectrophotometer. This study indicated that laminate films thinner than 1.5mil are not durable enough, while at thicknesses of 5mil the correlation error between spectrophotometer and densitometer readings is too large. The birefringence of the laminate films in use makes them unsuitable for polarized light densitometry; ANSI standards, however, do not specify that Status T be used with polarized light measurement.

Procedures for Using Status T Reference

T-Ref™ is used to evaluate a densitometer's response. The densitometer is first calibrated according to the manufacturer's instructions using designated set-up materials. The T-Ref is read as an evaluation tool. The difference between the measured values and the certified values derived by the standards laboratory provides an estimate of the compliance of the densitometer with ANSI/ISO standards. Selected targets of a T-Ref may be read on a daily basis and control charts used for process monitoring.

Method 1 When the densitometer is set up according to manufacturer instructions using the standard designated by the manufacturer, the T-Ref provides an overall check of the densitometric measurement system, including both the set-up standard as well as the instrument. Specifically:

1. The values for the white target indicate the zero-setting level as determined by the designated set-up standards.

2. The values for the black target measure the photometric level of the densitometer as adjusted by the designated set-up standards.

3. If, and only if, the measured values of the white and black targets are within tolerance (the greater of ±.02 or 2%) of the certified values noted for the black and white targets, the values read from the color targets test the spectral conformance.

Method 2 When the white and black targets as read in Method One depart from the certified T-Ref values, these targets may be used to set the photometric response of the densitometer, and the values of the color targets can then test

spectral compliance. The red density of the cyan target, the green density of the magenta target, and the blue density of the yellow target together test the densitometer's spectral response.

As indicated previously, differences between the densitometer's values read from the cyan, magenta, and yellow targets and the certified values indicate departure from spectral compliance. Because the values as read on the densitometer are the result of a measurement process, as are those of the certified values, the differences are considered not important when they are less than the greater of $\pm$.02 or 2% density at each density level.

Despite offering high assurance of Status T conformance, matching the values on the reference does not guarantee a Status T response because this is not a complete spectroradiometric analysis of the densitometer. However, from a practical standpoint, offsetting errors providing equal integrated energy values in spite a spectral mismatch at the component level represents a rather low probability. Some degree of instrument metamerism is still not a major error source in process control since the inks on the T-Ref and the inks in the process are spectrally similar.

Certification and Traceability to Standards

Standard Reference Materials (SRMs) are certified at an intermediate standards laboratory, such as the one operated by PSI Associates. When calibrating T-Refs, each target is certified by reading it four times on four separate days. The targets are read on a reflection spectrophotometer having a 45^0-0^0 geometry that is calibrated with reference materials and transfer standards whose values are traceable to the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards (NBS). The influx light has spectral quality described by CIE as Illuminant A. The spectrophotometer reads a black hole[5] with $D > 4.0$. Wavelength is traced to standard with a certified Dydmimium glass and sharp cutting filters. The radiometric integrity is certified using a reflection SRM from NIST. Other SRM's include an amber glass and tiles traced to other intermediate laboratories, including the Munsell Laboratory at RIT. To further assure calibration accuracy, the PSI standards laboratory is involved in an ongoing Measurement Assurance Program (MAP) with other laboratories, each of which maintains a traceable reference to NIST.

The exact level of reference for absolute reflectance is the subject of a continuing ANSI subcommittee round-robin testing. The work of this committee has provided a 45^0-0^0 value for absolute reflectance that is within $\pm$1.0% of correct. Previous work of this committee has suffered from problems introduced by transfer standards that were geometry dependent. Some of these transfer standards were also reading-area size dependent for both the illumination and collection. Many

laboratories are using the same reflectance values for 45^0-0^0 absolute reflectance as are used for full diffuse sphere collections. This requires the assumption that the transfer standard is a Lambertian reflector.

Short range (2 week) controls on the spectrophotometer readings establish control limits of ±0.0005 density on precision positioned tiles and long range (22 months to date) limits of ±0.001 density. Archived T-Refs read over this period have maintained control limits of ±0.002 and ±0.004, respectively. The greater variation in T-Refs as a control tool probably is related to sample positioning variation.

Non-uniformity of the sample, or of the SRM, is an error source that must be considered. Repeatable values can be assigned to non-uniform targets if read with an instrument that has a uniform area response. Conversely, repeatable values can be assigned to uniform targets, even with non-uniform reading instruments. Because neither printing ink laydown nor commercial densitometers can be perfectly uniform, the role of measurement process analysis becomes important. It is essential that the certifying instrument be as uniform as possible and that the SRM targets be selected for minimum variation.

The spectrophotometer illuminates a 6mm circular area at the sample plane and reads a 4mm circular spot. The illumination and collection are uniform enough that a "wedged" target varies no more the ±0.001 in density as it is rotated in 60^0 increments. The same target varies more than ±0.01 in density with the 60^0 rotation as read on many densitometers.

T-Ref Precision

As indicated previously, in the certification production cycle each target on each T-Ref is read four times on four calibration runs of the spectrophotometer. The densities from these runs are averaged and each value compared to the average density. The largest departure from average on the five targets' four runs is reported on the T-Ref label. A typical value for the maximum deviation is 0.003 to 0.004; samples with deviations greater than 0.006 are rejected.

T-Ref Accuracy

T-Ref certified values are reported to the same tolerances that NIST provides on its reflection density SRM, namely, the greater of the 0.02 density or 2% of the density. With excellent precision and good agreement with other intermediate standard laboratories, it is still not possible to report accuracy to a higher degree of certainty than either NIST or other primary standards laboratories report their transfer standards.

Laboratory and Field Tests

T-Refs have been treated in environmental chambers to examine the effects of elevated temperature, humidity, and light fading. Results indicate that the upper test limit, 90°C and 60%RH, is not a good environment for the laminated T-Ref. Conditions that are extreme for humans, however, such as 38°C and 60%RH, pose no real threat to T-Refs performance.

Light fading tests were made using 1K lux and 15K lux of fluorescent light as well as 10K lux and 50K lux of daylight. Light levels for these tests were uniform and monitored with instruments recording level and integrated exposure. The T-Refs were read at regular time intervals during this test. Results indicate that T-Ref inks are fairly stable and resistant to fading in a wide range of lighting conditions.

Along with these controlled environment tests, randomly selected T-Refs were also exposed to both practical environmental lighting conditions, such as those found in pressrooms, prepress areas, offices, and lighitng booths, as well as to extreme environmental lighting conditions, such as Arizona sunlight on the back window shelf of a car. When the T-Ref is protected with its synthetic nonwoven wrapper, the changes are small--even when the wrapper has faded. Further, selected T-Refs have been read on a daily basis at PSI Associates for almost two years. Those protected in the folder have shown a change of about -0.006 in density, a change that might be attributed to surface heat. Other T-Refs in the PSI laboratory that have been left open on a bench-top show changes in some targets of as much as -0.009 after two years. These practical test results correspond with the fading data from the accelerated tests.

Expiration Dates for T-Refs

When the T-Ref program started, a cautious expiration date of 6 months was suggested. Practical experience and accelerated tests have shown that with reasonably careful storage and use they are useful for at least a year, if not longer. One method of keeping a working standard in a measurement process is to have two standards; one is used on a routine basis while the second, or back up, standard is stored in a secure location. The working standard and the back up standard are both read on a long-interval basis, such as each month. When a change is found in the working standard, it should be retired and the back up standard put into service. A new back up should then be obtained and new crossover data collected.

Impact of Using T-Ref As A Control Tool

T-Refs have proven valuable to the organizations where it has been necessary to communicate density data among separated production locations. In several

cases, the agreement reported was better than one would expect from analysis of system errors.

Note that readings from two or more densitometers should not be compared using a single set of measurements of one set of color bars or quality control targets. While this is the ultimate requirement for data interchange, any single set of readings includes the variation introduced by the individual densitometers and the sample itself.

Densitometry Measurement Is A Process

All measurements must be considered to be the result of a process. For example, in matching two or more densitometers, results will differ depending upon whether each densitometer is set up to its own T-Ref or if a master (common) T-Ref is used for set-up and each controlled on its own Reference. Remember that each measurement represents a "snapshot" value of a process and that a number of steps are required to obtain a single density reading. Each of these steps is a potential source of variability, and the precision of the final measurement is the result of the contributions of variation at each step of the process.

Any value obtained as the result of the measurement is obtained by comparing the quantity being assessed with a calibrated standard or reference. A procedure is implied by the act of comparison. The final value depends upon the accuracy of the reference, the procedure for comparison, the test of equality and the determination of need to recheck the process before reporting the data. The accuracy of the measurement depends on the validity of the set up standards and the precision of the set up process.

Typical variations that may be expected for a good measurement system are:

Step	Operation	Variance (σ_i)
1	Read Set-Up Standards	0.003
2	Repeat at one position	0.002
3	Sample Uniformity (0.003-0.009)	0.006
4	Signal Processing Drift	0.002

The overall variance (σ_T) is found by the formula:

$$\sigma_T = \sqrt{\Sigma\ \sigma_i^2}$$

$$\sigma_T = 0.0073$$

Density differences less than σ_T should not be considered real differences in readings. If a large number of samples is read four or five times, the variation in the reading for any target will lie between 0.003 and 0.011, or vary around the average reading for that target $\pm$0.001 to $\pm$0.005. These typical variations for a good measurement system are mostly masked by a display that shows only two numbers to the right of the decimal point. However, some data points will spread as much as $\pm$0.01 when the data are rounded.

There is little that the user can do to minimize the differences introduced by the causes listed above. Understanding the sources of variability will help users understand whether the measured change is a real change versus a change created by measurement system variability. This understanding will avoid increased re-calibrations and variability that will occur from operating in an overcontrol state.

To understand the variability of a set of densitometers, enough data must be obtained to establish the normal operating bias of the two instruments. That bias should be introduced in their control and set-up procedures. None of these biases should be introduced in conflict with the manufacturer's suggested operating and control procedure. These biases should be determined with samples designed to have a minimum of reading area sensitivity. T-Refs and color reference cards supplied by densitometer manufacturers are better tools for instrument balance than production quality control targets. Because measurements are always premised on a process, the reading from each densitometer represents a single state. The bias of two instruments must be determined form the average of many readings.

A good guideline when making densitometer re-adjustment or correction suggests only doing so when when a valid trend is present. Knowing when a trend exists calls for using a control chart. Rather than recalibrating the densitometer with each set of control readings, the user reads the designated set-up standard and records the values. If the plotted data varies around the average in a random manner, the user should not reset the instrument. If the chart exhibits a verified trend, the user should make half the indicated correction and continue to monitor performance.

If the measurement system exhibits random variability about its average reading level, frequent re-adjustment may increase the swing of the data values. Should the instrument be re-adjusted when it is at a random high value, the almpoint will be incorrectly reset to a new low value. The random nature of variance would then show an extreme low action limit. This frequent adjustment is over-control and is a source of added variability.

Future Developments

The success of the T-Ref as a functional SRM for graphic arts densitometry has suggested similar SRMs for the photographic industry. The increased interest in colorimetry as a process control tool has started to move this measurement instrument from a scientific laboratory environment to that of production quality control; functional SRMs for this area have been proposed as well.

Literature Cited

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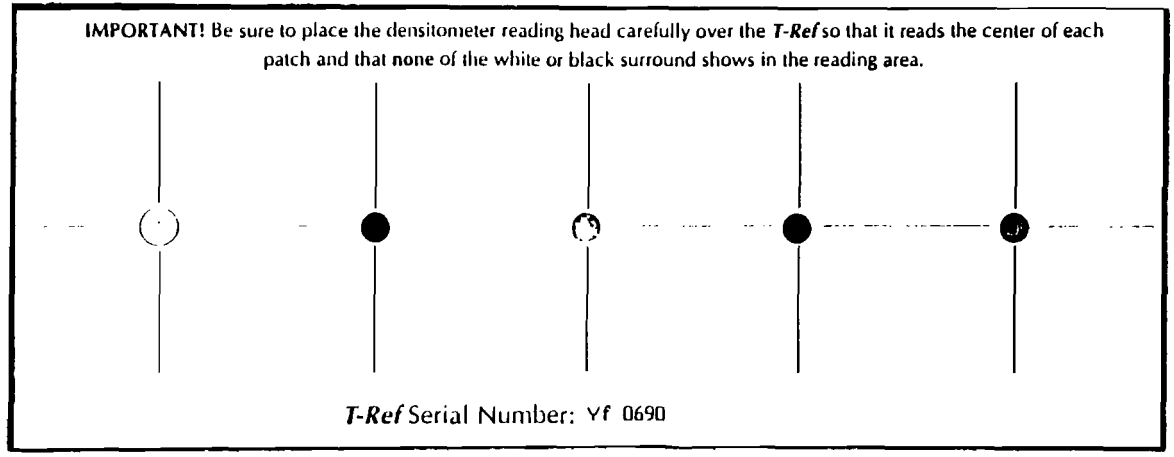

Figure 1
Layout of targets on the T-Ref™.
Targets are 5mm in diameter except white, which is 7mm.