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Using the contrast ratio method and achromatic transmission densitometry as a substitute for Status A transmission densitometry with the Photographic Activity Test For Enclosure Materials

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Using the contrast ratio method and achromatic transmission densitometry as a substitute for Status A transmission densitometry with the Photographic Activity Test For Enclosure Materials

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Certificate of Approval

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This is to certify that the Master's Thesis of

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has been approved by the Thesis Committee as satisfactory for the Thesis requirement for the Master of Science degree at the convocation of May 2013

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Abstract

The discontinuation of conventional photographic spot-reading transmission densitometers –including the widely adopted X–Rite model 310– due to the rapid decrease in demand for analogic photographic laboratory work has had a broadly felt effect in the conservation community. In the cultural heritage conservation field, instruments like the X–Rite 310 are widely used, specifically in the performance of the Photographic Activity Test (PAT) for the preservation of photographic materials. In the present research, five possible alternate metrics were investigated as substitutes for the increasingly unavailable spot reading transmission densitometers in Status-A readings as mandated by the current PAT. The analyzed metrics were: (1) ratio in reflection using normal illumination geometry and circumferential 45° viewing (0/45:c), (2) contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component included (d/8:i), (3) contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component excluded (d/8:e), (4) Ortho–transmission densitometry and (5) UV– transmission densitometry.

The contrast ratio metric can be obtained with commonly available reflection spectrophotometers, such as the X–Rite 939 and the X–Rite SP64. The use of contrast ratio metric could open up new possibilities for measurement in the field of art reproduction and cultural heritage preservation to analyze changes in density and opacity. The proposed work analyzed the readings obtained by three measurement instruments:

(1) X–Rite 361T, (2) X–Rite 939 and (3) X–Rite SP64, in a set of three achromatic transmission step-wedges (15–Step Transmission Stouffer© Graphic Arts T1530CC step-wedge) used as a surrogate for the colloidal silver strip used in the PAT.

The goal was to evaluate the performance of the five proposed metrics and geometries as a possible alternative to transmission densitometry measurements when recording data using the Photographic Activity Test.

The results indicate that there exists a near-perfect linear relationship between the readings using the X–Rite 361T in Ortho-transmission densitometry channel and the readings from the Status-A transmission density using the X–Rite 310 across the entire densitometric range represented by the Stouffer wedge. The UV channel measurements also exhibit a near seamless linear regression model with the Status-A readings. Both relationships were found to be statistically significant. On the other hand, the measurements with the setups using contrast ratio measurements did not exhibit the same linear relationship when the entire measurement range is considered. However, in readings of less than .95 opacity, the contrast ratio measurements did exhibit a meaningful linear relationship when compared to the Status-A transmission readings with a density value of less than 1.8, albeit still with lower correlation than both readings with the X–Rite 361T.

Chapter 1:

Introduction

It is common for photographs and prints to come in contact with enclosures and mounting materials like papers, boards, plastics, labels, tapes, inks, and adhesives. These items can greatly affect the stability and permanence of photographic materials both when stored in the dark and when exposed to light due to the physical and chemical interaction among these variables. Because these materials are typically in close contact with the photographs and printed images, they must be carefully selected. For this reason, it is strongly recommended by conservators that the storage, enclosure, and mounting materials pass the Photographic Activity Test (PAT). This test is a standard method described in the ISO 18916:2007(E) Imaging materials – Processed imaging materials – Photographic activity test; and it analyses the possibility of chemical influence on processed photographs originated by materials in close contact (ISO 18916, 2007).

The standard testing method explained in the ISO 18916:2007(E) is a predictive test of chemical interactions between the storage–enclosure and photographic materials, such as processed silver–gelatin, color (chromogenic dyes–gelatin), inkjet prints (dye and pigment based inks), thermal–dye–diffusion–transfer prints, digitally–printed dye–diffusion–transfer prints, liquid and dry toner–base prints and diazo images. These

interactions could be exemplified as the single reaction with the silver image to produce fading and other forms of image degradation and as staining of the non–image areas.

According to the ISO 18916:2007(E), the test consists of incubating the enclosure material or its component against the surfaces of two sensitive detectors during a 15-day period at a 70°C ± 1°C temperature and 86 % RH ± 3%. The detectors are: (1) *image interaction detector*, which is an unprocessed colloidal silver in gelatin on polyester base used in the Image Interaction Test, and (2) *stain detector* that is a conventional non-resin-coated black-and-white photographic paper processed to minimum density (D_{min}) according to the manufacturer's instructions used during the Stain Test.

The photographic density of these detectors is measured before and after incubation (at four different locations per sample) and the density changes compared with those obtained when the detectors are incubated against a filter paper control. In the standard, it is established to measure the Status A blue diffuse density of the detector strips using a densitometer having spectral conformance to ISO 5–3 Photography – Density measurements – Part 3: Spectral conditions, and geometric conformance to ISO 5–2 Photography and graphic technology – Density measurements – Part 2: Geometric conditions for transmission density and ISO 5–4 Photography and graphic technology – Density measurements – Part 4: Geometric conditions for reflection density for the measurements. For the image interaction detector, it is used transmission density on the colloidal silver and for the stain detector the reflection density on the photographic paper.

In the Photographic Activity Test, the densitometric measurements have typically been obtained using spot-reading transmission photographic transmission densitometers,

such as the X–Rite model 310. This instrument has been widely used in the photographic industry as a process-control tool for monitoring the consistency of both black-and-white, and color negatives and prints. This device has also been used to measure the density or its variations in the materials used for the production of cultural heritage objects.

As the demand for conventional-analogic photographic materials and laboratories has decreased, so has the need for spot reading photographic densitometers. The manufacturers have largely discontinued spot-reading photographic densitometers, and it is expected that replacement parts and service will also soon likely be discontinued. Although strip-reading photographic densitometers are widely used with photographic minilabs, these instruments are not especially well suited for the spot reading needs of conservators. It is likely only a matter of time before replacement parts are exhausted and consequently the maintenance services for spot-reading photographic densitometers will be ceased. Without a suitable replacement instrument that would meet the needs of conservators on the horizon, it is necessary to ascertain if there is an alternative method that could be effectively used to measure differences in color and density in photographic materials and printed images and to perform the PAT. Therefore, it is desirable to find one such alternate method which could meet the needs of photograph conservators with more common and widely available instrumentation.

Although the availability of spot-reading transmission densitometers for the Photographic Industry is decreasing, it could be said that accessibility to spot-reading reflection spectrophotometers is increasing. There is a recent trend of frequent releases of new models of these reflectance devices by major companies. For example, Konica

Minolta introduced a new instrument in 2010, and Datacolor and X–Rite are currently introducing new models. Therefore, a metric such as contrast ratio that is measured by a spot reading reflection spectrophotometer could be widely supported in the foreseeable future.

Specifically, in the field of Conservation and Preservation of Photographs, a common procedure for utilizing the X–Rite 310 Color Transmission/Reflection Densitometer is for the conservator to measure the particle density in different black-and-white shades of photographic negatives and prints, and the cyan, magenta and yellow dyes in color photography. The results obtained with this device provide information about the material state of image-forming substances. This procedure yields quantitative information regarding the state of the silver particles and/or the dyes in a photographic object at a specific date. If these photographic materials are exhibited and/or used to make new prints or reproductions, possible degradation in the image–forming substances will result in differences in appearances that could be precisely measured.

In order to mimic the conditions that could cause degradation, conservators could directly exhibit them, or directly expose them to artificial degradation factors such as high-illumination intensity, high heat, and high content of humidity in the environment. It is a standard practice, in the conservation field, to record the quantified state both before and after those activities, and specify the variation in density of the image-forming substances due to the exposition of the photographic object to the factor-time binomial degradation.

For example, the main deterioration of black-and-white photographic materials is a result of the inherent transformation of the silver particles and can be understood as the decrease or diminution in density of the silver in various degrees. The decrease of density is observed as a change in color, usually called yellowing, and –in severe cases, the degradation can result in the complete fading and disappearance of the image. These visual consequences are the result of physical and chemical changes in the metallic silver particles that involve: (1) the decrease in the size and/or change of shape of the silver particle per se, (2) the chemical oxidation from a silver particle (Ag^0) to an silver ion (Ag^+) that is invisible, and (3) the combination of the silver ion with other elements like sulfur forming new compounds like silver sulfur (Ag_2S) that has different physical and chemical properties and characteristics.

It is due to the reasons stated above that measuring the difference in density and color in negatives and positives is very relevant for photo conservators. Using the same or similar measuring practices with alternative instrumentation and color metrics could help determine if there is an alternative procedure that is a reasonable substitute for the now discontinued X–Rite 310 Color Transmission/Reflection Densitometer.

This research included he review and evaluation of data obtained using a set of diverse methods metrics using three distinct measurement instruments to determine if similar measurements for the spot transmission densitometry can be recorded with any of the examined measurement devices and metrics. The main goal of this research was to find if there is a plausible relationship between the transmission densitometric readings in Status A with the proposed metrics, in order to reach the suitable substitution method for

the Image Interaction Test of the PAT. In this manner, the measurement method applied can be selected depending on the available instrumentation. The proposed metrics were:

- Contrast ratio in reflection using circumferential 45° illumination and normal viewing geometry (0/45:c)
- Contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component included (d/8:i)
- Contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component excluded (d/8:e)
- Ortho Status in transmission densitometry
- UV in transmission densitometry

The metric known as contrast ratio is obtained through a reflection spectrophotometer such as the X–Rite 939 and the X–Rite SP64, and entails reading objects that are not completely opaque over both a white and a black background. As such, contrast ratio is a measurement of the opacity of the object, and could possibly be utilized as a surrogate for transmission readings. Furthermore, the colorimetric values of the object can be recorded over the white standard. By noting the differences in the contrast ratio values, as well as the differences in the colorimetric values, the researcher quantified the differences between the standard and the transmission values obtained with the X–Rite 310. Therefore, the goal of this portion of the study was to evaluate if this contrast ratio as measured in reflection using different geometries could be used to substitute for the Status A readings with a transmission densitometer as mandated by the Photographic Activity Test.

A second set of readings were done using the X–Rite 361T for measuring transmission densitometry in two channels: Ortho and UV. This device is widely used in the printing industry as a process control tool and it is currently available in the spot reading instrumentation market.

In this research, the Image Interaction Test of the PAT was not entirely performed due to the characteristics of the test in which obtaining even and consistent scale of densities is unpredictable. Therefore, an achromatic transmission step-wedge was utilized as a surrogate for the colloidal silver strips required of the PAT; three 15–Step Transmission Stouffer© Graphic Arts T1530CC step-wedges were used during the data measurement phase of this research.

Chapter 2:

Theoretical Basis

The concepts of light, color and density measurements are of the utmost importance to study possible replacement measuring devices for the PAT. They are part of the densitometry and radiometry domains; therefore this chapter encapsulates the fundamental notions of these two fields.

Fundamentals Concepts of Color and Density Measurements

Within the area of color and density measurements, the literature can be organized into those works that examine these topics from a standpoint of physics, while other published works can be described as analyzing the specific instrument geometries. Many published works establish that the scientific foundation of color and density measurements is based on the fundamental concepts of how light can be quantified and measured, which means how the flow of light energy or the energy propagation of light can be quantified in a physical system and how the "brightness" sensation can be related to this measurement.

The analysis and understanding of how light is measured involves knowledge from the radiometry and photometry fields. It is clear that visual characteristics, such as

color, transparency and gloss are a consequence of the light-matter interaction, which is a very complex phenomenon from a theoretical, abstract point of view due to the many factors involved. However, suitable knowledge of radiometry, can help to understand some aspects of this interaction (IS&T (1999), Berns (2000), Lee (2005), and Wyszecki and Stiles (2000)).

When light strikes an object, it is either absorbed or propagated. Propagation involves transmission, reflection, refraction, diffraction, scattering and polarization. In fact, the light illuminating an object's surface is partially reflected, partially absorbed, and partially transmitted (IS&T, 1999). Reflection can be regular, diffuse or retro, while transmission can be regular or diffuse (Berns, 2000). These phenomena are related to the physical-chemical characteristics and properties of the object that modulate the radiant flux and distribute it in various directions through the object as illustrated in Figure 1.

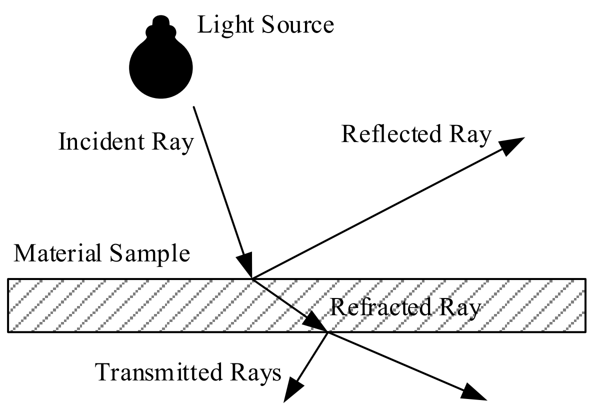

Figure 1. Propagation of Light

Basically, to quantify to what level the object can modulate the light a simple measurement described by the factor that is equal to the ratio of one radiant flux to the

reference is used. In other words, the radiant flux propagated in the direction to be measured divided by the reference radiant flux. The reference radiant flux is the incident flux (from the light source), the propagated flux passed through the system when the object is removed, or the propagated flux through the system when the object is replaced by a reference standard. For practical application a logarithmic measure is more useful than the arithmetic (IS&T, 1999). This modulation is a dimensionless measure, which basically describes the density of the material.

In radiometry, the concepts and measurements of optical energy flow are described using geometrical optics. For example, Snell's law determines the path by which a ray is transmitted from one medium to another. However, this description as all measurements, presents some considerations, likely rays cannot converge in a single specific point, and the physical optics of diffraction influence this measurement (Lee, 2005).

Radiometric Measurements

There are different metrics or quantities used to characterize a material through the measurement of the energy or light. Optical energy flow is described by different quantities: (1) quantities associated with light rays that are functions of both position and direction, such as radiance, (2) quantities associated with surfaces or volumes which are functions of only position or only direction, but not both, such as radiant exposure and (3) quantities that are not associated with geometry, such as energy (Lee, 2005).

The instruments used for metering these quantities have a basic design composed by a light source and a detector (Salvaggio, 2007). The light source could be described as a point source, which is an idealization that has a spatial location but no physical dimension when the distance between the source and the sensor is large. For example, a star can be treated as a point source even if it is much larger than the Earth. If the source's physical dimension is smaller than one-tenth of the distance between the light source and the object, and the error in the radiometric calculation is on the order of 10%, the concept of point source is used (Lee, 2005).

The basic concepts to understand color and densitometric measurements are:

- Radiant Flux, Φ: the radiant flux is the energy flow per unit time through a specific point in space and in a specific direction and it is a function of both the position and direction; therefore the radian flux is related with a light beam. The unit of radiant light energy is the joule Q.
- Intensity, I; intensity also called radiant intensity is the quantity that describes the light output from the point source or the radiant flux leaving the point source that is described as the radiant flux per unit solid angle (Lee, 2005).
- Radiance, L: it is the quantity which describes the amount of light coming from a surface. This measurement is used when the light source is large enough to be treated as a point source. For example, when measuring the light reflected from a wall. Most surfaces reflect light (excluding the specular highlight) with approximately equal radiance in all directions.

Quantities, such as radiant flux and radiance are measured in terms of radiant energy; however, when different wavelengths are measured by their visual efficiency in generating the sensation of "brightness", the resulting concepts are luminous flux, luminance, and illuminance (Lee, 2005).

A radiation source whose radiance (L) is completely independent of the viewing angle is called a Lambertian-source when it is self-emitting or a Lambertian surface either when it is reflecting or transmitting. A Lambertian surface, theoretically, reflects or transmits 100% of the incident light and it is referred as a perfect reflecting or transmitting diffuser. This idealized reflector or transmitter is used in the definition of radiance factor, which is a quantity that describes how bright a surface looks to an imaging system (Lee, 2005).

Quantities associated with both the position and direction are:

- Radiant Flux Density, W: it is a quantity that describes how much light passes through a surface area.
- Irradiance, E: this term is used to describe the radiant flux per unit area irradiating on a surface.
- Radiant Exitance, M: the radiant exitance is the radiant flux per unit area that is leaving the surface.

Reflectance, ρ

Reflectance is a measure of how strongly a material reflects the light. It is defined by the ratio of the radiant flux of the reflected light, Φ_r to the incident light, Φ_i. In general, the value of reflectance depends on the geometry, the polarization, and the

spectral composition of the incident and reflected light. Light that reflects off from the surface of the material causes specular gloss, texture, distinctness-of-image gloss, and luster (Berns, 2000).

Since energy cannot be created in a passive material, reflectance cannot be greater than 1. A Lambertian surface with reflectance equal to 1 is called a perfect (reflecting) diffuser. Theoretically, in calculating the reflectance, the total amount of reflected light is used regardless of how it is distributed angularly. Visually, reflectance does not directly correspond with the appearance of a reflecting surface. For example, a mirror in a dark room illuminated by a spotlight does not look bright from the off-specular angle, even if its reflectance is very high (Lee, 2005).

The measurement used to characterize the visual appearance of a surface is the radiance factor. This measurement is a relative measure that correlates better with what it is seen by the human eye than reflectance, ρ. For example, safety reflectors for bicycles are specific materials that reflect light strongly in certain directions. These materials may have reflectance factors greater than 1 for a specific lighting and reflecting geometry. The radiance factor is divided in:

- Reflectance factor: it is defined as the ratio of the radiant flux reflected in the direction delimited by the measurement cone to that reflected in the same direction by a perfect reflecting diffuser identically irradiated.
- Transmittance factor: this measurement is used to characterize transmissive materials, and it is defined by the ratio of the transmitted radiant flux by the sample to the measurement when the specimen is removed from the sampling

aperture of the measuring device or by the measurement of a perfect transmitting diffuser (ISO 5-2, 1991).

Although the basic definitions of the radiometric measurements are summarized without reference to the spectral composition of the light that is measured, in practice, the response of the instrument performs in accordance with the wavelength. Although most radiometric measurements are simple to describe, they are very difficult to perform accurately because there are many factors that influence the measurement and introduce errors.

Densitometry

According to Fraser (2005), in optics, density is the degree to which materials absorb light. In other words, density is the ratio of how much light is incident on the surface sample and how much light is transmitted or reflected; therefore, the higher the density, the less light that can be reflected or transmitted because the material had absorbed most of the light (e.g.: Sharma (2004), Southworth (1989)). Density is defined as the common logarithm of the ratio of the incident light received by the sample to the light transmitted or reflected by or throughout the sample (Kessler, 2007); therefore densitometric values are relative measurements and dimensionless. The following equation is employed to calculate density:

$$D = \log \frac{I_o}{I} \qquad (1)$$

Where: D = density

I_0 = incident irradiance

I = output irradiance

In a graphic material, such as a print or a photograph, the light–stopping ability of the image-forming materials is expressed as density. Density describes the opacity of the material, which is the reciprocal of the reflectance or the transmittance. Transmittance is defined as the ratio of the total radiant flux transmitted by a material to the total radiant flux incident on the sampling aperture (ISO 5-2, 1991).

$$D = \log \frac{1}{T} \qquad (2)$$

Where: D = density

T = transmittance

Transmission Density

Transmission density is a measure of the ability of a material to transmit the radiant flux. Basically, it involves two modes of geometry: (1) diffuse transmission density, and (2) projection transmission density.

1. Diffuse Transmission Density: it is a measure of the modulation of light by a material/film that is diffusely illuminated/irradiated on one side and measured/viewed from the other (ISO 5-2, 1991). This geometry is

specifically used for film that is diffusely illuminated to expose an underlying photosensitive layer, as is done in some contact printers. Currently, very few measurement devices of this type are available.

2. Projection Transmission Density: it is a measure of the modulation of light by a material/film that is illuminated/specular irradiated by the cone of radiant flux on one side and viewed/projected from the other by the cone of radiant flux suspended by a projection lens/specular collection system (ISO 5-2, 1991). This geometry is predominantly related to the measurements of photographic images to be projected with a system employing optical condensers.

The geometry of projection transmission density simulates the geometric conditions of a small area on a negative or transparency in the frame of a typical projection system employing optical condensers. These kinds of condensers are normally utilized in the manufacture of parts that are used in equipment for viewing microfilms, motion pictures, and transparencies, and to make projection prints (IS&T, 1999).

The measured density is a variable depending on a half-angle of the cone of incident flux and the half-angle of the cone suspended by the projection lens, at the sampling aperture (ISO 5-2, 1991).

Transmission density, D_T, is defined as the natural logarithm to the base 10 of the reciprocal of the transmittance factor (ISO 5-2, 1991), and it is calculated as shown in the following equation:

$$D_T = log_{10}\frac{1}{T} = log_{10}\frac{\phi_i}{\phi_t} \quad (3)$$

Where: D_T = transmission density

T = transmittance

Φ_t = transmittance flux

Φ_i = incident flux

Reflection Density

Reflection density (sometimes referred to as reflectance density, although technically they are the result of different measurements) is a measure of the ability of a material to reflect the radiant flux. The measurement of the reflection density is complex due to the different phenomena happening in the material; the first effect is produced by an external reflection on the surface of the material, and the second effect is caused by many internal reflections (IS&T, 1999). Surface and internal reflections from and within the different areas of an image cause a non-linear relation between reflection and transmission densities. The non-linearity in the low-density regions is due to multiple internal reflections, and that in the high-density areas is due to surface reflection as seen in Figure 2.

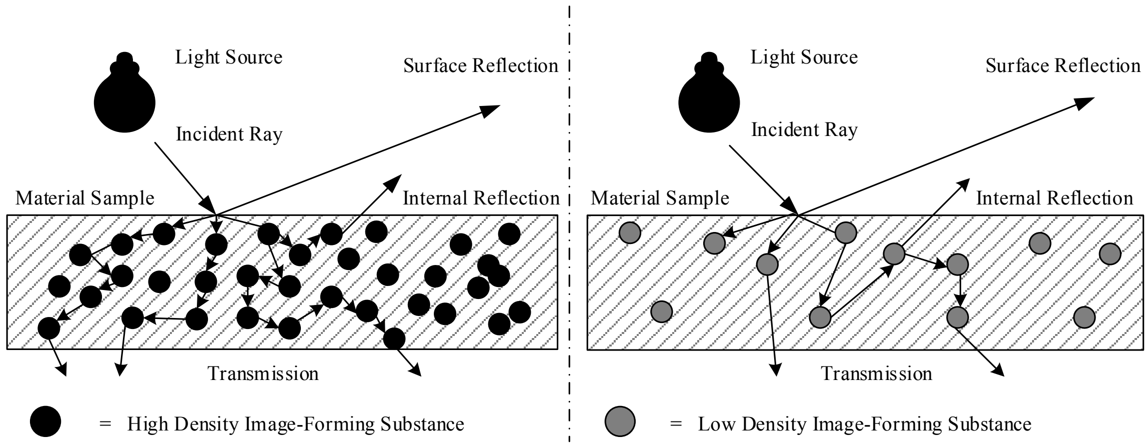

Figure 2. Multiple Reflections

The measured value of a reflection density is highly dependent on the geometric conditions; therefore the exact specification of the conditions is required. The geometric conditions will be explained further in this section.

Reflectance density, D_R, is defined as the negative logarithm to the base 10 of the reflectance.

$$D_\rho = -log_{10}\,\rho = -log_{10}\frac{\phi_r}{\phi_i} \quad (4)$$

Where: D_ρ = reflectance density

ρ = reflectance

Φ_r = reflected flux

Φ_i = incident flux

Reflection density, D_R, is defined as the negative logarithm to the base 10 of the reflectance factor, R. The reflectance factor is the ratio of the reflected flux, Φ_r, to the

absolute reference reflected flux of a perfectly reflecting and perfectly diffusing material, Φ_{rA}, under the same geometrical and spectral measurement conditions (ISO 5-4, 2009).

$$D_R = -log_{10} R = -log_{10} \frac{\phi_r}{\phi_{rA}} \tag{5}$$

Where: D_R = reflection density

R = reflectance factor

Φ_r = reflected flux

Φ_{rA} = absolute reference reflected flux

The instrument used to measure density is the densitometer and it is the basic quality-control measurement device for printing applications. Essentially, densitometers can be divided into two categories: reflection and transmission. Densitometers measure the amount of light and not color features, per se. Despite the same measuring conditions, the values from different instruments are not always identical. This can be due to differences in the spectral transparency of the filters (like aging), the spectral distribution of the light sources, or the measurement geometry itself.

To ensure that the densitometers behave adequately, there are a series of standard response curves or spectral responses to maintain consistency. Status filters are placed in the densitometer to achieve those appropriate spectral responses, each status corresponds to a different spectral response that uses different filters (Peres, 2007). The X–Rite 310 Color Transmission/Reflection Densitometer uses the Status A and Status M response curves.

Table 1
Main Status Filters

Filter	Used for:
Status A	Color transparencies that will be viewed directly
Status D	Measuring color prints
Status G	Measuring inks in photomechanical reproductions
Status M	Color negatives and transparencies that would be printed
Status V	Visual densitometry

In summary, a densitometer is an instrument, which measures the degree of darkness or the optical density of a semitransparent material by transmission or a reflecting surface by reflection. It is important to note that densitometers are not designed to specifically measure color, but rather measure density metrics.

Spectrophotometry

Spectrophotometry is the quantitative measuring of: (1) spectral reflectance, (2) intensity ratios between each wavelength of light shone onto a surface, and (3) light of the same wavelength reflected back to the detector in the instrument (Fraser, 2005). Spectral reflectance is similar to the reflectance, ρ, measured by a densitometer; however, density is a single value that represents the total number of photons reflected or transmitted, while spectral reflectance is a set of values that represent the number of photons being reflected or transmitted at different wavelengths. In other words, in spectroradiometry, the amounts of radiation are measured using narrow bands of wave

lengths placed at regular intervals through the electromagnetic spectrum (Hunt and Pointer, 2011).

In general, a spectrodensitometer is a device that has a spectrophotometer for measuring luminous energy at many frequencies throughout the electromagnetic spectrum, and the spectral data can usually be displayed in convenient units such as CMY, density, L*a*b* or XYZ. The instruments typically used in the graphic arts divide the visible spectrum into 10 nm or 20 nm bands, and produce a value for each band. Very sophisticated devices, typically known as laboratory-grade instrumentation, can divide the spectrum into a larger number of narrower bands, some small as at 2 nm intervals.

Geometric Conditions

The description of the material's color is based on measures in which spectral or colorimetric data are collected for a specific combination among the position of the light source, the object/material/sample, and the detector; each of them varying independently in a three-dimensional space. From these data, the color of the material can be defined for any real-life illuminating and viewing conditions (Cook, 1982-cited in Berns, 2000).

Although, theoretically, many combinations of angles between the light source, the sample and the detector are possible, in practice there are a few standardized geometries used in the design of the instruments (Berns, 2000). The International Commission on Illumination (CIE) has defined technical regulations, such as standard observer, standard sources, standard illuminants, and standard geometry of illumination.

Differences in instrument responses occur depending upon the geometry of the influx (radiant flux incident on a sample surface or a sampling aperture) and that of the efflux (radiant flux emanating from a sample surface or a sampling aperture, and measured by a detector). Thus, the geometry must be exactly described with the half angle of a cone and the direction of its axis (IS&T, 1999). International Standard ISO 5-2 describes the geometric conditions for transmission densitometry, and ISO 5-4 describes the geometric conditions for reflection densitometry.

In the case of the transmission geometry the influx cone has a half-angle from 0° to 90°. When the angles of efflux are as large as 5° or 10° the measurements are considered as ‘projection density’. The density is increased, as the system tends toward a specular design.

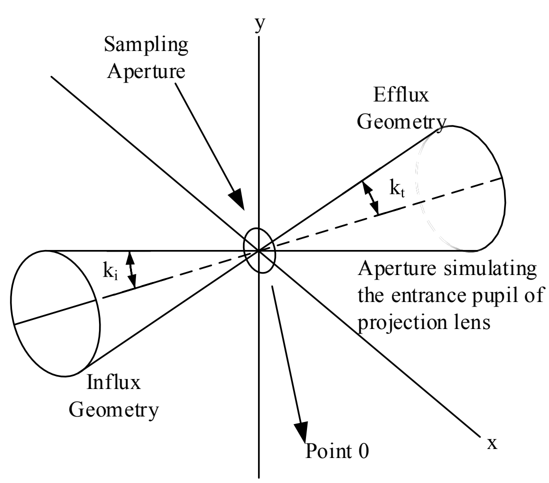

Figure 3. Basic Transmission Geometry

It was mentioned previously that the reflection density is considerably dependent on the geometric conditions. The basic designs of the instruments were based in how prints or graphic reproductions are viewed. Usually, they are illuminated at the angles

between 40° and 50° to the normal on the surface, and viewed along the normal. This illumination reduces the surface glare and maximizes the density range of an image. Consequently, the instrument's geometry is typically designed to satisfy the conditions of a 45° illumination and a normal collection or a normal illumination and a 45° collection (IS&T, 1999).

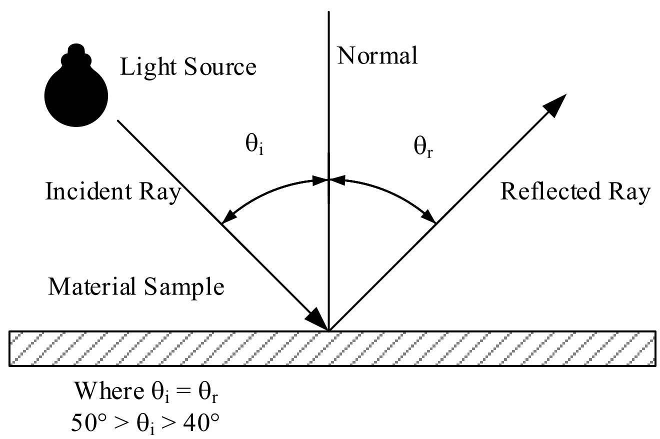

Figure 4. Normal Illumination

The CIE has specified four geometries for reflectance measurements divided by pairs: (1) 45°/normal and normal/45°, and (2) diffuse/normal and normal/diffuse. The designation refers to illumination angle/viewing angle alternatively referred to as influx/efflux. The measurement instruments are designed with a specific geometry and could be referred to as bidirectional for 45°/normal and normal/45° geometries or integrating spheres for diffuse/normal and normal/diffuse geometries.

45°/normal and normal/45°

In the geometry 45°/normal the sample is illuminated by an incident ray at an angle of 45° from the normal and is measured from the normal. In the opposite arrangement, normal/45°, the object is illuminated at a normal angle to its surface and the measurements are made at a 45° angle from the normal. These two geometrical conditions are used in applications where the color of the object may have many degrees of gloss. The ratio between reflected light over incident light is very small, since only a small fraction of the reflected flux can be recorded by the detector (Hunt and Pointer, 2011). The instruments designed with 45°/normal geometry can present three arrangements: (1) one light source, (2) two lights sources in which the second source is placed at the opposite angle of the first light source, azimuthal angle, and (3) one light source that is reflected in all azimuthal angles, annularly, or at many angles, circumferentially (Berns, 2000).

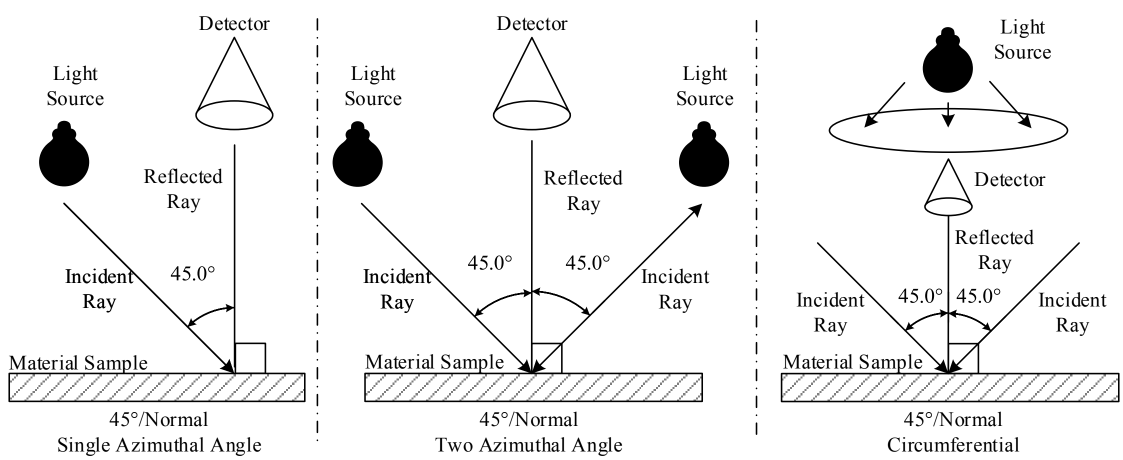

Figure 5. 45°/Normal Pairs of Geometries

Diffuse/normal and normal/diffuse

Diffuse/normal and normal/diffuse are two specific geometries which refer to the use of integrating spheres rather than directional lighting. An integrating sphere is a hollow metal sphere coated with a highly reflecting diffuse material. This instrument collects all the light reflected from the surface of the sample through an opening into the sphere called a port. Integrating spheres designed for color measurement use the normal angle between 6° and 8°.

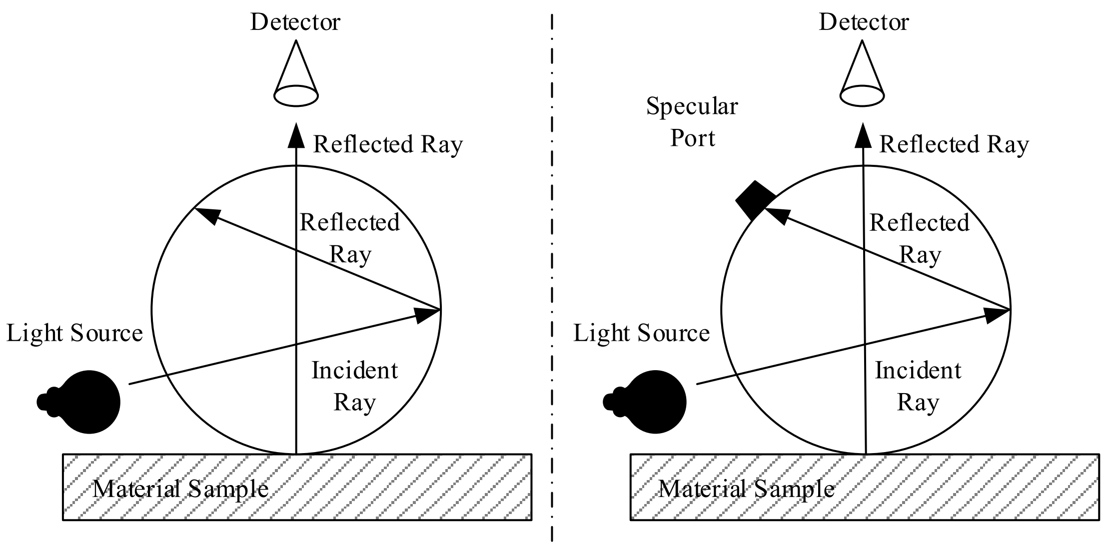

Figure 6. Diffuse/Normal Pair of Geometries

By placing the specular detector port at the opposite angle, the specular reflection can be either included or excluded from the measurement. The specular reflection would consist of uniform white light added to the visual evaluation is the sample, regardless of how the sample is rotated.

- Specular Component Included: in this geometry a material with identical properties to the sphere's interior is placed in the specular port. This geometry corresponds to completely diffuse illumination in which any specular reflection and texture would not be included. Integrating sphere measurements with specular component included are labeled as t/0, 0/t, SIN, SPIN, and SPI. The abbreviation, d/8:i, is used to refer to the diffuse illumination and 8° viewing with the specular component included.
- Specular Component Excluded: in this geometry a black trap is placed in the specular port. This geometry corresponds to completely diffuse illumination in which the specular reflection is excluded and texture will not be observable. Integrating sphere measurements with specular component excluded are labeled as d/0, 0/d, SEX, SPEX, SPE. The abbreviation d/8:e is used to refer to the diffuse illumination and 8° viewing with the specular component excluded.

To achieve a better correlation to visual measurements, the specular reflections should be excluded from the color measurement; however, it is recognized that no instrument completely eliminates the specular component (Berns, 2000).

Table 2

Summary of Measurement Geometries Abbreviations (Berns, 2000)

Abbreviation	Measurement Geometry
d/8:i	Diffuse illumination and 8° viewing with the specular component included
d/8:e	Diffuse illumination and 8° viewing with the specular component excluded
45/0:c	Circumferential 45° illumination and normal viewing
0/45:c	Normal viewing and circumferential 45° illumination
0/0	Normal viewing and normal collection

Chapter 3:

Review of the Literature in the Conservation Field

In the conservation of cultural heritage, densitometers and spectrodensitometers have been used to measure changes in density that could involve lightening or darkening, and also changes in color. In 2000, the Conservation Center of Los Angeles County Museum of Art conducted a research to evaluate the possible changes in color inkjet prints due to the exposition to two indoor lighting conditions: (1) north skylight filtered through by a window glass, and (2) light exposures that simulated museum exhibition conditions, like tungsten lighting filtered with a UV blocking plastic glazing. To measure any appearance modifications the X–Rite 939 Portable Spectrodensitometer (which measures reflectance spectroscopy) was employed. This instrument uses a gas filled tungsten light source and 0°/45° geometry to collect reflected light. CIE L* a* and b* and Density T were recorded and the values were computed using the X-Rite QA Master software for a D65 illuminant and a 10° observer (Schaeffer, Healey and Norton, 2000). The goal of this research was to determine which describing appearance system is more sensitive to measuring minimum fading before any changes in the appearance of the inkjet prints are noticeable by eye to ensure that inkjet prints can be exposed in about 20 exhibitions, with dark storage in between them, before appearance changes are observed.

Photography. A Conservation Overview

Analogic and digitally printed photographs are complex multilayer objects, which combine a great variety of materials where each has a specific function. In general, the physical structure could be divided in three main components (Lavédrine, 2003):

1. Support: also called base provides the physical structure for the image. It could be transparent or opaque, made on materials such as metal plates, glass plates, plain paper, coated paper and plastic films.
2. Binder: it provides cohesion of the materials that generate the photographic image. The main material used since the end of the nineteen-century is gelatin. However, others organic polymers have been used, for example: albumin and successively collodion (cellulose nitrate). However, there are processes that do not present a binder.
3. Image–forming substance or final image material: it is the material that contains the image.

In addition to the overall physical fragility that many materials and objects show and the irreversible transformation due to the effects of time and environmental conditions; photographic materials tend to be extremely vulnerable due to their inherent nature to react with multiple degradation factors, such as incorrect processing, environmental conditions (temperature and percentage of relative humidity), presence of pollutants, other materials in close contact, and incorrect storage and handling.

Although, the entire structure and constitutive materials of the photographs are susceptible to deterioration, the main concern is the significant degradation of the image-forming substances, which are considerably chemically reactive. The final image material is the most important part of a photograph (positive or negative) because it physically contains the pictorial information of the recorded element (Reilly, 1986). The final image material is formed by substances that selectively absorb and diffract, or diffuse light (Lavédrine, 2003).

In the monochromatic processes, the image is typically formed by silver particles, although other non-silver materials could be found according to the photographic process employed, as illustrated in Table 3. The image–forming substances used in the different color processes could be dyes or pigments.

Table 3
Examples of Monochromatic Photographic Processes

Process	Image-forming substance
Salted Paper Print Albumen Print Gelatin Printing-Out Paper Collodion Printing-Out Paper	Photolytic Silver
Calotype Negatives Wet-Collodion Processes	Physically Developed Silver
Gelatin Developing-Out Paper	Filamentary Silver
Cyanotype	Ferrous Ferricyanide and Ferric Ferrocyanide
Platinotype	Metallic Platinum
Carbon Print	Carbon Black
Bichromated Gum Arabic	Pigments

Protection of Photographs: The Significance of the Enclosures

The protection of photographic materials has been defined by an enclosure system composed of a set of physical barriers that have a specific function. According to Bertrand Lavédrine, this system is divided in three levels of protection (Lavédrine, 2003):

Level I. Filing envelopes and boxes

Level II. Storage furniture

Level III. Storage areas

The enclosure system does not just serve to organize and store the different objects, collections or archives; it establishes a microenvironment that could contribute to the conservation of the objects or significantly diminish it. Therefore, a deep understanding of the nature, materiality and processes of degradation of the photographs and printed images in conjunction with a comprehension of their interaction with the environmental conditions and with other materials is required to design a system that will not be destructive for the photographs and printed materials.

The materials that are in direct and close contact with the photographs constitute Level I in Lavédrine's classification. Processed photographs in archival collections require a high degree of individual packaging to protect them. This level is the first physical barrier against harmful factors and it also provides protection from particles, abrasion and inappropriate handling. The individual packaging also keeps the photographic materials from contaminating each other due to the generation of damaging compounds during the processes of degradation. A wide variety of paper and plastics

materials is commercially available, such as albums, boxes, sleeves, envelopes, folders, mat boards, and interleaving tissues. Because these materials are in intimate contact with the object, their selection must be carefully analyzed. It is highly recommended that these materials pass the Photographic Activity Test.

Photographic Activity Test

The parameters of the Photographic Activity Test have been analyzed since 1978 when it was described in the ANSI Standard PH1.53–1978. Since that time detector materials, environmental conditions, procedures, and incubation times have been modified to optimize the test.

In the ISO 18916:2007I, three main tests are described according to the deterioration effect: (1) Image Interaction Test, which measures the density changes in the image, (2) Stain Test: measurable density increase in the stain detector, and (3) Mottle Test: visual evaluation of localized non-uniform visual density variation in the image interaction detector. There are also four specific procedures related to the material being tested: (1) adhesives, inks and paints, (2) labels and tape, (3) dye coupler reactivity test, and (4) diazo images.

Image Interaction Test

The Image Interaction Test is described in the ISO 18916:2007(E), section 5, which explains procedure, calculation and requirements. For this test, two stacks of two image interaction test sandwiches are required, namely: (1) colloidal silver detector with

the enclosure material, and (2) the colloidal silver image interaction detector without the enclosure material.

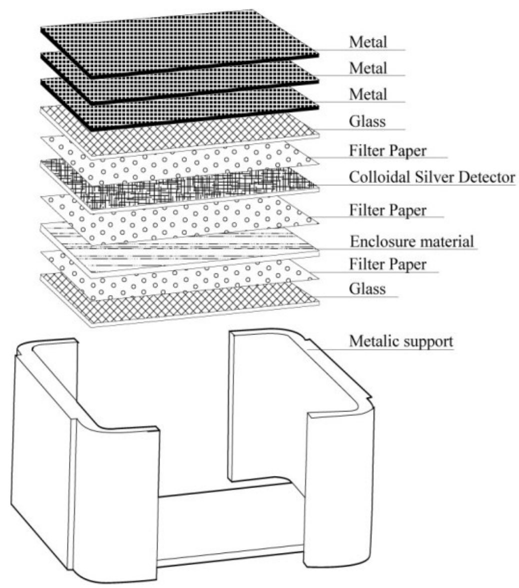

Figure 7. Stratigraphy of the Stack with Enclosure Material

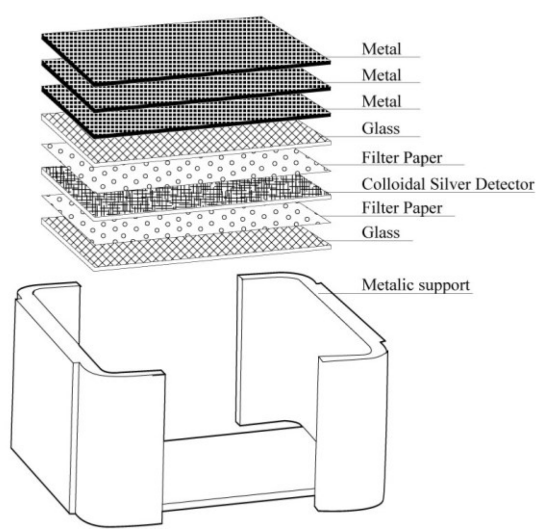

Figure 8. Stratigraphy of the Stack without Enclosure Material

The image interaction of the colloidal silver detector is calculated by the subtraction of the final Status–A blue diffuse–transmission density from the initial blue density. The image interaction mean of these density changes is then calculated (according with the number of readings). The mean of the image-interaction values produced by the filter paper controls is also calculated.

To calculate the percentage of image interaction effect in the colloidal silver using the densitometric measures, the following equation is employed:

$$X = \frac{\Delta D_e - \Delta D_f}{\Delta D_f} \times 100 \qquad (6)$$

Where: X = image interaction difference, expressed as a percentage

ΔD_e = density change of the enclosure detector

ΔD_f = density change of the filter paper control detector.

The standard establishes that the enclosure material must not produce a percentage image interaction effect in the colloidal-silver fade detectors greater than a relative difference of more than ± 20 % compared to the control (ISO 18916, 2007 and Kilde, 2001).

Colloidal Silver

For the precise recognition of potential image degradation, the image detector should be susceptible to density changes. The colloidal silver has the size, shape, and spacing of the individual silver particles to present density changes if it is close and/or in contact with harmful materials and/or environments. In fact, the colloidal silver shows the

greatest change in response to the incubation conditions. Colloidal–silver coatings showed large density changes when incubated in contact with known harmful materials. In addition to overall density changes, they also became mottled in the presence of reactive substances. These materials were found to be much more sensitive to image interaction and mottle than conventional filamentary silver images. Consequently, colloidal silver is very suitable as an image interaction detector in the PAT, because maximum sensitivity is desired.

When colloidal silver is incubated at 70 °C and 86 % RH, some of the visible metallic silver (Ag^0) is oxidized to invisible ionic silver (Ag^+). This generally results in a density decrease. Moreover, when colloidal silver is incubated in the presence of oxidizing agents, increased oxidation and consequently a greater density decrease is obtained. Therefore, if colloidal silver incubated in contact with an enclosure material shows a greater density decrease than when incubated in contact with a filter paper control, it indicates the presence of oxidizing agents in the enclosure material. In consequence, the detector density with the enclosure is less than the detector density with the filter paper control after incubation. However, if incubation in the PAT causes an increase in density of the colloidal silver detector, this may reflect reduction of any present ionic silver. Alternatively, it can also reflect oxidation since the density can either increase or decrease, depending upon the size of the original colloidal silver particles. In both scenarios, a significant density difference between the detector in the enclosure material and the one in the filter paper indicates an objectionable degree of chemical

activity of the material proposed for as storage-enclosure, which should be then be rejected according to the PAT.

Chapter 4:

Research Objectives

The goal of this work was to find a substitute of conventional photographic spot-reading transmission densitometers, such as the X–Rite model 310, due to their discontinuation by their respective manufacturers. It is plausible that the services and replacement parts for densitometers will be discontinued at some point in the future, as well. This could have broad deleterious effects in the conservation community because these instruments are widely used, specifically in the performance of the Photographic Activity Test (PAT) specified in the ISO 18916:2007 Imaging materials – Processed imaging materials – Photographic activity test.

In the present research work, five possible alternative metrics and geometries were investigated and evaluated the performance as potential substitutes for the increasingly unavailable spot reading transmission densitometers in Status A readings as mandated by the current PAT.

The metrics analyzed were: (1) contrast ratio in reflection using normal illumination geometry and circumferential 45° viewing (0/45:c), (2) contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component included (d/8:i), (3) contrast ratio in reflection using diffuse illumination and 8° viewing

geometry with specular component excluded (d/8:e), (4) Ortho–transmission densitometry, and (5) UV– transmission densitometry.

The readings for these metrics were obtained with the following three measuring instruments: (1) X–Rite 361T, (2) X–Rite 939 and (3) X–Rite SP64, in a set of three achromatic transmission step-wedges (15–Step Transmission Stouffer© Graphic Arts T1530CC step-wedge) used as a surrogate of the colloidal silver strip used in the PAT.

In summary, the goal of this research was to find if there is a plausible relationship between the transmission densitometric readings in Status A with the proposed metrics, in order to reach a suitable substitution method for the Image Interaction Test of the Photography Activity Test; so that the measurement method applied in it can be selected depending on the available instrumentation.

Chapter 5:

Methodology

The development of the experiment phase involved two main steps:

1. Data collection: Measurement of the three achromatic transmission step-wedges (15-Step Transmission Stouffer© Graphic Arts T1530CC step-wedge) with four different instrumentation devices:

   Transmission Densitometers

   - X–Rite 310 Color Transmission Densitometer
   - X–Rite 361T Transmission Densitometer

   Reflection Spectrodensitometers

   - X–Rite 939 0°/45° Portable Spectrodensitometer
   - X–Rite SP64 Portable Sphere Spectrophotometer

2. Data analysis.

Data Collection

Measurements are usually made by comparison with a standard source. In this research, the standard source was the transmission densitometric values measured by the X–Rite 310 Color Transmission Densitometer in Status A. Three main measurement

instruments were selected to evaluate the possible relation of their different metrics in function of the transmission densitometry used in the Photography Activity Test.

Due to the variability of the measurements in different devices and to achieve adequate accuracy, all instruments must be calibrated to a known measurement, which refers to an absolute value of radiant power for that precise reference. The calibration option is commonly offered by the instrument manufacturers as part of the instrument's designs. Therefore all instruments used in this research were properly calibrated according to the manufacturer specifications.

For the purposes of this research, three achromatic transmission step-wedges (15-Step Transmission Stouffer© Graphic Arts T1530CC step-wedge) were used as a surrogate for the colloidal silver strip. All the samples measured were classified as non-self-luminous and diffusing samples. To measure non-self-luminous materials, it is required to illuminate them with a source that emits light throughout the spectrum.

In summary, all metrics are functions in which a comparison is made "between the radiant power of a beam of light after it has been reflected from or transmitted by, the sample, and the radiant power of a similar beam after it has been reflected from, or transmitted by, a calibrated working standard" (Hunt and Pointer, 2011). For diffusing samples, as the step-wedge used in this experiment, the working standard was a white reflecting surface.

Measurement Instruments

X–Rite 361T Transmission Densitometer

The X–Rite 361T is a spot-transmission densitometer widely used by publishers, service agencies, trade shops, and printers. This measurement device is used to monitor the quality of the film output during the different processes, such as image setter linearization, exposure adjustment, processor quality control, and verifying duplicated or contacted films. In the printing industry, the X–Rite 361T is also used to perform instrument calibration to a known density reference or to a known dot reference. The 361T has a built-in UV response mode for measurement of otherwise invisible film base fog. An ordinary densitometer is not sensitive to UV blocking that can occur in the seemingly clear film base. The UV response of the X–Rite 361T can also be used to evaluate diazo films.

X–Rite 939 0°/45° Portable Spectrodensitometer

The X–Rite 939 is an instrument that is normally used by printing companies and ink manufacturers for evaluation of the spectral and colorimetric values of ink and/or a substrate, as well as for density measurements, dot–area measurements of press sheets and proof, and also for ink formulation. This device is representative of many reflection spectrodensitometers commonly utilized in the printing industry.

X–Rite SP64 Portable Sphere Spectrophotometer

The X–Rite SP64 is a spherical hand held spectrophotometer used for diverse color measurement applications for laboratory, plant and field operations. This instrument measures opacity, color strength in chromatic, apparent and tri-stimulus calculations. A summary of instrument specifications is shown in Tables 4 and 5.

Table 4
Instrument Specifications I

Device	X–Rite 310T	X–Rite 361T
Type	Color Transmission Densitometer	Transmission Densitometer
Measurement	Density	Density Dot area
Measurement Range	0.0 *D* – 4.0 *D*	0.0 *D* – 6.0 *D*
Repeatability	±0.01 D	
Response	Status A/M	Ortho and UV
Conformance	ANSI PH 2.19	ANSI PH 2.19 ISO 5-2

Table 5
Instrument Specifications II

Device	X–Rite 939	X–Rite SP64
Type	Reflection Spectrodensitometer	Sphere Reflection Spectrophotometer
Measuring Geometrics	0/45°	d/8°
Light Source	Gas-filled tungsten lamp	Gas-filled tungsten lamp
Standard Observers	2° and 10°	2° and 10°
Spectral Range	400-700nm	400-700nm
Measurement Range	0 to 200% reflectance	0 to 200% reflectance

A plausible application of these devices for characterization of photographic materials could be obtained by the comparison of the blank-and-white gamut and/or color, which can be ascertained from the relations, between the X–Rite 310 used in the PAT and a second device. The following pairs were analyzed:

- Status A transmission densitometry and contrast ratio in reflection using circumferential 45° illumination and normal viewing geometry (0/45:c)
- Status A transmission densitometry and contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component included (d/8:i)
- Status A transmission densitometry and contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component excluded (d/8:e)
- Status A transmission densitometry and Ortho-transmission densitometry
- Status A transmission densitometry and UV-transmission densitometry

Color Metric: Contrast Ratio

The challenge of using a reflective instrument to mimic the results obtained by a transmission instrument could be met by using a metric known as contrast ratio. Theoretically, it is possible to use the contrast ratio metric to approach to the results obtained by a transmission densitometer, such as the X–Rite 310. Contrast ratio is defined as the ratio of intensity between the brightest white and the darkest black of a

particular device or a particular environment. Contrast ratio data could be used to define a color when the opacity of the color is less than 100%. This metric is based in three different types of measurements: (1) a measurement of the color over a black substrate, (2) a measurement of the color over a white substrate, and (3) a measurement of the white substrate.

Method

The research work involved the following activities:

1. Instrument calibration: all measurement devices were calibrated according to the specifications established by the manufacturer.
2. Measurements: three15-Step Transmission Stouffer© Graphic Arts T1530CC step-wedges were measured with each of the instruments.

   Transmission Density: for this quantity two devices were used: (1) X–Rite 310 Color Transmission Densitometer and (2) X–Rite 361T Transmission Densitometer. In both cases the step-wedge was placed in the light bed of the respective instrument.

   Contrast ratio: for this measurement two instruments were used: (1) X–Rite 939 0°/45° Portable Spectrodensitometer and (2) X–Rite SP64 Portable Sphere Spectrophotometer.
3. Data collection: the measurements displayed by the instrument were recorded in a spreadsheet using Microsoft Excel for Mac 2011, as show in Table 6.

Table 6
Example of Spread Sheet

Measurement Instrument	X-Rite 310			*Alternative Device*		
Metric	Transmission Densitometry			*Alternative Metric*		
ID Step Wedge	1	2	3	1	2	3
Step 1						

4. Contrast Ratio Metric Calculation Procedure

4.1. Click "Contrast Ratio Method" on an associated dialog box to open the "Contrast Ratio" dialog box in X–Rite Color Master software.

Note: It is possible to open the dialog box from multiple locations in the program.

4.2. Averaging: from the Averaging list, select the averaging method.

Note: If a single measurement will be used, select "No Averaging". It is possible to use a different averaging method for each of the required measurement types.

4.3. Record the measurement data by using the "View" list to select how to save the measurements if a sphere or angle instrument are used.

Note: For a sphere instrument, select the specular data type (specular component included or excluded) to be used for the measurements. For an angle instrument, select the measurement angle, which will be used.

4.4. Take each of the three required measurements types (color over a black substrate, color over the white substrate, and white substrate). When the program is ready for a specific measurement, it displays a message over the appropriate graph (e.g. when the program is ready for the measurement of your color over the black

substrate, it displays the message “Measure Over Black” above the “Over Black” graph). The program displays a separate reflectance graph for each required measurement. It is also possible to use different entry methods for each of the required measurements.

Note: If necessary, it is possible to use alternate entry methods instead of taking the measurements with the instrument. Practitioners utilizing the alternate entry method would click “Manual Entry” to manually enter reflectance values or click “Paste” to paste the color values from the Clipboard.

4.5. Under Save Option, select the values that you want to use to define the color. Select Predicted to use the color values as predicted for 100% opacity. Based on each measurement taken, the system predicts what the color values would be if the color was 100% opaque.

Note: Select Over White to use the color values from the measurement of your color over the white substrate; select “Over Black” to use the color values from the measurement of your color over the black substrate

4.6. Click “OK” to save the color information.

5. Data analysis: Because this research is based in an experiment, the measurements of the system under study, involves analyzing the system using the same procedure to determine if the implementation of the proposed device and color-ratio metric caused the values of the measurements to be modified. In this analysis Descriptive Statistics were be employed.

6. Data comparisons: The resultant data were compared to address the research questions

Variables

Criterion Variable: The criterion variable, otherwise described as dependent or (y) variable, is the Status A transmission densitometry readings.

Predictor Variables: The predictor variables, otherwise known as independent or (x) variables are divided in two categories: (1) Contrast ratio readings and (2) transmission densitometry readings from the substitute instruments as is illustrated in Figure 9.

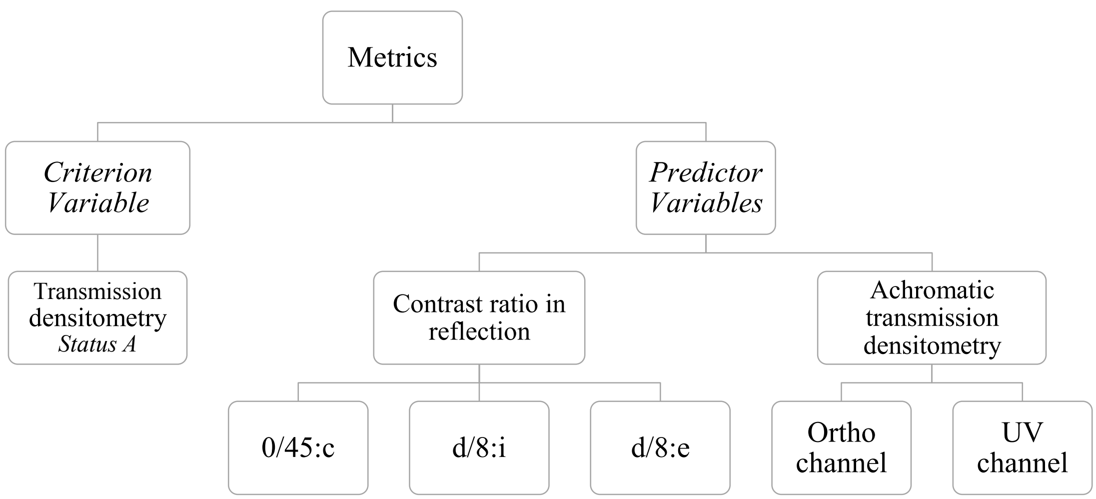

Figure 9. Analyzed Metrics and Variables

Data Analysis

For each of the measuring setups, 3 series of 14 measurements were taken given the steps in the transmission strips. The readings of each substitute reading instrument are paired with the X–Rite 310 Color transmission densitometry measurements that were obtained at the same time. These 42 pairs of readings are then input into the linear estimator function of Excel. The strip-based readings of the substitute instruments are used as independent variable while the X–Rite 310 transmission readings are set as the dependent variable in the linear relationship estimation. Then this function estimates all the necessary statistics to evaluate the linearity of the relation and its statistical significance. From the returned values of the estimation function (linest), the coefficient of determination (r^2) allows us to determine how much of the relation can be determined by a linear relationship, the closer to one the better.

The *F*-statistic permits determine if the relation is statistically significant by allowing us to reject the null hypothesis of this relationship occurring by chance. Finally, this function also provides the slope and the intercept to create a linear equation that represents the predicted accompanying X–Rite 310 transmission measurement given the reading from the substitute instrument.

Chapter 6:

Results

The experiments carried out in this work show the possibility of a relationship between the Status A transmission densitometry readings required for the Photographic Activity Test (PAT) standard and the readings of measuring systems based on readings from transmission densitometers or reflection spectrodensitometers. The linear relationship demonstrated with the proposed measuring systems could enable the substitution of the already discontinued Status A densitometer in appraisals equivalent to the PAT.

The methodology that was followed examined the samples and a linear relationship was estimated between the reading with the alternative reading instruments and the transmission densitometry in Status A. Next, the probability that the relationship found came from random data is calculated and rejected in the cases where this is unlikely given the F-statistic and the coefficient of determination.

Using a 15-step near-achromatic transmission wedge as a substitute for the incubated colloidal silver referenced in the existing PAT, the Status-A transmission densitometry measurements with the X-Rite 310 were the criterion variable in the present study. Two groups of alternative instruments/metrics were utilized as predictor variables: achromatic transmission densitometry and contrast ratio as measured in reflection.

Achromatic transmission densitometry was measured using both the Ortho and the UV standards with an X–Rite model 361T Transmission Densitometer. Contrast ratio was measured in reflection using both the X–Rite SP64 Portable Spherical Spectrophotometer and the X–Rite 939 0°/45° Portable Spectrodensitometer. Spherical readings were taken in both the Specular Component Included (d/8:i) and the Specular Component Excluded (d/8:e) modes using the X–Rite SP64. Five separate bivariate linear regressions were utilized to compare each continuous predictor variable with the continuous criterion variable as shown in Figure 10.

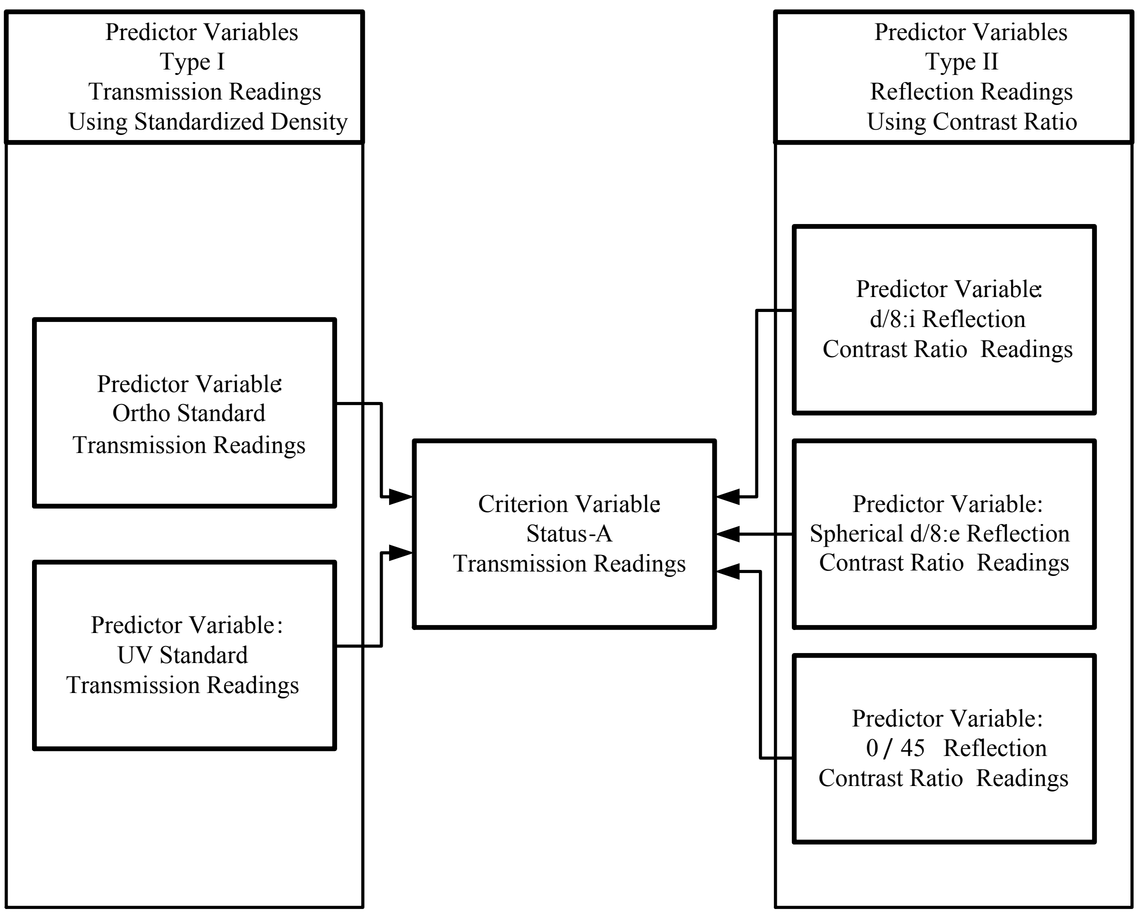

Figure 10. Criterion and Predictor Variables

Linear Regression Results

Data collected from the average of 3 readings of each steps of the near-achromatic step wedge (15–Step Transmission Stouffer© Graphic Arts T1530CC step-wedge) is presented in Table 7.

Table 7

Average Readings of Criterion and Predictor Variables

Measurement Instrument	X–Rite 310	X–Rite 361T		X–Rite 939	X-Rite SP64	
Metric	Status A	Ortho	UV	0/45:c	d/8:i	d/8:e
Step Wedge ID	$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{x}$
1	0.33	0.33	0.36	12.11	33.71	16.89
2	0.60	0.61	0.62	30.57	61.11	36.89
3	0.90	0.92	0.91	64.19	86.06	69.15
4	1.19	1.21	1.19	87.45	96.20	90.38
5	1.51	1.53	1.49	97.12	99.12	99.11
6	1.82	1.84	1.78	99.31	99.42	101.01
7	2.14	2.16	2.09	99.74	99.84	99.53
8	2.45	2.46	2.38	99.44	99.94	99.88
9	2.76	2.78	2.67	100.53	99.75	99.56
10	3.07	3.09	2.97	99.40	99.25	99.91
11	3.37	3.39	3.25	99.28	99.59	99.18
12	3.70	3.72	3.58	100.04	99.58	99.71
13	3.99	3.99	3.87	101.42	99.44	98.15
14	4.35	4.36	4.27	100.16	99.07	101.20

According to these results, it is apparent that the reflection readings using contrast ratio approach 100% opacity near step five of the wedge, which corresponds to a Status-A density of approximately 1.5. The contrast ratio readings are generally undifferentiated above step five. In contrast, the transmission densitometric readings using the UV and Ortho standards are differentiated throughout the entire range represented by the wedge.

In the following table the estimated linear relationships as well as coeficient of determination are presented. The resultant values of the first experiments in the first two rows indicate that the values for the criterion variable closely fit the curve as predicted by the linear model. The lower value for the bottom three rows shows a much poorer fit by the obtained models using contrast ratio in the complete range. The last two columns of the table show the results of applying the F-test for the significance of the fit of the model. The degrees of freedom of the F distribution used for the test are (1, 40) given that the number of samples n=42 and that the model has 2 parameters.

Table 8

Test for significance of the linear regression between the transmission densitometry in Status A and the alternative metric

Metric (x)	Status A Regression Equation (y)	r^2	F-Statistic (1, 40)	Significance Level (>)
Ortho–transmission densitometry	$y = -0.0156 + 1.0003x$	0.9999	564589	0.99
UV–transmission densitometry	$y = -0.0383 + 1.0404x$	0.9998	160759	0.99
Contrast ratio in 0/45:c	$y = -0.5031 + 0.033x$	0.5431	48	0.99
Contrast ratio in d/8:i	$y = -1.6545 + 0.0435x$	0.4328	31	0.99
Contrast ratio in d/8:e	$y = -0.6647 + 0.0343x$	0.5077	41	0.99

A linear regression established that both transmission densitometry readings using the Ortho standard and a UV filter could statistically significantly predict Status-A transmission readings. For Ortho transmission densitometry with $F(1, 40) = 564589$, $p < 0.01$ and the Ortho standard accounted for 99.99% of the explained variability in the Status-A readings. The regression equation is: Status A = -0.0156 + 1.0003 Ortho Density. For UV transmission densitometry the regression equation is: Status A = -

0.0383 + 1.0404 UV Density considering with $F(1, 40) = 160759$, $p < 0.01$. Applying the obtained linear equation. Figures 11 and 12 illustrate the relationship between the actual readings and the transmission densitometry values predicted by the linear equation.

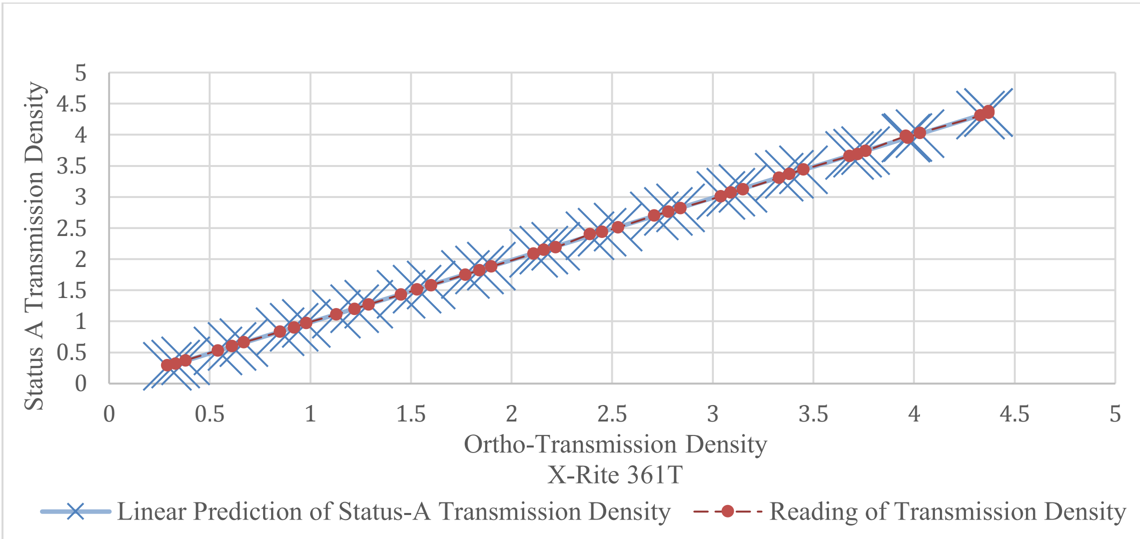

Figure 11. Criterion and Predictor Variable Relationship: Ortho-Transmission Density

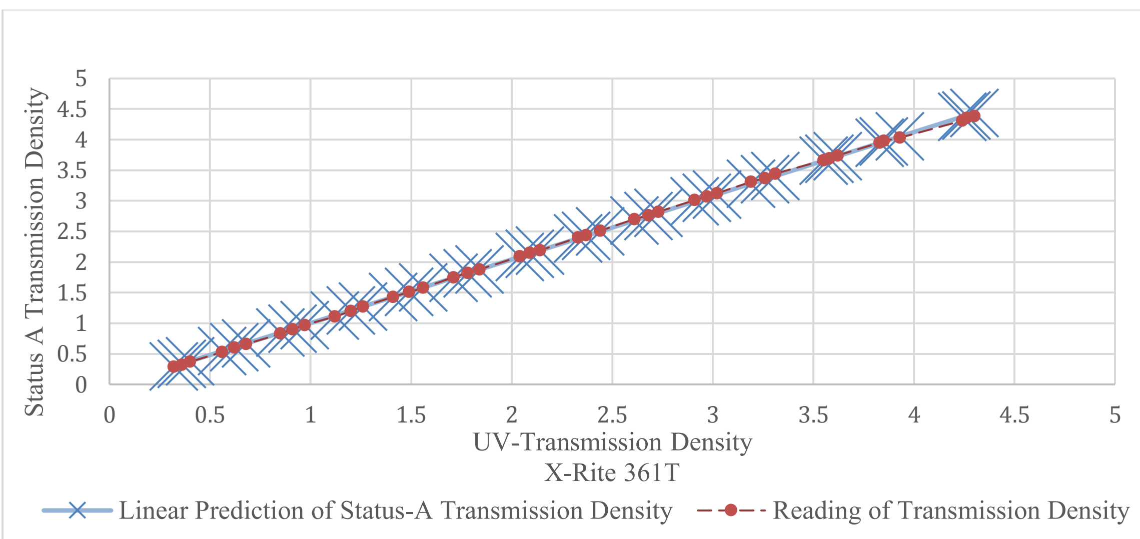

Figure 12. Criterion and Predictor Variable Relationship: UV-Transmission Density

When using contrast ratio to evaluate the entire range of densities, unsatisfactory predictions for the linear models were obtained, as illustrated in Figures 13, 14 and 15 for the X-Rite 939 and X-Rite SP64 measurement devices. The linear predictions show a high level of non-linearity at values higher than 90% of opacity.

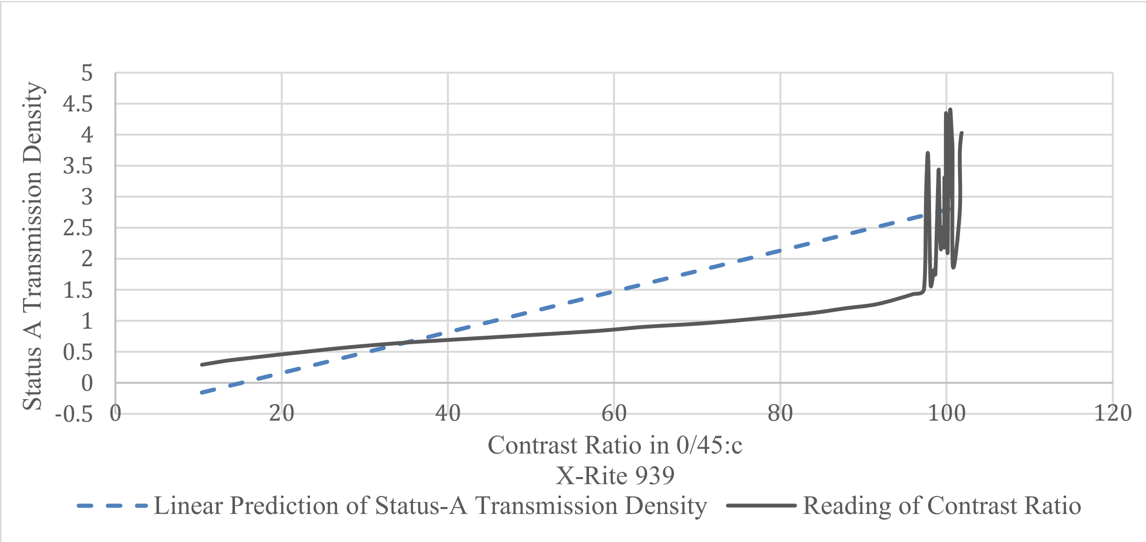

Figure 13. Criterion and Predictor Variable Relationship: Contrast Ratio in 0/45:c

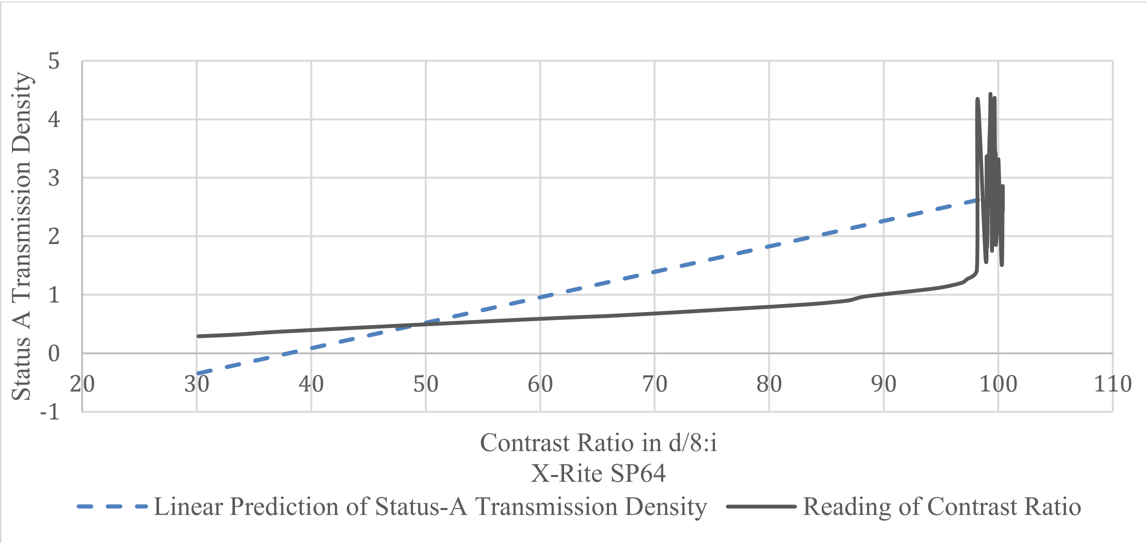

Figure 14. Criterion and Predictor Variable Relationship: Contrast Ratio in d/8:i

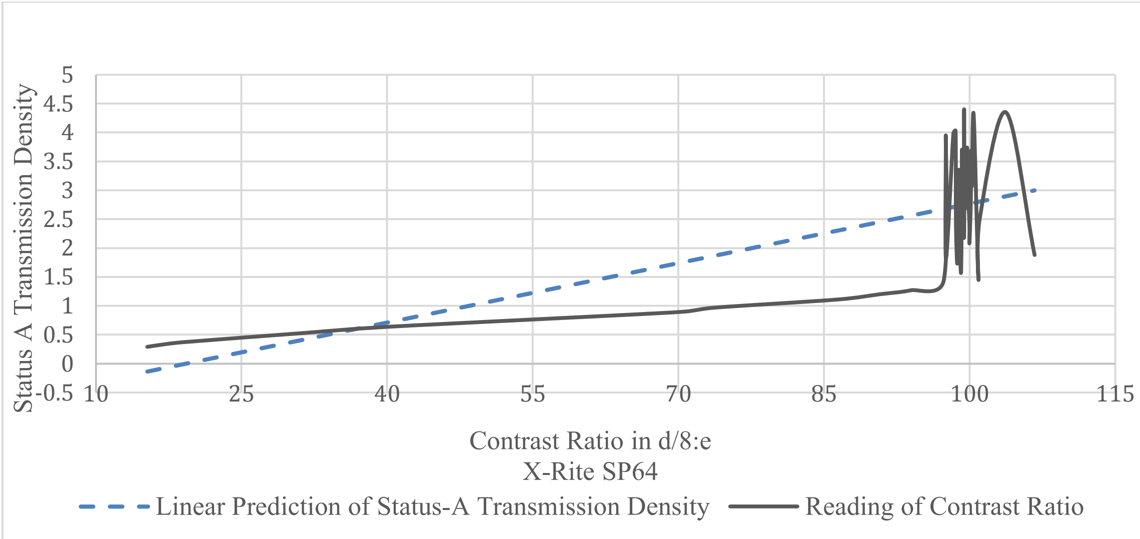

Figure 15. Criterion and Predictor Variable Relationship: Contrast Ratio in d/8:e

Contrast Ratio Linearity Region Below 95% opacity

Given the results from the contrast ratio readings, it was decided to perform the same linear regression analysis while limiting the contrast ratio below the 95% opacity where it seems more likely that a linear relation could exist. The resulting analysis are illustrated in Table 9 and graphically shown in Figures 16, 17 and 18.

Table 9

Test for significance of the linear regression between the transmission densitometer and alternative metric in regions below a 95 contrast ratio

Metric (x)	Status A Regression Equation (y)	r^2	*F*-Statistic	Significance Level (>)
Contrast ratio in 0/45:c	$y = 0.2149 + 0.011x$	0.9905	*F* (1, 10)=1040 n=12	0.99
Contrast ratio in d/8:i	$y = -0.861 + 0.0117x$	0.9766	*F* (1, 8) = 333 n=10	0.99
Contrast ratio in d/8:e	$y = 0.1436 + 0.0115x$	0.9910	*F* (1, 10) = 1102 n=12	0.99

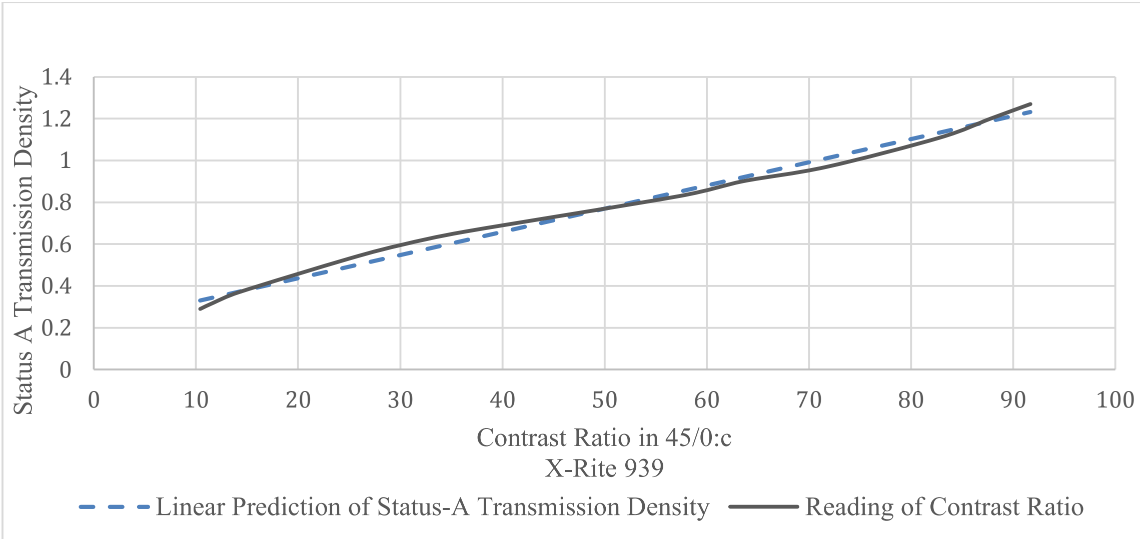

Figure 16. Criterion and Predictor Variable Relationship: Contrast Ratio in 0/45:c, n=12

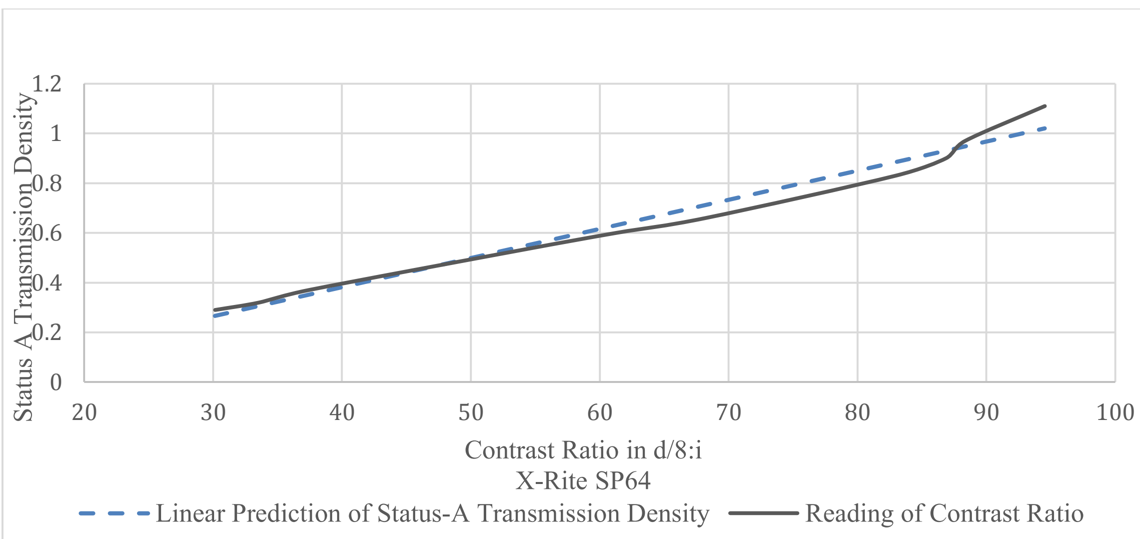

Figure 17. Criterion and Predictor Variable Relationship: Contrast Ratio in d/8:i, n=10

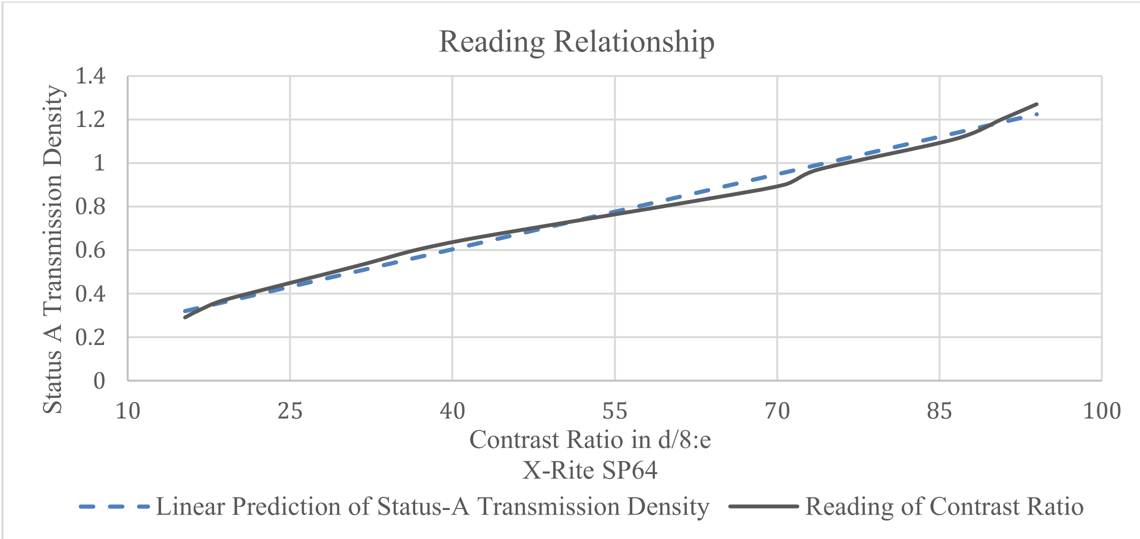

Figure 18. Criterion and Predictor Variable Relationship: Contrast Ratio in d/8:e, n=12

A final data analysis was performed in which the sample was limited to the data below 2.0 density values. This condition may not prove to be a limitation in application given that many samples, including colloidal silver, do not normally exceed a transmission density of 1.5. Further, the PAT currently examines a change of 20% as being relevant, therefore a correlation to Status-A at density values lower than 2.0 may be relevant in future applications if the starting opacity of the chosen test material begins at a low-density value.

Since a linear regression was utilized to compare the predictor variables to the criterion variable, it is important to analyze the assumed linearity of the data. Scatter plots of the criterion variable against each predictor variable are provided to allow a visual inspection for the presence of a linear relationship. A visual analysis of each scatterplot assures that the assumption of linearity is supported as illustrated in Figure 19.

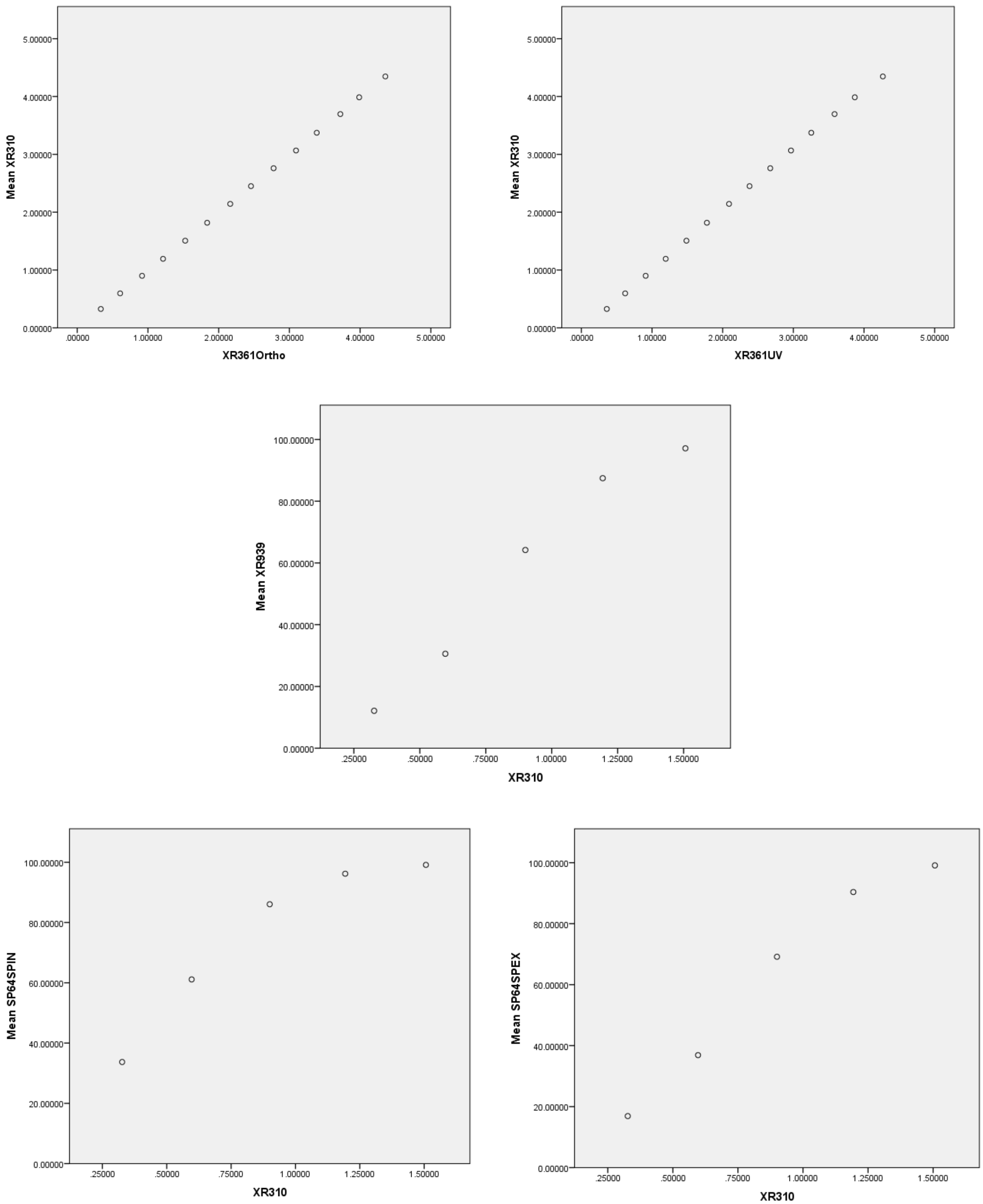

Figure 19. Scatter Plots of Criterion and Predictor Variables

Another assumption of linear regression is that the variance of the errors is constant across each observation. This is examined to determine whether the errors of prediction, also known as residuals, are equal across the standardized predicted values. This is commonly known as a test for homoscedasticity: and a visual evaluation of the respective graphs indicates that required homoscedasticity is met for the collected data, as illustrated in figures 20 and 21.

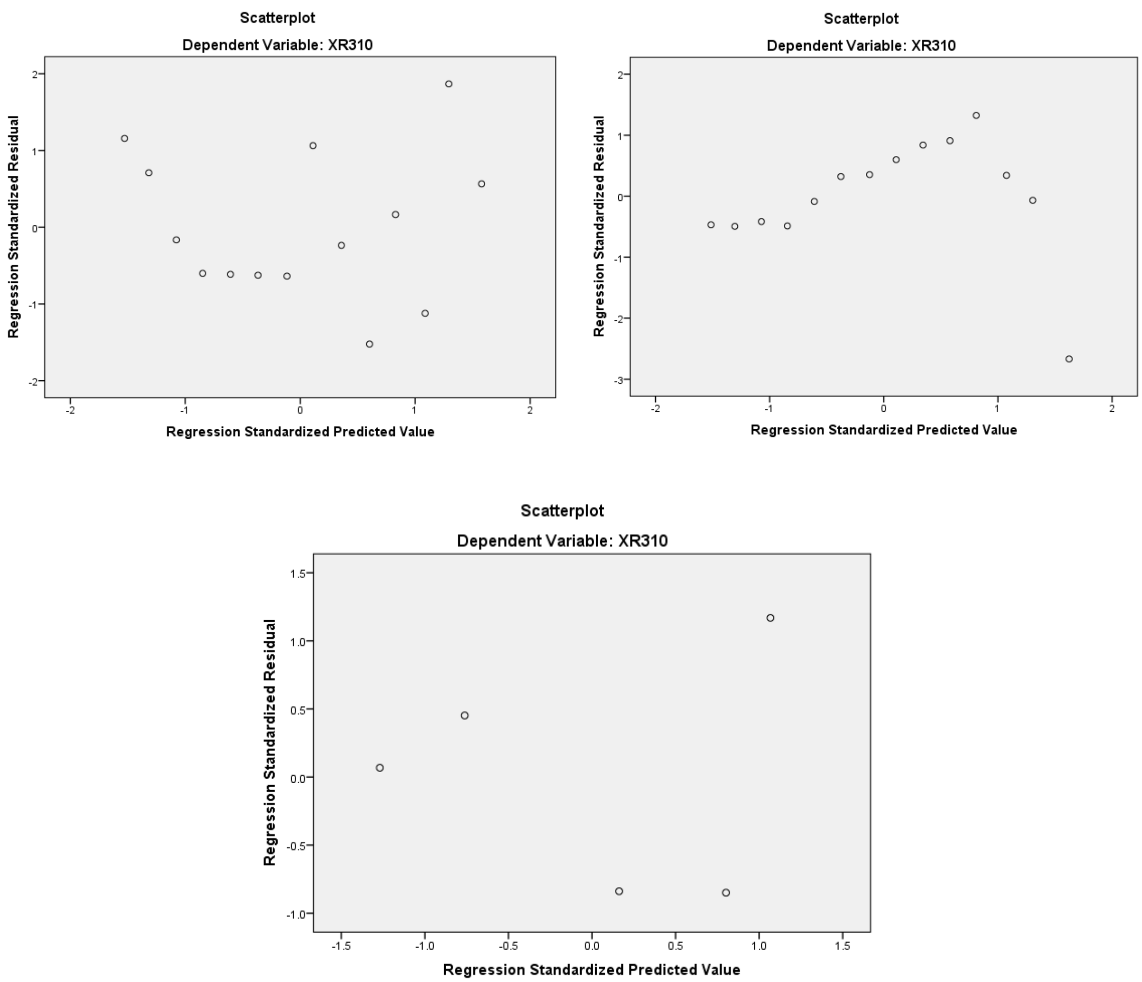

Figure 20. Variance of the Errors I: Ortho-Transmission, UV-Transmission and Contrast Ratio (0/45:c)

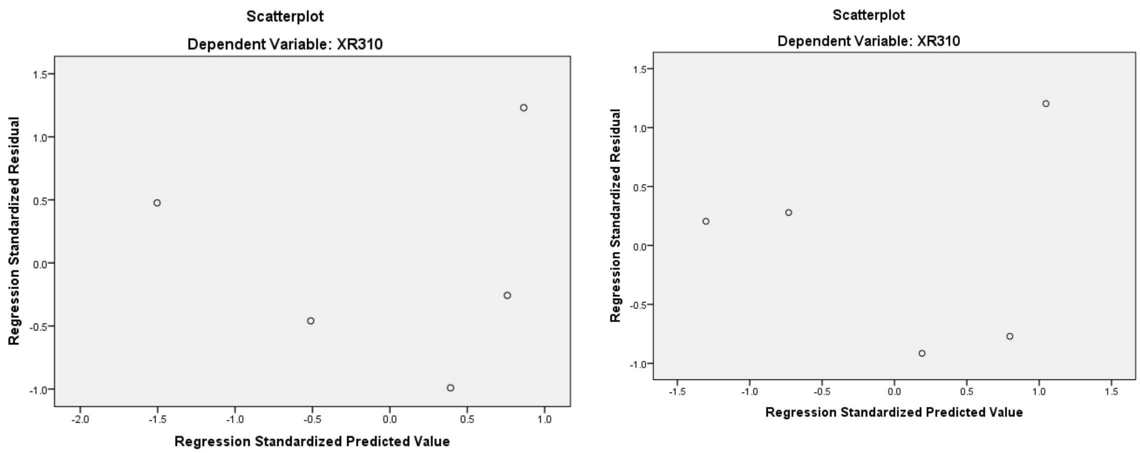

Figure 21. Variance of the Errors II: Contrast Ratio (d/8:i) and Contrast Ratio (d/8:e)

To ascertain if the residuals are normally distributed, the Normal P-P plots are displayed for visual analyses. Due to the small sample size, it is determined that evaluations of histograms would be of little use here. With the Normal P-P plots, normally distributed residuals will be represented by points along the diagonal line. In each case, although the points do not align perfectly along the diagonal, they are sufficiently close to indicate that the residuals approximately follow a normal distribution, as illustrated in Figure 22. As a linear regression is fairly robust against deviations from normality, it can be safely established that these results can be used for further analysis with no requirement to further transform the data.

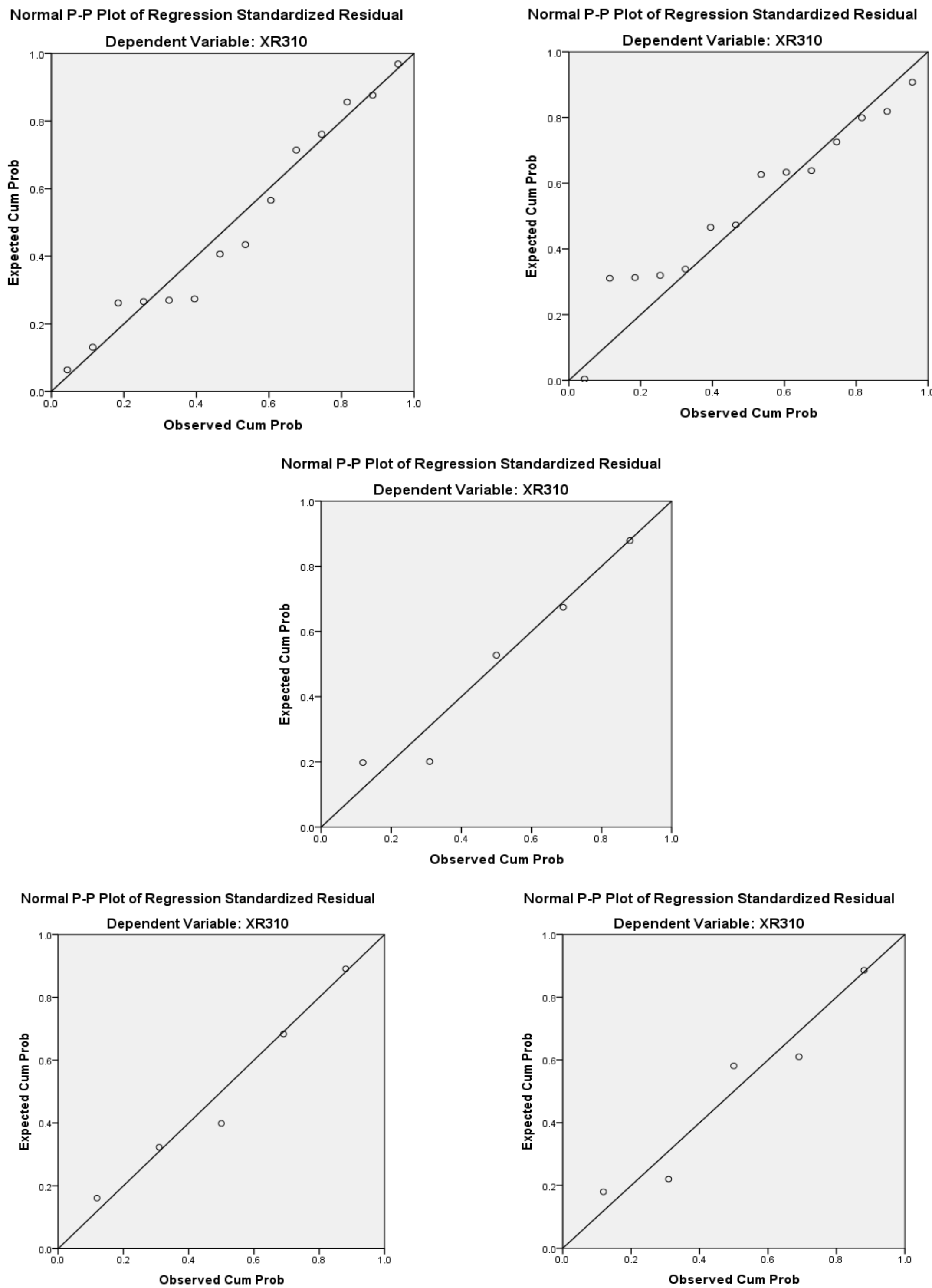

Figure 22. Normal P-P Plots

Result Discussion

Ortho Transmission Densitometry

A linear regression established that the particular variable transmission densitometry using the Ortho standard could predict Status A transmission densitometry values when using a near-achromatic sample with high statistical significance $F(1, 12) = 361{,}589$, $p < 0.001$ and Ortho transmission densitometry accounted for > 99% of the explained variability in Status A densitometry. The obtained regression equation was: Status A Transmission Densitometry = -0.016 + 1.0 Ortho Transmission Densitometry.

UV Transmission Densitometry

A linear regression of established that the particular variable transmission densitometry using the UV standard could statistically significantly predict Status A transmission densitometry when using a near-achromatic sample $F(1, 12) = 530{,}099$, $p < 0.001$ and UV transmission densitometry accounted for > 99% of the explained variability in Status A densitometry. The regression equation was Status A Transmission Densitometry = -0.038 + 1.04 UV Transmission Densitometry.

Contrast Ratio Specular Included

A linear regression established that the particular variable contrast ratio using the Spherical geometry Specular Included standard could statistically significantly predict

Status A transmission densitometry when using a near-achromatic sample at densities less than 1.5 $F(1, 3) = 24.234$, $p < 0.05$ and Specular Included Contrast Ratio accounted for 85.5% of the explained variability in Status A densitometry. The regression equation was: Status A Transmission Densitometry = -0.297 + 0.16 Contrast Ratio d/8:i.

Contrast Ratio Specular Excluded

A linear regression of established that the particular variable contrast ratio using the Spherical Geometry Specular Excluded standard could statistically significantly predict Status A transmission densitometry when using a near-achromatic sample at densities less than 1.5: $F(1, 3) = 83.318$, $p < 0.05$ and Specular Excluded Contrast Ratio accounted for 95.4% of the explained variability in Status A densitometry. The regression equation was: Status A Transmission Densitometry = 0.84 + 0.13 Contrast Ratio d/8:e.

Contrast Ratio 0/45:c

A linear regression of established that the particular variable contrast ratio using the 0/45 geometry could statistically significantly predict Status A transmission densitometry when using a near-achromatic sample at densities less than 1.5: $F(1, 3) = 94.716$, $p < 0.05$ and 0/45 Contrast Ratio accounted for 95.9% of the explained variability in Status A densitometry. The regression equation was: Status A Transmission Densitometry = 0.167 + 0.13 Contrast Ratio 0/45:c.

Chapter 7:

Summary and Conclusions

Summary

The increase in consumption of digitally printed images and digital imaging has caused significant changes in the practices of the Graphic and the Imaging industries. The amount of work done in analogic photographic laboratories has dramatically decreased and consequently the manufacturers of process control equipment have changed their production to adapt to the current needs of the industry. Instruments like the spot-reading transmission densitometers, like the X–Rite 310 Color Transmission/Reflection Densitometer, which were widely used during the analogic photographic era are nowadays discontinued by their manufacturers. This trend has had an adverse effect in the conservation community, which requires reviewing and modifying some of their testing procedures that require using this type of instrumentation.

In the field of cultural heritage conservation, instrumentation such as densitometers and spectrodensitometers have been used to measure changes in density and color to monitor the degradation of the materials due to environmental conditions and other materials. Specifically, for the preservation of photographic materials, color transmission spot-reading densitometers have been used in the performance of the

Photographic Activity Test (PAT). The PAT is a standard testing method described in the ISO 18916:2007 that evaluates the probability of chemical interactions between the storage–enclosure materials and processed photographs and prints.

The main goal of this research was to find if there is a statistical significant relationship between the transmission densitometric readings in Status A as specified in the PAT, usually measured using the X–Rite 310 Color Transmission/Reflection Densitometer, with the alternate proposed metrics in order to find an appropriate substitution instrumentation for the Image Interaction Test required in the PAT. The proposed metrics were:

- Contrast ratio in reflection using circumferential 45° illumination and normal viewing geometry (0/45:c)
- Contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component included (d/8:i)
- Contrast ratio in reflection using diffuse illumination and 8° viewing geometry with specular component excluded (d/8:e)
- Ortho Status in transmission densitometry
- UV in transmission densitometry

Three measurement instruments were used: (1) X–Rite 361T, (2) X–Rite 939 and (3) X–Rite SP64, in a set of three achromatic transmission step-wedge (15–Step Transmission Stouffer© Graphic Arts T1530CC step-wedge) used as a surrogate of the colloidal silver strip used in the PAT, in comparison with the readings obtained using the X–Rite 310 in Status A.

Conclusions and Future Work

This section will discuss relevant limitations of the present study, followed by conclusions and suggestions for future research in this topic. Although laboratory-grade instrumentation may be available, it is not normally used in the practical application of the PAT. In fact, historically standards committees have worked to ensure that the standards would be written in such a way that they could be met with production-grade instrumentation. Therefore, this study focused on the evaluation of commonly available production grade instruments.

Similar to other research projects in which measurement procedures are executed, human error may have influenced data; while this possibility is remote, it is worth considering it.

The main limitation of the present study was the decision to use a near-achromatic transmission standardized step-wedges as a substitute for the colloidal silver that is mandated in the PAT. The characteristics of colloidal silver are such that they are uniquely suited to the requirements of the PAT, however at the time of writing, it was understood that the traditional sole provider of colloidal silver, Agfacolor, has just recently discontinued its availability. Therefore, conservation laboratories can only perform the PAT with any existing colloidal silver that they have in stock. It is clear, therefore, that a revised PAT will need to be developed using a material other than colloidal silver. As previously stated, spot reading Status-A transmission densitometers

are also not commonly available, it makes sense that revisions to PAT would include a different metric as well as a different material. The present study, limited to the examination of an alternative metric, provides the foundation for a potential future revision to PAT. As such, it was also beneficial to use a standardized surrogate for colloidal silver in this case.

Future researchers should be dedicated to selecting an optimal metric for their purposes given that the current measured target was near-achromatic. Materials that exhibit a colorcast may be better analyzed by a particular metric versus other options. It is necessary to emphasize that some of the instrumentation evaluated is designed to measure a near-achromatic sample (i.e.: X-Rite 361T measuring both Ortho and UV transmission densitometry) and others are spectrophotometers designed for color readings in reflection, but in this research these devices were repurposed for reading opacity using the contrast ratio metric (i.e.: X-Rite SP64 and X-Rite 939). While some instrument and metric combinations may outperform others with the near-achromatic sample, others may be more relevant for measuring samples which exhibit a colorcast.

The results of this investigation clearly indicate that for near-achromatic samples, broadly available transmission densitometers, capable of reading the Ortho or UV standards channels, can confidently function as a substitute for instruments designed to read Status A in transmission. Future research in this area may choose to evaluate samples that exhibit a colorcast to fully ascertain if Ortho or UV transmission readings can serve as a reasonable substitute for Status A applications. The X–Rite 361T is capable of measuring transmission densitometry in two channels: Ortho and UV. This

device is widely used in the printing industry as a process control tool and it is currently available in the spot reading instrumentation market.

The evaluated data shows a near-perfect linear relationship among the readings using the X–Rite 361T in Ortho-transmission densitometry channel and the ones from the Status A transmission density using the X–Rite 310 along its whole measuring range. The UV channel measurements also had a continuous linear regression model with the Status A readings. Both relations were found to be statistically significant.

On the other hand, the measurements using contrast ratio did not exhibit the same linear relationship when the entire measurement range is considered. However, in readings with less than 95% opacity, the contrast ratio measurements did exhibit a meaningful linear relationship when compared to the Status A transmission readings with a density value less than 1.8, albeit still with lower correlation than both readings with the X–Rite 361T.

The proposed contrast ratio metric can be obtained with commonly available reflection spectrophotometers, such as the X–Rite 939 and the X–Rite SP64. The use of this contrast ratio metric can create new measurement opportunities in the field of art reproduction and cultural heritage preservation. These measurements can be used to describe and analyze changes in density and opacity, which would modify the appreciation of the printed and photographic images. This metric requires reading objects that are not completely opaque over both a white and a black background; thus, contrast ratio is a measurement of the opacity of the object, and could be utilized as a surrogate for transmission readings.

Additionally, the colorimetric values of the object can be recorded over the white standard. By noticing the differences in the contrast ratio values, as well as the differences in the colorimetric values, primarily in lightness (L*), changes in density could be quantified similarly to the Status A transmission values obtained with the X–Rite 310, although new thresholds would be required to define if a material passes or fails the PAT.

The contrast ratio metric with a reflection spectrophotometers exhibits limitations when higher densities are measured. These units maximize their readings of opacity in samples which exceed a density of 2.0, in such cases, opacity measured using the contrast ratio method is expressed near 100%; subsequent readings of higher densities show variance that can best be expressed as 'noise'. This finding indicates an important boundary condition for future research that may seek to employ this technique, it holds promise for those who may need to measure samples with a transmission density of less than 2.0 where a colorcast is present. Such samples may include colloidal silver if available, as well as potential substitute materials should the sample material required in the present PAT remains inaccessible.

One relevant finding of the present research is the effect of reflection instrument geometry on opacity derived from contrast ratio. Spherical instruments that excluded the specular component displayed a better correlation to Status A transmission, as did 0/45:c instrumentation. This is likely due to the surface characteristics of the near-neutral sample measured. Possible future investigations may choose to select this particular instrument geometry when the opacity of film products is measured using contrast ratio

based on the findings of this research. For sample materials with other types of surface characteristics that modify the smoothness of the surface: however, analysis of both types of Spherical metrics (i.e.: Specular Included and Specular Excluded) as well as 0/45 circumferential geometries may be re-tested.

It is understood that the chosen substitute for colloidal silver -an achromatic transmission step-wedge does not exhibit the color characteristics of the colloidal silver. In addition, the near achromatic transmission step-wedge has densities that exceed what is possible with colloidal silver. As a future substitute for colloidal silver in a potential new version of the PAT has yet to be determined, data are presented for the metrics tested in two ways: first, the data is examined comparing density values under 3.0. Further, it is important to recognized that data be examined across the entire range of the achromatic step wedge, so that potential future users of these data can select the appropriate range for their application based on the chosen material.

As the imaging industry continues to evolve and change it is likely that materials which were once commonly available will likely become increasingly scarce. As previously mentioned, colloidal silver falls into this category. Other film and imaging products will also likely be subject to diminishing availability due to decreased market demand. Therefore, alternative materials and metrics need to be continually evaluated and analyzed. This is critical for conservation efforts, but may also have implications in production workflows. For example, the need to evaluate the opacity of materials may be met by the use of reflective instrumentation and the contrast ratio metric in certain

applications. It is hoped that the present analysis provides a foundation for potential future practitioners in the field of conservation and imaging production.

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Appendix 1:

Table of Equations

Table 10
Equations

Equation Number	Equation	Where:
1	$$D = \log\frac{I_o}{I}$$	D = density I_0 = incident irradiance I = output irradiance
2	$$D = \log\frac{1}{T}$$	D = density T = transmittance
3	$$D_T = log_{10}\frac{1}{T} = log_{10}\frac{\phi_i}{\phi_t}$$	D_T = transmission density T = transmittance Φ_t = transmittance flux Φ_i = incident flux
4	$$D_\rho = -log_{10}\,\rho = -log_{10}\frac{\phi_r}{\phi_i}$$	D_ρ = reflectance density ρ = reflectance Φ_r = reflected flux Φ_i = incident flux
5	$$D_R = -log_{10}\,R = -log_{10}\frac{\phi_r}{\phi_{rA}}$$	D_R = reflection density R = reflectance factor Φ_r = reflected flux Φ_{rA} = absolute reference reflected flux
6	$$X = \frac{\Delta D_e - \Delta D_f}{\Delta D_f} \times 100$$	X = image interaction difference, expressed as a percentage Δ De= density change of the enclosure detector Δ Df = density change of the filter paper control detector.

Appendix 2:

Average Readings of Criterion and Predictor Variables

Table 11

Average Readings of Criterion and Predictor Variables

Measurement Instrument	X–Rite 310	X–Rite 361T		X–Rite 939	X-Rite SP64	
Metric	Status A	Ortho	UV	0/45:c	d/8:i	d/8:e
Step / Wedge ID	$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{x}$	$\bar{x}$
1	0.33	0.33	0.36	12.11	33.71	16.89
2	0.60	0.61	0.62	30.57	61.11	36.89
3	0.90	0.92	0.91	64.19	86.06	69.15
4	1.19	1.21	1.19	87.45	96.20	90.38
5	1.51	1.53	1.49	97.12	99.12	99.11
6	1.82	1.84	1.78	99.31	99.42	101.01
7	2.14	2.16	2.09	99.74	99.84	99.53
8	2.45	2.46	2.38	99.44	99.94	99.88
9	2.76	2.78	2.67	100.53	99.75	99.56
10	3.07	3.09	2.97	99.40	99.25	99.91
11	3.37	3.39	3.25	99.28	99.59	99.18
12	3.70	3.72	3.58	100.04	99.58	99.71
13	3.99	3.99	3.87	101.42	99.44	98.15
14	4.35	4.36	4.27	100.16	99.07	101.20

Appendix 3:

Original Collected Data

Table 12
Raw Data I

Measurement Instrument	X–Rite 310			X–Rite 361T					
Metric	Transmission Densitometry Status A			Ortho-transmisssion Densitometry			UV-transmission Densitometry		
Step / Wedge ID	1	2	3	1	2	3	1	2	3
1	0.29	0.37	0.32	0.29	0.38	0.33	0.32	0.4	0.36
2	0.53	0.66	0.6	0.54	0.67	0.61	0.56	0.68	0.62
3	0.83	0.97	0.9	0.85	0.98	0.92	0.85	0.97	0.91
4	1.11	1.27	1.2	1.13	1.29	1.22	1.12	1.26	1.2
5	1.43	1.58	1.51	1.45	1.6	1.53	1.41	1.56	1.49
6	1.75	1.88	1.82	1.77	1.9	1.84	1.71	1.84	1.78
7	2.09	2.19	2.15	2.11	2.22	2.16	2.04	2.14	2.09
8	2.4	2.51	2.44	2.39	2.53	2.45	2.33	2.44	2.37
9	2.7	2.82	2.76	2.71	2.84	2.78	2.61	2.73	2.68
10	3.01	3.12	3.07	3.04	3.15	3.09	2.91	3.02	2.97
11	3.31	3.44	3.37	3.33	3.45	3.38	3.19	3.31	3.26
12	3.66	3.74	3.69	3.68	3.76	3.72	3.55	3.62	3.58
13	3.95	4.03	3.98	3.97	4.03	3.96	3.83	3.93	3.85
14	4.31	4.38	4.35	4.33	4.37	4.37	4.24	4.3	4.26

Table 13

Raw Data II

Measurement Instrument	X–Rite 939			X–Rite SP64					
Metric	Contrast Ratio in 0/45:c			Contrast Ratio in d/8:i			Contrast Ratio in d/8:e		
Step / Wedge ID	1	2	3	1	2	3	1	2	3
1	10.41	14.19	11.72	30.15	37.41	33.58	15.3	18.91	16.47
2	24.94	36.36	30.42	53.81	68.24	61.29	31.44	42.59	36.63
3	57.33	71.78	63.46	82.96	88.36	86.87	62.96	73.82	70.66
4	82.86	91.7	87.78	94.54	97.3	96.75	86.45	93.97	90.72
5	95.99	98.09	97.29	98.14	98.92	100.31	97.33	99.1	100.91
6	98.66	100.77	98.49	99.46	99.77	99.03	98.75	106.7	97.57
7	100.13	99.75	99.34	99.61	99.99	99.91	99.99	99.44	99.17
8	99.74	99.36	99.22	99.75	99.65	100.41	98.6	101.05	99.98
9	99.9	100.09	101.6	99.44	100.39	99.43	99.68	100.13	98.88
10	100.43	100.23	97.55	99	99.16	99.6	99.72	99.78	100.23
11	99.75	99.07	99.03	100.02	99.75	99	98.88	99.46	99.21
12	97.79	100.73	101.6	99.49	99.66	99.59	99.21	99.75	100.16
13	100.66	101.83	101.76	99.29	99.49	99.55	97.55	98.56	98.33
14	100.11	100.43	99.94	99.69	99.33	98.2	100.42	99.44	103.74

Appendix 4:

Intermediate Computations

Table 14

Computed Intermediate Values

Computatio/ Metric	Ortho	UV	0/45:c	d/8:i	d/8:e	0/45:c	d/8:i	d/8:e
Slope (m)	1.0003	1.0404	0.0329	0.0435	0.0343	0.0111	0.0117	0.0115
Intercept (b)	-0.0156	-0.0383	-0.5031	-1.6545	-0.6647	0.2149	-0.0861	0.1436
SE of Slope	0.0013	0.0026	0.0048	0.0079	0.0053	0.0003	0.0006	0.0003
SE of Intercept	0.0035	0.0066	0.4275	0.7306	0.4816	0.0196	0.0433	0.0209
Coef of Deter (r^2)	0.9999	0.9998	0.5431	0.4328	0.5077	0.9905	0.9766	0.9910
SE of Pred Values	0.0108	0.0202	0.8655	0.9642	0.8984	0.0352	0.0466	0.0342
F-statistic	564589	160759	48	31	41	1040	333	1102
F-test df	40	40	40	40	40	10	8	10
SS red	65.5690	65.5573	35.6119	28.3826	33.2889	1.2871	0.7248	1.2878
SS resid	0.0046	0.0163	29.9617	37.1910	32.2847	0.0124	0.0174	0.0117
SS Total	65.5736	65.5736	65.5736	65.5736	65.5736	1.2995	0.7422	1.2995
n	42	42	42	42	42	12	10	12