

EFFECTS OF MEASUREMENT GEOMETRY ON SPECTRAL REFLECTANCE AND COLOR

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Abstract: Measurements of candidate materials for calibration of outdoor color imagery were made using integrating sphere and $45^\circ/0^\circ$ geometry. The differing results are discussed using CIELAB linear color space in terms of the measurement geometry and specularly of the material. Implications for calibration of outdoor photography are discussed with an example.

Background

During a review of spectral measurements of standards for calibration of color digital imagery it was observed that different CIELAB color coordinate results were obtained for different measurement geometries. Such results should affect the digital photographic measurements of color outdoors and therefore warranted further investigation. This report summarizes the results of the investigations into the effects of measurement geometry on spectral reflectance and CIELAB values using integrating sphere and $45^\circ/0^\circ$ measurement geometries. An example of the phenomenology involved is presented and the effects of measurement errors are considered.

Procedure

Integrating Sphere Geometry. A series of felt targets intended to serve as calibration standards for outdoor digital color photography were measured using a Perkin Elmer Lambda 9 spectrophotometer equipped with a Labsphere RSA-PE-90 six inch integrating sphere. Total reflectances with this device were made at the 8° incidence (near-normal) peripheral port. Reflectances were recorded at every nanometer (nm) and color space calculations performed at 5nm resolution.

$45^\circ/0^\circ$ Geometry. The same felt materials were measured on a macro instrument consisting of an Optronics Lab OL-754 PMT spectroradiometer operated at 5 nm resolution. Illumination came from either one or two Macbeth Spectralight II luminaires designed to emulate D_{65} illumination. Specimens were mounted on a vertical panel and illuminated from one or both sides at 45° to the specimen normal. The spectroradiometer was placed along the specimen normal at a distance such that the specimen completely filled the instrument mapped field of view. Calibration utilized the same setup with a NIST-traceable white calibration panel.

Data Reduction. Multiple scans were performed on the macro instrument and the results automatically averaged by the spectroradiometer. All calculations were performed in a spreadsheet including reflectivity, tristimulus values, chromaticity values, and $L^*a^*b^*$ values using the methodology described in ASTM Standard E-308 using tabular values obtained from the U.S. representative of CIE. All results are presented in terms of CIELAB values because this color space is linear and because the results more readily interpreted in terms of color space. The Laboratory standard for CIELAB values is the 1964 supplemental standard (10°) observer with D_{65} illumination

Results

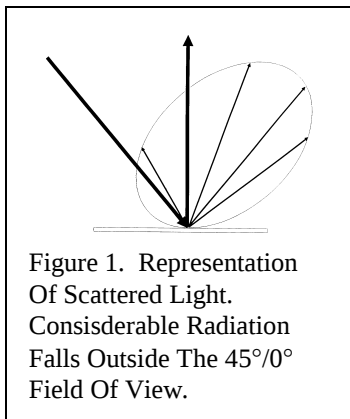
The results are presented in two parts to provide clearer presentation of both the results: tabular color space values and spectral reflectivity and their implications.

Differences In Tabular Values. The spectral reflectivities were converted to CIELAB values for intercomparison. The results are shown in the linear color space CIE $L^*a^*b^*$ values in Table 1 for each of the materials for each of the two measurements. The typical thresholds of reproducibility of CIELAB values from routine measurements for such calculated values, based on lab experience, are ca. ± 1.5 -2.0 for L^* and 1.0-1.5 for a^* and b^* on a day-to-day basis; these observations are discussed further below. Significant differences are shown in the highlighted text. The comparable values in Table 1 that should be regarded as significantly different are shown in bold type. The largest changes in a^* and b^* values are more than the threshold of reproducibility. The differences in the luminosity parameter, L^* , on the other hand, are in the range 4-20 and are well beyond simple measurement error and should be regarded as significantly different.

Table 1.
Comparison of Macro Instrument & Lambda 9 Values
For CIE L^* , a^* , b^* Values

	Macro Instrument Values			Lambda 9 Values		
	L^*	a^*	b^*	L^*	a^*	b^*
Black	13.6	1.2	-2.5	20.4	-0.5	-1.2
Medium Green	24.1	-12.5	5.4	30.8	-15.0	6.2
Bright Green	21.8	-9.4	11.2	25.5	-8.5	12.5
Brown	25.8	7.7	7.6	30.7	7.6	7.7
Red	20.8	39.1	14.8	33.6	21.2	27.0
Blue	19.6	9.8	-33.7	20.9	10.4	-36.3

From these results a simple theory based on the interplay of bidirectional reflectance and measurement geometry is postulated. In the integrating sphere measurement, all the energy reflected from the material is eventually directed to the detector while in $45^\circ/0^\circ$ -geometry measurement a significant portion of the specular component of reflected energy is lost; see Figure 1. In this figure the incident radiation from the left is scattered; the ellipse and light arrows represent the scattering in all directions. The upward pointing heavy arrow represents that portion of the radiation directed toward the measurement sensor operating in $45^\circ/0^\circ$ geometry. Assuming for the felt material that the color component of reflected energy arises from radiation entering into the reflective medium and re-emerging as scattered diffuse radiation with wavelength-selected intensity (color). Then it is to be expected that the a^* and b^* components would be largely unaffected by specularly mechanisms while significant amounts of the



specular component of reflected radiation, expressed as the CIE L^* value, are directed to all parts of the ellipse and away from the specimen normal along which the instrument views the specimen in $45^\circ/0^\circ$ measurement geometry.

A test of this theory is to compare the macro instrument values for illumination from one side of the sample (single lamp) with those from both sides (two lamps). If the explanation above is correct, such measurements should produce similar values for a^* and b^* and distinctly greater values for L^* for the one-lamp *versus* two-lamp measurements. These measurements were performed and the results are shown in Table 3. As expected from the theory the measurements show that the L^* values are significantly greater with two lamps than with one, and that the a^* and b^* values are

substantially unchanged. The results of the measurements testing these predictions are shown in Table 3. The results of the testing will also demonstrate the measurement-to-measurement reproducibility limits discussed above.

Comparison of the one-lamp and two-lamp values in Table 2 finds that the a^* and b^* values are in good agreement, independent of illumination, with the exception of Blue and Red. For these the values observed are greater than expected based on measurement reproducibility for the values. In all cases the L^* value for two lamps is distinctly greater than for one lamp. On the basis of these results the materials appear to have an unexpected degree of specularity. The differences in a^* values for Red and b^* values for Blue are not

Table 2.
Effects Of One Lamp And Two Lamps On CIE $L^*a^*b^*$ Values

	One Lamp			Two Lamps		
	L^*	a^*	b^*	L^*	a^*	b^*
Black	7.2	0.0	-1.8	11.9	0.0	-2.1
Medium Green	18.4	-12.0	3.6	25.5	-15.3	6.0
Bright Green	14.3	-8.3	8.6	20.9	-10.0	10.1
Brown	19.0	6.8	5.1	26.1	8.4	6.1
Red	14.3	33.5	9.4	20.8	41.1	12.0
Blue	13.4	8.1	-29.1	19.1	9.8	-35.0

explained by the theory, however. It is clear that the optical appearance of the proposed calibration materials is sensitive to the geometry of illumination and observation. The behavior of a^* and b^* when changing illumination in the $45^\circ/0^\circ$ geometry are not explained and required further investigation.

Effects Of Geometry And Specularity on Spectra. Figure 2 compares the spectral reflectances observed for the various materials with the integrating sphere and $45^\circ/0^\circ$ geometries. In these plots is seen a distinct dependence of reflectance differences on wavelength. The difference results can be classified into “well-behaved” materials where the differences in reflectivity are small, and those “poorly-behaved” materials in which there are strong reflectivity differences with wavelength. Within experimental limits in all cases the total reflectance, as expected, lies above that for the $45^\circ/0^\circ$ geometry.

Figure 3 plots the calculated differences in reflectivity that are exhibited in the spectra of Figure 2. Here the degree of variation in reflectivity with wavelength is more quickly and easily seen. In the Black spectrum, and to a lesser extent in Medium Green, the reflectivity values and their differences are small, and the geometry-dependent differences in the CIELAB values (Table 1) are small. At the other extreme the Red and Blue materials show much larger differences especially in the red end of the spectrum. In both examples there is also an abrupt rise to large values of reflectivity in the same portion of the spectrum. These are the materials with strong geometry dependence of the a^* and b^* values on geometry. In an intermediate situation, Bright Green displays an abrupt rise in reflectivity and a distinct but somewhat smaller difference in the geometry-dependent reflectivity and no significant difference between the a^* and b^* values for the two geometries suggesting that the measurement geometry is not the cause of the shifts of CIELAB values.

Relationship To Bidirectional Reflectance

This variation in wavelength with geometry has been interpreted in terms of bidirectional reflectance (BDR) and measurement geometry. Where there is a difference in reflectivity due to geometry there is a difference in the effects of specularity due to the presence of only a partial specular lobe in the $45^\circ/0^\circ$ geometry that is contained in (but is less than) the total reflectivity of the integrating sphere measurement. Where the reflectivities for the two geometries are the same there is Lambertian behavior because the specular lobe is absent. The difference in reflectivity ascribed to measurement geometry is

manifested by a non-Lambertian behavior in the material, and this behavior is wavelength dependent. Specularity and non-Lambertian behavior are the province of bidirectional reflectance. There are few examples of significant changes in BDR as a function of wavelength over short wavelength intervals. The results here support the idea that there is an important, sensitive relationship between BRDF and wavelength that is not well explored. The importance for the function of CCD materials is not understood.

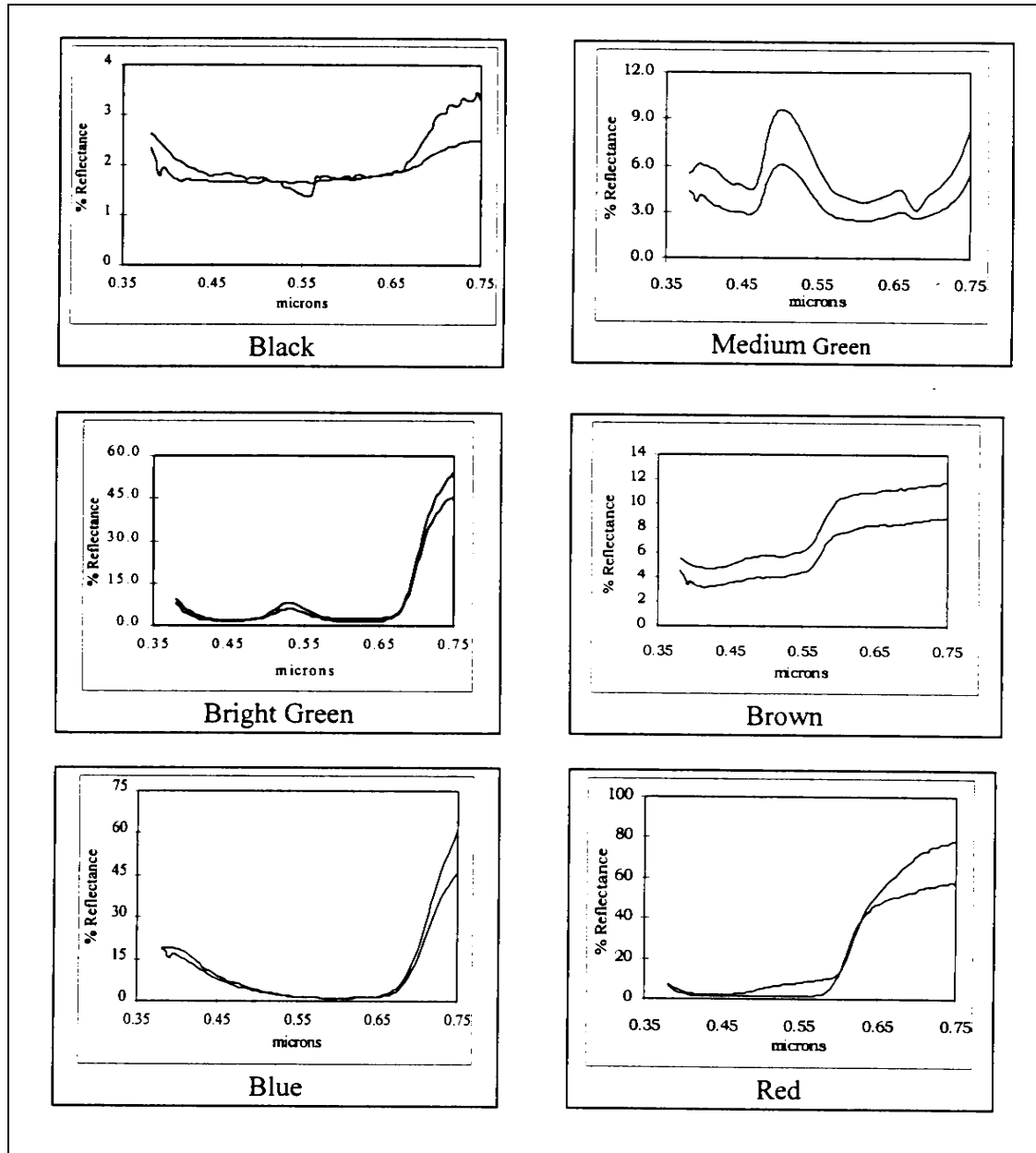


Figure 2. Comparison Of Reflectance Spectra
For Different Measurement Geometries.

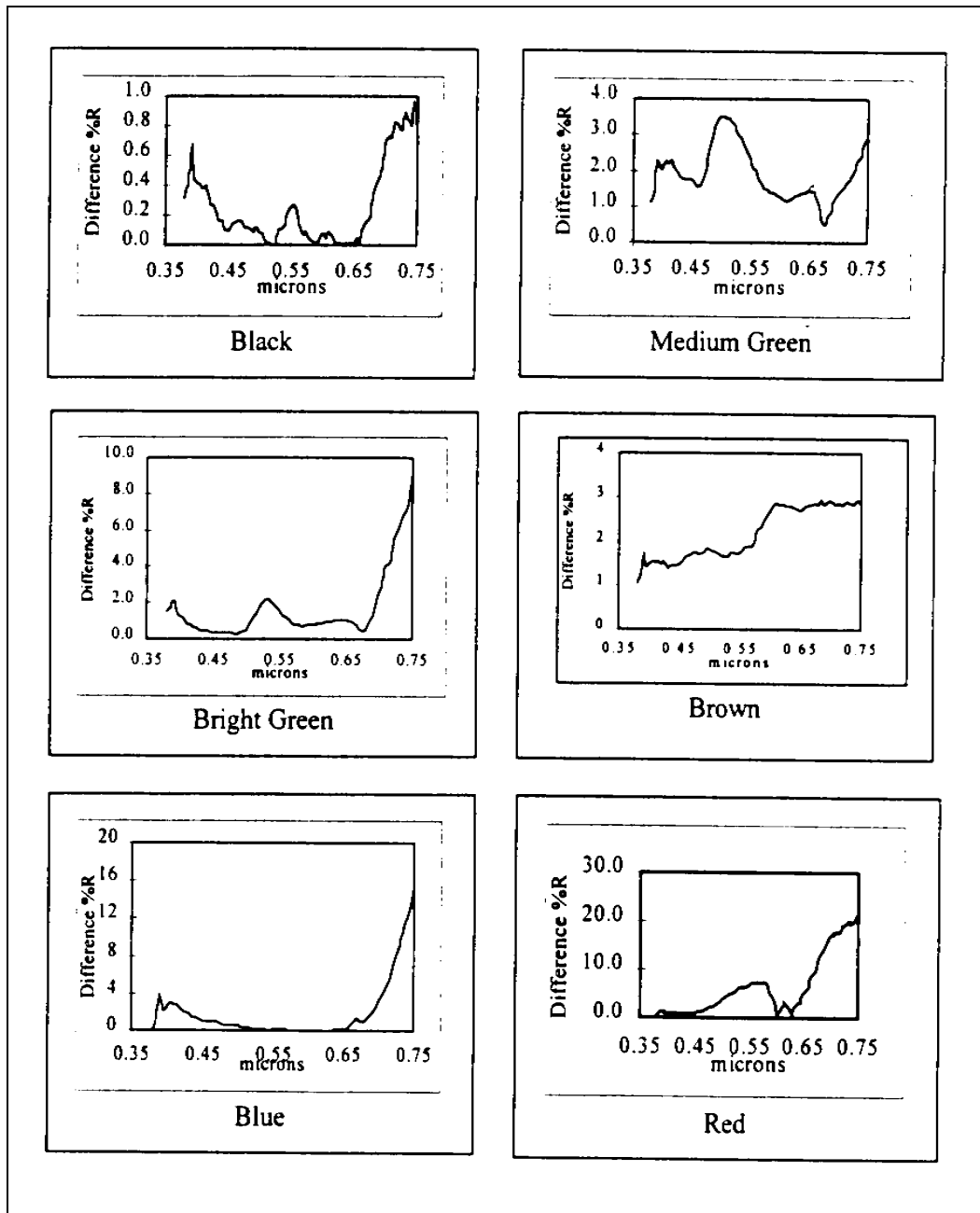


Figure 3. Calculated Differences In Spectral Reflectivity
For Felt Materials.

Implications For Field Calibration

The felt specimens evaluated and reported here were intended to serve as standard colored panels for the calibration of outdoor digital color imagery. An important issue arises here concerning the suitability of the materials for that application: is the difference observed in calibration measurement important to the intended application? Several factors impinge on the answer.

1. Camouflage materials typically have dark, muted colors with a high degree of variability (texturing and/or patterning) that are not necessarily represented by the calibration specimens tested here.
2. Camouflage today is typically an average representation of a background that may or may not have been "tuned" for a specific location.

3. Digital color imagery typically is displayed in computer analytical software as RGB colors which do not translate perfectly into CIE-related systems.
 4. There are a number of factors (geographic location, season of the year, time of day, direction of viewing, short term meteorology to name a few) that impact the selection of colors for camouflage.
- Except for development of a catalog of outdoor colors or camouflage “tuning” to a specific location and season, camouflage color selection can be only an average or approximation of typical conditions, and the accuracy of color descriptors *required* and therefore satisfied by a range of color parameters.

Perhaps the questions to be answered by digital color measurement should address acceptable latitudes for color parameters. For answering such questions concerning acceptable color parameter ranges, the highest quality calibration materials are required. Established in this study is the postulated discovery of non-Lambertian qualities as a function of wavelength in calibration panels where least expected. This suggests that highly Lambertian calibration panels would be the most desirable for calibration purposes. Data from the 1997 Meppen Trials provides some clues.

The 1997 Meppen Trials. In the summer of 1997 a NATO field test to study color relationships was held at Meppen, Germany. The test included imagery of a treeline with several gray calibration panels for which color pictures digitally converted to black-and-white photographs were available.

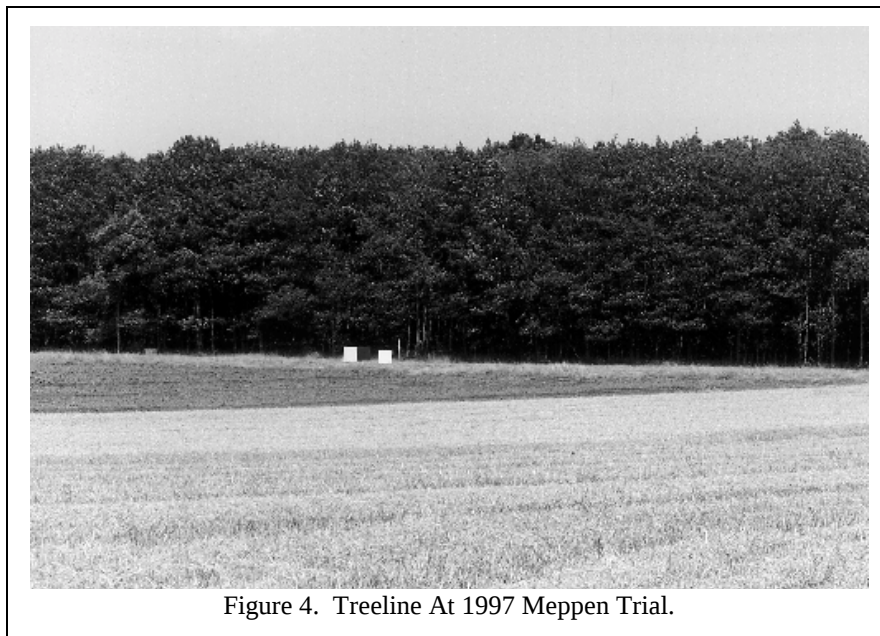


Figure 4. Treeline At 1997 Meppen Trial.

Figure 4 is a picture of the NATO Meppen treeline at a distance of several hundred meters. The neutral gray test calibration panels can be seen just to the left of the center of the image at the junction of the tilled field and the stand of trees. The images available for analysis had been converted to black and white by averaging the three color components and storing the result in the form of a

black-and-white image. The portion containing the targets was cropped and enlarged for analysis. The three panels were made of pressed polytetrafluoroethylene (PTFE) beads, a material well known for its near-Lambertian properties. From left to right in all the figures the (nominal) broadband reflectivities are 49%, 5%, and 99%. Figure 5 shows the image segments analyzed; the time of day has been added to each image segment. Of interest here is the variation in imagery gray values of these three panels and the foliage behind them.

The treeline faces south of southwest and the sun does not fall on the calibration targets or the visible portion of the treeline until late morning; the bottom branches are not illuminated until nearly noon as can be seen in the photographs of Figure 5. Visual inspection of the segments in Figure 5 shows that both the brightness and relative brightness of the panel changes relative to one another and the treeline over the course of the day. These differences were analyzed using conventional image analysis techniques; the

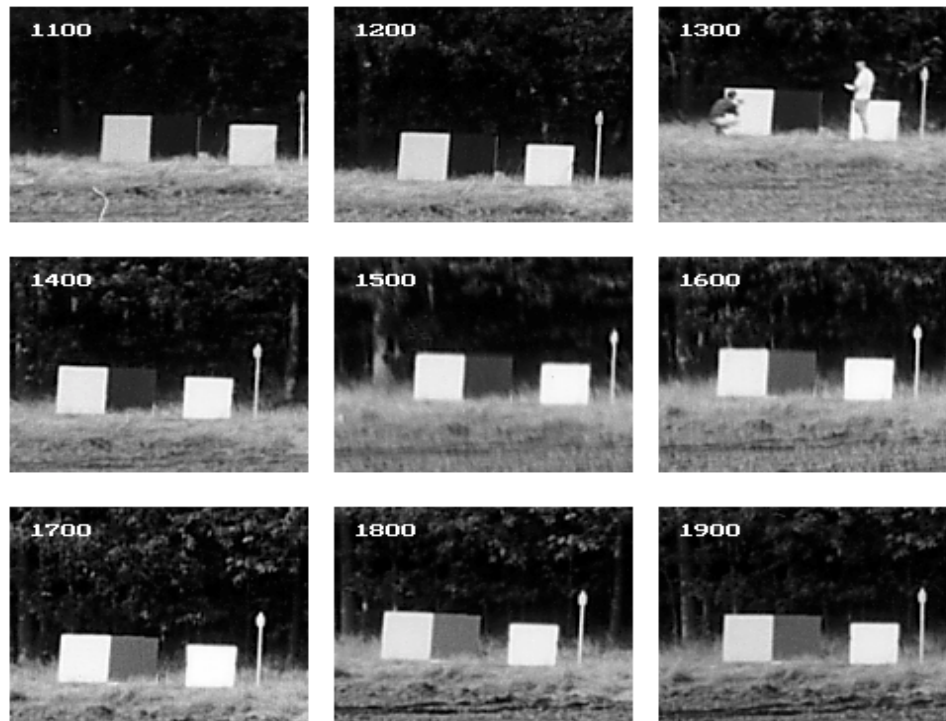


Figure 5. Meppen Calibration Panels At Different Times Of Day.

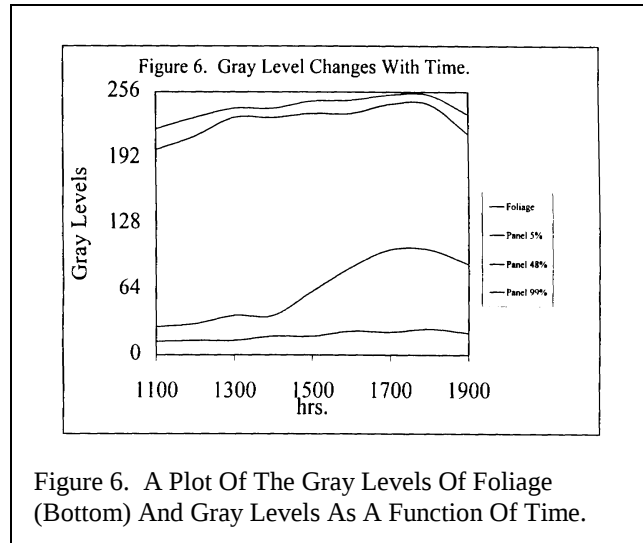
portions of the images containing the 99% panel are almost completely saturated from early to late gray level results for the panels are shown in Table 3 as a function of time. Table 3 clearly shows that the afternoon, and that the portion of the image containing the 48% panel is approaching complete saturation in mid to late afternoon. The black (5%) panel values rise monotonically until nearly dark (1730) at which time they begin to fall.

Table 3.
Variation In Panel Brightness With Time

<u>Time</u>	<u>Foliage</u>	<u>5% Panel</u>	<u>48% Panel</u>	<u>99% Panel</u>
1100	13	27	200	220
1200	14	30	213	231
1300	14	38	231	240
1400	18	38	231	240
1500	18	62	235	247
1600	23	86	235	248
1700	22	103	244	253
1800	25	103	244	253
1900	21	89	215	234

The values over time for the two brightest panels suggest severe amounts of saturation in both the 48 and 99 reflectivity panels. While the gray levels of the foliage appear in the photograph to be constant

with time, the measured values show a general modest upward trend with time. The same behavior is seen in the 5% reflectivity panel as well. Figure 6 is a plot of gray values as a function of time. The 48% and 99% curves come very close to one another in early afternoon as the 48% panel becomes more saturated. Most surprising is the 5% curve which rises at much higher proportions than the others. Quite possibly the 48% and 99% curves would have matched this performance if saturation had not occurred. The general monotonic drift of the gray levels with some secondary phenomenon causing modest variations within the overall trend may well arise from film exposure and processing. That is, the Lambertian qualities of the panels may or may not be a factor in the image calibration process; there is no direct evidence here to support Lambertian behavior as an important factor. The commercial literature on the surface optical properties of PTFE panels suggests that they are quite Lambertian, but it is unclear that this is true at all reasonable (nongrazing) angles of incidence.



Summary And Recommendations

Summary. Evidence has been presented that differences in reflectance attributable to differences in measurement geometry are believed to be the result of bidirectional reflectance (BDR) and that this variation of BDR is wavelength dependent over short wavelength intervals measured. Good results in calibrating digital color imagery were obtained using carefully selected procedures and apparently diffuse commercial color standards but not felt fabrics; the role of non-Lambertian qualities in calibration panels is not established. It has been shown for photographic film systems that exposure and processing are likely important quality parameters, especially for highly reflective panels. Whether this is important for digital systems is not established.

Recommendations. These recommendations apply to measurements for the highest quality results and area based on the principle that calibration and measurement should use the same technology or geometry for both processes. For outdoor measurement, 45°/0° geometry most closely mimics measurement geometry and should be used for calibration of the standards. Calibration panels with lower reflectance levels (lower luminosity) are more valuable for calibrating visual band imagery. To avoid possible complications with non-Lambertian behavior, color measurements should only be made with diffuse light; avoid all direct illumination. Such diffusely illuminated images do not look pretty in briefing slides and reports, but they expected to produce the most reliable measurements.

Acknowledgment

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