APPLICATIONS
TUTORIAL
NOTES

WEDNESDAY – FRIDAY
JUNE 7 – 9, 2006
MOSCONNE CONVENTION CENTER
SAN FRANCISCO, CALIFORNIA
APPLICATIONS TUTORIAL A-6:

DISPLAY MEASUREMENTS
FOR
FLAT-PANEL DISPLAYS

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Summary
In this tutorial, problems encountered in making common measurements on flat-panel displays are reviewed, equipment limitations are explored, and properly managed stray light is stressed. Reflection description and measurement apparatus robustness are reviewed in detail. The attendee will learn how to tell which HDTV will look best in his/her living room.

*Optoelectronics Division, Electronics and Electrical Engineering, Technology Administration, U.S. Department of Commerce. This is a contribution of the National Institute of Standards and Technology and is not subject to copyright.
### Preliminaries

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DISPLAY METROLOGY

Measurements of displays seem simple to most, but there can be serious problems if we are not careful. This seminar is more about display metrology than specific display measurements.

I was telling a non-technical friend that I was involved in making display measurements. He laughed and exclaimed, "What's so hard about that?" Um... it was very hard to explain. How embarrassing!

REPRODUCIBILITY & REPEATABILITY

WORLD-WIDE REPRODUCIBILITY:
1. 5% UNCERTAINTY IN LUMINANCE
2. 0.005 UNCERTAINTY IN COLOR (xy)

YOUR LABORATORY REPEATABILITY:
1. 0.1% UNCERTAINTY IN LUMINANCE, OR SMALLER
2. 0.001 UNCERTAINTY IN COLOR (xy), OR SMALLER

This seminar assumes you need the best you can get from your equipment. For example, if you are monitoring changes in a manufacturing process to determine the best way to increase luminance, you will want careful measurements. A luminance uncertainty of 5% will probably not keep you happy – or your boss! On the other hand, your boss may not understand the difficulties involved in making what appears to be such simple measurements. This seminar hopefully helps you with information to be convincing in getting what you need in time and equipment.

UNCERTAINTY — WHAT IS IT? — NEW TERMINOLOGY!

The 5% uncertainty means expanded uncertainty with a coverage factor of two. (In the older terminology we used to say a two-sigma uncertainty.) The combined standard uncertainty is the combination of all contributing uncertainty factors, Type A and Type B (we used to classify uncertainties as systematic and random). The expanded uncertainty is the combined standard uncertainty times the coverage factor.

Combined Standard Uncertainty

\[ u_c = \sqrt{\sum u^2} \]

Expanded Uncertainty

\[ U = ku_c \]

The coverage factor k times the combined standard uncertainty.


PROPA GATION OF ERRORS

Luminance uncertainty U may be 5%. That means that for any single measurement of L, its relative expanded uncertainty with the k=2 coverage factor is 5%.

Contrast measurements are ratios of measurements of luminances. If made with different luminance meters the uncertainty is \(\sqrt{2} U\).

However, if made with the same luminance meter, the uncertainty can be much smaller than U. Depending upon the linearity of the luminance meter over the range of luminances involved, the uncertainty of a contrast measurement can be even down to the repeatability of your luminance meter, 0.1% or so.

Reason: Cross-term in uncertainty expansion is no longer zero because the Ls are no longer independent random variables, but cross-term practically cancels the first two terms, rendering the contrast measurement with much less uncertainty.
DARKROOM MEASUREMENTS

Accurate measurements of displays under reflection from the ambient environment require careful attention to the arrangement of illuminants and placement of detector. Apparatus geometry is everything! To create reproducible measurement results can be very problematic. Reflection will be handled separately. Darkroom measurements are often required to serve as the basis of the measurements of emissive displays. Reason: A darkroom is a very reproducible ambient environment—few reflections to worry about.

DIRECT-VIEW EMISSIVE DISPLAYS ASSUMED

This seminar assumes direct-view emissive displays unless otherwise specified (e.g., projection displays, reflective displays). NOTE: Some contend that a liquid-crystal display (LCD) is not an emissive display but a transmissive one. Not true, the pixel surface is transmissive, but the display is emissive and will be referred to as such in this seminar.

REFLECTIVE DISPLAYS—NOT MEASURED IN DARKROOMS

Reflective displays need to be measured under carefully controlled and geometrically well-defined lighting conditions. They fall under reflection measurements.

Luminance Meter Terminology

Field of View
Angular Field of View
Angular Aperture
Luminance meter with viewport
Measurement Field
Measurement Field Angle
Acceptance Area
Focus on object being measured.

Get CIE Publication No. 69 for complete details.

FPDM: Basis for Measurement Methods

VESPA FPDM — Flat Panel Display Measurements Standard

Features:

- **VERSION 2.0**

  - Specification of good metrology for displays
  - Self-contained measurement procedures
  - Buffet of measurements—use what you need
  - Easy to use and read
  - Extensible—more will be added as needed
  - Adaptable—affords a variety of equipment
  - Accommodating—special needs permitted
  - Metrology Section, Technical Discussions Section
  - Includes diagnostics, cautions and hints
  - A reasonably priced document ($40) of over 320 pages—

VESPA 408-957-9279 (call them for a copy) www.vespa.org
Unrealistic adjustment to enhance specifications

Some "manufacturer setup specifications" dictate adjusting for brightest white to get $L_W$, then adjusting for darkest black to get $L_K$ — gives much greater contrast ratio that way.

Never mind that the display couldn't be used with those adjustments...

Tweak for $L_W$

Tweak for $L_K$

Nobody would want to use the display with those adjustments!
FPDM requires display setup to be reasonable!

Adjust display settings to obtain the best possible image under darkroom conditions or other carefully specified ambient conditions. Then...

...measure full-screen $L_W$ and $L_K$ without changing the settings.

These are the luminance values to be reported and used to calculate contrast (full-screen darkroom contrast).

WARM-UP TIME MAY BE NEEDED

During the warm-up of the display is a good time to examine the display for defects and problems. Try out many different patterns and images suitable to the intended display task. [FPDM 301-2D]


SETUP CONDITIONS REMAIN FIXED

During a series of measurements the task-specific setup conditions should not be changed to improve any single measurement, unless the task calls for such changes. [FPDM 301-2E, 305-3]

This has to do with honesty. We want to measure the display the way it will be used. Unless the task calls for tweaking the display for various needs, the controls should be set after the display is fully warmed up and all measurements should be made at that setting.

ADJUSTMENT OF DISPLAY SETTINGS

If the display provides adjustments but the manufacturer doesn’t supply specific instructions on how to adjust these controls, here is a procedure.

1. Place the display in the environment in which it will be used.
2. Make whatever adjustments are needed using the kind of targets and patterns that will be anticipated for the task.
3. Then place the display in a darkroom (a good one!) and make the measurements without the contributions of stray light.
4. Measurements with reflections from the ambient environment must be made VERY carefully. This is not trivial!!!!!!

NEVER make critical display measurements in uncontrolled ambient environments. Reflections can be very hard to control and can seriously affect the measurement results—much more than you will think. Ambient environments must be carefully controlled to create reproducible measurement results. (Your eye is quasi-logarithmic whereas your measurement instrumentation is linear—very different “results” can be obtained! Do be careful.)

VIEWING DIRECTION

Often the measurement direction is from the normal of the screen, but not always. Some displays are optimized to be viewed from an off-normal direction.

Manufacturing specifications should provide this angle, if not, it is often assumed to be a normal ($\theta = 0^\circ$) viewing direction.

$\pm 0.25^\circ$ UNCERTAINTY:

Viewing direction angle (if normal or otherwise) should be determined to approximately $0.25^\circ$. Not hard! Width of little finger at full arm extension is approximately 1". Moon and Sun subtend $0.5^\circ$. 
Setup, Cont.

MEASUREMENT FIELD ANGLE
Angle usually limited to 2° or less. 1° is common.

ANGULAR APERTURE
Most don't think about this. We try to keep this also 2° or less.

CENTER SCREEN MEASUREMENTS
Common measurement point is screen center, unless otherwise required (e.g., sampled uniformity, etc.).

DARKROOM
Black walls are nice to keep reflections down. Popular criterion is illuminance at surface of screen to be 1 lux or less (preferably less): E ≤ 1 lx.

NUMBER OF PIXELS MEASURED
Measurement field large enough for 500 pixels (circle of 26 pixel diameter) is very safe. Smaller than this requires verification that the number of pixels measured provides the same result if 500 pixels were measured. Try to keep measurement region less than 10% of smallest screen dimension.

ENVIRONMENT
Must worry about temperature, humidity, air pressure. Often have no control over how the display is powered.

Gray Scale

Gray Scale

INPUT

Gray Level (Command Level)
\( V_i = 0, 1, 2, \ldots, 255 \) (8-bit)

OUTPUT

Gray Shade

\( L = L_K, L_1, L_2, \ldots, L_W \)

Typical form: \( L_i = aV_i^\gamma + L_K \), \( a = \frac{L_W - L_K}{255^\gamma} \)

Typical values of \( \gamma \) range from 2.2 to 2.6 or even 3.0.

See [302-5A] Determination of "Gamma"

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Full-Screen Center Measurements

What could possibly go wrong with such a straight-forward measurement?

PLenty!

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[FPDM 302-1 through -8, -10]

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Full-Screen Center Measurements, Cont.

Velling Glare Can Affect Full-Screen Measurements

Measurement of Full-Screen White
Comparison of two identical luminances having different angular sizes. Same screen with & without mask (1.5° or 15° vertical angular diameter of white area from lens of detector)

1.5° Subtense with Mask

15° Subtense without Mask

Increase in measured luminance with mask removed:

- Instrument #1 0.4%
- Instrument #2 1.3%
- Instrument #3 4.8%

We will discuss velling glare and how to compensate for it later.

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Full-Screen Center Measurements

Short Integration Times — Possible Errors from Refresh of Screen

If screen refreshes (as with a CRT) and it is bright so that the detector uses a short integration time, can get measurement errors from the light of 31 frame. Average many measurements or use good (and calibrated) neutral density filter to reduce luminance.

4 Refreshes
5 Refreshes

Same measurement window in both cases, but depending upon when the measurement is made, a relative deviation of up to 20% (or 20%) can be seen in this case.

Box Measurements

With colors on black normally get few veiling-glare problems.

Veiling-glare (VG) problems especially arise with...

- CHECKERBOARDS [FPDM 304-9]
- LOADING [FPDM 304-8]
- HALATION [FPDM 304-7]
- etc. Can get color contamination from VG.

Box Measurements, Cont.

Veiling Glare Can Affect Box Measurements

Measurement of Black Rectangle on White

This shows how important it is to anticipate veiling glare in the detection system. Same screen with & without mask (1.5° mask hole, 15° vertical angular diameter of white area from lens of detector)

1.5° Subtense with Mask

15° Subtense without Mask

Increase in measured luminance with mask removed:

Instrument #1 50 %
Instrument #2 325 %
Instrument #3 1200 %

Box Measurements, Cont.

Veiling Glare – Stray Light Within Detector

Complex Lens

Object

Iris

Image

Original

Veiling Glare

Lens Flare

Reflection off of internal lens structure

Reflection between lens surfaces
Box Measurements, Cont.

Use of Masks — Flat and Frustum

With some very high contrast displays, the back reflections off flat masks can cause substantial errors.

Box Measurements, Cont.

45° FRUSTUM MASK

Gloss black plastic frustum minimizes light reflecting back onto screen also minimizes light from rest of screen reaching lens.

Box Measurements, Cont.

Frustum Mask Compared to Flat Mask

Only if the flat mask is placed very near or on the surface of the FPD screen can it compare with the frustum mask. CRTs have thick glass faceplates.

NOTE: Flat mask near or on screen may cause heating; can also mechanically corrupt luminance when touching the screen especially for soft LCD screens.

Avoid Vignette (vin-yet’) from Mask

Keep in mind that if the mask is too close to the lens it can interfere with the measurement (especially when the hole is smaller than the lens).
Box Measurements, Cont.

Halation — With and Without Masks (LCD Display)

![Graph showing luminance in CCD counts against percentage of diagonal with and without masks.]

Detail (Small-Area) Measurements

Veiling-glare often presents a VERY serious impediment to obtaining accurate measurements of small dark areas amid bright regions.

What we present in this section provides a MUCH better approximation to the true value of the black level than we would obtain if we didn't do anything.

Note

[FPDM 303-1, 2, 3, 5, 6, 7]

Small Area Measurements, Cont.

Replica Masks

![Image of replica masks with contrast measurements.]

Look, I've been measuring contrast for years, and I've never had to worry about veiling glare!

RUSTIC METROLOGY

Replicas, Same Size As Black Region

Replica masks must be close to (+10%, -10%) the size of the black area to be measured.

Um, the contrast of the display went up a factor of ten when we used a replica mask. Um, have you seen those results yet???
Small Area Measurements, Cont.

Replica Mask with Diagnostic Filter Mask

- White pixels
- Black pixels
- Filter calibration
- Mask calibration
- Filter-white calibration
- Transmission: $T = \frac{L_w}{L_b}$
- Corrected white: $L_{w_c} = L_w - L_w^c$
- Corrected black: $L_{b_c} = L_b - L_b^c$
- Contrast: $C = \frac{L_w}{L_b}$

Check: Does $(L_w - L_b)(L_w + L_b) = ?? \pi$?

If so, measurement is probably good. (At least a lot better than if we didn't do anything!)

NOTE: If using a CCD camera, it is always a good idea to have from 10 to 20 CCD pixels (or dots) covering any line or area you wish to measure. Don't be stingy!

Small Area Measurements, Cont.

Line Replica Mask for Line & Grille Contrast Measurements

Line contrast is:

$C = \frac{S_1 - S_2}{S_1 + S_2}$

Line mask material can be obtained from graphic-arts supply stores (black charting tape), black hair, black nylon thread, or cut from black plastic sheets. We can also cut a very narrow slightly tapered wedge of black opaque plastic and measure $S_2$ across the part with the appropriate width.

NFS with additional frustum to prevent reflections from apparatus.

Small Area Measurements, Cont.

Effects of background change on NFS#1 results

CONCLUSION: The FPD is working well with no profound cross-coupling or shadowing. Everything stays within ±4% of average.

Data Normalized to NFS#1 Average

1300% Error
Small Area Measurements, Cont.

**EXPECTATIONS TO HIGH??!!!**

If a < 100% error (without using a SLET or frustrum) in measuring dark areas amidst a white screen shocks us... then our expectations are too high! We don't understand the limitation of our equipment, and our use of it with impunity can yield disastrous results.

How much better it is to be alerted to the complications and take measures to correct the problem... or don't attempt the measurement.

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**Uniformity Measurements**

Nonuniformities of dark gray can be very revealing.

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**Effective Resolution — From Grille Measurements**

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<tr>
<th>THRESHOLDS</th>
<th>For text, e.g., $C_t = 0.5$</th>
<th>For images, e.g., $C_i = 0.25$</th>
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<tr>
<td>$C_M = \frac{L_w - L_K}{L_w + L_K}$</td>
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**EXAMPLE OF MEASUREMENT OF DETAIL**

- Measure $L_w$ and $L_K$ accurately for each grille
- Calculate Michelson contrasts (contrast modulation)
- Determine intercepts $n$, $n_t$, and $n_i$
- $n = \frac{\text{# Pixels (H or V)}}{\text{Grille Line Width (pixels)}}$

Some refer to this as a modulation transfer function (MTF) measurement. Often MTF measurements employ sine modulations at less than full contrast, and few, if any, ever worry about veiling glare or corruption in making MTF measurements.

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**Uniformity Measurements, Cont.**

**Viewing Point Location**

Default viewpoint is at "infinity" so that detector measures along normals, unless otherwise specified.

Measurements made as if viewed from "infinity" along normals — default

If only a viewing angle is specified, not a viewing point, then we measure all points as if at infinity but at the viewing angle from the normal (be careful about keeping the screen in focus).
Uniformity Measurements, Cont.

Sampled Uniformity Measurement Points

9-point, 25-point, 13-point, 9-point centered in 3x3 matrix, etc.

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+ + +
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+ + +
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+ + +

9 - pt. centered in 3x3 matrix

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+ + +
+ + +
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+ + +
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+ + +

13 - pt ANSI (5 % corners)

Uniformity Measurements, Cont.

Array Detector Problems

Photopic Response

Sensitivity to IR can seriously corrupt what was intended to be a luminance measurement. These filters can be expensive (from $500 to $1000 [US] or more).

Flat-Field Correction (FFC)

Nonuniformity partially corrected by FFC. FFC may change with lens and object configurations.

We are assuming a background subtraction is performed before the FFC. The FFC can change for the type of lens used, the f-stop, the focus, the size of the light-area measured and its distance, etc. Very difficult to accurately create because a truly uniform source of sufficient size is hard to obtain and because the correction needed can change so much with conditions. Be careful. What will serve as a FFC for one configuration may not for another!!!

Uniformity Measurements, Cont.

Area Uniformity Measurements Using Array Detectors

Nonuniformities invisible to the eye are readily seen using a linear detector.

Horizontal Luminance Profile of Center

Array Detector Problems

Array Detector Problems

The flat-field correction (FFC) attempts to correct for pixel-to-pixel sensitivity nonuniformity and cosθ fall-off if a lens or aperture is used.

The FFC may only be partially successful. Any pixel-to-pixel nonlinearity, differing linearity, and spectral sensitivity nonuniformity will affect the success of using the FFC in addition to the problems stated previously. Obtaining a 1% uncertainty using a FFC may be a big challenge.
Uniformity Measurements, Cont.

Array Detector Problems

\[ \cos^4 \theta \text{ Falloff} \]

\[ \frac{1}{10}^\circ = \text{width of little finger at arm's length or width of thumbnail at arms length (calibration required before use)} \]

\[ \frac{1}{2}^\circ = \text{sun, moon angular diameter} \]

Spatial Aliasing (Moiré Patterns)

Viewing Angle Measurements

Measurement Field Size Changes with Angle

One problem is that the size of the spot measured with common detector increases as \(1/\cos \theta\) with angle \(\theta\) from the normal. Causes a violation of measuring less than 10% of the screen. Oh well... Difficult to improve, but probably not important for most applications.

\[ \frac{1}{10} \text{ Screen Vertical} \]

- Measurement Field at Normal
- Measurement Field at 60° ~ 2x
- Measurement Field at 70° ~ 2x
Front Projection & Stray Light, Cont.

Accounting for Stray Light in Room – Projection Mask

Use a projection mask (wider than the lens diameter) placed from 35 cm to 60 cm from the screen. Objects in room and room walls reflect light from the white screen back into black area. This can be a serious corruption of the black even in a darkroom and even using a black screen!

Comparing well with SLET (± 1 %) in a darkroom and can possibly be used in a darkened room.

Front Projection & Stray Light, Cont.

Stray-Light Elimination Tube (SLET)

Can permit accurate measurements even in high-ambient lighting.

Even in a black-walled darkroom using a black screen with a checkerboard displayed, significant errors of several tens of percent can be made if we are not careful.
Making Luminance Measurements

Screen gain is very directional. Can avoid screen effects by using calibrated diffuse white standard and converting to illuminance.

Grille Measurements to Establish Resolution

[See FPDM 303-7: Resolution from Contrast Modulation]
Reflection Terminology & Standards, Cont.

Canonical Reflection Terminology

1. Reflectance Factor $R$
2. Uniform Diffuser, Perfect Reflecting Diffuser
3. Reflectance $\rho$
4. Luminance Factor $\beta$
5. Diffuse Reflectance $\rho_d$ (we will extend: $\rho_d = \rho_r + \rho_h$)
6. Specular Reflectance $\zeta$ (CIE uses "regular" and $\rho_s$)

Helpful Notation: source/detector subscripts

Specify angle $\theta$ in degrees or use "d" for diffuse (can also use "d" for diffuse with specular included and "de" for diffuse with specular excluded [letting it out through a hole]; if needed).

Examples: $R_{de}$, $R_{de}(d)$, $R_{de}$, $R_{de}(d)$, $R_{de}$, $R_{de}(d)$

References: CIE Publication 817.4, 545, 544

Reflection Terminology & Standards, Cont.

Uniform diffuser: $L = qE$

Lambertian surface: A surface where the luminance $L$ is the same from all observation directions and only depends upon the magnitude of the illumination $E$, $L = qE$, where $q$ (luminance coefficient) is a constant. It obeys Lambert's law $l = l_0cos\theta$, where $l$ is the luminous intensity, $l_0$ is the luminous intensity in the direction of the normal of the surface, and $\theta$ is the angle from the normal.

Perfect reflecting diffuser:

Perfectly white uniform diffuser such that $L = E/s$, i.e., reflectance = 1.

CIE 17.4: 845-04-44 "diffusion; scattering"

Process by which the spatial distribution of a beam of radiation is changed when it is deviated in many directions by a surface or by a medium, without change of frequency of its monochromatic components."

'Note — A distinction is made between selective diffusion and non-selective diffusion according to whether or not the diffusing properties vary with the wavelength of the incident radiation.'

CIE 17.4: 845-04-54 "perfect reflecting diffuser"

Ideal isotropic diffuser with a reflectance equal to 1."
Reflection Terminology & Standards, Cont.

Reflectance \( \rho \):  
Ratio of the reflected flux to the incident flux for a given geometry of source and detector:

\[
\rho = \frac{\Phi_r}{\Phi_i}
\]

Detector

\( \Phi_r \)

\( \Phi_i \)

Apparatus Geometry

Specular reflectance (defined later)

CIE 17.4: 845-04-58 "reflectance (for incident radiation of given spectral composition, polarization and geometrical distribution) (\( \rho \)) unit: 1

Ratio of the reflected radiant or luminous flux to the incident flux in the given conditions."

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Reflection Terminology & Standards, Cont.

Specular Reflectance \( \zeta \): \( \zeta \) is notation used here

(CIE: Regular Reflectance \( \rho_r \))

Ratio of the specularly (regularly) reflected flux to the incident flux for a given geometry of source and detector:

\[
\zeta = \frac{\Phi_r}{\Phi_i}
\]

Detector

\( \Phi_r \)

\( \Phi_i \)

Apparatus Geometry

CIE 17.4: 845-04-60 "regular reflectance (\( \rho_r \)) unit: 1

Ratio of the regularly reflected part of the (whole) reflected flux to the incident flux."

CIE 17.4: 845-04-45 "regular reflection; specular reflection

Reflection in accordance with the laws of geometrical optics, without diffusion."

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Reflection Terminology & Standards, Cont.

Diffuse Reflectance \( \rho_d \):

Ratio of the diffusely reflected flux to the incident flux for a given geometry of source and detector:

\[
\rho_d = \frac{\Phi_d}{\Phi_i}
\]

Detector

\( \Phi_d \)

\( \Phi_i \)

Apparatus Geometry

CIE 17.4: 845-04-62 "diffuse reflectance (\( \rho_d \))

Ratio of the diffusely reflected part of the (whole) reflected flux, to the incident flux. Unit: 1

Notes:
1. \( \rho = \rho_r \rho_d \)
2. The results of the measurements of \( \rho \) and \( \rho_d \) depend on the instruments and the measuring techniques used.

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Reflection Terminology & Standards, Cont.

Luminance Factor \( \beta \):

Ratio of the luminance of the object to that of a perfect reflecting diffuser for identical illumination conditions (we still really need to completely specify the apparatus geometry):

\[
\beta = \frac{\pi L_0}{E}
\]

Detector

\( \beta \)

\( L_0 \)

\( E \)

Apparatus Geometry

Note: Luminance coefficient:

\( \sigma = \beta / \pi \)

Thus, the luminance factor \( \beta \) implicitly assumes that the detector aperture area size is not important because we don't specify the detection cone as in the case of reflectance factor \( \rho \).

CIE 17.4: 845-04-66 "luminance factor (at a surface element of a non-self-radiating medium, in a given direction, under specified conditions of illumination) (\( \beta \))

Ratio of the luminance of the surface element in the given direction to that of a perfect reflection or transmitting diffuser identically illuminated. Unit: 1"

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Reflection Terminology & Standards, Cont.

Reciprocity Law: (Due to Helmholtz)
Light is reversible (wave equation is invariant to time-direction), so we can interchange the source and detector provided the geometry is preserved.

Examples:

Source/Detector have same geometry

Reflection Terminology & Standards, Cont.

Comparisons of different reflectance measurement quantities:

Reflectance factor:
\[ R = \frac{\Phi_d}{\Phi_p} = \frac{\Omega_d}{\Omega_p} \]
\[ R = \frac{I_\Omega}{I_p} = \frac{L_\Omega}{L_p} = \frac{\pi L}{E} \]

Luminance factor:
\[ \beta = \frac{L}{L_p} = \frac{\pi L}{E} \]

Reflectance:
\[ \rho = \frac{\Phi_d}{\Phi_p} = \frac{I_\Omega}{I_p} = L \cos \theta \]
\[ \rho = \frac{\Omega_d}{\Omega_p} = \frac{L_\cos \theta}{L_p} = \frac{(L/E) \Omega \cos \theta}{E} \]

BRDF:
\[ B = \frac{L}{E} \] (B = BRDF, is covered below)

Perfect reflecting diffuser:
\[ L_d = E/\pi = \text{constant} \]

SUMMARY: Use Reflectance Factor R

In general, reflection measurement experts tell me that we should be reporting the reflectance factor R in most cases. Then we specify the illumination geometry, the detector geometry, and the configuration of the angular aperture of the detector. However, the use of the reflectance \( \rho \) and the luminance factor \( \beta \) is quite historical in the display industry, so you will likely continue to see their use.

\[ R \rightarrow \rho \quad \text{for} \quad \Omega \rightarrow 0 \]

Diffuse: \( R \rightarrow \rho \quad \text{for} \quad \Omega \rightarrow 2\pi \)

Reciprocity \( \rho_{dm} = \rho_{md} \)

Calibration of Black Glass

Folded

Uniform Source

Specular Reflectance

Black
Glass

\[ \frac{\zeta(\theta)}{L(\theta)} = \frac{L_s}{L_g} \]

Unfolded

Luminance Meter: Focused on Source

Note that how you clean the black glass can affect its reflectance.
Reflection Terminology & Standards, Cont.

Black Glass

Use of Black Glass

Black Glass Reflectance Depends Upon Angle

Useful for making measurements of source in specular reflection configuration without having to reposition source or detector; just replace display with black glass.

Sample data only for demonstration purposes.

How we clean these can also affect the specular reflectance result ± 1% or more.

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Reflection Terminology & Standards, Cont.

White Reflectance Standard

- Possible to obtain types that can be refurbished in your lab (e.g., 220 to 240 grit water-proof emery paper using circular-linear combined motion under running water).
- Make sure it is sufficiently thick (some need to be 10 mm depth or more, whatever the manufacturer states is necessary). A 50 mm diameter disk may be required.
- Over 99% reflectance (e.g., \( \rho_{99} \)) quasi-Lambertian... BUT watch out!!! ... What kind of reflectance is this 99% value???

CAUTION: These are not perfectly Lambertian.

The reflectance (e.g., of 0.99) is obtained under specific conditions of illumination and reflected-light measurement (e.g., \( \rho_{99,0} \) of \( \rho_{99} \)). The reflectance will not necessarily be the same for all angles and all configurations!!! If you need to use it for a certain configuration (other than the configuration for which it was calibrated and related configurations), then it must be calibrated for that special configuration. We cannot necessarily use the 99% value for just any configuration we want (blindly hoping that it will be OK). An illuminance meter might be better.

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Reflection Terminology & Standards, Cont.

Example ONLY: don't use these results for your own purposes!!!

Reciprocity gives: \( \beta_{0/0} = \beta_{0/d} \)

But... must be same sample under same conditions to work. How the sample is prepared and its history will both affect results.

Three-Component Model of Reflection

Oversimplified Models — Possible Ambiguity

Lambertian ("Diffuse") component assumption:

Display surface measured as if it were matte paint.

\( \beta = \text{luminance factor}, \quad q = \text{luminance coefficient}, \quad E = \text{illuminance}, \quad L = \text{observed luminance}. \)

\[ L = qE = \frac{E}{\pi} \]

Note: Strictly speaking this equation is for a Lambertian material; "diffuse" means scattered out of specular direction and is not limited to Lambertian materials.

Specular component assumption:

Display surface treated as if it were a mirror.

\( \zeta = \text{specular reflectance}, \quad L_s = \text{source luminance} \)

\[ L = \zeta L_s \]

Three Component Reflection Model, Cont.

Oversimplified Model: Easy to Measure, Robust, \( |E| \text{ OK} \)

Unfortunately, many FPDs are not well characterized by just these two components — an oversimplified model.

FPDs Can Permit a Strongly Diffusing Surface Near Pixels

Like wax paper over printing...

Legibility depends upon distance of strong diffusion layer from surface containing information

Problem: Simple Models Inadequate for All Surfaces

Neither Lambertian nor specular models may work!
Three Component Reflection Model, Cont.

THREE COMPONENTS OF REFLECTION FOR DISPLAYS

1. SPECULAR (producing a distinct virtual image of the source)

2. LAMBERTIAN (like matte paint)

3. HAZE (fuzzy ball in specular direction)

Reflectance can be thought of as having three components:

\[ p = p_s + p_d + p_h \]

where the diffuse reflectance is \( p_d = p_l + p_w \)

a) Lambertian (\( p_l \))

b) Specular (\( p_s \))

c) Haze (\( p_h \))

d) \( p_l + p_s \)

e) \( p_h \)

Three Component Reflection Model, Cont.

Specular, Lambertian, Haze

Virtual Image (if there is a specular component)

Specular Only

Haze Only

Lambertian Only

All Three

Three Component Reflection Model, Cont.

BRDF — Three Components:

Bidirectional Reflectance Distribution Function — A generalization of \( L = qE \)

\[ dL(\theta, \phi) = B(\theta, \phi, \theta, \phi; \lambda, \rho)dE(\theta, \phi) \]

We will drop the wavelength \( \lambda \) and polarization \( \rho \) dependence.

\[ B = D_L + S + D_H \]

\[ S = 2\zeta \left( \sin^2 \theta - \sin^2 \phi \right) \delta(\theta_0 - \theta) \delta(\phi_0 - \phi) \Rightarrow \text{Specular} \]

\[ D_H = H(\theta, \phi, \theta_0, \phi_0) \Rightarrow \text{Haze (diffuse)} \]

\[ L(\theta, \phi) = qE + \int_{\gamma} H(\theta, \phi, \theta_0, \phi_0) \cos(\theta) d\Omega \]

NOTE: The BRDF formalism is even an oversimplification for some displays. Could use the bidirectional scattering distribution function (BSDF) to be more precise — messier.

Three Component Reflection Model, Cont.

Like the Lambertian component, the haze is proportional to the illuminance; but like the specular component, it follows the specular direction.

The luminance of the specular component remains constant with change in distance. The peak of the haze changes with distance (according to illuminance). Because the haze peak adds to the specular image, it can appear that the specular image is changing its luminance, but that is not the case. Look carefully at the specular image, you will see it is not changing its luminance when you separate the specular image from the haze peak.
Three Component Reflection Model, Cont.

Reflection of laser beam onto white card gives the BRDF projected onto a plane.

Lambertian
Specular
Haze

What's all this talk about BRDF and haze?
All you need is a light source at 45° and you're done!
Why make everything so complicated?

RUSTIC METROLOGY

FPD

Three Component Reflection Model, Cont.

Simple BRDF (In Plane)

Extremes:
Lambertian (flat)
Specular (spike)
Haze is in between

Haze characteristics:
Proportional to illuminance
Directed in specular direction

NOTE: 3 to 5 orders of magnitude possible (or more—your eye has no trouble seeing this range)

SPECIALELY PREPARED SAMPLE \( \theta_i + \theta_s + \theta_f \)

B(κ, λ) = \[ \frac{L_{\text{spec}}(\theta_i, \phi_i, \gamma_i, \theta_s, \phi_s, \gamma_s) \cos(\theta_i) \cos(\gamma_i) d\theta_i d\phi_i d\gamma_i}{L_{\text{back}}(\theta_i, \phi_i, \gamma_i) d\theta_i d\phi_i d\gamma_i} \]

Remember that not all components must be present.

Three Component Reflection Model, Cont.

BRDF for 3° Specular Configuration (ar-1)

Lambertian Component
Specular Peak
Haze Peak

Light Source Relative Angle (degrees)

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Three Component Reflection Model, Cont.

Some displays don’t have a specular or a non-trivial Lambertian component... ONLY haze.

- CRT with haze but no AR
- FPD with haze only but no AR
- CRT with haze and AR
- FPD with haze (very slight specular) but no AR

Notice vertical range of $10^3$ or $10^4$.
Notice various widths of haze peaks.
Three Component Reflection Model, Cont.

In the most general case, when there is a Lambertian, specular, and haze component, there are at least four parameters that are needed to specify the reflection characteristics since haze has a peak and a width (at the very least).

KEY POINT

If we only make one simple measurement or two, the problem is underdetermined and an infinite number of displays can measure the same and look different to the eye! This underscores the need to make several different measurements to adequately characterize reflection from displays.

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Three Component Reflection Model, Cont.

With Haze, Measurements Can Be Sensitive to the Geometry of the Apparatus...
- Lens diameter (?)
- Focus
- Source size
- Source distance

Example: 1° misalignment of apparatus can result in 30% errors in measured reflected luminance.

Haze Reflection Need Not Be Symmetrical.
Star patterns and spikes further complicate a full characterization of reflection, accomplished only via a complete BRDF.

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Simple Reflection Measurement Methods

BRDF measurements are hard; simpler and faster methods are desired (required).

Acceptable Methods Must Be...

- Robust: Results not subject to small apparatus imperfections or irregularities or choice of equipment
- Reproducible: Same results obtained with same displays around the world
- Unambiguous: Apparatus configuration and requirements clearly presented and all important concerns made obvious

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Simple Reflection Measurement Methods, Cont.

Which Measurement Methods are Most Robust?

A. New Port
B. New Specular
C. Large Specular
H. Diffuse
I. Large Specular
J. Broad Specular
K. Small Specular
Simple Reflection Measurement Methods, Cont.

Assumptions for Method Consideration

- What are we looking for and what are we NOT saying here?
- HAZE PRESENT: Assume haze is non-trivial in what follows, or that we have a general display with all three reflection components being non-trivial.
- EASY, ROBUST, UNAMBIGUOUS, EXTENSIBLE: We are looking for reflection measurements that are easy to make, robust, and useful for ALL types of displays with a variety of reflection properties.
- ROBUSTNESS VS. REPRODUCIBILITY: A method that is not robust is not necessarily a bad method, it simply is a method that requires very careful alignment of the apparatus and does not lend itself to quick industrial-setting measurements. They might only be used for careful laboratory measurements. Robustness is an indication of how easily reproducibility can be achieved.

Simple Reflection Measurement Methods, Cont.

A. Ring Light Source

- REFLECTION COMPONENT UTILIZATION: Avoids haze peak and specular. Captures the tail of the haze (depending upon width) and some contributions from the Lambertian.
- ROBUSTNESS: Fairly robust and insensitive to small changes in setup parameters. Works with haze because 'when one side goes up the other goes down' in exploiting the BRDF — not a severe change in the haze wings.
- SYMMETRY: Symmetrically integrates contributions from all rotation angles about the normal.

Simple Reflection Measurement Methods, Cont.

B. Small Side Source at 30° and 15°

- REFLECTION COMPONENT UTILIZATION: Avoids haze peak and specular. Captures the tail of the haze (depending upon width) and some contributions from the Lambertian.
- ROBUSTNESS: Problematic! Very sensitive to small changes in alignment of detector with normal and to small changes in position of the source, particularly when observing near the specular direction. Angles must be carefully measured.
- SYMMETRY: Not symmetric, results greatly affected if BRDF is not rotationally symmetric.

Simple Reflection Measurement Methods, Cont.

C. Large Side Source at 30°

- REFLECTION COMPONENT UTILIZATION: Avoids haze peak and specular. Captures a segment of the haze profile.
- ROBUSTNESS: Not robust because of the geometric sensitivity to the side of the haze peak where the haze is not small and varies rapidly with a change of source angle.
- SYMMETRY: Not symmetric.
**D. Viewport Source**

- **Reflection Component Utilization:** Avoids the specular and haze peak, but because of the relatively narrow viewport, the near peak of the haze comes into play making the result very sensitive to viewport geometry.

- **Robustness:** Not robust because of the near-peak part of the haze component contributes. (It is not like the ring light where only the wings of the haze contribute—where the changes with angle are much smaller.)

- **Symmetry:** Symmetrically integrates contributions from all rotation angles about the normal.

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**E. Small Specular Source**

- **Reflection Component Utilization:** Combines the specular, the haze peak, and the region of the haze near the peak. Little Lambertian contribution compared to specular and haze.

- **Robustness:** Problematic. Can be very sensitive to apparatus settings and geometry. Haze contributions seriously affect results. Typically, source subtense is 1° or more in regime where the haze changes rapidly. But... people like to use this; so be careful!

- **Symmetry:** Symmetrically integrates contributions from all rotation angles about the normal.

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**F. Large Specular Source**

- **Reflection Component Utilization:** Captures the specular and haze peak and the substantial part of the haze profile.

- **Robustness:** Fairly robust and insensitive to small changes in setup parameters. Works with haze because 'when one side goes up the other goes down' in exploiting the BRDF—but not near the haze peak.

- **Symmetry:** Symmetrically integrates contributions from all rotation angles about the normal.

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**G. Proximal Specular Source**

- **Reflection Component Utilization:** Combines all three components.

- **Robustness:** Somewhat robust. Robustness suffers because of lack of symmetry in reflection component exploitation.

- **Symmetry:** Not entirely symmetric. Symmetrically integrates contributions from all rotation angles about the normal near the peak of the BRDF but non-symmetrically exploits the wings of the haze and Lambertian.
Diffuse Reflectance

or hemispherical directional reflectance \( (\beta_{\text{diff}} = \rho_{\text{Hd}}) \)

- **A Worst-Case Situation**: Uniform light surround with normal of display tilted approximately 8° to 10° from axis of measurement hole.
- **Reproducible**: A variety of apparatus can be used to reproduce sufficiently the uniform hemispherical surround conditions.
- **Robust**: Results tend to be insensitive to apparatus configuration and angular alignment.

**NOT TRUE**!
- Beach on a cloudy day. Snow field on a cloudy day. Light living room with light furniture and even illumination. Bubble helmet! In cloud! Not so uncommon after all. People don't like it because it is laugh on their displays, visible low contrast values.

**IF THERE IS GOING TO BE ONLY ONE MEASUREMENT TO MAKE, THIS IS IT!!! (... my opinion...)**

**"Best" Methods Summary**

- All these are robust and integrate the effects of any complicated haze or specular reflection profiles.

  - **Diffuse Source (H):**
  - **Ring Light Source (A):**
  - **Large Specular Source (F):**

**Note**

**A variety of apparatus can be used. Reproducibility of 5% is not hard to achieve.**
Diffuse Reflectance ($\rho_{\text{diff}} = \rho_{\text{ref}}$), Cont.

Using Integrating Sphere

1. Measure darkroom $L_w$ & $L_d$
   ($L_w = L_d = 0$ for reflective)
2. Measure display $L_s$ & $L_d$ in sphere
   (h = high for white, d = dark for black)
3. Measure Illuminance for white $E_w$ and black $E_b$
4. Calculate reflectances
   \( \rho_w = \frac{\pi(L_w - L_d)L_d}{E_w} \)
   \( \rho_b = \frac{\pi(L_d - L_s)L_d}{E_b} \)
5. Scale to design illumination: Determine contrast
   C under desired design ambient illuminance $E_d$
   \[ C = \frac{E_w - L_d}{E_b - L_d}. \]

Diffuse Reflectance ($\rho_{\text{diff}} = \rho_{\text{ref}}$), Cont.

Sampling sphere method

Illuminance determined from monitor photodiode current

\[ C = \beta \rho_b \text{ for reflective displays} \]

Photodiode monitor is photopic, baffled to avoid direct rays from source or display.

Shame on me for creating such a busy slide! 😋
NOTE
VERY IMPORTANT!!!
On all diffuse-type measurements, be sure that the luminance meter's measurement result is not being corrupted!
The luminance meter may have to be positioned sufficiently far away from the measurement port when making measurements of the screen to avoid stray-light corruption from the bright interior walls surrounding the sample port compared to the relatively dark display (especially if showing black). Be careful!

Motion Artifacts

There are numerous types of motion artifacts. Here is a sampling:

- Judder
- Moving Edge Blurring
  This is often normalized to a response time called moving-edge response time (name is standardized in FPDMUPDT [an update document]). In the literature you can also find it called motion picture response time (MPRT).
- Moving Line Spreading & Contrast Degradation
- Wireframe Flicker or Moving Line Flicker
- Color Breakup, Color Smearing, etc. ...

Some of these are artifacts of the display. Some can also be artifacts from the combination of the display and how the eye sees things.
Motion Artifacts, Cont.

**CRT Display**

Smooth-Pursuit Eye Tracking

(Animated)

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Motion Artifacts, Cont.

**FPD Hold-Type Display**

Smooth-Pursuit Eye Tracking

(Animated)

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Motion Artifacts, Cont.

FPD Hold-Type Display with perfect transitions between levels

Position of Edge

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(Animated)

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Motion Artifacts, Cont.

FPD Hold-Type Display with finite transition times

Position

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(Animated)

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A-6/64
Motion Artifacts, Cont.

Lines Moving Across Screen
Try to follow and see blur; stare in one place appears sharp.

(Animated)

Motion Artifacts, Cont.

Color Breakup
Color breakup can arise from color sequential displays if their sub-frame refresh frequency is too slow.

(That's supposed to be a thrown snowball.)

Motion Artifacts, Cont.

Wireframe Flicker
Some displays exhibit a pronounced flicker when a wireframe is slowly moved across the screen. Probably won't work here because the motion is too fast.

(Animated)

Motion Artifacts, Cont.

Color Smearing

(Animated)
Tips on Buying a New FPD

Applying what we’ve discussed...

WARNING!!!

Reading or listening to the following material may cause permanent damage to your present ability to enjoy practically any image on any display screen. Learning the following guidelines will cause you to see some of the subtle differences in displays so they no longer look all alike.

BE CAREFUL! PROCEED AT YOUR OWN RISK!

If you already have purchased a new display, absorbing this material may not be the wisest thing to do. You have a few seconds to leave the room.

You’ve been warned!

Just a few extra slides added for clarity... sorry.

Tips on Buying a New FPD, Cont.

Proper Ambient

Some displays will perform best in a very dark surround. Some will perform best in a bright surround. Attempt to evaluate the display in the environment into which you intend to place it.

Shadows and Details

Shadow detail: For example, here is a 128-level smearing gray scale. How many of the dark grays are pushed to black? For that matter, how many of the light grays are pushed to white? There is only one way to find out. Repeat the process at different gray areas.

Comparison of Shadows and Details

The difference in shadow detail is quite apparent.
REFLECTION PROPERTIES

Some displays will reflect light so that you can see the distinct reflected image of the source because they have a strong specular component. Other displays will diffuse the light so that you just see a fuzzy ball of light instead of a distinct image of the source—a strong haze component. How large that fuzzy ball is will depend upon the microstructure of the surface treatment. This diffusing treatment is often called anti-glare or non-glare. Some displays will have both properties as well as a third Lambertian component (like dark gray matte paint). You will want to keep in mind your living-room lighting and window configuration when you examine candidate displays. Some displays will allow the mirror-like reflections but will reduce them considerably by using an anti-reflection coating. You can often recognize such coatings by the dim magenta, dim blue, or dim green reflections of lights.

PLACEMENT

Some of the problems with reflections can be reduced by placing the display so that you avoid seeing bright objects such as windows or lamps in its reflection.

SPECIFICATIONS

Unfortunately, specifications claimed for displays cannot always be used to compare them. They may not employ measurement standards like the FPDM but use their own methods. Use and trust your eyes. What you see can be exactly what you get. Some displays will exhibit the same luminance when they show a small white area or fill the screen with white. Other displays will show a bright white small area but become much dimmer when displaying full-screen white. So when you evaluate the display, be sure to view a wide variety of scenes.

Contrast: 500:1
Luminance: 300 cd/m²

Contrast: 500:1
Luminance: 300 cd/m²

VIEWING ANGLE

The problems with viewing angles are gradually being eliminated. However, if you will have kids on the floor looking at the display while you sit on the sofa or if you have a room filled with people viewing the display from all different angles, then the display’s viewing angle properties may be important to you. So, check it out. Move around and see what it does with the colors and especially the blacks. Some displays suffer most viewing-angle problems when viewed from the lower right or left. Often static images are useful in such evaluations. Look for contrast reductions as well as color shifts.
Courses & Services at NIST

- NIST Display Metrology Short Course
  It is being offered several times a year (hands on lab work).
  See http://www.fpdli.nist.gov
  or http://www.fpd.nist.gov and follow the links.
- NIST Photometry Short Course
- NIST Spectroradiomertetry Short Course
- NIST Colorimetry of Displays — A Calibration Facility
  Based Upon the Four-Color Matrix Method for Correction of Triadimensionsal Colorimeters
- NIST Laser Measurement Short Course
  http://www.boulder.nist.gov/itl/15measure.tml
- NIST Flat Panel Display Laboratory — Publications, Links, Overview
- This seminar: http://www.fpdli.nist.gov → Seminars and Courses