SEMINAR
Display Measurements for Flat Panel Displays

SID2006 — San Francisco, CA

June 4-9, 2006

Friday Seminar, June 9

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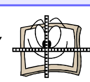
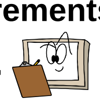
Preliminaries

- SETUP OF THE DISPLAY 
- TYPES OF MEASUREMENTS
  - Full-Screen Measurements
  - Box Measurements
  - Uniformity Measurements
  - Viewing-Angle Measurements
  - Detail Measurements
  - Temporal Measurements
  - Reflection Measurements
  - Motion-Artifact Measurements
  - Other Measurements… 

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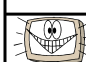
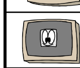
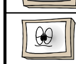
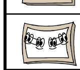
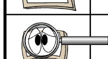
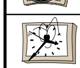
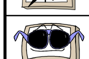
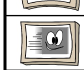
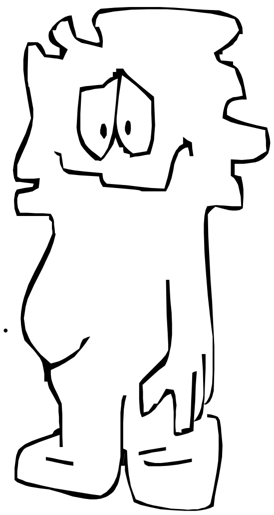
	✓		
	✓		
	✓		✓
	✓		✓
	✓		✓
	✓	✓	
	✓		
	✓	✓	✓

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:***
  - **5 % UNCERTAINTY IN LUMINANCE**
  - **0.005 UNCERTAINTY IN COLOR (x,y)**
- ***YOUR LABORATORY REPEATABILITY:***
  - **0.1 % UNCERTAINTY IN LUMINANCE, OR SMALLER**
  - **0.001 UNCERTAINTY IN COLOR (x,y), 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.

$u_c = \sqrt{\Sigma u_i^2} =$ **Combined Standard Uncertainty**
Addition of all individual contributions to the uncertainties from considerations of statistical, random, experience, specifications, data, etc., contributions; calculated via the root-sum-of-squares method.

$U = ku_c =$ **Expanded Uncertainty**
The coverage factor k times the combined standard uncertainty.

See: Barry N. Taylor and Chris E. Kuyatt, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, 1994 Edition.
Get it at: http://physics.nist.gov/Pubs/guidelines/TN1297/tn1297s.pdf

PROPAGATION OF ERRORS

$U = ku_c$ **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%.**

$C = \frac{L_W}{L_K}$ **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.

$$(\delta C)^2 = \left(\frac{\partial C}{\partial L_W}\right)^2 (\delta L_W)^2 + \left(\frac{\partial C}{\partial L_K}\right)^2 (\delta L_K)^2 + 2\frac{\partial C}{\partial L_W}\frac{\partial C}{\partial L_K}\delta L_W \delta L_K$$

Reason: Cross term in uncertainty expansion is no longer zero because the δL 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 requires *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.

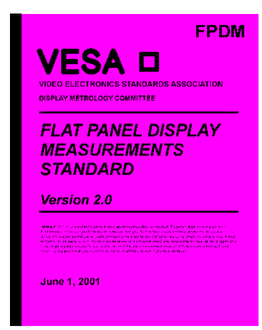
REFLECTIVE DISPLAYS—NOT MEASURED IN DARKROOMS

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

FPDM: Basis for Measurement Methods

VESA FPDM — Flat Panel Display Measurements Standard

Features: **VERSION 2.0**

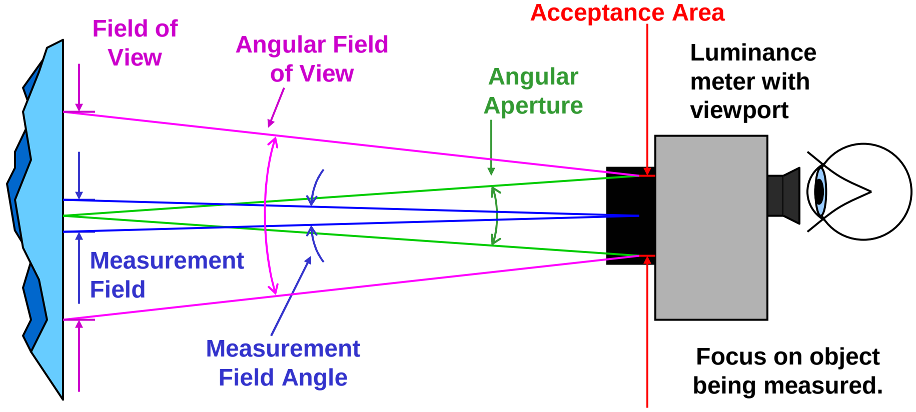


- Specification of good metrology for displays
- Self-contained measurement procedures
- Buffet of measurements—use what you need
- Easy to use and read
- Extensible—more will be added as needed
- Adaptable—affords a variety of equipment
- Accommodating—special needs permitted
- Metrology Section, Technical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

  VESA 408-957-9270 (call them for a copy) www.vesa.org

Preliminaries, Cont.

Luminance Meter Terminology

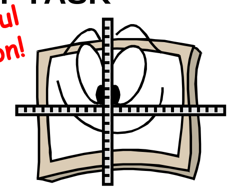


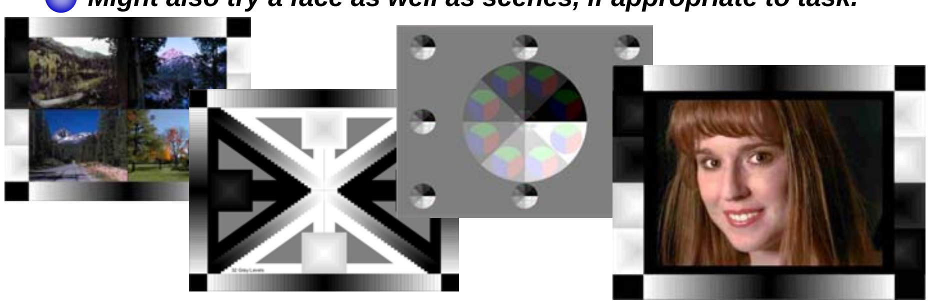
Get CIE Publication No. 69 for complete details.

Setup — Task Dependent

- PROPER SETUP DEPENDS UPON DISPLAY TASK
  - *How will the display be used?*
  - *What environment (ambient, surround)?*
  - *Are there manufacturing setup specifications?*
  - *Gray scales near black and near white are often useful, but may not be sufficient. [FPDM 301-3A]*
  - *Might also try a face as well as scenes, if appropriate to task.*

for useful operation!





A face *may* show up problems that are difficult to see with other patterns simply because our human vision processing is very sensitive to faces.

Setup, Cont.

Setup, Cont.

Patterns & faces available: www.fpd.nist.gov → Patterns

Setup, Cont.

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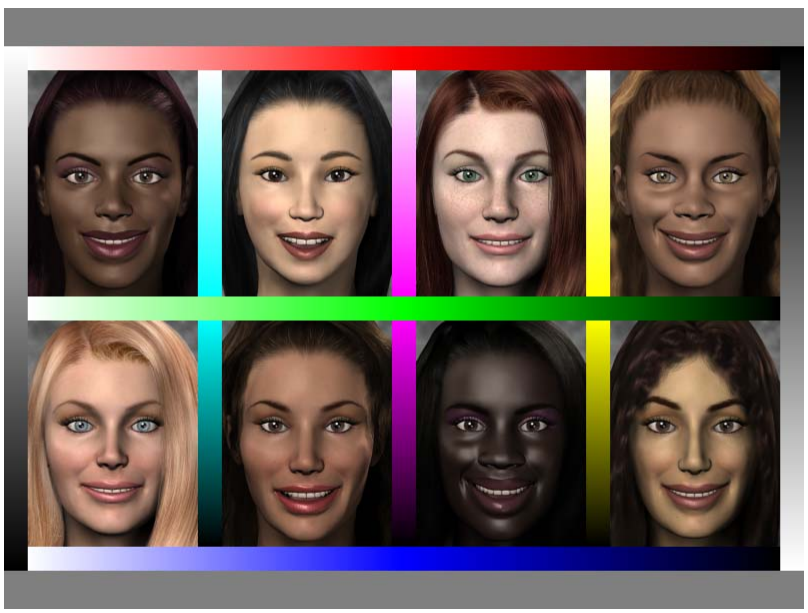
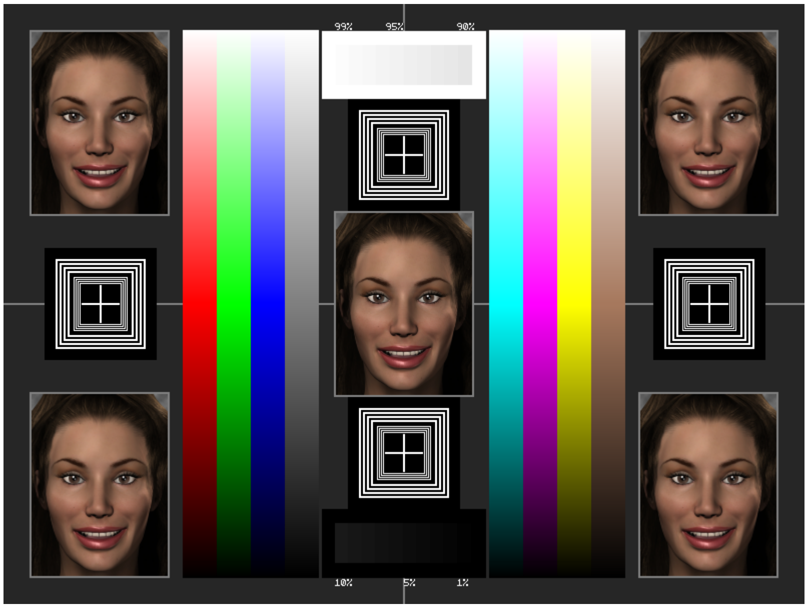
Setup, Cont.



Patterns & faces available: www.fpd.nist.gov → Patterns

Setup, Cont.



Patterns & faces available: www.fpd.nist.gov → Patterns

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Setup, Cont.

Patterns & faces available: www.fpd.nist.gov → Patterns

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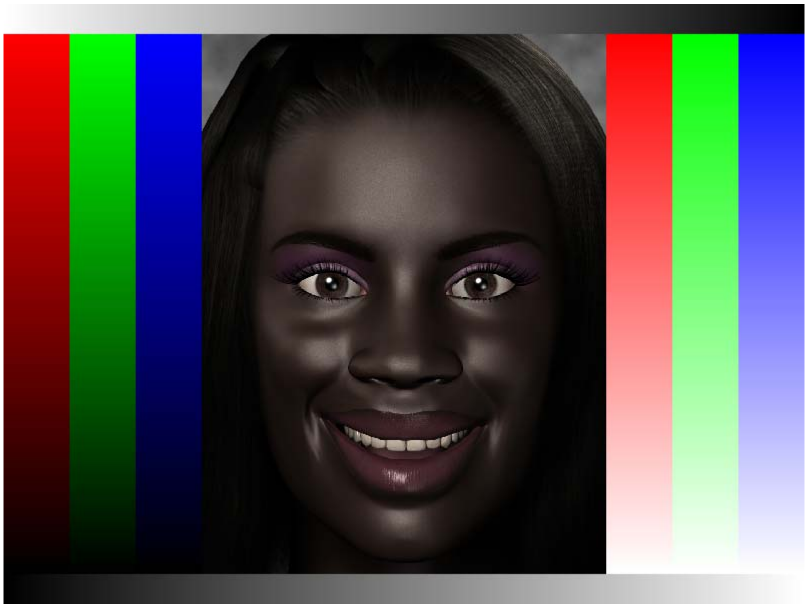
Setup, Cont.



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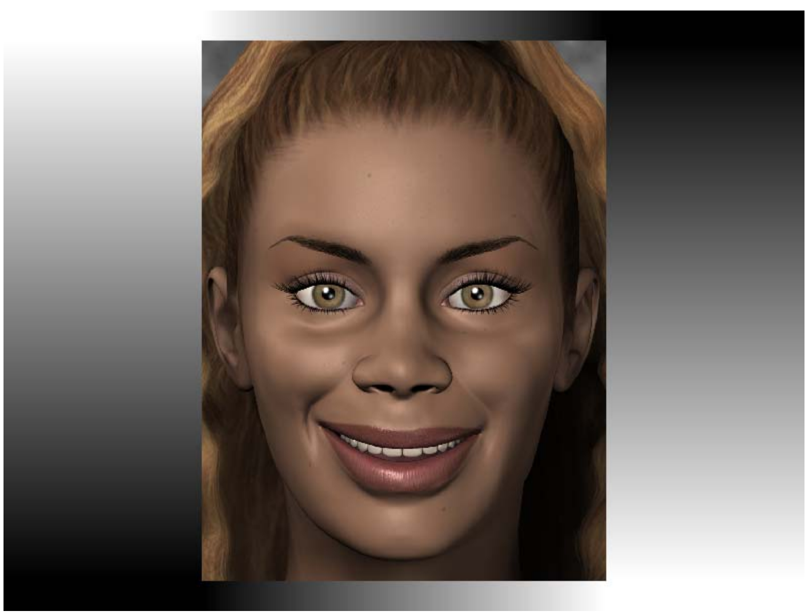
Setup, Cont.



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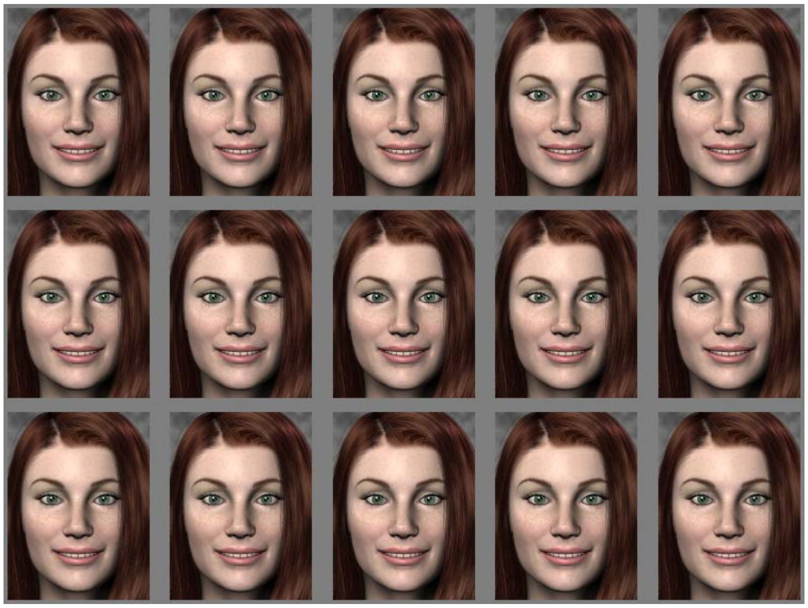
Setup, Cont.



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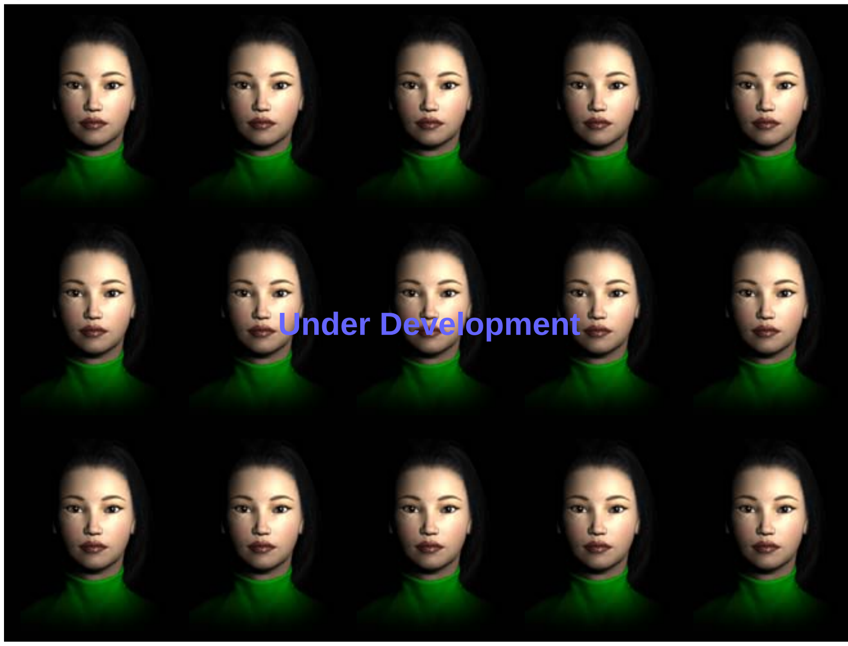
Setup, Cont.

Setup, Cont.



Setup, Cont.

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…

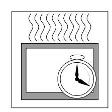
L_W

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

L_K

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

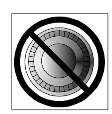
WARM-UP TIME MAY BE NEEDED



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]

For examples of patterns see: http://www.fpdl.nist.gov/patterns.html or ftp://ftp.fpdl.nist.gov/pub/patterns/

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.***

Setup, Cont.

ADJUSTMENT OF DISPLAY SETTINGS

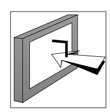
If the display provides adjustments but the manufacturer doesn't supply specific instructions on how to adjust these controls, here is a procedure: ← for useful operation!

- **Place the display in the environment in which it will be used.**
- **Make whatever adjustments are needed using the kind of targets and patterns that will be anticipated for the task.**
- **Then place the display in a darkroom (a good one!) and make the measurements without the contributions of stray light.**
- **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.)**

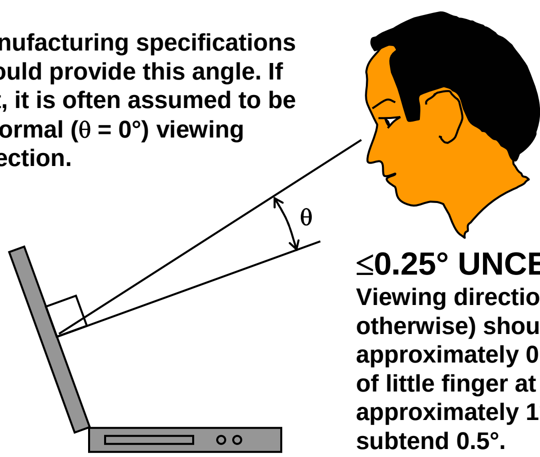
Setup, Cont.

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 ($\theta = 0°$) viewing direction.

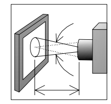


$\leq$0.25° UNCERTAINTY:

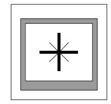
Viewing direction angle (if normal or otherwise) should be determined to approximately 0.25°. Not hard! Width of little finger at full arm extension is approximately 1°. Moon and Sun subtend 0.5°.

Setup, Cont.

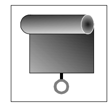
- **MEASUREMENT FIELD ANGLE**
  Angle usually limited to 2° or less, 1° is common.



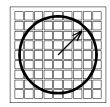
- **ANGULAR APERTURE**
  Most don't think about this. We try to keep this also 2° or less.
- **CENTER SCREEN MEASUREMENTS**
  Common measurement point is screen center, unless otherwise required (e.g. sampled uniformity, etc.).



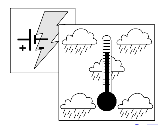
- **DARKROOM**
  Black walls are nice to keep reflections down. Popular criterion is illuminance at surface of screen to be 1 lux or less (preferably less): $E \leq 1$ lx.



- **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.

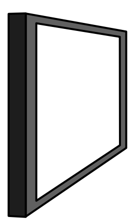


Gray Scale

Gray Scale

INPUT

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



OUTPUT

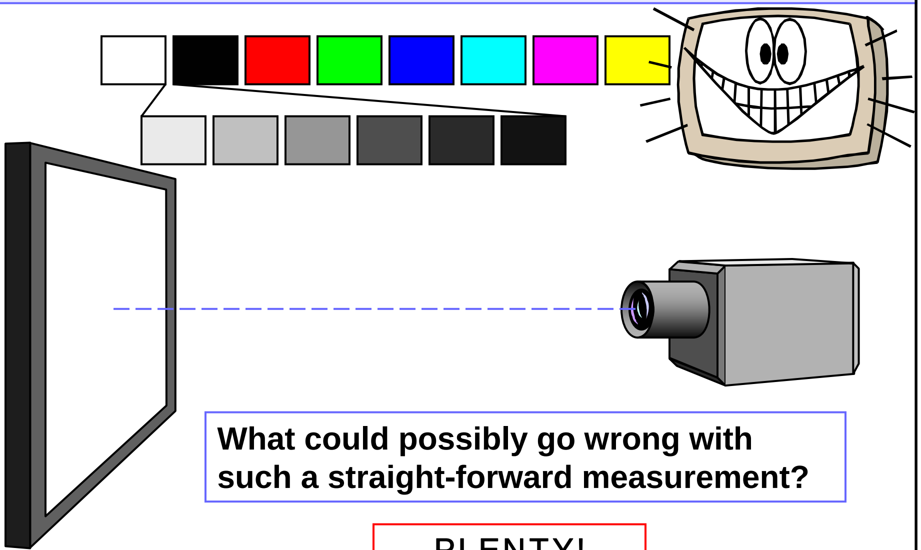
Gray Shade
$L = L_K, L_1, L_2, \ldots, L_W$

Typical form: $L_i = aV_i^{\gamma} + L_K$, $a = \dfrac{L_W - L_K}{255^{\gamma}}$

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

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

Full-Screen Center Measurements



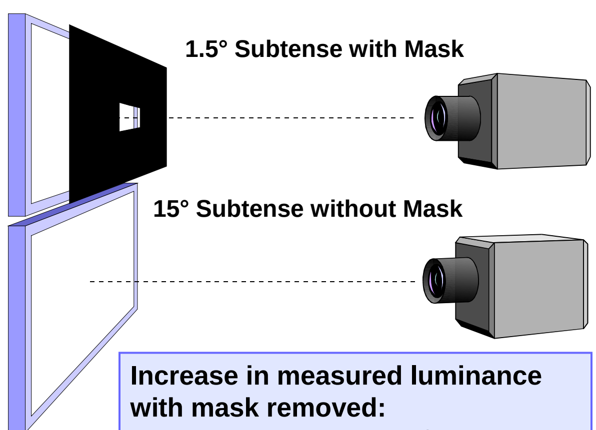
What could possibly go wrong with such a straight-forward measurement?

PLENTY!

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

Veiling 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)

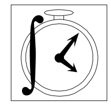


Increase in measured luminance with mask removed:

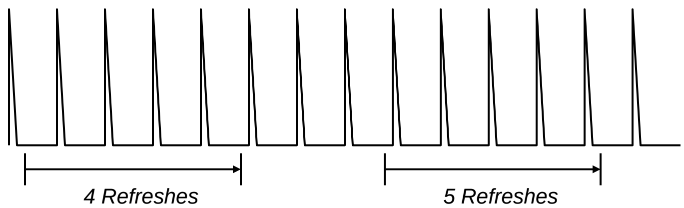
Instrument #1 0.4 %
Instrument #2 1.3 %
Instrument #3 4.8 %

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

Short Integration Times — Possible Errors from Refresh of Screen

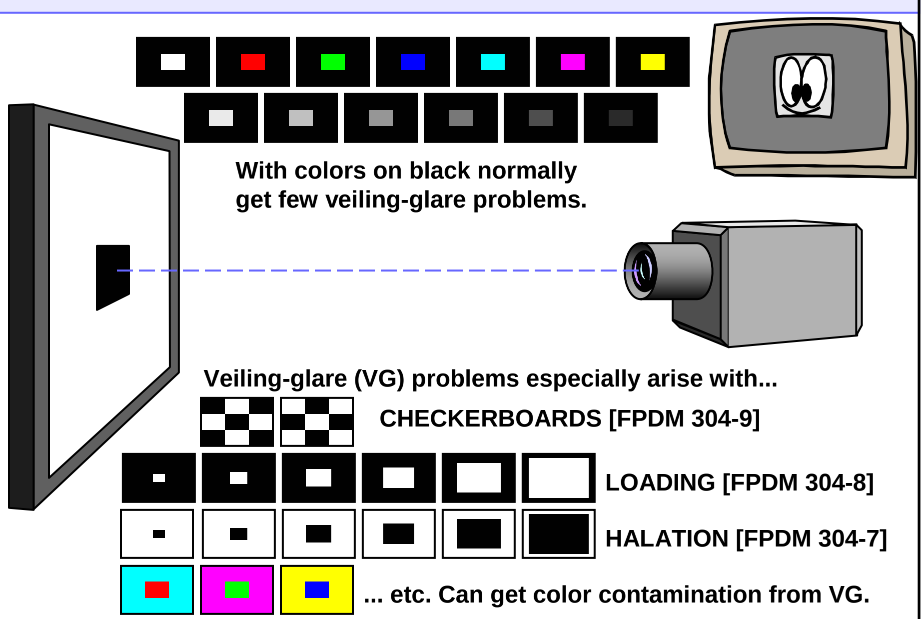


If screen refreshes (as with a CRT) and it is bright so that the detector uses a short integration time, can get measurement errors from the light of ±1 frame. Average many measurements or use good (and calibrated) neutral density filter to reduce luminance.



Same measurement window in both cases, but depending upon when the measurement is made, a relative deviation of up to 20% (or 25%) can be seen in this case.

Box Measurements

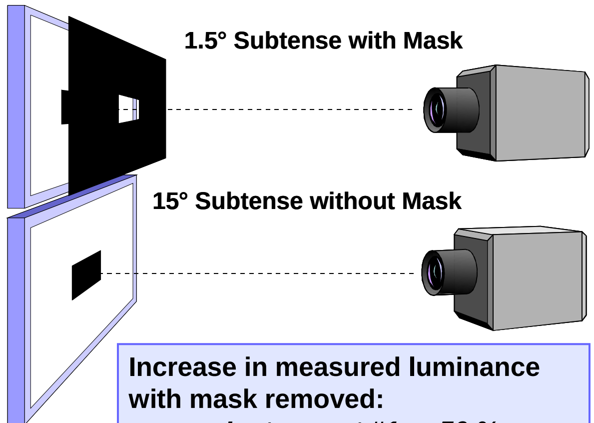


[FPDM 304-1 through 304-11]

Veiling Glare Can Affect Box Measurements

Measurement of Black Rectangle on White

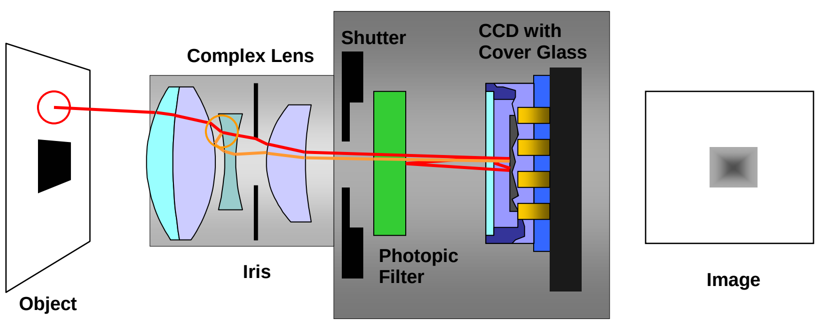
This shows how important it is to anticipate veiling glare in the detection system. Same screen with & without mask (1.5° mask hole, 15° vertical angular diameter of white area from lens of detector)



Increase in measured luminance with mask removed:

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

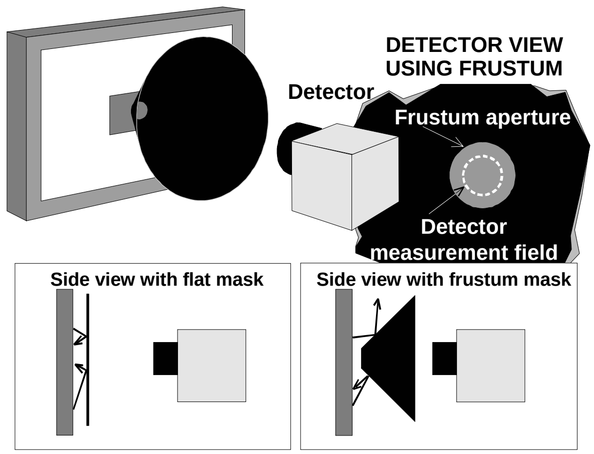
Veiling Glare – Stray Light Within Detector



Reflection off of internal lens structure

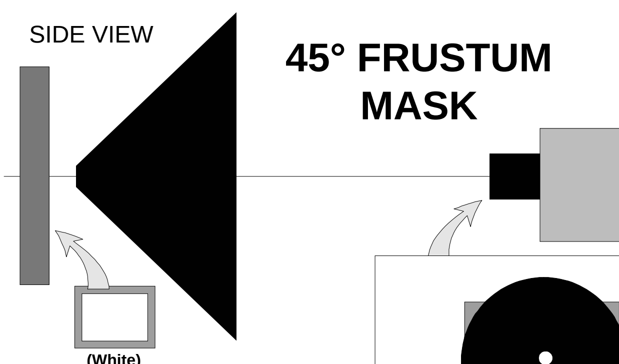
Reflection between lens surfaces

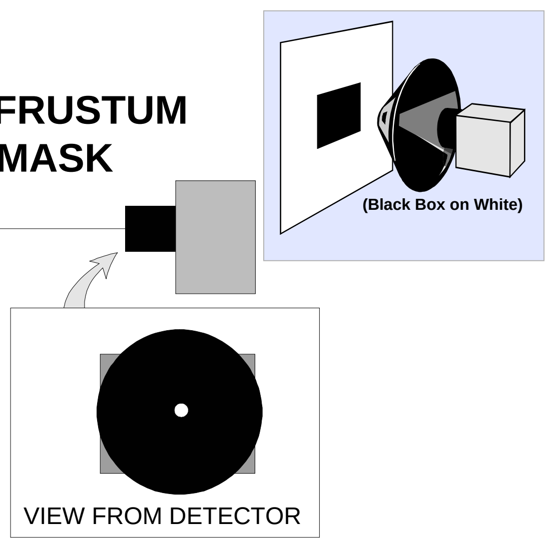
Use of Masks — Flat and Frustum



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

45° FRUSTUM MASK



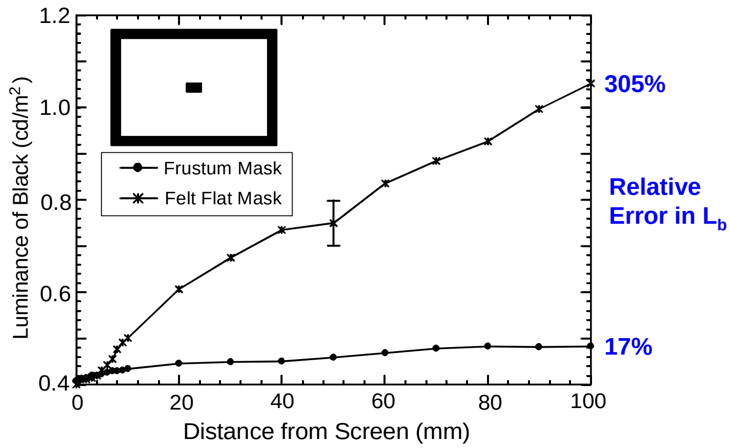


Gloss black plastic frustum minimizes light reflecting back onto screen also minimizes light from rest of screen reaching lens.

Frustum Mask Compared to Flat Mask

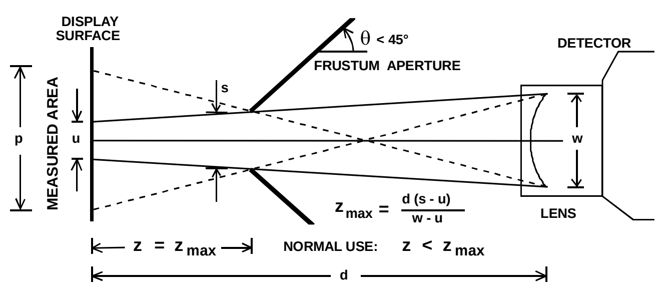
Only if the flat mask is placed very near or on the surface of the FPD screen can it compare with the frustum mask. (CRTs have thick glass faceplates.)

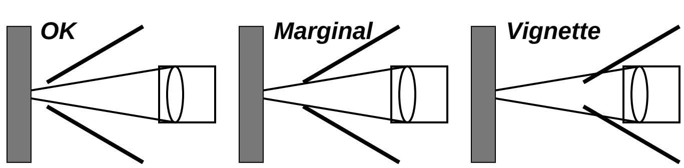
NOTE: Flat mask near or on screen may cause heating; can also mechanically corrupt luminance when touching the screen especially for soft LCD screens.



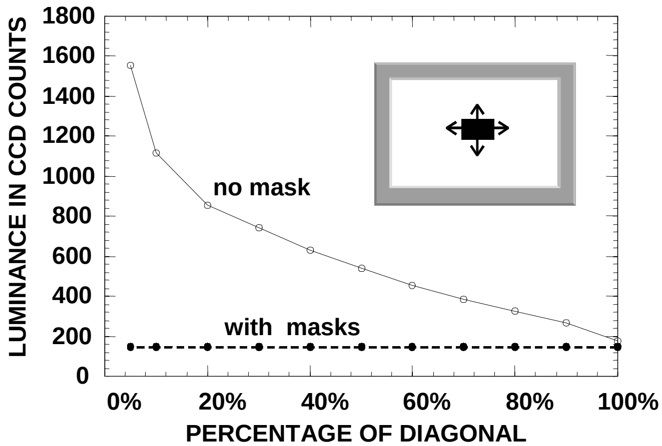
Avoid Vignette (vin-yet´) from Mask

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).

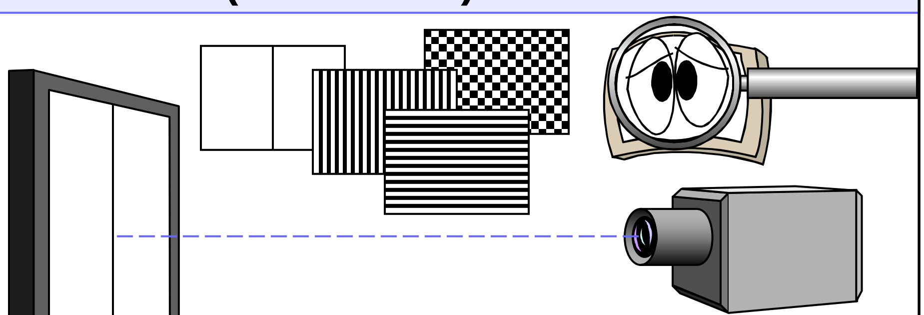




Halation — With and Without Masks (LCD Display)



Detail (Small-Area) Measurements



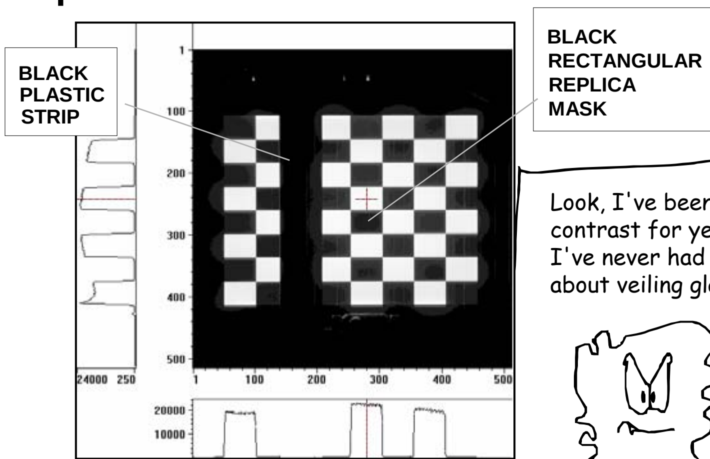
Veiling-glare often presents a VERY serious impediment to obtaining accurate measurements of small dark areas amid bright regions.

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

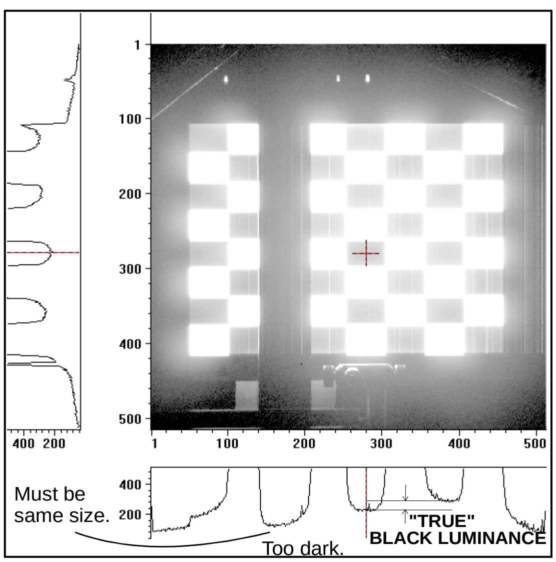
[FPDM 303-1, 2, 3, 5, 6, 7]

Replica Masks

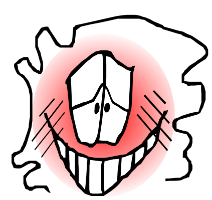


RUSTIC METROLOGY

Replicas, Same Size As Black Region

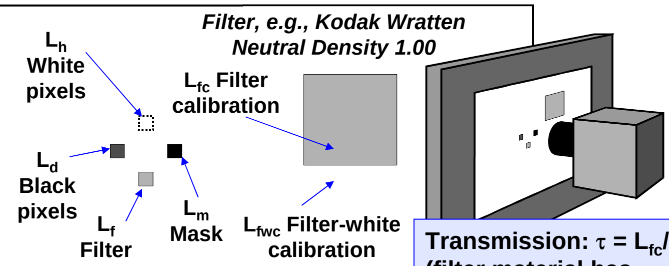


Replica masks must be close to (+0%, -10 %) the size of the black area to be measured.



Um... The contrast of the display went up a factor of ten when we used a replica mask. Um... have you sent those results out yet???

Replica Mask with Diagnostic Filter Mask



Corrected white: $L_W = L_h - L_m$

Corrected black: $L_K = L_d - L_m$

Contrast: $C = L_W / L_K$

Transmission: $\tau = L_{fc}/L_{fwc}$ (filter material has temperature dependence). *Use frustum mask to measure luminances here in a uniform part of screen.*

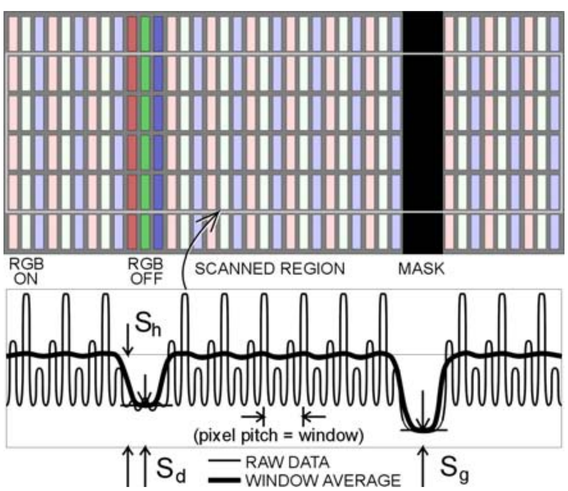
Check: Does $(L_f - L_m)/L_W = \tau$???

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 more) covering any line or area you wish to measure. Don't be stingy!

Note

Line Replica Mask for Line & Grille Contrast Measurements



Line contrast is:

$$C = \frac{S_h - S_g}{S_d - S_g}$$

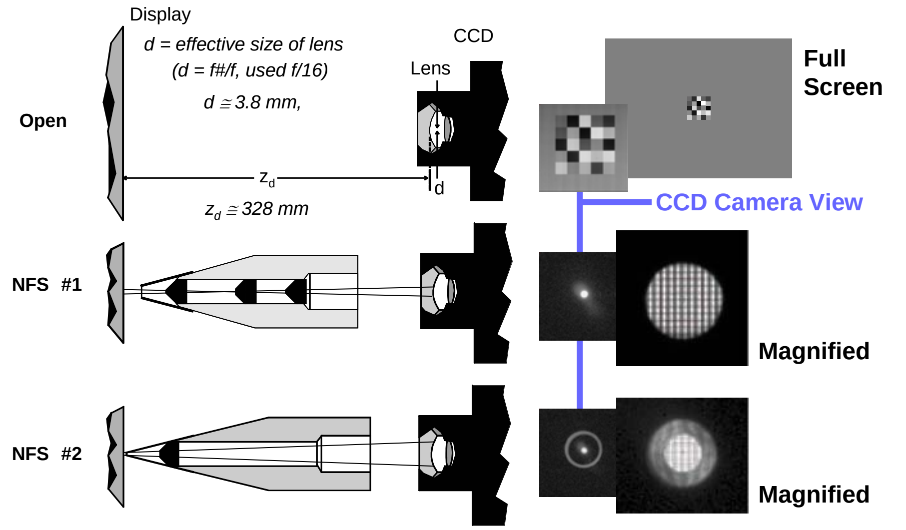
Line mask material can be obtained from graphic-arts supply stores (black charting tape), black hair, black nylon thread, or cut from black plastic sheets. We can also cut a very narrow slightly tapered wedge of black opaque plastic and measure S_g across the part with the appropriate width.)

S_g is the veiling glare corruption.

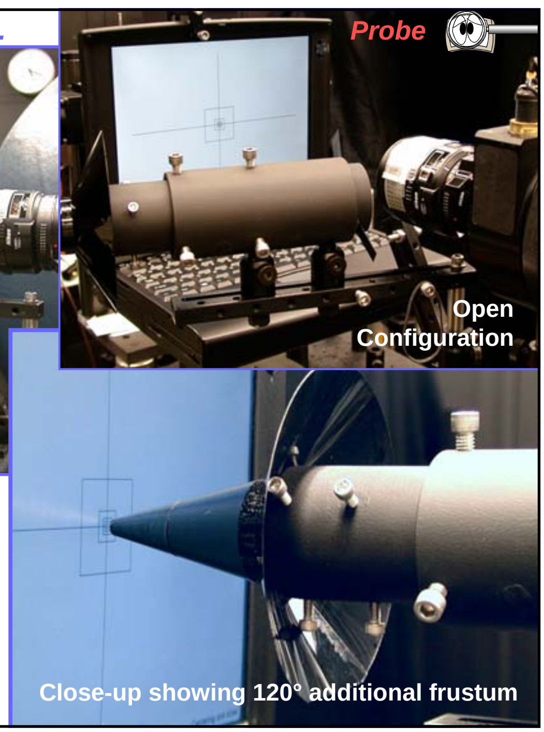
S can be a measured area or the moving window-averaged signal (proportional to luminance) as from a CCD camera.

Narrow Frustum SLET (NFS) or Probe

SLET = Stray Light Elimination Tube



Credit: A. Badano and M. J. Flynn, "Method for measuring veiling glare in high performance display devices," Applied Optics, Vol. 39, No. 13, pp. 2059-2066, May 2000.



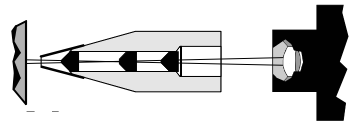
NFS with additional frustum to prevent reflections from apparatus.

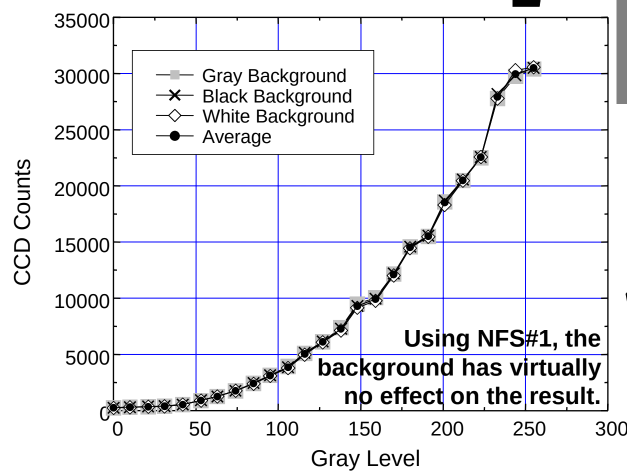
Small Area Measurements, Cont.

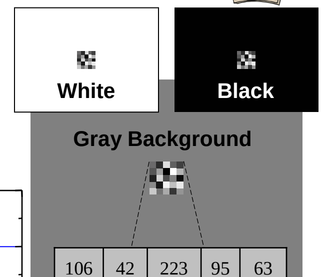
Probe

Effects of background change on NFS#1 results

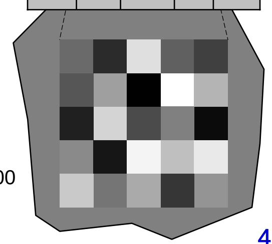
NFS#1







106	42	223	95	63
85	159	0	255	180
31	212	74	127	10
138	21	244	191	233
201	116	170	53	148



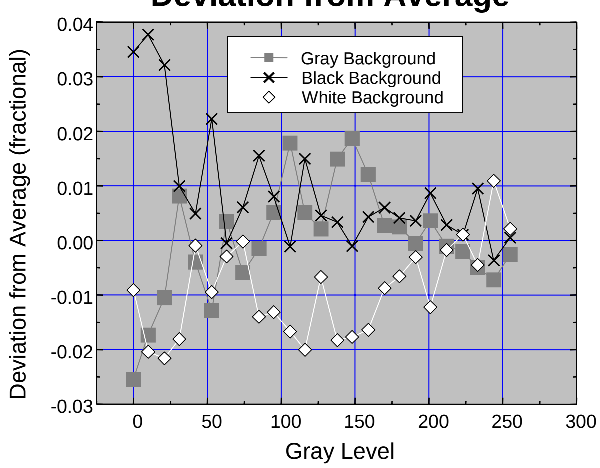
Small Area Measurements, Cont.

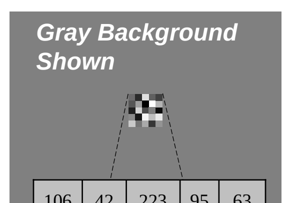
Probe

Effects of background change on NFS#1 results

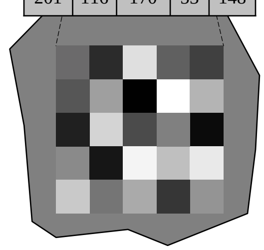
CONCLUSION: The FPD is working well with no profound cross-coupling or shadowing. Everything stays within ±4% of average.

Deviation from Average

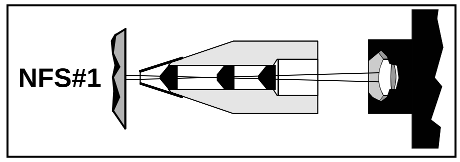


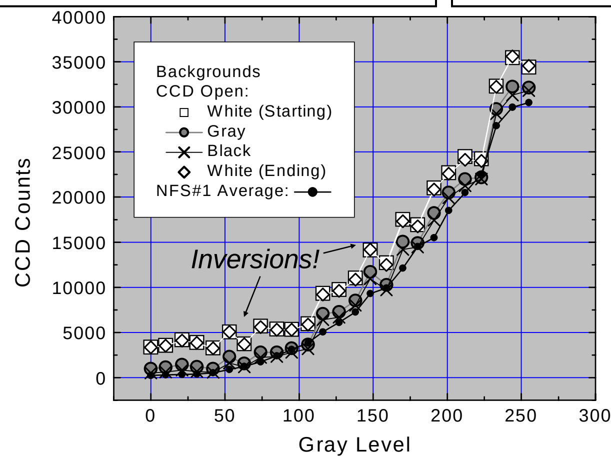


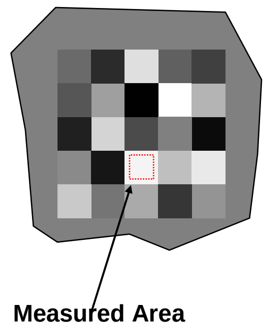
106	42	223	95	63
85	159	0	255	180
31	212	74	127	10
138	21	244	191	233
201	116	170	53	148



Effects of background change on NFS#1 results vs. Open

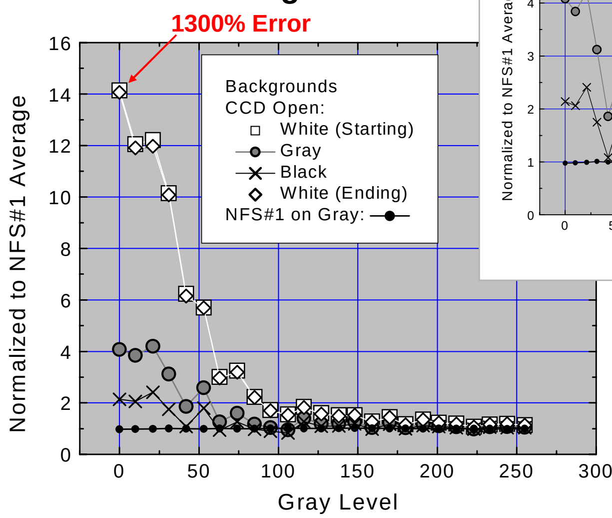


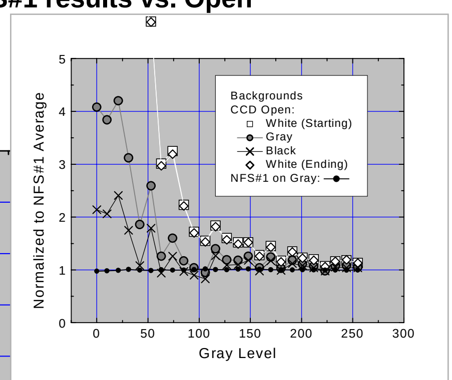


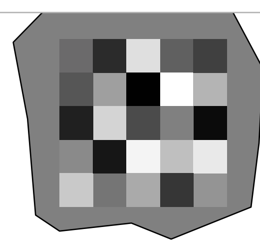


Effects of background change on NFS#1 results vs. Open

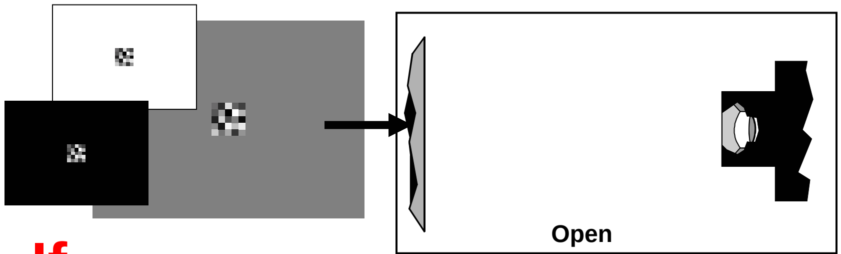
Data Normalized to NFS#1 Average





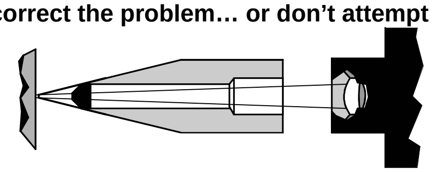


EXPECTATIONS TO HIGH??? !!!!

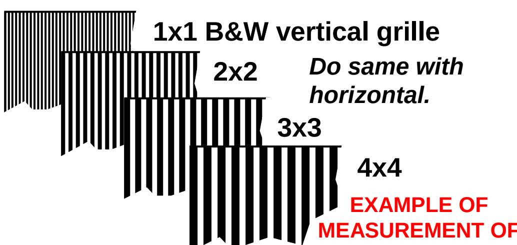


If a ≅1000% error (without using a SLET or frustum) in measuring dark areas amidst a white screen **shocks** us… then our expectations are too high! We don't understand the limitation of our equipment, and our use of it with impunity can yield disastrous results.

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

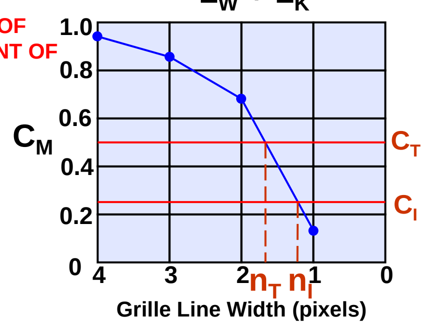


Effective Resolution — From Grille Measurements



THRESHOLDS
For text, e.g., $C_T = 0.5$
For images, e.g., $C_I = 0.25$

$$C_M = \frac{L_W - L_K}{L_W + L_K}$$

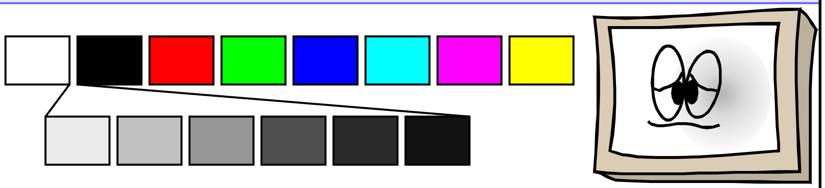


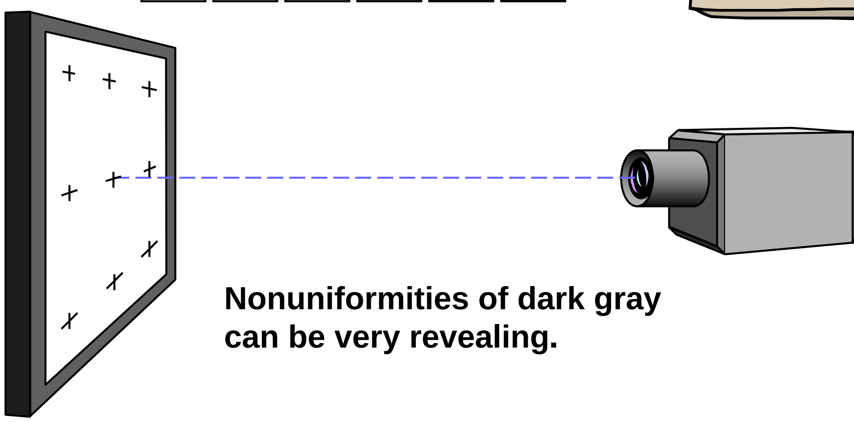
- Measure L_K and L_W accurately for each grille
- Calculate Michelson contrasts (contrast modulation)
- Determine intercepts n, n_T & n_I
- $$\text{Eff. Res.} = \frac{\#\text{ Pixels (H or V)}}{n}$$

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 corruption in making MTF measurements.

[FPDM 303-7]

Uniformity Measurements



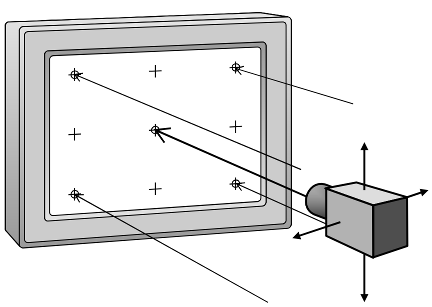


Nonuniformities of dark gray can be very revealing.

[FPDM 306-1 through 306-6]

Uniformity Measurements, Cont.

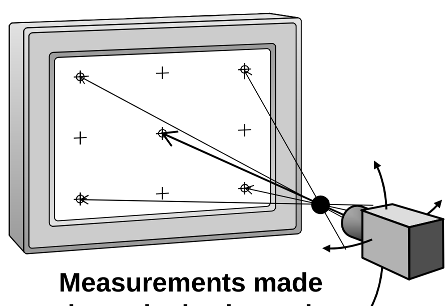
Viewing Point Location



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).



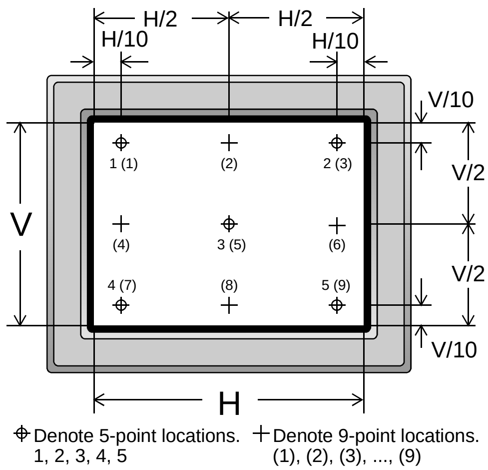
Measurements made through viewing point

[FPDM 306-1 through 306-6]

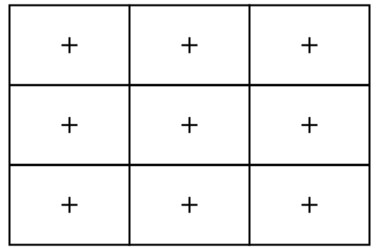
Uniformity Measurements, Cont.

Sampled Uniformity Measurement Points

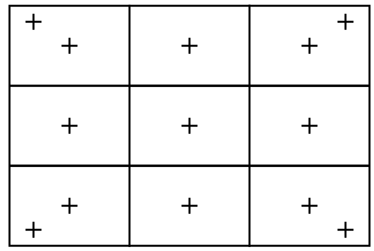
9-point, 25-point, 13-point, 9-point centered in 3x3 matrix, etc.



VESA locations (10 % corners)



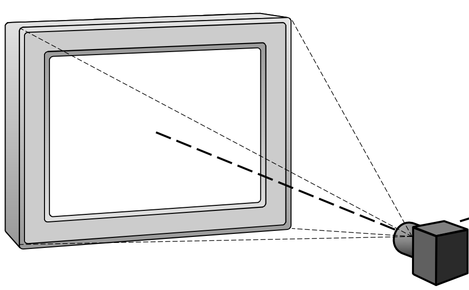
9 – pt centered in 3x3 matrix



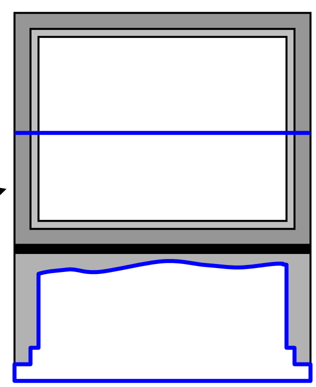
13 – pt ANSI (5 % corners)

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

Photopic Response

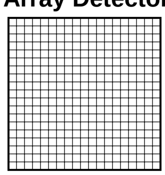
Sensitivity to IR can seriously corrupt what was intended to be a luminance measurement. These filters can be expensive (from $500 to $1000 [US] or more).

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!!

Array Detector



Raw pixel output: R_{ij}

Background (no light): B_{ij}

Flat-field correction: F_{ij}

<u>Final signal</u>: $S_{ij} = F_{ij}(R_{ij} - B_{ij})$

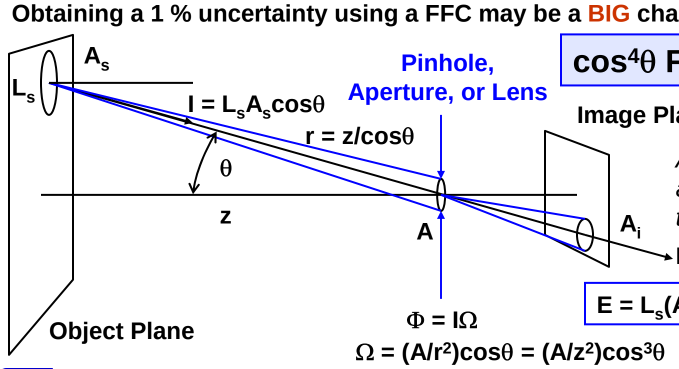
The flat-field correction (FFC) attempts to correct for

- **pixel-to-pixel sensitivity nonuniformty**
- **$1/\cos^4\theta$ falloff 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.

$\cos^4\theta$ Falloff

Boring Alert



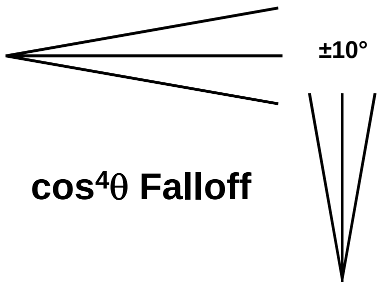
Assuming no attenuation by the lens.

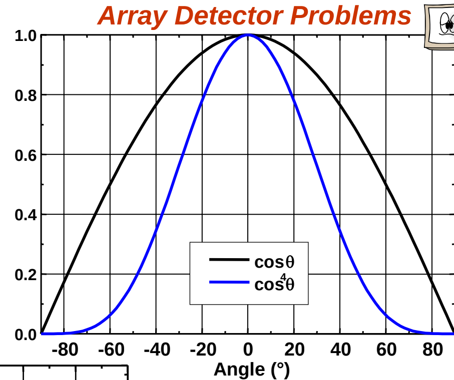
$$E = L_s(A_s/A_i)(A/z^2)\cos^4\theta$$

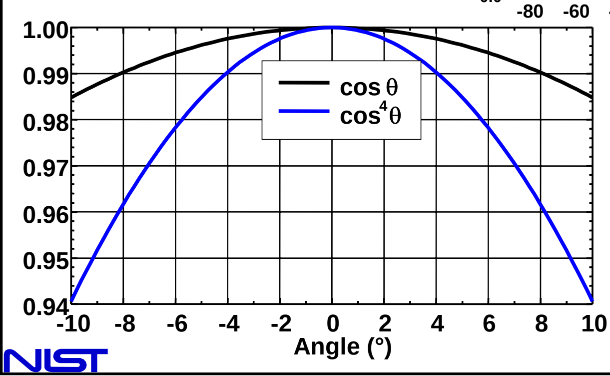
$$\Phi = I\Omega$$

$$\Omega = (A/r^2)\cos\theta = (A/z^2)\cos^3\theta$$

$\cos^4\theta$ Falloff

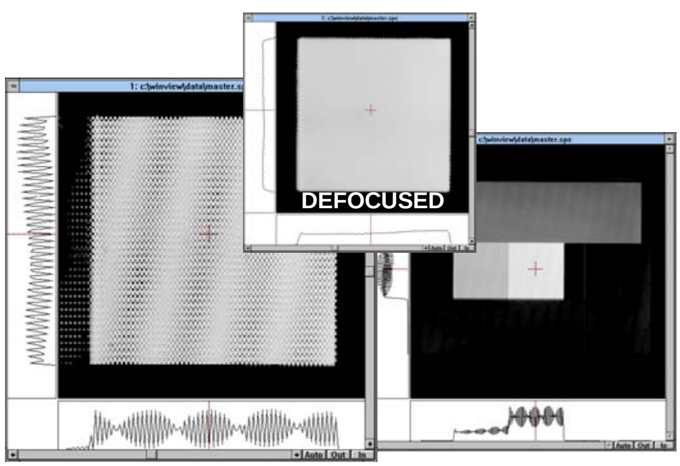




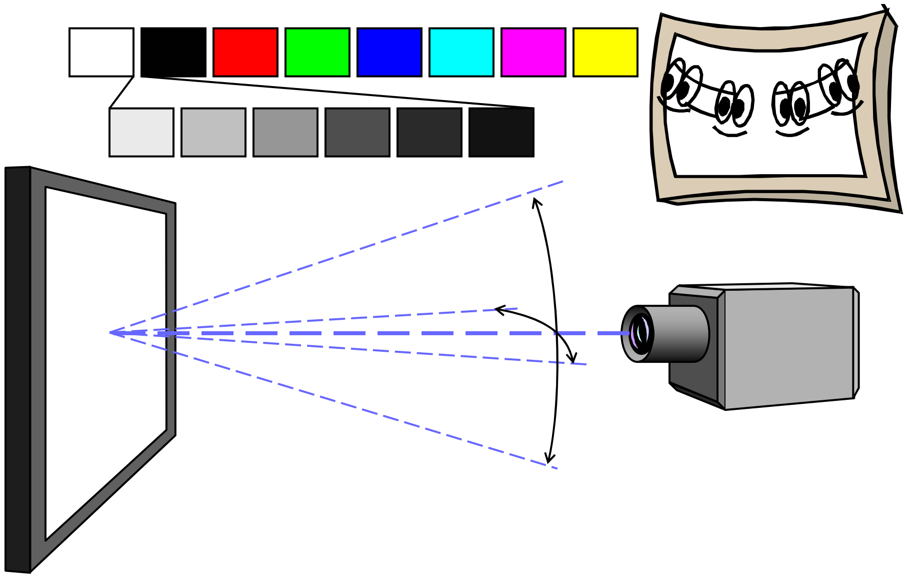


1° = width of little finger at arm's length or width of thumbnail at arms length (calibration required before use!).
½° = sun, moon angular diameter.

Spatial Aliasing (Moiré Patterns)



Viewing Angle Measurements

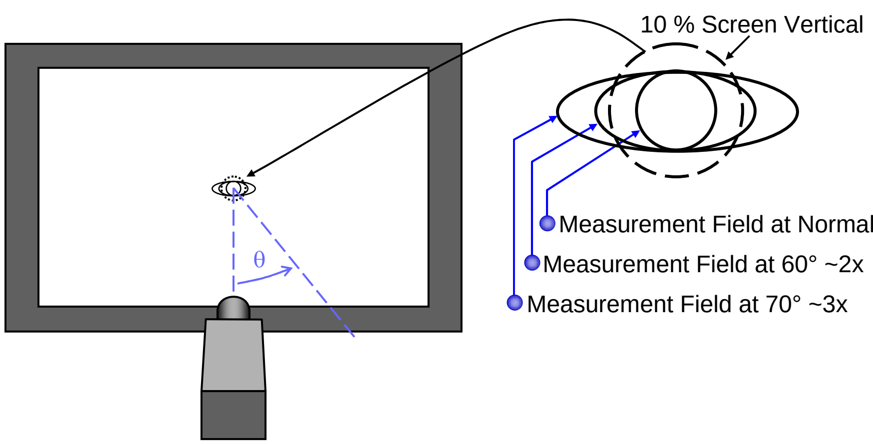


[FPDM 307-1 through 307-6]

Viewing Angle Measurements, Cont.

Measurement Field Size Changes with Angle

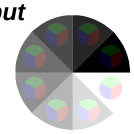
One problem is that the size of the spot measured with common detector increases as 1/cosθ with angle θ from the normal. Causes a violation of measuring less than 10 % of the screen. Oh well… Difficult to improve, but probably not important for most applications.

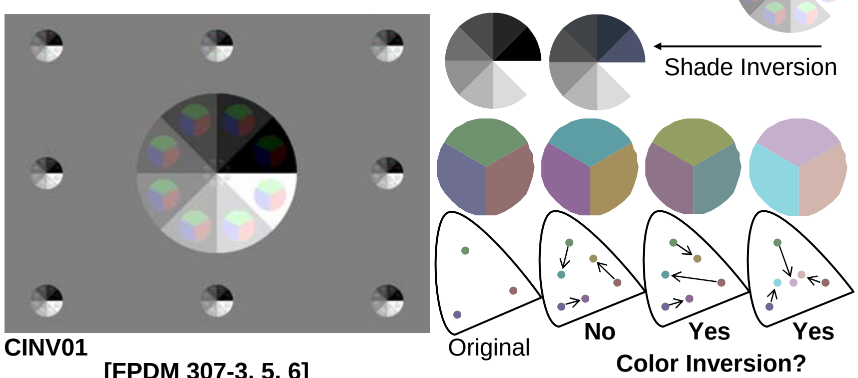


[FPDM 307-1 through 307-6]

Viewing Angle Measurements, Cont.

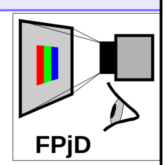
- **A color inversion chart is helpful in identifying location of viewing angle properties, otherwise a great deal of data must be collected to characterize the screen fully:**
  - ***Inversions (or reversals, where the gray shades cross over or color triads invert)***
  - ***Confluences (tangency or convergence, coming together but not crossing, color triad collapses to a line)***
  - ***Close approaches for both gray shades and colors***





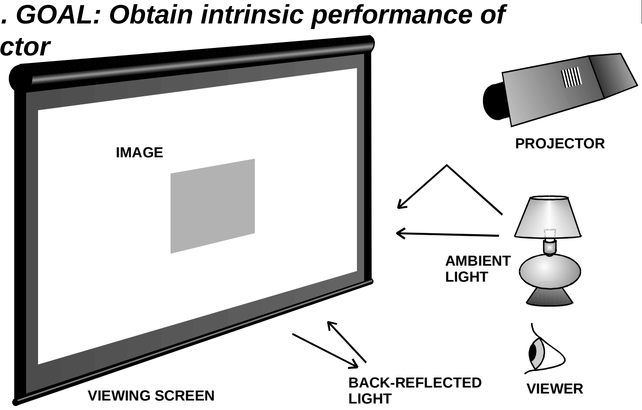
[FPDM 307-3, 5, 6]

Front Projection & Stray Light



Accounting for Stray Light

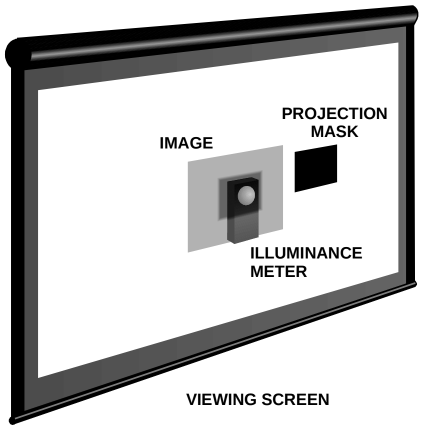
Projector should not be blamed for the less than perfect viewing conditions of the screen and room. GOAL: Obtain intrinsic performance of projector

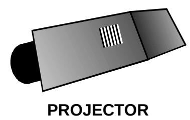


Even in a black-walled darkroom using a black screen with a checkerboard displayed, significant errors of several tens of percent can be made if we are not careful.

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!



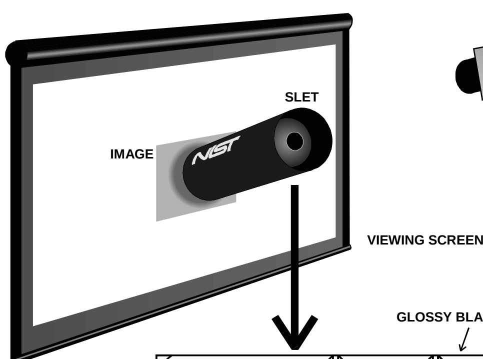


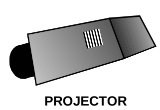
Illuminance measured behind the mask must be subtracted from the measurement without the mask to obtain an accurate measurement of black or white.

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

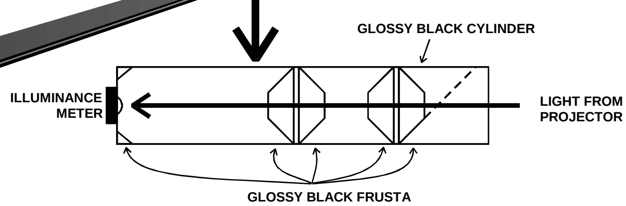
Stray-Light Elimination Tube (SLET)

Can permit accurate measurements even in high-ambient lighting.



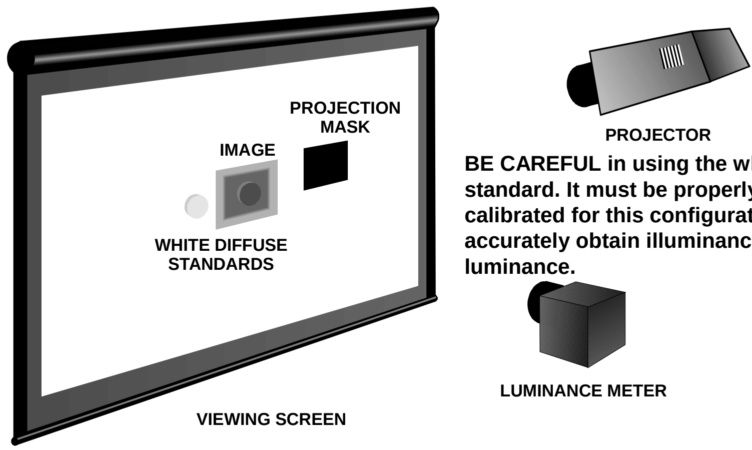


Can permit accurate measurements even in high-ambient lighting.



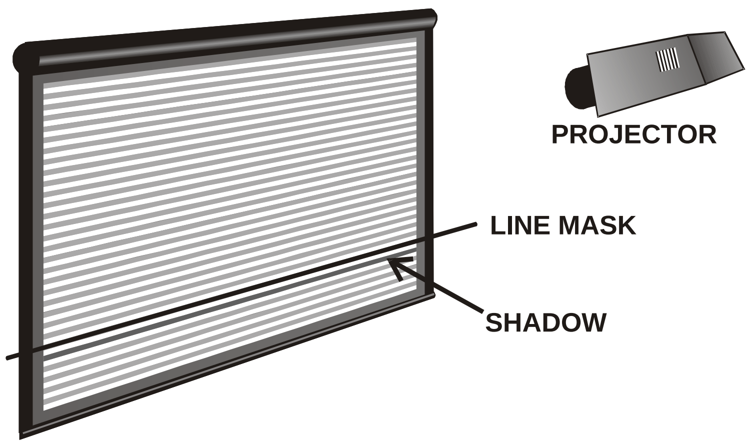
Making Luminance Measurements

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



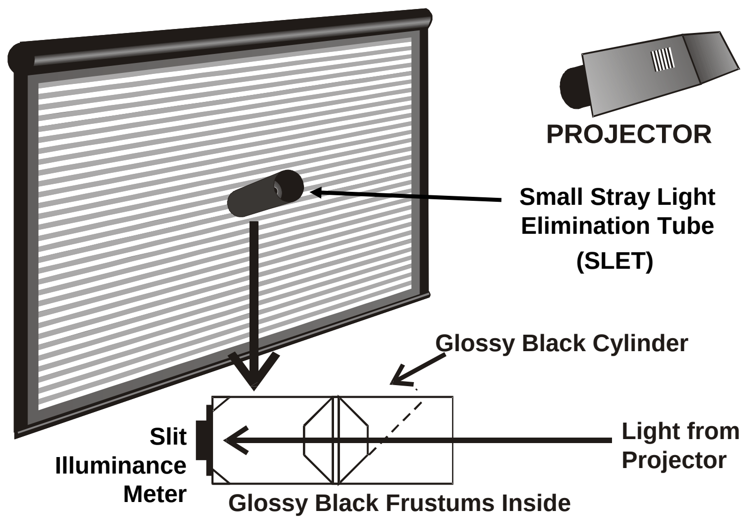
BE CAREFUL in using the white standard. It must be properly calibrated for this configuration to accurately obtain illuminance from luminance.

Grille Measurements to Establish Resolution



[See FPDM 303-7: Resolution from Contrast Modulation]

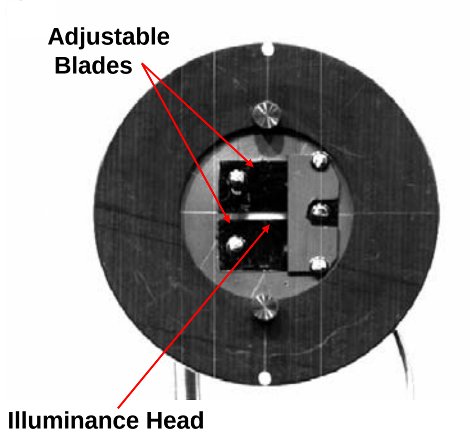
Direct Measurement Using Slit Illuminance Meter

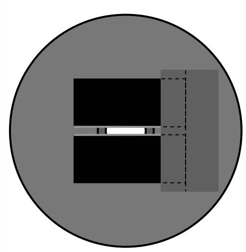


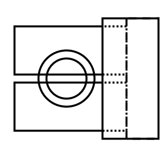
Front Projection & Stray Light, Cont.

Slit Illuminance Meter

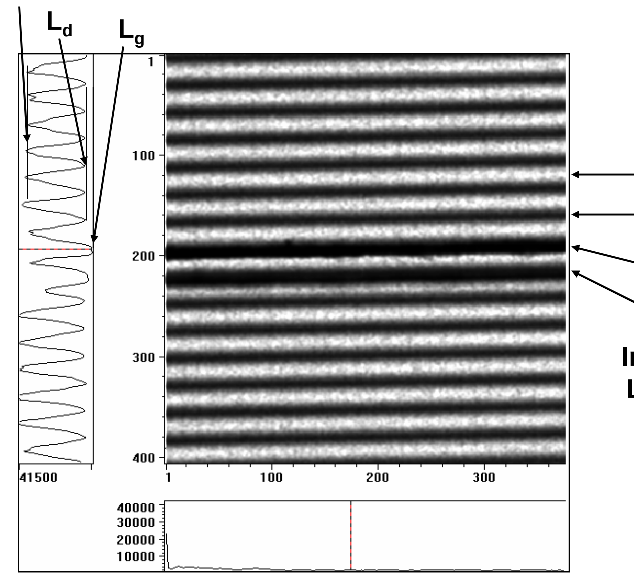
Small illuminance head placed behind razor-blade adjustable slit with razor blades painted gloss black. Unit mounts on back of small SLET.







CCD Photograph of Grille Pattern with Line-Mask Shadow



Intrinsic Projector Line Luminances

$L_W = L_h - L_g$

$L_K = L_d - L_g$

Grille Contrast

$C_g = L_W/L_K$

Reflection Terminology & Standards

Canonical Reflection Terminology

- **Reflectance Factor *R***
- **Uniform Diffuser, Perfect Reflecting Diffuser**
- **Reflectance** ρ
- **Luminance Factor** β
- **Diffuse Reflectance** ρ_d **(we will extend:** $\rho_d = \rho_L + \rho_H$ **)**
- **Specular Reflectance** ζ **(CIE uses "regular" and** ρ_r**)**

Helpful Notation: source/detector subscripts

Specify angle θ ***in degrees or use "d" for diffuse (can also use "di" for diffuse with specular included and "de" for diffuse with specular excluded [letting it out through a hole], if needed).***

Examples: $R_{d/8}$, $R_{45/0}$, $\rho_{d/45}$, $\rho_{45/d}$, $\rho_{45/di}$, $\rho_{45/de}$, $\beta_{d/10}$, $\beta_{45/0}$, $\beta_{0/45}$

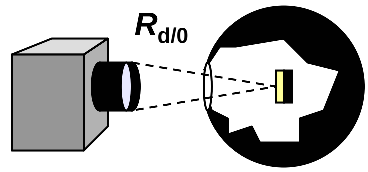
References: CIE Publication #17.4, #46, & #44

Reflection Terminology & Standards, Cont.

Reflectance Factor *R*:

Ratio of the reflected flux from the material within a specified detection cone to the flux that would be reflected from a perfect (reflecting) diffuser (perfectly white Lambertian surface) under the same specified illumination:

$$\mathbf{R} = \left(\frac{\Phi_{\text{material}}}{\Phi_{\text{perfect diffuser}}} \right)_{\text{Cone}} \Bigg|_{\text{For Specified Illumination Conditions}}$$



CIE 17.4: 845-04-64 "reflectance factor [*R*] (at a surface element, for the part of the reflected radiation contained in a given cone with apex at the surface element, and for incident radiation of given spectral composition, polarization and geometrical distribution)

Ratio of the radiant or luminous flux reflected in the directions delimited by the given cone to that reflected in the same directions by a perfect reflecting diffuser identically irradiated or illuminated. *Notes*

1. — For regularly reflecting surfaces that are irradiated or illuminated by a beam of small solid angle, the reflectance factor may be much larger than 1 if the cone includes the mirror image of the source.
2. — If the solid angle of the cone approaches 2π sr, the reflectance factor approaches the reflectance for the same conditions of irradiation.
3. — If the solid angle of the cone approaches zero, the reflectance factor approaches the radiance or luminance factor for the same conditions of irradiation.**"**

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 illuminance E, L = qE, where q (luminance coefficient) is a constant. It obeys Lambert's law $I = I_0\cos\theta$***, where I is the luminous intensity,*** I_0 ***is the luminous intensity in the direction of the normal of the surface, and*** θ ***is the angle from the normal.***

Perfect reflecting diffuser:

Perfectly white uniform diffuser such that $L = E/\pi$***, 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.'

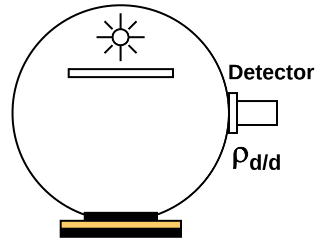
CIE 17.4: 845-04-54 "**perfect reflecting diffuser**

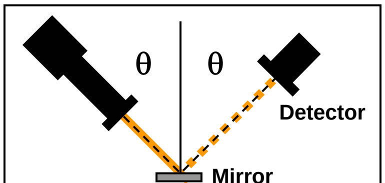
Ideal isotropic diffuser with a reflectance equal to 1."

Reflectance ρ :

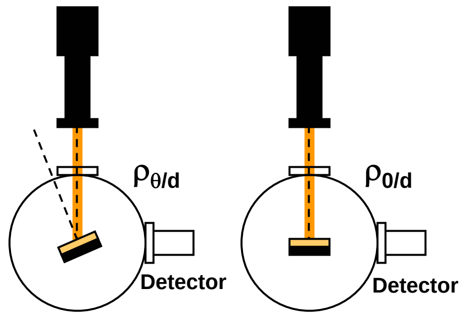
Ratio of the reflected flux to the incident flux for a given geometry of source and detector:

$$\rho = \left.\frac{\Phi_r}{\Phi_i}\right|_{\text{Apparatus Geometry}}$$





Specular reflectance (defined later)



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

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

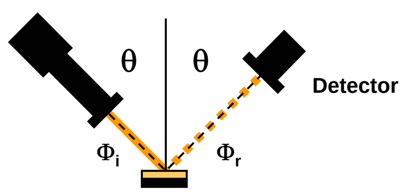
Specular Reflectance ζ: (ζ is notation used here)

(CIE: Regular Reflectance ρ_r)

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

$$\zeta = \left.\frac{\Phi_r(\text{specular})}{\Phi_i}\right|_{\text{Apparatus Geometry}}$$

NOTE: CIE uses symbol ρ_r and calls it “regular reflectance.” We use ζ to avoid confusion of subscripts.



CIE 17.4: 845-04-60 “**regular reflectance** (ρ_r) unit: 1

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

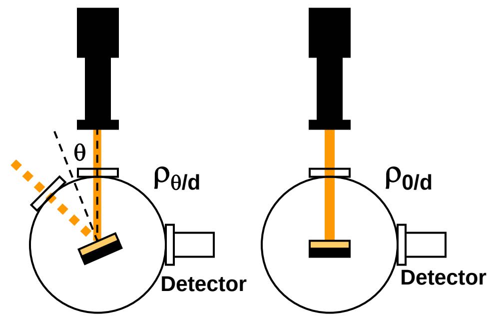
CIE 17.4: 845-04-45 “**regular reflection; specular reflection**

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

Diffuse Reflectance ρ_d :

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

$$\rho_d = \left. \frac{\Phi_r(\text{diffuse})}{\Phi_i} \right|_{\text{Apparatus Geometry}}$$



CIE 17.4: 845-04-62 "**diffuse reflectance** (ρ_d)

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

Notes 1. — $\rho = \rho_r + \rho_d$

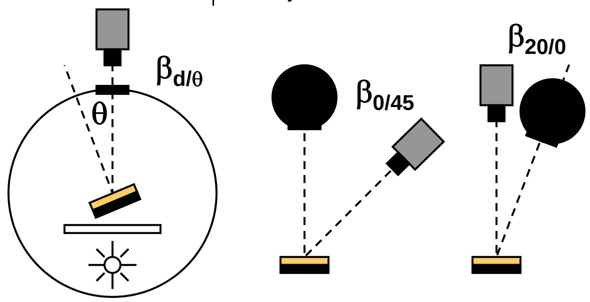
2. — The results of the measurements of ρ_r and ρ_d depend on the instruments and the measuring techniques used."

Luminance Factor β :

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):

$$\beta = \left. \frac{\pi \mathbf{L}}{\mathbf{E}} \right|_{\text{Apparatus Geometry}}$$

Note: luminance coefficient:
$q \equiv \beta / \pi$



Thus, the luminance factor β 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 R.

CIE 17.4: 845-04-69 "**luminance factor** (at a surface element of a non-self-radiating medium, in a given direction, under specified conditions of illumination) (β_v, β)

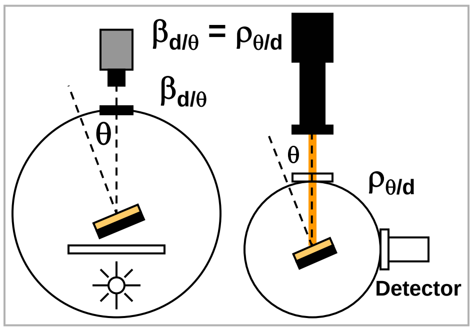
Ratio of the luminance of the surface element in the given direction to that of a perfect reflection or transmitting diffuser identically illuminated. Unit: 1"

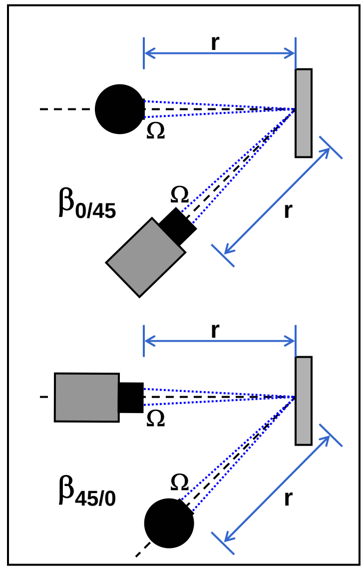
Reflection Terminology & Standards, Cont.

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 reflection measurement quantities:

Reflectance factor:

$$R = \Phi_r/\Phi_p = I\Omega_d/I_p\Omega_d =$$
$$= I/I_p = L/L_p = \pi L/E$$

Luminance factor:

$$\beta = L/L_p = \pi L/E$$

Reflectance:

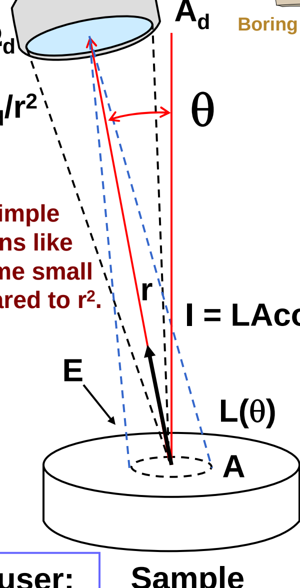
$$\rho = \Phi_r/\Phi_i = I\Omega_d/EA = LA\cos\theta\Omega_d/EA$$
$$= (L/E)\,\Omega_d\cos\theta$$

BRDF:

$B = L/E$ (B = BRDF, is covered below)

$$\Phi_d = I\,\Omega_d$$
$$\Omega_d = A_d/r^2$$

NOTE: Simple expressions like these assume small areas compared to r².



Perfect reflecting diffuser:
$L_p = E/\pi$ = constant

SUMMARY: Use Reflectance Factor R

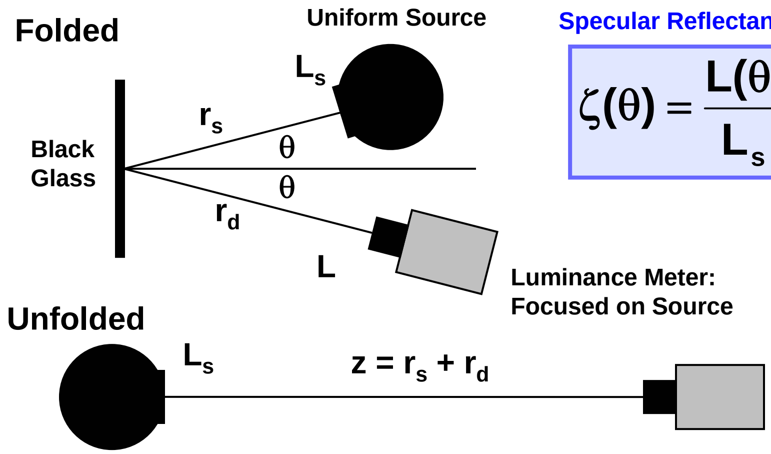
In general, reflection measurement experts tell me that we should be reporting the reflectance factor R in most cases. Then we specify the illumination geometry, the detector geometry, and the configuration of the angular aperture of the detector. However, the use of the reflectance ρ and the luminance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

$$R \to \beta \quad \text{for} \quad \Omega \to 0$$

$$\text{Diffuse: } R \to \rho \quad \text{for} \quad \Omega \to 2\pi$$

$$\text{Reciprocity} \quad \beta_{d/\theta} = \rho_{\theta/d}$$

Calibration of Black Glass



Specular Reflectance

$$\zeta(\theta) = \frac{L(\theta)}{L_s}$$

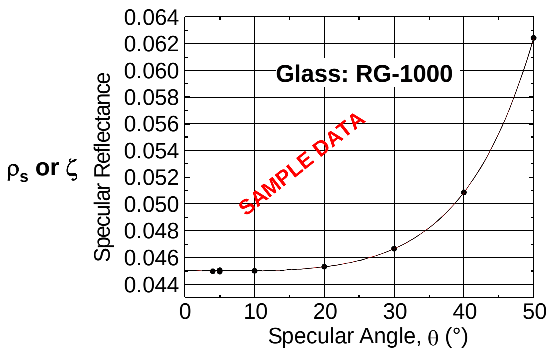
Luminance meter must measure the same region of the source at the same (unfolded) distance from the source to get L_s.

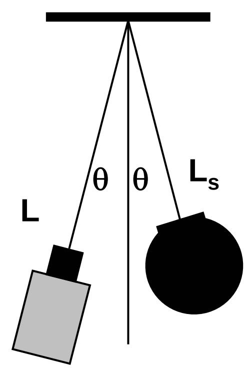
Note that how you clean the black glass can effect its reflectance.

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.

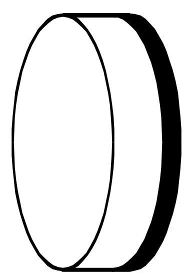




Sample data only for demonstration purposes.

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

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. $\rho_{d/0}$), quasi-Lambertian… BUT watch out!!! … What kind of reflectance is this 99% value???***

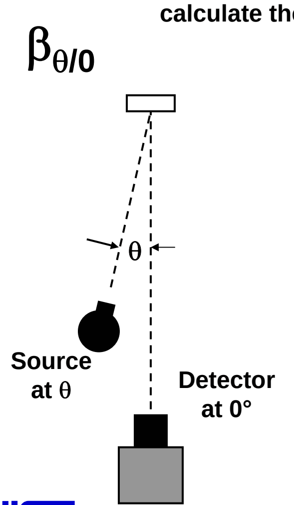
CAUTION: These are not perfectly Lambertian.

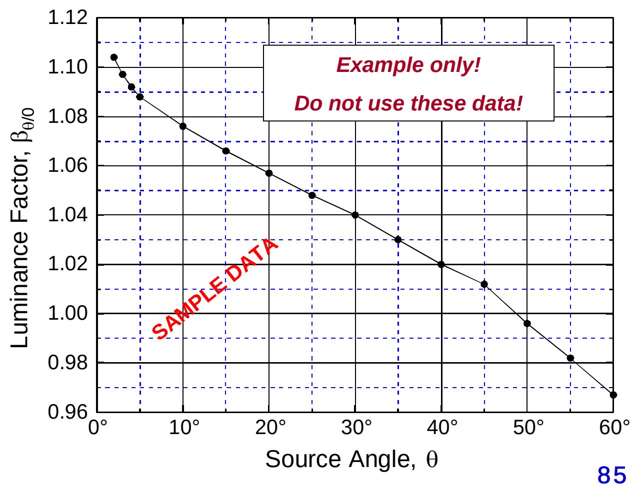
The reflectance (e.g., of 0.99) is obtained under specific conditions of illumination and reflected-light measurement (e.g., $\rho_{6/d}$ or $\rho_{d/0}$). The reflectance will not necessarily be the same for all angles and all configurations!!! If you need to use it for a certain configuration (other 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.

Luminance Factor of White Standard Example

Examples ONLY; don't use these results for your own purposes!!!

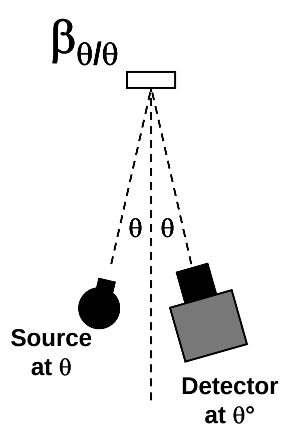
This shows that you cannot plop one of these in your apparatus, measure its luminance, assume a luminance factor of 0.99 and calculate the illuminance—it just isn't that simple.

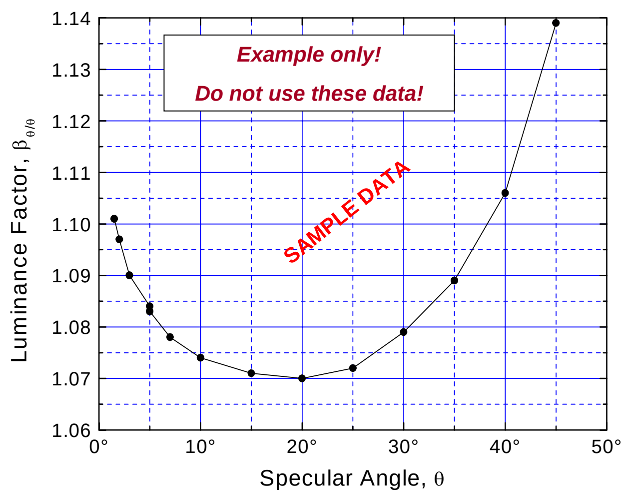




Example ONLY; don't use these results for your own purposes!!!

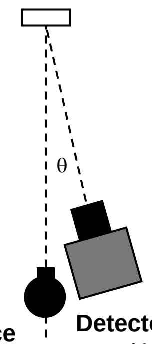
Specular configuration $\beta_{\theta/\theta}$ has very different characteristics from $\beta_{\theta/0}$ configuration.

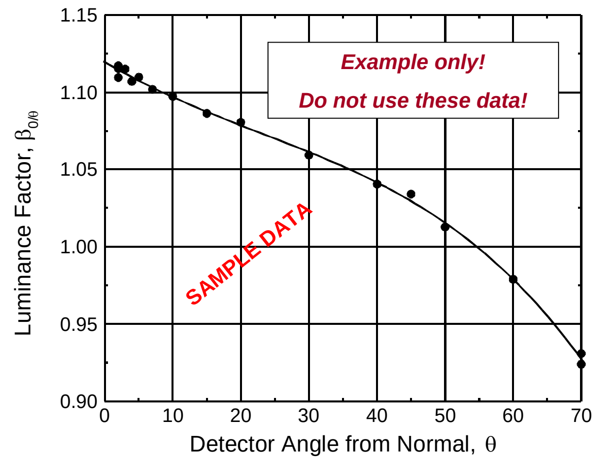




Example ONLY; don't use these results for your own purposes!!!

$\beta_{0/\theta}$



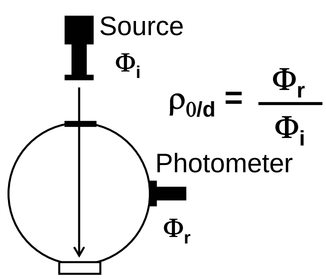


Reciprocity gives: $\beta_{0/\theta} = \beta_{\theta/0}$

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

Reciprocity permits two uses of the calibrated reflectance of a reflectance standard. For example…

Suppose the calibrated reflectance is ρ = 0.99 (or more precisely, $\rho_{d/0}$)

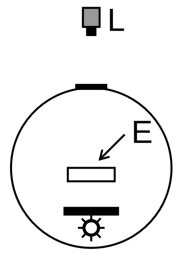


$$\rho_{0/d} = \frac{\Phi_r}{\Phi_i}$$

Then we can safely measure *E* from *L* using the luminance factor

$$\beta_{0/d} = 0.99$$

ONLY for the 0/d configuration.



$$E = \pi L / \beta_{d/0}$$

when sample is quasi-Lambertian

Don't use such a calibration in any other configuration unless you are certain. The basic lesson is: Geometry is often VERY important. With diffuse illumination (as above) angles off normal will provide the same results and are safe to use for our purposes.

Three-Component Model of Reflection

Oversimplified Models — Possible Ambiguity

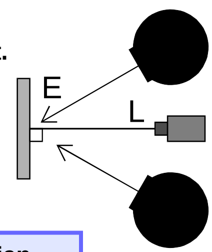
Lambertian ("Diffuse") component assumption:

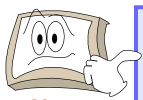
Display surface measured as if it were matte paint.

β = luminance factor, q = luminance coefficient,

E = illuminance, L = observed luminance.

$$L = qE = \frac{\beta}{\pi}E$$





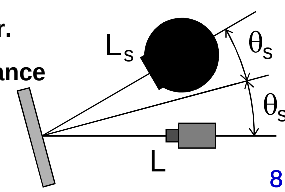
Strictly speaking this equation is for a Lambertian material; "diffuse" means scattered out of specular direction and is **not** limited to Lambertian materials.

Specular component assumption:

Display surface treated as if it were a mirror.

ζ = specular reflectance, L_s = source luminance

$$L = \zeta L_s$$

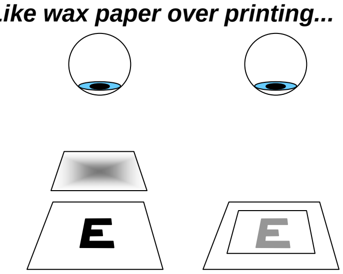


Oversimplified Model: Easy to Measure, Robust, IF OK

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...



Some FPDs allow diffusing surface close to pixels.

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 COMPONENTS OF REFLECTION FOR DISPLAYS

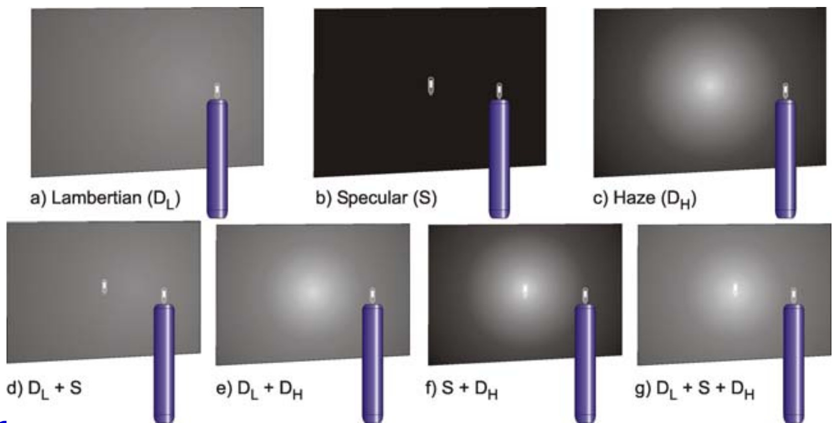
1. SPECULAR (producing a distinct virtual image of the source)

DIFFUSE (has TWO components):

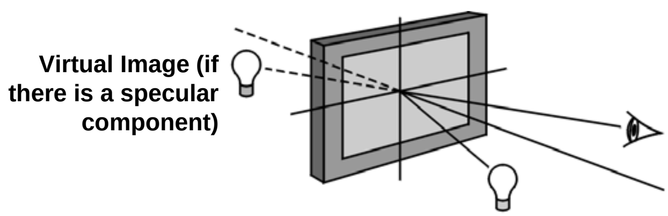
2. LAMBERTIAN (like matte paint)
3. HAZE (fuzzy ball in specular direction)

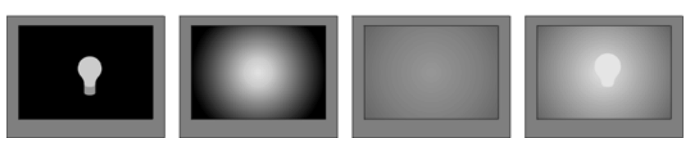
Note

Reflectance can be thought of as having three components: $\rho = \rho_L + \rho_S + \rho_H$, where the diffuse reflectance is $\rho_d = \rho_L + \rho_H$.

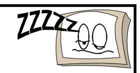


Specular, Lambertian, Haze

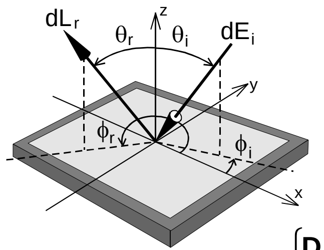




Specular Only | *Haze Only* | *Lambertian Only* | *All Three*



BRDF — Three Components:



Bidirectional Reflectance Distribution Function —A generalization of L = qE.

$$dL_r(\theta_r,\phi_r) = B(\theta_i,\phi_i,\theta_r,\phi_r;\lambda,p)dE_i(\theta_i,\phi_i)$$

We will drop the wavelength λ and polarization *p* dependence.

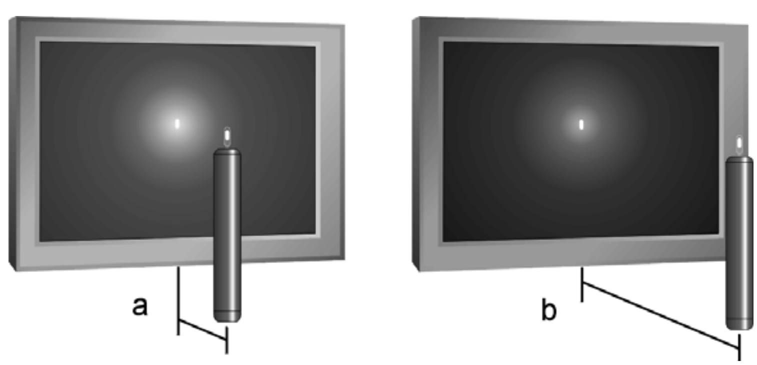
$$B = D_L + S + D_H \quad \begin{cases} D_L = q = \rho/\pi & \Rightarrow \text{Lambertian (perfectly diffuse)} \\ S = 2\zeta\delta(\sin^2\theta_r - \sin^2\theta_i)\,\delta(\phi_r - \phi_i \pm \pi) & \Rightarrow \text{Specular} \\ D_H = H(\theta_i,\phi_i,\theta_r,\phi_r) & \Rightarrow \text{Haze (diffuse)} \end{cases}$$

$$L_r(\theta_r,\phi_r) = qE + \zeta L_s(\theta_r,\phi_r \pm \pi) + \int_0^{2\pi}\int_0^{\pi/2} H(\theta_i,\phi_i,\theta_r,\phi_r)L_i(\theta_i,\phi_i)\cos(\theta_i)d\Omega.$$

dE, element of illuminance

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

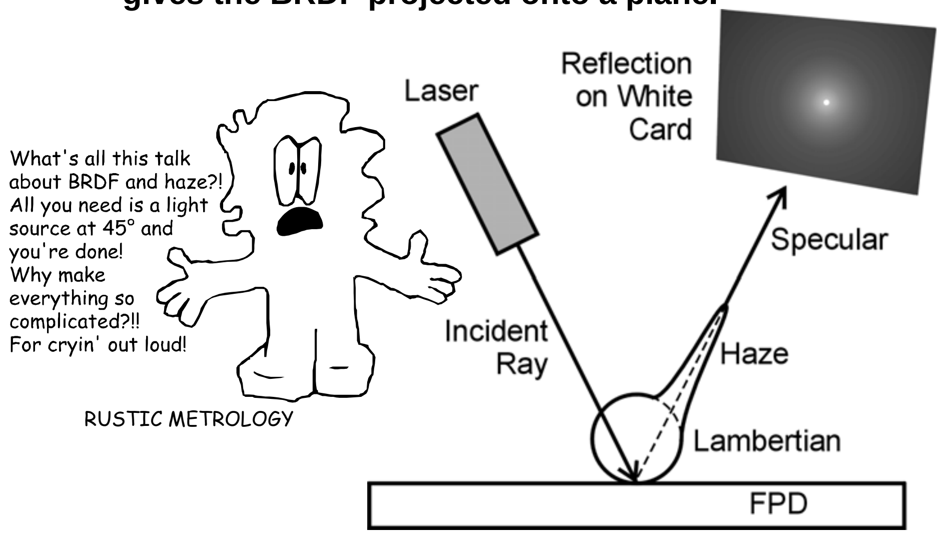
Like the Lambertian component, the haze is proportional to the illuminance; but like the specular component, it follows the specular direction.



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.

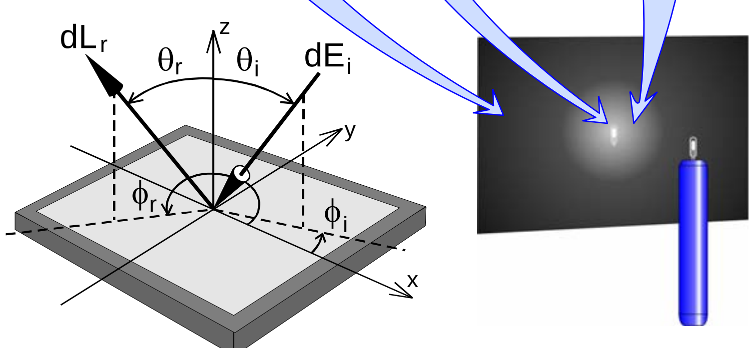


Three Component Reflection Model, Cont.

Observed Luminance **=** ***Lambertian Component*** **+** ***Specular Component*** **+** ***Haze Component***

$$L_r(\theta_r,\phi_r) = qE + \zeta L_s(\theta_r,\phi_r \pm \pi) + \int_0^{2\pi}\int_0^{\pi/2} H(\theta_i,\phi_i,\theta_r,\phi_r)L_i(\theta_i,\phi_i)\cos(\theta_i)d\Omega.$$

Background gray | **Distinct image** | **Fuzzy ball**



Remember that not all components must be present.

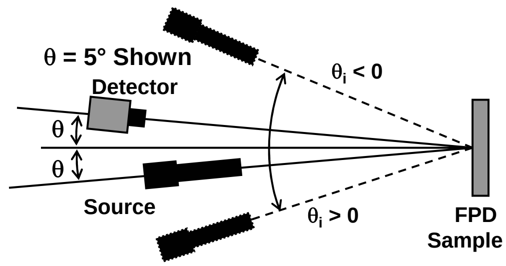
Simple BRDF (In Plane)

Extremes:

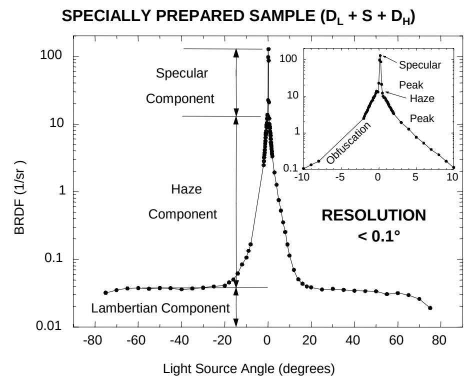
- **Lambertian (flat)**
- **Specular (spike)**
- **Haze is in between**

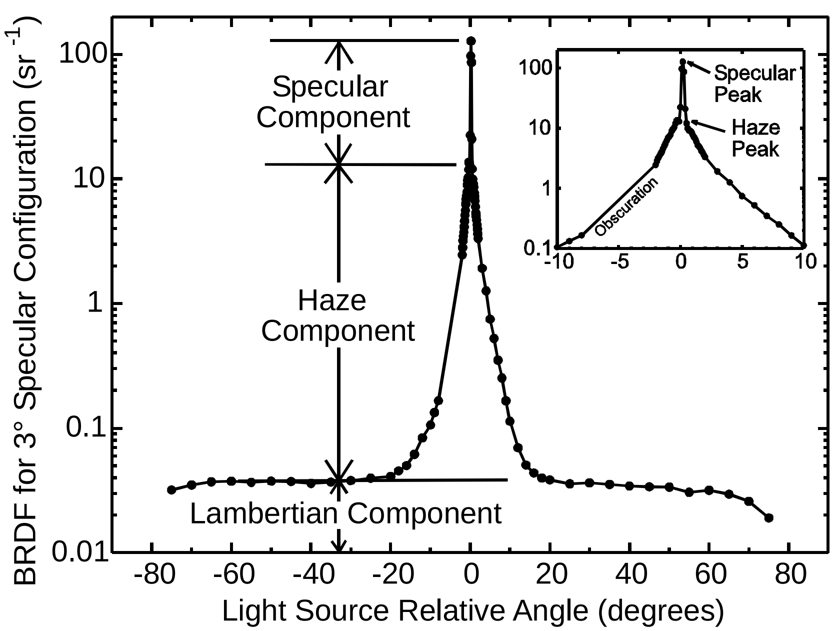
Haze characteristics:

- **Proportional to illuminance**
- **Directed in specular direction**

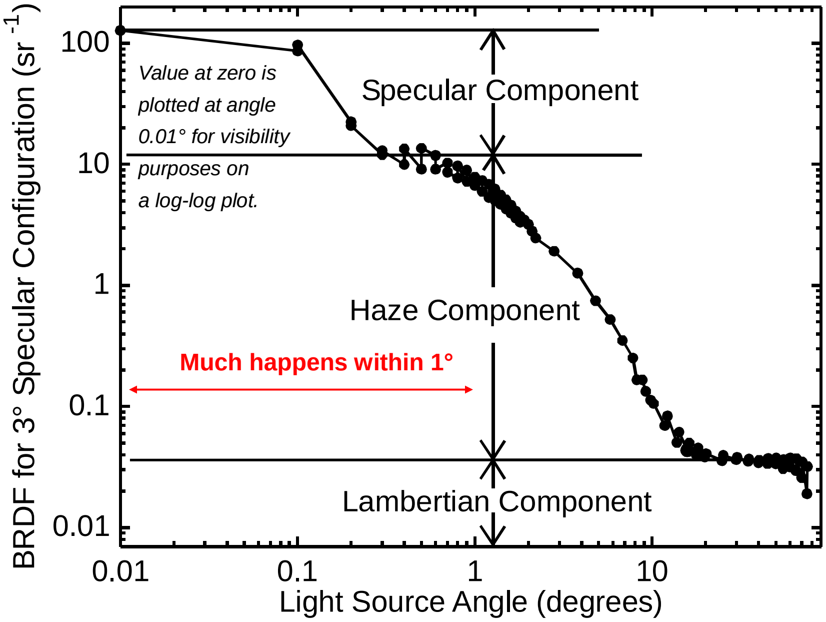


NOTE: 3 to 5 orders of magnitude possible (or more!—your eye has no trouble seeing this range!)



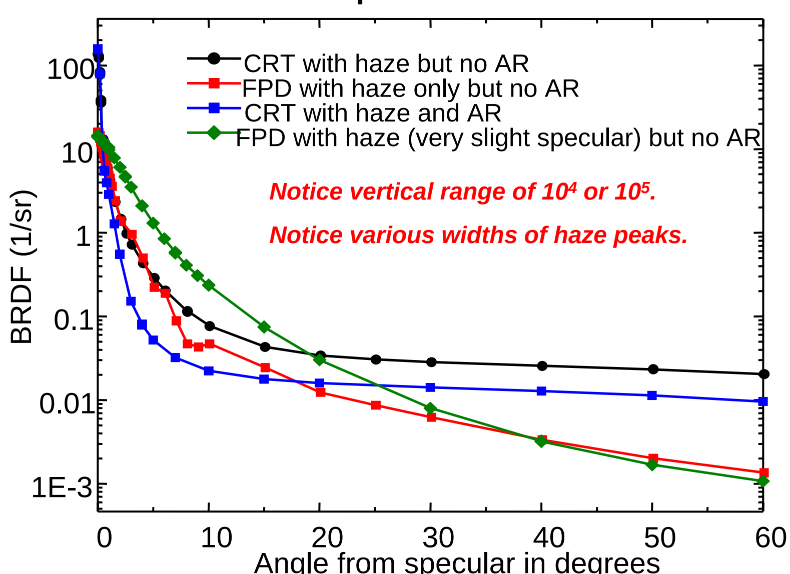


Three Component Reflection Model, Cont.

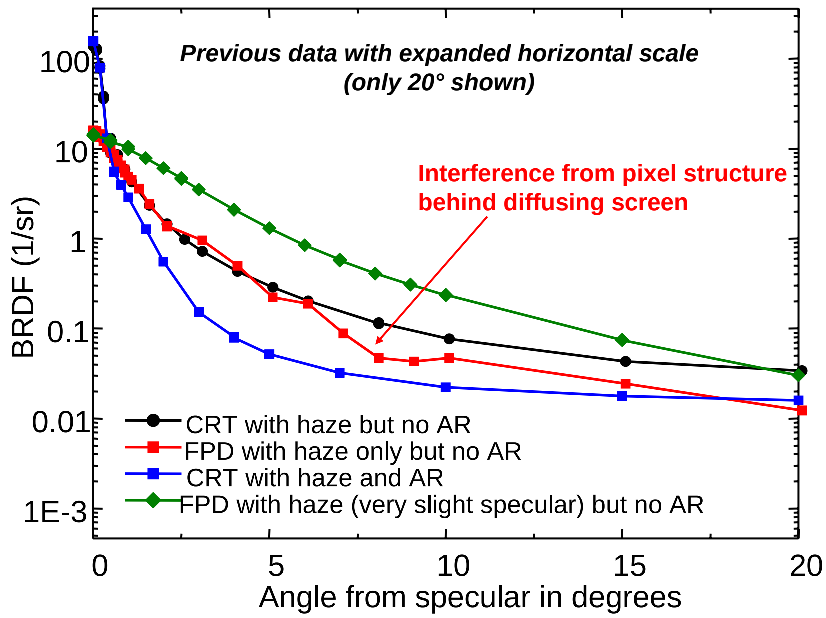


Three Component Reflection Model, Cont.

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

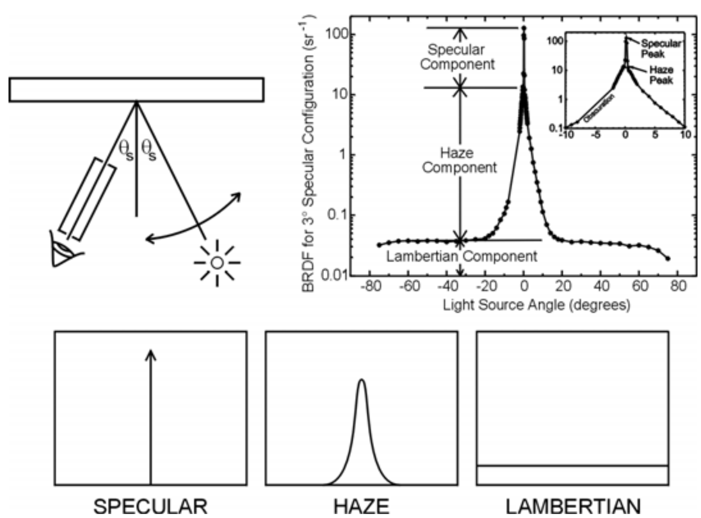


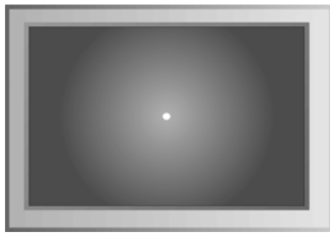
Three Component Reflection Model, Cont.



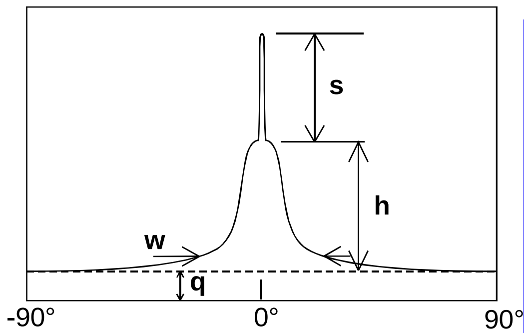
Three Component Reflection Model, Cont.

Three components in BRDF often seen in CRTs



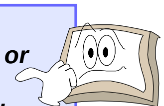


In the most general case, when there is a Lambertian, specular, and haze component, there are at least four parameters that are needed to specify the reflection characteristics since haze has a peak and a width (at the very least).



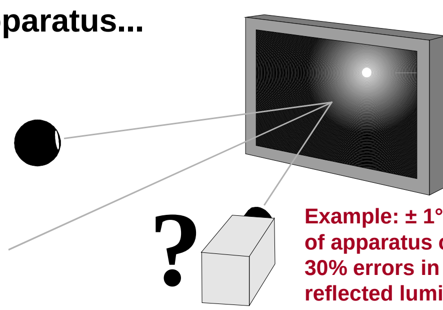
KEY POINT

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.



With Haze, Measurements Can Be Sensitive to the Geometry of the Apparatus...

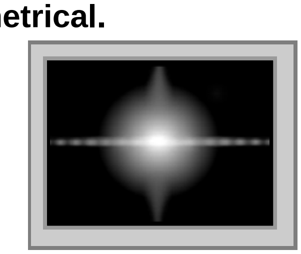
- Lens diameter (?)
- Focus
- Source size
- Source distance
- ...?



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.

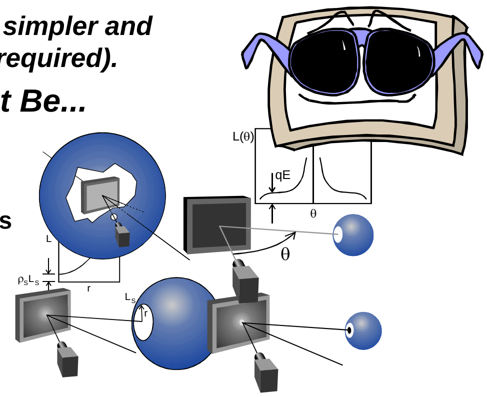


Simple Reflection Measurement Methods

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

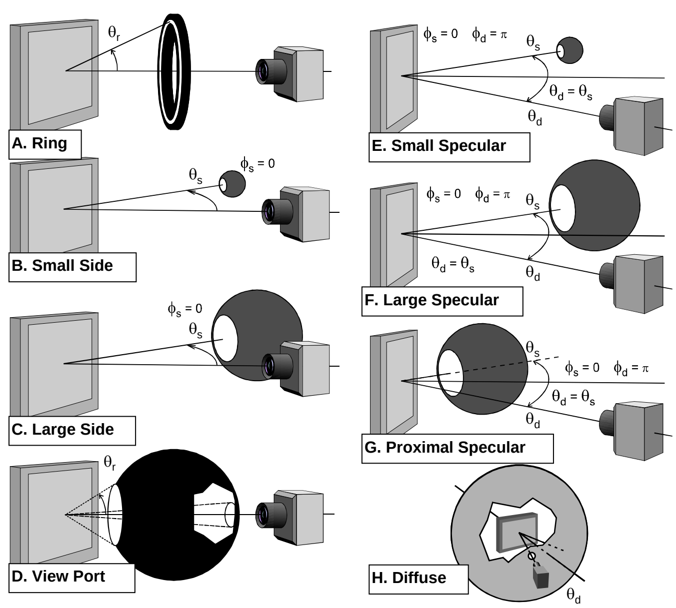


OBJECTIVE: To find the minimum set of measurements to adequately quantify reflection performance for a variety of applications.

ROBUSTNESS IS THE KEY!

Simple Reflection Measurement Methods, Cont.

Which Measurement Methods are Most Robust?



Simple Reflection Measurement Methods, Cont.

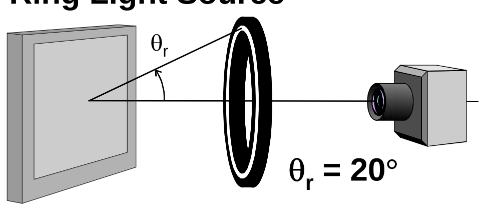
Assumptions for Method Consideration

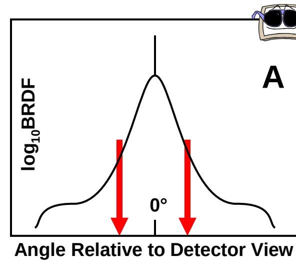
What are we looking for and what are we NOT saying here?

- **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 are 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

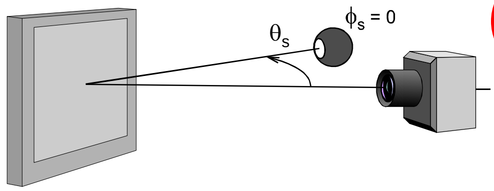


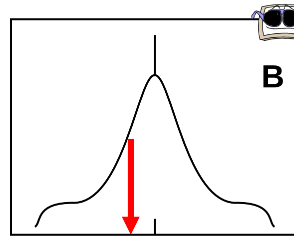


- **REFLECTION COMPONENT UTILIZATION:** ***Avoids haze peak and specular. Captures the tail of the haze (depending upon width) and some contributions from the Lambertian.***
- **ROBUSTNESS:** ***Fairly robust and insensitive to small changes in setup parameters. Works with haze because 'when one side 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°



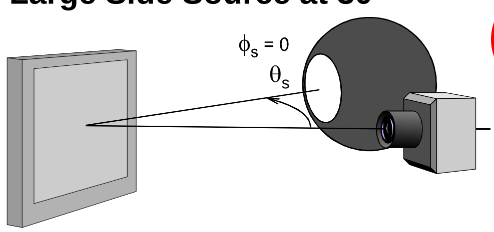


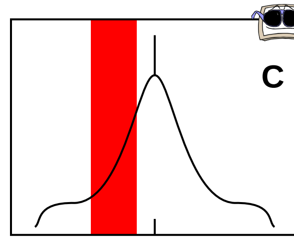
- **REFLECTION COMPONENT UTILIZATION:** ***Avoids haze peak and specular. Captures the tail of the haze (depending upon width) and some contributions from the Lambertian.***
- **ROBUSTNESS:** ***Problematic! Very sensitive to small changes in alignment of detector with normal and to small changes in 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.***

NOTE: The robustness of this measurement method improves as the angle increases. It may be fairly robust at 45° from the normal.

Simple Reflection Measurement Methods, Cont.

C. Large Side Source at 30°



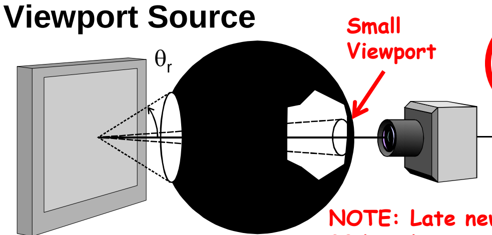


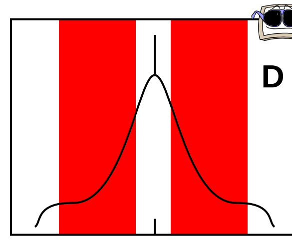
- **REFLECTION COMPONENT UTILIZATION:** ***Avoids haze peak and specular. Captures a segment of the haze profile.***
- **ROBUSTNESS:** ***Not robust because of the geometric sensitivity to the side of the haze peak where the haze is not small and varies rapidly with a change of source angle.***
- **SYMMETRY:**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

NOTE: The robustness of this measurement method improves as the angle increases. It may be fairly robust at 45° from the normal.

Simple Reflection Measurement Methods, Cont.

D. Viewport Source



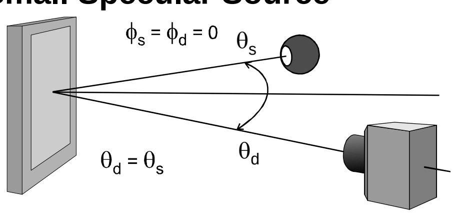


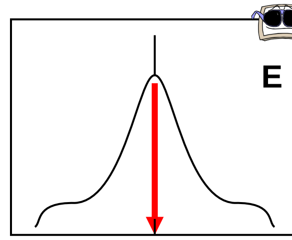
NOTE: Late news… If viewport subtense is large (say 30°) and exit port is near screen, then this may be a very robust measurement. Future research!

- **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.***

Simple Reflection Measurement Methods, Cont.

E. Small Specular Source

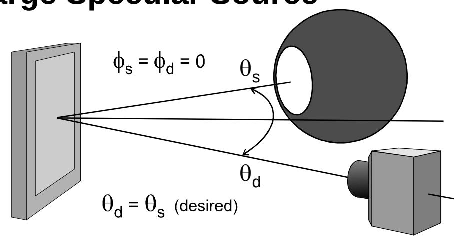


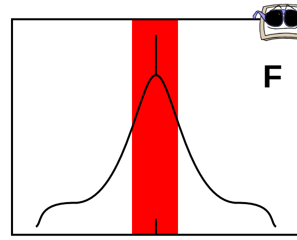


- **REFLECTION COMPONENT UTILIZATION:** ***Combines the specular, the haze peak, and the region of the haze near the peak. Little Lambertian contribution compared to specular and haze.***
- **ROBUSTNESS:** ***Problematic. Can be very sensitive to apparatus settings and geometry. Haze contributions seriously 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.***

Simple Reflection Measurement Methods, Cont.

F. Large Specular Source

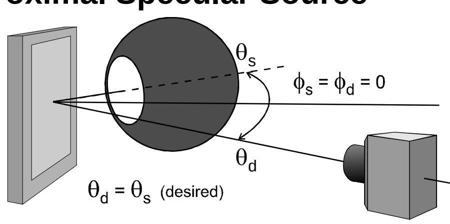


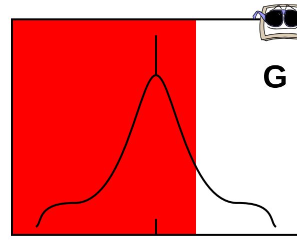


- **REFLECTION COMPONENT UTILIZATION:** ***Captures the specular and haze peak and the substantial part of the haze profile.***
- **ROBUSTNESS:** ***Fairly robust and insensitive to small changes in setup parameters. Works with haze because 'when one side goes up the other goes down' in exploiting the BRDF—but not near the haze peak.***
- **SYMMETRY:** ***Symmetrically integrates contributions from all rotation angles about the normal.***

Simple Reflection Measurement Methods, Cont.

G. Proximal Specular Source

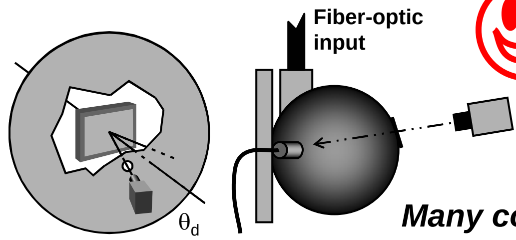


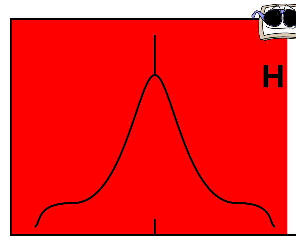


Source is closer than pictured here.

- **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.***

H. Diffuse Source



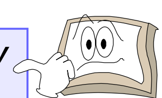


Many configurations can be employed.

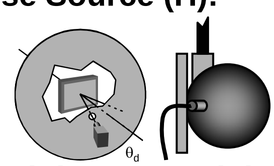
- **REFLECTION COMPONENT UTILIZATION:** ***Integrates all three components, specular, Lambertian, haze.***
- **ROBUSTNESS:** ***Wonderfully robust! Many different types of apparatus yield same results. Insensitive to exact angle of detector from normal.***
- **SYMMETRY:** ***Symmetrically integrates contributions from all rotation angles about the normal.***

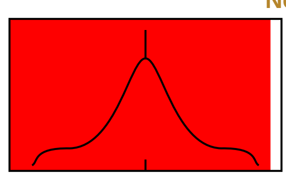
"Best" Methods Summary

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

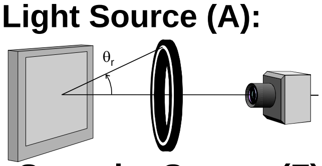


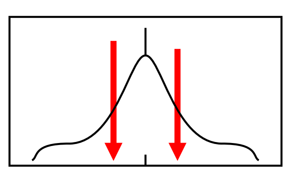
- **Diffuse Source (H):**



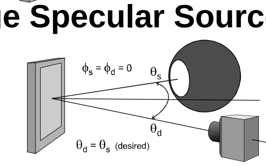


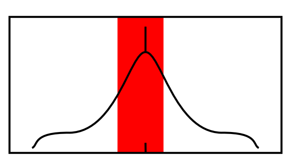
- **Ring Light Source (A):**





- **Large Specular Source (F):**

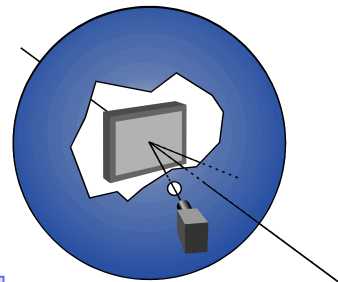




Diffuse Reflectance

or hemispherical directional reflectance ($\beta_{d/\theta} = \rho_{\theta/d}$)

- ***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.



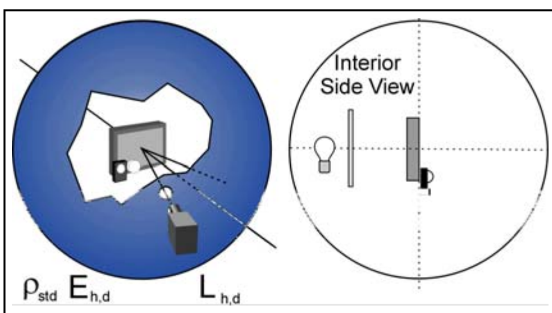
Many say, "not practical," "not realistic,"….

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

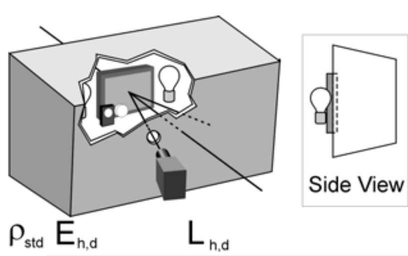
IF THERE IS GOING TO BE ONLY <u>ONE</u> MEASUREMENT TO MAKE, THIS IS IT!!! (… my opinion…)

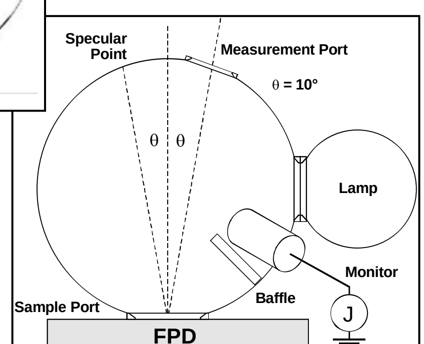
NIST

Diffuse Reflectance ($\beta_{d/\theta} = \rho_{\theta/d}$), Cont.



A variety of apparatus can be used. Reproducibility of 5% is not hard to achieve.





Under all conditions the illuminance from the source off the walls MUST be much greater than the illuminance from the display's back reflections. Otherwise with LCDs can get polarization errors introduced.

Note

NIST

Diffuse Reflectance ($\beta_{d/\theta} = \rho_{\theta/d}$), Cont.

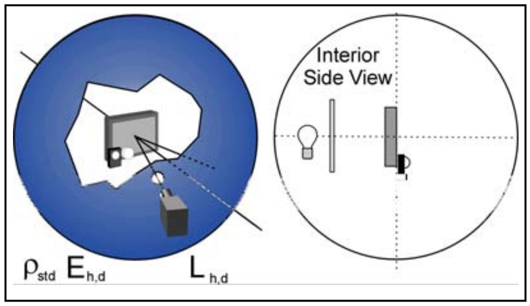
Using Integrating Sphere

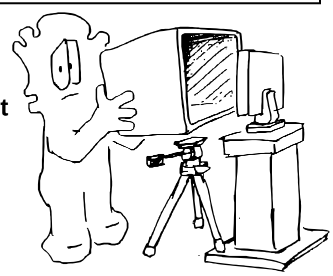
- **Measure darkroom L_K & L_W ($L_K = L_W = 0$ for reflective)**
- **Measure display L_h & L_d in sphere (h = high for white, d = dark for black)**
- **Measure illuminance for white E_h and black E_d**
- **Calculate reflectances**

$$\rho_W = \pi(L_h - L_W)/E_h \qquad \rho_K = \pi(L_d - L_K)/E_d$$

- **Scale to design illumination: Determine contrast C under desired design ambient illuminance E_0**

$$C = \left.\frac{\frac{\rho_W E_0}{\pi} + L_W}{\frac{\rho_K E_0}{\pi} + L_K}\right|_{\text{Emissive}}, \quad C = \left.\frac{\rho_W}{\rho_K}\right|_{\text{Reflective}}$$





You might be a Rustic if you use a beer cooler as an integrating sphere.

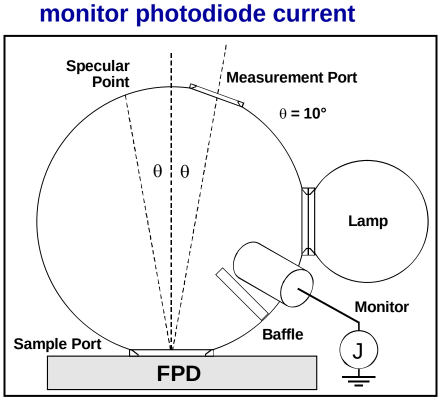
RUSTIC METROLOGY

Ambient Contrast [FPDM 308-2]

Diffuse Reflectance ($\beta_{d/\theta} = \rho_{\theta/d}$), Cont.

Sampling sphere method

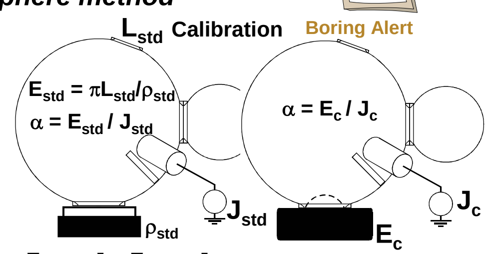
Illuminance determined from monitor photodiode current



$L_{W,K}$ for full-screen white, black in darkroom.

$L_{h,d}$, etc. for full-screen white, black with sphere.

C = contrast under design ambient illuminance E_0.

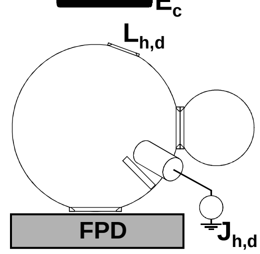


$E_h = \alpha J_h$, $E_d = \alpha J_d$

$\beta_W = \pi(L_h - L_W)/E_h$

$\beta_K = \pi(L_d - L_K)/E_d$

$$C = \frac{\frac{\beta_W E_0}{\pi} + L_W}{\frac{\beta_K E_0}{\pi} + L_K}$$



Ambient Contrast [FPDM 308-2]

C = β_W/β_K for reflective displays

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

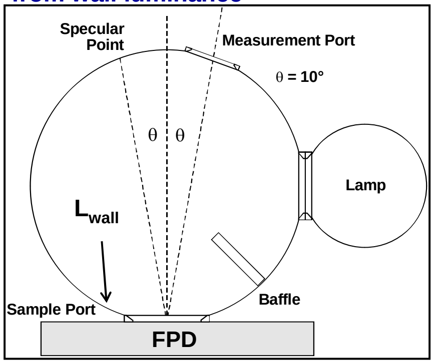
Shame on me for creating such a busy slide!

Diffuse Reflectance ($\beta_{d/\theta} = \rho_{\theta/d}$), Cont.

Sampling sphere method, cont.

Boring Alert

Illuminance determined from wall luminance



Can also measure wall luminance L_w near sample port

The measurement region may need to be baffled too so that the wall luminance is uniform in the measurement region.

Calibration: $L_{wall} = L_c$

With meter…

$k = E_c / L_c$

With white std…

$E_{std} = \pi L_{std}/\rho_{std}$

$E_{std} = k\, L_c$

$k = (\pi L_{std})/(L_c \rho_{std})$

$E_h = k\, L_{w\text{-}h}$, $E_d = k\, L_{w\text{-}d}$

$\beta_W = \pi(L_h - L_W)/E_h$

$\beta_K = \pi(L_d - L_K)/E_d$

$$C = \frac{\dfrac{\beta_W E_0}{\pi} + L_W}{\dfrac{\beta_K E_0}{\pi} + L_K}$$

Ambient Contrast [FPDM 308-2]

$C = \beta_W/\beta_K$ for reflective displays

$L_{W,K}$ = full-screen white, black in darkroom.
$L_{h,d}$, = luminance of white, black with sphere.
$L_{w\text{-}h,d}$ = wall luminance white, black with sphere.
C = contrast under design ambient illuminance E_0.

This method is preferable for strong colors because the same luminance meter is used to measure the sample and the wall (the photodiode may not have the same photopic response as the meter).

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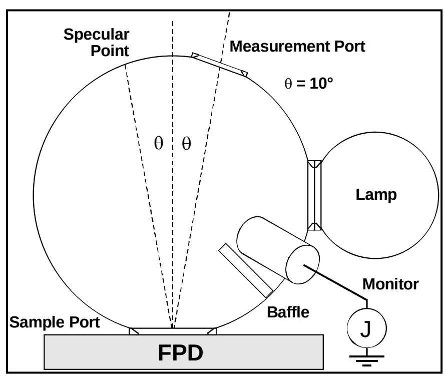
Diffuse Reflectance ($\beta_{d/\theta} = \rho_{\theta/d}$), Cont.

Sampling-Sphere Notes

- **Measurement port must not be too large or it can interfere with the measurement. What is shown here may be too large!**
- **Measurement port must be large enough to not interfere with the luminance measurement (port must not intersect rays contributing to the result).**
  - ***The above two requirements suggest the larger the sampling sphere the better.***
- **Wall measurements have an advantage in that the same photopic response is used for the screen and wall luminances. (Also eliminates the need for photopic photodiode.)**
- **The luminance meter must be far enough away that bright areas inside the sphere don't shine into the lens (veiling glare) for screen measurements.**
- **No direct rays from the lamp should fall upon the sample port region.**
- **If there is a front protective glass removed from the pixel surface, then the size of the sample port may have to be much larger than the separation distance.**
- **The interior wall luminance from the lamp should be MUCH greater than the wall luminance caused by the display.**



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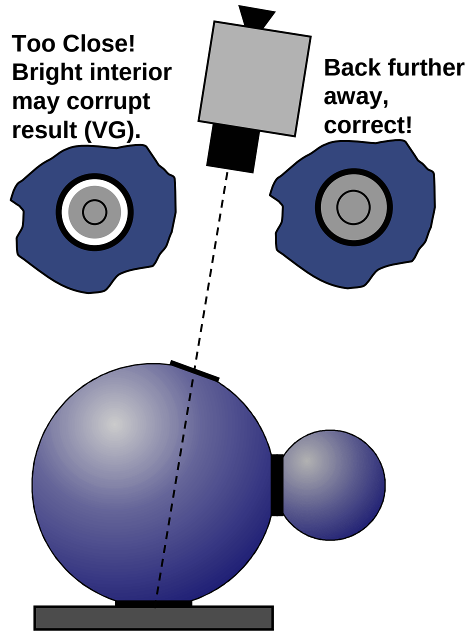
Diffuse Reflectance ($\beta_{d/\theta} = \rho_{\theta/d}$), Cont.

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. …**

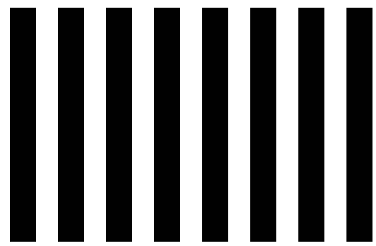
Some of these are artifacts of the display. Some can also be artifacts from the combination of the display and how the eye sees things.

Motion Artifacts, Cont.

Judder

Judder: Jerkiness in motion arising from motion that does not cause blur (can arise from low frame rate).

Probably the frame rate of the projection display is high enough to cause only blur. However the refresh will be interrupted because of the operating system computations; so a jerkiness may be observed that simulates judder.



(Animated)

Motion Artifacts, Cont. **Boxes Moving Across Screen at Different Speeds**

Try to follow and see blur; stare in one place appears sharp?

+ + + +

CAN

YOU

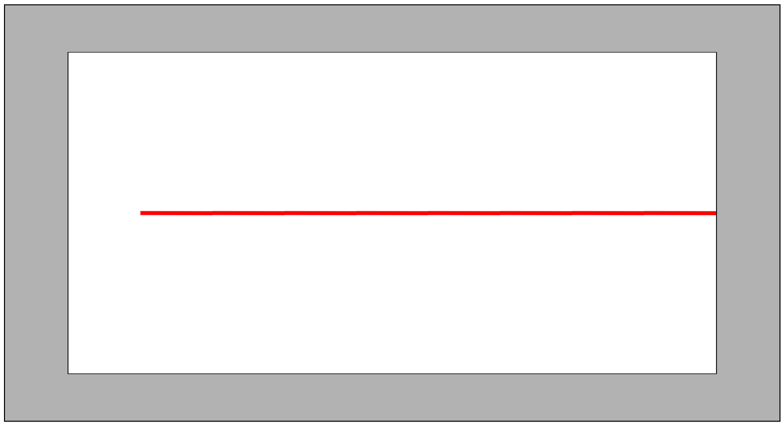
READ

THIS

WELL?

(Animated)

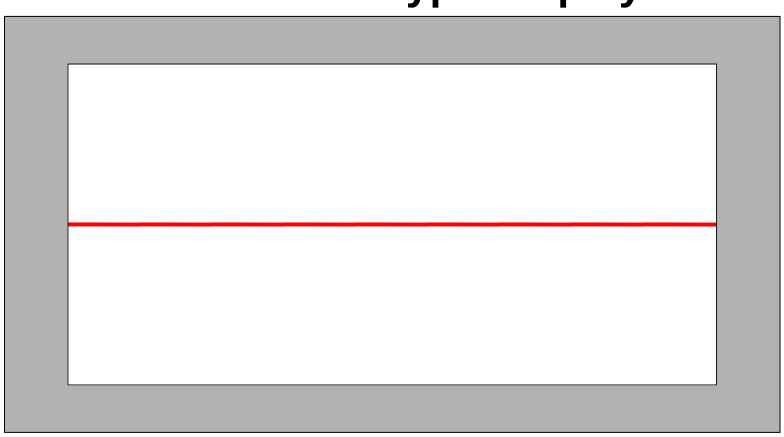
CRT Display



Smooth-Pursuit Eye Tracking

(Animated)

FPD Hold-Type Display

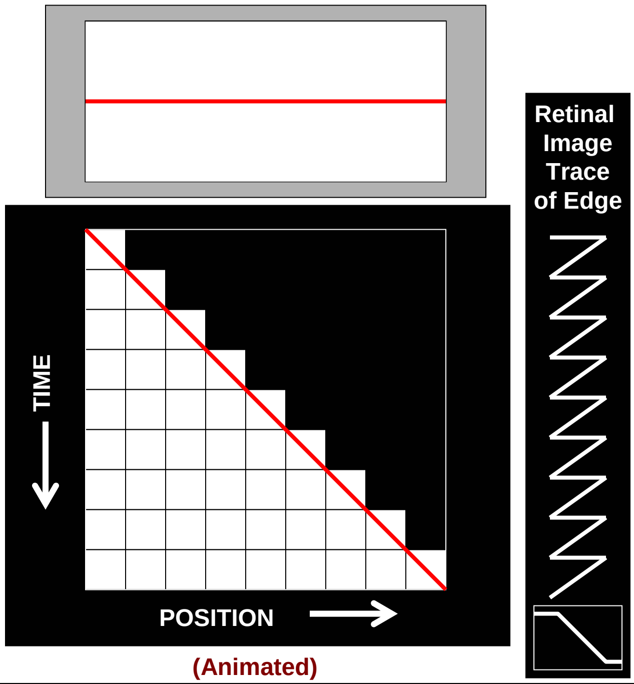


Smooth-Pursuit Eye Tracking

(Animated)

Motion Artifacts, Cont.

FPD Hold-Type Display with perfect transitions between levels



(Animated)

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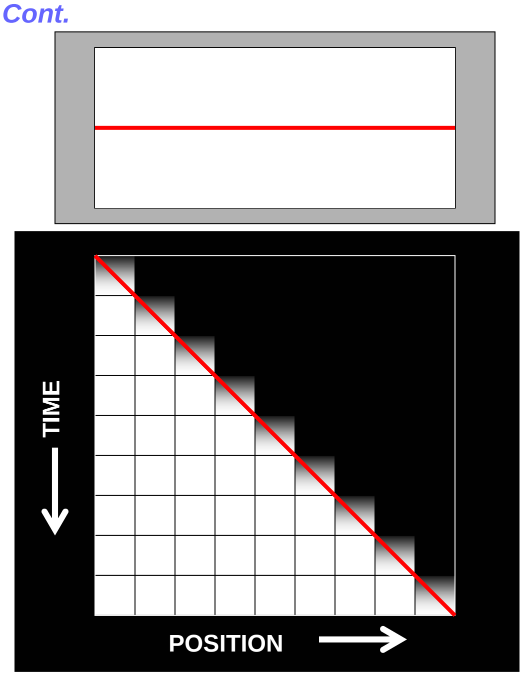
Motion Artifacts, Cont.

FPD Hold-Type Display with finite transition times

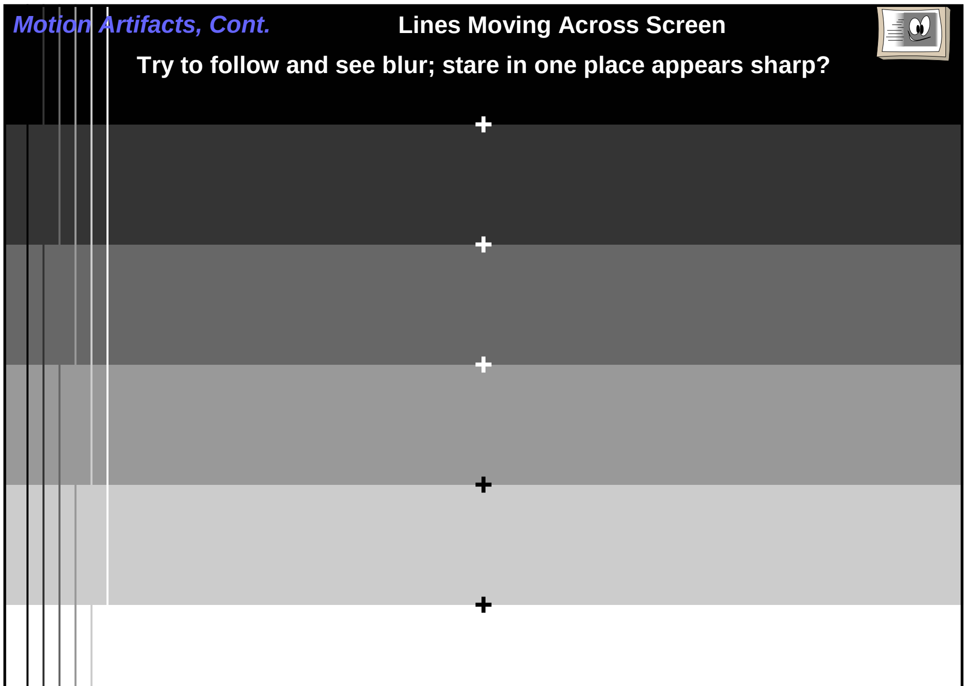


(Animated)

NIST

Lines Moving Across Screen

Try to follow and see blur; stare in one place appears sharp?

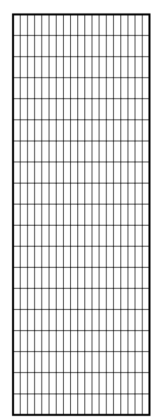


(Animated)

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.



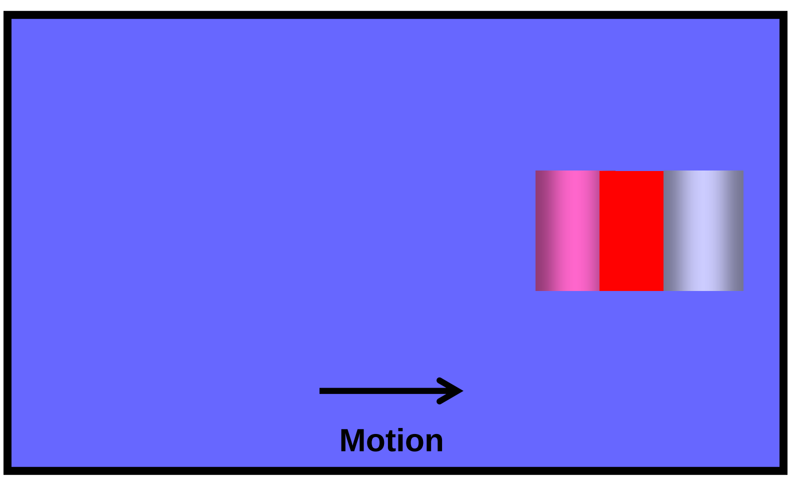
(Animated)

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.)

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!

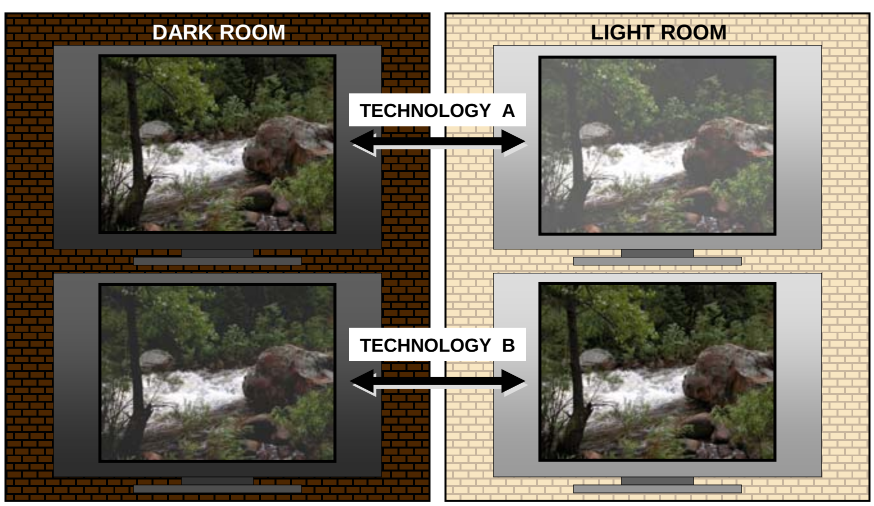
IF YOU ALREADY HAVE PURCHASED A NEW DISPLAY, ABSORBING THIS MATERIAL MAY NOT BE THE WISEST THING TO DO. YOU HAVE A FEW SECONDS TO LEAVE THE ROOM.

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.

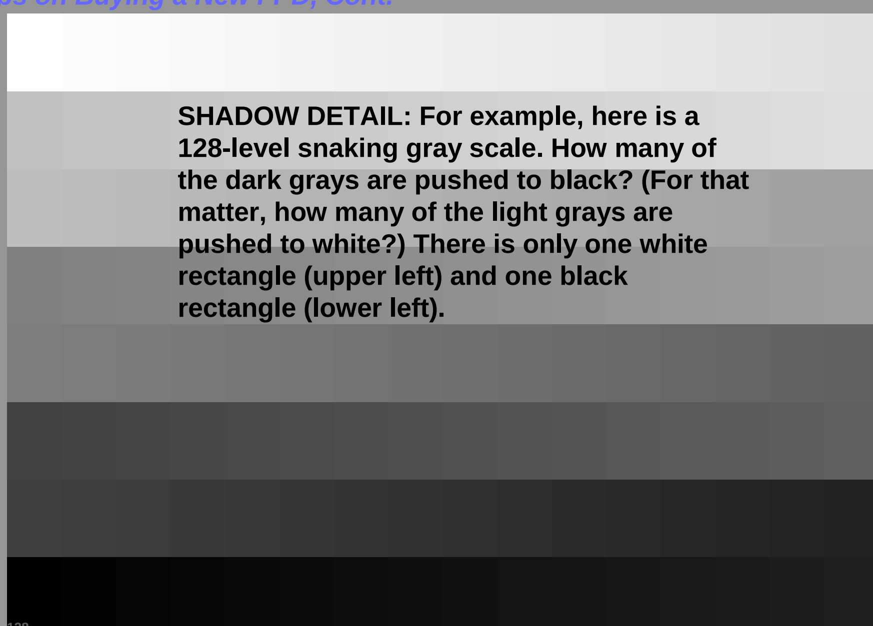


Tips on Buying a New FPD, Cont.

- **LOOK AT THE BLACKS !!!!!**
  Most displays exhibit sufficient brightness or you wouldn't consider them in the first place. Often the real test of the display is how it shows its blacks when it is placed in an environment similar to your home. Consider both large-area blacks and small-area blacks. Some displays will show wonderful blacks in a bright environment, but those same blacks will be seen as dark gray when that display is placed in a dark room. Some displays will show wonderful blacks in a dark room, but they will be washed out by reflections in a bright room. Also look for shadow detail in the dark regions.

Darkness of small-area blacks are very important.

Tips on Buying a New FPD, Cont.



SHADOW DETAIL: For example, here is a 128-level snaking 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 white rectangle (upper left) and one black rectangle (lower left).

Each rectangle represents a step of two gray levels: 0 (black), 2, 4, 6, 8, … 248, 250, 252, 255 (white, last step is three gray levels). — Pattern name SSW128.

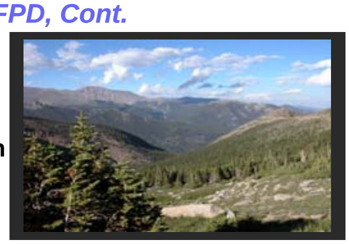
Tips on Buying a New FPD, Cont.

- **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.

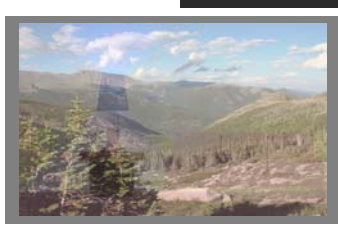
Tips on Buying a New FPD, Cont.

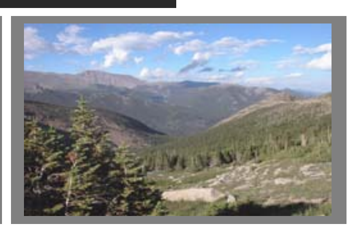
Light Living Room Effects on Image

Darkroom Image



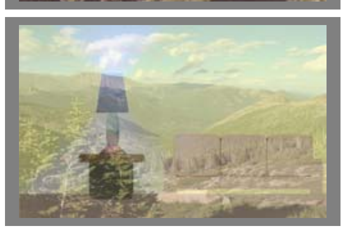
Specular & Lambertian with AR

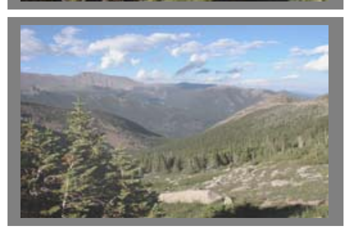




Haze only, with AR

Specular & Lambertian no AR





Haze only, no AR

Tips on Buying a New FPD, Cont.

- **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/m^2

Contrast: 500:1
Luminance: 300 cd/m^2

Tips on Buying a New FPD, Cont.

- **VIEWING ANGLE**

The problems with viewing angle 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.

Tips on Buying a New FPD, Cont.

- STATIC IMAGES
  Should you be able to view static images on the screen (if the display can be hooked up to a computer), then there are a large variety of images you can use, dark scenes, light scenes, but especially faces. Moving scenes may indicate motion artifacts, but generally don't give you enough time to consider the reflection properties, viewing angle properties, the whites (both small and large area), and the blacks (both small and large area).

  http://www.fpdl.nist.gov → Click on Patterns

  Available Patterns from NIST:

  Setup & Testing

  Faces

  Natural Scenes

  FTP whatever you want.

  All in the public domain!

Courses & Services at NIST

- NIST Display Metrology Short Course
  It is being offered several times a year (hands on lab work).
  See http://www.fpdl.nist.gov
  or http://www.fpd.nist.gov and follow the links.
- NIST Photometry Short Course
  http://physics.nist.gov/Divisions/Div844/facilities/photo/Photometry_Course.html
- NIST Spectroradiometry Short Course
  http://physics.nist.gov/Divisions/Div844/events/srsc.html
- NIST Colorimetry of Displays — A Calibration Facility
  http://physics.nist.gov/Divisions/Div844/facilities/photo/Projects/colorimetry_of_displays.htm
  Based Upon the Four-Color Matrix Method for
  Correction of Tristimulus Colorimeters
- NIST Laser Measurement Short Course
  http://www.boulder.nist.gov/div815/lmsc.htm
- NIST Flat Panel Display Laboratory — Publications, Links, Overview
  http://www.fpdl.nist.gov ("FPDL") or http://www.fpd.nist.gov
- This seminar: http://www.fpdl.nist.gov/ → Seminars and Courses


THANKS FOR LISTENING!
NOTE: We are offering a Display-Metrology Short Course with a one-day lecture and two days of hands-on laboratory work. If you are interested, please visit
www.fpd.nist.gov
and follow the links.
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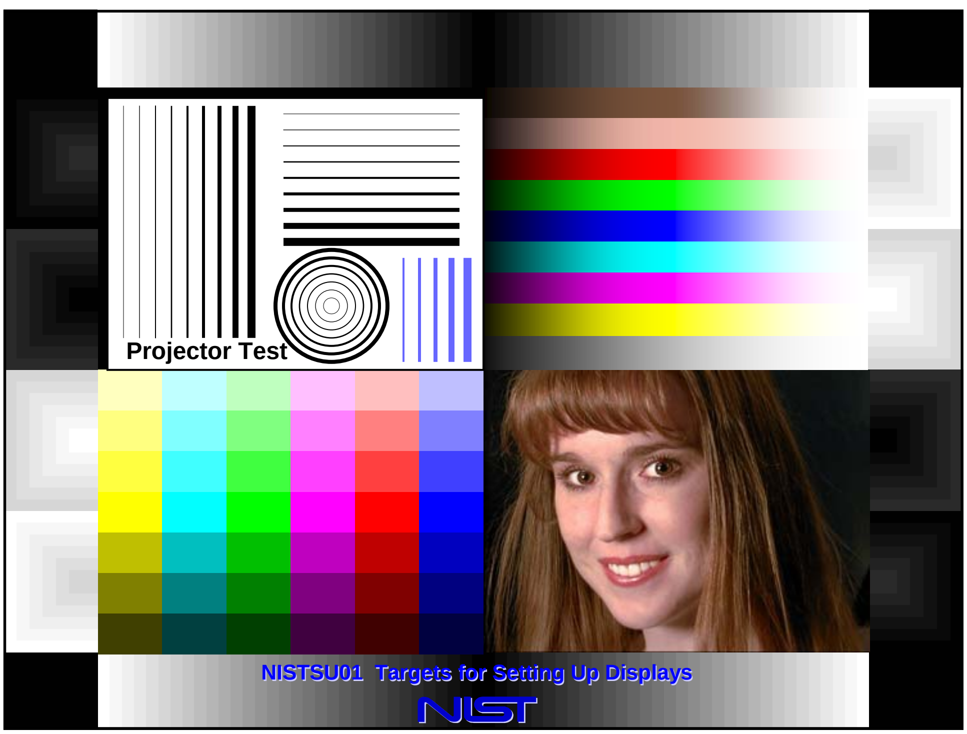
303-497-4599 kelley@nist.gov
NOTE: Certain commercial equipment, instruments, materials, systems, and trade names may be identified in this seminar in order to specify or identify technologies adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the systems or products identified are necessarily the best available for the purpose.
NIST
FLAT PANEL DISPLAY LABORATORY


Projector Test
NISTSU01 Targets for Setting Up Displays
NIST