Introduction to Colour Science

NPGR025

Unit 4: Measurement Technology

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Sources:
Wyszecki & Stiles
Device Manuals
The Web

Overview

- Photometry – Intensity measurements
- Colorimetry – Colour value measurements
- Spectroradiometry – Measuring of spectral distributions

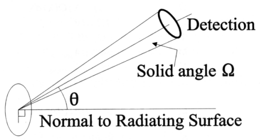
Radiometry vs. Photometry

- **Radiometry** is the science and technology of the measurement of electromagnetic radiation over the whole spectrum of electromagnetic waves
- **Spectroradiometry** concerns itself with the spectral composition of electromagnetic radiation
- **Photometry** and **spectrophotometry** are the same in terms of the visible spectrum, and the average human observer

Radiometric Quantities

Quantity	Symbol	Defining equation	Units
Radiant energy	Q, Q_e		J (joule)
Radiant energy density	w, w_e	dQ/dV	J m^{-3}
Radiant power or flux	Φ, Φ_e	dQ/dt	J s^{-1} or W (watt)
Radiant exitance	M, M_e	$d\Phi/dA_{source}$	W m^{-2}
Irradiance	E, E_e	$d\Phi/dA_{surface}$	W m^{-2}
Radiant intensity	I, I_e	$d\Phi/d\Omega$	W sr^{-1}
Radiance	L, L_e	$d^2\Phi/d\Omega(dA \cos\theta)$ $dI/dA \cos\theta$	W m^{-2} sr^{-1}
Emissivity	ϵ	$M/M_{blackbody}$	

All radiometric units are derived SI units



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Photometric Quantities

Quantity	Symbol	Defining equation	Units
Luminous energy	Q_v	$K_m \int V(\lambda) Q(\lambda)\, d\lambda$	lm s
Luminous energy density	w_v	dQ_v/dV	lm s m^{-3}
Luminous flux	Φ_v	dQ_v/dt	lm (lumen)
luminous exitance	M_v	$d\Phi_v/dA_{\text{source}}$	lm m^{-2}
Illuminance	E_v	$d\Phi_v/dA_{\text{surface}}$	lm m^{-2}
Luminous intensity	I_v	$d\Phi_v/d\Omega$	lm s^{-1} or cd (candela)
Luminance	L_v	$d^2\Phi_v/d\Omega(dA \cos\theta)$ $dI_v/dA \cos\theta$	cd m^{-2}
Luminous efficacy	K	Φ_v/Φ	lm W^{-1}

Except for the last one in the list, the corresponding units use the same symbol with different subscript (e for radiometry, and v for photometry)

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Lumen

- The basic unit of photometry is the lumen (lm)
- The key difference to the radiometric units is not so much that it only considers the visible spectrum, but that its definition contains the relative photopic luminous efficacy function

$$\Phi_V = 683 \int_\lambda \Phi(\lambda)\, V(\lambda)\, d\lambda$$

- $\Phi(\lambda)$ is the spectroradiometric power distribution of the source

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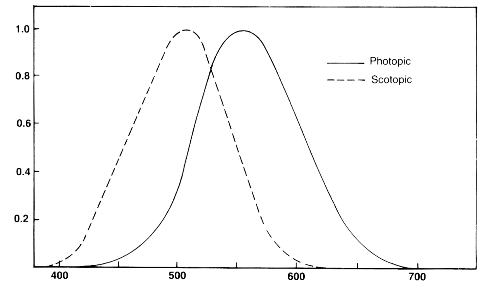
Relative Luminous Efficiency

- Photopic – adapted to bright light (cones)
- Scotopic – adapted to the dark (rods)
- Mesopic – intermediate



Conversions

- As a consequence of V(λ) being part of their relationship, conversion of photometric to radiometric units (and vice versa) is only possible when the spectral distribution of the light source or colour stimulus in question is known
- Monochromatic light sources – such as lasers – are a kind of exception, since their SPD is trivial

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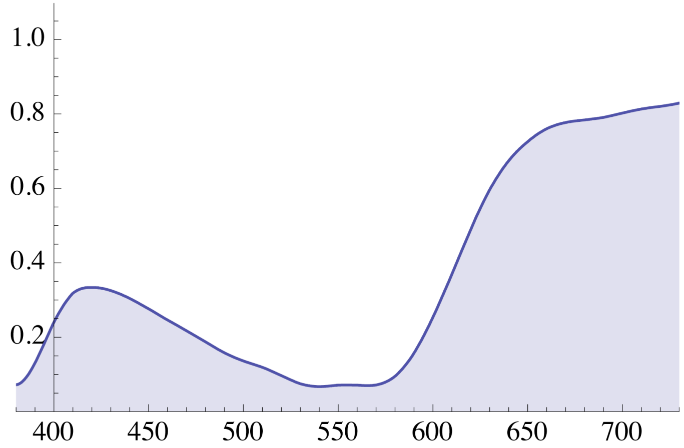
Radiometric Quantity



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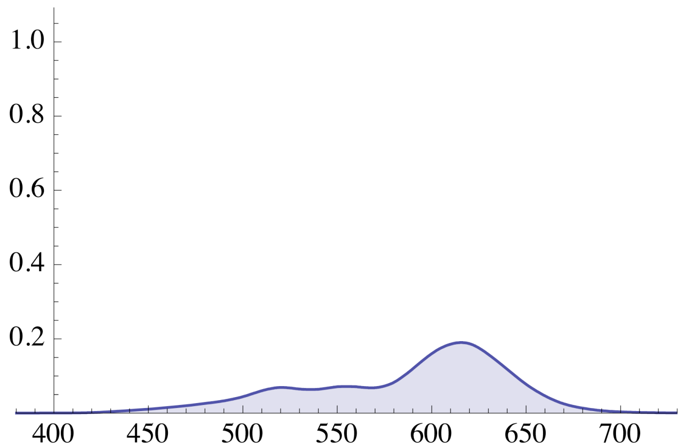
Photometric Quantity



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Transmittance and Reflectance

- Transmittance is the ratio of the transmitted radiant or luminous flux to the incident radiant or luminous flux
  - Refracted transmittance is known as regular, otherwise as diffuse
- Similarly, reflectance is the ratio between reflected and incoming flux
  - Reflectance according to the laws of reflection is known as specular, otherwise as diffuse

Spectroradiometric Standards

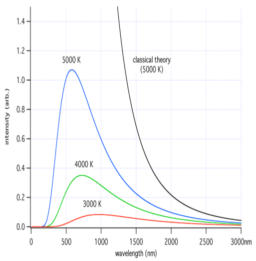
- All accurate measurements of optical radiation are going to involve the use of a reference standard in some way
- This can be:
  - A source of known emissivity
  - A detector with an exactly known response
  - A surface with exactly known reflectivity
- Two basic types of emission standards exist: blackbodies and reference lamps

Blackbody Standards

- Advantage of blackbody radiation: known spectral power distribution
- Problem: maintaining constant temperature
- Basic idea: during a phase change such as freezing, the phase maintains a constant temperature to within very close tolerances
- During its freezing process a given material offers a reliable reference standard for blackbody radiation

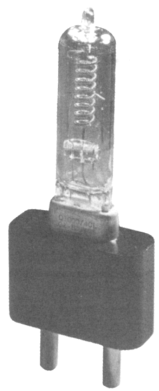
Blackbody Standards

- Advantage: potentially very accurate
- Disadvantage: except for the infrared portion of the spectrum, a blackbody radiator has to operate at temperatures around at least 2500K
- IR: commercial devices exist
- Visible: only used for reference standards in national standards laboratories



Reference Lamps

- Blackbodies not being practical, NIST started to use specially designed lamps of known SPD as standards
- Repeatability of lamp manufacturing is good enough to duplicate these standard lamps
- Burning time of these devices is limited

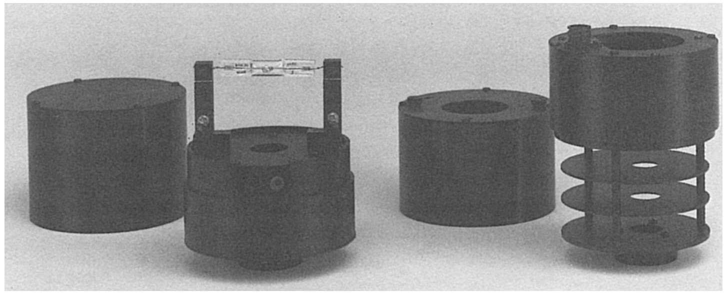


Reference Lamps

- NIST FEL standard lamp is the mother standard for derivatives, but expensive and hard to obtain
- A family of tungsten halogen lamps of 1000, 200 and 45 W was developed for general use
- Problem common to all lamps: small filament area makes uniform large-area irradiation difficult – and diffuse filters would alter lamp SPD
- Calibration of mount geometry necessary

Pre-aligned Standards

- Parts of a modular system that includes integrating spheres, to which these devices can be mounted

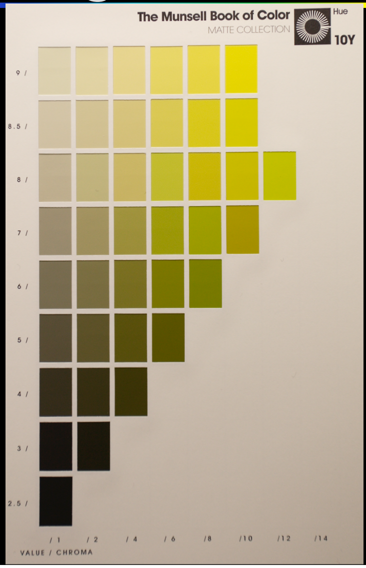


Variant of RL: Viewing Booths

- Viewing booths offer precisely controlled viewing environments for colour comparisons and product evaluations
- Lamps are calibrated to exact standards, and have to be regularly exchanged
- Illuminants chosen from standardised lights (D65, A, CWF etc.)

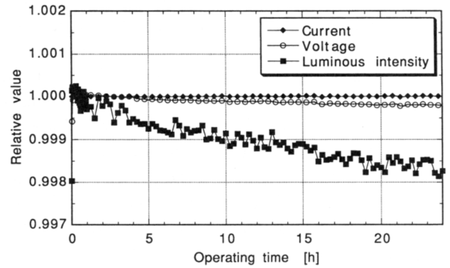
Viewing Booth Example 1

Viewing Booth Example 2



Lamp Ageing

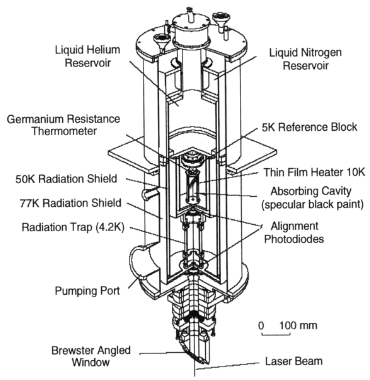
- New incandescent lamps lose 10% brightness during the first few percent of lamp life -> seasoning of standard lamps
- Even after seasoning, all incandescent bulbs suffer some degradation over time due to filament thinning, bulb blackening, etc.



- Storage stability!

Detector Standards

- Various types of exactly calibrated detectors exist, such as
  - Absolute cryogenic radiometers
  - Silicon photodiode trap detectors
- Rarely used outside national standards laboratories or similar institutions



Reflectance Standards

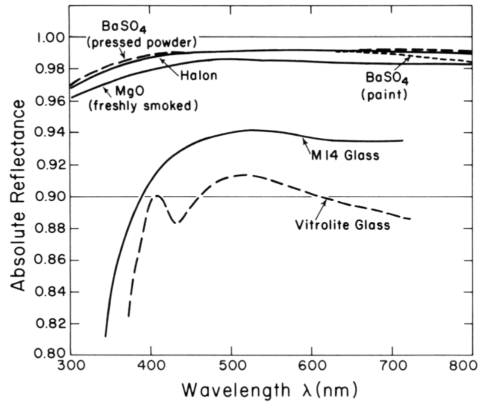
- Two types of standard are used:
  - Transfer standards (materials of precisely known reflectivity) are used to bring the calibration of different instruments into line
  - Working standards are used to calibrate one particular instrument. Individual samples are usually permanently associated with the instrument they calibrate.

Reflectance Standards

- All reflectance standards used for instrument calibration should be or have:
  - Mechanically robust
  - Stable against ambient conditions
  - Opaque, uniform surface
  - Easy to clean
  - Near uniform spectral response across visible spectrum and UV
  - No fluorescence effects

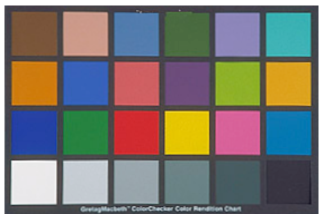
Common Reflectance Standards

- (Smoked Magnesium Oxide MgO)
- Barium Sulphate BaSO4
- Halon tablets
- Ceramic plates
- White enamel plates
- Opal glass



Colour Reflectance Standards

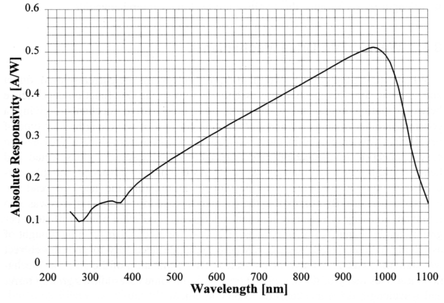
- Normally not used to calibrate instruments, but to have objects of predefined SPD that one can include in scenes
- Old standard: NPL ceramic tiles
- New standard: GretagMacbeth ColorChecker
- (many others exist)
  - 24 patches
  - 18 colours (1 fluorescent)
  - 6 greys



Spectro-Radiometer Design

- Two (three) key components are needed:
  - A reliable broadband sensor for light with a known spectral response curve
  - A reliably controllable monochromator to scan the entire visible spectrum
  - (only for fluorescent reflectance measurements: tuneable monochrome lightsource)
- Additionally, provisions for repeatable and controlled specimen mounting and illumination have to be made

Silicone Photodiodes

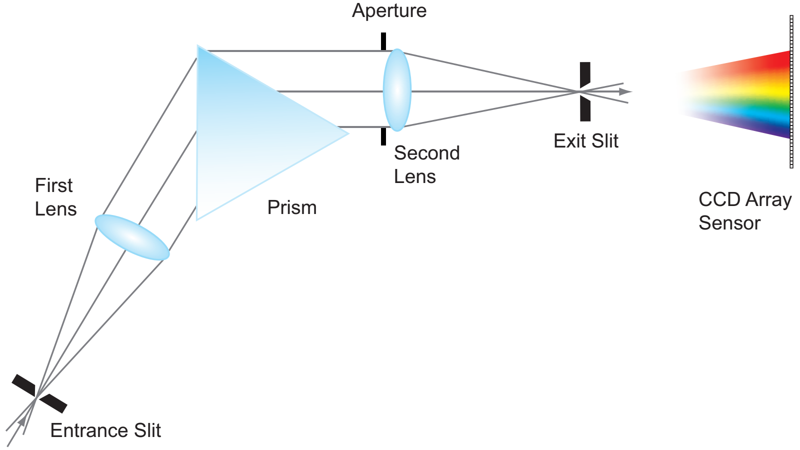


- The light-sensitive elements in most radiometric and photometric instruments are silicon photo-diodes
- These devices yield a wavelength-dependent current per radiant energy that hits them
- Used as absolute detector for monochrome l.

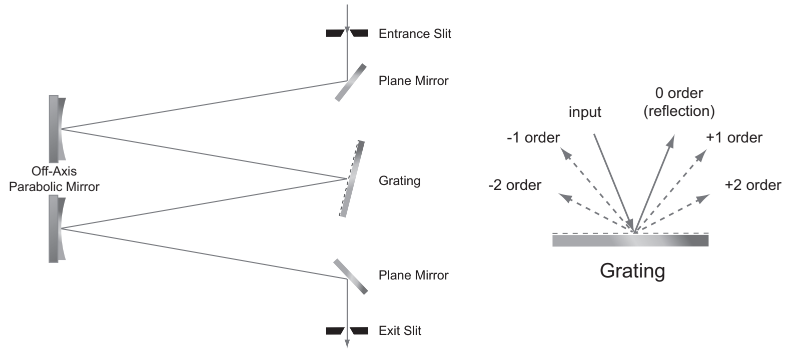
Monochromators

- Main sources of monochrome light and/or wavelength selection:
  - Filters – inflexible (one per sample, no intermediaries), plus usually too wide-band
  - Lyot filters
  - Lasers – inflexible (same as above), expensive
  - Prisms – nonlinear wavelength dependency, but pure output
  - Gratings – linear dependency on wavelength, but higher-order diffraction effects affect purity of result

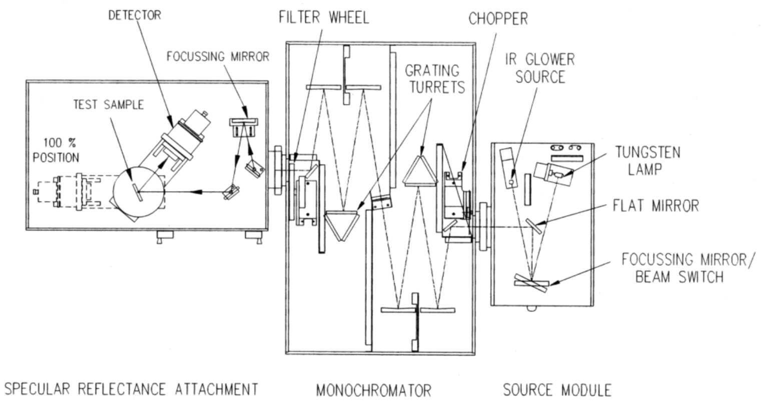
Prism Monochromator



Grating Type Monochromator

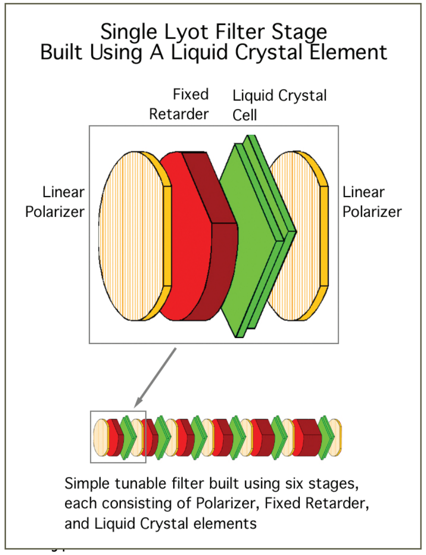


Spectro-Radiometer Components

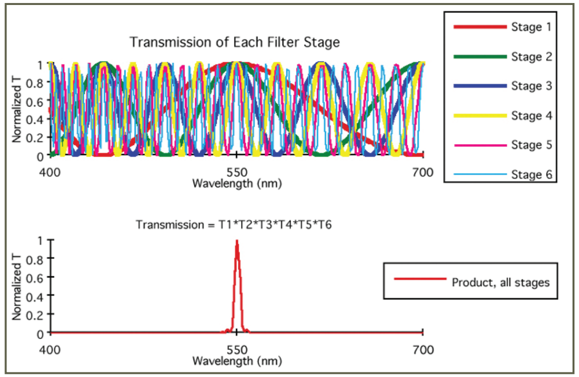


(Tunable) Lyot Filters

- Basic idea: use a cascade of birefringent materials to achieve a narrow bandpass
  - Lyot filter
- Tunable version: insert materials of controllable birefringence into the optical path



Lyot Filter Cascade



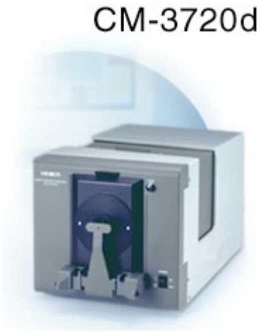
- Each Lyot element is a bandpass of certain width
- A cascade results in a single transmission band

Lyot filter example: CRi VariSpec

- 55ms switching time
- No vibrations
- Can be used in front of digicams etc.
- Different models for various wavelength ranges
  - No one-size-fits-all filter possible

Professional Spectro-Radiometer 1

- Internal arrangements basically as shown in previous sketch
- 10nm resolution from 380 to 780nm, 18 kg
- Two gratings, 15cm sphere
- Extremely high inter-device agreement
- Capable of eliminating fluorescence effects



Professional Spectro-Radiometer 2

- Internal arrangements differs from sketch - direct light path to grating
- Intended for light measurements
- 0.9 nm resolution from 380 to 780nm, 5 kg
- 1 degree measurement angle
- Various lenses (wide angle, tele etc.) available

Gretag Macbeth Spectrolino

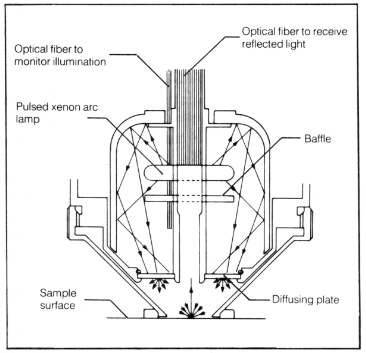
- Handheld device
- 10nm resolution, 380 to 780nm
- Has to be attached to a computer via serial port
- Not particularly useful without the accompanying software
- Serial interface fully documented
- Differences to previous device: less repeatability, less inter-device agreement
- Modern version: EyeOne (USB)

Spectroscan

- Used for fast, routine scanning of opaque and transparent colour charts
- Colour charts are produced to calibrate printing equipment
- A Spectrolino is used as the measurement tool

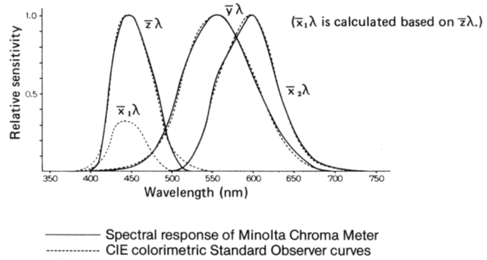
Chroma Meters 1

- Principle: a diffusor spreads light over three photocells which are covered by CIE XYZ-related filters
- Available in self-illuminating and passive versions
- Only records chroma and luminance values which are specific to a given illuminant



Chroma Meters 2

- Cannot be used to predict appearance
- Still very useful for industrial quality control
- Good at finding colour discrepancies in production environments
- Much simpler and cheaper than spectrophotometers



Minolta ChromaMeter

- Typical device for industrial use
- Principle unchanged over past decades
- New devices are just more user-friendly
- Separate data processor and measurement head
- Head can be used separately and/or connected to a computer

Chroma Meter vs. SPM Summary

- Chroma Meter
  - Much simpler and cheaper, can be miniaturised
  - Only useful for self-luminous devices
  - Or if one is only interested in colours viewed under the in-built light source
- Spectrophotometers
  - Not miniaturisable beneath a certain size
  - Not needed for self-luminous devices, but can be used for measuring them
  - Needed to predict the appearance of printed output under varying illuminants