Preprint: Optics and Photonics News, September 2001, **12**(9), 38-40 (2001)

Photometry, Sensing Light and Color

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We are surrounded in daily life by products that emit light: light bulbs and fixtures in homes and offices, TV sets, computer monitors, headlights and taillights of cars, LED indicators, and the displays found in many electronic products. Our basic safety often depends on the reliability of light sources. In transportation, for example, light sources are used for signaling and illumination: traffic lights and signs on roads, railways and airport runways, vehicular identification lighting, and navigation beacons. Products are specified for light output and color, which in turn depend on the requirements of the application. These parameters must be measured to ensure the product meets the specifications required in each case. Signal lights are routinely serviced to maintain minimum required output light intensity and periodically tested to ensure compliance with federal regulations.

With the proliferation of quality systems in manufacturing such as ISO9000 (a series of standards from International Organization for Standardization), the accurate measurement of the light and color generated by particular products has become increasingly important. Since light-emitting products are designed to be seen by people or to illuminate other objects that need to be seen, the measurement process must take into consideration the human eye's response to light. The field of photometry deals with the measurement of light weighted according to human visual response. In 1924, based on research by scientists at the U.S. National Bureau of Standards (NBS), the Commission Internationale de l'Éclairage (CIE) published the internationally standardized human visual response, and the basis of photometry was established. This standardized function, shown in Fig.1, is called the spectral luminous efficiency function (for photopic vision), and denoted as V(λ).Instruments that measure photometric quantities, called photometers, are designed to possess a spectral response matched as closely as possible to this function. For the same reason, the measurement of color, called colorimetry, is performed on the basis of human color perception. A set of three visual spectral response curves, standardized by CIE, are used in this process. Colorimeters are made to match these standardized spectral response functions called CIE colorimetric standard observers, shown in Fig. 2.

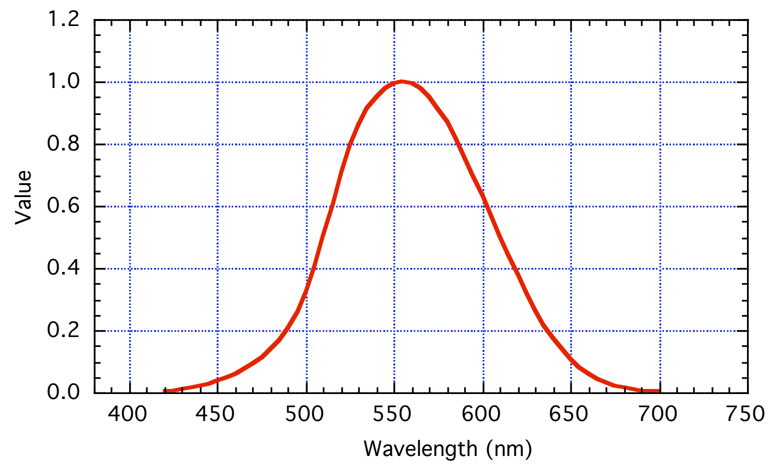


Figure 1. CIE 1924 Spectral luminous efficiency (for photopic vision).

Light is measured in many different ways and in various geometrical configurations. Luminous intensity (measured in candelas,) measures how bright a light source looks from a distance. The candela, originally called the candle, was first introduced as a unit of luminous intensity in the 19th century, when the unit was defined to be the horizontal intensity of a standard candle. The candle was renamed when it was first defined on an international level in 1948 as the amount of radiation emitted from a platinum blackbody. When the Système International (SI) was

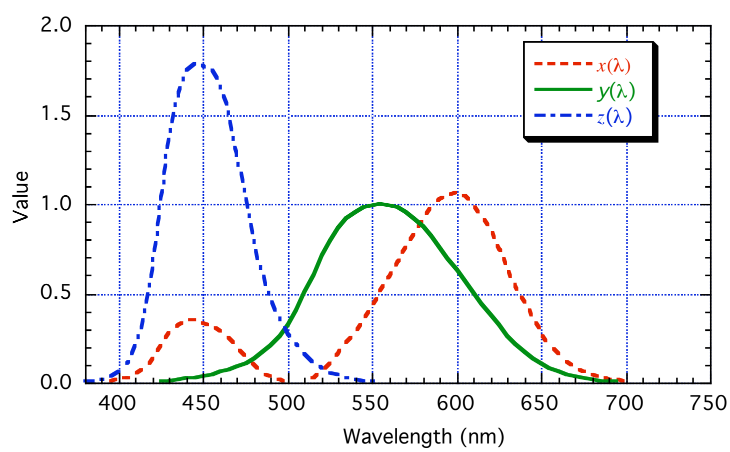


Figure 2. CIE 1931 2° Colorimetric Standard Observers

established in 1960, the candela was adopted as one of the seven base units of measurement. The candela was redefined in 1979 in relation to optical power (watt), although it maintained the magnitude consistent with the previous unit. Thus, the luminous intensity of a typical dining room candle (in horizontal direction) is still approximately 1 candela. According to the new definition, 1 candela is equal to 1/683 watt per steradian at 555 nm, and weighted according to the V(λ) function at other wavelengths.

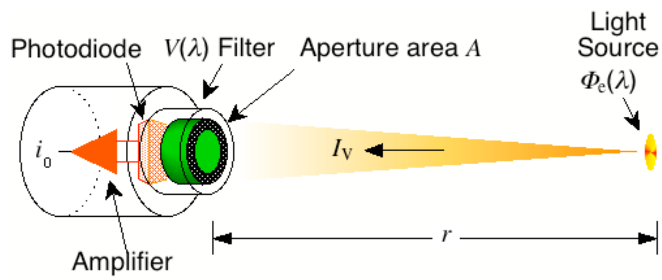
There are a number of other important photometric quantities:

- probably the most important quantity used to specify lamp products is *luminous flux*, measured in lumens, which is the total amount of flux emitted from a light source or flux beam;
- *illuminance*, measured in lux (equal to lumen per square meter) is the density of luminous flux falling on a given surface;
- *luminance*, measured in candelas per square meter, represents the brightness of a surface---such as a display---that emits, reflects, or transmits light.

Since about 20% of all electricity used in the U.S. is expended for lighting, even a 1% improvement in the energy efficiency of lamps* would make a huge difference in overall energy consumption. The Energy Policy Act, passed by Congress in 1992, requires all lamp products sold in the U.S. to meet the minimum efficacy requirements set for each lamp type. Lamps that don't meet the requirements cannot legally be sold. With the passage of the Act, the accurate measurement of total luminous flux has become more critical than ever for lamp manufacturers. To ensure compliance with federal law, the lamp measurement laboratories in all lamp manufacturers in the U.S. are required to be accredited by an authorized accreditation body. If the measurement uncertainty is large, manufacturing tolerances must be commensurately narrowed.

To assure agreement of measured values in the U.S. and abroad, the National Institute of Standards and Technology (NIST) establishes and maintains these basic photometric units and disseminates them to industry, assuring that all measurements can be traced to one national standard. The NIST photometric scales have been primarily disseminated via standard lamps and standard detectors. The Convention du Mètre, signed in 1875 assures that all metrological units are defined internationally, and that units realized and disseminated in different countries are periodically compared to assure that national scales are within an acceptable agreement. NIST plays an active role in international comparisons of photometric units.

The candela is established at NIST, traceable to the absolute cryogenic radiometer[1] using a standard photometer as illustrated in Fig. 3. The detector-based candela brought significant improvement in uncertainty of the unit over the previous blackbody-based method. The lumen is established by a spatial integration of flux from a light source over the entire solid angle (4π). Until recently, establishment of the lumen required the use of a goniophotometer, a costly precision mechanical instrument with a moving arm, installed in a large dark room. NIST researchers recently developed a novel method to establish the lumen using an integrating sphere (see Fig. 4). The new technique has comparable accuracy to most sophisticated goniophotometers, although it is less costly and requires much less space to implement. NIST



$$I_V\ [\mathrm{cd}] = \frac{i_0\, r^2}{R_V} \longleftarrow R_V\ [\mathrm{A/lx}] = \frac{A \int_\lambda \Phi_e(\lambda)\, s(\lambda)\, d\lambda}{K_m \int_\lambda \Phi_e(\lambda)\, V(\lambda)\, d\lambda}$$

$$K_m = 683\ \mathrm{lm/W}$$

Figure 3. Realization of the NIST detector-based candela.

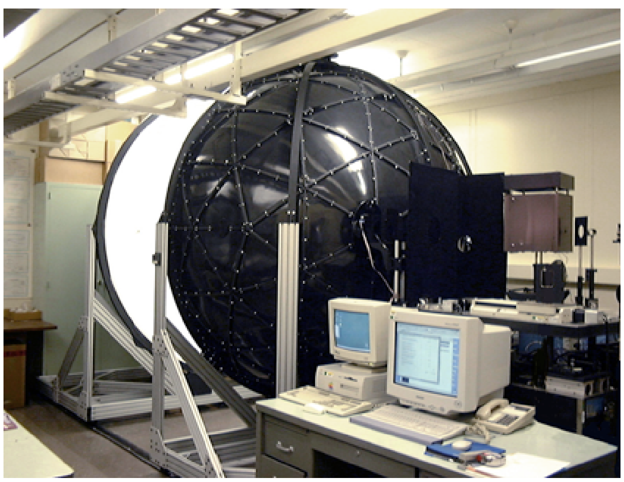


Figure 4. NIST integrating sphere facility for realization of the lumen.

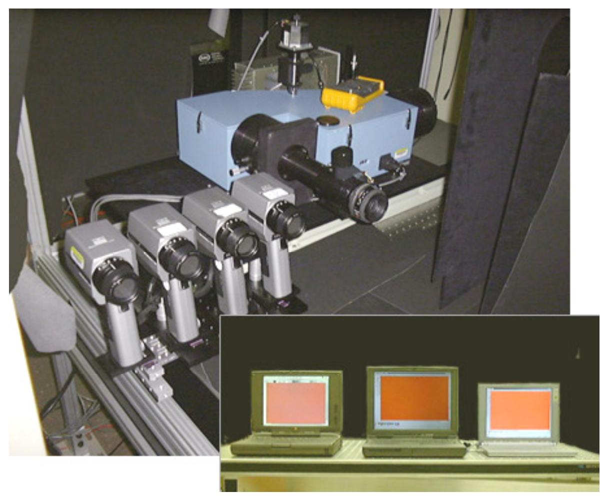


Figure 5. NIST calibration facility for colorimetry of displays

first successfully established the lumen using this new technique several years ago. Since then, a few other national laboratories have adopted this approach.

The uncertainties of the photometric base unit maintained in major national laboratories, including NIST, are about 0.5%[1]. Based on this, the best uncertainty achieved in industry is about 1 %. In practice, however, much larger uncertainties are often seen, in particular in products such as LEDs, displays, or flashing signal lights, which differ substantially, in spectrum, shape, or light distribution, from the standard lamps provided by NIST. Industries that produce these products require higher measurement accuracies than now available. To accommodate such new and evolving industrial needs, one direction of NIST's research in photometry and colorimetry has been to widen the range of measurement scales and calibration services. This requires research

[1] with coverage factor, k=2, thus at 95 % confidence level.

not only on transfer standards but also on measurement methods that can be easily adapted by industry engineers to meet their own specific requirements. For example, we recently developed an improved technique for calibrating colorimeters for displays (Fig. 5) that allows automatic correction of errors for any colors of a display by measuring only four of its colors. Another example is the recent establishment of the NIST scale for flashing light (lx·s). Calibration services are now provided for flash photometers to measure aircraft anticollision lights (white and red) used by airlines and the avionic industry. A current area of active research is the establishment of LED photometric standards.

Several critical applications, among them the lumen scale maintained by lamp companies worldwide and the illuminance scale maintained by the photographic industry, require even lower uncertainties than those available at national metrology laboratories. To accommodate such needs, research has focused on reducing the uncertainty of the NIST photometric base unit to 0.1%. A number of subtle, sophisticated technical difficulties need to be overcome before this goal can be realized. One area of research involves the conversion from a radiometric quantity (normally derived using monochromatic sources with a narrow beam geometry) to a photometric quantity (normally derived using broadband sources in a uniform illumination geometry). One needs to consider in detail the interaction of light at the edges of the aperture, interreflections between filter surfaces, detector nonuniformity, control of stray light, etc. Another difficulty is the stability of the reference-transfer standards. Once the candela is realized with a 0.1 % uncertainty, the uncertainty of the lumen needs to be improved to a similar degree. Several radiometry projects are underway at NIST to develop new technologies to eliminate or greatly reduce the uncertainty components so the 0.1% goal can be achieved in the near future.

The $V(\lambda)$ function has been used as a basis of photometry for 75 years, and the physical measurement of light is well established. While the $V(\lambda)$ function will continue to serve its purpose as far as the legal metrology of light is concerned, there are many cases in which a person's visual response does not match photometric measurements. For example, in a fairly dark environment such as on a lighted road at night, it is well known that the peak of the human eye's response will shift from the green toward the blue spectral region as the eye adapts to the lower light level. Visual response under these conditions, called mesopic vision, has not been standardized yet, though the response for very dark environments (scotopic vision) has. It is also known that saturated colors---such as the red in a red traffic signal---look brighter than white light with the same luminance or luminous intensity. Such visual effects have not been standardized for metrology use. In another example, the visual response for flashing lights (effective intensity)---important for signaling applications---has not been standardized though several models are already in use. Research on these visual phenomena and perception in a wider range of visual environments is being carried out worldwide, and may be available for physical photometry in the future.

The National Bureau of Standards (now NIST) played an important role in establishing photometry 75 years ago, and NIST has been contributing to this important field ever since. For the 21st century, NIST will continue to take a leadership role in advancing our understanding of photometry and colorimetry, providing new technologies, standards and services to U.S. industry.

References

1. S.W. Brown, B.C. Johnson, and K.R. Lykke, Opt. Photon. News, **12** (2), 24-9 (2001).

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