The measurement of light: 'the' candela and New Zealand's candela

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The origin of the candela

For much of our history, subjective measurements of light made with only the aid of our visual system have been sufficient for survival and risk mitigation. However, demand for better information in making decisions has resulted in the development of measurement tools and the codification of agreed scales. Today the candela, the unit for brightness of a light source, is defined to be one of the seven base units of the International System of Units (SI).

Long before the definition of the candela, scales for brightness of light sources were in use, with evidence of astronomers making note of the relative brightness of stars as long ago as 100 BC [1]. Without any technology for recording that light, however, progress to establish universal scales relied on human observers making subjective judgements against references such as 'twilight' and much later against standard lamps such as that defined by the British Metropolitan Gas Act of 1860.

Progress to transfer the scale for source brightness from the human visual system to an objective scale is therefore a relatively recent one, driven largely by the availability of new methods of measurement and the commercial needs of electric lighting manufacturers. These two drivers arose in the late 19th Century although it was to be some time before the full potential of the first would be fully realised.

The first driver was the development of a method of absolute radiometry, i.e. the measurement of optical power, which was developed independently by Ångström and Kurlbaum in the 1890s [2]. It was based on the principle of electrical substitution which involved irradiating an absorbing cavity with the incident radiant flux, allowing the temperature of the cavity to rise to some equilibrium value. When a shutter was closed to remove the heating effect of the incident light, electrical heating was provided to maintain the temperature. The optical power was then determined by measuring the electrical power provided to the cavity.

The other coincident impetus for improvement in measurement scales was the burgeoning electric lighting industry. It required a system that could measure the intensity, as perceived by the human visual system, of a light source of any spectral shape. At the time, lamps were being compared to a variety of standard lamps (Britain, France and Germany all had their own) chosen originally to serve the needs of gas lighting. As the new electric lighting was of a different spectral distribution, direct comparisons were becoming difficult, not to mention that the 'standard' lamps varied somewhat in brightness and spectral shape themselves, depending on environmental conditions.

To resolve this, two components were required—a knowledge of the spectral sensitivity of the human visual system, and a more reliable standard light source of known and unvarying spectral shape and brightness.

The first component was worked on in the first two decades of the 20th Century by asking subjects in darkened rooms to match the brightness of two patches of different coloured light. In 1924, Gibson reviewed several such studies, combined their data with some of his own results, and produced a function describing the relative sensitivity of the average human system to different wavelengths of light [3]. It was adopted by the Commission Internationale d'Eclairage (CIE) in 1924 as the CIE Standard Photometric Observer and is shown in Figure 1.

The second component was to decide on a universal standard lamp. The CIE worked with the International Committee for Weights and Measures (CIPM) to define one, and in 1948, the

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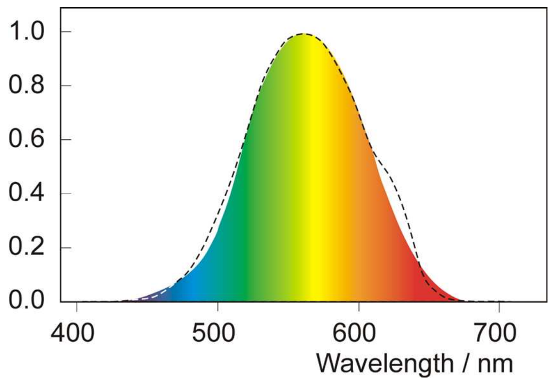

Figure 1. The relative response of the eye to different wavelengths—the photopic response curve. The dashed line shows the response of one good-quality light meter.

CIPM adopted a definition for a new unit, a candela, to be the luminous intensity of a Planckian radiator at the temperature of freezing platinum. The candela was subsequently introduced to the SI as one of the base units. The known spectral shape of a Planckian blackbody, along with the standard photometric observer function, allowed the luminous intensity of any source to be uniquely specified, and the field of photometry was given a firm footing. The candela was, and remains, the only SI base unit to describe a human perception rather than an objective physical reality.

Having such a definition was a tremendous step forward in the establishment of the photometric scale, but actual realisation of blackbodies of the required temperature proved difficult and variable. Meanwhile progress in absolute radiometry was being made by cooling the electrical substitution radiometers of the 1890s to cryogenic (liquid helium) temperatures. This process minimised many of the sources of uncertainty and provided a route to improve the realisation of an alternatively defined light source. In response, a new definition of the candela was adopted by the CIPM in 1979:

> *The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.*

This definition effectively pinned the absolute value of the peak (555 nm, ~ 540 × 10^{12} hertz) of the photometric observer function, relating it to a radiometric quantity measured in watt per steradian. (A steradian is the solid angle subtended at the centre of a sphere of unit radius by unit area on the sphere surface.) It also opened the field up to different methods of physical realisation and several are in use at national metrology institutes (NMIs) around the world today.

Realisations of the candela

The most common method of realising a radiometric scale from which the photometric scale can be derived is the cryogenic electrical substitution radiometer, used with selected laser lines to calibrate the irradiance responsivity of silicon photodiodes. The optical power of each laser line is measured by the radiometer and then the diode is placed in the beam and its responsivity at those wavelengths is determined.

As the relative spectral responsivity of silicon photodiodes can be accurately modelled by taking into account losses primarily due to reflectance from the front surface and non-unity internal quantum efficiencies, the responsivity at any wavelength within the region for which the model is valid can be interpolated. This type of realisation is considered a 'detector-based' method.

In contrast, a 'source-based' method relies on the known spectral radiant power of either a blackbody radiator at a known temperature or electron storage rings which emit synchrotron radiation. Blackbody radiators have the advantage that they emit unpolarised radiation over very broad wavelength ranges, the difficulty lying primarily in measuring the temperature, particularly of high-temperature blackbodies required for significant visible radiation.

Synchrotron radiation on the other hand is highly versatile, as it is emitted over a very broad spectral range and is available over a dynamic range of up to 12 decades [3]. The main obstacle is cost and availability, with most synchrotrons being dedicated to the emission of x-rays for purposes other than radiometry. Only two NMIs (National Institute of Standards and Technology (NIST) of the USA and Physikalisch Technische Bundesanstalt (PTB) of Germany) routinely use synchrotron radiation in scale realisation.

New Zealand's own candela

New Zealand's candela was imported in 1953, shortly after its definition, via gas-filled projector lamps calibrated for luminous intensity at the National Physical Laboratory (UK's NMI). These and similar lamps (see Figure 2) were the basis for the dissemination of the candela to New Zealand industry for 35 years until the 1980s. The first realisation of the candela in New Zealand was made in 1989 using two room-temperature absolute radiometers that were constructed in 1984 by Visiting Fellow Franz Hengstberger, to calibrate several newly-purchased standard lamps of improved design. In 1992, a scale of spectral responsivity was established on optical-grade silicon photodiodes of known internal quantum efficiency by measurement of their reflectance losses. An international comparison demonstrated that this scale was in excellent agreement with those of other countries. When a cryogenic radiometer was purchased in the mid-1990s, this spectral responsivity scale was refined so that an improved realisation of the candela (with lower measurement uncertainties) became available in 1997 [4]. Today, New Zealand's 'own' candela is realised using this cryogenic radiometer onto locally-made photometers and is maintained at NZ's NMI, the Measurement Standards Laboratory of New Zealand (MSL) within Callaghan Innovation.

Shortly after commissioning the cryogenic radiometer, New Zealand participated in the first and only CIPM measurement comparison of cryogenic radiometry involving 17 NMIs around the world between 1996 and 1999 [5]. This comparison established the equivalence of cryogenic radiometers and provided confidence in the suitability of this technology as a basis for the future of radiometry and photometry.

Currently the New Zealand candela is realised using the detector-based method [6] according to the following steps. First a radiometric scale of amps/watt is realised onto a silicon photodiode-based detector via the cryogenic radiometer and a series of laser wavelengths. The full spectral responsivity is interpolated from modelling of the silicon responsivity and is in turn used to calibrate a photodiode to be used in a photometer—an instrument to measure the luminous intensity of an arbitrary light source. Knowing the spectral response of this second diode,

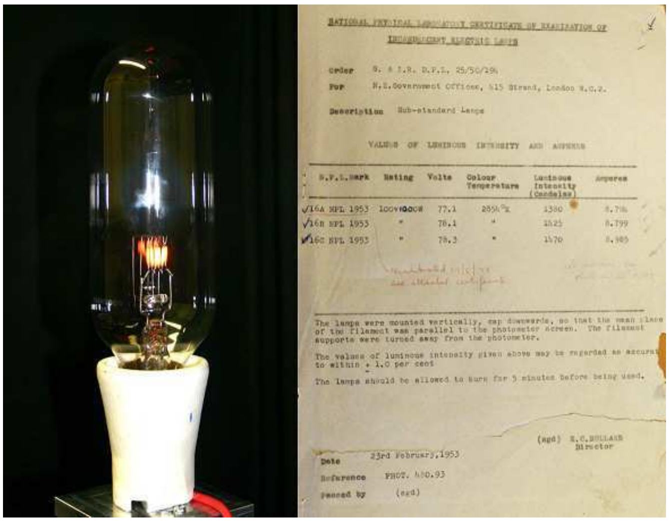

Figure 2. One of the first lamps to arrive in New Zealand calibrated in candelas along with its 1953 calibration certificate.

a filter made of up to eight layers of coloured glass is designed and fabricated so that the final spectral responsivity of the diode with the filter matches as closely as possible the Standard Photometric Observer function (Figure 1). After recalibration against the reference detector along with dimensional calibration of the area of its aperture, this photometer can be used to transfer the scale to users' lightmeters or luminance meters, in use every day across a range of New Zealand industries including meatworks, the oil industry, lighting engineering, panel displays and even surgical theatres.

MSL continues to participate in international comparisons of luminous intensity to ensure the ongoing stability of its own scales and to contribute to the stability of the international realisation of the unit. Details of the results of all such comparisons are available on the key comparison database of the International Bureau of Weights and Measures (BIPM) (http://kcdb.bipm.org/).

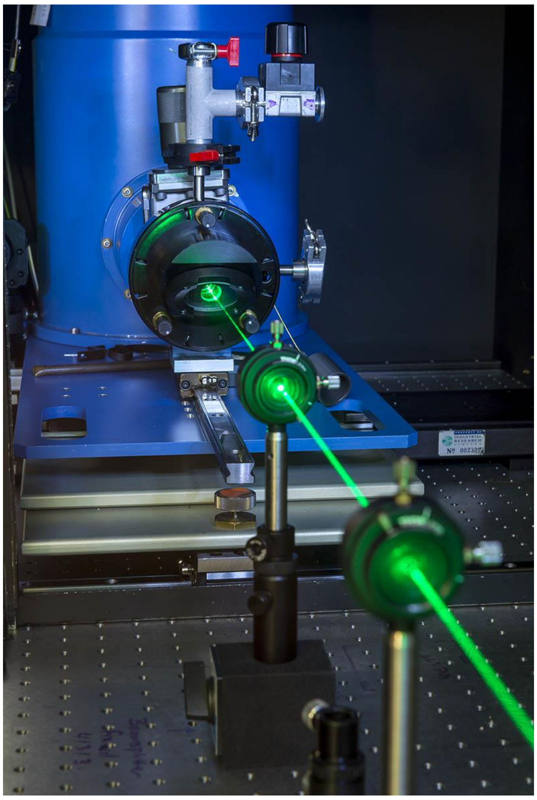

Figure 3. MSL's cryogenic radiometer.

It should be noted that the result of such comparisons is not to adjust scales to account for differences between one measurement and an international average. Rather, provided the value submitted by a participant is consistent with those of other participants within the estimated uncertainties, no adjustment is made. The candela realised at MSL, for example, is retained 'as measured' and therefore can be considered a genuinely 'New Zealand candela'.

It should also be noted that such comparisons do not guarantee that a universal systematic error in the realisation is eliminated. The majority of NMIs realise the candela via similar detector-based methods, and therefore it is entirely possible that some source of systematic error is yet to be found.

The future for the candela

A promising new method for realisation of the absolute radiometric scale is looking to challenge the supremacy of the electrical substitution radiometer. As mentioned above, the relative response of silicon photodiodes is known well enough to enable interpolation of responsivity between calibrated points. Recent work on the design of a photodiode that has a predictable almost-unity quantum efficiency and that is mounted with another identical photodiode in a 'trap' assembly geometrically arranged to eliminate loss due to surface reflections has been provisionally shown to produce a predictable quantum efficient detector (PQED) (Figure 4).

The advantages of this detector are twofold: its absolute responsivity is thought to be able to be known to levels beyond those currently achievable (1 ppm as opposed to the current limit of ~ 10 ppm with cryogenic radiometers) and it is a cheaper, more reliable system that can be operated at liquid nitrogen temperatures. The PQED scale of absolute radiometric power is about to be compared against a series of cryogenic radiometers around the world and will come up against the MSL system in 2016. If the PQED meets expectations, it may soon replace cryogenic radiometers as the preferred route to realisation of the candela.

Figure 4. The predictable quantum efficient detector (PQED) may replace the cryogenic radiometer as the preferred route to physically realise the candela from its definition.

The success of the PQED may also aid in meeting a rapidly approaching challenge for optical metrology, namely that of photon counting. The rise of quantum and photonic technologies will require the development of reliable measurement in the single-photon regime. For those measurements to be traceable to the SI, there will need to be direct links made between the different instrumentations employed to make radiometric measurements at different flux levels. Reliable sources and detectors covering the full range from classical high flux levels to the few-photon level are currently being developed and tested for their metrological suitability. In response, the very definition of the candela is under reconsideration—to extend its definition to explicitly relate the radiant intensity at classical levels to photon intensity—ensuring it will meet emerging needs for metrology in this regime [3].

The development of the candela from being measured quite literally 'by eye' to being a well-defined and widely used unit of measurement has both followed and led technological advances in turn. MSL is contributing to the future of the candela to ensure that it will meet all measurement needs. In the meantime, accurate and reproducible measurements of light contribute to better decision making and risk mitigation, positively impacting the health and economic success of all New Zealanders.

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