RADIOMETRIC AND PHOTOMETRIC MEASUREMENTS AT THE LNE-INM/CNAM

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Abstract : Optical radiation can be measured according two ways. One way is radiometry which deals with the physical aspect of optical radiation and the other way is photometry which is concerned by the action of optical radiation on the eye of an observer. The results of radiometric measurements are expressed in the usual physical SI units and photometric quantities have their own SI units. This paper describes the use of a cryogenic radiometer for realizing radiometric references. It gives also the links existing between radiometric and photometric units and explains how to realize the candela which is the photometric base unit in the SI system of luminous intensity and the lumen which is the photometric unit for flux, starting from the cryogenic radiometer as reference.

1. INTRODUCTION

The various quantities defined for radiometric measurements are used for characterizing the power transferred by optical radiation and use physical units. The photometric measurements are used to quantify the visual effect of radiation on the human eye. But, as eye is a very complicated organ and not the same for everybody, it is necessary to define a standard observer which is mainly described by the luminous efficiency function V(λ) [1]. They use special SI units, the photometric units. At present time radiometric and photometric measurements are closely linked through the present definition of the candela.

In this paper, the present radiometric reference of the LNE-INM/CNAM is described. Then the use of this radiometric reference for realizing the photometric units is presented.The two major photometric quantities for which the laboratory is providing standards are the luminous intensity and the luminous flux.

2. RADIOMETRIC REFERENCES

2.1 Operating principle

Cryogenic radiometers are recognised as by far the most accurate radiometric standards. [2] The principle of this apparatus is very simple and more than 100 years old. It is based on the electrical substitution. In a first step, the optical radiation to be measured is put into an absorbing cavity giving a rise in temperature of this cavity. In a second step, the optical radiation is replaced by an electrical heating in order to get the same rise in temperature. If the radiometer would be perfect, the optical power will be equal to the electrical power. In practice, it is necessary to do several corrections to get the accurate results. Working at very low temperature allows to increase the responsivity of the device and to reduce dramatically the correction factors and their associated uncertainties.

The cryogenic radiometer used for the present measurement is the LaseRad system from Cambridge Research Instrumentation. Customized specifications provide an operating power range around 1 mW, and enable measurements to be carried out between 250 nm – 2000 nm. [3]

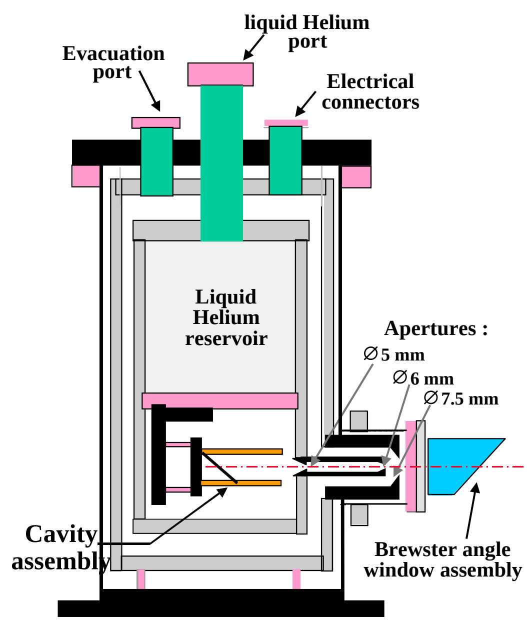

Figure 1- Schematic drawing of the cryogenic radiometer.

2.2 Description of the system

The design of the cryogenic radiometer is shown in figure 1. Its basic element is the highly absorptive cavity which heats up when it is either irradiated or electrically heated. The cavity is mounted horizontally and is thermally linked to the helium liquid reservoir. Both are placed in a high-vacuum enclosure, which is closed by a quartz window. To minimize reflective losses, this window can be conveniently adjusted to the Brewster angle. Considering the shape and the location of the cavity, the radiometer can only be used with collimated laser beam of diameter up to 2 mm.

2.3 Correction factors

To know accurately the radiant power in the laser beams, which are used in transfer detector calibration, several corrections must be applied to the cryogenic radiometer laser power measurement. These corrections are listed in table 1 which gives an example of the value of these different correction factors for the wavelength of 543 nm as well as the uncertainty on their determination.

Table 1 – Correction factors and uncertainty budget of the cryogenic radiometer

Measurement	Correction	Relative uncertainty (1σ)
Cavity absorptance	0.99988	1×10^{-5}
Window transmission	0.99974	3×10^{-5}
Heating non-equivalence	1.00000	1×10^{-5}
Electrical power measurement	1.00000	3×10^{-5}
Global correction	**0.99960**	**5×10^{-5}**

2.4 Spectral responsivity detector calibration

The calibration of a detector is carried out at some laser wavelengths by direct comparison to the cryogenic radiometer. The experimental set-up used for these measurements is shown in figure 2. The light emitted by the laser is power stabilized by a feedback photodiode and a liquid crystal modulator. The achieved stability is in the range of few parts in 10^5 during the time needed for a comparison, typically 15 minutes. The spatial filter adjust the beam size to the right diameter and removed the stray light. The test detector is compared to the cryogenic radiometer by putting, successively the two detectors into the laser beam using a translation stage.

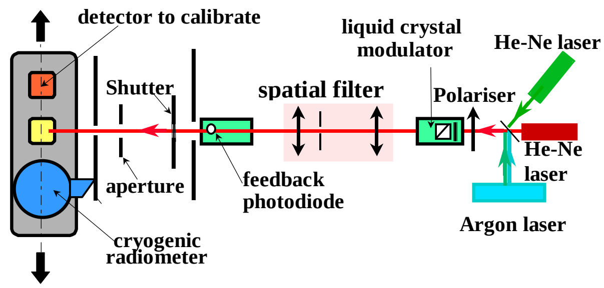

Figure 2 – Experimental set-up for calibrating detectors against the cryogenic radiometer

The uncertainty on the results of these calibrations depends on the stability of the detector under test. At present time, the best transfer detectors are Si photodiode trap detectors. They are calibrated with a global standard uncertainty comprised between 1 or 2 parts in 10^4, in the visible range [4].

To extend the spectral responsivity calibration of the detector all over the spectral range, in a second step we use a relative spectral responsivity measurement set-up. The measurement of the relative spectral responsivity is carried out by comparison of the response of the test detector to that of a non selective cavity shape pyroelectric detector, when they are irradiated by the same monochromatic flux. In this calibration, the major cause of uncertainty is coming from the low responsivity of the cavity shape pyroelectric detector giving a signal to noise ratio in the range of 10^3 and a standard uncertainty of about $2\ 10^{-3}$ in the visible range used for detector calibration.

3. REALISATION OF THE CANDELA

3.1 Principle of measurement

The present definition of the candela is : The candela is the luminous intensity, in a given direction, of a source that emits a monochromatic radiation of frequency 540.10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.[5] It can be also written in a numerical form according to the following equation.

$$I_v = K_m \int_\lambda I_{e,\lambda}(\lambda).V(\lambda).d\lambda$$

This definition gives only the numerical relationship between the luminous quantities and the radiometric quantities. The luminous intensity I_v is linked to the spectral radiant intensity distribution $I_{e,\lambda}$ (λ), weighted by the V(λ) function and multiplied by K_m. V(λ) is the spectral luminous efficiency of standard observer defined by the CIE in 1924 and K_m is the maximum luminous efficiency which fixes the relationship between luminous and radiant quantities. By definition K_m is equal to 683 lm/W.

The principle used to realize the candela is directly linked to the definition. The source to be calibrated in luminous intensity I_v, irradiates through a filter, a radiometer able to measure the irradiance it receives, E_e in an absolute way, in Wm^{-2}. The transmittance of the filter $\tau(\lambda)$ matches as closely as possible the $V(\lambda)$ function. In these conditions the luminous irradiance is given by

$$E_v = (K_m . E_e).F$$

In this equation the term

$$F = \frac{\int_\lambda S_{e,\lambda}(\lambda).V(\lambda).d\lambda}{\int_\lambda S_{e,\lambda}(\lambda).\tau(\lambda).d\lambda}$$

With : $S_{e,\lambda}(\lambda)$ relative spectral distribution of the source to be calibrated,

$\tau(\lambda)$ transmission of the real filter,

$V(\lambda)$ spectral luminous efficiency function.

is the spectral matching factor which takes into account for the discrepancy between the perfect $V(\lambda)$ filter and the realized filter.

3.2 Standard photometers

For realizing the luminous intensity unit according to the principle described previously, it is necessary to built standard photometers directly calibrated by comparison to the cryogenic radiometer.[6] These standard photometers are made with silicon trap detectors, a set of colored glass filters which adjust the spectral responsivity of the detector to match the $V(\lambda)$ function, and a calibrated aperture (figure 3).

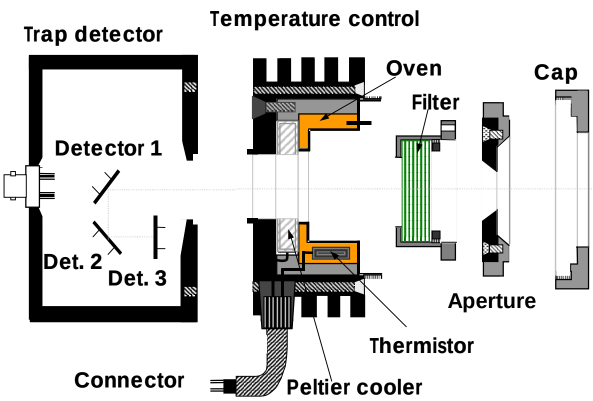

Figure 3 – Schematic drawing of a standard photometer.

The aperture and the $V(\lambda)$ filter are put in a temperature controlled housing.

For characterizing these photometers we have had to realize experimental set-up for measuring the spectral responsivity of detectors (described previously), the spectral transmittance of filters and the area of apertures.

3.3. Characterization of the V(λ) filters

Using the relative spectral responsivity of the trap detector selected for realizing the photometers and the $V(\lambda)$ function, we have determined the theoretical filter to match $V(\lambda)$. From glass filter catalogue from Schott, we have selected some glasses which seem appropriate for approximating the ideal filter. Then, we have determined the number of suitable filters and calculated their thickness to approximate the ideal filter. Three filters were calculated, realized and measured on our experimental set-up for filter transmittance measurement.[7]

The results of the study of the $V(\lambda)$ filter is shown in figure 4 which displays the deviation of the realized filters from the ideal filters. In the visible spectral range the relative standard uncertainties are usually less than 10^{-3}.

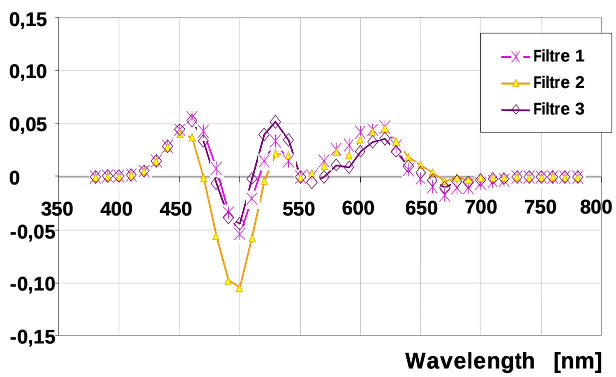

Figure 4 – Transmittance of the realized V(λ) filter.

3.4. Aperture measurements

To measure the area of each aperture we have used a non contact method developed in our laboratory.[8] The relative uncertainties achievable for aperture from 6 to 10 mm in diameter are in the range from 3.10^{-4} to 5.10^{-5}.

3.5. Photometer calibration

The components previously studied have been put together to realize five photometers. The complete photometers were calibrated directly, in absolute spectral responsivity by comparison to a transfer detector calibrated against the cryogenic radiometer on an experimental set-up using a double monochromator. The luminous responsivity and the spectral matching factor (SMF) were calculated for each photometer using the absolute spectral responsivity. The results of this study are given in the table 3.

Table 3 – Responsivity of the standard photometers

Photometer	Responsivity A/lx	SMF
PH-04-A	$2.5115.10^{-8}$	1.0022
PH-04-B	$1.4848.10^{-8}$	1.0063
PH-04-C	$2.3335.10^{-8}$	1.0038
PH-04-D	$1.6304.10^{-8}$	1.0151
PH-04-E	$9.6814.10^{-9}$	1.0369

3.6. Luminous intensity measurement

The standard photometers are designed to measure illuminance in the plane of its entrance aperture. So to calibrate incandescent standard lamps in luminous intensity we have to measure accurately the distance between the filament of the lamp and the aperture of the photometer. This is done on a photometric bench with a very good quality ruler and precision indexes.

3.7. Uncertainty budget

The components of the present uncertainty budget are detailed in table 4. The first component is the reproducibility of measurements (type A). The second one is related to the geometrical parameters. The uncertainties on electrical measurements for the photometer as well as for the lamp are components three and four. The uncertainty on the luminous responsivity which includes mainly the uncertainty on the spectral responsivity of the photometer is the last one and the highest. The present total relative standard uncertainty is 0.22 (k=1).

Table 4 – Uncertainty budget for the realization of the candela (relative values).

Reproducibility	0.01
Solid angle	0.07
Photometer current	0.06
Lamp intensity	0.06
Luminous responsivity	0.19
Global uncertainty (1σ)	**0.22**

4. LUMINOUS FLUX MEASUREMENT

4.1 Principle of measurement

Traditionally a luminous flux standard lamp is a lamp for which the luminous flux is measured in the space all around it. The luminous intensity distribution can be measured with a goniophotometer. The performances of this apparatus must be as high as possible in order to keep the added uncertainties lower or at least of the same order of magnitude as the uncertainties achieved in realizing the candela.

4.2 The goniophotometer : To realize the luminous flux unit, the lumen, a large size goniophotometer (7 m diameter) has been built (figure 5).[9]

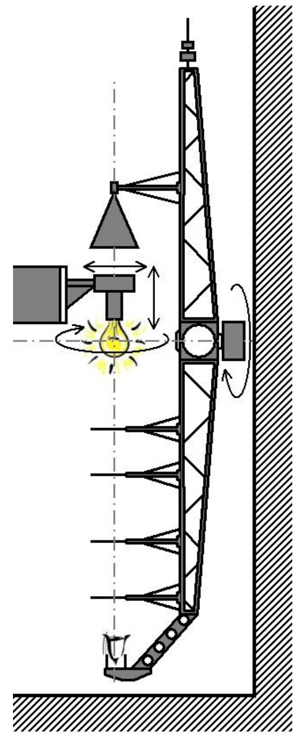

Figure 5 – Schematic drawing of the goniophotometer.

A standard lamp of luminous flux must be operated in a prescribed burning position, generally vertical, cap up. For this reason the goniophotometer realizes the spatial measurement of the luminous intensity according to the following method : the lamp is rotated around its vertical axis over a full circle (360°). The photometer is rotated in a vertical plane containing the axis of the lamp. Its rotation is only a half of a circle (180°). The lamp is put at the center of the circle described by the photometer. These two rotations allow measuring the luminous intensity distribution of the lamp all over the space around it.

The main characteristics of the apparatus are :

- Distance between source and detector : 3.4 m
- Photometer V(λ) corrected, diameter : 60 mm
- Speed of motion of the detector : 4°/s
- Uncertainty on the angular setting : 0.02°

Before and after each set of luminous flux measurement, the photometer is calibrated using luminous intensity standard lamps. A set of measurement lasts about one month.

The total flux emitted by the lamp is calculated by integrating the luminous intensity distribution over 4π steradians.

4.3 Incandescent standard lamps

The standard lamps usually used for maintaining the luminous flux unit, the lumen, are incandescent lamps specially manufactures in order to be stable and reproducible, with a smooth intensity distribution. They are supplied by DC current. For this type of lamps the temporal aspects of the “on the fly” measurements is relatively easy to take into account for.[10]

The achievable uncertainty is 4.10^{-3}. In this uncertainty, $2.2.10^{-3}$ are coming from the realization of the luminous intensity unit.

5 CONCLUSION

It is a long way between the primary standard, the cryogenic radiometer, and the lamps used for transferring the luminous flux unit to industry. It involves a lot of specific measurements in almost all the fields of activities of the radiometry, spectro-radiometry, photometry and spectro-photometry.

Due to this large quantity of extra measurements needed to realize luminous flux standard lamps, the traceability is not very easy to determine and need to be carefully check at each step. Another consequence of that is also the deterioration of the uncertainty along the chain. Starting with an uncertainty of approximately 0.01% at the top of the calibration chain we have only 0.4% at the end for the realization of luminous flux standard lamps.

Nevertheless, in spite the need of numerous additional measurements for characterizing the photometers and the goniophotometer, the achievable uncertainty is perfectly acceptable for most of the common use.

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