Towards a new realization of the SI-base unit "Candela"

Schneider, P., Sperling, A., Salffner, K., Nevas, S.
Fachbereich 4.1 Photometrie und angewandte Radiometrie
Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
Philipp.Schneider@ptb.de

1 Introduction

The SI-base unit "Candela" for luminous intensity at Physikalisch-Technische Bundesanstalt (PTB) is achieved through a traceability chain to the radiometric national standard of PTB following the definition of the "Candela" in 1979 [1]. The unit is realised with a network of photometers and luminous intensity standard lamps [2]. By means of the planned new realization the traceability route will become shorter and a lower uncertainty in the realization of luminous intensity and the derived photometric units will become possible.

2 Realisation and maintenance of the unit: State of the art

For the realization of the unit "Candela", calibrated detectors and light sources are used. In the first step of the traceability chain for calibration of photometers the radiant power of a monochromatic source (laser) is compared to the electrical power necessary to substitute this optical power within a cryogenic radiometer. This substitution is used to determine the spectral power responsivities of Si-trap detectors at a set of discrete wavelengths compared to the cryogenic radiometer [3]. By using a macroscopic model for the spectral responsivity function of the Si-trap detectors, the measured discrete responsivity values resulting from the comparison with the cryogenic radiometer are interpolated over the full spectral range of interest. The spectral power responsivities of these trap detectors are then transferred to other trap detectors, photodiodes and filtered radiometers and converted into spectral irradiance responsivities. In the next step of detector traceability the spectral irradiance responsivity values are transferred into the integral photometric responsivities of photometers with respect to the spectral distribution of radiation according to the Illuminant A (2856 K). On the source side the relative spectral distribution of a source (luminous intensity standard lamp) is measured traceable to the national primary standard for spectral irradiance, which is a high-temperature blackbody radiator. The measured spectral distributions are also traceable to the cryogenic radiometer via filter radiometers used to determine the temperature of the blackbody radiator.

Using this traceability chain the unit distributed by PTB is build on a network of several photometers and groups of standard lamps. The purpose of this network is to ensure an excellent stability of the unit [2]. The "Candela" is realized on annual terms with lamps of this network which represents the unit as it was realized in 1979 for the change of the definition. The lamps maintain the luminous intensity at 2042 K (the melting point of platinum) and other temperatures e.g. close to the 2856 K and in between, granting longer lifetimes of the lamps for lower distribution temperatures. In this way differences between the realized unit and the maintained unit can be detected.

The realization of the unit using the traceability route as mentioned above results in an uncertainty for the luminous intensity of about $u(I) \geq 2{,}5 \cdot 10^{-3} (k = 2)$. The maintenance via the ensemble of incandescent lamps, though is achieved with an uncertainty of only about $u(I) \geq 5 \cdot 10^{-4}$ $(k = 2)$ and a stability of $\left|\frac{\Delta I}{I}\right| = 2 \cdot 10^{-4}$. The uncertainty and the stability of the maintained unit are mainly composed of the electrical and mechanical properties of the lamps and their aging behaviour. For comparison the values of 10 years are depicted in Figure 1.

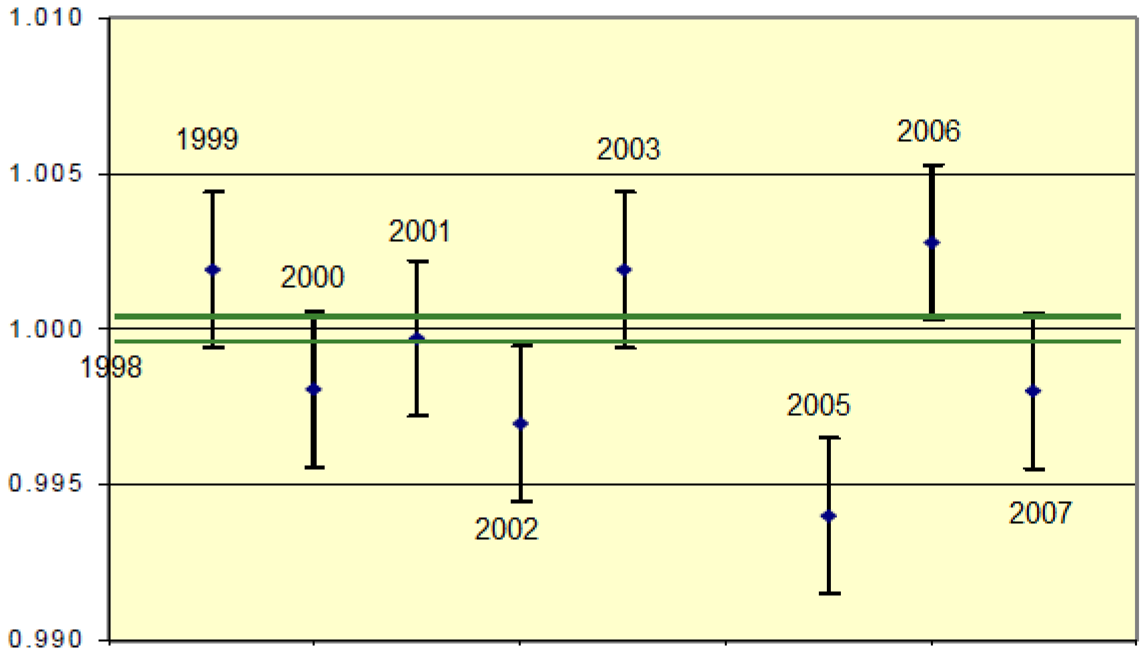

Figure 1: Comparison of the maintenance (green stripes) and the realization (blue rhombs) of the "Candela" with one photometer over the course of 10 years (from [4]).

3 Advantages of the new realization

The current realization chain for the unit “Candela” has an order of magnitude larger uncertainties than those for the maintenance based chain on the standard lamp group. The knowledge of the properties and the expected long-term behaviour of these lamps are included in the maintained unit and its uncertainty, though posing the problem of a unit based on artifacts. These artifacts are affected by aging, which can only be predicted to a certain amount, and they cannot be easily replaced. A new realization with lower uncertainty would allow for checking the aging of lamp groups and to change over from maintenance by lamps to maintenance by detectors. Additionally the photometric units derived from luminous intensity, like luminance or luminous flux, can be provided with a lower standard uncertainty too.

4 Reducing the uncertainty

For achieving a lower uncertainty all known contributions to the uncertainty budget of the current realization have been evaluated, e.g. the spectral responsivity of the detectors used in photometer calibration, change from power to irradiance mode, interference correction, stray light, etc. To reduce the evaluated uncertainties in the “Candela”-realization a photometric trap detector, also called $V(\lambda)$-trap detector, will be build. This detector can be calibrated in terms of radiant power responsivity directly against the cryogenic radiometer. Using a specially designed spectral filter the spectral responsivity of the trap-detector-filter combination will be matched to the luminous efficiency function $V(\lambda)$ and the remaining deviations of the filter will be determined by an accurate relative measurement. The $V(\lambda)$-trap detector can then be directly used to realize the luminous intensity as well as to determine the temperature of the high-temperature black body, shortening the traceability route dramatically as can be seen in the graphical comparison of Figure 2. Therefore, by reducing the contribution of errors due to transferring the responsivities between different detectors and by using correlations, the total uncertainty along the traceability route is reduced.

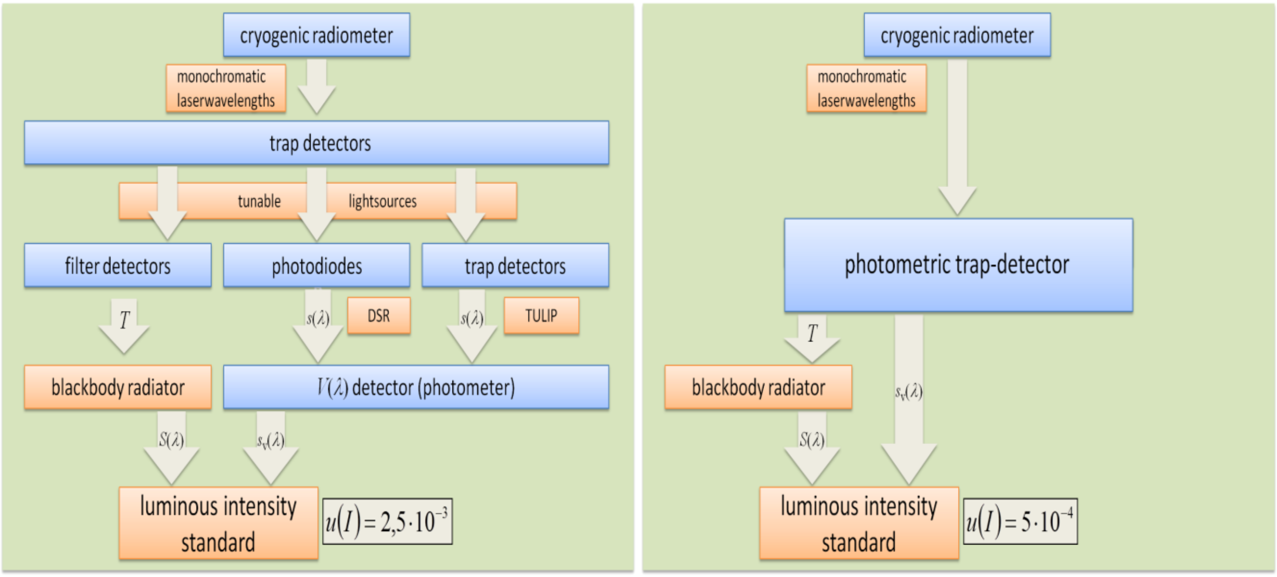

Figure 2: Comparison of the current traceability chain and the new traceability chain using the $\boldsymbol{V(\lambda)}$trap detector.

In *Figure 3* a first sketch of the $V(\lambda)$-trap detector is shown, consisting of an aperture, the filter, the trap detector and a CCD-camera. The CCD-camera is placed behind the trap detector during characterisation and alignment steps in order to track the illumination of the photodiodes and the transmitted light. The design of the detector will be adapted according to simulation and characterisation measurement results for the different parts of the detector.

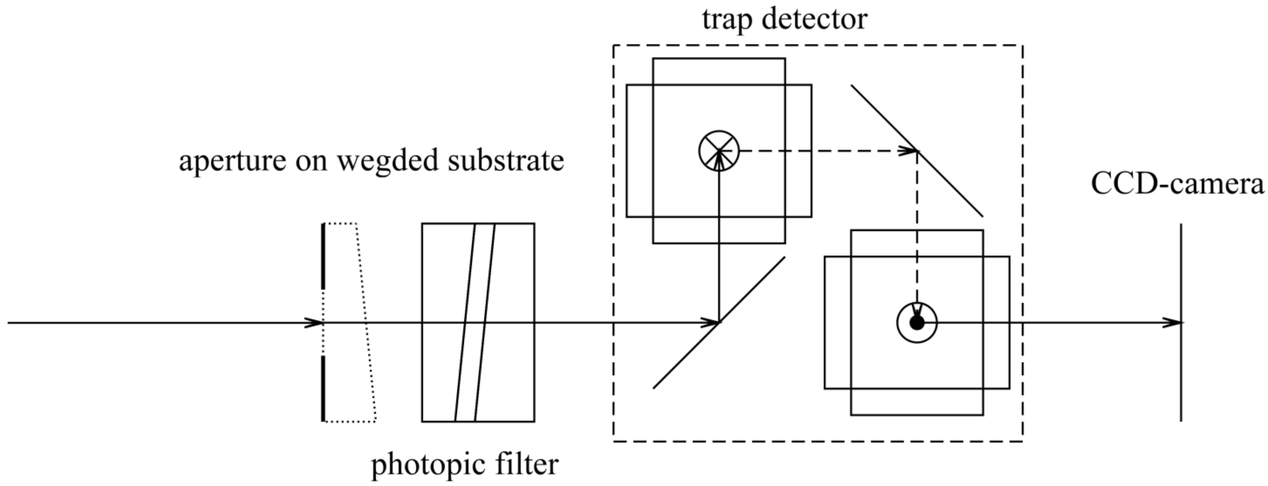

Figure 3: Scheme of the $V(\lambda)$-trap detector.

A six-element transmission trap-detector, consisting of six Si-photodiodes, is being used as a detector. This configuration provides several advantages including an improved spatial homogeneity of the responsivity and absolute sensitivity in comparison with single photodiode detectors or three element reflection type trap detectors which are often used instead. The improvement in the measured homogeneity can be seen in Figure 4. In addition interference effects due to inter-reflections between filter/aperture interfaces and the diode surfaces are avoided because the light reflected from the photodiode surfaces is transmitted through the trap detector. The polarisation dependency of trap detectors is greatly reduced by a special orientation of the photodiodes described by Gardner [5] and measured by Kübarsepp et al [6].

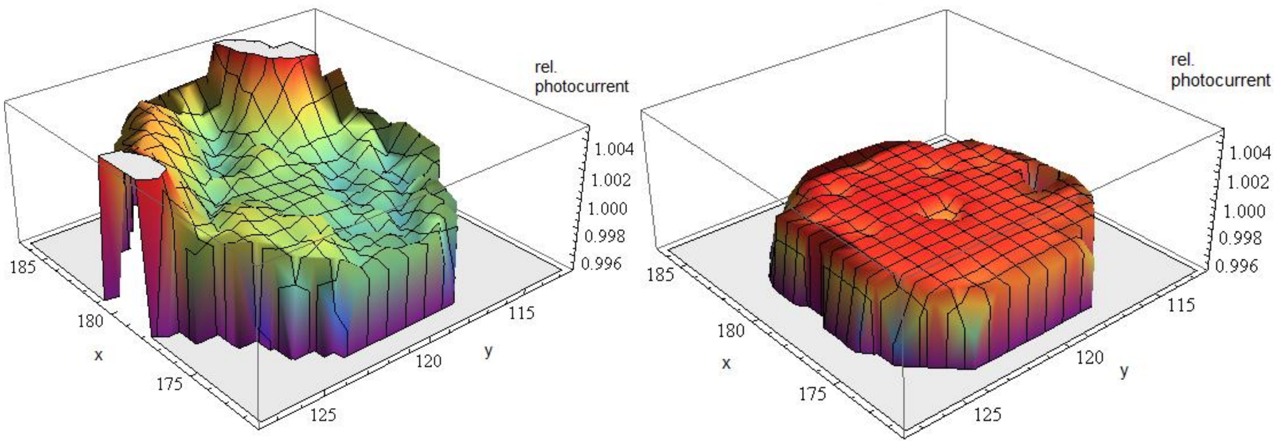

Figure 4: Spatial homogeneity of a single Si-photodiode (left) and of a six-element trap detector (right). The values are normalised to those at the center of the scanned area.

Current photometers usually use filters consisting of plane parallel glass filters directly in front of the photodiode. Inter-reflections from the parallel surfaces can cause interference oscillations in the responsivity ([7], [8]) which add to the uncertainty budget, especially of collimated laser radiation is used for spectral calibration. In normal use of a photometer these oscillations pose no problems. However for the design of the new standard for the realization of the “Candela” this interference has to be taken into account and should be minimised using for example wedged filters or glass substrates. The filter used to match the trap detectors spectral responsivity to the luminous efficiency function has been simulated. The effects of wedges inserted in a filter in comparison to filters consisting only of parallel filters are modelled and characterised. First measurements comparing plane glass filters with an attached wedged glass to filters consisting only of plane glasses suggest a reduction of interference oscillation of about one order-of-magnitude. By characterising different filters and in parallel simulating the results of the measurements the design of the filter for the $V(\lambda)$-trap will be optimised.

5 Conclusion and Outlook

To reduce the uncertainty in the realization of the SI-base unit “Candela” for luminous intensity at PTB a new realization is planned. This will allow a distribution of the photometric quantities with a lower uncertainty. To achieve this goal a new detector is designed and built. The limiting contributions to the measurement uncertainty of the current realization are evaluated and will be reduced, by simulating the detector components and by characterising measurements of the new detector and its components. Additionally the new detector will allow a shorter traceability route completely avoiding the use of additional transfer standards. Further characterising measurements e.g. polarisation dependency of the trap detector and angular dependency of the whole $V(\lambda)$-trap as well as calibration of the trap detector for radiant power responsivity with the cryogenic radiometer of the PTB are planned and will be done in future.

Acknowledgements

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