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EM Spectrograph Tests

Document Title

Intercalibration of Silicon Photodiodes

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Contents

1 Introduction - Motivation

In this document we present the photometric intercalibration of several silicon photodiodes. This work has been motivated by our needs for the DESI project:

- The accurate measurement of the throughput of the DESI spectrograph, planned to be done during the acceptation tests of the first DESI spectrograph [**?**]; the throughput measurement will use calibrated photodiodes from GigaHertz Optik/DKD to measure the injected flux in the spectrograph, and compare this flux to the one recorded on each of the 3 CCD cameras, one per arm of the DESI spectrograph. These photodiodes have already been calibrated by the seller; what we present here are cross-check measurements.
- The photometric characterization of several arc lamps and continuum lamps for the DESI in-situ calibration system, as we need to properly estimate the illumination power delivered from end to end by the calibration system we design.

2 Silicon photodiodes

The silicon photodiodes studied are listed in the table 1 below.

The photodiode NIST-S2281-1758 calibrated by the NIST (in charge of the definition of the optical Watt unit) is the most precisely calibrated photodiode available to us, with relative errors of the order of 0.2% on most of the spectral range, and it is therefore used as the main metrologic reference in this work.

Si photodiode reference	**provider**	**calibration**	**date**	**geometry**	**area**	**refs**
NIST-S2281-1758	Hamamatsu	NIST	2008-01-07	circular	$100\,\mathrm{mm}^2$	sect. A
DKD-MD-37-SU100-2-30853	Gigahertz-Optik	DKD	2015-11-30	$10 \times 10\,\mathrm{mm}$	$100\,\mathrm{mm}^2$	sect. B
DKD-MD-37-SU100-2-30854	Gigahertz-Optik	DKD	2015-11-30	$10 \times 10\,\mathrm{mm}$	$100\,\mathrm{mm}^2$	sect. B
Thorlabs-FDS10x10-00001	Thorlabs	—	—	$10 \times 10\,\mathrm{mm}$	$100\,\mathrm{mm}^2$	sect. C

Table 1: Silicon photodiodes studied in this report. Detailled specifications and calibration reports are provided in sections A, B and C.

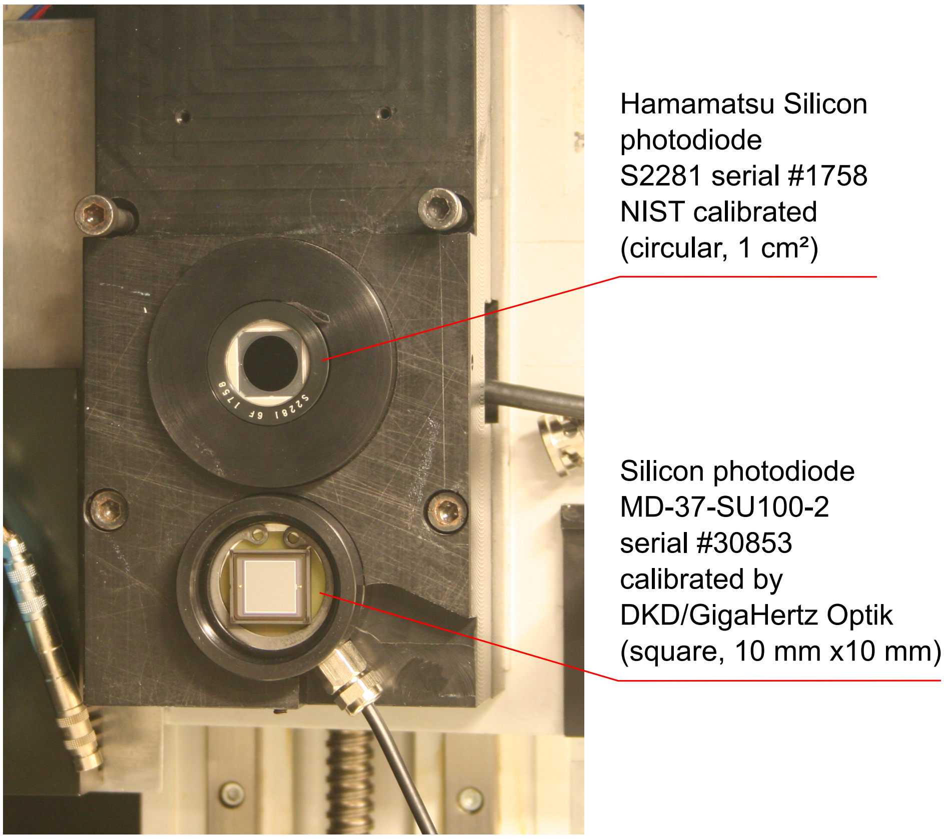

Figure 1: Photodiodes (NIST and DKD-30853) mounted on the sensor plateform attached to the XY motorized stage on the calibration optical bench. This allow to successively center each photodiode in front of the monochromator exit slit by moving the plateform up and down. Using the same XY motorized stage, the light beams could also be mapped with a sub-millimetric resolution.

3 Optical setup

The calibration work presented here has be done with the spectrophotometric optical test bench originally developped for the DICE experiment [Regnault, N. et al., 2015; Guyonnet, 2012]; this facility is located at Laboratoire de Physique Nucléaire et de Hautes Énergies (LPNHE), UMR-7585, CNRS-IN2P3, on the main campus of Université Pierre et Marie Curie (UPMC), Sorbonne Universités, in Paris, France.

The optical bench is presented on fig. 2. Enclosed in a $4\,\mathrm{m} \times 2\,\mathrm{m} \times 2\,\mathrm{m}$ dedicated dark box, it consists of a stable 2.5 m optical bench, equiped with 5 motorized stages: a XY stage to move the light sources, and a XYZ stage to move a vertical plateform where several sensors (photodiodes, CCD camera, *etc.*) may be attached (see fig. 1). The accuracy of both XY motors is of the order of $10\,\mu$m.

3.1 Light sources

Several light sources may be used on this bench. For the photodiode intercalibration, we used a highly stable multi-LED light source (see fig. 3), developped for the DICE project (SNDICE-I and SNDICE-II at CFHT, Hawai'i, SkyDICE for Skymapper, Siding Springs, StarDICE at Observatoire de Haute-Provence, see Regnault, N. et al. [2015]).

This light source provides 24 flat 1-degree LED beams, each beam with a narrow wavelength coverage of 10-30 nm. The wavelength coverage for the 24 LEDs is presented on fig. 4.

The LED current for each channel can be modulated with high precision, and the resulting light flux is very stable (up to 10^{-4} in a thermalised environment).

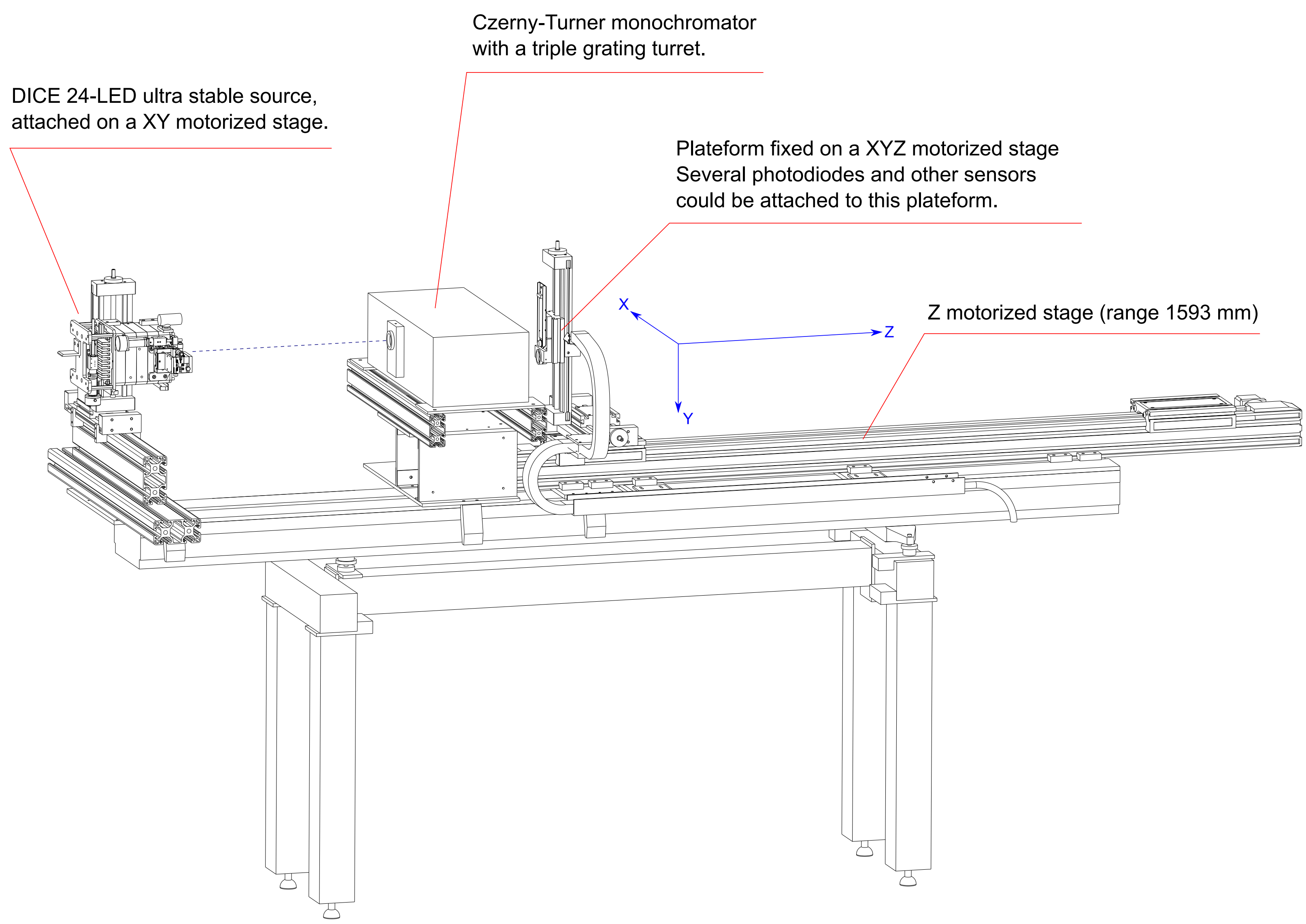

Figure 2: Spectrophotometric optical bench used for this work. The NIST photodiode is permanently mounted on the sensor plateform; several other sensors (photodiodes, CCD camera, etc) may be mounted on the same plateform to be characterized. The whole setup is enclosed inside a $4\,\mathrm{m} \times 2\,\mathrm{m} \times 2\,\mathrm{m}$ dark box. The bafflings and the dark box are not shown here. The whole test bench can be thermalised between 0 and 25 celsius. It has been used at 20-22 celsius for the work presented here.

When mounted on the optical bench, LED beams are parallel to the bench optical axis. Using the XY stage, each light beam can be centered on the entrance of the monochromator (see below) when the bench is used in spectrometric mode.

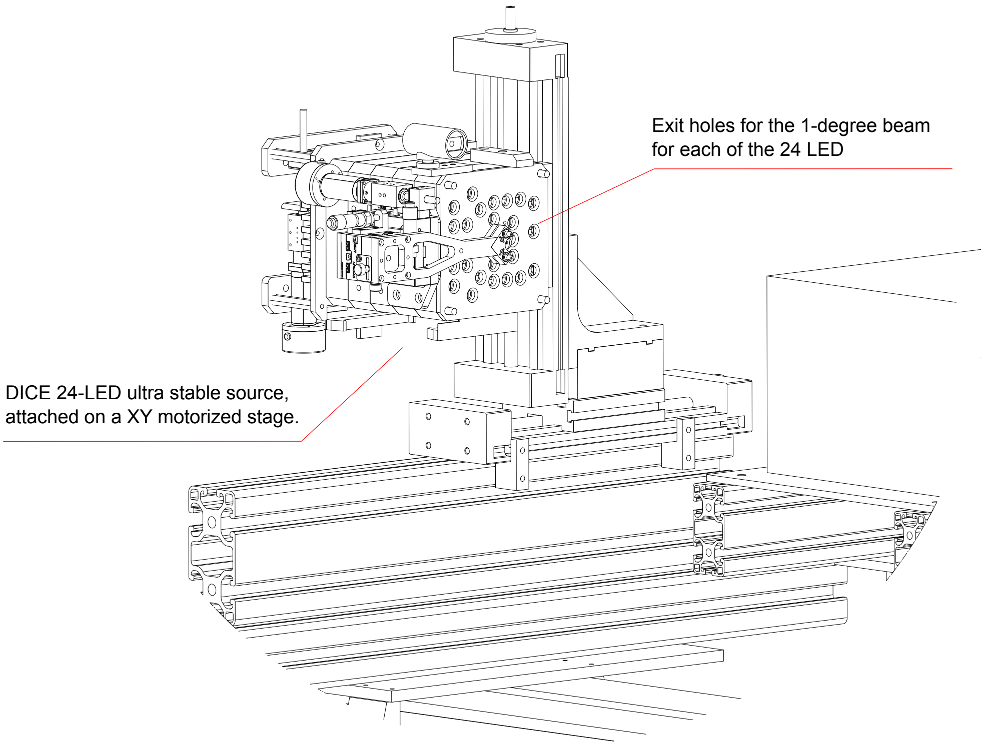

Figure 3: The DICE calibration source, installed on a XY motorized stage.

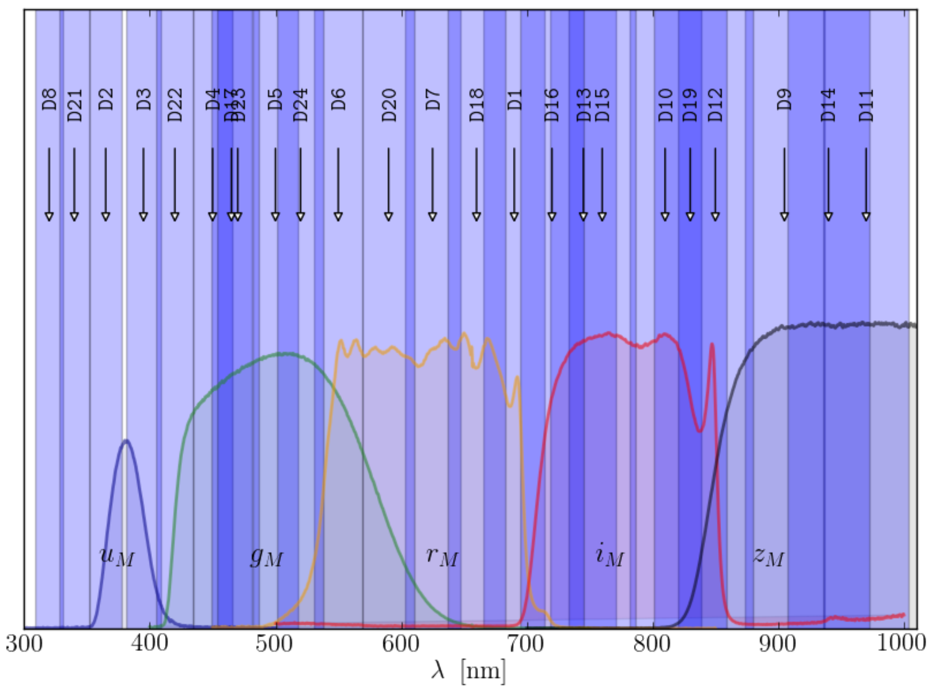

Figure 4: Spectral coverage for the 24 LED of the DICE calibration source.

3.2 Monochromator

To measure light power in a selected wavelength narrow range, a monochromator can be installed on the optical bench (see fig. 2). We use a Czerny-Turner monochromator DK-240 from Spectral Products (serial #11010), with a focal length of 240 mm (f/# 3.9). This monochromator is removed when the optical bench is used in photometric mode; it is installed at a precise fixed position on the bench when used for spectrometric measurements.

The monochromator has a triple grating turret, with 3 gratings from Newport described in table 2; their efficiency is shown on figure 5. These gratings allow to cover the wavelength range from 300 nm to 1000 nm; the resulting wavelength resolution can reach 0.01 nm (depending of the slit width used).

The monochromator is equiped with motorized entrance and exit slits, whose width is adjustable from 30 μm to 3 mm. When the entrance and exit slits are set to the same width, the monochromator dispersion relationship is 3.2 nm/mm.

grating	reference	grooves/mm	blaze angle	blaze wavelength
#1	3000-4-11-6-19-4	1200	10.4 deg	302.52 nm
#2	1597-5-3-9-12-4-4-7	1200	17.4 deg	507.01 nm
#3	MR136-15-8-18-1-3-1-4-1-9	1200	26.7 deg	776.67 nm

Table 2: Gratings used with the Spectral Products DK-240 monochromator.

In this work, the slit width has been set to 0.625 mm, which corresponds to a 2 nm coverage. As both slit are rectangular, the spectral response for an very narrow spectral line is a triangular function (convolution of the rectangular transmission functions of the entrance and the exit slits) with a half-width of 2 nm (fig. 5).

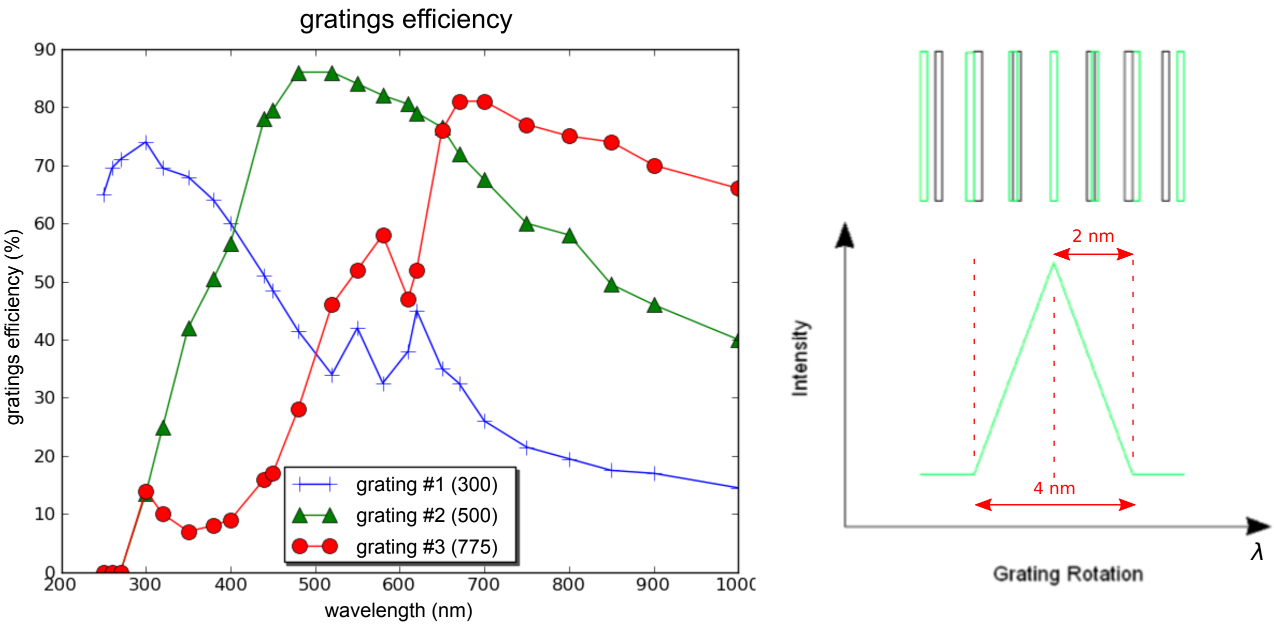

Figure 5: Left: efficiency for the 3 gratings used with the Spectral Products DK-240 monochromator. Right: Monochromator response for a narrow spectral line (as obtained with low pressure arc lamps for instance) when both the entrance and exit slits are set to 0.625 mm (adapted from Guyonnet [2012]).

The monochromator wavelength calibration has been done in this slit configuration (0.625 mm for the entrance and exit slits) using a HgAr lamp (PenRay 6035 from Newport/Oriel).

3.3 Ammeters

The photocurrent of the studied photodiodes is measured with ammeters/electrometers from Tektronix/Keithley, mainly several Keithley 6514 picoammeters, and a bi-channel Keithley-6482 picoammeter. The measured photocurrents vary between 0.1 pA to 100 pA, which is the photocurrent range obtained in our optical setups, which correspond to illumination powers from approx. 0.1 pW to 1 nW.

#id	ammeter model	provider	resolution	serial	calibration date
#1	Keithley 6514	Tektronix	1 fA	1118345	2008-XX-XX
#2	Keithley 6514	Tektronix	1 fA	4036939	2015-05-05
#3	Keithley 6514	Tektronix	1 fA	4131086	20XX-XX-XX
#4	Keithley 6482 (2-channel)	Tektronix	1 fA	1410711	2016-01-29

Table 3: Picoammeters used to measure the photodiode photocurrent.

4 Measurement procedure

The principle of our measure is the following: to estimate the power responsivity of the studied photodiode at a given wavelength, we produce a thin monochromatic light beam using our highly stable light source and our monochromator: once centered on the monochromator optical axis, both the studied photodiode and the reference photodiode (NIST) will receive the same light beam, and we record the photocurrent measured in both photodiodes with two picoammeters.

In our setup, the exit slit of the monochromator is 0.625 mm $\times$ 3.0 mm wide: as the photodiodes are placed at a distance of 25 mm from the exit slit, the resulting beam is 1.1 mm $\times$ 3.5 mm wide on the photodiode surface, and is entirely contained in the surface of each photodiode (see table 1) when the photodiode is properly centered in front of the monochromator exit slit (see below).

4.1 Beam mapping

A critical assumption in this work is that the photodiodes we compare all received the exact same amount of monochromatic light at each wavelength and LED current level. As the geometry of the sensitive area of is not always the same for all the studied photodiodes, we map the monochromatic light beam for each photodiode, by moving the XY plateform (where the photodiodes are attached) perpendicularly to the optical axis and measuring the corresponding photocurrent. The beam map have been done with a resolution of 0.5 mm.

For each photodiode, the resulting beam map is the spatial convolution between the photodiode sensitive area (circular or rectangular, depending of the model, see table 1) and the light beam spatial distribution in the photodiode plane.

Some of the resulting maps are presented on figures 6 and 7. Each map presents a large plateau where the photocurrent is uniform and independent of the photodiode position, which corresponds to all the XY positions where the light beam from the monochromator exit slit is entirely contained inside the photodiode surface.

The beam mapping has been done at different wavelengths, and for the three monochromator gratings, and produce the same beam maps.

For the intercalibration, the XY reference position for each photodiode is chosen at the center of this plateau.

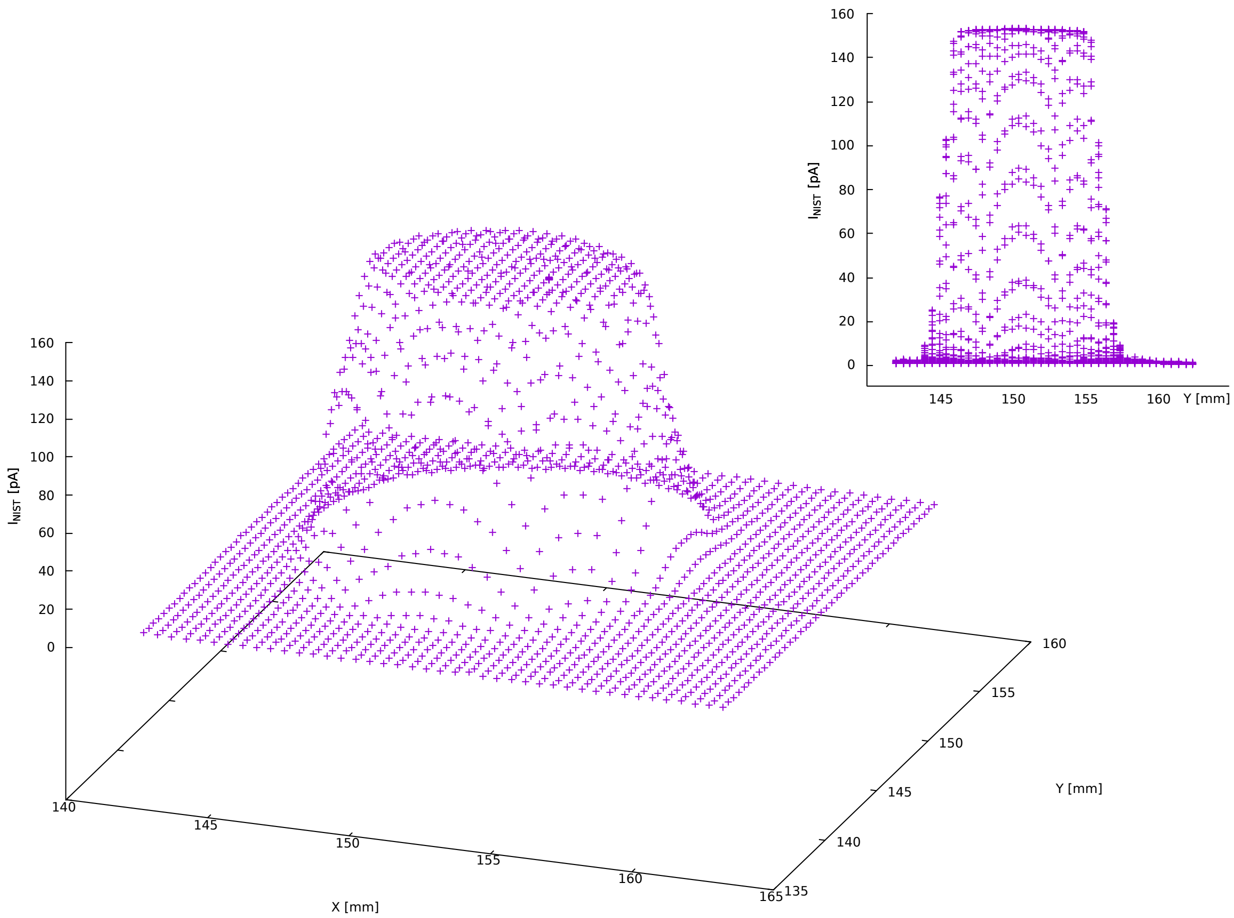

Figure 6: Mapping of the monochromatic light from the monochromator exit slit by moving the NIST photodiode with the XY motorized stage. The map has been done with a resolution of 0.5 mm. The resulting map is the convolution of the rectangular light beam with the 1 cm^2 circular sensitive area of the NIST. The photocurrent plateau corresponds to XY position where the NIST photodiode catch the entire light beam.

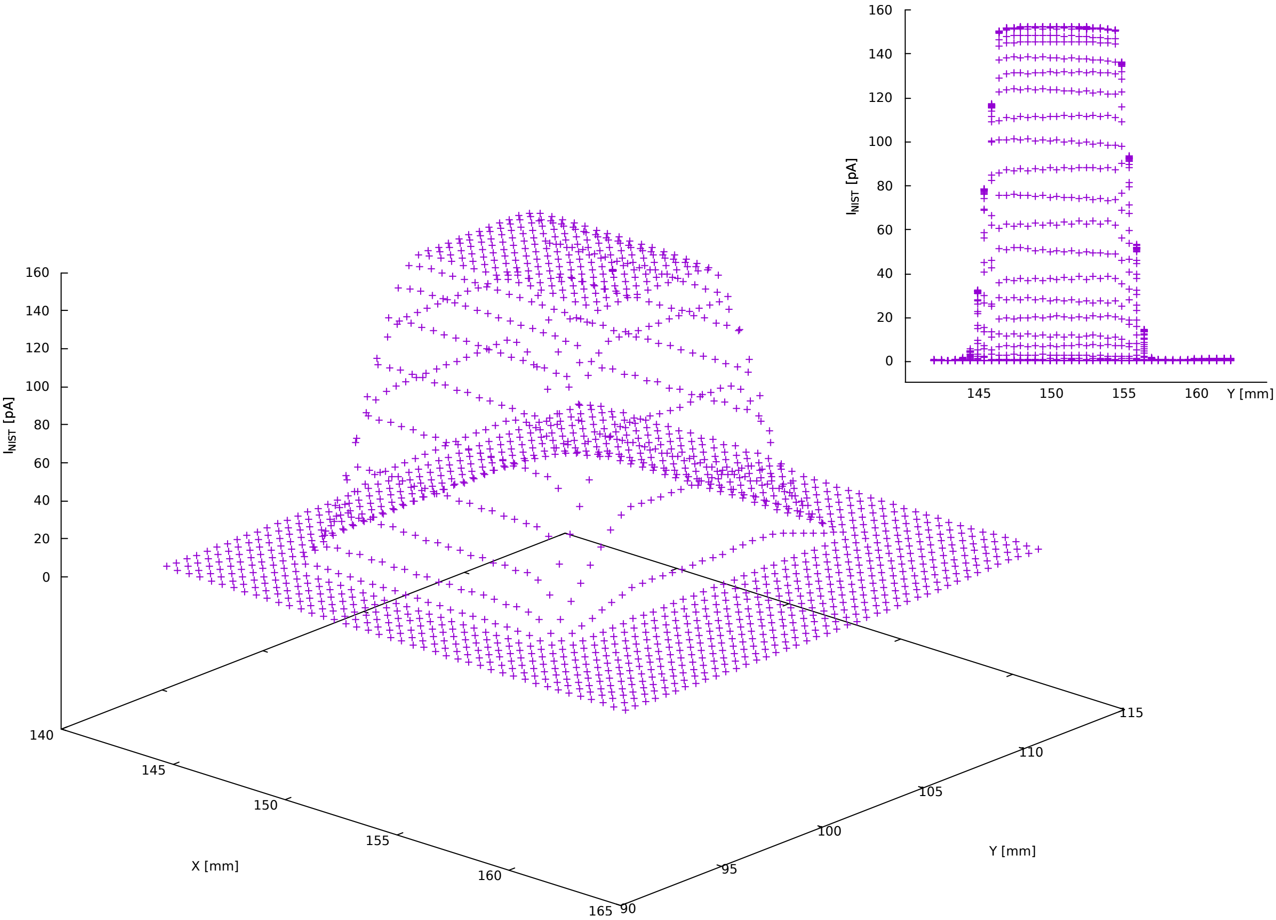

Figure 7: Mapping of the monochromatic light from the monochromator exit slit by moving the DKD-30853 photodiode with the XY motorized stage. The map has been done with a resolution of 0.5 mm. The resulting map is the convolution of the rectangular light beam with the $10\,mm \times 10\,mm$ *square sensitive area of the DKD-30853. The photocurrent plateau corresponds to XY position where the DKD photodiode catch the entire light beam. (All the studied DKD and the Thorlabs photodiode have the same geometry).*

4.2 Data acquisition sequence

Here we described the measurement procedure used. To measure the power responsivity of a given photodiode, we compare its photocurrent to the one produced by the NIST calibrated photodiode, for the same light beam (in wavelength and power).

To minimize the effects of possible variations in the source and/or the monochromator, we place successively the two photodiodes in front of the monochromator exit slit, by moving the sensor plateform, for each LED, each LED current value and each monochromator wavelength, and repeating several times the operation in a given $(I_{\mathrm{LED}}, \lambda)$ configuration. The whole task is automatized and run without any human intervention. By exchanging repeatedly the photodiodes, we get rid of any time dependency of the source and/or monochromator characteristics. Furthermore, a perfect knowledge of the monochromator throughput is not requested.

In practice, once the photodiodes are installed on the sensor plateform, we first map the light beam from the monochromator exit slit for several LEDs and wavelengths (see above in section 4.1). Using these maps we choose a reference XY position of the sensor plateform for each photodiode, in order to get the whole light beam inside the photodiode surface in that reference position.

Then, for each of the 24 DICE LEDs, successively,

1. Using the XY motorized stage, the DICE source is moved to properly align the selected LED beam (1-degree wide) with the monochromator entrance slit;

2. Then, we do a current ramp for the selected LED, from 1% to the full nominal current (20 mA to 50 mA depending of the LED), following these steps:

   (a) Before turning the LED on, the dark current is measured for each photodiode (NIST, DKD, *etc.*);

   (b) The LED is turned on with the chosen current;

   (c) We wait 120 seconds for the LED thermal stabilisation at this current level;

   (d) For each wavelength λ in the wavelength range of the selected LED:
      i. The monochromator is set to λ;

      ii. For each photodiode on the XYZ plateform:
         A. Using the sensor XY stage, the selected photodiode is moved in front of the monochromator exit slit, in a position where it catches the whole beam;

         B. The photodiode photocurrent is measured with its connected picoammeter.

   (e) The LED is turned off.

During this procedure, the ambiant and monochromator temperatures are monitored, to be able to correct the small dependency of the monochromator wavelength calibration with the temperature. The DICE temperature (both for the stable current source and the LEDs) is also continuously monitored.

5 Modeling the photodiode dark current

As the acquisition procedure described above may take several hours (typically around 10-12 hours), we monitor the dark current of each photodiode, to be able to subtract it from our photocurrent measurements. This allows to get rid at the same time of the slow drift of the dark current and of the picoammeter pedestal. To avoid increasing the noise, we model the slow variations of the dark current by polynomials (See fig. 8).

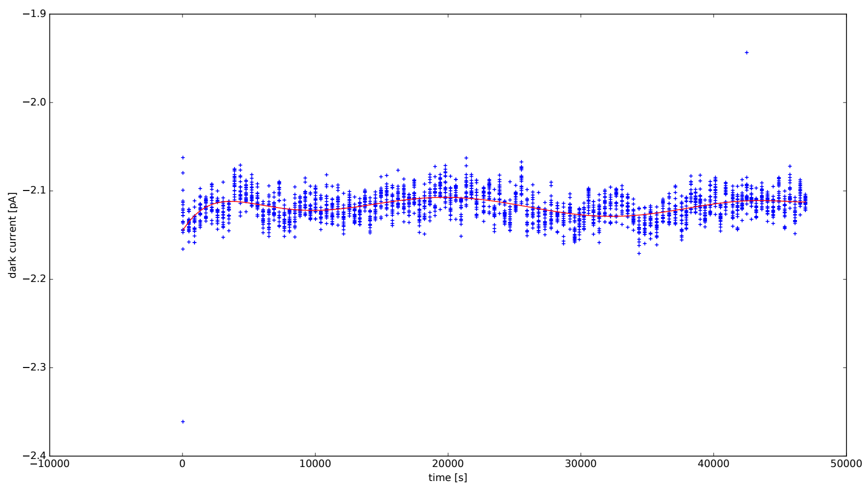

Figure 8: Variations of the photodiode dark current with time during the intercalibration procedure. We fit a empirical model (polynomials) to remove the slow drift of the dark current.

6 Responsivity ratio

For a given illumination power φ [W], with the monochromatic beam contained in the photodiode surface, the photocurrent measured for photodiode PhD may be written as:

$$I_{\mathrm{PhD}}(\varphi) = I_{\mathrm{PhD}}^{\mathrm{dark}} + s_{\mathrm{PhD}}(\lambda)\varphi(\lambda)$$

where $s_{\mathrm{PhD}}(\lambda)$ is the photodiode responsivity (in A/W), and where

$$I_{\mathrm{PhD}}^{\mathrm{dark}} = I_{\mathrm{PhD}}(\varphi = 0)$$

is the dark current of the photodiode. In practice, this will also take into account slow drifts of the picoammeter reference.

By illuminating successively two photodiodes with the same monochromatic beam, and measuring the resulting photocurrent for both, we may estimate the *responsivity ratio* r between these photodiodes. For instance, when we intercalibrate a given photodiode PhD with the reference NIST one, we can estimate, at each selected wavelength λ, the responsivity ratio between both photodiodes:

$$r_{\mathrm{PhD/NIST}} = \frac{s_{\mathrm{PhD}}(\lambda)}{s_{\mathrm{NIST}}(\lambda)} = \frac{I_{\mathrm{PhD}}(\varphi(\lambda)) - I_{\mathrm{PhD}}^{\mathrm{dark}}}{I_{\mathrm{NIST}}(\varphi(\lambda)) - I_{\mathrm{NIST}}^{\mathrm{dark}}}$$

In practice, as we measured both photocurrents at a given wavelength λ for several levels of illumination by varying the LED current, once both dark currents have been subtracted the responsivity ratio r is obtained by a linear fit of this dataset. An example of this is shown on figure 9.

This procedure also allows to check the linearity of the photodiodes and the ammeters on the used illumination range.

This procedure is applied at all the selected wavelengths, thus producing an estimate of the responsivity ratio r between each studied photodiode and the NIST one, used as the reference.

The resulting responsivity ratio for the DKD-MD-37-SU100-2-30853 (respectively for the DKD-MD-37-SU100-2-30854) is shown on figure 12 (resp. 14) below.

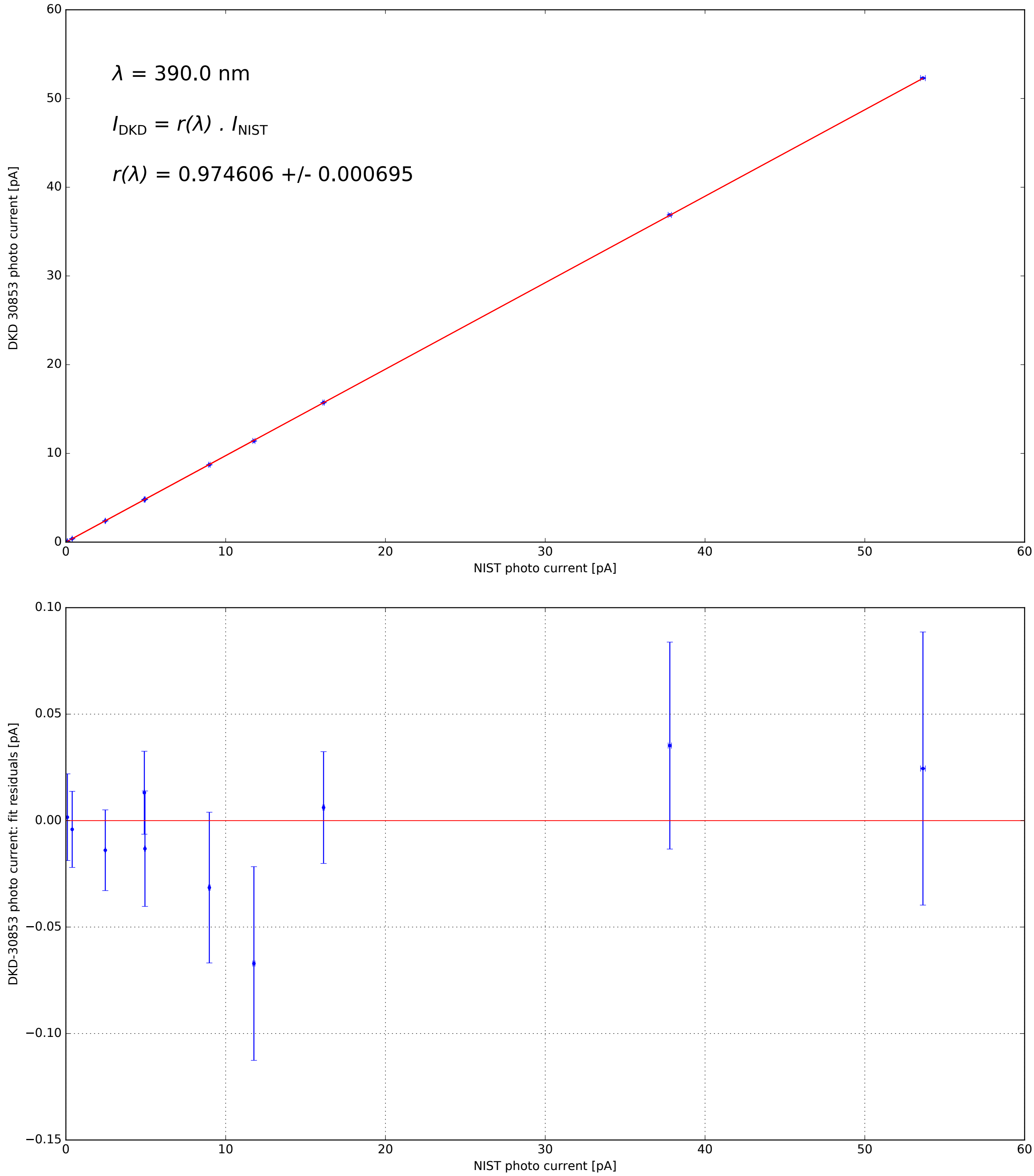

Figure 9: Top: DKD photo current vs. NIST photo current, for several illumination levels at $\lambda = 390$ nm; Dark currents have been subtracted before the linear adjustement of the responsivity ratio $r(\lambda)$. Bottom: residuals of the linear adjustement.

7 Removing ammeter calibration systematics

The described measurement of the responsivity ratio may be affected by calibration biases of the picoammeter used to measure the photocurrent. Luckily, there is a simple way to get rid of calibration biases of both picoammeters at the same time, by doing the measurements twice while swapping the two picoammeters.

Let suppose that both ammeters (named "1" and "2") are slightly miscalibrated:

$$
\begin{aligned}
I_{\mathrm{NIST}}^{\mathrm{meas},1} &= (1+\alpha_1) I_{\mathrm{NIST}}^{\mathrm{true}} + \beta_1 \\
I_{\mathrm{PhD}}^{\mathrm{meas},2} &= (1+\alpha_2) I_{\mathrm{PhD}}^{\mathrm{true}} + \beta_2
\end{aligned}
$$

where I^{true} is the true photocurrent, $I^{\mathrm{meas},i}$ the current value as measured by ammeter #i, and α_i, β_i the miscalibration parametrisation for ammeter #i.

As we subtract the measured dark currents, we are not sensitive to calibration biases β_1 and β_2, but we may be affected by α_i factors.

For a given light flux $\phi(\lambda)$, illuminating successively both photodiodes, the responsivity ratio $r_{\mathrm{PhD/NIST}}$ we estimate may be written as :

$$
r_{\mathrm{PhD/NIST}} = \frac{I_{\mathrm{PhD}}^{\mathrm{meas}}(\phi) - I_{\mathrm{PhD}}^{\mathrm{meas}}(0)}{I_{\mathrm{NIST}}^{\mathrm{meas}}(\phi) - I_{\mathrm{NIST}}^{\mathrm{meas}}(0)}
$$

With the NIST photodiode connected to ammeter 1 and the other photodiode connected to ammeter 2, we get :

$$
r_{\mathrm{PhD,2/NIST,1}} = \frac{I_{\mathrm{PhD}}^{\mathrm{meas},2}(\phi) - I_{\mathrm{PhD}}^{\mathrm{meas},2}(0)}{I_{\mathrm{NIST}}^{\mathrm{meas},1}(\phi) - I_{\mathrm{NIST}}^{\mathrm{meas},1}(0)} = \frac{(1+\alpha_2)\left[I_{\mathrm{PhD}}^{\mathrm{true}}(\phi) - I_{\mathrm{PhD}}^{\mathrm{true}}(0)\right]}{(1+\alpha_1)\left[I_{\mathrm{NIST}}^{\mathrm{true}}(\phi) - I_{\mathrm{NIST}}^{\mathrm{true}}(0)\right]}
$$

When we exchange both ammeters, connecting the NIST photodiode to ammeter 2, and the other one to ammeter 1, we then measure :

$$
r_{\mathrm{PhD,1/NIST,2}} = \frac{I_{\mathrm{PhD}}^{\mathrm{meas},1}(\phi) - I_{\mathrm{PhD}}^{\mathrm{meas},1}(0)}{I_{\mathrm{NIST}}^{\mathrm{meas},2}(\phi) - I_{\mathrm{NIST}}^{\mathrm{meas},2}(0)} = \frac{(1+\alpha_1)\left[I_{\mathrm{PhD}}^{\mathrm{true}}(\phi) - I_{\mathrm{PhD}}^{\mathrm{true}}(0)\right]}{(1+\alpha_2)\left[I_{\mathrm{NIST}}^{\mathrm{true}}(\phi) - I_{\mathrm{NIST}}^{\mathrm{true}}(0)\right]}
$$

Combining both measurements, we can get rid of any ammeter miscalibration by using the following estimator of the responsivity ratio r :

$$
\sqrt{r_{\mathrm{PhD,2/NIST,1}} \times r_{\mathrm{PhD,1/NIST,2}}} = \sqrt{\frac{(1+\alpha_2)}{(1+\alpha_1)} \times \frac{(1+\alpha_1)}{(1+\alpha_2)}} \times \frac{\left[I_{\mathrm{PhD}}^{\mathrm{true}}(\phi) - I_{\mathrm{PhD}}^{\mathrm{true}}(0)\right]}{\left[I_{\mathrm{NIST}}^{\mathrm{true}}(\phi) - I_{\mathrm{NIST}}^{\mathrm{true}}(0)\right]} = \frac{\left[I_{\mathrm{PhD}}^{\mathrm{true}}(\phi) - I_{\mathrm{PhD}}^{\mathrm{true}}(0)\right]}{\left[I_{\mathrm{NIST}}^{\mathrm{true}}(\phi) - I_{\mathrm{NIST}}^{\mathrm{true}}(0)\right]}
$$

The resulting estimate of the responsivity ratio is shown on figure 10 for the DKD-MD-37-SU100-2-30853 and on figure 11 for the DKD-MD-37-SU100-2-30854 photodiode.

Figure 10: Responsivity ratio between photodiodes DKD-MD-37-SU100-2-30853 and NIST vs. wavelength. The responsivity ratio is measured twice, once in the original configuration and once by swapping the Keithley-6514 picoammeters (dots), and then both measurements are combined (line) to get rid of both Keithley calibration biases.

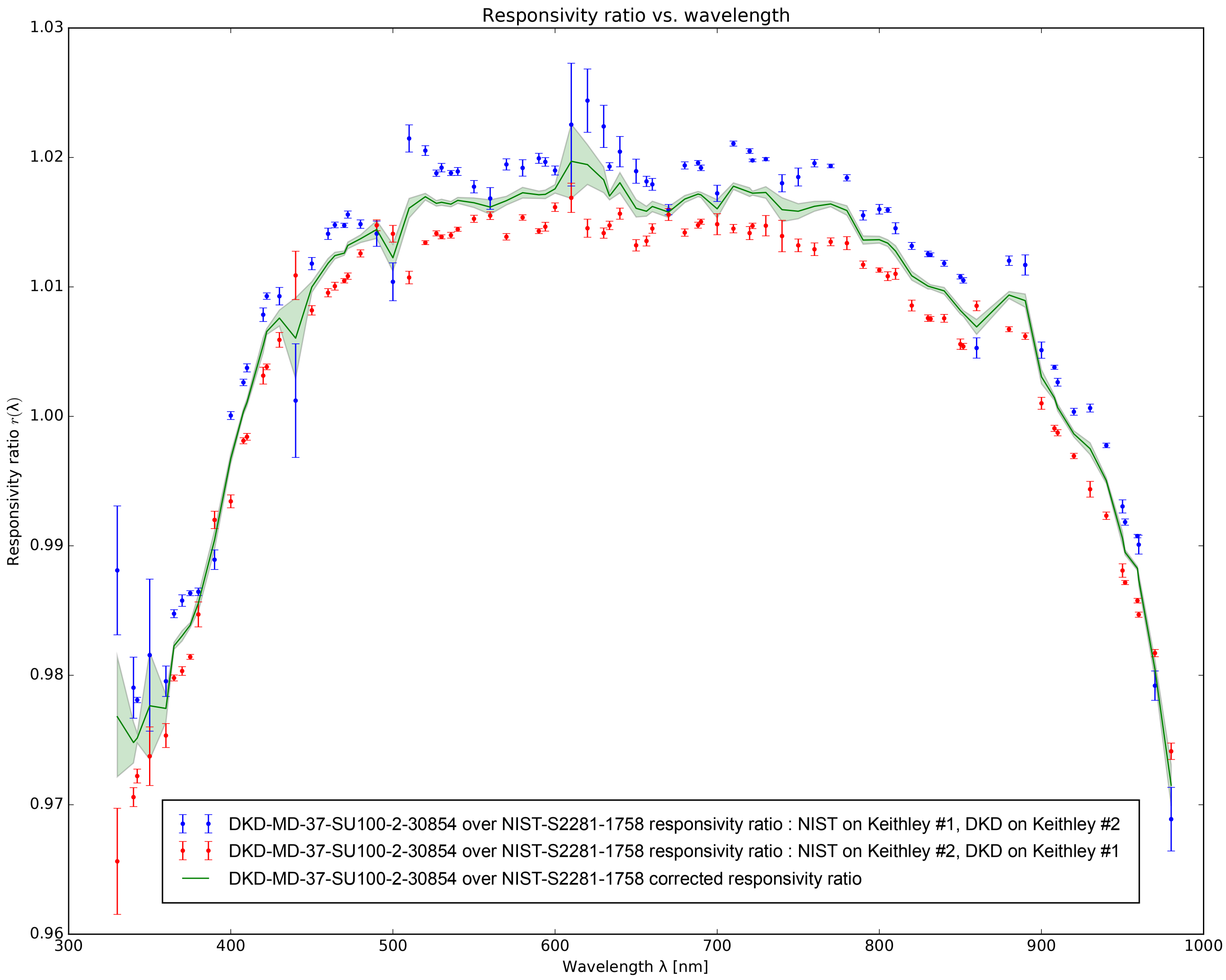

Figure 11: Responsivity ratio between photodiodes DKD-MD-37-SU100-2-30854 and NIST vs. wavelength. The responsivity ratio is measured twice, once in the original configuration and once by swapping the Keithley-6514 picoammeters (dots), and then both measurements are combined (line) to get rid of both Keithley calibration biases.

8 Responsivity and quantum efficiency

Once the responsivity ratio between the studied photodiode and the NIST one has been measured, and under the hypothesis that the NIST calibration has not changed (which is not absolutely certain, as the calibration has been done in 2008), we can use our measure of the responsivity ratio to independently establish an absolute calibration for all the studied photodiodes:

$$s_{\mathrm{PhD}}(\lambda) = r_{\mathrm{PhD/NIST}} \times s_{\mathrm{NIST}}(\lambda)$$

This result may also be expressed as the photodiode quantum efficiency (QE) [e^-/photon] :

$$QE_{\mathrm{PhD}}(\lambda) = \frac{hc}{\lambda e} \times s_{\mathrm{PhD}}(\lambda)$$

The resulting estimates of the responsivity and quantum efficiency is shown on fig. 12 and 13 for the DKD-MD-37-SU100-2-30853, on fig. 14 and 15 for the DKD-MD-37-SU100-2-30854, and on fig. 16 for the Thorlabs-FDS10x10-00001.

For the DKD-MD-37-SU100-2-30853 and DKD-MD-37-SU100-2-30854 photodiodes, the power responsivity and quantum efficiency we measured are compatibles with the calibration provided by Gigahertz-Optik/DKD.

For the Thorlabs-FDS10x10-00001 photodiode, the responsivity and QE curves are very similar with the typical curves from the specifications of the Thorlabs/FDS10x10 products.

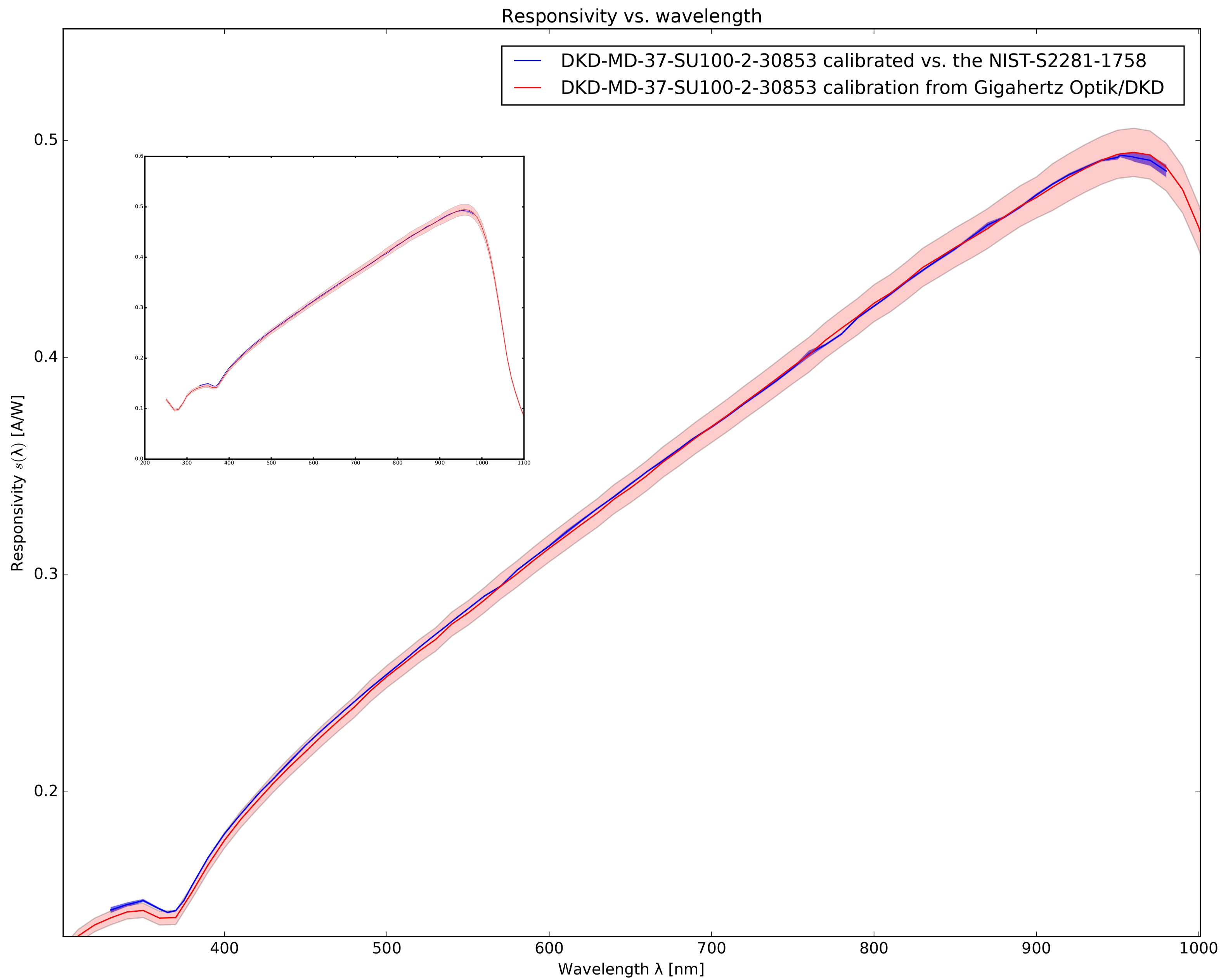

Figure 12: Our estimate of the responsivity [A/W] for the DKD-MD-37-SU100-2-30853 photodiode, assuming the NIST calibration for the NIST photodiode (in blue, 1-sigma contour). It is compared with the official calibration for the same photodiode done by Gigahertz Optik/DKD (in red, 1-sigma contour).

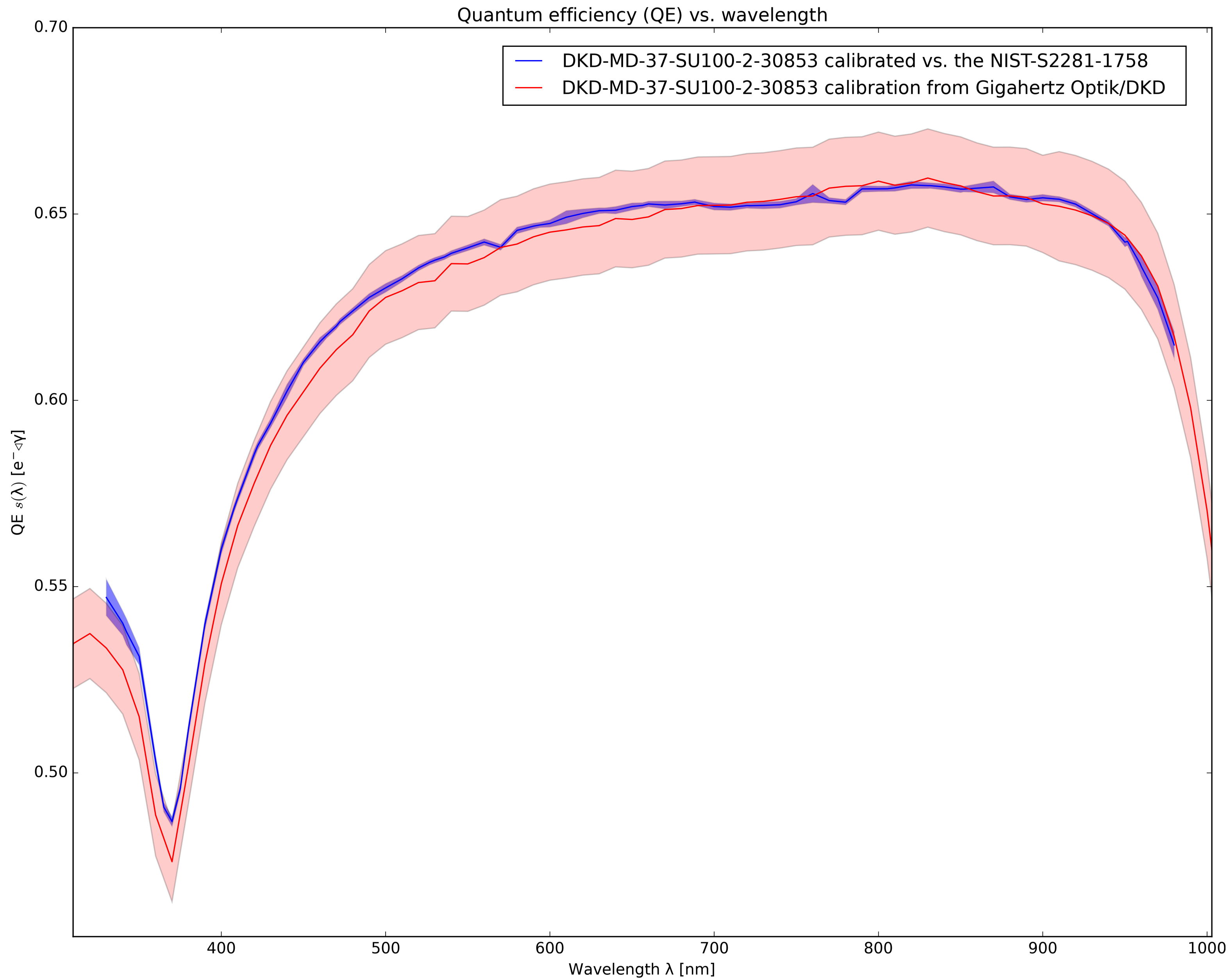

Figure 13: Our estimate of the quantum efficiency (QE) [e^-/photon] for the DKD-MD-37-SU100-2-30853 photodiode, assuming the NIST calibration for the NIST photodiode (in blue, 1-sigma contour). It is compared with the official calibration for the same photodiode done by Gigahertz Optik/DKD (in red, 1-sigma contour).

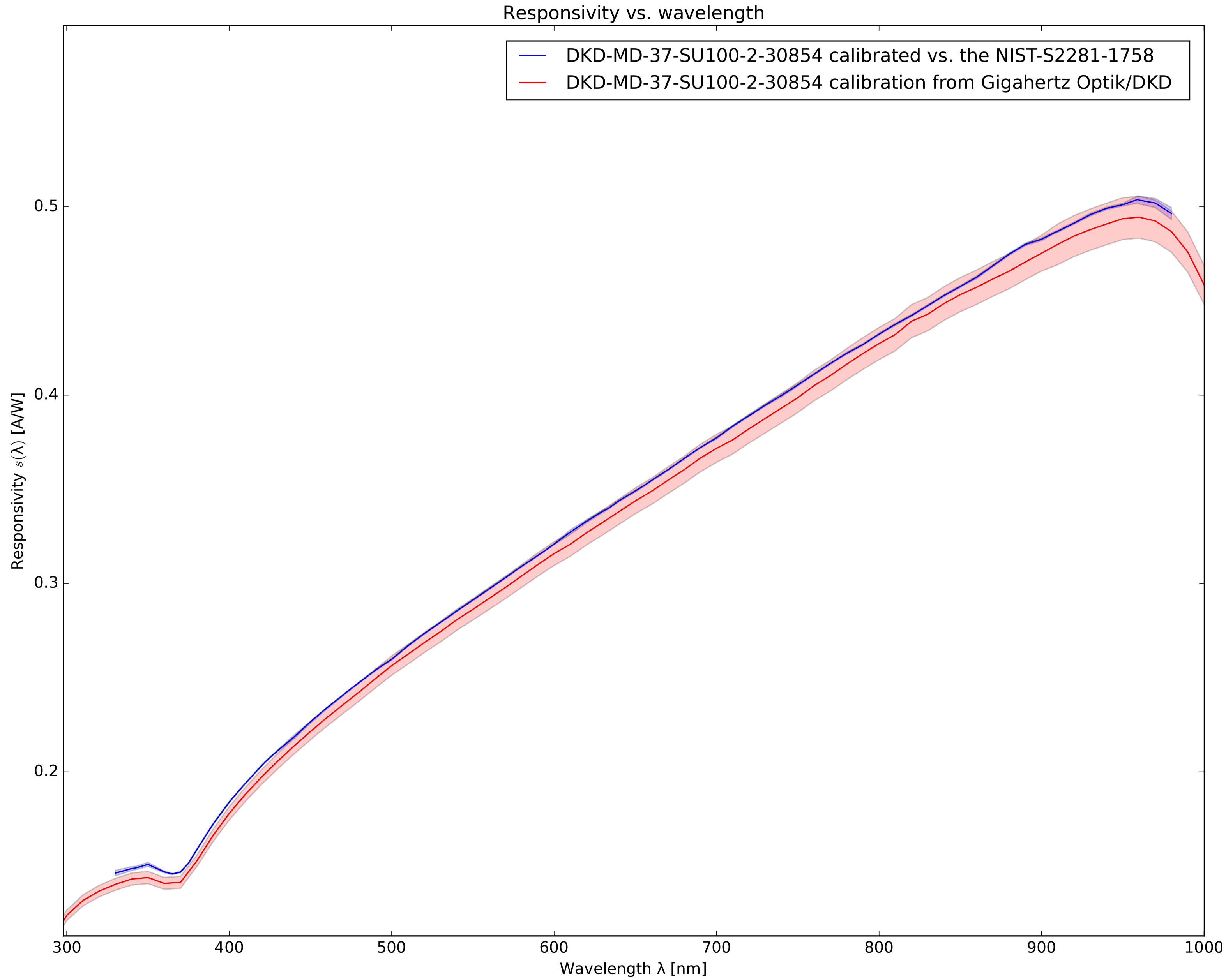

Figure 14: Our estimate of the responsivity [A/W] for the DKD-MD-37-SU100-2-30854 photodiode, assuming the NIST calibration for the NIST photodiode (in blue, 1-sigma contour). It is compared with the official calibration for the same photodiode done by Gigahertz Optik/DKD (in red, 1-sigma contour).

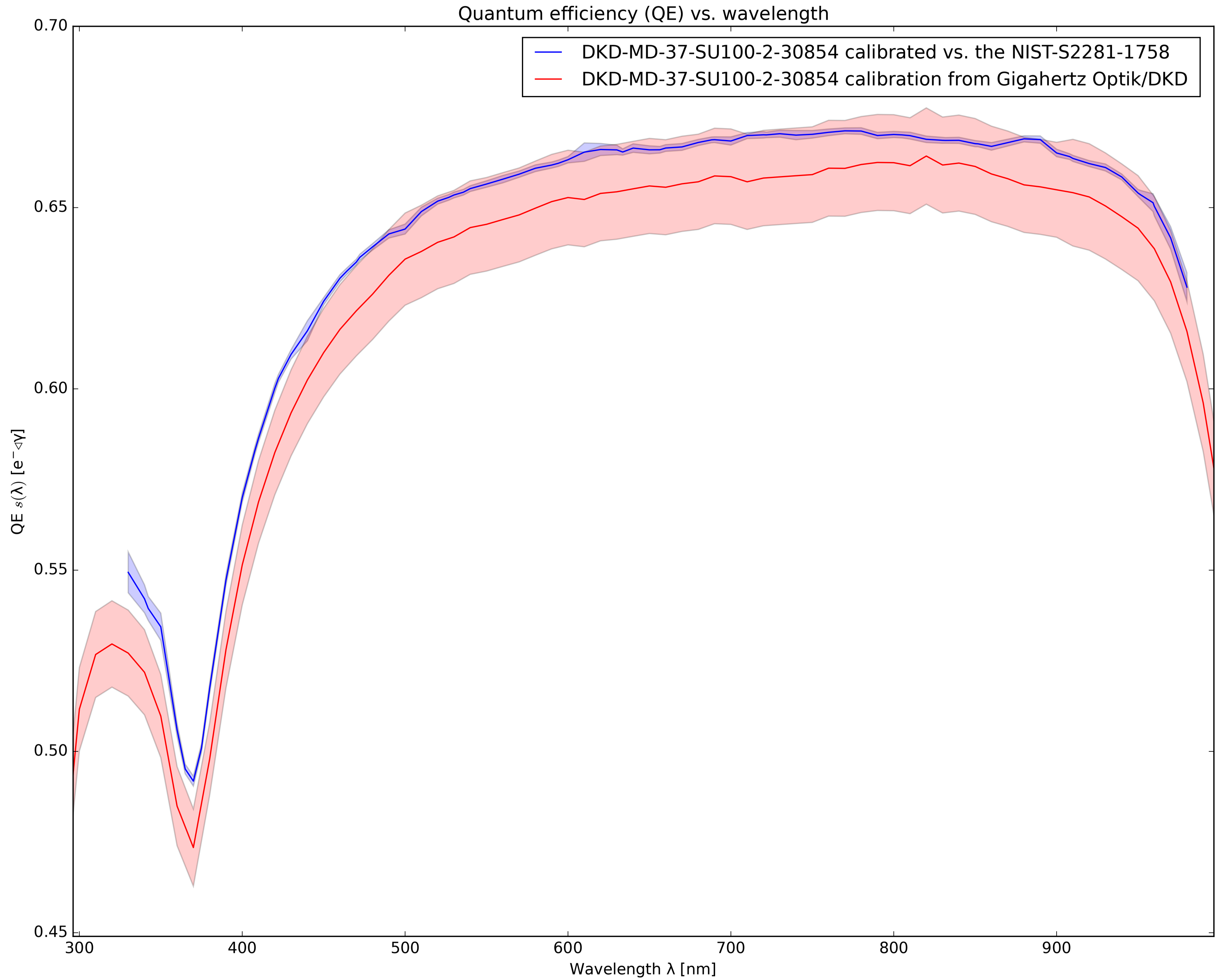

Figure 15: Our estimate of the quantum efficiency (QE) [e^-/photon] for the DKD-MD-37-SU100-2-30854 photodiode, assuming the NIST calibration for the NIST photodiode (in blue, 1-sigma contour). It is compared with the official calibration for the same photodiode done by Gigahertz Optik/DKD (in red, 1-sigma contour).

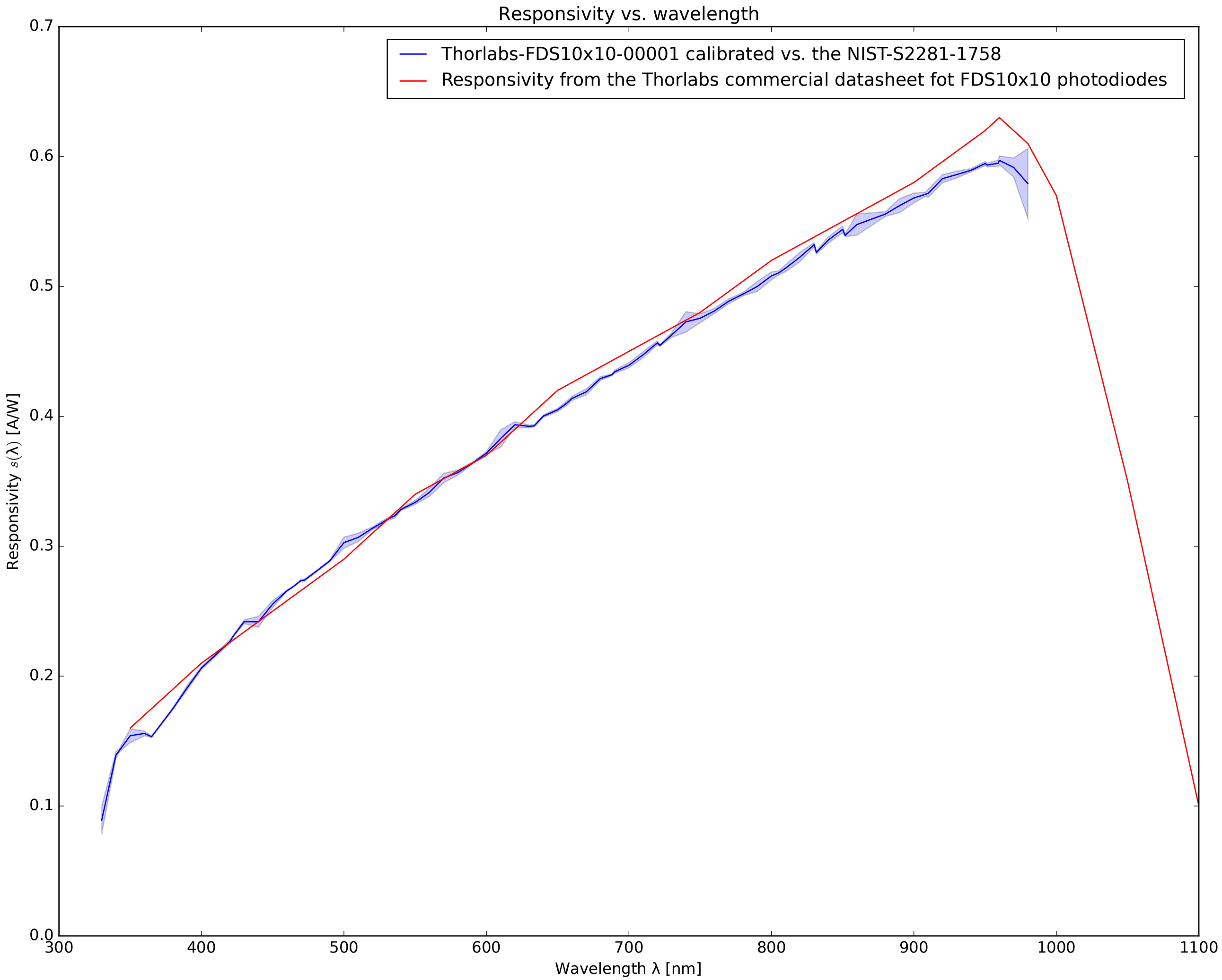

Figure 16: Our estimate of the responsivity [A/W] for the Thorlabs-FDS10x10-00001 photodiode, assuming the NIST calibration for the NIST photodiode (in blue, 1-sigma contour). It is compared with the commercial datasheet from Thorlabs (in red, no errors are provided by Thorlabs).

9 Conclusions

Using the spectrophotometric testbench of the LPNHE, Paris, we measured the power responsivity and the quantum efficiency of several silicon photodiodes for the DESI project. For the two photodiodes provided and calibrated by Gigahertz Optik/DKD, our measurements are compliants with the provided calibration. For the uncalibrated photodiode from Thorlabs, the power responsivity we measured is compatible with the photodiode datasheet.

References

Guyonnet, A. (2012). *The SNDICE project : realization of an optoelectronic device for the photometric calibration of the MegaCam wide field imager at CFHT*. Phd thesis, Université Paris 7 - Denis Diderot.

Regnault, N., Guyonnet, A., Schahmanèche, K., Le Guillou, L., Antilogus, P., Astier, P., Barrelet, E., Betoule, M., Bongard, S., Cuillandre, J.-C., Juramy, C., Pain, R., Rocci, P.-F., Tisserand, P., and Villa, F. (2015). The dice calibration project design, characterization, and first results. A&A, 581:A45.

A Hamamatsu NIST S2281 1758

In this section, we include the official calibration documents for the NIST-S2281-1758 photodiode, calibrated by the NIST, that we bought for the DICE project through the Canada-France-Hawai'i Telescope (CFHT).

Si photodiode reference	provider	calibration	date	geometry	area
NIST-S2281-1758	Hamamatsu	NIST	2008-01-07	circular	$100\,mm^2$

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899-

REPORT OF CALIBRATION

NIST Test # 39077C - Spectral Responsivity

for

Hamamatsu Silicon Photodiode Model S2281, S/N I758

Issued to:

Canada-France-Hawaii Telescope Corporation
Attn.: Dr. Kevin Holt
65-1238 Mamalahoa Highway
Kamuela, HI 96743

(See your Purchase Order No. 15644, dated December 7, 2007)

1. Description of Calibration Material

The test photodiode, serial number I758, is a Hamamatsu model S2281 silicon photodiode in an anodized aluminum mount. The active area of the photodiode is ≈ 1 cm^2.

2. Description of Calibration

The spectral radiant power responsivity of the test photodiode was calibrated in the region from 200 nm to 1100 nm using two NIST measurement facilities traceable to NIST absolute cryogenic radiometers.

The spectral radiant power responsivity of the test photodiode was determined from 200 nm to 345 nm in 5 nm increments by comparisons to silicon photodiode working standards, U503 and U506, using the monochromator-based NIST Ultraviolet Spectral Comparator Facility (UV SCF) [1]. The spectral comparisons between the test photodiode and working standard photodiodes were performed using a double monochromator illuminated by an argon arc as the tunable monochromatic source. The circular exit aperture of the UV SCF monochromator was imaged (≈*f*/5) on the test photodiode resulting in a beam diameter of 1.5 mm at the diode. The beam was centered on, and underfilled, the photosensitive area.

The spectral radiant power responsivity of the test photodiode was determined from 350 nm to 1100 nm in 5 nm increments by comparisons to silicon photodiode working standards, H630 and H633, using the monochromator-based NIST Visible to Near-Infrared Spectral Comparator Facility (Vis/NIR SCF) [1]. The spectral comparisons between the test photodiode and working standard photodiodes were performed using a double monochromator illuminated by a quartz-halogen lamp as the tunable monochromatic source. The circular exit aperture of the Vis/NIR SCF monochromator was imaged (≈ *f*/9) on the test photodiode resulting in a beam diameter of 1.1 mm at the diode. The beam was centered on, and underfilled, the photosensitive area.

The wavelength scale of each monochromator was calibrated with several laser and emission lines to within an uncertainty of ± 0.1 nm over the entire spectral range. The bandpass (FWHM) of the UV SCF and Vis/NIR SCF monochromators was 4 nm. The short-circuit photocurrent from the test photodiode and each working standard photodiode was measured with a calibrated transimpedance amplifier. Beam power fluctuations were monitored with a beamsplitter and silicon photodiode. The spectral radiant power responsivity scale is based on the NIST reference absolute cryogenic radiometer. The laboratory temperatures during this calibration were:

UV SCF 23.7 °C ± 0.5 °C
Vis/NIR SCF 23.5 °C ± 0.5 °C.

The spatial uniformity of the responsivity across the test photodiode photosensitive area was measured at 500 nm using the described Vis/NIR comparator facility. The uniformity was measured in 0.5 mm increments using a 1.1 mm diameter beam.

3. Results of Calibration

The spectral radiant power responsivity of the test photodiode is listed in A/W at each wavelength in table 1 and is plotted in figure 1. The uncertainty in the NIST spectral radiant power responsivity scale is described in Ref. 1 and 2. The relative expanded uncertainty ($k = 2$) for this measurement is listed at each wavelength in table 1 and plotted in figure 1.

Figure 2a is a plot of the uniformity of the test photodiode at 500 nm showing 0.2 % contours of the deviations from the responsivity at the photodiode center. Figure 2b is a 3-dimensional plot showing the responsivity relative to the center of the photodiode.

Table 1
Spectral Power Responsivity of Hamamatsu Silicon Photodiode Model S2281, S/N I758

Wavelength [nm]	Spectral Power Responsivity [A/W]	Relative Expanded Uncertainty ($k = 2$) [%]	Wavelength [nm]	Spectral Power Responsivity [A/W]	Relative Expanded Uncertainty ($k = 2$) [%]
200	0.115	6.0	400	0.1845	0.38
205	0.115	4.3	405	0.1891	0.36
210	0.117	3.9	410	0.1937	0.34
215	0.120	3.7	415	0.1980	0.34
220	0.1213	1.2	420	0.2022	0.32
225	0.1228	1.2	425	0.2061	0.32
230	0.1273	1.3	430	0.2098	0.30
235	0.1334	1.2	435	0.2136	0.28
240	0.1332	1.2	440	0.2173	0.28
245	0.1300	1.2	445	0.2208	0.26
250	0.1251	1.3	450	0.2243	0.24
255	0.1190	1.2	455	0.2277	0.24
260	0.1137	1.2	460	0.2312	0.24
265	0.1081	1.1	465	0.2344	0.22
270	0.1031	1.1	470	0.2377	0.22
275	0.1023	1.1	475	0.2410	0.22
280	0.1056	1.1	480	0.2441	0.22
285	0.1115	1.2	485	0.2473	0.22
290	0.1184	1.1	490	0.2504	0.22
295	0.1272	1.1	495	0.2535	0.22
300	0.1344	1.1	500	0.2566	0.22
305	0.1388	1.1	505	0.2597	0.22
310	0.1417	1.0	510	0.2627	0.22
315	0.1442	1.0	515	0.2658	0.20
320	0.1464	1.1	520	0.2688	0.20
325	0.1481	1.1	525	0.2718	0.20
330	0.1497	1.1	530	0.2748	0.20
335	0.1512	1.1	535	0.2777	0.20
340	0.1525	1.1	540	0.2807	0.20
345	0.1531	1.1	545	0.2836	0.20
350	0.1543	0.56	550	0.2865	0.20
355	0.1524	0.54	555	0.2894	0.20
360	0.1503	0.50	560	0.2924	0.20
365	0.1484	0.48	565	0.2953	0.20
370	0.1493	0.48	570	0.2981	0.20
375	0.1540	0.46	575	0.3010	0.20
380	0.1609	0.46	580	0.3039	0.20
385	0.1674	0.42	585	0.3068	0.20
390	0.1738	0.40	590	0.3096	0.20
395	0.1795	0.40	595	0.3125	0.20

Table 1 (cont.)
Spectral Power Responsivity of Hamamatsu Silicon Photodiode Model S2281, S/N I758

Wavelength [nm]	Spectral Power Responsivity [A/W]	Relative Expanded Uncertainty ($k = 2$) [%]	Wavelength [nm]	Spectral Power Responsivity [A/W]	Relative Expanded Uncertainty ($k = 2$) [%]
600	0.3154	0.20	800	0.4266	0.20
605	0.3182	0.20	805	0.4293	0.20
610	0.3210	0.20	810	0.4321	0.20
615	0.3239	0.20	815	0.4349	0.20
620	0.3267	0.20	820	0.4376	0.20
625	0.3295	0.20	825	0.4403	0.20
630	0.3323	0.20	830	0.4431	0.20
635	0.3351	0.20	835	0.4458	0.20
640	0.3379	0.20	840	0.4486	0.20
645	0.3407	0.20	845	0.4512	0.20
650	0.3436	0.20	850	0.4540	0.20
655	0.3463	0.20	855	0.4568	0.20
660	0.3491	0.20	860	0.4594	0.20
665	0.3519	0.20	865	0.4622	0.20
670	0.3547	0.20	870	0.4650	0.20
675	0.3575	0.20	875	0.4677	0.20
680	0.3603	0.20	880	0.4704	0.20
685	0.3631	0.20	885	0.4731	0.20
690	0.3659	0.20	890	0.4758	0.20
695	0.3686	0.20	895	0.4786	0.20
700	0.3714	0.20	900	0.4813	0.20
705	0.3742	0.20	905	0.4840	0.20
710	0.3769	0.20	910	0.4867	0.20
715	0.3797	0.20	915	0.4893	0.20
720	0.3825	0.20	920	0.4920	0.20
725	0.3852	0.20	925	0.4946	0.20
730	0.3880	0.20	930	0.4971	0.20
735	0.3908	0.20	935	0.4995	0.20
740	0.3936	0.20	940	0.5017	0.20
745	0.3963	0.20	945	0.5039	0.20
750	0.3991	0.20	950	0.5059	0.20
755	0.4019	0.20	955	0.509	0.66
760	0.4046	0.20	960	0.510	0.72
765	0.4073	0.20	965	0.511	0.76
770	0.4101	0.20	970	0.512	0.82
775	0.4129	0.20	975	0.512	0.88
780	0.4156	0.20	980	0.511	0.94
785	0.4183	0.20	985	0.509	1.0
790	0.4211	0.20	990	0.506	1.0
795	0.4238	0.20	995	0.502	1.1

Table 1 (cont.)
Spectral Power Responsivity of Hamamatsu Silicon Photodiode Model S2281, S/N I758

Wavelength [nm]	Spectral Power Responsivity [A/W]	Relative Expanded Uncertainty ($k = 2$) [%]	Wavelength [nm]	Spectral Power Responsivity [A/W]	Relative Expanded Uncertainty ($k = 2$) [%]
1000	0.497	1.2	1050	0.339	2.0
1005	0.490	1.2	1055	0.314	2.1
1010	0.481	1.3	1060	0.287	2.2
1015	0.470	1.4	1065	0.262	2.3
1020	0.458	1.4	1070	0.242	2.4
1025	0.443	1.5	1075	0.224	2.5
1030	0.426	1.6	1080	0.207	2.6
1035	0.407	1.7	1085	0.190	2.7
1040	0.386	1.8	1090	0.174	2.8
1045	0.364	1.9	1095	0.158	2.9
			1100	0.144	2.9

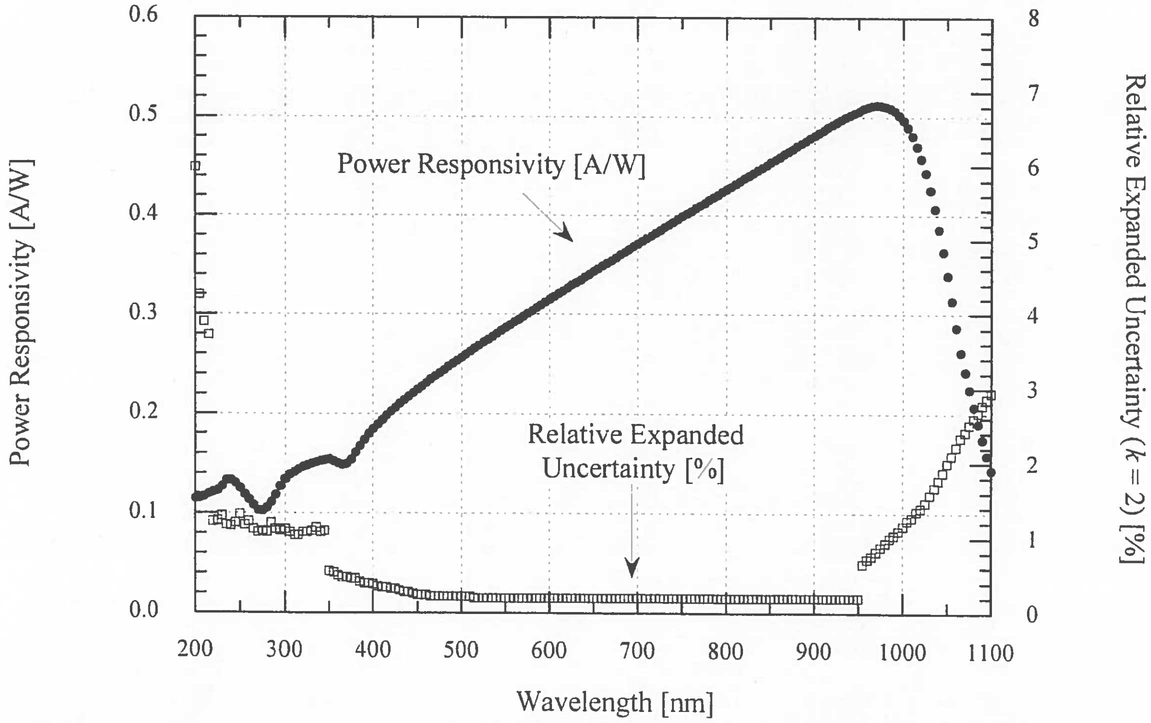

Figure 1. Spectral power responsivity of Hamamatsu silicon photodiode model S2281, S/N I758.

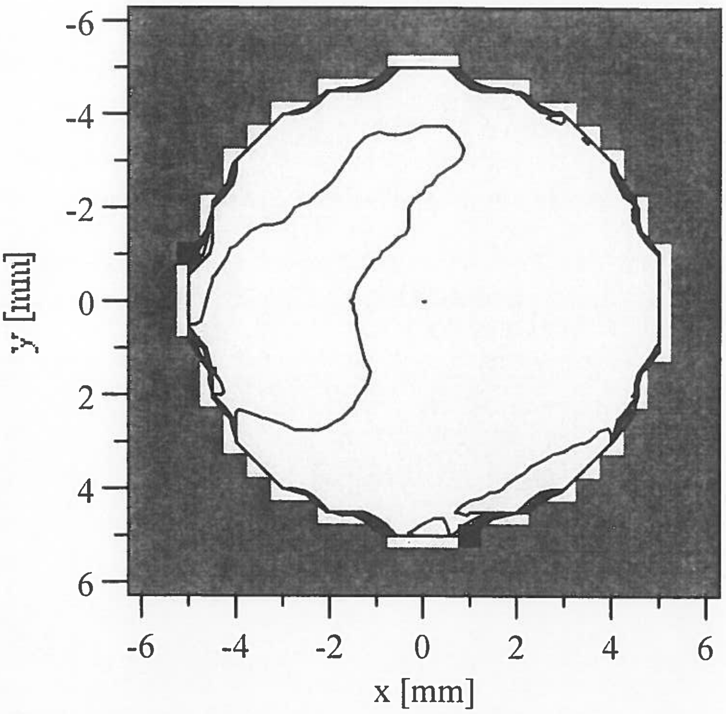

Figure 2a. Responsivity uniformity of Hamamatsu silicon photodiode model S2281, S/N I758: 0.2 % contours at 500 nm, 1.1 mm resolution, 0.5 mm/Step.

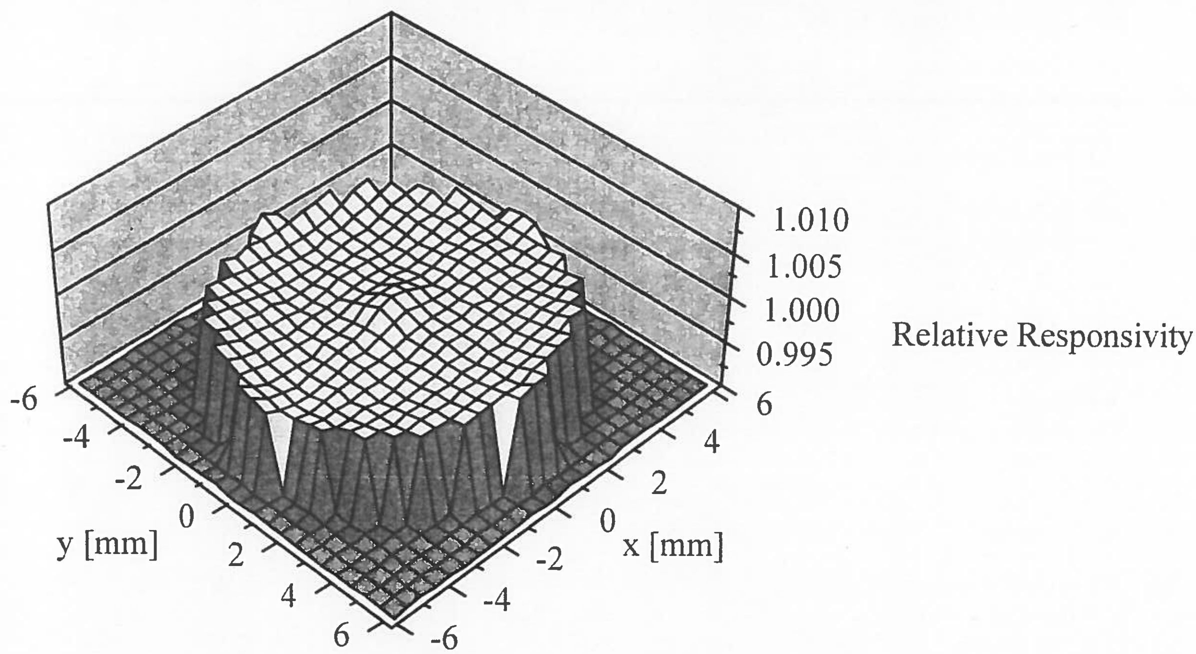

Figure 2b. Surface plot of the responsivity relative to the center of photodiode for Hamamatsu silicon photodiode model S2281, S/N I758 at 500 nm, 0.5 mm/Step.

4. General Information

The uncertainty of the spectral radiant power responsivity will be larger than reported in section 3 if the irradiation geometry is significantly different from the test conditions described in section 2. The uncertainty will also increase if the ambient temperature is significantly different from reported in section 2 (The temperature coefficient of this photodiode is typically less than 0.01 % / °C in the 380 nm to 900 nm region and increases outside this region.). Such uncertainty components should be evaluated by the customer. The spectral responsivity of photodiodes is subject to drift over time. Periodic calibration is recommended.

The appendix provides operating instructions for the test photodiode.

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References:

[1] T. C. Larason, S. S. Bruce, and A. C. Parr, Spectroradiometric Detector Measurements: Part I - Ultraviolet Detectors and Part II - Visible to Near-Infrared Detectors, Natl. Inst. Stand. Technol., Spec. Publ. 250-41 (1998).

[2] P. S. Shaw, T. C. Larason, R. Gupta, S. W. Brown, R. E. Vest, and K. R. Lykke, The new ultraviolet spectral responsivity scale based on cryogenic radiometry at Synchrotron Ultraviolet Radiation Facility III, Rev. Sci. Instrum. **72** (5), 2242-2247 (2001).

Appendix: OPERATING INSTRUCTIONS FOR NIST PHOTODIODE

The NIST characterized photodiode consists of a silicon photodiode with a quartz window and a BNC connector.

A. The photodiode should be rigidly mounted on a dual-axis tilt mount such that the photodiode can be tilted about two orthogonal axes. The photodiode should be adjusted to be perpendicular to the incident radiation.

B. The incident beam of radiation should be smaller than the active area, and should be centered in the photodiode active area.

C. The photodiode should be connected with a BNC cable to an electrometer grade amplifier (transimpedance amplifier) which measures the current from the photodiode.

D. The diode window can be cleaned with lens tissue and spectral grade solvent.

B Photodiodes calibrated by DKD/Gigahertz Optik

In this section, we include the official calibration documents for the DKD-MD-37-SU100-2-30853 and DKD-MD-37-SU100-2-30854 photodiodes, calibrated by the Gigahertz-Optik (certified by the German standards service, the *Deutscher Kalibrerdienst* aka "DKD"), that we bought for the DESI project.

Si photodiode reference	provider	calibration	date	geometry	area
DKD-MD-37-SU100-2-30853	Gigahertz-Optik	DKD	2015-11-30	$10 \times 10\,\mathrm{mm}$	$100\,\mathrm{mm}^2$
DKD-MD-37-SU100-2-30854	Gigahertz-Optik	DKD	2015-11-30	$10 \times 10\,\mathrm{mm}$	$100\,\mathrm{mm}^2$

Kalibrierlaboratorium für optische Strahlungsmessgrößen
Calibration laboratory for optical radiometry

GIGAHERTZ-OPTIK GMBH

26231-01
WERK
2015-11

Werkskalibrierschein
Calibration Certificate

Kalibrierzeichen
Calibration mark

Gegenstand *Object*	**Silizium Photodiode im Gehäuse mit Datenstecker Anschluss** *Silicon detector with data connector*
Hersteller *Manufacturer*	**Gigahertz-Optik GmbH**
Typ *Type*	**MD-37-SU100-2**
Fabrikate/Serien-Nr. *Serial number*	**30853**
Auftraggeber *Customer*	**Acal BFi France S.A.S** **ZI La Petite Montagne Sud, CE1834 Lisses** **4, Allee du Cantal** **F-91018 EVRY Cedex**
Auftragsnummer *Order No.*	**319467 / OP / 000 / 21000 / (26231)**
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	**5**

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).

Methoden und Verfahren der Kalibrierung entsprechen den Anforderungen der ISO17025. Die internen Transfernormale werden regelmäßig gegen Normale kalibriert, welche einen DKD/DAkkS-Kalibrierschein haben oder rückführbar auf ein Normal mit DKD/DAkkS-Kalibrierschein kalibriert sind oder gegen Normale eines nationalen Metrologieinstituts kalibriert sind.

Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

This calibration certificate documents the traceability to national standards, which realise the units of measurement according to the International System of Units (SI).

Methods and procedures of calibration meet the requirements of ISO17025. The intern used transfer standards were regular calibrated against standards, which have DKD/DAkkS certificates or are traceable to a standard with DKD/DAkkS or National Metrology Institute certificate.

The user is obliged to have the object recalibrated at appropriate intervals.

Stempel *Seal*	Datum *Date*	Stellv. Leiter des Kalibrierlaboratoriums *Deputy Head of the calibration laboratory*
Kalibrierlaboratorium • Optische Strahlungs-messgrößen • Gigahertz-Optik GmbH	30. November 2015	Dipl.-Ing. (FH) Stephan Fenk

• Gigahertz-Optik GmbH • An der Kälberweide 12 • 82299 Türkenfeld • Tel. +49 (0)8193-93700-0 • Fax +49 (0)8193-93700-50 •

1. Beschreibung des Kalibriergegenstandes:
Es handelt sich um einen Silizium Messkopf, Typ MD-37-SU100-2, Seriennummer 30853. Der Signalabgriff erfolgt mittels Datenstecker Anschluss..

1. Description of the calibration object:
The calibration object is a Silicon detector head, type MD-37-SU100-2, serial number 30853. The current will be taken by data connection.

2. Messverfahren:
Die spektrale Empfindlichkeit $s(\lambda)_{\Phi}$ wurde durch Vergleich mit einem Bezugsnormal BN-9102-111, (73345 PTB 13, 10.2013, due to 10.2016), IET 1004 bestimmt, dessen spektrale Empfindlichkeit auf die nationalen Normale der Physikalisch-Technische Bundesanstalt (PTB) zurückgeführt wird. Bestrahlt wurde mit der durch einen Gitterdoppel-monochromator zerlegten Strahlung einer Halogenglühlampe. Die spektrale Empfindlichkeit der Photodiode ergibt sich aus dem gemessenen Ausgangsstrom I zu $s(\lambda)_{\Phi} = I/\Phi(\lambda)$.

2. Measurement:
The spectral responsivity $s(\lambda)_{\Phi}$ was measured by comparison with a transfer standard BN-9102-111, (73345 PTB 13, 10.2013, due to 10.2016), IET 1004, which was calibrated in reference to the PTB. The measurements were made using a double monochromator. The radiation was made from a Halogen lamp. The spectral responsivity of the photodiode is given by the ratio of the output current I to $s(\lambda)\Phi = I/\Phi(\lambda)$.

3. Messbedingungen:
Art der Bestrahlung: $s(\lambda)_{\Phi}$
Der Empfänger befand sich im konvergenten Strahlungsbündel, das von einem etwa auf dem Empfängerfenster liegenden Bild des Monochromatoraustrittsspaltes ausging. Die Bündelachse stand senkrecht und zentrisch zur Frontfläche des Empfängerfensters.
Die Messung des Ausgangsstromes erfolgte mittels Optometer P-9201-4-TF, SN 6075/2, IET1589 bei einer Raumtemperatur von (24 ± 2) °C.

3. Conditions during the calibration:
The photodiode was set in a convergent beam. The beam axis has been almost perpendicular and centric to the entrance of the monochromator output. The output current of the photodiode was measured by using an Optometer P-9201-4-TF, SN 6075/2, IET1589. The temperature of the room was (24 ± 2) °C.

4. Messergebnisse:
Spektrale Empfindlichkeit $s(\lambda)_{\Phi}$ in Abhängigkeit von der Wellenlänge λ
Siehe hierzu die Seiten 4 - 5 mit graphischer und numerischer Darstellung. Die numerischen Werte der spektralen Empfindlichkeit $s(\lambda)_{\Phi}$ sind in A/W gegenüber der Wellenlänge λ in nm aufgeführt. Die graphische Darstellung dient nur der Veranschaulichung. Verbindlich sind nur die numerischen Werte der Tabelle.

4. Result of the measurement:
Spectral responsivity $s(\lambda)_{\Phi}$ versus wavelength
Page 4 - 5 shows the graphic and numerical data. The numerical data of the spectral responsivity $s(\lambda)_{\Phi}$ are shown versus the wavelength (λ), unit (A/W). Only the numerical data are guaranteed.

Die spektrale Bandbreite Δλ des Monochromators betrug:
The spectral bandwidth Δλ of the monochromator was:
250 nm – 1100 nm: 10 nm

Für die relative Messunsicherheit gilt folgende Aufspaltung:
For the relative uncertainty is following table responsible:

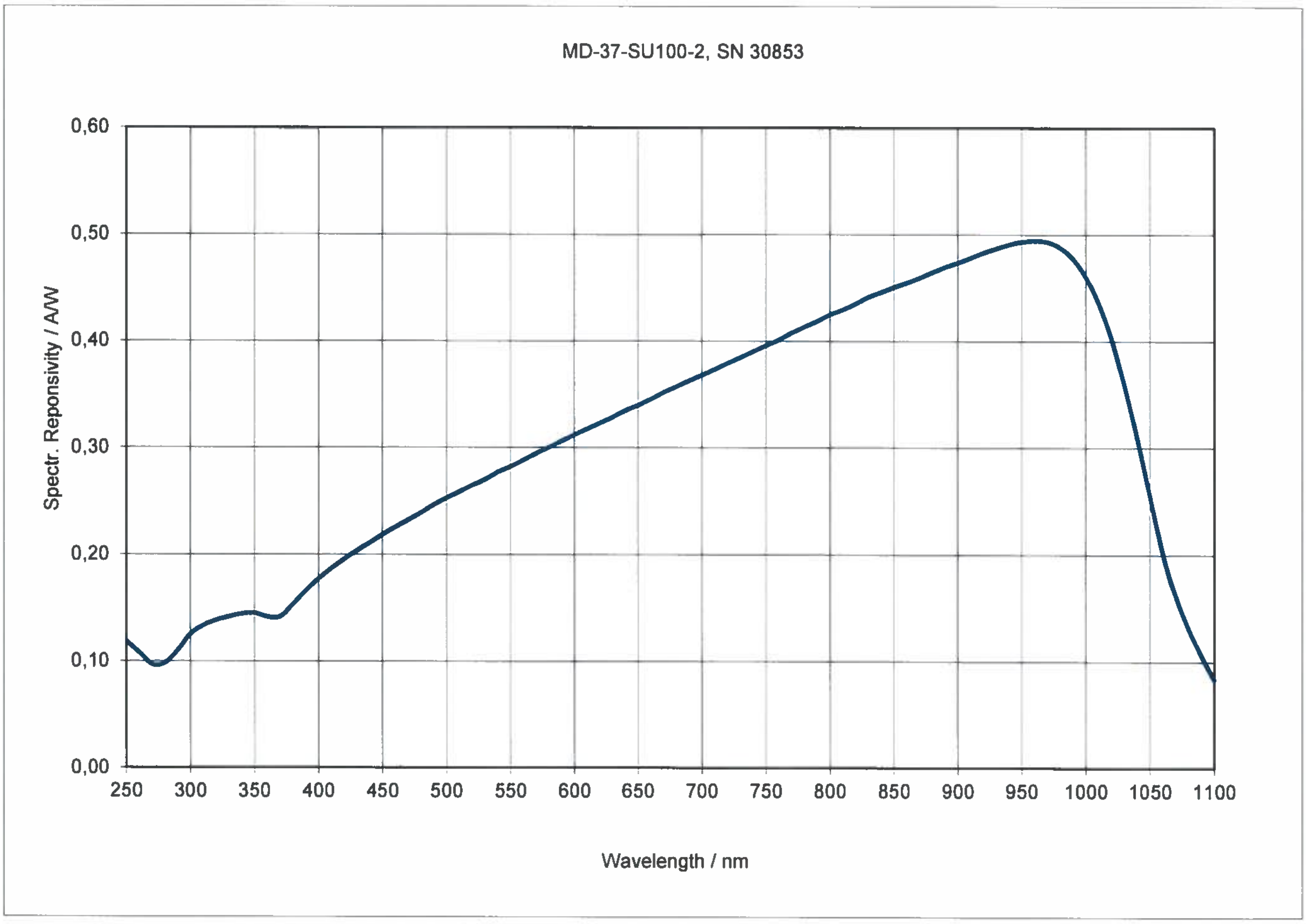
Wellenlänge in nm *Wavelength*	Relative Messunsicherheit in % *Relative uncertainty*
250 - 370	± 4,5
380 - 900	± 4
910 - 1070	± 4,5
1080 - 1100	± 5

Die angegebene Messunsicherheit (k = 2) setzt sich zusammen aus den Unsicherheiten des Kalibrierverfahrens und des Kalibriergegenstandes während der Kalibrierung. Ein Anteil für die Langzeitstabilität des Kalibriergegenstandes ist nicht enthalten.
The measuring insecurity (k = 2) stated is composed of the insecurities of the calibration method and of the calibrating object during the calibration. A share for the long term stability of the calibrated item is not included.

5. Bemerkungen:
Die oben angegebene Kalibriernummer 26231-01-WERK-2015-11 ist am Messkopf MD-37-SU100-2, Seriennummer 30853 angebracht. Der Kalibrierwert ist im Datenstecker des Messkopfes eingespeichert und kann mittels Menü aufgerufen werden.
Eine Abhängigkeit der spektralen Empfindlichkeit von anderen als den angegebenen Betriebsbedingungen oder Einflußgrößen ist nicht untersucht worden. Es ist mit einer wellenlängenabhängigen Alterung der spektralen Empfindlichkeit zu rechnen.
Eine Rekalibrierung innerhalb eines Jahres ist zu empfehlen.

5. Remarks:
The calibration report number 26231-01-WERK-2015-11 is marked on the detector head, type MD-37-SU100-2, serial number 30853. The calibration factor is stored into the data plug in of the detector head. It can be chosen by menu.
Dependence of the spectral responsivity from other as the given conditions is not examined. It is reckon in a wavelength dependence spectral responsivity during the life of the detector head.
Yearly recalibration is recommended.

Grafische Darstellung der Messwerte:
Graphic of the measured data:



Numerische Darstellung der Messwerte:
Numerical value of the measured data:

Wavelength / nm	Spectral responsivity / A/W	Wavelength / nm	Spectral responsivity / A/W	Wavelength / nm	Spectral responsivity / A/W
250,0	0,1186	540,0	0,2773	830,0	0,4416
260,0	0,1081	550,0	0,2824	840,0	0,4461
270,0	0,0970	560,0	0,2883	850,0	0,4508
280,0	0,0986	570,0	0,2947	860,0	0,4550
290,0	0,1102	580,0	0,3003	870,0	0,4595
300,0	0,1256	590,0	0,3064	880,0	0,4648
310,0	0,1337	600,0	0,3122	890,0	0,4698
320,0	0,1387	610,0	0,3177	900,0	0,4738
330,0	0,1420	620,0	0,3233	910,0	0,4786
340,0	0,1447	630,0	0,3287	920,0	0,4831
350,0	0,1454	640,0	0,3349	930,0	0,4872
360,0	0,1419	650,0	0,3400	940,0	0,4909
370,0	0,1421	660,0	0,3456	950,0	0,4937
380,0	0,1538	670,0	0,3519	960,0	0,4946
390,0	0,1665	680,0	0,3573	970,0	0,4934
400,0	0,1777	690,0	0,3630	980,0	0,4878
410,0	0,1873	700,0	0,3683	990,0	0,4775
420,0	0,1957	710,0	0,3736	1000,0	0,4601
430,0	0,2039	720,0	0,3793	1010,0	0,4354
440,0	0,2115	730,0	0,3847	1020,0	0,4023
450,0	0,2186	740,0	0,3903	1030,0	0,3588
460,0	0,2258	750,0	0,3960	1040,0	0,3087
470,0	0,2326	760,0	0,4014	1050,0	0,2549
480,0	0,2391	770,0	0,4080	1060,0	0,2011
490,0	0,2466	780,0	0,4136	1070,0	0,1611
500,0	0,2531	790,0	0,4190	1080,0	0,1315
510,0	0,2589	800,0	0,4251	1090,0	0,1062
520,0	0,2649	810,0	0,4297	1100,0	0,0840
530,0	0,2702	820,0	0,4354		

Kalibrierlaboratorium für optische Strahlungsmessgrößen
Calibration laboratory for optical radiometry

GIGAHERTZ-OPTIK GMBH

26231-02
WERK
2015-11

Werkskalibrierschein
Calibration Certificate

Kalibrierzeichen
Calibration mark

Gegenstand *Object*	**Silizium Photodiode im Gehäuse mit Datenstecker Anschluss** *Silicon detector with data connector*
Hersteller *Manufacturer*	**Gigahertz-Optik GmbH**
Typ *Type*	**MD-37-SU100-2**
Fabrikate/Serien-Nr. *Serial number*	**30854**
Auftraggeber *Customer*	**Acal BFi France S.A.S** **ZI La Petite Montagne Sud, CE1834 Lisses** **4, Allee du Cantal** **F-91018 EVRY Cedex**
Auftragsnummer *Order No.*	**319467 / OP / 000 / 21000 / (26231)**
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	**5**

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).

Methoden und Verfahren der Kalibrierung entsprechen den Anforderungen der ISO17025. Die internen Transfernormale werden regelmäßig gegen Normale kalibriert, welche einen DKD/DAkkS-Kalibrierschein haben oder rückführbar auf ein Normal mit DKD/DAkkS-Kalibrierschein kalibriert sind oder gegen Normale eines nationalen Metrologieinstituts kalibriert sind.

Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

This calibration certificate documents the traceability to national standards, which realise the units of measurement according to the International System of Units (SI).

Methods and procedures of calibration meet the requirements of ISO17025. The intern used transfer standards were regular calibrated against standards, which have DKD/DAkkS certificates or are traceable to a standard with DKD/DAkkS or National Metrology Institute certificate.

The user is obliged to have the object recalibrated at appropriate intervals.

Dieser Kalibrierschein darf nur vollständig und unverändert weiterverbreitet werden. Auszüge oder Änderungen bedürfen der Genehmigung des Kalibrierlaboratoriums der Firma Gigahertz-Optik Gesellschaft für technische Optik mbH.
Kalibrierscheine ohne Unterschrift und Stempel haben keine Gültigkeit.

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Calibration certificates without signature and seal are not valid.

Stempel *Seal*	Datum *Date*	Stellv. Leiter des Kalibrierlaboratoriums *Deputy Head of the calibration laboratory*
Kalibrierlaboratorium • Optische Strahlungs-messgrößen • Gigahertz-Optik GmbH	30. November 2015	Dipl.-Ing. (FH) Stephan Fenk

1. Beschreibung des Kalibriergegenstandes:
Es handelt sich um einen Silizium Messkopf, Typ MD-37-SU100-2, Seriennummer 30854. Der Signalabgriff erfolgt mittels Datenstecker Anschluss..

1. Description of the calibration object:
The calibration object is a Silicon detector head, type MD-37-SU100-2, serial number 30854. The current will be taken by data connection.

2. Messverfahren:
Die spektrale Empfindlichkeit $s(\lambda)_{\Phi}$ wurde durch Vergleich mit einem Bezugsnormal BN-9102-111, (73345 PTB 13, 10.2013, due to 10.2016), IET 1004 bestimmt, dessen spektrale Empfindlichkeit auf die nationalen Normale der Physikalisch-Technische Bundesanstalt (PTB) zurückgeführt wird. Bestrahlt wurde mit der durch einen Gitterdoppel-monochromator zerlegten Strahlung einer Halogenglühlampe. Die spektrale Empfindlichkeit der Photodiode ergibt sich aus dem gemessenen Ausgangsstrom I zu $s(\lambda)_{\Phi} = I/\Phi(\lambda)$.

2. Measurement:
The spectral responsivity $s(\lambda)_{\Phi}$ was measured by comparison with a transfer standard BN-9102-111, (73345 PTB 13, 10.2013, due to 10.2016), IET 1004, which was calibrated in reference to the PTB. The measurements were made using a double monochromator. The radiation was made from a Halogen lamp. The spectral responsivity of the photodiode is given by the ratio of the output current I to $s(\lambda)\Phi = I/\Phi(\lambda)$.

3. Messbedingungen:
Art der Bestrahlung: $s(\lambda)_{\Phi}$
Der Empfänger befand sich im konvergenten Strahlungsbündel, das von einem etwa auf dem Empfängerfenster liegenden Bild des Monochromatoraustrittsspaltes ausging. Die Bündelachse stand senkrecht und zentrisch zur Frontfläche des Empfängerfensters.
Die Messung des Ausgangsstromes erfolgte mittels Optometer P-9201-4-TF, SN 6075/2, IET1589 bei einer Raumtemperatur von (24 ± 2) °C.

3. Conditions during the calibration:
The photodiode was set in a convergent beam. The beam axis has been almost perpendicular and centric to the entrance of the monochromator output. The output current of the photodiode was measured by using an Optometer P-9201-4-TF, SN 6075/2, IET1589. The temperature of the room was (24 ± 2) °C.

4. Messergebnisse:
Spektrale Empfindlichkeit $s(\lambda)_{\Phi}$ in Abhängigkeit von der Wellenlänge λ
Siehe hierzu die Seiten 4 - 5 mit graphischer und numerischer Darstellung. Die numerischen Werte der spektralen Empfindlichkeit $s(\lambda)_{\Phi}$ sind in A/W gegenüber der Wellenlänge λ in nm aufgeführt. Die graphische Darstellung dient nur der Veranschaulichung. Verbindlich sind nur die numerischen Werte der Tabelle.

4. Result of the measurement:
Spectral responsivity $s(\lambda)_{\Phi}$ versus wavelength
Page 4 - 5 shows the graphic and numerical data. The numerical data of the spectral responsivity $s(\lambda)_{\Phi}$ are shown versus the wavelength (λ), unit (A/W). Only the numerical data are guaranteed.

Die spektrale Bandbreite $\Delta\lambda$ des Monochromators betrug:
The spectral bandwidth $\Delta\lambda$ of the monochromator was:
250 nm – 1100 nm: 10 nm

Für die relative Messunsicherheit gilt folgende Aufspaltung:
For the relative uncertainty is following table responsible:

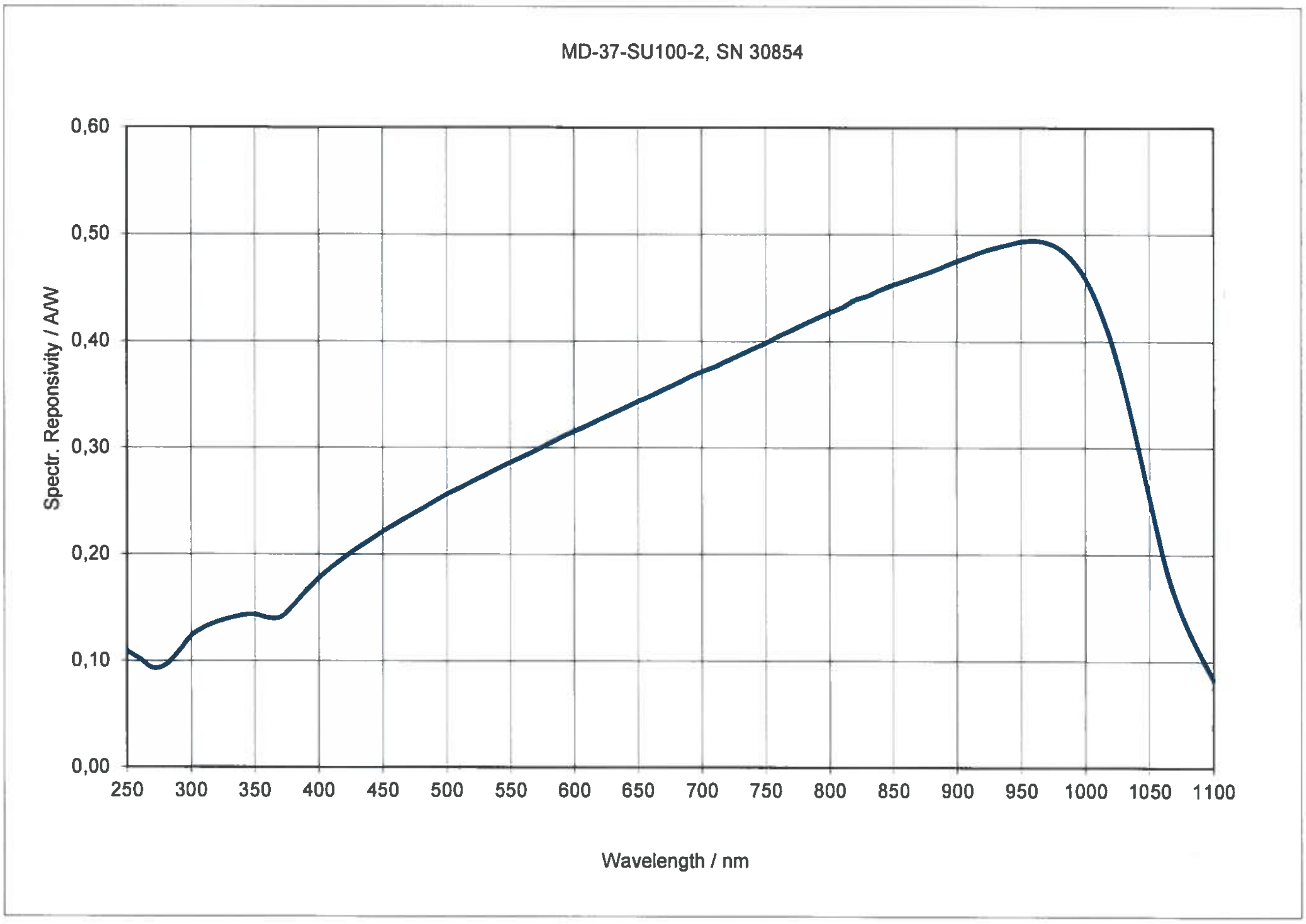
Wellenlänge in nm *Wavelength*	Relative Messunsicherheit in % *Relative uncertainty*
250 - 370	± 4,5
380 - 900	± 4
910 - 1070	± 4,5
1080 - 1100	± 5

Die angegebene Messunsicherheit (k = 2) setzt sich zusammen aus den Unsicherheiten des Kalibrierverfahrens und des Kalibriergegenstandes während der Kalibrierung. Ein Anteil für die Langzeitstabilität des Kalibriergegenstandes ist nicht enthalten.
The measuring insecurity (k = 2) stated is composed of the insecurities of the calibration method and of the calibrating object during the calibration. A share for the long term stability of the calibrated item is not included.

5. Bemerkungen:
Die oben angegebene Kalibriernummer 26231-02-WERK-2015-11 ist am Messkopf MD-37-SU100-2, Seriennummer 30854 angebracht. Der Kalibrierwert ist im Datenstecker des Messkopfes eingespeichert und kann mittels Menü aufgerufen werden.
Eine Abhängigkeit der spektralen Empfindlichkeit von anderen als den angegebenen Betriebsbedingungen oder Einflußgrößen ist nicht untersucht worden. Es ist mit einer wellenlängenabhängigen Alterung der spektralen Empfindlichkeit zu rechnen.
Eine Rekalibrierung innerhalb eines Jahres ist zu empfehlen.

5. Remarks:
The calibration report number 26231-02-WERK-2015-11 is marked on the detector head, type MD-37-SU100-2, serial number 30854. The calibration factor is stored into the data plug in of the detector head. It can be chosen by menu.
Dependence of the spectral responsivity from other as the given conditions is not examined. It is reckon in a wavelength dependence spectral responsivity during the life of the detector head.
Yearly recalibration is recommended.

Grafische Darstellung der Messwerte:
Graphic of the measured data:



Numerische Darstellung der Messwerte:
Numerical value of the measured data:

Wavelength / nm	Spectral responsivity / A/W	Wavelength / nm	Spectral responsivity / A/W	Wavelength / nm	Spectral responsivity / A/W
250,0	0,1093	540,0	0,2807	830,0	0,4430
260,0	0,1016	550,0	0,2863	840,0	0,4487
270,0	0,0935	560,0	0,2921	850,0	0,4534
280,0	0,0966	570,0	0,2979	860,0	0,4573
290,0	0,1088	580,0	0,3040	870,0	0,4617
300,0	0,1238	590,0	0,3101	880,0	0,4658
310,0	0,1317	600,0	0,3159	890,0	0,4707
320,0	0,1367	610,0	0,3209	900,0	0,4754
330,0	0,1403	620,0	0,3270	910,0	0,4801
340,0	0,1431	630,0	0,3325	920,0	0,4845
350,0	0,1439	640,0	0,3382	930,0	0,4879
360,0	0,1408	650,0	0,3439	940,0	0,4909
370,0	0,1413	660,0	0,3490	950,0	0,4937
380,0	0,1526	670,0	0,3548	960,0	0,4945
390,0	0,1661	680,0	0,3604	970,0	0,4925
400,0	0,1779	690,0	0,3666	980,0	0,4868
410,0	0,1881	700,0	0,3718	990,0	0,4760
420,0	0,1973	710,0	0,3763	1000,0	0,4587
430,0	0,2058	720,0	0,3822	1010,0	0,4336
440,0	0,2138	730,0	0,3877	1020,0	0,3999
450,0	0,2214	740,0	0,3932	1030,0	0,3574
460,0	0,2287	750,0	0,3987	1040,0	0,3073
470,0	0,2356	760,0	0,4051	1050,0	0,2539
480,0	0,2424	770,0	0,4104	1060,0	0,2002
490,0	0,2495	780,0	0,4164	1070,0	0,1597
500,0	0,2564	790,0	0,4221	1080,0	0,1305
510,0	0,2624	800,0	0,4274	1090,0	0,1055
520,0	0,2686	810,0	0,4322	1100,0	0,0835
530,0	0,2744	820,0	0,4393		

C Thorlabs photodiodes

In this section, we include the commercial documentation for the Thorlabs FDS10x10 photodiode, of which we bought several items for various experiments at LPNHE. The photometric measurements of the DESI calibration lamps are done with one of them (Thorlabs-FDS10x10-00001).

Si photodiode reference	**provider**	**calibration**	**date**	**geometry**	**area**
Thorlabs-FDS10x10-00001	Thorlabs	—	—	$10 \times 10\,\mathrm{mm}$	$100\,\mathrm{mm}^2$

Silicon Photodiode

FDS10X10

Description

The Thorlabs FDS10X10, silicon photodiode is ideal for measuring both pulsed and CW fiber light with sensitivity from 340 to 1100 nm. The detector is housed in a ceramic package with an anode and cathode connection. Under reverse bias application, the photodiode anode produces a current, which is a function of the incident light power and the wavelength. The responsivity $\Re(\lambda)$, can be read from Figure 1 to estimate the amount of photocurrent per incident light energy. The photodiode current can be converted to a voltage by placing a load resistor (R_L) between the photodiode anode and the circuit ground. The output voltage is derived as:

$$V_o = P \times \Re \times R_L$$

The bandwidth, f_{BW}, and the rise time response, t_R, are determined from the diode capacitance, C_J, and the load resistance, R_L, as shown below. The diode capacitance can be lowered by placing a bias voltage from the photodiode cathode to the circuit ground.

$$f_{BW} = \frac{1}{(2\pi)R_L C_J},\ t_R = \frac{0.35}{f_{BW}}$$

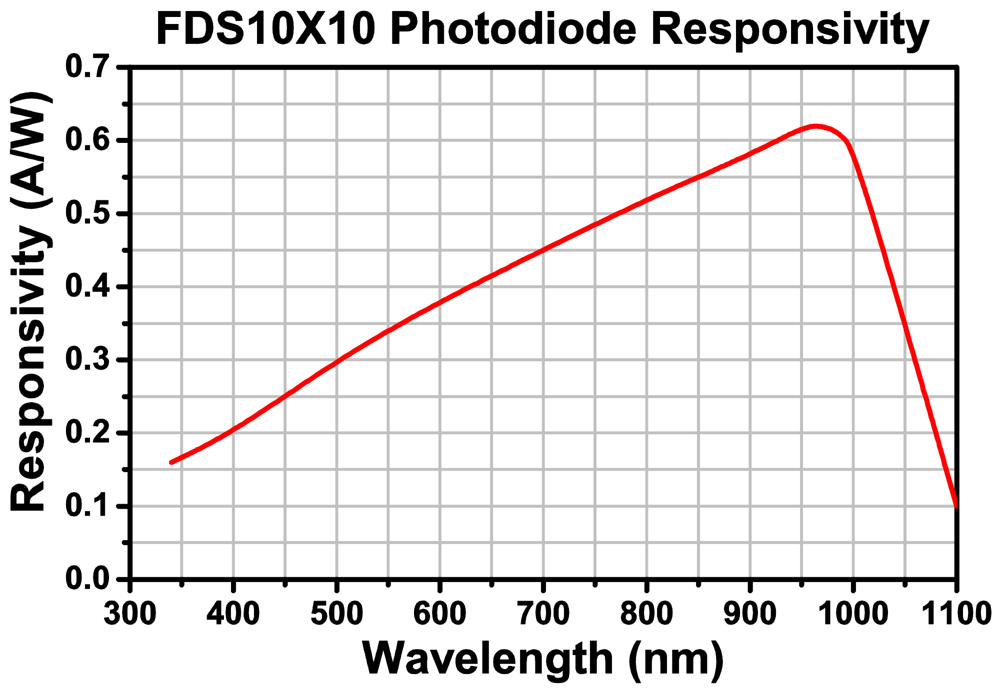
Specifications

Specification		Value
Wavelength Range	λ	340 - 1100 nm
Peak Wavelength	λ_p	960 nm
Responsivity	$\Re(\lambda_p)$	0.62 A/W
Active Area		100 mm^2
Rise/Fall Time (R_L=50 Ω, 5 V)	t_r/t_f	150 ns / 150 ns
NEP, Typical (960 nm)	W/√Hz	1.50×10^{-14}
Dark Current (5 V)	I_d	200 pA
Capacitance (5 V)	C_j	380 pF
Package		Ceramic
Sensor Material		Silicon (Si)

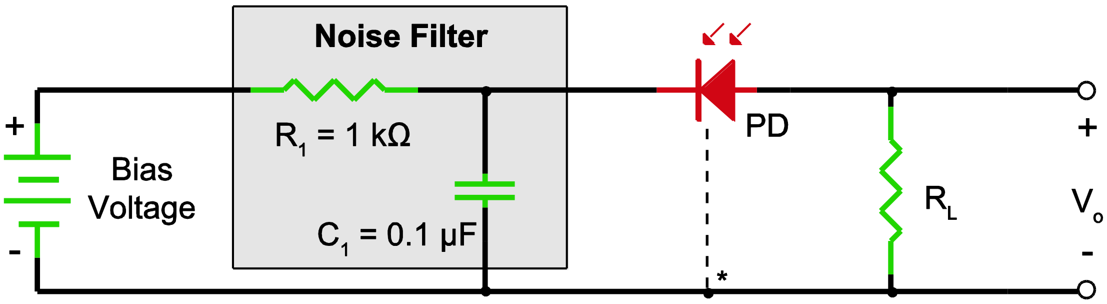
Maximum Rating	
Max Bias (Reverse) Voltage	5 V
Operating Temperature	-40 to +75 °C
Storage Temperature	-55 to +125 °C

November 12, 2014
24706-S01, Rev C

Typical Spectral Intensity Distribution

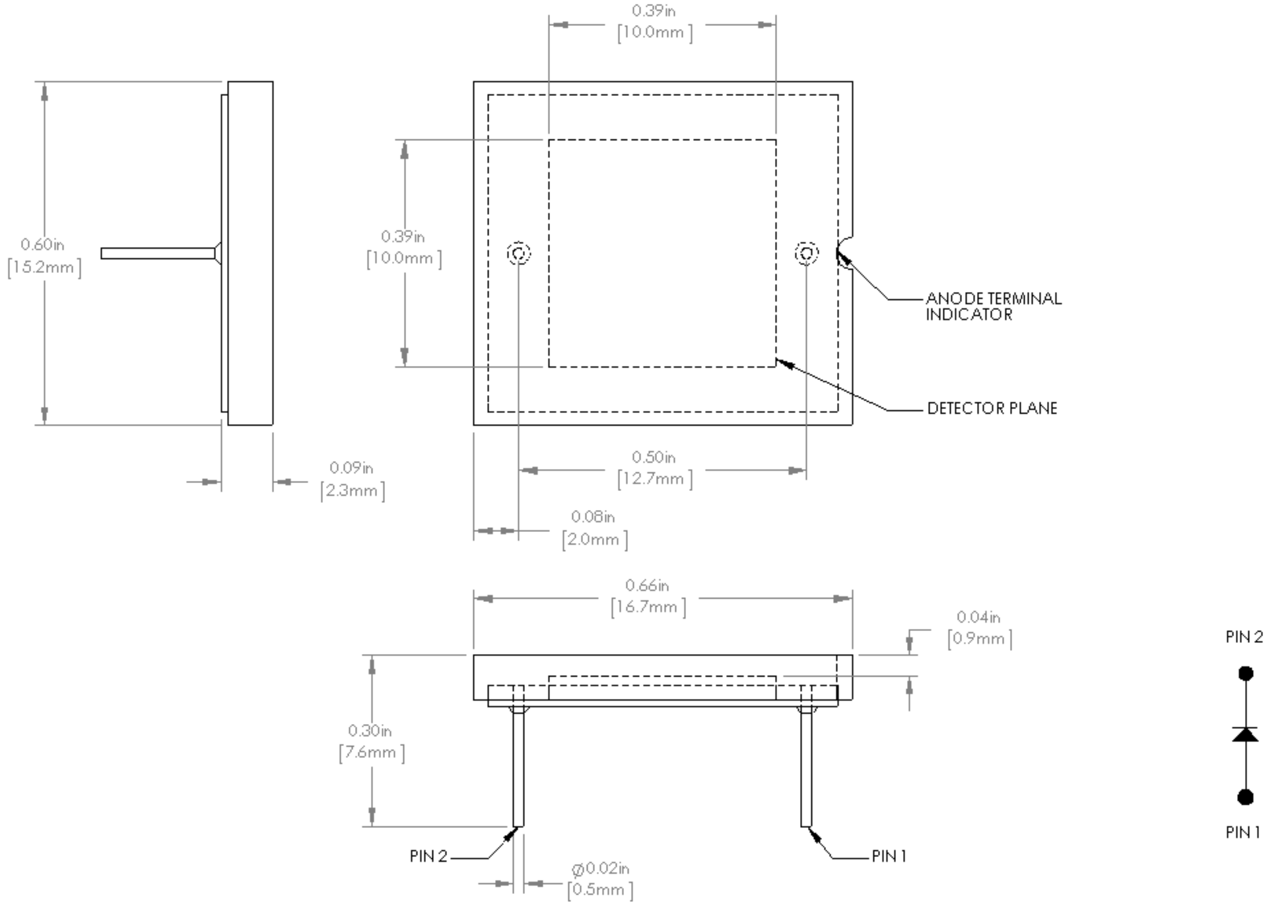


Recommended Circuit



* Case ground for PD with a third lead.

Drawing



0.39in
[10.0mm]
0.60in
[15.2mm]
0.39in
[10.0mm]
ANODE TERMINAL
INDICATOR
DETECTOR PLANE
0.09in
[2.3mm]
0.50in
[12.7mm]
0.08in
[2.0mm]
0.66in
[16.7mm]
0.04in
[0.9mm]
0.30in
[7.6mm]
PIN 2
PIN 1
⌀0.02in
[0.5mm]
PIN 2
PIN 1

Precautions and Warranty Information

These products are ESD (electrostatic discharge) sensitive and as a result are not covered under warranty. In order to ensure the proper functioning of a photodiode care must be given to maintain the highest standards of compliance to the maximum electrical specifications when handling such devices. The photodiodes are particularly sensitive to any value that exceeds the absolute maximum ratings of the product. Any applied voltage in excess of the maximum specification will cause damage and possible complete failure to the product. The user must use handling procedures that prevent any electro static discharges or other voltage surges when handling or using these devices.

Thorlabs, Inc. Life Support and Military Use Application Policy is stated below:

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