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Multi-kilowatt cw laser power measurement comparison between national standards

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Abstract

We present here the first comparison between National Metrology Institutes of high accuracy continuous wave optical power measurements in the kilowatt regime. The National Institute of Standards and Technology (NIST) performed measurements with a power meter relying on photon momentum. The Physikalisch-Technische Bundesanstalt (PTB) performed measurements with a modified off-the-shelf thermal power meter. The non-absorbing photon momentum measurement approach permits the two power meters to measure the same laser beam optical path simultaneously, resulting in a direct comparison of the meters supported by an optical system to accommodate differences in instrument settling times. The results show agreement within the expanded uncertainties for each instrument. NIST and PTB illustrate a degree of equivalence of 0.49% with an expanded uncertainty of 1.37% ($k = 2$) for an average result across all power levels.

Keywords: primary standard, radiation pressure, optical power calibration, kilowatt

1. Introduction

The industrial need for precision multi-kilowatt continuous wave (cw) optical power measurements is growing in both the private and public sectors. High-power laser applications include laser-based welding and metal additive manufacturing as well as defense and research, and the market has responded with a competitive variety of measurement devices for high-power optical radiation. The traceability of these power meters to the International System of Units (SI) requires that National Metrology Institute(s) (NMI) maintain high-accuracy calibration standards at these power levels. A previous high-power comparison was performed via a transfer standard, but only up to 550 W [1]. Laser power comparisons between NMIs have not yet been demonstrated at the kilowatt level, nor has there been any comparison between NMIs involving a radiation-pressure-based laser power meter. Multi-kilowatt cw standards exist at both the National Institute of Standards and Technology (NIST) and the Physikalisch-Technische Bundesanstalt (PTB). The NIST instrument is a primary standard based on radiation pressure and measures high-power laser beams in the kilowatt regime with expanded uncertainties of 1.6% or lower. The PTB instrument is a secondary standard that uses a thermal approach for 0.8% uncertainty or lower and is traceable to PTBs primary standard for optical radiation.

Intercomparison of laser power measurements between NIST and PTB has been frequent for over 20 years [1–3]. However, high-power measurements and calibrations involve not only technical challenges in the procedure and

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measurement technique, but also in the facility management and supporting hardware and infrastructure. Given this, facilities that are capable of accurate kilowatt laser power measurement are limited. Both NIST and PTB have developed low-uncertainty measurement systems capable of serving industry [4–6]. Each high-power laser laboratory configuration involves infrastructure for precision water flow and calibration is both time intensive and carries a significant safety hazard due to the high laser irradiance. These factors make high-power calibration difficult and uncommon, therefore this work addresses a unique area.

This paper presents the direct comparison of laser power measurements performed by these two power meters in the kilowatt regime. In the following sections we will describe each device, measurement method, and implementation. Additionally, the uncertainty components of each measurement instrument will be discussed and the degree of equivalence (DOE) for their comparison will be quantified.

2. Measurement detectors

2.1. Radiation pressure power meter (RPPM)

The NIST RPPM described in detail previously [6] is a precision force sensor that measures optical power using the radiation force delivered to a sensing mirror when a laser beam reflects from its surface. The laser power P_{RPPM} is related to the force F on the sensing mirror as

$$P_{\text{RPPM}} = cF/2r\cos(\theta) \tag{1}$$

where c is the speed of light, θ is the laser light's angle of incidence (AOI), and $r = R+(1-R)\alpha/2$ accounts for the mirror reflectance R and the fraction α of non-reflected light absorbed by the mirror. The mirror is isolated against air current by an outer housing with anti-reflection-coated entrance and exit windows. The 1 mm thick fused silica windows have transmission exceeding 0.9996 and reflectance of 0.0002 per surface. The mirror (a 1 mm thick distributed Bragg reflector stack deposited on a fused silica wafer) has reflectivity exceeding 0.99997 at a 45° AOI. The force sensor has a rise time of 0.83 s prompting a 7 s settling time before the measurement begins to ensure force readings are within 0.1% of their final value.

NIST utilized a meter that relies on radiation pressure for this measurement due to its high-power capacity, portability, and ease of use. Additionally, the RPPM operates by reflecting optical radiation that is incident on the ultra-high reflectivity mirror to a workpiece or other object farther along the optical path (in this case another power meter). This non-absorbing method allowed for NIST and PTB to simultaneously measure the same laser power. The RPPM is a primary standard power meter, defined as a measurement device that does not derive its calibration from another device measuring the same quantity. Since the RPPM measures the imparted force of photons, it is calibrated using small mass artifacts [7]. As such, the SI-traceability for the RPPM is through the kilogram (figure 1).

RPPM power measurements have been successfully performed up to 140 kW cw [8]. The device has also shown strong

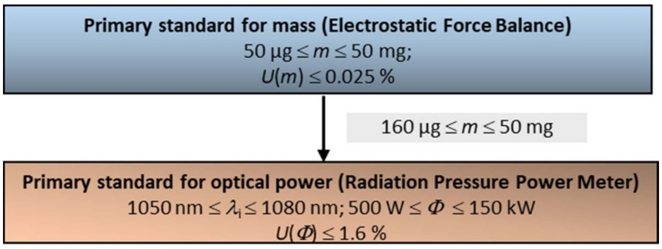

Figure 1. The traceability for the RPPM is drawn from calibrated mass artifacts to the kilogram. The RPPM is calibrated from 162 μg to 50 mg (as indicated by the grey box).

agreement with repeated comparisons at NIST with the high-power calorimeter used for calibrations [4, 9].

2.2. Electronically calibrated power monitor (EC-PM)

The measurement device utilized by PTB is a modified commercial-off-the-shelf power meter known as the EC-PM. The meter is a water-cooled absorption cavity that monitors input and output water temperatures for high-accuracy determination of laser power input. The modifications are to permit electrical substitution calibration of the device by a DC electrical heater (the original device has an AC electrical heater). However, currently these modifications are not utilized, and the EC-PM is calibrated optically through laser power using a transfer standard power meter. This calibration by transfer standard is one of the steps [10, 11] that make up the traceability chain (figure 2) leading to the primary standard—the PTB cryogenic radiometer [12]. The SI-traceability for the cryogenic radiometer is through the volt and ohm.

The incident laser light enters the device aperture and is reflected off a broadband highly reflective focusing mirror into the absorbing cavity. Both the absorbing cavity and focusing mirror are water-cooled. The geometry of the cavity resembles a cavity blackbody with a small entrance aperture and large inner surface area, and as such >99% light is absorbed [13]. The difference in water temperature (ΔT) between the outlet and inlet of the absorber cavity is monitored as well as the mass flow rate $\dot{m}_{\text{w}}$ (in units of kg s^{-1}). The measured laser power $P_{\text{EC-PM}}$ is given as

$$P_{\text{EC-PM}} = f_{\text{c}}\dot{m}_{\text{w}}c_{\text{w}}\Delta T \tag{2}$$

where f_{c} is the calibration factor obtained from the transfer standard and c_{w} is the specific heat capacity of water. The value of f_{c} is 1.0234 from calibration via the transfer standard as described in [5]. The EC-PM relies on thermal power measurement techniques, and as such, has a much slower response time than the RPPM. Measurements require a 60 s settle time. In the case of a calibration, a lowpass filter may be configured to model different rise times of the device under test (DUT). This allows for adjustment of a monitor detector's behavior in the calibration setup to accurately perform a DUT calibration.

The EC-PM has a capacity of 4.5 kW of optical radiation, however, it is currently used up to about 2 kW at a nominal wavelength of 1065 nm [5] and 10.6 μm, since lasers with

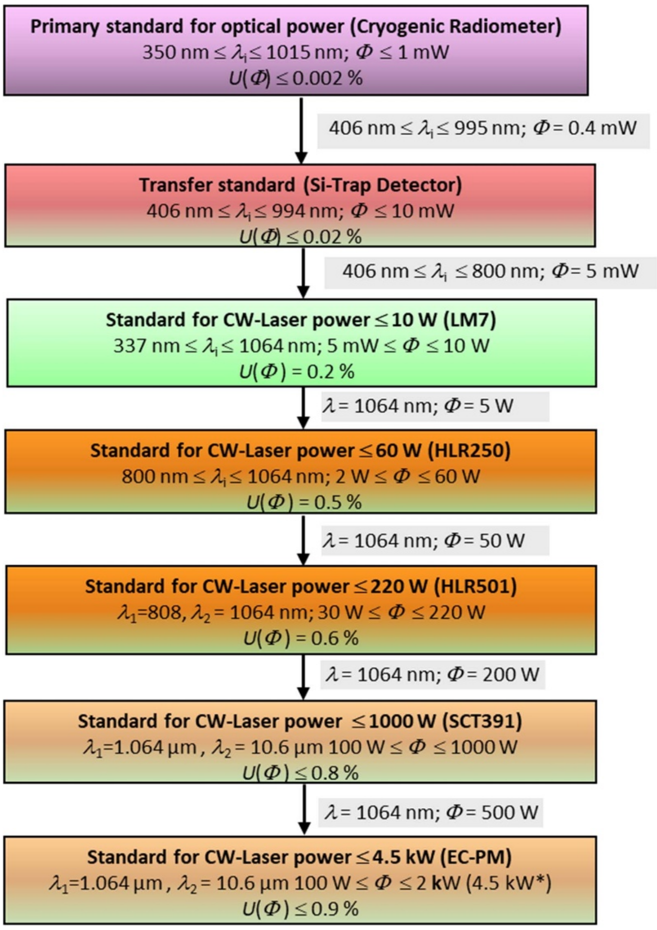

Figure 2. The traceability chain for EC-PM detector calibration. The * indicates additional usable range using electrical calibration. Each grey box indicates the calibration parameters for the specific step in the chain.

higher optical power are not available at the PTB laboratory. To achieve SI traceability at higher power levels would also require electrical-substitution-based calibration.

3. Measurement configuration

3.1. Optical layout

The measurement layout is illustrated in figure 3. Laser light from a 2.5 kW fiber-coupled diode laser was launched free-space and measured simultaneously by the RPPM, the EC-PM, and a photodiode monitor detector transfer standard. This monitor detector was used to simplify the comparison between the EC-PM and RPPM given the drastic difference in their settling times. The laser light is sampled by a beam splitter directing approximately 8% of the light to the entrance of a water-cooled integrating sphere (150 mm internal diameter) with an embedded InGaAs photodiode. A transimpedance amplifier was used to report the photodiode response as a voltage signal proportional to the incident power on the photodiode. This voltage signal over the duration of each laser injection was provided to both NIST and PTB to use in evaluating the

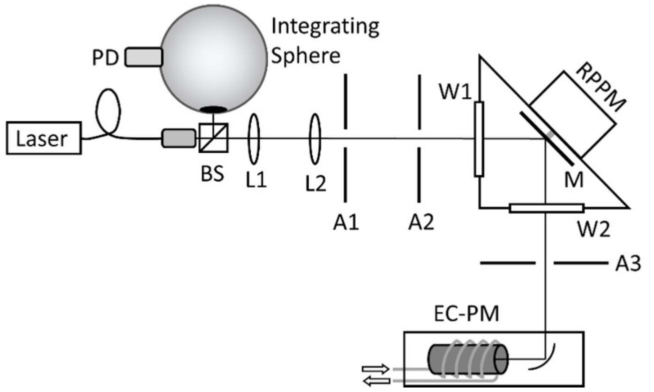

Figure 3. Experimental setup for comparison of NIST radiation pressure power meter (RPPM) to PTB electronically calibrated power monitor (EC-PM). BS is the beam splitter directing ∼8% of the laser light to the water-cooled integrating sphere and monitor detector (PD). The lenses (L1 and L2) roughly collimate the beam and there are three apertures (A1, A2, and A3) that prevent stray light and backscattered light from affecting the measurement. The RPPM mirror (M) and windows (W1 and W2) are precision coated optics to minimize scatter and absorptance.

responsivity R of the photodiode-sphere combination (in units of volts per watt). The agreement between the RPPM and EC-PM was then quantified by comparing the respective responsivities R_{RPPM} and $R_{\mathrm{EC\text{-}PM}}$.

After the beam splitter, the light beam was expanded and collimated with a pair of lenses yielding a 16 mm diameter (99% extent of beam) laser beam incident on the RPPM sensing mirror which then reflected to the EC-PM. Aperture A1 (60 mm diameter) was used to block a diffraction ring of light originating from the laser fiber tip. Aperture A2 was placed ahead of the RPPM and was used to prevent any stray reflected light from reaching the integrating sphere and photodiode.

In comparing the power at the RPPM sensing mirror, and the power at the EC-PM entrance, any source of measurement inequivalence between the two must be minimized and quantified. The 0.04% reflection at the RPPM's exit window (W2) was considered when calculating RPPM's measured power. The reflection presents a loss to the power going to EC-PM and an extra force on the RPPM sensing mirror. The power reported by the RPPM was corrected following the technique described in [14] to report the power expected at the entrance to the EC-PM located 60 cm from the RPPM.

Aperture A3 minimized heating of the RPPM from backscattered light from the EC-PM and limited the amount of such light incident on the RPPM sensing mirror to avoid double measurement. The diameter of the apertures A2 and A3 (25 mm and 50 mm, respectively) were large enough to assure that the beam was not clipped as verified by repeated measurements with and without A2 and A3.

A red guide beam at milliwatt power levels was used for initial optical alignment. For the RPPM, this permitted alignment of the sensing mirror to $45 \pm 0.1°$ from normal incidence. The EC-PM was then aligned with the exit beam from the RPPM.

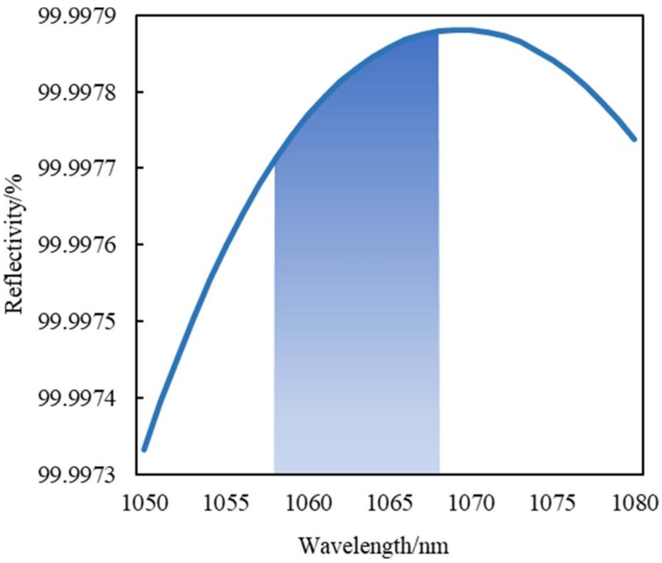

Figure 4. Reflection percentage as a function of wavelength for the RPPM high-reflector sensing mirror. The shaded area denotes the wavelength variation of the laser across its power output range. Note that across the range the reflection is >99.9977%.

To correct any wavelength-dependence in the lenses the alignment of the experiment was tested with the 1065 nm laser light at low power. This guaranteed that all reflected light from the RPPM was being captured by the EC-PM and no overfill conditions were present.

We carried out the measurement comparison with between 40 and 55 laser injections at each of four laser powers (nominally 0.5 kW, 1 kW, 1.5 kW, and 2 kW). At each power, 4–5 measurement series were performed with up to 11 injections each with the laser off for 60 s and then on for 60 s. The RPPM, EC-PM, and photodiode collected data during each series and the input power level was changed between series to effectively randomize the measurement order. Since the EC-PM required one injection before its thermal equilibrium point could be stabilized, the first injection of each series was not used for the comparison.

3.2. Laser

The laser used for the comparison was a fiber-coupled diode laser with custom collimating optics. This source is comprised of multiple diode stacks each with individual diode bars, which are then coupled to a single beam using proprietary technology. Due to the temperature dependence and drive current variation of each diode, the output wavelength varies slightly with laser power from 1058 nm at 0.4 kW to 1068 nm at 2 kW. We found this wavelength change presented an insignificant effect on the RPPM windows and mirror—see figure 4 indicating this change in mirror reflectivity over the potential wavelength range.

The EC-PM is also unaffected by the slight power dependence of the source wavelength. The highly absorbing EC-PM cavity has a broad-band absorption spectrum due to its multiple internal reflections and black coating with water cooling of the absorber and mirror. Potential slight changes in mirror reflectivity with laser wavelength adjust where the light is absorbed (mirror or cavity) but do not affect the output/input water temperature difference.

While the source wavelength will affect the photodiode response, the non-absorbing capability of the RPPM allows for both meters to measure the same optical beam path, thus measuring the same optical effects in the path. This eliminates any optical path inequivalence between the two devices.

4. Results and analysis

4.1. Comparison results

Table 1 shows the photodiode responsivity measured by each of the power meters over the range of laser powers. The uncertainty for PTB measurements was independent of power as the measurement uncertainty for the EC-PM is dominated by Type B (non-statistical) evaluations inherent to the device. The RPPM's uncertainty is dominated by a fixed statistical noise (Type A) due to environmental vibration and air currents yielding a signal-to-noise ratio that increases with laser power.

At each injected laser power, the photodiode responsivity was calculated as the ratio of injection-averaged photodiode voltage divided by the injection-averaged power meter (EC-PM or RPPM) result. These responsivities were averaged over the multiple injections and laser powers as follows.

For the EC-PM, after ignoring the initial injection, the measured powers and photodiode voltage signals of subsequent injections were averaged together to report a single number for each series. The photodiode responsivity using this value is represented in figure 5 as 'PTB series'. While the RPPM reported a value for each injection in a series, the averaging method of EC-PM was mimicked to report a single responsivity value for each series, denoted 'NIST series'. The 'NIST/PTB avg' values represent the average of all responsivities obtained at a specific power level (for example, 5 series of nominally 10 injections each at 0.5 kW). These 'NIST/PTB avg' values are shown in table 1. The error bars in figure 5 and column 4 of table 1 are expanded uncertainty ($k = 2$ for a nominal 95% confidence interval).

Since the EC-PM and RPPM have differing response times, they required unique analysis procedures. The RPPM power measurement calculated the incident power of each injection using a baseline-removal method. The baseline 'dark' value was evaluated by averaging the signal for 10 s before and after each laser injection. The laser turn-on and turn-off points were identified using the photodiode signal as it has a much faster response time (<10 ns). The RPPM was allowed to equilibrate for 7 s after the laser turn-on, and then the signal was averaged until the turn-off time. Another 7 s delay allowed for equilibration prior to sampling the 'dark' value after the 'laser off' time. A linear correction was applied to remove any drift between the pre- and post- injection baseline measurements. This evaluation procedure is described in more detail in [6].

The EC-PM is a thermal detector with a slow thermal response. To ensure a temporal match between the EC-PM and photodiode signals, the photodiode voltage was convolved

Table 1. Measurement results for each NMI at each power level with their associated measurement uncertainties.

Nominal laser power/kW	NMI	Monitor photodiode responsivity/V/W	Expanded uncertainty ($k = 2$, 95% confidence)
0.5	PTB	0.000 7402	0.80%
	NIST	0.000 7409	1.22%
1	PTB	0.000 7399	0.80%
	NIST	0.000 7443	1.10%
1.5	PTB	0.000 7417	0.80%
	NIST	0.000 7459	1.07%
2	PTB	0.000 7493	0.80%
	NIST	0.000 7546	1.05%

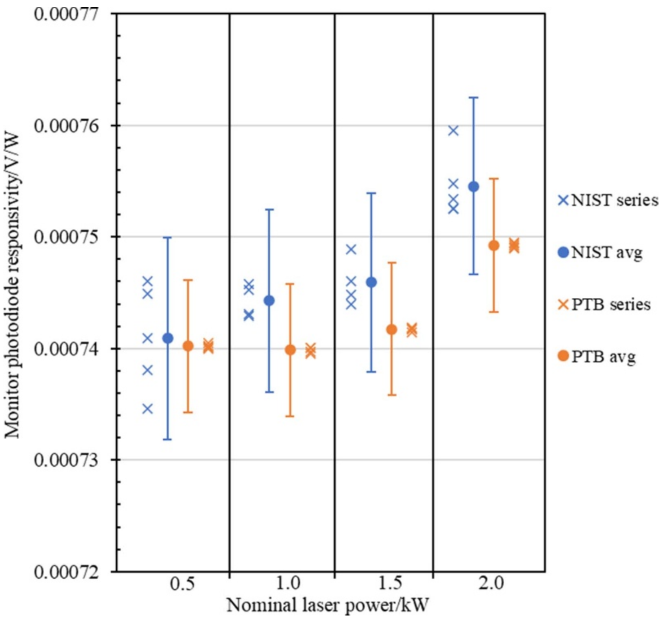

Figure 5. Photodiode responsivity as reported by NIST and PTB measurements. Each series of laser injections is denoted as series and the average of all series of injections is denoted as avg.

with the EC-PM's impulse response function. A single measurement value for the EC-PM power and the convolved photodiode voltage were then taken at the end of each laser injection and at the end of each cool-down phase (for the 'dark' value for baseline removal). The ratio of the two yielded a photodiode responsivity for each injection. This was averaged over all the injections of a complete run, omitting the first injection. Due to the long time constant of the EC-PM and the modified monitor diode signal, each reading can be interpreted as a weighted average over the injection/cool-down time.

4.2. Uncertainty

The established uncertainty for the determination of the photodiode responsivity using each device is quantified in the following section and tables below. For the EC-PM the definitions of each uncertainty component associated with a factor for the performed measurements are shown in table 2. The

Table 2. Uncertainty contributions for the determination of the photodiode responsivity using the EC-PM.

Term	Uncertainty definition	Standard uncertainty ($k = 1$, 68% confidence)
u_{fk}	Calibration factor of EC-PM	$3.8 \cdot 10^{-3}$
u_{res}	EC-PM resolution	$200 \cdot 10^{-6}$
u_{H}	Inhomogeneity of EC-PM	$577 \cdot 10^{-6}$
u_{S}	Stray light	$577 \cdot 10^{-6}$
$u_{\beta\phi}$	Power dependence of EC-PM	$577 \cdot 10^{-6}$
u_{M}	Convolved photodiode monitor signal	$239 \cdot 10^{-6}$

Table 3. Uncertainty contributions for the determination of the photodiode responsivity using the RPPM.

Term	Uncertainty definition	Standard uncertainty ($k = 1$, 68% confidence)
u_{scale}	Scale calibration correction	$2.4 \cdot 10^{-3}$
u_{H-V}	Horizontal to vertical force equivalence	$2.1 \cdot 10^{-3}$
u_{mirror}	Mirror reflectivity	$4.3 \cdot 10^{-4}$
u_{angle}	Angle of incidence	$2.0 \cdot 10^{-3}$
u_{PD}	Averaged photodiode monitor signal	$2.8 \cdot 10^{-4}$
u_{stat}	Statistical uncertainty (power dependent, see equation (3))	$4.8 \cdot 10^{-3}$ (0.5 kW) $4.0 \cdot 10^{-3}$ (1 kW) $3.8 \cdot 10^{-3}$ (1.5 kW) $3.7 \cdot 10^{-3}$ (2 kW)

expanded uncertainty of the monitor diodes sensitivity (calculated from the quadrature sum of the uncertainties of table 2) is 0.8%, independent of the power measured, and contains a coverage factor of $k = 2$. The uncertainty of the monitor signal was estimated using the Monte Carlo method.

For the RPPM, the expanded uncertainty has a power-dependent term that is reduced with increasing power. This reduction is shown in table 1. Table 3 below defines each uncertainty component for the RPPM.

As described in [6], the statistical uncertainty is determined at the location of the measurements via two lab-specific noise factors. The vibrational noise factor σ_p (in units of Watts) and the drift non-linearity factor γ_p (unitless) were assessed at the pilot laboratory (PTB) prior to the comparison. Their values were 10.4 W and 0.0036, respectively. Since the σ_p noise factor is independent of laser power, its contribution to relative uncertainty decreases with increasing power. The statistical uncertainty of the measurements considers these two components as follows:

$$u_{\mathrm{stat}} = \sqrt{\left[\frac{\sigma_p}{P}\frac{1}{\sqrt{N}}\right]^2 + {\gamma_p}^2}. \tag{3}$$

For this comparison P is the power level being measured and N is the number of laser injections. Equation (3) differs

Table 4. Chi-squared values and consistency check.

Power/kW	χ^2_{obs}	$\chi^2_{0.05}$	Consistency
0.5	0.017	3.841	Satisfied
1	0.763	3.841	Satisfied
1.5	0.710	3.841	Satisfied
2	1.144	3.841	Satisfied

Table 5. Bilateral degree of equivalence for PTB and NIST (degree of equivalence and its uncertainty are reported here as relative values).

Power/kW	DOE	Expanded uncertainty of DOE ($k = 2$, 95% confidence)
0.5	0.10%	1.46%
1	0.60%	1.36%
1.5	0.56%	1.34%
2	0.71%	1.32%
Average	0.49%	1.37%

slightly from the uncertainty contribution in [6] because we are establishing uncertainty for many laser injections as opposed to a single injection. Each additional component of the uncertainty in table 3 is added in quadrature with u_{stat}.

4.3. Consistency and DOE

The analysis of the measurement agreement between the responsivities reported by PTB and NIST will be described using the procedures set forth by the International Bureau of Weights and Measurements in appendix B of [15] and as implemented by Spidell *et al* [3]. A series of calculations were performed to determine each laboratory's agreement via a Chi-squared consistency check. PTB reports a lower uncertainty for these measurements, and as such their responsivity values were chosen as the reference for calculations. These calculations were performed at each power level measured. Table 4 below shows the results of the Chi-squared consistency check to determine agreement between laboratories across all power levels. Specifically, the observed chi-squared value χ^2_{obs} is calculated using the fractional discrepancy between the two laboratories while accounting for the weight of each measurement towards the consensus responsivity and uncertainty. The standard chi squared value ($\chi^2_{0.05}$) is obtained using a chi-squared probability table assuming a single degree of freedom (only two laboratories were compared) and a significance level of 0.05 for a 5% chance of making a false-positive error. Agreement (consistency) is satisfied when $\chi^2_{obs} < \chi^2_{0.05}$.

Additionally, the degree of equivalence (DOE) was evaluated for the comparison. This indicates the fractional degree to which the measurement value (in this case NIST) disagrees with the reference value (in this case PTB), shown in table 5. A DOE of 0% indicates perfect agreement.

5. Discussion and conclusion

The results show good agreement between NIST and PTB across the power level range of the comparison, with an average DOE of 0.49% and an average equivalence uncertainty of 1.37%. The DOE is less than the uncertainty at each power level which indicates consistency between the measurements and the calculated uncertainties of the two NMIs.

Both power meters identified a power-dependent responsivity of the photodiode (figure 5). Figure 5 also illustrates the well-known power-dependent statistical noise of the RPPM [6]. Environmental noise (vibration, air currents etc.) provide a fixed noise floor to the RPPM's force sensor measurement. The fractional noise contribution to the RPPM measurement thus decreases with increasing laser power. Previous measurements of several tens of kilowatts have indicated that increasing laser power can achieve a sub-percent measurement uncertainty before other error sources begin to dominate.

The non-absorptive nature of the RPPM greatly simplified the measurement and implementation of the device into the calibration setup. It also allowed for direct (simultaneous) power comparison between the two detectors. This may allow for future evaluation of nonlinearities and drift sources that may be intrinsic to the photodiode or other components in the PTB calibration setup. Additionally, the electrical substitution calibration method of the EC-PM may permit higher power measurements. Future work could involve utilizing this extended range for comparison to lower-uncertainty radiation-pressure-based power meters [16].

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