Bilateral Supplementary comparison of cryogenic radiometers SIM.PR-S3 NIST - Inmetro

March 2016

Sumário

Introduction

NIST (USA) and Inmetro (Brazil) performed a bilateral comparison of cryogenic radiometers. The subject of this comparison is to give metrological equivalence to the measurement of optical power performed at Inmetro, using the reference value of this quantity derived from CCPR-S3 comparison.

A technical protocol was written based on the CCPR-S3 comparison protocol of cryogenic radiometers. The protocol was approved and it is available at KCDB webpage with the identifier SIM.PR-S3.

Each laboratory provided two detectors – silicon-based 3-photodiode reflexive trap detectors – for this bilateral comparison.

Inmetro provided 2 three-elements trap detectors containing Hamamatsu 1337-1010N (windowless) photodiodes. These individual detectors were constructed at Inmetro by selecting suitable photodiodes in housings purchased from Rantell Elekter. The trap detectors are identified by their serial numbers PT058 and PT061, respectively.

NIST provided 2 Graseby detectors, model QED150, identified by serial numbers TSD004 and TSD009.

Those detectors were measured at nominal wavelengths of 457.9 nm and 514.5 nm of Ar^+; 632.8 nm of HeNe by each laboratory.

Bilateral comparison

Time schedule

Table 1 shows the time schedule of the comparison. The four detectors were first measured at NIST from April to June 2012. Then they were sent to Inmetro and measured in October and November 2012. They were returned back to NIST for the 3rd round measurement in December 2012 and January 2013 .

Table 1. Comparison time schedule

Measurement round	INM	Period
1st	*NIST*	*April 2012 to June 2012*
2nd	*Inmetro*	*October 2012 to November 2012*
3rd	*NIST*	*December 2012 to January 2013*

Transfer detectors stability

The average relative change of responsivity of the trap detectors at each wavelength for the measurements performed at NIST are displayed in Table 2. The change is bigger for shorter wavelengths, which is an expected behavior for this kind of detector.

Table 2. Average relative change of responsivity of four detectors for the first and last round of measurement at NIST.

Wavelength (nm)	633	514	458
10^4 × relative responsivity change of trap detectors	*-3,4*	*-3,0*	*-5,6*

The magnitude of the relative change of responsivity is considered as a source of uncertainty ($u_{transfer}$) for the dectector stability in the comparison.

Additional information on the transfer detectors stability is presented on Appendix A.

Procedure and experimental conditions

Inmetro

Summary of the experimental conditions:

a) Cryogenic radiometer type: CryoRad II from Cambridge Research Instruments, Inc;
b) Sources: Ar+ laser, He-Ne laser;
c) Nominal power: 100 µW;
d) Beam diameter: 2 mm;
e) Room Temperature: 23 °C ± 1 °C.

The experimental setup at Inmetro is depicted in Fig. 1 and consisted of HeNe and an Ar^{+} laser sources, operated at 632.8 nm and at 514.5 nm and 458 nm, respectively. The linearly polarized laser beam is spatially filtered and actively stabilized in power at around 100 μW. The cryogenic radiometer absorbing cavity and the trap detector are positioned at the same distance from the source. The diameter of the gaussian beam at the detection plane is typically 2 mm full-width at half-maximum (FWHM). The Brewster-angled cryogenic radiometer's window was carefully aligned at each wavelength. The temperature of the room was kept at 23 °C ± 1 °C and the humidity was 50 % ± 10 %.

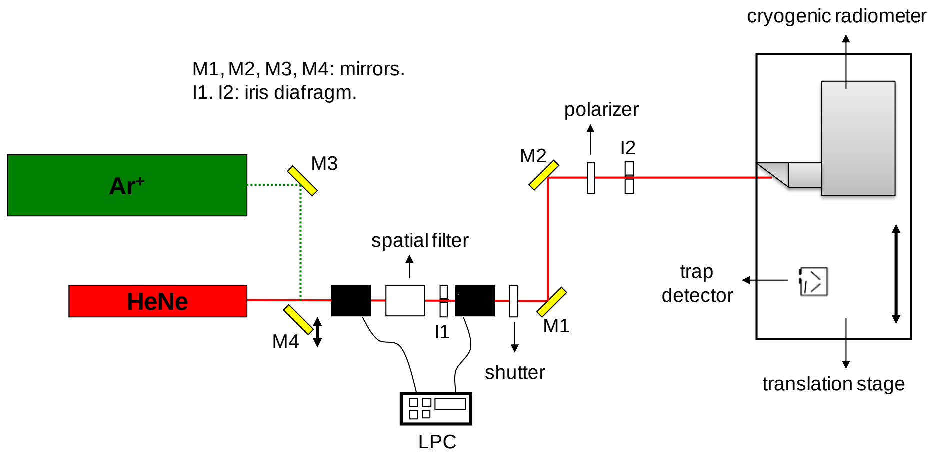

Fig. 1: Experimental setup: Inmetro.

The cryogenic radiometer and the trap detector are alternately submitted to the same power stabilized, p-polarized optical beam. The optical power (at the cryogenic radiometer) and the photocurrent (at the trap detector) are acquired at each wavelength to determine the spectral power responsivity of the trap detector.

The trap detector is aligned relative to laser beam. The detectors are tilted so that the residual reflection is approximately collinear with the input beam. Then, the detectors are translated along the x and y axes for aligning the beam at the center of the device. The position is further adjusted by a maximum signal search.

Each trap detector was measured at least 5 times consecutively at each wavelength. The experiment cycle was repeated at least 3 times, with the detector being realigned before each repetition.

NIST

Summary of the experimental conditions:

a) Cryogenic radiometer type: Primary Optical Watt Radiometer (POWR) made at NIST;
b) Sources: Ar+ laser, He-Ne laser;
c) Nominal power: 100 µW;
d) Beam diameter: 2 mm;
e) Room Temperature: 23 °C ± 1 °C.

The schematic of the NIST experimental setup is shown in Fig. 2. The NIST POWR and devices-under-test (DUT) are placed on a movable stage. Instead of tunable lasers as shown in Fig. 2, output from Ar^+ and He-Ne lasers were used for these measurements. The setup at NIST is fundamentally similar to the one used at Inmetro.

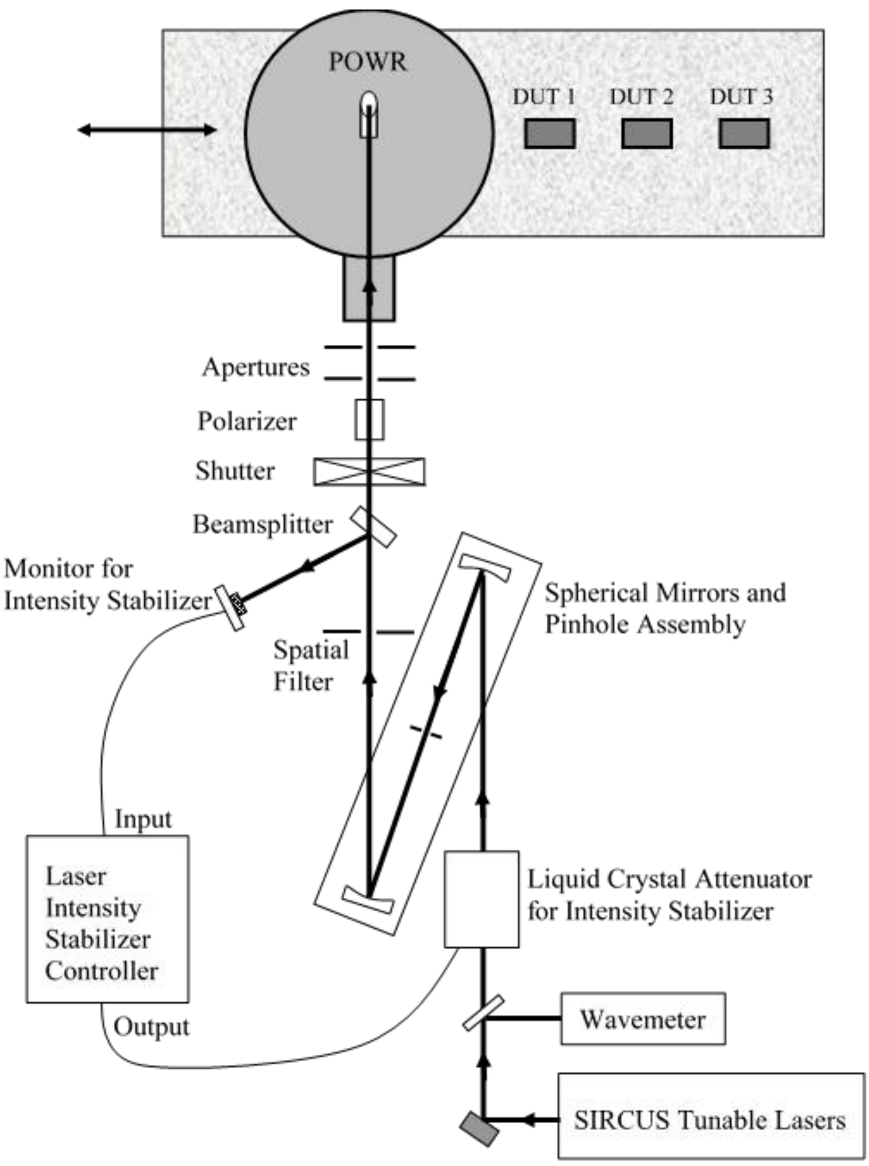

Fig. 2: Experimental Setup: NIST

To measure the optical power responsivity of transfer detectors using POWR with laser sources, each DUT is mounted along with the POWR cryostat on a single large servo-motor-controlled translation stage as shown in Fig. 2. By translating this stage horizontally these DUTs, along with POWR, are each aligned to the laser light sequentially. After the initial alignment, this stage is then used to select the any of the DUT's, or the POWR cavity, one at a time, to receive the laser beam.

Uncertainty Budget

Inmetro

The sources of uncertainty for the calibration of the spectral responsivity of the trap detectors are presented in Table 3. Uncertainties #1 through #5 are originated from the optical power measurement at cryogenic radiometer. The cavity absorbance was characterized by the cryogenic radiometer manufacturer prior to the radiometer assembly and constitutes the only source that was not verified at Inmetro. The window transmittance is measured yearly. Uncertainties #3 and #4 are also characterized annually, usually near the period of measurements. The repeatability of the optical power measurement, presented in Table 3 as #5, will depend on the standard deviation of the acquired radiometer data for each specific measurement. The presented value is a typical repeatability of the radiometer. Uncertainties #6, #7 and #8 of Table 3 are related to the photocurrent measurement. This amplifier converts the photocurrent generated by the detector in voltage which is measured by the digital voltmenter (DVM). Both pieces of equipment were calibrated at Inmetro and the uncertainties correspond to the values reported at the certificates of calibration plus equipment uncertainties (e.g. resolution and temporal stability). The repeatability of detector measurements corresponds to the standard deviation of the electrical current measurement and depends upon the condition of measurement. Finally, the reproducibility (# 9) describes the variation between the results gathered at distinct conditions of measurement. This component is obtained by the standard deviation of measurements after resetting the equipment or after realignment of the detector at the setup. The combined uncertainty presented in Table 3 describes the $k = 1$ typical uncertainty of measurement and is obtained by the root sum square of the components.

Table 3. Contributions to the relative uncertainty for calibration of trap detectors.

#	**Source of Uncertainty**	**Relative standard uncertainty**
1	Cavity absorbance	3.3E-06
2	Window transmittance	1.0E-04
3	Non-equivalence	2.3E-05
4	Electrical Power Meas.	1.2E-05
5	Repeatability Radiometer	6.2E-05
6	DVM calibration	8.5E-05
7	Amplifier calibration	7.6E-05
8	Repeatability of Detector Meas.	3.0E-05
9	Reproducibility	1.0E-04
	Combined Uncertainty	**2.0E-04**

NIST

The uncertainty budget for the NIST measurements is shown below.

Table 4. Components of the combined uncertainty for the measurements of the power responsivity of a trap detector in the silicon trap transfer-standard wavelength range using POWR at NIST.

Components	**Uncertainty (%) *k*=1**
Type B Uncertainties/Corrections:	
Window Transmittance (*T*)	0.005
Nonequivalence (*N*)	0.002
Cavity Absorptance (*A*)	$<1x10^{-4}$
Scattered Optical Power Factor (f_s)	0.006
Electrical Power Scale (P_{meas}/P_{true})	0.0023
Trap Spatial Uniformity (U_s)	0.01
Trap Amplifier Gain (*G*)	0.004
Type A Uncertainty in %	0.014
Combined uncertainty in %	**0.02**

Results

The relative difference between the responsivity values measured at NIST and Inmetro, $\Delta_{NIST\text{-}Inmetro}$, is calculated using:

$$\Delta_{Inmetro-NIST} = \frac{R_{Inmetro} - R_{NIST}}{R_{NIST}}, \tag{1}$$

where $R_{Inmetro}$ is the Inmetro responsivity calibration values and R_{NIST} is the mean value of the first and third calibration values performed at NIST. Table 5 shows the relative difference for each trap and the average difference at each wavelength.

Table 5: Relative difference in trap calibration $\Delta_{NIST\text{-}Inmetro}$.

	Wavelength (nm)		
	632.8	514.5	458
Detector	$10^4 \times$ relative difference		
PT059 – Inmetro	-8.1	-7.1	-5.4
PT061 – Inmetro	-9.5	-5.1	-5.0
TSD004 – NIST	-8.4	-7.4	-7.0
TSD009 – NIST	-8.1	-7.9	-7.8
Average	-8.5	-6.9	-6.3

The relative combined standard uncertainty of the comparison is calculated by:

$$u_{NIST-Inmetro} = \sqrt{u_{NIST}^2 + u_{Inmetro}^2 + u_{transfer}^2}. \tag{2}$$

Table 6 summarizes the calculation of the uncertainty of the comparison.

Table 6: Relative combined standard uncertainty of the comparison.

	Wavelength (nm)		
	632.8	514.5	458
Source of uncertainty	10^4 × relative standard uncertainty		
u_{NIST}	2.0	2.0	2.0
$u_{Inmetro}$	2.0	2.0	2.0
$u_{transfer}$	3.4	3.0	5.6
$u_{NIST\text{-}Inmetro}$	4.5	4.1	6.2

Figure 1 shows the results of the spectral responsivity for the transfer detectors used in the comparison. The error bars indicate the expanded uncertainty of the comparison (*k*=2).

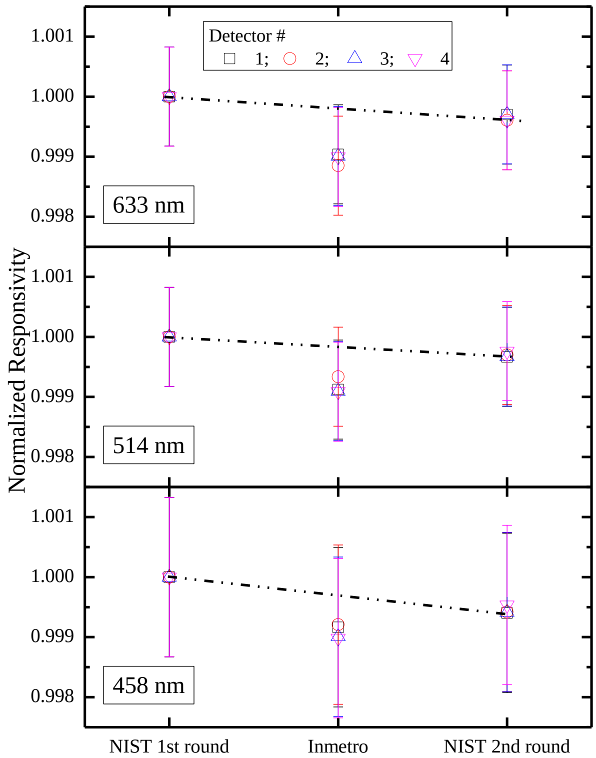

Figure 1: Spectral responsivity of the detectors measured at nominal wavelengths of (a) 633 nm, (b) 514 nm and (c) 458 nm. The results were normalized by the first measurement at each wavelength.

The results of the measurements at both institutes agree under the normalized error criterion for all wavelengths. The normalized error is shown in Table 7 and calculated using:

$$E_n = \frac{\Delta_{Inmetro-NIST}}{U_{NIST-Inmetro}}, \qquad (3)$$

where $U_{NIST-Inmetro}$ is the expanded uncertainty of the comparison.

Table 7: Normalized error at each wavelength of the comparison.

Wavelength / nm	633	514	458
Normalized error	-0.96	-0.84	-0.51

Link with CCPR-S3

At the comparison CCPR-S3 comparison, NIST performed measurements at wavelengths 488 nm, 514.5 nm and 632.8 nm. Therefore, Inmetro's results presented above can be linked to the CCPR-S3 reference values at the wavelengths 514.5 nm and 632.8 nm. The wavelength 458 nm was not part of the CCPR-S3 comparison.

The difference $\Delta_{Inmetro\text{-}Ref}$ from the CCPR-S3 reference value is given at each wavelength by:

$$\Delta_{Inmetro-Ref} = \Delta_{Inmetro-NIST} + \Delta_{NIST-Ref}, \tag{4}$$

where $\Delta_{Inmetro\text{-}NIST}$ is defined in equation (1) and $\Delta_{NIST\text{-}Ref}$ is the deviation of the NIST results from the CCPR-S3 reference value.

The uncertainty $u_{Innmetro\text{-}Ref}$ associated with the diference between Inmetro results and the reference values is determined by the uncertainty of this bilateral comparison ($u_{Inmetro\text{-}Nist}$) and the uncertainty associated with $\Delta_{Nist\text{-}Ref}$ in CCPR-S3 ($u_{Nist\text{-}Ref}$):

$$u_{Inmetro-ref} = \sqrt{u^2_{Inmetro-Nist} + u^2_{NIST-ref}}. \tag{5}$$

The difference $\Delta_{NIST\text{-}Ref}$ and its associated uncertainty $u_{Nist\text{-}Ref}$ at each wavelength can be obtained from the BIPM Report BIPM-2000/9, page 54. These values are reproduced at Table 8.

Table 8: Relative difference of NIST results to the CCPR-S3 reference values and associated uncertainties.

Wavelength / nm	633	514
$10^4 \times \Delta_{Nist\text{-}Ref}$	2.4	5.2
$10^4 \times u_{Nist\text{-}Ref}$	4.1	3.2

The relative difference $\Delta_{Inmetro\text{-}Ref}$ between the Inmetro results and the CCPR-S3 reference value at each wavelength and the associated uncertainty $u_{Inmetro\text{-}Ref}$ are presented in Table 9.

Table 9: Relative difference of Inmetro results to the CCPR-S3 reference values and associated uncertainties.

Wavelength / nm	633	514
$10^4 \times \Delta_{\mathrm{Inmetro\text{-}Ref}}$	-6.1	-1.7
$10^4 \times \mathrm{u}_{\mathrm{Inmetro\text{-}Ref}}$	6.1	5.2

Conclusions

A bilateral comparison of cryogenic radiometer's was performed between the NIST (pilot) and the Inmetro. Four trap detectors were used as transfer standards. The devices were measured at both institutes in a one-year time span. The results for both institutes agree under the normalized error criterion, in spite of the systematic off-set of Inmetro's results. The results of this comparison also show agreement with a combined standard uncertainty of 6.1 parts per 10^4 and the differences to the CCPR-S3 reference value were -1.7 and -6.1 parts in 10^4.

Appendix A1 – Further information on detectors temporal stability

The detectors used in the measurements exhibited a considerable drift from the first to the second round of measurements at NIST. This drift, which was considered in the measurement uncertainty, is more pronounced for the 458 nm wavelength. This kind of ageing behaviour was also an issue for the CCPR S3 comparison and might indicate that these types of trap detectors are not well suitable as transfer detectors for this kind of comparison.

Figure A1 depicts the spectral responsivity at nominal wavelengths of 458 nm, 514 nm and 633 nm for a trap detector which was held at Inmetro.

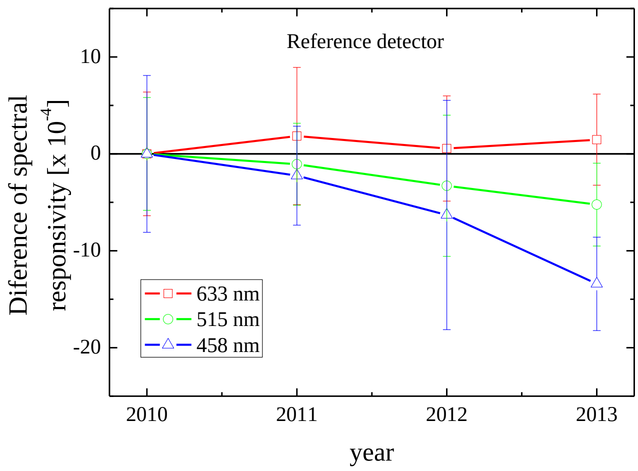

Figure A1. Variation of spectral responsivity of a trap detector at nominal wavelengths of 633 nm, 514 nm and 458 nm as measured at Inmetro over the course of three years.

The results clearly show a spectrally-dependent temporal behaviour of the responsivity. Again, the shorter the wavelength in the range, the bigger the drift. The maximum variation is about 0.06% at 458 nm, then reduces to 0.02% at 515 nm, and becomes 0.01% at 633 nm.