EUROMET Comparison

Project No. 156

EUROMET.PR-S2

Responsivity of detectors for radiant power of lasers

Final Report

(in compliance with Draft B of "Radiant Power of High Power Lasers – Part 1")

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Contents

1 General information on the comparison

1.1 Under the Mutual Recognition Arrangement (MRA)[1] the metrological equivalence of national measurement standards will be determined by a set of key comparisons (KCs) chosen and organised by the Consultative Committees of the CIPM working closely with the Regional Metrology Organisations (RMOs). This set of key comparisons has to be added by supplementary comparisons (SCs) organised by the RMOs.

1.2 At their meeting in Delft in April 12.-13. 1999, the EUROMET Photometry and Radiometry contact persons decided to start a supplementary comparison on radiant power of high power lasers (EUROMET project 156). The PTB was assigned to act as a pilot laboratory. This comparison was split into two parts. The first part, starting in January 2005, covers the following lasers, wavelengths and power levels:

Laser	Wavelength	Power
Argon ion	514.5 nm	1 W
Nd:YAG	1064 nm	1 W
Nd:YAG	1064 nm	10 W
CO_2	10.6 µm	1 W
CO_2	10.6 µm	5 W

Instead of Nd:YAG also other Nd- or Yb lasers operating between 1030 nm and 1080 nm might be used in the comparison. The expected difference for the responsivity compared to the wavelength of 1064 nm should be taken into account, also in the uncertainty budget. Although this SC is organized within a EUROMET project, it is a global comparison carried out worldwide.

1.3 This technical protocol has been drawn up by a small working group, comprising the PTB, the NPL and the LNE.

1.4 The technical protocol was agreed on by all participants and was sent out on February 2nd, 2005. The procedures outlined in the technical protocol cover the technical procedure to be followed during measurement of the transfer detectors. The procedure, which follows the guidelines established by the EUROMET[2], is based on current best practise in the use of standard detectors and takes account of the experience of the working group.

1.5 The organisation of the whole comparison was described in the technical protocol.

1.6 According to the technical protocol (Section 5.4), after receipt of all measurement reports from the participating laboratories, the pilot laboratory has analyzed the results and prepared a first pre-draft "A" report on the comparison following the draft guidelines of the CCPR KCWG[3]. This pre-draft "A" report included measurement reports of the participants and submitted uncertainty tables, but no results. This was circulated to the participants for comments, additions and corrections. During this phase participants were at liberty to correct their submitted uncertainties, but only in an increased direction and supported by an explanation. In addition, a report summarising the participants own results and relative data showing the performance of the transfer standards was circulated individually to each participant in order to confirm them prior to the publication of Draft A. Subsequently, the procedure outlined in the BIPM Guidelines[3] was followed, which will mean that no results can be changed for whatever reason by any participant except for errors of the pilot lab.

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1 MRA, Mutual Recognition Arrangement, BIPM, 1999.
2 EUROMET guidance document no. 3: Guidelines for the organisation of comparisons
3 Guidelines for CCPR Comparison Report Preparation, CCPR Key Comparison Working Group, Rev. 1, March 2006

2 Laboratory contact persons

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3 Total schedule and data of the comparison

The schedule of the comparison can be seen from the data in Table 1. The dates for “receipt confirmation and completion confirmation” give the total time the transfer detectors were at the corresponding NMI. The dates for “Record of exposure”, “Description of facility” and “Results” are the dates, when the data were received at PTB.

Table 1: Data of the comparison

Country	Receipt Confirmation	Damage	Completion Confirmation	Damage/Remarks	Record of exposure	Description of facility	Results
DE	1.1.2005	No	7.2.2005	No	21.2.2005	21.2.2005	21.2.2005
SE	16.2.2005	No	15.3.2005	No	5.5.2005	5.5.2005	5.5.2005
US	8.4.2005	No	11.7.2005	No	11.7.2005	11.7.2005	11.7.2005
FR	19.5.2005	No	6.6.2005	No	13.7.2005	13.7.2005	13.7.2005
DE	16.6.2005	No	14.7.2005	No	13.7.2005	13.7.2005	13.7.2005
ZA	12.8.2005	No	13.10.2005	No	13.10.2005	13.10.2005	13.10.2005
AU	24.11.2005	No	30.1.2006	Yes / Molectron	-	-	shift to end
NL	-	-	-	-	-	-	withdrawn
DE	25.4.2006	No	2.5.2006	Molectron repaired	3.5.2006	3.5.2006	3.5.2006
JP	1.6.2006	No	4.7.2006	No	9.8.2006	9.8.2006	9.8.2006
GB	10.7.2006	No	15.8.2006	No	13.11.2007	13.11.2007	13.11.2007
RO	6.10.2006	No	31.1.2007	No	24.1.2007	24.1.2007	24.1.2007
DK	-	-	-	-	-	-	withdrawn
DE	22.1.2007	No	9.2.2007	No	20.2.2007	20.2.2007	20.2.2007
AU	19.3.2007	No	14.6.2007	No	5.11.2007	5.11.2007	5.11.2007
UA	-	-	-	-	-	-	withdrawn
DE	2.7.2007	No	13.9.2007	No	13.9.2007	13.9.2007	13.9.2007

4 Exposure times

In Table 2 and Table 3 the exposure times for the two transfer detectors are listed.

Table 2: Overview of the exposure times for the Ophir 30A-A3 transfer detector

	Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Total exposure time (min)
DE	Argon	514.5	1	10	
	Nd:YAG	1064	1	10	
	Nd:YAG	1064	10	10	
	CO_2	10600	1	10	
	CO_2	10600	5	10	
			Sum	50	50
SE	Argon	514.5	1	10	
	Nd:YAG	1064	1		
	Nd:YAG	1064	10		
	CO_2	10600	1	15	
	CO_2	10600	5	15	
			Sum	40	40
US	Argon	514.5	1	3	
	Nd:YAG	1064	1	3	
	Nd:YAG	1064	10	2	
	CO_2	10600	1	4	
	CO_2	10600	5	2	
			Sum	14	14
FR	Argon	514.5	1	70	
	Nd:YAG	1064	1	21	
	Nd:YAG	1064	10	21	
	CO_2	10600	1	20	
	CO_2	10600	5	20	
			Sum	152	152
DE	Argon	514.5	1	10	
	Nd:YAG	1064	1	10	
	Nd:YAG	1064	10	10	
	CO_2	10600	1	10	
	CO_2	10600	5	10	
			Sum	50	50
ZA	Argon	514.5	1	5	
	Nd:YAG	1064	1	5	
	Nd:YAG	1064	10	6	
	CO_2	10600	1	5	
	CO_2	10600	3	5	
			Sum	26	26
AU	Argon	514.5	1	Measurements were cancelled, due to problems with the Molectron transfer detector.	
	Nd:YAG	1064	1		
	Nd:YAG	1064	10		
	CO_2	10600	1		
	CO_2	10600	5		
			Sum	0	0

	Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Total exposure time (min)
DE	Argon	514.5	1	15	
	Nd:YAG	1064	1	15	
	Nd:YAG	1064	10	15	
	CO_2	10600	1	15	
	CO_2	10600	5	15	
			Sum	75	75
JP	Argon	514.5	1	40	
	Nd:YAG	1064	1	30	
	Nd:YAG	1064	10	30	
	CO_2	10600	1	30	
	CO_2	10600	5	30	
			Sum	160	160
GB	Argon	514.5	1		
	Nd:YAG	1064	1	3	
	Nd:YAG	1064	10	2	
	CO_2	10600	1	3	
	CO_2	10600	5	3	
			Sum	11	11
RO	Argon	514.5	1	180	
	Nd:YAG	1064	1	125	
	Nd:YAG	1064	10		
	CO_2	10600	1		
	CO_2	10600	5		
			Sum	305	305
DE	Argon	514.5	1	15	
	Nd:YAG	1064	1	15	
	Nd:YAG	1064	10	15	
	CO_2	10600	1	15	
	CO_2	10600	5	15	
			Sum	75	75
AU	Argon	514.5	1	70	
	Nd:YAG	1064	1	60	
	Nd:YAG	1064	10	40	
	CO_2	10600	1	60	
	CO_2	10600	5	50	
			Sum	280	280
DE	Argon	514.5	1	15	
	Nd:YAG	1064	1	15	
	Nd:YAG	1064	10	15	
	CO_2	10600	1	15	
	CO_2	10600	5	15	
			Sum	75	75
				Total sum	**1313**

Table 3: Overview of the exposure times for the Molectron PM10 transfer detector

	Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Total exposure time (min)
DE	Argon	514.5	1	10	
	Nd:YAG	1064	1	10	
	Nd:YAG	1064	10	10	
	CO_2	10600	1	10	
	CO_2	10600	5	10	
			Sum	50	50
SE	Argon	514.5	1	10	
	Nd:YAG	1064	1		
	Nd:YAG	1064	10		
	CO_2	10600	1	15	
	CO_2	10600	5	15	
			Sum	40	40
US	Argon	514.5	1	3	
	Nd:YAG	1064	1	3	
	Nd:YAG	1064	10	2	
	CO_2	10600	1	4	
	CO_2	10600	5	2	
			Sum	15	15
FR	Argon	514.5	1	42	
	Nd:YAG	1064	1	18	
	Nd:YAG	1064	10	18	
	CO_2	10600	1	17	
	CO_2	10600	5	17	
			Sum	112	112
DE	Argon	514.5	1	10	
	Nd:YAG	1064	1	10	
	Nd:YAG	1064	10	10	
	CO_2	10600	1	10	
	CO_2	10600	5	10	
			Sum	50	50
ZA	Argon	514.5	1	5	
	Nd:YAG	1064	1	5	
	Nd:YAG	1064	10	6	
	CO_2	10600	1	5	
	CO_2	10600	3	5	
			Sum	26	26
AU	Argon	514.5	1	Measurements were cancelled, due to problems with the Molectron transfer detector.	
	Nd:YAG	1064	1		
	Nd:YAG	1064	10		
	CO_2	10600	1		
	CO_2	10600	5		
			Sum	0	0

	Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Total exposure time (min)
DE	Argon	514.5	1	15	
	Nd:YAG	1064	1	15	
	Nd:YAG	1064	10	15	
	CO_2	10600	1	15	
	CO_2	10600	5	15	
			Sum	75	75
JP	Argon	514.5	1	40	
	Nd:YAG	1064	1	30	
	Nd:YAG	1064	10	30	
	CO_2	10600	1	30	
	CO_2	10600	5	30	
			Sum	160	160
GB	Argon	514.5	1		
	Nd:YAG	1064	1	3	
	Nd:YAG	1064	10	2	
	CO_2	10600	1	3	
	CO_2	10600	5	3	
			Sum	11	11
RO	Argon	514.5	1	150	
	Nd:YAG	1064	1	135	
	Nd:YAG	1064	10		
	CO_2	10600	1		
	CO_2	10600	5		
			Sum	285	285
DE	Argon	514.5	1	15	
	Nd:YAG	1064	1	15	
	Nd:YAG	1064	10	15	
	CO_2	10600	1	15	
	CO_2	10600	5	15	
			Sum	75	75
AU	Argon	514.5	1	40	
	Nd:YAG	1064	1	40	
	Nd:YAG	1064	10	40	
	CO_2	10600	1	10	
	CO_2	10600	5	10	
			Sum	140	140
DE	Argon	514.5	1	15	
	Nd:YAG	1064	1	15	
	Nd:YAG	1064	10	15	
	CO_2	10600	1	15	
	CO_2	10600	5	15	
			Sum	75	75
				Total sum	**1114**

5 Performance of the transfer detectors

According to the technical protocol, section 5.4 (page 9), the pre-Draft A also included the performance of the transfer detectors. Therefore, in order to be able to evaluate the performance of the transfer detectors, both detectors were measured several times by the PTB (pilot laboratory) during this intercomparison. For comparison, also an Ophir detector of the same type as one of the transfer detectors was measured. This detector, Ophir 30–A4 stayed at PTB during the whole intercomparison and was only used for the purpose of the intercomparison, i.e. measured at the same time as the transfer detectors were measured at PTB. In the following, the detailed results for each detector and each measurand are listed in Table 4 - Table 6 and are shown in Figure 1 - Figure 3.

The detectors exhibited a change in the responsivity over time, most probably caused by the transport and the illumination during the measurements. Therefore it is suggested to take into account this changes in the spectral responsivity for the evaluation of the results of the participants. This was performed in the following way, i.e. using a linear interpolation based on the measurements carried out at the pilot lab (PTB):

$$s^*_{NMI} = s_{NMI} \cdot \left(1 + \left(s(\mathrm{PTB})_{n+1} - s(\mathrm{PTB})_n\right)\frac{\Delta N_{NMI}}{\Delta N}\right) = s_{NMI} \cdot (1 + \Delta s)$$

where s^*_{NMI} (s_{NMI}) is the corrected (submitted) spectral responsivity for each participating laboratory, $s(\mathrm{PTB})_{n+1}$ and $s(\mathrm{PTB})_n$ are the normalized spectral responsivities measured at PTB before and after the individual measurement of the NMI, respectively, ΔN is the number of measurements between the two PTB measurements + 1, and ΔN_{NMI} is the number of the measurement for the individual NMI between two PTB measurements. For illustration and clarification, in Table 7 and Table 8 the values for $s(\mathrm{PTB})_n$, $s(\mathrm{PTB})_{n+1}$, ΔN, ΔN_{NMI} and Δs are given for each NMI for both transfer detectors used for all measurands. For comparison and completeness, also the data for the Ophir 30–A4 detector are given in Table 9.

Maximum corrections Δs are

for the Molectron PM10: Δs_{max} = -0.00153, 1 + Δs_{max} = 0.99847

for the Ophir 30–A3: Δs_{max} = +0.00143, 1 + Δs_{max} = 1.00143

for the Ophir 30–A4: Δs_{max} = +0.00208, 1 + Δs_{max} = 1.00208

Table 4: Performance of the transfer detector Molectron PM10. λ: wavelength, Φ: radiant power, s/s_{mean}: normalized standard uncertainty (with respect to the mean value of the measurements performed at PTB), $u(s/s_{mean})$: standard uncertainty, k: expansion factor, Δ: deviation with respect to the mean value.

	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	514.5	1.0	1.0004	0.0008	2.0	0.04%
Jul 05	514.5	1.0	1.0003	0.0009	2.0	0.03%
Apr 06	514.5	1.0	0.9999	0.0009	2.0	-0.01%
Jan 07	514.5	1.0	1.0000	0.0010	2.0	0.00%
Sep 07	514.5	1.0	0.9994	0.0010	2.0	-0.06%
Mean Value	**514.5**	**1.0**	**1.0000**	**0.0004**	**2.0**	**0.00%**

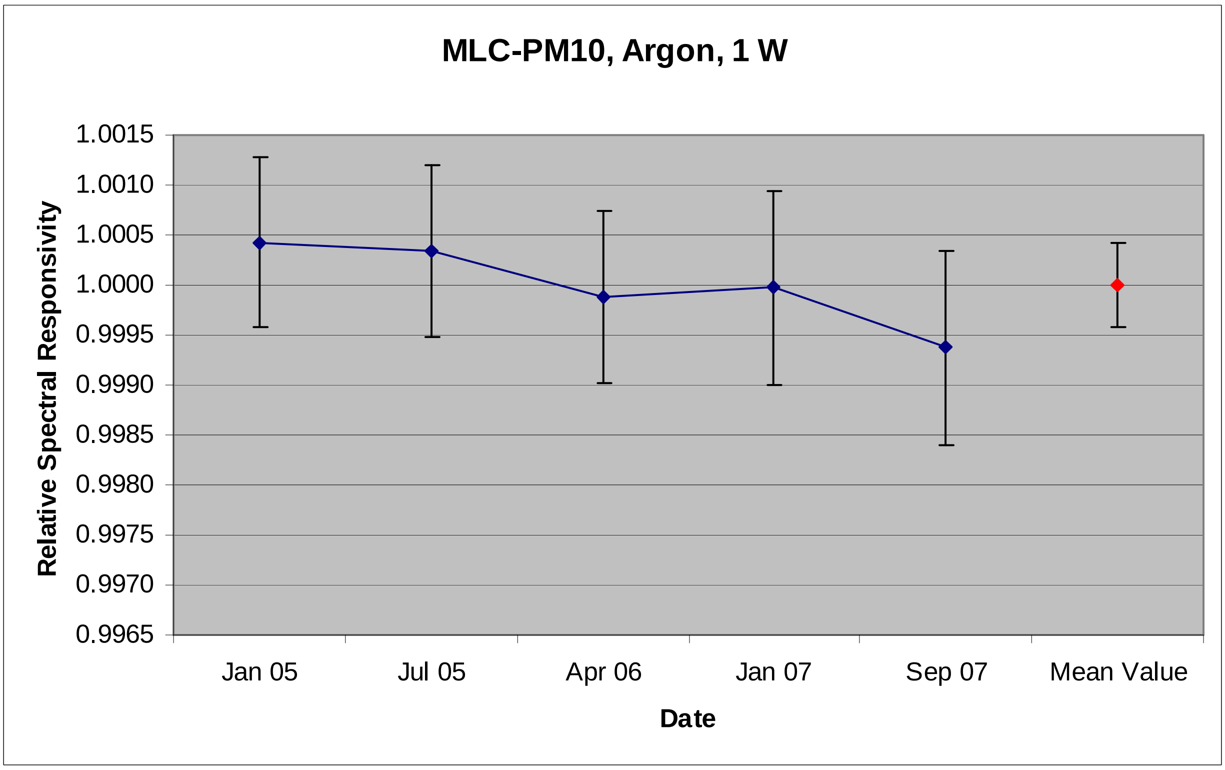
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	1064	1.0	1.0018	0.0017	2.1	0.18%
Jul 05	1064	1.0	0.9998	0.0016	2.1	-0.02%
Apr 06	1064	1.0	1.0003	0.0016	2.1	0.03%
Jan 07	1064	1.0	0.9998	0.0015	2.0	-0.02%
Sep 07	1064	1.0	0.9983	0.0027	2.1	-0.17%
Mean Value	**1064**	**1.0**	**1.0000**	**0.0013**	**2.0**	**0.00%**

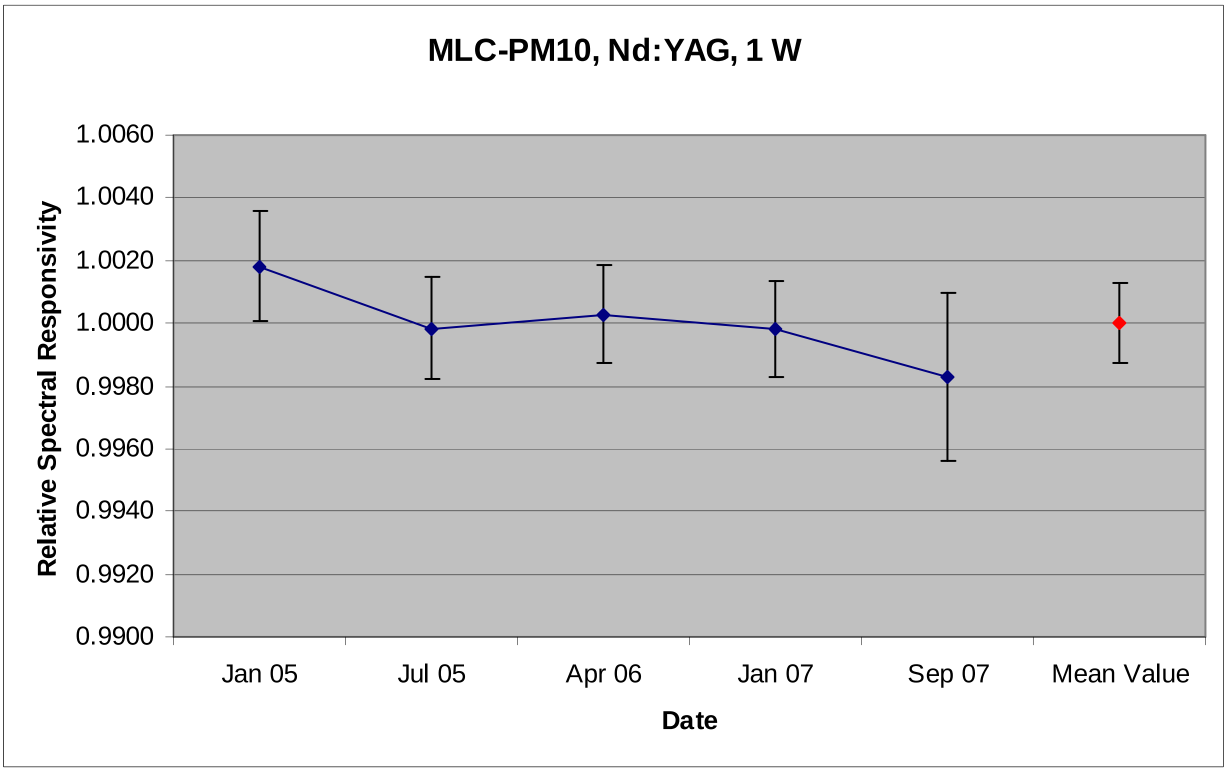
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	1064	10.0	1.0016	0.0019	2.1	0.16%
Jul 05	1064	10.0	1.0004	0.0018	2.0	0.04%
Apr 06	1064	9.9	1.0007	0.0018	2.0	0.07%
Jan 07	1064	10.1	0.9987	0.0020	2.1	-0.13%
Sep 07	1064	9.9	0.9986	0.0022	2.1	-0.14%
Mean Value	**1064**	**10.0**	**1.0000**	**0.0013**	**2.0**	**0.00%**

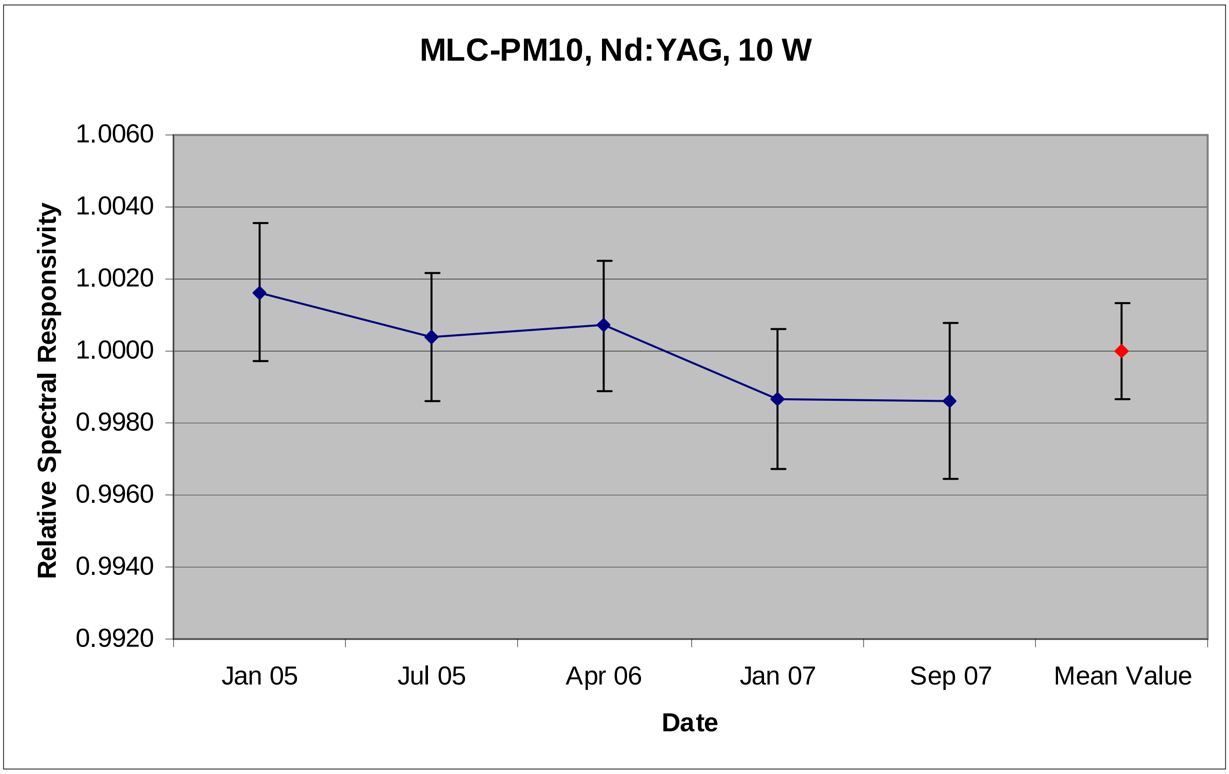
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	10600	1.1	1.0016	0.0022	2.1	0.16%
Jul 05	10600	1.0	1.0008	0.0022	2.1	0.08%
Apr 06	10600	1.0	1.0009	0.0021	2.1	0.09%
Jan 07	10600	1.0	0.9991	0.0020	2.0	-0.09%
Sep 07	10600	1.0	0.9976	0.0020	2.0	-0.24%
Mean Value	**10600**	**1.0**	**1.0000**	**0.0016**	**2.0**	**0.00%**

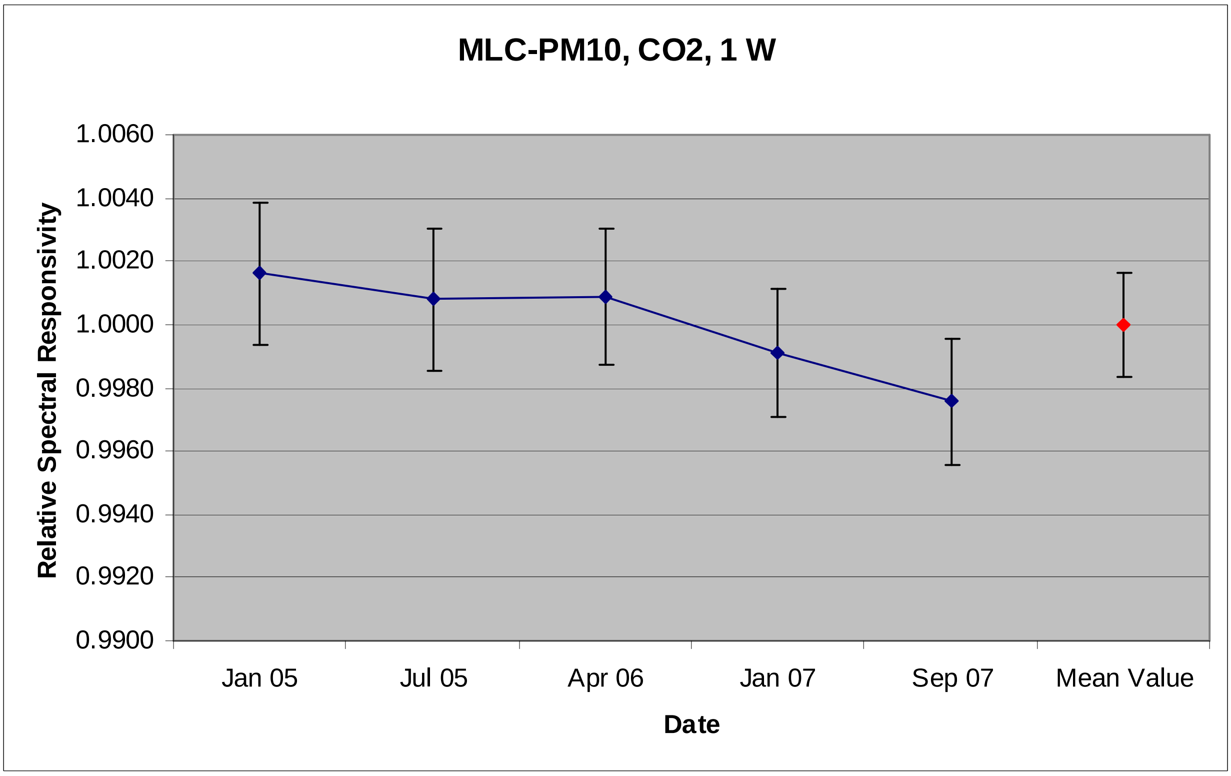
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	10600	5.0	1.0022	0.0024	2.1	0.22%
Jul 05	10600	5.0	1.0009	0.0022	2.0	0.09%
Apr 06	10600	5.1	1.0003	0.0021	2.0	0.03%
Jan 07	10600	5.1	0.9993	0.0021	2.0	-0.07%
Sep 07	10600	5.0	0.9973	0.0022	2.0	-0.27%
Mean Value	**10600**	**5.0**	**1.0000**	**0.0018**	**2.0**	**0.00%**

Figure 1: The following figures show the performance of the transfer detector Molectron PM10 for the different measurands at PTB over the time of the comparison, normalized to the mean value of the measurements performed at PTB.






MLC-PM10, Nd:YAG, 10 W
Relative Spectral Responsivity
1.0060
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
0.9920
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date


MLC-PM10, CO2, 1 W
Relative Spectral Responsivity
1.0060
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
0.9920
0.9900
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date

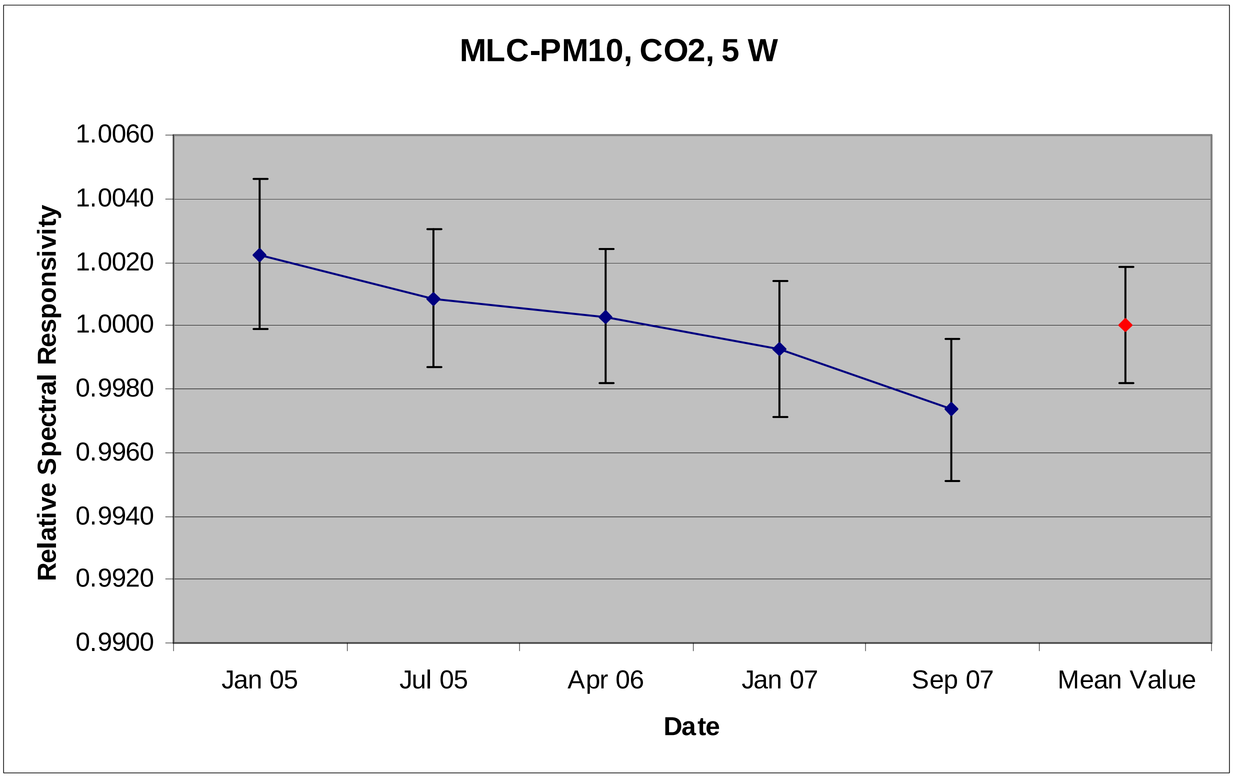
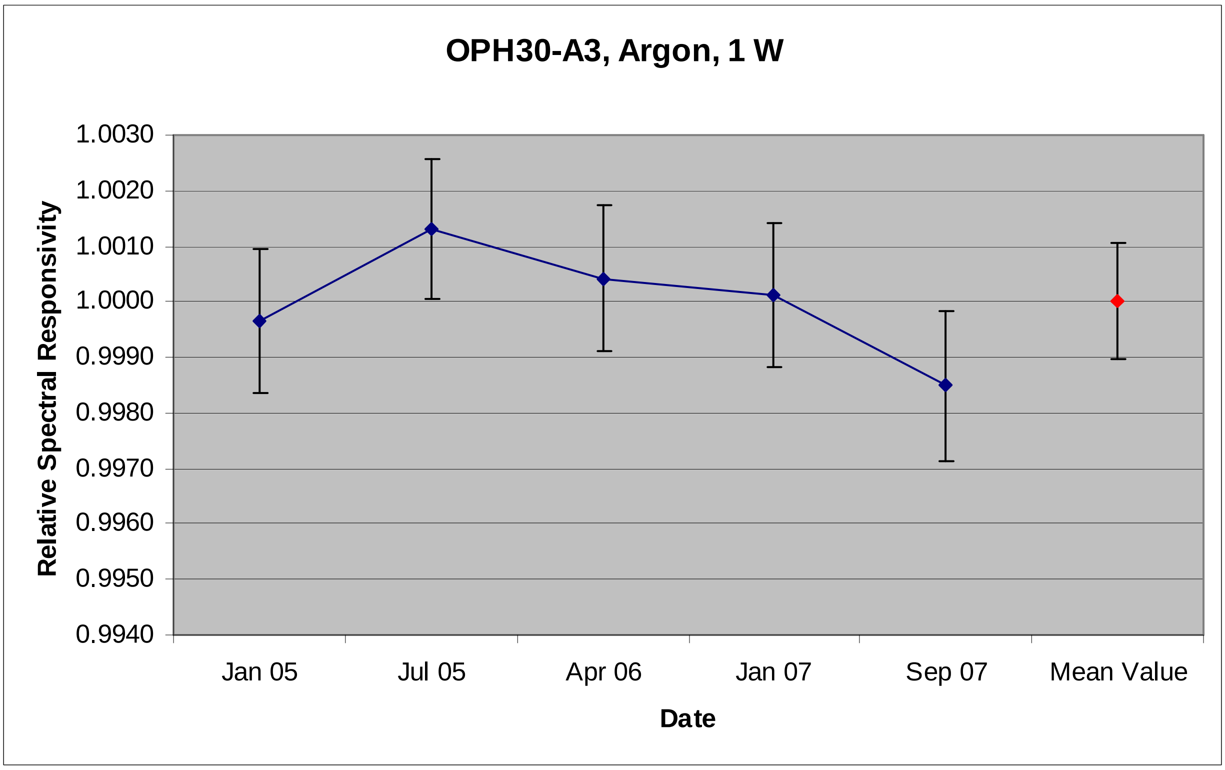
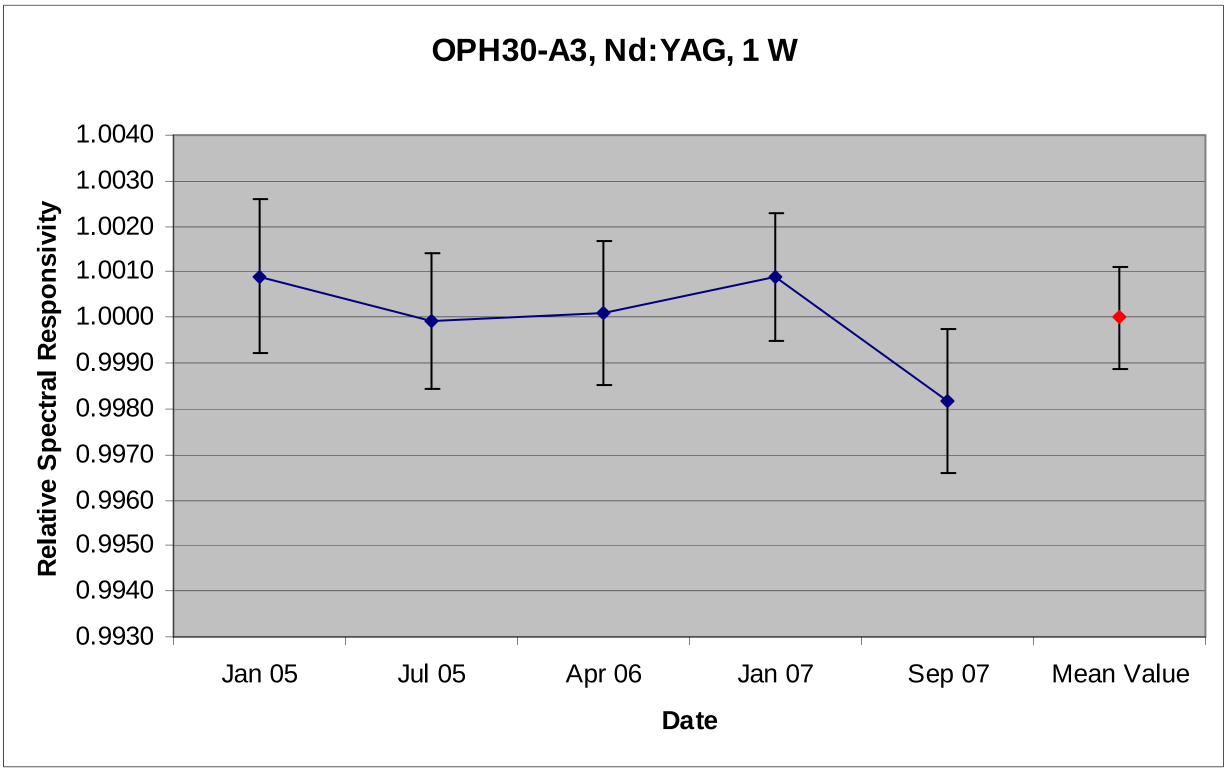

MLC-PM10, CO2, 5 W
Relative Spectral Responsivity
1.0060
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
0.9920
0.9900
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date

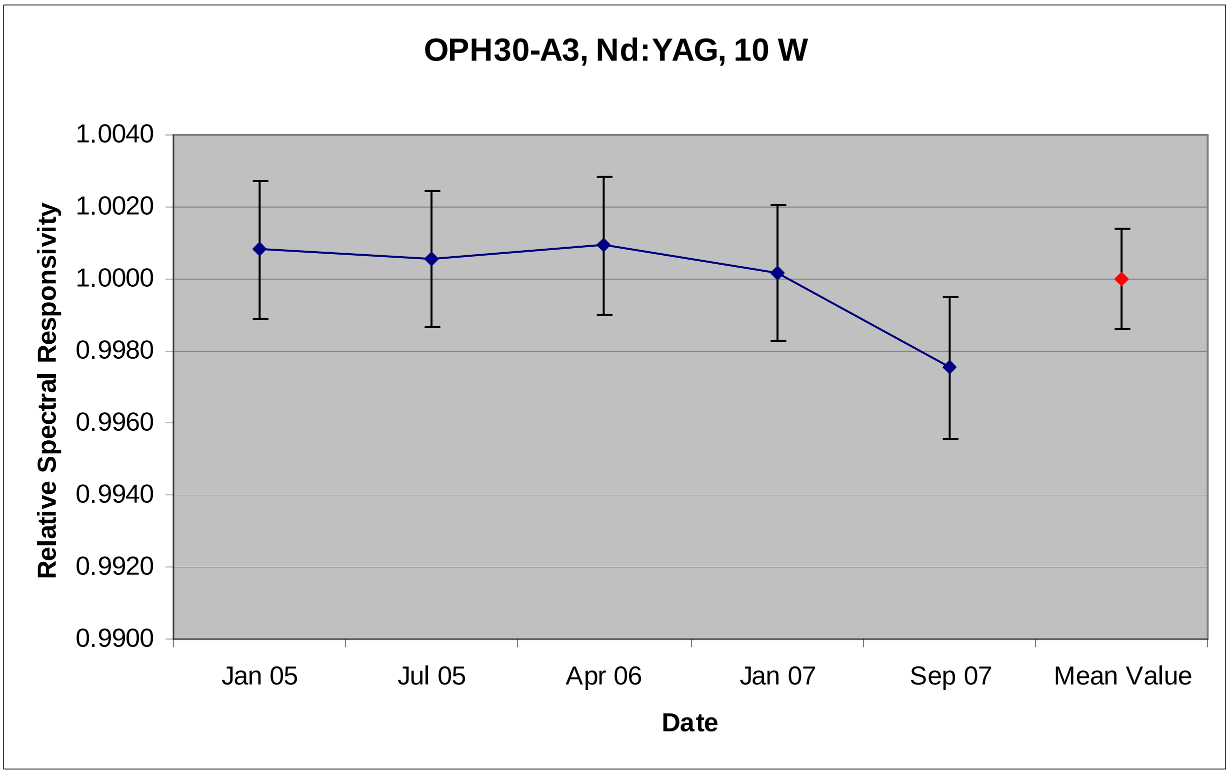
Table 5: Performance of the transfer detector Ophir 30–A3. λ: wavelength, Φ: radiant power, s/s_{mean}: normalized standard uncertainty (with respect to the mean value of the measurements performed at PTB), $u(s/s_{mean})$: standard uncertainty, k: expansion factor, Δ: deviation with respect to the mean value.

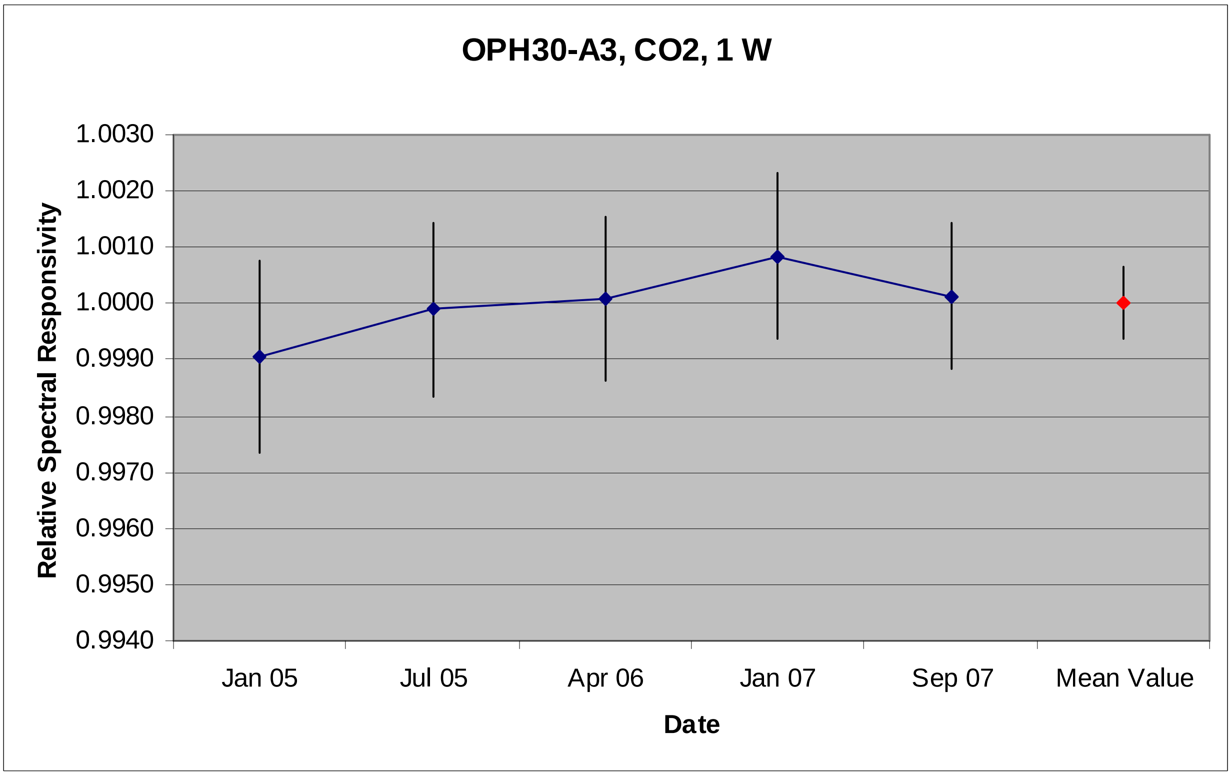
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	514.5	1.0	0.9997	0.0013	2.0	-0.03%
Jul 05	514.5	1.0	1.0013	0.0013	2.0	0.13%
Apr 06	514.5	1.0	1.0004	0.0013	2.0	0.04%
Jan 07	514.5	1.0	1.0001	0.0013	2.0	0.01%
Sep 07	514.5	1.0	0.9985	0.0013	2.0	-0.15%
Mean Value	**514.5**	**1.0**	**1.0000**	**0.0010**	**2.0**	**0.00%**
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	1064	1.0	1.0009	0.0017	2.1	0.09%
Jul 05	1064	1.0	0.9999	0.0015	2.0	-0.01%
Apr 06	1064	1.0	1.0001	0.0016	2.1	0.01%
Jan 07	1064	1.0	1.0009	0.0014	2.0	0.09%
Sep 07	1064	1.0	0.9982	0.0016	2.1	-0.18%
Mean Value	**1064**	**1.0**	**1.0000**	**0.0011**	**2.0**	**0.00%**
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	1064	10.0	1.0008	0.0019	2.1	0.08%
Jul 05	1064	10.1	1.0006	0.0019	2.1	0.06%
Apr 06	1064	9.9	1.0009	0.0019	2.1	0.09%
Jan 07	1064	10.0	1.0002	0.0019	2.0	0.02%
Sep 07	1064	10.2	0.9975	0.0020	2.1	-0.25%
Mean Value	**1064**	**10.0**	**1.0000**	**0.0014**	**2.0**	**0.00%**
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	10600	1.0	0.9991	0.0017	2.1	-0.09%
Jul 05	10600	1.0	0.9999	0.0015	2.1	-0.01%
Apr 06	10600	1.0	1.0001	0.0015	2.1	0.01%
Jan 07	10600	1.0	1.0008	0.0015	2.1	0.08%
Sep 07	10600	1.0	1.0001	0.0013	2.0	0.01%
Mean Value	**10600**	**1.0**	**1.0000**	**0.0006**	**2.0**	**0.00%**
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	10600	5.0	0.9994	0.0017	2.1	-0.06%
Jul 05	10600	5.0	1.0000	0.0015	2.1	0.00%
Apr 06	10600	5.1	0.9994	0.0014	2.1	-0.06%
Jan 07	10600	5.1	1.0013	0.0014	2.0	0.13%
Sep 07	10600	5.0	0.9999	0.0014	2.0	-0.01%
Mean Value	**10600**	**5.0**	**1.0000**	**0.0008**	**2.0**	**0.00%**

Figure 2: The following figures show the performance of the transfer detector Ophir 30–A3 for the different measurands at PTB over the time of the comparison, normalized to the mean value of the measurements performed at PTB.






OPH30-A3, Nd:YAG, 10 W
Relative Spectral Responsivity
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
0.9920
0.9900
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date


OPH30-A3, CO2, 1 W
Relative Spectral Responsivity
1.0030
1.0020
1.0010
1.0000
0.9990
0.9980
0.9970
0.9960
0.9950
0.9940
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date

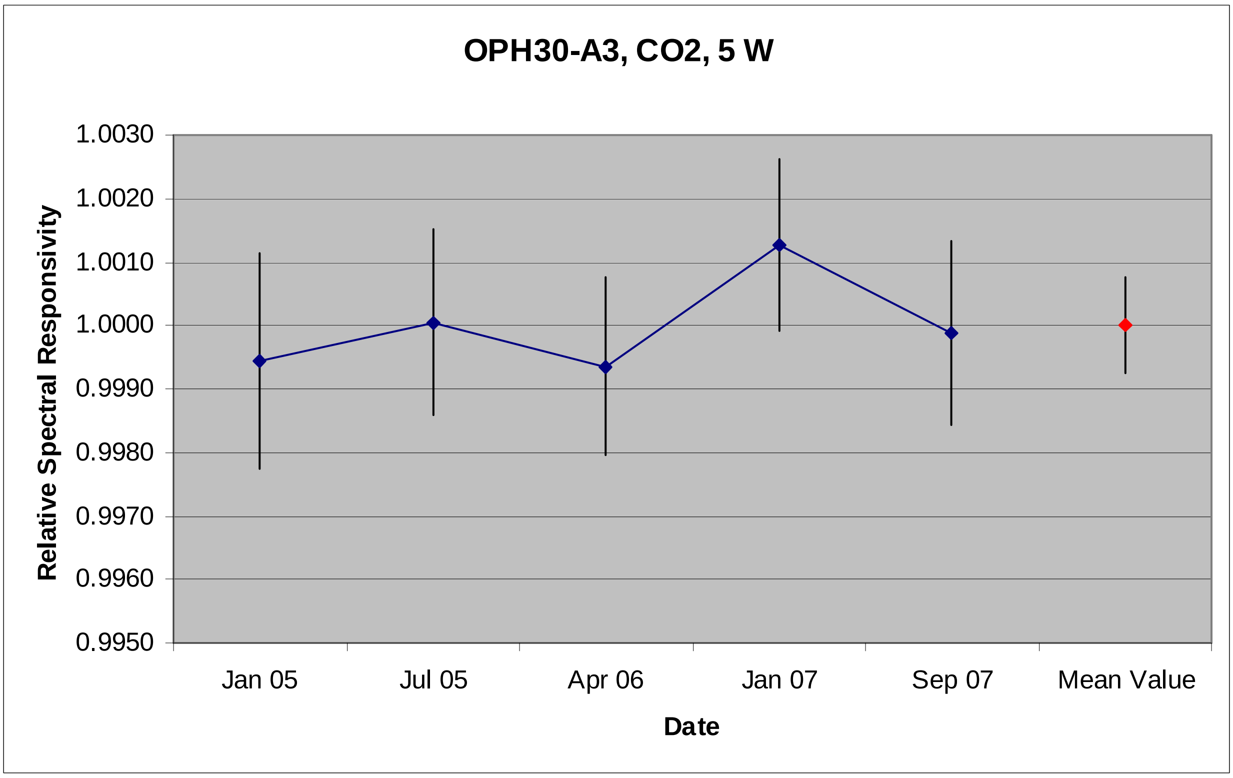

OPH30-A3, CO2, 5 W
Relative Spectral Responsivity
1.0030
1.0020
1.0010
1.0000
0.9990
0.9980
0.9970
0.9960
0.9950
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date

Table 6: Performance of the transfer detector Ophir 30–A4. λ: wavelength, Φ: radiant power, s/s_{mean}: normalized standard uncertainty (with respect to the mean value of the measurements performed at PTB), $u(s/s_{mean})$: standard uncertainty, k: expansion factor, Δ: deviation with respect to the mean value.

	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	514.5	1.0	0.9987	0.0013	2.1	-0.13%
Jul 05	514.5	1.0	0.9999	0.0012	2.0	-0.01%
Apr 06	514.5	1.0	0.9996	0.0012	2.0	-0.04%
Jan 07	514.5	1.0	1.0008	0.0013	2.1	0.08%
Sep 07	514.5	1.0	1.0010	0.0013	2.0	0.10%
Mean Value	**514.5**	**1.0**	**1.0000**	**0.0009**	**2.0**	**0.00%**

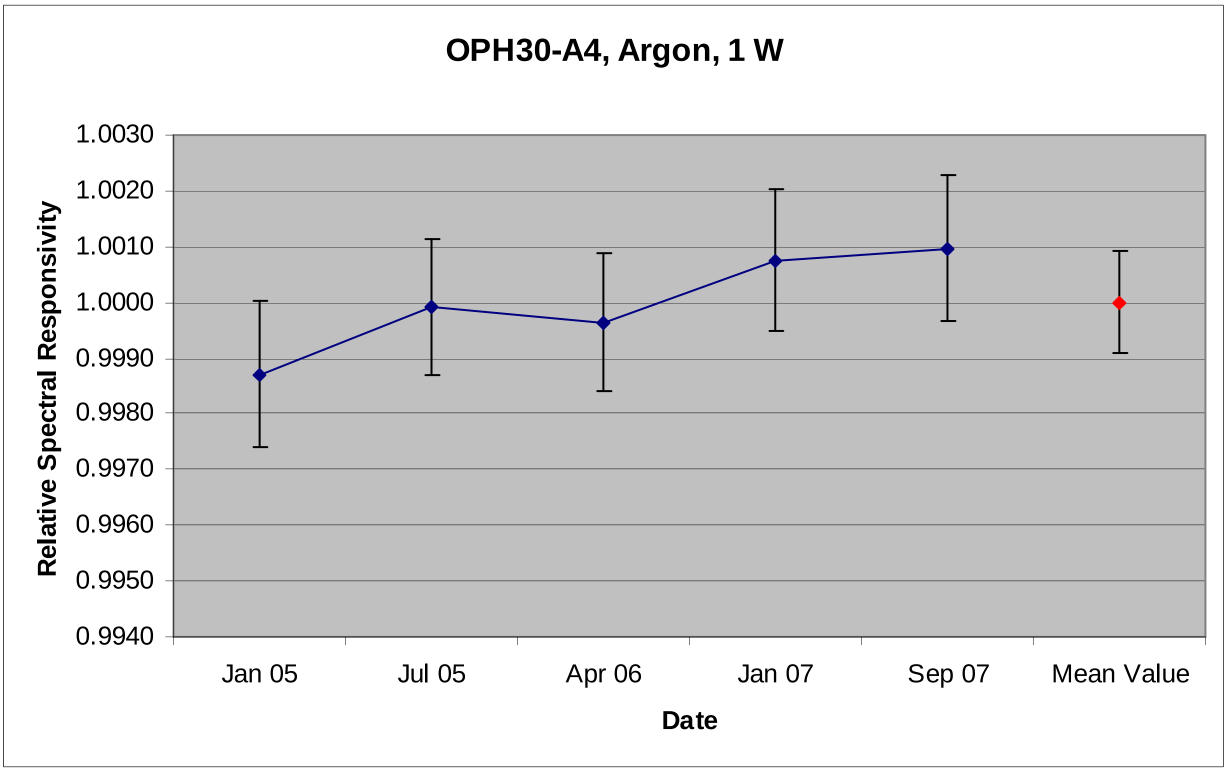
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	1064	1.1	1.0003	0.0013	2.3	0.03%
Jul 05	1064	1.0	0.9993	0.0013	2.2	-0.07%
Apr 06	1064	1.0	1.0000	0.0013	2.1	0.00%
Jan 07	1064	1.0	1.0002	0.0009	2.0	0.02%
Sep 07	1064	1.0	1.0002	0.0012	2.1	0.02%
Mean Value	**1064**	**1.0**	**1.0000**	**0.0004**	**2.0**	**0.00%**

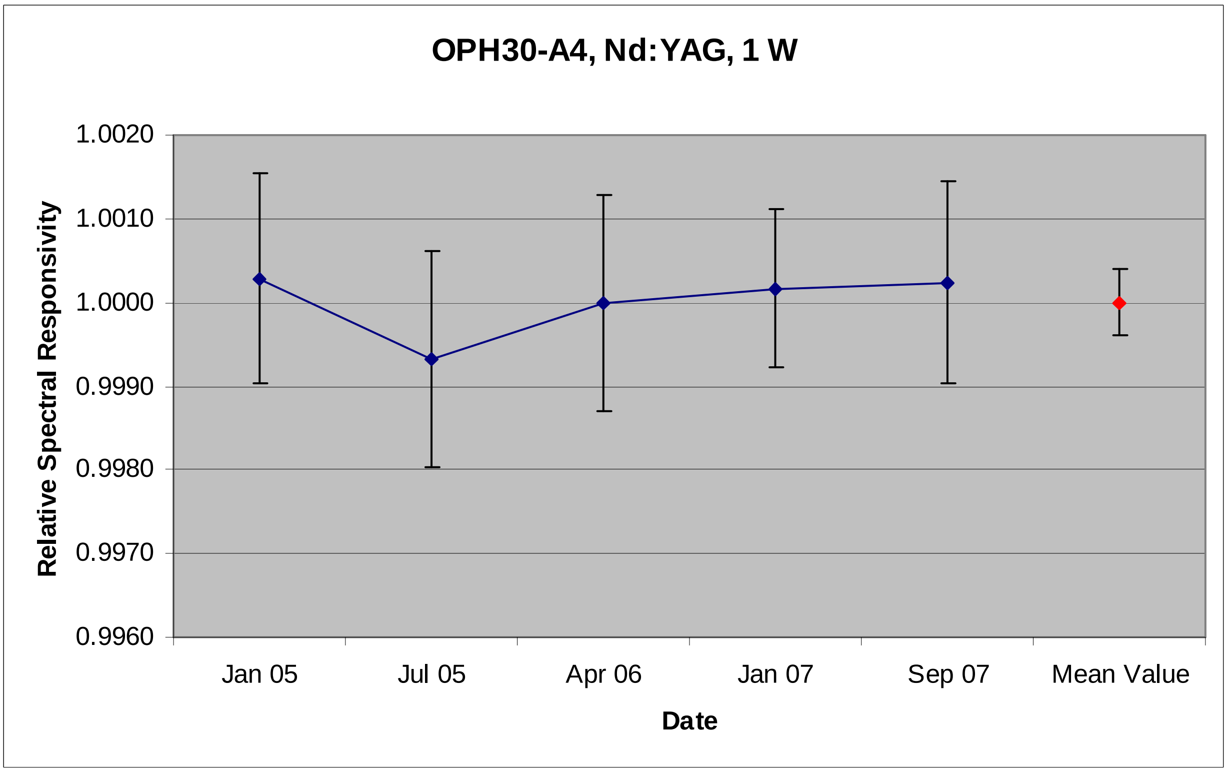
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	1064	10.3	1.0003	0.0014	2.0	0.03%
Jul 05	1064	10.0	1.0004	0.0015	2.0	0.04%
Apr 06	1064	9.8	1.0009	0.0018	2.1	0.09%
Jan 07	1064	9.9	0.9999	0.0015	2.1	-0.01%
Sep 07	1064	9.6	0.9985	0.0015	2.1	-0.15%
Mean Value	**1064**	**9.9**	**1.0000**	**0.0009**	**2.0**	**0.00%**

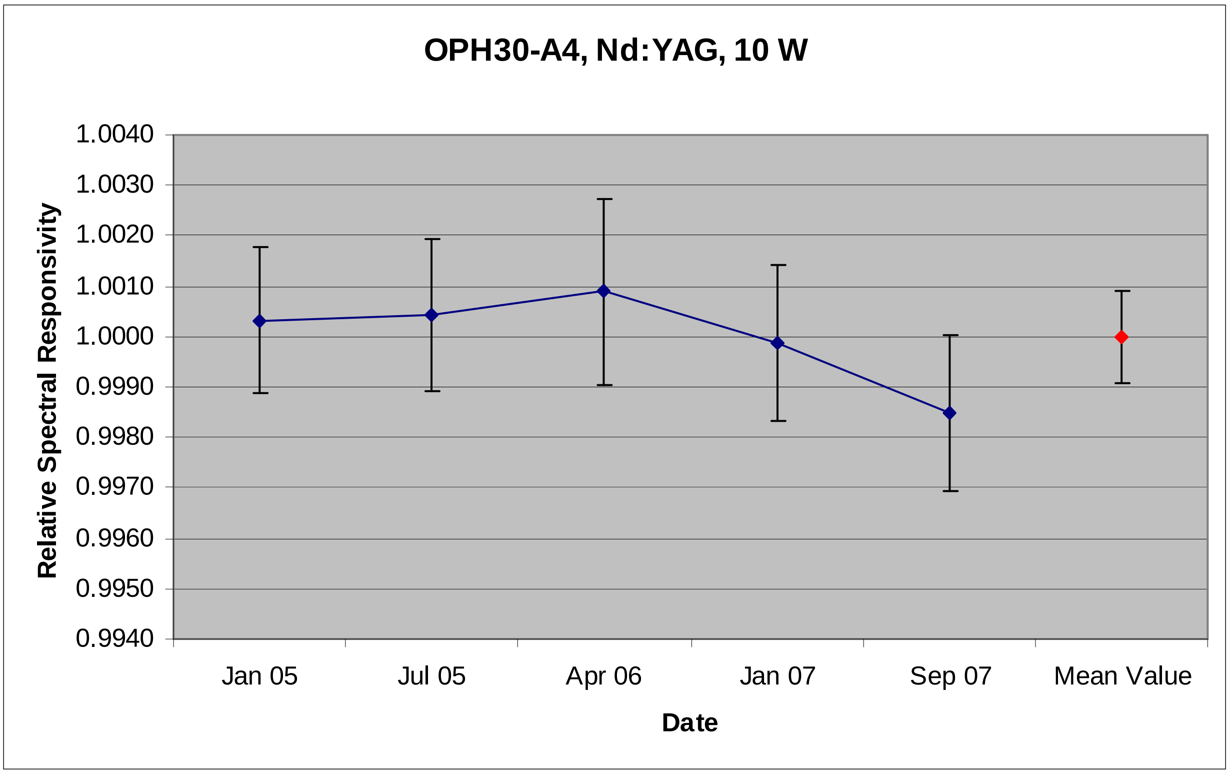
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	10600	1.0	0.9994	0.0025	2.3	-0.06%
Jul 05	10600	1.0	0.9988	0.0017	2.0	-0.12%
Apr 06	10600	1.0	0.9998	0.0016	2.0	-0.02%
Jan 07	10600	1.0	1.0021	0.0017	2.0	0.21%
Sep 07	10600	1.0	0.9999	0.0018	2.0	-0.01%
Mean Value	**10600**	**1.0**	**1.0000**	**0.0013**	**2.0**	**0.00%**

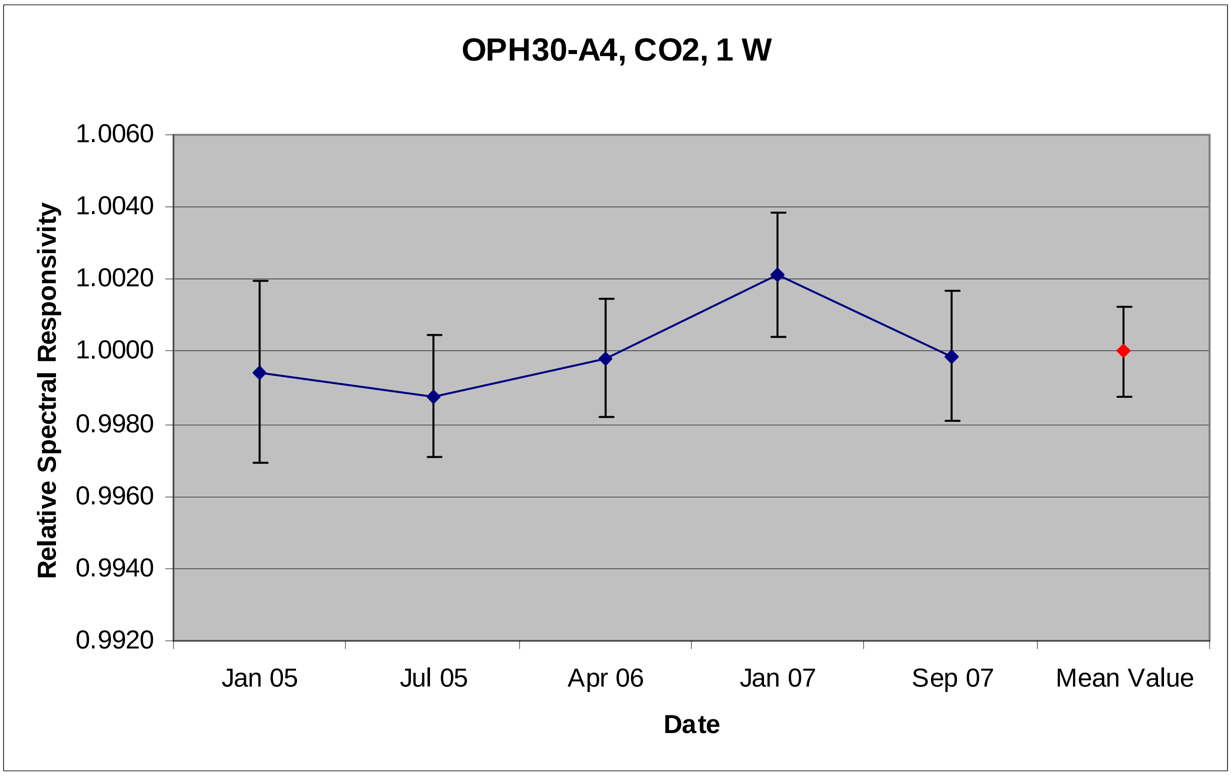
	λ (nm)	Φ (W)	s/s_{mean}	$u(s/s_{mean})$	k	Δ
Jan 05	10600	5.2	0.9993	0.0020	2.1	-0.07%
Jul 05	10600	5.0	0.9990	0.0017	2.0	-0.10%
Apr 06	10600	5.0	0.9994	0.0017	2.0	-0.06%
Jan 07	10600	5.1	1.0022	0.0018	2.1	0.22%
Sep 07	10600	5.0	1.0000	0.0018	2.0	0.00%
Mean Value	**10600**	**5.1**	**1.0000**	**0.0013**	**2.0**	**0.00%**

Figure 3: The following figures show the performance of the transfer detector Ophir 30–A4 for the different measurands at PTB over the time of the comparison, normalized to the mean value of the measurements performed at PTB.






OPH30-A4, Nd:YAG, 10 W
Relative Spectral Responsivity
1.0040
1.0030
1.0020
1.0010
1.0000
0.9990
0.9980
0.9970
0.9960
0.9950
0.9940
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date


OPH30-A4, CO2, 1 W
Relative Spectral Responsivity
1.0060
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
0.9920
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date

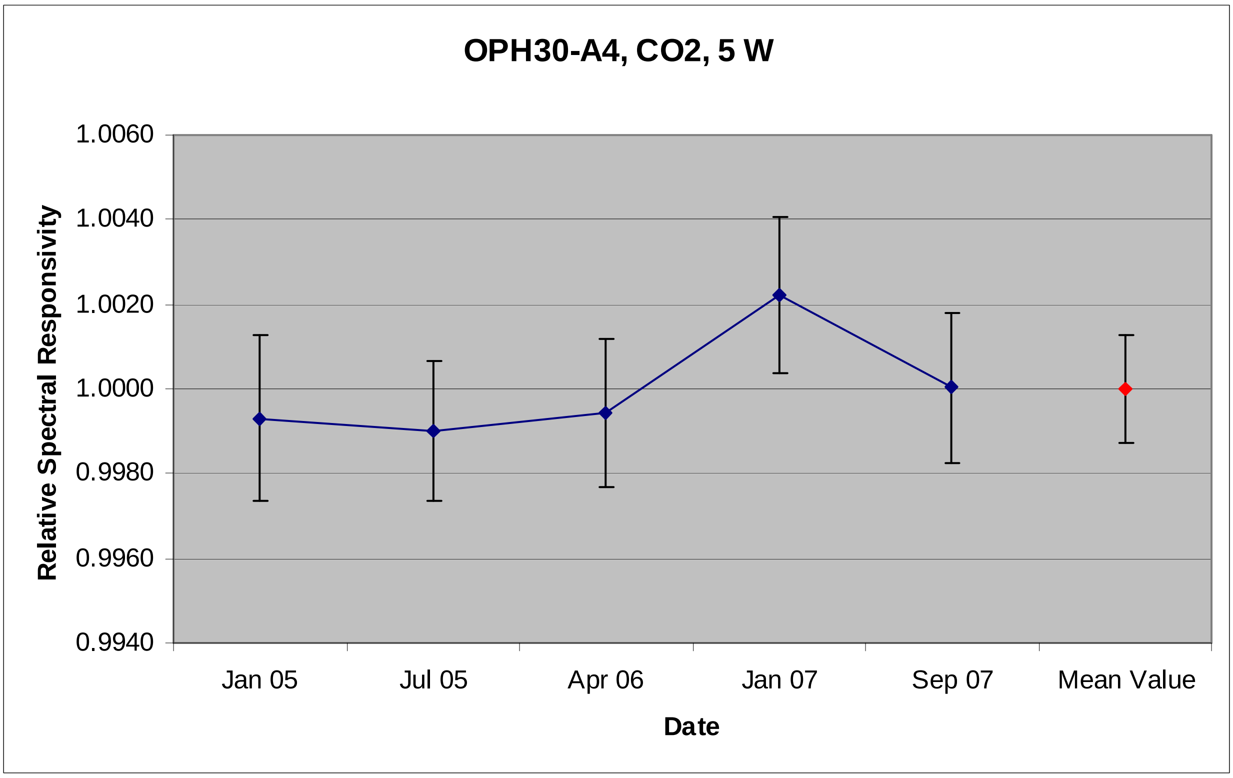

OPH30-A4, CO2, 5 W
Relative Spectral Responsivity
1.0060
1.0040
1.0020
1.0000
0.9980
0.9960
0.9940
Jan 05
Jul 05
Apr 06
Jan 07
Sep 07
Mean Value
Date

Table 7: Correction Δs for the Molectron PM10 transfer detector, details see text.

Argon, 1 W					
NMI	$s(\mathrm{PTB})_n$	$s(\mathrm{PTB})_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.0004	1.0003	4	0	0.00000
SE	1.0004	1.0003	4	1	-0.00002
US	1.0004	1.0003	4	2	-0.00005
FR	1.0004	1.0003	4	3	-0.00007
DE	1.0003	0.9999	4	0	0.00000
ZA	1.0003	0.9999	3	1	-0.00015
AU	1.0003	0.9999	3	2	-0.00030
DE	0.9999	1.0000	3	0	0.00000
JP	0.9999	1.0000	4	1	0.00002
GB	0.9999	1.0000	4	2	0.00005
RO	0.9999	1.0000	4	3	0.00007
DE	1.0000	0.9994	4	0	0.00000
AU	1.0000	0.9994	2	1	-0.00030
DE	0.9994		2	0	0.00000
				Max	**-0.00030**

Nd:YAG, 1 W					
NMI	$s(\mathrm{PTB})_n$	$s(\mathrm{PTB})_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.0018	0.9998	4	0	0.00000
SE	1.0018	0.9998	4	1	-0.00050
US	1.0018	0.9998	4	2	-0.00099
FR	1.0018	0.9998	4	3	-0.00149
DE	0.9998	1.0003	4	0	0.00000
ZA	0.9998	1.0003	3	1	0.00015
AU	0.9998	1.0003	3	2	0.00031
DE	1.0003	0.9998	3	0	0.00000
JP	1.0003	0.9998	4	1	-0.00012
GB	1.0003	0.9998	4	2	-0.00024
RO	1.0003	0.9998	4	3	-0.00035
DE	0.9998	0.9983	4	0	0.00000
AU	0.9998	0.9983	2	1	-0.00077
DE	0.9983		2	0	0.00000
				Max	**-0.00149**

Nd:YAG, 10 W					
NMI	s(PTB)$_n$	s(PTB)$_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.0016	1.0004	4	0	0.00000
SE	1.0016	1.0004	4	1	-0.00030
US	1.0016	1.0004	4	2	-0.00060
FR	1.0016	1.0004	4	3	-0.00090
DE	1.0004	1.0007	4	0	0.00000
ZA	1.0004	1.0007	3	1	0.00010
AU	1.0004	1.0007	3	2	0.00020
DE	1.0007	0.9987	3	0	0.00000
JP	1.0007	0.9987	4	1	-0.00051
GB	1.0007	0.9987	4	2	-0.00102
RO	1.0007	0.9987	4	3	-0.00153
DE	0.9987	0.9986	4	0	0.00000
AU	0.9987	0.9986	2	1	-0.00003
DE	0.9986		2	0	0.00000
				Max	**-0.00153**

CO2, 1 W					
NMI	s(PTB)$_n$	s(PTB)$_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.0016	1.0008	4	0	0.00000
SE	1.0016	1.0008	4	1	-0.00021
US	1.0016	1.0008	4	2	-0.00041
FR	1.0016	1.0008	4	3	-0.00062
DE	1.0008	1.0009	4	0	0.00000
ZA	1.0008	1.0009	3	1	0.00003
AU	1.0008	1.0009	3	2	0.00005
DE	1.0009	0.9991	3	0	0.00000
JP	1.0009	0.9991	4	1	-0.00045
GB	1.0009	0.9991	4	2	-0.00089
RO	1.0009	0.9991	4	3	-0.00134
DE	0.9991	0.9976	4	0	0.00000
AU	0.9991	0.9976	2	1	-0.00076
DE	0.9976		2	0	0.00000
				Max	**-0.00134**

CO2, 5 W					
NMI	s(PTB)$_n$	s(PTB)$_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.0022	1.0009	4	0	0.00000
SE	1.0022	1.0009	4	1	-0.00034
US	1.0022	1.0009	4	2	-0.00068
FR	1.0022	1.0009	4	3	-0.00103
DE	1.0009	1.0003	4	0	0.00000
ZA	1.0009	1.0003	3	1	-0.00019
AU	1.0009	1.0003	3	2	-0.00038
DE	1.0003	0.9993	3	0	0.00000
JP	1.0003	0.9993	4	1	-0.00025
GB	1.0003	0.9993	4	2	-0.00050
RO	1.0003	0.9993	4	3	-0.00076
DE	0.9993	0.9973	4	0	0.00000
AU	0.9993	0.9973	2	1	-0.00097
DE	0.9973		2	0	0.00000
				Max	**-0.00103**

Table 8: Correction Δs for the Ophir 30–A3 transfer detector, details see text.

Argon, 1 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	0.9997	1.0013	4	0	0.00000
SE	0.9997	1.0013	4	1	0.00042
US	0.9997	1.0013	4	2	0.00083
FR	0.9997	1.0013	4	3	0.00125
DE	1.0013	1.0004	4	0	0.00000
ZA	1.0013	1.0004	3	1	-0.00030
AU	1.0013	1.0004	3	2	-0.00059
DE	1.0004	1.0001	3	0	0.00000
JP	1.0004	1.0001	4	1	-0.00008
GB	1.0004	1.0001	4	2	-0.00016
RO	1.0004	1.0001	4	3	-0.00023
DE	1.0001	0.9985	4	0	0.00000
AU	1.0001	0.9985	2	1	-0.00081
DE	0.9985		2	0	0.00000
				Max	**0.00125**

Nd:YAG, 1 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.001	1.000	4	0	0.00000
SE	1.001	1.000	4	1	-0.00025
US	1.001	1.000	4	2	-0.00049
FR	1.001	1.000	4	3	-0.00074
DE	1.000	1.000	4	0	0.00000
ZA	1.000	1.000	3	1	0.00006
AU	1.000	1.000	3	2	0.00011
DE	1.000	1.001	3	0	0.00000
JP	1.000	1.001	4	1	0.00020
GB	1.000	1.001	4	2	0.00040
RO	1.000	1.001	4	3	0.00060
DE	1.001	0.998	4	0	0.00000
AU	1.001	0.998	2	1	-0.00137
DE	0.998		2	0	0.00000
				Max	**-0.00137**

Nd:YAG, 10 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.0008	1.0006	4	0	0.00000
SE	1.0008	1.0006	4	1	-0.00006
US	1.0008	1.0006	4	2	-0.00012
FR	1.0008	1.0006	4	3	-0.00018
DE	1.0006	1.0009	4	0	0.00000
ZA	1.0006	1.0009	3	1	0.00012
AU	1.0006	1.0009	3	2	0.00024
DE	1.0009	1.0002	3	0	0.00000
JP	1.0009	1.0002	4	1	-0.00019
GB	1.0009	1.0002	4	2	-0.00038
RO	1.0009	1.0002	4	3	-0.00057
DE	1.0002	0.9975	4	0	0.00000
AU	1.0002	0.9975	2	1	-0.00132
DE	0.9975		2	0	0.00000
				Max	**-0.00132**

CO2, 1 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	0.999	1.000	4	0	0.00000
SE	0.999	1.000	4	1	0.00021
US	0.999	1.000	4	2	0.00042
FR	0.999	1.000	4	3	0.00063
DE	1.000	1.000	4	0	0.00000
ZA	1.000	1.000	3	1	0.00006
AU	1.000	1.000	3	2	0.00013
DE	1.000	1.001	3	0	0.00000
JP	1.000	1.001	4	1	0.00019
GB	1.000	1.001	4	2	0.00038
RO	1.000	1.001	4	3	0.00057
DE	1.001	1.000	4	0	0.00000
AU	1.001	1.000	2	1	-0.00036
DE	1.000		2	0	0.00000
				Max	**0.00063**

CO2, 5 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	0.9994	1.0000	4	0	0.00000
SE	0.9994	1.0000	4	1	0.00015
US	0.9994	1.0000	4	2	0.00030
FR	0.9994	1.0000	4	3	0.00045
DE	1.0000	0.9994	4	0	0.00000
ZA	1.0000	0.9994	3	1	-0.00023
AU	1.0000	0.9994	3	2	-0.00046
DE	0.9994	1.0013	3	0	0.00000
JP	0.9994	1.0013	4	1	0.00048
GB	0.9994	1.0013	4	2	0.00095
RO	0.9994	1.0013	4	3	0.00143
DE	1.0013	0.9999	4	0	0.00000
AU	1.0013	0.9999	2	1	-0.00069
DE	0.9999		2	0	0.00000
				Max	**0.00143**

Table 9: Correction Δs for the Ophir 30–A4 transfer detector, details see text. The data for Ophir 30–A4 are just given for comparison and for completeness.

Argon, 1 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	0.9987	0.9999	4	0	0.00000
SE	0.9987	0.9999	4	1	0.00030
US	0.9987	0.9999	4	2	0.00060
FR	0.9987	0.9999	4	3	0.00091
DE	0.9999	0.9996	4	0	0.00000
ZA	0.9999	0.9996	3	1	-0.00009
AU	0.9999	0.9996	3	2	-0.00019
DE	0.9996	1.0008	3	0	0.00000
JP	0.9996	1.0008	4	1	0.00028
GB	0.9996	1.0008	4	2	0.00056
RO	0.9996	1.0008	4	3	0.00084
DE	1.0008	1.0010	4	0	0.00000
AU	1.0008	1.0010	2	1	0.00010
DE	1.0010		2	0	0.00000
				Max	**0.00091**

Nd:YAG, 1 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.0003	0.9993	4	0	0.00000
SE	1.0003	0.9993	4	1	-0.00024
US	1.0003	0.9993	4	2	-0.00048
FR	1.0003	0.9993	4	3	-0.00073
DE	0.9993	1.0000	4	0	0.00000
ZA	0.9993	1.0000	3	1	0.00023
AU	0.9993	1.0000	3	2	0.00045
DE	1.0000	1.0002	3	0	0.00000
JP	1.0000	1.0002	4	1	0.00004
GB	1.0000	1.0002	4	2	0.00009
RO	1.0000	1.0002	4	3	0.00013
DE	1.0002	1.0002	4	0	0.00000
AU	1.0002	1.0002	2	1	0.00004
DE	1.0002		2	0	0.00000
				Max	**-0.00073**

Nd:YAG, 10 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	1.0003	1.0004	4	0	0.00000
SE	1.0003	1.0004	4	1	0.00002
US	1.0003	1.0004	4	2	0.00004
FR	1.0003	1.0004	4	3	0.00006
DE	1.0004	1.0009	4	0	0.00000
ZA	1.0004	1.0009	3	1	0.00016
AU	1.0004	1.0009	3	2	0.00032
DE	1.0009	0.9999	3	0	0.00000
JP	1.0009	0.9999	4	1	-0.00025
GB	1.0009	0.9999	4	2	-0.00051
RO	1.0009	0.9999	4	3	-0.00076
DE	0.9999	0.9985	4	0	0.00000
AU	0.9999	0.9985	2	1	-0.00069
DE	0.9985		2	0	0.00000
				Max	**-0.00076**

CO2, 1 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	0.9994	0.9988	4	0	0.00000
SE	0.9994	0.9988	4	1	-0.00017
US	0.9994	0.9988	4	2	-0.00033
FR	0.9994	0.9988	4	3	-0.00050
DE	0.9988	0.9998	4	0	0.00000
ZA	0.9988	0.9998	3	1	0.00035
AU	0.9988	0.9998	3	2	0.00069
DE	0.9998	1.0021	3	0	0.00000
JP	0.9998	1.0021	4	1	0.00058
GB	0.9998	1.0021	4	2	0.00115
RO	0.9998	1.0021	4	3	0.00173
DE	1.0021	0.9999	4	0	0.00000
AU	1.0021	0.9999	2	1	-0.00111
DE	0.9999		2	0	0.00000
				Max	**0.00173**

CO2, 5 W					
NMI	$s(PTB)_n$	$s(PTB)_{n+1}$	ΔN	ΔN_{NMI}	Δs
DE	0.9993	0.9990	4	0	0.00000
SE	0.9993	0.9990	4	1	-0.00007
US	0.9993	0.9990	4	2	-0.00014
FR	0.9993	0.9990	4	3	-0.00021
DE	0.9990	0.9994	4	0	0.00000
ZA	0.9990	0.9994	3	1	0.00014
AU	0.9990	0.9994	3	2	0.00027
DE	0.9994	1.0022	3	0	0.00000
JP	0.9994	1.0022	4	1	0.00069
GB	0.9994	1.0022	4	2	0.00138
RO	0.9994	1.0022	4	3	0.00208
DE	1.0022	1.0000	4	0	0.00000
AU	1.0022	1.0000	2	1	-0.00109
DE	1.0000		2	0	0.00000
				Max	**0.00208**

6 Method for establishing the Supplementary Comparison Reference Value (SCRV) and the Degrees of Equivalence

It is known that reference values are only evaluated based on Key Comparisons (KCs), these are the Key Comparison Reference Values (KCRVs). However, we believe that it is desirable or at least useful to evaluate a reference value also in the case of this worldwide SC, see the Technical protocol (chapter 7, page 7). For simplification, we call this value Supplementary Comparison Reference Value (SCRV).

Performance of the transfer detectors

It was agreed in the pre-Draft A (see page 17, “Performance of the transfer detectors” and tables 9 – 11 in the pre-Draft A) that the change of the responsivity over time is taken into account by a linear interpolation based on the measurements carried out at the pilot lab (PTB):

$$s^*_{\mathrm{NMI}} = s_{\mathrm{NMI}} \cdot \left(1 + \left(s(\mathrm{PTB})_{\mathrm{n+1}} - s(\mathrm{PTB})_{\mathrm{n}}\right)\frac{\Delta N_{\mathrm{NMI}}}{\Delta N}\right) = s_{\mathrm{NMI}} \cdot (1 + \Delta s)$$

where s^*_{NMI} (s_{NMI}) is the corrected (submitted) spectral responsivity for each participating laboratory, $s(\mathrm{PTB})_{\mathrm{n+1}}$ and $s(\mathrm{PTB})_{\mathrm{n}}$ are the normalized spectral responsivities measured at PTB before and after the individual measurement of the NMI, respectively, ΔN is the number of measurements between the two PTB measurements + 1, and ΔN_{NMI} is the number of the measurement for the individual NMI between two PTB measurements.

Maximum corrections Δs_{max} are

for the Ophir 30–A3: Δs_{max} = +0.00143, 1 + Δs_{max} = 1.00143,

for the Molectron PM10: Δs_{max} = -0.00153, 1 + Δs_{max} = 0.99847.

Determination of the cut-off, the SCRV and the Degrees of Equivalence

The weighted mean of the spectral responsivity values of all NMIs represent the SCRV. Following the Guidelines for CCPR Comparison Report Preparation the weight is calculated with cut-off, which is calculated as the average of the NMIs uncertainties which are less than or equal to the median of the uncertainties of all NMIs. The cut-off uncertainty $u_{\text{cut-off}}$ is then average of the four institutes stating the lowest uncertainties:

$$u_{\text{cut-off}} = \frac{1}{4}\sum_{1=1}^{4} u_{\mathrm{rel}}(s_{\mathrm{i}}) \text{ for } u_{\mathrm{rel}}(s_{\mathrm{i}}) \leq median\{u_{\mathrm{rel}}(s_{\mathrm{k}})_{\mathrm{k}=1...7(8)}\}$$

where $u_{rel}(s_i)$ is the relative uncertainty stated by the participant *i* and the median is calculated from the seven (eight for Nd:YAG, 1 W) participants.

In Table 10 the relative uncertainties of all participants for each measurand are listed together with the mean value, the cut-off value and adjusted uncertainties. In Figure 4 and Figure 5 the results, i.e. the standard uncertainty for each participant as well as the median and the cut-off value, are shown graphically.

For each participant, the relative uncertainty for the NMI representative value $u_{\mathrm{rel}}(s_{\mathrm{i}})$ is then adjusted by the cut-off, see also Table 10:

$$u_{\mathrm{adj}}(s_{\mathrm{i}}) = \begin{cases} u_{\mathrm{rel}}(s_{\mathrm{i}}) & \text{for } u_{\mathrm{rel}}(s_{\mathrm{i}}) \geq u_{\mathrm{cut-off}} \\ u_{\mathrm{cut-off}} & \text{for } u_{\mathrm{rel}}(s_{\mathrm{i}}) < u_{\mathrm{cut-off}} \end{cases}$$

The weight w_{i} for the participant *i* is then calculated as

$$w_{\mathrm{i}} = \frac{u_{\mathrm{adj}}(s_{\mathrm{i}})^{-2}}{\sum_{i=1}^{7,8} u_{\mathrm{adj}}(s_{\mathrm{i}})^{-2}}$$

and shown graphically in Figure 6 and Figure 7. The SCRV of the comparison is calculated as

$$s_{\mathrm{SCRV}} = \sum_{i=1}^{7,8} w_{\mathrm{i}} s_{\mathrm{i}}$$

with the relative standard uncertainty

$$u_{\mathrm{rel}}(s_{\mathrm{SCRV}}) = \sqrt{\frac{1}{\sum_{i=1}^{7,8} u_{\mathrm{adj}}(s_{\mathrm{i}})^{-2}}}\,.$$

These results directly lead to the unilateral and bilateral Degrees of Equivalence (DoE). The unilateral DoE of NMI *i* is given by

$$D_{\mathrm{i}} = \frac{s_{\mathrm{i}} - s_{\mathrm{SCRV}}}{s_{\mathrm{SCRV}}}$$

with its expanded uncertainty

$$U_{\mathrm{i}} = k\sqrt{u_{\mathrm{rel}}(s_{\mathrm{SCRV}})^2 + u_{\mathrm{rel}}(s_{\mathrm{i}})^2}\ ;\ k = 2.$$

In the same way the bilateral DoE of NMI *i* to NMI *m* is calculated as

$$D_{\mathrm{i,m}} = D_{\mathrm{i}} - D_{\mathrm{m}} = \frac{s_{\mathrm{i}} - s_{\mathrm{m}}}{s_{\mathrm{SCRV}}}$$

with

$$U_{\mathrm{i,m}} = k\sqrt{u_{\mathrm{rel}}(s_{\mathrm{i}})^2 + u_{\mathrm{rel}}(s_{\mathrm{m}})^2 + u_{\mathrm{rel}}(s_{\mathrm{SCRV}})^2}\ ,\ k = 2.$$

This definition follows the convention for the analysis of Key Comparisons and provides bilateral DoEs that are symmetrical and consistent with the unilateral DoEs.

The simple data analysis presented here and the resulting parameters give satisfactory information to compare the participants’ abilities in calibrating laser power meters in terms of spectral responsivity.

Table 10: Relative uncertainty $u_{rel}(s_i)$ of the spectral responsity for each detector and each participant, the adjusted uncertainty $u_{adj}(s_i)$, the weight w_i, the median, the cut-off value of the uncertainty and the number of participants for each measurand.

Ophir30	**Argon**			**Nd:YAG 1 W**			**Nd:YAG 10 W**			**CO_2 1 W**			**CO_2 5 W**		
-A3	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i
DE	0.10%	0.34%	0.2698	0.13%	0.36%	0.2310	0.14%	0.38%	0.2516	0.16%	0.42%	0.2731	0.15%	0.43%	0.2781
SE	0.46%	0.46%	0.1525							2.57%	2.57%	0.0074	2.78%	2.78%	0.0066
US	0.43%	0.43%	0.1733	0.44%	0.44%	0.1538	0.53%	0.53%	0.1283	0.54%	0.54%	0.1676	0.53%	0.53%	0.1805
FR	0.39%	0.39%	0.2147	0.44%	0.44%	0.1538	0.44%	0.44%	0.1876	0.61%	0.61%	0.1295	0.47%	0.47%	0.2343
ZA	2.00%	2.00%	0.0080	2.02%	2.02%	0.0073	1.98%	1.98%	0.0092	2.47%	2.47%	0.0080	2.49%	2.49%	0.0082
JP	0.47%	0.47%	0.1446	0.47%	0.47%	0.1352	0.47%	0.47%	0.1641	0.56%	0.56%	0.1565	0.56%	0.56%	0.1613
GB				0.43%	0.43%	0.1605	0.62%	0.62%	0.0932	0.44%	0.44%	0.2579	0.62%	0.62%	0.1310
RO	0.93%	0.93%	0.0371	1.12%	1.12%	0.0236									
AU				0.47%	0.47%	0.1348	0.47%	0.47%	0.1661						
Median	0.46%		1.0	0.45%		1.0	0.47%		1.0	0.56%		1.0	0.56%		1.0
Cut-off	**0.34%**			**0.36%**			**0.38%**			**0.42%**			**0.43%**		
Number	7			8			7			7			7		

PM10	**Argon**			**Nd:YAG 1 W**			**Nd:YAG 10 W**			**CO_2 1 W**			**CO_2 5 W**		
	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i	$u_{rel}(s_i)$	$u_{adj}(s_i)$	w_i
DE	0.09%	0.33%	0.2678	0.24%	0.39%	0.2075	0.17%	0.38%	0.2423	0.16%	0.42%	0.2701	0.18%	0.44%	0.2713
SE	0.43%	0.43%	0.1564							2.35%	2.35%	0.0088	2.49%	2.49%	0.0084
US	0.43%	0.43%	0.1540	0.44%	0.44%	0.1592	0.53%	0.53%	0.1242	0.54%	0.54%	0.1663	0.54%	0.54%	0.1774
FR	0.36%	0.36%	0.2198	0.43%	0.43%	0.1652	0.39%	0.39%	0.2268	0.61%	0.61%	0.1317	0.46%	0.46%	0.2424
ZA	2.00%	2.00%	0.0071	2.01%	2.01%	0.0077	2.03%	2.03%	0.0085	2.50%	2.50%	0.0078	2.50%	2.50%	0.0083
JP	0.47%	0.47%	0.1299	0.47%	0.47%	0.1387	0.47%	0.47%	0.1571	0.56%	0.56%	0.1547	0.56%	0.56%	0.1639
GB				0.43%	0.43%	0.1645	0.62%	0.62%	0.0915	0.43%	0.43%	0.2605	0.63%	0.63%	0.1284
RO	0.66%	0.66%	0.0649	1.14%	1.14%	0.0237									
AU				0.48%	0.48%	0.1335	0.48%	0.48%	0.1496						
Median	0.43%		1.0	0.46%		1.0	0.48%		1.0	0.56%		1.0	0.56%		1.0
Cut-off	**0.33%**			**0.39%**			**0.38%**			**0.42%**			**0.44%**		
Number	7			8			7			7			7		

Figure 4. Relative standard uncertainties, median and cut-off for the Ophir 30-A3 transfer detector.

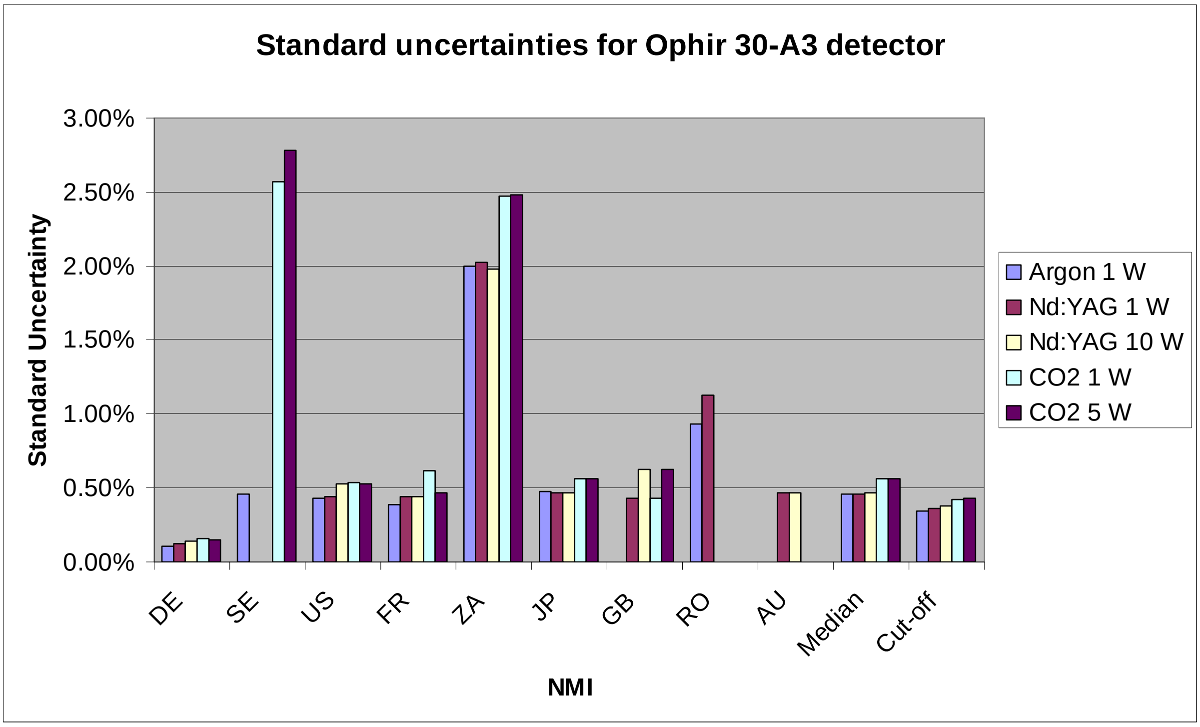


Figure 5. Relative standard uncertainties, median and cut-off for the Molectron PM10 transfer detector.

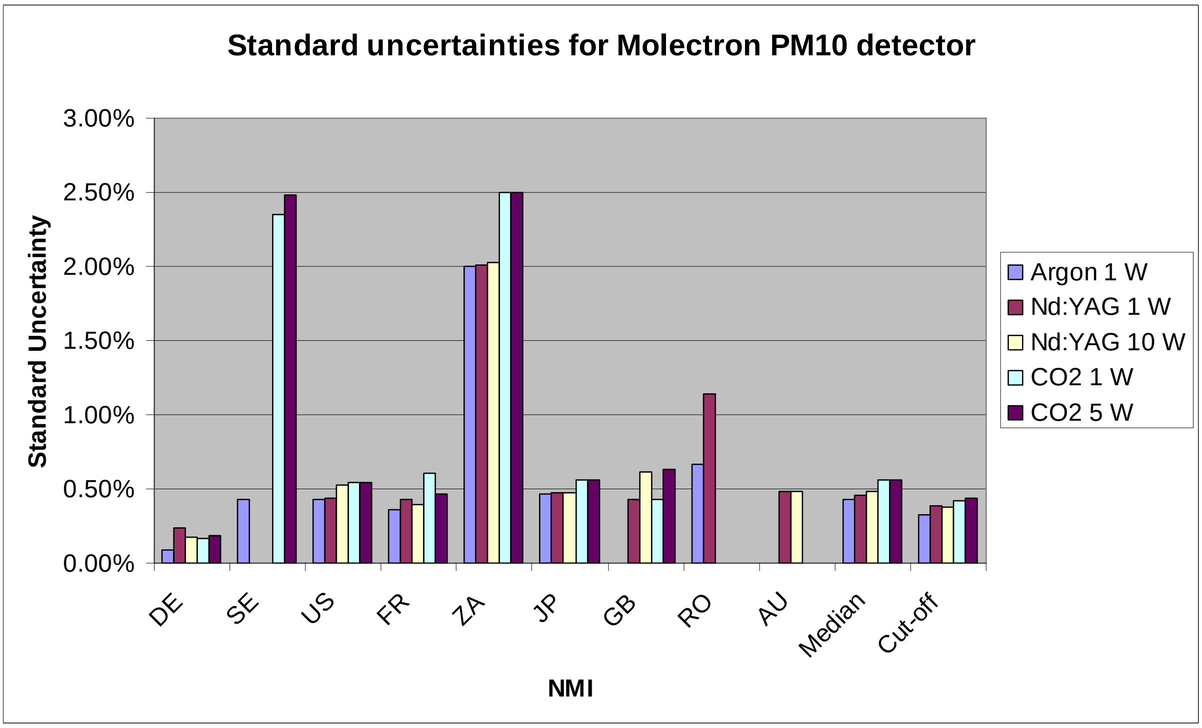


Figure 6. Weights for the Ophir 30-A3 detector.

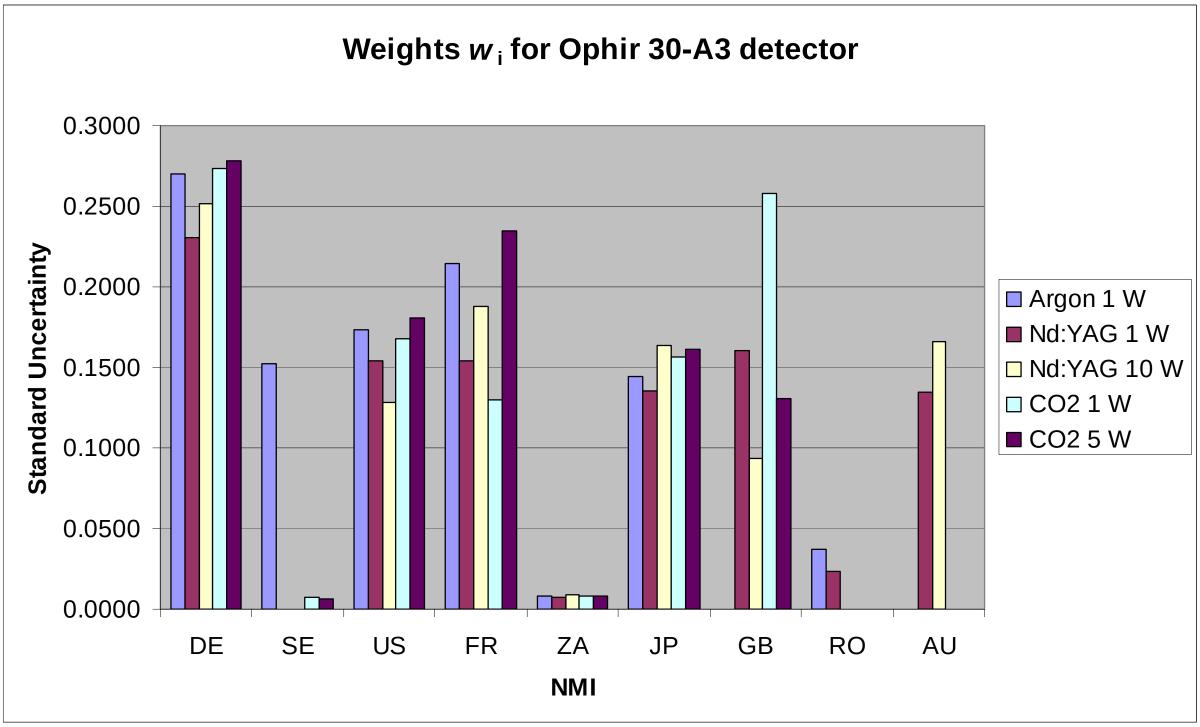
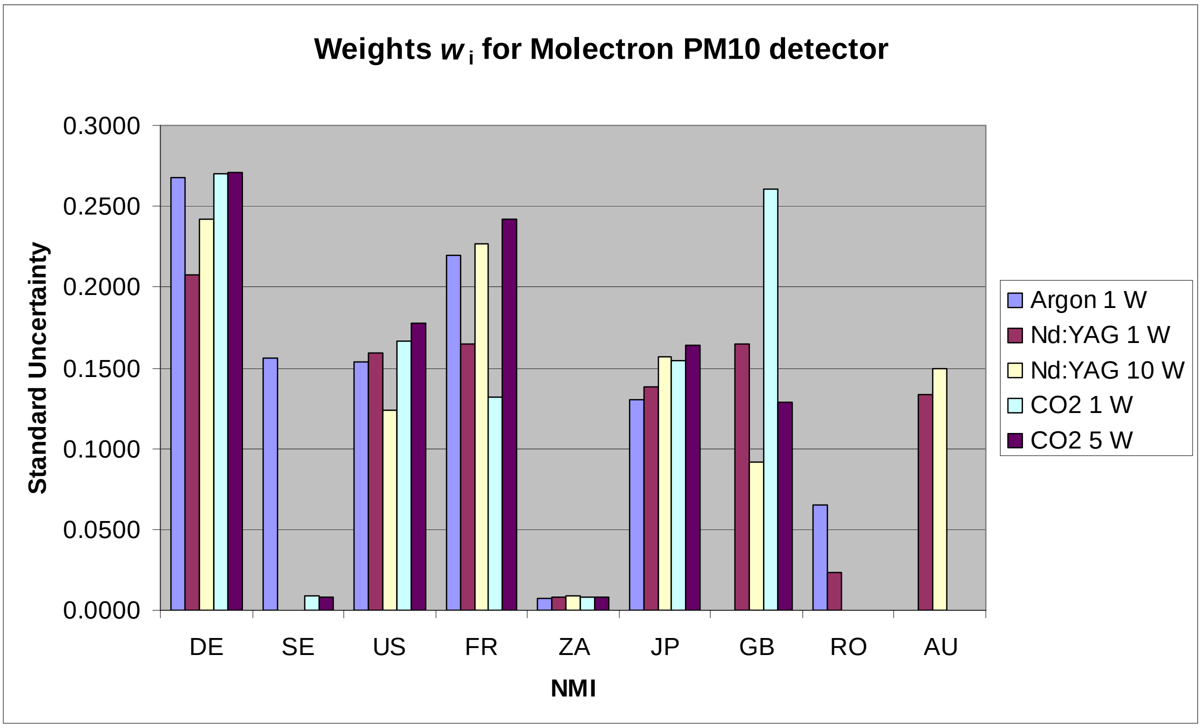


Figure 7. Weights for the Molectron PM10 detector.



7 Identification of Outliers

The CCPR has not agreed a formal policy on outliers. However, if a reference value is involved, care has to be taken that outliers do not skew the reference value. The currently favoured limit is three standard deviations from the reference value produced without the proposed outliers, using their adjusted standard uncertainty value. In this comparison, the following procedure was used: the deviations from the weighted mean value for each participant were listed and graphically shown. The data were made anonymous and send to all participants on March 30th (file: "Method for establishing the Supplementary Comparison Reference Value"). All participants were ask to propose outliers. If outliers are proposed, the pilot lab would have to recalculate the weighted mean value without the value of the proposed outlier and in case the deviation of the value from the proposed outlier is more than three adjusted standard deviations from the new calculated weighted mean with cut-off value, this participant will be removed for this measurand from the comparison. The cut-off value, the weighted mean and the Degrees of Equivalence would have to be recalculated for all measurands, for which outliers are proposed.

Based on the distributed data, outliers were not proposed by any participant. This means, that all results contribute to the calculation of the SCRV.

8 Results: SCRV and DoE for the EUROMET.PR-S2 intercomparison

8.1 Summary of participants´ results

In Table 11 the spectral responsivities, the absolute and relative standard uncertainties and the expansion factors reported by the participating NMIs for each measurand based on their uncertainty budgets are given. The detailed measurement reports including uncertainty analysis submitted by the participants are given in the appendix D.

Table 11: Responsivities, absolute standard uncertainties, relative standard uncertainties and expansion factors for the measurements of the participating NMIs for the different measurands. λ: wavelength, Φ: laser power, s: spectral responsivity, $u(s)$: standard uncertainty of the spectral responsivity, k: expansion factor.

Results of PTB (Germany)						
OPHIR						
Laser	**λ**	**Φ**	**s**	**$u(s)$**	**$u(s)$**	**k**
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.01	1.5052	0.0016	0.10%	2.0
Nd:YAG	1064	1.01	1.4650	0.0018	0.13%	2.0
Nd:YAG	1064	10.05	1.4418	0.0020	0.14%	2.0
CO2	10600	1.03	1.5392	0.0024	0.16%	2.0
CO2	10600	5.04	1.5270	0.0023	0.15%	2.0
MOLECTRON						
Laser	**λ**	**Φ**	**s**	**$u(s)$**	**$u(s)$**	**k**
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.01	1.6661	0.0015	0.09%	2.0
Nd:YAG	1064	1.01	1.6296	0.0039	0.24%	2.0
Nd:YAG	1064	10.05	1.6038	0.0028	0.17%	2.0
CO2	10600	1.03	1.7174	0.0028	0.16%	2.0
CO2	10600	5.04	1.7045	0.0031	0.18%	2.0

Results of SP (Sweden)						
OPHIR						
Laser	**λ**	**Φ**	**s**	**$u(s)$**	**$u(s)$**	**k**
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.5050	0.0069	0.46%	2.06
Nd:YAG	1064					
Nd:YAG	1064					
CO2	10600	1.00	1.5980	0.0410	2.57%	2.23
CO2	10600	5.00	1.5830	0.0440	2.78%	2.23
MOLECTRON						
Laser	**λ**	**Φ**	**s**	**$u(s)$**	**$u(s)$**	**k**
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.6640	0.0071	0.43%	2.06
Nd:YAG	1064					
Nd:YAG	1064					
CO2	10600	1.00	1.7860	0.0420	2.35%	2.23
CO2	10600	5.00	1.7700	0.0440	2.49%	2.23

Results of NIST (USA)						
OPHIR						
Laser	***λ***	***Φ***	***s***	***u(s)***	***u(s)***	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.02	1.5070	0.0065	0.43%	2.26
Nd:YAG	1064	1.01	1.4500	0.0064	0.44%	2.26
Nd:YAG	1064	10.20	1.4320	0.0076	0.53%	2.26
CO2	10600	1.00	1.5340	0.0083	0.54%	2.23
CO2	10600	5.30	1.5180	0.0080	0.53%	2.26
MOLECTRON						
Laser	***λ***	***Φ***	***s***	***u(s)***	***u(s)***	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.02	1.6660	0.0072	0.43%	2.26
Nd:YAG	1064	1.01	1.6110	0.0071	0.44%	2.26
Nd:YAG	1064	10.20	1.5920	0.0084	0.53%	2.26
CO2	10600	1.00	1.7200	0.0093	0.54%	2.23
CO2	10600	5.30	1.7060	0.0092	0.54%	2.26

Results of LNE (France)						
OPHIR						
Laser	***λ***	***Φ***	***s***	***u(s)***	***u(s)***	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.4753	0.0057	0.39%	2.14
Nd:YAG	1064	1.01	1.4318	0.0063	0.44%	4,03
Nd:YAG	1064	10.13	1.4145	0.0062	0.44%	4,03
CO2	10600	1.05	1.5136	0.0093	0.61%	4,60
CO2	10600	4.96	1.5049	0.0070	0.47%	3,36
MOLECTRON						
Laser	***λ***	***Φ***	***s***	***u(s)***	***u(s)***	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.6390	0.0059	0.36%	2.13
Nd:YAG	1064	1.01	1.5970	0.0069	0.43%	4,03
Nd:YAG	1064	10.13	1.5811	0.0062	0.39%	4,03
CO2	10600	1.05	1.6975	0.0103	0.61%	4,60
CO2	10600	4.96	1.6887	0.0078	0.46%	3,36

Results of NMISA (South Africa)						
OPHIR						
Laser	**λ**	**Φ**	***s***	***u*(*s*)**	***u*(*s*)**	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.4990	0.0300	2.00%	2.0
Nd:YAG	1064	1.00	1.4350	0.0290	2.02%	2.0
Nd:YAG	1064	10.00	1.4140	0.0280	1.98%	2.0
CO2	10600	1.00	1.5370	0.0380	2.47%	2.0
CO2	10600	3.00	1.5290	0.0380	2.49%	2.0
MOLECTRON						
Laser	**λ**	**Φ**	***s***	***u*(*s*)**	***u*(*s*)**	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.6480	0.0330	2.00%	2.0
Nd:YAG	1064	1.00	1.5960	0.0320	2.01%	2.0
Nd:YAG	1064	10.00	1.5760	0.0320	2.03%	2.0
CO2	10600	1.00	1.7230	0.0430	2.50%	2.0
CO2	10600	3.00	1.7210	0.0430	2.50%	2.0

Results of NMIJ/AIST (Japan)						
OPHIR						
Laser	**λ**	**Φ**	***s***	***u*(*s*)**	***u*(*s*)**	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.5080	0.0071	0.47%	2.1
Nd:YAG	1064	1.00	1.4700	0.0069	0.47%	2.1
Nd:YAG	1064	9.10	1.4510	0.0068	0.47%	2.1
CO2	10600	1.00	1.5210	0.0085	0.56%	2.1
CO2	10600	5.00	1.5160	0.0085	0.56%	2.1
MOLECTRON						
Laser	**λ**	**Φ**	***s***	***u*(*s*)**	***u*(*s*)**	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.6660	0.0078	0.47%	2.1
Nd:YAG	1064	1.00	1.6330	0.0077	0.47%	2.1
Nd:YAG	1064	9.10	1.6130	0.0076	0.47%	2.1
CO2	10600	1.00	1.6970	0.0095	0.56%	2.1
CO2	10600	5.00	1.6910	0.0095	0.56%	2.1

Results of NPL (UK)						
OPHIR						
Laser	**λ**	**Φ**	***s***	***u*(*s*)**	***u*(*s*)**	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5					
Nd:YAG	1064	1.00	1.4859	0.0064	0.43%	2.0
Nd:YAG	1064	10.01	1.4633	0.0091	0.62%	2.0
CO2	10600	1.05	1.5621	0.0068	0.43%	2.0
CO2	10600	5.13	1.5594	0.0097	0.62%	2.0
MOLECTRON						
Laser	**λ**	**Φ**	***s***	***u*(*s*)**	***u*(*s*)**	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5					
Nd:YAG	1064	1.00	1.6402	0.0071	0.43%	2.0
Nd:YAG	1064	10.01	1.6360	0.0101	0.62%	2.0
CO2	10600	1.05	1.7384	0.0075	0.43%	2.0
CO2	10600	5.13	1.7330	0.0110	0.62%	2.0

Results of INFLPR (Romania)						
OPHIR						
Laser	**λ**	**Φ**	***s***	***u*(*s*)**	***u*(*s*)**	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.4984	0.0139	0.93%	2.1
Nd:YAG	1064	1.00	1.4689	0.0165	1.12%	2.3
Nd:YAG	1064					
CO2	10600					
CO2	10600					
MOLECTRON						
Laser	**λ**	**Φ**	***s***	***u*(*s*)**	***u*(*s*)**	***k***
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5	1.00	1.6624	0.0110	0.66%	2.1
Nd:YAG	1064	1.00	1.6291	0.0186	1.14%	2.3
Nd:YAG	1064					
CO2	10600					
CO2	10600					

Results of NMI Australia (Australia)						
OPHIR						
Laser	λ	Φ	*s*	*u*(*s*)	*u*(*s*)	*k*
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5					
Nd:YAG	1064	1.00	1.4890	0.0070	0.47%	2.1
Nd:YAG	1064	10.00	1.5030	0.0070	0.47%	2.1
CO2	10600					
CO2	10600					
MOLECTRON						
Laser	λ	Φ	*s*	*u*(*s*)	*u*(*s*)	*k*
	(nm)	**(W)**	**(mV/W)**	**(mV/W)**		
Argon	514.5					
Nd:YAG	1064	1.00	1.6650	0.0080	0.48%	2.1
Nd:YAG	1064	10.00	1.6570	0.0080	0.48%	2.1
CO2	10600					
CO2	10600					

8.2 Results for each measurand, supplementary comparison reference value (SCRV) and unilateral Degree of Equivalence (DoE)

The results for the spectral responsivity for each measurand and each NMI together with the SCRV and the unilateral DoE (i.e. the deviations of the NMI representative values to the SCRV) are listed and displayed in the following tables and figures:

Table 12 gives a summary of results obtained with the Ophir transfer detector, i.e. the spectral responsivity s, the standard uncertainty $u(s)$, the unilateral Degree of Equivalence D_i, its standard uncertainty $u_i(D_i)$ and its expanded uncertainty $U_i(D_i)$ are listed together with the supplementary comparison reference value (SCRV).

Table 13 gives the corresponding summary for the results obtained with the Molectron transfer detector.

Figure 8 gives in the upper graph the spectral responsivity, the standard uncertainty, the mean value, the weighted mean value and the SCRV (weighted mean with cut-off) for each participant obtained with the Ophir transfer detector. In the lower graph the deviation from the mean value, from the weighted mean value and from the SCRV, i.e. the unilateral Degree of Equivalence for each participant, is given.

Figure 10 gives the corresponding graphs for the Molectron transfer detector.

Figure 9 summarises graphically the unilateral Degrees of Equivalence and their uncertainty for each participant and each measurand.

Figure 11 gives the corresponding graphs for the Molectron transfer detector.

Summary of the results obtained with the Ophir transfer detector

Table 12: Summary of results of the Ophir transfer detector. In the table the results of each participant are listed, these are the spectral responsivity *s*, the standard uncertainty *u*(*s*), the unilateral Degree of Equivalence D_i, its standard uncertainty $u_i(D_i)$ and its expanded uncertainty $U_i(D_i)$ are listed together with the supplementary comparison reference value (SCRV).

Argon 1 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.5052	0.10%	0.36%	0.16%	0.32%
SE	1.5056	0.46%	0.39%	0.47%	0.95%
US	1.5083	0.43%	0.56%	0.45%	0.89%
FR	1.4771	0.39%	-1.51%	0.40%	0.81%
ZA	1.4986	2.00%	-0.09%	2.00%	4.01%
JP	1.5079	0.47%	0.54%	0.49%	0.97%
GB					
RO	1.4980	0.93%	-0.12%	0.94%	1.87%
AU					
SCRV	**1.4998**	**0.12%**	**0.00%**	**0.12%**	**0.24%**

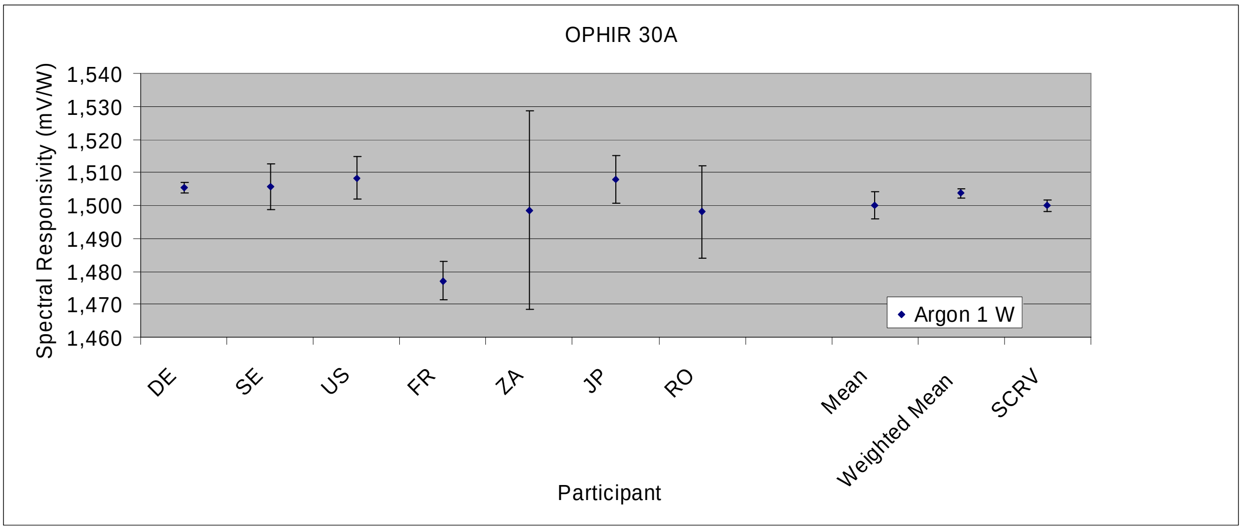
Nd:YAG 1 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.4650	0.13%	0.22%	0.17%	0.34%
SE					
US	1.4493	0.44%	-0.85%	0.46%	0.91%
FR	1.4307	0.44%	-2.12%	0.46%	0.91%
ZA	1.4351	2.02%	-1.82%	2.02%	4.05%
JP	1.4703	0.47%	0.59%	0.48%	0.97%
GB	1.4865	0.43%	1.70%	0.45%	0.89%
RO	1.4698	1.12%	0.55%	1.13%	2.26%
AU	1.4870	0.47%	1.73%	0.48%	0.97%
SCRV	**1.4617**	**0.12%**	**0.00%**	**0.12%**	**0.24%**

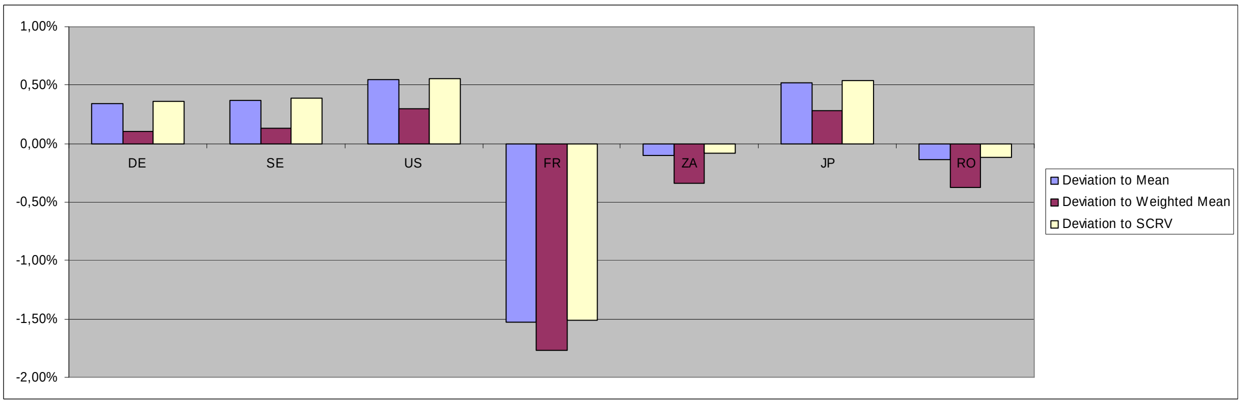
Nd:YAG 10 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.4418	0.14%	-0.45%	0.19%	0.39%
SE					
US	1.4318	0.53%	-1.14%	0.55%	1.09%
FR	1.4142	0.44%	-2.35%	0.46%	0.91%
ZA	1.4142	1.98%	-2.36%	1.98%	3.97%
JP	1.4507	0.47%	0.16%	0.49%	0.97%
GB	1.4627	0.62%	0.99%	0.64%	1.27%
RO					
AU	1.5010	0.47%	3.64%	0.48%	0.97%
SCRV	**1.4483**	**0.13%**	**0.00%**	**0.13%**	**0.26%**

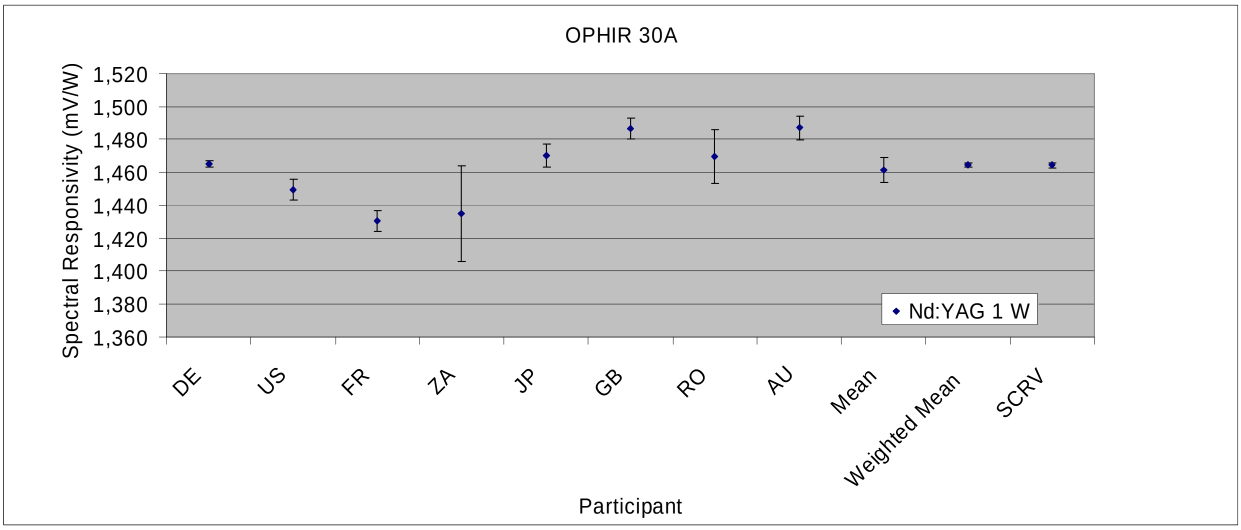
CO_2 1 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.5392	0.16%	-0.11%	0.21%	0.43%
SE	1.5983	2.57%	3.73%	2.57%	5.14%
US	1.5346	0.54%	-0.40%	0.56%	1.12%
FR	1.5146	0.61%	-1.71%	0.63%	1.26%
ZA	1.5371	2.47%	-0.24%	2.48%	4.95%
JP	1.5213	0.56%	-1.27%	0.58%	1.15%
GB	1.5627	0.44%	1.42%	0.46%	0.92%
RO					
AU					
SCRV	**1.5409**	**0.14%**	**0.00%**	**0.14%**	**0.29%**

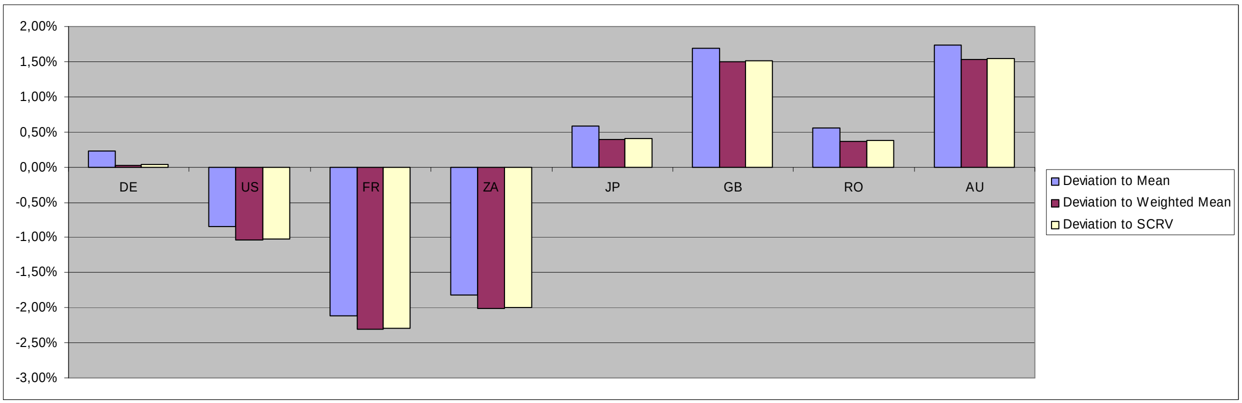
CO_2 5 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.5270	0.15%	0.22%	0.21%	0.42%
SE	1.5832	2.78%	3.91%	2.78%	5.57%
US	1.5185	0.53%	-0.34%	0.55%	1.10%
FR	1.5056	0.47%	-1.18%	0.49%	0.98%
ZA	1.5286	2.49%	0.33%	2.49%	4.98%
JP	1.5167	0.56%	-0.45%	0.58%	1.16%
GB	1.5609	0.62%	2.45%	0.64%	1.28%
RO					
AU					
SCRV	**1.5236**	**0.15%**	**0.00%**	**0.15%**	**0.30%**

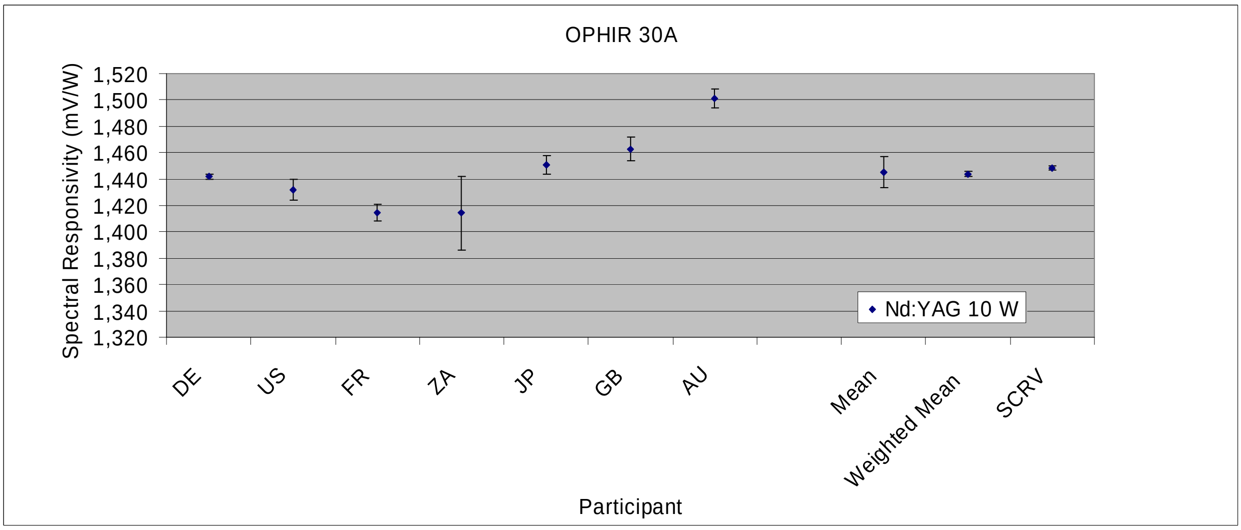
Figure 8: Upper graph: Spectral responsivity, standard uncertainty, mean value, weighted mean value and SCRV (weighted mean with cut-off) for each participant obtained with the Ophir transfer detector. Lower graph: Deviation from the mean value, from the weighted mean value and from the SCRV (i.e. the unilateral Degree of Equivalence) for each participant.

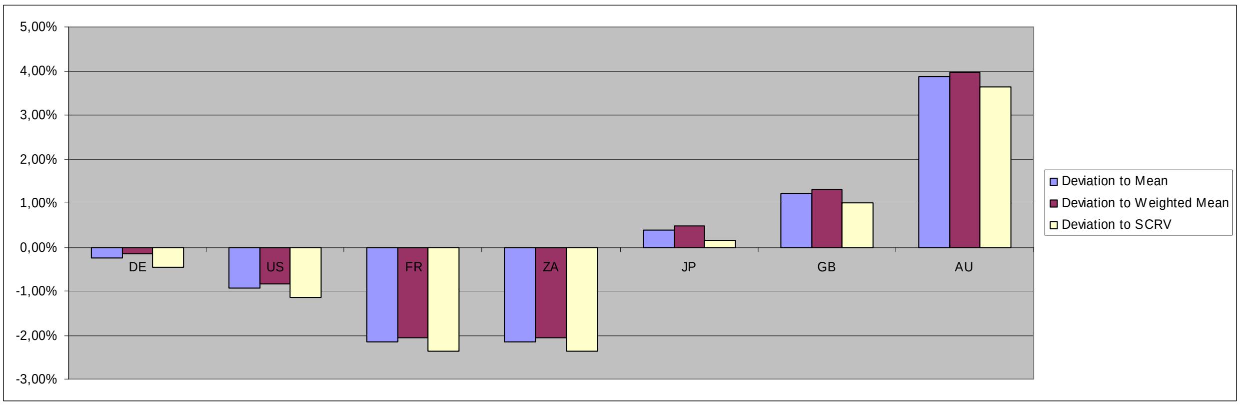


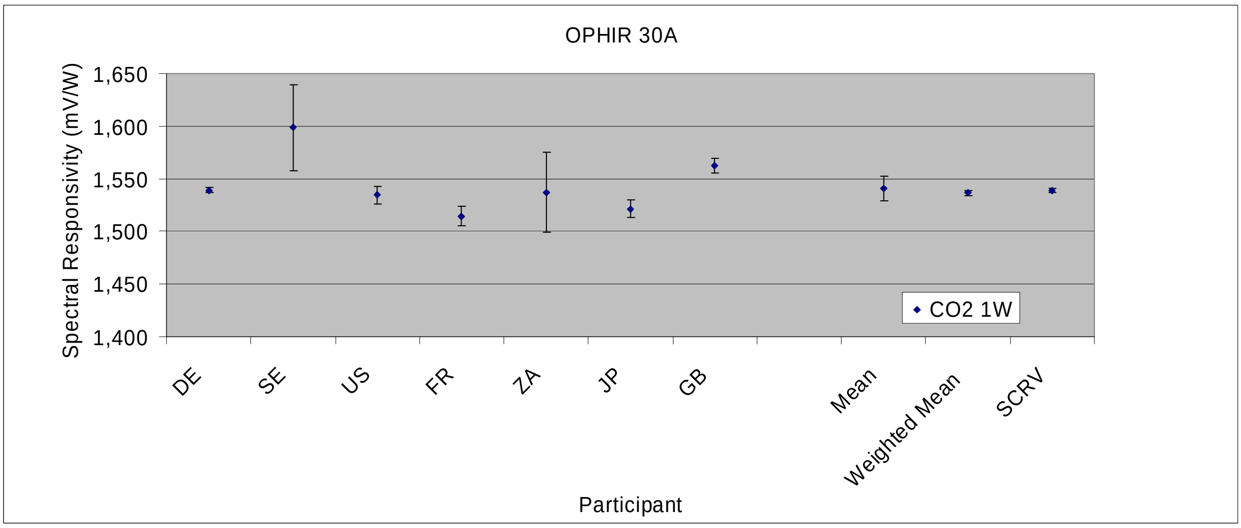


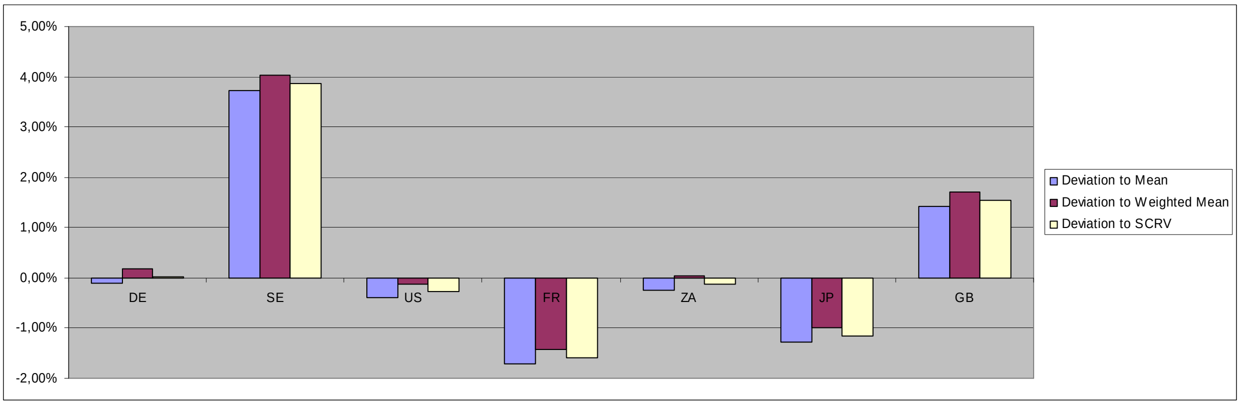

OPHIR 30A
Spectral Responsivity (mV/W)
1,520
1,500
1,480
1,460
1,440
1,420
1,400
1,380
1,360
Nd:YAG 1 W
DE
US
FR
ZA
JP
GB
RO
AU
Mean
Weighted Mean
SCRV
Participant

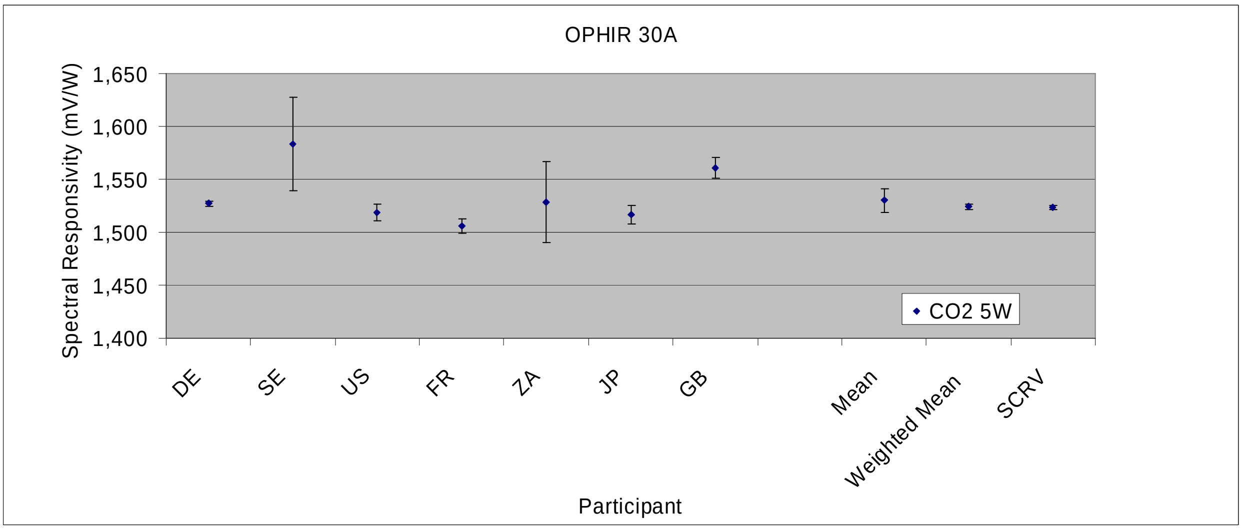

2,00%
1,50%
1,00%
0,50%
0,00%
-0,50%
-1,00%
-1,50%
-2,00%
-2,50%
-3,00%
DE
US
FR
ZA
JP
GB
RO
AU
Deviation to Mean
Deviation to Weighted Mean
Deviation to SCRV

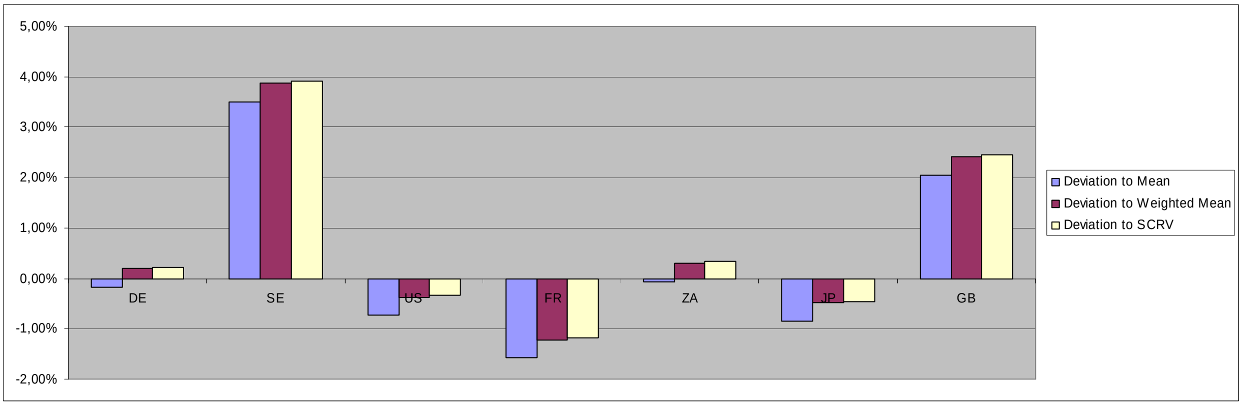

OPHIR 30A
Spectral Responsivity (mV/W)
1,520
1,500
1,480
1,460
1,440
1,420
1,400
1,380
1,360
1,340
1,320
Nd:YAG 10 W
DE
US
FR
ZA
JP
GB
AU
Mean
Weighted Mean
SCRV
Participant


5,00%
4,00%
3,00%
2,00%
1,00%
0,00%
-1,00%
-2,00%
-3,00%
DE
US
FR
ZA
JP
GB
AU
Deviation to Mean
Deviation to Weighted Mean
Deviation to SCRV


OPHIR 30A
Spectral Responsivity (mV/W)
1,650
1,600
1,550
1,500
1,450
1,400
CO2 1W
DE
SE
US
FR
ZA
JP
GB
Mean
Weighted Mean
SCRV
Participant

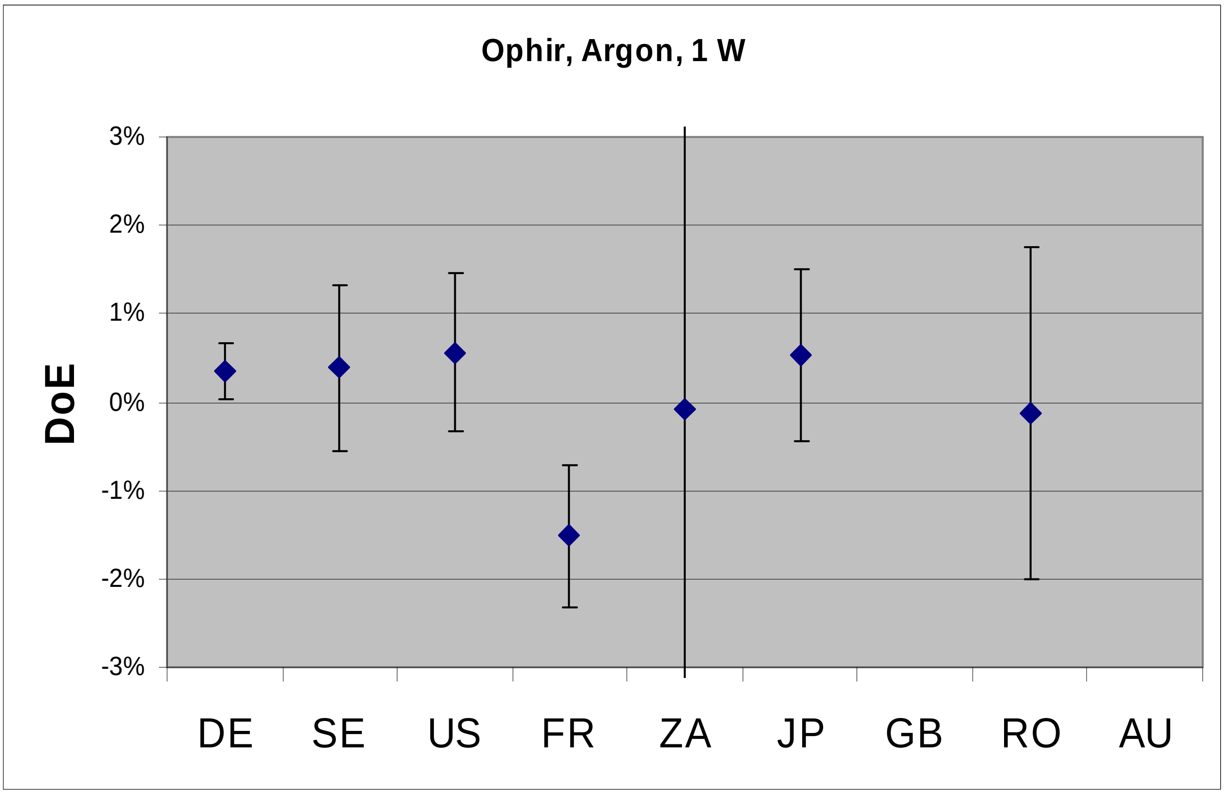

5,00%
4,00%
3,00%
2,00%
1,00%
0,00%
-1,00%
-2,00%
DE
SE
US
FR
ZA
JP
GB
Deviation to Mean
Deviation to Weighted Mean
Deviation to SCRV

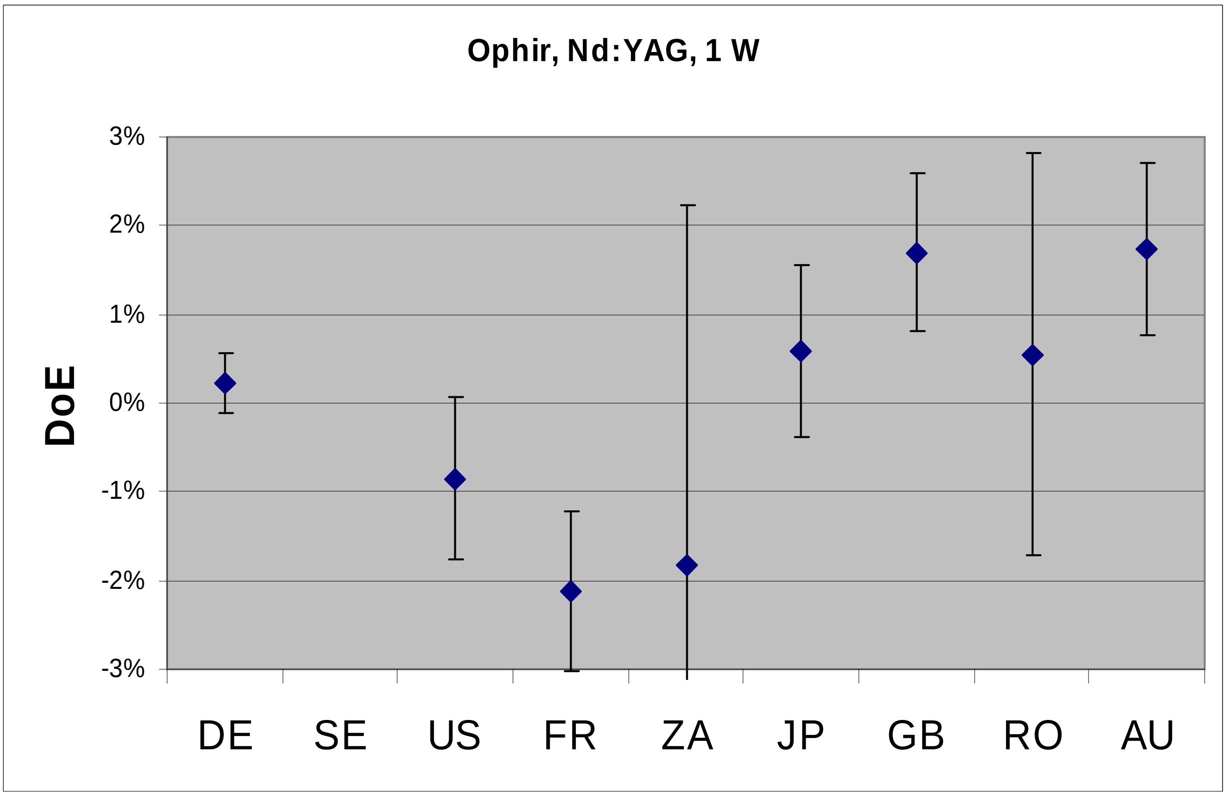

OPHIR 30A
Spectral Responsivity (mV/W)
1,650
1,600
1,550
1,500
1,450
1,400
CO2 5W
DE
SE
US
FR
ZA
JP
GB
Mean
Weighted Mean
SCRV
Participant

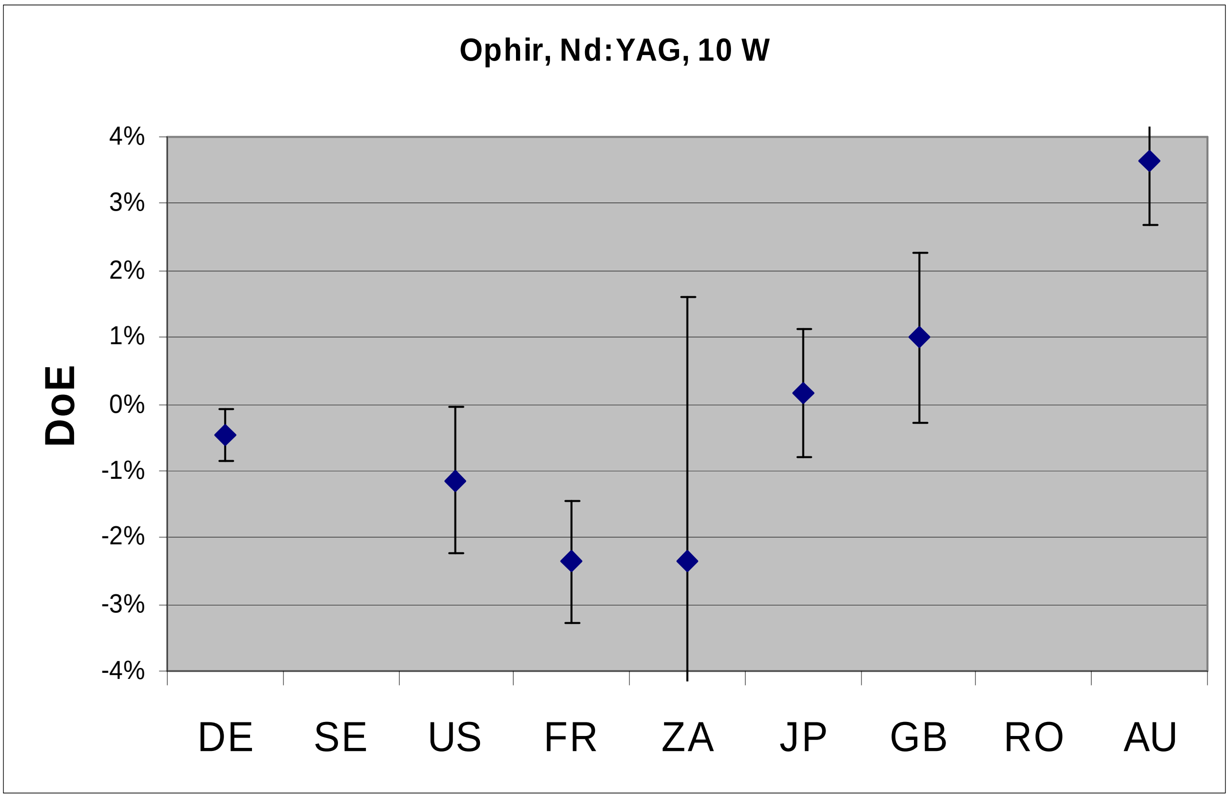

5,00%
4,00%
3,00%
2,00%
1,00%
0,00%
-1,00%
-2,00%
DE
SE
US
FR
ZA
JP
GB
Deviation to Mean
Deviation to Weighted Mean
Deviation to SCRV

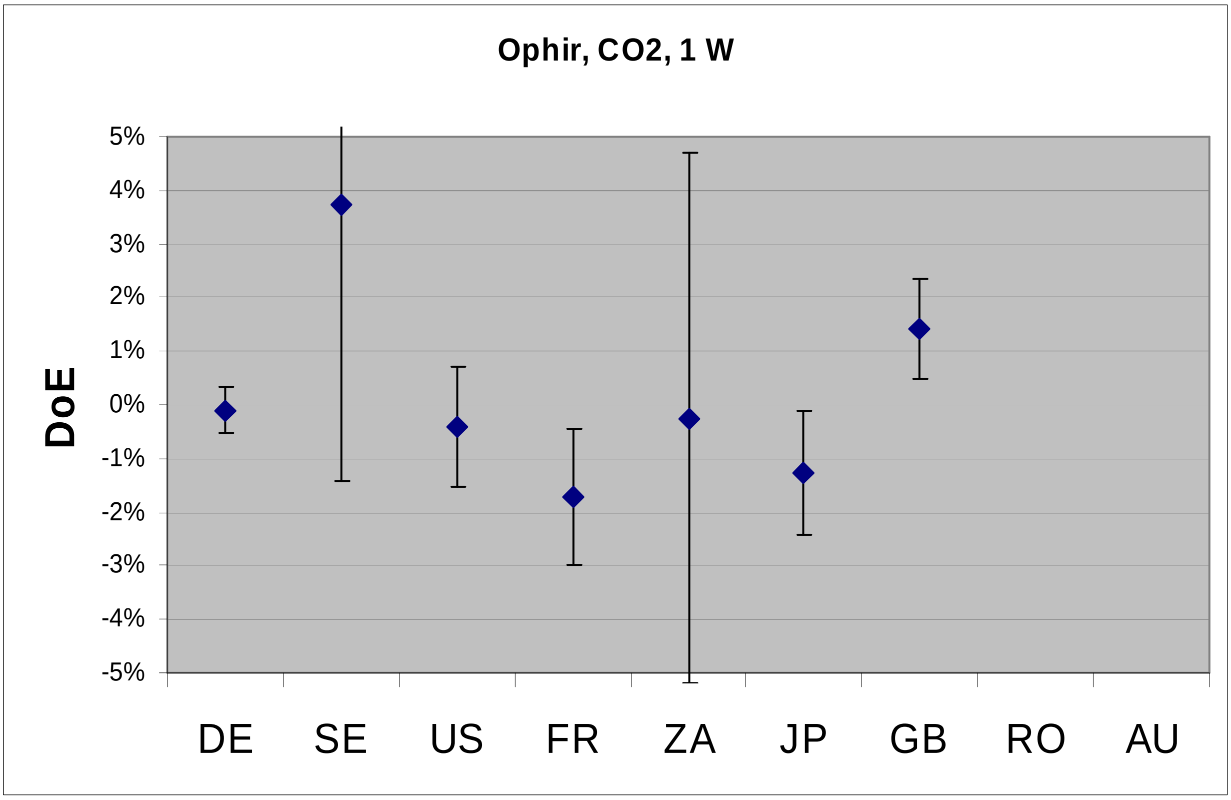
Summary of the unilateral Degrees of Equivalence for the Ophir detector

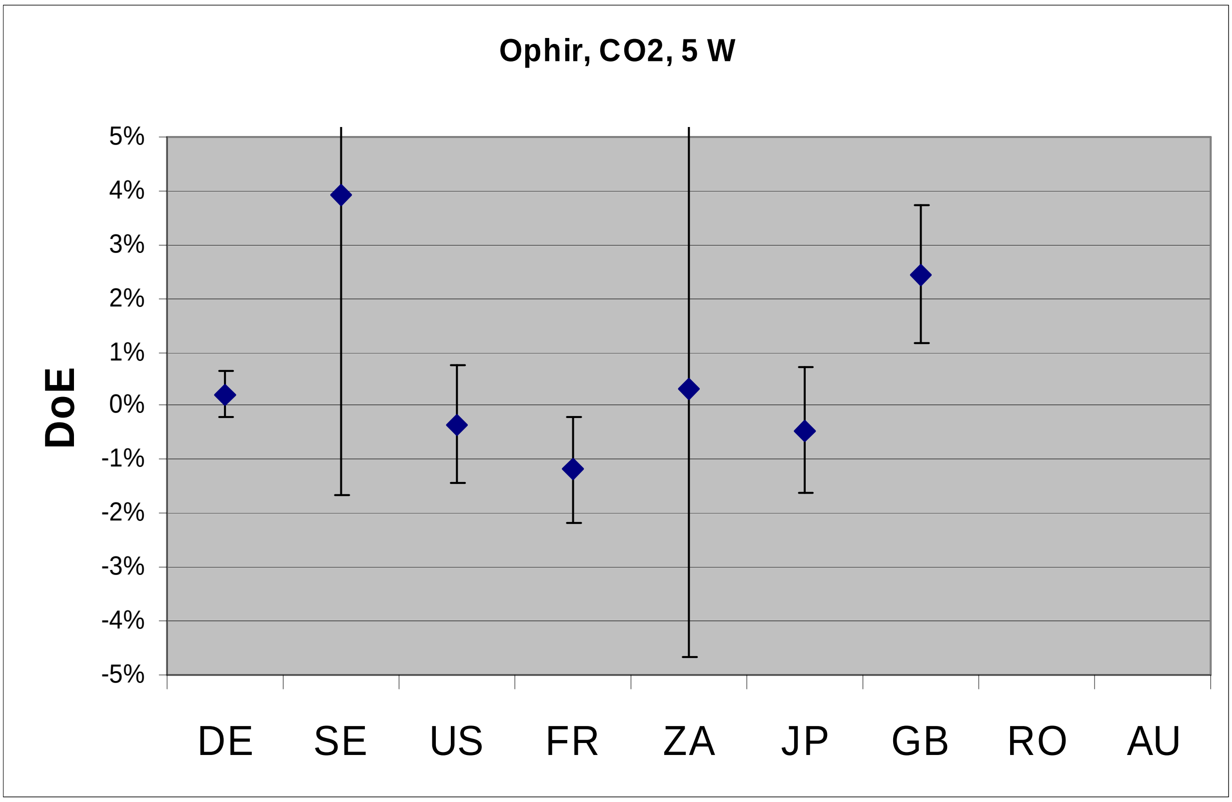
Figure 9: Unilateral Degree of Equivalence (DoE) for each participant and each measurand for the Ophir transfer detector.






Ophir, Nd:YAG, 10 W
DoE
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
DE
SE
US
FR
ZA
JP
GB
RO
AU


Ophir, CO2, 1 W
DoE
5%
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
-5%
DE
SE
US
FR
ZA
JP
GB
RO
AU


Ophir, CO2, 5 W
DoE
5%
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
-5%
DE
SE
US
FR
ZA
JP
GB
RO
AU

Summary of the results obtained with the Molectron transfer detector

Table 13: Summary of results of the Molectron transfer detector. In the table the results of each participant are listed, these are the spectral responsivity *s*, the standard uncertainty *u*(*s*), the unilateral Degree of Equivalence D_i, its standard uncertainty $u_i(D_i)$ and its expanded uncertainty $U_i(D_i)$ are listed together with the supplementary comparison reference value (SCRV).

Argon 1 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.6661	0.09%	0.41%	0.13%	0.27%
SE	1.6640	0.43%	0.27%	0.44%	0.88%
US	1.6659	0.43%	0.39%	0.44%	0.88%
FR	1.6389	0.36%	-1.24%	0.37%	0.75%
ZA	1.6477	2.00%	-0.70%	2.01%	4.01%
JP	1.6660	0.47%	0.40%	0.48%	0.96%
GB					
RO	1.6625	0.66%	0.19%	0.67%	1.34%
AU					
SCRV	**1.6594**	**0.10%**	**0.00%**	**0.10%**	**0.20%**

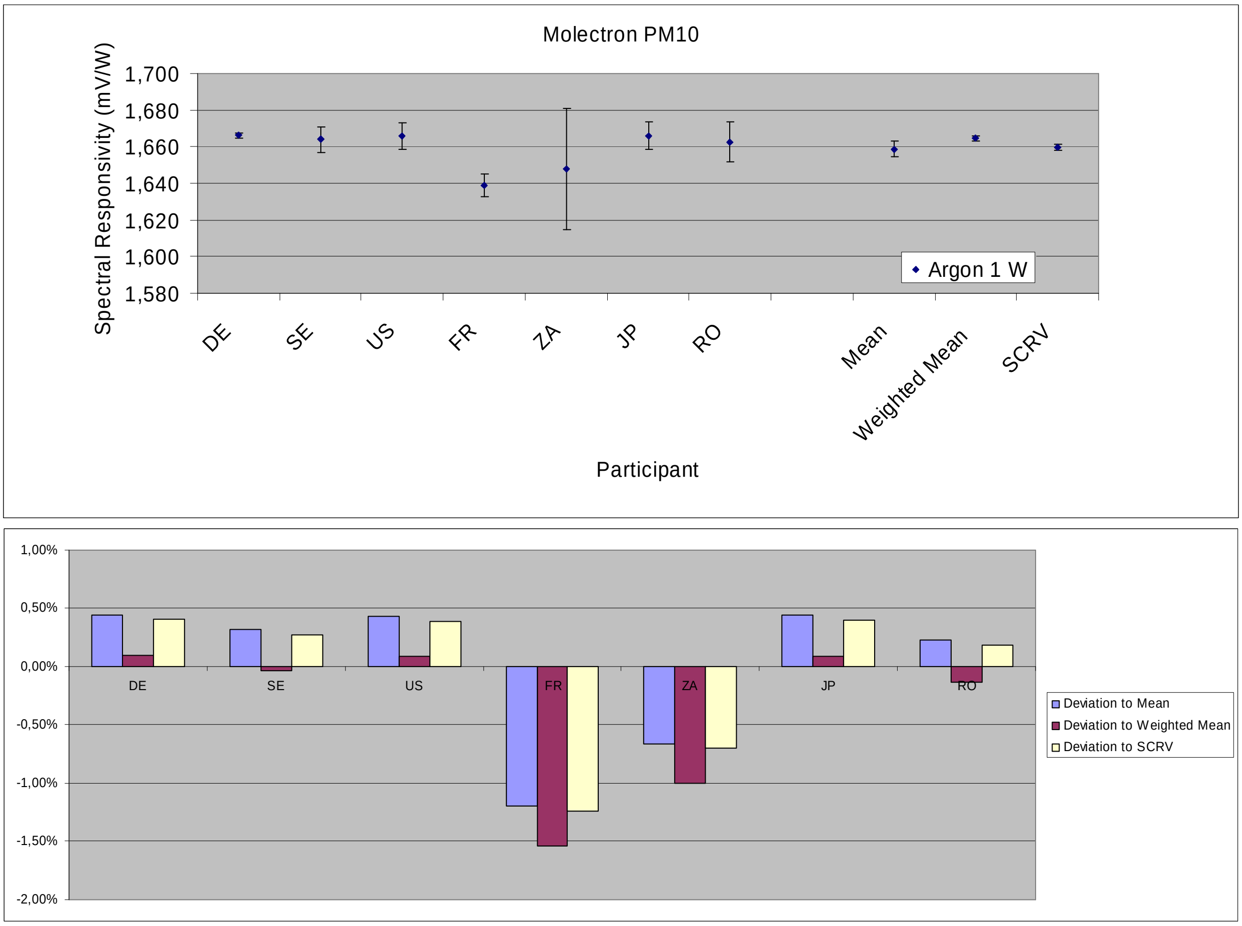
Nd:YAG 1 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.6296	0.24%	0.32%	0.26%	0.52%
SE					
US	1.6094	0.44%	-0.92%	0.45%	0.91%
FR	1.5946	0.43%	-1.83%	0.45%	0.89%
ZA	1.5962	2.01%	-1.73%	2.01%	4.02%
JP	1.6328	0.47%	0.52%	0.48%	0.97%
GB	1.6398	0.43%	0.95%	0.45%	0.89%
RO	1.6285	1.14%	0.26%	1.15%	2.29%
AU	1.6637	0.48%	2.42%	0.49%	0.98%
SCRV	**1.6243**	**0.11%**	**0.00%**	**0.11%**	**0.22%**

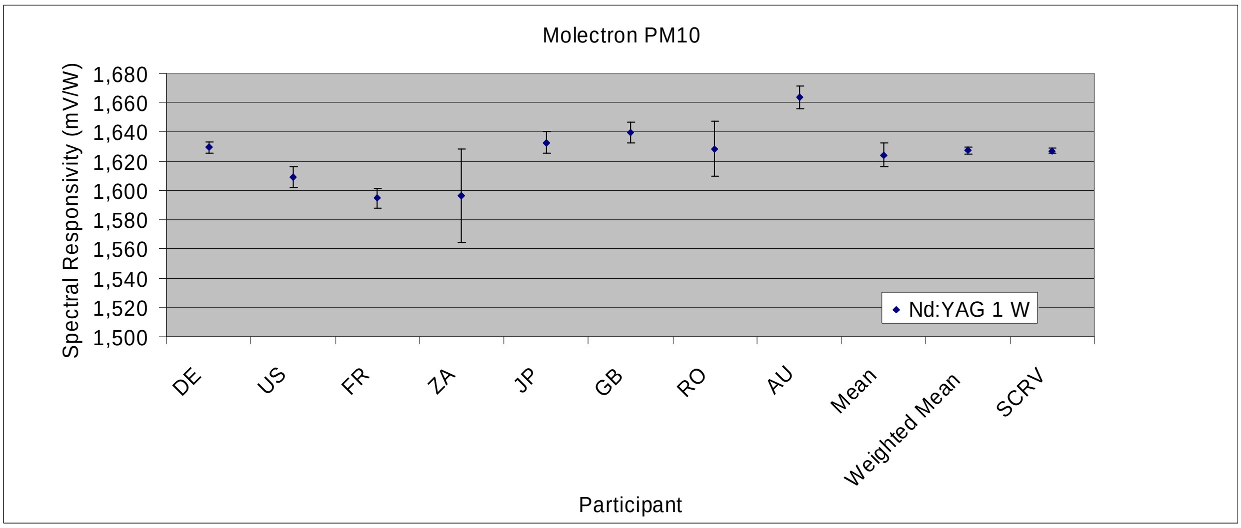
Nd:YAG 10 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.6038	0.17%	-0.29%	0.21%	0.41%
SE					
US	1.5910	0.53%	-1.09%	0.54%	1.09%
FR	1.5797	0.39%	-1.80%	0.41%	0.82%
ZA	1.5762	2.03%	-2.02%	2.03%	4.07%
JP	1.6122	0.47%	0.22%	0.49%	0.97%
GB	1.6343	0.62%	1.60%	0.63%	1.26%
RO					
AU	1.6569	0.48%	3.01%	0.50%	0.99%
SCRV	**1.6086**	**0.12%**	**0.00%**	**0.12%**	**0.23%**

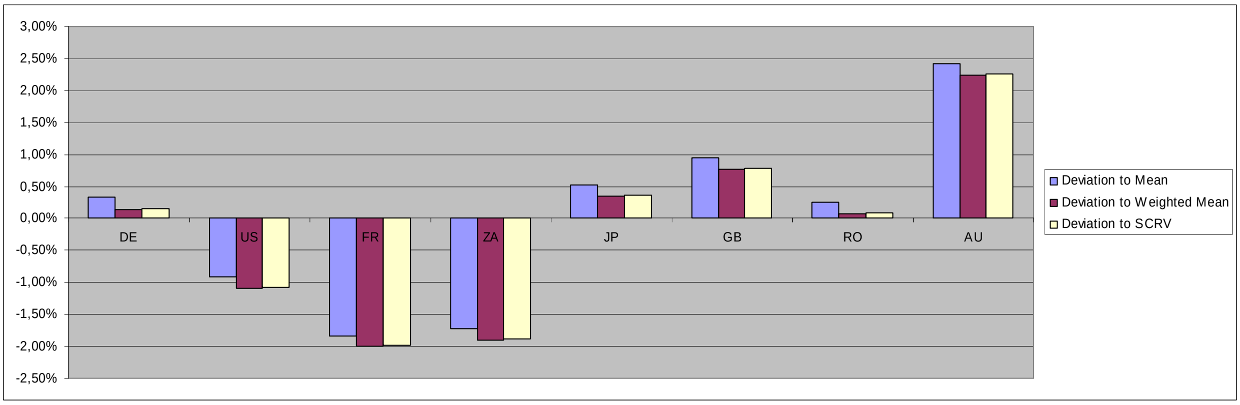
CO_2 1 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.7174	0.16%	-0.32%	0.21%	0.42%
SE	1.7856	2.35%	3.63%	2.36%	4.71%
US	1.7193	0.54%	-0.22%	0.56%	1.11%
FR	1.6964	0.61%	-1.54%	0.62%	1.24%
ZA	1.7230	2.50%	0.00%	2.50%	5.00%
JP	1.6962	0.56%	-1.55%	0.57%	1.15%
GB	1.7369	0.43%	0.80%	0.45%	0.90%
RO					
AU					
SCRV	**1.7230**	**0.13%**	**0.00%**	**0.13%**	**0.26%**

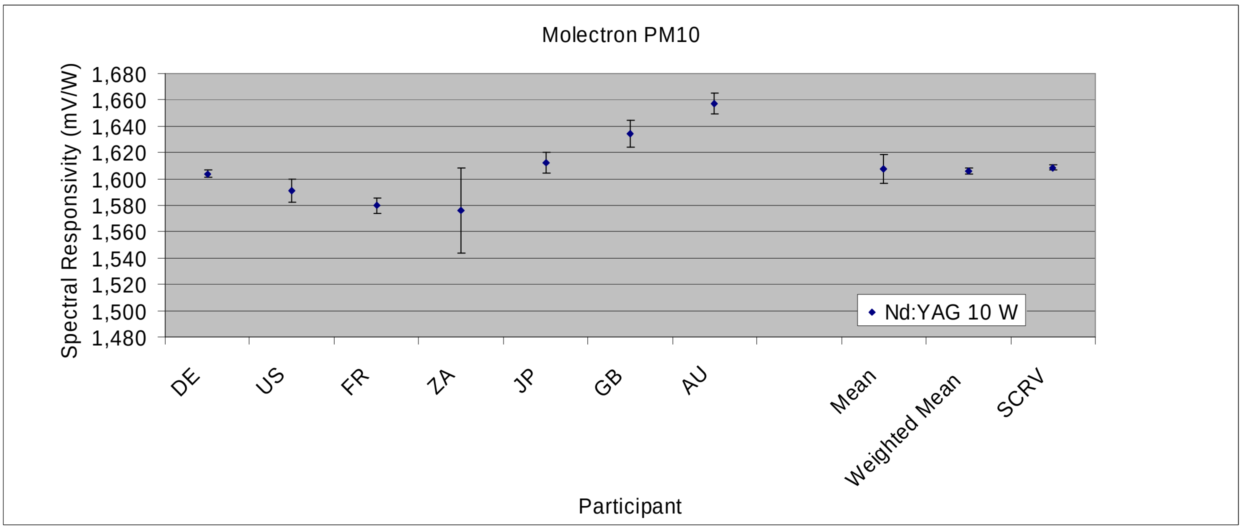
CO_2 5 W					
Participant	***s***	***u*(*s*)**	**D_i**	**$u_i(D_i)$**	**$U_i(D_i)$**
DE	1.7045	0.18%	0.13%	0.23%	0.45%
SE	1.7694	2.49%	3.94%	2.49%	4.98%
US	1.7048	0.54%	0.15%	0.56%	1.11%
FR	1.6870	0.46%	-0.90%	0.48%	0.96%
ZA	1.7207	2.50%	1.08%	2.50%	5.00%
JP	1.6906	0.56%	-0.69%	0.58%	1.15%
GB	1.7321	0.63%	1.75%	0.65%	1.30%
RO					
AU					
SCRV	**1.7023**	**0.13%**	**0.00%**	**0.13%**	**0.27%**

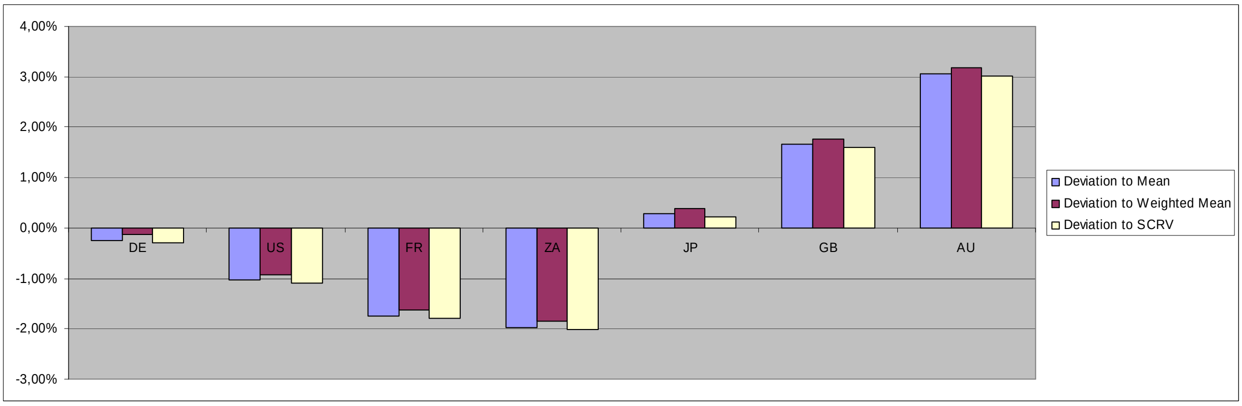
Figure 10: Upper graph: Spectral responsivity, standard uncertainty, mean value, weighted mean value and SCRV (weighted mean with cut-off) for each participant obtained with the Molectron transfer detector. Lower graph: Deviation from the mean value, from the weighted mean value and from the SCRV (i.e. the unilateral Degree of Equivalence) for each participant.

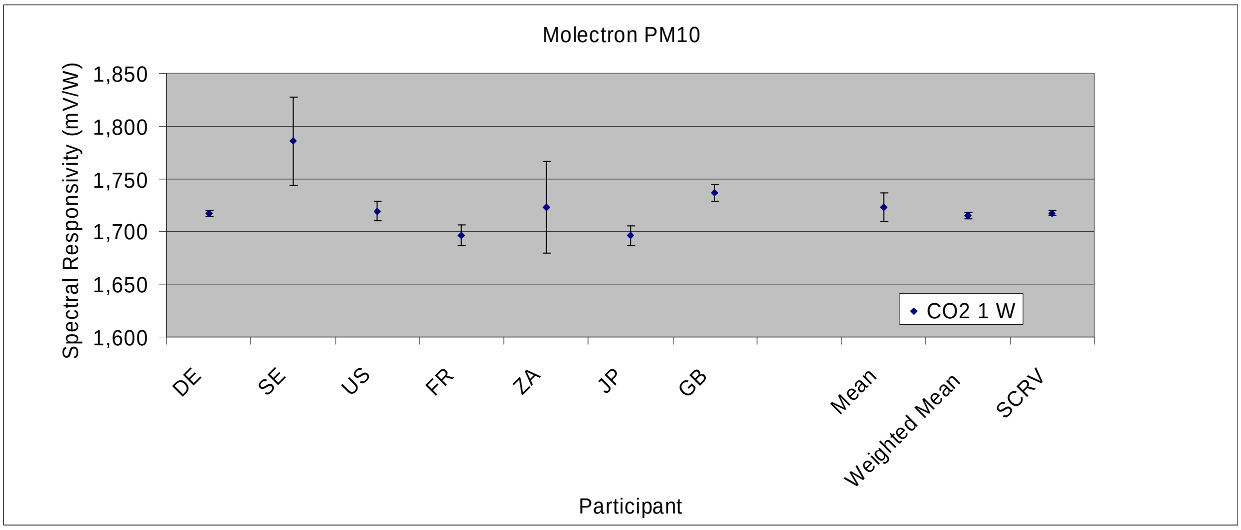


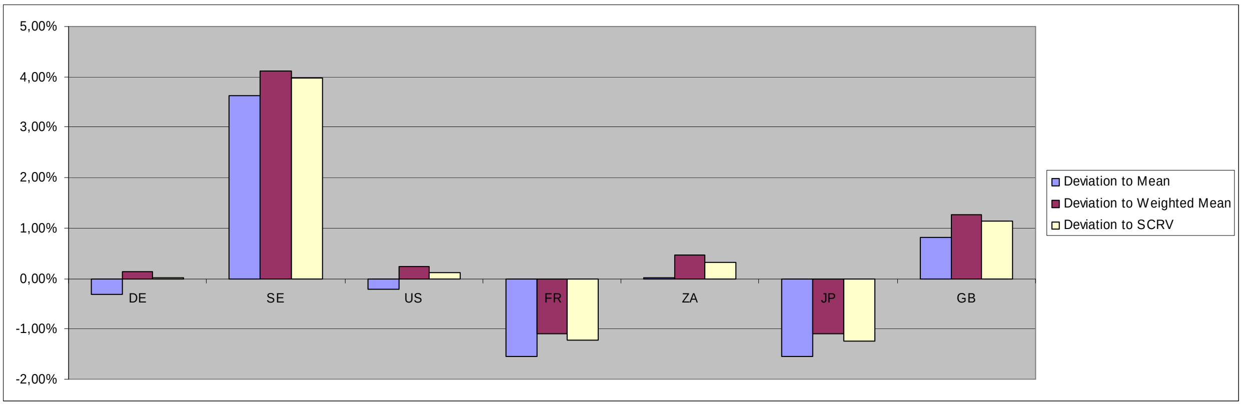

Molectron PM10
Spectral Responsivity (mV/W)
1,680
1,660
1,640
1,620
1,600
1,580
1,560
1,540
1,520
1,500
Nd:YAG 1 W
DE
US
FR
ZA
JP
GB
RO
AU
Mean
Weighted Mean
SCRV
Participant

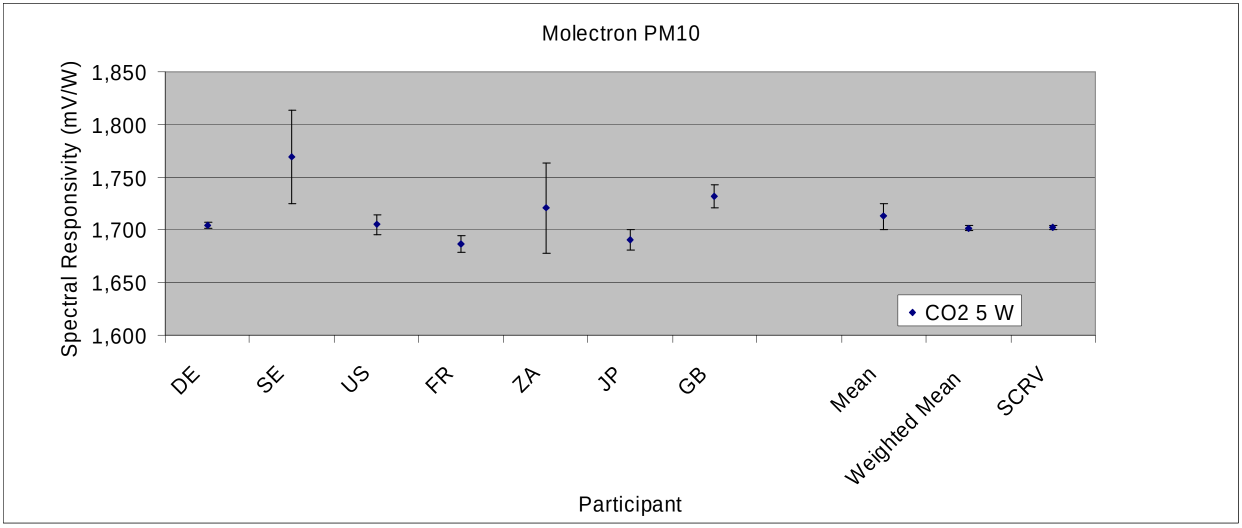

3,00%
2,50%
2,00%
1,50%
1,00%
0,50%
0,00%
-0,50%
-1,00%
-1,50%
-2,00%
-2,50%
DE
US
FR
ZA
JP
GB
RO
AU
Deviation to Mean
Deviation to Weighted Mean
Deviation to SCRV

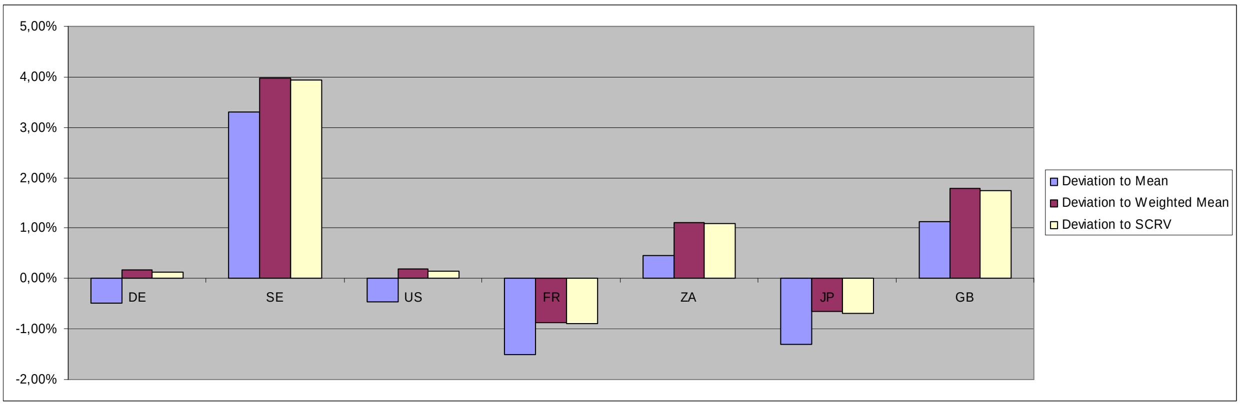

Molectron PM10
Spectral Responsivity (mV/W)
1,680
1,660
1,640
1,620
1,600
1,580
1,560
1,540
1,520
1,500
1,480
Nd:YAG 10 W
DE
US
FR
ZA
JP
GB
AU
Mean
Weighted Mean
SCRV
Participant


4,00%
3,00%
2,00%
1,00%
0,00%
-1,00%
-2,00%
-3,00%
DE
US
FR
ZA
JP
GB
AU
Deviation to Mean
Deviation to Weighted Mean
Deviation to SCRV


Molectron PM10
Spectral Responsivity (mV/W)
1,850
1,800
1,750
1,700
1,650
1,600
CO2 1 W
DE
SE
US
FR
ZA
JP
GB
Mean
Weighted Mean
SCRV
Participant

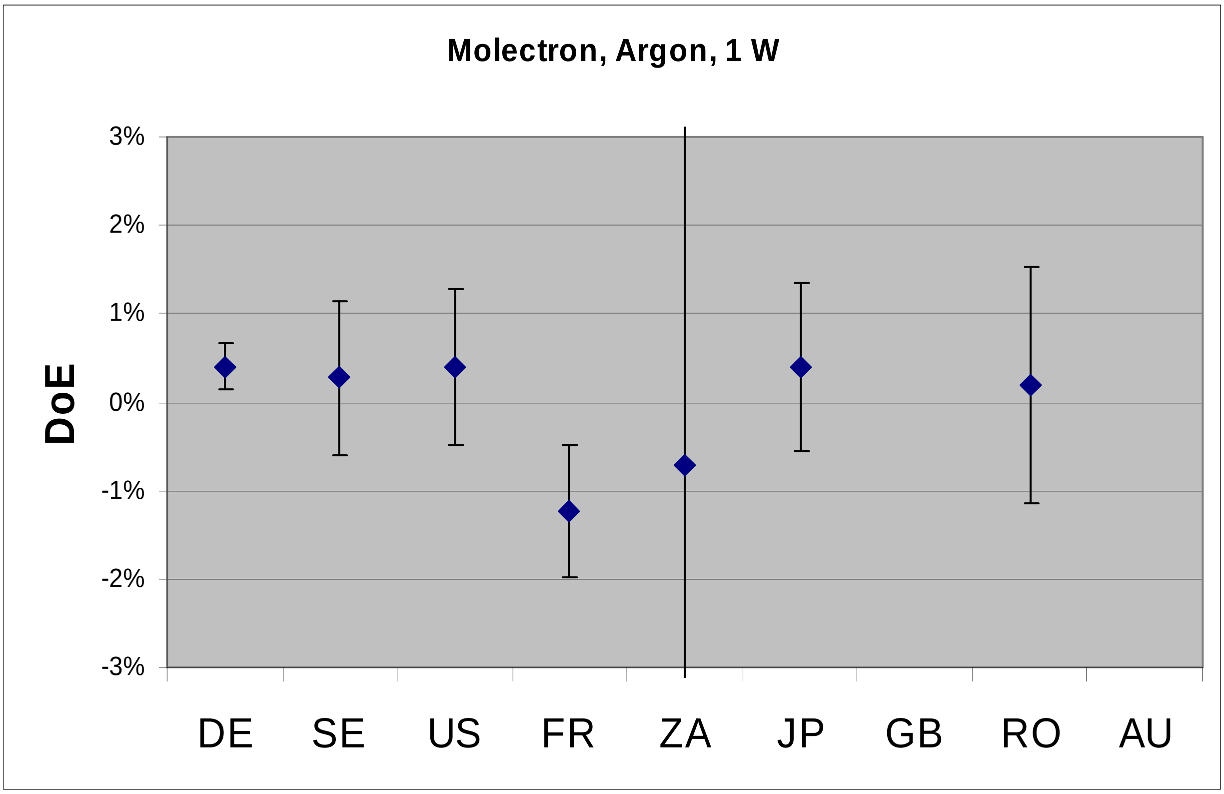

5,00%
4,00%
3,00%
2,00%
1,00%
0,00%
-1,00%
-2,00%
DE
SE
US
FR
ZA
JP
GB
Deviation to Mean
Deviation to Weighted Mean
Deviation to SCRV

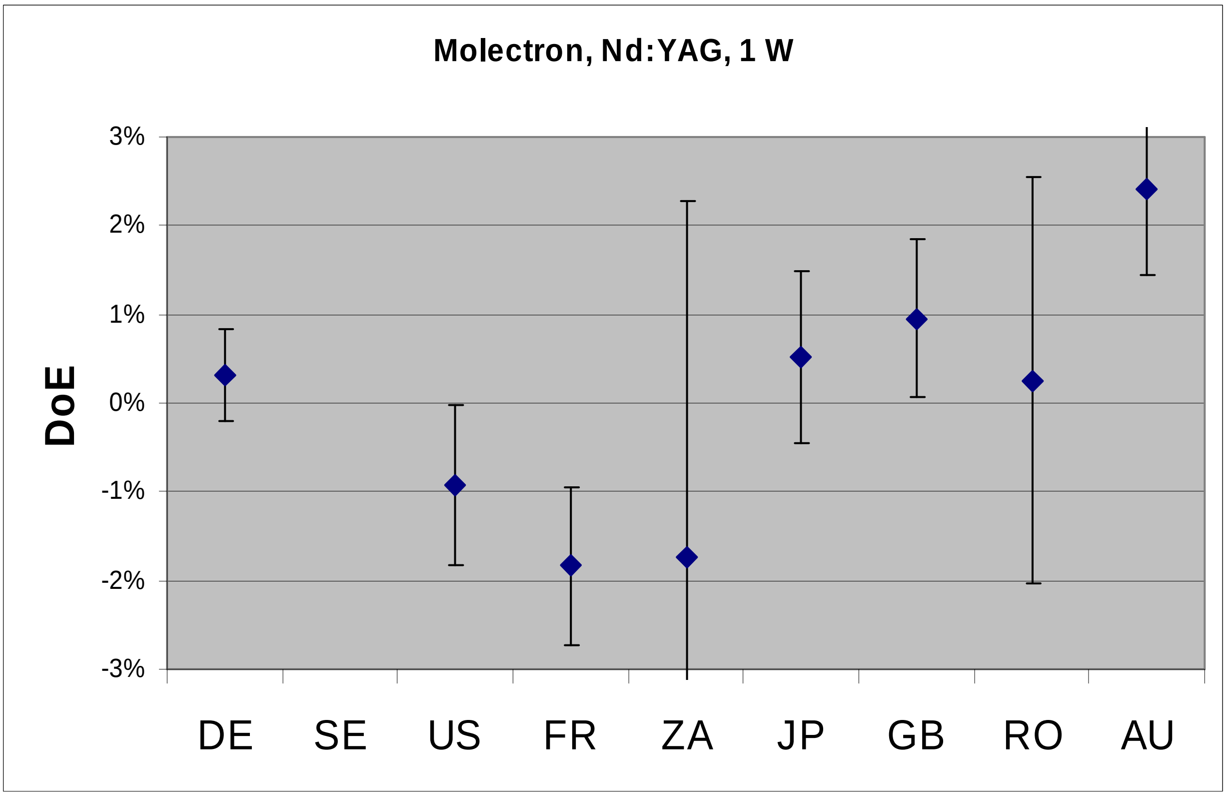

Molectron PM10
Spectral Responsivity (mV/W)
1,850
1,800
1,750
1,700
1,650
1,600
CO2 5 W
DE
SE
US
FR
ZA
JP
GB
Mean
Weighted Mean
SCRV
Participant

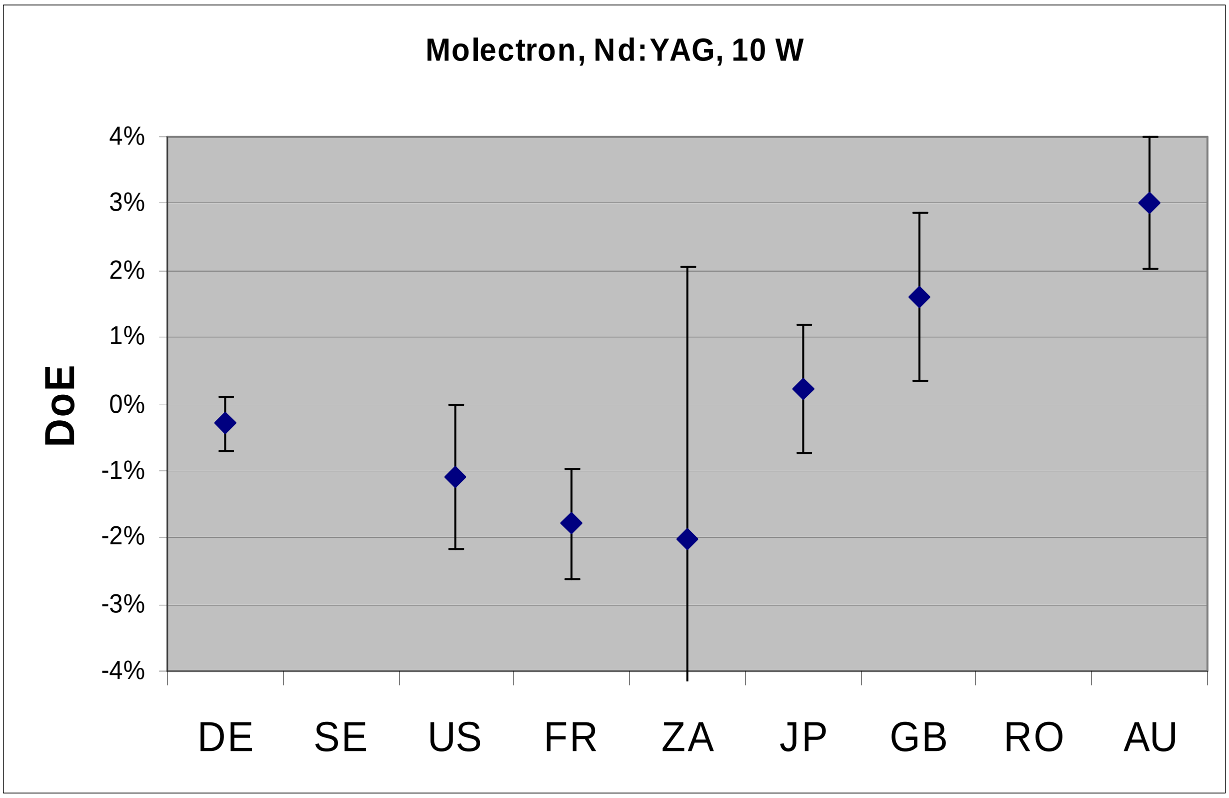

5,00%
4,00%
3,00%
2,00%
1,00%
0,00%
-1,00%
-2,00%
DE
SE
US
FR
ZA
JP
GB
Deviation to Mean
Deviation to Weighted Mean
Deviation to SCRV

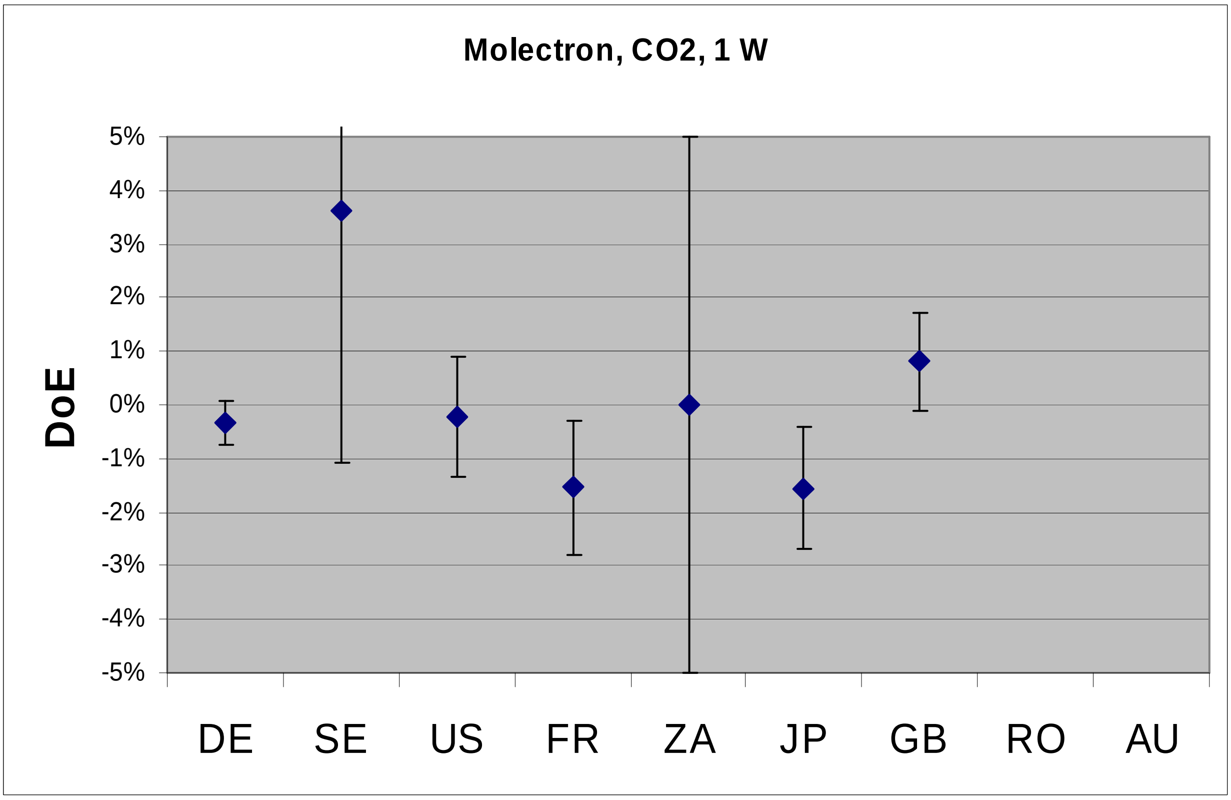
Summary of the unilateral Degrees of Equivalence for the Molectron detector

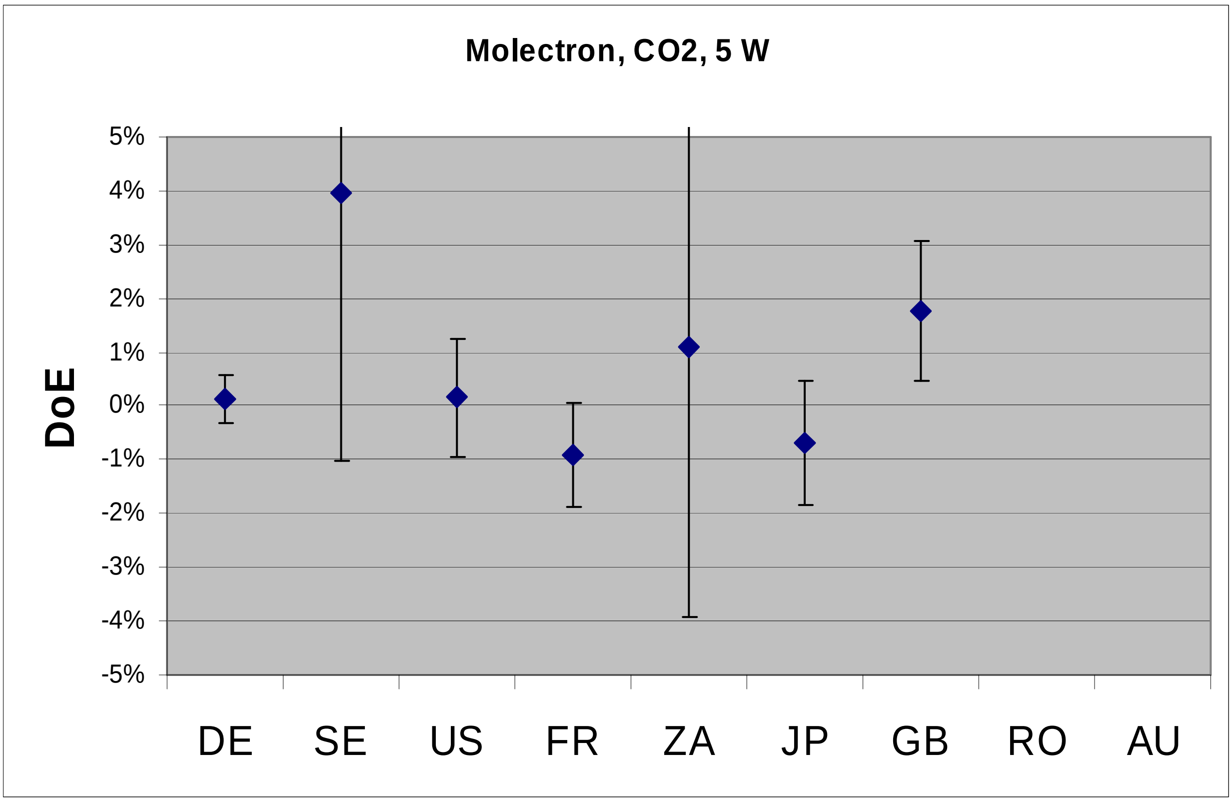
Figure 11: Unilateral Degree of Equivalence (DoE) for each participant and each measurand for the Molectron transfer detector.






Molectron, Nd:YAG, 10 W
DoE
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
DE
SE
US
FR
ZA
JP
GB
RO
AU


Molectron, CO2, 1 W
DoE
5%
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
-5%
DE
SE
US
FR
ZA
JP
GB
RO
AU


Molectron, CO2, 5 W
DoE
5%
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
-5%
DE
SE
US
FR
ZA
JP
GB
RO
AU

8.3 Bilateral Degree of Equivalence

The results for the bilateral Degree of Equivalence are listed in the following tables (Table 14) for each combination of participants and each measurand followed by Figures (Figure 12) depicting the bilateral DoEs between all participants.

Table 14: Bilateral Degree of Equivalence $D_{i,m}$ and associated $U_{i,m}$ for the participants.

Bilateral DoE, $U_{i,m}$	**DE**		**SE**		**US**		**FR**		**ZA**		**JP**		**GB**		**RO**		**AU**	
DE	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**
Ophir, Argon, 1 W			-0.03%	1.03%	-0.20%	0.98%	1.87%	0.90%	0.45%	4.03%	-0.18%	1.05%			0.48%	1.92%		
Ophir, Nd:YAG, 1 W					1.07%	1.00%	2.34%	1.00%	2.05%	4.07%	-0.36%	1.05%	-1.47%	0.99%	-0.33%	2.30%	-1.50%	1.06%
Ophir, Nd:YAG, 10 W					0.69%	1.19%	1.90%	1.03%	1.91%	4.00%	-0.62%	1.08%	-1.45%	1.35%			-4.09%	1.07%
Ophir, CO2, 1 W			-3.84%	5.17%	0.30%	1.23%	1.60%	1.36%	0.14%	4.98%	1.16%	1.26%	-1.52%	1.05%				
Ophir, CO2, 5 W			-3.69%	5.59%	0.56%	1.22%	1.40%	1.10%	-0.11%	5.01%	0.67%	1.27%	-2.23%	1.38%				
Molectron, Argon, 1 W			0.13%	0.94%	0.01%	0.95%	1.64%	0.82%	1.11%	4.02%	0.01%	1.02%			0.22%	1.38%		
Molectron, Nd:YAG, 1 W					1.24%	1.07%	2.15%	1.05%	2.05%	4.06%	-0.20%	1.12%	-0.63%	1.06%	0.07%	2.36%	-2.10%	1.13%
Molectron, Nd:YAG, 10 W					0.80%	1.18%	1.50%	0.95%	1.72%	4.10%	-0.52%	1.08%	-1.90%	1.34%			-3.30%	1.10%
Molectron, CO2, 1 W			-3.96%	4.74%	-0.11%	1.21%	1.22%	1.33%	-0.33%	5.02%	1.23%	1.25%	-1.13%	1.02%				
Molectron, CO2, 5 W			-3.81%	5.01%	-0.02%	1.23%	1.03%	1.10%	-0.95%	5.03%	0.82%	1.27%	-1.62%	1.40%				

Bilateral DoE, $U_{i,m}$	**DE**		**SE**		**US**		**FR**		**ZA**		**JP**		**GB**		**RO**		**AU**	
SE	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**DE**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**	**$D_{i,m}$**	**$U_{i,m}$**
Ophir, Argon, 1 W	0.03%	1.03%			-0.18%	1.32%	1.90%	1.27%	0.47%	4.13%	-0.15%	1.38%			0.51%	2.11%		
Ophir, Nd:YAG, 1 W																		
Ophir, Nd:YAG, 10 W																		
Ophir, CO2, 1 W	3.84%	5.17%			4.13%	5.27%	5.44%	5.30%	3.97%	7.14%	5.00%	5.28%	2.31%	5.23%				
Ophir, CO2, 5 W	3.69%	5.59%			4.25%	5.68%	5.10%	5.66%	3.58%	7.47%	4.37%	5.69%	1.47%	5.72%				
Molectron, Argon, 1 W	-0.13%	0.94%			-0.12%	1.26%	1.51%	1.17%	0.98%	4.11%	-0.13%	1.31%			0.09%	1.61%		
Molectron, Nd:YAG, 1 W																		
Molectron, Nd:YAG, 10 W																		
Molectron, CO2, 1 W	3.96%	4.74%			3.85%	4.85%	5.18%	4.88%	3.63%	6.87%	5.19%	4.86%	2.83%	4.80%				
Molectron, CO2, 5 W	3.81%	5.01%			3.79%	5.11%	4.84%	5.08%	2.86%	7.06%	4.63%	5.12%	2.19%	5.15%				

Bilateral DoE, $U_{i,m}$	**DE**		**SE**		**US**		**FR**		**ZA**		**JP**		**GB**		**RO**		**AU**	
US	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	**DE**	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$
Ophir, Argon, 1 W	0.20%	0.98%	0.18%	1.32%			2.07%	1.23%	0.65%	4.11%	0.02%	1.34%			0.68%	2.09%		
Ophir, Nd:YAG, 1 W	-1.07%	1.00%					1.27%	1.31%	0.97%	4.16%	-1.44%	1.35%	-2.55%	1.30%	-1.40%	2.45%	-2.58%	1.35%
Ophir, Nd:YAG, 10 W	-0.69%	1.19%					1.21%	1.45%	1.22%	4.12%	-1.30%	1.49%	-2.13%	1.70%			-4.78%	1.48%
Ophir, CO2, 1 W	-0.30%	1.23%	-4.13%	5.27%			1.30%	1.71%	-0.16%	5.09%	0.87%	1.63%	-1.82%	1.47%				
Ophir, CO2, 5 W	-0.56%	1.22%	-4.25%	5.68%			0.85%	1.50%	-0.67%	5.11%	0.11%	1.63%	-2.78%	1.71%				
Molectron, Argon, 1 W	-0.01%	0.95%	0.12%	1.26%			1.63%	1.18%	1.10%	4.11%	-0.01%	1.32%			0.20%	1.62%		
Molectron, Nd:YAG, 1 W	-1.24%	1.07%					0.91%	1.29%	0.81%	4.12%	-1.44%	1.34%	-1.87%	1.29%	-1.18%	2.47%	-3.34%	1.36%
Molectron, Nd:YAG, 10 W	-0.80%	1.18%					0.71%	1.38%	0.93%	4.22%	-1.31%	1.47%	-2.69%	1.68%			-4.10%	1.49%
Molectron, CO2, 1 W	0.11%	1.21%	-3.85%	4.85%			1.33%	1.68%	-0.22%	5.13%	1.34%	1.62%	-1.02%	1.45%				
Molectron, CO2, 5 W	0.02%	1.23%	-3.79%	5.11%			1.05%	1.49%	-0.93%	5.13%	0.84%	1.63%	-1.60%	1.73%				

Bilateral DoE, $U_{i,m}$	**DE**		**SE**		**US**		**FR**		**ZA**		**JP**		**GB**		**RO**		**AU**	
FR	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	**DE**	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$
Ophir, Argon, 1 W	-1.87%	0.90%	-1.90%	1.27%	-2.07%	1.23%			-1.43%	4.10%	-2.05%	1.29%			-1.39%	2.06%		
Ophir, Nd:YAG, 1 W	-2.34%	1.00%			-1.27%	1.31%			-0.30%	4.16%	-2.71%	1.35%	-3.81%	1.30%	-2.67%	2.45%	-3.85%	1.35%
Ophir, Nd:YAG, 10 W	-1.90%	1.03%			-1.21%	1.45%			0.01%	4.08%	-2.52%	1.36%	-3.35%	1.59%			-5.99%	1.36%
Ophir, CO2, 1 W	-1.60%	1.36%	-5.44%	5.30%	-1.30%	1.71%			-1.46%	5.12%	-0.44%	1.73%	-3.12%	1.59%				
Ophir, CO2, 5 W	-1.40%	1.10%	-5.10%	5.66%	-0.85%	1.50%			-1.51%	5.08%	-0.73%	1.54%	-3.63%	1.64%				
Molectron, Argon, 1 W	-1.64%	0.82%	-1.51%	1.17%	-1.63%	1.18%			-0.53%	4.08%	-1.64%	1.23%			-1.43%	1.55%		
Molectron, Nd:YAG, 1 W	-2.15%	1.05%			-0.91%	1.29%			-0.10%	4.12%	-2.35%	1.33%	-2.78%	1.28%	-2.09%	2.47%	-4.25%	1.35%
Molectron, Nd:YAG, 10 W	-1.50%	0.95%			-0.71%	1.38%			0.22%	4.16%	-2.02%	1.29%	-3.40%	1.52%			-4.80%	1.31%
Molectron, CO2, 1 W	-1.22%	1.33%	-5.18%	4.88%	-1.33%	1.68%			-1.54%	5.16%	0.01%	1.71%	-2.34%	1.55%				
Molectron, CO2, 5 W	-1.03%	1.10%	-4.84%	5.08%	-1.05%	1.49%			-1.98%	5.10%	-0.21%	1.53%	-2.65%	1.64%				

Bilateral DoE, $U_{i,m}$	DE		SE		US		FR		ZA		JP		GB		RO		AU	
ZA	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	DE	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$
Ophir, Argon, 1 W	-0.45%	4.03%	-0.47%	4.13%	-0.65%	4.11%	1.43%	4.10%			-0.62%	4.13%			0.04%	4.43%		
Ophir, Nd:YAG, 1 W	-2.05%	4.07%			-0.97%	4.16%	0.30%	4.16%			-2.41%	4.17%	-3.52%	4.15%	-2.37%	4.64%	-3.55%	4.17%
Ophir, Nd:YAG, 10 W	-1.91%	4.00%			-1.22%	4.12%	-0.01%	4.08%			-2.52%	4.10%	-3.35%	4.18%			-6.00%	4.09%
Ophir, CO2, 1 W	-0.14%	4.98%	-3.97%	7.14%	0.16%	5.09%	1.46%	5.12%			1.03%	5.09%	-1.66%	5.05%				
Ophir, CO2, 5 W	0.11%	5.01%	-3.58%	7.47%	0.67%	5.11%	1.51%	5.08%			0.78%	5.12%	-2.12%	5.15%				
Molectron, Argon, 1 W	-1.11%	4.02%	-0.98%	4.11%	-1.10%	4.11%	0.53%	4.08%			-1.10%	4.13%			-0.89%	4.23%		
Molectron, Nd:YAG, 1 W	-2.05%	4.06%			-0.81%	4.12%	0.10%	4.12%			-2.25%	4.14%	-2.68%	4.12%	-1.99%	4.63%	-4.15%	4.14%
Molectron, Nd:YAG, 10 W	-1.72%	4.10%			-0.93%	4.22%	-0.22%	4.16%			-2.24%	4.19%	-3.62%	4.26%			-5.02%	4.19%
Molectron, CO2, 1 W	0.33%	5.02%	-3.63%	6.87%	0.22%	5.13%	1.54%	5.16%			1.56%	5.13%	-0.80%	5.08%				
Molectron, CO2, 5 W	0.95%	5.03%	-2.86%	7.06%	0.93%	5.13%	1.98%	5.10%			1.77%	5.14%	-0.67%	5.18%				

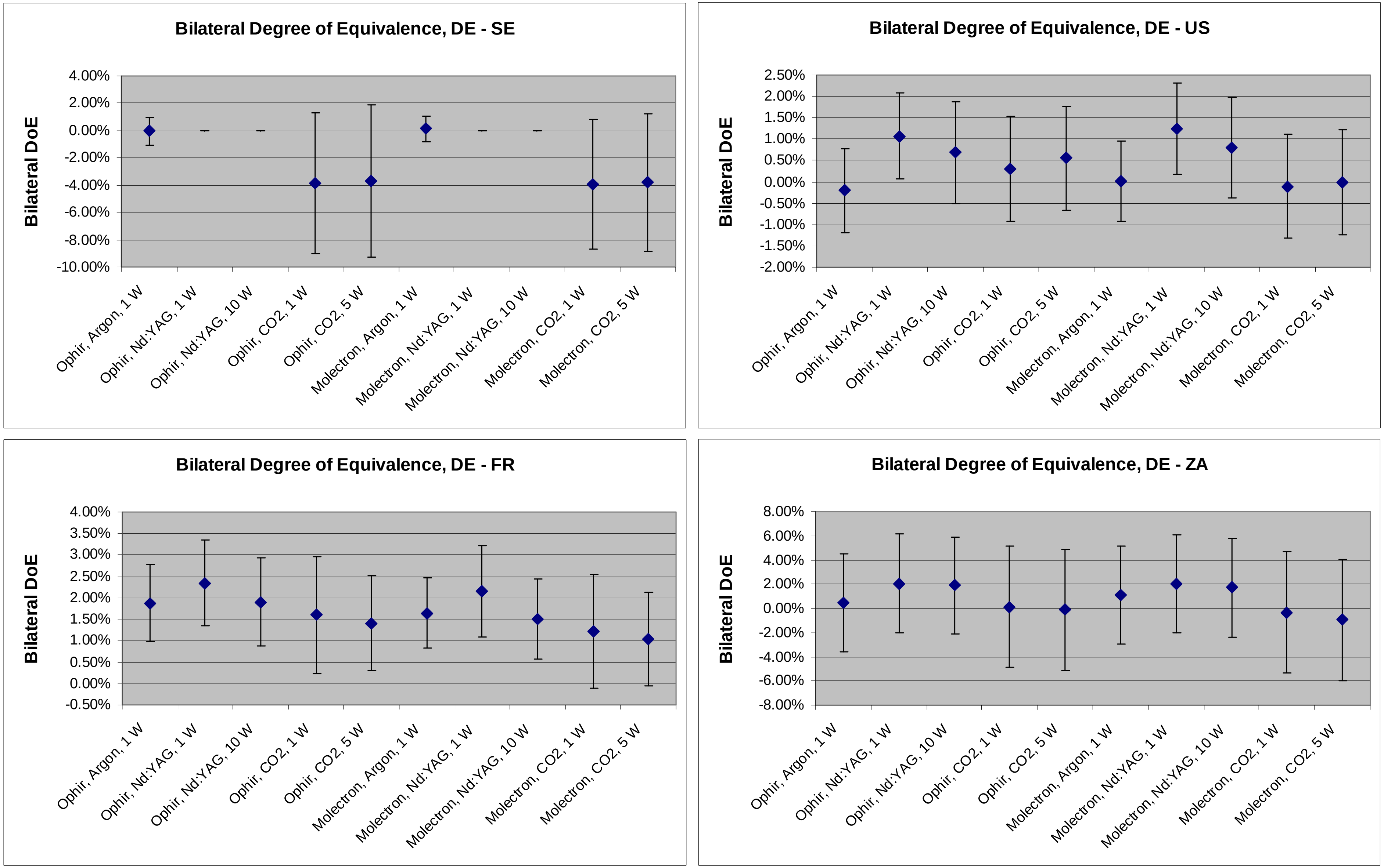
Bilateral DoE, $U_{i,m}$	DE		SE		US		FR		ZA		JP		GB		RO		AU	
JP	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	DE	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$
Ophir, Argon, 1 W	0.18%	1.05%	0.15%	1.38%	-0.02%	1.34%	2.05%	1.29%	0.62%	4.13%					0.66%	2.13%		
Ophir, Nd:YAG, 1 W	0.36%	1.05%			1.44%	1.35%	2.71%	1.35%	2.41%	4.17%			-1.11%	1.34%	0.04%	2.47%	-1.14%	1.39%
Ophir, Nd:YAG, 10 W	0.62%	1.08%			1.30%	1.49%	2.52%	1.36%	2.52%	4.10%			-0.83%	1.62%			-3.47%	1.40%
Ophir, CO2, 1 W	-1.16%	1.26%	-5.00%	5.28%	-0.87%	1.63%	0.44%	1.73%	-1.03%	5.09%			-2.69%	1.50%				
Ophir, CO2, 5 W	-0.67%	1.27%	-4.37%	5.69%	-0.11%	1.63%	0.73%	1.54%	-0.78%	5.12%			-2.90%	1.75%				
Molectron, Argon, 1 W	-0.01%	1.02%	0.13%	1.31%	0.01%	1.32%	1.64%	1.23%	1.10%	4.13%					0.21%	1.66%		
Molectron, Nd:YAG, 1 W	0.20%	1.12%			1.44%	1.34%	2.35%	1.33%	2.25%	4.14%			-0.43%	1.33%	0.26%	2.50%	-1.90%	1.40%
Molectron, Nd:YAG, 10 W	0.52%	1.08%			1.31%	1.47%	2.02%	1.29%	2.24%	4.19%			-1.38%	1.60%			-2.78%	1.41%
Molectron, CO2, 1 W	-1.23%	1.25%	-5.19%	4.86%	-1.34%	1.62%	-0.01%	1.71%	-1.56%	5.13%			-2.36%	1.48%				
Molectron, CO2, 5 W	-0.82%	1.27%	-4.63%	5.12%	-0.84%	1.63%	0.21%	1.53%	-1.77%	5.14%			-2.44%	1.76%				

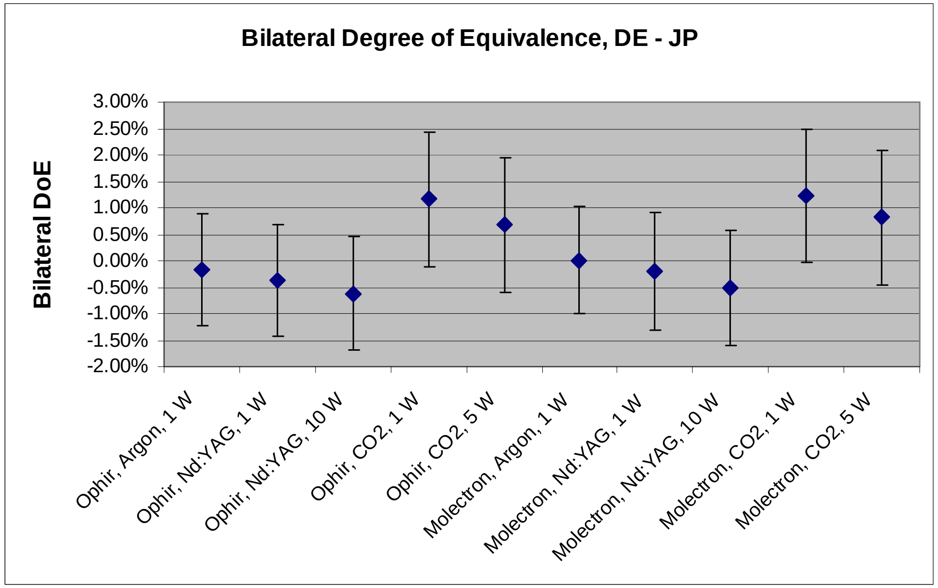
Bilateral DoE, $U_{i,m}$	**DE**		**SE**		**US**		**FR**		**ZA**		**JP**		**GB**		**RO**		**AU**	
GB	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	**DE**	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$
Ophir, Argon, 1 W																		
Ophir, Nd:YAG, 1 W	1.47%	0.99%			2.55%	1.30%	3.81%	1.30%	3.52%	4.15%	1.11%	1.34%			1.15%	2.44%	-0.03%	1.34%
Ophir, Nd:YAG, 10 W	1.45%	1.35%			2.13%	1.70%	3.35%	1.59%	3.35%	4.18%	0.83%	1.62%					-2.64%	1.62%
Ophir, CO2, 1 W	1.52%	1.05%	-2.31%	5.23%	1.82%	1.47%	3.12%	1.59%	1.66%	5.05%	2.69%	1.50%						
Ophir, CO2, 5 W	2.23%	1.38%	-1.47%	5.72%	2.78%	1.71%	3.63%	1.64%	2.12%	5.15%	2.90%	1.75%						
Molectron, Argon, 1 W																		
Molectron, Nd:YAG, 1 W	0.63%	1.06%			1.87%	1.29%	2.78%	1.28%	2.68%	4.12%	0.43%	1.33%			0.69%	2.47%	-1.47%	1.35%
Molectron, Nd:YAG, 10 W	1.90%	1.34%			2.69%	1.68%	3.40%	1.52%	3.62%	4.26%	1.38%	1.60%					-1.41%	1.62%
Molectron, CO2, 1 W	1.13%	1.02%	-2.83%	4.80%	1.02%	1.45%	2.34%	1.55%	0.80%	5.08%	2.36%	1.48%						
Molectron, CO2, 5 W	1.62%	1.40%	-2.19%	5.15%	1.60%	1.73%	2.65%	1.64%	0.67%	5.18%	2.44%	1.76%						

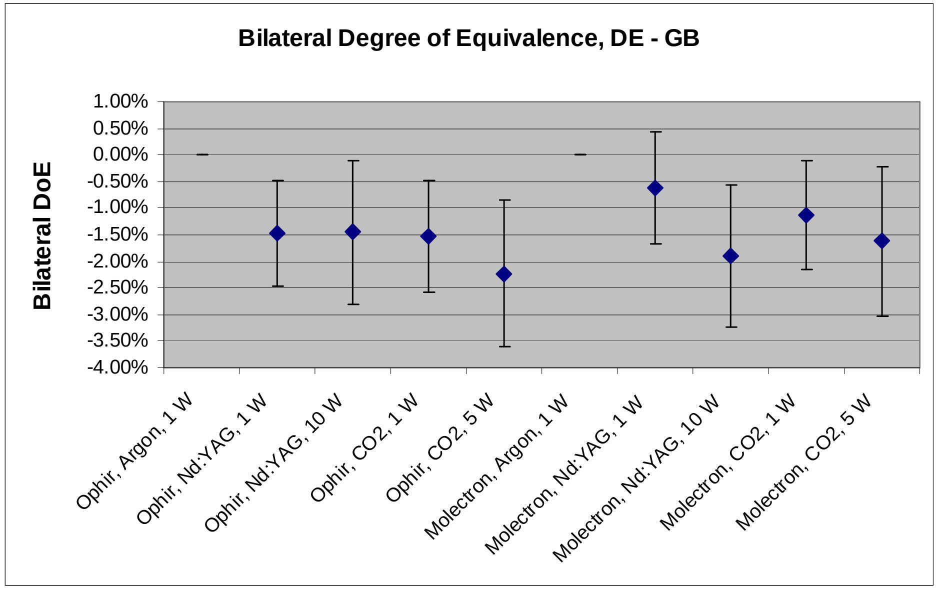
Bilateral DoE, $U_{i,m}$	**DE**		**SE**		**US**		**FR**		**ZA**		**JP**		**GB**		**RO**		**AU**	
RO	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	**DE**	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$
Ophir, Argon, 1 W	-0.48%	1.92%	-0.51%	2.11%	-0.68%	2.09%	1.39%	2.06%	-0.04%	4.43%	-0.66%	2.13%						
Ophir, Nd:YAG, 1 W	0.33%	2.30%			1.40%	2.45%	2.67%	2.45%	2.37%	4.64%	-0.04%	2.47%	-1.15%	2.44%			-1.18%	2.47%
Ophir, Nd:YAG, 10 W																		
Ophir, CO2, 1 W																		
Ophir, CO2, 5 W																		
Molectron, Argon, 1 W	-0.22%	1.38%	-0.09%	1.61%	-0.20%	1.62%	1.43%	1.55%	0.89%	4.23%	-0.21%	1.66%						
Molectron, Nd:YAG, 1 W	-0.07%	2.36%			1.18%	2.47%	2.09%	2.47%	1.99%	4.63%	-0.26%	2.50%	-0.69%	2.47%			-2.17%	2.50%
Molectron, Nd:YAG, 10 W																		
Molectron, CO2, 1 W																		
Molectron, CO2, 5 W																		

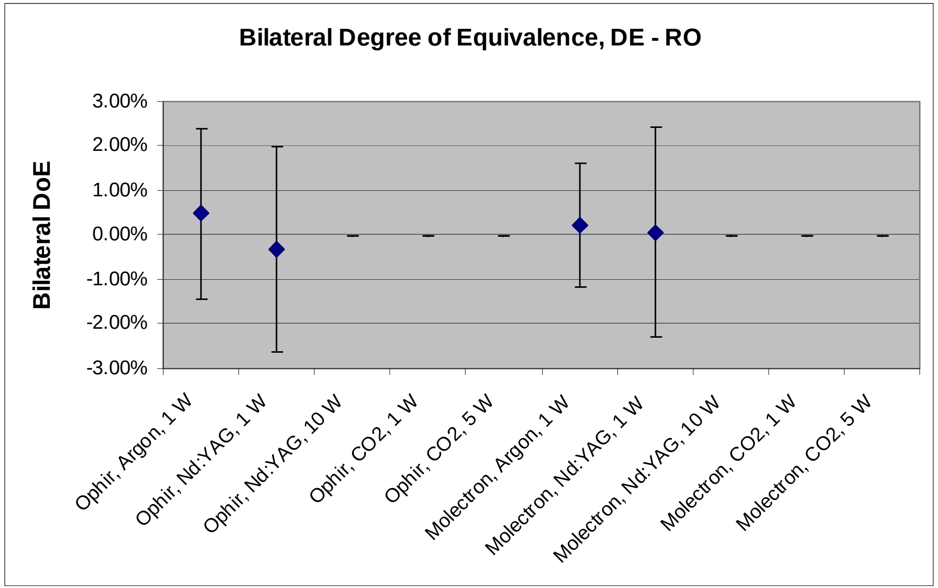
Bilateral DoE, $U_{i,m}$	**DE**		**SE**		**US**		**FR**		**ZA**		**JP**		**GB**		**RO**		**AU**	
AU	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	**DE**	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$	$D_{i,m}$	$U_{i,m}$
Ophir, Argon, 1 W																		
Ophir, Nd:YAG, 1 W	1.50%	1.06%			2.58%	1.35%	3.85%	1.35%	3.55%	4.17%	1.14%	1.39%	0.03%	1.34%	1.18%	2.47%		
Ophir, Nd:YAG, 10 W	4.09%	1.07%			4.78%	1.48%	5.99%	1.36%	6.00%	4.09%	3.47%	1.40%	2.64%	1.62%				
Ophir, CO2, 1 W																		
Ophir, CO2, 5 W																		
Molectron, Argon, 1 W																		
Molectron, Nd:YAG, 1 W	2.10%	1.13%			3.34%	1.36%	4.25%	1.35%	4.15%	4.14%	1.90%	1.40%	1.47%	1.35%	2.17%	2.50%		
Molectron, Nd:YAG, 10 W	3.30%	1.10%			4.10%	1.49%	4.80%	1.31%	5.02%	4.19%	2.78%	1.41%	1.41%	1.62%				
Molectron, CO2, 1 W																		
Molectron, CO2, 5 W																		

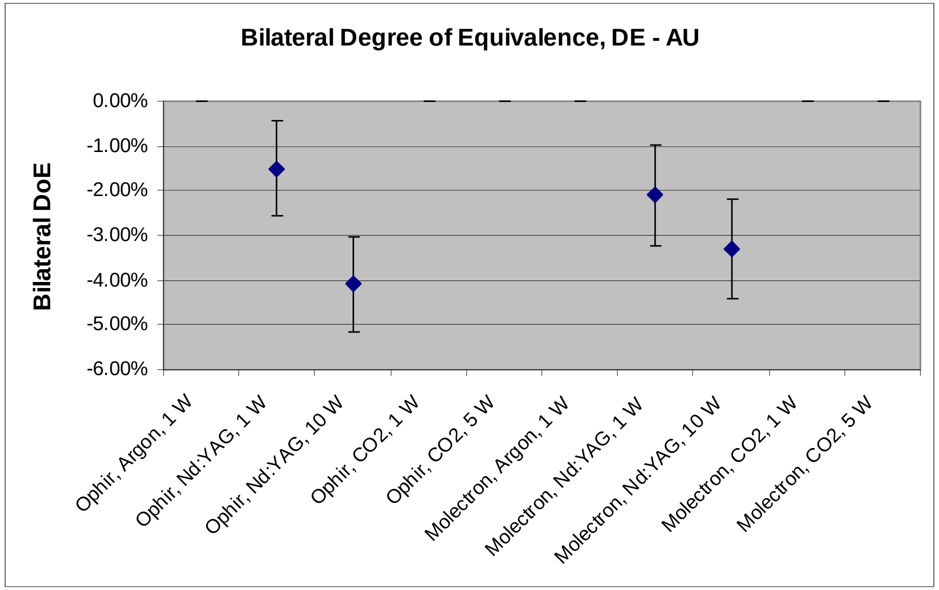
Figure 12: Bilateral Degrees of Equivalence between all participants

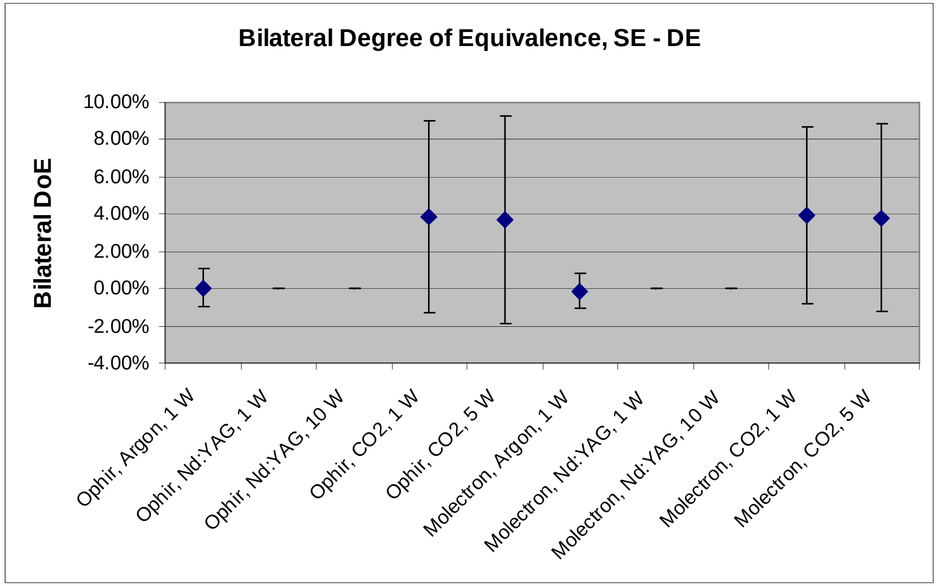



Bilateral Degree of Equivalence, DE - JP
Bilateral DoE
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
-0.50%
-1.00%
-1.50%
-2.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, DE - GB
Bilateral DoE
1.00%
0.50%
0.00%
-0.50%
-1.00%
-1.50%
-2.00%
-2.50%
-3.00%
-3.50%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, DE - RO
Bilateral DoE
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
-3.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, DE - AU
Bilateral DoE
0.00%
-1.00%
-2.00%
-3.00%
-4.00%
-5.00%
-6.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, SE - DE
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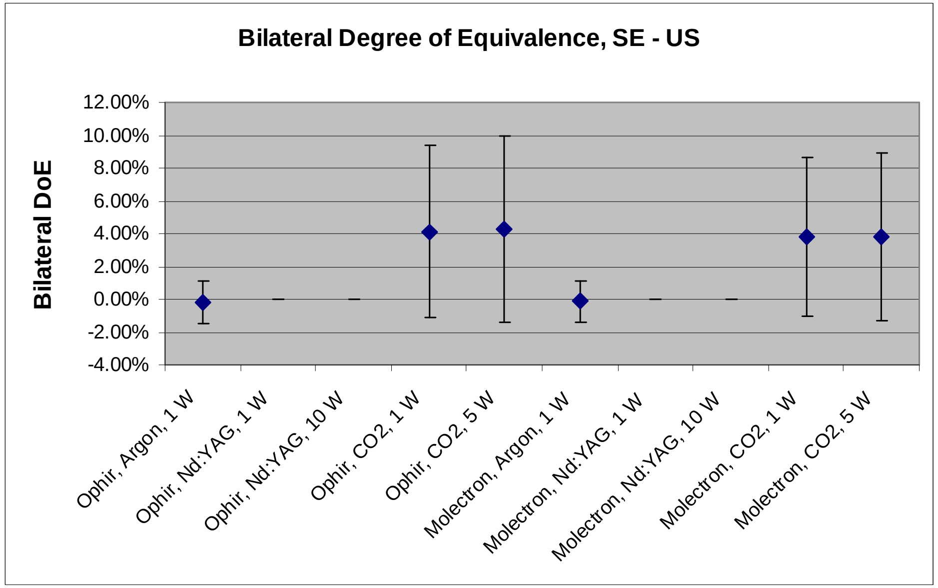
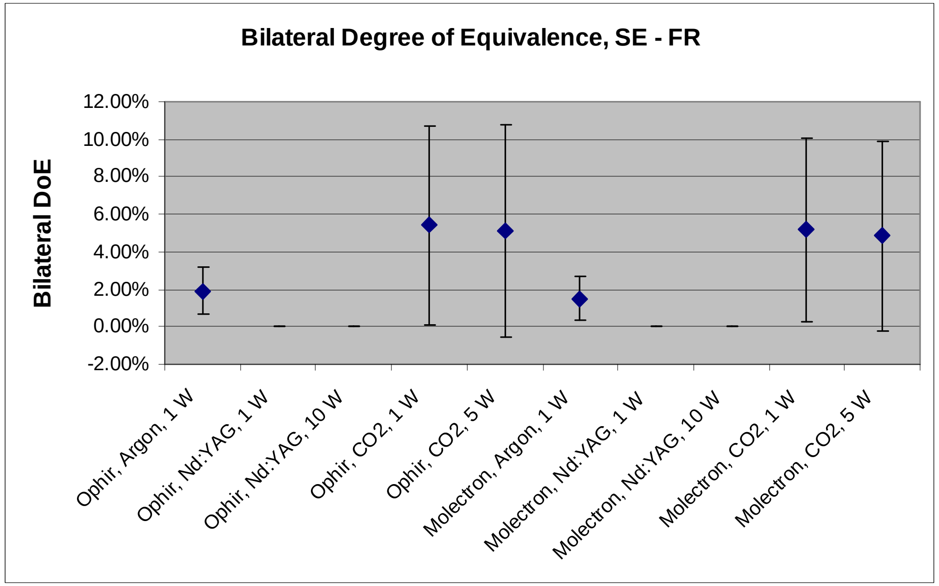
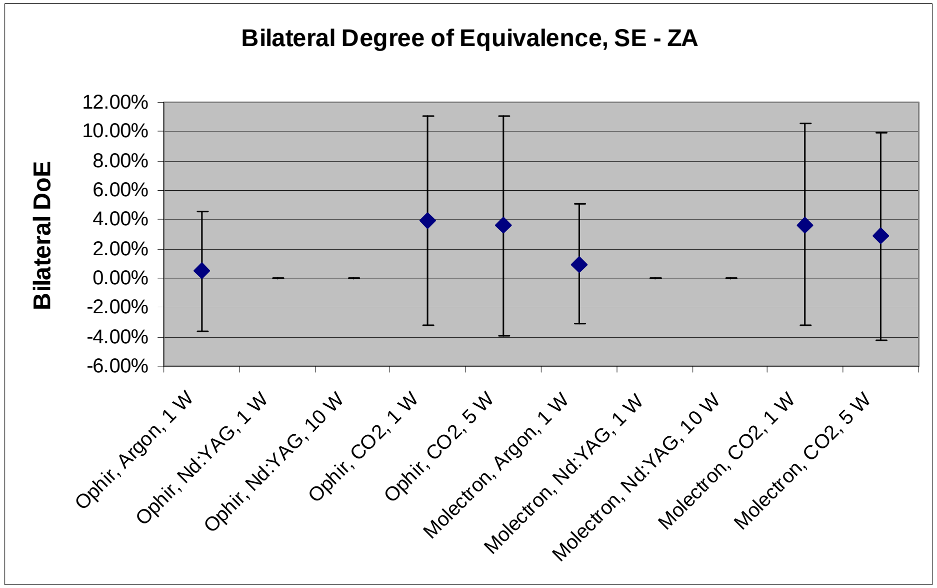
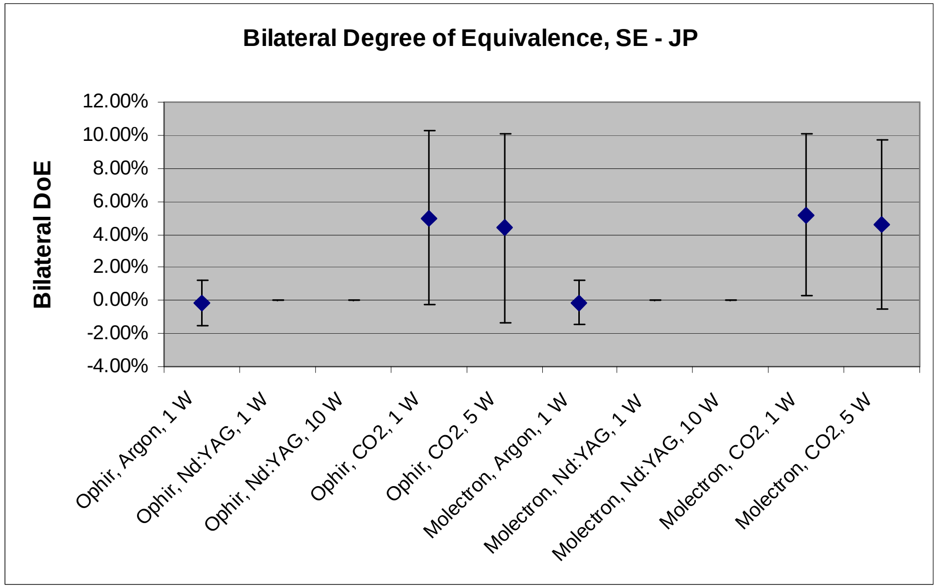
8.00%
6.00%
4.00%
2.00%
0.00%
-2.00%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, SE - US
Bilateral DoE
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%
-2.00%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, SE - FR
Bilateral DoE
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%
-2.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, SE - ZA
Bilateral DoE
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%
-2.00%
-4.00%
-6.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, SE - JP
Bilateral DoE
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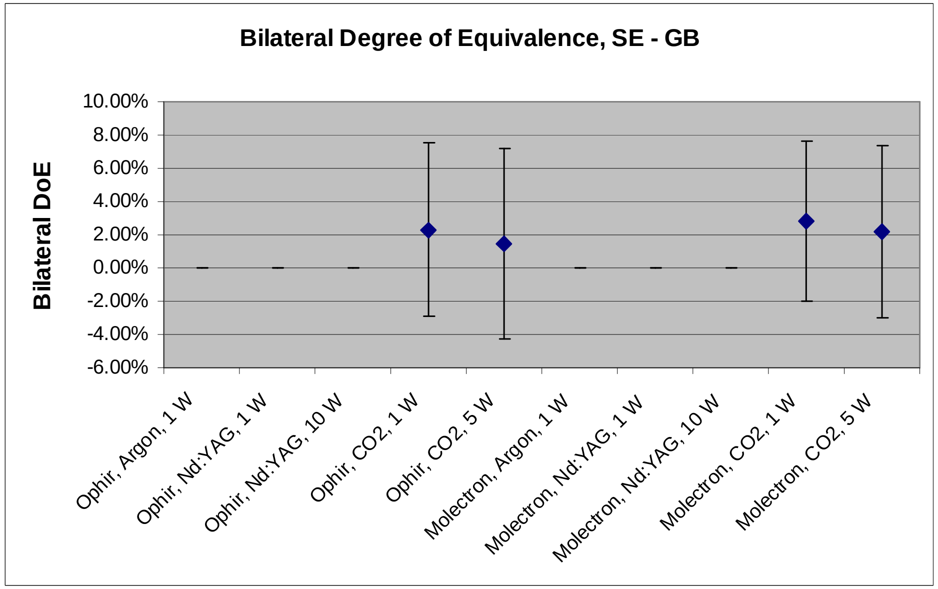
8.00%
6.00%
4.00%
2.00%
0.00%
-2.00%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W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Bilateral DoE
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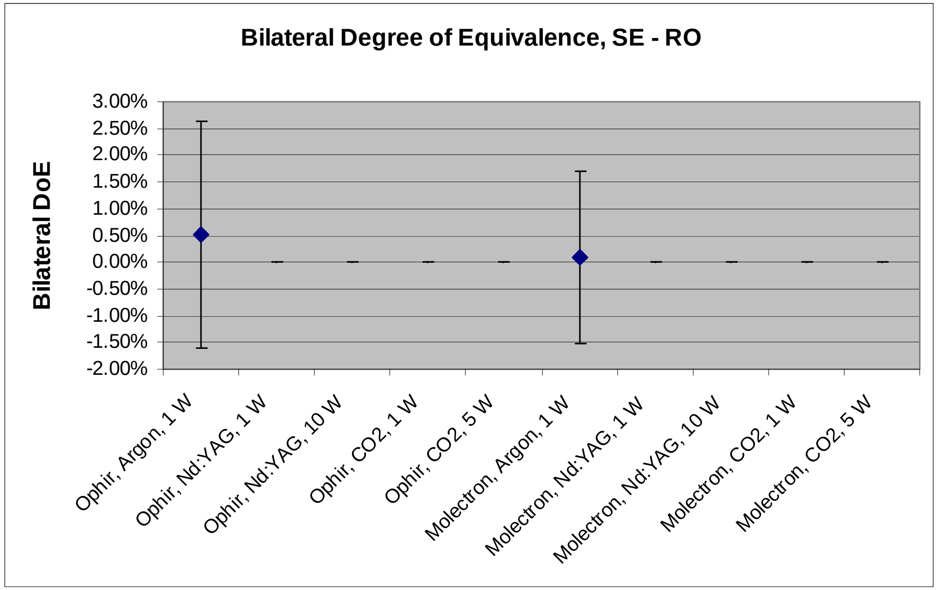
4.00%
2.00%
0.00%
-2.00%
-4.00%
-6.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, SE - RO
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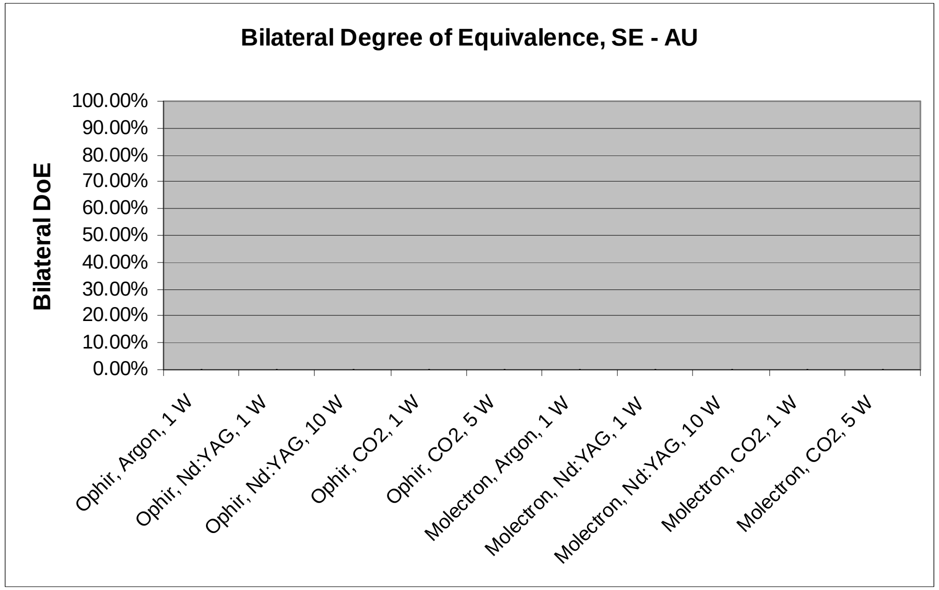
2.00%
1.50%
1.00%
0.50%
0.00%
-0.50%
-1.00%
-1.50%
-2.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W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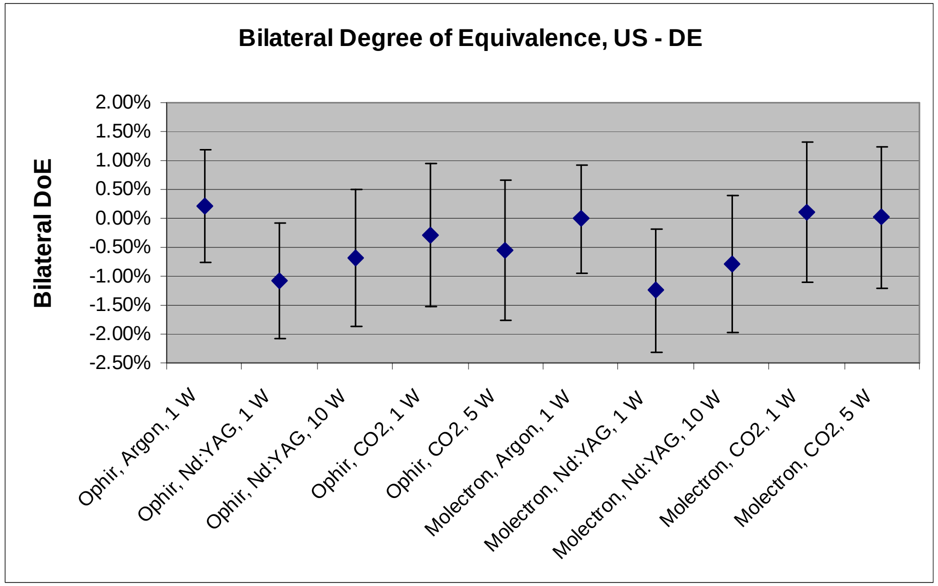
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, US - DE
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-1.00%
-1.50%
-2.00%
-2.50%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
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Molectron, Nd:YAG, 10 W
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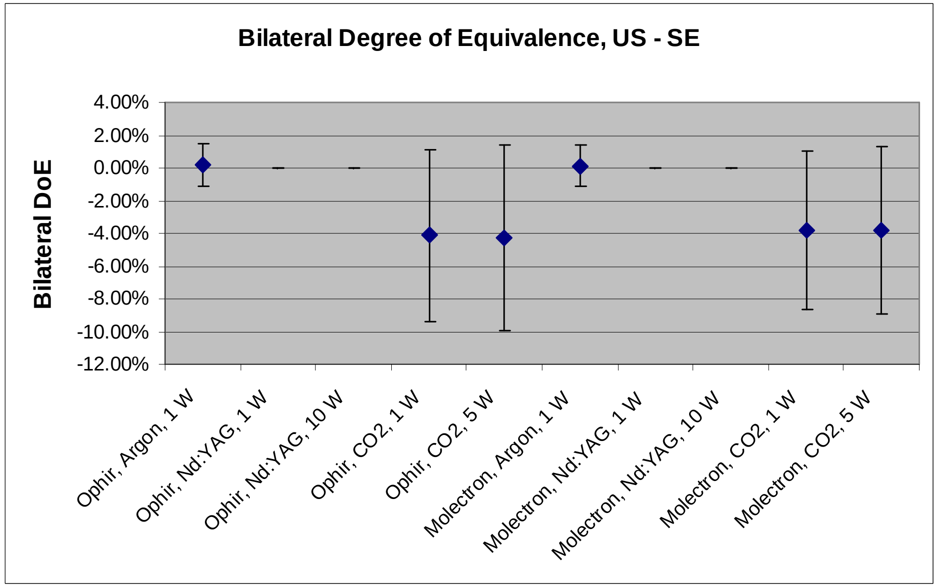
Molectron, CO2, 5 W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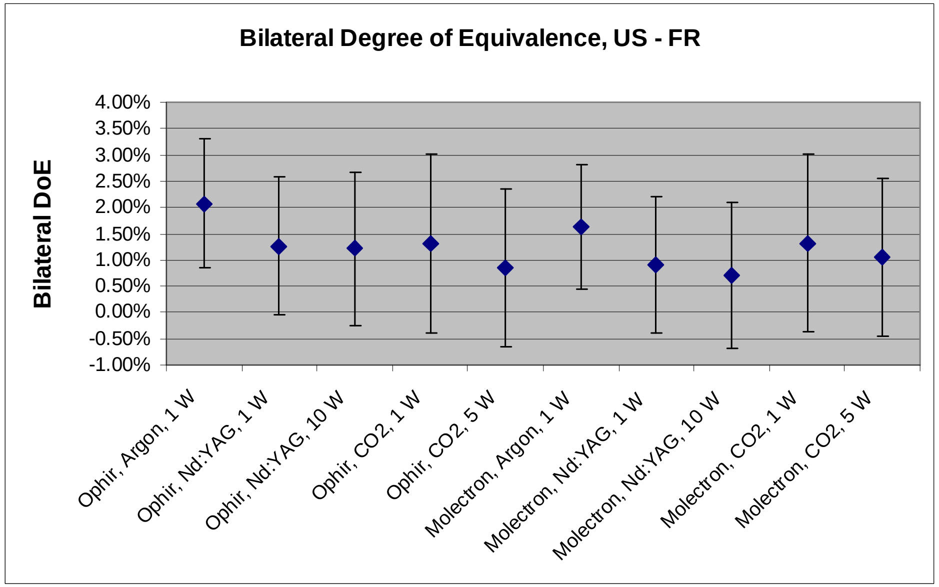
-12.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, US - FR
Bilateral DoE
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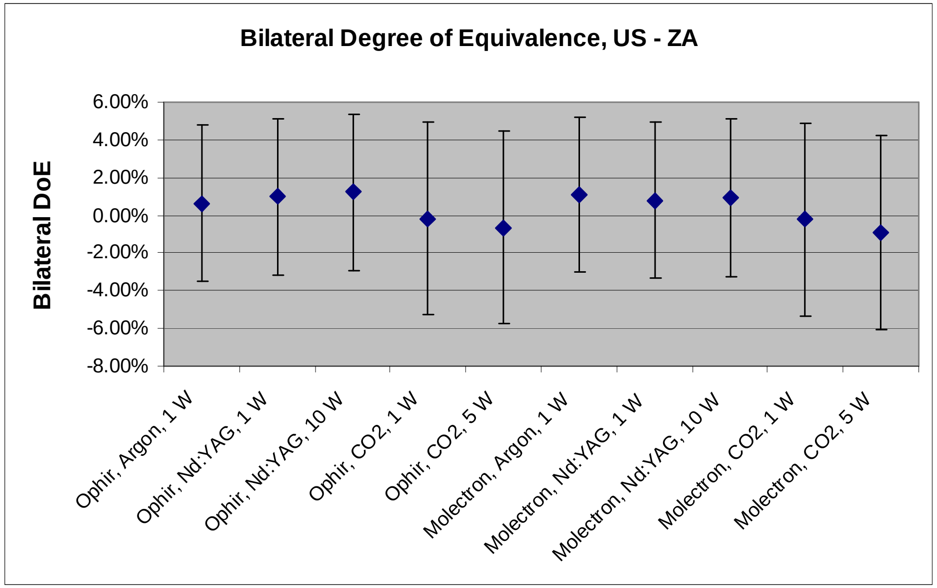
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
-0.50%
-1.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, US - ZA
Bilateral DoE
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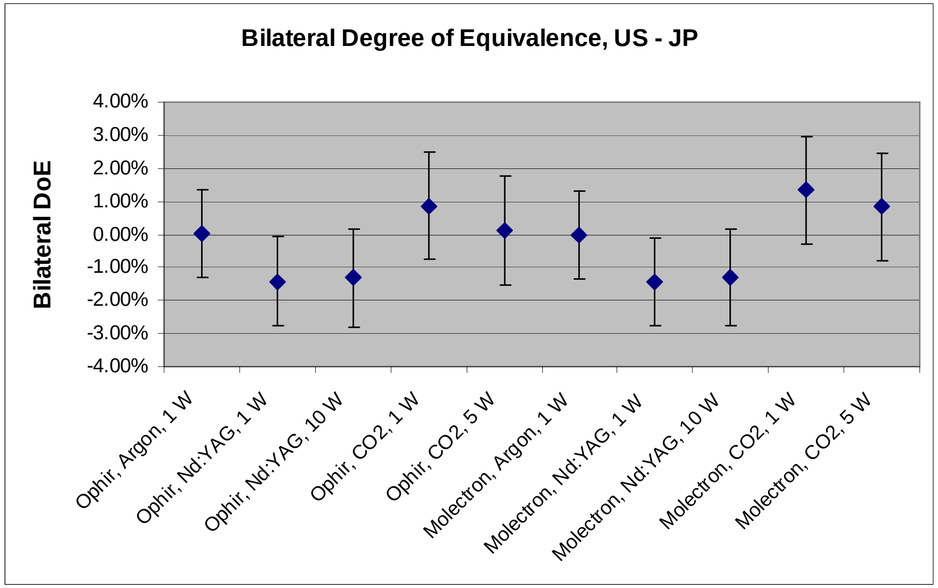
-6.00%
-8.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, US - JP
Bilateral DoE
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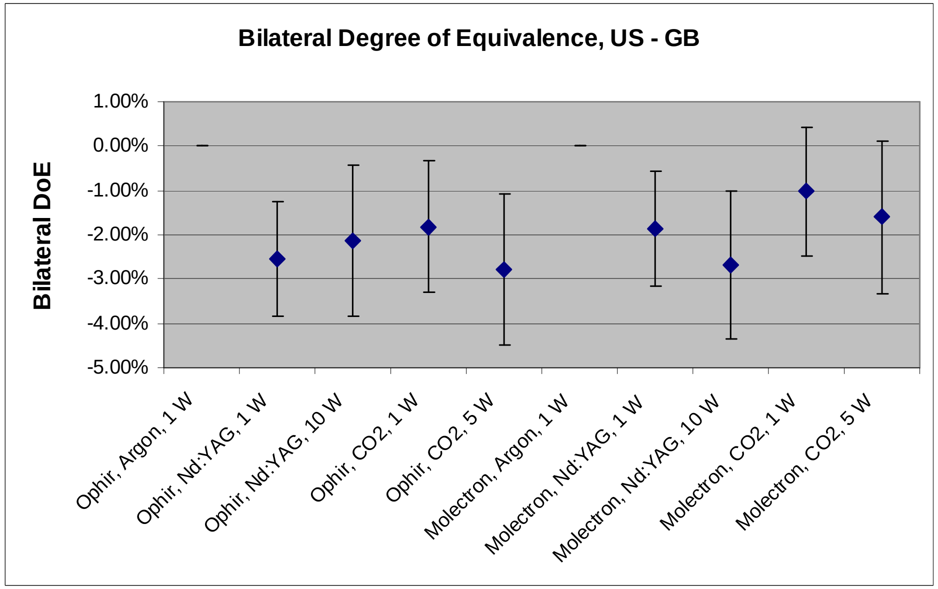
-3.00%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, US - GB
Bilateral DoE
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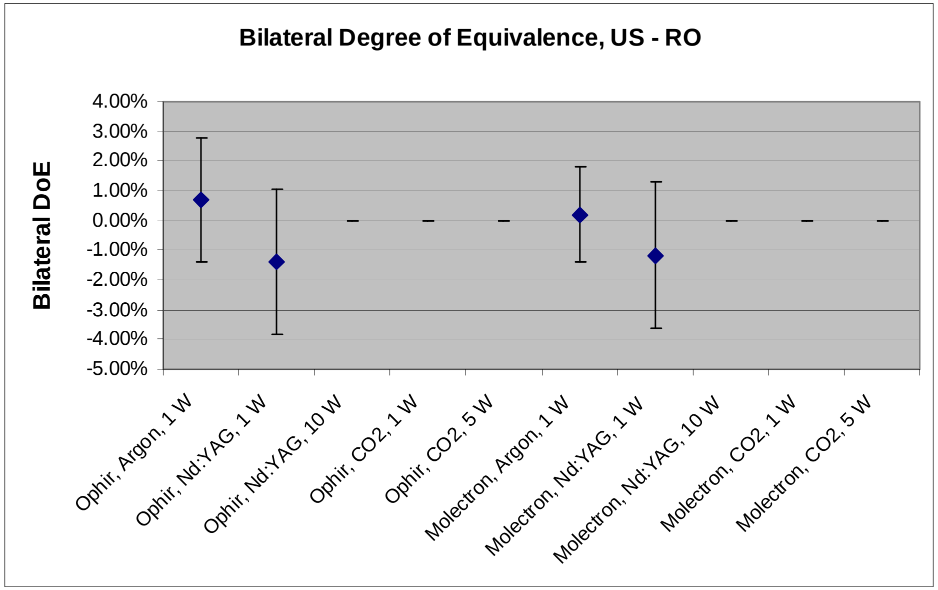
-2.00%
-3.00%
-4.00%
-5.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, US - RO
Bilateral DoE
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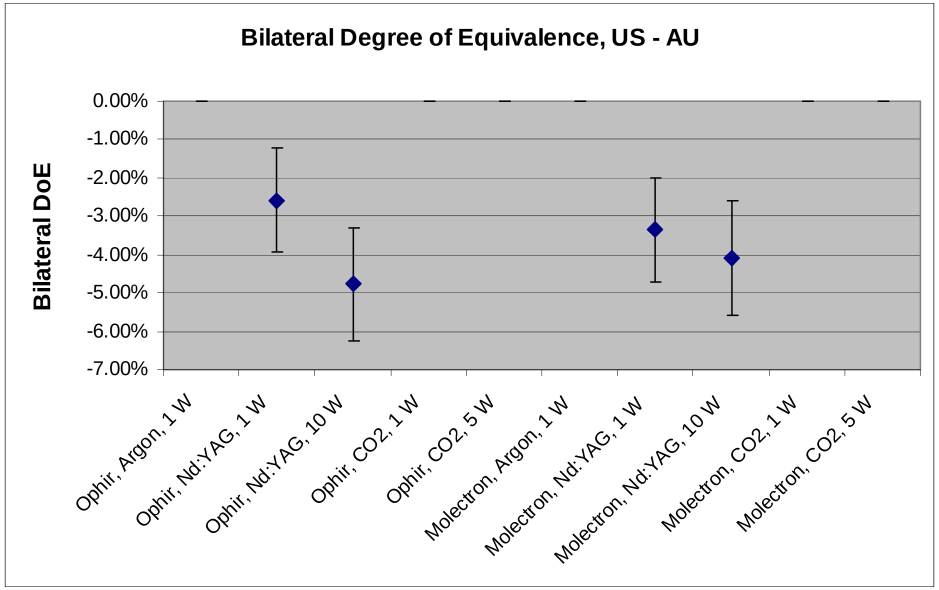
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
-3.00%
-4.00%
-5.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, US - AU
Bilateral DoE
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-1.00%
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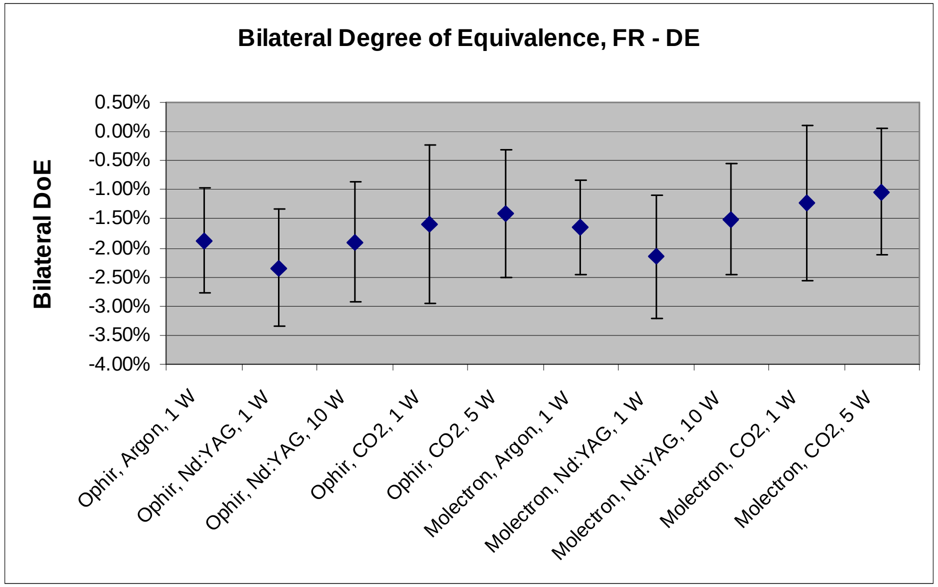
-3.00%
-4.00%
-5.00%
-6.00%
-7.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, FR - DE
Bilateral DoE
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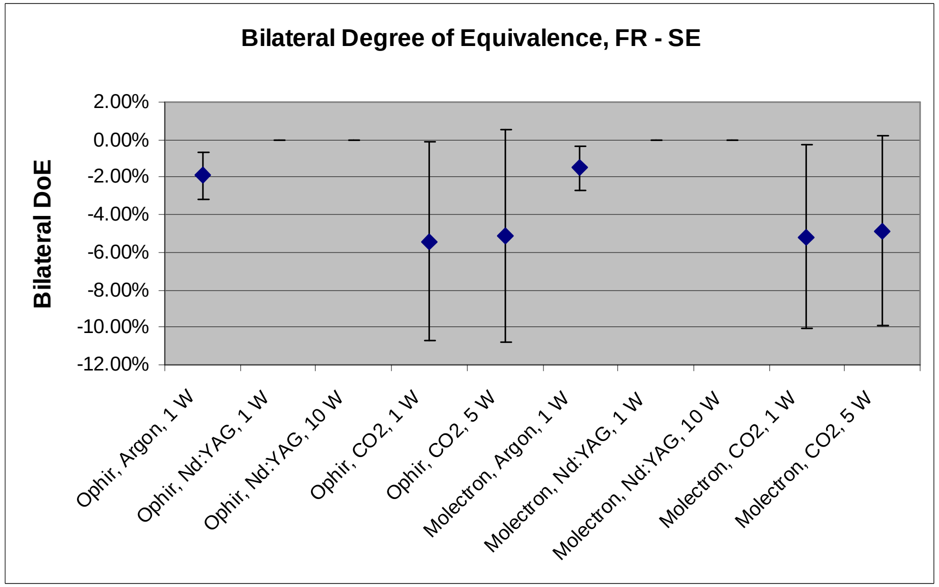
-0.50%
-1.00%
-1.50%
-2.00%
-2.50%
-3.00%
-3.50%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, FR - SE
Bilateral DoE
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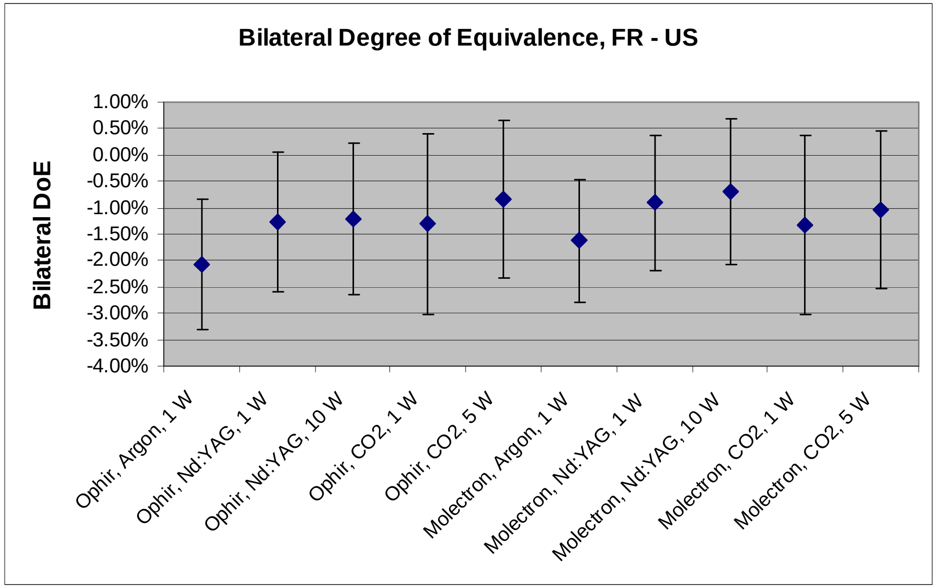
0.00%
-2.00%
-4.00%
-6.00%
-8.00%
-10.00%
-12.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W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Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
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Molectron, CO2, 1 W
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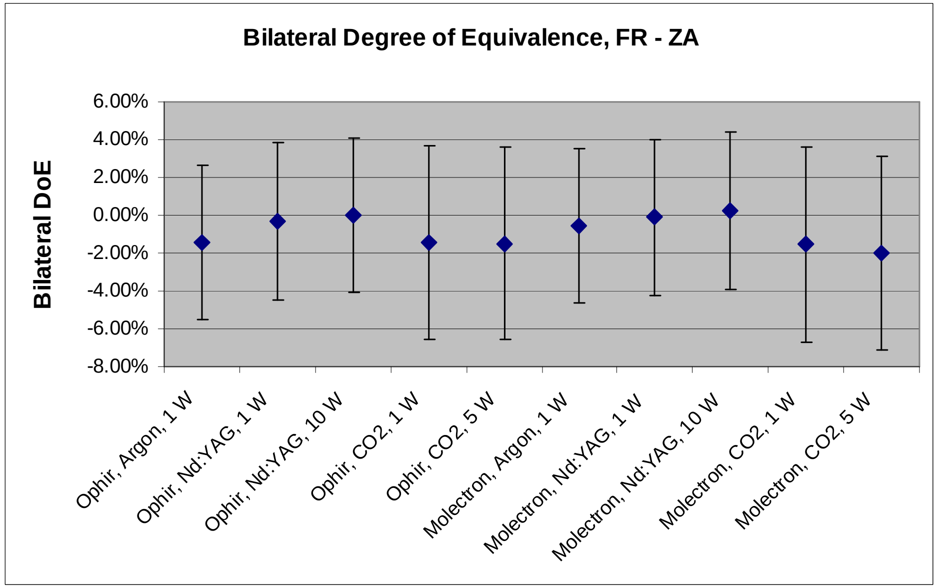
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Ophir, CO2, 1 W
Ophir, CO2, 5 W
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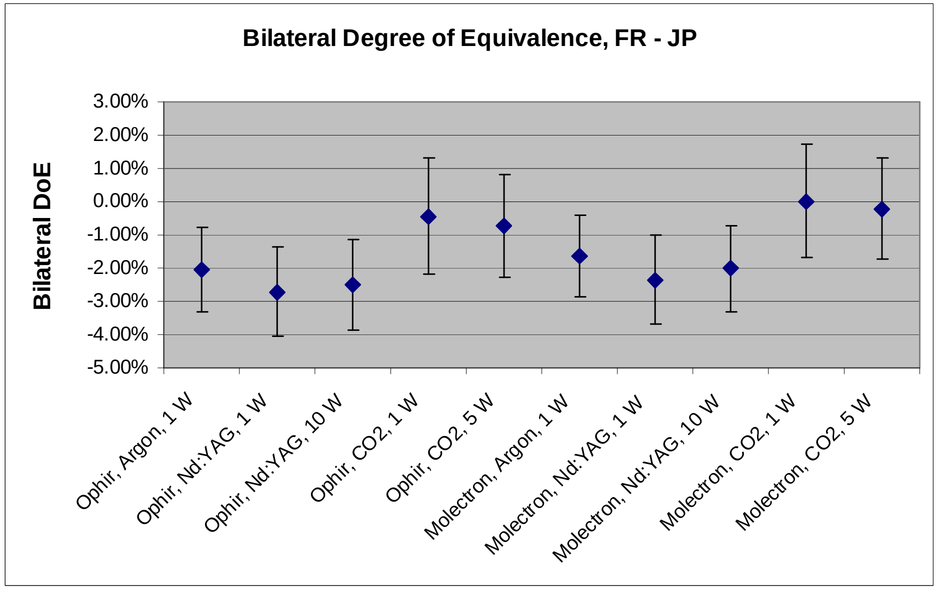
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Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
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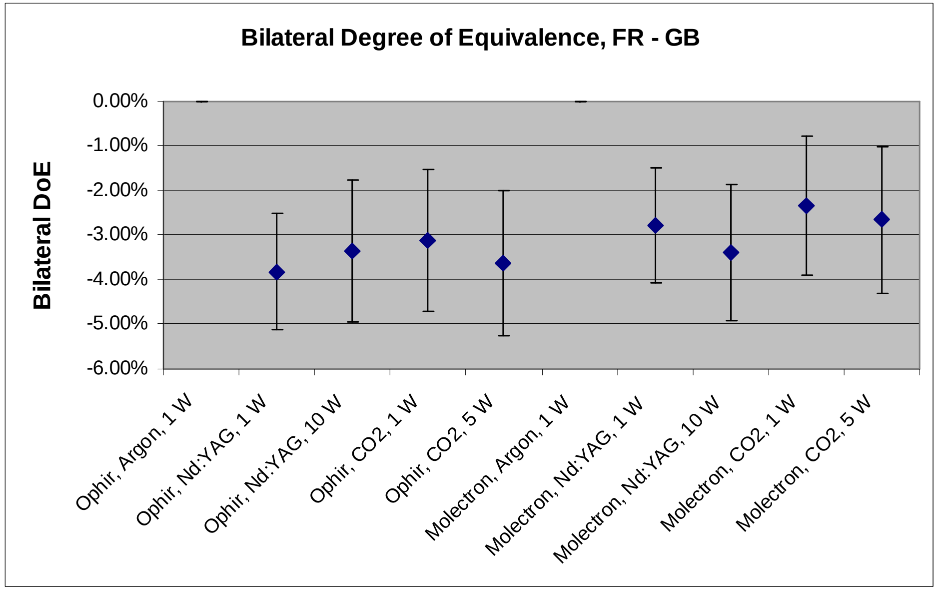
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Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
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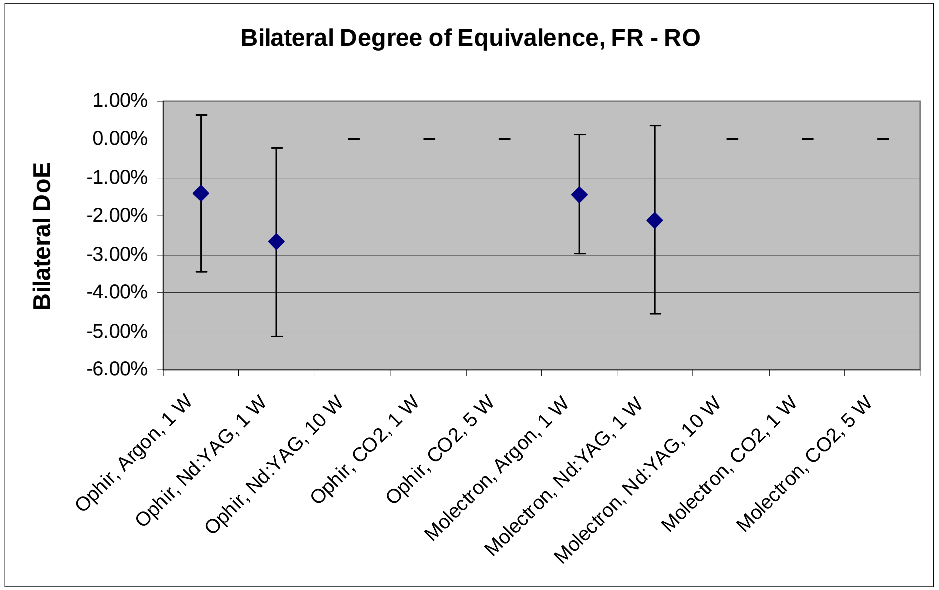
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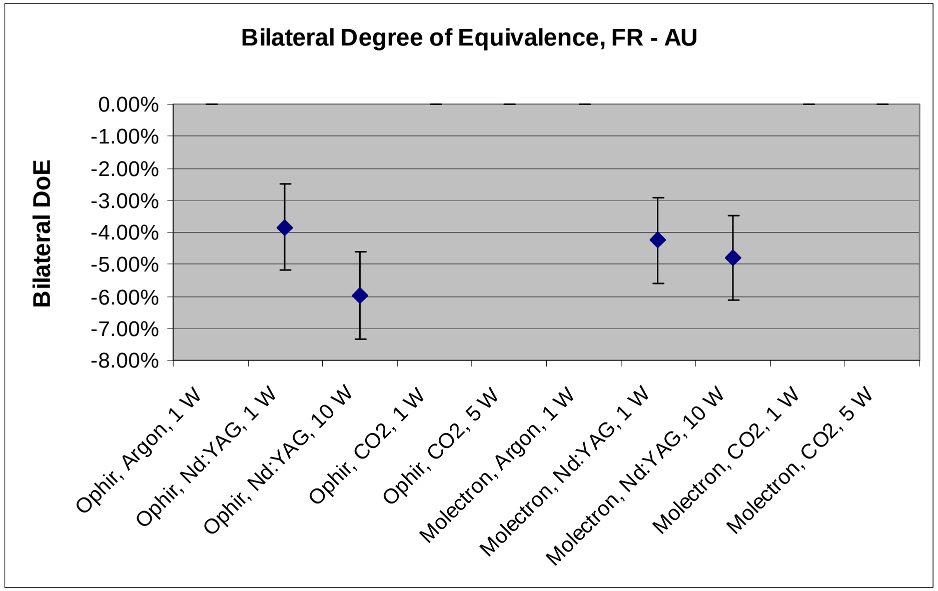
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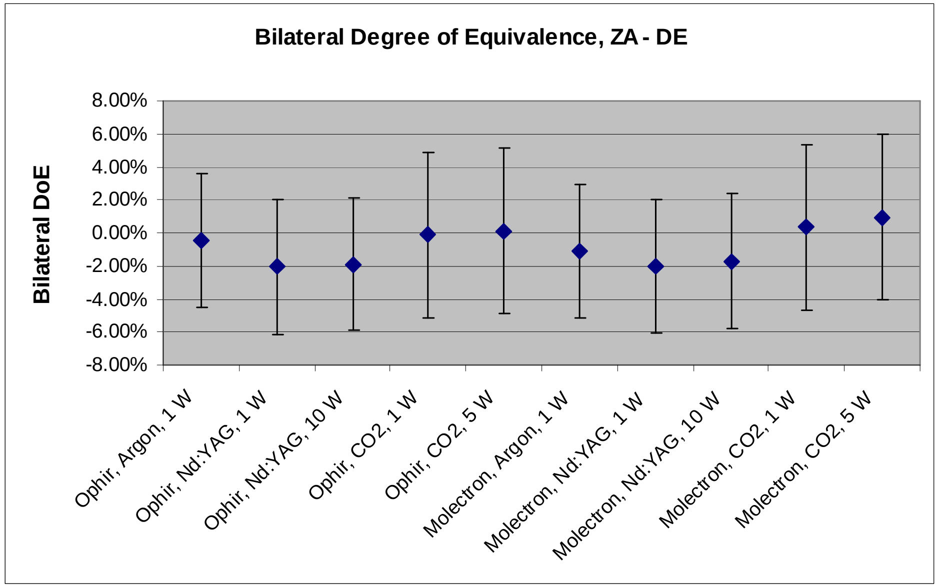
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Ophir, CO2, 5 W
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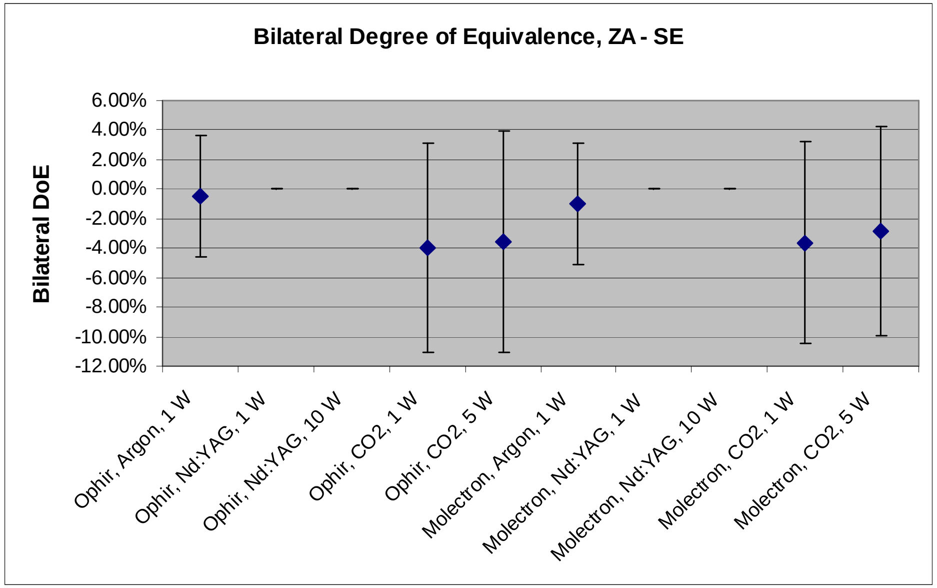
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Ophir, CO2, 5 W
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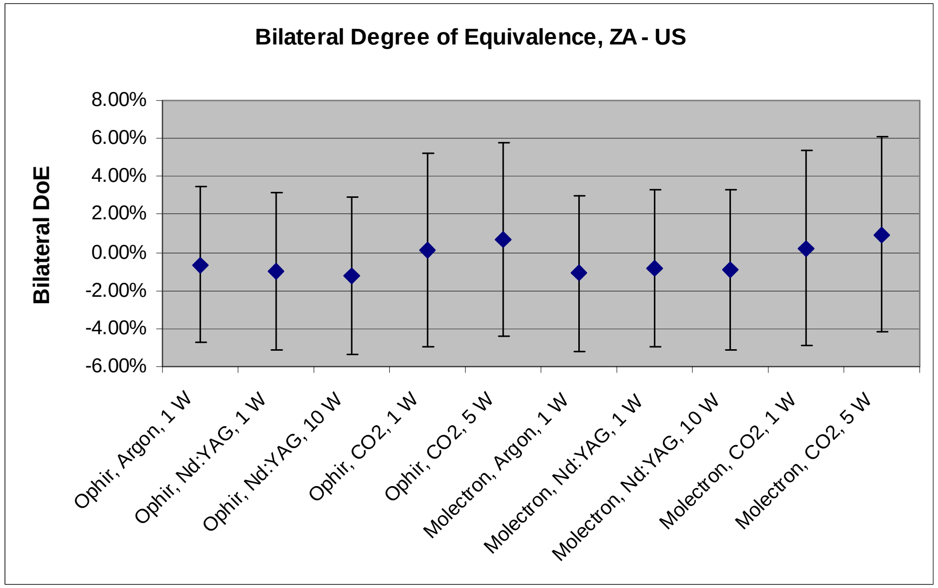
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Ophir, Nd:YAG, 10 W
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Ophir, CO2, 5 W
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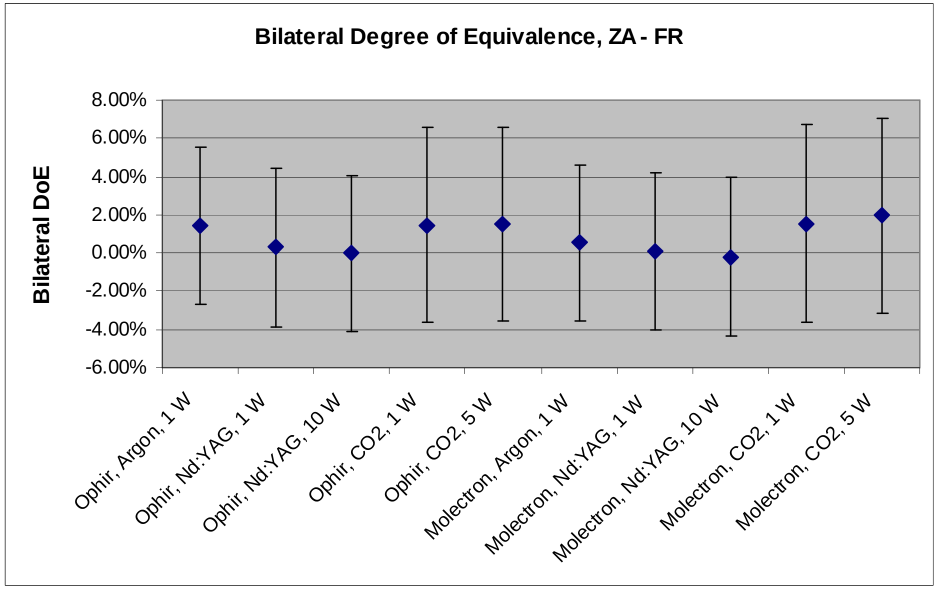
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Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
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Molectron, CO2, 1 W
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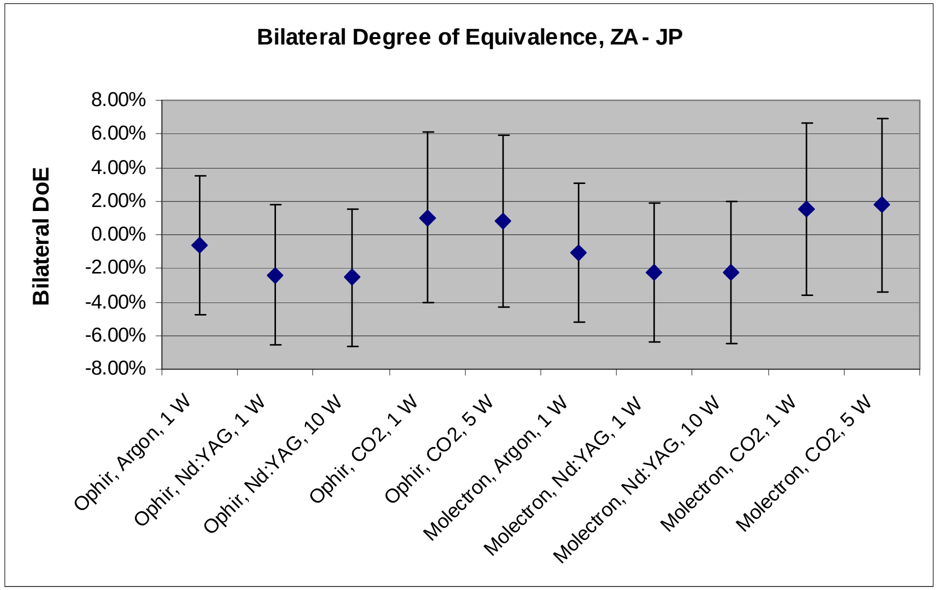
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Ophir, CO2, 1 W
Ophir, CO2, 5 W
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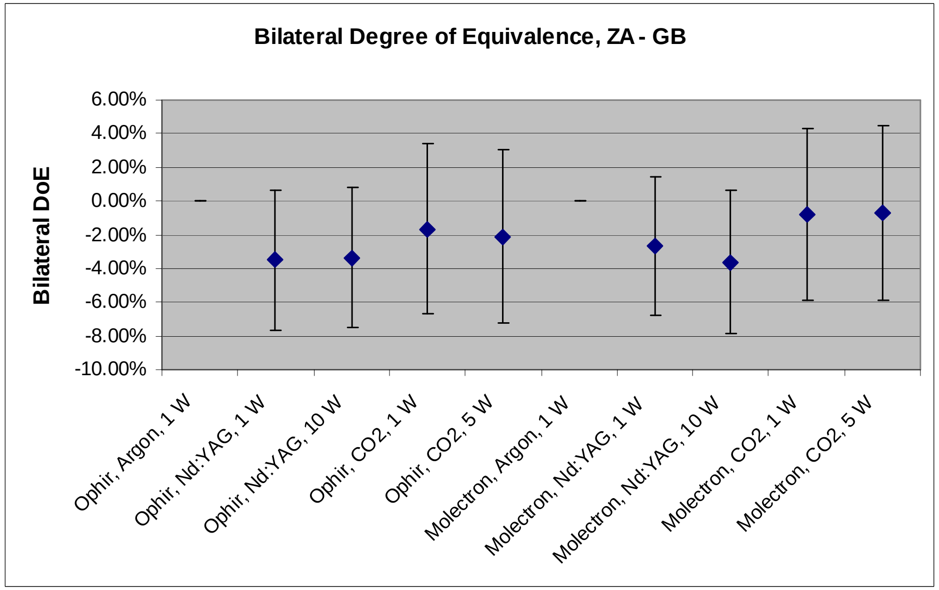
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Ophir, CO2, 1 W
Ophir, CO2, 5 W
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Molectron, Nd:YAG, 10 W
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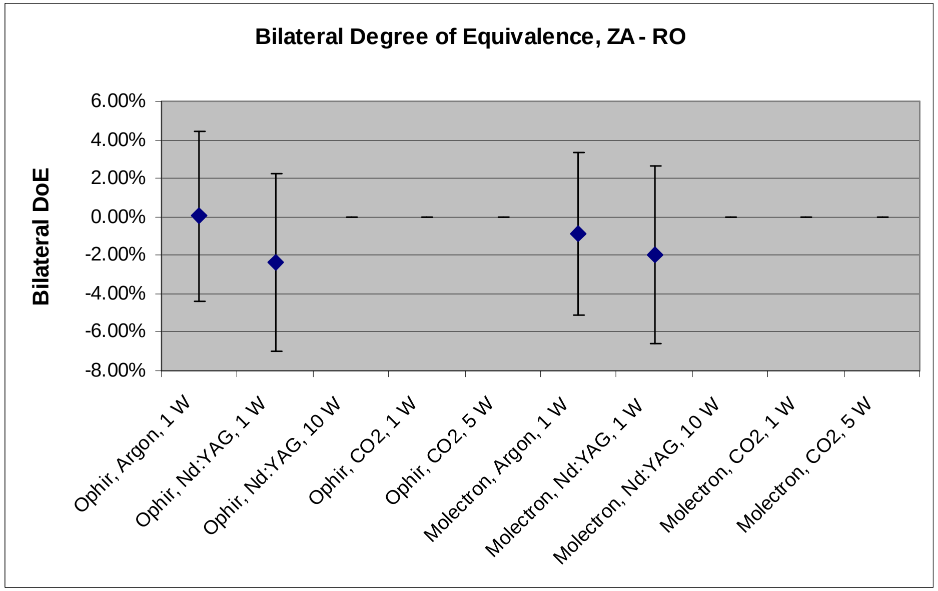
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Ophir, CO2, 5 W
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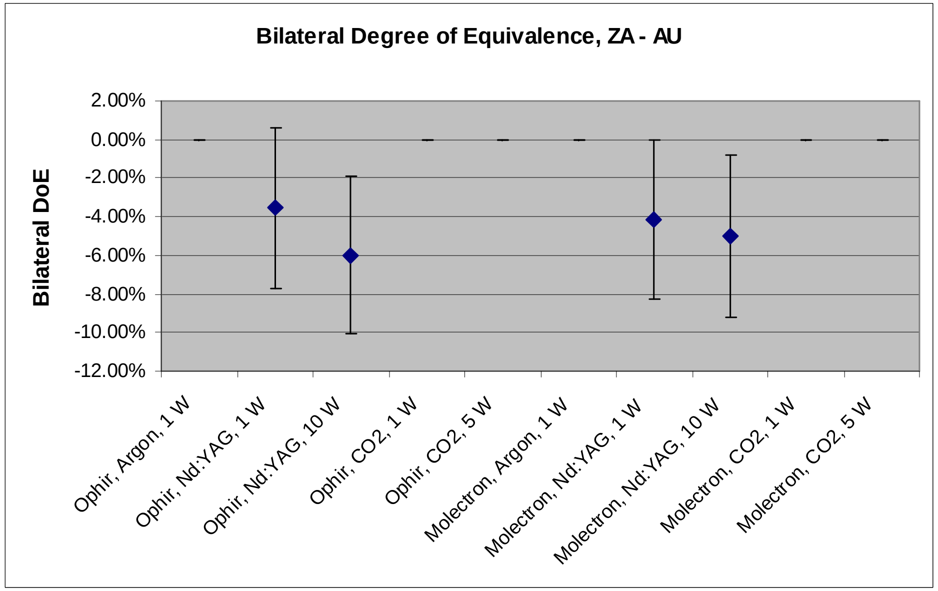
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Ophir, CO2, 5 W
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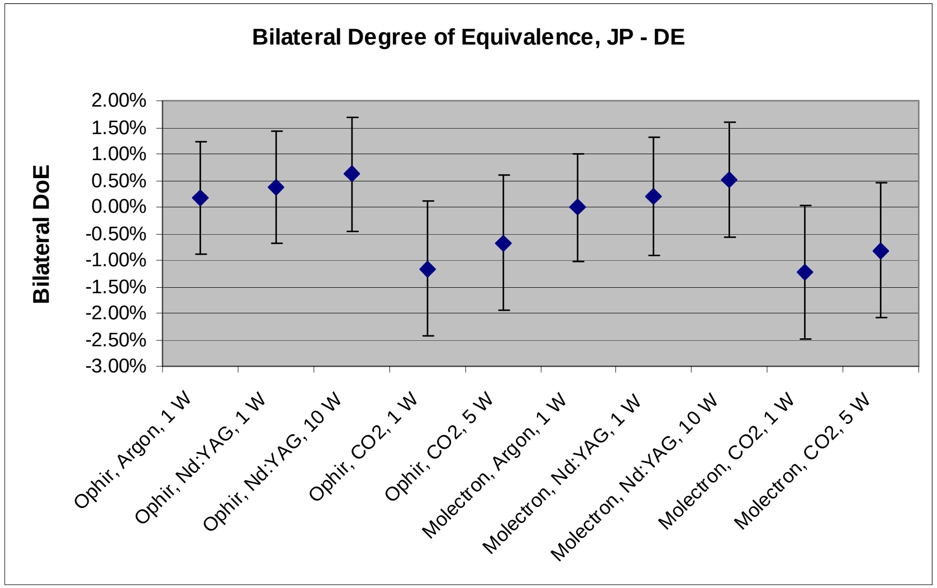
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Ophir, CO2, 1 W
Ophir, CO2, 5 W
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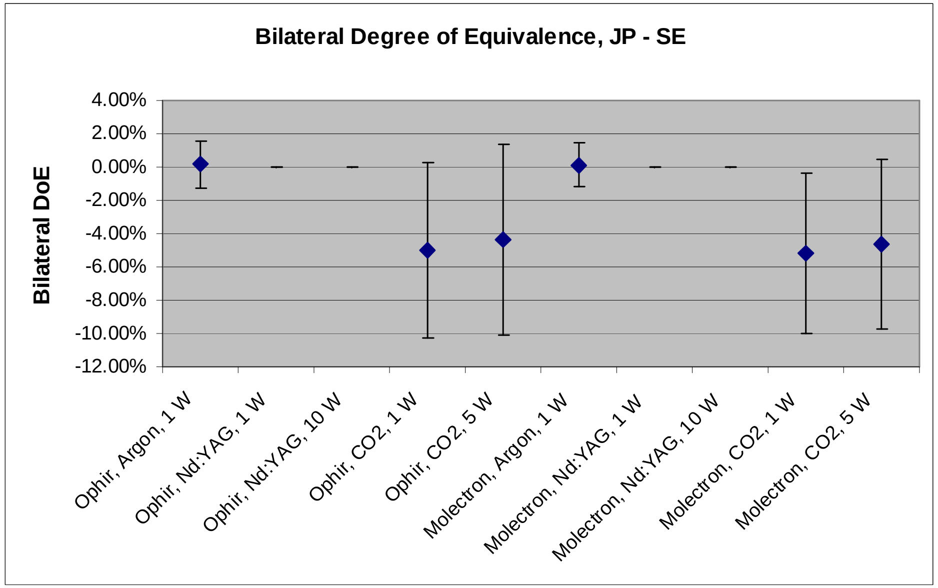
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Ophir, CO2, 5 W
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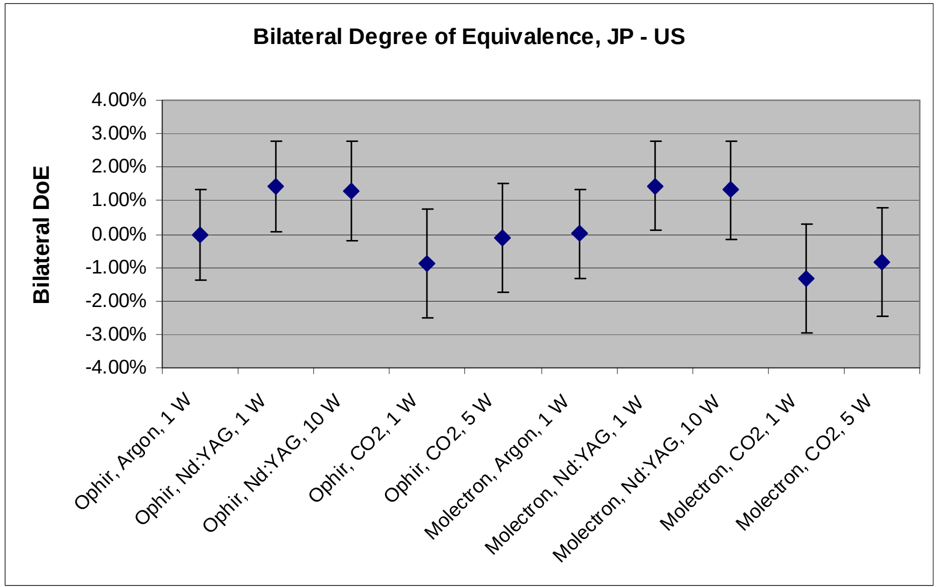
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Ophir, CO2, 5 W
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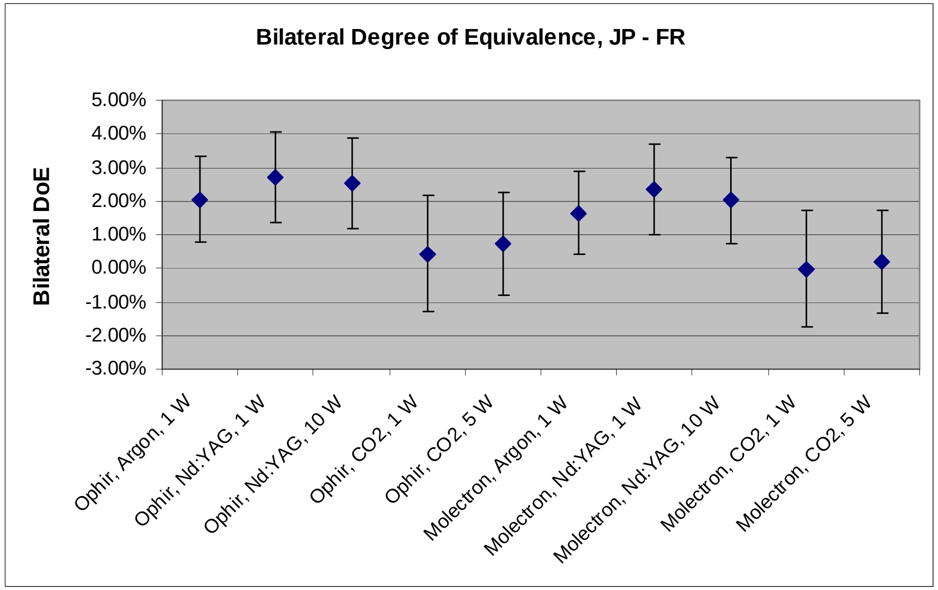
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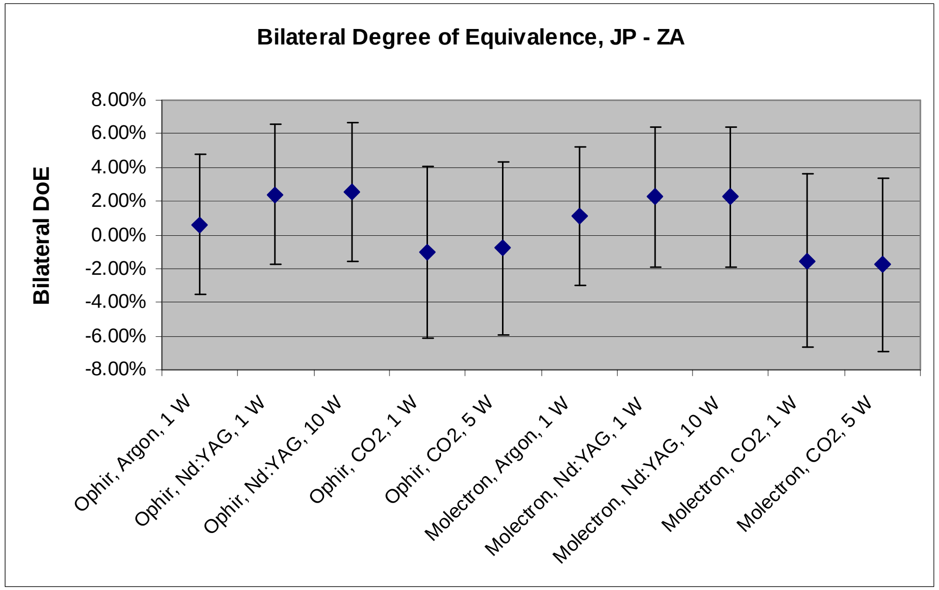
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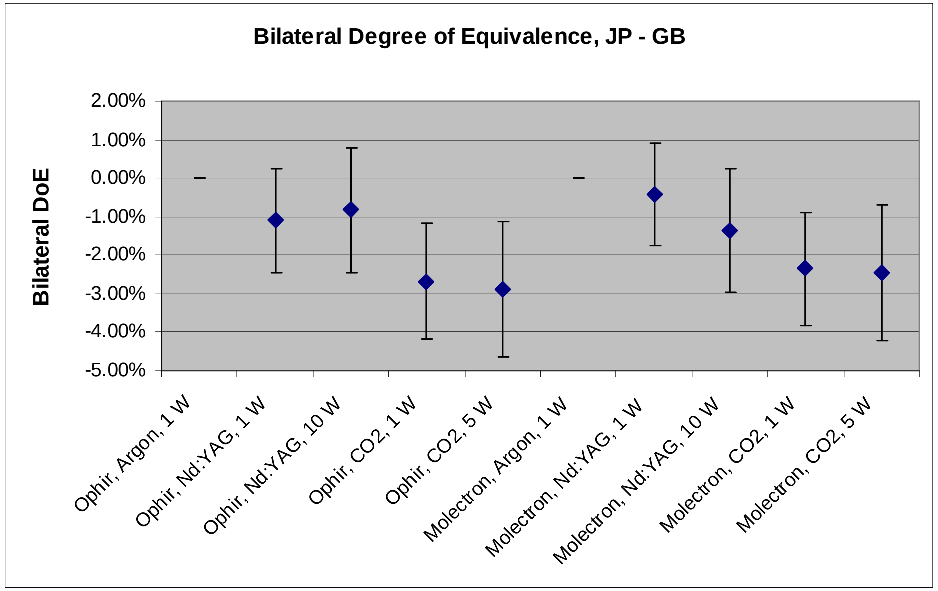
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Ophir, CO2, 1 W
Ophir, CO2, 5 W
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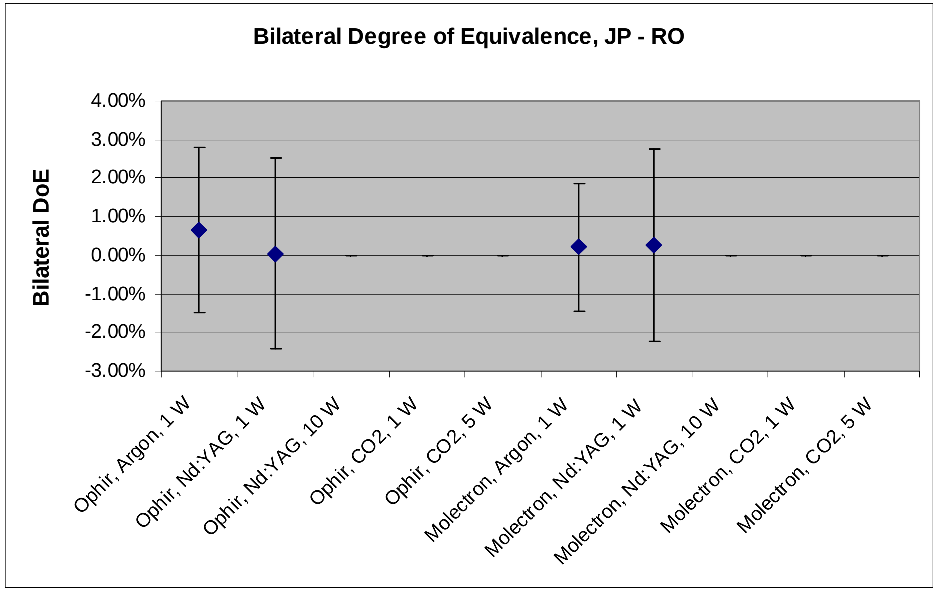
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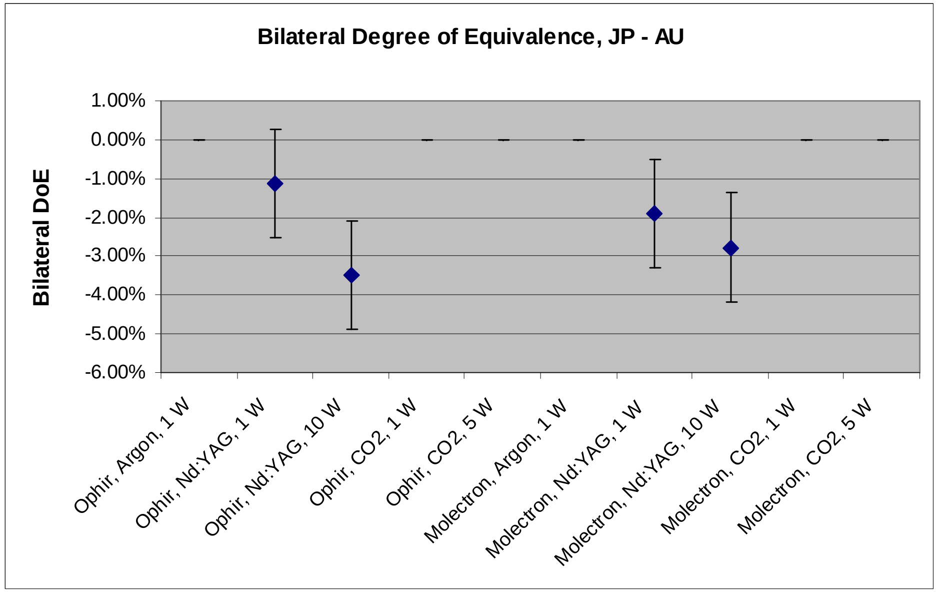
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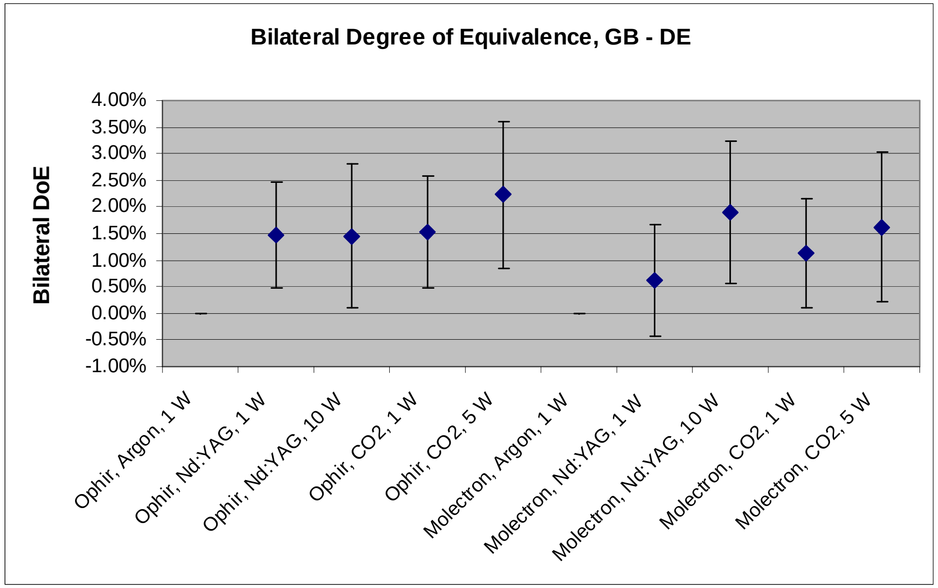
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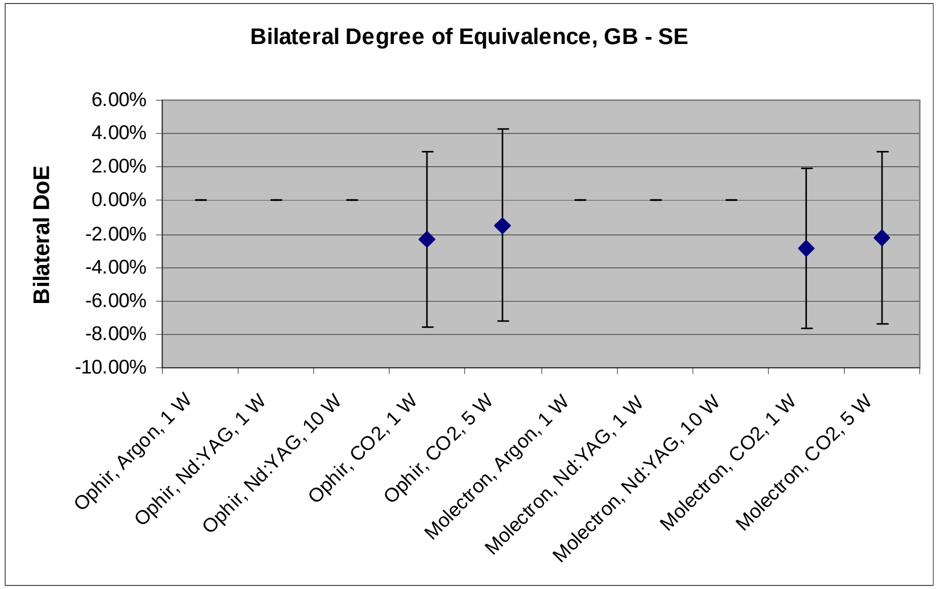
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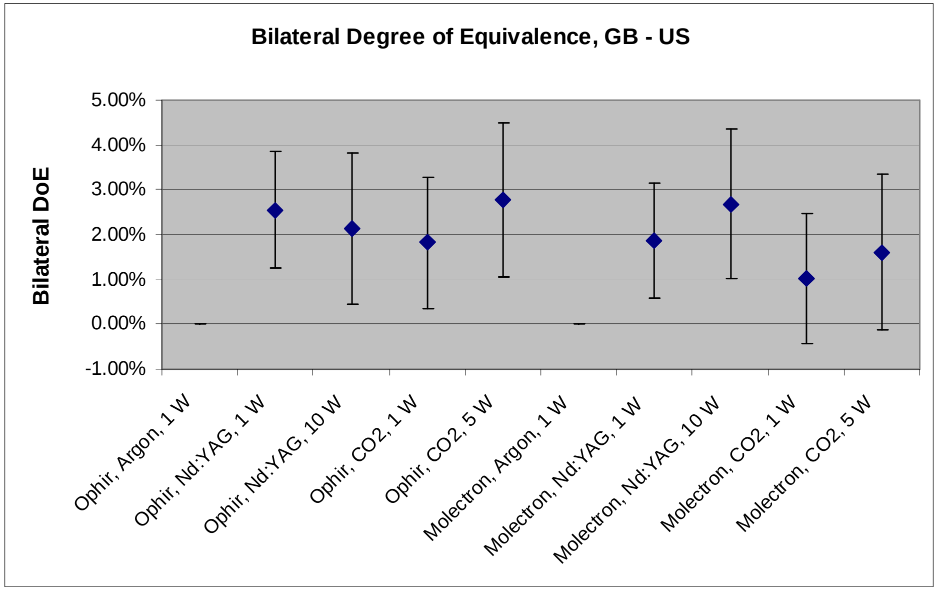
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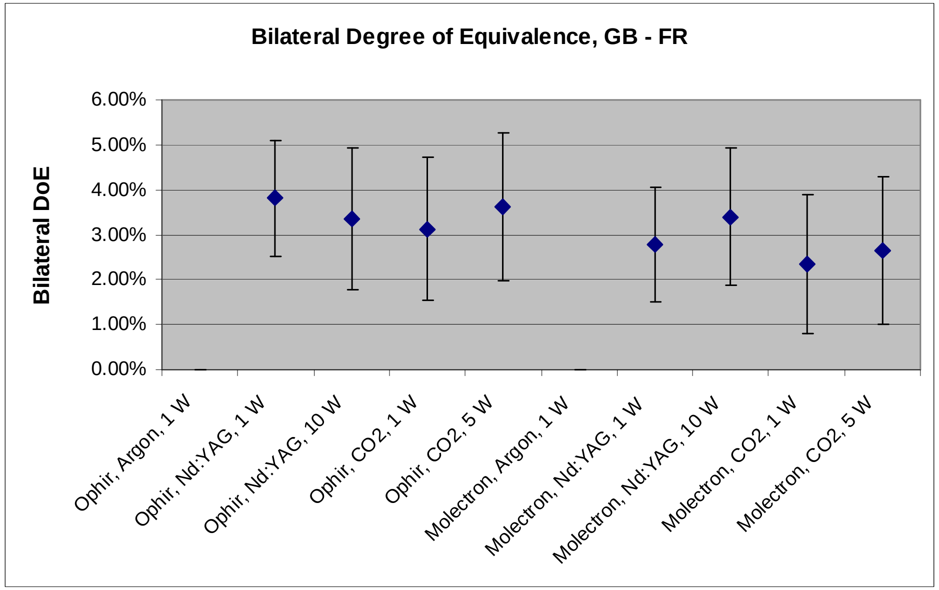
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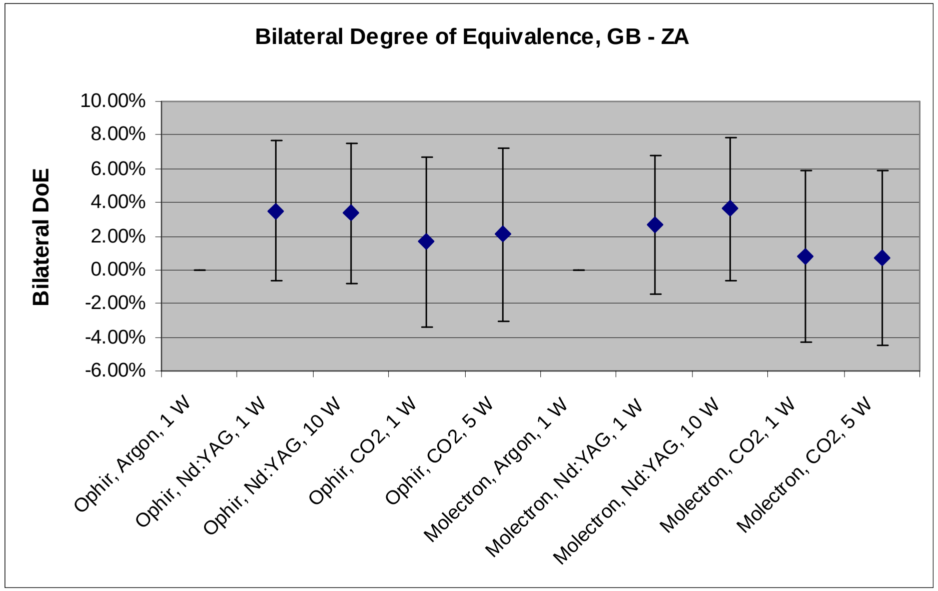
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Ophir, CO2, 1 W
Ophir, CO2, 5 W
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Molectron, Nd:YAG, 1 W
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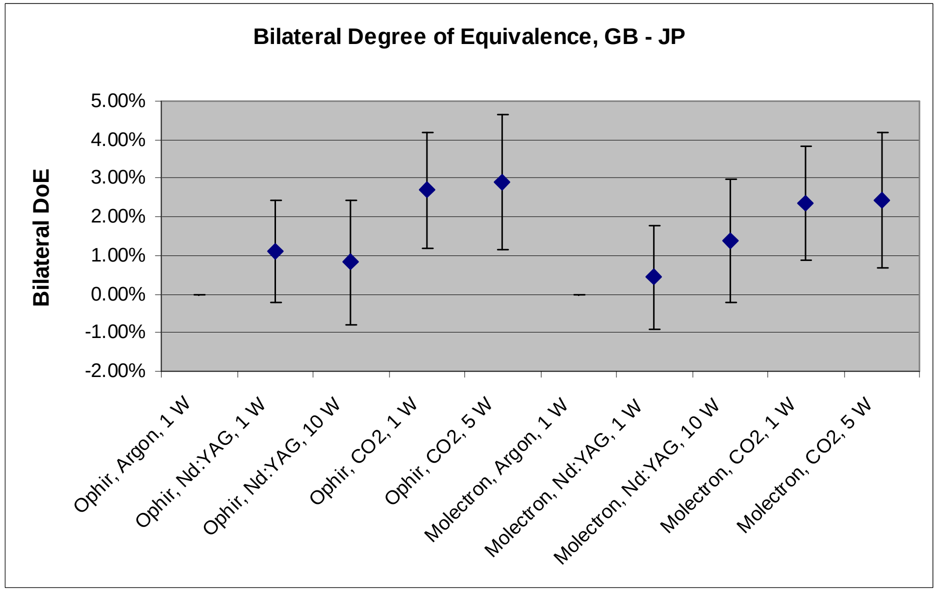
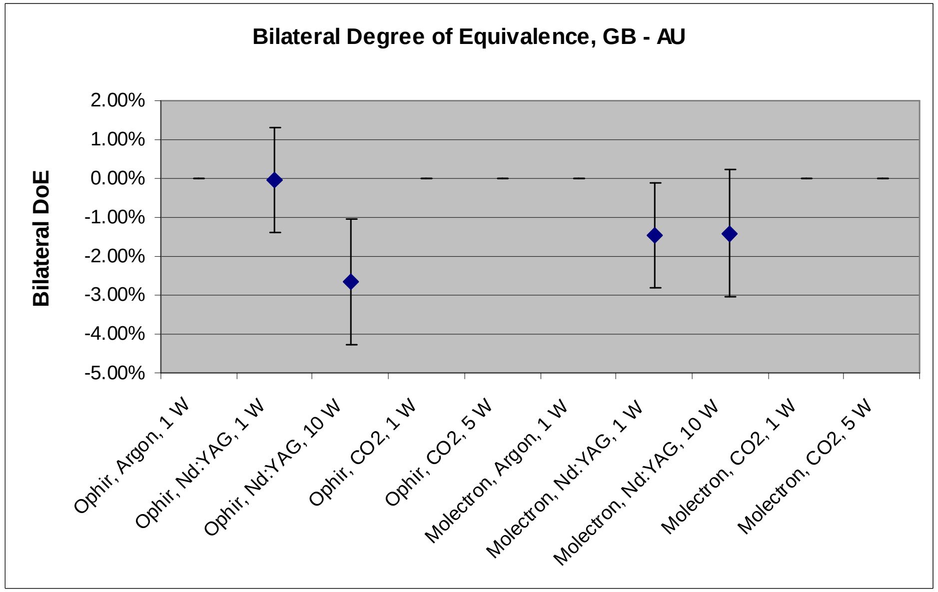
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, GB - JP
Bilateral DoE
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, GB - AU
Bilateral DoE
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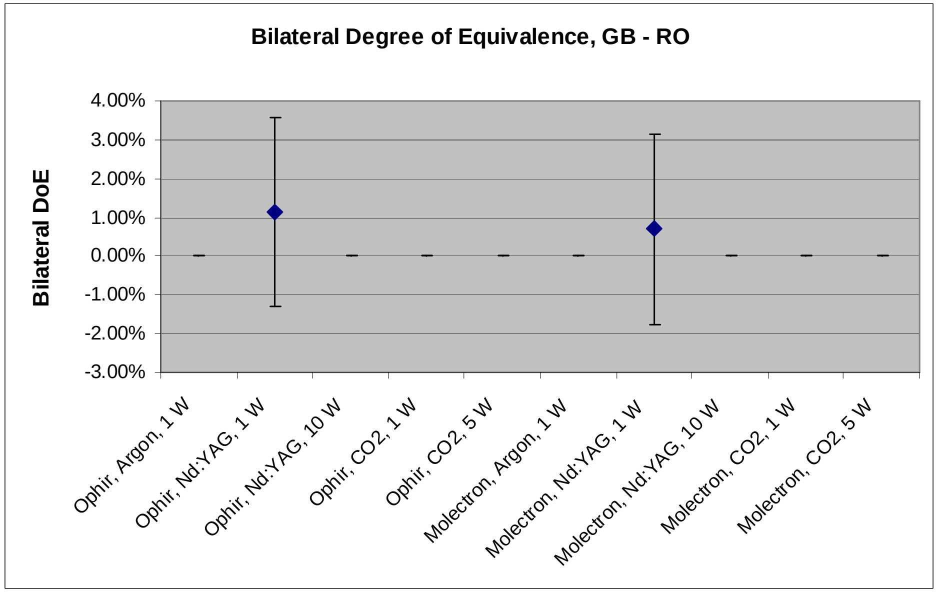
0.00%
-1.00%
-2.00%
-3.00%
-4.00%
-5.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, GB - RO
Bilateral DoE
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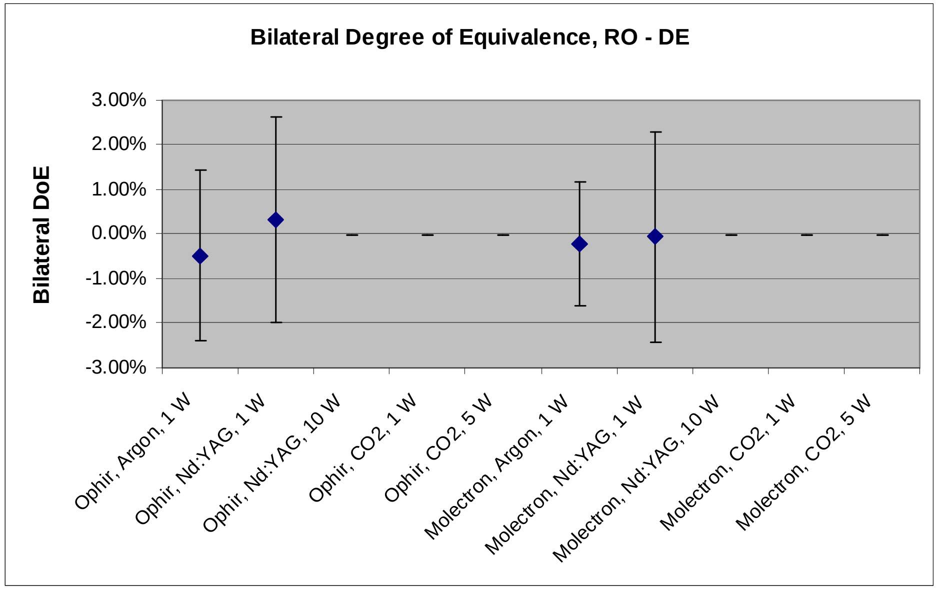
2.00%
1.00%
0.00%
-1.00%
-2.00%
-3.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, RO - DE
Bilateral DoE
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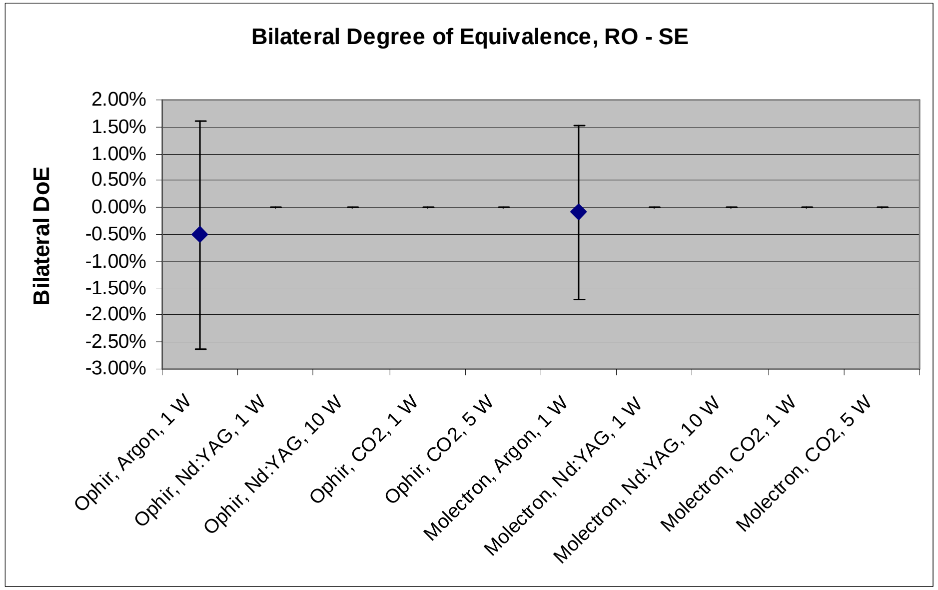
2.00%
1.00%
0.00%
-1.00%
-2.00%
-3.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, RO - SE
Bilateral DoE
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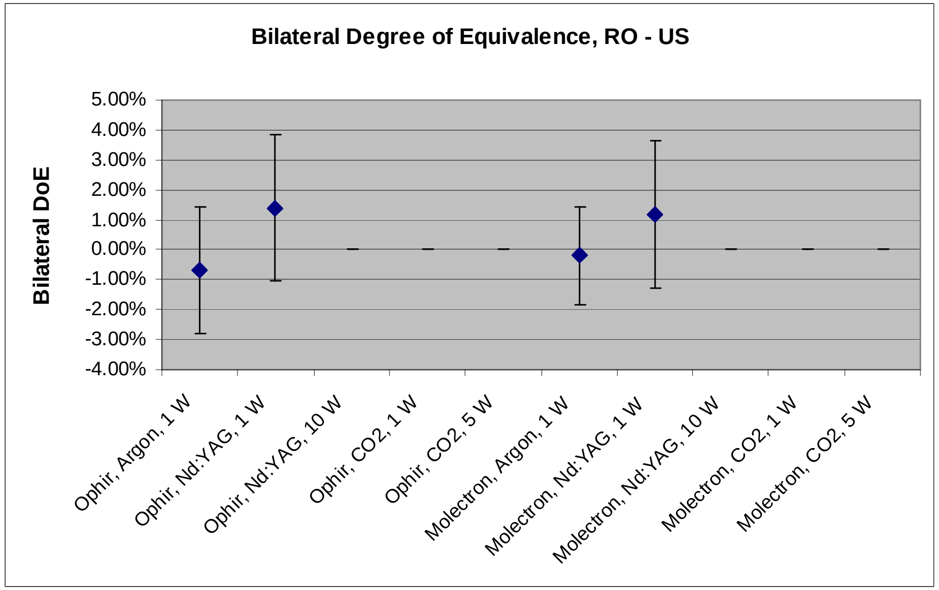
0.00%
-0.50%
-1.00%
-1.50%
-2.00%
-2.50%
-3.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W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Bilateral DoE
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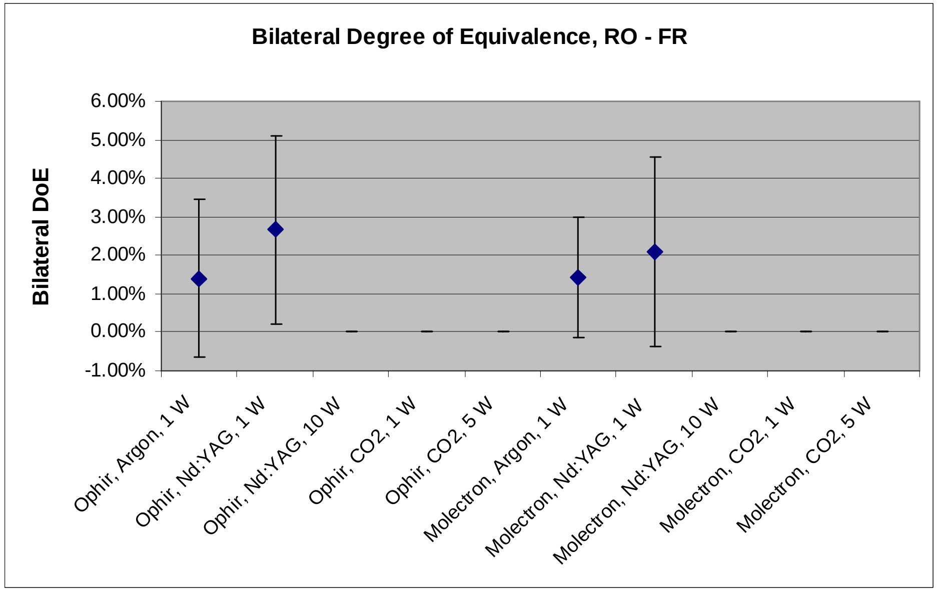
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
-3.00%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, RO - FR
Bilateral DoE
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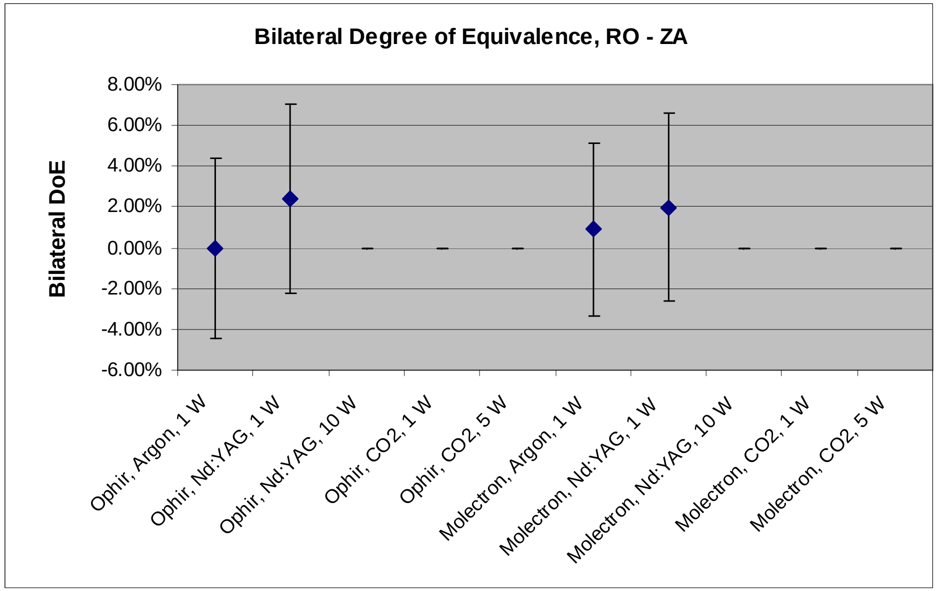
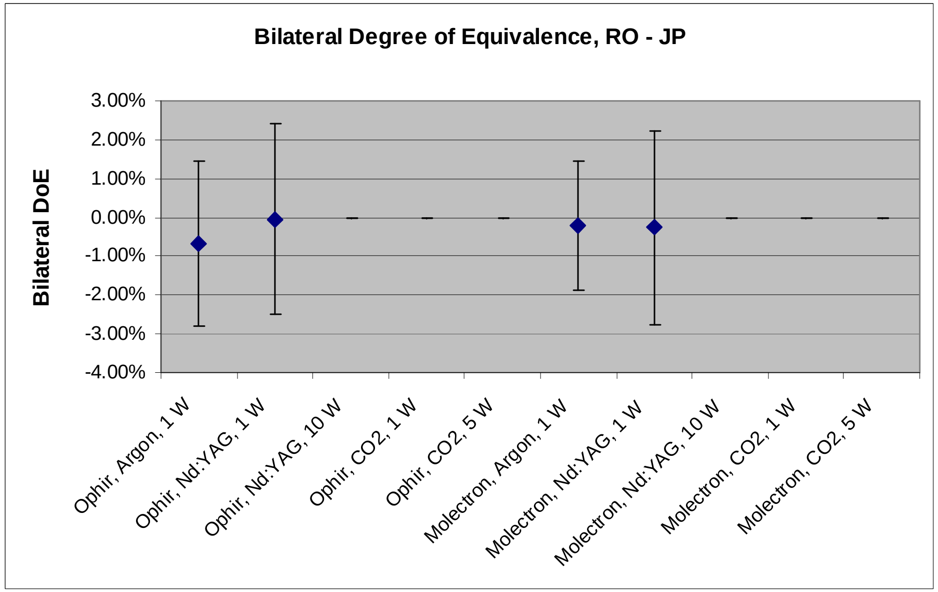
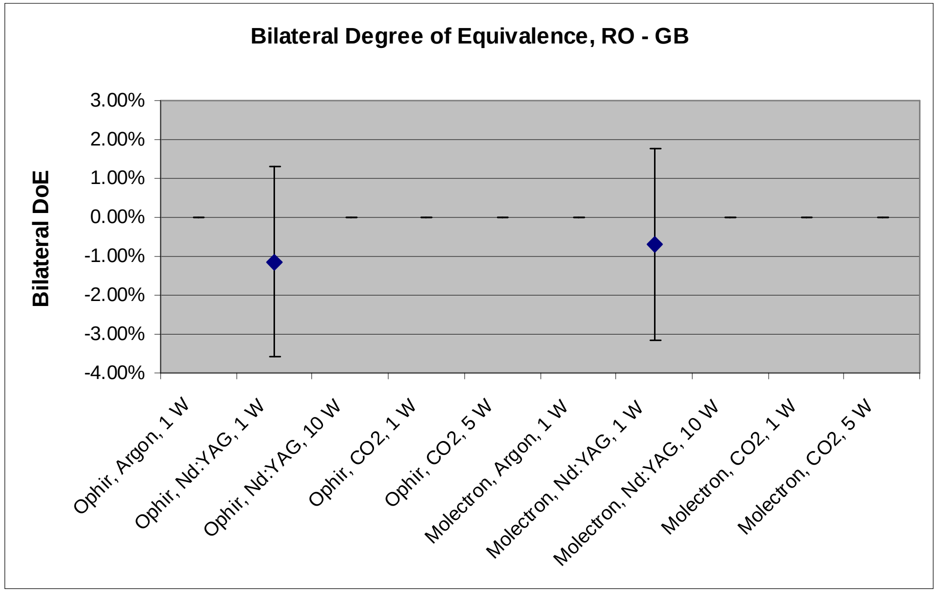
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, RO - ZA
Bilateral DoE
8.00%
6.00%
4.00%
2.00%
0.00%
-2.00%
-4.00%
-6.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, RO - JP
Bilateral DoE
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
-3.00%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, RO - GB
Bilateral DoE
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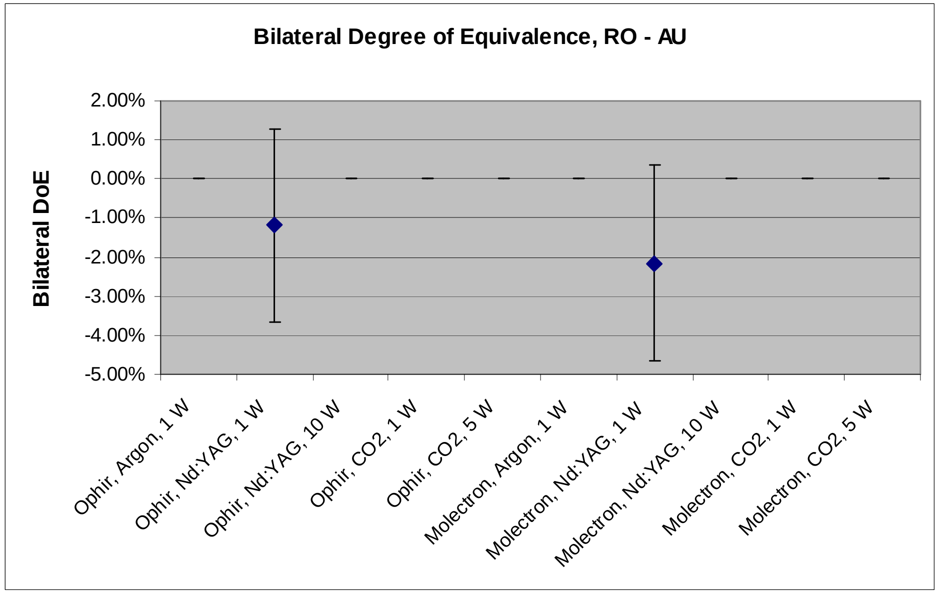
1.00%
0.00%
-1.00%
-2.00%
-3.00%
-4.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, RO - AU
Bilateral DoE
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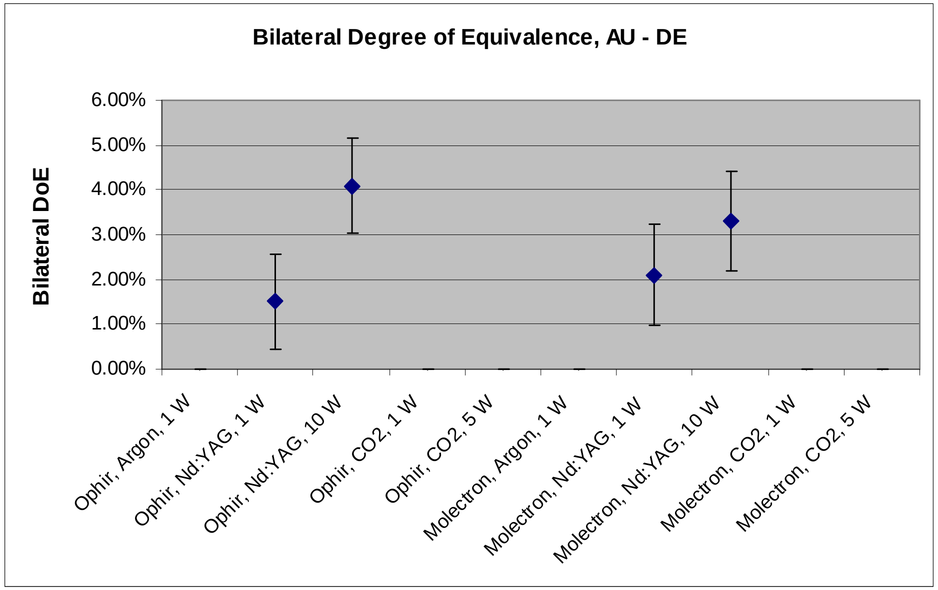
1.00%
0.00%
-1.00%
-2.00%
-3.00%
-4.00%
-5.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, AU - DE
Bilateral DoE
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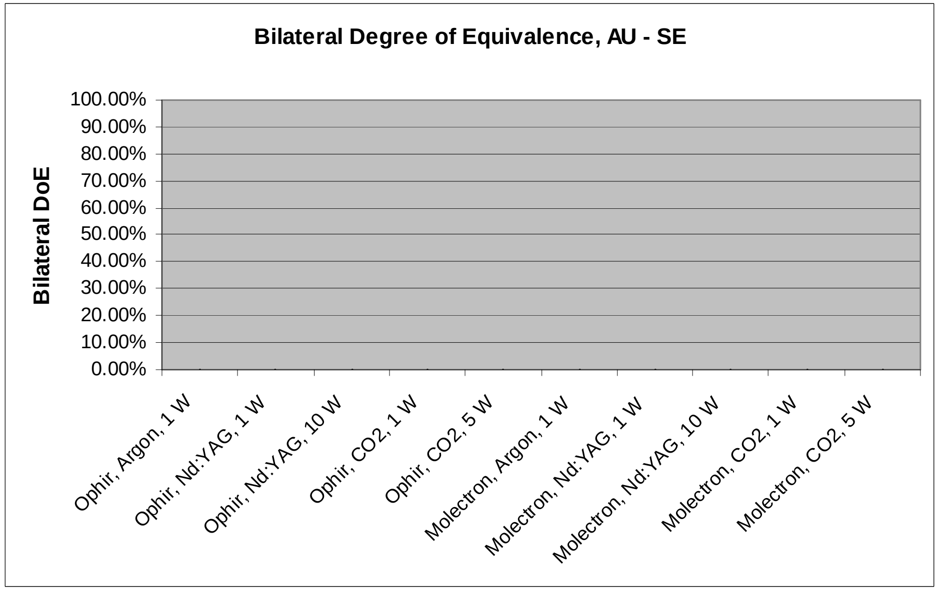
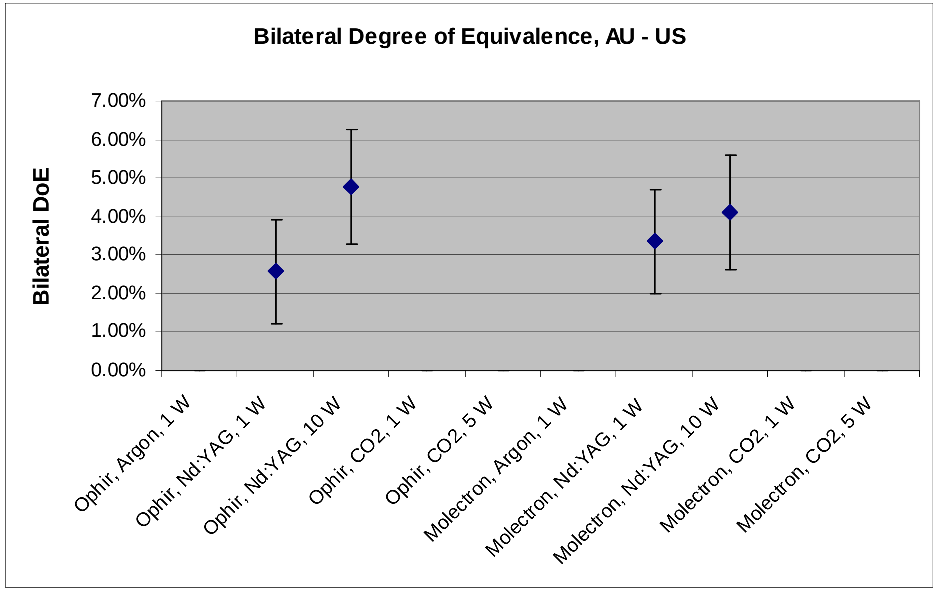
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, AU - SE
Bilateral DoE
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, AU - US
Bilateral DoE
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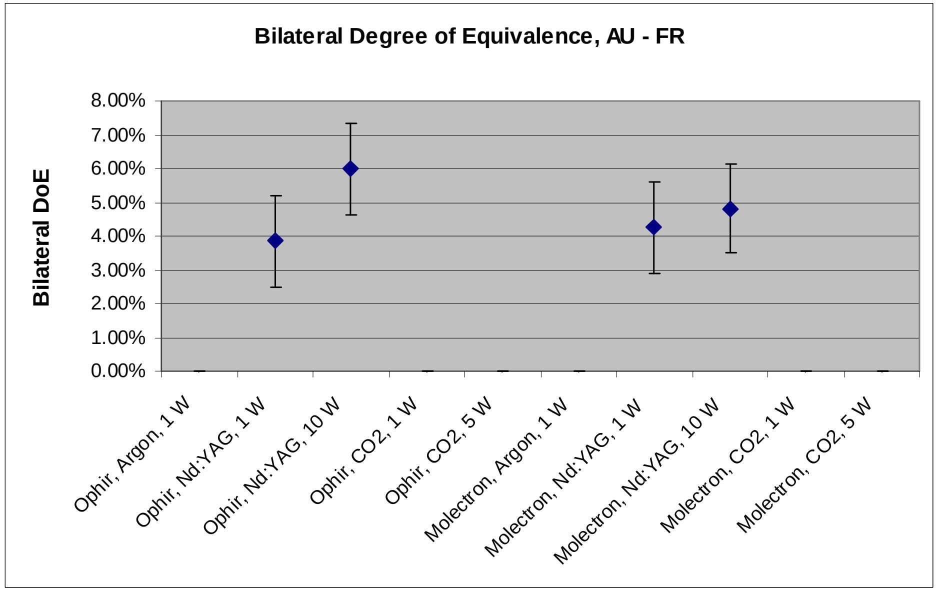
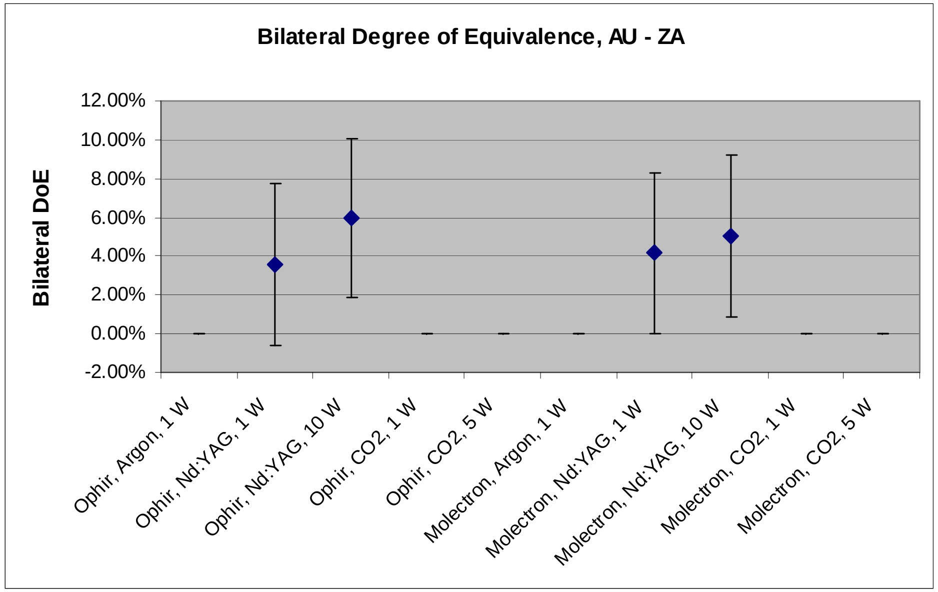
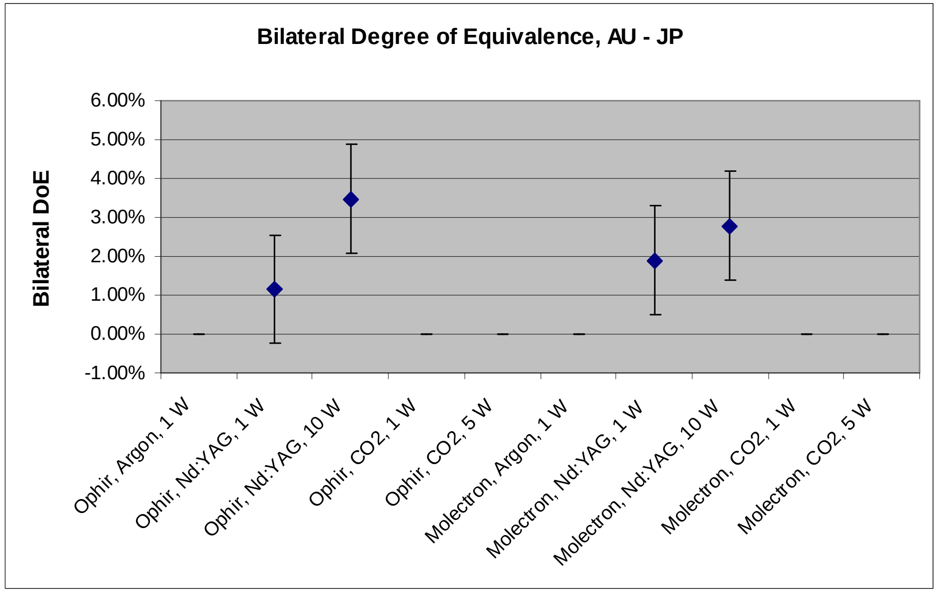
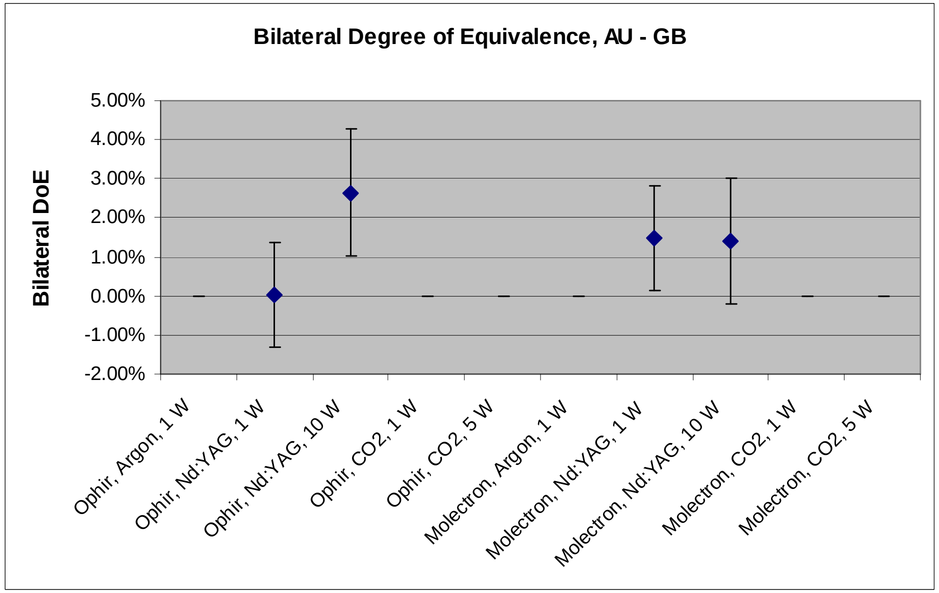
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, AU - FR
Bilateral DoE
8.00%
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, AU - ZA
Bilateral DoE
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%
-2.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, AU - JP
Bilateral DoE
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, AU - GB
Bilateral DoE
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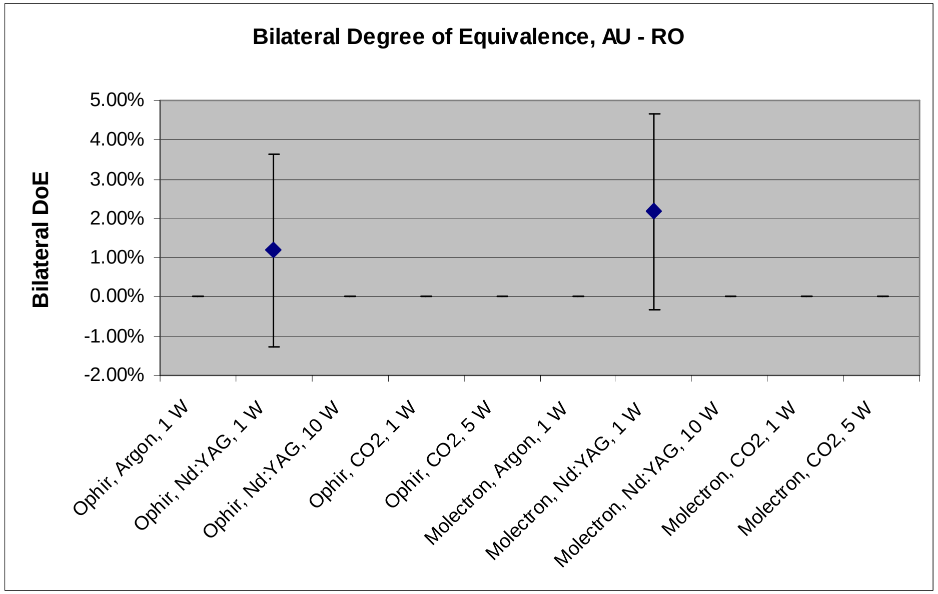
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W


Bilateral Degree of Equivalence, AU - RO
Bilateral DoE
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4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
Ophir, Argon, 1 W
Ophir, Nd:YAG, 1 W
Ophir, Nd:YAG, 10 W
Ophir, CO2, 1 W
Ophir, CO2, 5 W
Molectron, Argon, 1 W
Molectron, Nd:YAG, 1 W
Molectron, Nd:YAG, 10 W
Molectron, CO2, 1 W
Molectron, CO2, 5 W

9 Conclusions

The EUROMET.PR-S2 intercomparison of Radiant Power of High Power Lasers for five measurands was carried as a combined round-robin / star type comparison. In total 9 participants took part, 5 from Europe (National Metrology Institutes of France, Germany (pilot), Great Britain, Romania, Sweden) and 4 outside Europe (National Metrology Institutes of Australia, Japan, South Africa and The United States of America). Therefore, this comparison can be considered as a worldwide one. The measurements took place from January 2005 to September 2007.

All participants supplied detailed reports of their measurements including full uncertainty statements. All measurement results reported by the participants were be used for the intercomparison and no measurement was subject of rejection. The analysis method introduced in section 6 follows the Guidelines for CCPR Comparison Report Preparation and has been accepted by all participants.

For the calculation of the supplementary key comparison reference value no participant had to be excluded and the used weighted mean with cut-off has been supported by all participants.

The unilateral Degrees of Equivalence (DoE) calculated for each participant are in approx. 63 % consistent with their uncertainties at the $k = 2$ level and in approx. 81 % consistent within $k = 3$.

10 Appendix A: List of Figures

11 Appendix B: List of Tables

12 Appendix C: Timeline of the comparison

Technical Protocol agreed:	2004-01-12
	2005-02-02 (last changes)
Start of Measurements:	2005-01-01
End of Measurements:	2007-09-13
All reports received:	2007-11-13
Pre-Draft “A” published:	2009-03-03
First draft of Draft “A”:	2009-07-29
Draft “A” approved:	2009-10-02
Draft “B” submitted:	2009-10-02
Final report submitted	2010-03-29

13 Appendix D: Measurement reports and uncertainty tables of the participants

1. PTB, Germany, DE
2. SP, Sweden, SE
3. NIST, United States of America, US
4. LNE, France, FR
5. NMISA, South Africa, ZA
6. NMIJ, Japan, JP
7. NPL, United Kingdom, GB
8. NILPRP, Romania, RO
9. NMIA, Australia, AU

The results for the supplementary comparison reference values (SCRVs) and the unilateral degrees of equivalence are given in Table 12 and Table 13. The results for the bilateral degrees of equivalence are given in Table 13.

Appendix 1

Germany (PTB) report

Description of the measurement facility and primary scale

Make and type of primary standard

See calibration chain in the detailed measurement description:

Cryogenic radiometer → Si-Trap-detector → Standard detectors LM7

Laboratory transfer standards used (if any):

For Argon (514.5 nm): LM7

For Nd:YAG (1064 nm): 1 W: LM7 → LM6; 10 W: LM7 → LM6 → HLR301

For CO_2 (10.6 µm): LM7

Description of measuring technique (please include a diagram):

See detailed measurement description

Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty:

Recalibration of standards:
LM7: January 2005 and May 2007
LM6: February 2005
HLR301: February 2005 and February 2007

Breakdown of uncertainty: Quality management system, work instruction ("Arbeitsanweisung") "QM-AA-4.13K-Ar-Kr-HeNe" from October 2001 and August 2005.

Uncertainty tables are given in the detailed measurement description.

Description of calibration laboratory conditions: e.g. temperature, humidity etc.

See results.

Laboratory: PTB

Date: 21.02.2005, 13.07.2005, 03.05.2006, 20.02.2007, 13.09.2007

Signature: F. Brandt

Record of detector radiant exposure

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	10 – 15	
Nd:YAG	1064	1	10 – 15	
Nd:YAG	1064	10	10 – 15	
CO_2	10600	1	10 – 15	
CO_2	10600	5	10 – 15	

Detector: MOLECTRON Type PM10

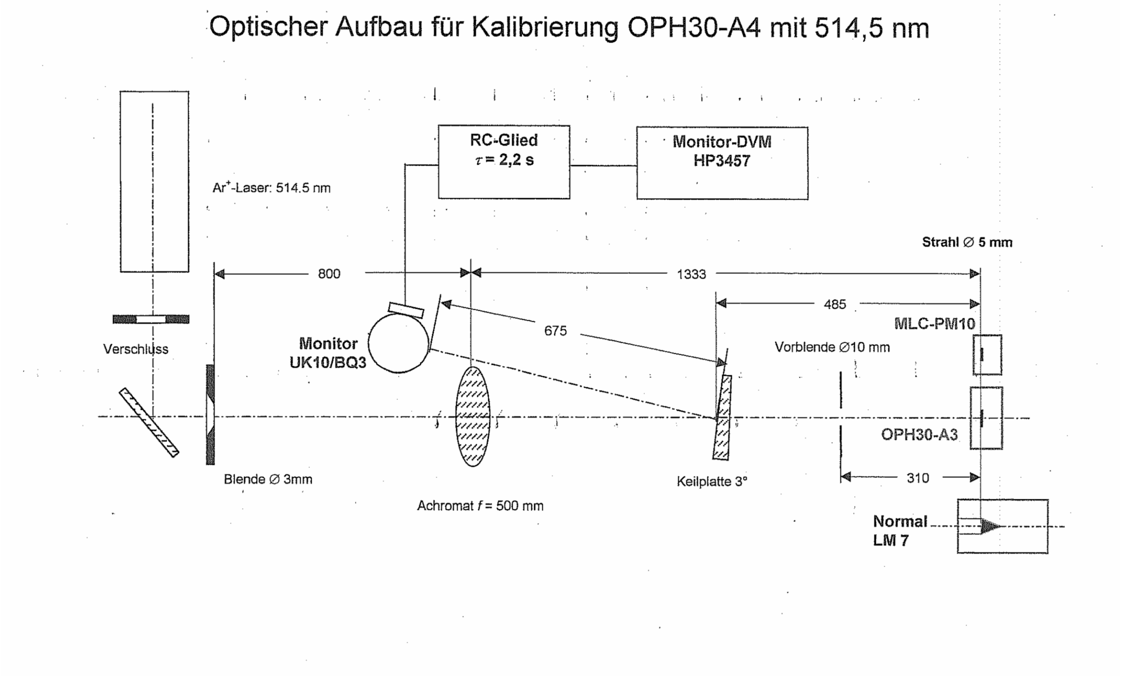
Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	10 – 15	
Nd:YAG	1064	1	10 – 15	
Nd:YAG	1064	10	10 – 15	
CO_2	10600	1	10 – 15	
CO_2	10600	5	10 – 15	

Laboratory: PTB

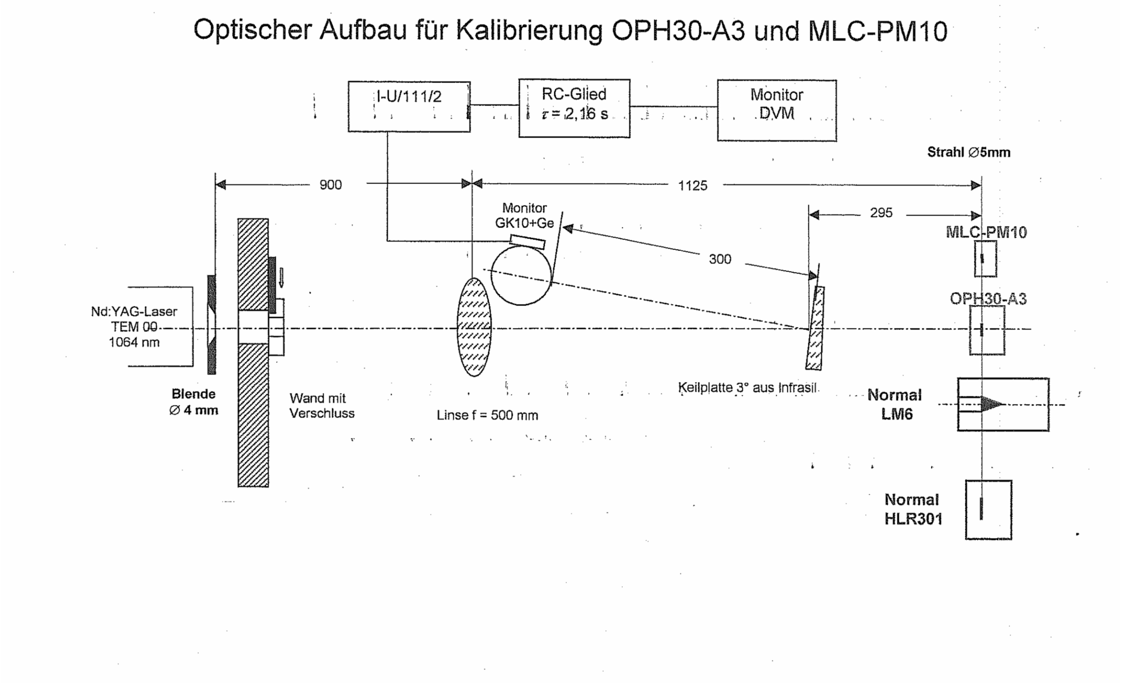
Date: 21.02.2005, 13.07.2005, 03.05.2006, 20.02.2007, 13.09.2007

Signature: F. Brandt

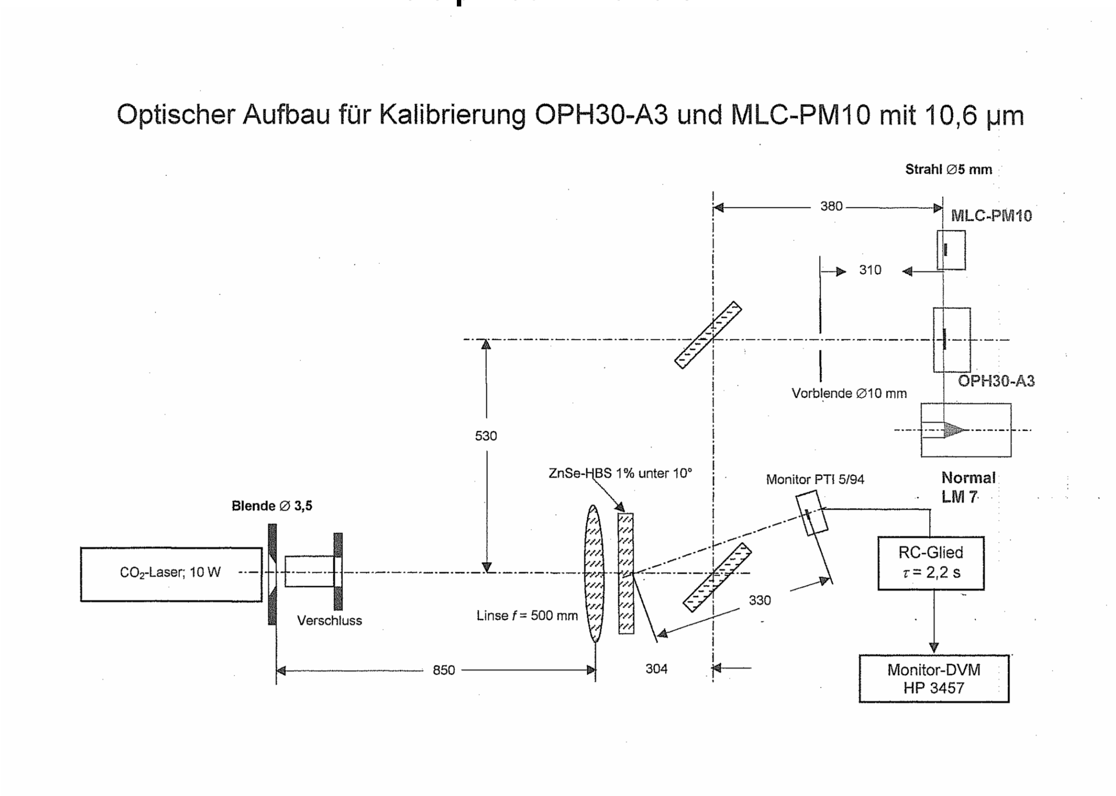
Setup for the calibration of the OPH30-A3, MLC-10PM and OPH30-A4 detectors at 514.5 nm at 1 W



Setup for the calibration of the OPH30-A3, MLC-10PM and OPH30-A4 detectors at 1064 nm at 1 W and 10 W



Setup for the calibration of the OPH30-A3, MLC-10PM and OPH30-A4 detectors at 10.6 µm at 1 W and 5 W



Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1.0	5.0	22.0 ± 0.5	5	x	see detailed report	see detailed report	see detailed report
Nd:YAG	1064	1.0	5.0	22.0 ± 0.5	7	x	see detailed report	see detailed report	see detailed report
Nd:YAG	1064	10.0	5.0	22.0 ± 0.5	5	x	see detailed report	see detailed report	see detailed report
CO_2	10600	1.0	5.0	22.0 ± 0.5	8	x	see detailed report	see detailed report	see detailed report
CO_2	10600	5.0	5.0	22.0 ± 0.5	7	x	see detailed report	see detailed report	see detailed report

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1.0	5.0	22.0 ± 0.5	5	x	see detailed report	see detailed report	see detailed report
Nd:YAG	1064	1.0	5.0	22.0 ± 0.5	7	x	see detailed report	see detailed report	see detailed report
Nd:YAG	1064	10.0	5.0	22.0 ± 0.5	5	x	see detailed report	see detailed report	see detailed report
CO_2	10600	1.0	5.0	22.0 ± 0.5	8	x	see detailed report	see detailed report	see detailed report
CO_2	10600	5.0	5.0	22.0 ± 0.5	7	x	see detailed report	see detailed report	see detailed report

Laboratory: PTB

Date: 21.02.2005, 13.07.2005, 03.05.2006, 20.02.2007, 13.09.2007 Signature: F. Brandt

Calibration of MLC-PM10 with LM7 at 514.5 nm at 1 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.0133%	4	1.0	1.3E-04	3.3%
F_{s0}	1	A	1	-	0.0240%	13	1.0	2.4E-04	10.7%
F_{VN}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	2.5%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	2.5%
F_{k}	1	A	1	-	0.0620%	150	1.0	6.2E-04	71.3%
$F_{\aleph}$	1	B rectangular	1	0.000120	0.0069%	infinity	1.0	6.9E-05	0.9%
F_{H}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	3.9%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	3.9%
$F_{\aleph T}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.6%
$F_{\aleph\varnothing}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.6%
s_{k}	**1**	**result**	**1**	**-**	**0.0734%**	**221**			

s_{Pr}: measured spectral responsivity of MLC-10PM
F_{s0}: factor for the normalized spectral responsivity of the standard LM7
F_{VN}: factor for the voltage measurement of the standard LM7
F_{VPr}: factor for the voltage measurement of MLC-10PM
F_{k}: factor for the correction factor of the standard LM7
$F_{\aleph}$ℵfactor for the absorption of the standard LM7
F_{H}: factor of the inhomogeneity of the standard LM7
F_{S}: factor for stray light
$F_{\aleph T}$: factor for the correction of the temperature dependence of the standard LM7
$F_{\aleph\varnothing}$: factor for the correction of the power dependence of the standard LM7
s_{k}: corrected spectral responsivity of MLC-10PM

Calibration of MLC-PM10 with LM6 at 1064 nm at 1 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.0858%	6	1.0	8.6E-04	50.9%
F_{s0}	1	A	1	-	0.0790%	180	1.0	7.9E-04	43.2%
F_{VN}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.9%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.9%
F_{H}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	1.4%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	1.4%
$F_{T\blacklozenge}$	1	B rectangular	1	0.000220	0.0127%	infinity	1.0	1.3E-04	1.1%
s_{k}	**1**	**result**	**1**	**-**	**0.1202%**	**23**			

s_{Pr}: measured spectral responsivity of MLC-10PM

F_{s0}: factor for the normalized spectral responsivity of the standard LM6

F_{VN}: factor for the voltage measurement of the standard LM6

F_{VPr}: factor for the voltage measurement of MLC-10PM

F_{H}: factor of the inhomogeneity of the standard LM6

F_{S}: factor for stray light

$F_{T\blacklozenge}$: factor for the correction of the temperature and power dependence of the standard LM6

s_{k}: corrected spectral responsivity of MLC-10PM

Calibration of MLC-PM10 with HLR301 at 1064 nm at 10 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.0878%	4	1.0	8.8E-04	40.1%
F_{s0}	1	A	1	-	0.1000%	56	1.0	1.0E-03	52.0%
F_{VN}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.7%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.7%
F_{H}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	1.1%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	1.1%
F_{η}	1	B rectangular	1	0.000500	0.0289%	infinity	1.0	2.9E-04	4.3%
s_{k}	**1**	**result**	**1**	**-**	**0.1386%**	**22**			

s_{Pr}: measured spectral responsivity of MLC-10PM

F_{s0}: factor for the normalized spectral responsivity of the standard HLR301

F_{VN}: factor for the voltage measurement of the standard HLR301

F_{VPr}: factor for the voltage measurement of MLC-10PM

F_{H}: factor of the inhomogeneity of the standard HLR301

F_{S}: factor for stray light

F_{η}: factor for the correction of the power dependence of the standard HLR301

s_{k}: corrected spectral responsivity of MLC-10PM

Calibration of MLC-PM10 with LM7 at 10.6 µm at 1 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.1122%	7	1.0	1.1E-03	54.0%
F_{s0}	1	A	1	-	0.0240%	13	1.0	2.4E-04	2.5%
F_{VN}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.6%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.6%
F_k	1	A	1	-	0.0620%	150	1.0	6.2E-04	16.5%
F_{ξ}	1	B rectangular	1	0.000850	0.0491%	infinity	1.0	4.9E-04	10.3%
F_H	1	B rectangular	1	0.001000	0.0577%	infinity	1.0	5.8E-04	14.3%
F_S	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	0.9%
$F_{\xi T}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.1%
$F_{\xi 6}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.1%
s_k	**1**	**result**	**1**	**-**	**0.1526%**	**24**			

s_{Pr}: measured spectral responsivity of MLC-10PM

F_{s0}: factor for the normalized spectral responsivity of the standard LM7

F_{VN}: factor for the voltage measurement of the standard LM7

F_{VPr}: factor for the voltage measurement of MLC-10PM

F_k: factor for the correction factor of the standard LM7

F_{ξ}ξ factor for the absorption of the standard LM7

F_H: factor of the inhomogeneity of the standard LM7

F_S: factor for stray light

$F_{\xi T}$: factor for the correction of the temperature dependence of the standard LM7

$F_{\xi 6}$: factor for the correction of the power dependence of the standard LM7

s_k: corrected spectral responsivity of MLC-10PM

Calibration of MLC-PM10 with LM7 at 10.6 µm at 5 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.1095%	6	1.0	1.1E-03	53.0%
F_{s0}	1	A	1	-	0.0240%	13	1.0	2.4E-04	2.5%
F_{VN}	1	B rectangular	1	0.000150	0.0087%	infinity	1.0	8.7E-05	0.3%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.6%
F_{k}	1	A	1	-	0.0620%	150	1.0	6.2E-04	17.0%
$F_{\div}$	1	B rectangular	1	0.000850	0.0491%	infinity	1.0	4.9E-04	10.6%
F_{H}	1	B rectangular	1	0.001000	0.0577%	infinity	1.0	5.8E-04	14.7%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	0.9%
$F_{\div T}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.1%
$F_{\div\{}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.1%
s_{k}	**1**	**result**	**1**	**-**	**0.1504%**	**21**			

s_{Pr}: measured spectral responsivity of MLC-10PM
F_{s0}: factor for the normalized spectral responsivity of the standard LM7
F_{VN}: factor for the voltage measurement of the standard LM7
F_{VPr}: factor for the voltage measurement of MLC-10PM
F_{k}: factor for the correction factor of the standard LM7
$F_{\div}$÷factor for the absorption of the standard LM7
F_{H}: factor of the inhomogeneity of the standard LM7
F_{S}: factor for stray light
$F_{\div T}$: factor for the correction of the temperature dependence of the standard LM7
$F_{\div\{}$: factor for the correction of the power dependence of the standard LM7
s_{k}: corrected spectral responsivity of MLC-10PM

Calibration of OPH30-3A with LM7 at 514.5 nm at 1 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.0253%	4	1.0	2.5E-04	10.9%
F_{s0}	1	A	1	-	0.0240%	13	1.0	2.4E-04	9.8%
F_{VN}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	2.3%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	2.3%
F_{k}	1	A	1	-	0.0620%	150	1.0	6.2E-04	65.6%
$F_{\neg}$	1	B rectangular	1	0.000120	0.0069%	infinity	1.0	6.9E-05	0.8%
F_{H}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	3.6%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	3.6%
$F_{\neg T}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.6%
$F_{\neg\vartheta}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.6%
s_{k}	**1**	**result**	**1**	**-**	**0.0765%**	**152**			

s_{Pr}: measured spectral responsivity of OPH30-3A
F_{s0}: factor for the normalized spectral responsivity of the standard LM7
F_{VN}: factor for the voltage measurement of the standard LM7
F_{VPr}: factor for the voltage measurement of OPH30-3A
F_{k}: factor for the correction factor of the standard LM7
$F_{\neg}$¬factor for the absorption of the standard LM7
F_{H}: factor of the inhomogeneity of the standard LM7
F_{S}: factor for stray light
$F_{\neg T}$: factor for the correction of the temperature dependence of the standard LM7
$F_{\neg\vartheta}$: factor for the correction of the power dependence of the standard LM7
s_{k}: corrected spectral responsivity of OPH30-3A

Calibration of OPH30-3A with LM6 at 1064 nm at 1 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.0934%	6	1.0	9.3E-04	55.2%
F_{s0}	1	A	1	-	0.0790%	180	1.0	7.9E-04	39.5%
F_{VN}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.8%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.8%
F_{H}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	1.3%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	1.3%
$F_{T\blacklozenge}$	1	B rectangular	1	0.000220	0.0127%	infinity	1.0	1.3E-04	1.0%
s_{k}	**1**	**result**	**1**	**-**	**0.1258%**	**19**			

s_{Pr}: measured spectral responsivity of OPH30-3A

F_{s0}: factor for the normalized spectral responsivity of the standard LM6

F_{VN}: factor for the voltage measurement of the standard LM6

F_{VPr}: factor for the voltage measurement of OPH30-3A

F_{H}: factor of the inhomogeneity of the standard LM6

F_{S}: factor for stray light

$F_{T\blacklozenge}$: factor for the correction of the temperature and power dependence of the standard LM6

s_{k}: corrected spectral responsivity of OPH30-3A

Calibration of OPH30-3A with HLR301 at 1064 nm at 10 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.0763%	4	1.0	7.6E-04	33.6%
F_{s0}	1	A	1	-	0.1000%	56	1.0	1.0E-03	57.7%
F_{VN}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.8%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.8%
F_{H}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	1.2%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	1.2%
$F_{\circ}$	1	B rectangular	1	0.000500	0.0289%	infinity	1.0	2.9E-04	4.8%
s_{k}	**1**	**result**	**1**	**-**	**0.1317%**	**29**			

s_{Pr}: measured spectral responsivity of OPH30-3A

F_{s0}: factor for the normalized spectral responsivity of the standard HLR301

F_{VN}: factor for the voltage measurement of the standard HLR301

F_{VPr}: factor for the voltage measurement of OPH30-3A

F_{H}: factor of the inhomogeneity of the standard HLR301

F_{S}: factor for stray light

$F_{\circ}$: factor for the correction of the power dependence of the standard HLR301

s_{k}: corrected spectral responsivity of OPH30-3A

Calibration of OPH30-3A with LM7 at 10.6 µm at 1 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.1197%	7	1.0	1.2E-03	57.2%
F_{s0}	1	A	1	-	0.0240%	13	1.0	2.4E-04	2.3%
F_{VN}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.5%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.5%
F_{k}	1	A	1	-	0.0620%	150	1.0	6.2E-04	15.4%
$F_{\neg}$	1	B rectangular	1	0.000850	0.0491%	infinity	1.0	4.9E-04	9.6%
F_{H}	1	B rectangular	1	0.001000	0.0577%	infinity	1.0	5.8E-04	13.3%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	0.8%
$F_{\neg T}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.1%
$F_{\neg\vartheta}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.1%
s_{k}	**1**	**result**	**1**	**-**	**0.1582%**	**21**			

s_{Pr}: measured spectral responsivity of OPH30-3A
F_{s0}: factor for the normalized spectral responsivity of the standard LM7
F_{VN}: factor for the voltage measurement of the standard LM7
F_{VPr}: factor for the voltage measurement of OPH30-3A
F_{k}: factor for the correction factor of the standard LM7
$F_{\neg}$¬factor for the absorption of the standard LM7
F_{H}: factor of the inhomogeneity of the standard LM7
F_{S}: factor for stray light
$F_{\neg T}$: factor for the correction of the temperature dependence of the standard LM7
$F_{\neg\vartheta}$: factor for the correction of the power dependence of the standard LM7
s_{k}: corrected spectral responsivity of OPH30-3A

Calibration of OPH30-3A with LM7 at 10.6 µm at 5 W

quantity	unit	type	value	intervall	standard deviation	degree of freedom	sensitivity coefficient	uncertainty contribution	index
s_{Pr}	1	A	1	-	0.1114%	6	1.0	1.1E-03	53.8%
F_{s0}	1	A	1	-	0.0240%	13	1.0	2.4E-04	2.5%
F_{VN}	1	B rectangular	1	0.000150	0.0087%	infinity	1.0	8.7E-05	0.3%
F_{VPr}	1	B rectangular	1	0.000200	0.0115%	infinity	1.0	1.2E-04	0.6%
F_{k}	1	A	1	-	0.0620%	150	1.0	6.2E-04	16.7%
$F_{\neg}$	1	B rectangular	1	0.000850	0.0491%	infinity	1.0	4.9E-04	10.4%
F_{H}	1	B rectangular	1	0.001000	0.0577%	infinity	1.0	5.8E-04	14.5%
F_{S}	1	B rectangular	1	0.000250	0.0144%	infinity	1.0	1.4E-04	0.9%
$F_{\neg T}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.1%
$F_{\neg\rho}$	1	B rectangular	1	0.000100	0.0058%	infinity	1.0	5.8E-05	0.1%
s_{k}	**1**	**result**	**1**	**-**	**0.1518%**	**21**			

s_{Pr}: measured spectral responsivity of OPH30-3A
F_{s0}: factor for the normalized spectral responsivity of the standard LM7
F_{VN}: factor for the voltage measurement of the standard LM7
F_{VPr}: factor for the voltage measurement of OPH30-3A
F_{k}: factor for the correction factor of the standard LM7
$F_{\neg}$¬ factor for the absorption of the standard LM7
F_{H}: factor of the inhomogeneity of the standard LM7
F_{S}: factor for stray light
$F_{\neg T}$: factor for the correction of the temperature dependence of the standard LM7
$F_{\neg\rho}$: factor for the correction of the power dependence of the standard LM7
s_{k}: corrected spectral responsivity of OPH30-3A

Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of free-dom
Argon	**514.5**	**1,0**	**5,0**	**22,0 ± 0,5**	**5**	**1,5047**	**0,025**	**0,0012**	**150**
Nd:YAG	**1064**	**1,0**	**5,0**	**22,0 ± 0,5**	**7**	**1,4671**	**0,093**	**0,0018**	**19**
Nd:YAG	**1064**	**10,0**	**5,0**	**22,0 ± 0,5**	**5**	**1,4423**	**0,076**	**0,0019**	**29**
CO_2	**10600**	**1,0**	**5,0**	**22,0 ± 0,5**	**8**	**1,4377**	**0,120**	**0,0024**	**21**
CO_2	**10600**	**5,0**	**5,0**	**22,0 ± 0,5**	**7**	**1,5261**	**0,111**	**0,0023**	**20**

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of free-dom
Argon	**514.5**	**1,0**	**5,0**	**22,0 ± 0,5**	**5**	**1,6668**	**0,013**	**0,0012**	**220**
Nd:YAG	**1064**	**1,0**	**5,0**	**22,0 ± 0,5**	**7**	**1,6325**	**0,086**	**0,0020**	**22**
Nd:YAG	**1064**	**10,0**	**5,0**	**22,0 ± 0,5**	**5**	**1,6064**	**0,088**	**0,0022**	**22**
CO_2	**10600**	**1,0**	**5,0**	**22,0 ± 0,5**	**8**	**1,7202**	**0,112**	**0,0026**	**23**
CO_2	**10600**	**5,0**	**5,0**	**22,0 ± 0,5**	**7**	**1,7083**	**0,109**	**0,0026**	**21**

Laboratory: ....**PTB-4.13**...

Date: ....**2005-02-21**.................... Signature: ....

Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of free-dom
Argon	**514.5**	**1,0**	**5,0**	**22,0 ± 0,5**	**5**	**1,5072**	**0,009**	**0,0011**	**230**
Nd:YAG	**1064**	**1,0**	**5,0**	**22,0 ± 0,5**	**7**	**1,4649**	**0,056**	**0,0015**	**54**
Nd:YAG	**1064**	**10,1**	**5,0**	**22,0 ± 0,5**	**6**	**1,4426**	**0,068**	**0,0018**	**48**
CO_2	**10600**	**1,0**	**5,0**	**22,0 ± 0,5**	**7**	**1,5390**	**0,096**	**0,0022**	**27**
CO_2	**10600**	**5,0**	**5,0**	**22,0 ± 0,5**	**6**	**1,5271**	**0,072**	**0,0019**	**44**

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of free-dom
Argon	**514.5**	**1,0**	**5,0**	**22,0 ± 0,5**	**6**	**1,6667**	**0,019**	**0,0013**	**210**
Nd:YAG	**1064**	**1,0**	**5,0**	**22,0 ± 0,5**	**6**	**1,6293**	**0,059**	**0,0017**	**41**
Nd:YAG	**1064**	**10,0**	**5,0**	**22,0 ± 0,5**	**5**	**1,6045**	**0,050**	**0,0019**	**58**
CO_2	**10600**	**1,0**	**5,0**	**22,0 ± 0,5**	**7**	**1,7188**	**0,113**	**0,0026**	**19**
CO_2	**10600**	**5,0**	**5,0**	**22,0 ± 0,5**	**6**	**1,7060**	**0,059**	**0,0020**	**75**

Laboratory: ....**PTB-4.13**..

Date: ....**2005-07-12**.................... Signature: ....

Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1,0	5,0	22,0 ± 0,5	4	1,50587	0,035	0,0012	66
Nd:YAG	1064	1,0	5,0	22,0 ± 0,5	7	1,4651	0,069	0,0016	34
Nd:YAG	1064	9,9	5,0	22,0 ± 0,5	7	1,4431	0,068	0,0018	48
CO_2	10600	1,0	5,0	22,0 ± 0,5	6	1,5393	0,083	0,0020	31
CO_2	10600	5,1	5,0	22,0 ± 0,5	6	1,5260	0,057	0,0018	84

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1,0	5,0	22,0 ± 0,5	4	1,6659	0,018	0,0013	190
Nd:YAG	1064	1,0	5,0	22,0 ± 0,5	6	1,6301	0,035	0,0015	130
Nd:YAG	1064	9,9	5,0	22,0 ± 0,5	7	1,6050	0,061	0,0020	56
CO_2	10600	1,0	5,0	22,0 ± 0,5	6	1,7190	0,091	0,0024	25
CO_2	10600	5,1	5,0	22,0 ± 0,5	6	1,7050	0,023	0,0018	820

Laboratory: ....PTB-4.13...

Date: ....2006-05-04.................... Signature: ....[signature]..........

Measurement results

Detector: OPHIR Type 30A

k = 1

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1.0	5.0	22.0 ± 0.5	4	1.5054	0.017	0.00116	230
Nd:YAG	1064	1.0	5.0	22.0 ± 1.0	5	1.4663	0.063	0.00124	240
Nd:YAG	1064	10.0	5.0	22.0 ± 1.0	7	1.4420	0.060	0.00178	65
CO_2	10600	1.0	5.0	22.0 ± 0.5	6	1.5405	0.079	0.00207	42
CO_2	10600	5.1	5.0	22.0 ± 0.5	5	1.5289	0.036	0.00172	280

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1.0	5.0	22.0 ± 0.5	4	1.6661	0.035	0.00146	90
Nd:YAG	1064	1.0	5.0	22.0 ± 1.0	5	1.6293	0.028	0.00143	270
Nd:YAG	1064	10.1	5.0	22.0 ± 1.0	7	1.6017	0.098	0.00233	25
CO_2	10600	1.0	5.0	22.0 ± 0.5	6	1.7159	0.047	0.00199	170
CO_2	10600	5.1	5.0	22.0 ± 0.5	5	1.7033	0.028	0.00192	570

Laboratory: PTB 4.13

Date: 2007-02-20 Signature: [signature]

Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	k=1 Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1,0	5,0	22,0±0,5	6	1,5030	0,023	0,00129	240
Nd:YAG	1064	1,0	5,0	22,0±0,5	9	1,4623	0,075	0,00163	36
Nd:YAG	1064	10,2	5,0	22,0±0,5	8	1,4382	0,085	0,00198	39
CO_2	10600	1,0	5,0	22,0±0,5	4	1,5394	0,022	0,00174	670
CO_2	10600	5,0	5,0	22,0±0,5	5	1,5268	0,055	0,00187	92

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1,0	5,0	22,0±0,5	4	1,6651	0,019	0,00146	290
Nd:YAG	1064	1,0	5,0	22,0±0,5	18	1,6268	0,220	0,00386	22
Nd:YAG	1064	9,9	5,0	22,0±0,5	13	1,6016	0,134	0,00275	30
CO_2	10600	1,0	5,0	22,0±0,5	4	1,7133	0,010	0,00195	1000
CO_2	10600	5,0	5,0	22,0±0,5	5	1,7000	0,055	0,00213	97

Laboratory: PTB 4.13

Date: 2007-09-13 Signature: [signature]

Appendix 2

Sweden (SP) report

Description of the measurement facility and primary scale

Make and type of primary standard...
Cryogenic radiometer LaseRad CRI, (SP inv. no. 502447), with stabilized HeNe and Argon lasers

....

Laboratory transfer standards used (if any):..

Trap detector (SP inv. no. 502444)..

Radiometer UDT 350 (SP inv. no. 500638) with integrating sphere UDT 2500 (SP inv. no. 500229)

Radiometer Laser Precision Rm-6600 (SP inv. no. 501447) with thermal detector RKT-150 (SP inv. no. 501449)

....

....

Description of measuring technique (please include a diagram):...................................

The objects were measured using standard substitution technique. Beam diameter was estimated to be (5 ± 1) mm for Argon and (5 ± 2) mm for CO2. The measurement objects were connected to voltmeter HP3458A (SP inv. no 502575) according to the instructions. After appropriate stabilization times, about 20 readings were taken automatically. This was then repeated a number of times. Note that for 514 nm, the reported number of measurements in the result tables correspond to measurement series.

Due to the CO2-laser's instability, which mainly was periodic, the measurement schedule described above gave very large standard deviations. It was therefore supplemented with another method taking readings manually trying to estimate maximum reading during a period of 1-2 minutes (approx. corresponding to the laser's instability period). These measurements were used for calculating the final results. The automatically recorded measurement series were used to estimate uncertainties. ....

....

....

Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty:...

For 514 nm:

May 2004:	Crygenic substitution radiometer → Trap detector
March 2005:	Trap → Sphere (Si) at low power level
	Sphere linearity control up to about 2,5 W
	Sphere → Measurement objects at 1 W (Ophir and Molectron)

For 10,6 µm:

March 2005:	Sphere → RKT-150 thermal detector at 514 nm
	RKT-150 linearity control up to about 2,5 W at 514 nm
	RKT-150 correction for change in detector absorption from 514 nm → 10,6 µm
	RKT-150 → Measurement objects at 1 W and 5 W at 10,6 µm

Please note that below, the first components in each table are common for both objects and power levels. The repeatability components are detector/power specific.

Measurement uncertainty (k=1) at 514 nm, 1 W:...

Trap absolute	0,05%
Sphere calibration	0,25%
Sphere linearity	0,15%
Laser (stability, beam etc.)	0,03%
Repeatability Ophir	0,35%
Repeatability Molectron	0,31%

Measurement uncertainty (k=1) at 10,6 nm, 1 W and 5 W:

Thermal detector RKT-150 at 514 nm	0,4%
RKT-150 power linearity 1 W	0,4%
RKT-150 power linearity 5 W	1,0%
RKT-150 correction 514 → 10,6 µm*	1,7%
Repeatability Ophir 1 W**	1,8%
Repeatability Ophir 5 W**	1,9%
Repeatability Molectron 1 W**	1,6%
Repeatability Molectron 5 W**	1,5%

* Based on absorption curve from manufacturer

** Estimated from two different kinds of measurements. Mainly dependent on laser stability

Description of calibration laboratory conditions: e.g. temperature, humidity etc ....

Temperature was 22,8 C +/- 0,5 C, humidity was 40 % ....

....

Laboratory: **SP Swedish National Testing and Research Institute**

Date: **May 05, 2005** Signature: ....

Record of detector radiant exposure

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	10	1-2 W
Nd:YAG	1064	-		
Nd:YAG	1064	-		
CO_2	10600	1	15	
CO_2	10600	5	15	

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	10	1-2 W
Nd:YAG	1064	-	-	
Nd:YAG	1064	-	-	
CO_2	10600	1	15	
CO_2	10600	5	15	

Laboratory: **SP Swedish National Testing and Research Institute**

Date: **May 05, 2005** Signature: ....

Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W) K=1	Degrees of freedom
Argon	514.5	1	5±1	22,8 ± 0,5 °C	7	1,505	0,35	± 0,0069	25
Nd:YAG	1064	-							
Nd:YAG	1064	-							
CO_2	10600	1	5±2	22,8 ± 0,5 °C	8	1,598	1,8	± 0,041	10
CO_2	10600	5	5±2	22,8 ± 0,5 °C	8	1,583	1,9	± 0,044	10

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W) K=1	Degrees of freedom
Argon	514.5	1	5±1	22,8 ± 0,5 °C	6	1,664	0,31	± 0,0071	25
Nd:YAG	1064	-							
Nd:YAG	1064	-							
CO_2	10600	1	5±2	22,8 ± 0,5 °C	8	1,786	1,6	± 0,042	10
CO_2	10600	5	5±2	22,8 ± 0,5 °C	8	1,770	1,5	± 0,044	10

Laboratory: **SP Swedish National Testing and Research Institute**

Date: **May 05, 2005** Signature: ....

Appendix 3

USA (NIST) report

Description of the measurement facility and primary scale

NIST provides absolute responsivity measurements for continuous wave (CW) laser power meters that are traceable to System Internationale (SI) units [1, 2] through electrical standards at laser wavelengths of 514.5 nm, 1064 nm and 10.6 µm. [3, 4, 5]

The EUROMET meters were compared against the NIST primary standard calorimeters. The NIST primary standard calorimeters are described in Ref. 6.

Make and Type of Primary Standard

1. (514.5 nm, 1 W; 1064 nm, 1 W) The primary standard was the NIST Laser Optimized Cryogenic Radiometer (LOCR). The NIST LOCR is traceable to fundamental SI units through electrical standards. [7]
2. All other laser wavelengths and powers: the EUROMET meters were compared against NIST K-series Calorimeter, the NIST primary standard for high power CW laser measurements. [8]

Laboratory transfer standards used

1. (514.5 nm, 1 W; 1064 nm, 1 W) The NIST C-series Calorimeters were used as laboratory transfer standards. [5] See Fig. 5 for a diagram of the traceability path.
2. All other powers and wavelengths: no transfer standards were used.

Description of measuring technique:

1. (Argon Ion laser, 514.5 nm, 1 W) and (Nd:YAG laser, 1064 nm) The EUROMET meters, also referred to as the test detectors, were compared to NIST standards calorimeters at laser wavelengths of 514.5 nm (Argon Ion laser) and 1064 nm (CW Nd:YAG laser). The laser beam had a nominal diameter of 5 mm on the detector surface, and the test detector was centered on the incident laser beam. The power impinging upon the test detector was measured concurrently using a calibrated beamsplitter and a NIST standard calorimeter (See Fig. 1). The beamsplitter ratio was calibrated for each data set using two NIST standard calorimeters. Before the measurements began, the test detector was allowed to reach equilibrium with the laboratory environment. Readings were recorded from the test detector display.
2. (Nd:YAG laser, 1064 nm, 10 W) The test detectors were compared to NIST standard calorimeters at a laser wavelength of 1064 nm using a CW Nd:YAG laser. The laser beam passed through an aperture 25 mm in diameter, and was centered on the detector's absorbing surface. The diameter of the laser beam was 5 mm. The laser energy impinging upon the test detector was compared to a NIST standard calorimeter; a monitor detector was used to detect the laser power changes during the measurements. Before the measurements began, the test detector was allowed to reach equilibrium with the laboratory environment. See Figure 2 for a diagram of the measurement system.
3. (CO_2 laser, 10.6 µm, 1 W) The laser power detector head was compared to NIST standard calorimeters at a laser wavelength of 10.6 µm using a CW CO_2 laser. The laser beam passed through an aperture 25 mm in diameter, and was centered on the detector's absorbing surface. The diameter of the laser beam was 5 mm. The laser energy impinging upon the test detector was compared to a NIST standard calorimeter; a monitor detector was used to detect the laser power changes during the measurements. Before the measurements began, the test detector was allowed to reach equilibrium with the laboratory environment. See Figure 3 for a diagram of the measurement system.
4. (CO_2 laser, 10.6 µm, 5.3 W) The laser power detector head was compared to NIST standard calorimeters at a laser wavelength of 10.6 µm using a CW CO_2 laser. The laser beam passed through an aperture 25 mm in diameter, and was centered on the detector's absorbing surface. The diameter of the laser beam was 5 mm. The laser energy impinging upon the test detector was compared to a NIST standard calorimeter; a monitor detector was used to detect the laser power changes during the measurements. Before the measurements began, the test detector was allowed to reach equilibrium with the laboratory environment. See Figure 4 for a diagram of the measurement system.

Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty:...

1. (514.5 nm, 1 W; 1064 nm, 1 W) The NIST C-series calorimeters were used as laboratory transfer standards. See Figure 5 for a diagram of the traceability path. The procedure for realizing the traceability are described in Ref. 9. At the time of this report, the date of the laser realization was February 2005. The uncertainty assessment is presented in Tables 1 and 2.
2. All other laser wavelengths and powers: the NIST K-series Calorimeter are traceable to fundmental SI units through electrical standards. At the time of this report, the date of the laser realization was March 2003. The uncertainty assessment is presented in Tables 3 and 4.

Description of calibration laboratory conditions: e.g. temperature, humidity etc ....

The temperature was stable at 23 °C ± 1 °C over the duration of the measurements. Average humidity was recorded at 34 % ± 1 % over the duration of the measurements.

References

[1] Barry N. Taylor, The International System of Units (SI), NIST Special Publication 330, 2001 Edition.

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[3] D. E. West and L. B. Schmidt, A System for Calibrating Laser Power Meter for the Range 5-1000 W, NBS Technical Note 685 (1977).

[4] X. Li, T. R. Scott, C. L. Cromer, D. Keenan, F. Brandt, and K. Möstl, Power measurement standards for high-power lasers: comparison between the NIST and the PTB, Metrologia 37, 445-447 (2000).

[5] J.A. Hadler, C.L. Cromer, J.H. Lehman, NIST Measurement Services: cw Laser Power and Energy Calibrations at NIST, NIST SP250-75 (2007).

[6] E.D. West, W.E. Case, A.L. Rasmussen, L.B. Schmidt, A Reference Calorimeter for Laser Energy Measurements, NBS JRES, 76A: 13-26; 72.

[7] D. Livigni, High-Accuracy Laser Power and Energy Meter Calibration Service, NIST SP250-62 (2003).

[8] X. Li, J.A. Hadler, C.L. Cromer, J.H. Lehman, M.L. Dowell, NIST Measurement Services: High Power Laser Calibrations at NIST, NIST SP250-77 (2008).

[9] J.H. Lehman, I. Vayshenker, D.J. Livigni, J.A. Hadler, Intramural Comparison of NIST laser and Optical Fiber Power Calibrations, J. Res. Natl. Inst. Stand. Technol. 109, 291-298 (2004).

Laboratory: National Institute of Standards and Technology

Date: 29 June 2005 Signature: Marla L. Dowell

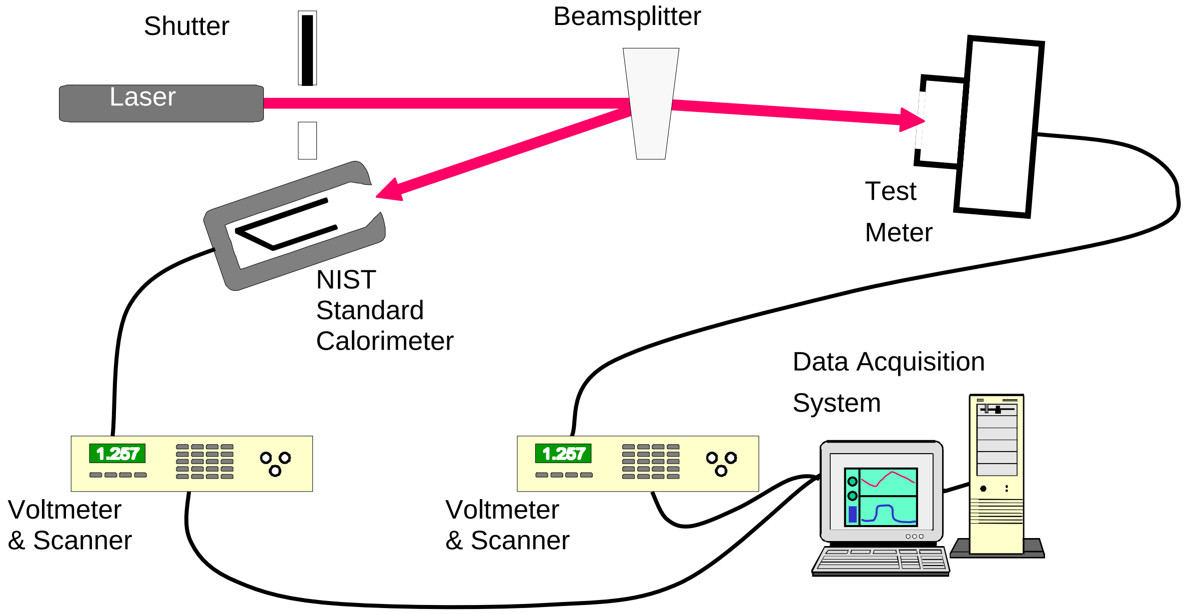


Figure 1. Schematic of measurement system for laser power of 1 W at laser wavelengths of 514.5 and 1064 nm.

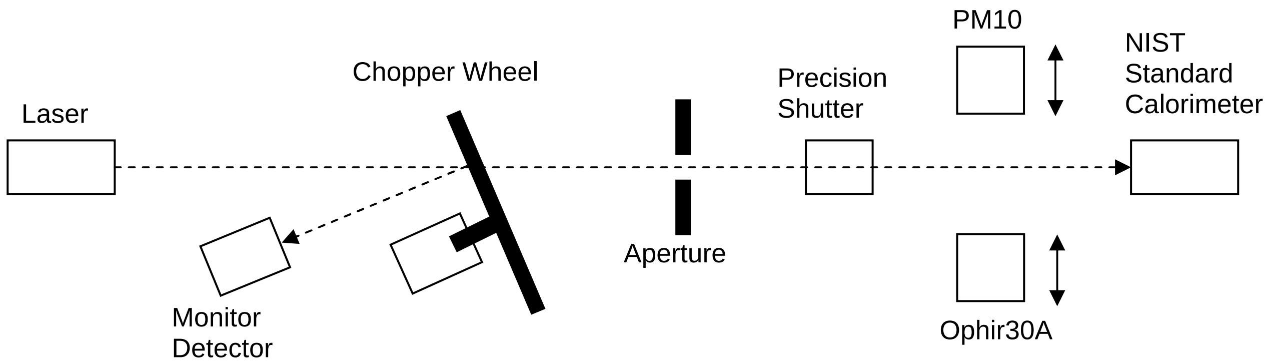


Figure 2. Schematic of measurement system for laser power of 10 W at a laser wavelength of 1064 nm.

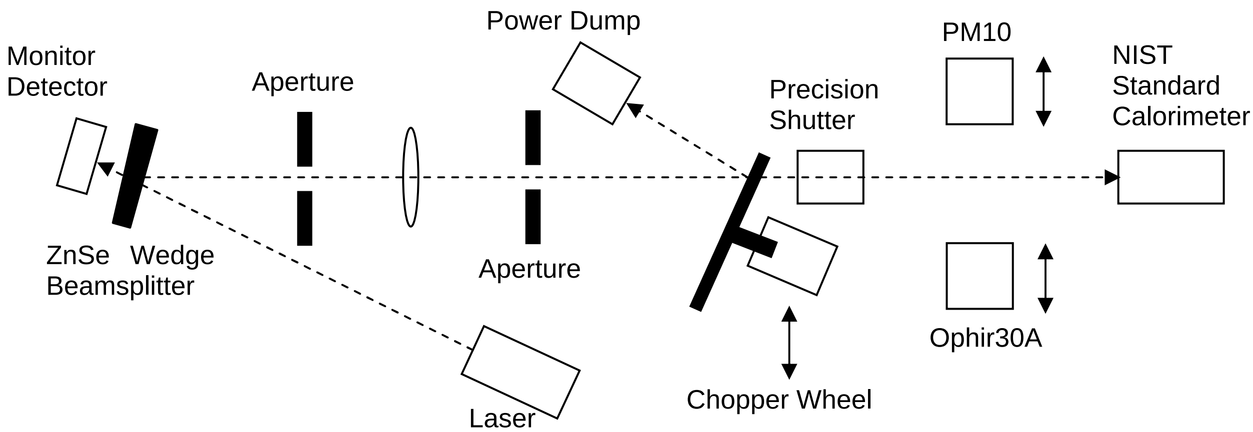


Figure 3. Schematic of measurement system for laser power of 1 W at a laser wavelength of 10.6 μm.

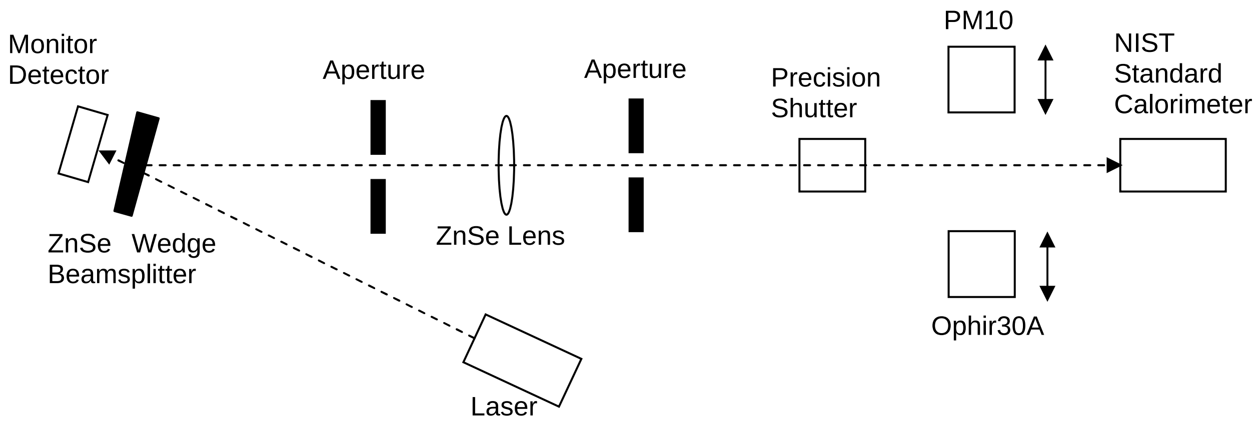


Figure 4. **Schematic of measurement system for laser power of 5 W at a laser wavelength of 10.6 μm.**

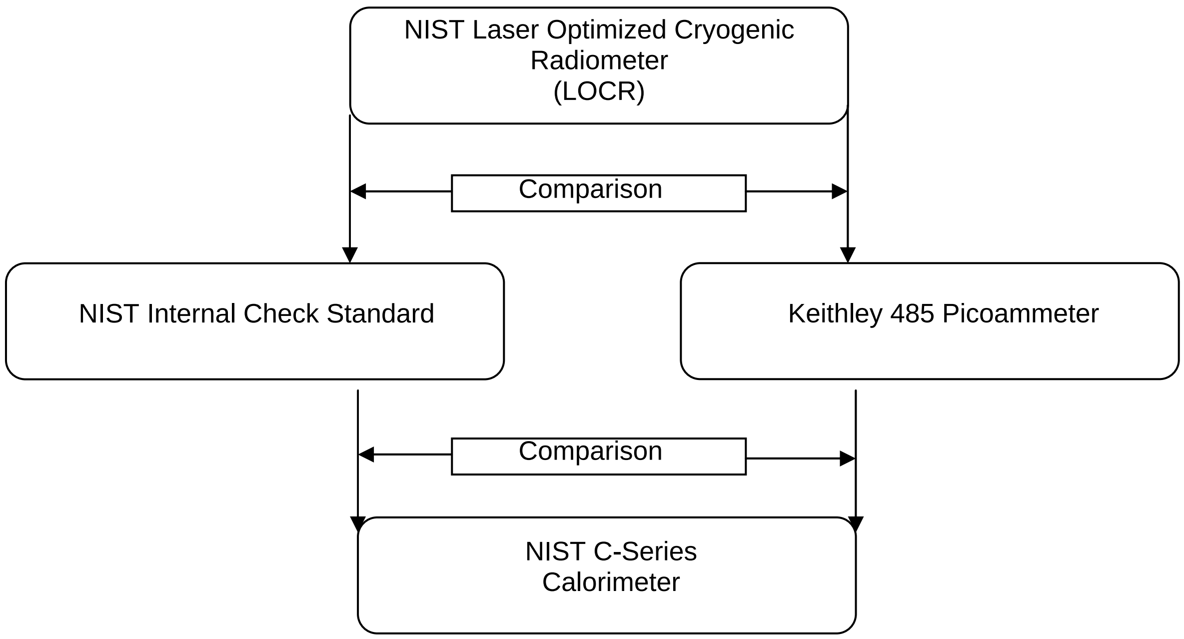


Figure 5 **Schematic of traceability scale for the NIST C-series Calorimeter. The NISTC-series Calorimeter is traceable to fundamental SI units through intramural comparisons using internal check standards with the NIST Laser Optimized Cryogenic Radiometer.**

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.15 %		
Absorptivity	0.01 %		
Electronics	0.10 %	0.10 %	30
Heater leads	0.01 %		
Window Transmittance	0.11 %	0.02 %	6
Measurements			
Injection time	0.05 %		
Laser power drift	0.50 %		
Standard meter ratio	0.50 %	0.09 %	8
Test Meter ratio		0.02 %	4
Expanded uncertainty (k=2)	0.86 %		
Expanded uncertainty (k=1)	0.43 %		

Table 1a Uncertainty Breakdown for Ophir Type 30A at a laser wavelength of 514.5 nm and laser power of 1.02 W. Type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. Type B evaluation of standard uncertainty is based on scientific judgment using all the relevant information available, which may include items such as previous measurement data, manufacturer's specifications, data provided in calibration and other reports, and/or uncertainties assigned to reference data taken from handbooks. N is the number of individual measurements for a particular Type A component; k is the coverage factor chosen based on the confidence level desired. For the purposes of the EUROMET comparison, a coverage factor of k=1 has been chosen for specifying expanded uncertainties, however, it is NIST policy to specify a coverage factor of k=2.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.15 %		
Absorptivity	0.01 %		
Electronics	0.10 %	0.10 %	30
Heater leads	0.01 %		
Window Transmittance	0.11 %	0.02 %	6
Measurements			
Injection time	0.05 %		
Laser power drift	0.50 %		
Standard meter ratio	0.50 %	0.25 %	8
Test Meter ratio		0.07 %	4
Expanded uncertainty (k=2)	0.88 %		
Expanded uncertainty (k=1)	0.44 %		

Table 1b Uncertainty Breakdown for Ophir Type 30A at a laser wavelength of 1064 nm and laser power of 1.01 W.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.15 %		
Absorptivity	0.01 %		
Electronics	0.10 %	0.10 %	30
Heater leads	0.01 %		
Window Transmittance	0.11 %	0.02 %	6
Measurements			
Injection time	0.05 %		
Laser power drift	0.50 %		
Standard meter ratio	0.50 %	0.06 %	8
Test Meter ratio		0.01 %	4
Expanded Uncertainty (k=2)	0.86 %		
Expanded Uncertainty (k=1)	0.43 %		

Table 2a Uncertainty Breakdown for Molectron Type PM10 at a laser wavelength of 514.5 nm and laser power of 1.01 W. Type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. Type B evaluation of standard uncertainty is based on scientific judgment using all the relevant information available, which may include items such as previous measurement data, manufacturer's specifications, data provided in calibration and other reports, and/or uncertainties assigned to reference data taken from handbooks. N is the number of individual measurements for a particular Type A component; k is the coverage factor chosen based on the confidence level desired. For the purposes of the EUROMET comparison, a coverage factor of k=1 has been chosen for specifying expanded uncertainties, however, it is NIST policy to specify a coverage factor of k=2.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.15 %		
Absorptivity	0.01 %		
Electronics	0.10 %	0.10 %	30
Heater leads	0.01 %		
Window Transmittance	0.11 %	0.02 %	6
Measurements			
Injection time	0.05 %		
Laser power drift	0.50 %		
Standard meter ratio	0.50 %	0.17 %	8
Test Meter ratio		0.15 %	4
Expanded Uncertainty (k=2)	0.88 %		
Expanded Uncertainty (k=1)	0.44 %		

Table 2b Uncertainty Breakdown for Molectron Type PM10 at a laser wavelength of 1064 nm and laser power of 1.01 W.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.25 %		
Absorptivity	0.59 %		
Electronics	0.34 %		
Heater Leads	0.10 %		
Electrical Calibration		0.10 %	8
Measurements			
Optical Shutter	0.15 %		
Laser/System Instability	0.50 %		
Standard meter ratio		0.15 %	6
Test Meter Ratio		0.18 %	10

Expanded Uncertainty (k=2) 1.05 %

Expanded Uncertainty (k=1) 0.53 %

Table 3a Uncertainty Breakdown for Ophir Type 30A at a laser wavelength of 1064 nm and laser power of 10.2 W. Type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. Type B evaluation of standard uncertainty is based on scientific judgment using all the relevant information available, which may include items such as previous measurement data, manufacturer's specifications, data provided in calibration and other reports, and/or uncertainties assigned to reference data taken from handbooks. N is the number of individual measurements for a particular Type A component; k is the coverage factor chosen based on the confidence level desired. For the purposes of the EUROMET comparison, a coverage factor of k=1 has been chosen for specifying expanded uncertainties, however, it is NIST policy to specify a coverage factor of k=2.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.25 %		
Absorptivity	0.59 %		
Electronics	0.34 %		
Heater Leads	0.10 %		
Electrical Calibration		0.10 %	8
Measurements			
Optical Shutter	0.15 %		
Laser/System Instability	0.50 %		
Attenuator	0.16 %		
Standard meter ratio		0.19 %	6
Test Meter Ratio		0.11 %	10

Expanded Uncertainty (k=2) 1.07 %

Expanded Uncertainty (k=1) 0.54 %

Table 3b Uncertainty Breakdown for Ophir Type 30A at a laser wavelength of 10.6 μm and laser power of 1.0 W.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.25 %		
Absorptivity	0.59 %		
Electronics	0.34 %		
Heater Leads	0.10 %		
Electrical Calibration		0.10 %	8
Measurements			
Optical Shutter	0.15 %		
Laser/System Instability	0.50 %		
Standard meter ratio		0.25 %	6
Test Meter Ratio		0.13 %	10

Expanded Uncertainty (k=2) 1.05 %

Expanded Uncertainty (k=1) 0.53 %

Table 3c Uncertainty Breakdown for Ophir Type 30A at a laser wavelength of 10.6 μm and laser power of 5.3 W.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.25 %		
Absorptivity	0.59 %		
Electronics	0.34 %		
Heater Leads	0.10 %		
Electrical Calibration		0.10 %	8
Measurements			
Optical Shutter	0.15 %		
Laser/System Instability	0.50 %		
Standard meter ratio		0.15 %	6
Test Meter Ratio		0.36 %	10

Expanded Uncertainty (k=2) 1.06 %

Expanded Uncertainty (k=1) 0.53 %

Table 4a Uncertainty Breakdown for Molectron Type PM10 at a laser wavelength of 1064 nm and laser power of 10.2 W. Type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. Type B evaluation of standard uncertainty is based on scientific judgment using all the relevant information available, which may include items such as previous measurement data, manufacturer's specifications, data provided in calibration and other reports, and/or uncertainties assigned to reference data taken from handbooks. N is the number of individual measurements for a particular Type A component; k is the coverage factor chosen based on the confidence level desired. For the purposes of the EUROMET comparison, a coverage factor of k=1 has been chosen for specifying expanded uncertainties, however, it is NIST policy to specify a coverage factor of k=2.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.25 %		
Absorptivity	0.59 %		
Electronics	0.34 %		
Heater Leads	0.10 %		
Electrical Calibration		0.10 %	8
Measurements			
Optical Shutter	0.15 %		
Laser/System Instability	0.50 %		
Attenuator	0.16 %		
Standard meter ratio		0.19 %	6
Test Meter Ratio		0.17 %	10
Expanded Uncertainty (k=2)	1.07 %		
Expanded Uncertainty (k=1)	0.54 %		

Table 4b Uncertainty Breakdown for Molectron Type PM10 at a laser wavelength of 10.6 μm and laser power of 1.0 W.

Source	Type B δ	Type A S_r	N
Standard Calorimeter			
Inequivalence	0.25 %		
Absorptivity	0.59 %		
Electronics	0.34 %		
Heater Leads	0.10 %		
Electrical Calibration		0.10 %	8
Measurements			
Optical Shutter	0.15 %		
Laser/System Instability	0.50 %		
Standard meter ratio		0.25 %	6
Test Meter Ratio		0.20 %	10
Expanded Uncertainty (k=2)	1.07 %		
Expanded Uncertainty (k=1)	0.54 %		

Table 4c Uncertainty Breakdown for Molectron Type PM10 at a laser wavelength of 10.6 μm and laser power of 5.3 W.

Record of detector radiant exposure

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1.02	3.33	
Nd:YAG	1064	1.01	3.33	
Nd:YAG	1064	10.2	2	
CO_2	10600	1.0	4	
CO_2	10600	5.3	2	

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1.01	3.33	
Nd:YAG	1064	1.01	3.33	
Nd:YAG	1064	10.2	2	
CO_2	10600	1.0	4	
CO_2	10600	5.3	2	

Laboratory: NIST
Date: …29 June 2005…   Signature: Marla L. Dowell

Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1.02	5	23	4	1.507	0.02	$6.46x10^{-3}$	9
Nd:YAG	1064	1.01	5	23	4	1.450	0.07	$6.35x10^{-3}$	9
Nd:YAG	1064	10.2	5	23	10	1.432	0.18	$7.52x10^{-3}$	9
CO_2	10600	1.0	5.5	23	10	1.534	0.11	$8.05x10^{-3}$	10
CO_2	10600	5.3	5.5	23	10	1.518	0.13	$8.05x10^{-3}$	9

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1.02	5	23	4	1.666	0.01	$7.13x10^{-3}$	9
Nd:YAG	1064	1.01	5	23	4	1.611	0.15	$7.06x10^{-3}$	9
Nd:YAG	1064	10.2	5	23	10	1.592	0.26	$8.44x10^{-3}$	9
CO_2	10600	1.0	5.5	23	10	1.720	0.17	$9.03x10^{-3}$	10
CO_2	10600	5.3	5.5	23	10	1.706	0.20	$9.13x10^{-3}$	9

Laboratory: …NIST…………………………………………………….

Date: 28 June 2005 Signature: …Marla L. Dowell……………………………..

Appendix 4

France (LNE) report

LNE
Le progrès, une passion à partager

LABORATOIRES DE TRAPPES
29, avenue Roger Hennequin – 78197 TRAPPES Cedex
Tél. : 01 30 69 10 00 – Fax : 01 30 69 12 34

CALIBRATION REPORT

EUROMET Comparison
Project No. 156
EUROMET.PE-S2

Radiant Power of High Power Lasers – Part 1

1. DETECTORS IDENTIFICATION

Detector n°1 :

Manufacturer : OPHIR
Model : 30A-SH
Reference : 1Z02168
Serial number : 68953
Identification : OPH30A3 / PTB 990740981/0001

Detector n°2 :

Manufacturer : MOLECTRON
Model : PM10
Reference : /
Serial number : 0130A00
Identification : PTB 200004392/0001

2. CALIBRATION CONDITIONS

2.1. OBJECT

The calibration of both detectors is done at the power levels and wavelength indicated in the table below, according to the technical protocol « Radiant Power of High Power Lasers – Part 1 » §1.2.

Laser	Wavelength [nm]	Power Level [W]
Argon ion	514.5	1
Nd:YAG	1064	1
Nd:YAG	1064	10
CO2	10600	1
CO2	10600	5

2.2. DATES OF CALIBRATION

20th May – 06th June 2005.

2.3. OPERATOR

Olivier ENOUF

2.4. DESCRIPTION OF THE LASER SOURCES

Sources

Type	:	Laser Argon Spectra-Physics 2040
Beam diameter on the detector	:	5 mm
Beam diameter on LNE reference	:	8 mm

Type	:	Laser YAG Spectron
Beam diameter on the detector	:	5 mm
Beam diameter on LNE reference	:	8 mm

Type	:	CO2 Laser MPB
Beam diameter on the detector	:	5 mm
Beam diameter on LNE reference	:	8 mm

2.5. CALIBRATION METHOD

The detector is calibrated by substitution to the reference detector described below.

The indicator is a navoltmeter HP34420A. An adaptator LEMO size 2/15-pin Sub-D for Ophir 30A and LEMO size 2/25-pin Sub-D for Molectron PM10 is used to connect radiometers to the indicator, according to the technical protocol § 3.1.3.

The number of independent measurements for each calibration point is stated in the result table.

For each comparison, the measurement are recorded during 1 minute after 45 seconds of stabilization for the OPHIR detector and 1 minute for the MOLECTRON according to the technical protocol « Radiant Power of High Power Lasers – Part 1 » §4.3.4.

2.6. LNE REFERENCE

The LNE Reference is WLR2 with nanovoltmeter HP34420A as indicator.

For each comparison, the measurements on the LNE standard are recorded during 1 minute after a 6 minutes stabilization time.

The reference radiometer is a conduction radiometer, constituted by a finned body and a blackened conical absorber. It is calibrated by electrical substitution.

3. CALIBRATION RESULTS

Detector : OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514,5	1,0005	5	23,4	15	1,4753	0,1	0,0057	14
Nd:YAG	1064	1,0096	5	22,9	6	1,4318	0,2	0,0063	5
Nd:YAG	1064	10,126	5	22,9	6	1,4145	0,2	0,0062	5
CO_2	10600	1,0480	5	23,1	5	1,5136	0,1	0,0093	4
CO_2	10600	4,9573	5	23,1	9	1,5049	0,1	0,0070	8

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514,5	1,0016	5	22,9	16	1,6390	0,05	0,0059	15
Nd:YAG	1064	1,0096	5	22,9	6	1,5970	0,10	0,0069	5
Nd:YAG	1064	10,126	5	22,9	6	1,5811	0,10	0,0062	5
CO_2	10600	1,0480	5	23,1	5	1,6975	0,10	0,0103	4
CO_2	10600	4,9615	5	23,1	9	1,6887	0,05	0,0078	8

4. UNCERTAINTIES

According to the technical protocol §6, the uncertainty budget for each detector is described below for a coverage factor of k=1.

The main components are :

Incident power : this component refers to the reference radiometer and includes thermopile fluctuations, voltmeter calibration uncertainty and drift, electrical to optical conversion equivalence, parasitic resistance at the boundaries of the heating coil, sensitivity drift, ageing of the cone, ambient temperature and beam geometry influence.

Beam geometry : The uncertainty of the responsivity on the radiometers OPHIR 30A and MOLECTRON PM10 are defined by the effect of a beam offset of 0.5 mm and determined by interpolation of a beam offset of +/-2 mm. This evaluation is done for a diameter beam of 5 mm ± 1 mm at $1/e^2$.

Thermopile noise : it's the standard deviation of the measurements done with the argon laser for each detector.

The total uncertainty is the quadratic sum of all the components above. The other uncertainty components are negligible.

OPHIR 30A

Laser	Wavelength [nm]	Nominal Power [W]	Uncertainty Incident Power [%]	Standard Responsivity [%]	Beam Geometry [%]	Thermopile Noise [%]	Total uncertainty [%]	Total uncertainty [mV/W]
Argon	514,5	1	0,36	0,10	0,10	0,040	0,39	0,0057
Yag	1064	1	0,38	0,20	0,10	0,039	0,44	0,0063
Yag	1064	10	0,38	0,20	0,10	0,004	0,44	0,0062
CO_2	10600	1	0,60	0,10	0,10	0,036	0,62	0,0093
CO_2	10600	5	0,46	0,05	0,10	0,008	0,47	0,0070

MOLECTRON PM10

Laser	Wavelength [nm]	Nominal Power [W]	Uncertainty Incident Power [%]	Standard Responsivity [%]	Beam Geometry [%]	Thermopile Noise [%]	Total uncertainty [%]	Total uncertainty [mV/W]
Argon	514,5	1	0,36	0,00	0,02	0,013	0,36	0,0059
Yag	1064	1	0,38	0,20	0,02	0,014	0,43	0,0069
Yag	1064	10	0,38	0,10	0,02	0,001	0,39	0,0062
CO_2	10600	1	0,60	0,10	0,02	0,012	0,61	0,0103
CO_2	10600	5	0,46	0,05	0,02	0,003	0,46	0,0078

Appendix 5

South Africa (NMISA) report

Description of the measurement facility and primary scale

This form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated, please use separate sheets of paper as appropriate.

Make and type of primary standard

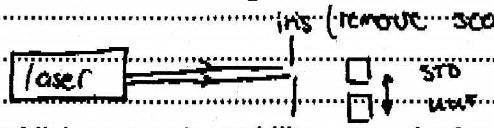
Oxford Instruments cryogenic radiometer (Radiox)

Laboratory transfer standards used (if any):

Absolute room temperature radiometer (Absrad)
Ophir 300W black detector

Description of measuring technique (please include a diagram):

• Direct comparison
(used iris / viewfinder for accurate repositioning)
No filtering or focussing externally



Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty: (k=1) uncertainties

Radiox → Absrad → Ophir 03A-P → Ophir 300W → UUT
(0,1%) (0,4%) (1%) (1,7%)

(last realisation with Radiox in March 2005)

Description of calibration laboratory conditions: e.g. temperature, humidity etc

National laser centre (NLC lab1 : CO_2) 24°C ± 2°C ; 50% RH ± 15% RH
" " " " lab2 : Nd-YAG) 22°C ± 2°C ; " "
University of Pretoria (UP lab1 : Argon) 20°C ± 2°C ; " "

Laboratory: CSIR NML

Date: 10 Oct 2005 Signature: [signature]

Record of detector radiant exposure

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	5	
Nd:YAG	1064	1	5	
Nd:YAG	1064	10	6	
CO_2	10600	1	5	
CO_2	10600	3	5	

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	5	
Nd:YAG	1064	1	5	
Nd:YAG	1064	10	6	
CO_2	10600	1	5	
CO_2	10600	3	5	

Laboratory: CSIR NML

Date: 10 Oct 2005 Signature: [signature]

Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	(k = 1) Uncertainty (mV/W)	Degrees of freedom
Argon	488	1	5	20	6	1,499	0,3	0,030	∞
Nd:YAG	1064	1	5	22	6	1,435	0,4	0,029	∞
Nd:YAG	1064	10	5	22	6	1,414	0,4	0,028	∞
CO_2	10600	1	5	24	6	1,537	0,6	0,038	∞
CO_2	10600	3	5	24	6	1,529	0,6	0,038	∞

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	(k = 1) Uncertainty (mV/W)	Degrees of freedom
Argon	488	1	5	20	6	1,648	0,3	0,033	∞
Nd:YAG	1064	1	5	22	6	1,596	0,4	0,032	∞
Nd:YAG	1064	10	5	22	6	1,576	0,4	0,032	∞
CO_2	10600	1	5	24	6	1,723	0,6	0,043	∞
CO_2	10600	3	5	24	6	1,721	0,6	0,043	∞

Laboratory: CSIR NML

Date: 10 Oct 2005 Signature: [signature]

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	
Procedure No	OR\RA-0002

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9)

Description:	Calibration of an optical power meter	**Type & Serial Number**	Black detector	**Range:**	100 mW - 10 W, 514nm

Metrologist: Pierre Botha

Mathematical Model: none

Symbol	Input Quantity (Source of Uncertainty) (X_i)	Estimated Input Quantity (x_i)	Estimated Uncertainty	Unit	Probability Distribution (N, R, T, U)	k=	Divisor factor	Standard Uncertainty $U(X_i)$	Sensitivity Coefficient c_i	Unit	Standard Uncertainty Contribution $U_i(y)$	Reliability %	Degrees of Freedom ν	Remarks
	▼ Standards and Reference Equipment (Uncorrelated) ▼										Unit			
Std														
	Calibration of STD detector		3.420E+00	%	Normal k = 2		2.00	1.710E+00	1.000E+00	%	1.710E+00	100	infinite	From certificate
	Long-term drift of STD		1.000E-01	%	Normal k = 2		2.00	5.000E-02	1.000E+00	%	5.000E-02	100	infinite	Digital readout
	Laser stability		3.000E-01	%	Rectangular √3		1.73	1.732E-01	1.000E+00	%	1.732E-01	100	infinite	Empirical test RA-02
	Stray light		5.000E-02	%	Rectangular √3		1.73	2.887E-02	1.000E+00	%	2.887E-02	100	infinite	Observed during the calibration (worst case)
	Voltage measurement of UUT		3.000E-03	%	Rectangular √3		1.73	1.732E-03	1.000E+00	%	1.732E-03	100	infinite	Observed during the calibration (worst case)
	Absorbance of STD		5.000E-01	%	Normal k = 2		2.00	2.500E-01	1.000E+00	%	2.500E-01	100	infinite	Spectral characteristic of black detectors
	Linearity of STD		1.000E+00	%	Normal k = 2		2.00	5.000E-01	1.000E+00	%	5.000E-01	100	infinite	Empirical test RA-13
	Uniformity of STD		7.000E-01	%	Normal k = 2		2.00	3.500E-01	1.000E+00	%	3.500E-01	100	infinite	
	Stability of STD		2.000E-01	%	Normal k = 2		2.00	1.000E-01	1.000E+00	%	1.000E-01	100	infinite	
Res	Resolution of Standard / Equipment (If applicable)		5.000E-02		Rectangular √3		1.73	2.887E-02	1.000E+00	%	2.887E-02	100	infinite	
	▼ Standards and Reference Equipment (Correlated) ▼							**NOTE!**	***ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED***					
	▼ Unit Under Test / Calibration (Uncorrelated) ▼							**NOTE!**	***ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED***					
	Linearity of UUT		1.000E+00	%	Rectangular √3		1.73	5.774E-01	1.000E+00	%	5.774E-01	100	infinite	Includes range-to-range mismatch
	Stability of UUT		2.000E-01	%	Rectangular √3		1.73	1.155E-01	1.000E+00	%	1.155E-01	100	infinite	Empirical test RA-01
Res	Resolution of UUT (If applicable)		4.000E-02	%	Rectangular √3		1.73	2.309E-02	1.000E+00	%	2.309E-02	100	infinite	Digital readout
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		3.000E-01	%	Normal K = 1		1.00	3.000E-01	1.000E+00	%	3.000E-01		5	No of Readings 6
	▼ Unit Under Test / Calibration (Correlated) ▼							**NOTE!**	***ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED***					

About UBM	TOTAL COMBINED UNCERTAINTY			Unit			
Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼		1.845E+00	V_{eff}	infinite	Checked and Approved By:
	Expanded Uncertainty	95,45 %	K = 2	3.69E+00	k =	2.00	(k=1) 2%
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼		1.960E+00	V_{eff}	infinite	
	Expanded Uncertainty	95,45 %	K = 2	3.92E+00	k =	2.00	[signature]

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	
Procedure No	OR\RA-0002

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9)

Description:	Calibration of an optical power meter	**Type & Serial Number**	Black detector	**Range:**	100 mW - 10 W, 1064nm	**Metrologist**	Pierre Botha

Mathematical Model: none

Symbol	Input Quantity (Source of Uncertainty) (X_i)	Estimated Input Quantity (x_i)	Estimated Uncertainty	Unit	Probability Distribution (N, R, T, U)	k= ▼	Divisor factor	Standard Uncertainty $U(X_i)$	Sensitivity Coefficient C_i	Unit	Standard Uncertainty Contribution $U_i(y)$	Reliability %	Degrees of Freedom ν	Remarks
	▼ Standards and Reference Equipment (Uncorrelated) ▼										Unit			
Std														
	Calibration of STD detector		3.420E+00	%	Normal k = 2		2.00	1.710E+00	1.000E+00	%	1.710E+00	100	infinite	From certificate
	Long-term drift of STD		1.000E-01	%	Normal k = 2		2.00	5.000E-02	1.000E+00	%	5.000E-02	100	infinite	Digital readout
	Laser stability		4.000E-01	%	Rectangular √3		1.73	2.309E-01	1.000E+00	%	2.309E-01	100	infinite	Empirical test RA-02
	Stray light		5.000E-02	%	Rectangular √3		1.73	2.887E-02	1.000E+00	%	2.887E-02	100	infinite	Observed during the calibration (worst case)
	Voltage measurement of UUT		3.000E-03	%	Rectangular √3		1.73	1.732E-03	1.000E+00	%	1.732E-03	100	infinite	Observed during the calibration (worst case)
	Absorbance of STD		5.000E-01	%	Normal k = 2		2.00	2.500E-01	1.000E+00	%	2.500E-01	100	infinite	Spectral characteristic of black detectors
	Linearity of STD		1.000E+00	%	Normal k = 2		2.00	5.000E-01	1.000E+00	%	5.000E-01	100	infinite	Empirical test RA-13
	Uniformity of STD		7.000E-01	%	Normal k = 2		2.00	3.500E-01	1.000E+00	%	3.500E-01	100	infinite	
	Stability of STD		2.000E-01	%	Normal k = 2		2.00	1.000E-01	1.000E+00	%	1.000E-01	100	infinite	
Res	Resolution of Standard / Equipment (If applicable)		5.000E-02		Rectangular √3		1.73	2.887E-02	1.000E+00	%	2.887E-02	100	infinite	
	▼ Standards and Reference Equipment (Correlated) ▼							**NOTE!**	*ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED*					
	▼ Unit Under Test / Calibration (Uncorrelated) ▼							**NOTE!**	*ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED*					
	Linearity of UUT		1.000E+00	%	Rectangular √3		1.73	5.774E-01	1.000E+00	%	5.774E-01	100	infinite	Includes range-to-range mismatch
	Stability of UUT		2.000E-01	%	Rectangular √3		1.73	1.155E-01	1.000E+00	%	1.155E-01	100	infinite	Empirical test RA-01
Res	Resolution of UUT (If applicable)		4.000E-02	%	Rectangular √3		1.73	2.309E-02	1.000E+00	%	2.309E-02	100	infinite	Digital readout
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		4.000E-01	%	Normal K = 1		1.00	4.000E-01	1.000E+00	%	4.000E-01		5	No of Readings 6
	▼ Unit Under Test / Calibration (Correlated) ▼							**NOTE!**	*ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED*					

About UBM	TOTAL COMBINED UNCERTAINTY			Unit			
Best Measurement Capability (ExcludingUUT contribution)		Combined Uncertainty (Normal)	▼ Level of Confidence ▼	1.851E+00	V_{eff}	infinite	Checked and Approved By:
		Expanded Uncertainty	95,45 % K = 2	3.71E+00	k =	2.00	(k=1) 2%.
Uncertainty of Measurement (Including UUT contribution)		Combined Uncertainty (Normal)	▼ Level of Confidence ▼	1.983E+00	V_{eff}	infinite	
		Expanded Uncertainty	95,45 % K = 2	3.97E+00	k =	2.00	

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	
Procedure No	OR\RA-0002

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 [ISBN 92-67-10188-9]

Description:	Calibration of an optical power meter	Type & Serial Number	Black detector	Range:	100 mW - 10 W 10um	Metrologist: Pierre Botha

Mathematical Model: none

Symbol	Input Quantity (Source of Uncertainty) X_i	Estimated Input Quantity x_i	Estimated Uncertainty	Unit	Probability Distribution (N, R, T, U)	k=	Divisor factor	Standard Uncertainty $u(x_i)$	Sensitivity Coefficient c_i	Unit	Standard Uncertainty Contribution $u_i(y)$ Unit	Reliability %	Degrees of Freedom ν	Remarks
	▼ Standards and Reference Equipment (Uncorrelated) ▼													
Std														
	Calibration of STD detector		4.300E+00	%	Normal k = 2		2.00	2.150E+00	1.000E+00	%	2.150E+00	100	infinite	From certificate
	Long-term drift of STD		1.000E-01	%	Normal k = 2		2.00	5.000E-02	1.000E+00	%	5.000E-02	100	infinite	Digital readout
	Laser stability		1.000E+00	%	Rectangular √3		1.73	5.774E-01	1.000E+00	%	5.774E-01	100	infinite	Empirical test RA-02
	Stray light		5.000E-02	%	Rectangular √3		1.73	2.887E-02	1.000E+00	%	2.887E-02	100	infinite	Observed during the calibration (worst case)
	Voltage measurement of UUT		3.000E-03	%	Rectangular √3		1.73	1.732E-03	1.000E+00	%	1.732E-03	100	infinite	Observed during the calibration (worst case)
	Absorbtance of STD		5.000E-01	%	Normal k = 2		2.00	2.500E-01	1.000E+00	%	2.500E-01	100	infinite	Spectral characteristic of black detectors
	Linearity of STD		1.000E+00	%	Normal k = 2		2.00	5.000E-01	1.000E+00	%	5.000E-01	100	infinite	Empirical test RA-13
	Uniformity of STD		7.000E-01	%	Normal k = 2		2.00	3.500E-01	1.000E+00	%	3.500E-01	100	infinite	
	Stability of STD		2.000E-01	%	Normal k = 2		2.00	1.000E-01	1.000E+00	%	1.000E-01	100	infinite	
Res	Resolution of Standard / Equipment (If applicable)		5.000E-02		Rectangular √3		1.73	2.887E-02	1.000E+00	%	2.887E-02	100	infinite	
	▼ Standards and Reference Equipment (Correlated) ▼								**NOTE!**		ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED			
	▼ Unit Under Test / Calibration (Uncorrelated) ▼								**NOTE!**		ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED			
	Linearity of UUT		1.000E+00	%	Rectangular √3		1.73	5.774E-01	1.000E+00	%	5.774E-01	100	infinite	Includes range-to-range mismatch
	Stability of UUT		2.000E-01	%	Rectangular √3		1.73	1.155E-01	1.000E+00	%	1.155E-01	100	infinite	Empirical test RA-01
Res	Resolution of UUT (If applicable)		4.000E-02	%	Rectangular √3		1.73	2.309E-02	1.000E+00	%	2.309E-02	100	infinite	Digital readout
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		6.000E-01	%	Normal K = 1		1.00	6.000E-01	1.000E+00	%	6.000E-01		5	No of Readings 6
	▼ Unit Under Test / Calibration (Correlated) ▼								**NOTE!**		ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED			

About UBM

TOTAL COMBINED UNCERTAINTY			Unit			
Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	2.325E+00	V_{eff}	infinite	Checked and Approved By:
	Expanded Uncertainty	95,45 % K = 2	4.66E+00	k =	2.00	(k=1) 2,5%
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	2.472E+00	V_{eff}	infinite	[signature]
	Expanded Uncertainty	95,45 % K = 2	4.95E+00	k =	2.00	

Appendix 6

Japan (NMIJ) report

Report on radiant power of high power lasers – Part 1 (EUROMET Comparison, PR-S2) at the NMIJ/AIST

M. Endo, S. Kimura

National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST)

1. Make and type of primary standard

Figure 1 shows the laser power measurement equipment using our primary standard calorimeter, MLC-2. The principle of the measurement is based on an isothermal type calorimeter using thermoelectric elements. The isothermal type calorimeter used in this comparison measurements was designed and built at NMIJ/AIST. Their critical parameters have been evaluated at relevant laser wavelengths. Accurate quantitative responsivity characterization of the calorimeter is accomplished by electrical heater calibrations. The detail is described in the paper [1]. The calorimeter can be used for a dynamic range of laser power from 0.1 W to 10 W in the wavelength region from 0.4 µm to 11 µm. This calorimeter has two absorbing units (AUs) usable for wide wavelength regions. The practical operating parameters for the calorimeter are summarized in Table 1. The AU consists of a disk absorber, a cylindrical cover, and a dc calibrating heater. The diameter of the disk is 50 mm and its thickness is 0.9 mm. The front surface of one disk (disk-1) is made of ultra-black Nickel-Phosphorus alloy with good absorption for 0.4 µm to 2 µm wavelength while the other disk (disk-2) is made of carbon-doped ceramic with high melting point for the wavelength region of 1.5 µm to 11 µm. The disk is tilted from normal by 30 degrees so that any specular reflection from the surface will be absorbed on the internal black-coating wall of the cylindrical cover. The effective diameter of the aperture of the disk absorber is more than three times the beam diameter, so that the portion of the incident laser beam leaked out from the absorber is very small. The characteristics of the isothermal type calorimeter are shown in Table 2.

2. Laboratory transfer standards used (if any). We did not use any laboratory transfer standard.

3. Description of measuring technique

The comparison is carried out through the calibration of two transfer detectors, the laser power meter heads OPHIR 30A and MOLECTRON PM10. These detectors are provided by the pilot laboratory.

Figure 2 shows laser power calibration system by an exchange comparison method. The system consists of a power stabilized laser sources at wavelengths of 514.5 nm (Argon ion laser), 1.064 µm (Nd:YVO_4 laser, 100 kHz repetition rate) and 10.6 µm (CO_2 laser), lenses, an electromagnetic shutter, beam apertures, a beam splitter, a monitor detector and two stages for positioning the NMIJ/AIST primary standard calorimeter (MLC-2) and the transfer detectors. The laser beam is switched off or on using the shutter. The beam splitter used in this system has been characterized for all specific wavelengths. The beam reflected from the beam splitter is directed on to the monitor detector. Small angle of incidence minimizes polarization uncertainties. The monitor detector is used to monitor the laser power stability during the calibration measurement. The transmitted beam is directed on to the calorimeter or the transfer detectors, which are placed just before the calorimeter during their measurements.

The laser power irradiating the calorimeter and the monitor output are measured simultaneously to obtain the spectral responsivity of the monitor detector. This step is then repeated to re-check the responsivity of the monitor. MLC-2 is aligned to the incident beam center using a positioning stage. Then calorimetric measurement is carried out and incident laser power is determined.

The transfer detector is then moved to just before the calorimeter. The detector is aligned to the beam using X-Y translation stage, so that the beam goes to the center of the sensitive surface of the detector and the output voltages of the transfer detectors are measured with a calibrated high precision digital voltmeter (Agilent 34420A).

The measurand is the spectral responsivity of the detectors. The spectral responsivity of the detector is determined as the ratio of the output voltage of the transfer detector to the power measured by the calorimeter in mV/W.

The calibration measurement is performed 15 times for each transfer detector following the normal procedure of calibration by the NMIJ/AIST. In each time of the detectors are exposed for 60 s before voltage reading. The value recorded for this time is the mean of ten data each taken every one second. The offset voltage of the detectors is also measured and this value was used for compensation of the measured value. The measurement is performed automatically by a computer controlled system. The mean value and the standard deviations of the measurements are calculated.

The approximate exposure time of each detector to the laser radiation during operation are given in Table 5. Calibration measurement, alignments and spatial uniformity test are included in the exposure time.

4. Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty

Instruments used for this comparison is managed based on primary standard and the results of calibrations are traceable to SI unit as shown in Fig. 3.

The evaluation of the uncertainty has been made based on the ISO Guide [2]. The uncertainty due to difference of wavelength generally depends on the reflection characteristics of absorbers. The uncertainty evaluation has been referenced in the paper [3]. The uncertainty budgets are shown in Table 3, 4, where, the uncertainty factors of equivalence, heater power, deviation of control system, spatial uniformity and scatter of measurement are that of the standard calorimeter. The uncertainty of the transfer detector includes spatial uniformity of the sensor, laser power stability, beam profile, temperature, etc., but it is considered to be superimposed in the scatter of calibration measurement.

5. Description of calibration laboratory conditions: e.g. temperature, humidity etc

The room temperature of calibration is (22.5°± 0.5°) C and the humidity is (65 % ± 15 %). The transfer detectors are held in the room for more than one day before calibration.

6. Results of the comparison

The beam profile of our laser outputs was nearly Gaussian. The actual beam size was 4.6 mm, 5.1 mm and 5.2 mm in diameter at $1/e^2$ intensity points at 514.5 nm, 1.064 µm and 10.6 µm wavelengths, respectively. These measurements have been using pin-hole method and knife edge method.

The standard uncertainties of the NMIJ/AIST laser power measurements were evaluated in accordance with international document standards, and total relative standard uncertainty (k = 1) for this comparison is 0.5 % at the wavelength of 514.5 nm and 1.064 µm, and 0.6 % at the wavelength of 10.6 µm. The measurement results of the comparison are given in Table 6.

References

[1] M. Endo and T. Inoue, " A Double Calorimeter for 10 W Level Laser Power Measurements," *IEEE Trans. Instrum. Meas.*, vol. 54, No. 2, pp. 688-691, 2005.

[2] "ISO, Guide to the Expression of Uncertainty in Measurement," International Organization for Standardization, Geneva, Switzerland, 1993.

[3] T. Inoue and K. Sato, “Broadband rf power standard for 7mm coaxial waveguide in the frequency range of 10 MHz – 18 GHz, -evaluation of uncertainty-,” *Bulletin of the Electrotechnical Laboratory,* vol. 64, No. 1, pp. 11-17, 2000.

Appendix (Answer for the Appendix F in the technical protocol)

Appendix F:List of influence parameters for calibration of laser power heads

The uncertainty budget should at least take into account the following components (even if it is stated that the contribution of one or the other of the components listed below is negligible):

- measured responsivity of transfer detector: Table 6
- responsivity of laboratory standard: Table 2
- voltage measurement of transfer detector: “Voltmeter” in Table 3,4
- voltage measurement of standard: Table 3 for the MLC-2, U1 (voltage, resistance measurement of the disk), Table 4 for the MLC-2, U2 (voltage, resistance measurement of the disk and cylindrical cover)
- absorptance of standard: “Reflection” in Table 3 for the MLC-2, U1 (absorptance: <99 %, 0.48 µm to 1.6 µm for the disk-1), “Reflection” in Table 4 for MLC-2, U2 (absorptance: about 95 % at 10.6 µm for the disk-2)
- non homogeneity of transfer (if operating conditions (laser beam diameter, beam profile, position) differ): 1. actual beam diameter and beam profile: in the text

  2. actual beam position: ±0.2 mm offset at the center
- non homogeneity of standard: ±2 mm offset at the center
- temperature dependence of transfer detector (only if required): not considered for the range of 22.5 °C± 0.5 °C
- temperature dependence of standard: not considered for the range of 22.5 °C± 0.5 °C
- power dependence of transfer detector (only if required) : not considered
- power dependence of standard: we use different coefficients by the power level
- stability of transfer detector (based on the information from the pilot laboratory)
- stability of standard during the calibration process
- stability of standard between its own calibrations (long term drift)

- different wavelength (only if required)

- stray light: we ignored stray light

- power stability of laser source and set-up (e.g. with or without monitoring system): 514.5 nm (Argon ion laser): 0.1 %/30 min, 1.064 µm (Nd:YVO_4 laser): 0.4 %/30 min, 10.6 µm (CO_2 laser): 0.7 %/30 min

- (humidity): in the text

- (pressure): influenced by a change of atmospheric pressure, but ignore this influence because there were only negligible changes of atmospheric pressure during the comparison measurements

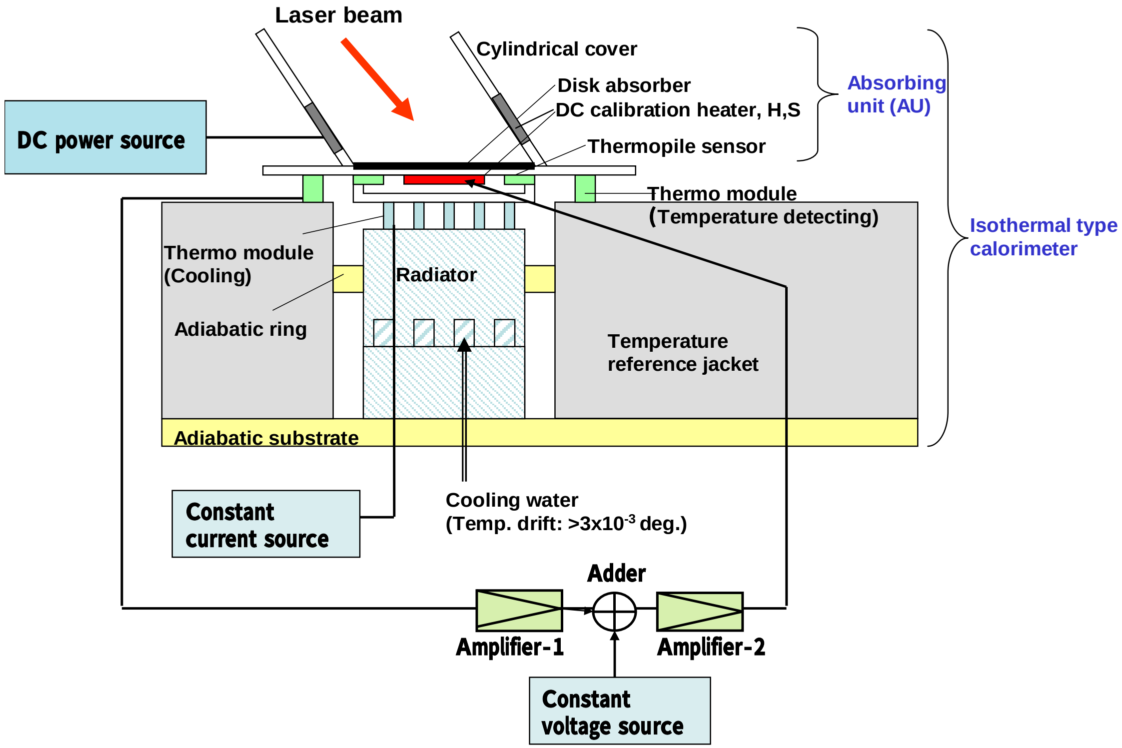


Fig. 1. Principle of the calorimeter system.

Actual calorimeter has two disk absorbers (disk-1 for 0.4 to 2 μm wavelength and disk-2 for 1.5 to 11 μm wavelength) usable for a wide wavelength region. To remove the effects of surrounding temperature drift, the calorimeter works by a differential connection.

Table 1

OPERATING PARAMETERS OF THE CALORIMETER

Power range	from 0.1 to 10 W
Maximum power intensity	＞12 kW/cm^2
Wavelengths	from 0.4 to 11 μm
Beam diameter	from 1.0 to 8.0 mmΦ

Table 2

BASIC CHARACTERISTICS OF THE ISOTHERMAL TYPE CALORIMETER

Thermo-module (for temperature detecting)	7 pairs of thermoelectric elements x 8
Thermo-module (for cooling)	31 pairs of thermoelectric elements x 1
Sensitivity	55 mV/W
Noise equivalent power	1.8 μW
Time constant without control with control	110 sec 6.9 sec

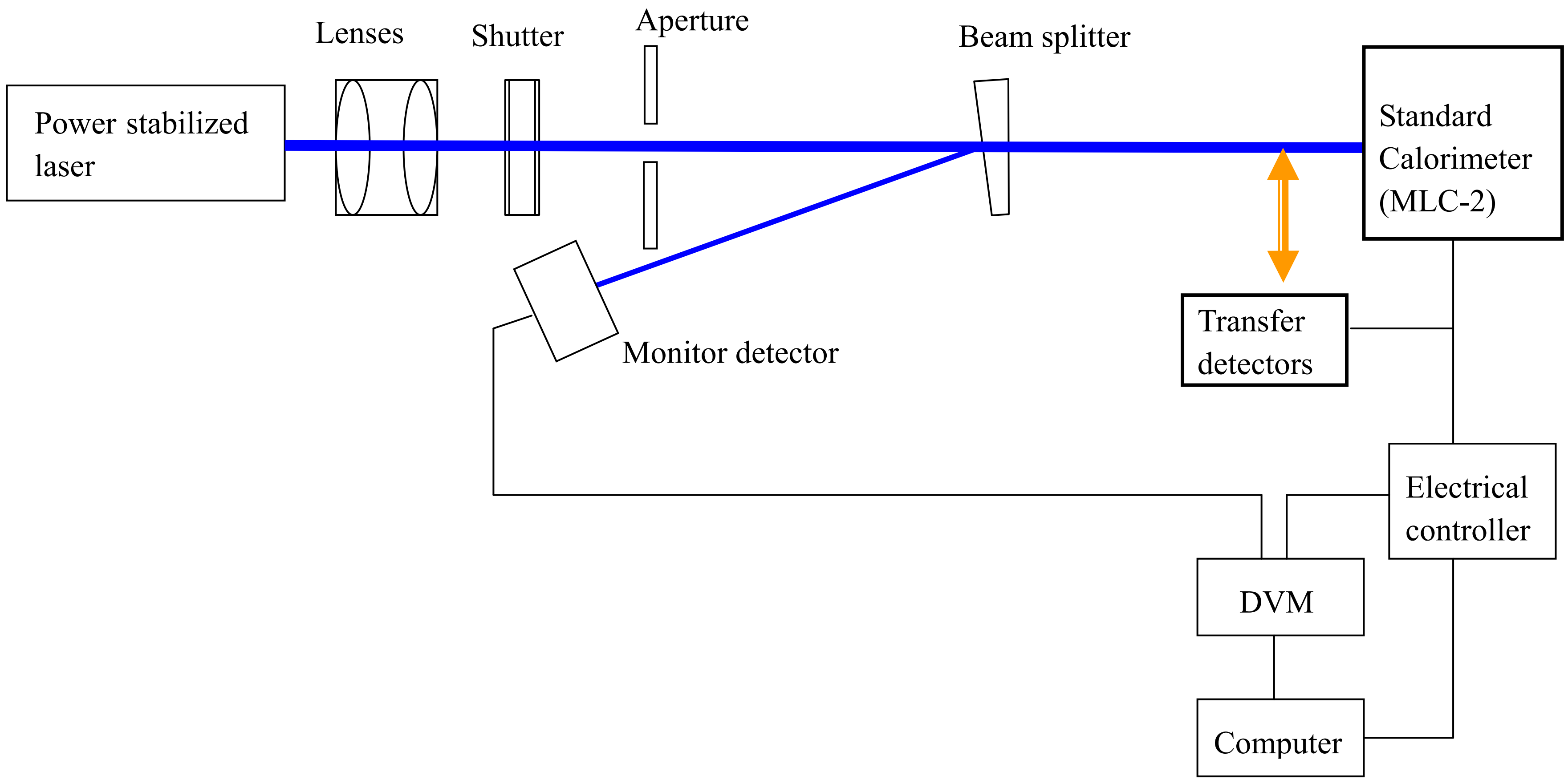


Fig. 2. Principal setup for calibration of 1–10 W laser power detectors at the NMIJ/AIST

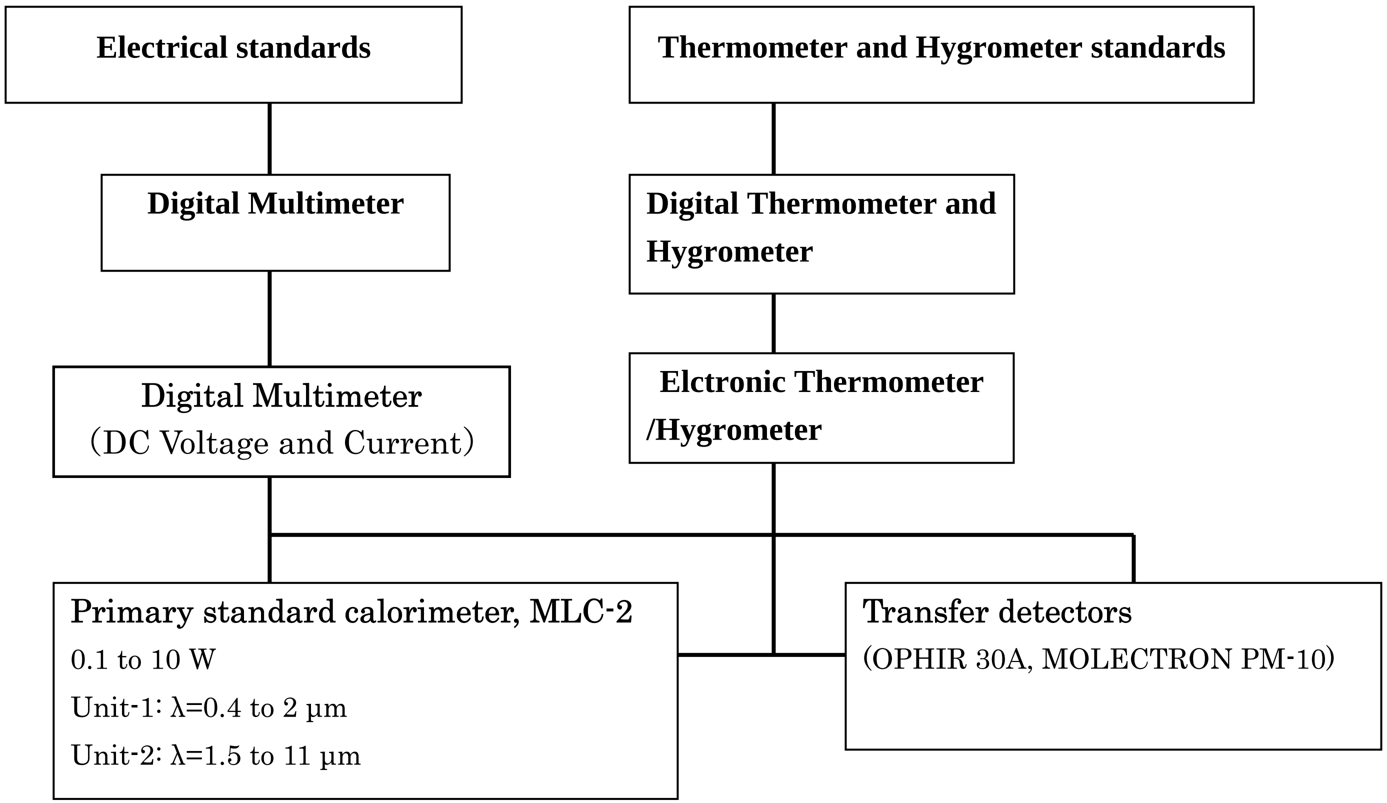


Fig. 3 Traceability chart of laser power calibration at the NMIJ/AIST

Table 3 Uncertainty budget, MLC-2,U1

0.515μm, 1 W and 1.06 μm, 1～10 W

Uncertainty factor		Degree of freedom	Magnitude (%)	Type	Probability distribution	Standard uncertainty (%)
Primary standard (MLC-2,U1)						
Equivalence (substitution coefficient between dc and laser power)	Disk-1	*	0.21	B	uniform	0.12
	Cylindrical cover	*	0.03	B	uniform	0.02
	Reflection	*	0.01	B	uniform	0.01
DC instrument-heater power (voltage, resistance)	Disk-1	*	0.10	B	uniform	0.06
	Cylindrical cover	-	-			
Deviation of control system		*	0.02	B	uniform	0.01
Spatial uniformity	2mm×2mm	*	0.18	B	uniform	0.10
Scatter-standard meas.		14	0.21	A	normal	0.21
Comparison (laser power meter head)						
Voltmeter-comparison, n=15		14	0.01	A	normal	0.01
Scatter-comparison, n=15, (alignment, laser power stability, monitor, beam profile)		14	0.39	A	normal	0.39
A-type uncertainty	ucA					0.44
B-type uncertainty	ucB					0.17
Combined standard uncertainty						0.47
Effective degrees of freedom of A-type uncertainty		22				
Effective degrees of freedom		28				
Coverage factor		2.05				
Standard uncertainty (k=1)						0.47

*: infinity

Table 4 Uncertainty budget, MLC-2,U2

10.6 µm, 1～10 W

Uncertainty factor		Degree of freedom	Magnitude (%)	Type	Probability distribution	Standard uncertainty
Primary standard (MLC-2,U2)						
Equivalence (substitution coefficient between dc and laser power)	Disk-2	*	0.21	B	uniform	0.12
	Cylindrical cover	*	0.23	B	uniform	0.13
	Reflection	*	0.03	B	uniform	0.02
DC instrument-heater power (voltage, resistance)	Disk-2	*	0.10	B	uniform	0.06
	Cylindrical cover	*	0.01	B	uniform	0.01
Deviation of control system		*	0.02	B	uniform	0.01
Spatial uniformity	2mm×2mm	*	0.20	B	uniform	0.12
Scatter-standard meas.		14	0.27	A	normal	0.27
Comparison (laser power meter head)						
Voltmeter-comparison, n=15		14	0.01	A	normal	0.01
Scatter-comparison, n=15, (alignment, laser power stability, monitor, beam profile)		14	0.44	A	normal	0.44
A-type uncertainty	ucA					0.52
B-type uncertainty	ucB					0.22
Combined standard uncertainty						0.56
Effective degrees of freedom of A-type uncertainty		23				
Effective degrees of freedom		33				
Coverage factor		2.04				
Standard uncertainty (k=1)						0.56

*: infinity

Table 5. Record of detector radiant exposure

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	40	Spatial uniformity test (10 min) + alignments (15 min) + power meas. (1 min, 15 times)
Nd:YVO_4	1064	1	30	alignments (15 min) + power meas. (1 min, 15 times)
Nd:YVO_4	1064	9.1	30	alignments (15 min) + power meas. (1 min, 15 times)
CO_2	10600	1	30	alignments (15 min) + power meas. (1 min, 15 times)
CO_2	10600	5	30	alignments (15 min) + power meas. (1 min, 15 times)

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	40	Spatial uniformity test (10 min) + alignments (15 min) + power meas. (1 min, 15 times)
Nd:YVO_4	1064	1	30	alignments (15 min) + power meas. (1 min, 15 times)
Nd:YVO_4	1064	9.1	30	alignments (15 min) + power meas. (1 min, 15 times)
CO_2	10600	1	30	alignments (15 min) + power meas. (1 min, 15 times)
CO_2	10600	5	30	alignments (15 min) + power meas. (1 min, 15 times)

Laboratory: National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology
Date: 09th August, 2006 Signature:

Table 6. Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1	4.6	22.5±0.5	15	1.508	0.05	0.0071	28
Nd:YVO_4	1064	1	5.1	22.5±0.5	15	1.470	0.15	0.0069	28
Nd:YVO_4	1064	9.1	5.1	22.5±0.5	15	1.451	0.17	0.0068	28
CO_2	10600	1	5.2	22.5±0.5	15	1.521	0.29	0.0085	33
CO_2	10600	5	5.2	22.5±0.5	15	1.516	0.22	0.0085	33

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (°C)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	1	4.6	22.5±0.5	15	1.666	0.05	0.0078	28
Nd:YVO_4	1064	1	5.1	22.5±0.5	15	1.633	0.19	0.0077	28
Nd:YVO_4	1064	9.1	5.1	22.5±0.5	15	1.613	0.19	0.0076	28
CO_2	10600	1	5.2	22.5±0.5	15	1.697	0.20	0.0095	33
CO_2	10600	5	5.2	22.5±0.5	15	1.691	0.22	0.0095	33

Laboratory: National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology

Date: 09th August, 2006   Signature:

Appendix 7

United Kingdom (NPL) report

REPORT ON NPL RESULTS FOR EUROMET 156

A multilateral intercomparison of laser power calibration
between NPL and other NMI's

M.A. Basu, S.R.G.Hall

1 Introduction

1.1 Scope of intercomparison

Laser	Wavelength	Power
Argon ion	514.5 nm	1 W
Nd:YAG	1064 nm	1 W
Nd:YAG	1064 nm	10 W
CO_2	10.6 μm	1 W
CO_2	10.6 μm	5 W

For the international intercomparison measurements are required at 1053 nm (Nd:YLF laser - our nearest available wavelength to 1064 nm) at 1 W and 10 W. Measurements are also required at 10,600 nm (CO2) at 1 W and 5 W. NPL adhered to the specified measurement conditions of: 5 mm spot size (truncated Gaussian), ambient temp 22 ± 1 °C, and power on the Devices under test (DuT) was within 10% of the specified value. NPL followed PTB's recommended method of alignment. Humidity was not recorded but was known to be non-condensing.

NPL's secondary laboratory standard for laser power is a Laser Instrumentation 14BT thermopile, which has been calibrated against the NPL cryogenic radiometer. A Laser Instrumentation 17S thermopile is used as a secondary standard at powers up to 1 W, and a Coherent 201 radial thermopile is used for powers greater than 1 W.

2 Results

http://www.ophiropt.com/laser/support/laser_power_meters_faq.htm#general06

What is spec on uniformity over the surface?
A: It is not published in the brochures but uniformity over surface is generally +/- 2%

30A / 30A-P

CW & Pulsed Measurements 20mW - 30W 6mJ - 30J

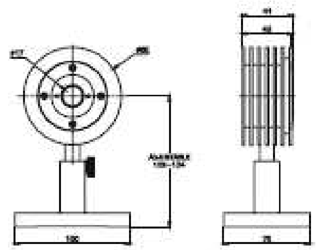
Recommended Use: General, powers to 30W
Special Features: 30A: Fast response, wide dynamic range
30A-P: Flat spectral response for pulsed lasers

Absorber:	Broadband, 0.19 - 20µm , P type 0.15 - 6µm			
Aperture:	Ø17mm			
Digital Power Scales:	30W / 3W			
Maximum Average Power Density:	Broadband 25KW/cm², P type 50W/cm²			
Power Noise Level:	BB: 1mW, P: 3mW			
Power Accuracy:	±3%			
Maximum Energy Density J/cm² a	single shot		10 - 30Hz	
Head type:	BB	P	BB	P
<100ns	0.3	10	0.3	1
0.5ms	2	10	2	1
2ms	2	10	2	1
10ms	2	10	2	1
Response Time with Display (0-95%):	BB: 0.8s, P: 2.5s			
Linearity with Power:	± 1%			
Energy Scales:	30J / 3J			
Energy Threshold:	BB: 6mJ, P: 30mJ			
Linearity with Energy:	±1.5% ±50µJ			
Cooling:	Convection			

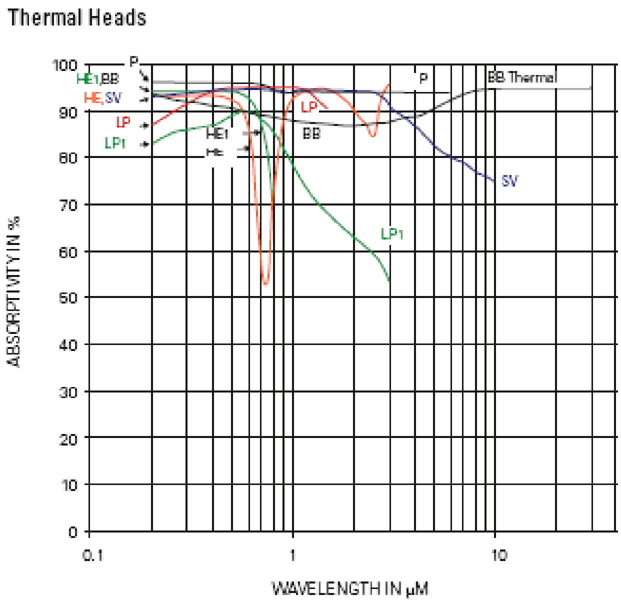
Note: a. For shorter wavelengths derate to values shown:

Wavelengths	Derate to value
355nm	40%
266nm	10%
193nm	10%

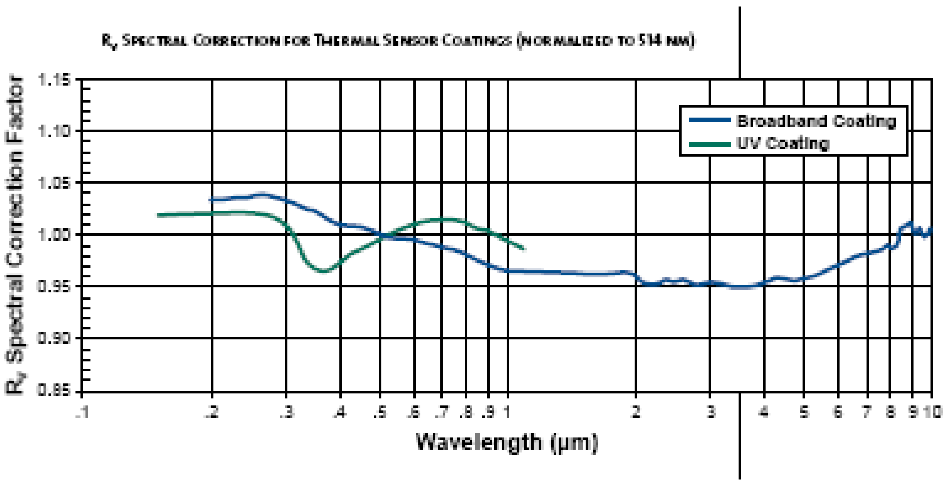
30A-P



http://www.coherent.com/Lasers/index.cfm?fuseaction=show.page&id=703&loc=830



Name	PM10
Wavelength Range (µm)	0.19 - 11
Active Area Diameter (mm)	19
Max Power (W)	10
Intermittent Power (<5 min) (W)	30
Calibration Wavelength (nm)	514
Calibration Uncertainty (%)	1
Maximum Average Power Density (kW/cm²)	26
Maximum Pulse Energy Density (J/cm²)	0.6
Response Time (sec.)	2
Detector Coating	Broadband
Description	--
Dimensions (mm)	Ø 63 x 36
Part Number	0012-0920



Make and type of primary standard..
Oxford Instruments mechanically cooled cryogenic radiometer.....
There is no Type designation....................................
....
....
Laboratory transfer standards used (if any):...
Laser Instrumentation 17S was used for powers up to 1 W
Coherent 201 is used for powers greater than 1 W
Molectron PM150-B..
....
....
Description of measuring technique (please include a diagram): ....

3 Measurement technique

NPL used two methods to measure the PTB devices: Ratio method and substitution method. Due to the ratio method's superior rejection of laser output instability and ambient temperature instability effects, it was the preferred method, but the substitution method was also used and the consistency of the two methods compared. For the YLF measurements at 10 W the substitution method alone was used because the YLF laser cannot source adequate power to achieve 10 W on the detector using the ratio method optical setup.

Three different NPL secondary reference detectors were used and the results were compared for consistency.

3.2 Ratio method description

The ratio method is a means of simultaneously measuring a laboratory standard reference device (Ref) and the Device under Test (DuT). Apertures are centred on the laser beams and set to a diameter which results in a total power level ($1-1/e^2$) times the total power of the unapertured beam. Lenses are used to image the apertures to form 5 mm diameter spots on the detectors. Providing that both devices have similar response times, this technique minimises any effect of laser stability and ambient temperature fluctuations. The optical setup is shown in Fig 1. Measurements are performed twice; with the Ref and DuT swapped between measurements. This allows the small difference in the powers of the two beams to be calculated and hence the relative sensitivity of the DuT can be calculated.

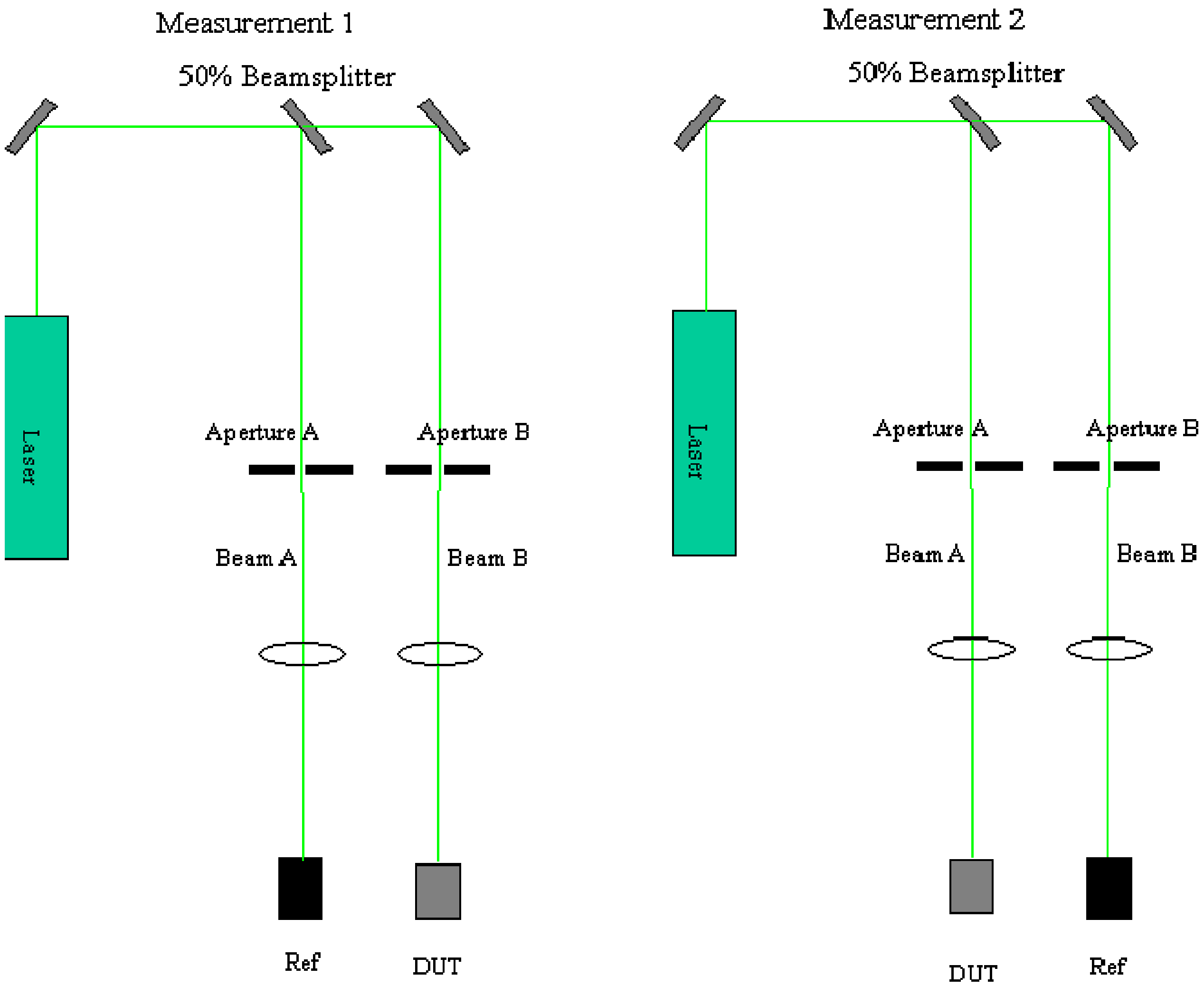


Fig 1. Ratio method.

With the ratio method, two sets of measurements are made using two beams. The relative intensities of the two beams need not be known nor be identical and the resultant sensitivity is given by the geometric mean of the two measurements.

$$S_{DUT} = S_{ref}\sqrt{\left(\frac{V_{DUT}^{1}}{V_{ref}^{2}}\right)\left(\frac{V_{DUT}^{2}}{V_{ref}^{1}}\right)}$$

where the superscripts 1 and 2 refer to the beams. The ratios are for measurements a and b.

The uncertainty contribution from the measurements is

$$\frac{1}{2}\sqrt{\left(u_a^2 + u_b^2\right)}$$

where u_a and u_b are the percentage standard deviations from the two measurements. If $u_b = u_a$ (which will normally be approximately true) then the uncertainty is: $\frac{u_a}{\sqrt{2}}$

We should note that the uncertainty (standard deviation) is smaller using the ratio method although the total number of measurements is double that of the substitution method.

3.3 Substitution method

The substitution method involves alternately placing the Ref and DuT in the beam for measurement. An aperture is centred on laser beam and set to a diameter, which results in a total power level ($1\text{-}1/e^2$) times the total power of the unapertured beam (Gaussian distribution). A lens is used to image the aperture to form a 5 mm diameter spot on the detector. Providing that the laser stability and environmental conditions are stable, this method gives good results. The advantage of this method over the substitution method is that it allows for measurements at powers greater than 50% of the laser's maximum output; hence it was used for YLF measurements at 10 W. The optical setup is shown in Fig 2.

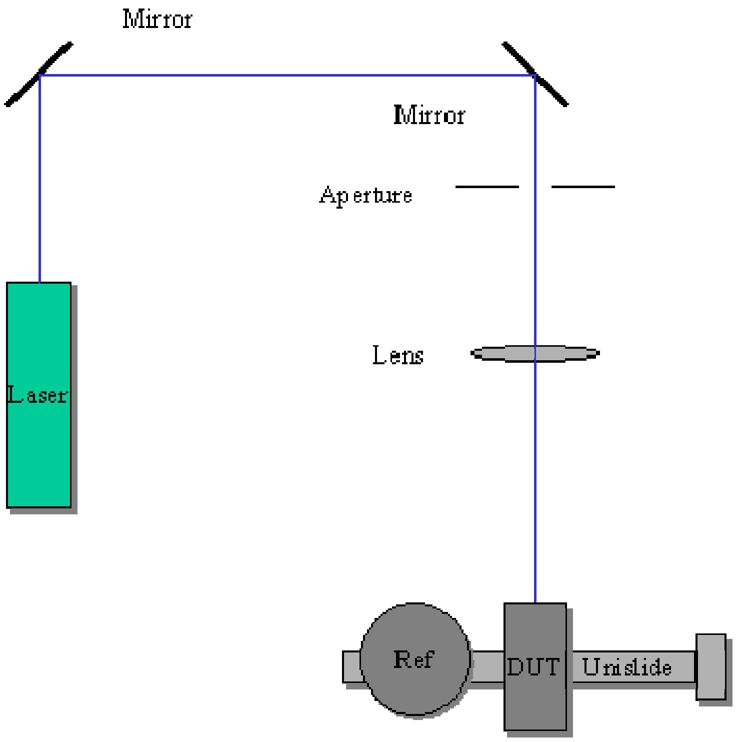


Fig 2 Substitution method setup. The unislide is a motor driven translation stage which places each detector in the beam in turn.

3.4 YLF results

The results and their associated uncertainties are given in Table I.

Table I

Device	Power W	Sensitivity V/W	Uncertainty % (k = 1)	Degrees of freedom (ν_{eff})
Ophir 30A-SH	1	0.001486	0.427	12994
Ophir 30A-SH	10	0.001463	0.616	91573
Coherent PM10	1	0.001640	0.432	4946
Coherent PM10	10	0.001636	0.615	150039

3.1 CO_2 results

The results and their associated uncertainties are given in Table II.

Table II

Device	Power W	Sensitivity V/W	Uncertainty % (k = 1)	Degrees of freedom (Veff)
Ophir 30A-SH	1	0.001562	0.431	5650
Ophir 30A-SH	5	0.001559	0.619	53848
Coherent PM10	1	0.001738	0.429	7651
Coherent PM10	5	0.001733	0.618	66715

It was noted that the Ophir device shows an unusually large non-linearity for the YLF results (see Table III). As a confirmation it was also measured at 10 W on the CO_2 laser; the non-linearity was evident in the CO_2 results.

Table III power nonlinearity *

For PM10 the ratio between 1 W and 5 W is	0.31
For PM10 the ratio between 1 W and 10 W is	0.26
For 30A-SH the ratio between 1 W and 5 W is	0.17
For 30A-SH the ratio between 1 W and 10 W is	1.52

*

$$\left[\frac{S_{Hi} - S_{Lo}}{\frac{(S_{Hi} - S_{Lo})}{2}}\right] \times 100 = \text{power nonlinearity } \%$$

S_{Hi} = Sensitivity at higher power

S_{Lo} = Sensitivity at lower power

3.2 Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty:

3.2.1 Description of the measurement facility and primary scale

The laser calibration chain (see Figure 3) is based on the radiometrically determined watt, derived from the electrical watt using a cryogenic radiometer. The primary standard is transferred to a thermopile detector, calibrated for cw radiation in the visible spectrum at a power of around 1 milliwatt. The response of this detector is essentially spectrally flat in the visible and near infrared, and is used to provide our cw power standards at the watt level and above at several wavelengths by using chopper wheels with accurately determined transmission ratios.

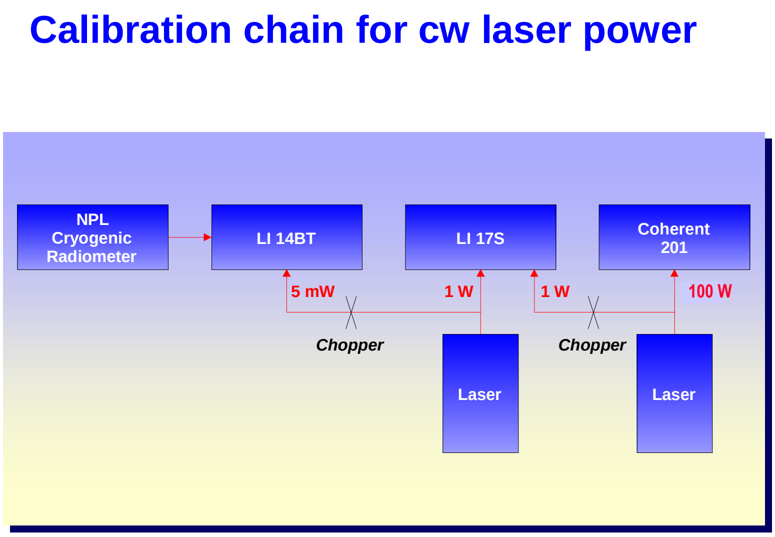


Fig 3 Traceability chain for cw laser power

3.2.2 *Uncertainty table for contributions to the transfer detector calibration*

Table IV

Source of Uncertainty	Notes on uncertainty contributions
-responsivity of laboratory standard	normal
-measured responsivity of transfer detector (note that this can be due to the ratio measurement method or the substitution method depending on the measurement see sect 3.2)	normal
-voltage measurement of transfer detector	normal
-voltage measurement of standard	normal
-absorptance of standard	normal
-non homogeneity of transfer (if operating conditions (laser beam diameter, beam profile, position) differ)	normal
-non homogeneity of standard	rectangular
-temperature dependence of transfer detector (only if required)	N/A
-temperature dependence of standard	Already incorporated into secondary standard uncertainty
-power dependence of transfer detector (only if required)	Not required
-power dependence of standard	Already incorporated into secondary standard uncertainty[1]
-stability of transfer detector (based on the information from the pilot laboratory)	Not required
-stability of standard during the calibration process	Already incorporated into secondary standard uncertainty
-stability of standard between its own calibrations (long term drift)	Already incorporated into secondary standard uncertainty
-different wavelength (only if required)	Already incorporated into secondary standard uncertainty
-stray light	Measurement method makes this negligible
-power stability of laser source and set-up (e.g. with or without monitoring system)	Measurement with and without monitoring show this is negligible
-(humidity)	Non-condensing so negligible
-(pressure)	negligible

1 Traceability For High Power Fibre Optic Measurements. SRG Hall, TCE Jones, AG Roddie, 6th Optical Fibre Measurement Conference September 2001 ISBN 0 946754 40 3

3.3 Uncertainty Budgets for transfer detector calibration

The combined uncertainty from these tables are then transferred to tables XII and XIII

Table V PM10 1W 1.053 microns

Proc Ref	Symbol	Source of Uncertainty		Value %		Value %	Probability Distribution	Divisor	ci		ui(y) %		ui(y) %	vi
17s		Calibration of secondary standard	+	0.8	-	0.8	Normal	2	1	+	0.4	-	0.4	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
min SEM for ratio		DUT vs Reference	+	0.1075	-	0.1075	Normal	1	1	+	0.10753	-	0.10753	19
			+											
		absorptance of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of transfer	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		erature dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		temperature dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
PTB		dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		power dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		tector (based on the information from the pilot laboratory)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		stability of standard during the calibration process	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		of standard between its own calibrations (long term drift)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		different wavelength (only if required)	+	0.1	-	0.1	Normal	1	1	+	0.1	-	0.1	1E+20
		stray light	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		ource and set-up (e.g. with or without monitoring system)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(humidity)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(pressure)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
														veff
	uc(y)	Combined uncertainty					t-distribution	1		+	0.43193	-	0.43193	4946.36

Table VI PM10 10W 1.053 microns

Proc Ref	Symbol	Source of Uncertainty		Value %		Value %	Probability Distribution	Divisor	ci		ui(y) %		ui(y) %	vi
17s		Calibration of secondary standard	+	1.2	-	1.2	Normal	2	1	+	0.6	-	0.6	1E+20
0.01?		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
min SEM for ratio		DUT vs Reference	+	0.0541	-	0.0541	Normal	1	1	+	0.0541	-	0.0541	9
			+											
		absorptance of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of transfer	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		erature dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		temperature dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
PTB		dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		power dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		tector (based on the information from the pilot laboratory)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		stability of standard during the calibration process	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		of standard between its own calibrations (long term drift)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		different wavelength (only if required)	+	0.1	-	0.1	Normal	1	1	+	0.1	-	0.1	1E+20
		stray light	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		ource and set-up (e.g. with or without monitoring system)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(humidity)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(pressure)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
														veff
	uc(y)	Combined uncertainty					t-distribution	1		+	0.61476	-	0.61476	150039

Table VII Ophir 30A 1W 1.053 microns

Proc Ref	Symbol	Source of Uncertainty		Value %		Value %	Probability Distribution	Divisor	ci		ui(y) %		ui(y) %	vi
17s		Calibration of secondary standard	+	0.8	-	0.8	Normal	2	1	+	0.4	-	0.4	1E+20
0.01?		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
min SEM for ratio		DUT vs Reference	+	0.0834	-	0.0834	Normal	1	1	+	0.08341	-	0.08341	19
			+											
		absorptance of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of transfer	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		erature dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		temperature dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
PTB		dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		power dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		ector (based on the information from the pilot laboratory)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		stability of standard during the calibration process	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		of standard between its own calibrations (long term drift)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		different wavelength (only if required)	+	0.1	-	0.1	Normal	1	1	+	0.1	-	0.1	1E+20
		stray light	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		ource and set-up (e.g. with or without monitoring system)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(humidity)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(pressure)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
														veff
	uc(y)	Combined uncertainty					t-distribution	1		+	0.42656	-	0.42656	12994.7

Table VIII Ophir 30A 10W 1.053 microns

Proc Ref	Symbol	Source of Uncertainty		Value %		Value %	Probability Distribution	Divisor	ci		ui(y) %		ui(y) %	vi
17s		Calibration of secondary standard	+	1.2	-	1.2	Normal	2	1	+	0.6	-	0.6	1E+20
0.01?		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
min SEM for ratio		DUT vs Reference	+	0.0613	-	0.0613	Normal	1	1	+	0.06128	-	0.06128	9
			+											
		absorptance of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of transfer	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		erature dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		temperature dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
PTB		dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		power dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		ector (based on the information from the pilot laboratory)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		stability of standard during the calibration process	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		of standard between its own calibrations (long term drift)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		different wavelength (only if required)	+	0.1	-	0.1	Normal	1	1	+	0.1	-	0.1	1E+20
		stray light	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		ource and set-up (e.g. with or without monitoring system)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(humidity)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(pressure)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
														veff
	uc(y)	Combined uncertainty					t-distribution	1		+	0.61543	-	0.61543	91573.3

Table IX PM10 1W 10.6 microns

Proc Ref	Symbol	Source of Uncertainty		Value %		Value %	Probability Distribution	Divisor	ci		ui(y) %		ui(y) %	vi
17s		Calibration of secondary standard	+	0.8	-	0.8	Normal	2	1	+	0.4	-	0.4	1E+20
0.01?		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
min SEM for ratio		DUT vs Reference	+	0.0958	-	0.0958	Normal	1	1	+	0.0958	-	0.0958	19
			+											
		absorptance of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of transfer	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		erature dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		temperature dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
PTB		dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		power dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		tector (based on the information from the pilot laboratory)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		stability of standard during the calibration process	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		of standard between its own calibrations (long term drift)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		different wavelength (only if required)	+	0.1	-	0.1	Normal	1	1	+	0.1	-	0.1	1E+20
		stray light	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		ource and set-up (e.g. with or without monitoring system)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(humidity)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(pressure)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
														veff
	uc(y)	Combined uncertainty					t-distribution	1		+	0.42916	-	0.42916	7651.54

Table X PM10 5W 10.6 microns

Proc Ref	Symbol	Source of Uncertainty		Value %		Value %	Probability Distribution	Divisor	ci		ui(y) %		ui(y) %	vi
17s		Calibration of secondary standard	+	1.2	-	1.2	Normal	2	1	+	0.6	-	0.6	1E+20
0.01?		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
min SEM for ratio		DUT vs Reference	+	0.0802	-	0.0802	Normal	1	1	+	0.08023	-	0.08023	19
			+											
		absorptance of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of transfer	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		erature dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		temperature dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
PTB		dependence of transfer detector (only if required)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		power dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		tector (based on the information from the pilot laboratory)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		stability of standard during the calibration process	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		of standard between its own calibrations (long term drift)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		different wavelength (only if required)	+	0.1	-	0.1	Normal	1	1	+	0.1	-	0.1	1E+20
		stray light	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		ource and set-up (e.g. with or without monitoring system)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(humidity)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(pressure)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
														veff
	uc(y)	Combined uncertainty					t-distribution	1		+	0.61761	-	0.61761	66715.6

Table XI Ophir 30A 1W 10.6 microns

Proc Ref	Symbol	Source of Uncertainty		Value %		Value %	Probability Distribution	Divisor	ci		ui(y) %		ui(y) %	vi
17s		Calibration of secondary standard	+	0.8	-	0.8	Normal	2	1	+	0.4	-	0.4	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
min SEM for ratio		DUT vs Reference	+	0.1038	-	0.1038	Normal	1	1	+	0.10379	-	0.10379	19
			+											
		absorptance of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of transfer	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
erature dependence of transfer detector (only if required)			+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		temperature dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
PTB	dependence of transfer detector (only if required)		+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		power dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
:ector (based on the information from the pilot laboratory)			+	0	-	0	Normal	1	1	+	0	-	0	1E+20
	stability of standard during the calibration process		+	0	-	0	Normal	1	1	+	0	-	0	1E+20
of standard between its own calibrations (long term drift)			+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		different wavelength (only if required)	+	0.1	-	0.1	Normal	1	1	+	0.1	-	0.1	1E+20
		stray light	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
ource and set-up (e.g. with or without monitoring system)			+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(humidity)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(pressure)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
														veff
	uc(y)	Combined uncertainty					t-distribution	1		+	0.43101	-	0.43101	5650.62

Table XII Ophir 30A 5W 10.6 microns

Proc Ref	Symbol	Source of Uncertainty		Value %		Value %	Probability Distribution	Divisor	ci		ui(y) %		ui(y) %	vi
17s		Calibration of secondary standard	+	1.2	-	1.2	Normal	2	1	+	0.6	-	0.6	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
		Agilent nVmeter / MUX ref channel	+	0.1	-	0.1	Normal	2	1	+	0.05	-	0.05	1E+20
min SEM for ratio		DUT vs Reference	+	0.0847	-	0.0847	Normal	1	1	+	0.08473	-	0.08473	19
			+											
		absorptance of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of transfer	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		non homogeneity of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
erature dependence of transfer detector (only if required)			+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		temperature dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
PTB	dependence of transfer detector (only if required)		+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		power dependence of standard	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
:ector (based on the information from the pilot laboratory)			+	0	-	0	Normal	1	1	+	0	-	0	1E+20
	stability of standard during the calibration process		+	0	-	0	Normal	1	1	+	0	-	0	1E+20
of standard between its own calibrations (long term drift)			+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		different wavelength (only if required)	+	0.1	-	0.1	Normal	1	1	+	0.1	-	0.1	1E+20
		stray light	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
ource and set-up (e.g. with or without monitoring system)			+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(humidity)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
		(pressure)	+	0	-	0	Normal	1	1	+	0	-	0	1E+20
														veff
	uc(y)	Combined uncertainty					t-distribution	1		+	0.61821	-	0.61821	53848.2

. ...
....
....
....
Description of calibration laboratory conditions: e.g. temperature, humidity etc ....
....
....

Laboratory: ………NPL…………………………………………………………………………
Date: …………………………………………… Signature: ………………………………..

Record of detector radiant exposure
Detector: OPHIR Type 30A

Table XIII

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	N/A	N/A	
Nd:YAG	1064	1	3	
Nd:YAG	1064	10	1.5	
CO2	10600	1	3	
CO2	10600	5	3	

Detector: MOLECTRON Type PM10

Table XIV

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	N/A	N/A	
Nd:YAG	1064	1	3	
Nd:YAG	1064	10	1.5	
CO2	10600	1	3	
CO2	10600	5	3	

Laboratory: …NPL……………………………………………………………………………
Date: …………………………………………… Signature: ………………………………..

4 Measurement results

Table XV **Detector: OPHIR Type 30A**

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (℃)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	-	-	-	-	-	-	-	
Nd:YAG	1064	1.00	5	22	20	1.4859	0.427	6.4E-03	12995
Nd:YAG	1064	10.01	5	22	10	1.4633	0.615	9.1E-03	91573
CO2	10600	1.05	5	22	20	1.5621	0.431	6.8E-03	5650.6
CO2	10600	5.13	5	22	20	1.5594	0.618	9.7E-03	53848

Table XVI Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (℃)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5	-	-	--	-	-	-	-	
Nd:YAG	1064	1.00	5	22	20	1.6402	0.432	7.1E-03	4946.4
Nd:YAG	1064	10.01	5	22	10	1.6360	0.615	1.01E-02	150039
CO2	10600	1.05	5	22	20	1.7384	0.429	7.5E-03	7651.5
CO2	10600	5.13	5	22	20	1.7330	0.618	1.10E-02	66716

Laboratory: NPL UK…………………………………………………………………………………………
Date: ……………………………… Signature: ………………………………..

Appendix 8

Romania (NILPRP) report

Report on the results for the comparison carried out by the in the frame of the EUROMET Project 156-Part 1

A. *Description of the measurement facility and primary standard*

a) Make and type of primary standard

The primary standard used was a thermal, surface absorbing L30A-SH-V smart head coupled to channel "A" of a dual-channel Ophir LaserStar power meter. The measuring head has a cover with a central 4 mm diameter aperture used to center the detector into the laser beam.

b) Laboratory transfer standards used

It is not the case as far as the primary standard was used to perform the measurements.

c) Description of measuring technique

Two laboratory set-ups were used, one for each type of laser (Ar^+, Nd:YAG).

I. Set-up for the measurement of the Ar^+ laser power

A sketch of the set-up is given in Figure 1. The laser is a Coherent 4 W multi-line Innova 70 laser. At the start-up the laser was operated in the current control mode, at the maximum current value. After the laser starts the control is switched to "power stabilized mode". The internal prism of the laser was used to tune it to the wavelength of λ = 514.5 nm, parameter measured at the beginning of every operating day by a calibrated wavelength meter having the uncertainty of its calibration of +/- 0.05 nm at 514.5 nm. At the laser output, the beam diameter was about 2 mm, with a Gaussian distribution.

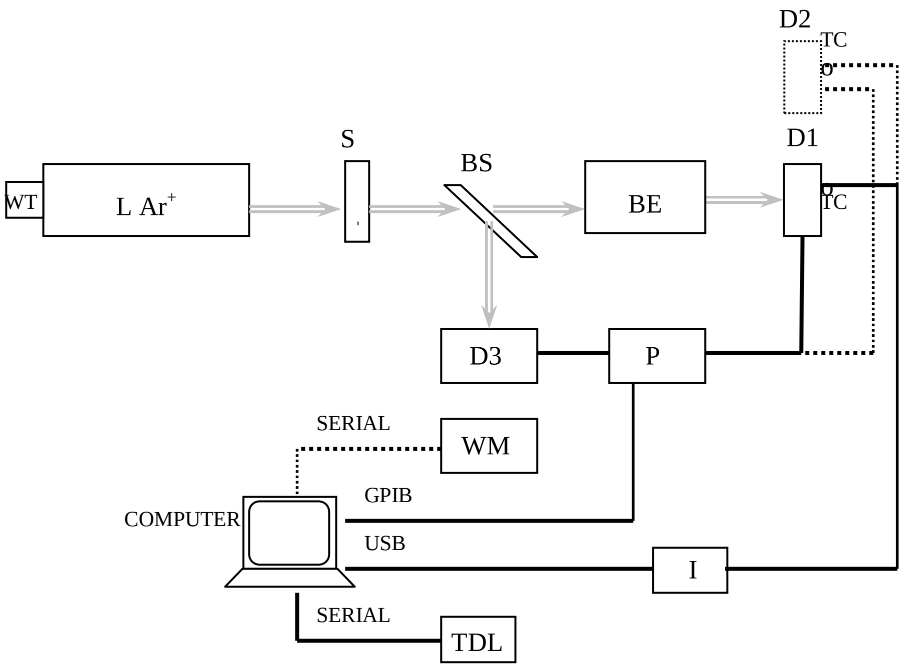


Figure1. Set-up for the measurement of the Ar^+ laser power: WT - wavelength tuning; LAr^+ - Ar^+ laser; S - shutter; BS - beam splitter; BE - beam expander; D1=L30A - primary standard, D2= 30A (PM10) - transfer standard; D3= 3A-IS - monitoring detector; P - laser power meter; I - data acquisition interface; TDL -temperature data logger; WM - wavelength meter; TC - thermocouple.

Before any measurements the laser was left to enter a stable operation regime for about 1 h. The measuring method was of a simple substitution type one, with the monitoring of the laser power stability: the laser power was first measured by the Laboratory primary standard, which was replaced by the two transfer detectors. The laser beam was divided by a beam-splitter into two beams: one to monitor the laser power stability, and the other one to perform the comparison. The ratio between the two powers was about 15 %. Before each measurement the wavelength selecting prism was adjusted to have the maximum power at the output (for the selected wavelength). The monitoring beam was detected by an integrating sphere type detector (3A-IS) coupled to channel “B’ of the LaserStar display. The beam collecting geometry was set to collect all the reflected laser power. The beam used for the measurements passed through an expanding device in order to have a beam diameter of about 4.5 - 5 mm in the detecting plane. The laser current was modified until the optical power available on the measuring arm was about 1 W, when the Laboratory primary standard was exposed to the laser radiation. Each time a measurement was done the primary standard of the Laboratory (L30-A-SH-V) was mounted on a XY micrometer stage, which can be operated manually. The stage makes possible the vertical and the horizontal (perpendicular to the laser beam direction) movement of the detector. The position of the stage along the laser beam path was kept fixed. The Laboratory primary standard can be interchanged with the PTB standards, so that in all cases the laser beam can be centered on the detector aperture. Between the measurements, the primary standard of the Laboratory and the PTB transfer standards were kept with the protective cover on. The PTB transfer standards were connected to the inputs of the Agilent 34420A nano-voltmeter provided by PTB for this comparison: the Ophir 30A to channel “Ch1”, and the Molectron PM10 to the channel “Ch2”. The laser beam power was monitored for all the measurements done with the Laboratory primary standard or with the PTB transfer standards. The measurement sequence was: the Laboratory primary standard, the transfer standard 30A, the transfer standard PM10. Before measuring any of the detectors, they are exposed to laser radiation with the protective cover on, but with the cap of the cover aperture removed. The detector was moved in the plane perpendicular to the direction of the laser beam until a maximum level is achieved at the LaserStar display or at the Agilent instrument. At the point the Laboratory standard was measured, the detector cover was removed and the laser current was adjusted in order to have a power level of ~ 1 W as indicated by the Laboratory primary standard. The power level at the monitoring detector was registered. After the Laboratory standard was replaced by one of the PTB transfer standards the detector was fully exposed to laser radiation and the laser current was adjusted to have almost the same power level at the monitoring detector.

All the data during the measurements were collected and saved automatically, by using the StarCom program for Ophir or the Agilent “IntuiLink Multimeter” software. When collecting data from the Laboratory primary standard, the StarCom software was operated in the “ratio A/B” mode, so that data from both the measuring channel and the monitoring channel were acquired. During the measurements performed on the PTB standards, the data acquisition over channel “B” was done using a Virtual Instrument developed in LabVIEW.

The temperature variation in the Laboratory was monitored with a Veriteq data logger (Spectrum 2000), placed in the vicinity of the measuring set-up. The logger was connected to a laptop through serial a link. The detectors’ temperature during their exposure to laser radiation was performed with a “J” type thermocouple, coupled to a National Instruments (NI cRIO-9211) through USB connection.

The duration for the acquisition in the case of the Ar^+ varied between 10 min and 20 min. The acquisition rate for the LaserStar was done every one second, while the acquisition interval for the

Agilent instrument was set to 2 s. The wavelength set for the two channels of the LaserStar power meter was 515 nm. The power range for channel "A" was 3 W, while for channel "B" was 300 mW. The Agilent nano-voltmeter was set to its maximum resolution (7 ½ digits).

II. Set-up for the measurement of the Nd:YAG laser power

A sketch of the set-up is given in Figure 2. The laser is a diode-pumped Nd:YAG laser developed in our Institute. The laser was operated at the laser diode's driving current of 14.1 A. At the laser output the beam diameter was about 2 mm with a Gaussian distribution.

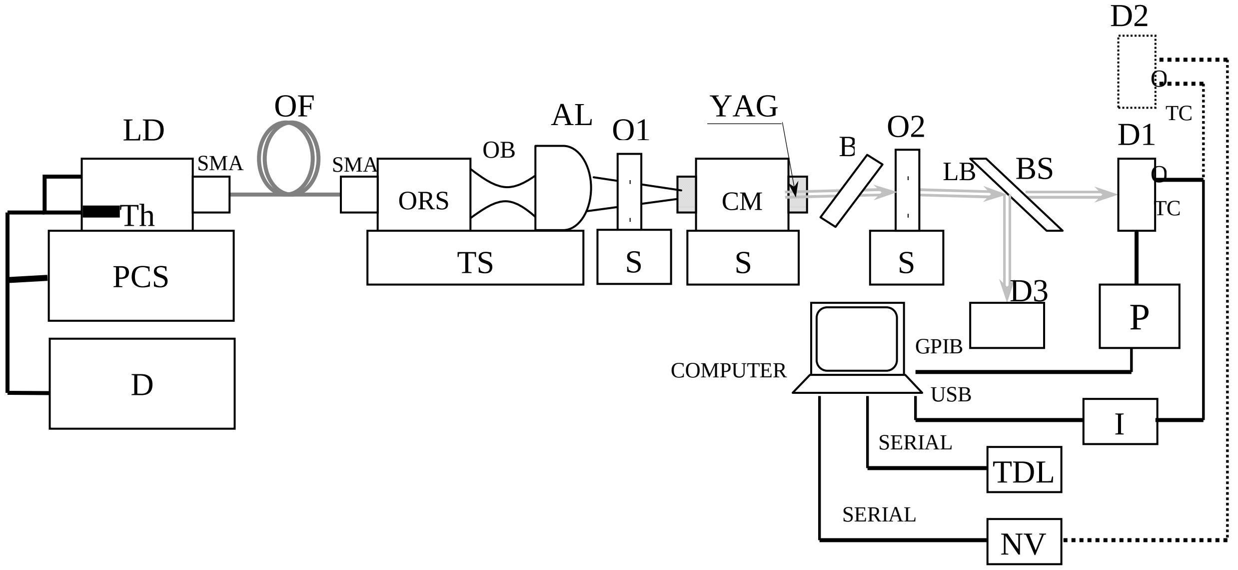


Figure 2. Set- up for the measurement of the Nd:YAG laser power: D - current driver for the laser diode; PCS - Peltier cooling system; Th - thermistor; LD - pumping laser diode; OF - optical fiber; SMA - SMA optical fiber connector; ORS - optical re-imaging system; TS - translation stage; AL - aspheric lens; OB - optical pumping beam at λ = 808 nm; YAG - active media Nd:YAG; CM - water cooled mount; S - high precision XY stage; O1, O2 - mirrors; LB - laser beam at λ = 1064 nm; B - Brewster optical plate; BS - beam splitter; D1=L30A - primary standard; D2= 30A (PM10) - transfer standard; D3= 3A-P-CAL - monitoring detector; P - laser power meter; I - data acquisition interface; TDL - temperature data logger; NV - nano-voltmeter; TC - thermocouple.

Before any measurements the laser was left to enter a stable operation regime for about 20 min. The laser cooling system was of an open circuit type one. The measuring method was of a simple substitution type one, with the monitoring of the laser power stability: the laser power was first measured by the Laboratory primary standard, which was replaced by the two transfer detectors. The laser beam was divided by a beam-splitter into two beams: one to monitor the laser power stability, and the other one to perform the comparison. The ratio between the two powers was about 2 %. The monitoring beam was detected by a 3AP head coupled to channel "B' of the LaserStar display. The beam collecting geometry was set to collect all the reflected laser power. The laser natural divergence was used to have a beam diameter of about 4.5 - 5 mm in the detecting plane. The laser diode current was modified until the optical power available on the measuring arm was about 1 W, when the Laboratory primary standard was exposed to the laser radiation. Each time a measurement was done, the primary standard of the Laboratory (L30-A-SH-V) was mounted on a

XY micrometer stage, which can be operated manually. The stage makes possible the vertical and the horizontal (perpendicular to the laser beam direction) movement of the detector. The position of the stage along the laser beam path was kept fixed. The Laboratory primary standard can be interchanged with the PTB standards, so that in all cases the laser beam can be centered on the detector aperture. Between the measurements the primary standard of the Laboratory and the PTB transfer standards were kept with the protective cover on. The PTB transfer standards were connected to the inputs of the Agilent 34420A nanovoltemer provided by PTB for this comparison: the Ophir 30A to channel "Ch1", and the Molectron PM10 to the channel "Ch2". The laser beam power was monitored for all the measurements (with the Laboratory primary standard or with the PTB transfer standards). The measurement sequence was: the Laboratory primary standard, the transfer standard 30A, the transfer standard PM10. Before measuring any of the detectors they are exposed to laser radiation with the protective cover on, but with the cap of the cover aperture removed. The detector was moved in the plane perpendicular to the direction of the laser beam until a maximum level is achieved at the LaserStar display or at the Agilent instrument. At no moment the pumping laser diode operation was stopped, only the emission of the Nd:YAG laser was cancelled during the change of the primary standard with the transfer detector, by increasing the loss in its cavity. The power level at the monitoring detector was registered. After the Laboratory standard was replaced by one of the PTB transfer standards, the detector was fully exposed to laser radiation and the laser current was adjusted to have almost the same power level at the monitoring detector.

All the data during the measurements were collected and saved automatically, by using the StarCom program for Ophir or the Agilent "IntuiLink Multimeter" software. When collecting data from the Laboratory primary standard, the StarCom software was operated in the "ratio A/B" mode, so that data from both the measuring channel and the monitoring channel were acquired. During the measurements performed on the PTB standards, the data acquisition over channel "B" was done using a Virtual Instrument developed in LabVIEW.

The temperature variation in the Laboratory was monitored with a Veriteq data logger (Spectrum 2000), placed in the vicinity of the measuring set-up. The logger was connected to a laptop through serial link. The detectors' temperature during their exposure to laser radiation was performed with a "J" type thermocouple, coupled to a National Instruments (NI cRIO-9211) through USB connection.

The duration for the acquisition in the case of the Ar^+ varied between 10 min and 15 min. The acquisition rate for the LaserStar was done every one second, while the acquisition interval for the Agilent instrument was set to 2 s. The wavelength set for the channel "A" of the LaserStar power meter was YAG, while for channel "B" was ">800". The power range for channel "A" was 3 W, while for channel "B" was 30 mW. The Agilent nanovoltmeter was set to its maximum resolution (7 ½ digits).

d) Establishment or traceability route of primary scale including date of last realization and breakdown of uncertainty

I. The primary standard calibrated at PTB, at λ = 514.5 nm, December 12-19, 2005, f_k = 0.998 +/- 0.002 (1 W), with a coverage factor k = 2.0.

II. The primary standard calibrated at PTB, at λ = 1064 nm, December 12-19, 2005 f_k = 0.979 +/- 0.003 (1 W), with a coverage factor k = 2.0.

e) Description of calibration laboratory condition

The measurements were carried out into two facilities. In the case of the Ar^+, the background optical radiation was 12 nW, while for the Nd:YAG measurements it was 3 μW. The mean ambient temperature for the Ar^+ laser measurements was 22.35 ^{O}C, while for the Nd:YAG laser measurements was 22.75 ^{O}C.

B. Record of the detector radiant exposure

I. Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Approximate **total** exposure time (min)	Comments
Argon	514.4	1	180	Min. exposure per measurement (min) = 10 Max. exposure per measurement (min) = 20
Nd:YAG	1064	1	125	Min. exposure per measurement (min) = 12 Max. exposure per measurement (min) = 15

II. Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Approximate **total** exposure time (min)	Comments
Argon	514.4	1	150	Min. exposure per measurement (min) = 10 Max. exposure per measurement (min) = 20
Nd:YAG	1064	1	135	Min. exposure per measurement (min) = 12 Max. exposure per measurement (min) = 20

C. Measurement results

I. Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Mean Temperature of the transfer detector (^{O}C)	No. of Mess.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainity (mV/W)	Degree of freedom
Argon	514,5	1							
Nd:YAG	1064	1							

II. Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Mean Temperature (^{O}C)	No. of Mess.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainity (mV/W)	Degree of freedom
Argon	514,5	1							
Nd:YAG	1064	1							

D. Observations

Dr. Dan SPOREA

Date: January 24.2006

Signature

E. Uncertainty Budget

1. <u>The measurement of the Ar^+ laser power (1 W)</u>

A. The Ophir 30A transfer detector

Uncertainty budget for the measurement of the Ar^+ laser power with the primary standard (before the calibration correction):

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 10 repeated readings (u_{PS})	mW	2.45	normal	1	2.45	9	
Display resolution ($a_{PS\ Dpl}$ / 2)	mW	0.05	rectangular	√3	0.03	2	50%
Wavelength dependence ($a_{PS\ \lambda}$)	mW	0.04	rectangular	√3	0.02	8	25%
Spatial variation of the responsivity ($a_{PS\ sr}$)	mW	3.98	rectangular	√3	2.30	2	50%
Mean value of the estimated standard deviation of ***each*** measurement (s_{DPS})	mW	2.67	rectangular	√3	1.54	2	50%
						v_{PS}	
Combined standard uncertainty ($u_{c\ PS}$)	mW		assumed normal		**3.69**	**8**	

Uncertainty budget for the measurement of the Ar^+ laser power with the primary standard (after the calibration correction)

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Combined standard uncertainty before the calibration correction (u_{c_PS})	mW				3.69	8	
Relative uncertainty before the calibration correction (u_{C_PS}/ P_{PS})					0.0037144		
Calibration uncertainty		0.002	normal	2	0.001		
Relative calibration uncertainty (u_{CAL_Ar}/ CF)					0.001002		
Relative uncertainty after the calibration correction ($u_{C\_PS\_CAL}$/ P_{PS_CAL})					0.00384717		
Absolute calibration uncertainty	mW				0.9940	2	25%
						v_{PS_CAL}	
Combined standard uncertainty after the calibration correction ($u_{c\_PS\_CAL}$)	mW				**3.82**	**8**	

Uncertainty budget for the measurement of the Ar^+ laser power with the transfer detector coupled to the nanovoltmeter:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 10 repeated readings (u_{nv})	mV	0.00747879	normal	1	0.00747879	9	
Display resolution ($a_{nv\ Dpl}$ / 2)	mV	0.00000005	rectangular	√3	0.00000003	2	50%
Calibration uncertainty (a_{nv_CAL})	mV	0.0005	rectangular	√3	0.00028868	2	50%
Mean value of the estimated standard deviation of ***each*** measurement (s_{Dnv})	mV	0.00520094	rectangular	√3	0.00300276	2	50%
						v_{nv}	
Combined standard uncertainty ($u_{c\ nv}$)	mV		assumed normal		**0.00806426**	**10**	
Relative uncertainty ($u_{c\ nv}$/ V_{nv})					0.00546809		

Uncertainty budget for the measurement of the Ar^+ laser power with the monitoring detector during the measurements done with the primary standard:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 10 repeated readings ($u_{MD\ PS}$)	mW	0.33	normal	1	0.33	9	
Display resolution ($a_{MD\ PS\ Dpl}$ / 2)	mW	0.05	rectangular	√3	0.03	2	50%
Mean value of the estimated standard deviation of ***each*** measurement ($s_{DMD\ PS}$)	mW	0.38	rectangular	√3	0.22	2	50%
						$v_{MD\ PS}$	
Combined standard uncertainty ($u_{c\ MD\ PS}$)	mW		assumed normal		**0.40**	**10**	
Relative uncertainty ($u_{c\ MD\ PS}$/ $P_{MD\ PS}$)					0.00260969		

Uncertainty budget for the measurement of the Ar^+ laser power with the monitoring detector during the measurements done with the transfer detector:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 10 repeated readings ($u_{MD\ TD}$)	mW	0.82	normal	1	0.82	9	
Display resolution ($a_{MD\ TD\ Dpl}$ / 2)	mW	0.05	rectangular	√3	0.03	2	50%
Mean value of the estimated standard deviation of ***each*** measurement ($s_{DMD\ TD}$)	mW	0.64	rectangular	√3	0.37	2	50%
						$v_{MD\ PS}$	
Combined standard uncertainty ($u_{c\ MD\ TD}$)	mW		assumed normal		**0.89**	**11**	
Relative uncertainty ($u_{c\ MD\ PS}$/ $P_{MD\ TD}$)					0.00591121		

The relative uncertainty for the spectral responsivity of the transfer detector Ophir 30A

u(s) = 0.93 %

B. The Molectron PM10 transfer detector

Uncertainty budget for the measurement of the Ar^+ laser power with the primary standard (before the calibration correction):

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 11 repeated readings (u_{PS})	mW	1.55	normal	1	1.55	10	
Display resolution ($a_{PS\ Dpl}$ / 2)	mW	0.05	rectangular	√3	0.03	2	50%
Wavelength dependence ($a_{PS\ \lambda}$)	mW	0.04	rectangular	√3	0.02	8	25%
Spatial variation of the responsivity ($a_{PS\ sr}$)	mW	3.97	rectangular	√3	2.29	2	50%
Mean value of the estimated standard deviation of ***each*** measurement (s_{DPS})	mW	2.25	rectangular	√3	1.30	2	50%
						v_{PS}	
Combined standard uncertainty ($u_{c\ PS}$)	mW		assumed normal		3.05	5	

Uncertainty budget for the measurement of the Ar^+ laser power with the primary standard (after the calibration correction) is:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Combined standard uncertainty before the calibration correction (u_{c_PS})	mW				3.05	5	
Relative uncertainty before the calibration correction (u_{C_PS}/ P_{PS})					0.00307959		
Calibration uncertainty		0.002	normal	2	0.001		
Relative calibration uncertainty (u_{CAL_Ar}/ CF)					0.001002		
Relative uncertainty after the calibration correction ($u_{C\_PS\_CAL}$/ P_{PS_CAL})					0.00323850		
Absolute calibration uncertainty	mW				0.991	2	25%
						v_{PS_CAL}	
Combined standard uncertainty after the calibration correction ($u_{c\_PS\_CAL}$)	mW				**3.20**	**5**	

Uncertainty budget for the measurement of the Ar^+ laser power with the transfer detector coupled to the nanovoltmeter:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 11 repeated readings (u_{nv})	mV	0.00569887	normal	1	0.00569887	10	
Display resolution ($a_{nv\ Dpl}$ / 2)	mV	0.00000005	rectangular	√3	0.00000003	2	50%
Calibration uncertainty (a_{nv_CAL})	mV	0.0005	rectangular	√3	0.00028868	2	50%
Mean value of the estimated standard deviation of ***each*** measurement (s_{Dnv})	mV	0.00402743	rectangular	√3	0.00232524	2	50%
						v_{nv}	
Combined standard uncertainty ($u_{c\ nv}$)	mV		assumed normal		**0.00616175**	**12**	
Relative uncertainty ($u_{c\ nv}$/ V_{nv})					0.00373471		

Uncertainty budget for the measurement of the Ar^+ laser power with the monitoring detector during the measurements done with the primary standard:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 11 repeated readings ($u_{MD\ PS}$)	mW	0.23	normal	1	0.23	10	
Display resolution ($a_{MD\ PS\ Dpl}$ / 2)	mW	0.05	rectangular	√3	0.03	2	50%
Mean value of the estimated standard deviation of ***each*** measurement ($s_{DMD\ PS}$)	mW	0.33	rectangular	√3	0.19	2	50%
						$v_{MD\ PS}$	
Combined standard uncertainty ($u_{c\ MD\ PS}$)	mW		assumed normal		**0.30**	**8**	
Relative uncertainty ($u_{c\ MD\ PS}$/ $P_{MD\ PS}$)					0.00195519		

Uncertainty budget for the measurement of the Ar^+ laser power with the monitoring detector during the measurements done with the transfer detector:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 11 repeated readings ($u_{MD\ TD}$)	mW	0.55	normal	1	0.55	10	
Display resolution ($a_{MD\ TD\ Dpl}$ / 2)	mW	0.05	rectangular	√3	0.03	2	50%
Mean value of the estimated standard deviation of ***each*** measurement ($s_{DMD\ TD}$)	mW	0.45	rectangular	√3	0.26	2	50%
						$v_{MD\ PS}$	
Combined standard uncertainty ($u_{c\ MD\ TD}$)	mW		assumed normal		**0.60**	**12**	
Relative uncertainty ($u_{c\ MD\ PS}$/ $P_{MD\ TD}$)					0.00395090		

The relative uncertainty for the spectral responsivity of the transfer detector Molectron PM10

u(s) = 0.66 %

2. The measurement of the Nd:YAG laser power (1 W)

A. The Ophir 30A transfer detector

Uncertainty budget for the measurement of the Nd:YAG laser power with the primary standard (before the calibration correction):

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 10 repeated readings (u_{PS})	mW	3.67	normal	1	3.67	8	
Display resolution ($a_{PS\ Dpl}$ / 2)	mW	0.05	rectangular	√3	0.03	2	50%
Spatial variation of the responsivity ($a_{PS\ sr}$)	mW	4.01	rectangular	√3	2.31	2	50%
Mean value of the estimated standard deviation of ***each*** measurement (s_{DPS})	mW	1.89	rectangular	√3	1.09	2	50%
						v_{PS}	
Combined standard uncertainty ($u_{c\ PS}$)	mW		assumed normal		**4.47**	**10**	

Uncertainty budget for the measurement of the Nd:YAG laser power with the primary standard (after the calibration correction) is:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Combined standard uncertainty before the calibration correction (u_{c_PS})	mW				**4.47**	**10**	
Relative uncertainty before the calibration correction (u_{C_PS}/ P_{PS})					0.00446743		
Calibration uncertainty		0.003	normal	2	0.0015		
Relative calibration uncertainty (u_{CAL_Ar}/ CF)					0.00153218		
Relative uncertainty after the calibration correction ($u_{C\_PS\_CAL}$/ P_{PS_CAL})					0.00472287		
Absolute calibration uncertainty	mW				1.5024	2	25%
						v_{PS_CAL}	
Combined standard uncertainty after the calibration correction ($u_{c\_PS\_CAL}$)	mW				4.63	**10**	

Uncertainty budget for the measurement of the Nd:YAG laser power with the transfer detector coupled to the nanovoltmeter:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 10 repeated readings (u_{nv})	mV	0.00586462	normal	1	0.00586462	8	
Display resolution ($a_{nv\ Dpl}$ / 2)	mV	0.00000005	rectangular	√3	0.00000003	2	50%
Calibration uncertainty (a_{nv_CAL})	mV	0.0005	rectangular	√3	0.00028868	2	50%
Mean value of the estimated standard deviation of ***each*** measurement (s_{Dnv})	mV	0.00209891	rectangular	√3	0.00121181	2	50%
						v_{nv}	
Combined standard uncertainty ($u_{c\ nv}$)	mV		assumed normal		**0.00599546**	**8**	
Relative uncertainty ($u_{c\ nv}$/ V_{nv})					0.00416381		

Uncertainty budget for the measurement of the Nd:YAG laser power with the monitoring detector during the measurements done with the primary standard:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 9 repeated readings ($u_{MD\ PS}$)	mW	0.06	normal	1	0.06	8	
Display resolution ($a_{MD\ PS\ Dpl}$ / 2)	mW	0.005	rectangular	√3	0.003	2	50%
Mean value of the estimated standard deviation of ***each*** measurement ($s_{DMD\ PS}$)	mW	0.12	rectangular	√3	0.07	2	50%
						$v_{MD\ PS}$	
Combined standard uncertainty ($u_{c\ MD\ PS}$)	mW		assumed normal		**0.09**	**4**	
Relative uncertainty ($u_{c\ MD\ PS}$/ $P_{MD\ PS}$)					0.00532726		

Uncertainty budget for the measurement of the Nd:YAG laser power with the monitoring detector during the measurements done with the transfer detector:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 9 repeated readings ($u_{MD\ TD}$)	mW	0.06	normal	1	0.06	8	
Display resolution ($a_{MD\ TD\ Dpl}$ / 2)	mW	0.005	rectangular	√3	0.003	2	50%
Mean value of the estimated standard deviation of ***each*** measurement ($s_{DMD\ TD}$)	mW	0.20	rectangular	√3	0.12	2	50%
						$v_{MD\ PS}$	
Combined standard uncertainty ($u_{c\ MD\ TD}$)	mW		assumed normal		**0.13**	**3**	
Relative uncertainty ($u_{c\ MD\ PS}$/ $P_{MD\ TD}$)					0.00762195		

The relative uncertainty for the spectral responsivity of the transfer detector Ophir 30A

u(s) = 1.12 %

B. The Molectron PM10 transfer detector

Uncertainty budget for the measurement of the Nd:YAG laser power with the primary standard (before the calibration correction):

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 10 repeated readings (u_{PS})	mW	3.67	normal	1	3.67	8	
Display resolution ($a_{PS\ Dpl}$ / 2)	mW	0.05	rectangular	√3	0.03	2	50%
Spatial variation of the responsivity ($a_{PS\ sr}$)	mW	4.01	rectangular	√3	2.31	2	50%
Mean value of the estimated standard deviation of ***each*** measurement (s_{DPS})	mW	1.89	rectangular	√3	1.09	2	50%
						v_{PS}	
Combined standard uncertainty ($u_{c\ PS}$)	mW		assumed normal		**4.47**	**10**	

Uncertainty budget for the measurement of the Nd:YAG laser power with the primary standard (after the calibration correction) is:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Combined standard uncertainty before the calibration correction ($u_{c\ PS}$)	mW				**4.47**	**10**	
Relative uncertainty before the calibration correction (u_{C_PS}/ P_{PS})					0.00446743		
Calibration uncertainty		0.003	normal	2	0.0015		
Relative calibration uncertainty (u_{CAL_Ar}/ CF)					0.00153218		
Relative uncertainty after the calibration correction ($u_{C\_PS\_CAL}$/ P_{PS_CAL})					0.00472287		
Absolute calibration uncertainty	mW				1.5024	2	25%
						$v_{PS\ CAL}$	
Combined standard uncertainty after the calibration correction ($u_{c\ PS\ CAL}$)	mW				4.63	**10**	

Uncertainty budget for the measurement of the Nd:YAG laser power with the transfer detector coupled to the nanovoltmeter:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 10 repeated readings (u_{nv})	mV	0.00677740	normal	1	0.00677740	8	
Display resolution ($a_{nv\ Dpl}$ / 2)	mV	0.00000005	rectangular	√3	0.00000003	2	50%
Calibration uncertainty (a_{nv_CAL})	mV	0.0005	rectangular	√3	0.00028868	2	50%
Mean value of the estimated standard deviation of ***each*** measurement (s_{Dnv})	mV	0.00259235	rectangular	√3	0.00149670	2	50%
						v_{nv}	
Combined standard uncertainty ($u_{c\ nv}$)	mV		assumed normal		**0.00694670**	**8**	
Relative uncertainty ($u_{c\ nv}$/ V_{nv})					0.00434539		

Uncertainty budget for the measurement of the Nd:YAG laser power with the monitoring detector during the measurements done with the primary standard:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 9 repeated readings ($u_{MD\ PS}$)	mW	0.06	normal	1	0.06	8	
Display resolution ($a_{MD\ PS\ Dpl}$ / 2)	mW	0.005	rectangular	√3	0.003	2	50%
Mean value of the estimated standard deviation of ***each*** measurement ($s_{DMD\ PS}$)	mW	0.12	rectangular	√3	0.07	2	50%
						$v_{MD\ PS}$	
Combined standard uncertainty ($u_{c\ MD\ PS}$)	mW		assumed normal		**0.09**	**4**	
Relative uncertainty ($u_{c\ MD\ PS}$/ $P_{MD\ PS}$)					0.00532726		

Uncertainty budget for the measurement of the Nd:YAG laser power with the monitoring detector during the measurements done with the transfer detector:

Source of uncertainty	Unit	Value (+/-)	Probability distribution	Divisor	Standard uncertainty	Degrees of freedom (v_i)	Confidence level
Standard uncertainty of mean of 9 repeated readings ($u_{MD\ TD}$)	mW	0.07	normal	1	0.07	8	
Display resolution ($a_{MD\ TD\ Dpl}$ / 2)	mW	0.005	rectangular	√3	0.003	2	50%
Mean value of the estimated standard deviation of ***each*** measurement ($s_{DMD\ TD}$)	mW	0.20	rectangular	√3	0.12	2	50%
						$v_{MD\ PS}$	
Combined standard uncertainty ($u_{c\ MD\ TD}$)	mW		assumed normal		**0.13**	**3**	
Relative uncertainty ($u_{c\ MD\ PS}$/ $P_{MD\ TD}$)					0.00778137		

The relative uncertainty for the spectral responsivity of the transfer detector Molectron PM10

u(s) = 1.14 %

January 27, 2009
Dan Sporea
Head of Laboratory

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Appendix 9

Australia (NMIA) report

Description of the measurement facility and primary scale

Make and type of primary standard: Oxford Instruments "Radiox" cryogenic radiometer for absolute responsivity at specific laser wavelengths in the range 265 – 1550 nm (1994).
NMIA-made gold black bolometers as standards of relative spectral responsivity for the spectral range 220 to 2400 nm.

Laboratory transfer standards used: Telcom Devices 35PD 10M-CFP windowless plane InGaAs photodiode (denoted TD3), Scientech AC25HD 10 W surface absorbing reference laser calorimeter (denoted LC3, s/n 3663), a coated fused silica beam-splitter.

Description of measuring technique: For each set of measurements, the appropriate laser was set up at a suitable constant power level and each detector alternately aligned to the laser beam. The 1064 nm measurements were carried out using a US Laser 404 CW Nd:YAG laser. For the ~1 W measurements, the laser was operated at ~20 W and a 5 % beam-splitter used to obtain ~1 W. For the higher power measurements, the laser was operated at ~8 W without any attenuator. The 1 W and 8 W measurements were linearly extrapolated to give the responsivity at 10 W. The beam diameter was measured to be 5 mm and so no spatial modification of the beam was used.

The detector alignment process involved firstly tilting the detector for normal incidence to the beam and subsequently translating it in the plane normal to the beam until the beam was centred on the alignment aperture. The alignment apertures were then removed. This process was repeated each time a detector was placed in the beam. Typically, the reference calorimeter was measured first followed by the Ophir detector and finally the Molectron detector. This sequence was then repeated a number of times. For each of these measurements, a zero was taken by blocking the beam with a shutter, waiting for the reading to settle then reading the zero value. Then, the shutter was opened, a waiting period of at least 60 s observed until it was confirmed that the reading had settled and then a power measurement taken. All final power measurements were zero-corrected. Signal voltages from the Ophir and Molectron detectors were measured with an Agilent 34420A multimeter and voltages from the NMIA reference calorimeter were measured using a Keithley K2000 voltmeter. The interconnecting cables supplied by the pilot laboratory were used to connect the comparison detectors to the multimeter.

Establishment or traceability route of primary scale including date of last realisation and breakdown of uncertainty: The InGaAs detector (TD3) was calibrated against the cryogenic radiometer at a wavelength of 1294.83 nm using a fibre-coupled single-emitter diode laser in March, 2003. Due to the use of non-polarization-preserving fibre for the coupling and the variable laser polarization, an AR-coated window at near-normal incidence was used in place of the usual Brewster window on the cryogenic radiometer. Measurements of the window transmission, loss and uniformity were made. This calibration of TD3 at 1294.83 nm was combined with two previous calibrations to determine the rate of drift of the responsivity of TD3 at 1294.83 nm, and then linear extrapolation to the date of calibration of LC3 was performed.

The relative spectral responsivity of TD3 was measured against reference gold-black bolometers in January, 2002. This measurement was combined with several earlier measurements to determine the rate of drift of the ratio of spectral responsivities at 1294.83 nm and at 1064 nm. Linear extrapolation of this ratio to the date of calibration of LC3 was then performed. The absolute responsivity at 1294.83 nm (determined as described above) was combined with the ratio of spectral responsivities to determine the absolute spectral responsivity of TD3 at 1064 nm. These calculations were done using values extrapolated to the date of calibration of LC3.

TD3 was, in turn, used to calibrate LC3 at 1064 nm using a coated fused silica plate as a beam-splitter in order to scale to higher power. This calibration was done in March, 2004. LC3 was then used as the reference detector in the comparison measurements, i.e. the Ophir and Molectron detectors from the pilot laboratory were measured relative to LC3.

The combined standard uncertainty u_c (k = 1) in the calibration of the LC3 reference calorimeter is ± 0.42 % at 1064.1 nm. The table on the following pages shows a detailed breakdown of the uncertainties contributing to each stage of the comparison.

Description of calibration laboratory conditions: e.g. temperature, humidity etc: Laboratory temperature was stabilised and measured to be in the range 21.7 – 22.1 ^{0}C during the comparison measurements. Laboratory humidity was stabilised but not measured.

Uncertainty budget for Euromet PR-S2, NMI Australia

1064 nm at 1 and 10 W

All values are standard uncertainty *u* (*k*=1 or "1-sigma") in percent

	u	c	$(c\ u)^2$	(c u) subtotal	Type	ν	$(c\ u)^4/\nu$
A. Common uncertainty components							
Absolute responsivity of TD3 at 1294.83nm							
Cryogenic radiometer measurements							
Window transmission	0.013	1	0.000174		B	100	3.04E-10
Window alignment/realignment	0.01	1	0.0001		B	100	1.00E-10
Window non-uniformity	0.003	1	0.000009		B	100	8.10E-13
Window-optical axis misalignment	0.002	1	0.000004		B	100	1.60E-13
Window birefringence	0.002	1	0.000004		B	100	1.60E-13
Beam confinement	0.005	1	0.000025		B	100	6.25E-12
Scattering and diffraction	0.001	1	0.000001		B	100	1.00E-14
Nonequivalence	0.004	1	0.000016		B	100	2.56E-12
Cavity absorption	0.0015	1	0.00000225		B	100	5.06E-14
Cavity contamination	0.004	1	0.000016		B	100	2.56E-12
Electrical power	0.002	1	0.000004		B	100	1.60E-13
				0.019			
TD3 measurements							
Photodetector alignment	0.007	1	0.000049		B	100	2.40E-11
Amplifier gain	0.014	1	0.0002		B	100	4.00E-10
Voltage measurement	0.01	1	0.0001		B	100	1.00E-10
Laser wavelength/linewidth	0.01	1	0.0001		B	100	1.00E-10
				0.021			
Common							
Repeatability	0.03	1	0.00107591		A	14	8.27E-08
Drift	0.015	1	0.000225		B	10	5.06E-09
				0.036			
				0.046			
Relative responsivity of TD3 (1064nm cf 1294.83nm)							
Nonlinearity of TD3	0.01	1	0.0001		B	100	1.00E-10
Nonlinearity of bolometers	0.02	1	0.0004		B	100	1.60E-09
Thermal impedance of gold black	0.05	1	0.0025		B	100	6.25E-08
Spatial uniformity of TD3	0.02	1	0.0004		B	100	1.60E-09
Repeatability	0.06	1	0.0036		A	10	1.30E-06
				0.084			
				0.084			
Absolute responsivity of LC3 at 1064nm							
TD3 measurements							
Drift in absolute responsivity	0.072	1	0.00522289		B	10	2.73E-06
Drift in relative responsivity	0.056	1	0.00313233		B	10	9.81E-07
Amplifier gain	0.014	1	0.0002		B	100	4.00E-10
Voltage measurement	0.01	1	0.0001		B	100	1.00E-10
Spatial uniformity	0.02	1	0.0004		B	100	1.60E-09
Angular misalignment	0.01	1	0.0001		B	100	1.00E-10
Nonlinearity	0.1	1	0.01		B	10	1.00E-05
Temperature effects	0.0045	1	2.0099E-05		B	100	4.04E-12
				0.138			
LC3 measurements							
Angular misalignment	0.015	1	0.000225		B	30	1.69E-09
				0.015			
Beam-splitter ratio							
Repeatability	0.16	1	0.02567445		A	28	2.35E-05
Drift	0.33	1	0.10938595		B	10	1.20E-03
Angular misalignment	0.004	1	0.000016		B	30	8.53E-12
Nonlinearity of TD3	0.10	1	0.01		B	30	3.33E-06
Nonlinearity of BS with irradiance	0.1	1	0.01		B	10	1.00E-05
				0.394			
Common							
Repeatability	0.039	1	0.00153051		A	13	1.80E-07
Drift	0.030	1	0.0009		B	10	8.10E-08
				0.049			
				0.421			

Transfer from LC3 to comparison detectors

LC3 measurements							
Drift in absolute responsivity	0.015	1	0.000225		B	10	5.06E-09
Spatial nonuniformity	0.06	1	0.0036		B	30	4.32E-07
Angular misalignment	0.015	1	0.000225		B	100	5.06E-10
Voltage measurement	0.01	1	0.0001		B	100	1.00E-10
Nonlinearity of LC3	0.02	1	0.0004		B	30	5.33E-09
Temperature effects	0.1	1	0.01		B	30	3.33E-06
				0.121			
Detector measurements							
Angular misalignment	0.015	1	0.000225		B	100	5.06E-10
Voltage measurement	0.01	1	0.0001		B	100	1.00E-10
				0.018			
				0.122			
				(c u)		Effective ν	Σ (c u)^4/ν
Subtotal (added in quadrature to each detector below)				**0.448 %**		**32.2**	**1.25E-03**

Uncertainties due to changes in humidity and barometric pressure are assumed to be negligible in comparison with this result.

B. 1064nm 1W Ophir

Subtotal from above	0.448	1	0.20088786		B	32	1.25E-03
Repeatability	0.081	1	0.00660829		A	30	1.46E-06
							1.25E-03
Combined standard uncertainty and effective ν				**0.46 %**		**34.3**	

C. 1064nm 1W Molectron

Subtotal from above	0.448	1	0.20088786		B	32	1.25E-03
Repeatability	0.203	1	0.04135897		A	14	1.22E-04
							1.37E-03
Combined standard uncertainty and effective ν				**0.49 %**		**42.7**	

D. 1064nm 10W Ophir

Subtotal from above	0.448	1	0.20088786		B	32	1.25E-03
Repeatability	0.133	1	0.0177971		A	14	2.26E-05
Linear extrapolation to 10 W	0.01	1	0.0001		B	30	3.33E-10
Nonlinearity of Ophir	0.02	1	0.0004		B	30	5.33E-09
							1.28E-03
Combined standard uncertainty and effective ν				**0.47 %**		**37.7**	

E. 1064nm 10W Molectron

Subtotal from above	0.448	1	0.20088786		B	32	1.25E-03
Repeatability	0.148	1	0.02202716		A	14	3.47E-05
Linear extrapolation to 10 W	0.01	1	0.0001		B	30	3.33E-10
Nonlinearity of Molectron	0.02	1	0.0004		B	30	5.33E-09
							1.29E-03
Combined standard uncertainty and effective ν				**0.47 %**		**38.8**	

Laboratory: …………NMIA……………………………………………………….

Date: …5th November 2007 … Signature: ……………………………….

Record of detector radiant exposure

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	< 70	
Nd:YAG	1064	1	< 60	
Nd:YAG	1064	8.3	< 40	
CO_2	10600	2	< 60	
CO_2	10600	5.7	< 50	

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Approx. exposure time (min)	Comments
Argon	514.5	1	< 40	
Nd:YAG	1064	1	< 40	
Nd:YAG	1064	8.3	< 40	
CO_2	10600	1.5	~ 10	
CO_2	10600	5.5	~ 10	

Laboratory: ………………………NMIA……………………………………………

Date: ……5th November 2007 …… Signature: ………………………………..

Measurement results

Detector: OPHIR Type 30A

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (℃)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5								
Nd:YAG	1064	1	5	21.8	31	1.489	0.45	0.007	34.3
Nd:YAG	1064	10	5	22.0	15	1.503	0.52	0.007	37.7
CO_2	10600								
CO_2	10600								

Detector: MOLECTRON Type PM10

Laser	Wavelength (nm)	Power (W)	Beam diameter (mm)	Temperature (℃)	No. of Meas.	Spectral responsivity (mV/W)	Relative Std. Dev. (%)	Uncertainty (mV/W)	Degrees of freedom
Argon	514.5								
Nd:YAG	1064	1	5	21.8	15	1.665	0.79	0.008	42.7
Nd:YAG	1064	10	5	22.0	15	1.657	0.57	0.008	38.8
CO_2	10600								
CO_2	10600								

Laboratory: ………………NMIA……………………………………………………………

Date: ……5th November 2007 …… Signature: ………………………………..