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'THE EXAMINATION OF BASE PARAMETERS FOR ITS-90 SCALE REALISATION IN RADIATION THERMOMETRY'

EUROMET.T-S1

(EUROMET PROJECT 658)

MAIN MEASUREMENT REPORT (FINAL VERSION)

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‘THE EXAMINATION OF BASE PARAMETERS FOR ITS-90 SCALE REALISATION IN RADIATION THERMOMETRY’

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ABSTRACT

This report describes the measurement procedures and results from the participants in the EUROMET project 658: ‘The examination of base parameters for ITS-90 scale realisation’.

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INTRODUCTION

Over the years, a number of international comparisons of temperature scales have been carried out in the field of radiation thermometry. These have involved the transfer of either tungsten ribbon lamps[1,2], radiation thermometers[3,4] or, more recently, metal-carbon eutectic fixed-points[5,6], and were designed to compare the ITS-90 (International Temperature Scale of 1990) realisation at different National Metrology Institutes (NMIs). Uncertainties were assigned to the temperature scale realisation in each laboratory, taking into consideration such factors as fixed-point measurements, and calibration and measurement uncertainties of any artefact used in the realisation (for example, linearity, stability, calibration, spectral response and size-of-source effect (SSE) of a radiation thermometer; calibration and stability of a tungsten ribbon lamp or blackbody radiation source) to give an overall uncertainty for the scale realisation[7].

The EUROMET project 658 was instigated to investigate the stated uncertainties of some of the underlying parameters in the temperature scale realisation (the SSE, linearity and spectral response of a radiation thermometer) by comparing the results of measurements made by each participant using the methods normally used in their laboratory. Additionally, participants were asked to calculate the emissivity of a number of different designs of blackbody cavity using the software normally used at their institute. This was done to investigate whether there were any differences in the results obtained using different calculation methods and using slightly different assumptions. Participants were asked to measure as many of the parameters as possible.

Two precision radiation thermometers (an IKE LP3 belonging to PTB and a VEGA TSP2 belonging to IMGC) were chosen for the comparison for circulation among the participants. The thermometers were transported, not hand-carried, between each laboratory.

The protocol for the comparison is given in Appendix 1. This detailed the essential information needed to ensure that results could be compared, such as the working distances for the thermometers, but it was not too prescriptive, allowing participants to use the particular equipment and procedures they would usually use. In this way, any systematic differences in the different methods could be determined.

This report describes the measurement procedures used at each of the laboratories, and compares the results and measurement uncertainties obtained by each participant. Brief

[1] McEvoy, H. C., Raven, K. M., Pokhodoun, A. I., Matveyev, M. S., in *Proceedings of Tempmeko '96*, Torino, IMEKO TC12, 1997, pp 273 to 277

[2] Ricolfi, T., Battuello, M., Bosma, R., van der Ham, E. W. M., Fischer, J., Hartmann, J., in *Proceedings of Tempmeko 2001*, VDE VERLAG GmbH, 2002, pp 839 to 844

[3] Machin, G., Gibson, C., Johnson, B. C., Yoon, H. W., in *Proceedings of Tempmeko '99*, Delft, IMEKO / NMi Van Swinden Laboratorium, 1999, pp 576 to 581

[4] Anhalt, K., Hartmann, J., Hollandt, J., Machin, G., Lowe, D., McEvoy, H., Sakuma, F., Ma, L., in *Proceedings of Tempmeko 2004*, Cavtat –Dubrovnik, LPM/FSB, 2004, pp 1063 to 1068

[5] Machin, G., Yamada, Y., Lowe, D., Sasajima, N., Sakuma, F., Fan Kai, in *Proceedings of Tempmeko 2001*, VDE VERLAG GmbH, 2002, pp 851 to 856

[6] Machin, G., Gibson, C. E., Lowe, D., Allen, D. W., Yoon, H. W., in *Proceedings of Tempmeko 2004*, Cavtat – Dubrovnik, LPM/FSB, 2004, pp 1057 to 1062

[7] Fischer, J., et al, in *'Temperature: its Measurement and Control in Science and Industry'*, Vol. 7, American Institute of Physics 2003, pp 631 to 638

information about the measurement methods and apparatus of each participant is given, with more detailed information in the laboratory measurement reports (in Appendices).

THE PARTICIPANTS

The participating institutes were: NPL (UK), CNR-IMGC (now INRiM) (IT), PTB (DE), VSL (NL), BNM-INM/CNAM (now LNE-INM/CNAM) (FR), TUBITAK-UME (TR), CEM (ES).

THE TWO RADIATION THERMOMETERS

A summary of the technical specifications of the PTB LP3 and the IMGC VEGA TSP2.11 radiation thermometers is given in Table 1 (more information is given in Appendix 1 of the protocol).

Table 1– the specifications for the two radiation thermometers used in the comparison

Parameter	Radiation thermometer	
	IKE LP3	VEGA TSP2.11
Operating wavelength / nm	650 and 900[1]	900
Target size at working distance	(0.5 mm at 400 mm)[2] (1.7 mm at 1000 mm)[2]	1.2 x 1.5 mm at 550 mm; 2 x 2.7 mm at 1000 mm
Temperature range / K	1000 to 3200	873 to 3173
Temperature coefficient	N/A	N/A

[1] For this comparison measurements were only made at 650 nm;
[2] Note that these were the specifications originally given. The LP3 lenses were subsequently changed immediately prior to the comparison.

THE SCHEDULE FOR THE CIRCULATION

The original timetable for the circulation of the two thermometers was as follows:

Institute	Time periods
NPL	1 July 2003 to 30 September 2003
VSL	1 October 2003 to 30 November 2003
PTB	1 December 2003 to 28 February 2004
CEM	1 March 2004 to 30 April 2004
UME	1 May 2004 to 30 June 2004
BNM-INM/Cnam	1 July 2004 to 30 September 2005
IMGC	1 October 2004 to 30 November 2004

Unfortunately, whilst at PTB, a problem occurred with the VEGA TSP2 thermometer and it had to be withdrawn from the comparison. The circulation continued with the LP3 only. The VEGA thermometer results presented here are from IMGC measurements made immediately before the start of the comparison and NPL only.

The comparison schedule was slightly delayed, with the circulation finishing at the end of January 2005 with the return of the LP3 to PTB. On arrival at PTB the LP3 was found to have suffered damage and was repaired. Repeat measurements of the size-of-source effect (SSE) were subsequently made at PTB during the Spring of 2005.

Information about the different measurements is given in the Sections below along with the results. No measurement report was received from VSL so no results from VSL are included.

MEASUREMENT METHODS, RESULTS AND DISCUSSION

1. Size-of-source-effect measurements

1.1 SSE apparatus used at each institute

The size-of-source effect (SSE) was measured using the 'indirect method', i.e. with the central portion of the field-of-view of the thermometer being obscured by means of a blackened disc or spot placed in front of the source. Measurements were made both with the thermometer viewing the spot and viewing an unobscured part of the source. The SSE was calculated using the expression:

SSE = (on spot measurement – background) / (off-spot measurement – background)

3 mm and 6 mm diameter spot sizes were used. The specified thermometer working distances for the measurements were 700 mm for the LP3 and 550 mm for the VEGA TSP2. Measurements were to be made at all aperture sizes available at the institute.

If the laboratory wished, additional measurements could be made using the 'direct' method, i.e. by aligning the thermometer onto the centre of a blackbody aperture and varying the size of the aperture. In the event, all of the participants measured the SSE using the 'indirect' method only, using an integrating sphere as the source according to the following Table (for further details see also the reports from the individual participants in the Appendices). Where the information is not available, it has been replaced with a dash (-).

Institute	Sphere diameter / mm	Aperture diameter / mm	Sphere coating	Light source	Description of spots
NPL	~150	50	Spectralon	tungsten halogen lamp	blackbodies in Perspex plates
PTB	250	70	-	luminance standard LN3 from LMT, Berlin	-
CEM	-	100	-	24 V, 260 W XENOPHOT lamp	black cardboard spots on glass plates
UME	170	60	$BaSO_4$	4 x 20W halogen lamps	glass masks with pupils
INM	-	-	-	-	spots on quartz plates
IMGC	-	100	$BaSO_4$	lamp	blackbodies

1.2 The results of the SSE measurements

The results of the measurements from all the participants, along with the estimated k = 2 measurement uncertainties, are given in Tables 2 to 8 for the LP3 with the 3mm diameter spot, Tables 9 to 14 for the LP3 with the 6 mm diameter spot, and Tables 15 to 18 for the VEGA TSP2 thermometer. The results of the PTB measurements with the LP3 following the breakage and repair are given in Table 8 and Figure 1 for information but have not been included in the subsequent data analysis.

1.2.1 The SSE results for the LP3

1.2.1.1 The results of the LP3 measurements with the 3 mm diameter spot

Table 2

NPL results		
Aperture diameter /mm	Average SSE	U (k = 2)
5	0.000180	0.000060
6	0.000235	0.000060
7	0.000285	0.000060
9	0.000366	0.000060
12	0.000483	0.000060
15	0.000593	0.000060
18	0.000694	0.000060
20	0.000752	0.000060
25	0.000879	0.000060
30	0.000994	0.000060
40	0.001180	0.000060
50	0.001325	0.000060

Table 3

PTB results		
Aperture diameter /mm	Average SSE	U (k = 2)
13	0.000560	0.000480
20	0.000780	0.000460
25	0.000920	0.000460
34	0.001170	0.000440
46	0.001340	0.000480
59	0.001540	0.000480
70	0.001760	0.000460

Table 4

CEM results		
Aperture diameter /mm	Average SSE	U (k = 2)
3.2	0.000000	-
10.4	0.000420	0.00004
14.1	0.000510	0.00004
19.5	0.000690	0.00004
24.1	0.000830	0.00007
28.9	0.000980	0.00008
33.8	0.001090	0.00011
39.1	0.001210	0.00016
49.1	0.001370	0.00025
59.0	0.001570	0.00035
69.3	0.001750	0.00044
100.0	0.002370	0.00073

Table 5

UME results		
Aperture diameter /mm	Average SSE	U (k = 2)
4	0.000121	0.000032
6	0.000230	0.000032
8	0.000339	0.000032
10	0.000419	0.000032
15	0.000613	0.000032
20	0.000799	0.000032
30	0.001071	0.000032
40	0.001307	0.000032
52	0.001482	0.000032

Table 6

INM results		
Aperture diameter /mm	Average SSE	U (k = 2)
5.7	0.000210	0.00004
8	0.000318	0.00006
10	0.000408	0.00008
12.5	0.000511	0.00010
16.3	0.000649	0.00010
21.2	0.000811	0.00020
27.6	0.000989	0.00020
35.8	0.001180	0.00020

Table 7

IMGC results		
Aperture diameter /mm	Average SSE	U (k = 2)
8	0.00041	0.000017
10	0.00054	0.000023
12	0.00064	0.000027
15	0.00078	0.000033
20	0.00098	0.000041
25	0.00116	0.000049
30	0.00129	0.000054
35	0.00143	0.000060
40	0.00155	0.000065
50	0.00176	0.000074
60	0.00196	0.000082
70	0.00216	0.000091
80	0.00237	0.000100
90	0.00256	0.000108
100	0.00277	0.000116

Table 8

PTB results II, at end of comparison		
Aperture diameter /mm	Average SSE	U (k = 2)
3	0.00012	-
5	0.00029	-
7	0.00039	-
10	0.00054	-
15	0.00082	-
20	0.00106	-
25	0.00127	-
30	0.00145	-
40	0.00176	-
50	0.00200	-
60	0.00219	-
70	0.00240	-
75	0.00250	-

1.2.1.2 The results of the LP3 measurements with the 6 mm diameter spot

Table 9

NPL results		
Aperture diameter /mm	Average SSE	U (k = 2)
7	0.000050	0.000050
9	0.000124	0.000050
12	0.000240	0.000050
15	0.000349	0.000050
18	0.000452	0.000050
20	0.000518	0.000050
25	0.000643	0.000050
30	0.000758	0.000050
40	0.000947	0.000050
50	0.001103	0.000050

Table 10

PTB results		
Aperture diameter /mm	Average SSE	U (k = 2)
13	0.000300	0.000580
20	0.000510	0.000580
25	0.000640	0.000600
34	0.000840	0.000580
46	0.001060	0.000520
59	0.001250	0.000540
70	0.001460	0.000620

Table 11

CEM results		
Aperture diameter /mm	Average SSE	U (k = 2)
6.3	0.000000	-
14.1	0.000420	0.000050
19.5	0.000590	0.000070
24.1	0.000740	0.000070
28.9	0.000800	0.000080
33.8	0.000910	0.000100
39.1	0.001020	0.000120
49.1	0.001180	0.000180
59.0	0.001360	0.000250
69.3	0.001510	0.000310
100.0	0.002110	0.000610

Table 12

UME results		
Aperture diameter /mm	Average SSE	U (k = 2)
8	0.000102	0.000032
10	0.000190	0.000032
15	0.000365	0.000032
20	0.000534	0.000032
30	0.000806	0.000032
40	0.001020	0.000032
52	0.001200	0.000032

Table 13

INM results		
Aperture diameter /mm	Average SSE	U ($k = 2$)
8	0.000088	0.00002
10	0.00018	0.00004
12.5	0.00028	0.00006
16.3	0.00042	0.00008
21.2	0.00058	0.00010
27.6	0.00076	0.00020
35.8	0.00095	0.00020

Table 14

IMGC results		
Aperture diameter /mm	Average SSE	U ($k = 2$)
10	0.00022	0.000004
12	0.00033	0.000006
15	0.00047	0.000008
20	0.00068	0.000012
25	0.00085	0.000015
30	0.00099	0.000018
35	0.00112	0.000020
40	0.00123	0.000022
50	0.00146	0.000026
60	0.00166	0.000030
70	0.00186	0.000034
80	0.00206	0.000037
90	0.00225	0.000041
100	0.00247	0.000044

1.2.2 Graphs plotting the SSE results for the LP3

The SSE results from all the participants are plotted in Figures 1 and 2 for ease of comparison along with the $k = 2$ measurement uncertainties.

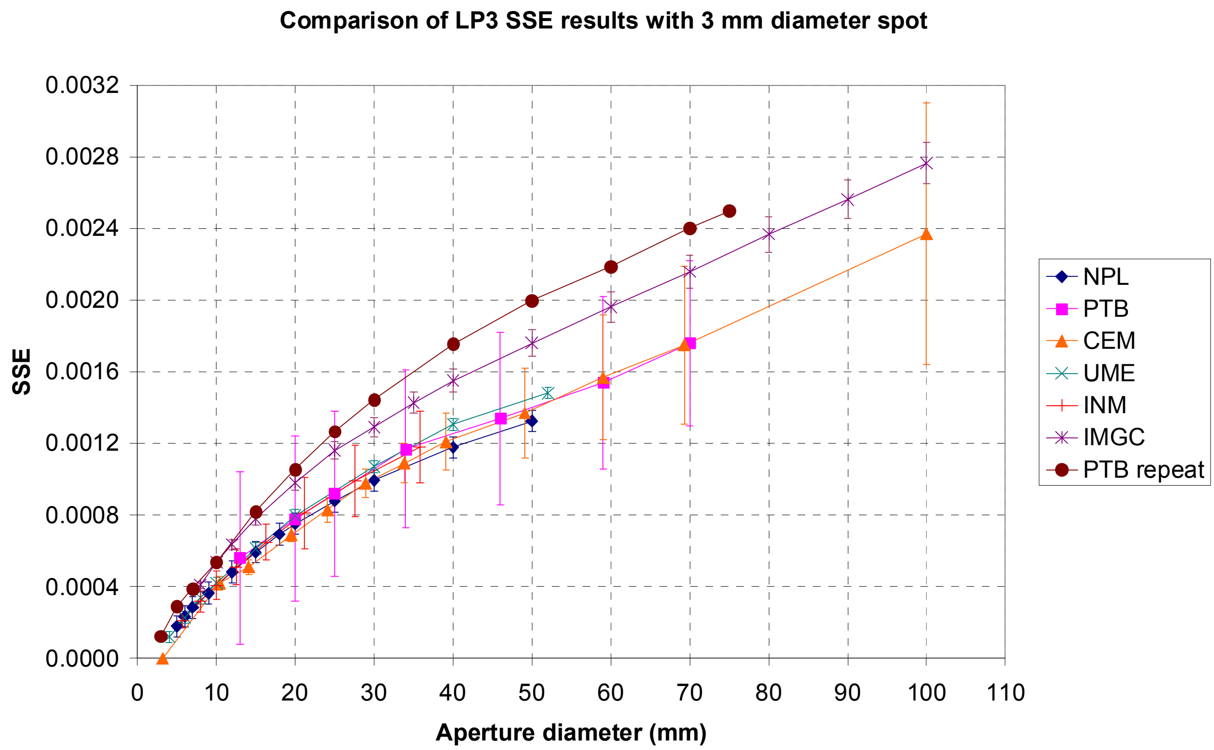


Figure 1– comparison of the LP3 SSE results with the 3 mm diameter spot.

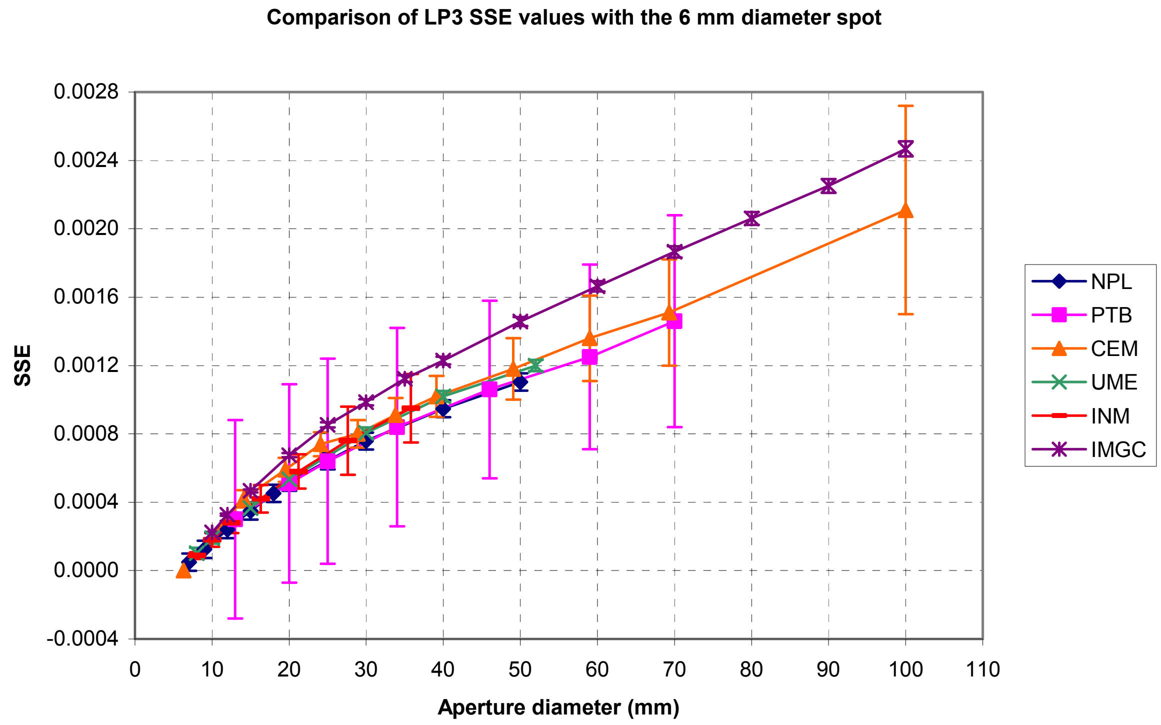


Figure 2– comparison of the LP3 SSE results with the 6 mm diameter spot.

1.2.3 The SSE results for the VEGA thermometer

The results of the VEGA measurements are given in Tables 15 to 18. The SSE measurements were made at x10^8 gain. Looking at the components of the SSE measurement uncertainty, the values for the VEGA and LP3 should be similar. For the purpose of this data evaluation and analysis, therefore, the VEGA uncertainties were assumed to be the same as for the LP3 measurements, namely 4.2% of the SSE value for measurements made with the 3 mm diameter spot and 1.8% of the SSE value for measurements made with the 6 mm diameter spot (see the IMGC measurement report in the Appendices). For the NPL measurements the maximum uncertainty for each aperture with each spot size was taken to be the uncertainty for all the apertures with that spot size.

Table 15

IMGC results – 3mm spot		
Aperture diameter /mm	Average SSE	U (k = 2)
10	0.00589	0.00025
12	0.00653	0.00027
15	0.00723	0.00030
20	0.00823	0.00035
25	0.00890	0.00037
30	0.00933	0.00039
35	0.00971	0.00041
40	0.01000	0.00042
50	0.01123	0.00047
60	0.01176	0.00049
70	0.01211	0.00051
80	0.01236	0.00052
90	0.01257	0.00053
100	0.01274	0.00054

Table 16

NPL results – 3 mm spot		
Aperture diameter /mm	Average SSE	U (k = 2)
5	0.002669	0.000090
6	0.003615	0.000090
7	0.004246	0.000090
9	0.005328	0.000090
12	0.006397	0.000090
15	0.007151	0.000090
18	0.007884	0.000090
20	0.008222	0.000090
25	0.008882	0.000090
30	0.009355	0.000090
40	0.010019	0.000090
50	0.011241	0.000090

Table 17

IMGC results – 6 mm spot		
Aperture diameter /mm	Average SSE	U (k = 2)
10	0.002143	0.000039
12	0.002800	0.000050
15	0.003544	0.000064
20	0.004562	0.000082
25	0.005238	0.000094
30	0.005683	0.000102
35	0.006056	0.000109
40	0.006377	0.000115
50	0.007623	0.000137
60	0.008168	0.000147
70	0.008536	0.000154
80	0.008788	0.000158
90	0.009002	0.000162
100	0.009190	0.000165

Table 18

NPL results – 6 mm spot		
Aperture diameter /mm	Average SSE	U (k = 2)
7	0.000519	0.000080
9	0.001558	0.000080
12	0.002670	0.000080
15	0.003417	0.000080
18	0.004159	0.000080
20	0.004502	0.000080
25	0.005093	0.000080
30	0.005585	0.000080
40	0.006282	0.000080
50	0.007511	0.000080

1.2.4 Graphs plotting the SSE results for the VEGA TSP2

The SSE are plotted in Figures 3 to 4 for ease of comparison, along with the estimated k = 2 measurement uncertainties.

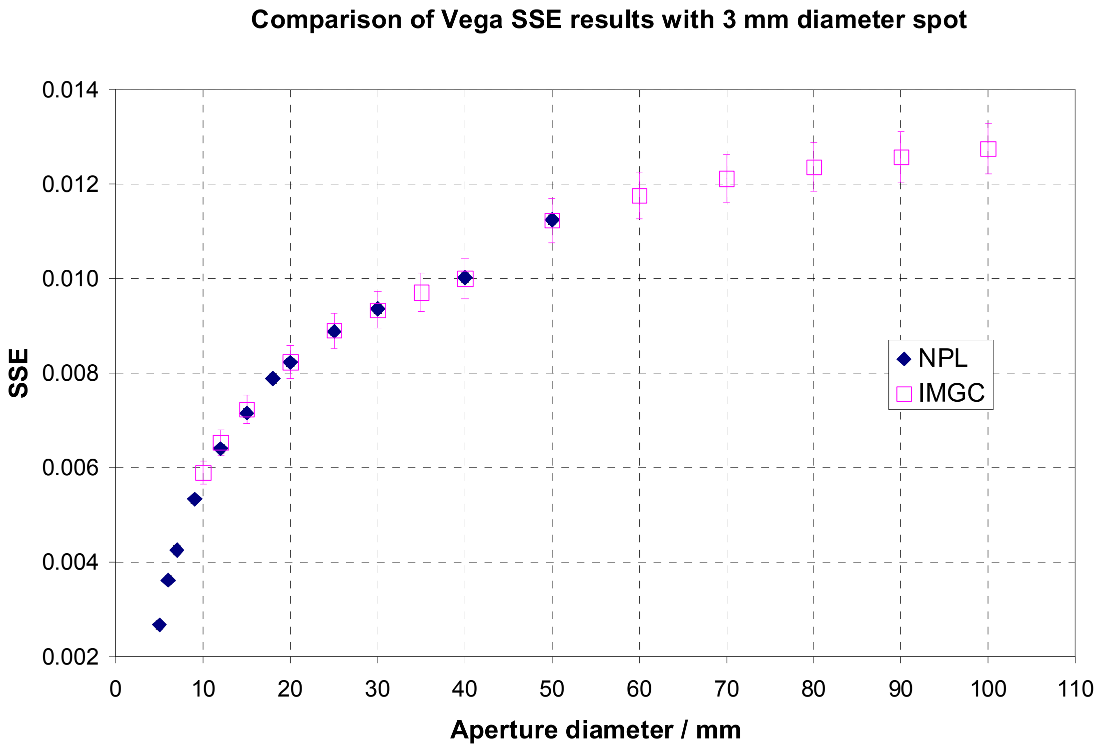


Figure 3– comparison of the VEGA TSP2 SSE results with the 3 mm diameter spot

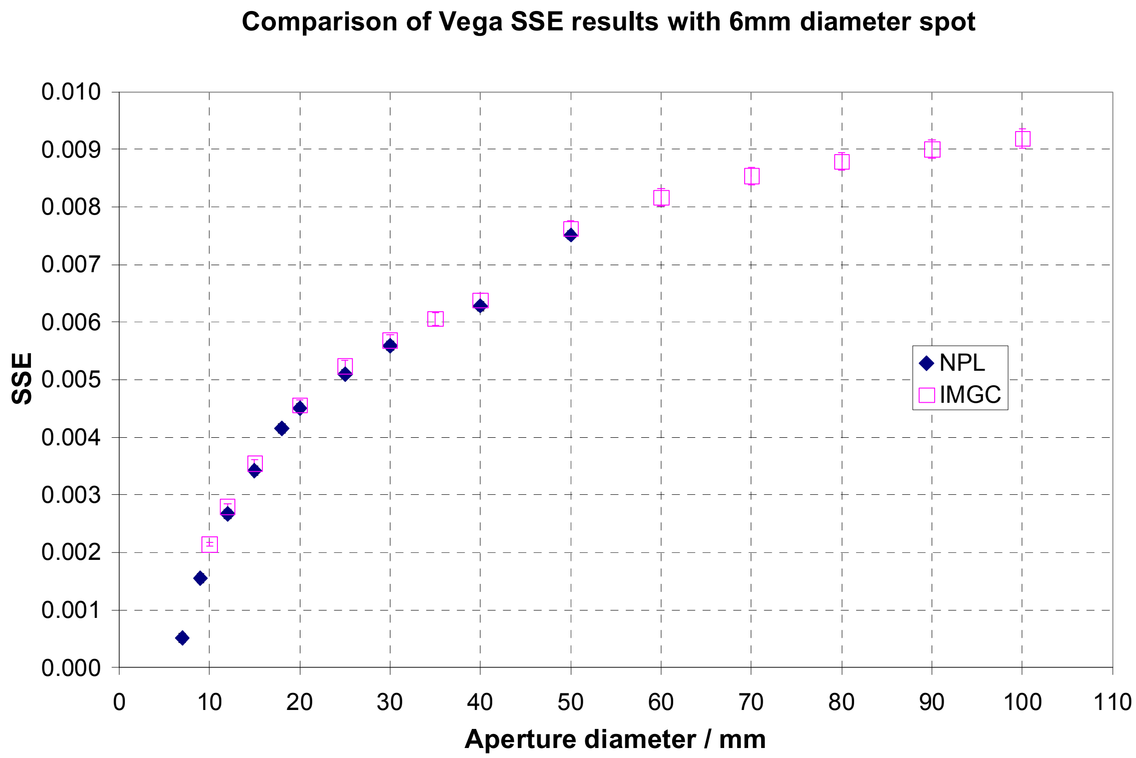


Figure 4– comparison of the VEGA TSP2 SSE results with the 6 mm diameter spot

1.3 Analysis of the results of the SSE measurements, discussions and conclusions

1.3.a Analysis of the LP3 results

The SSE measurements had been made using the aperture sizes available at each institute. This resulted in the measurements being made at a range of different aperture sizes, with only some overlap between institutes. In order to be able to directly compare all the results, and so that a comparison reference value could be calculated, the data sets from each participant were firstly fitted using a Chebyshev polynomial expression[8]. This polynomial expression was then used to provide, for each participant, the interpolated SSE over the range of apertures used by that participant. The average SSE value could then be calculated for specific aperture diameters in order to provide a comparison reference value at these diameters. The specific aperture diameters chosen were every 5 mm from 5 mm (for the 3 mm diameter spot) or 10 mm (for the 6 mm diameter spot) to 40 mm and then every 10 mm to 100 mm aperture diameter. These values were chosen as being representative of the aperture diameters used by the institutes.

The order of the polynomial fit for each participant was chosen to be <n/2, with n being the number of supplied data pairs (aperture diameter, SSE) from that participant, and ensuring that the fit was a good approximation to the data considering the estimated uncertainties of the measurements. The rms residual for each fit was used as an additional uncertainty component and was combined in quadrature with the participant's measurement uncertainty. The total uncertainty values were interpolated, if necessary, to give the values at each of the chosen aperture diameters. Information about the fitting, including Chebyshev coefficients and residuals and total combined uncertainties, is given in Tables 115 to 126 in Appendix 2. (Note that the first data point of each of the CEM measurement sets where the SSE was zero, i.e for the 3.2 and 6.3 mm aperture diameters respectively, was not included in the fitting.)

In order to compare the results more rigorously a comparison reference value was needed. For each chosen aperture diameter the mean, weighted mean (weighted with respect to the laboratory measurement uncertainty) and median SSE values were therefore calculated from the fitted data (Tables 19 and 20). The differences (laboratory – mean or median) were then calculated and the results are shown in Tables 21 to 32 and Figures 5 to 10. Discontinuities occur when the number of data sets (participants) changes.

[8] The Chebyshev coefficients are obtained using values of x transformed to lie in the range (-1/+1) by the equation: $xx = ((x - xmin) - (xmax - x))/(xmax - xmin)$, $xmin$ and $xmax$ being the minimum and maximum aperture diameters respectively.

The coefficients $a(0)$, $a(1)$, …, $a(n)$ are given for the Chebyshev series:

$$y = 0.5 * a(0) + \sum_{j=1}^{n} (a(j) * T(j))$$

where $T(j)$ is defined as $\cos(j*z)$ and where $\cos(z) = xx$

Aperture diameter / mm	Arithmetic mean SSE value	Weighted mean SSE value	Median SSE value
5	0.000181	0.000180	0.000181
10	0.000431	0.000471	0.000409
15	0.000631	0.000666	0.000613
20	0.000802	0.000827	0.000782
25	0.000949	0.000975	0.000928
30	0.001077	0.001102	0.001052
35	0.001192	0.001216	0.001161
40	0.001300	0.001320	0.001250
50	0.001474	0.001476	0.001411
60	0.001704	0.001933	0.001586
70	0.001892	0.002133	0.001756
80	0.002149	0.002350	0.002149
90	0.002349	0.002552	0.002349
100	0.002568	0.002756	0.002568

Table 19 – the calculated arithmetic and weighted mean and the median SSE values for the 3 mm diameter spot results

Aperture diameter / mm	Arithmetic mean SSE value	Weighted mean SSE value	Median SSE value
10	0.000187	0.000214	0.000181
15	0.000397	0.000450	0.000371
20	0.000564	0.000637	0.000538
25	0.000706	0.000790	0.000684
30	0.000829	0.000916	0.000813
35	0.000938	0.001029	0.000927
40	0.001037	0.001130	0.001019
50	0.001209	0.001301	0.001175
60	0.001433	0.001657	0.001361
70	0.001618	0.001861	0.001531
80	0.001888	0.002058	0.001888
90	0.002080	0.002248	0.002080
100	0.002288	0.002465	0.002288

Table 20 – the calculated arithmetic and weighted mean and the median SSE values for the 6 mm diameter spot results

Aperture diameter / mm	Difference (NPL – mean SSE)	Difference (NPL - weighted mean SSE)	Difference (NPL - median SSE)	Total (k = 2) uncertainty (fitted data)
5	3.089E-06	4.579E-06	3.089E-06	6.053E-05
10	-2.215E-05	-6.250E-05	0.000E+00	6.053E-05
15	-3.626E-05	-7.128E-05	-1.854E-05	6.053E-05
20	-5.184E-05	-7.765E-05	-3.259E-05	6.053E-05
25	-6.760E-05	-9.369E-05	-4.716E-05	6.053E-05
30	-8.336E-05	-1.082E-04	-5.847E-05	6.053E-05
35	-9.910E-05	-1.237E-04	-6.870E-05	6.053E-05
40	-1.201E-04	-1.400E-04	-6.978E-05	6.053E-05
50	-1.486E-04	-1.510E-04	-8.637E-05	6.053E-05

Table 21 – differences between NPL results and averages, 3 mm diameter spot

Aperture diameter / mm	Difference (PTB – mean SSE)	Difference (PTB - weighted mean SSE)	Difference (PTB - median SSE)	Total (k = 2) uncertainty (fitted data)
15	-5.649E-06	-4.067E-05	1.208E-05	4.765E-04
20	-7.555E-06	-3.337E-05	1.169E-05	4.623E-04
25	-1.216E-05	-3.824E-05	8.286E-06	4.623E-04
30	-2.031E-05	-4.517E-05	4.579E-06	4.512E-04
35	-3.178E-05	-5.641E-05	-1.381E-06	4.457E-04
40	-5.031E-05	-7.017E-05	0.000E+00	4.623E-04
50	-6.680E-05	-6.919E-05	-4.531E-06	4.822E-04
60	-1.402E-04	-3.692E-04	-2.232E-05	4.804E-04
70	-1.355E-04	-3.768E-04	0.000E+00	4.623E-04

Table 22 – differences between PTB results and averages, 3 mm diameter spot

Aperture diameter / mm	Difference (CEM – mean SSE)	Difference (CEM - weighted mean SSE)	Difference (CEM - median SSE)	Total (k = 2) uncertainty (fitted data)
10	-4.391E-05	-8.427E-05	-2.177E-05	5.517E-05
15	-7.057E-05	-1.056E-04	-5.284E-05	5.517E-05
20	-8.410E-05	-1.099E-04	-6.485E-05	5.517E-05
25	-8.845E-05	-1.145E-04	-6.800E-05	8.141E-05
30	-8.731E-05	-1.122E-04	-6.241E-05	9.402E-05
35	-8.325E-05	-1.079E-04	-5.286E-05	1.259E-04
40	-8.285E-05	-1.027E-04	-3.254E-05	1.732E-04
50	-6.227E-05	-6.466E-05	0.000E+00	2.628E-04
60	-1.179E-04	-3.469E-04	0.000E+00	3.610E-04
70	-1.362E-04	-3.775E-04	-6.856E-07	4.510E-04
80	-2.157E-04	-4.172E-04	-2.157E-04	5.442E-04
90	-2.158E-04	-4.194E-04	-2.158E-04	6.376E-04
100	-1.976E-04	-3.855E-04	-1.976E-04	7.310E-04

Table 23 – differences between CEM results and averages, 3 mm diameter spot

Aperture diameter / mm	Difference (UME – mean SSE)	Difference (UME - weighted mean SSE)	Difference (UME - median SSE)	Total (k = 2) uncertainty (fitted data)
5	-3.089E-06	-1.600E-06	-3.089E-06	3.578E-05
10	-8.918E-06	-4.927E-05	1.323E-05	3.578E-05
15	-9.156E-06	-4.418E-05	8.571E-06	3.578E-05
20	-1.077E-05	-3.658E-05	8.478E-06	3.578E-05
25	-9.271E-06	-3.536E-05	1.117E-05	3.578E-05
30	-3.615E-06	-2.847E-05	2.128E-05	3.578E-05
35	4.666E-06	-1.996E-05	3.506E-05	3.578E-05
40	6.360E-06	-1.350E-05	5.667E-05	3.578E-05
50	-8.405E-06	-1.079E-05	5.387E-05	3.578E-05

Table 24 – differences between UME results and averages, 3 mm diameter spot

Aperture diameter / mm	Difference (INM – mean SSE)	Difference (INM - weighted mean SSE)	Difference (INM - median SSE)	Total (k = 2) uncertainty (fitted data)
10	-2.406E-05	-6.441E-05	-1.910E-06	8.002E-05
15	-2.630E-05	-6.132E-05	-8.571E-06	1.000E-04
20	-2.773E-05	-5.354E-05	-8.478E-06	1.800E-04
25	-2.873E-05	-5.482E-05	-8.286E-06	2.000E-04
30	-2.947E-05	-5.433E-05	-4.579E-06	2.000E-04
35	-2.901E-05	-5.364E-05	1.381E-06	2.000E-04

Table 25 – differences between INM results and averages, 3 mm diameter spot

Aperture diameter / mm	Difference (IMGC – mean SSE)	Difference (IMGC - weighted mean SSE)	Difference (IMGC - median SSE)	Total (k = 2) uncertainty (fitted data)
10	9.903E-05	5.868E-05	1.212E-04	2.508E-05
15	1.479E-04	1.129E-04	1.657E-04	3.448E-05
20	1.820E-04	1.562E-04	2.012E-04	4.220E-05
25	2.062E-04	1.801E-04	2.267E-04	5.001E-05
30	2.241E-04	1.992E-04	2.490E-04	5.492E-05
35	2.385E-04	2.138E-04	2.689E-04	6.083E-05
40	2.469E-04	2.270E-04	2.972E-04	6.576E-05
50	2.861E-04	2.837E-04	3.484E-04	7.467E-05
60	2.581E-04	2.908E-05	3.759E-04	8.261E-05
70	2.717E-04	3.033E-05	4.071E-04	9.155E-05
80	2.157E-04	1.423E-05	2.157E-04	1.005E-04
90	2.158E-04	1.214E-05	2.158E-04	1.085E-04
100	1.976E-04	9.779E-06	1.976E-04	1.164E-04

Table 26 – differences between IMGC results and averages, 3 mm diameter spot

Aperture diameter / mm	Difference (NPL – mean SSE)	Difference (NPL - weighted mean SSE)	Difference (NPL - median SSE)	Total (k = 2) uncertainty (fitted data)
10	-2.381E-05	-5.093E-05	-1.813E-05	5.036E-05
15	-4.672E-05	-9.990E-05	-2.080E-05	5.036E-05
20	-4.959E-05	-1.224E-04	-2.390E-05	5.036E-05
25	-5.895E-05	-1.426E-04	-3.727E-05	5.036E-05
30	-7.297E-05	-1.605E-04	-5.704E-05	5.036E-05
35	-8.490E-05	-1.762E-04	-7.390E-05	5.036E-05
40	-8.977E-05	-1.830E-04	-7.163E-05	5.036E-05
50	-1.061E-04	-1.977E-04	-7.196E-05	5.036E-05

Table 27 – differences between NPL results and averages, 6 mm diameter spot

Aperture diameter / mm	Difference (PTB – mean SSE)	Difference (PTB - weighted mean SSE)	Difference (PTB - median SSE)	Total (k = 2) uncertainty (fitted data)
15	-3.404E-05	-8.723E-05	-8.120E-06	5.802E-04
20	-5.100E-05	-1.238E-04	-2.531E-05	5.802E-04
25	-6.278E-05	-1.464E-04	-4.109E-05	6.002E-04
30	-7.121E-05	-1.587E-04	-5.529E-05	5.891E-04
35	-7.871E-05	-1.700E-04	-6.771E-05	5.752E-04
40	-8.667E-05	-1.799E-04	-6.853E-05	5.502E-04
50	-9.410E-05	-1.857E-04	-5.996E-05	5.264E-04
60	-1.574E-04	-3.816E-04	-8.505E-05	5.475E-04
70	-1.612E-04	-4.044E-04	-7.391E-05	6.202E-04

Table 28 – differences between PTB results and averages, 6 mm diameter spot

Aperture diameter / mm	Difference (CEM – mean SSE)	Difference (CEM - weighted mean SSE)	Difference (CEM - median SSE)	Total (k = 2) uncertainty (fitted data)
15	5.838E-05	5.188E-06	8.429E-05	6.549E-05
20	4.019E-05	-3.262E-05	6.589E-05	7.965E-05
25	2.569E-05	-5.793E-05	4.738E-05	8.141E-05
30	1.436E-05	-7.315E-05	3.029E-05	9.220E-05
35	4.714E-06	-8.661E-05	1.571E-05	1.107E-04
40	-4.182E-06	-9.740E-05	1.395E-05	1.316E-04
50	-1.015E-05	-1.018E-04	2.399E-05	1.908E-04
60	-7.240E-05	-2.965E-04	0.000E+00	2.588E-04
70	-8.730E-05	-3.305E-04	0.000E+00	3.219E-04
80	-1.732E-04	-3.435E-04	-1.732E-04	4.182E-04
90	-1.702E-04	-3.381E-04	-1.702E-04	5.146E-04
100	-1.788E-04	-3.556E-04	-1.788E-04	6.112E-04

Table 29 – differences between CEM results and averages, 6 mm diameter spot

Aperture diameter / mm	Difference (UME – mean SSE)	Difference (UME - weighted mean SSE)	Difference (UME - median SSE)	Total (k = 2) uncertainty (fitted data)
10	-2.134E-06	-2.925E-05	3.547E-06	3.298E-05
15	-2.913E-05	-8.232E-05	-3.217E-06	3.298E-05
20	-3.148E-05	-1.043E-04	-5.789E-06	3.298E-05
25	-2.763E-05	-1.113E-04	-5.944E-06	3.298E-05
30	-2.138E-05	-1.089E-04	-5.456E-06	3.298E-05
35	-1.710E-05	-1.084E-04	-6.100E-06	3.298E-05
40	-1.814E-05	-1.113E-04	0.000E+00	3.298E-05
50	-3.414E-05	-1.258E-04	0.000E+00	3.298E-05

Table 30 – differences between UME results and averages, 6 mm diameter spot

Aperture diameter / mm	Difference (INM – mean SSE)	Difference (INM - weighted mean SSE)	Difference (INM - median SSE)	Total (k = 2) uncertainty (fitted data)
10	-9.228E-06	-3.634E-05	-3.547E-06	4.020E-05
15	-2.270E-05	-7.589E-05	3.217E-06	7.344E-05
20	-1.990E-05	-9.272E-05	5.789E-06	9.608E-05
25	-1.574E-05	-9.936E-05	5.944E-06	1.572E-04
30	-1.047E-05	-9.799E-05	5.456E-06	2.000E-04
35	-4.900E-06	-9.623E-05	6.100E-06	2.000E-04

Table 31 – differences between INM results and averages, 6 mm diameter spot

Aperture diameter / mm	Difference (IMGC – mean SSE)	Difference (IMGC - weighted mean SSE)	Difference (IMGC - median SSE)	Total (k = 2) uncertainty (fitted data)
10	3.517E-05	8.057E-06	4.085E-05	1.077E-05
15	7.421E-05	2.102E-05	1.001E-04	1.281E-05
20	1.118E-04	3.896E-05	1.375E-04	1.562E-05
25	1.394E-04	5.578E-05	1.611E-04	1.803E-05
30	1.617E-04	7.415E-05	1.776E-04	2.059E-05
35	1.809E-04	8.957E-05	1.919E-04	2.236E-05
40	1.988E-04	1.055E-04	2.169E-04	2.417E-05
50	2.445E-04	1.529E-04	2.786E-04	2.786E-05
60	2.298E-04	5.700E-06	3.022E-04	3.162E-05
70	2.485E-04	5.326E-06	3.358E-04	3.544E-05
80	1.732E-04	2.886E-06	1.732E-04	3.833E-05
90	1.702E-04	2.273E-06	1.702E-04	4.220E-05
100	1.788E-04	1.938E-06	1.788E-04	4.512E-05

Table 32 – differences between IMGC results and averages, 6 mm diameter spot

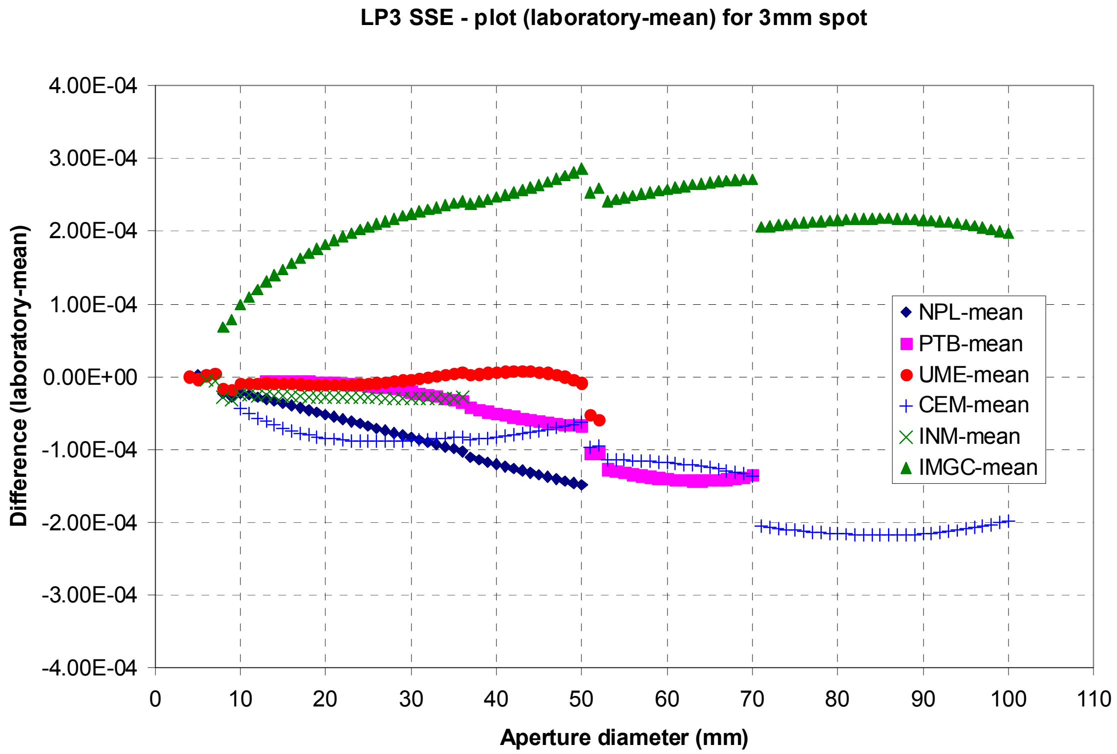


Figure 5 – Plot of results (laboratory – mean) (fitted data) for the 3 mm diameter spot

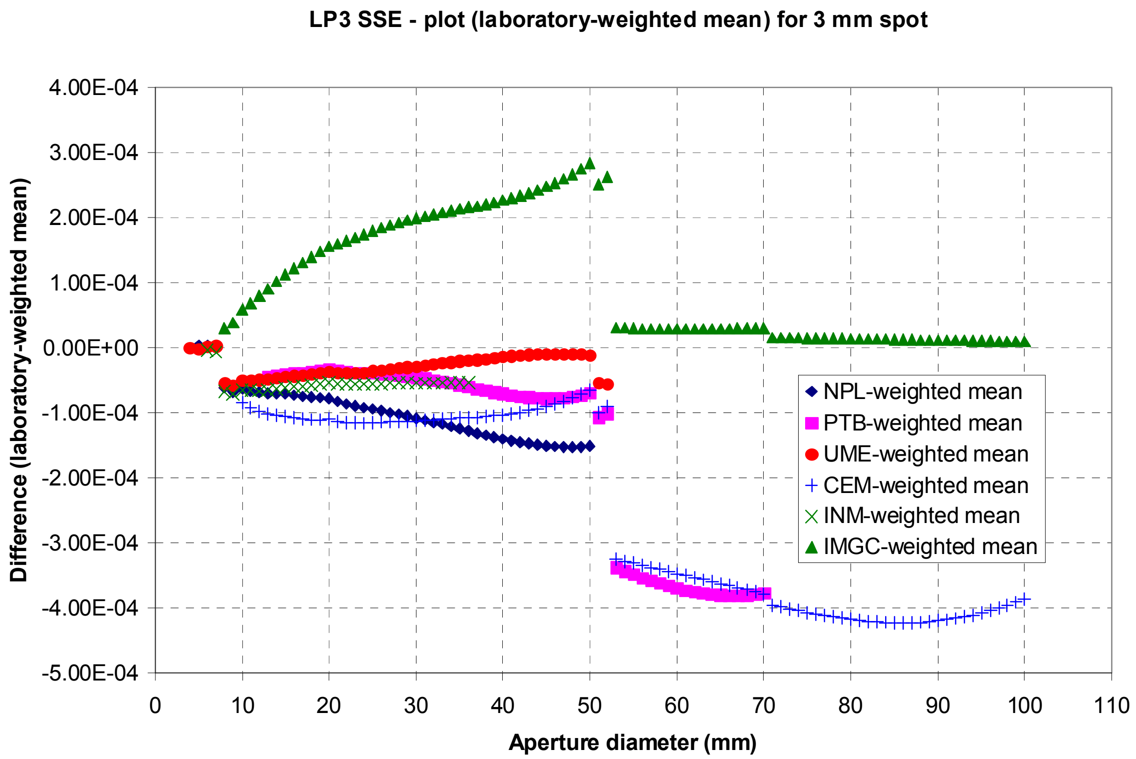


Figure 6 – Plot of results (laboratory – weighted mean) (fitted data) for the 3 mm diameter spot

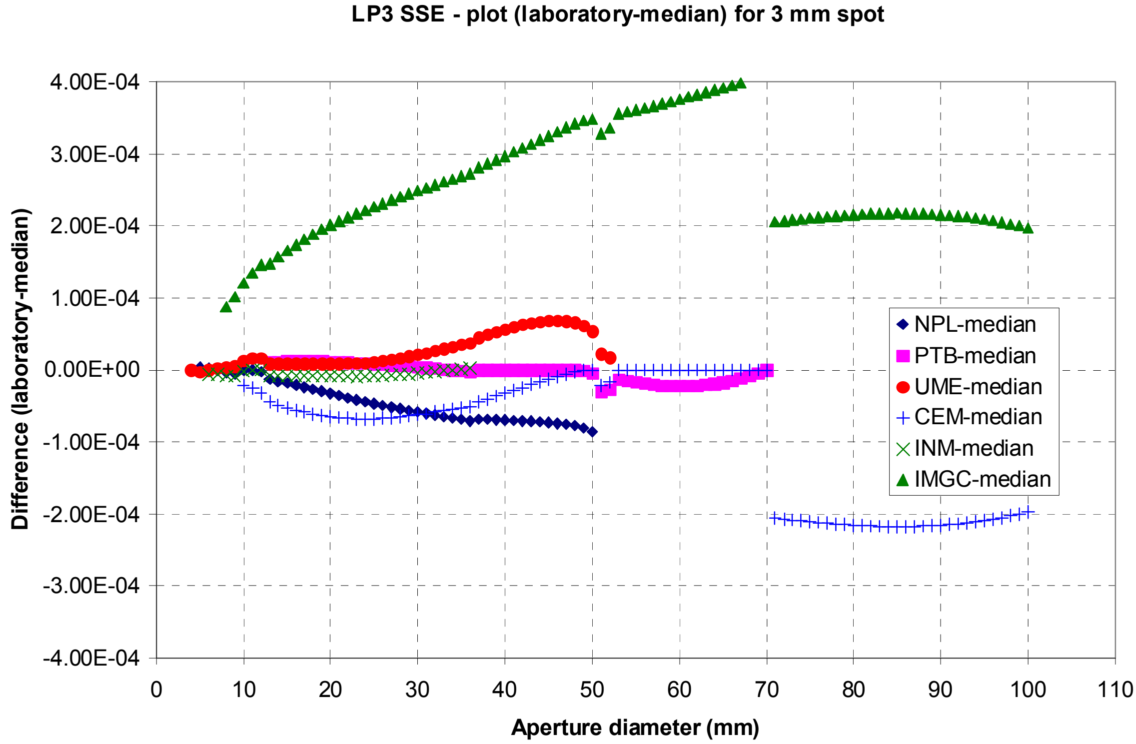


Figure 7 - Plot of results (laboratory – median) (fitted data) for the 3 mm diameter spot

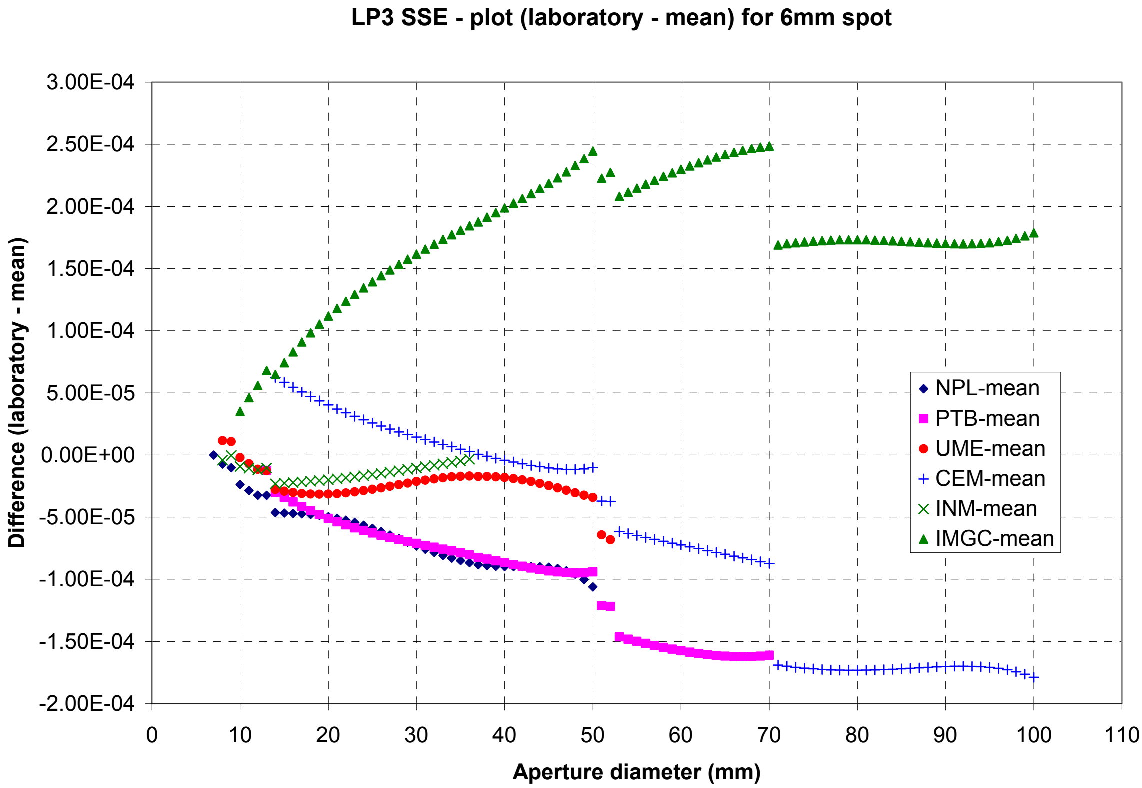


Figure 8 - Plot of results (laboratory – mean) (fitted data) for the 6 mm diameter spot

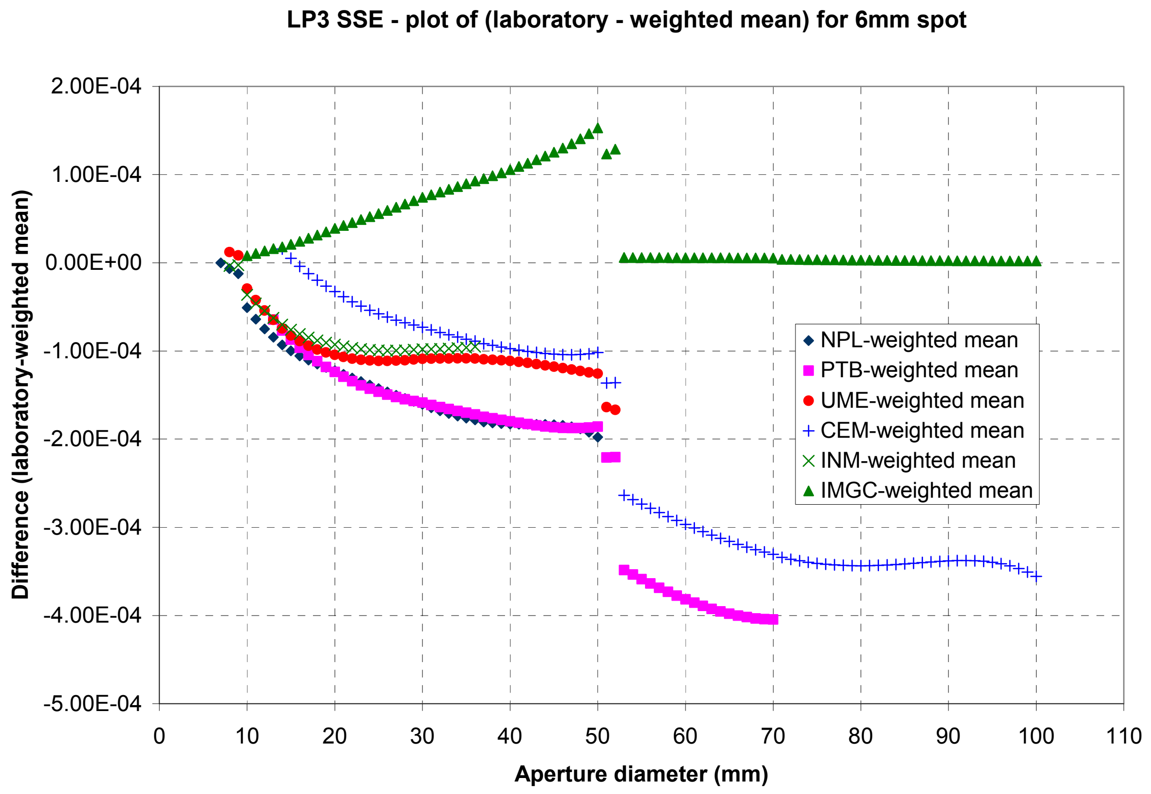


Figure 9 - Plot of results (laboratory – weighted mean) (fitted data) for the 6 mm diameter spot

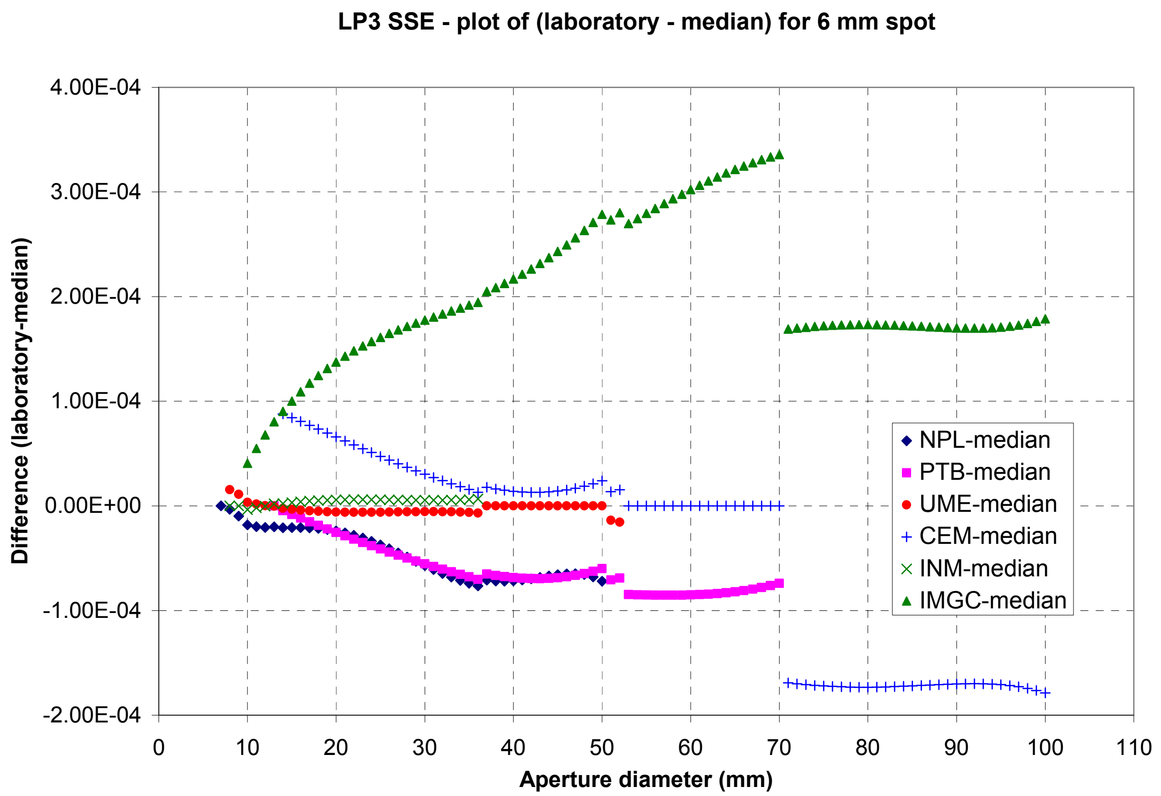


Figure 10 - Plot of results (laboratory – median) (fitted data) for the 6 mm diameter spot

The IMGC values are significantly higher than those of the other participants, possibly indicating the start of the problem with the LP3, which was found to be damaged shortly afterwards. It was therefore decided to exclude the IMGC results from the calculations of the means and median. The new means and median values are given in Tables 33 to 34, and the differences (laboratory – mean or median excluding IMGC) are given in Tables 35 to 46 and Figures 11 to 16. The IMGC and CEM differences for apertures above 70 mm diameter are given for completeness.

Aperture diameter / mm	Arithmetic mean SSE value	Weighted mean SSE value	Median SSE value
5	0.000181	0.000180	0.000181
10	0.000406	0.000411	0.000408
15	0.000601	0.000602	0.000605
20	0.000765	0.000766	0.000774
25	0.000907	0.000916	0.000920
30	0.001033	0.001047	0.001048
35	0.001144	0.001166	0.001160
40	0.001238	0.001272	0.001233
50	0.001402	0.001429	0.001409
60	0.001575	0.001578	0.001575
70	0.001756	0.001756	0.001756
80	0.001933	0.001933	0.001933
90	0.002133	0.002133	0.002133
100	0.002371	0.002371	0.002371

Table 33 – the calculated arithmetic and weighted mean and the median SSE values for the 3 mm diameter spot results, excluding the IMGC results

Aperture diameter / mm	Arithmetic mean SSE value	Weighted mean SSE value	Median SSE value
10	0.000175	0.000178	0.000177
15	0.000382	0.000376	0.000368
20	0.000541	0.000536	0.000532
25	0.000678	0.000676	0.000678
30	0.000797	0.000797	0.000808
35	0.000902	0.000903	0.000921
40	0.000987	0.000999	0.000985
50	0.001148	0.001154	0.001145
60	0.001318	0.001345	0.001318
70	0.001494	0.001515	0.001494
80	0.001715	0.001715	0.001715
90	0.001910	0.001910	0.001910
100	0.002110	0.002110	0.002110

Table 34 – the calculated arithmetic and weighted mean and the median SSE values for the 6 mm diameter spot results, excluding the IMGC results

Aperture diameter / mm	Difference (NPL – mean SSE)	Difference (NPL - weighted mean SSE)	Difference (NPL - median SSE)	Total (k = 2) uncertainty (fitted data)
5	3.089E-06	4.579E-06	3.089E-06	6.053E-05
10	2.613E-06	-1.875E-06	9.549E-07	6.053E-05
15	-6.676E-06	-7.423E-06	-9.964E-06	6.053E-05
20	-1.544E-05	-1.582E-05	-2.411E-05	6.053E-05
25	-2.636E-05	-3.536E-05	-3.887E-05	6.053E-05
30	-3.855E-05	-5.305E-05	-5.389E-05	6.053E-05
35	-5.140E-05	-7.335E-05	-6.732E-05	6.053E-05
40	-5.837E-05	-9.189E-05	-5.351E-05	6.053E-05
50	-7.711E-05	-1.036E-04	-8.410E-05	6.053E-05

Table 35 – differences between NPL results and averages (excl. IMGC), 3 mm diameter spot

Aperture diameter / mm	Difference (PTB – mean SSE)	Difference (PTB - weighted mean SSE)	Difference (PTB - median SSE)	Total (k = 2) uncertainty (fitted data)
15	2.394E-05	2.319E-05	2.065E-05	4.765E-04
20	2.884E-05	2.846E-05	2.017E-05	4.623E-04
25	2.908E-05	2.009E-05	1.657E-05	4.623E-04
30	2.450E-05	9.997E-06	9.159E-06	4.512E-04
35	1.592E-05	-6.030E-06	0.000E+00	4.457E-04
40	1.141E-05	-2.211E-05	1.627E-05	4.623E-04
50	4.728E-06	-2.176E-05	-2.265E-06	4.822E-04
60	-1.116E-05	-1.427E-05	-1.116E-05	4.804E-04
70	3.428E-07	3.513E-07	3.428E-07	4.623E-04

Table 36 – differences between PTB results and averages (excl. IMGC), 3 mm diameter spot

Aperture diameter / mm	Difference (CEM – mean SSE)	Difference (CEM - weighted mean SSE)	Difference (CEM - median SSE)	Total (k = 2) uncertainty (fitted data)
10	-1.916E-05	-2.364E-05	-2.081E-05	5.517E-05
15	-4.098E-05	-4.173E-05	-4.427E-05	5.517E-05
20	-4.770E-05	-4.808E-05	-5.638E-05	5.517E-05
25	-4.721E-05	-5.620E-05	-5.972E-05	8.141E-05
30	-4.249E-05	-5.700E-05	-5.783E-05	9.402E-05
35	-3.556E-05	-5.751E-05	-5.148E-05	1.259E-04
40	-2.113E-05	-5.465E-05	-1.627E-05	1.732E-04
50	9.259E-06	-1.723E-05	2.265E-06	2.628E-04
60	1.116E-05	8.057E-06	1.116E-05	3.610E-04
70	-3.428E-07	-3.343E-07	-3.428E-07	4.510E-04
80	0.000E+00	0.000E+00	0.000E+00	5.442E-04
90	0.000E+00	0.000E+00	0.000E+00	6.376E-04
100	0.000E+00	0.000E+00	0.000E+00	7.310E-04

Table 37 – differences between CEM results and averages (excl. IMGC), 3 mm diameter spot

Aperture diameter / mm	Difference (UME – mean SSE)	Difference (UME - weighted mean SSE)	Difference (UME - median SSE)	Total (k = 2) uncertainty (fitted data)
5	-3.089E-06	-1.600E-06	-3.089E-06	3.578E-05
10	1.584E-05	1.135E-05	1.418E-05	3.578E-05
15	2.043E-05	1.968E-05	1.714E-05	3.578E-05
20	2.563E-05	2.525E-05	1.696E-05	3.578E-05
25	3.197E-05	2.297E-05	1.946E-05	3.578E-05
30	4.120E-05	2.670E-05	2.586E-05	3.578E-05
35	5.236E-05	3.041E-05	3.644E-05	3.578E-05
40	6.808E-05	3.456E-05	7.294E-05	3.578E-05
50	6.312E-05	3.663E-05	5.613E-05	3.578E-05

Table 38 – differences between UME results and averages (excl. IMGC), 3 mm diameter spot

Aperture diameter / mm	Difference (INM – mean SSE)	Difference (INM - weighted mean SSE)	Difference (INM - median SSE)	Total (k = 2) uncertainty (fitted data)
10	7.030E-07	-3.784E-06	-9.549E-07	8.002E-05
15	3.289E-06	2.542E-06	0.000E+00	1.000E-04
20	8.672E-06	8.292E-06	0.000E+00	1.800E-04
25	1.251E-05	3.514E-06	0.000E+00	2.000E-04
30	1.534E-05	8.381E-07	0.000E+00	2.000E-04
35	1.868E-05	-3.268E-06	2.762E-06	2.000E-04

Table 39 – differences between INM results and averages (excl. IMGC), 3 mm diameter spot

Aperture diameter / mm	Difference (IMGC – mean SSE)	Difference (IMGC - weighted mean SSE)	Difference (IMGC - median SSE)	Total (k = 2) uncertainty (fitted data)
10	1.238E-04	1.193E-04	1.221E-04	2.508E-05
15	1.775E-04	1.768E-04	1.742E-04	3.448E-05
20	2.184E-04	2.180E-04	2.097E-04	4.220E-05
25	2.475E-04	2.385E-04	2.349E-04	5.001E-05
30	2.689E-04	2.544E-04	2.535E-04	5.492E-05
35	2.862E-04	2.642E-04	2.703E-04	6.083E-05
40	3.086E-04	2.751E-04	3.135E-04	6.576E-05
50	3.576E-04	3.312E-04	3.507E-04	7.467E-05
60	3.871E-04	3.840E-04	3.871E-04	8.261E-05
70	4.075E-04	4.075E-04	4.075E-04	9.155E-05
80	4.315E-04	4.315E-04	4.315E-04	1.005E-04
90	4.315E-04	4.315E-04	4.315E-04	1.085E-04
100	3.952E-04	3.952E-04	3.952E-04	1.164E-04

Table 40 – differences between IMGC results and averages (excl. IMGC), 3 mm diameter spot

Aperture diameter / mm	Difference (NPL – mean SSE)	Difference (NPL - weighted mean SSE)	Difference (NPL - median SSE)	Total (k = 2) uncertainty (fitted data)
10	-1.209E-05	-1.498E-05	-1.458E-05	5.036E-05
15	-3.187E-05	-2.603E-05	-1.758E-05	5.036E-05
20	-2.724E-05	-2.149E-05	-1.811E-05	5.036E-05
25	-3.107E-05	-2.872E-05	-3.132E-05	5.036E-05
30	-4.063E-05	-4.061E-05	-5.159E-05	5.036E-05
35	-4.872E-05	-5.035E-05	-6.780E-05	5.036E-05
40	-4.008E-05	-5.150E-05	-3.737E-05	5.036E-05
50	-4.498E-05	-5.118E-05	-4.198E-05	5.036E-05

Table 41 – differences between NPL results and averages (excl. IMGC), 6 mm diameter spot

Aperture diameter / mm	Difference (PTB – mean SSE)	Difference (PTB - weighted mean SSE)	Difference (PTB - median SSE)	Total (k = 2) uncertainty (fitted data)
15	-1.919E-05	-1.335E-05	-4.903E-06	5.802E-04
20	-2.864E-05	-2.290E-05	-1.952E-05	5.802E-04
25	-3.490E-05	-3.255E-05	-3.515E-05	6.002E-04
30	-3.888E-05	-3.886E-05	-4.983E-05	5.891E-04
35	-4.253E-05	-4.416E-05	-6.161E-05	5.752E-04
40	-3.698E-05	-4.840E-05	-3.427E-05	5.502E-04
50	-3.298E-05	-3.918E-05	-2.998E-05	5.264E-04
60	-4.252E-05	-6.951E-05	-4.252E-05	5.475E-04
70	-3.695E-05	-5.822E-05	-3.695E-05	6.202E-04

Table 42 – differences between PTB results and averages (excl. IMGC), 6 mm diameter spot

Aperture diameter / mm	Difference (CEM – mean SSE)	Difference (CEM - weighted mean SSE)	Difference (CEM - median SSE)	Total (k = 2) uncertainty (fitted data)
15	7.322E-05	7.907E-05	8.751E-05	6.549E-05
20	6.255E-05	6.829E-05	7.167E-05	7.965E-05
25	5.357E-05	5.592E-05	5.332E-05	8.141E-05
30	4.670E-05	4.672E-05	3.574E-05	9.220E-05
35	4.089E-05	3.927E-05	2.181E-05	1.107E-04
40	4.551E-05	3.408E-05	4.822E-05	1.316E-04
50	5.097E-05	4.477E-05	5.397E-05	1.908E-04
60	4.252E-05	1.553E-05	4.252E-05	2.588E-04
70	3.695E-05	1.569E-05	3.695E-05	3.219E-04
80	0.000E+00	0.000E+00	0.000E+00	4.182E-04
90	0.000E+00	0.000E+00	0.000E+00	5.146E-04
100	0.000E+00	0.000E+00	0.000E+00	6.112E-04

Table 43 – differences between CEM results and averages (excl. IMGC), 6 mm diameter spot

Aperture diameter / mm	Difference (UME – mean SSE)	Difference (UME - weighted mean SSE)	Difference (UME - median SSE)	Total (k = 2) uncertainty (fitted data)
10	9.590E-06	6.695E-06	7.094E-06	3.298E-05
15	-1.429E-05	-8.445E-06	0.000E+00	3.298E-05
20	-9.124E-06	-3.382E-06	0.000E+00	3.298E-05
25	2.534E-07	2.603E-06	0.000E+00	3.298E-05
30	1.095E-05	1.097E-05	0.000E+00	3.298E-05
35	1.908E-05	1.745E-05	0.000E+00	3.298E-05
40	3.155E-05	2.013E-05	3.427E-05	3.298E-05
50	2.698E-05	2.078E-05	2.998E-05	3.298E-05

Table 44 – differences between UME results and averages (excl. IMGC), 6 mm diameter spot

Aperture diameter / mm	Difference (INM – mean SSE)	Difference (INM - weighted mean SSE)	Difference (INM - median SSE)	Total (k = 2) uncertainty (fitted data)
10	2.496E-06	-3.987E-07	0.000E+00	4.020E-05
15	-7.858E-06	-2.011E-06	6.433E-06	7.344E-05
20	2.454E-06	8.195E-06	1.158E-05	9.608E-05
25	1.214E-05	1.449E-05	1.189E-05	1.572E-04
30	2.186E-05	2.188E-05	1.091E-05	2.000E-04
35	3.128E-05	2.965E-05	1.220E-05	2.000E-04

Table 45 – differences between INM results and averages (excl. IMGC), 6 mm diameter spot

Aperture diameter / mm	Difference (IMGC – mean SSE)	Difference (IMGC - weighted mean SSE)	Difference (IMGC - median SSE)	Total (k = 2) uncertainty (fitted data)
10	4.690E-05	4.400E-05	4.440E-05	1.077E-05
15	8.905E-05	9.490E-05	1.033E-04	1.281E-05
20	1.341E-04	1.399E-04	1.433E-04	1.562E-05
25	1.673E-04	1.696E-04	1.670E-04	1.803E-05
30	1.940E-04	1.940E-04	1.831E-04	2.059E-05
35	2.171E-04	2.154E-04	1.980E-04	2.236E-05
40	2.484E-04	2.370E-04	2.512E-04	2.417E-05
50	3.056E-04	2.994E-04	3.086E-04	2.786E-05
60	3.448E-04	3.178E-04	3.448E-04	3.162E-05
70	3.728E-04	3.515E-04	3.728E-04	3.544E-05
80	3.464E-04	3.464E-04	3.464E-04	3.833E-05
90	3.403E-04	3.403E-04	3.403E-04	4.220E-05
100	3.576E-04	3.576E-04	3.576E-04	4.512E-05

Table 46 – differences between IMGC results and averages (excl. IMGC), 6 mm diameter spot

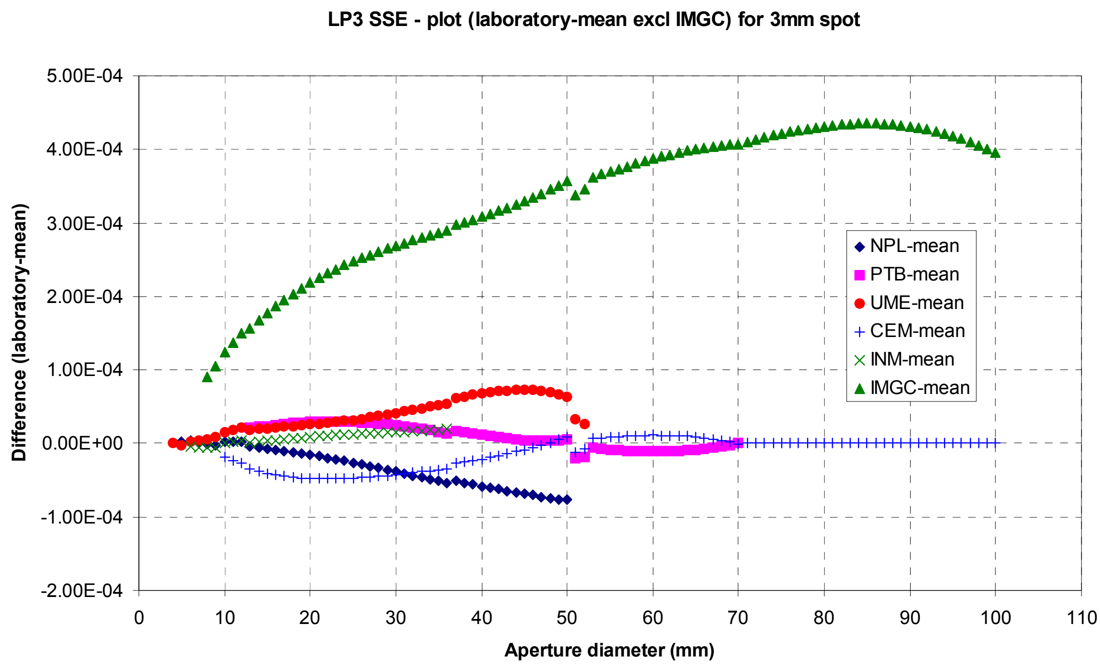


Figure 11 - Plot of results (laboratory – mean) (fitted data, excl, IMGC) for the 3 mm diameter spot

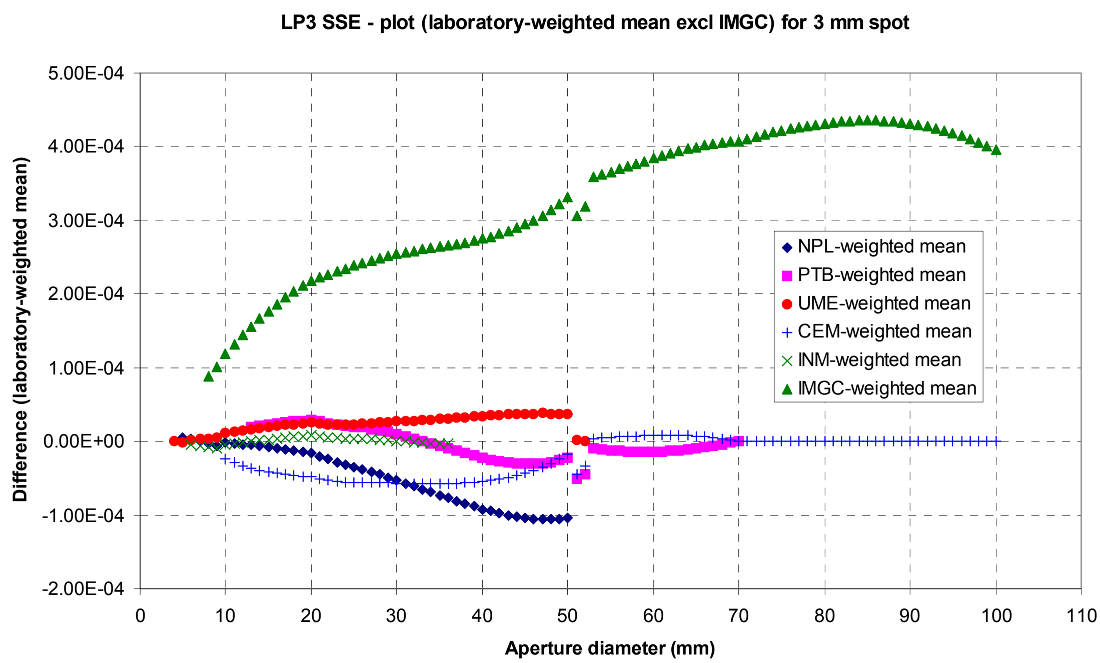


Figure 12 - Plot of results (laboratory – weighted mean) (fitted data, excl, IMGC) for the 3 mm diameter spot

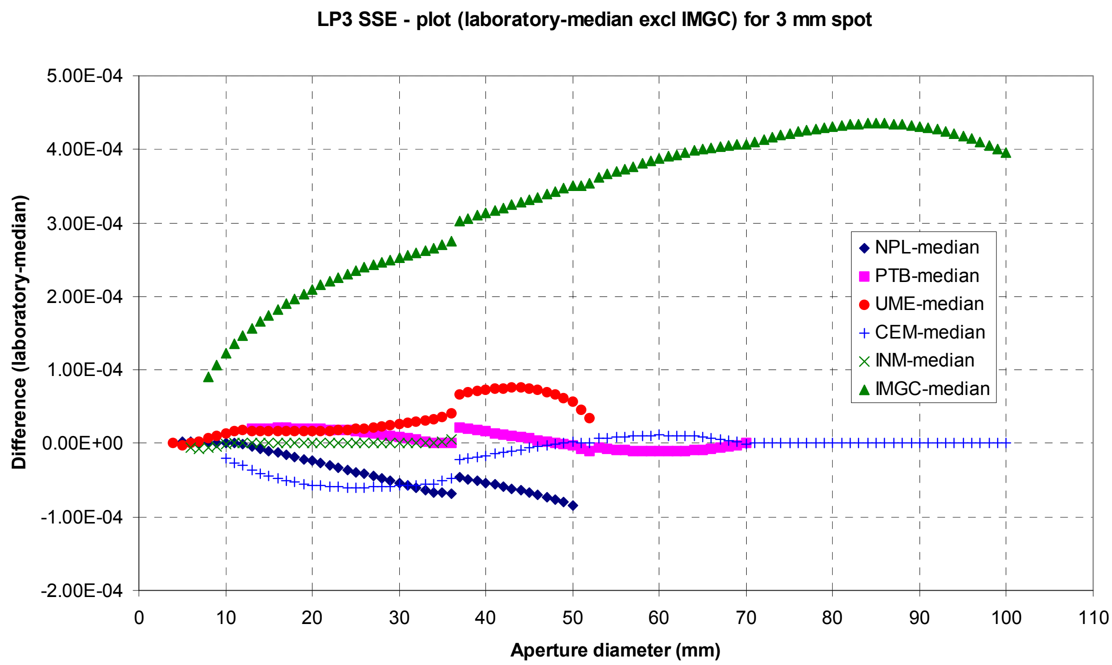


Figure 13 - Plot of results (laboratory – median) (fitted data, excl, IMGC) for the 3 mm diameter spot

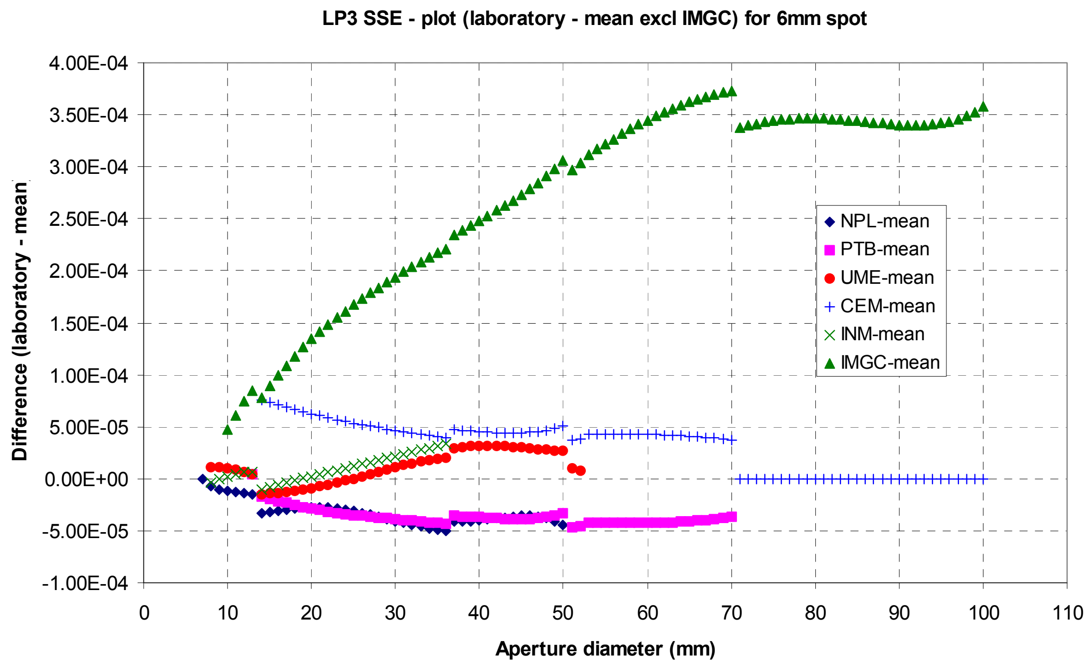


Figure 14 - Plot of results (laboratory – mean) (fitted data, excl, IMGC) for the 6 mm diameter spot

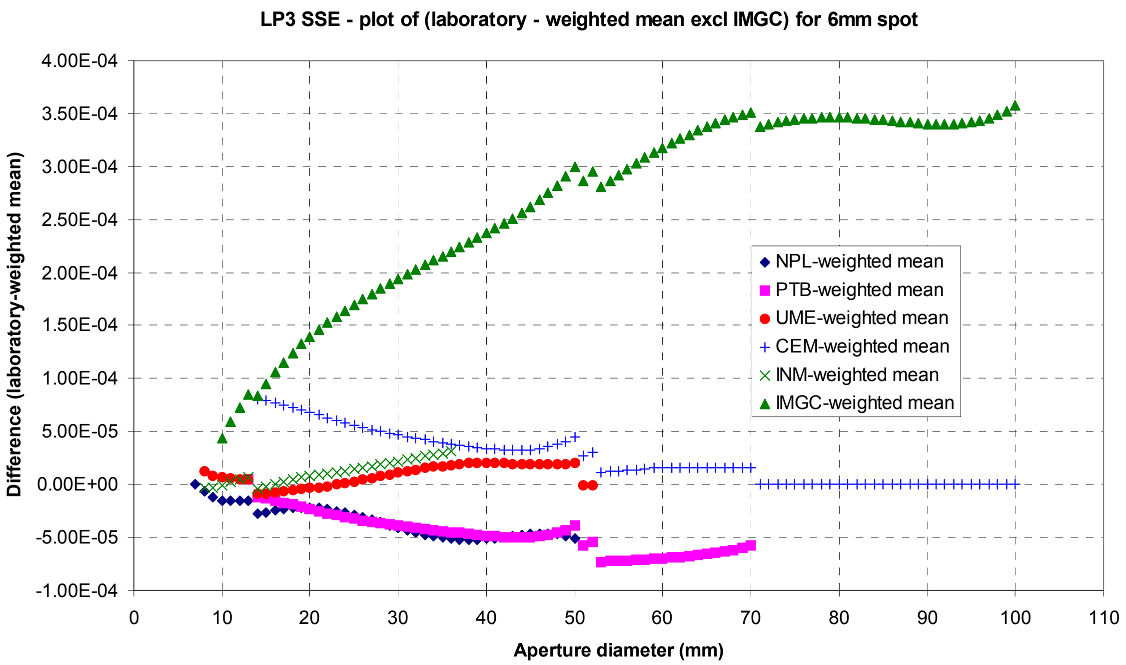


Figure 15 - Plot of results (laboratory – weighted mean) (fitted data, excl, IMGC) for the 6 mm diameter spot

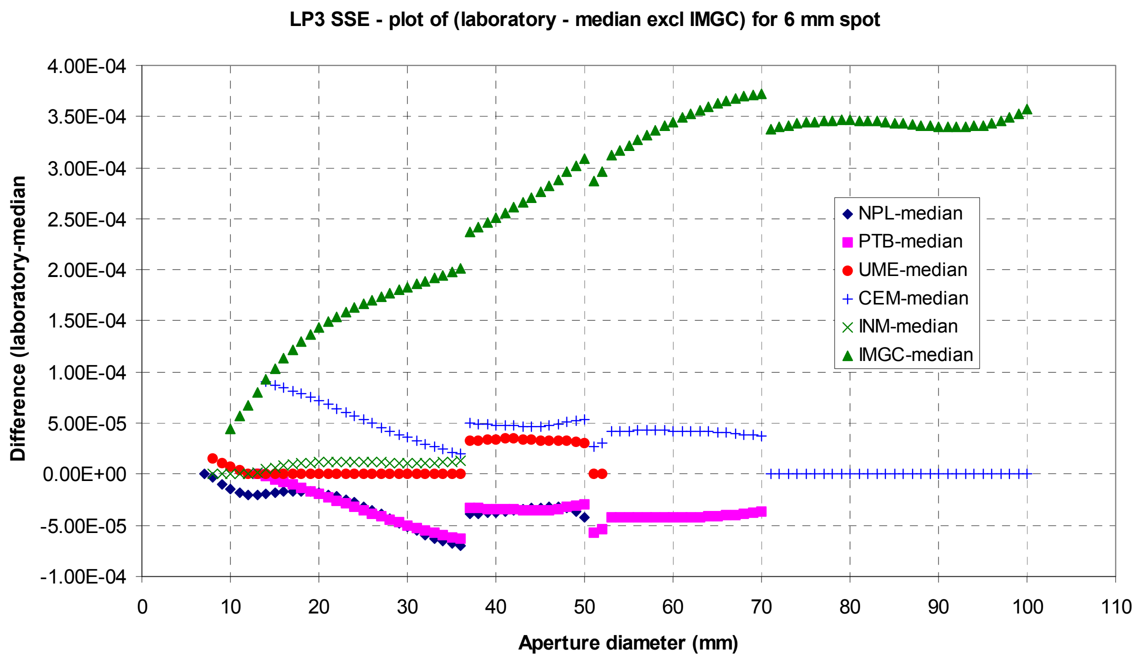


Figure 16 - Plot of results (laboratory – median) (fitted data, excl, IMGC) for the 6 mm diameter spot

Looking at the results shown in Figures 11 to 16 there is little to choose between using the median, weighted mean or arithmetic mean as the reference value. It was therefore decided simply to choose the median. Since the reference value was simply being used as a tool to facilitate the comparison of the results from each participant, it was not assigned an uncertainty. The calculated DOE and QDE_{95}[9] values for pairs of participants are given in Tables 127 to 153 in Appendix 3 (DOE and QDE_{95} values are, respectively, top right and bottom left sections of the Tables). The QDE_{95} values for each pair of labs (*i,j*) were calculated from the equation:

$$QDE_{95\,(i,j)} = \left|\Delta SSE\right|_{(i,j)} + \left\{1.645 + 0.3295\exp\left(\frac{-4.05\,\left|\Delta SSE\right|_{(i,j)}}{u_{(i,j)}}\right)\right\} u_{(i,j)}$$

where $\left|\Delta SSE\right|_{(i,j)}$ is the absolute difference in the SSE values between the two laboratories and $u_{(i,j)}$ is the combined $k = 1$ uncertainty. It should be noted that the DOE and QDE_{95} values for IMGC are affected by the failure of the LP3 thermometer which was not evident at the time of the IMGC measurements.

The difference between each laboratory and the median value at each aperture diameter, along with the estimated $k = 2$ measurement uncertainties, are given in the Figures accompanying the Tables.

1.3.b Discussion of the LP3 SSE results and conclusions

In general, most of the SSE results broadly agree with the comparison reference value within the measurement uncertainties. The main discrepancy is with the IMGC results, which are not in line with those from the other institutes. IMGC was the last laboratory to perform the measurements before the LP3 was returned to PTB, and on arrival at PTB it was found to be broken. There is a strong possibility, therefore, that the discrepancy in the IMGC results is due to the start of the problem with the LP3 rather than a problem with the IMGC measurements. This is backed up by the fact that the repeated SSE measurements at PTB, following the repair, show significantly higher values (Figure 1). In addition, the IMGC and NPL SSE results with the VEGA thermometer (Tables 15 to 18 and Figures 3 and 4) are in extremely good agreement.

1.3.c Analysis of the results of the VEGA measurements

The VEGA measurements at NPL and IMGC had mostly been carried out using apertures of the same diameter meaning that they could be directly compared. However, in order to allow a comparison at the three aperture diameters that were not common, i.e. at 10 mm, 18 mm and 35 mm diameters, the results for each laboratory were fitted using a Chebyshev polynomial and this was used to give SSE values at 10 mm and 35 mm diameter for the NPL results and 18 mm diameter for the IMGC results. The unfitted results were used for all the other aperture diameters, in order to use the raw data as much as possible.

The Chebyshev coefficients are given in the Tables 154 and 161 in Appendix 4, along with the raw data, fitted data and residuals. The values in italics are the interpolated values calculated from the fit. The residual of the fit at an aperture diameter close to each of the fitted data points was used as an additional uncertainty component for the fitted aperture diameter and was combined in quadrature with the laboratory measurement uncertainty at these points.

[9] For example, Wood, B. M., Douglas, R. J., *Metrologia*, 1998, **35**, pp 187-196

The arithmetic mean, weighted mean and median SSE values were calculated for each aperture diameter where measurements were available for both laboratories, i.e. from 10 to 50 mm diameter; the values are shown in Tables 47 and 48. The differences between the laboratory values and the average values are given in Tables 49 to 52 and plotted in Figures 17 to 22.

Aperture diameter / mm	Arithmetic mean SSE value	Weighted mean SSE value	Median SSE value
10	0.005813	0.005758	0.005813
12	0.006461	0.006410	0.006461
15	0.007189	0.007157	0.007189
18	0.007898	0.007886	0.007898
20	0.008224	0.008222	0.008224
25	0.008889	0.008882	0.008889
30	0.009344	0.009354	0.009344
35	0.009637	0.009575	0.009637
40	0.010009	0.010018	0.010009
50	0.011233	0.011241	0.011233

Table 47 – the calculated mean and median SSE values for the 3 mm diameter spot results

Aperture diameter / mm	Arithmetic mean SSE value	Weighted mean SSE value	Median SSE value
10	0.002049	0.002110	0.002049
12	0.002735	0.002763	0.002735
15	0.003480	0.003495	0.003480
18	0.004200	0.004196	0.004200
20	0.004532	0.004531	0.004532
25	0.005165	0.005154	0.005165
30	0.005634	0.005622	0.005634
35	0.005972	0.005949	0.005972
40	0.006329	0.006313	0.006329
50	0.007567	0.007540	0.007567

Table 48 – the calculated mean and median SSE values for the 6 mm diameter spot results

Aperture diameter / mm	Difference (NPL – mean SSE)	Difference (NPL - weighted mean SSE)	Difference (NPL - median SSE)	Total (k = 2) uncertainty
10	-0.000072	-0.000017	-0.000072	0.000091
12	-0.000064	-0.000013	-0.000064	0.00009
15	-0.000038	-0.000006	-0.000038	0.00009
18	-0.000014	-0.000002	-0.000014	0.00009
20	-0.000002	0.000000	-0.000002	0.00009
25	-0.000007	-0.000001	-0.000007	0.00009
30	0.000011	0.000001	0.000011	0.00009
35	-0.000069	-0.000007	-0.000069	0.000094
40	0.000010	0.000001	0.000010	0.00009
50	0.000008	0.000001	0.000008	0.00009

Table 49 – differences between NPL results and averages, 3 mm diameter spot

Aperture diameter / mm	Difference (NPL – mean SSE)	Difference (NPL - weighted mean SSE)	Difference (NPL - median SSE)	Total (k = 2) uncertainty
10	-0.000094	-0.000155	-0.000094	0.000083
12	-0.000065	-0.000093	-0.000065	0.00008
15	-0.000063	-0.000078	-0.000063	0.00008
18	-0.000041	-0.000037	-0.000041	0.00008
20	-0.000030	-0.000029	-0.000030	0.00008
25	-0.000072	-0.000061	-0.000072	0.00008
30	-0.000049	-0.000037	-0.000049	0.00008
35	-0.000084	-0.000061	-0.000084	0.000082
40	-0.000048	-0.000031	-0.000048	0.00008
50	-0.000056	-0.000028	-0.000056	0.00008

Table 50 – differences between NPL results and averages, 6 mm diameter spot

Aperture diameter / mm	Difference (IMGC – mean SSE)	Difference (IMGC - weighted mean SSE)	Difference (IMGC - median SSE)	Total (k = 2) uncertainty
10	0.000072	0.000127	0.000072	0.000247
12	0.000064	0.000116	0.000064	0.000274
15	0.000038	0.000070	0.000038	0.000304
18	0.000014	0.000027	0.000014	0.000335
20	0.000002	0.000004	0.000002	0.000345
25	0.000007	0.000013	0.000007	0.000374
30	-0.000011	-0.000022	-0.000011	0.000392
35	0.000069	0.000131	0.000069	0.000408
40	-0.000010	-0.000019	-0.000010	0.000420
50	-0.000008	-0.000015	-0.000008	0.000471

Table 51 – differences between IMGC results and averages, 3 mm diameter spot

Aperture diameter / mm	Difference (IMGC – mean SSE)	Difference (IMGC - weighted mean SSE)	Difference (IMGC - median SSE)	Total (k = 2) uncertainty
10	0.000094	0.000033	0.000094	0.000039
12	0.000065	0.000037	0.000065	0.000050
15	0.000063	0.000049	0.000063	0.000064
18	0.000041	0.000045	0.000041	0.000088
20	0.000030	0.000031	0.000030	0.000082
25	0.000072	0.000084	0.000072	0.000094
30	0.000049	0.000061	0.000049	0.000102
35	0.000084	0.000107	0.000084	0.000109
40	0.000048	0.000064	0.000048	0.000115
50	0.000056	0.000083	0.000056	0.000137

Table 52 – differences between IMGC results and averages, 6 mm diameter spot

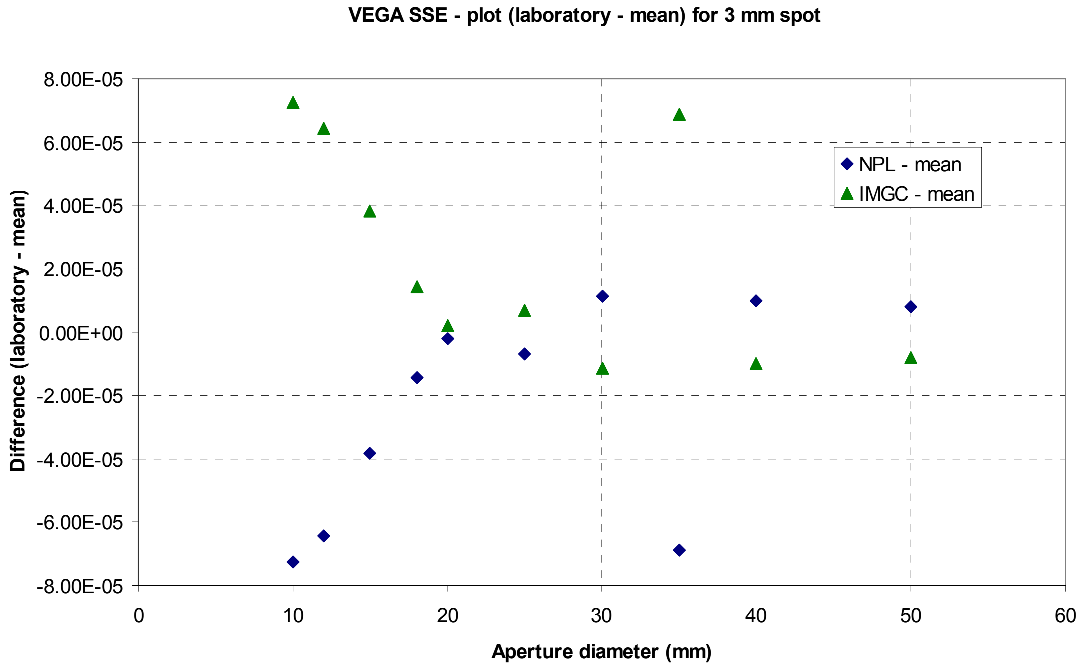


Figure 17 – Plot of results (laboratory – mean) (fitted data) for the 3 mm diameter spot

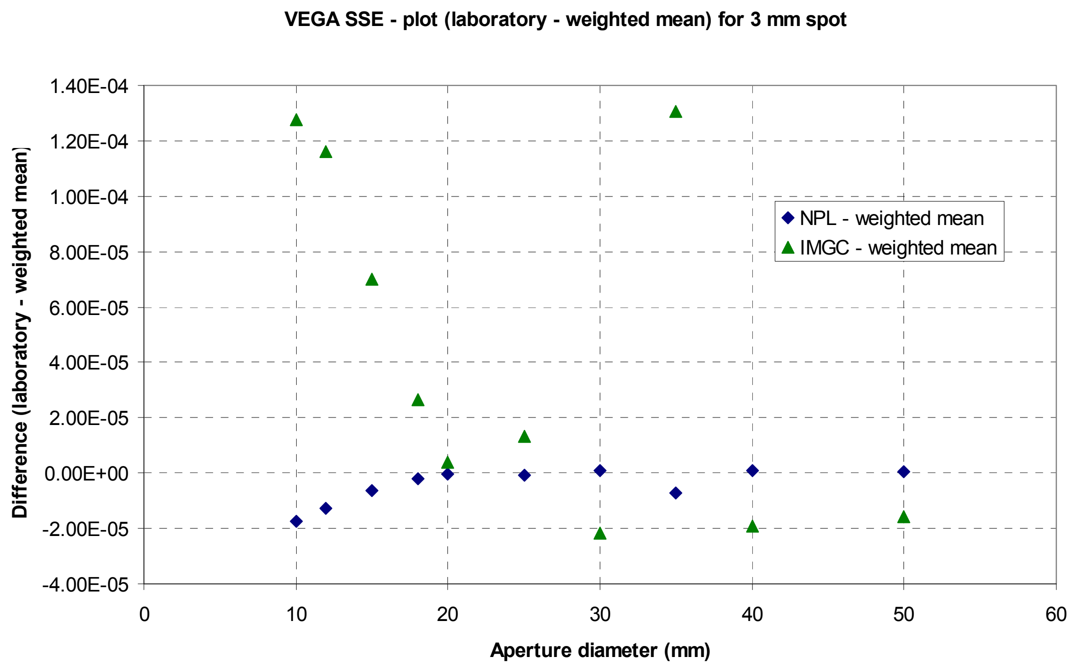


Figure 18 – Plot of results (laboratory – weighted mean) (fitted data) for the 3 mm diameter spot

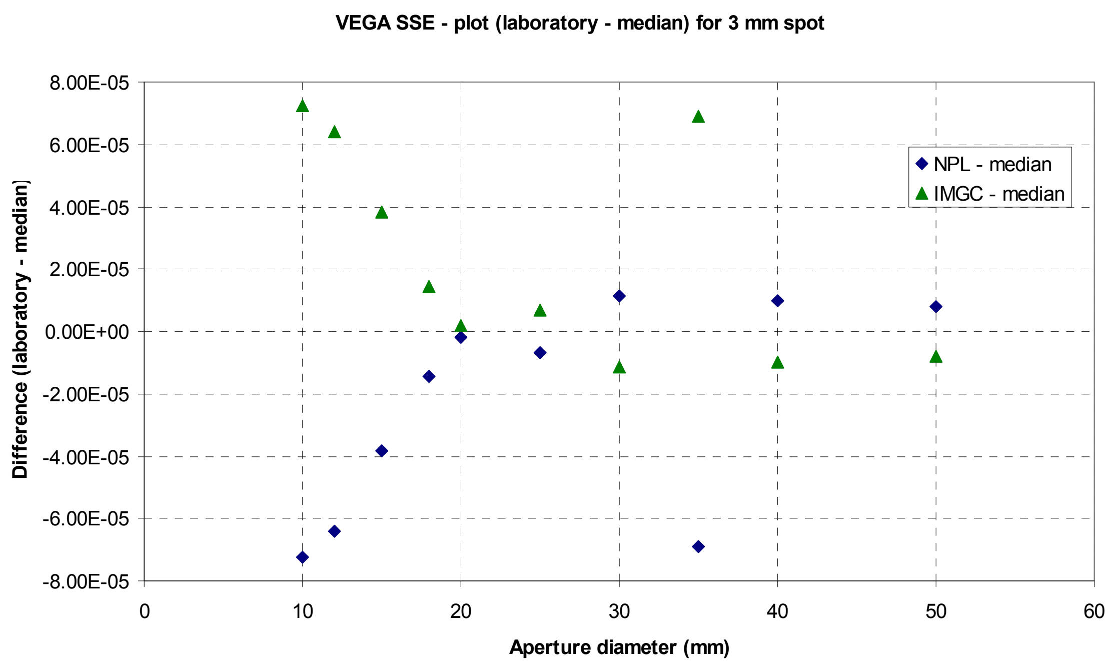


Figure 19 – Plot of results (laboratory – median) (fitted data) for the 3 mm diameter spot

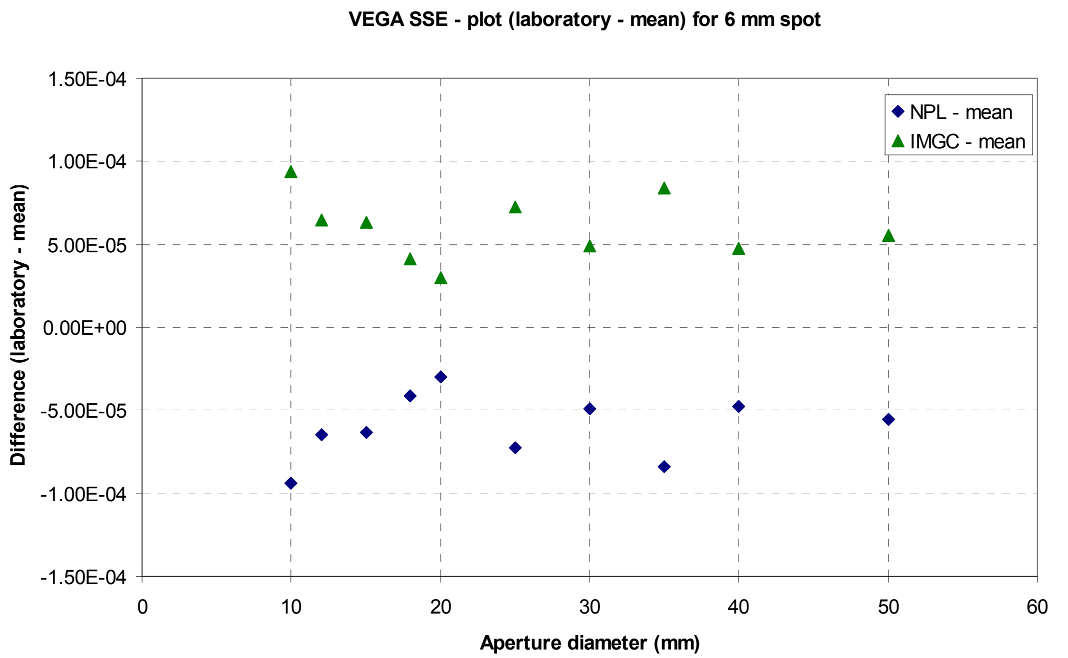


Figure 20 – Plot of results (laboratory – mean) (fitted data) for the 6 mm diameter spot

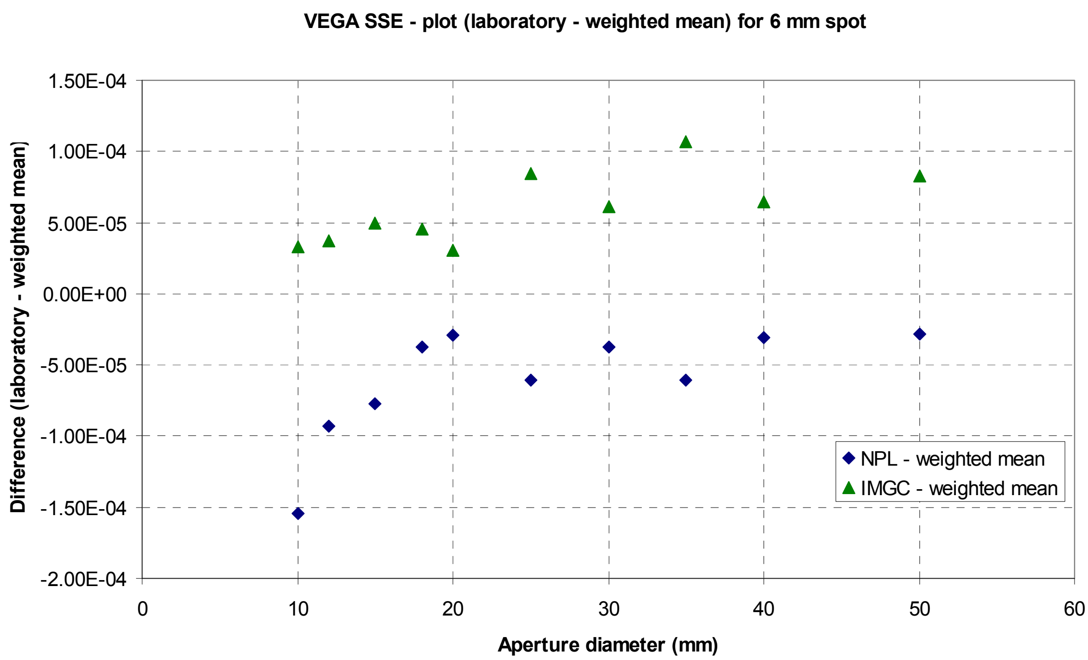


Figure 21 – Plot of results (laboratory – weighted mean) (fitted data) for the 6 mm diameter spot

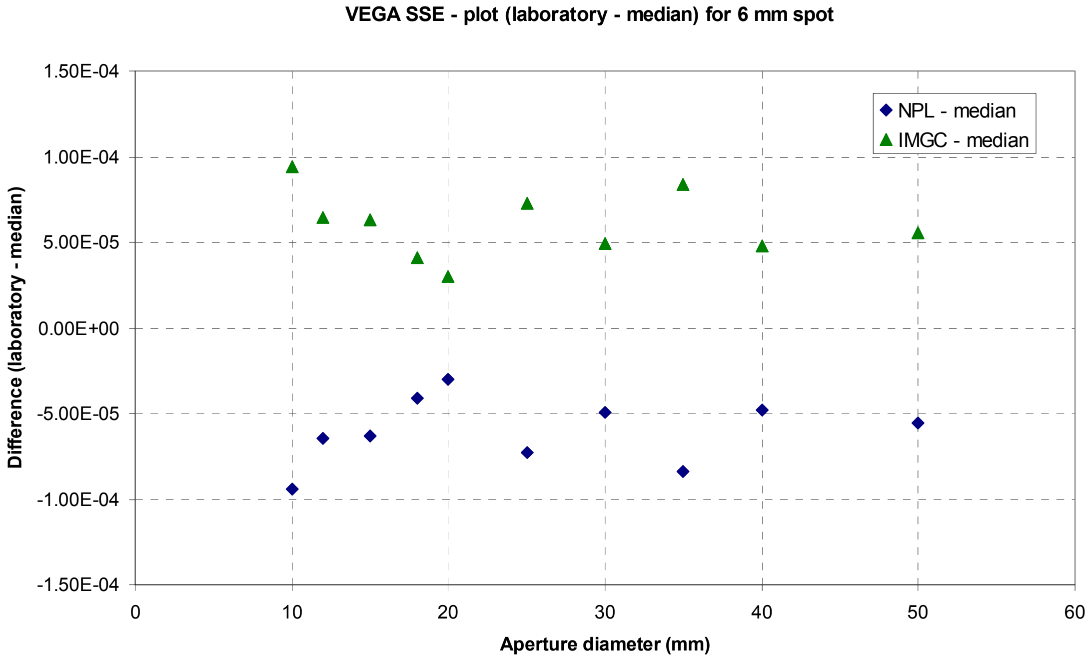


Figure 22 – Plot of results (laboratory – median) (fitted data) for the 6 mm diameter spot

The arithmetic mean SSE value at each aperture diameter was used as the comparison reference value. Since the reference value was simply being used as a tool to facilitate the comparison of the results from each participant, it was not assigned an uncertainty. The calculated DOE and QDE_{95} values for pairs of participants are given in Tables 162 to 181 in Appendix 5. The differences between the results and the mean value at each aperture diameter, along with the estimated $k = 2$ measurement uncertainties, are given in the Figures accompanying the Tables.

1.3.d Discussion of the VEGA SSE results and conclusions

In general, all the results are in very good agreement, with differences from the mean values within the measurement uncertainty and differences between the laboratories well within the combined measurement uncertainty.

2. Linearity measurements

2.1 Methods and apparatus used at each institute

The linearity measurements were made using each laboratory's usual local procedure, using either a radiance doubling or a double aperture technique, and covering as wide a range of signal levels as possible. The measurements with the LP3 were made at a working distance of 670 mm from the source and those for the VEGA thermometer at a working distance of 550 mm. (Note, however, that UME used a working distance of 550 mm for the LP3).

PTB use a multiple-temperature calibration method for calibrating radiation thermometers and do not routinely perform linearity measurements. Therefore, during the time of the PTB measurements, there was no linearity measuring facility available so these measurements were not made. UME, CEM and NPL used the radiance doubling technique, using two lamps as the radiance sources and a beam splitter, with shutters to block off one or other or both lamps. NPL made additional measurements with the LP3 using the double aperture technique, with a double aperture device, designed for the NPL LP2, mounted on the front of the LP3 objective housing. The device has two removable segments so that measurements can be made with either one half or both halves of the aperture open, or with the aperture fully closed. INM used a new facility consisting of a large rotatable wheel containing a series of ¼, ½ and fully open discs. The wheel was placed between the LP3 and the INM high temperature graphite blackbody, which was used to provide a stable radiance source. IMGC used a non-linearity device constructed at IMGC, consisting of a source and rotatable shutter, to measure the linearity using the double-aperture technique. Additional measurements were made with the device in the radiance doubling configuration. Further details of the methods used and the measurement uncertainty components can be found in the participant reports in the Appendices.

The non-linearity was calculated using the equation:

$$NL = 1 - [\{(S_1 - S_0) + (S_2 - S_0)\}/(S_{1+2} - S_0)]$$

where S_0 is the background signal, S_1 is the first signal component, S_2 is the second signal component and S_{1+2} is the sum of the two signal components.

2.2 The results of the linearity measurements

The results of the linearity measurements (which represent the average of the results obtained), along with the estimated k = 2 measurement uncertainties, are given in the following tables. 'RD' indicates the radiance doubling method; 'DA' indicates the double aperture method. Measurements were made using both ranges of the LP3, range 1 ('R1') and range 2 ('R2'), and with gains of 10^8, 10^7 and 10^6 for the VEGA TSP2 thermometer.

2.2.1 The results of the LP3 measurements

a) The NPL results

Method	Range	Average S_{1+2} photocurrent / A	Average non-linearity	U (k = 2)
RD	R1	4.57267E-13	6.34445E-03	2.00E-02
	R1	4.14237E-12	3.23831E-03	1.00E-02
	R1	1.01856E-11	7.46164E-04	1.00E-02
	R1	2.03450E-11	5.82851E-04	1.00E-03
	R1	4.29054E-11	3.38429E-05	5.00E-04
	R1	8.75823E-11	6.56591E-06	5.00E-04
	R1	2.01241E-10	3.07915E-05	5.00E-04
	R1	4.21723E-10	6.92040E-05	5.00E-05
	R1	8.41082E-10	6.56616E-05	5.00E-05
	R1	1.68213E-09	5.57599E-05	5.00E-05
	R1	3.35788E-09	3.50853E-05	5.00E-05
	R1	6.71789E-09	2.18800E-05	5.00E-05
RD	R2	6.71694E-09	6.93639E-05	5.00E-05
	R2	1.34339E-08	1.03648E-04	5.00E-05
	R2	2.37189E-08	5.48035E-05	5.00E-05
	R2	1.34564E-08	1.10615E-04	7.00E-05
	R2	2.38660E-08	-1.05519E-05	7.00E-05
	R2	4.76592E-08	5.98607E-06	7.00E-05
	R2	9.53897E-08	6.27837E-05	7.00E-05
	R2	1.90887E-07	-1.69542E-05	7.00E-05
	R2	2.62386E-07	-1.65209E-05	7.00E-05
DA	R1	4.30865E-11	5.31396E-05	1.00E-04
	R1	8.46268E-10	3.47928E-05	1.00E-04
	R1	3.41385E-09	2.50233E-05	1.00E-04
DA	R2	1.33240E-08	3.29391E-05	1.00E-04
	R2	2.05946E-08	4.42676E-05	1.00E-04
	R2	2.37618E-08	1.25665E-07	2.00E-04
	R2	4.76060E-08	1.49104E-04	2.00E-04
	R2	9.52289E-08	7.78604E-05	2.00E-04
	R2	1.70331E-07	3.38594E-05	2.00E-04

b) The CEM results

Method	Range	S_{1+2} photocurrent / A	Average non-linearity	U (k = 2)
RD	R1	7.69860E-13	1.72E-02	9.90E-03
	R1	1.55920E-12	2.80E-03	4.90E-03
	R1	3.12810E-12	0.00E+00	2.70E-03
	R1	6.27180E-12	8.00E-04	1.90E-03
	R1	1.25500E-11	3.00E-04	1.40E-03
	R1	2.50080E-11	-2.00E-04	1.20E-03
	R1	2.50550E-11	6.00E-04	1.20E-03
	R1	5.01810E-11	9.00E-04	9.00E-04
	R1	5.03590E-11	5.00E-04	9.00E-04
	R1	1.00290E-10	5.00E-04	7.00E-04
	R1	2.00410E-10	6.00E-04	5.00E-04
	R1	4.00400E-10	2.00E-04	5.00E-04
	R1	8.01530E-10	3.00E-04	5.00E-04
	R1	1.60190E-09	4.00E-04	5.00E-04
	R1	3.20200E-09	1.00E-04	5.00E-04
	R1	6.40090E-09	7.00E-04	5.00E-04
	R1	6.40150E-09	3.00E-04	5.00E-04
RD	R2	8.00680E-10	-1.00E-04	6.00E-04
	R2	8.01870E-10	9.00E-04	6.00E-04
	R2	1.60100E-09	4.00E-04	5.00E-04
	R2	3.20180E-09	4.00E-04	5.00E-04
	R2	6.40180E-09	2.00E-04	5.00E-04
	R2	1.24140E-08	4.00E-04	5.00E-04
	R2	3.19270E-09	-2.00E-04	6.00E-04
	R2	6.39760E-09	0.00E+00	6.00E-04
	R2	1.27800E-08	-4.00E-04	6.00E-04
	R2	2.55600E-08	-3.00E-04	6.00E-04
	R2	5.10580E-08	-3.00E-04	6.00E-04
	R2	1.02260E-07	3.00E-04	6.00E-04

c) The UME results (550 mm working distance)

Method	Range	Average S_{1+2} photocurrent / A	Average non-linearity	U (k = 2)
RD	(Not specified)	1.233E-11	-2.52E-03	1.53E-02
		6.254E-11	1.11E-03	1.87E-03
		2.165E-10	1.88E-04	1.14E-03
		2.560E-10	4.54E-04	8.36E-04
		7.185E-10	-2.39E-04	5.20E-04
		1.921E-09	3.39E-05	3.41E-04
		4.565E-09	-3.98E-05	2.39E-04
		9.474E-09	-1.79E-05	1.19E-04
		1.768E-08	2.90E-05	1.17E-04
		2.823E-08	-3.21E-05	1.05E-04

d) The INM results (the standard (k = 1) uncertainty was taken to be the values in the third column in the INM linearity results table)

Method	Range	Average S_{1+2} photocurrent / A	Average non-linearity	U (k = 2)
DA	(Not specified)	1.863E-10	1.3E-04	1.78E-04
		2.84E-10	2.9E-05	7.60E-05
		6.02E-10	-4.0E-05	6.40E-05
		7.06E-10	-7.6E-05	1.16E-04
		1.42E-09	-2.5E-05	9.80E-04
		2.26E-09	1.0E-05	1.16E-04
		4.78E-09	5.4E-05	7.00E-05
		6.44E-09	-8.3E-06	4.80E-05
		1.30E-08	-6.5E-08	1.80E-05
		1.92E-08	-2.0E-06	2.60E-05
		4.08E-08	2.8E-07	1.80E-05
		8.03E-08	-7.5E-06	1.66E-05
		1.62E-07	-6.2E-07	6.20E-06

e) The IMGC results

Method	Range	Average S_{1+2} photocurrent / A	Average non-linearity	U (k = 2)
DA	R1	3.80054E-11	5.26448E-06	2.00E-4
	R1	7.59531E-11	2.74004E-05	2.00E-4
	R1	1.51841E-10	-2.85466E-07	2.00E-4
	R1	3.04064E-10	1.24964E-05	2.00E-4
	R1	6.06308E-10	1.31941E-05	2.00E-4
	R1	1.21155E-09	1.77179E-05	2.00E-4
	R1	2.42973E-09	-3.84142E-06	2.00E-4
	R1	4.85504E-09	-9.61206E-06	2.00E-4
DA	R2	6.08136E-10	1.42475E-04	2.00E-4
	R2	1.21449E-09	2.79308E-05	2.00E-4
	R2	2.43254E-09	7.68552E-06	2.00E-4
	R2	4.85919E-09	2.14798E-05	2.00E-4
	R2	9.72530E-09	1.12729E-05	2.00E-4
	R2	1.94432E-08	8.05840E-06	2.00E-4
	R2	3.89024E-08	1.24679E-05	2.00E-4
	R2	7.78057E-08	1.48446E-05	2.00E-4
	R2	1.55575E-07	-1.00704E-05	2.00E-4
RD	R2	3.88913E-08	2.05943E-06	2.00E-4
	R2	7.78831E-08	-1.66991E-06	2.00E-4
	R2	1.55685E-07	-1.15650E-06	2.00E-4

2.2.2 Graphs plotting the non-linearity results for the LP3

The results of all the non-linearity measurements with the LP3 are plotted in Figures 23 and 24 for ease of comparison, along with the estimated k =2 measurement uncertainties.

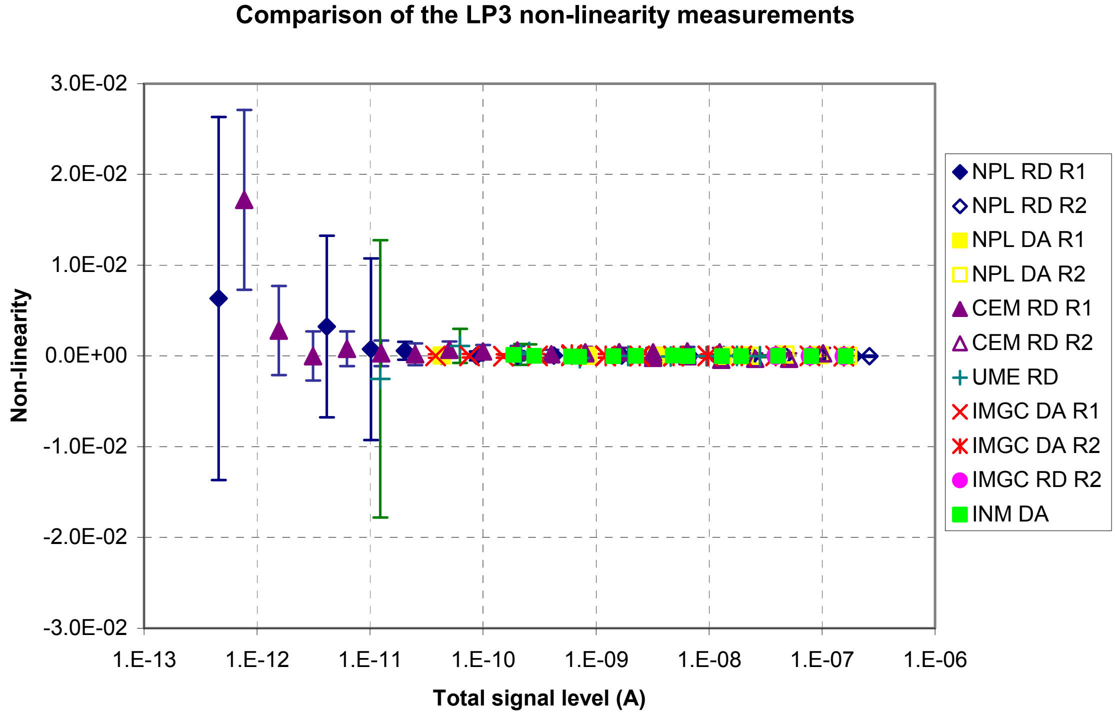


Figure 23 – results of all the non-linearity measurements with the LP3 (wide scale)

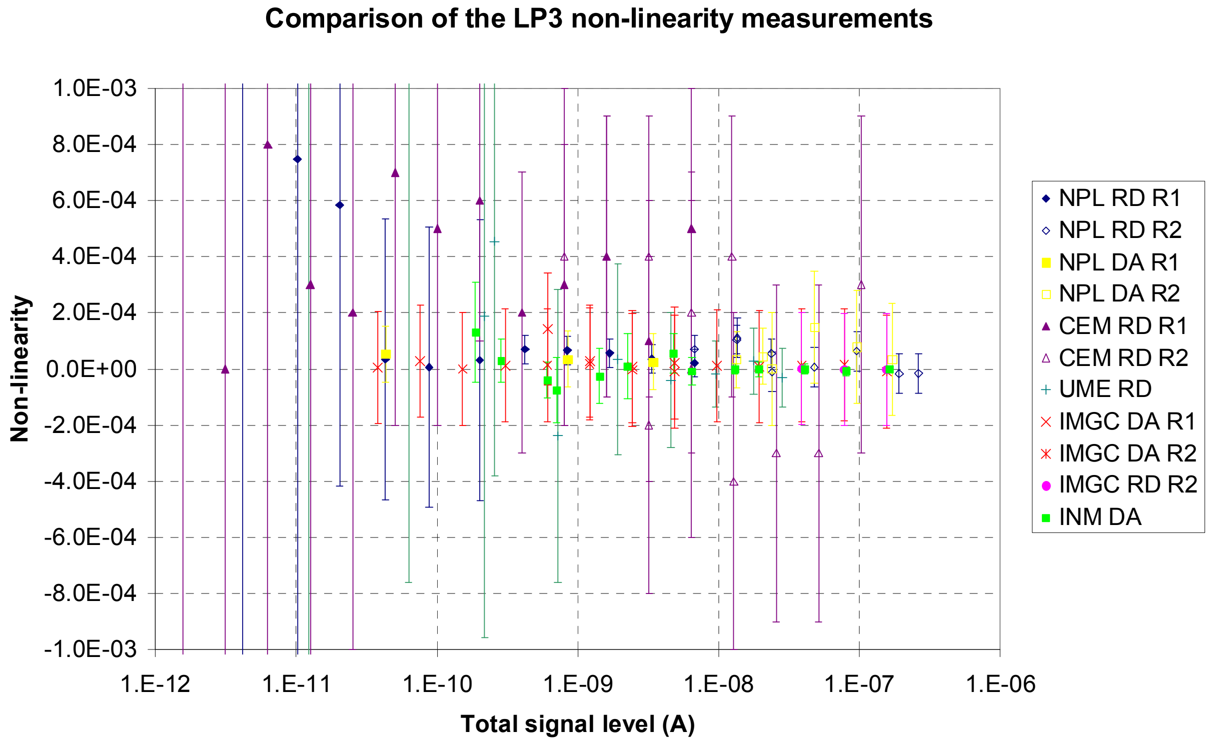


Figure 24 – results of all the non-linearity measurements with the LP3 (zoomed-in scale)

2.2.3 The results of the Vega TSP2 measurements

a) The NPL results are given in the following Table. The average S_{1+2} values were converted to a common gain setting of 10^8 using gain ratio values measured during the linearity measurements. The average measured gain ratios were 9.9529 for the $10^8/10^7$ ratio and 9.9994 for the $10^7/10^6$ ratio.

Method	Gain	Average S_{1+2} / V	Average S_{1+2} at 10^8 gain/ V	Average non-linearity	U (k = 2)
RD	10^8	3.94370E-02	3.94370E-02	-7.19479E-04	2.00E-03
	10^8	2.07812E-01	2.07812E-01	-6.42020E-04	1.00E-03
	10^8	4.07505E-01	4.07505E-01	1.10923E-03	1.00E-03
	10^8	8.11385E-01	8.11385E-01	6.59473E-05	3.00E-04
	10^8	9.48057E-01	9.48057E-01	2.64112E-05	3.00E-04
	10^8	1.21320E+00	1.21320E+00	-4.72438E-04	3.00E-04
	10^8	1.60359E+00	1.60359E+00	1.13603E-04	5.00E-05
	10^8	3.21653E+00	3.21653E+00	9.07827E-05	5.00E-05
	10^8	6.40632E+00	6.40632E+00	9.69089E-05	5.00E-05
	10^8	1.28150E+01	1.28150E+01	6.88380E-05	5.00E-05
	10^7	1.28677E+00	1.28071E+01	1.06059E-04	3.00E-05
	10^7	2.54906E+00	2.53705E+01	1.09287E-04	3.00E-05
	10^7	5.13123E+00	5.10706E+01	1.12881E-04	3.00E-05
	10^7	1.02442E+01	1.01959E+02	1.27783E-04	3.00E-05
	10^7	5.06938E+00	5.04550E+01	-1.01719E-05	1.00E-04
	10^7	1.02318E+01	1.01836E+02	1.65925E-05	1.00E-04
	10^6	1.02370E+00	1.01881E+02	5.06451E-05	8.00E-05
	10^6	2.04602E+00	2.03626E+02	4.09931E-05	8.00E-05
	10^6	4.09693E+00	4.07738E+02	7.31327E-05	8.00E-05
	10^6	5.39228E+00	5.36656E+02	7.53385E-06	8.00E-05

b) The IMGC results are given in the following Table. For the data evaluation and analysis the uncertainty values were assumed to be the same as for the LP3.

Method	S_{1+2} photocurrent / A	Average non-linearity	U (k = 2)
DA	1.37926E-05	-6.16563E-05	2.00E-04
DA	2.75477E-05	-6.12876E-05	2.00E-04
DA	5.51146E-05	-6.59108E-05	2.00E-04
DA	1.10344E-04	-6.61430E-05	2.00E-04
DA	2.20697E-04	-6.39306E-05	2.00E-04
DA	4.40856E-04	-5.50957E-05	2.00E-04
DA	8.81991E-04	-4.30269E-05	2.00E-04
DA	1.76399E-03	-4.29532E-05	2.00E-04
DA	3.52729E-03	-4.90580E-05	2.00E-04
RD	1.37757E-05	-1.00387E-04	2.00E-04
RD	2.75598E-05	-7.76674E-05	2.00E-04
RD	5.50704E-05	-5.76699E-05	2.00E-04
RD	1.10250E-04	-4.34376E-05	2.00E-04
RD	2.19698E-04	-2.21725E-05	2.00E-04
RD	4.40678E-04	-9.22896E-06	2.00E-04
RD	8.81868E-04	-4.48026E-06	2.00E-04
RD	1.76388E-03	3.00134E-05	2.00E-04
RD	3.52968E-03	1.90025E-05	2.00E-04

2.2.4 Graphs plotting the non-linearity results for the VEGA TSP2

The results of all the non-linearity measurements with the VEGA TSP2, along with the estimated k =2 measurement uncertainties, are plotted in Figures 25 to 27.

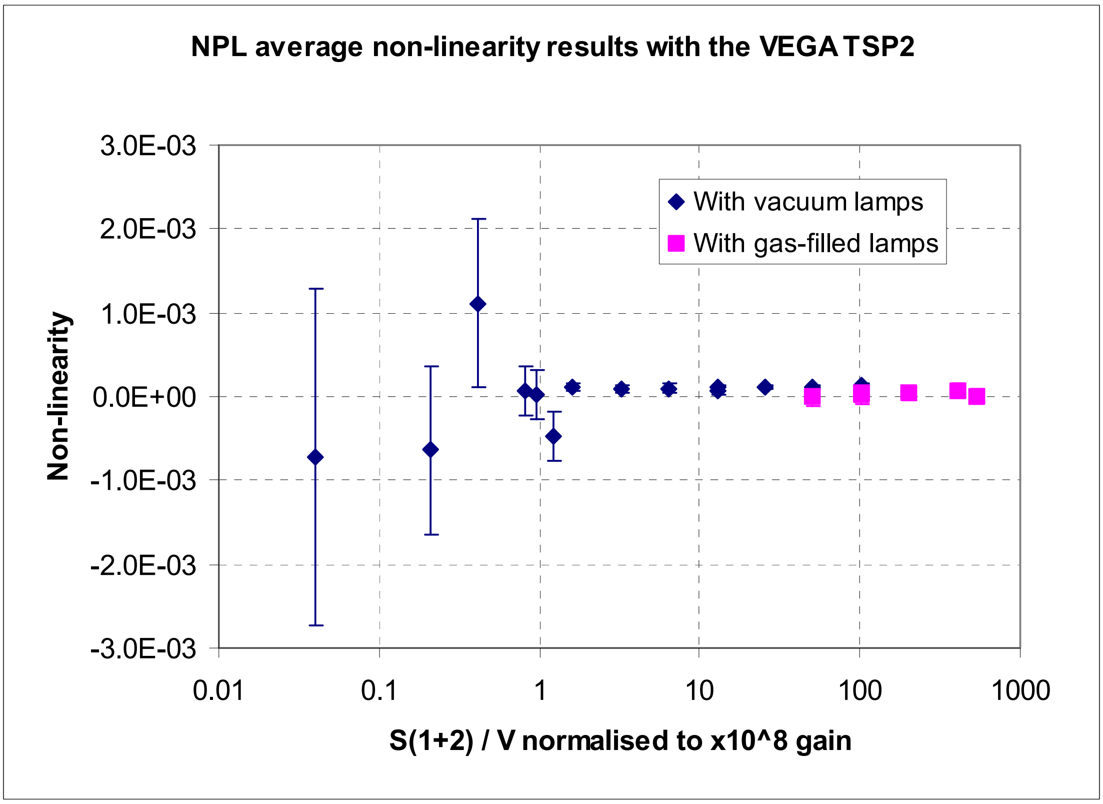


Figure 25 – plot of the results of NPL non-linearity measurements – full scale

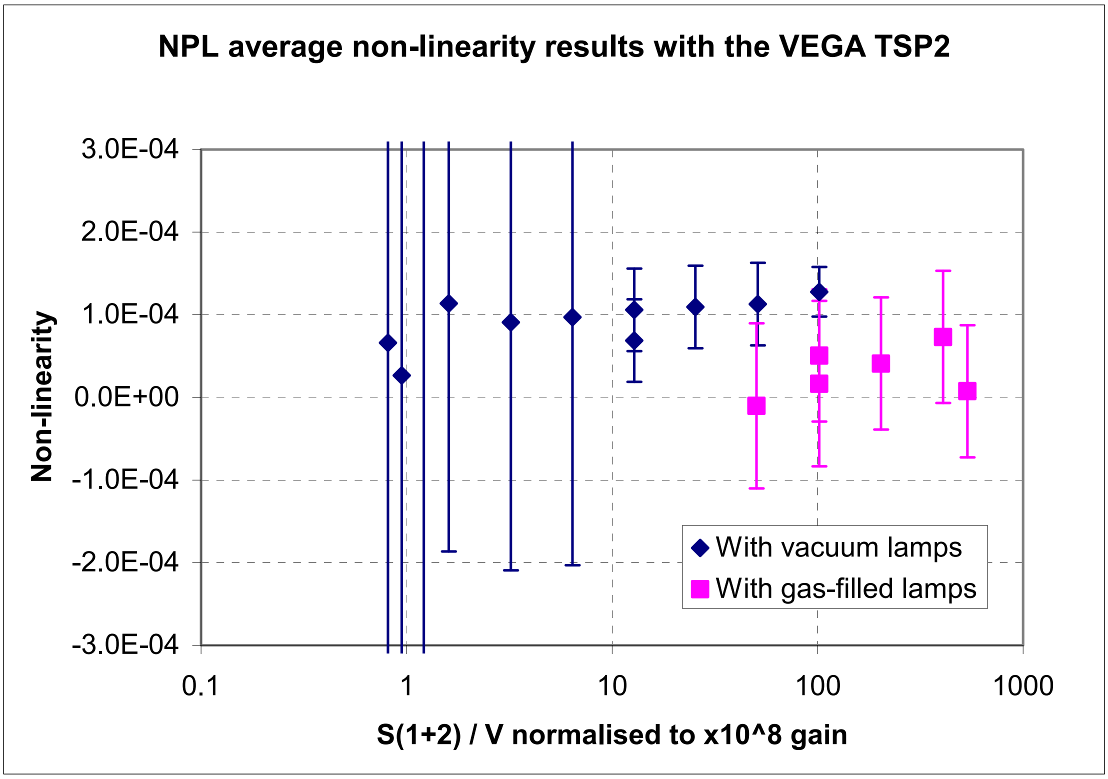


Figure 26 - plot of the results of NPL non-linearity measurements – zoomed-in scale

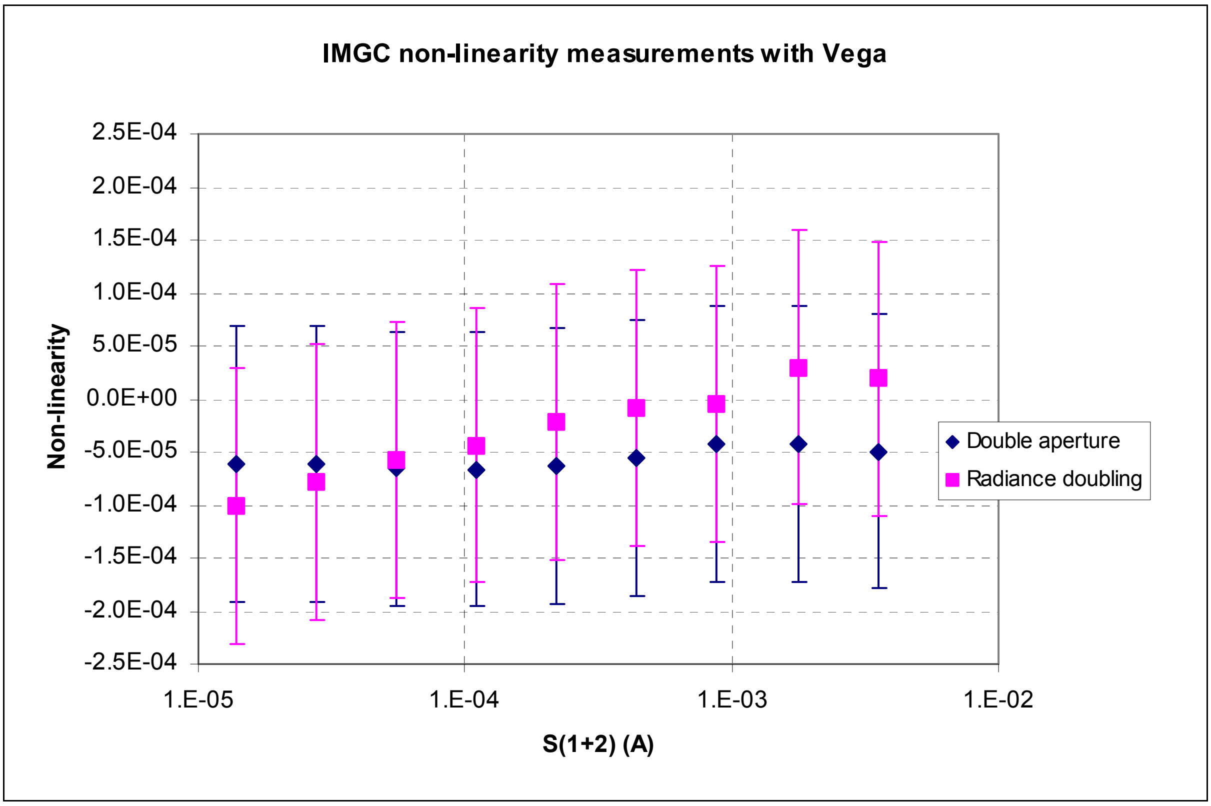


Figure 27 – plot of the results of the IMGC measurements of the non-linearity

The submitted IMGC results were given in terms of non-linearity versus the total output of the VEGA thermometer expressed as a photocurrent (using the amplifier gain to convert from output voltage to current) whereas the NPL results were in terms of the total VEGA thermometer output expressed as a voltage. In order to compare the results from the two laboratories, the output voltages of the NPL results were therefore also converted to a photocurrent (A) using the amplifier gain setting, i.e. by dividing the voltage (in V) by the gain setting:

Gain	Average S_{1+2} / V	Average S_{1+2} at 10^8 gain/ V	Average S_{1+2} / A	Average non-linearity	U (k = 2)
10^8	3.94370E-02	3.94370E-02	3.94370E-10	-7.19479E-04	2.00E-03
10^8	2.07812E-01	2.07812E-01	2.07812E-09	-6.42020E-04	1.00E-03
10^8	4.07505E-01	4.07505E-01	4.07505E-09	1.10923E-03	1.00E-03
10^8	8.11385E-01	8.11385E-01	8.11385E-09	6.59473E-05	3.00E-04
10^8	9.48057E-01	9.48057E-01	9.48057E-09	2.64112E-05	3.00E-04
10^8	1.21320E+00	1.21320E+00	1.21320E-08	-4.72438E-04	3.00E-04
10^8	1.60359E+00	1.60359E+00	1.60359E-08	1.13603E-04	5.00E-05
10^8	3.21653E+00	3.21653E+00	3.21653E-08	9.07827E-05	5.00E-05
10^8	6.40632E+00	6.40632E+00	6.40632E-08	9.69089E-05	5.00E-05
10^8	1.28150E+01	1.28150E+01	1.28150E-07	6.88380E-05	5.00E-05
10^7	1.28677E+00	1.28071E+01	1.28071E-07	1.06059E-04	3.00E-05
10^7	2.54906E+00	2.53705E+01	2.53705E-07	1.09287E-04	3.00E-05
10^7	5.13123E+00	5.10706E+01	5.10706E-07	1.12881E-04	3.00E-05
10^7	1.02442E+01	1.01959E+02	1.01959E-06	1.27783E-04	3.00E-05
10^7	5.06938E+00	5.04550E+01	5.04550E-07	-1.01719E-05	1.00E-04
10^7	1.02318E+01	1.01836E+02	1.01836E-06	1.65925E-05	1.00E-04
10^6	1.02370E+00	1.01881E+02	1.01881E-06	5.06451E-05	8.00E-05
10^6	2.04602E+00	2.03626E+02	2.03626E-06	4.09931E-05	8.00E-05
10^6	4.09693E+00	4.07738E+02	4.07738E-06	7.31327E-05	8.00E-05
10^6	5.39228E+00	5.36656E+02	5.36656E-06	7.53385E-06	8.00E-05

Table 53 – the NPL results with the VEGA thermometer output converted to photocurrent (A)

Figure 28 plots the results of all the NPL and IMGC measurements, with the VEGA thermometer output expressed in terms of photocurrent. However, the photocurrents for the NPL results can be seen to be significantly different from those of the IMGC results. This did not seem realistic, considering the overlap in photocurrents seen with the LP3 measurements using the same non-linearity apparatus (e.g. Figure 24 above). It was therefore assumed that the VEGA output for the IMGC measurements had been converted from millivolts to photocurrent, using the gain factor, and the IMGC results were therefore corrected to compensate (i.e. by dividing the average S_{1+2} values by 1000) (Table 54). The resulting plot of all the results is given in Figures 29 and 30.

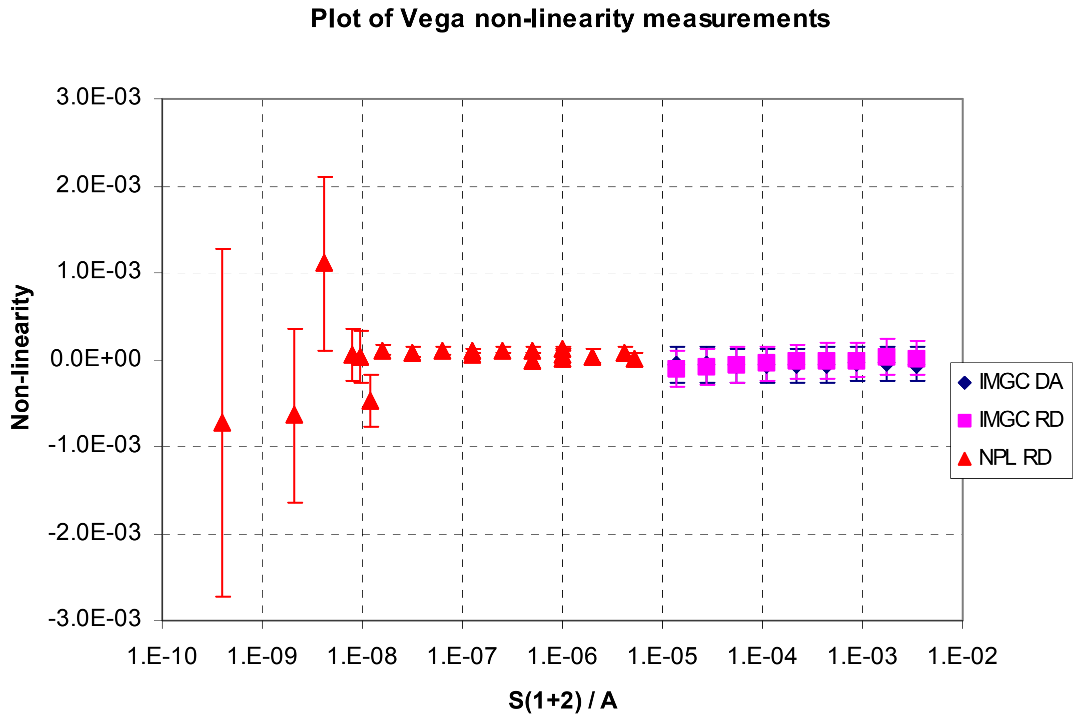


Figure 28 - plot of the VEGA non-linearity results with the output expressed as photocurrent

Method	S_{1+2} photocurrent / A	Corrected S_{1+2} photocurrent / A	Average non-linearity	U ($k = 2$)
DA	1.37926E-05	1.37926E-08	-6.16563E-05	2.00E-04
DA	2.75477E-05	2.75477E-08	-6.12876E-05	2.00E-04
DA	5.51146E-05	5.51146E-08	-6.59108E-05	2.00E-04
DA	1.10344E-04	1.10344E-07	-6.61430E-05	2.00E-04
DA	2.20697E-04	2.20697E-07	-6.39306E-05	2.00E-04
DA	4.40856E-04	4.40856E-07	-5.50957E-05	2.00E-04
DA	8.81991E-04	8.81991E-07	-4.30269E-05	2.00E-04
DA	1.76399E-03	1.76399E-06	-4.29532E-05	2.00E-04
DA	3.52729E-03	3.52729E-06	-4.90580E-05	2.00E-04
RD	1.37757E-05	1.37757E-08	-1.00387E-04	2.00E-04
RD	2.75598E-05	2.75598E-08	-7.76674E-05	2.00E-04
RD	5.50704E-05	5.50704E-08	-5.76699E-05	2.00E-04
RD	1.10250E-04	1.10250E-07	-4.34376E-05	2.00E-04
RD	2.19698E-04	2.19698E-07	-2.21725E-05	2.00E-04
RD	4.40678E-04	4.40678E-07	-9.22896E-06	2.00E-04
RD	8.81868E-04	8.81868E-07	-4.48026E-06	2.00E-04
RD	1.76388E-03	1.76388E-06	3.00134E-05	2.00E-04
RD	3.52968E-03	3.52968E-06	1.90025E-05	2.00E-04

Table 54 – the IMGC results for the VEGA non-linearity with the corrected S_{1+2} value

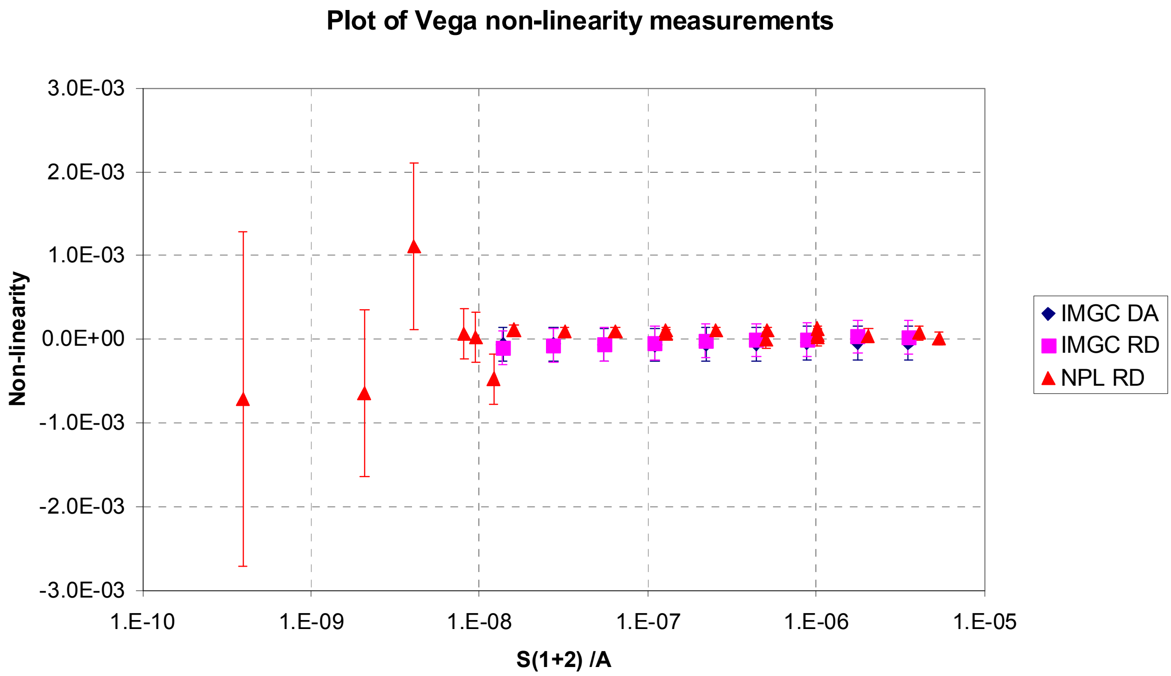


Figure 29 - plot of the VEGA non-linearity results with the corrected IMGC photocurrents (wide scale)

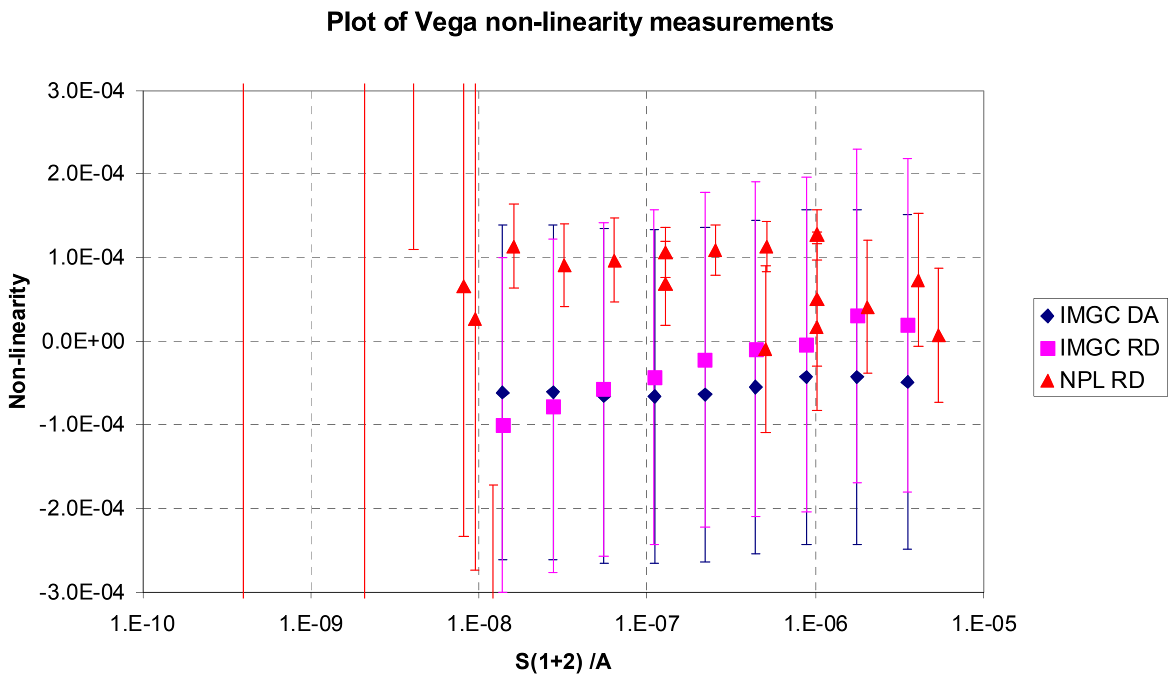


Figure 30 – plot of the VEGA non-linearity results with the corrected IMGC photocurrents (zoomed in)

2.3 Analysis of the non-linearity results and conclusions.

2.3.1 The results for the LP3

To provide a more complete analysis of the non-linearity results ideally a comparison reference value is needed. However, the non-linearity measurements had been made at different photocurrents by different participants, meaning that it was not possible to simply calculate a mean for each photocurrent. Also, it was felt not to be sufficient simply to assign a comparison reference value of zero, in case this masked any small non-linearity, though, with the exception of the results at very low photocurrents, the non-linearity can be seen to be essentially zero, with fluctuations around the zero point that are within the estimated measurement uncertainties. Looking at the trend in the results, there is some significant non-linearity at low photocurrents (1 x 10^{-13} to 1 x 10^{-12} A) with the non-linearity dropping to essentially zero above about 2 x 10^{-11}A. The results were therefore divided into three sections: from 1 x 10^{-13} to 1 x 10^{-12} A; from 1 x 10^{-12} to 2.5 x 10^{-11} A; above 2.5 x 10^{-11} A. The weighted mean, arithmetic mean and median were calculated for the results in each of the three sections (see Table 55). Since these values were simply being used as tools for evaluation purposes no uncertainties were assigned to them.

Photocurrent range / A	Arithmetic mean non-linearity value	Weighted mean non-linearity value	Median non-linearity value
1 x 10^{-13} to 1 x 10^{-12}	1.17722E-02	1.50636E-02	1.17722E-02
1 x 10^{-12} to 2.5 x 10^{-11}	6.35187E-04	4.08669E-04	5.91425E-04
Above 2.5 x 10^{-11}	9.76024E-05	4.96215E-06	2.62118E-05

Table 55 – the mean and median non-linearity values for different photocurrent ranges

The differences between the results of each laboratory and the mean, weighted mean (again, weighted with respect to the laboratory measurement uncertainty) and median linearity values are given in Tables 56 to 60 and Figures 31 to 36. There is very little difference in the plots so any of the different means could be used as the reference value.

For clarity, the results from each laboratory versus the weighted mean are plotted separately in Figures 37 to 41.

Range	Average S_{1+2} photocurrent /A	Difference (NPL – mean)	Difference (NPL – weighted mean)	Difference (NPL – median)
R1	4.57267E-13	-5.4278E-03	-8.7191E-03	-5.4278E-03
R1	4.14237E-12	2.6031E-03	2.8296E-03	2.6469E-03
R1	1.01856E-11	1.1098E-04	3.3750E-04	1.5474E-04
R1	2.03450E-11	-5.2336E-05	1.7418E-04	-8.5746E-06
R1	4.29054E-11	-6.3760E-05	2.8881E-05	7.6310E-06
R1	8.75823E-11	-9.1037E-05	1.6038E-06	-1.9646E-05
R1	2.01241E-10	-6.6811E-05	2.5829E-05	4.5797E-06
R1	4.21723E-10	-2.8398E-05	6.4242E-05	4.2992E-05
R1	8.41082E-10	-3.1941E-05	6.0699E-05	3.9450E-05
R1	1.68213E-09	-4.1843E-05	5.0798E-05	2.9548E-05
R1	3.35788E-09	-6.2517E-05	3.0123E-05	8.8734E-06
R1	6.71789E-09	-7.5722E-05	1.6918E-05	-4.3318E-06
R2	6.71694E-09	-2.8239E-05	6.4402E-05	4.3152E-05
R2	1.34339E-08	6.0458E-06	9.8686E-05	7.7436E-05
R2	2.37189E-08	-4.2799E-05	4.9841E-05	2.8592E-05
R2	1.34564E-08	1.3012E-05	1.0565E-04	8.4403E-05
R2	2.38660E-08	-1.0815E-04	-1.5514E-05	-3.6764E-05
R2	4.76592E-08	-9.1616E-05	1.0239E-06	-2.0226E-05
R2	9.53897E-08	-3.4819E-05	5.7822E-05	3.6572E-05
R2	1.90887E-07	-1.1456E-04	-2.1916E-05	-4.3166E-05
R2	2.62386E-07	-1.1412E-04	-2.1483E-05	-4.2733E-05
R1	4.30865E-11	-4.4463E-05	4.8177E-05	2.6928E-05
R1	8.46268E-10	-6.2810E-05	2.9831E-05	8.5810E-06
R1	3.41385E-09	-7.2579E-05	2.0061E-05	-1.1886E-06
R2	1.33240E-08	-6.4663E-05	2.7977E-05	6.7273E-06
R2	2.05946E-08	-5.3335E-05	3.9305E-05	1.8056E-05
R2	2.37618E-08	-9.7477E-05	-4.8365E-06	-2.6086E-05
R2	4.76060E-08	5.1502E-05	1.4414E-04	1.2289E-04
R2	9.52289E-08	-1.9742E-05	7.2898E-05	5.1649E-05
R2	1.70331E-07	-6.3743E-05	2.8897E-05	7.6475E-06

Table 56 – the differences of the NPL results from the mean, weighted mean and median linearity values

Range	Average S_{1+2} photocurrent /A	Difference (CEM – mean)	Difference (CEM – weighted mean)	Difference (CEM – median)
R1	7.69860E-13	5.4278E-03	2.1364E-03	5.4278E-03
R1	1.55920E-12	2.1648E-03	2.3913E-03	2.2086E-03
R1	3.12810E-12	-6.3519E-04	-4.0867E-04	-5.9143E-04
R1	6.27180E-12	1.6481E-04	3.9133E-04	2.0857E-04
R1	1.25500E-11	-3.3519E-04	-1.0867E-04	-2.9143E-04
R1	2.50080E-11	-8.3519E-04	-6.0867E-04	-7.9143E-04
R1	2.50550E-11	-3.5187E-05	1.9133E-04	8.5746E-06
R1	5.01810E-11	8.0240E-04	8.9504E-04	8.7379E-04
R1	5.03590E-11	4.0240E-04	4.9504E-04	4.7379E-04
R1	1.00290E-10	4.0240E-04	4.9504E-04	4.7379E-04
R1	2.00410E-10	5.0240E-04	5.9504E-04	5.7379E-04
R1	4.00400E-10	1.0240E-04	1.9504E-04	1.7379E-04
R1	8.01530E-10	2.0240E-04	2.9504E-04	2.7379E-04
R1	1.60190E-09	3.0240E-04	3.9504E-04	3.7379E-04
R1	3.20200E-09	2.3976E-06	9.5038E-05	7.3788E-05
R1	6.40090E-09	6.0240E-04	6.9504E-04	6.7379E-04
R1	6.40150E-09	2.0240E-04	2.9504E-04	2.7379E-04
R2	8.00680E-10	-1.9760E-04	-1.0496E-04	-1.2621E-04
R2	8.01870E-10	8.0240E-04	8.9504E-04	8.7379E-04
R2	1.60100E-09	3.0240E-04	3.9504E-04	3.7379E-04
R2	3.20180E-09	3.0240E-04	3.9504E-04	3.7379E-04
R2	6.40180E-09	1.0240E-04	1.9504E-04	1.7379E-04
R2	1.24140E-08	3.0240E-04	3.9504E-04	3.7379E-04
R2	3.19270E-09	-2.9760E-04	-2.0496E-04	-2.2621E-04
R2	6.39760E-09	-9.7602E-05	-4.9622E-06	-2.6212E-05
R2	1.27800E-08	-4.9760E-04	-4.0496E-04	-4.2621E-04
R2	2.55600E-08	-3.9760E-04	-3.0496E-04	-3.2621E-04
R2	5.10580E-08	-3.9760E-04	-3.0496E-04	-3.2621E-04
R2	1.02260E-07	2.0240E-04	2.9504E-04	2.7379E-04

Table 57 - the differences of the CEM results from the mean values

Range	Average S_{1+2} photocurrent /A	Difference (UME – mean)	Difference (UME – weighted mean)	Difference (UME – median)
-	1.23287E-11	-3.1506E-03	-2.9241E-03	-3.1069E-03
-	6.25387E-11	1.0157E-03	1.1084E-03	1.0871E-03
-	2.16497E-10	9.0374E-05	1.8301E-04	1.6176E-04
-	2.56045E-10	3.5638E-04	4.4902E-04	4.2777E-04
-	7.18502E-10	-3.3626E-04	-2.4362E-04	-2.6487E-04
-	1.92110E-09	-6.3719E-05	2.8922E-05	7.6719E-06
-	4.56486E-09	-1.3743E-04	-4.4787E-05	-6.6037E-05
-	9.47442E-09	-1.1554E-04	-2.2897E-05	-4.4146E-05
-	1.76832E-08	-6.8631E-05	2.4009E-05	2.7595E-06
-	2.82290E-08	-1.2968E-04	-3.7042E-05	-5.8292E-05

Table 58 - the differences of the UME results from the mean, weighted mean and median linearity values

Range	Average S_{1+2} photocurrent /A	Difference (INM – mean)	Difference (INM – weighted mean)	Difference (INM – median)
-	1.863E-10	3.2398E-05	1.2504E-04	1.0379E-04
-	2.840E-10	-6.8602E-05	2.4038E-05	2.7882E-06
-	6.020E-10	-1.3760E-04	-4.4962E-05	-6.6212E-05
-	7.060E-10	-1.7360E-04	-8.0962E-05	-1.0221E-04
-	1.420E-09	-1.2260E-04	-2.9962E-05	-5.1212E-05
-	2.260E-09	-8.7602E-05	5.0378E-06	-1.6212E-05
-	4.780E-09	-4.3602E-05	4.9038E-05	2.7788E-05
-	6.440E-09	-1.0590E-04	-1.3262E-05	-3.4512E-05
-	1.300E-08	-9.7667E-05	-5.0272E-06	-2.6277E-05
-	1.920E-08	-9.9602E-05	-6.9622E-06	-2.8212E-05
-	4.080E-08	-9.7322E-05	-4.6822E-06	-2.5932E-05
-	8.030E-08	-1.0510E-04	-1.2462E-05	-3.3712E-05
-	1.620E-07	-9.8222E-05	-5.5822E-06	-2.6832E-05

Table 59 - the differences of the INM results from the mean, weighted mean and median linearity values

Range	Average S_{1+2} photocurrent /A	Difference (IMGC – mean)	Difference (IMGC – weighted mean)	Difference (IMGC – median)
R1	3.80054E-11	-9.2338E-05	3.0233E-07	-2.0947E-05
R1	7.59531E-11	-7.0202E-05	2.2438E-05	1.1886E-06
R1	1.51841E-10	-9.7888E-05	-5.2476E-06	-2.6497E-05
R1	3.04064E-10	-8.5106E-05	7.5343E-06	-1.3715E-05
R1	6.06308E-10	-8.4408E-05	8.2319E-06	-1.3018E-05
R1	1.21155E-09	-7.9885E-05	1.2756E-05	-8.4940E-06
R1	2.42973E-09	-1.0144E-04	-8.8036E-06	-3.0053E-05
R1	4.85504E-09	-1.0721E-04	-1.4574E-05	-3.5824E-05
R2	6.08136E-10	4.4873E-05	1.3751E-04	1.1626E-04
R2	1.21449E-09	-6.9672E-05	2.2969E-05	1.7190E-06
R2	2.43254E-09	-8.9917E-05	2.7234E-06	-1.8526E-05
R2	4.85919E-09	-7.6123E-05	1.6518E-05	-4.7320E-06
R2	9.72530E-09	-8.6330E-05	6.3108E-06	-1.4939E-05
R2	1.94432E-08	-8.9544E-05	3.0963E-06	-1.8153E-05
R2	3.89024E-08	-8.5135E-05	7.5058E-06	-1.3744E-05
R2	7.78057E-08	-8.2758E-05	9.8824E-06	-1.1367E-05
R2	1.55575E-07	-1.0767E-04	-1.5033E-05	-3.6282E-05
R2	3.88913E-08	-9.5543E-05	-2.9027E-06	-2.4152E-05
R2	7.78831E-08	-9.9272E-05	-6.6321E-06	-2.7882E-05
R2	1.55685E-07	-9.8759E-05	-6.1187E-06	-2.7368E-05

Table 60 - the differences of the IMGC results from the mean, weighted mean and median linearity values

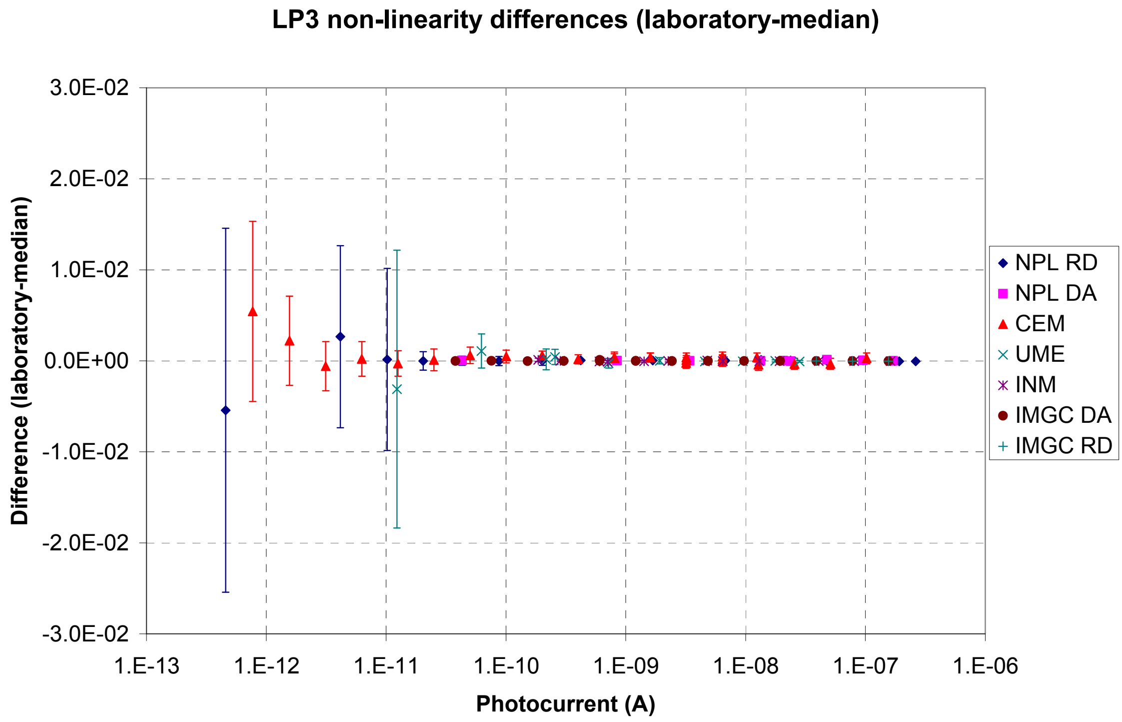


Figure 31 – laboratory differences from median, all results

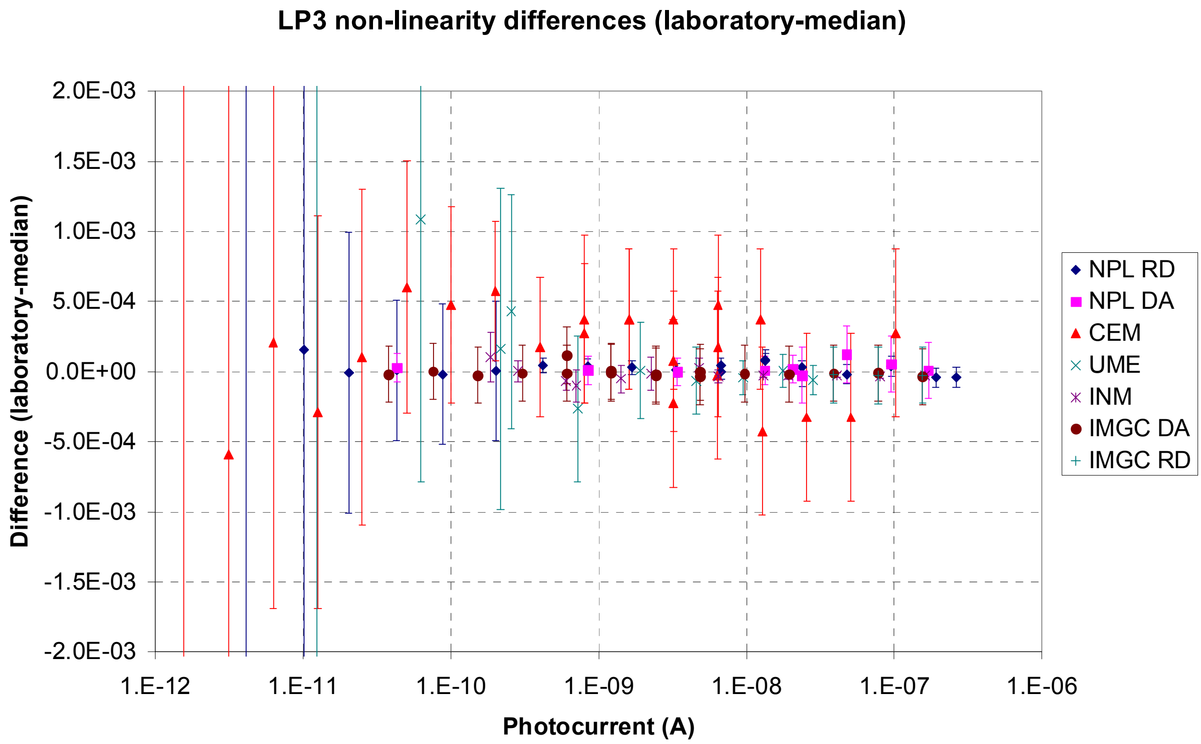


Figure 32 – laboratory differences from median, zoomed-in scale

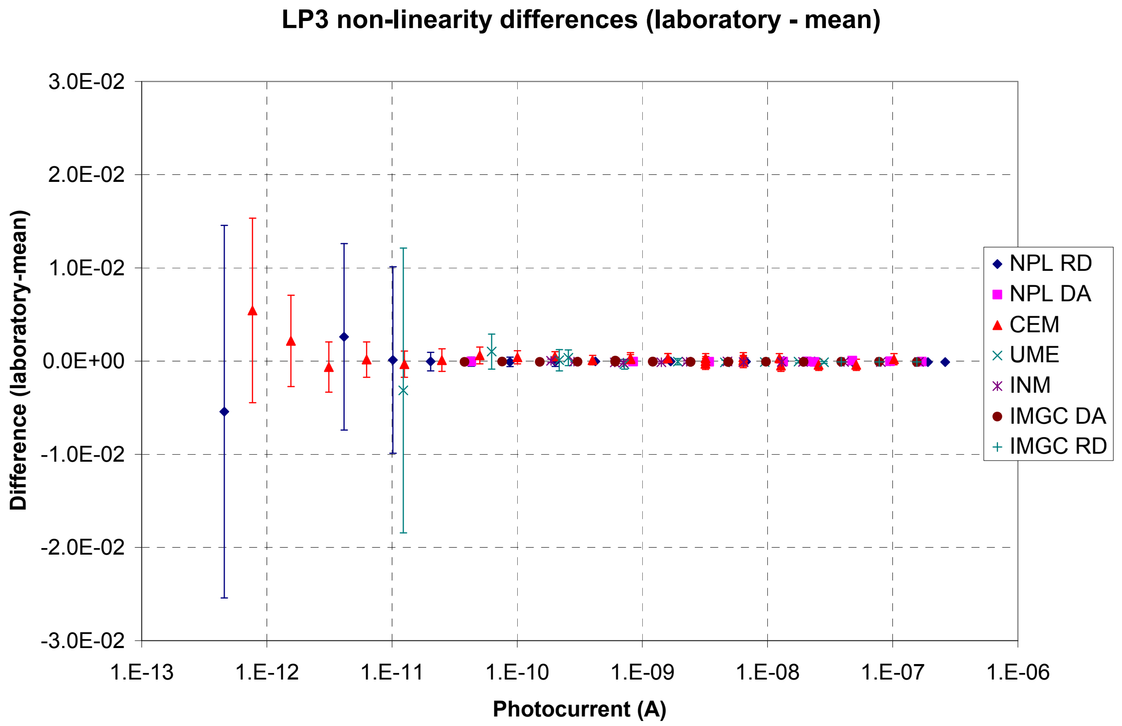


Figure 33 - – laboratory differences from mean, all results

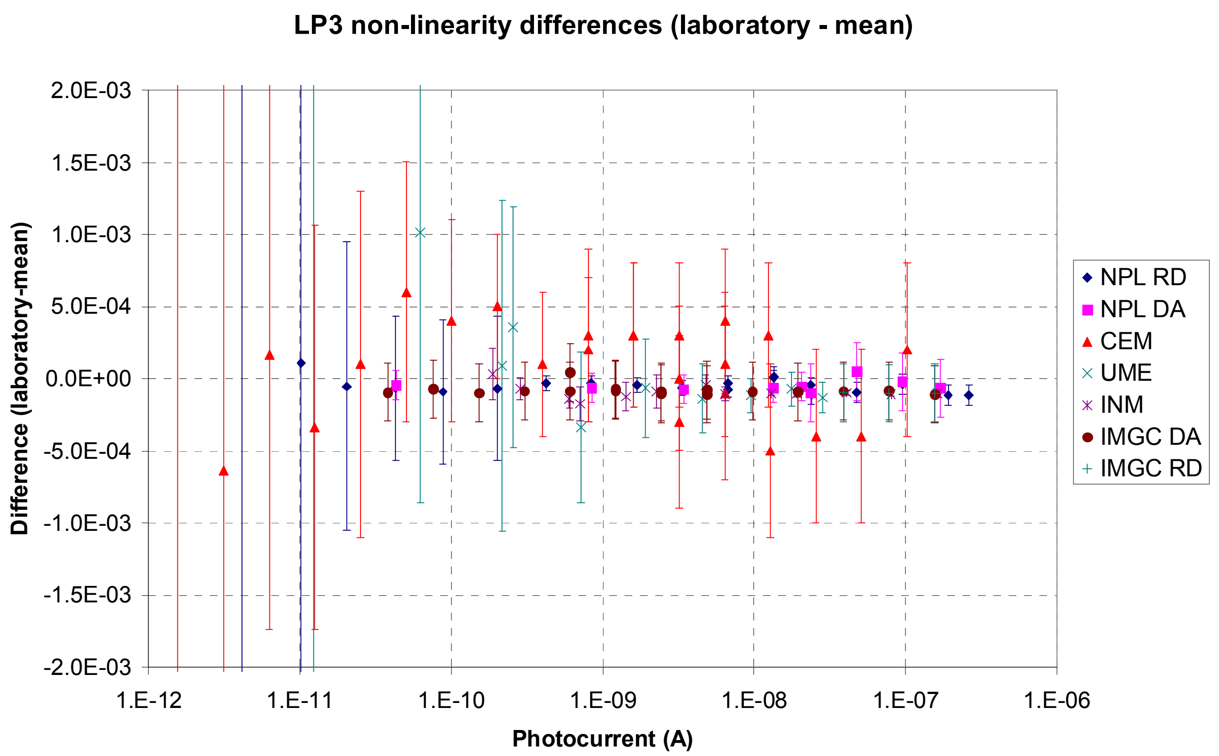


Figure 34 - – laboratory differences from mean, zoomed-in scale

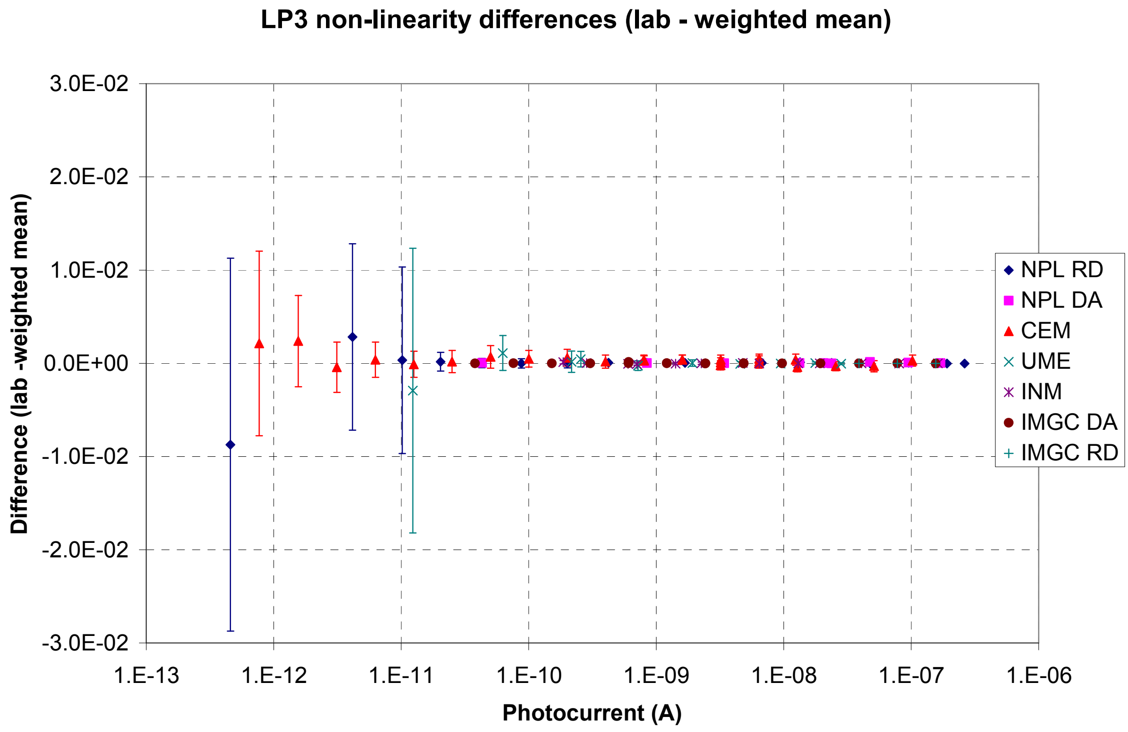


Figure 35 - laboratory differences from weighted mean, all results

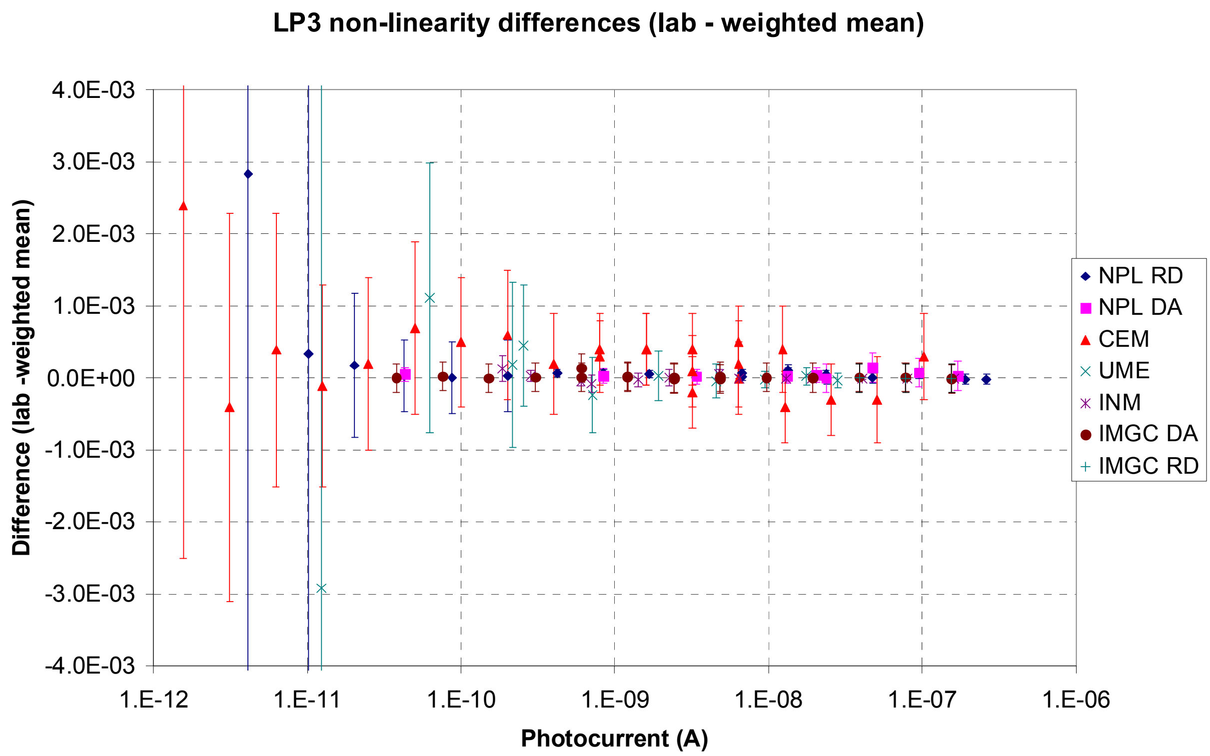


Figure 36 - laboratory differences from weighted mean, zoomed-in scale

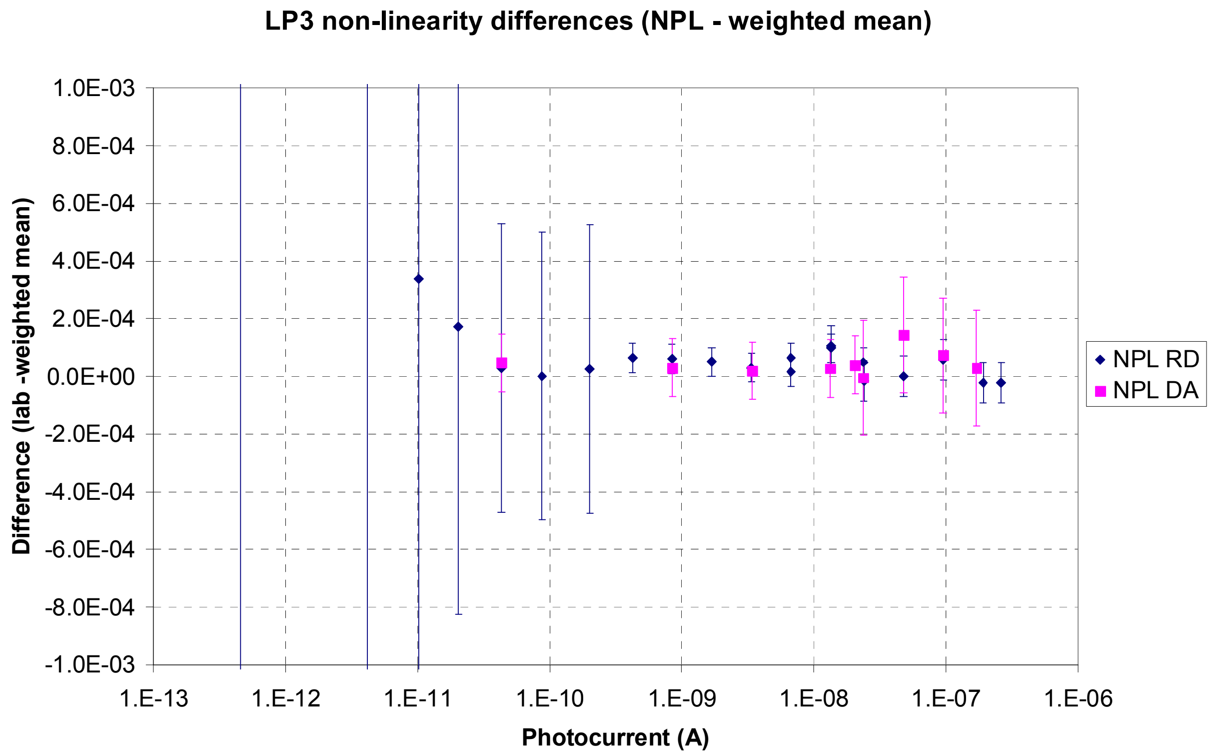


Figure 37 – differences of the NPL results from the weighted mean

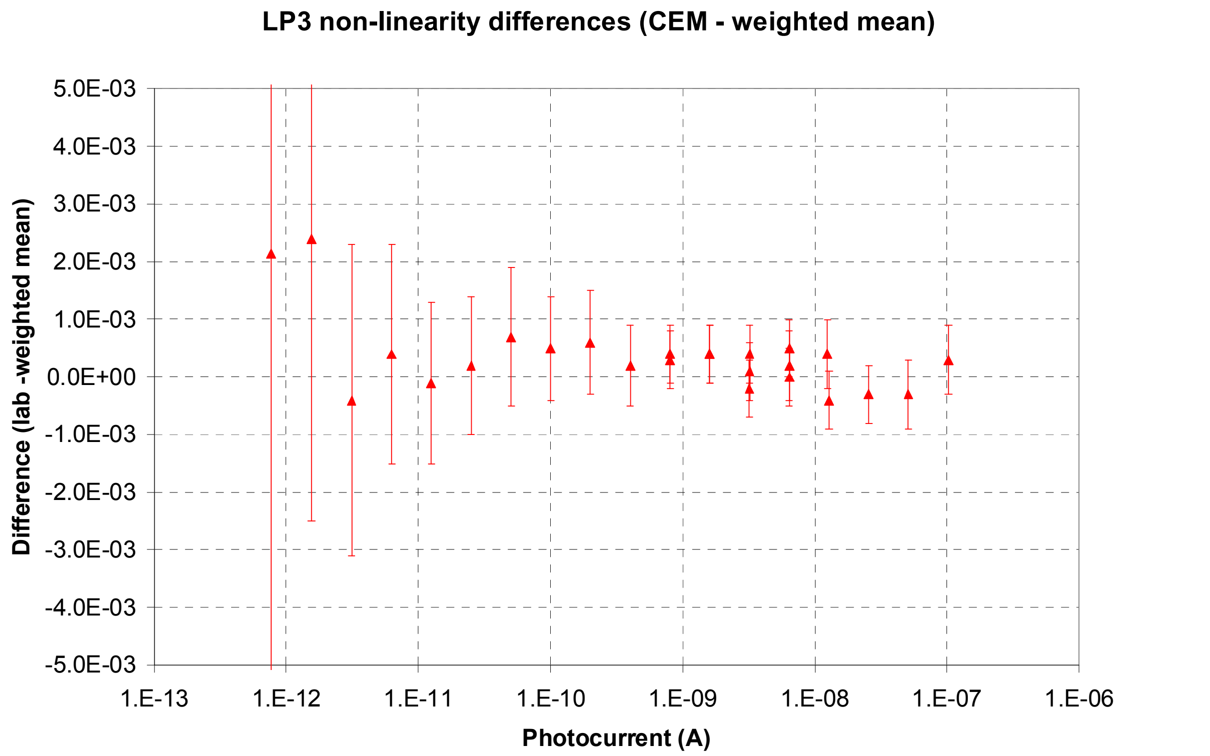


Figure 38 – differences of the CEM results from the weighted mean

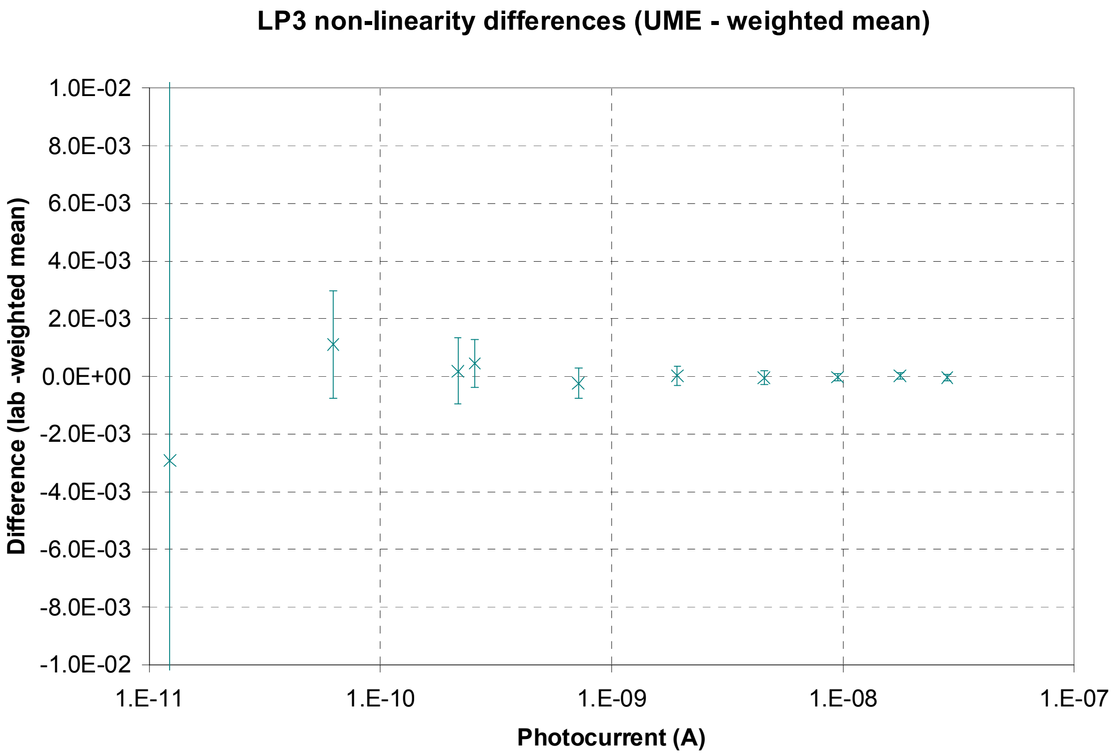


Figure 39 – differences of the UME results from the weighted mean

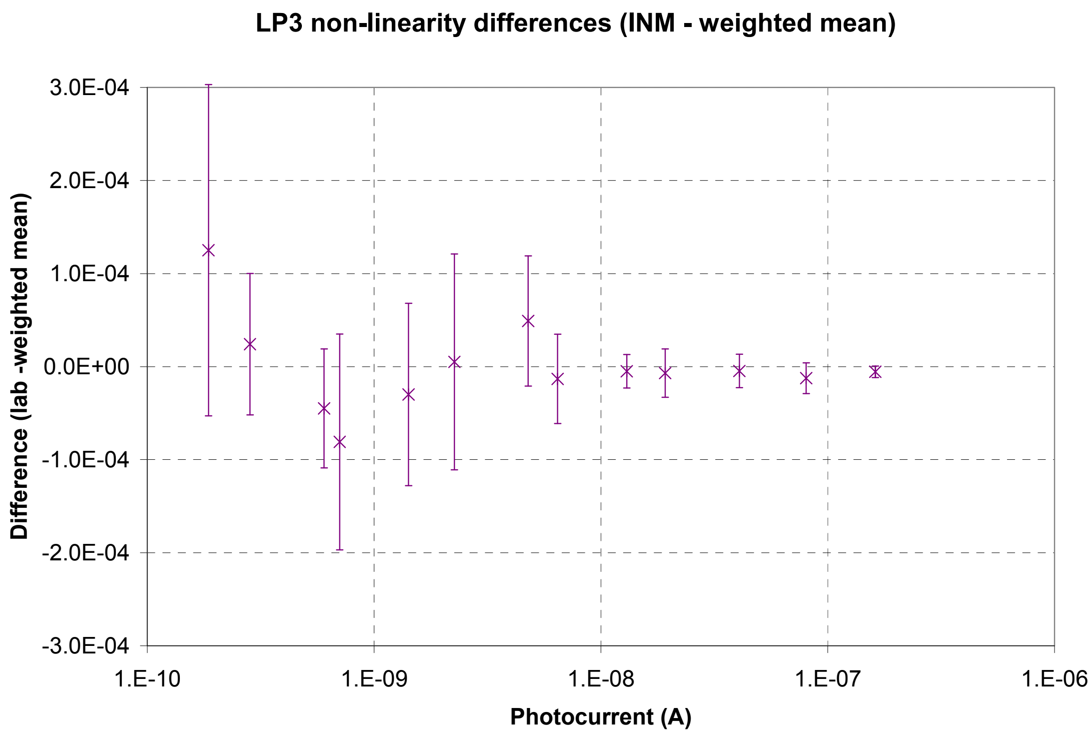


Figure 40 – differences of the INM results from the weighted mean

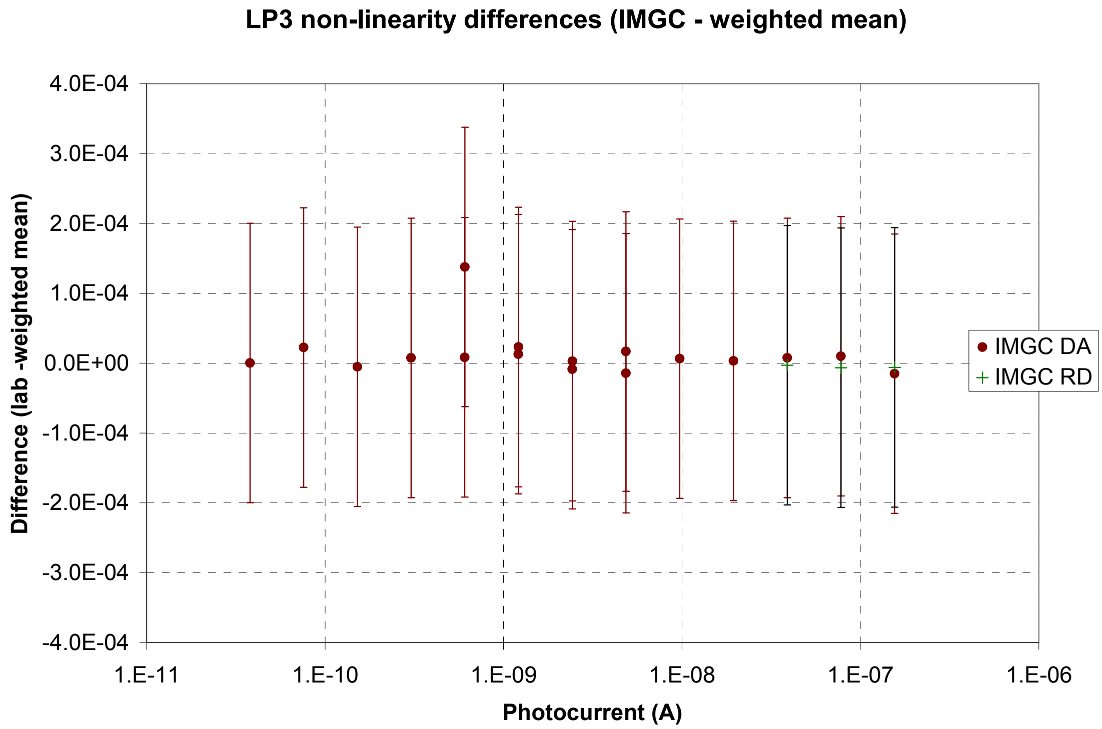


Figure 41 – differences of the IMGC results from the weighted mean

Since participants had carried out measurements at different photocurrents it was not appropriate to calculate DOE and QDE_{95} values for each pair of participants. Instead the evaluation of the results was simply done visually using the plots above. These show that the results from all the participants agree with each other within the measurement uncertainties.

2.3.1 The results for the VEGA TSP2

As with the results with the LP3, the non-linearity measurements had been made at different photocurrents by NPL and IMGC, meaning that it was not straightforward simply to calculate the average non-linearity at each photocurrent. It was therefore decided to calculate one average value for all the results at all photocurrents. At low photocurrents there is a large scatter in the non-linearity results and the uncertainties are large. These points (taken to be the first three points of the NPL results) were ignored and the arithmetic mean non-linearity was calculated for all the remaining points. This was calculated to be -4.294E-06 with a standard deviation of 1.054E-04.

The differences between all the non-linearity results and the arithmetic mean non-linearity values are shown in Tables 61 and 62 and Figures 42 and 43. The DOE and QDE_{95} values were not calculated as it was not thought to be necessary: enough information about the agreement between participants could be determined from a simple plot of the results. As can be seen, for photocurrents above 10^{-8} A in general the NPL non-linearity values are very slightly positive whereas the IMGC values are very slightly negative. This shows a slight systematic difference in the results. However, all the results are in agreement within the combined measurement uncertainties.

Gain	Average S_{1+2} photocurrent /A	Difference (NPL – mean)
10^8	3.94370E-10	-7.15185E-04
10^8	2.07812E-09	-6.37726E-04
10^8	4.07505E-09	1.11353E-03
10^8	8.11385E-09	7.02416E-05
10^8	9.48057E-09	3.07055E-05
10^8	1.21320E-08	-4.68144E-04
10^8	1.60359E-08	1.17898E-04
10^8	3.21653E-08	9.50770E-05
10^8	6.40632E-08	1.01203E-04
10^8	1.28150E-07	7.31323E-05
10^7	1.28071E-07	1.10353E-04
10^7	2.53705E-07	1.13582E-04
10^7	5.10706E-07	1.17175E-04
10^7	1.01959E-06	1.32077E-04
10^7	5.04550E-07	-5.87761E-06
10^7	1.01836E-06	2.08868E-05
10^6	1.01881E-06	5.49394E-05
10^6	2.03626E-06	4.52874E-05
10^6	4.07738E-06	7.74270E-05
10^6	5.36656E-06	1.18282E-05

Table 61 – the differences of the NPL results from the mean linearity value

Technique	Average S_{1+2} photocurrent /A	Difference (IMGC – mean)
DA	1.37926E-05	-5.73620E-05
DA	2.75477E-05	-5.69933E-05
DA	5.51146E-05	-6.16165E-05
DA	1.10344E-04	-6.18487E-05
DA	2.20697E-04	-5.96363E-05
DA	4.40856E-04	-5.08013E-05
DA	8.81991E-04	-3.87326E-05
DA	1.76399E-03	-3.86589E-05
DA	3.52729E-03	-4.47637E-05
RD	1.37757E-05	-9.60923E-05
RD	2.75598E-05	-7.33731E-05
RD	5.50704E-05	-5.33755E-05
RD	1.10250E-04	-3.91433E-05
RD	2.19698E-04	-1.78782E-05
RD	4.40678E-04	-4.93465E-06
RD	8.81868E-04	-1.85953E-07
RD	1.76388E-03	3.43077E-05
RD	3.52968E-03	2.32968E-05

Table 62 – the difference of the IMGC results from the mean linearity value

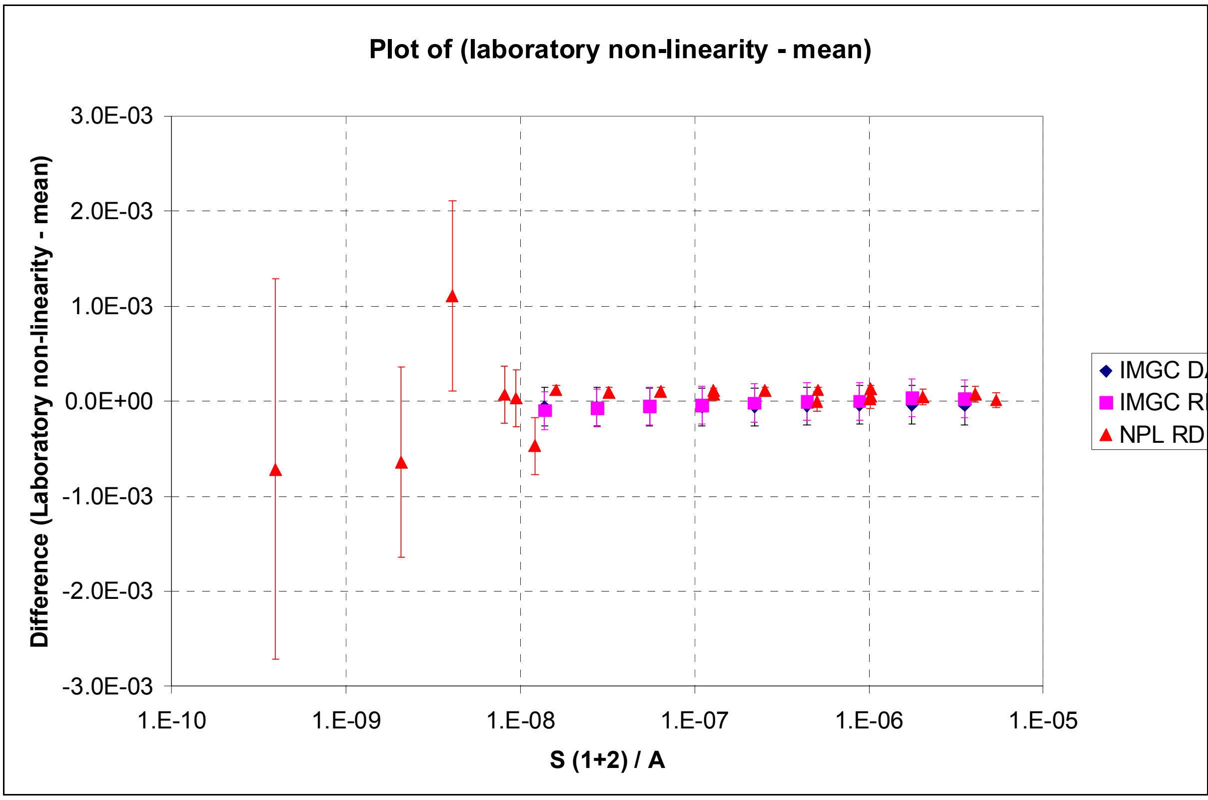


Figure 42 – plot of the differences between the laboratory non-linearity and the simple arithmetic mean for the VEGA (all data)

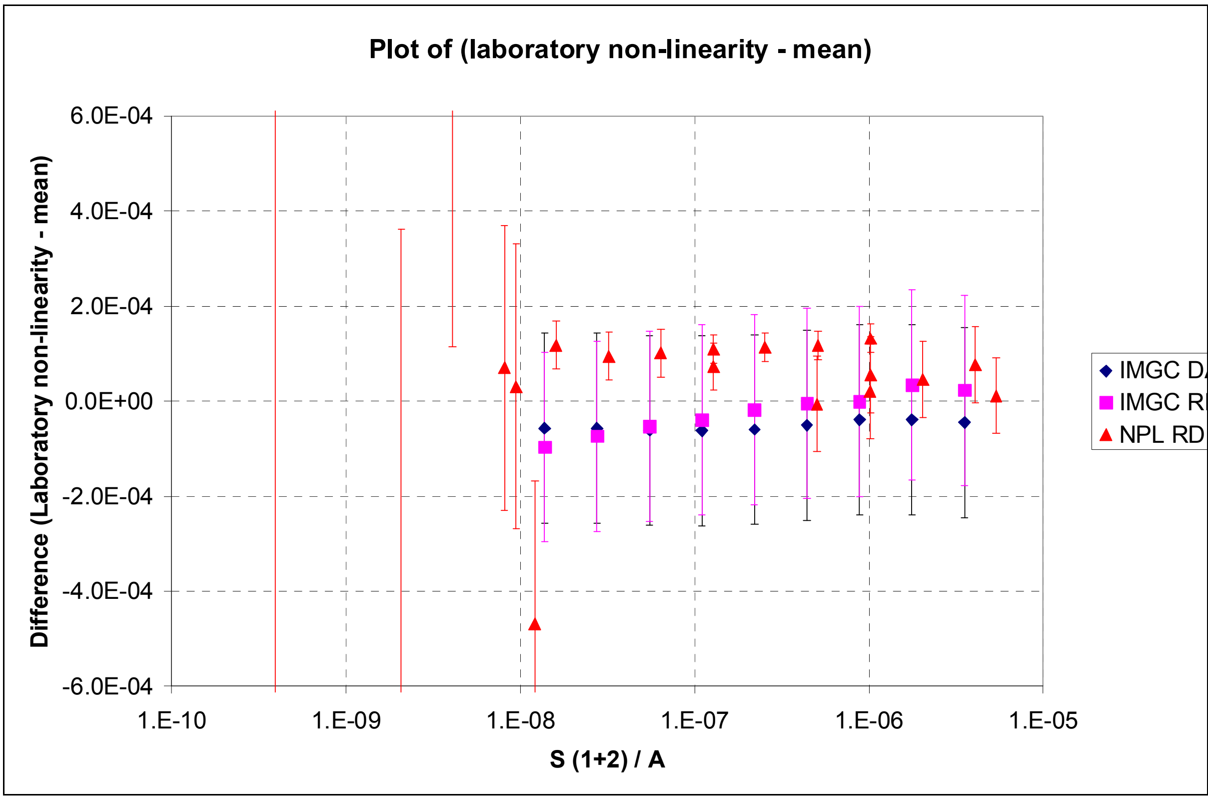


Figure 43 – plot of the differences between the laboratory non-linearity and the simple arithmetic mean for the VEGA (zoomed in)

3. The spectral responsivity / limiting effective wavelength measurements

3.1 Methods and apparatus used at each institute

The spectral responsivity and the limiting effective wavelength were determined using local procedures. The measurements were made at two different working distances to investigate the independence of the spectral responsivity facilities to working distance. These were 670 mm and 900 mm for the LP3 and 550 mm and 900 mm for the VEGA TSP2. If, due to the design of their apparatus these two distances were not practical, however, participants could choose two other distances, provided that they were significantly different.

Full details of the measurement procedures at each laboratory are given in the measurement reports in the Appendices. Brief information about the methods used is given below. Due to the fact that NPL did not measure the spectral responsivity of the VEGA TSP2 thermometer (see below), and it was subsequently withdrawn from the circulation before measurements had been carried out at PTB, spectral responsivity results are given for the LP3 only.

3.1.1 The NPL measurements

AT NPL the limiting effective wavelength of a radiation thermometer is calculated using the transmission profile of the interference filter and the (measured or assumed) spectral response of the detector. The filter transmission is measured using a scanning monochromator, calibrated at regular intervals during the measurement runs using emission line sources. A tungsten ribbon lamp is used as the radiance source at the input of the monochromator. For each measurement run two complete scans are performed: one with the interference filter in place, and one with no interference filter. The ratio of the two scans (i.e. filter in / filter out) gives the transmission profile of the interference filter. It was possible to make ‘filter out’ measurements with the LP3 by selecting one of the ‘blank’ spaces in the interference filter wheel. It was not possible to move the interference filter of the VEGA thermometer so no spectral responsivity measurements were made with this thermometer.

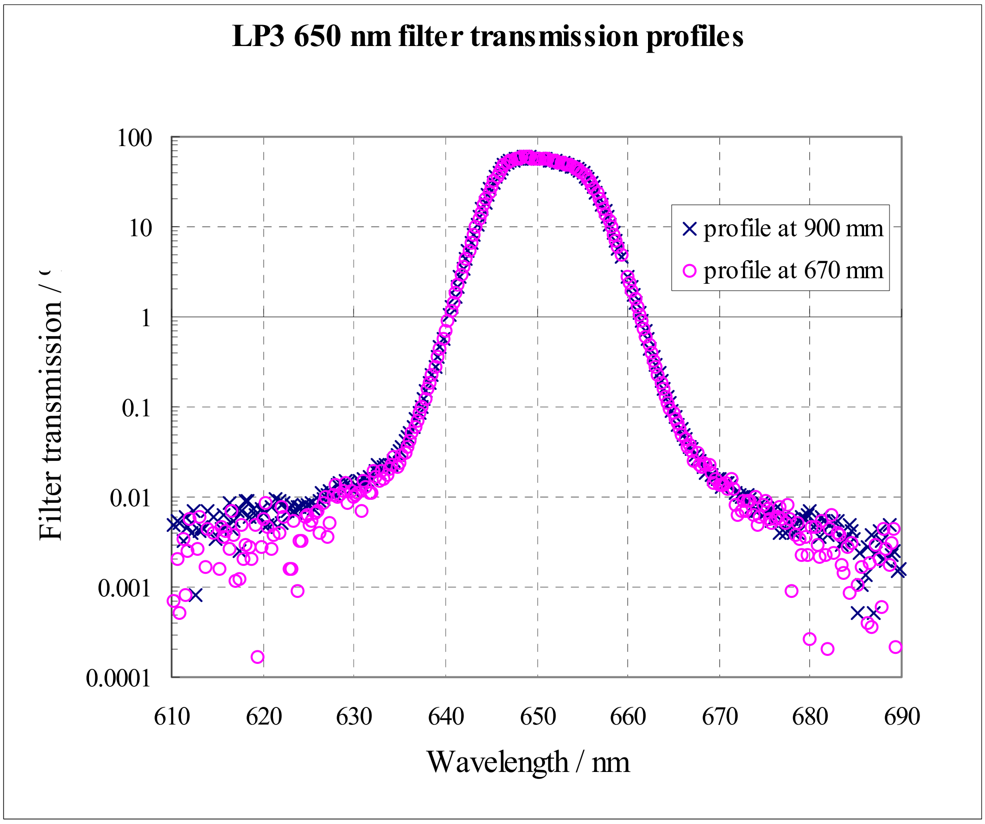
For the LP3 measurements the monochromator was scanned in steps of approximately 0.3 nm from 610 nm to 690 nm. Quick scans were also made from 500 nm to 1200 nm, into the wings of the filter, to check that there was no out-of-band transmission. Nothing significant was observed within the statistical noise in the measurements. The limiting effective wavelength of the thermometer was then calculated for specified temperatures using the filter transmission data, measured as above, and an assumed silicon photodiode detector response based on manufacturer’s data. The assumed detector response was in the form of a third-order polynomial taken to approximate the response of a silicon photodiode detector over the wavelength of interest. Software developed at NPL was used to solve the equation:

$$\frac{1}{\lambda_e} = \frac{\int \frac{1}{\lambda} s(\lambda)\tau(\lambda)\lambda^{-5}\left[\exp\left(\frac{c_2}{\lambda T}\right)-1\right]^{-1} d\lambda}{\int s(\lambda)\tau(\lambda)\lambda^{-5}\left[\exp\left(\frac{c_2}{\lambda T}\right)-1\right]^{-1} d\lambda} \quad \text{...........(1a)}$$

for different temperatures T, where λ_e is the limiting effective wavelength, $s(\lambda)$ is the detector response and $\tau(\lambda)$ is the filter transmission. The mean effective wavelength of the radiation thermometer for two temperatures T_{Au} and T_X is given by (1b):

$$\frac{1}{\lambda_e(T_{Au,X})} = \frac{1}{2}\left(\frac{1}{\lambda_e(T_{Au})} + \frac{1}{\lambda_e(T_X)}\right) \quad \text{................(1b)}$$

Measurements were made at a working distance of both 900 mm and 670 mm. An example of the measured transmission profile of the LP3 interference filter at the two different distances is given in the following plot.



The limiting effective and mean effective wavelength results are given in Tables 63 to 65 below.

3.1.2 The PTB measurements

The usual calibration method at the PTB is the multiple temperature calibration, where the photocurrent of the radiation thermometer is recorded while viewing a high temperature blackbody (HTBB) BB3200pg at various temperatures. The temperature of the HTBB is measured using absolute radiometry with interference filter radiometers at effective wavelengths of 676 nm and 800 nm and a tungsten strip lamp for temperature measurements according to the ITS-90 at an effective wavelength around 650 nm. This method was used to calibrate the LP3.

The resulting photocurrent I_{Photo} versus temperature T curve can be described using the well known ABC formalism according the equation:

$$I_{Photo} = \frac{C}{\exp\left(\frac{c_2}{AT + B}\right) - 1} \quad (2a)$$

The actual fit is performed to the inverse form of Equation 2a enabling a fit of temperature T as a function of photo current I_{Photo} according to

$$T = \frac{1}{A}\left(\frac{c_2}{\ln\left(\frac{C}{I_{photo}} + 1\right)} - B\right) \quad (2b)$$

Several equations for determining the effective wavelength using the ABC formalism of Equations (2a) and (2b) have been described in literature[10,11]. For a calibration of a radiation thermometer according to the multiple temperature point method knowledge of the spectral characteristics and, therefore, the limiting effective wavelength of the radiation thermometer is not necessary. For the sake of this comparison PTB performed calculations of the limiting effective wavelength according the following equations.

$$\lambda_{eff,1} = \frac{(AT + B)^2}{AT^2} \quad (3)$$

and

$$\lambda_{eff,2} = A + \frac{B}{T} \quad (4)$$

The mean effective wavelength was calculated according to equation (1b) above.

The multiple temperature calibration results, along with the k = 1 measurement uncertainties, are given in the following Table.

I_{Photo} / A	T_{ref} / K	$u(T_{ref})$ / K (k=1)
1.6339E-10	1344.6	0.3
7.6077E-10	1483.6	0.4
2.4837E-8	1936.9	0.5
5.6833E-8	2088.6	0.6
9.3621E-8	2192.0	0.6
1.3881E-7	2281.1	0.6
3.0235E-7	2480.4	0.7
8.1233E-7	2789.8	0.8
1.0573E-6	2885.8	0.8
1.7414E-6	3086.9	1.0
2.2553E-6	3202.3	1.0

[10] Jung, H. J., Verch, J., *Ein Rechenverfahren zur Auswertung Pyrometrischer Messungen,*Optik **38**, 1973, pp 95-109
[11] Sakuma, F., Kobayashi, M., in *Proceedings of Tempmeko '96*, Torino, IMEKO TC12, 1997, pp 273 to 277

The limiting and mean effective wavelength results along with the k = 2 measurement uncertainties are given in Tables 66 and 67 below.

3.1.3 The CEM measurements

The LP3 spectral responsivity, $R_{th}(\lambda)$, was measured with a monochromator calibrated, in wavelength, with an He-Ne laser, and obtained with equation (5).

$$R_{\mathrm{th}}(\lambda) = \frac{S_{\mathrm{th}}(\lambda) - Idc}{S_{\mathrm{m}}(\lambda)} \tag{5}$$

$S_{th}(\lambda)$ is the thermometer signal
$S_m(\lambda)$ is the monochromator output, that has been previously measured using a calibrated Si detector (see CEM measurement report).
Idc is the thermometer dark current.

For calculations it is more practical to normalise the spectral responsivity obtained in (5):

$$R_{\mathrm{th}}^{\mathrm{n}}(\lambda) = \frac{R_{\mathrm{th}}(\lambda)}{R_{\mathrm{th}}^{\mathrm{max}}} \tag{6}$$

$R_{\mathrm{th}}^{\mathrm{max}}$ is the maximum value of $R_{th}(\lambda)$

The limiting effective wavelength for a temperature T is calculated with equation (7):

$$\lambda_{\mathrm{eff}} = \frac{\int L_{\lambda}(T) R_{\mathrm{th}}^{\mathrm{n}}(\lambda) d\lambda}{\int L_{\lambda}(T) \frac{R_{\mathrm{th}}^{\mathrm{n}}(\lambda)}{\lambda} d\lambda} \tag{7}$$

where $L_{\lambda}(T) \propto \frac{1}{e^{c_2/\lambda T} - 1}$.

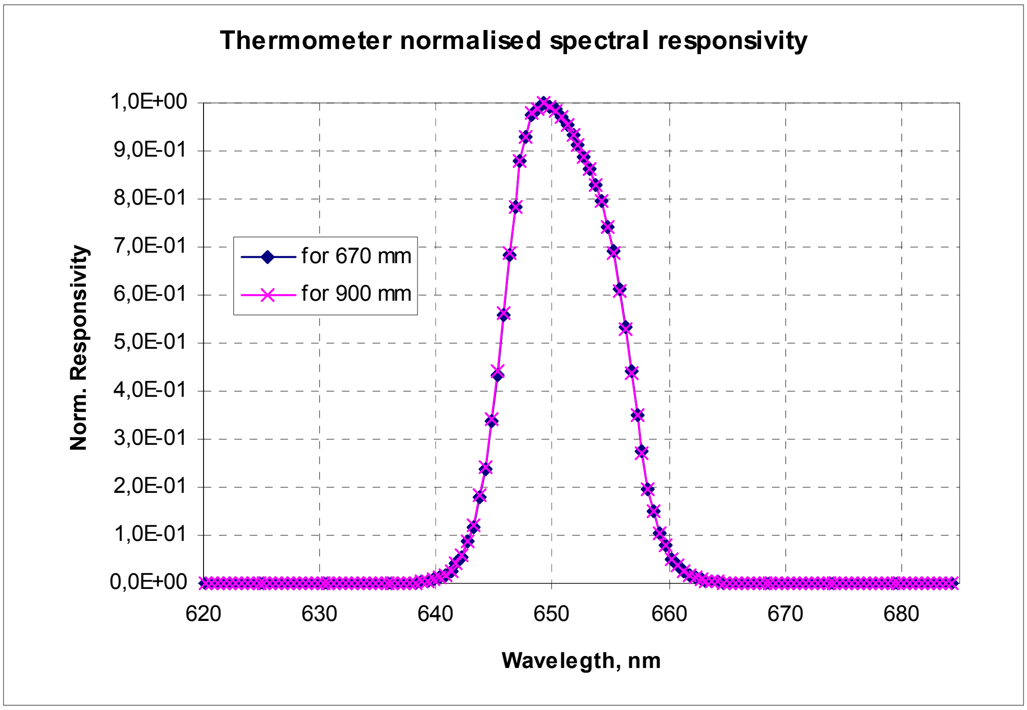
Equation (7) is numerically integrated using spectral responsivity from (6). The Romberg method with 128 intervals was used.

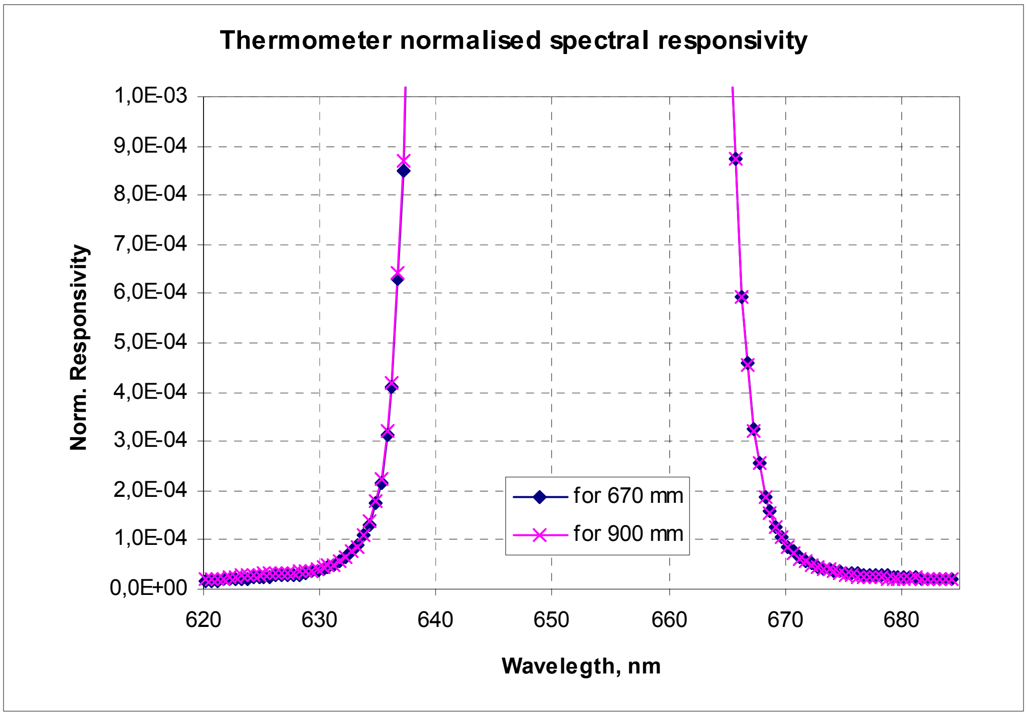
The mean effective wavelength between T_1 and T_2 was calculated using equation (1b) above.

The LP3 signal, $S_{th}(\lambda)$, was measured at each wavelength from 621 nm to 685 nm (with steps of 1 nm). 5 data (each 5 s) were taken for each wavelength. The mean value was calculated for each wavelength. Measurements were made at working distances of 670 mm and 900 mm.

In order to get the 128 intervals needed for numerical integration, a linear interpolation was carried out on the 64 data points measured.

Plots of the normalised spectral responsivity at the two different working distances are given in the following graphs.





The limiting effective wavelength and mean effective wavelength results along with the $k = 2$ measurement uncertainties are given in Tables 68 and 69 below.

3.1.4 The UME measurements

The UME procedure for obtaining a spectral responsivity of a standard radiation thermometer involves three steps.

Step I is the calibration of monochromator wavelength; this is accomplished by using rare-gas, neon, spectral calibration lamp. Prior to the comparison, the monochromator was calibrated between 400 nm and 1100 nm and the corrections of each wavelength were determined.

Step II involves obtaining the relative spectral responsivity of the transfer instrument. First the transfer instrument was scanned between 400 nm and 1100 nm in order to determine the out of band responsivity. No significant out of band responsivity was detected.

The measurements of the relative responsivity, $I_{LP3}(\lambda)$ of the LP3 were performed from 620 nm to 680 nm with 0,1 nm increments. A holographic grating with 1200 grooves/mm and a dispersion of 2.5 nm/mm was used.

Step III involves repeating the step II measurements, with reference detector, $I_{REF}(\lambda)$ namely the response of reference detector in the system. The reference detector is a Si-detector that has been spectrally calibrated against a trap detector using a double monochromator in the UME Optics laboratory, this calibration value is denoted by, $I_{REF\_ABS}(\lambda)$.

The spectral responsivity of the LP3 at each wavelength was calculated using the equation below

$$S_{LP3}(\lambda) = \frac{I_{REF\_ABS}(\lambda) * I_{LP3}(\lambda)}{I_{REF}(\lambda)}$$

Where

$S_{LP3}(\lambda)$	: Spectral responsivity calculated as a function of wavelength
$I_{REF\_ABS}(\lambda)$	: Absolute responsivity of reference detector
$I_{LP3}(\lambda)$	: Relative responsivity of the transfer instrument measured
$I_{REF}(\lambda)$	: Relative responsivity of reference detector measured

Spectral responsivity measurements were performed at two distances, i.e. at 550 mm and 900 mm.

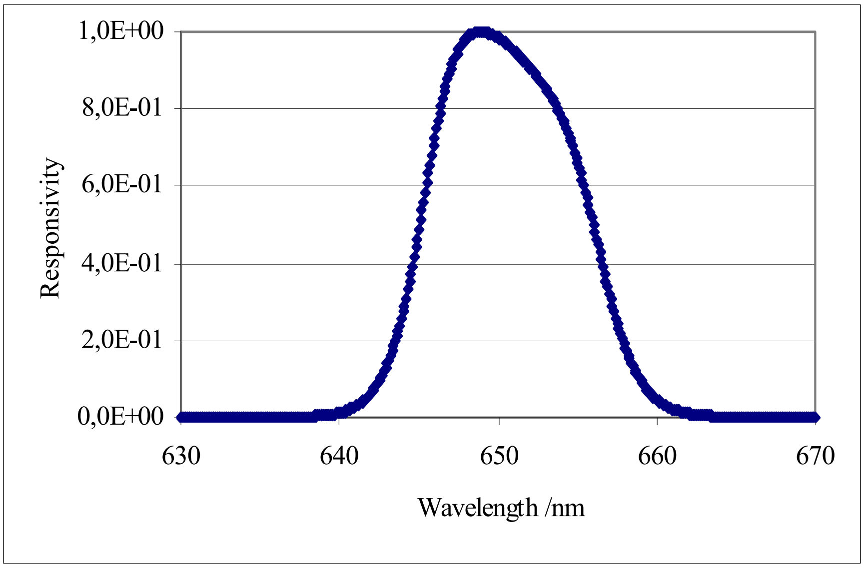
The limiting effective wavelength is defined as:

$$\frac{1}{\lambda_{eff}(T)} = \frac{\int_0^\infty \frac{1}{\lambda} L_\lambda(T) S_\lambda d\lambda}{\int_0^\infty L_\lambda(T) S_\lambda d\lambda}$$

Where $L_\lambda(T)$: the Planck function at the reference temperature, 1337,33K
S_λ : spectral responsivity determined

The numerical integration was performed between 620 nm and 680 nm. The mean effective wavelength was then determined from equation (1b) above.

The following figure shows the shape of the spectral responsivity function obtained at 550 mm



The limiting effective wavelength and mean effective wavelength results along with the $k = 2$ measurement uncertainties are given in Tables 70 and 71 below.

3.1.5 The BNM-INM measurements

The INM measurement results were withdrawn from the comparison not long after submission of their measurement report, because a problem was noticed with the monochromator after the completion of the measurements, so no data is presented here.

3.1.6 The IMGC measurements

The spectral responsivity of the LP3 was measured using a monochromator of 500 mm focal length with a 1200 grooves/mm holographic grating with 1.6 nm/mm dispersion.

The measurement procedure consisted of the following operations:

(a) *Wavelength calibration of the monochromator*. This is performed using a Ne spectral lamp as radiation source and a silicon photodiode as detector to localise the emission lines that are focused onto a circular diaphragm past the exit slit of the monochromator. Checks were also performed with the IKE LP3 used in place of the silicon photodiode (LP3 filters setting on A3B3).

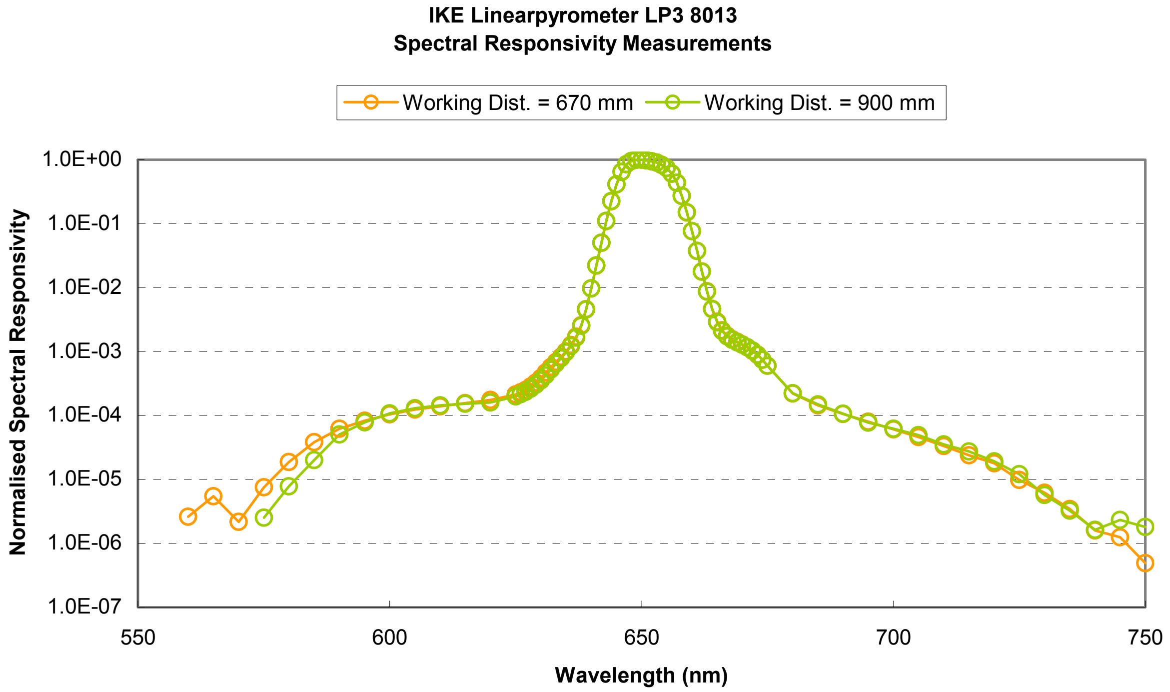
(b) *Measurement of the input spectral curve to the thermometer*. A tungsten-strip lamp in front of the entrance slit and a neutral pyroelectric detector with gold-black coating flush with the circular diaphragm are used for this measurement.

(c) *Measurement of the output spectral curve from the thermometer*. The pyroelectric detector is removed. The same spectral distribution previously measured with the neutral detector is then used as input curve to the thermometer and the corresponding output curve is measured. The covered spectral range was from 550 nm to 750 nm. Additional checks to investigate the presence of out-of-band transmittance were performed by scanning up to 1050 nm. For wavelengths longer than 750 nm no significant out-of-band transmittance was detected and only noise signals were measured

(d) *Calculation of the spectral responsivity*. The relative spectral responsivity of the thermometer is calculated as the ratio of the measured input and output curves.

(e) Values of 'limiting effective wavelength' and 'mean effective wavelength', according to the definition by Kostkowski and Lee, were calculated.

A plot of the normalised spectral responsivity at the two working distances is given in the following graph.



The limiting effective wavelength and mean effective results along with the k = 2 measurement uncertainties are given in Tables 72 and 73 below.

3.2 Results of the determination of the effective wavelength and associated uncertainties

The calculated values of the limiting effective and mean effective wavelengths from the measurements made at each of the different institutes are given in the following Tables, along with the associated total k = 2 measurement uncertainties.

3.2.1 The results of the NPL measurements

Temperature / K	Limiting effective wavelength / nm				
	Run 1	Run 2	Run 3	Average	U (*k*=2)
1000.0	651.165	651.160	651.159	651.161	0.16
1337.3	651.032	651.027	651.026	651.028	0.16
1500.0	650.990	650.985	650.983	650.986	0.16
2000.0	650.903	650.897	650.896	650.899	0.16
2500.0	650.850	650.845	650.843	650.846	0.16
3000.0	650.816	650.810	650.808	650.811	0.16
3500.0	650.791	650.786	650.784	650.787	0.16

Table 63: the results of the limiting effective wavelength calculations at 900 mm

Temperature / K	Limiting effective wavelength / nm			
	Run 1	Run 2	Average	U (*k*=2)
1000.0	651.173	651.155	651.164	0.16
1337.3	651.042	651.021	651.032	0.16
1500.0	650.999	650.979	650.989	0.16
2000.0	650.913	650.891	650.902	0.16
2500.0	650.861	650.839	650.850	0.16
3000.0	650.827	650.804	650.816	0.16
3500.0	650.802	650.780	650.791	0.16

Table 64: the results of the limiting effective wavelength calculations at 670 mm

Temperature / K	Mean effective wavelength / nm	
	At 900 mm	At 670 mm
1000.0	651.094	651.098
1337.3	651.028	651.032
1500.0	651.007	651.010
2000.0	650.963	650.967
2500.0	650.937	650.941
3000.0	650.919	650.924
3500.0	650.907	650.911

Table 65: the mean effective wavelength values calculated from Tables 63 and 64

3.2.2 The results of the PTB measurements

Temperature / K	Limiting effective wavelength from Equation 3 / nm	U (k=2) / nm	Limiting effective wavelength from Equation 4 / nm	U (k=2) / nm
1000.00	651.76	0.88	651.22	0.42
1337	651.49	0.80	651.09	0.36
1337.33	651.49	0.80	651.09	0.36
1500.00	651.40	0.76	651.04	0.36
2000.00	651.22	0.72	650.95	0.32
2500.00	651.12	0.70	650.90	0.32
3000.00	651.04	0.68	650.86	0.32
3500.00	650.99	0.68	650.84	0.30

Table 66: the PTB limiting effective wavelength results using both Equations (3) and (4)

Temperature / K	Mean effective wavelength from Equation 3 / nm	U (k=2) / nm	Mean effective wavelength from Equation 4 / nm	U (k=2) / nm
1000.00	651.62	0.88	651.15	0.42
1337	651.49	0.84	651.09	0.38
1337.33	651.49	0.84	651.09	0.38
1500.00	651.44	0.82	651.06	0.38
2000.00	651.35	0.80	651.02	0.36
2500.00	651.30	0.80	650.99	0.36
3000.00	651.27	0.78	650.98	0.36
3500.00	651.24	0.78	650.96	0.36

Table 67: the PTB mean effective wavelength results using both Equations (3) and (4)

3.2.3 The results of the CEM measurements

Temperature / K	Limiting effective wavelength / nm 900 mm distance	U (k=2) / nm
1000.0	651.29	0.21
1337.0	651.16	0.21
1337.33	651.16	0.21
1500.0	651.12	0.21
2000.0	651.04	0.21
2500.0	650.98	0.21
3000.0	650.95	0.21
3500.0	650.92	0.21

Temperature / K	Limiting effective wavelength / nm 670 mm distance	U (k=2) / nm
1000.0	651.31	0.21
1337.0	651.18	0.21
1337.33	651.18	0.21
1500.0	651.14	0.21
2000.0	651.05	0.21
2500.0	651.00	0.21
3000.0	650.97	0.21
3500.0	650.94	0.21

Table 68: the CEM limiting effective wavelength results

Temperature / K	Mean effective wavelength / nm 900 mm distance	U (*k*=2) / nm
1000.0	651.23	0.21
1337.0	651.16	0.21
1337.33	651.16	0.21
1500.0	651.14	0.21
2000.0	651.10	0.21
2500.0	651.07	0.21
3000.0	651.06	0.21
3500.0	651.04	0.21

Temperature / K	Mean effective wavelength / nm 670 mm distance	U (*k*=2) / nm
1000.0	651.25	0.21
1337.0	651.18	0.21
1337.33	651.18	0.21
1500.0	651.16	0.21
2000.0	651.12	0.21
2500.0	651.09	0.21
3000.0	651.07	0.21
3500.0	651.06	0.21

Table 69: the CEM mean effective wavelength results

3.2.4 The results of the UME measurements

Temperature / K	Limiting effective wavelength / nm 900 mm distance	U (*k*=2) / nm
1337.33	650.818	0.048

Temperature / K	Limiting effective wavelength / nm 550 mm distance	U (*k*=2) / nm
1337.33	650.776	0.048

Table 70: the UME limiting effective wavelength results

Temperature / K	Mean effective wavelength / nm 900 mm distance	U (*k*=2) / nm
1000.0	650.885	0.048
1337.0	650.818	0.048
1337.33	650.818	0.048
1500.0	650.796	0.048
2000.0	650.752	0.048
2500.0	650.726	0.048
3000.0	650.708	0.048
3500.0	650.696	0.048

Temperature / K	Mean effective wavelength / nm 550 mm distance	U (*k*=2) / nm
1000.0	650.841	0.048
1337.0	650.776	0.048
1337.33	650.776	0.048
1500.0	650.755	0.048
2000.0	650.712	0.048
2500.0	650.687	0.048
3000.0	650.670	0.048
3500.0	650.658	0.048

Table 71: the UME mean effective wavelength results

3.2.5 The results of the IMGC measurements

Temperature / K	Limiting effective wavelength / nm 900 mm distance	U (*k*=2) / nm
1000.00	651.4637	0.16
1337.33	651.3066	0.16
1500.00	651.2570	0.16
2000.00	651.1562	0.16
2500.00	651.0962	0.16
3000.00	651.0564	0.16
3500.00	651.0280	0.16

Temperature / K	Limiting effective wavelength / nm 670 mm distance	U (*k*=2) / nm
1000.00	651.4613	0.16
1337.33	651.3048	0.16
1500.00	651.2553	0.16
2000.00	651.1544	0.16
2500.00	651.0941	0.16
3000.00	651.0540	0.16
3500.00	651.0255	0.16

Table 72: the IMGC limiting effective wavelength results

Temperature / K	Mean effective wavelength / nm 900 mm distance	U (k=2) / nm
1000.00	651.3851	0.16
1337.33	651.3066	0.16
1500.00	651.2818	0.16
2000.00	651.2314	0.16
2500.00	651.2014	0.16
3000.00	651.1815	0.16
3500.00	651.1673	0.16

Temperature / K	Mean effective wavelength / nm 670 mm distance	U (k=2) / nm
1000.00	651.3830	0.16
1337.33	651.3048	0.16
1500.00	651.2800	0.16
2000.00	651.2296	0.16
2500.00	651.1994	0.16
3000.00	651.1794	0.16
3500.00	651.1651	0.16

Table 73: the IMGC mean effective wavelength results

3.3 Graphs of the effective wavelength results

A plot of all the calculated values of the limiting and mean effective wavelengths from each participant are plotted together in the following graphs for ease of comparison, along with the associated $k = 2$ measurement uncertainties.

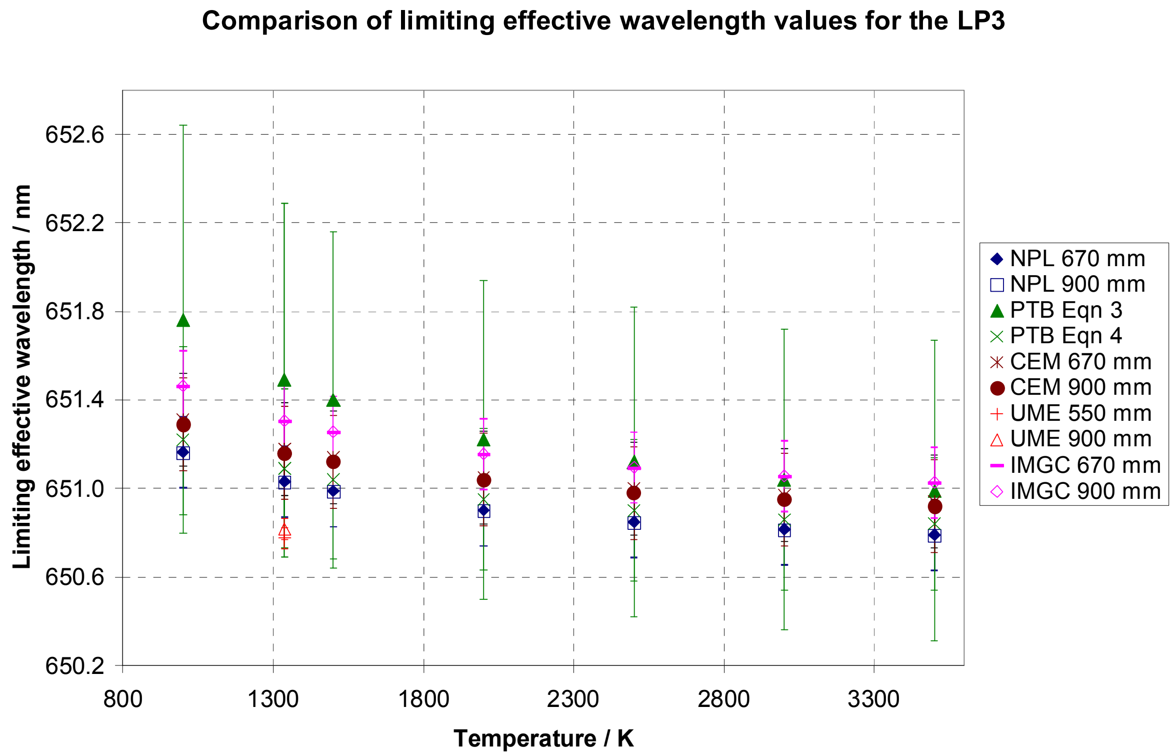


Figure 44 - Plot of the limiting effective wavelength results for the LP3 with the corresponding *k* = 2 uncertainty bars

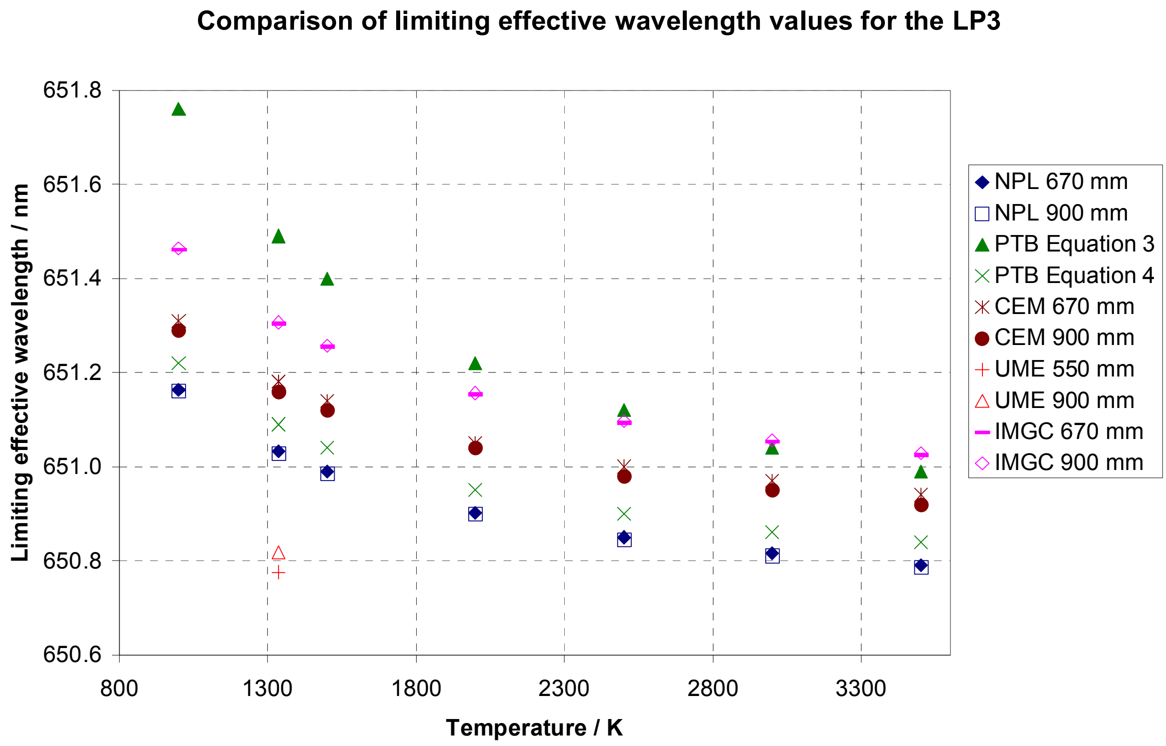


Figure 45 – plot of the limiting effective wavelength results with the LP3, with uncertainty bars removed for ease of seeing the results.

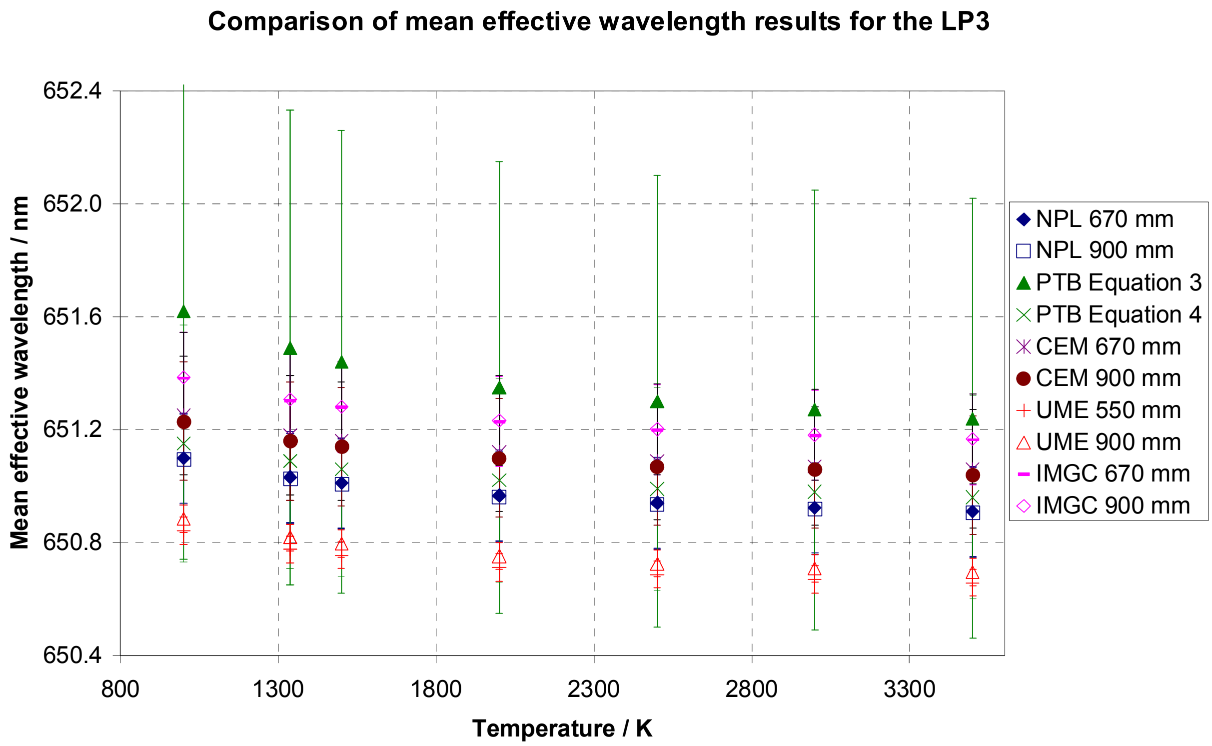


Figure 46 – plot of the mean effective wavelength results for the LP3 with corresponding *k* = 2 uncertainty bars

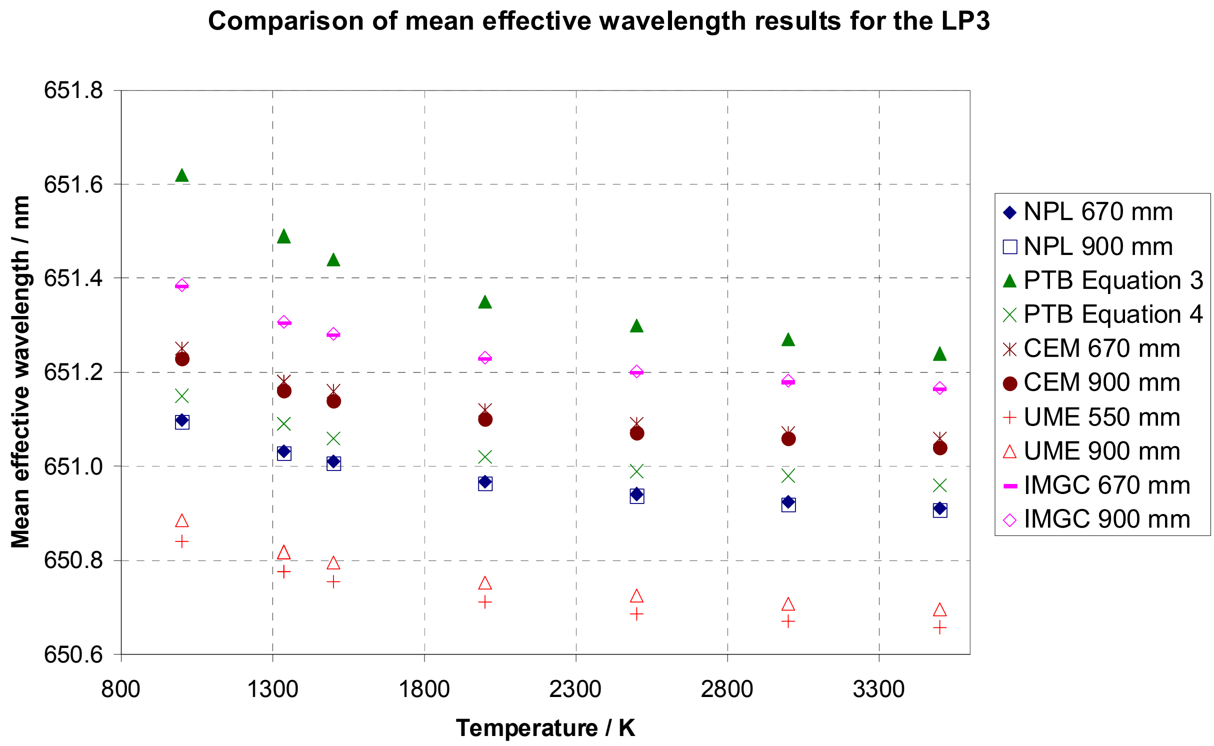


Figure 47 – plot of the mean effective wavelength results for the LP3 with the uncertainty bars removed for ease of viewing the results.

3.4 Analysis of the results, discussion and conclusion

The weighted mean, arithmetic mean and the median were calculated using all the results (Tables 74 and 75) and considered for the comparison reference value. The small measurement uncertainty values of UME compared to those of the other participants had a strong influence on the weighted mean value, making this unsuitable for the comparison reference value (see Tables 76 to 89). Although a weighted mean with 'uncertainty cut-off' was considered, it was decided, for ease and to avoid assigning a cut-off, to use the arithmetic mean for the reference value. Since the reference value was simply being used as a tool to facilitate the comparison of the results, it was not assigned an uncertainty value.

Temperature / K	Arithmetic mean value of limiting effective wavelength	Weighted mean value of limiting effective wavelength	Median value of limiting effective wavelength
1000	651.354	651.310	651.300
1337.33	651.119	650.869	651.125
1500	651.148	651.123	651.130
2000	651.046	651.030	651.045
2500	650.986	650.974	650.990
3000	650.945	650.937	650.960
3500	650.915	650.910	650.930

Table 74 – the arithmetic mean, weighted mean and median values for the limiting effective wavelength

Temperature / K	Arithmetic mean value of mean effective wavelength	Weighted mean value of mean effective wavelength	Median value of mean effective wavelength
1000	651.194	650.936	651.190
1337.33	651.119	650.869	651.125
1500	651.093	650.848	651.100
2000	651.045	650.804	651.060
2500	651.014	650.778	651.030
3000	650.996	650.760	651.020
3500	650.980	650.748	651.000

Table 75 - the arithmetic mean, weighted mean and median values for the mean effective wavelength

Laboratory reference	Limiting effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	651.164	-0.136	-0.190	-0.146
NPL 900 mm	651.161	-0.139	-0.193	-0.149
PTB Eqn 3	651.76	0.460	0.406	0.450
PTB Eqn 4	651.22	-0.080	-0.134	-0.090
CEM 670 mm	651.31	0.010	-0.044	0.000
CEM 900 mm	651.29	-0.010	-0.064	-0.020
UME 550 mm	-	-	-	-
UME 900 mm	-	-	-	-
IMGC 670 mm	651.4613	0.161	0.108	0.151
IMGC 900 mm	651.4637	0.164	0.110	0.154

Table 76 - laboratory differences for limiting effective wavelength values at 1000 K

Laboratory reference	Limiting effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	651.032	-0.093	-0.087	0.163
NPL 900 mm	651.028	-0.097	-0.091	0.159
PTB Eqn 3	651.49	0.365	0.371	0.621
PTB Eqn 4	651.09	-0.035	-0.029	0.221
CEM 670 mm	651.18	0.055	0.061	0.311
CEM 900 mm	651.16	0.035	0.041	0.291
UME 550 mm	650.776	-0.349	-0.343	-0.093
UME 900 mm	650.818	-0.307	-0.301	-0.051
IMGC 670 mm	651.3048	0.180	0.186	0.435
IMGC 900 mm	651.3066	0.182	0.188	0.437

Table 77 - laboratory differences for limiting effective wavelength values at 1337.3 K

Laboratory reference	Limiting effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.989	-0.141	-0.159	-0.134
NPL 900 mm	650.986	-0.144	-0.162	-0.137
PTB Eqn 3	651.4	0.270	0.252	0.277
PTB Eqn 4	651.04	-0.090	-0.108	-0.083
CEM 670 mm	651.14	0.010	-0.008	0.017
CEM 900 mm	651.12	-0.010	-0.028	-0.003
UME 550 mm	-	-	-	-
UME 900 mm	-	-	-	-
IMGC 670 mm	651.2553	0.125	0.107	0.132
IMGC 900 mm	651.257	0.127	0.109	0.134

Table 78 - laboratory differences for limiting effective wavelength values at 1500 K

Laboratory reference	Limiting effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.902	-0.143	-0.144	-0.128
NPL 900 mm	650.899	-0.146	-0.147	-0.131
PTB Eqn 3	651.22	0.175	0.174	0.190
PTB Eqn 4	650.95	-0.095	-0.096	-0.080
CEM 670 mm	651.05	0.005	0.004	0.020
CEM 900 mm	651.04	-0.005	-0.006	0.010
UME 550 mm	-	-	-	-
UME 900 mm	-	-	-	-
IMGC 670 mm	651.1544	0.109	0.108	0.125
IMGC 900 mm	651.1562	0.111	0.110	0.126

Table 79 - laboratory differences for limiting effective wavelength values at 2000 K

Laboratory reference	Limiting effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.85	-0.140	-0.136	-0.124
NPL 900 mm	650.846	-0.144	-0.140	-0.128
PTB Eqn 3	651.12	0.130	0.134	0.146
PTB Eqn 4	650.90	-0.090	-0.086	-0.074
CEM 670 mm	651.00	0.010	0.014	0.026
CEM 900 mm	650.98	-0.010	-0.006	0.006
UME 550 mm	-	-	-	-
UME 900 mm	-	-	-	-
IMGC 670 mm	651.0941	0.104	0.108	0.120
IMGC 900 mm	651.0962	0.106	0.110	0.123

Table 80 - laboratory differences for limiting effective wavelength values at 2500 K

Laboratory reference	Limiting effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.816	-0.144	-0.129	-0.121
NPL 900 mm	650.811	-0.149	-0.134	-0.126
PTB Eqn 3	651.04	0.080	0.095	0.103
PTB Eqn 4	650.86	-0.100	-0.085	-0.077
CEM 670 mm	650.97	0.010	0.025	0.033
CEM 900 mm	650.95	-0.010	0.005	0.013
UME 550 mm	-	-	-	-
UME 900 mm	-	-	-	-
IMGC 670 mm	651.054	0.094	0.109	0.117
IMGC 900 mm	651.0564	0.096	0.112	0.119

Table 81 - laboratory differences for limiting effective wavelength values at 3000 K

Laboratory reference	Limiting effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.791	-0.139	-0.124	-0.119
NPL 900 mm	650.787	-0.143	-0.128	-0.123
PTB Eqn 3	650.99	0.060	0.075	0.080
PTB Eqn 4	650.84	-0.090	-0.075	-0.070
CEM 670 mm	650.94	0.010	0.025	0.030
CEM 900 mm	650.92	-0.010	0.005	0.010
UME 550 mm	-	-	-	-
UME 900 mm	-	-	-	-
IMGC 670 mm	651.0255	0.095	0.110	0.116
IMGC 900 mm	651.028	0.098	0.113	0.118

Table 82 - laboratory differences for limiting effective wavelength values at 3500 K

Laboratory reference	Mean effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	651.098	-0.092	-0.096	0.162
NPL 900 mm	651.094	-0.096	-0.100	0.158
PTB Eqn 3	651.62	0.430	0.426	0.684
PTB Eqn 4	651.15	-0.040	-0.044	0.214
CEM 670 mm	651.25	0.060	0.056	0.314
CEM 900 mm	651.23	0.040	0.036	0.294
UME 550 mm	650.841	-0.349	-0.353	-0.095
UME 900 mm	650.885	-0.305	-0.309	-0.051
IMGC 670 mm	651.383	0.193	0.189	0.447
IMGC 900 mm	651.3851	0.195	0.191	0.449

Table 83 – laboratory differences for mean effective wavelength values at 1000 K

Laboratory reference	Mean effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	651.032	-0.093	-0.087	0.163
NPL 900 mm	651.028	-0.097	-0.091	0.159
PTB Eqn 3	651.49	0.365	0.371	0.621
PTB Eqn 4	651.09	-0.035	-0.029	0.221
CEM 670 mm	651.18	0.055	0.061	0.311
CEM 900 mm	651.16	0.035	0.041	0.291
UME 550 mm	650.776	-0.349	-0.343	-0.093
UME 900 mm	650.818	-0.307	-0.301	-0.051
IMGC 670 mm	651.3048	0.180	0.186	0.436
IMGC 900 mm	651.3066	0.182	0.188	0.437

Table 84 - laboratory differences for mean effective wavelength values at 1337.3 K

Laboratory reference	Mean effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	651.01	-0.090	-0.083	0.162
NPL 900 mm	651.007	-0.093	-0.086	0.159
PTB Eqn 3	651.44	0.340	0.347	0.592
PTB Eqn 4	651.06	-0.040	-0.033	0.212
CEM 670 mm	651.16	0.060	0.067	0.312
CEM 900 mm	651.14	0.040	0.047	0.292
UME 550 mm	650.755	-0.345	-0.338	-0.093
UME 900 mm	650.796	-0.304	-0.297	-0.052
IMGC 670 mm	651.28	0.180	0.187	0.432
IMGC 900 mm	651.2818	0.182	0.189	0.434

Table 85 – laboratory differences for mean effective wavelength values at 1500 K

Laboratory reference	Mean effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.967	-0.093	-0.077	0.163
NPL 900 mm	650.963	-0.097	-0.082	0.159
PTB Eqn 3	651.35	0.290	0.306	0.546
PTB Eqn 4	651.02	-0.040	-0.024	0.216
CEM 670 mm	651.12	0.060	0.076	0.316
CEM 900 mm	651.1	0.040	0.056	0.296
UME 550 mm	650.712	-0.348	-0.332	-0.092
UME 900 mm	650.752	-0.308	-0.293	-0.052
IMGC 670 mm	651.2296	0.170	0.185	0.426
IMGC 900 mm	651.2314	0.171	0.187	0.428

Table 86 - laboratory differences for mean effective wavelength values at 2000 K

Laboratory reference	Mean effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.941	-0.089	-0.073	0.163
NPL 900 mm	650.937	-0.093	-0.077	0.159
PTB Eqn 3	651.3	0.270	0.286	0.522
PTB Eqn 4	650.99	-0.040	-0.024	0.212
CEM 670 mm	651.09	0.060	0.076	0.312
CEM 900 mm	651.07	0.040	0.056	0.292
UME 550 mm	650.687	-0.343	-0.327	-0.091
UME 900 mm	650.726	-0.304	-0.288	-0.052
IMGC 670 mm	651.1994	0.169	0.185	0.422
IMGC 900 mm	651.2014	0.171	0.187	0.424

Table 87 - laboratory differences for mean effective wavelength values at 2500 K

Laboratory reference	Mean effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.924	-0.096	-0.072	0.164
NPL 900 mm	650.919	-0.101	-0.077	0.159
PTB Eqn 3	651.27	0.250	0.274	0.510
PTB Eqn 4	650.98	-0.040	-0.016	0.220
CEM 670 mm	651.07	0.050	0.074	0.310
CEM 900 mm	651.06	0.040	0.064	0.300
UME 550 mm	650.67	-0.350	-0.326	-0.090
UME 900 mm	650.708	-0.312	-0.288	-0.052
IMGC 670 mm	651.1794	0.159	0.183	0.419
IMGC 900 mm	651.1815	0.162	0.185	0.421

Table 88 - laboratory differences for mean effective wavelength values at 3000 K

Laboratory reference	Mean effective wavelength / nm	Laboratory – median / nm	Laboratory – mean / nm	Laboratory – weighted mean / nm
NPL 670 mm	650.911	-0.089	-0.069	0.163
NPL 900 mm	650.907	-0.093	-0.073	0.159
PTB Eqn 3	651.24	0.240	0.260	0.492
PTB Eqn 4	650.96	-0.040	-0.020	0.212
CEM 670 mm	651.06	0.060	0.080	0.312
CEM 900 mm	651.04	0.040	0.060	0.292
UME 550 mm	650.658	-0.342	-0.322	-0.090
UME 900 mm	650.696	-0.304	-0.284	-0.052
IMGC 670 mm	651.1651	0.165	0.185	0.417
IMGC 900 mm	651.1673	0.167	0.187	0.420

Table 89 - laboratory differences for mean effective wavelength values at 3500 K

Using the arithmetic mean as the comparison reference value, the differences between each pair of participants, along with DOE and QDE_{95} values, were calculated and these are given in Tables 182 to 195 in Appendix 6 with the accompanying graphs showing the differences from the mean. The QDE_{95} value was calculated from the equation:

$$QDE_{95(i,j)} = \left|\Delta\lambda\right|_{(i,j)} + \left\{1.645 + 0.3295\exp\left(\frac{-4.05\left|\Delta\lambda\right|_{(i,j)}}{u_{(i,j)}}\right)\right\} u_{(i,j)}$$

As can be seen, there is a large spread in the results: for the limiting effective wavelength at 1337 K there is a difference of almost 0.7 nm between the highest and lowest values (those of PTB and UME). This is equivalent to a temperature uncertainty of about 6 °C at 3500 K. Some of the spread could be explained by the different method that PTB used to measure the effective wavelength compared to the other laboratories. However, with the exception of the results from UME, the results of all the participants agree with each other to within the combined measurement uncertainties. It can also be seen that the results are not dependant on measurement distance.

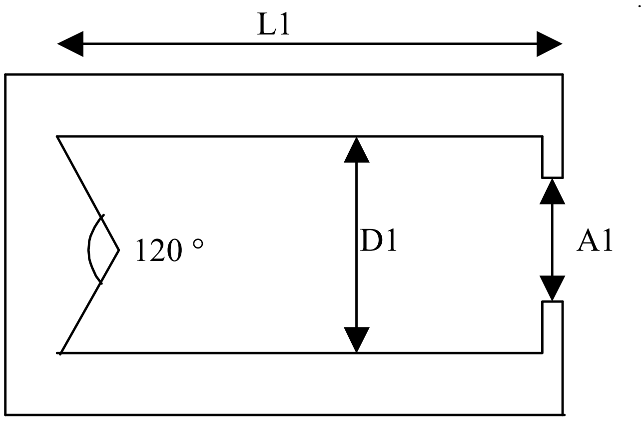
4. Emissivity calculations for a selection of blackbody cavities

The emissivity of a number of different designs of blackbody cavity was calculated using the software normally used at each institute. The designs for each of the cavities are given below. The emissivity was calculated for:

a) isothermal conditions;
b) non-isothermal conditions, assuming a linear temperature gradient of 10 °C along the length of the cavity, with the rear of the cavity being hotter. The rear of the cavity was assumed to be at a temperature of 962 °C and the calculation was performed for a wavelength of 0.9 μm.

4.1 Cavity designs for the emissivity calculations

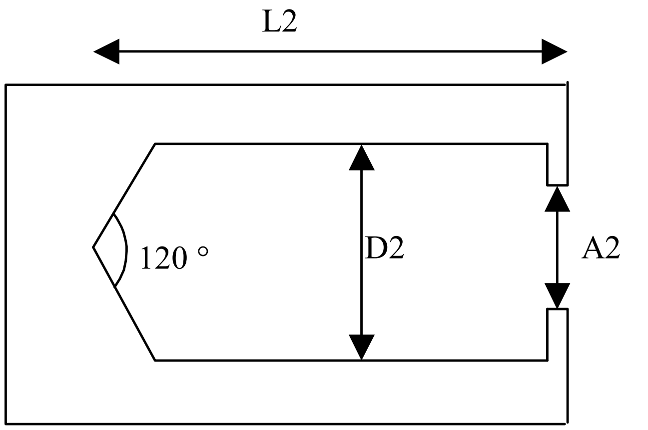
i) Design A



The emissivity of the walls of this cavity is assumed to be 0.92 and diffuse. Calculations were to be performed for the following values of L1, D1 and A1.

Design	L1 (mm)	D1 (mm)	A1 (mm)
A-1	97	7	3
A-2	27	3	3

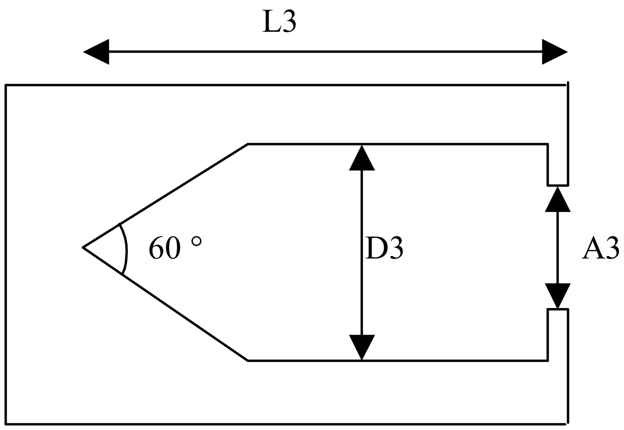
ii) Design B



The emissivity of the walls of this cavity is assumed to be 0.80 and diffuse. Calculations were to be performed for the following values of L2, D2 and A2.

Design	L2 (mm)	D2 (mm)	A2 (mm)
B-1	27	3	3
B-2	97	7	3
B-3	322	75	75
B-4	322	75	50

iii) Design C



The emissivity of the walls of this cavity is 0.80. Calculations were to be performed for the following values of L3, D3 and A3.

Design	L3 (mm)	D3 (mm)	A3 (mm)
C-1	27	3	3
C-2	97	7	3
C-3	322	75	75
C-4	322	75	50

4.2 The results of the calculations

Brief information about the calculation methods used in each institute is given below, along with the results. For further details refer to the participant measurement reports in the Appendices.

4.2.1 The calculations using the NPL software

The emissivity calculations were performed using software written at NPL to calculate the emissivity of a diffusely reflecting, isothermal, cylindrical cavity with a re-entrant cone on the back wall. It is also routinely used to calculate the emissivity of non-re-entrant cone cavities. The calculations are based on a method developed by de Vos[12,13]. The emissivity is calculated for an element on the cone surface. A correction term can also be calculated to allow for any temperature gradients, both along the length of the cavity and radially across the aperture.

[12] Redgrove, J. S. and Berry, K. S., in *High Temperatures – High Pressures* **15**, 1983, pp 1-11
[13] de Vos, J. C., in *Physica* **20**, 1954, pp 669-689

The results of the calculations for all the cavity designs are given in Table 90. The emissivity was calculated for different points of interest on the cone: towards the top (point), the middle and the bottom (base). For the non-isothermal emissivity calculations, the cone of the blackbody was assumed to be at a uniform temperature.

Design	L1 / mm	D1 / mm	A1 / mm	Wall emissivity	Gradient	Point of interest	Emissivity	Average emissivity
A-1	97	7	3	0.92	Isothermal	Middle	0.99998	
A-1	97	7	3	0.92	Isothermal	Bottom	0.99998	0.99998
A-1	97	7	3	0.92	Isothermal	Top	0.99998	
A-1	97	7	3	0.92	10 °C	Middle	0.99982	
A-1	97	7	3	0.92	10 °C	Bottom	0.99982	0.99982
A-1	97	7	3	0.92	10 °C	Top	0.99982	
A-2	27	3	3	0.92	Isothermal	Middle	0.99978	
A-2	27	3	3	0.92	Isothermal	Bottom	0.99979	0.99978
A-2	27	3	3	0.92	Isothermal	Top	0.99978	
A-2	27	3	3	0.92	10 °C	Middle	0.99946	
A-2	27	3	3	0.92	10 °C	Bottom	0.99947	0.99946
A-2	27	3	3	0.92	10 °C	Top	0.99946	
B-1	27	3	3	0.80	Isothermal	Middle	0.99943	
B-1	27	3	3	0.80	Isothermal	Bottom	0.99940	0.99943
B-1	27	3	3	0.80	Isothermal	Top	0.99945	
B-1	27	3	3	0.80	10 °C	Middle	0.99888	
B-1	27	3	3	0.80	10 °C	Bottom	0.99885	0.99888
B-1	27	3	3	0.80	10 °C	Top	0.99890	
B-2	97	7	3	0.80	Isothermal	Middle	0.99996	
B-2	97	7	3	0.80	Isothermal	Bottom	0.99996	0.99996
B-2	97	7	3	0.80	Isothermal	Top	0.99996	
B-2	97	7	3	0.80	10 °C	Middle	0.99967	
B-2	97	7	3	0.80	10 °C	Bottom	0.99967	0.99967
B-2	97	7	3	0.80	10 °C	Top	0.99967	
B-3	322	75	75	0.80	Isothermal	Middle	0.99725	
B-3	322	75	75	0.80	Isothermal	Bottom	0.99713	0.99729
B-3	322	75	75	0.80	Isothermal	Top	0.99749	
B-3	322	75	75	0.80	10 °C	Middle	0.99578	
B-3	322	75	75	0.80	10 °C	Bottom	0.99566	0.99582
B-3	322	75	75	0.80	10 °C	Top	0.99602	
B-4	322	75	50	0.80	Isothermal	Middle	0.99877	
B-4	322	75	50	0.80	Isothermal	Bottom	0.99871	0.99878
B-4	322	75	50	0.80	Isothermal	Top	0.99887	
B-4	322	75	50	0.80	10 °C	Middle	0.99719	
B-4	322	75	50	0.80	10 °C	Bottom	0.99713	0.99720
B-4	322	75	50	0.80	10 °C	Top	0.99729	
C-1	27	3	3	0.80	Isothermal	Middle	0.99963	
C-1	27	3	3	0.80	Isothermal	Bottom	0.99959	0.99963
C-1	27	3	3	0.80	Isothermal	Top	0.99968	
C-1	27	3	3	0.80	10 °C	Middle	0.99932	
C-1	27	3	3	0.80	10 °C	Bottom	0.99928	0.99932
C-1	27	3	3	0.80	10 °C	Top	0.99937	

Table 90: the results of the NPL emissivity calculations

Table 90 continued

Design	L1 / mm	D1 / mm	A1 / mm	Wall emissivity	Gradient	Point of interest	Emissivity	Average emissivity
C-2	97	7	3	0.80	Isothermal	Middle	0.99997	
C-2	97	7	3	0.80	Isothermal	Bottom	0.99997	0.99997
C-2	97	7	3	0.80	Isothermal	Top	0.99998	
C-2	97	7	3	0.80	10 °C	Middle	0.99980	
C-2	97	7	3	0.80	10 °C	Bottom	0.99980	0.99980
C-2	97	7	3	0.80	10 °C	Top	0.99981	
C-3	322	75	75	0.80	Isothermal	Middle	0.99805	
C-3	322	75	75	0.80	Isothermal	Bottom	0.99739	0.99799
C-3	322	75	75	0.80	Isothermal	Top	0.99853	
C-3	322	75	75	0.80	10 °C	Middle	0.99733	
C-3	322	75	75	0.80	10 °C	Bottom	0.99667	0.99727
C-3	322	75	75	0.80	10 °C	Top	0.99781	
C-4	322	75	50	0.80	Isothermal	Middle	0.99912	
C-4	322	75	50	0.80	Isothermal	Bottom	0.99882	0.99909
C-4	322	75	50	0.80	Isothermal	Top	0.99934	
C-4	322	75	50	0.80	10 °C	Middle	0.99832	
C-4	322	75	50	0.80	10 °C	Bottom	0.99802	0.99829
C-4	322	75	50	0.80	10 °C	Top	0.99854	

4.2.1.1 Emissivity uncertainties

The uncertainties in the determination of the emissivity of the cavity are given in Table 91. For the isothermal cavities the uncertainty was calculated from (i) the standard deviation of the average of the results from the middle, top and bottom of the cone surface, combined with (ii) an assumed uncertainty in the software calculation of the emissivity (taken to be 0.00001 in each case). For the non-isothermal cavities there is an additional uncertainty component to take into account the modelling of the temperature profile along the cavity. This is taken to be the standard deviation of the mean of the values obtained using slightly different interpretations of the temperature profiles, and has been included in uncertainty component (i).

Cavity design	Isothermal			Non-isothermal		
	u_i	u_{ii}	Total ($k = 2$)	u_i	u_{ii}	Total ($k = 2$)
A-1	0.00000	0.00001	0.00002	0.00004	0.00001	0.00008
A-2	0.00001	0.00001	0.00003	0.00014	0.00001	0.00029
B-1	0.00003	0.00001	0.00006	0.00009	0.00001	0.00017
B-2	0.00000	0.00001	0.00002	0.00003	0.00001	0.00006
B-3	0.00018	0.00001	0.00036	0.00026	0.00001	0.00053
B-4	0.00008	0.00001	0.00016	0.00021	0.00001	0.00043
C-1	0.00005	0.00001	0.00010	0.00014	0.00001	0.00027
C-2	0.00001	0.00001	0.00003	0.00006	0.00001	0.00012
C-3	0.00057	0.00001	0.00114	0.00070	0.00001	0.00141
C-4	0.00026	0.00001	0.00052	0.00050	0.00001	0.00100

Table 91: the uncertainties in the NPL determination of the emissivity of the different cavity designs

4.2.2 The results of the calculations using the PTB software

At PTB the emissivity of the blackbody cavities was determined using a Monte Carlo simulation basing on the inverse ray-tracing method. Full details of the procedure are given in reference 7 in the PTB measurement report. Briefly, a number of photons is inserted into the cavity considering a given optical geometry. The path of the photons is traced by assuming diffuse reflection at the cavity walls with the emissivity ε as probability of absorption. The path of the photon is traced until it is absorbed or re-emitted from the cavity. The isothermal absorptivity, and hence the emissivity, of the cavity is then the ratio of the absorbed to the inserted number of photons.

In case of a non-homogeneous temperature distribution the same procedure is used. However, the absorbed photon is weighted with the spectral radiance according Planck's law and the temperature of the location of absorption. Applying the Helmholtz reciprocity principle the location of absorption can be seen as the origin of an emitted photon. The spectral radiance emitted by the cavity is then the average of all emitted photons weighted with the respective spectral radiance. The actual non-isothermal emissivity is then the ratio of the average spectral radiance emitted by the non-isothermal cavity to the spectral radiance of an ideal blackbody at the reference temperature, in this case the temperature of the bottom of the cavity. For the calculation of the non-isothermal emissivity it is assumed that the whole of the bottom of the cavity is at the same temperature and the temperature gradient is only along the cylindrical part of the cavity. The program does not allow for the calculation of cavities with re-entrant cones. Therefore, calculations were performed only for the designs B and C of the blackbody cavity.

Cavity Type	ε_{iso}	$U(\varepsilon_{iso})$ (k=2)	ε_{noniso}	$U(\varepsilon_{noniso})$ (k=2)
B-1	0.99937	0.00002	0.99729	0.00002
B-2	0.99995	0.00002	0.99875	0.00002
B-3	0.99686	0.00002	0.99380	0.00002
B-4	0.99859	0.00002	0.99539	0.00002

Table 92: **Results for the emissivity calculation for the cavity of design B**

Cavity	ε_{iso}	$U(\varepsilon_{iso})$ (k=2)	ε_{noniso}	$U(\varepsilon_{noniso})$ (k=2)
C-1	0.99951	0.00002	0.99782	0.00002
C-2	0.99997	0.00002	0.99930	0.00002
C-3	0.99734	0.00002	0.99610	0.00002
C-4	0.99880	0.00002	0.99745	0.00002

Table 93: **Results for the emissivity calculation for the cavity of design C**

The relative uncertainty (k=2) of the calculation is $2\cdot10^{-5}$ as described in reference 8 of the PTB measurement report.

4.2.3 The results of the calculations using the CEM software

The calculations at CEM were performed using the STEEP 3 software from VIRIAL INC, which uses the Monte Carlo method to evaluate the emissivity of the cavity. The following assumptions were made during the calculations:

(i) The thermometer was focused in the cavity aperture;

(ii) The distance between radiation thermometer objective and cavity aperture d = 700 mm;

(iii) The diameter of the radiation thermometer objective Φ_{ort} = 48 mm;

(iv) The bottom cone is at a uniform temperature;

(v) The surface of aperture wall is at a uniform temperature.

The results of the calculations are given in the following Table.

Design	L1 / mm	D1 / mm	A1 / mm	Wall emissivity	Gradient	Emissivity
A-1	97	7	3	0.92	Isothermal	0.99998
A-1	97	7	3	0.92	10 °C	0.99961
A-2	27	3	3	0.92	Isothermal	0.99978
A-2	27	3	3	0.92	10 °C	0.99910
B-1	27	3	3	0.80	Isothermal	0.99939
B-1	27	3	3	0.80	10°C	0.99807
B-2	97	7	3	0.80	Isothermal	0.99994
B-2	97	7	3	0.80	10 °C	0.99901
B-3	322	75	75	0.80	Isothermal	0.99719
B-3	322	75	75	0.80	10 °C	0.99487
B-4	322	75	50	0.80	Isothermal	0.99873
B-4	322	75	50	0.80	10 °C	0.99626
C-1	27	3	3	0.80	Isothermal	0.99957
C-1	27	3	3	0.80	10 °C	0.99895
C-2	97	7	3	0.80	Isothermal	0.99996
C-2	97	7	3	0.80	10 °C	0.99940
C-3	322	75	75	0.80	Isothermal	0.99804
C-3	322	75	75	0.80	10 °C	0.99719
C-4	322	75	50	0.80	Isothermal	0.99911
C-4	322	75	50	0.80	10 °C	0.99815

Table 94: **Results for the CEM emissivity calculations**

Uncertainties for the calculation of the emissivity using the CEM software

DESIGN CAVITY	**Montecarlo computation**								
	e_{iso}	e_{Niso}	$u_{r\ random}$	$u_{s\ systematic\ iso}$	$u_{s\ systematic\ Nisc}$	$U_{c\ iso}$	$U_{c\ Niso}$	$U(k=2)$ iso	$U(k=2)$ N iso
A-1	0.999980	0.999609	0.0001	0.000001	0.000005	0.000100	0.000100	0.000200	0.000200
A-2	0.999775	0.999099	0.0001	0.000005	0.000005	0.000100	0.000100	0.000200	0.000200
B-1	0.999385	0.998074	0.0001	0.000005	0.000010	0.000100	0.000100	0.000200	0.000201
B-2	0.999941	0.999014	0.0001	0.000001	0.000005	0.000100	0.000100	0.000200	0.000200
B-3	0.997192	0.994874	0.0001	0.000010	0.000010	0.000100	0.000100	0.000201	0.000201
B-4	0.998729	0.996260	0.0001	0.000010	0.000010	0.000100	0.000100	0.000201	0.000201
C-1	0.999570	0.998947	0.0001	0.000005	0.000010	0.000100	0.000100	0.000200	0.000201
C-2	0.999956	0.999400	0.0001	0.000001	0.000005	0.000100	0.000100	0.000200	0.000200
C-3	0.998042	0.997185	0.0001	0.000010	0.000010	0.000100	0.000100	0.000201	0.000201
C-4	0.999112	0.998152	0.0001	0.000005	0.000010	0.000100	0.000100	0.000200	0.000201

4.2.4 The results of the calculations using the UME software

The emissivity calculations at UME were performed using a software program supplied by IMGC to UME. The program is not designed for cavities of design A. Information about the calculation procedure is given in the UME measurement report. The values presented in Table 95 below are the integrated emissivity values assuming a thermometer aperture diameter of 39 mm and working distance of 700mm. The k = 2 uncertainties are also given in the Table.

	Isothermal		Non-isothermal	
	Emissivity	U	Emissivity	U
B1	0.99310	0.00366	0.94192	0.03312
B2	0.99999	$<10^{-5}$	0.98336	0.00770
B3	0.98000	0.00770	0.92176	0.03433
B4	0.99938	0.00024	0.97704	0.01008
C1	0.99308	0.00310	0.94187	0.02873
C2	0.99999	$<10^{-5}$	0.98332	0.00609
C3	0.97988	0.00523	0.92154	0.02619
C4	0.99918	0.00021	0.97656	0.00783

Table 95– the results of the emissivity calculations using the software used at UME

4.2.5 The results of the calculations using the INM software

No emissivity calculations were performed at INM.

4.2.6 The results of the calculations using the IMGC software

The emissivity values were calculated using software developed at IMGC. The results of the calculations are given in Table 96 below. Cavities of design A are not used at IMGC and the software could not be used to calculate the emissivity for this design.

Two different “emissivity” values are presented in the table, namely effective emissivity and integrated emissivity. Effective emissivity is that of the base and is to be applied when a pyrometer is focused on the base wall of the cavity. Integrated emissivity, to be applied when a pyrometer is focused onto the aperture plane of the cavity, is calculated according to the geometrical characteristics of LP3, i.e., aperture of Ø39 mm at a working distance of 700 mm.

The computational software developed at IMGC is based on the analytical solution of the integral equations system proposed by Bedford and Ma (reference 4 in the IMGC measurement report). Different versions of the software have been developed to be operated with different computer systems and different programming languages. The estimate for the related total combined uncertainty (k = 2) of the emissivity is 0.0001.

Design	L2	D2	A2	Isothermal Cavity Emissivity Effective	Isothermal Cavity Emissivity Integrated	Non-isothermal Cavity Emissivity Effective	Non-isothermal Cavity Emissivity Integrated
B-1	27	3	3	0.99940	0.99308	0.99788	0.94191
B-2	97	7	3	0.99995	0.99999	0.99891	0.98321
B-3	322	75	75	0.99728	0.98000	0.99441	0.92175
B-4	322	75	50	0.99876	0.99937	0.99574	0.97681
Design	**L3**	**D3**	**A3**	Isothermal Cavity Emissivity **Effective**	Isothermal Cavity Emissivity **Integrated**	Non-isothermal Cavity Emissivity **Effective**	Non-isothermal Cavity Emissivity **Integrated**
C-1	27	3	3	0.99962	0.99307	0.99902	0.94186
C-2	97	7	3	0.99997	0.99999	0.99955	0.98311
C-3	322	75	75	0.99828	0.97988	0.99722	0.92154
C-4	322	75	50	0.99921	0.99917	0.99807	0.97630

Table 96 – the results of the emissivity calculations using the software at IMGC

4.3 Analysis of the results of the emissivity calculations

For ease of comparison, Tables 97 and 98 and Figures 48 and 49 show all the emissivity values together.

Cavity design	NPL	PTB	CEM	UME	IMGC effective	IMGC integrated
A-1	0.99998	-	0.99998	-	-	-
A-2	0.99978	-	0.99978	-	-	-
B-1	0.99943	0.99937	0.99939	0.99310	0.99940	0.99308
B-2	0.99996	0.99995	0.99994	0.99999	0.99995	0.99999
B-3	0.99729	0.99686	0.99719	0.98000	0.99728	0.98000
B-4	0.99878	0.99859	0.99873	0.99938	0.99876	0.99937
C-1	0.99963	0.99951	0.99957	0.99308	0.99962	0.99307
C-2	0.99997	0.99997	0.99996	0.99999	0.99997	0.99999
C-3	0.99799	0.99734	0.99804	0.97988	0.99828	0.97988
C-4	0.99909	0.99880	0.99911	0.99918	0.99921	0.99917

Table 97 - the results of all the calculations for the isothermal cavities

Cavity design	NPL	PTB	CEM	UME	IMGC effective	IMGC integrated
A-1	0.99982	-	0.99961	-	-	-
A-2	0.99946	-	0.99910	-	-	-
B-1	0.99888	0.99729	0.99807	0.94192	0.99788	0.94191
B-2	0.99967	0.99875	0.99901	0.98336	0.99891	0.98321
B-3	0.99582	0.99380	0.99487	0.92176	0.99441	0.92175
B-4	0.99720	0.99539	0.99626	0.97704	0.99574	0.97681
C-1	0.99932	0.99782	0.99895	0.94187	0.99902	0.94186
C-2	0.99980	0.99930	0.99940	0.98332	0.99955	0.98311
C-3	0.99727	0.99610	0.99719	0.92154	0.99722	0.92154
C-4	0.99829	0.99745	0.99815	0.97656	0.99807	0.97630

Table 98 - the results of all the calculations for the non-isothermal cavities

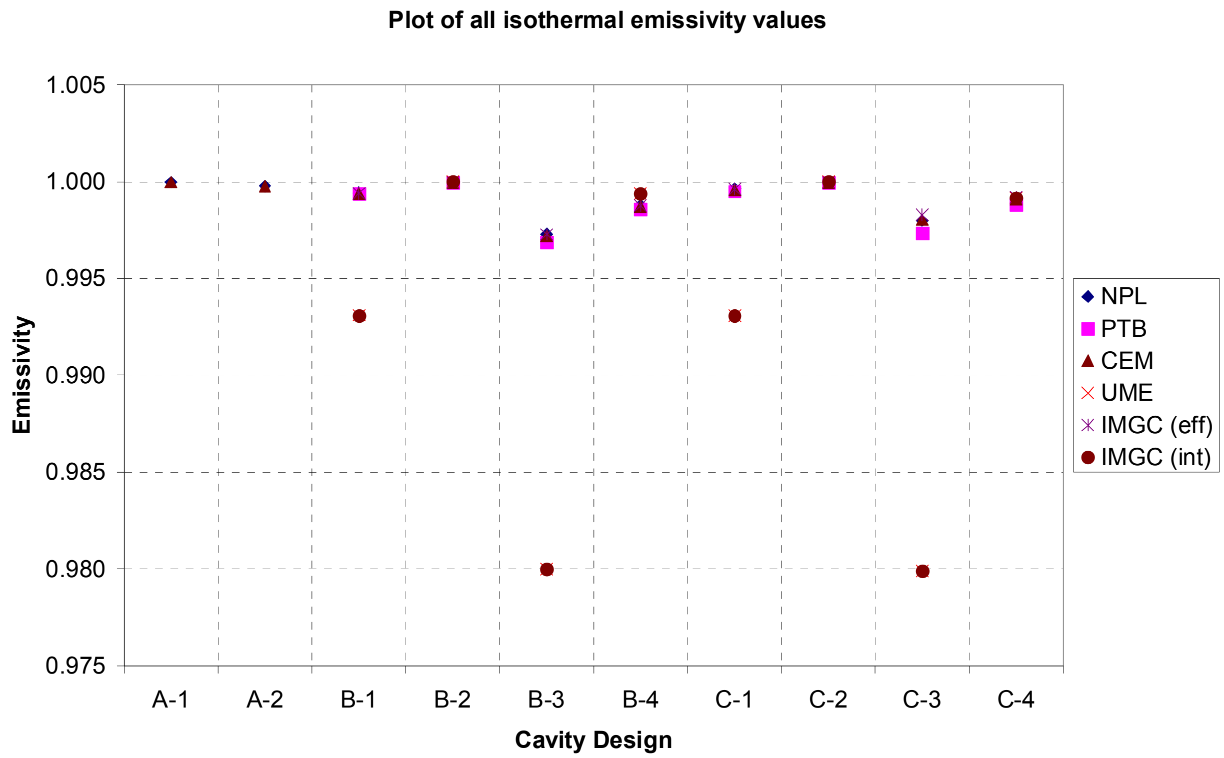


Figure 48 – plot of all the isothermal emissivity values

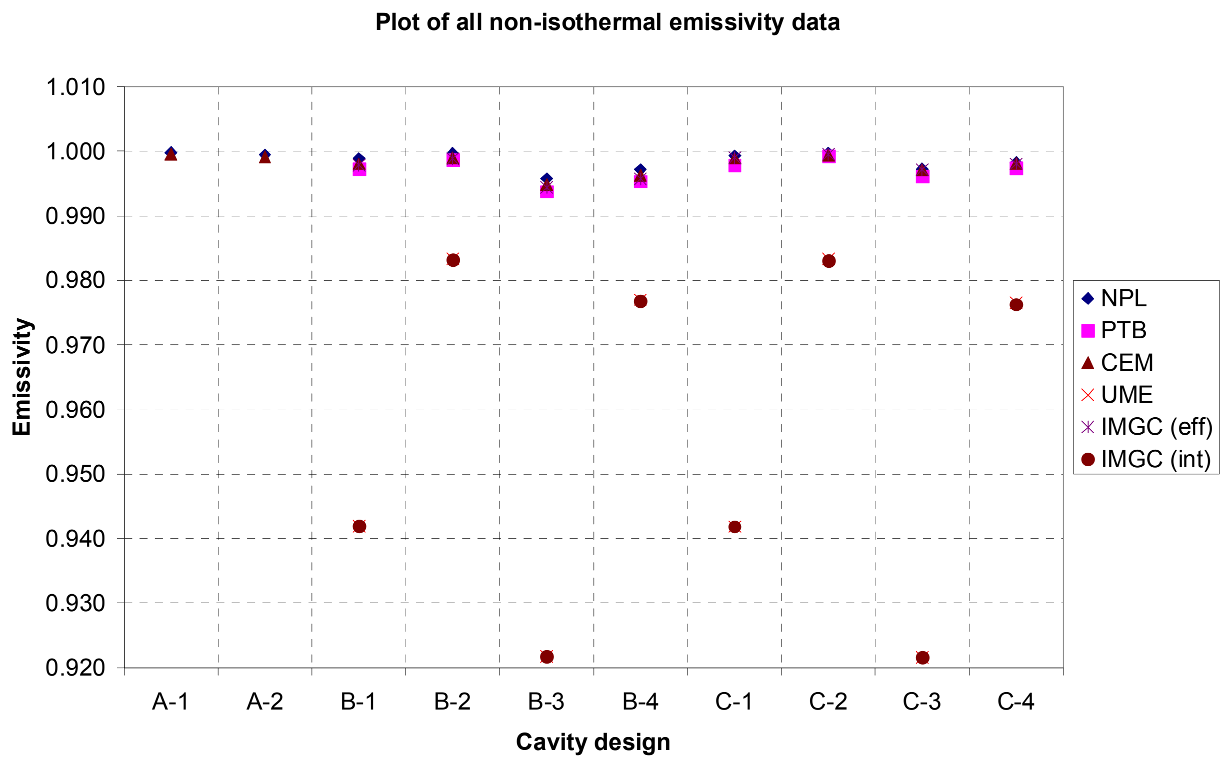


Figure 49 – plot of all the non-isothermal emissivity values

Three participants (NPL, PTB and IMGC) had calculated the effective emissivity of the cavities (i.e. assuming that a radiation thermometer was viewing the base of the cavity) and three (CEM, UME and IMGC) the integrated emissivity (i.e. in the aperture plane of the cavity). The data sets were therefore split into two groups and the weighted mean, arithmetic mean and median calculated for each group in order to select the most suitable to be the comparison reference value (Tables 99 to 102). Only NPL and CEM had calculated the emissivities for cavity designs A-1 and A-2, and NPL had calculated the effective emissivity whereas CEM had calculated the integrated emissivity. The results for cavity design A therefore had to be excluded from the subsequent data analysis, but see the note in the discussion.

Cavity design	Arithmetic mean emissivity value	Weighted mean emissivity value	Median emissivity value
B-1	0.99940	0.99938	0.99940
B-2	0.99995	0.99995	0.99995
B-3	0.99714	0.99688	0.99728
B-4	0.99871	0.99860	0.99876
C-1	0.99959	0.99952	0.99962
C-2	0.99997	0.99997	0.99997
C-3	0.99787	0.99738	0.99799
C-4	0.99903	0.99882	0.99909

Table 99 – the means and median values for the isothermal effective emissivity

Cavity design	Arithmetic mean emissivity value	Weighted mean emissivity value	Median emissivity value
B-1	0.99519	0.99434	0.99310
B-2	0.99997	0.99999	0.99999
B-3	0.98573	0.98341	0.98000
B-4	0.99916	0.99926	0.99937
C-1	0.99524	0.99437	0.99308
C-2	0.99998	0.99999	0.99999
C-3	0.98593	0.98348	0.97988
C-4	0.99915	0.99916	0.99917

Table 100 – the means and median values for the isothermal integrated emissivity

Cavity design	Arithmetic mean emissivity value	Weighted mean emissivity value	Median emissivity value
B-1	0.99802	0.99733	0.99788
B-2	0.99911	0.99884	0.99891
B-3	0.99468	0.99383	0.99441
B-4	0.99611	0.99541	0.99574
C-1	0.99872	0.99787	0.99902
C-2	0.99955	0.99932	0.99955
C-3	0.99686	0.99614	0.99722
C-4	0.99794	0.99747	0.99807

Table 101 – the means and median values for the non-isothermal effective emissivity

Cavity design	Arithmetic mean emissivity value	Weighted mean emissivity value	Median emissivity value
B-1	0.96063	0.95305	0.94192
B-2	0.98853	0.98637	0.98336
B-3	0.94613	0.93626	0.92176
B-4	0.98337	0.98067	0.97704
C-1	0.96089	0.95319	0.94187
C-2	0.98861	0.98637	0.98332
C-3	0.94676	0.93655	0.92154
C-4	0.98367	0.98063	0.97656

Table 102 – the means and median values for the non-isothermal integrated emissivity

Tables 103 to 114 and Figures 50 to 61 show the differences between the values from each participant and the arithmetic mean, weighted mean and median values for both the isothermal and the non-isothermal cavities. For comparison of the three effective emissivity data sets, the mean value was chosen to be the reference value. Since the reference value was simply being used as a tool to compare the results from the participants, no uncertainty was assigned to it. The QDE_{95} and DOE values for each pair of participants for each cavity design were also calculated (Tables 196 to 203 and 212 to 219 in Appendix 7, with accompanying plots showing the differences from the median). The QDE_{95} values were calculated from the equation:

$$QDE_{95(i,j)} = \left|\Delta\varepsilon\right|_{(i,j)} + \left\{1.645 + 0.3295\exp\left(\frac{-4.05\left|\Delta\varepsilon\right|_{(i,j)}}{u_{(i,j)}}\right)\right\} u_{(i,j)}$$

For the integrated emissivity values, there is a strong correlation between two out of the three data sets: UME and IMGC had used the same software (see discussion) and therefore the results were the same or very close. To aid comparison of all the data, the mean of all three data sets was used as a reference value and the QDE_{95} and DOE values calculated as above (see Tables 204 to 211 and 220 to 227 in Appendix 7, with the accompanying plots). However, this is for completeness and illustrative purposes only and the results are not felt to be particularly meaningful.

Cavity design	NPL value	Difference (NPL - mean)	Difference (NPL – weighted mean)	Difference (NPL – median)
B-1	0.99943	0.00003	0.00005	0.00003
B-2	0.99996	0.00001	0.00001	0.00001
B-3	0.99729	0.00015	0.00041	0.00001
B-4	0.99878	0.00007	0.00018	0.00002
C-1	0.99963	0.00004	0.00011	0.00001
C-2	0.99997	0.00000	0.00000	0.00000
C-3	0.99799	0.00012	0.00061	0.00000
C-4	0.99909	0.00006	0.00027	0.00000

Table 103 – difference between NPL results and average isothermal effective emissivity values

Cavity design	NPL value	Difference (NPL - mean)	Difference (NPL – weighted mean)	Difference (NPL – median)
B-1	0.99888	0.00086	0.00155	0.00100
B-2	0.99967	0.00056	0.00083	0.00076
B-3	0.99582	0.00114	0.00199	0.00141
B-4	0.99720	0.00109	0.00179	0.00146
C-1	0.99932	0.00060	0.00145	0.00030
C-2	0.99980	0.00025	0.00048	0.00025
C-3	0.99727	0.00041	0.00113	0.00005
C-4	0.99829	0.00035	0.00082	0.00022

Table 104 – difference between NPL results and average non-isothermal effective emissivity values

Cavity design	PTB value	Difference (PTB - mean)	Difference (PTB – weighted mean)	Difference (PTB – median)
B-1	0.99937	-0.00003	-0.00001	-0.00003
B-2	0.99995	0.00000	0.00000	0.00000
B-3	0.99686	-0.00028	-0.00002	-0.00042
B-4	0.99859	-0.00012	-0.00001	-0.00017
C-1	0.99951	-0.00008	-0.00001	-0.00011
C-2	0.99997	0.00000	0.00000	0.00000
C-3	0.99734	-0.00053	-0.00004	-0.00065
C-4	0.99880	-0.00023	-0.00002	-0.00029

Table 105 - difference between PTB results and average isothermal effective emissivity values

Cavity design	PTB value	Difference (PTB - mean)	Difference (PTB – weighted mean)	Difference (PTB – median)
B-1	0.99729	-0.00073	-0.00004	-0.00059
B-2	0.99875	-0.00036	-0.00009	-0.00016
B-3	0.99380	-0.00088	-0.00003	-0.00061
B-4	0.99539	-0.00072	-0.00002	-0.00035
C-1	0.99782	-0.00090	-0.00005	-0.00120
C-2	0.99930	-0.00025	-0.00002	-0.00025
C-3	0.99610	-0.00076	-0.00004	-0.00112
C-4	0.99745	-0.00049	-0.00002	-0.00062

Table 106 - difference between PTB results and average non-isothermal effective emissivity values

Cavity design	CEM value	Difference (CEM - mean)	Difference (CEM – weighted mean)	Difference (CEM – median)
B-1	0.99939	0.00420	0.00505	0.00629
B-2	0.99994	-0.00003	-0.00005	-0.00005
B-3	0.99719	0.01146	0.01378	0.01719
B-4	0.99873	-0.00043	-0.00053	-0.00064
C-1	0.99957	0.00433	0.00520	0.00649
C-2	0.99996	-0.00002	-0.00003	-0.00003
C-3	0.99804	0.01211	0.01456	0.01816
C-4	0.99911	-0.00004	-0.00005	-0.00006

Table 107 - difference between CEM results and average isothermal integrated emissivity values

Cavity design	CEM value	Difference (CEM - mean)	Difference (CEM – weighted mean)	Difference (CEM – median)
B-1	0.99807	0.03744	0.04502	0.05615
B-2	0.99901	0.01048	0.01264	0.01565
B-3	0.99487	0.04874	0.05861	0.07311
B-4	0.99626	0.01289	0.01559	0.01922
C-1	0.99895	0.03806	0.04576	0.05708
C-2	0.99940	0.01079	0.01303	0.01608
C-3	0.99719	0.05043	0.06064	0.07565
C-4	0.99815	0.01448	0.01752	0.02159

Table 108 - difference between CEM results and average non-isothermal integrated emissivity values

Cavity design	UME value	Difference (UME - mean)	Difference (UME – weighted mean)	Difference (UME – median)
B-1	0.99310	-0.00209	-0.00124	0.00000
B-2	0.99999	0.00002	0.00000	0.00000
B-3	0.98000	-0.00573	-0.00341	0.00000
B-4	0.99938	0.00022	0.00012	0.00001
C-1	0.99308	-0.00216	-0.00129	0.00000
C-2	0.99999	0.00001	0.00000	0.00000
C-3	0.97988	-0.00605	-0.00360	0.00000
C-4	0.99918	0.00003	0.00002	0.00001

Table 109 - difference between UME results and average isothermal integrated emissivity values

Cavity design	UME value	Difference (UME - mean)	Difference (UME – weighted mean)	Difference (UME – median)
B-1	0.94192	-0.01871	-0.01113	0.00000
B-2	0.98336	-0.00517	-0.00301	0.00000
B-3	0.92176	-0.02437	-0.01450	0.00000
B-4	0.97704	-0.00633	-0.00363	0.00000
C-1	0.94187	-0.01902	-0.01132	0.00000
C-2	0.98332	-0.00529	-0.00305	0.00000
C-3	0.92154	-0.02522	-0.01501	0.00000
C-4	0.97656	-0.00711	-0.00407	0.00000

Table 110 - difference between UME results and average non-isothermal integrated emissivity values

Cavity design	IMGC value	Difference (IMGC - mean)	Difference (IMGC – weighted mean)	Difference (IMGC – median)
B-1	0.99940	0.00000	0.00002	0.00000
B-2	0.99995	0.00000	0.00000	0.00000
B-3	0.99728	0.00014	0.00040	0.00000
B-4	0.99876	0.00005	0.00016	0.00000
C-1	0.99962	0.00003	0.00010	0.00000
C-2	0.99997	0.00000	0.00000	0.00000
C-3	0.99828	0.00041	0.00090	0.00029
C-4	0.99921	0.00018	0.00039	0.00012

Table 111 - difference between IMGC effective emissivity results and average isothermal effective emissivity values

Cavity design	IMGC value	Difference (IMGC - mean)	Difference (IMGC – weighted mean)	Difference (IMGC – median)
B-1	0.99788	-0.00014	0.00055	0.00000
B-2	0.99891	-0.00020	0.00007	0.00000
B-3	0.99441	-0.00027	0.00058	0.00000
B-4	0.99574	-0.00037	0.00033	0.00000
C-1	0.99902	0.00030	0.00115	0.00000
C-2	0.99955	0.00000	0.00023	0.00000
C-3	0.99722	0.00036	0.00108	0.00000
C-4	0.99807	0.00013	0.00060	0.00000

Table 112 - difference between IMGC effective emissivity results and average non-isothermal effective emissivity values

Cavity design	IMGC value	Difference (IMGC - mean)	Difference (IMGC – weighted mean)	Difference (IMGC – median)
B-1	0.99308	-0.00211	-0.00126	-0.00002
B-2	0.99999	0.00002	0.00000	0.00000
B-3	0.98000	-0.00573	-0.00341	0.00000
B-4	0.99937	0.00021	0.00011	0.00000
C-1	0.99307	-0.00217	-0.00130	-0.00001
C-2	0.99999	0.00001	0.00000	0.00000
C-3	0.97988	-0.00605	-0.00360	0.00000
C-4	0.99917	0.00002	0.00001	0.00000

Table 113 - difference between IMGC integrated emissivity results and average isothermal integrated emissivity values

Cavity design	IMGC value	Difference (IMGC - mean)	Difference (IMGC – weighted mean)	Difference (IMGC – median)
B-1	0.94191	-0.01872	-0.01114	-0.00001
B-2	0.98321	-0.00532	-0.00316	-0.00015
B-3	0.92175	-0.02438	-0.01451	-0.00001
B-4	0.97681	-0.00656	-0.00386	-0.00023
C-1	0.94186	-0.01903	-0.01133	-0.00001
C-2	0.98311	-0.00550	-0.00326	-0.00021
C-3	0.92154	-0.02522	-0.01501	0.00000
C-4	0.97630	-0.00737	-0.00433	-0.00026

Table 114 - difference between IMGC integrated emissivity results and average non-isothermal integrated emissivity values

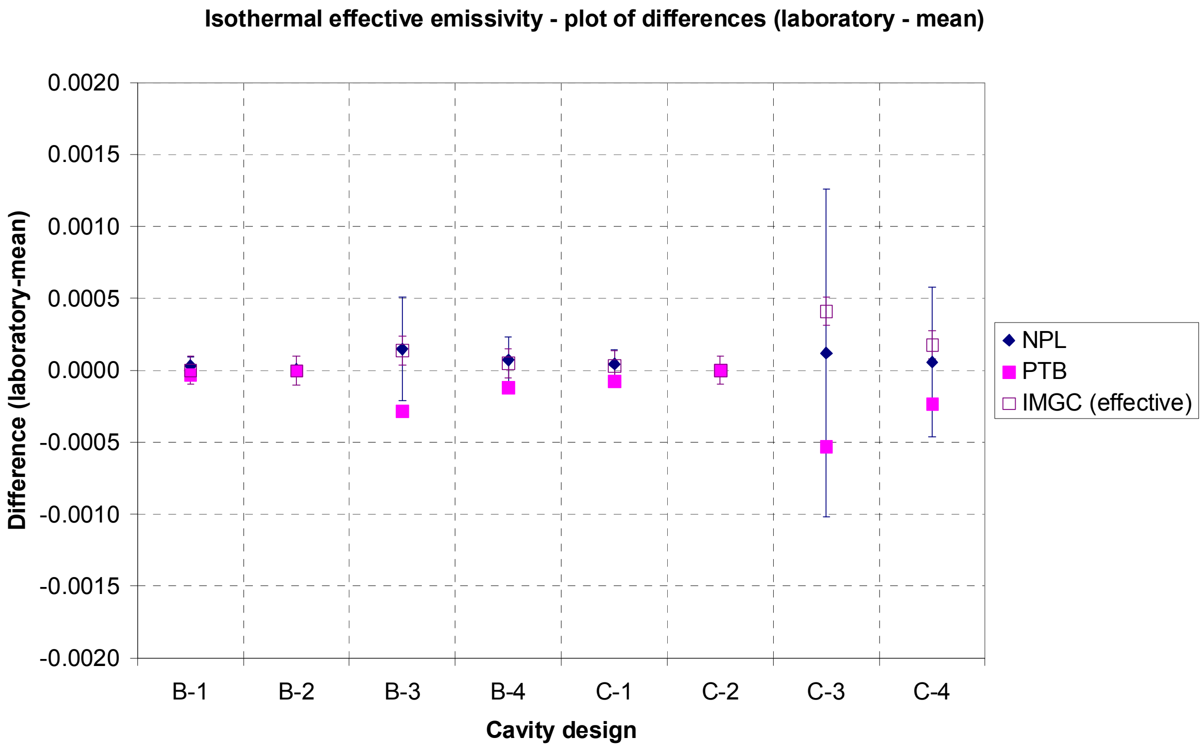


Figure 50 - plot of differences (laboratory – mean) for isothermal effective emissivity

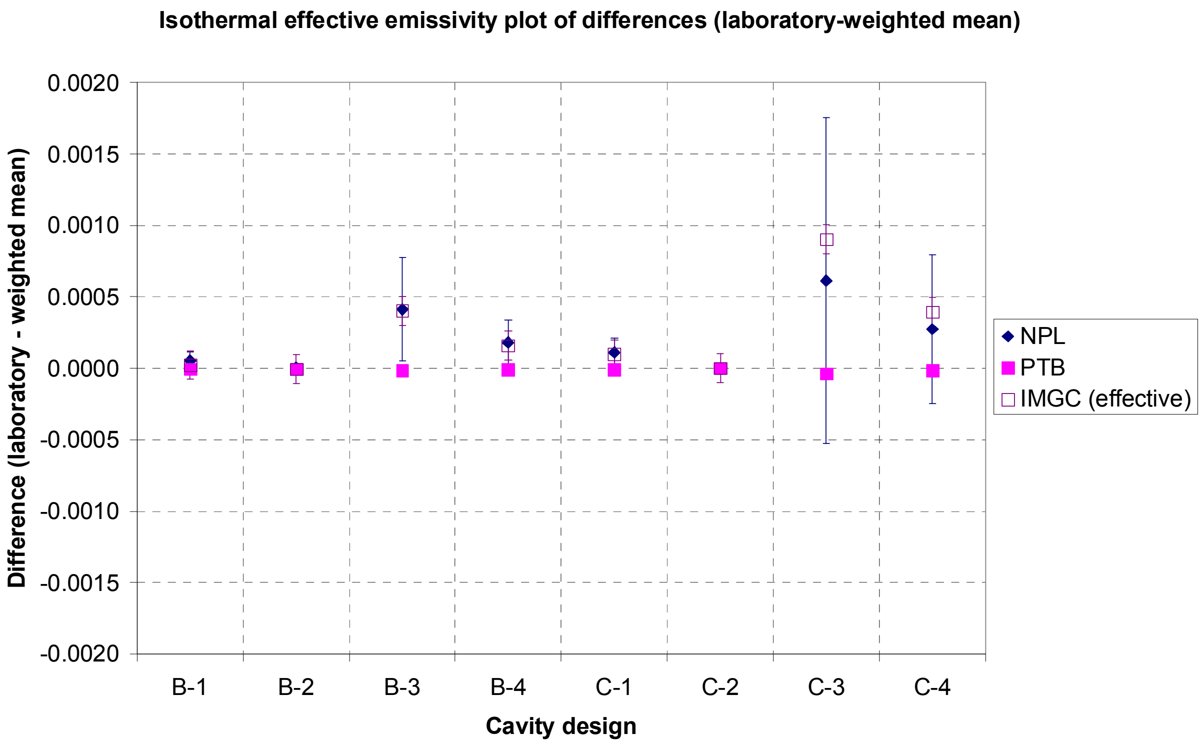


Figure 51 - plot of differences (laboratory – weighted mean) for isothermal effective emissivity

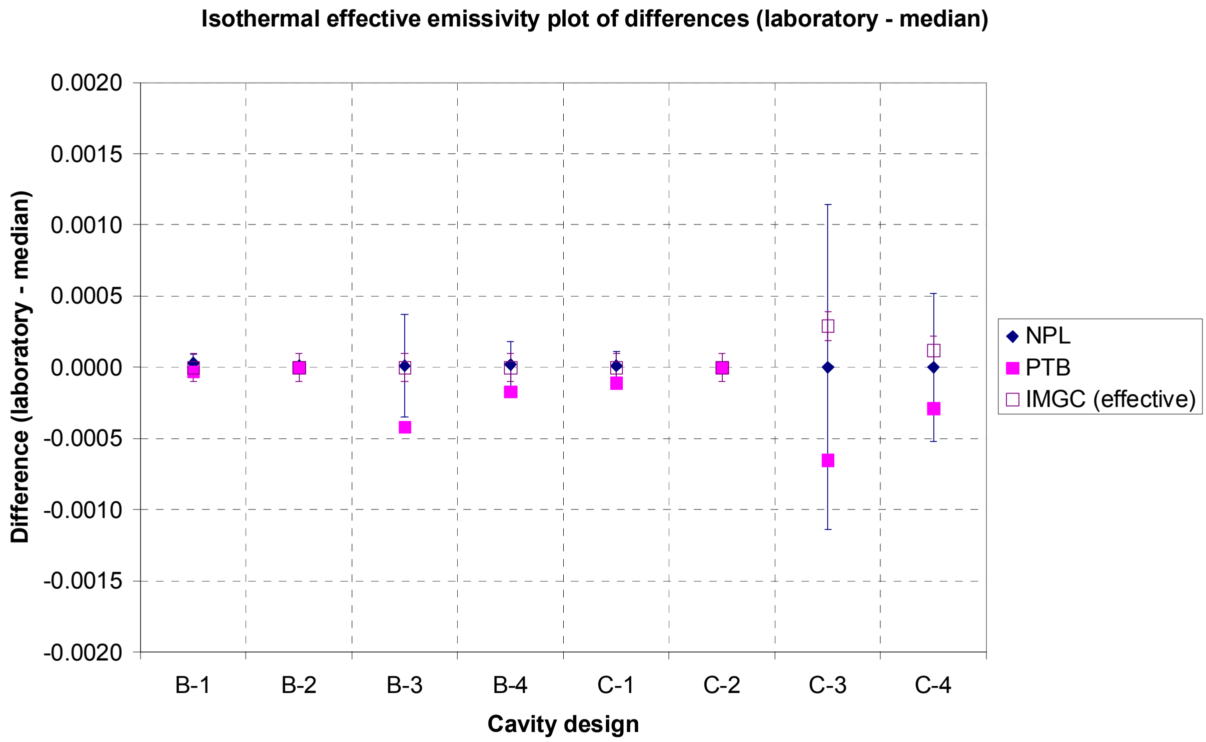


Figure 52 - plot of differences (laboratory – median) for isothermal effective emissivity

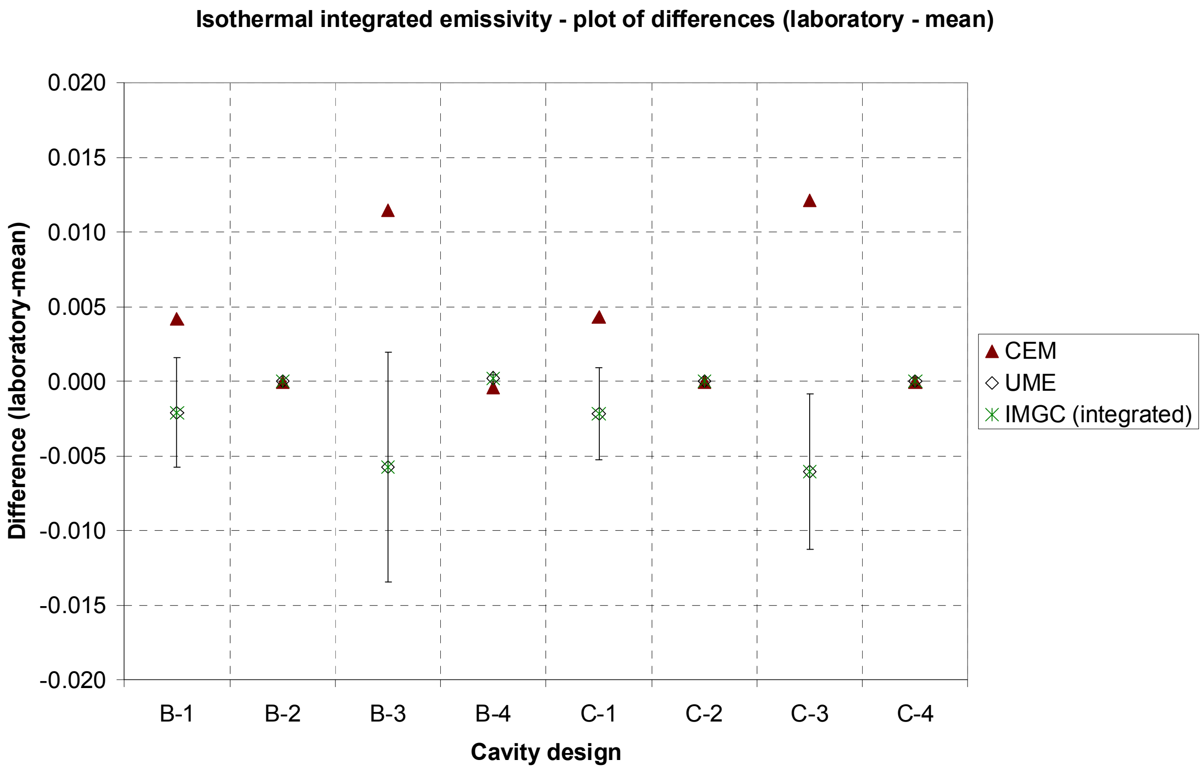


Figure 53 – plot of differences (laboratory – mean) for isothermal integrated emissivity

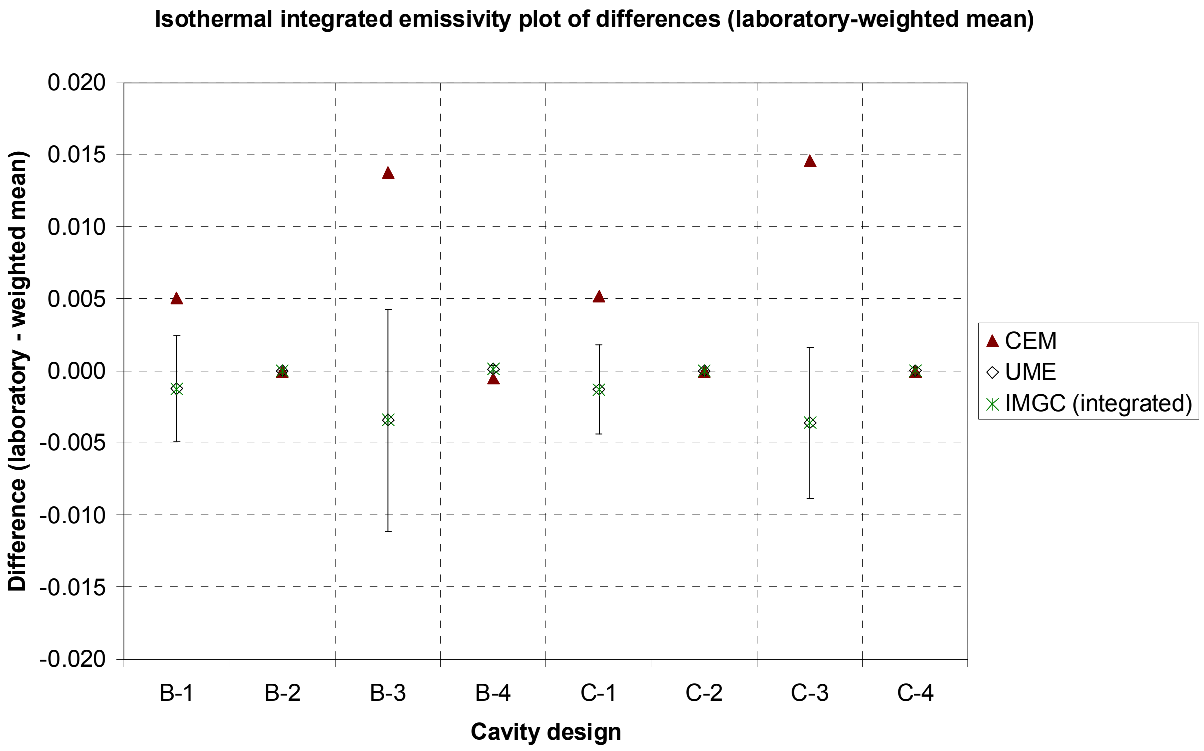


Figure 54 - plot of differences (laboratory–weighted mean) for isothermal integrated emissivity

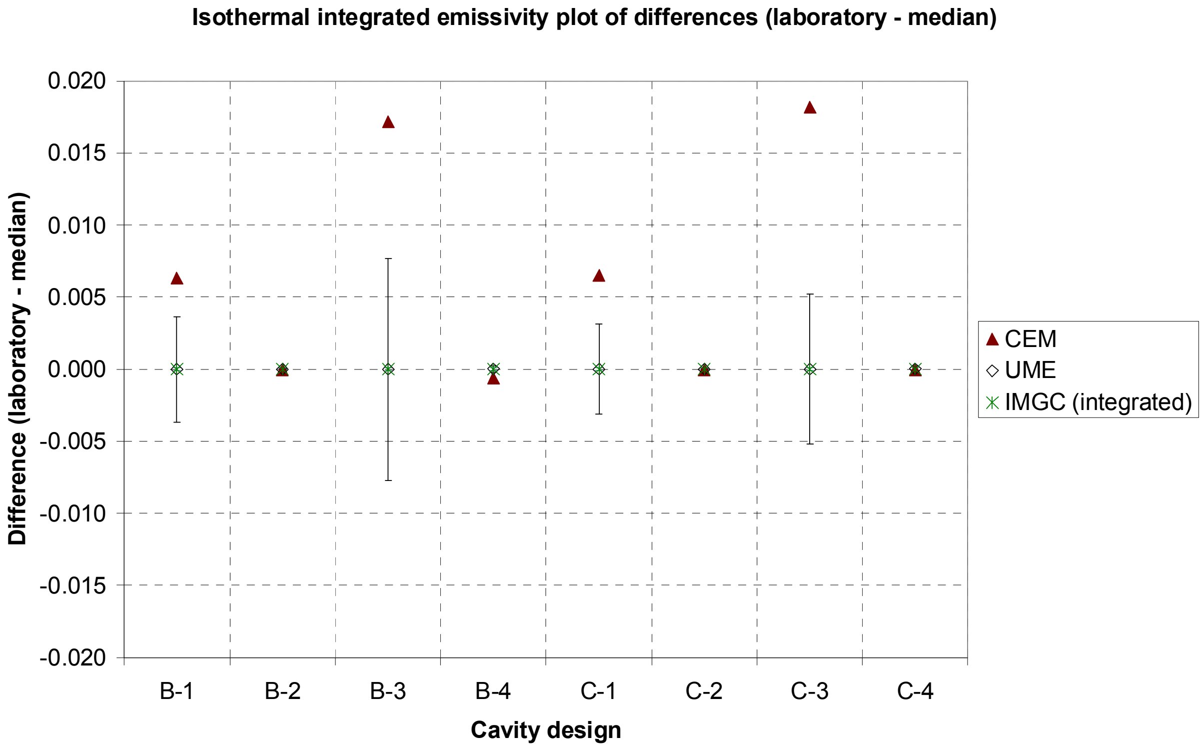


Figure 55 - plot of differences (laboratory – median) for isothermal integrated emissivity

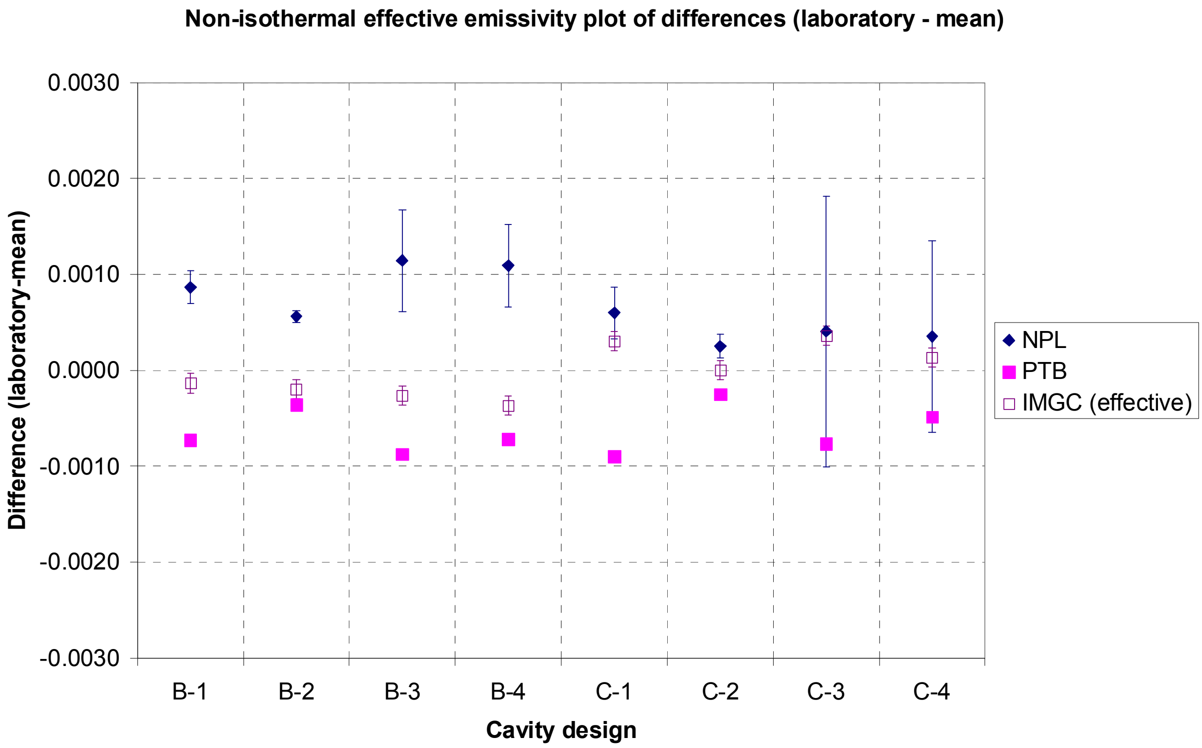


Figure 56 - plot of differences (laboratory – mean) for non-isothermal effective emissivity

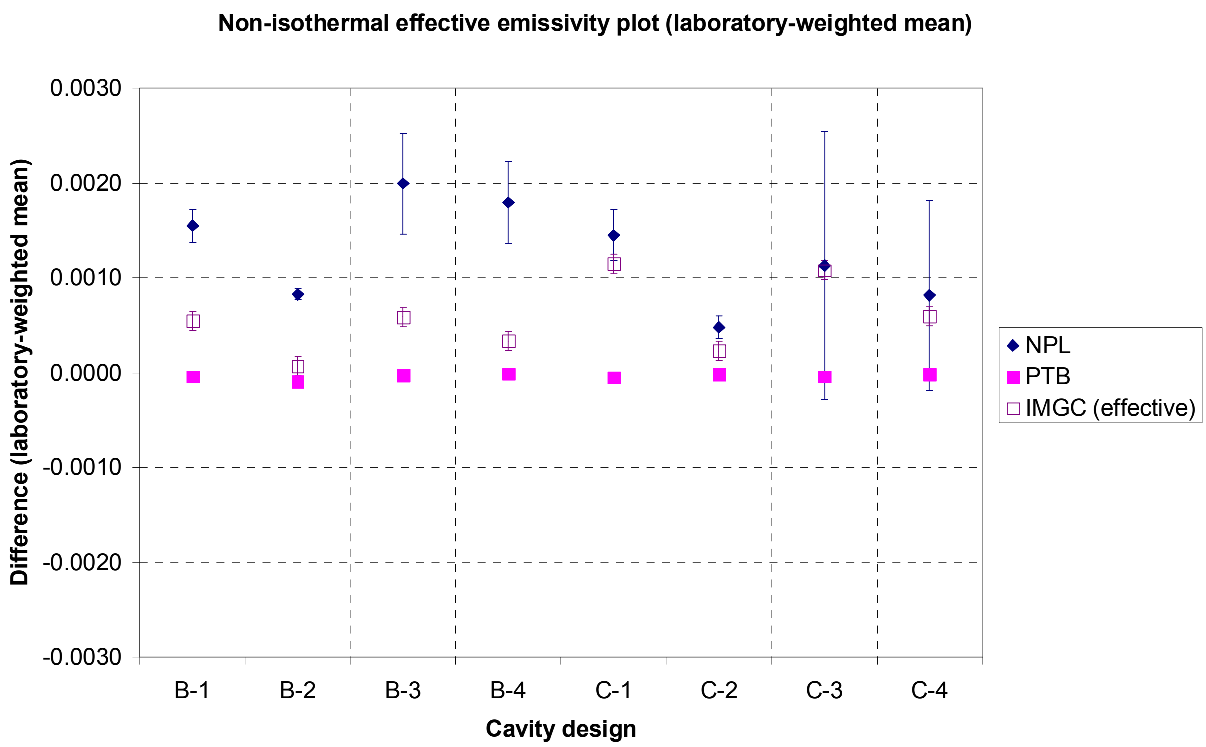


Figure 57 - plot of differences (laboratory – weighted mean) for non-isothermal effective emissivity

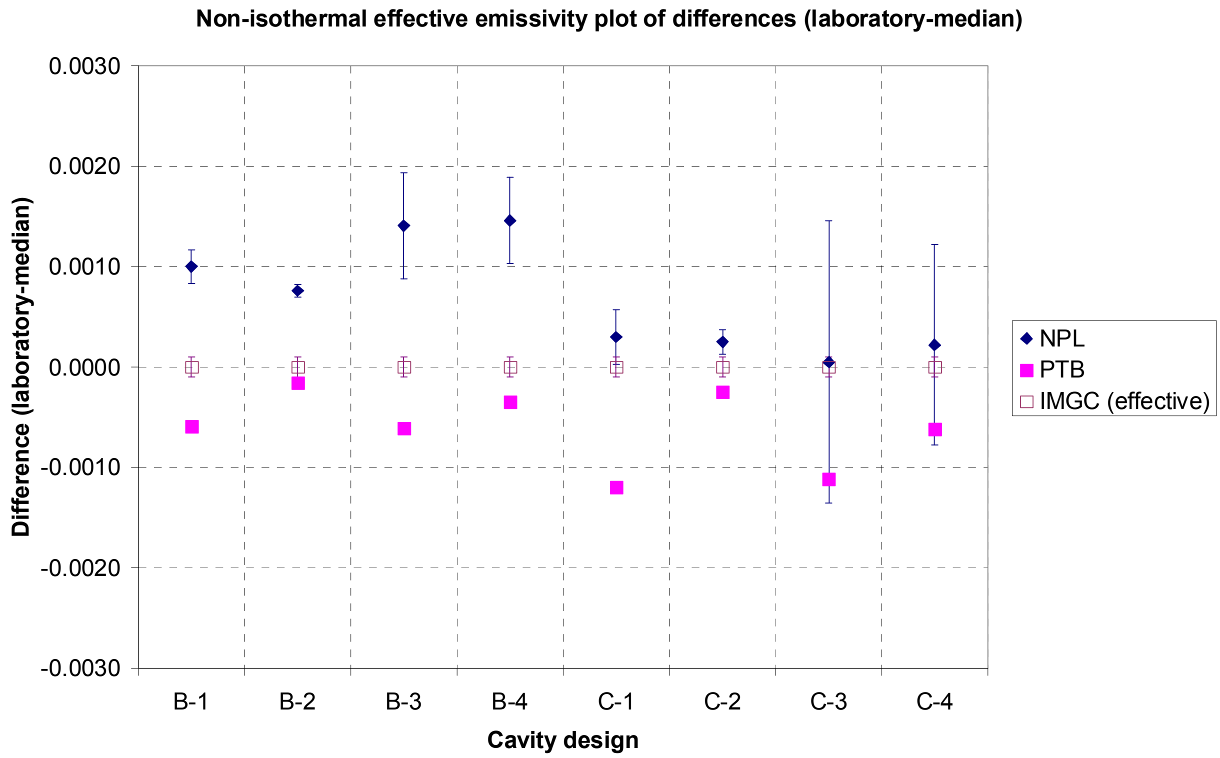


Figure 58 - plot of differences (laboratory – median) for non-isothermal effective emissivity

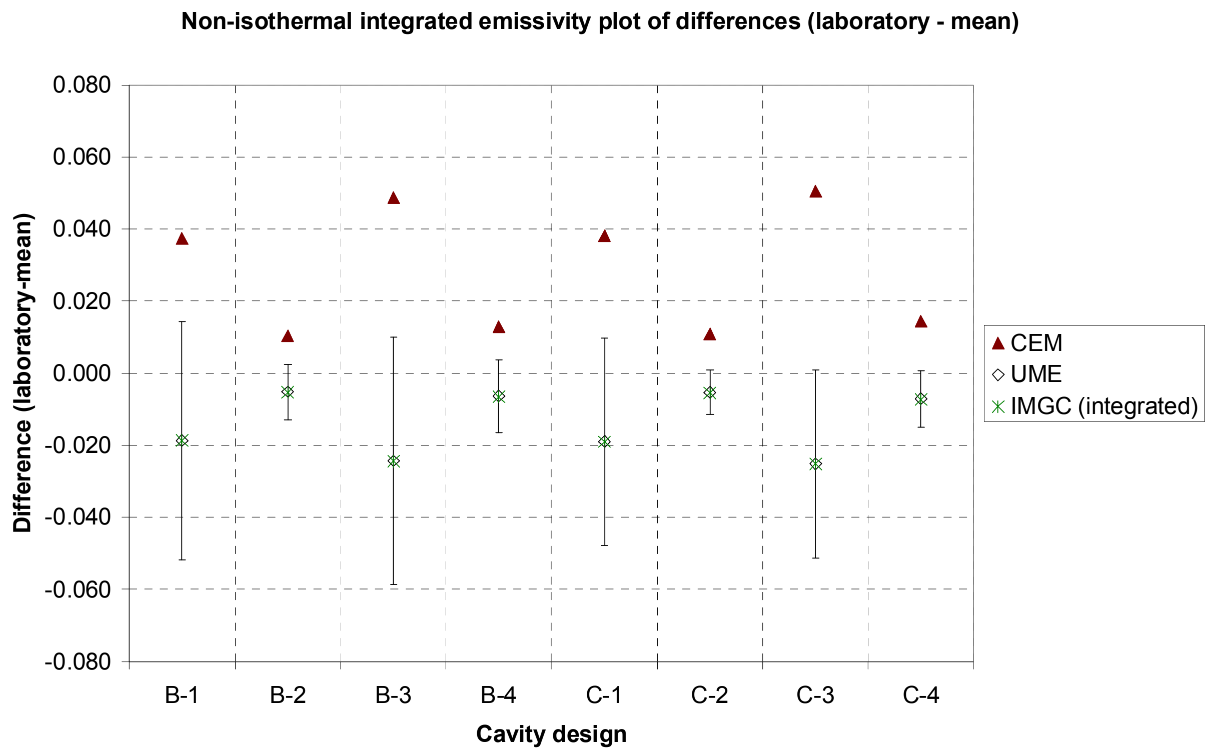


Figure 59 - plot of differences (laboratory – mean) for non-isothermal integrated emissivity

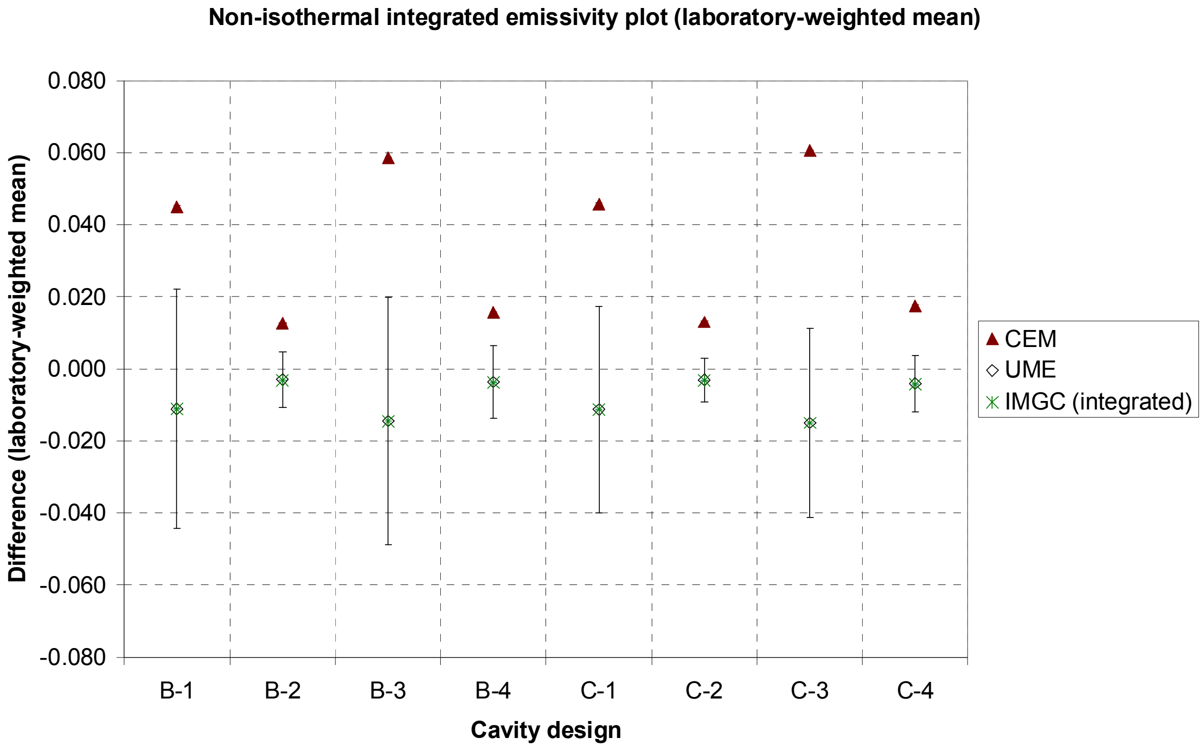


Figure 60 - plot of differences (laboratory – weighted mean) for non-isothermal integrated emissivity

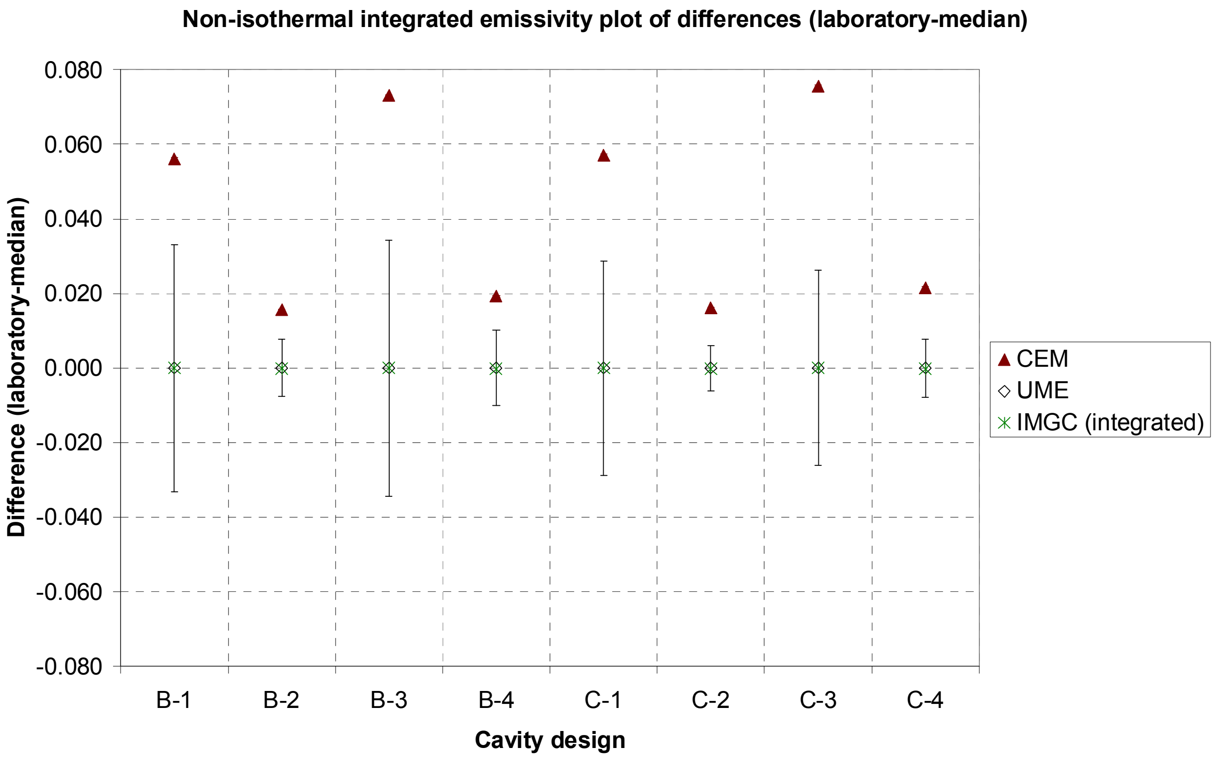


Figure 61 - plot of differences (laboratory – median) for non-isothermal integrated emissivity

4.4 Discussion of the emissivity results

From the plots and the results a number of points is evident.

For all cavity designs and for both the isothermal and non-isothermal cavities the integrated emissivity values from IMGC and UME are the same or in very close agreement. However, it is likely that the same software is used at both institutes so similar results would be expected. (It was subsequently confirmed that the same software was used).

It is interesting to note that the integrated emissivity values from UME and IMGC are often very different from the results of CEM, who also calculated the emissivity assuming that the radiation thermometer was focused on the plane of the aperture. The CEM results instead agree very well with the effective emissivity values calculated by the other participants (Tables 97 and 98).

Only NPL and CEM performed calculations for cavity designs A1 and A2. The results can be seen to be in very close agreement.

For the isothermal cavities that are of a good design, i.e. have a high emissivity (for example B1, B2, C1 and C2), all the effective emissivity results and the CEM integrated emissivity results are in good agreement. The integrated emissivity values from IMGC and UME are also in closer agreement to the effective emissivity values. For the isothermal cavities of a poorer design, especially for example B3, C3 and C4, there is much more variation in the results. This is especially true for cavity design C3, where there is a large spread in the results.

For the non-isothermal cavities there is a much wider variation in the effective emissivity values (Figures 56 to 61) and a lot of the results lie away from the reference value by more than the estimated uncertainties. Once again, the results for the cavities of a good design are in better agreement than those for the cavities of poorer design. There are also a couple of trends evident from the results: the NPL effective emissivity results are consistently higher than the PTB results.

The results show that the software used in each laboratory gives consistent results for well-designed, isothermal cavities (which make up the majority of those used for radiation thermometry). For cavities that are of poorer design and/or non-isothermal there are some discrepancies in the results obtained, which are often larger than the estimated uncertainties of the calculations.

5 Conclusions

The results in Sections 1 to 4 above show that, on the whole, that the results of the majority of the measurements made by participants agree within the combined measurement uncertainties. However, there are one or to issues that are apparent: in particular, there is a reasonably large spread in the values obtained for the limiting and mean effective wavelength of the LP3 and there are also large differences in the calculated emissivity values for some of the designs of cavity. These issues might require further investigation.

APPENDIX 1 – THE PROTOCOL FOR THE COMPARISON

PROTOCOL FOR THE EUROMET PROJECT 658 –

‘THE EXAMINATION OF BASE PARAMETERS FOR ITS-90

SCALE REALISATION IN RADIATION THERMOMETRY’

1. Organisation

The project will be coordinated by:

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3. Project end date

The project is due to be completed by October 2005

4. Circulation scheme

The two transfer thermometers will be circulated according to the following schedule:

Institute	Time periods
NPL	1 July 2003 to 30 September 2003
VSL	1 October 2003 to 30 November 2003
PTB	1 December 2003 to 28 February 2004
CEM	1 March 2004 to 30 April 2004
UME	1 May 2004 to 30 June 2004
BNM-INM/Cnam	1 July 2004 to 30 September 2005
IMGC	1 October 2004 to 30 November 2004

In the last week of each period the laboratory that is completing the measurements should arrange for the thermometers should be transferred to the next institute. The laboratory completing the measurements is also responsible for paying the transport costs for the transfer to the next institute. The institute receiving the thermometers should confirm to the coordinating laboratory by e-mail or fax that they have arrived safely. To make sure that the thermometers have not been damaged during transport, if possible a quick check should be made of the output of the thermometers when viewing a stable blackbody source at about 1000 °C (Ag point, Au point or variable temperature blackbody). A suitable working distance should be chosen, e.g. 700 mm. The results of the check, and the working distance, should also be e-mailed or faxed to the coordinator. At the end of the circulation IMGC should return the LP3 to PTB. The supplying laboratories should then confirm the performance of their instrument.

5. Transfer instruments

The two transfer thermometers are an IKE LP3, provided by PTB, and a VEGA TSP2.11 thermometer, provided by IMGC. Technical information about the thermometers is given in Appendix 1.

6. Initial measurements

6.1 Stabilisation: The stabilisation time for the thermometers is given in Appendix 1. It is recommended that the thermometers are left for at least 2 hours after switch-on before measurements are made to ensure that they are sufficiently stable. The thermometers should be left on for the duration of the measurements.

6.2 Lens cleaning Superficial dust should be blown off the front lens of the thermometers using clean air or other means, but otherwise the lens should NOT be cleaned. The protective lens caps should be placed on the front of each thermometer in-between measurements, and great care should be taken not to touch the front lens.

6.3 Positioning: The thermometers should be set up and aligned according to local procedures, with reference to the instruction manuals supplied with the thermometers.

7. Problems

Should any problems arise with the operation of the instruments, both the coordinator and the institute supplying the thermometer should be contacted.

8. Required measurements

The following gives information about the parameters to be measured for each thermometer. Each institute shall measure as many of the parameters as possible. Measurements should be made according to the usual method at each laboratory, but following the specific instructions given below. During the measurements of each of the parameters the ambient temperature (t_{amb}) and relative humidity (RH_{amb}) should be recorded.

Please note:

All the measurements with the **LP3** thermometer are to be made at a wavelength of **650 nm**.

All the measurements with the **VEGA** instrument are to be made at a wavelength of **900 nm**.

8.1 Size-of-source effect

The size-of-source effect (SSE) should be measured using the indirect method i.e. by obscuring the central portion of the field-of-view of the thermometer by means of a blackened disc or spot placed in front of the source.

Measurements should be made using spot sizes of **3.0 mm** diameter and **6.0 mm** diameter and all available apertures that are of a suitable diameter.

If a laboratory wishes additional measurements may be made using the direct method according to the local procedure.

The measurements with the **LP3** should be made at a wavelength of **650 nm** and at a working distance of **700 mm** from the source;

The measurements with the **VEGA** should be made at a wavelength of **900 nm** and at a working distance of **550 mm** from the source. Measurements should be made by firstly focussing the VEGA thermometer so that the target is in correct visual focus and then finding the position of optimum SSE by making small adjustments of the focus ring.

The results should be presented in the form of a table giving the SSE for each aperture size. The table should include columns for the following information: aperture size (mm), 'on spot' signal, 'off spot' signal, background signal, SSE, the individual uncertainty components in determining the SSE (u_1, u_2, u_3 ...), the total combined uncertainty $U_{SSE,}$ (t_{amb}) and (RH_{amb}).

If measurements have also been made using the direct method, a second table should give these results: aperture size (mm), signal, background signal, SSE, the individual uncertainty components in determining the SSE (u_1, u_2, u_3 ...), the total combined uncertainty $U_{SSE,}$ (t_{amb}) and (RH_{amb}).

8.2 Linearity

Linearity measurements should be made using the laboratory's usual local procedure, normally a radiance doubling method or a double-aperture technique, and covering as wide a range of signal levels as possible. The non-linearity (NL) should be calculated using the equation: $NL = 1 - [\{(S_1 - S_0) + (S_2 - S_0)\} / (S_{1+2} - S_0)]$ where S_0 is the background signal, S_1 is the first signal component, S_2 is the second signal component and S_{1+2} is the sum of the two signal components. The signals should be expressed in terms of photocurrent. The measurements of the **VEGA** thermometer should be made at a working distance of **550 mm** from the source; the measurements with the **LP3** should be made at a working distance of **670 mm** from the source.

The results should be presented in the form of a table giving the following information: S_0, S_1, S_2, S_{1+2}, NL, all the individual uncertainty components in determining the NL (u_1, u_2, u_3…), the total combined uncertainty, $U_{NL,}$ (t_{amb}) and (RH_{amb}).

8.3 Spectral responsivity / limiting effective wavelength

The spectral responsivity and the limiting effective wavelength should be determined, for each thermometer if possible, using local procedures. The limiting effective wavelength should be determined for a reference temperature of 1337.33 K. The methods used to determine the parameters should be clearly described.

Measurements should be made with the instruments at two different distances from the facility to investigate the sensitivity of the facility to distance. Measurements should be made as follows:

With the **LP3** measurements should be made at a wavelength of **650 nm** and at working distances of **670* mm** and **900* mm**;

With the **VEGA** thermometer measurements should be made at a wavelength of **900 nm** and at working distances of **550* mm** and **900* mm**.

*****(Note that if, due to the design of the facility, these distances are not practicable, two other distances may be chosen provided that they are significantly different. In this case, the chosen distances must be stated with the results).

The mean effective wavelength, $\overline{\lambda_{eff}}$, should also be calculated for the following temperatures: 1000 K, 1337 K, 1500 K, 2000 K, 2500 K, 3000 K and 3500 K.

The results of the spectral responsivity measurements should be presented in the form of a table or graph giving the spectral responsivity versus the wavelength. A second table should give the following information: limiting effective wavelength (nm), the individual uncertainty components in determining the spectral responsivity (u_1, u_2, u_3…), the individual components in determining the limiting effective wavelength (u_1, u_2, u_3…), the total combined uncertainty of the spectral responsivity measurements, U_{SR}, the total combined uncertainty for the limiting effective wavelength determination, $U_{\lambda eff}$, (t_{amb}) and (RH_{amb})

For the mean effective wavelength the results should be in the form of a table giving the following information: T (K), $\overline{\lambda_{eff}}$, the individual uncertainty components in determining $\overline{\lambda_{eff}}$ (u_1, u_2, u_3…) and the total combined uncertainty U$\overline{\lambda_{eff}}$.

8.4 Calculation of the emissivity of a selection of blackbody cavities

A selection of cavities of different designs is given in Appendix 2. The diffuse wall emissivity for each of the cavities is also given in Appendix 2. Using the software available at their institute participants should calculate, for each cavity,

a) the isothermal emissivity;
b) the non-isothermal emissivity, assuming a linear temperature gradient of 10 °C along the length of the cavity, with the rear of the cavity being hotter. For the calculation assume a temperature of 962 °C for the rear of the cavity and a wavelength of 0.9 µm.

Brief information should be given about any assumptions made during the calculations.

The results should be presented in the form of a table giving the calculated isothermal and non-isothermal emissivity of each of the cavity designs, the individual uncertainty components of the determination and the total combined uncertainty $U_{\varepsilon m}$.

9. Reporting of the results

The following information should be sent to the coordinator within one month of completing the measurements. Please supply both a paper copy and an electronic version.

9.1 Description of the equipment

All the equipment used for measuring each of the parameters should be described along with details of the measurement methods, calculations and any assumptions that have been made. The electronic version should be in the form of a Word document.

9.2 Results

The results should be supplied in the form of an Excel spreadsheet / workbook and presented as described in Section 8.

9.3. Uncertainties

The individual uncertainty components for each of the measured parameters should be listed along with the total combined uncertainty of the measurements. All uncertainties should be expressed as *k=2*; i.e. providing a level of confidence of approximately 95%.

Appendix 1 [of protocol]

Technical information about the thermometers

a) LP3

Wavelengths: 650 nm and 950 nm (for this comparison measurements will be made at 650 nm only)

Temperature range: 1000 K to 3200 K

Target size: (0.5 mm at 400 mm and 1.7 mm at 1000 mm)?

Working distance: this should be measured from the target to the front of the housing of the radiation thermometer

Warm up time: 1 hour from switch-on

Output: the output is in terms of both photocurrent and temperature. For this comparison only the photocurrent values should be used

Temperature coefficient N/A

Background measurements: these should be performed by placing the lens cap on the front of the radiation thermometer

a) VEGA

Wavelength: 900 nm

Temperature range: 873 K to 3173 K at 900 nm

Target size: 1.2 x 1.5 mm at 550 mm and 2 x 2.7 mm at 1000 mm

Working distance: this should be measured from the target to the front of the objective housing of the radiation thermometer

Warm up time: 40 minutes from switch-on

Output: the output is in terms of a voltage

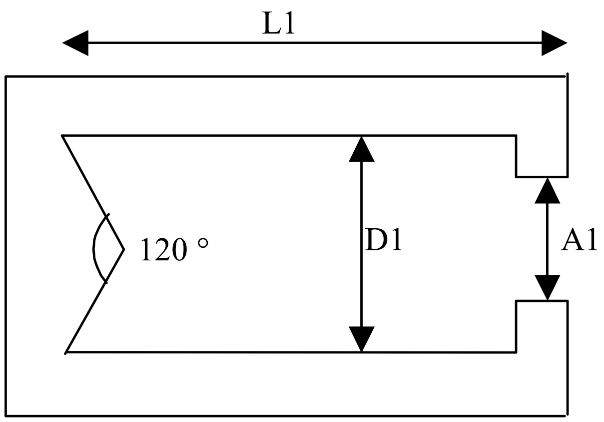
Temperature coefficient: N/A. The operating temperature of the detector and filter is 22.0 (± 0.1) °C

Background measurements: these should be performed by placing the lens cap on the front of the radiation thermometer

Appendix 2

Sample cavities for the calculation of emissivity

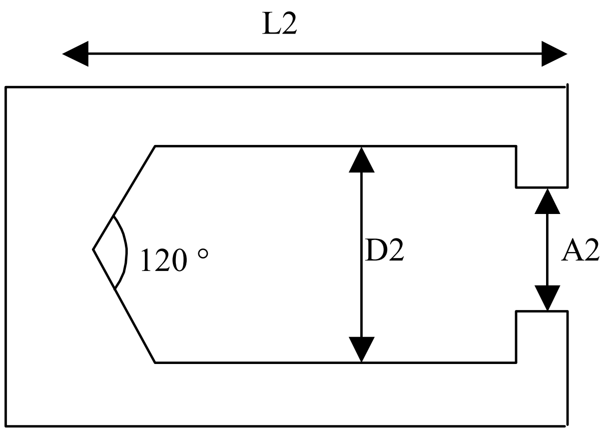
i) Design A



The assumed diffuse wall emissivity for this cavity is 0.92. Calculations are to be performed for the following values of L1, D1 and A1.

Design	L1 (mm)	D1 (mm)	A1 (mm)
A-1	97	7	3
A-2	27	3	3

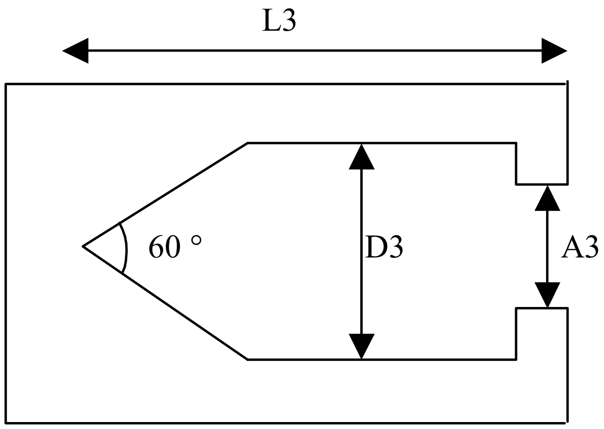
ii) Design B



The assumed diffuse wall emissivity for this cavity is 0.80. Calculations are to be performed for the following values of L2, D2 and A2.

Design	L2 (mm)	D2 (mm)	A2 (mm)
B-1	27	3	3
B-2	97	7	3
B-3	322	75	75
B-4	322	75	50

iii) Design C



The assumed wall emissivity for this cavity is 0.80. Calculations are to be performed for the following values of L3, D3 and A3.

Design	L3 (mm)	D3 (mm)	A3 (mm)
C-1	27	3	3
C-2	97	7	3
C-3	322	75	75
C-4	322	75	50

APPENDIX 2 – THE FITTING DATA FOR THE LP3 SSE MEASUREMENTS

Table 115 – fitting information for the NPL SSE data – 3 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
5	0.000180	0.000184	0.000004
6	0.000235	0.000233	-0.000002
7	0.000285	0.000279	-0.000006
9	0.000366	0.000367	0.000001
12	0.000483	0.000487	0.000004
15	0.000593	0.000595	0.000002
18	0.000694	0.000691	-0.000003
20	0.000752	0.000750	-0.000002
25	0.000879	0.000881	0.000002
30	0.000994	0.000994	0.000000
40	0.001180	0.001180	0.000000
50	0.001325	0.001325	0.000000
		Root mean square residual =	0.000004

Chebyshev polynomial coefficients (NPL, 3 mm diameter spot):

Index	Chebyshev coefficient
0	1.69972889E-03
1	5.54576764E-04
2	-9.24479856E-05
3	1.58003398E-05
4	-2.75706506E-06

Table 116 – fitting information for the NPL SSE data – 6 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
7	0.000050	0.000050	0.000000
9	0.000124	0.000125	0.000001
12	0.000240	0.000239	-0.000001
15	0.000349	0.000350	0.000001
18	0.000452	0.000452	0.000000
20	0.000518	0.000514	-0.000004
25	0.000643	0.000647	0.000004
30	0.000758	0.000756	-0.000002
40	0.000947	0.000947	0.000000
50	0.001103	0.001103	0.000000
		Root mean square residual =	0.000003

Chebyshev polynomial coefficients (NPL, 6 mm diameter spot):

Index	Chebyshev coefficient
0	1.30253049E-03
1	5.20348373E-04
2	-7.44092126E-05
3	1.25845362E-05
4	-5.22258113E-07
5	-6.29808572E-06

Table 117 – fitting information for the PTB SSE data – 3mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
13	0.000560	0.000549	-0.000011
20	0.000780	0.000794	0.000014
25	0.000920	0.000937	0.000017
34	0.001170	0.001141	-0.000029
46	0.001340	0.001346	0.000006
59	0.001540	0.001547	0.000007
70	0.001760	0.001756	-0.000004
Root mean square residual =			0.000023

Chebyshev polynomial coefficients (PTB, 3 mm diameter spot):

Index	Chebyshev coefficient
0	2.42734839E-03
1	5.69594883E-04
2	-6.08892501E-05
3	3.39004567E-05

Table 118 – fitting information for the PTB SSE data – 6 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
13	0.000300	0.000297	-0.000003
20	0.000510	0.000513	0.000003
25	0.000640	0.000643	0.000003
34	0.000840	0.000840	0.000000
46	0.001060	0.001051	-0.000009
59	0.001250	0.001259	0.000009
70	0.001460	0.001457	-0.000003
Root mean square residual =			0.000008

Chebyshev polynomial coefficients (PTB, 6 mm diameter spot):

Index	Chebyshev coefficient
0	1.85332736E-03
1	5.56485250E-04
2	-4.96067388E-05
3	2.33873981E-05

Table 119 – fitting information for the CEM SSE data – 3 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
10.4	0.00042	0.000402	-0.000018
14.1	0.00051	0.000530	0.000020
19.5	0.00069	0.000702	0.000012
24.1	0.00083	0.000836	0.000006
28.9	0.00098	0.000963	-0.000017
33.8	0.00109	0.001081	-0.000009
39.1	0.00121	0.001198	-0.000012
49.1	0.00137	0.001395	0.000025
59.0	0.00157	0.001569	-0.000001
69.3	0.00175	0.001744	-0.000006
100.0	0.00237	0.002371	0.000001
		Root mean square residual =	0.0000019

Chebyshev polynomial coefficients (CEM, 3 mm diameter spot):

Index	Chebyshev coefficient
0	2.88841103E-03
1	9.33455492E-04
2	-5.89622351E-05
3	5.10752605E-05
4	7.94052804E-07

Table 120 - fitting information for the CEM SSE data – 6mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
14.1	0.00042	0.000426	0.000006
19.5	0.00059	0.000590	0.000000
24.1	0.00074	0.000710	-0.000030
28.9	0.00080	0.000820	0.000020
33.8	0.00091	0.000920	0.000010
39.1	0.00102	0.001017	-0.000003
49.1	0.00118	0.001184	0.000004
59.0	0.00136	0.001344	-0.000016
69.3	0.00151	0.001519	0.000009
100.0	0.00211	0.002110	0.000000
		Root mean square residual =	0.000019

Chebyshev polynomial coefficients (CEM, 6 mm diameter spot):

Index	Chebyshev coefficient
0	2.60515050E-03
1	8.05532076E-04
2	-2.23503910E-05
3	3.61420321E-05
4	-1.23232008E-05

Table 121 – fitting information for the UME data – 3 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
4	0.000121	0.000123	0.000002
6	0.000230	0.000231	0.000001
8	0.000339	0.000331	-0.000008
10	0.000419	0.000422	0.000003
15	0.000613	0.000622	0.000009
20	0.000799	0.000791	-0.000008
30	0.001071	0.001074	0.000003
40	0.001307	0.001306	-0.000001
52	0.001482	0.001482	0.000000
		Root mean square residual =	0.000008

Chebyshev polynomial coefficients (UME, 3 mm diameter spot):

Index	Chebyshev coefficient
0	1.84411680E-03
1	6.69387551E-04
2	-1.09576642E-04
3	1.03701846E-05
4	-1.01609467E-05

Table 122 – fitting information for the UME data – 6 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
8	0.000102	0.000105	0.000003
10	0.000190	0.000185	-0.000005
15	0.000365	0.000368	0.000003
20	0.000534	0.000532	-0.000002
30	0.000806	0.000808	0.000002
40	0.001020	0.001019	-0.000001
52	0.001200	0.001200	0.000000
		Root mean square residual =	0.000004

Chebyshev polynomial coefficients (UME, 6 mm diameter spot):

Index	Chebyshev coefficient
0	1.46043136E-03
1	5.43569531E-04
2	-7.73511291E-05
3	3.81004116E-06

Table 123 – fitting information for the INM data – 3 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
5.7	0.000210	0.000210	0.000000
8.0	0.000318	0.000319	0.000001
10.0	0.000408	0.000407	-0.000001
12.5	0.000511	0.000510	-0.000001
16.3	0.000649	0.000651	0.000002
21.2	0.000811	0.000811	0.000000
27.6	0.000989	0.000988	-0.000001
35.8	0.001180	0.001180	0.000000
		Root mean square residual =	0.000001

Chebyshev polynomial coefficients (INM, 3 mm diameter spot):

Index	Chebyshev coefficient
0	1.49239251E-03
1	4.79160438E-04
2	-5.09748505E-05
3	5.78129745E-06

Table 124 – fitting information for the INM data – 6 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
8.0	0.000088	0.000090	0.000002
10.0	0.000180	0.000177	-0.000003
12.5	0.000280	0.000280	0.000000
16.3	0.000420	0.000421	0.000001
21.2	0.000580	0.000581	0.000001
27.6	0.000760	0.000759	-0.000001
35.8	0.000950	0.000950	0.000000
		Root mean square residual =	0.000002

Chebyshev polynomial coefficients (INM, 6 mm diameter spot):

Index	Chebyshev coefficient
0	1.12202086E-03
1	4.26061732E-04
2	-4.09729375E-05
3	4.13792781E-06

Table 125 – fitting information for the IMGC data – 3 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
8	0.000410	0.000415	0.000005
10	0.000537	0.000530	-0.000007
12	0.000636	0.000636	0.000000
15	0.000778	0.000779	0.000001
20	0.000981	0.000984	0.000003
25	0.001161	0.001155	-0.000006
30	0.001293	0.001301	0.000008
35	0.001429	0.001430	0.000001
40	0.001552	0.001547	-0.000005
50	0.001761	0.001760	-0.000001
60	0.001962	0.001962	0.000000
70	0.002159	0.002163	0.000004
80	0.002369	0.002364	-0.000005
90	0.002563	0.002565	0.000002
100	0.002766	0.002766	0.000000
		Root mean square residual =	0.000005

Chebyshev polynomial coefficients (IMGC, 3 mm diameter spot):

Index	Chebyshev coefficient
0	3.48214161E-03
1	1.10312040E-03
2	-1.25368041E-04
3	6.64544442E-05
4	-2.51098875E-05
5	5.64983817E-06

Table 126 – fitting information for the IMGC data – 6 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
10	0.000224	0.000222	-0.000002
12	0.000327	0.000328	0.000001
15	0.000467	0.000471	0.000004
20	0.000676	0.000676	0.000000
25	0.000853	0.000845	-0.000008
30	0.000985	0.000991	0.000006
35	0.001123	0.001119	-0.000004
40	0.001229	0.001236	0.000007
50	0.001457	0.001454	-0.000003
60	0.001664	0.001663	-0.000001
70	0.001865	0.001867	0.000002
80	0.002061	0.002061	0.000000
90	0.002251	0.002251	0.000000
100	0.002467	0.002467	0.000000
		Root mean square residual =	0.000005

Chebyshev polynomial coefficients (IMGC, 6 mm diameter spot):

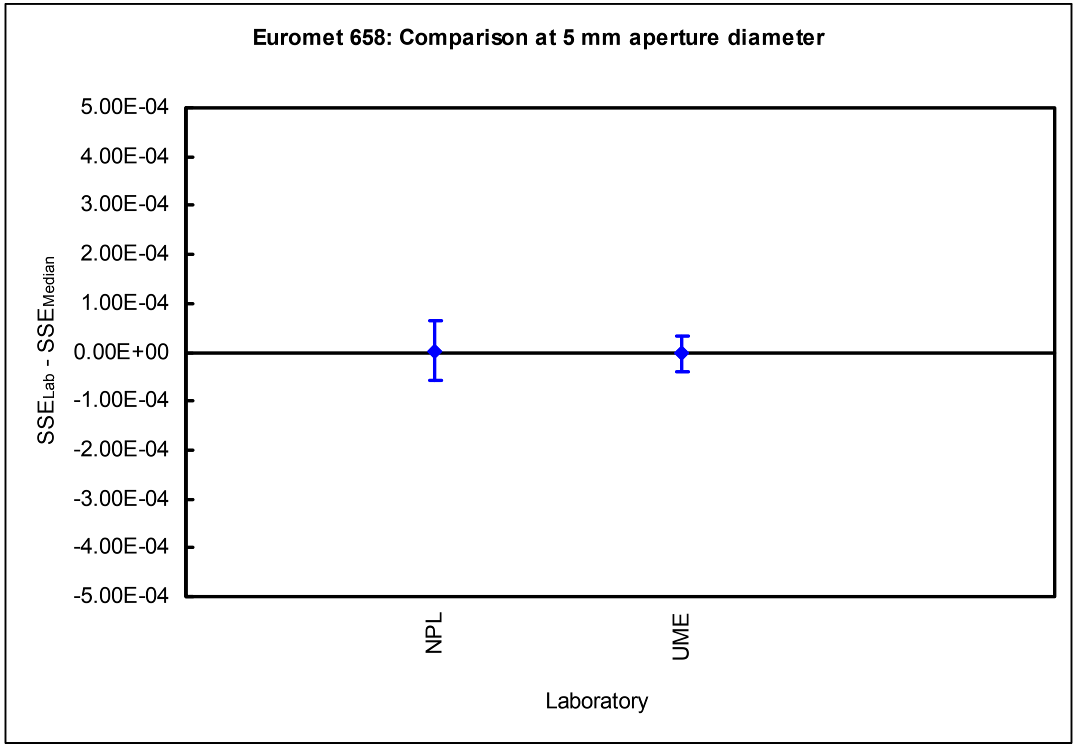
Index	Chebyshev coefficient
0	2.93997115E-03
1	1.05723373E-03
2	-1.08594344E-04
3	5.52567103E-05
4	-1.83003727E-05
5	1.01698718E-05
6	1.37744380E-06

APPENDIX 3 – THE QDE_{95} AND DOE VALUES FOR THE LP3 SSE RESULTS

Note: The QDE_{95} and DOE values for IMGC in Tables 127 to 153, and the results in the accompanying plots, were affected by a failure of the LP3 pyrometer that was not evident at the time of the measurements at IMGC.

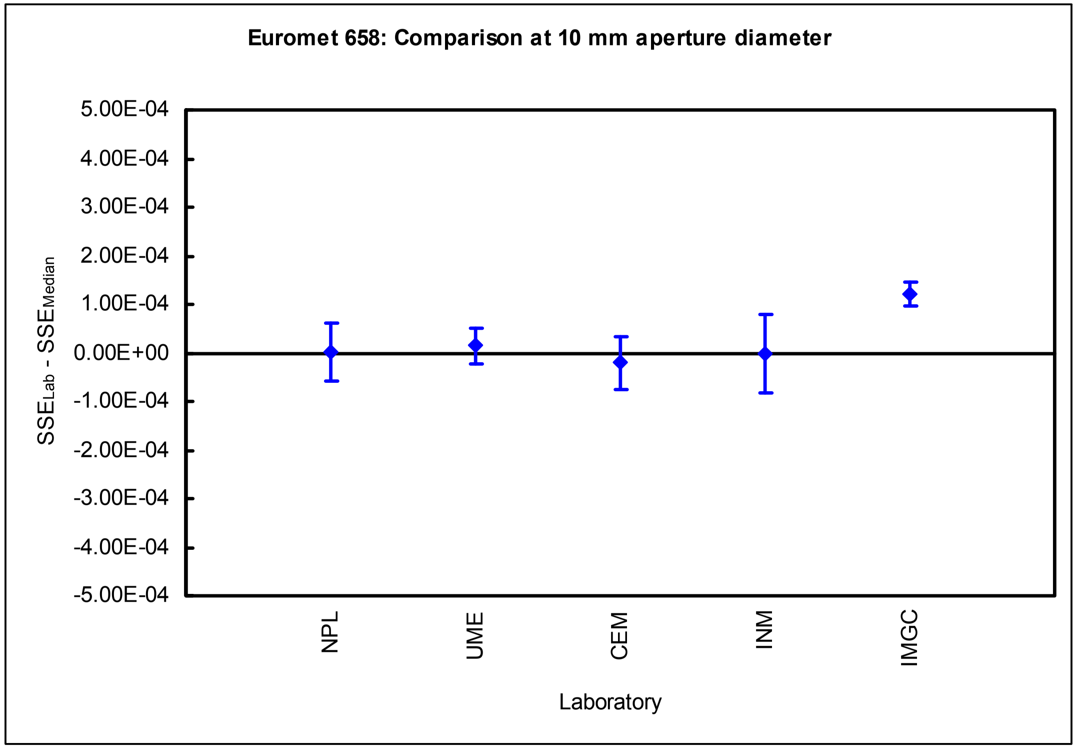
	NPL	UME
NPL	-	6.178E-06 ± 7.031E-05
UME	*6.970E-05*	-

Table 127 – LP3 comparison with the 3 mm diameter spot and the 5 mm diameter aperture



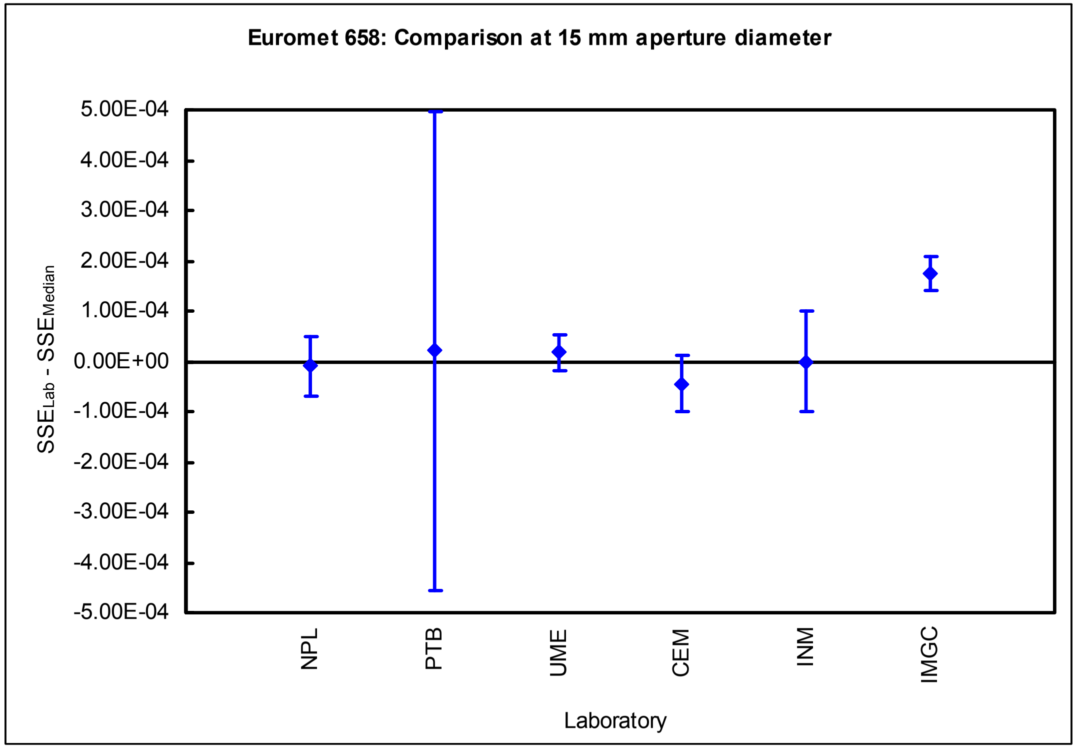
	NPL	UME	CEM	INM	IMGC
NPL	-	-1.323E-05 ± 7.031E-05	2.177E-05 ± 8.190E-05	1.910E-06 ± 1.003E-04	-1.212E-04 ± 6.552E-05
UME	*7.358E-05*	-	3.500E-05 ± 6.576E-05	1.514E-05 ± 8.766E-05	-1.080E-04 ± 4.369E-05
CEM	*9.070E-05*	*8.923E-05*	-	-1.986E-05 ± 9.720E-05	-1.429E-04 ± 6.061E-05
INM	*9.861E-05*	*9.080E-05*	*1.029E-04*	-	-1.231E-04 ± 8.386E-05
IMGC	*1.751E-04*	*1.439E-04*	*1.928E-04*	*1.921E-04*	-

Table 128 – LP3 comparison with the 3 mm diameter spot and the 10 mm diameter aperture



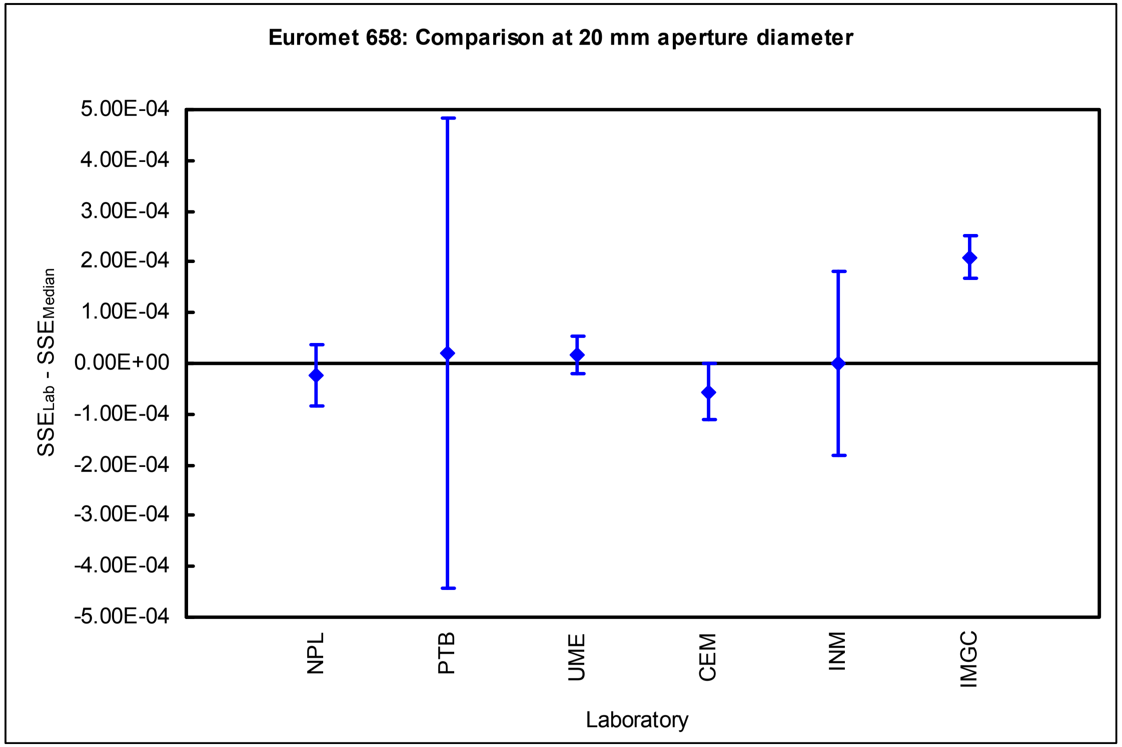
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	-3.061E-05 ± 4.803E-04	-2.711E-05 ± 7.031E-05	3.431E-05 ± 8.190E-05	-9.964E-06 ± 1.169E-04	-1.842E-04 ± 6.966E-05
PTB	*4.729E-04*	-	3.507E-06 ± 4.779E-04	6.492E-05 ± 4.797E-04	2.065E-05 ± 4.869E-04	-1.536E-04 ± 4.778E-04
UME	*8.545E-05*	*4.707E-04*	-	6.141E-05 ± 6.576E-05	1.714E-05 ± 1.062E-04	-1.571E-04 ± 4.969E-05
CEM	*1.021E-04*	*4.859E-04*	*1.155E-04*	-	-4.427E-05 ± 1.142E-04	-2.185E-04 ± 6.506E-05
INM	*1.158E-04*	*4.780E-04*	*1.092E-04*	*1.390E-04*	-	-1.742E-04 ± 1.058E-04
IMGC	*2.415E-04*	*5.524E-04*	*1.980E-04*	*2.720E-04*	*2.612E-04*	-

Table 129 – LP3 comparison with the 3 mm diameter spot and the 15 mm diameter aperture



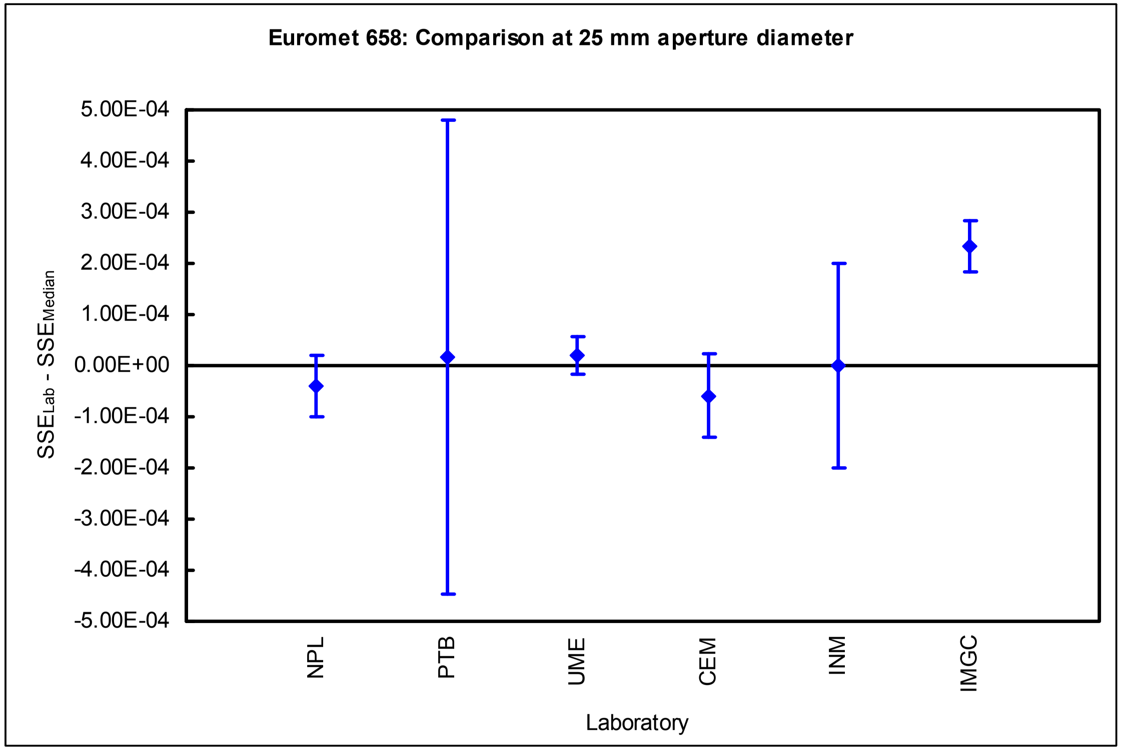
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	-4.428E-05 ± 4.662E-04	-4.107E-05 ± 7.031E-05	3.227E-05 ± 8.190E-05	-2.411E-05 ± 1.899E-04	-2.338E-04 ± 7.379E-05
PTB	*4.634E-04*	-	3.214E-06 ± 4.637E-04	7.655E-05 ± 4.656E-04	2.017E-05 ± 4.961E-04	-1.895E-04 ± 4.642E-04
UME	*9.900E-05*	*4.568E-04*	-	7.333E-05 ± 6.576E-05	1.696E-05 ± 1.835E-04	-1.928E-04 ± 5.533E-05
CEM	*1.002E-04*	*4.797E-04*	*1.274E-04*	-	-5.638E-05 ± 1.883E-04	-2.661E-04 ± 6.946E-05
INM	*1.915E-04*	*4.870E-04*	*1.822E-04*	*2.140E-04*	-	-2.097E-04 ± 1.849E-04
IMGC	*2.945E-04*	*5.742E-04*	*2.383E-04*	*3.232E-04*	*3.618E-04*	-

Table 130 – LP3 comparison with the 3 mm diameter spot and the 20 mm diameter aperture



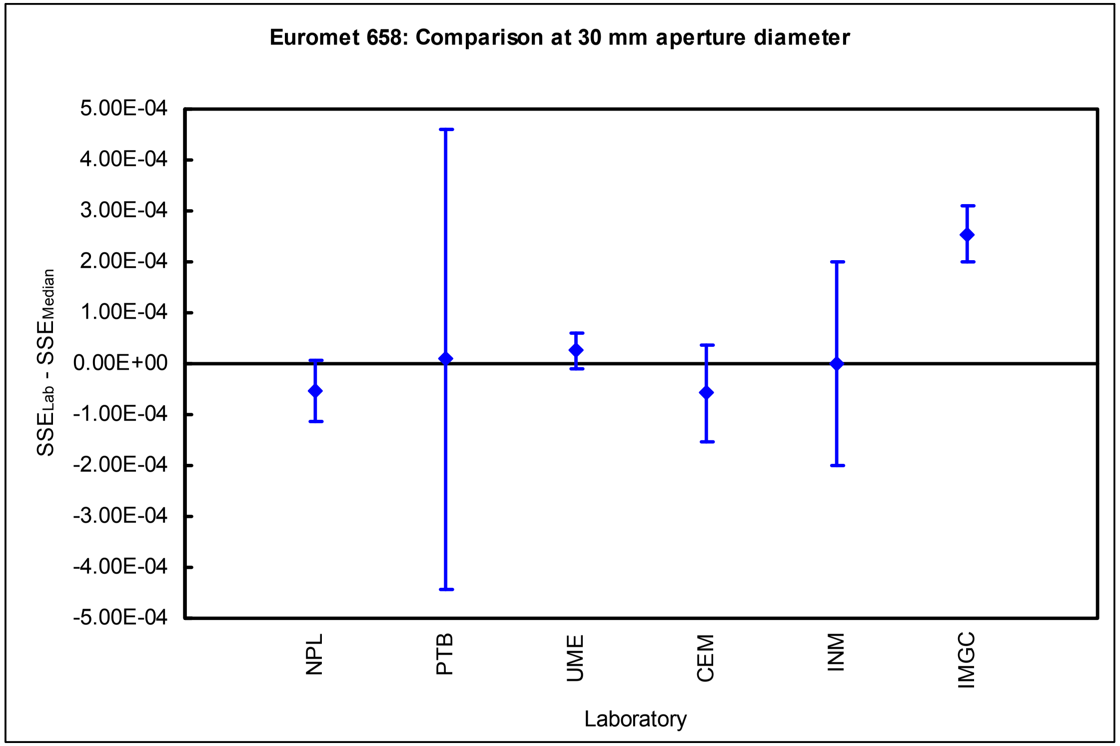
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	-5.544E-05 ± 4.662E-04	-5.833E-05 ± 7.031E-05	2.084E-05 ± 1.014E-04	-3.887E-05 ± 2.090E-04	-2.738E-04 ± 7.852E-05
PTB	*4.682E-04*	-	-2.888E-06 ± 4.637E-04	7.629E-05 ± 4.694E-04	1.657E-05 ± 5.037E-04	-2.184E-04 ± 4.650E-04
UME	*1.162E-04*	*4.569E-04*	-	7.918E-05 ± 8.893E-05	1.946E-05 ± 2.032E-04	-2.155E-04 ± 6.149E-05
CEM	*1.075E-04*	*4.831E-04*	*1.523E-04*	-	-5.972E-05 ± 2.159E-04	-2.947E-04 ± 9.555E-05
INM	*2.184E-04*	*4.944E-04*	*2.020E-04*	*2.411E-04*	-	-2.349E-04 ± 2.062E-04
IMGC	*3.384E-04*	*6.025E-04*	*2.661E-04*	*3.732E-04*	*4.045E-04*	-

Table 131 – LP3 comparison with the 3 mm diameter spot and the 25 mm diameter aperture



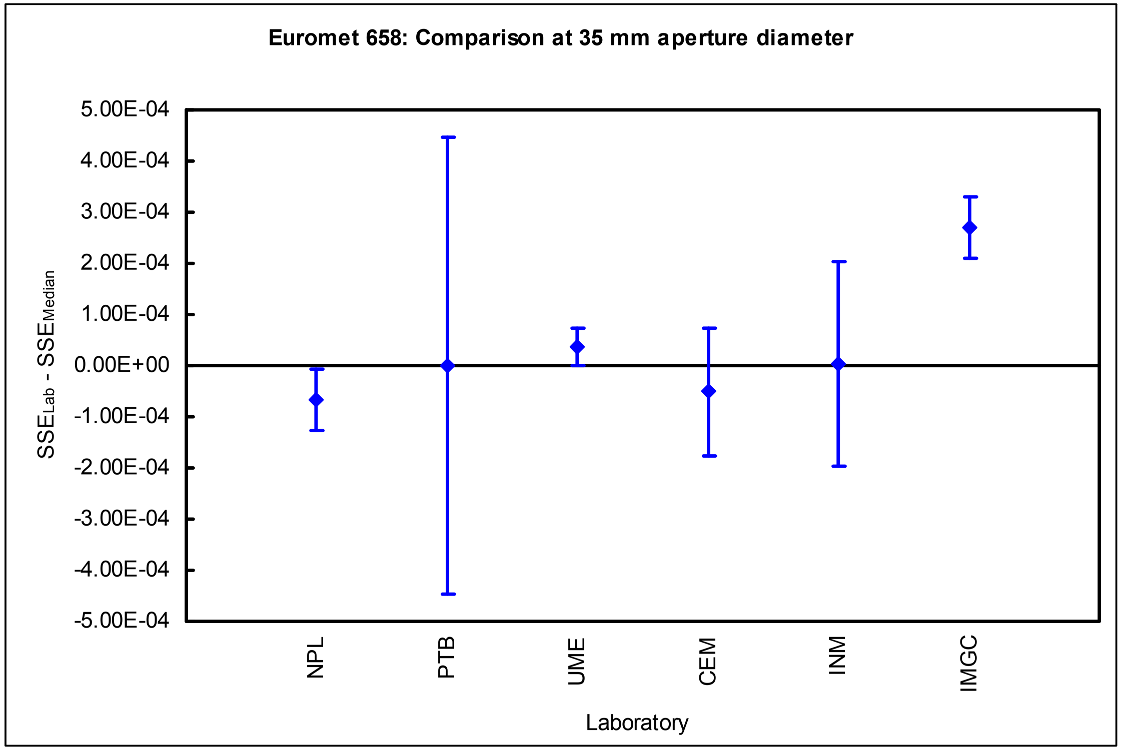
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	-6.305E-05 ± 4.553E-04	-7.975E-05 ± 7.031E-05	3.946E-06 ± 1.118E-04	-5.389E-05 ± 2.090E-04	-3.074E-04 ± 8.173E-05
PTB	*4.619E-04*	-	-1.670E-05 ± 4.527E-04	6.699E-05 ± 4.609E-04	9.159E-06 ± 4.936E-04	-2.444E-04 ± 4.546E-04
UME	*1.376E-04*	*4.443E-04*	-	8.369E-05 ± 1.006E-04	2.586E-05 ± 2.032E-04	-2.277E-04 ± 6.554E-05
CEM	*1.098E-04*	*4.695E-04*	*1.665E-04*	-	-5.783E-05 ± 2.210E-04	-3.114E-04 ± 1.089E-04
INM	*2.300E-04*	*4.851E-04*	*2.049E-04*	*2.440E-04*	-	-2.535E-04 ± 2.074E-04
IMGC	*3.747E-04*	*6.192E-04*	*2.816E-04*	*4.009E-04*	*4.241E-04*	-

Table 132 – LP3 comparison with the 3 mm diameter spot and the 30 mm diameter aperture



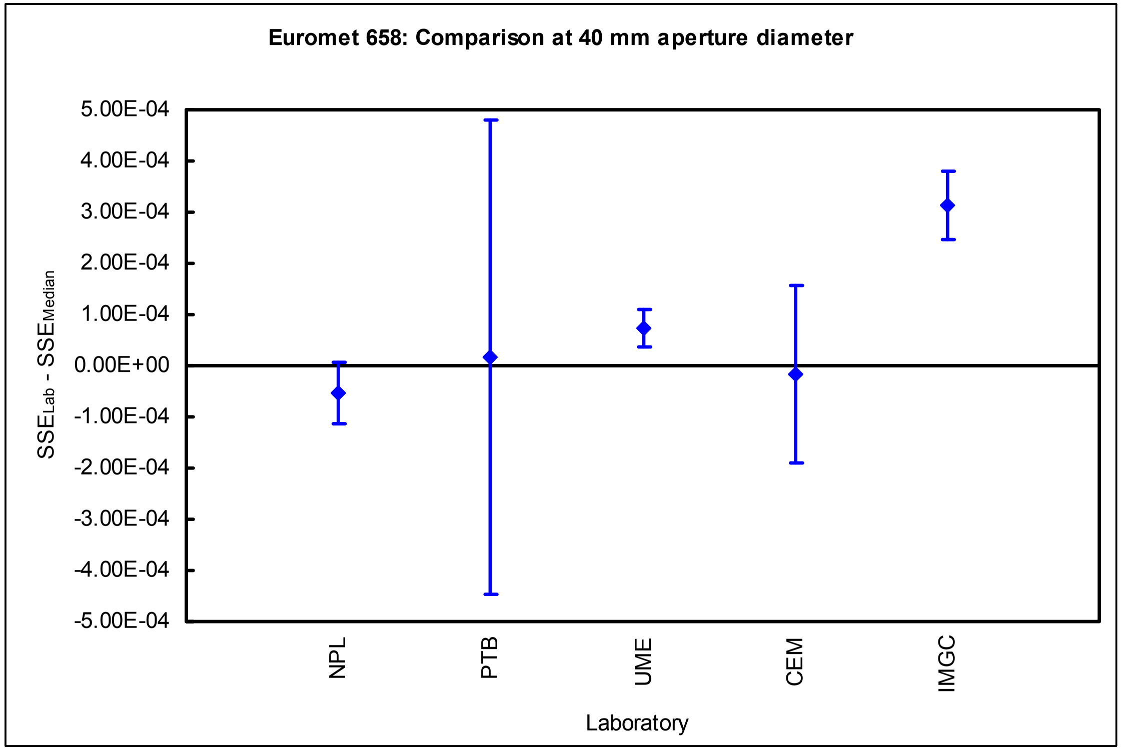
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	-6.732E-05 ± 4.498E-04	-1.038E-04 ± 7.031E-05	-1.584E-05 ± 1.397E-04	-7.008E-05 ± 2.090E-04	-3.376E-04 ± 8.581E-05
PTB	*4.593E-04*	-	-3.644E-05 ± 4.471E-04	5.148E-05 ± 4.631E-04	-2.762E-06 ± 4.885E-04	-2.703E-04 ± 4.498E-04
UME	*1.616E-04*	*4.423E-04*	-	8.792E-05 ± 1.309E-04	3.368E-05 ± 2.032E-04	-2.338E-04 ± 7.057E-05
CEM	*1.399E-04*	*4.634E-04*	*1.956E-04*	-	-5.424E-05 ± 2.363E-04	-3.217E-04 ± 1.398E-04
INM	*2.442E-04*	*4.815E-04*	*2.095E-04*	*2.547E-04*	-	-2.675E-04 ± 2.091E-04
IMGC	*4.082E-04*	*6.408E-04*	*2.919E-04*	*4.367E-04*	*4.394E-04*	-

Table 133 – LP3 comparison with the 3 mm diameter spot and the 35 mm diameter aperture



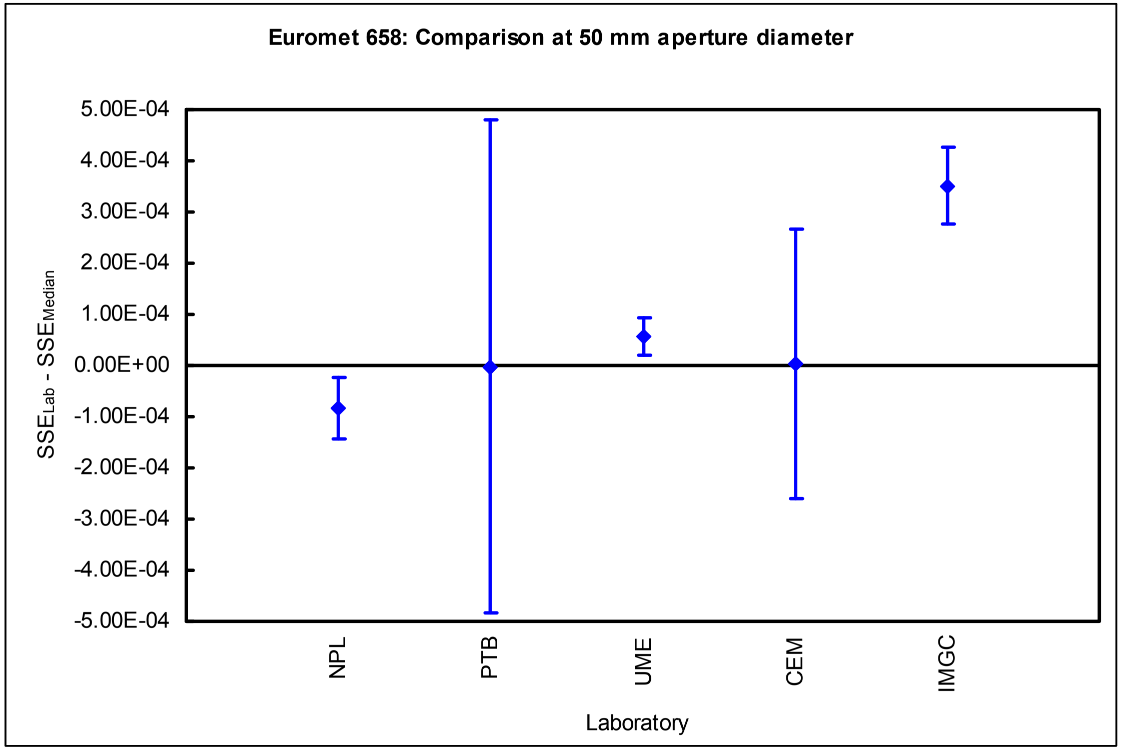
	NPL	PTB	UME	CEM	IMGC
NPL	-	-6.978E-05 ± 4.662E-04	-1.265E-04 ± 7.031E-05	-3.724E-05 ± 1.835E-04	-3.670E-04 ± 8.938E-05
PTB	*4.761E-04*	-	-5.667E-05 ± 4.637E-04	3.254E-05 ± 4.937E-04	-2.972E-04 ± 4.669E-04
UME	*1.843E-04*	*4.664E-04*	-	8.921E-05 ± 1.769E-04	-2.405E-04 ± 7.487E-05
CEM	*1.940E-04*	*4.863E-04*	*2.352E-04*	-	-3.297E-04 ± 1.853E-04
IMGC	*4.405E-04*	*6.817E-04*	*3.021E-04*	*4.821E-04*	-

Table 134 – LP3 comparison with the 3 mm diameter spot and the 40 mm diameter aperture



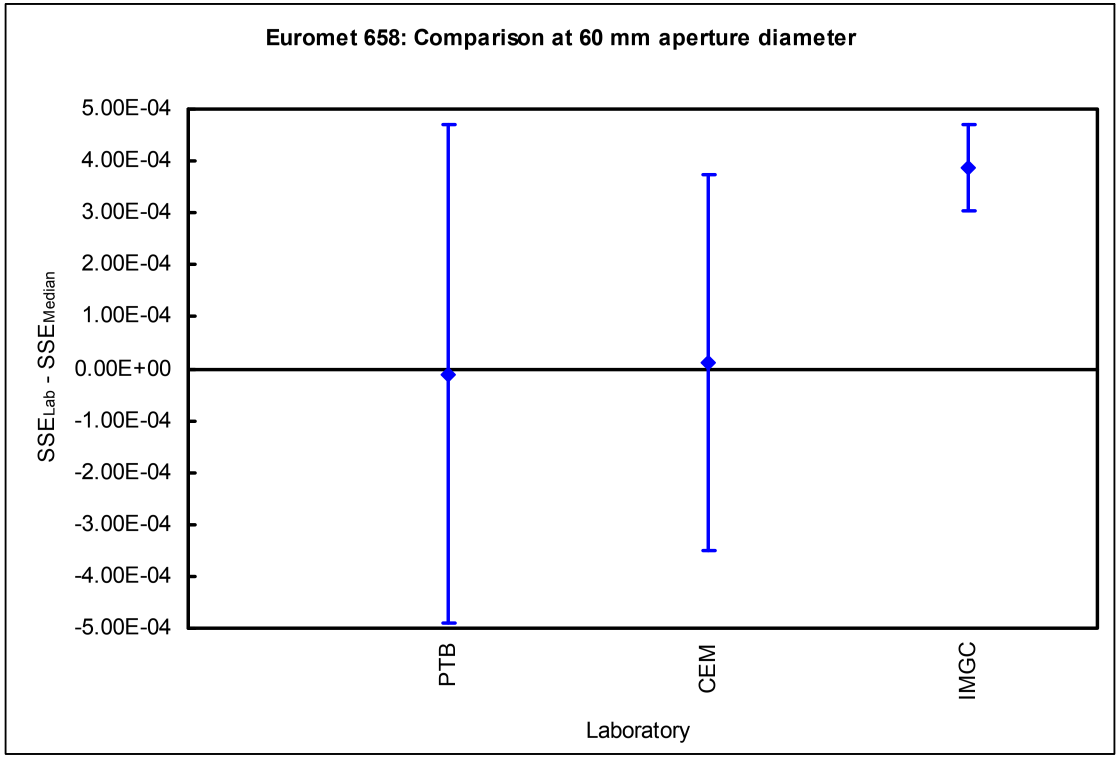
	NPL	PTB	UME	CEM	IMGC
NPL	-	-8.184E-05 ± 4.860E-04	-1.402E-04 ± 7.031E-05	-8.637E-05 ± 2.696E-04	-4.348E-04 ± 9.612E-05
PTB	*5.020E-04*	-	-5.840E-05 ± 4.835E-04	-4.531E-06 ± 5.491E-04	-3.529E-04 ± 4.879E-04
UME	*1.981E-04*	*4.860E-04*	-	5.387E-05 ± 2.652E-04	-2.945E-04 ± 8.280E-05
CEM	*3.115E-04*	*5.408E-04*	*2.804E-04*	-	-3.484E-04 ± 2.732E-04
IMGC	*5.138E-04*	*7.545E-04*	*3.626E-04*	*5.731E-04*	-

Table 135 – LP3 comparison with the 3 mm diameter spot and the 50 mm diameter aperture



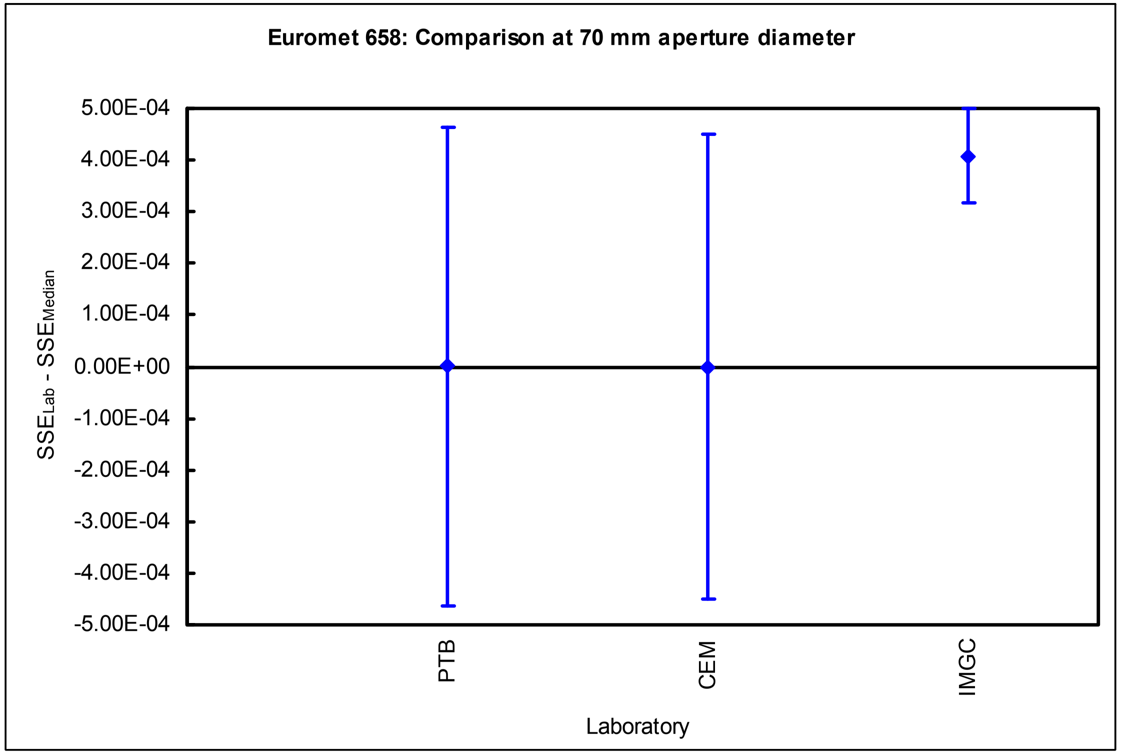
	PTB	CEM	IMGC
PTB	-	-2.232E-05 ± 6.009E-04	-3.983E-04 ± 4.874E-04
CEM	*5.899E-04*	-	-3.759E-04 ± 3.703E-04
IMGC	*7.993E-04*	*6.806E-04*	-

Table 136 – LP3 comparison with the 3 mm diameter spot and the 60 mm diameter aperture



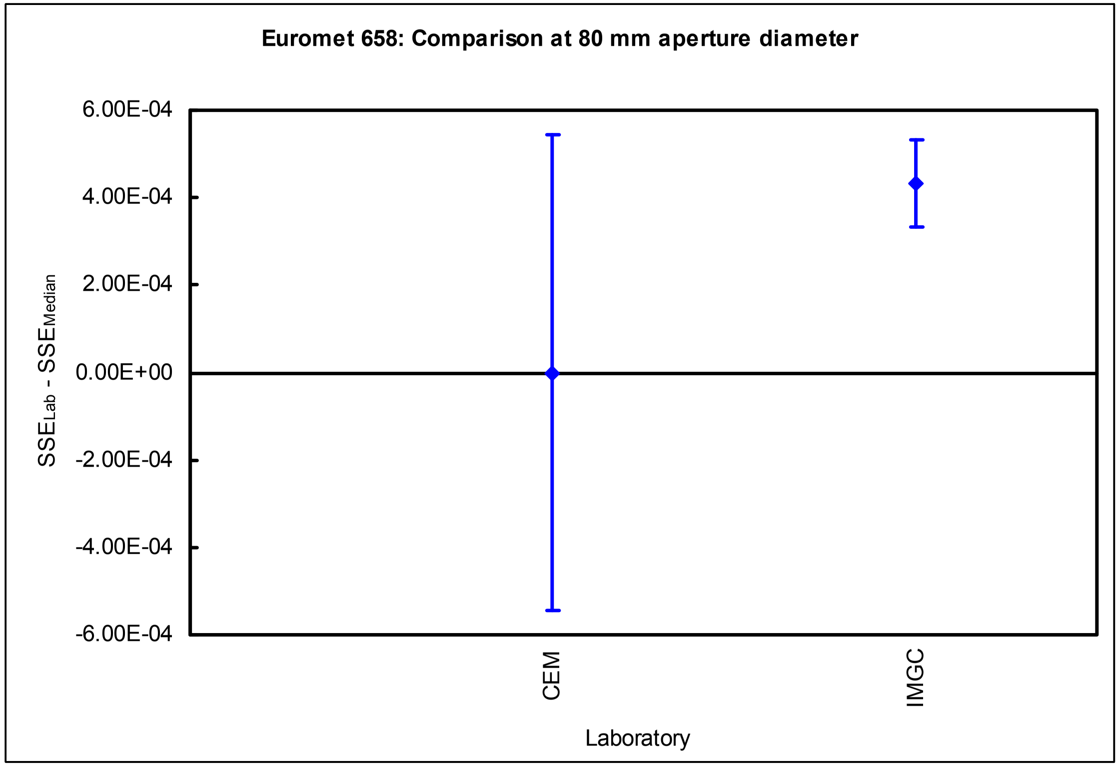
	PTB	CEM	IMGC
PTB	-	6.856E-07 ± 6.458E-04	-4.071E-04 ± 4.713E-04
CEM	*6.374E-04*	-	-4.078E-04 ± 4.602E-04
IMGC	*7.948E-04*	*7.864E-04*	-

Table 137 – LP3 comparison with the 3 mm diameter spot and the 70 mm diameter aperture



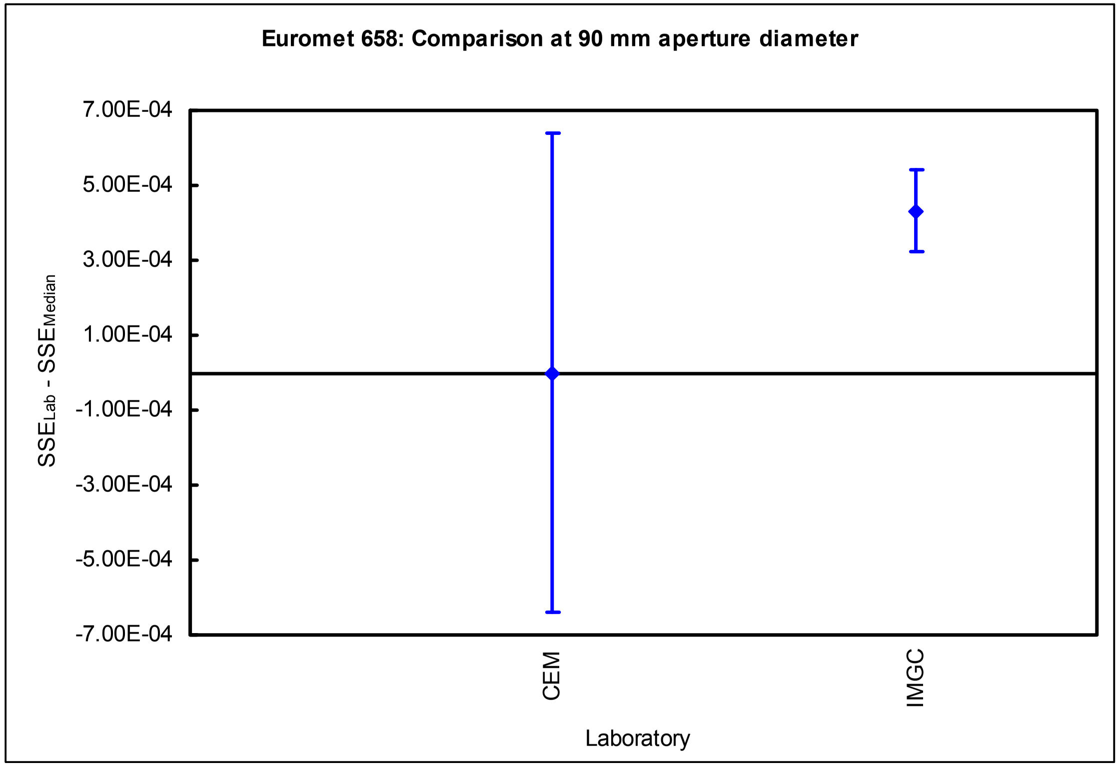
	CEM	IMGC
CEM	-	-4.315E-04 ± 5.534E-04
IMGC	*8.868E-04*	-

Table 138 – LP3 comparison with the 3 mm diameter spot and the 80 mm diameter aperture



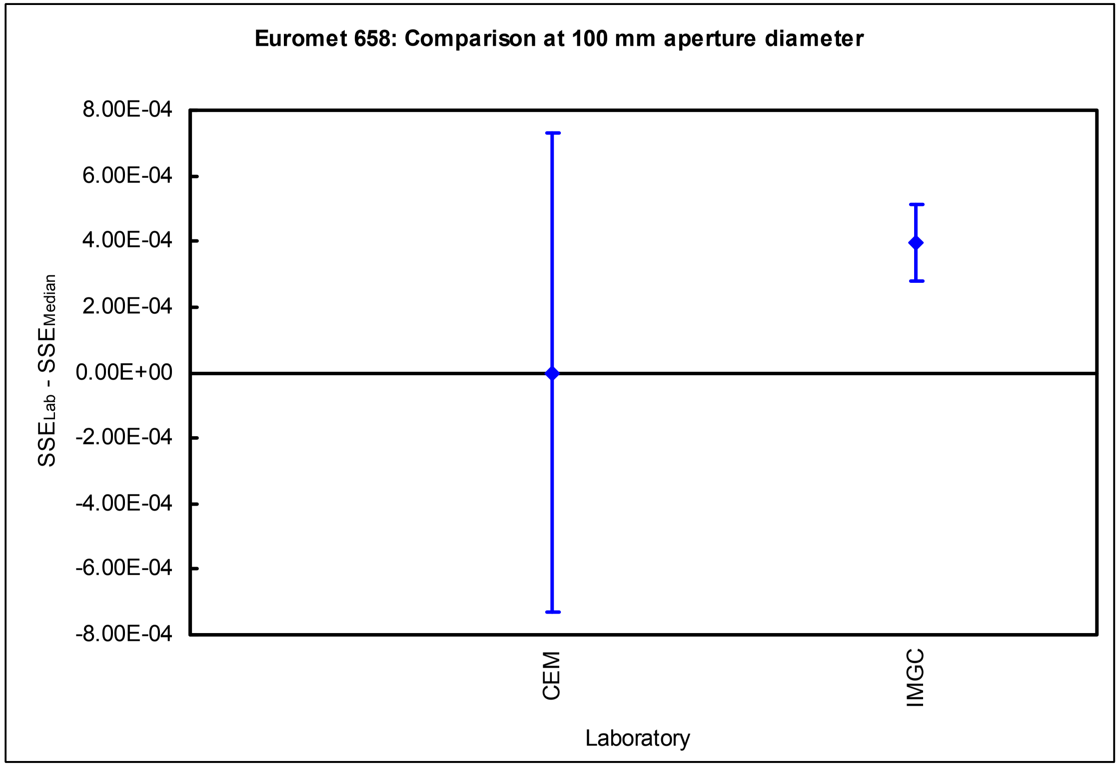
	CEM	IMGC
CEM	-	-4.315E-04 ± 6.467E-04
IMGC	*9.639E-04*	-

Table 139 – LP3 comparison with the 3 mm diameter spot and the 90 mm diameter aperture



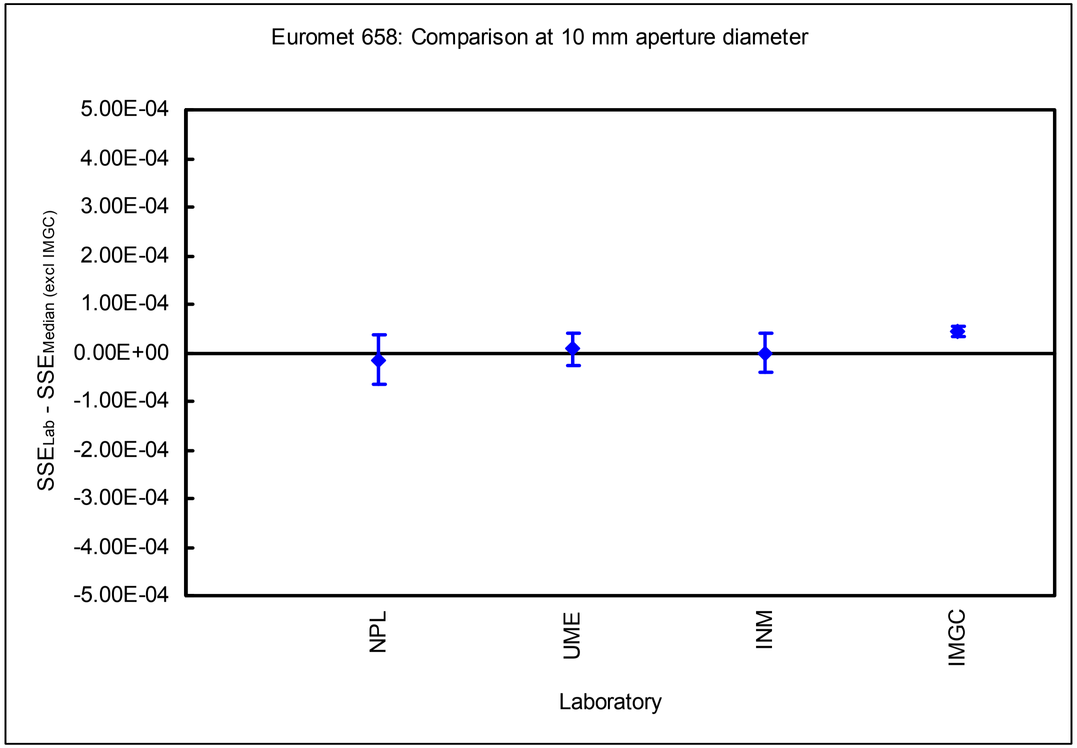
	CEM	IMGC
CEM	-	-3.952E-04 ± 7.402E-04
IMGC	*1.006E-03*	-

Table 140 – LP3 comparison with the 3 mm diameter spot and the 100 mm diameter aperture



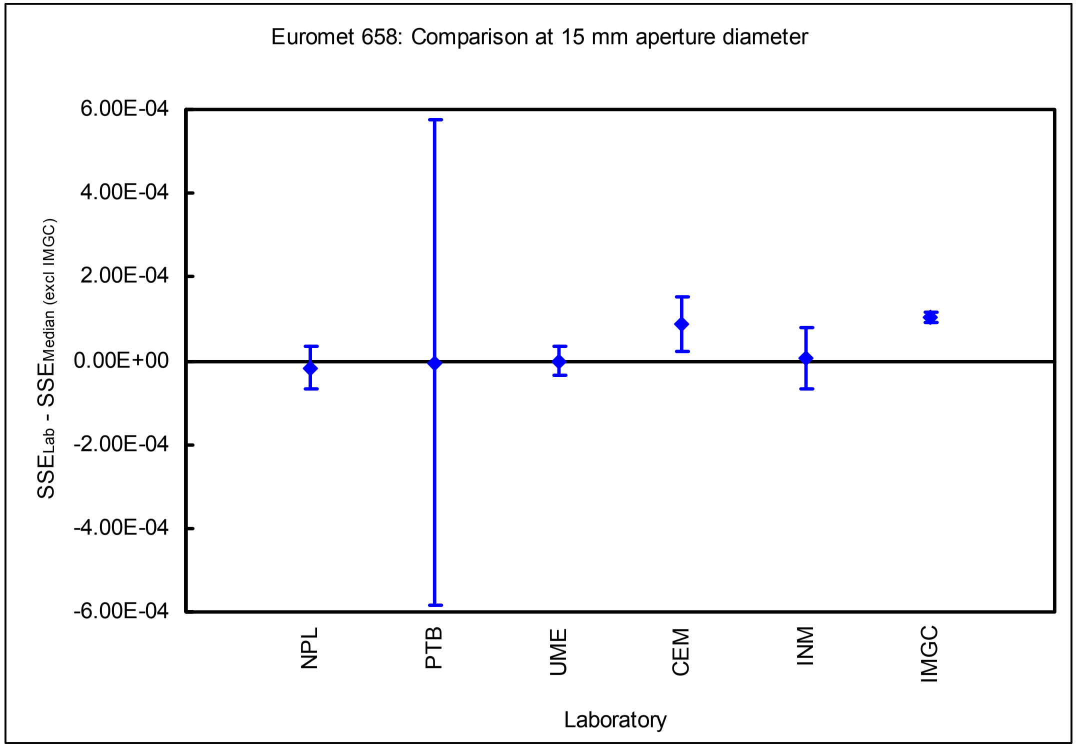
	NPL	UME	INM	IMGC
NPL	-	-2.168E-05 ± 6.020E-05	-1.458E-05 ± 6.444E-05	-5.898E-05 ± 5.150E-05
UME	*7.173E-05*	-	7.094E-06 ± 5.200E-05	-3.731E-05 ± 3.470E-05
INM	*6.928E-05*	*5.270E-05*	-	-4.440E-05 ± 4.162E-05
IMGC	*1.013E-04*	*6.585E-05*	*7.863E-05*	-

Table 141 – LP3 comparison with the 6 mm diameter spot and the 10 mm diameter aperture



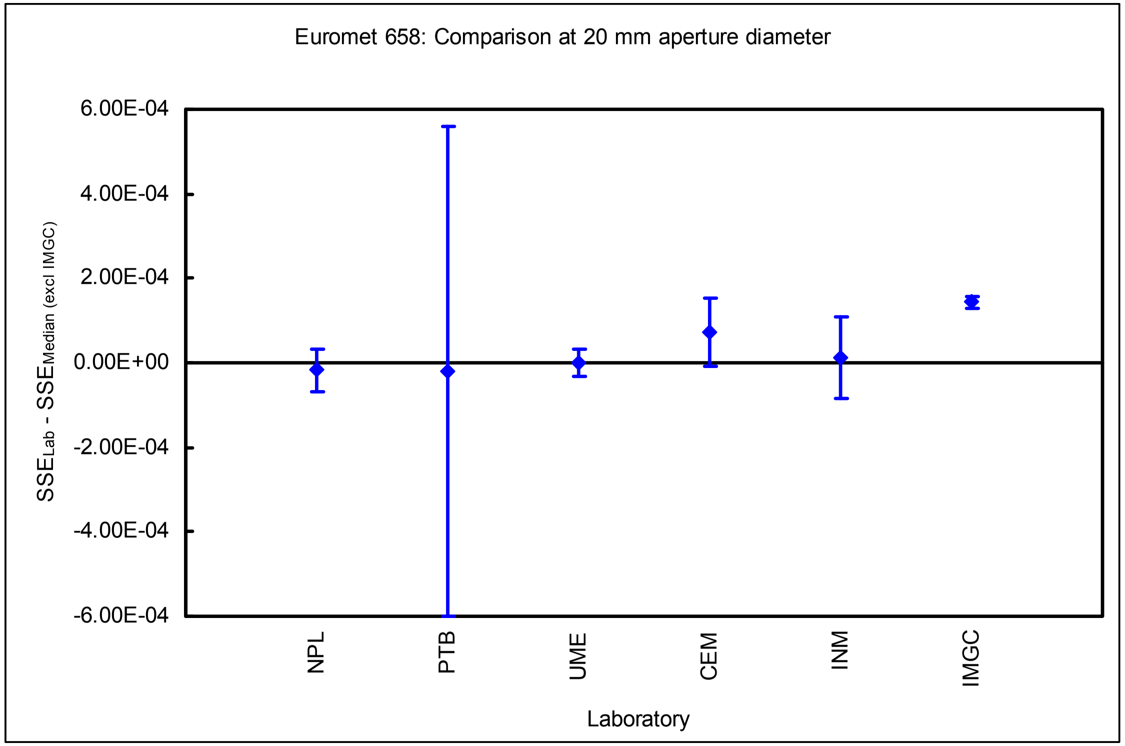
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	-1.268E-05 ± 5.824E-04	-1.758E-05 ± 6.020E-05	-1.051E-04 ± 8.261E-05	-2.402E-05 ± 8.905E-05	-1.209E-04 ± 5.196E-05
PTB	*5.721E-04*	-	-4.903E-06 ± 5.812E-04	-9.241E-05 ± 5.839E-04	-1.134E-05 ± 5.849E-04	-1.082E-04 ± 5.804E-04
UME	*6.803E-05*	*5.723E-04*	-	-8.751E-05 ± 7.332E-05	-6.433E-06 ± 8.051E-05	-1.033E-04 ± 3.538E-05
CEM	*1.730E-04*	*5.994E-04*	*1.478E-04*	-	8.108E-05 ± 9.840E-05	-1.583E-05 ± 6.673E-05
INM	*9.891E-05*	*5.747E-04*	*7.960E-05*	*1.620E-04*	-	-9.691E-05 ± 7.455E-05
IMGC	*1.637E-04*	*6.067E-04*	*1.324E-04*	*7.232E-05*	*1.582E-04*	-

Table 142 – LP3 comparison with the 6 mm diameter spot and the 15 mm diameter aperture



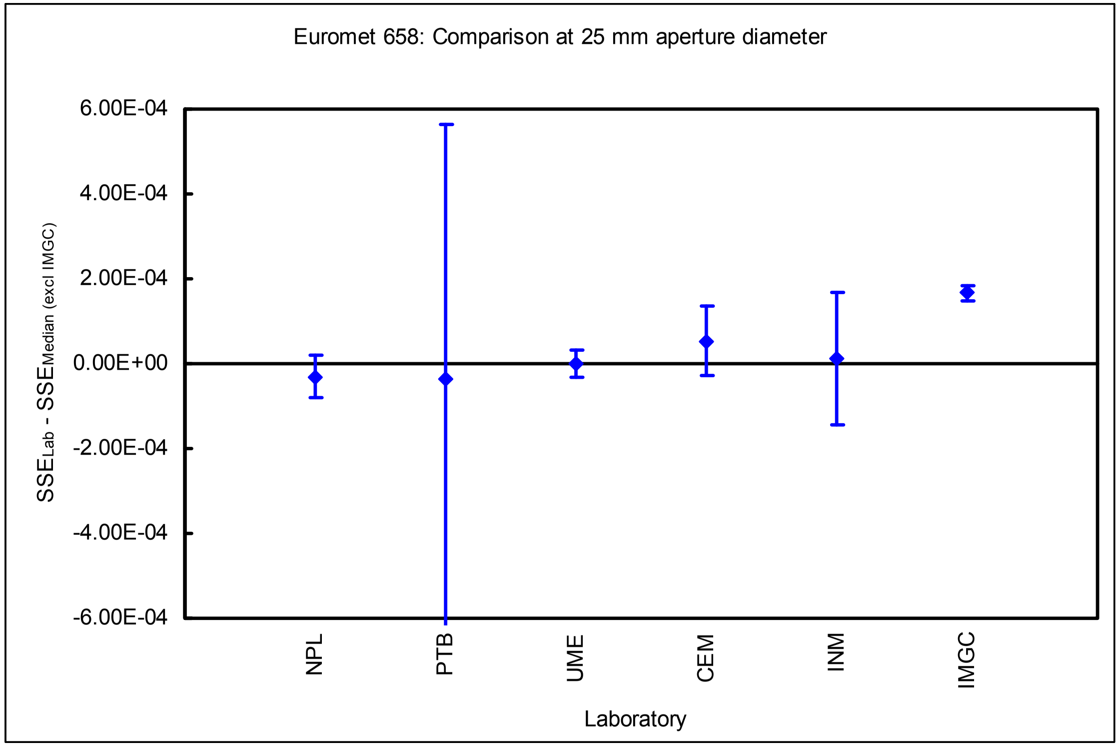
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	1.408E-06 ± 5.824E-04	-1.811E-05 ± 6.020E-05	-8.979E-05 ± 9.423E-05	-2.969E-05 ± 1.085E-04	-1.614E-04 ± 5.273E-05
PTB	*5.745E-04*	-	-1.952E-05 ± 5.812E-04	-9.119E-05 ± 5.857E-04	-3.110E-05 ± 5.881E-04	-1.628E-04 ± 5.804E-04
UME	*6.849E-05*	*5.705E-04*	-	-7.167E-05 ± 8.621E-05	-1.158E-05 ± 1.016E-04	-1.433E-04 ± 3.650E-05
CEM	*1.673E-04*	*6.002E-04*	*1.426E-04*	-	6.010E-05 ± 1.248E-04	-7.158E-05 ± 8.117E-05
INM	*1.209E-04*	*5.780E-04*	*1.018E-04*	*1.632E-04*	-	-1.317E-04 ± 9.734E-05
IMGC	*2.047E-04*	*6.500E-04*	*1.733E-04*	*1.384E-04*	*2.117E-04*	-

Table 143 – LP3 comparison with the 6 mm diameter spot and the 20 mm diameter aperture



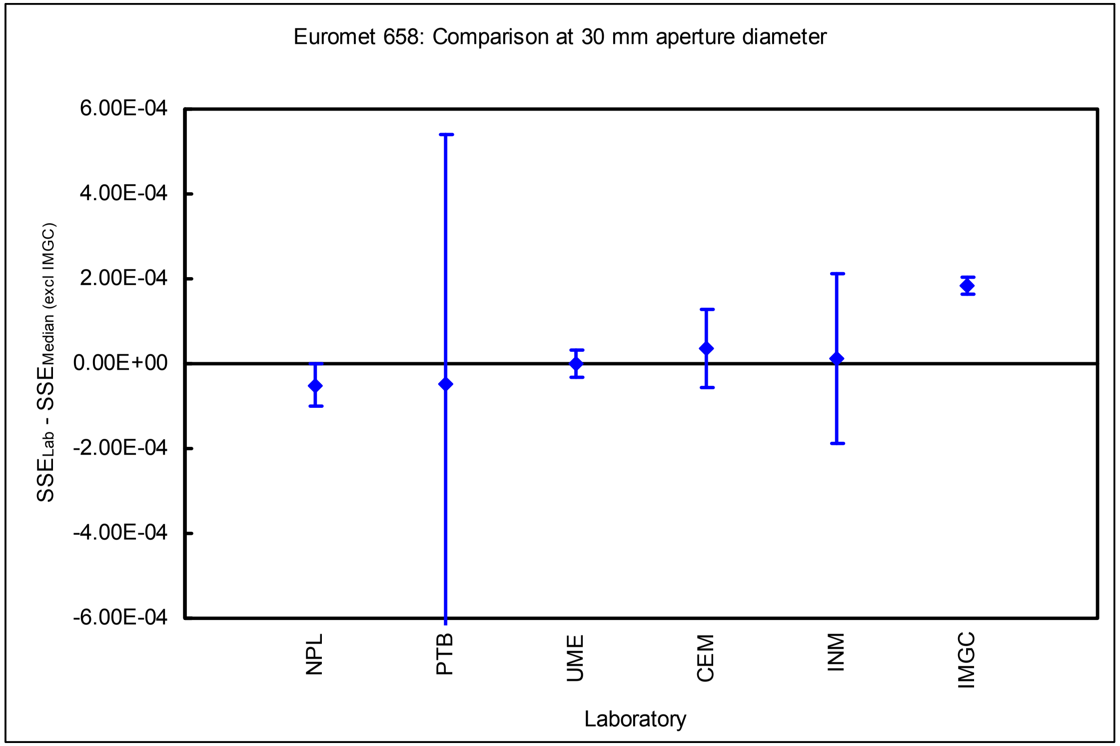
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	3.824E-06 ± 6.023E-04	-3.132E-05 ± 6.020E-05	-8.464E-05 ± 9.573E-05	-4.321E-05 ± 1.651E-04	-1.984E-04 ± 5.349E-05
PTB	*5.935E-04*	-	-3.515E-05 ± 6.011E-04	-8.847E-05 ± 6.057E-04	-4.704E-05 ± 6.205E-04	-2.022E-04 ± 6.005E-04
UME	*8.099E-05*	*5.912E-04*	-	-5.332E-05 ± 8.784E-05	-1.189E-05 ± 1.606E-04	-1.670E-04 ± 3.759E-05
CEM	*1.634E-04*	*6.172E-04*	*1.257E-04*	-	4.143E-05 ± 1.770E-04	-1.137E-04 ± 8.338E-05
INM	*1.822E-04*	*6.127E-04*	*1.585E-04*	*1.914E-04*	-	-1.551E-04 ± 1.582E-04
IMGC	*2.424E-04*	*7.026E-04*	*1.980E-04*	*1.823E-04*	*2.853E-04*	-

Table 144 – LP3 comparison with the 6 mm diameter spot and the 25 mm diameter aperture



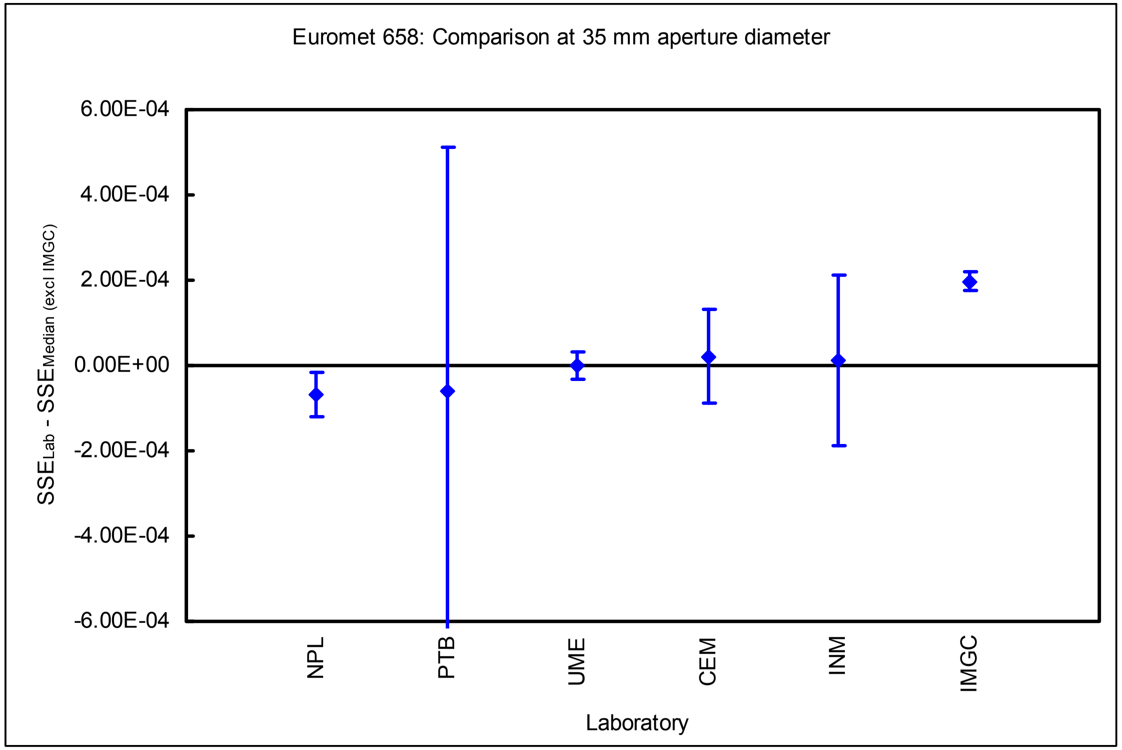
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	-1.755E-06 ± 5.913E-04	-5.159E-05 ± 6.020E-05	-8.733E-05 ± 1.051E-04	-6.250E-05 ± 2.063E-04	-2.346E-04 ± 5.441E-05
PTB	*5.832E-04*	-	-4.983E-05 ± 5.900E-04	-8.558E-05 ± 5.963E-04	-6.074E-05 ± 6.221E-04	-2.329E-04 ± 5.895E-04
UME	*1.011E-04*	*5.842E-04*	-	-3.574E-05 ± 9.792E-05	-1.091E-05 ± 2.027E-04	-1.831E-04 ± 3.888E-05
CEM	*1.738E-04*	*6.067E-04*	*1.171E-04*	-	2.483E-05 ± 2.203E-04	-1.473E-04 ± 9.447E-05
INM	*2.351E-04*	*6.189E-04*	*1.993E-04*	*2.206E-04*	-	-1.721E-04 ± 2.011E-04
IMGC	*2.794E-04*	*7.217E-04*	*2.150E-04*	*2.250E-04*	*3.376E-04*	-

Table 145 - LP3 comparison with the 6 mm diameter spot and the 30 mm diameter aperture



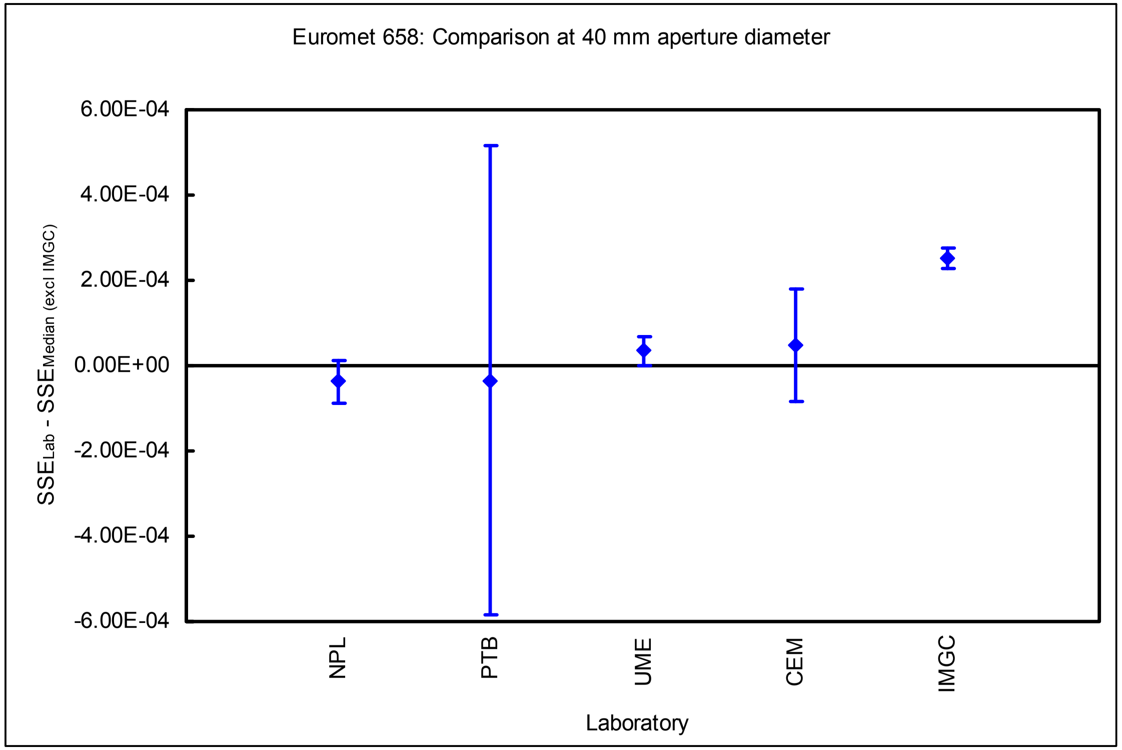
	NPL	PTB	UME	CEM	INM	IMGC
NPL	-	-6.190E-06 ± 5.774E-04	-6.780E-05 ± 6.020E-05	-8.961E-05 ± 1.216E-04	-8.000E-05 ± 2.063E-04	-2.658E-04 ± 5.510E-05
PTB	*5.683E-04*	-	-6.161E-05 ± 5.762E-04	-8.342E-05 ± 5.858E-04	-7.381E-05 ± 6.090E-04	-2.596E-04 ± 5.757E-04
UME	*1.173E-04*	*5.754E-04*	-	-2.181E-05 ± 1.155E-04	-1.220E-05 ± 2.027E-04	-1.980E-04 ± 3.985E-05
CEM	*1.897E-04*	*5.957E-04*	*1.210E-04*	-	9.614E-06 ± 2.286E-04	-1.762E-04 ± 1.130E-04
INM	*2.511E-04*	*6.123E-04*	*1.995E-04*	*2.245E-04*	-	-1.858E-04 ± 2.013E-04
IMGC	*3.111E-04*	*7.355E-04*	*2.308E-04*	*2.691E-04*	*3.514E-04*	-

Table 146 - LP3 comparison with the 6 mm diameter spot and the 35 mm diameter aperture



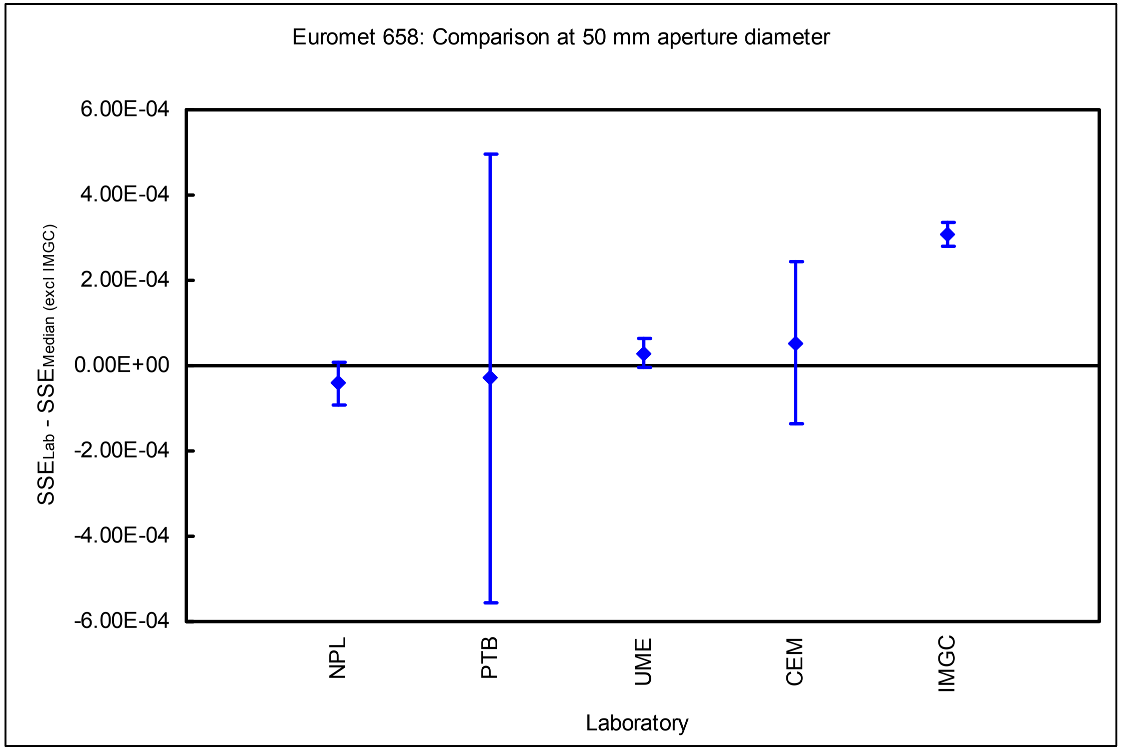
	NPL	PTB	UME	CEM	IMGC
NPL	-	-3.102E-06 ± 5.525E-04	-7.163E-05 ± 6.020E-05	-8.559E-05 ± 1.409E-04	-2.885E-04 ± 5.586E-05
PTB	*5.445E-04*	-	-6.853E-05 ± 5.512E-04	-8.248E-05 ± 5.658E-04	-2.854E-04 ± 5.508E-04
UME	*1.211E-04*	*5.551E-04*	-	-1.395E-05 ± 1.357E-04	-2.169E-04 ± 4.089E-05
CEM	*2.017E-04*	*5.764E-04*	*1.353E-04*	-	-2.029E-04 ± 1.338E-04
IMGC	*3.345E-04*	*7.398E-04*	*2.505E-04*	*3.130E-04*	-

Table 147 - LP3 comparison with the 6 mm diameter spot and the 40 mm diameter aperture



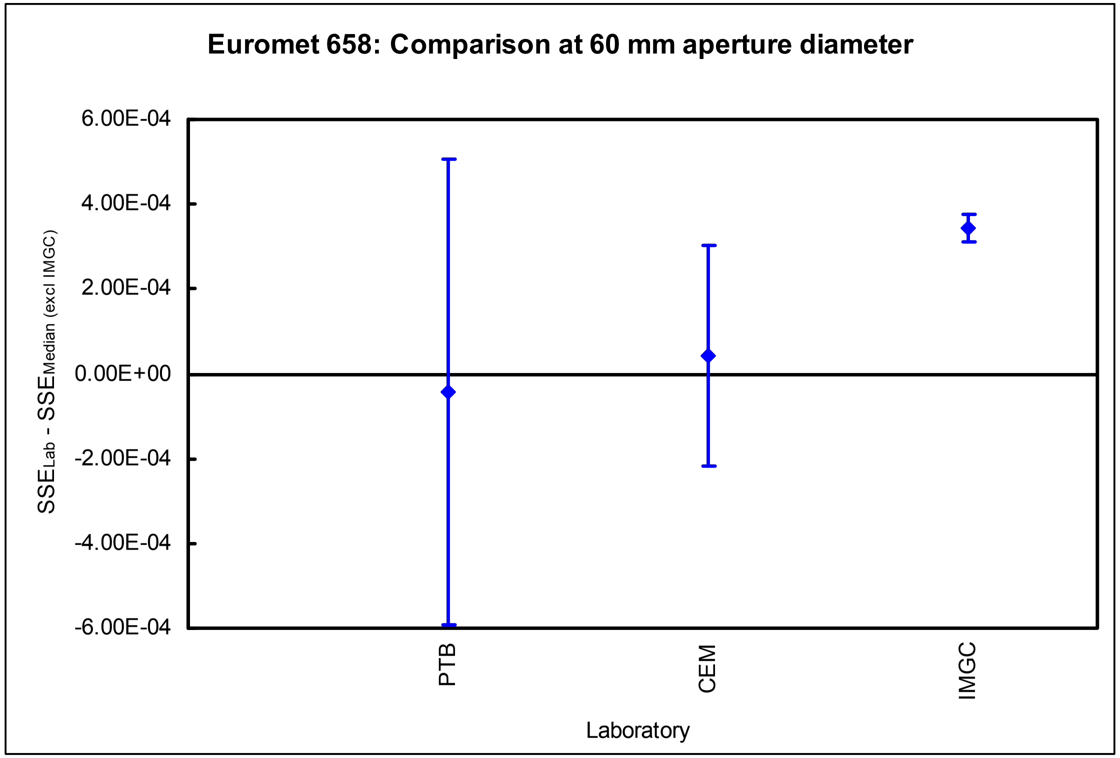
	NPL	PTB	UME	CEM	IMGC
NPL	-	-1.200E-05 ± 5.288E-04	-7.196E-05 ± 6.020E-05	-9.595E-05 ± 1.974E-04	-3.506E-04 ± 5.755E-05
PTB	*5.194E-04*	-	-5.996E-05 ± 5.274E-04	-8.395E-05 ± 5.599E-04	-3.386E-04 ± 5.271E-04
UME	*1.215E-04*	*5.284E-04*	-	-2.399E-05 ± 1.937E-04	-2.786E-04 ± 4.317E-05
CEM	*2.589E-04*	*5.719E-04*	*1.950E-04*	-	-2.547E-04 ± 1.928E-04
IMGC	*3.979E-04*	*7.726E-04*	*3.142E-04*	*4.133E-04*	-

Table 148 - LP3 comparison with the 6 mm diameter spot and the 50 mm diameter aperture



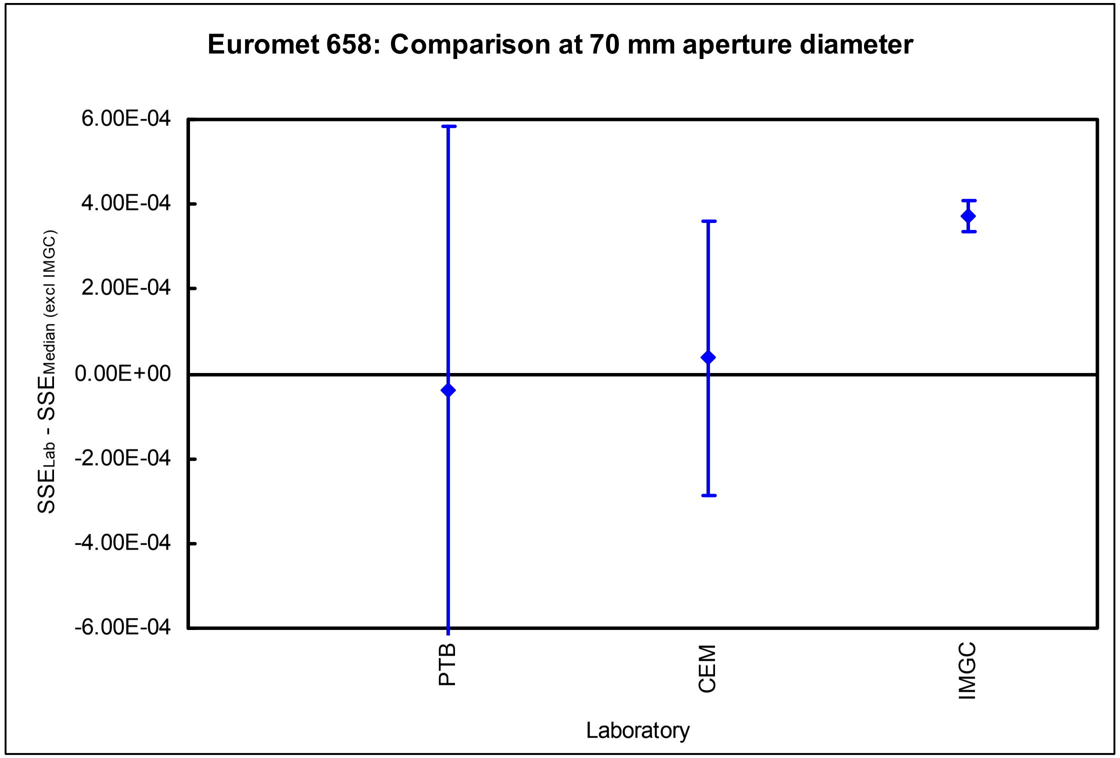
	PTB	CEM	IMGC
PTB	-	-8.505E-05 ± 6.056E-04	-3.873E-04 ± 5.484E-04
CEM	*6.151E-04*	-	-3.022E-04 ± 2.607E-04
IMGC	*8.387E-04*	*5.167E-04*	-

Table 149 - LP3 comparison with the 6 mm diameter spot and the 60 mm diameter aperture



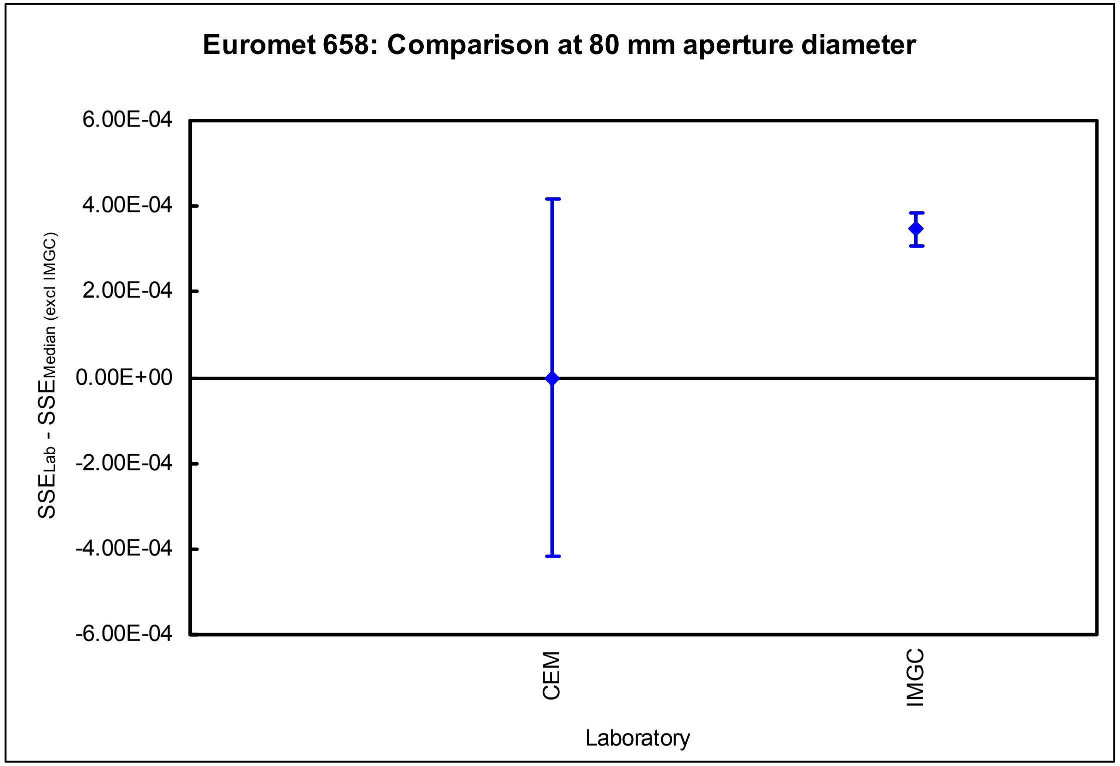
	PTB	CEM	IMGC
PTB	-	-7.391E-05 ± 6.988E-04	-4.097E-04 ± 6.212E-04
CEM	*6.975E-04*	-	-3.358E-04 ± 3.239E-04
IMGC	*9.212E-04*	*6.022E-04*	-

Table 150 - LP3 comparison with the 6 mm diameter spot and the 70 mm diameter aperture



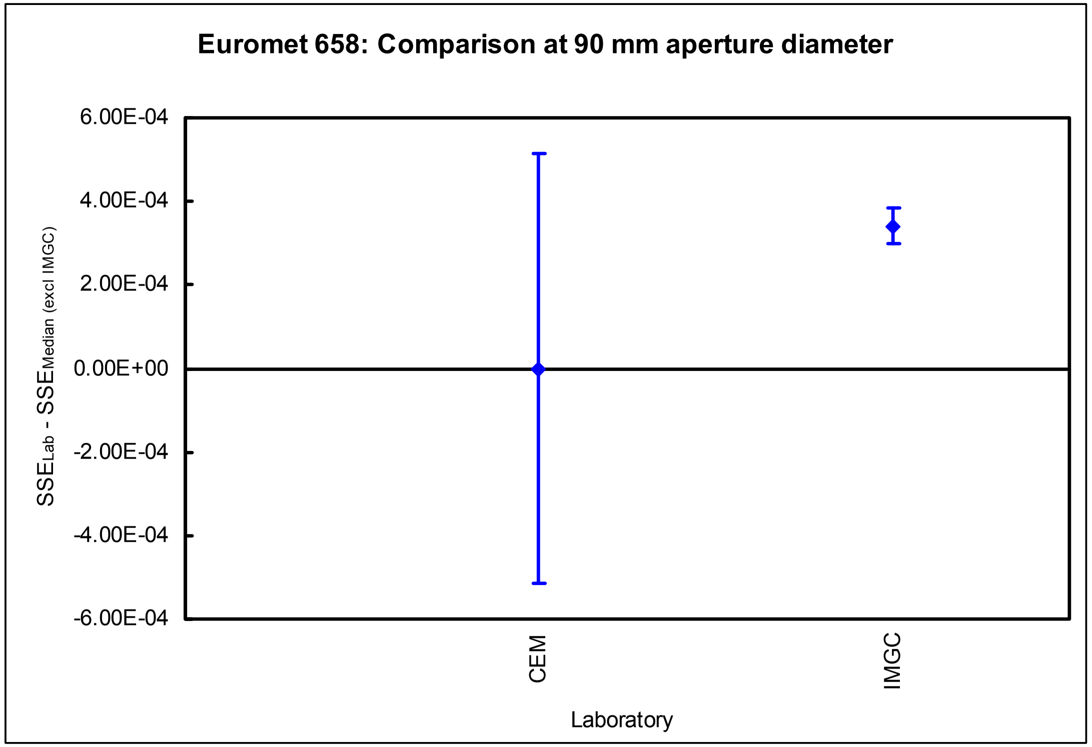
	CEM	IMGC
CEM	-	-3.464E-04 ± 4.199E-04
IMGC	*6.919E-04*	-

Table 151 - LP3 comparison with the 6 mm diameter spot and the 80 mm diameter aperture



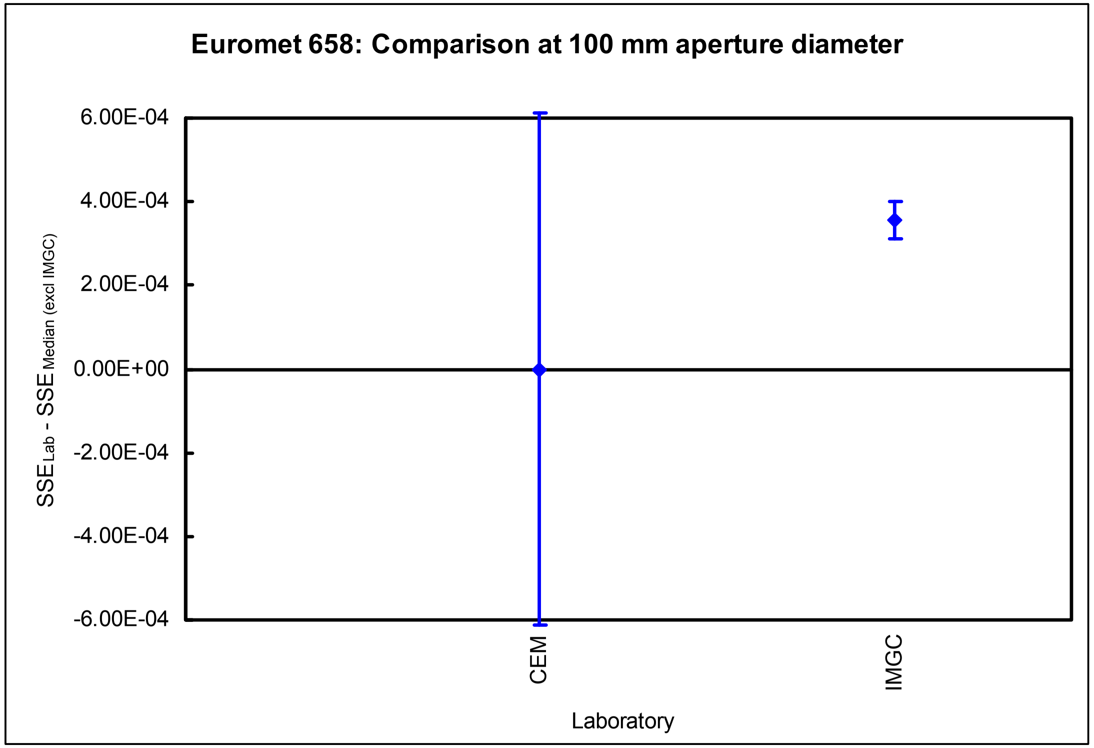
	CEM	IMGC
CEM	-	-3.403E-04 ± 5.164E-04
IMGC	*7.655E-04*	-

Table 152 - LP3 comparison with the 6 mm diameter spot and the 90 mm diameter aperture



	CEM	IMGC
CEM	-	-3.576E-04 ± 6.128E-04
IMGC	*8.625E-04*	-

Table 153 - LP3 comparison with the 6 mm diameter spot and the 100 mm diameter aperture



APPENDIX 4 – THE FITTING DATA FOR THE VEGA SSE MEASUREMENTS

Index	Chebyshev coefficient
0	1.65019379E-02
1	3.65005899E-03
2	-9.51100947E-04
3	6.22735144E-04
4	-1.79692926E-04
5	-4.31644870E-06
6	-1.47882909E-04

Table 154 – the Chebyshev coefficients for the NPL data with the 3 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
5	0.002669	0.002704	0.000035
6	0.003615	0.003557	-0.000058
7	0.004246	0.004259	0.000013
9	0.005328	0.005328	0.000000
10	-	*0.005741*	-
12	0.006397	0.006411	0.000014
15	0.007151	0.007189	0.000038
18	0.007884	0.007830	-0.000054
20	0.008222	0.008204	-0.000018
25	0.008882	0.008933	0.000051
30	0.009355	0.009332	-0.000023
35	-	*0.009568*	-
40	0.010019	0.010022	0.000003
50	0.011241	0.011241	0.000000

Table 155 – the fitted results for the NPL measurements with the 3 mm diameter spot

Index	Chebyshev coefficient
0	2.08848714E-02
1	3.06065592E-03
2	-1.02472456E-03
3	1.98966283E-04
4	-9.56139827E-05
5	1.42513276E-04
6	-7.92904998E-05
7	9.15442581E-06
8	8.68894563E-05

Table 156 - the Chebyshev coefficients for the IMGC data with the 3 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
10	0.005886	0.005918	0.000032
12	0.006526	0.006460	-0.000066
15	0.007227	0.007250	0.000023
18	-	*0.007912*	-
20	0.008226	0.008266	0.000040
25	0.008896	0.008884	-0.000012
30	0.009332	0.009288	-0.000044
35	0.009706	0.009668	-0.000038
40	0.009999	0.010119	0.000120
50	0.011225	0.011129	-0.000096
60	0.011757	0.011816	0.000059
70	0.012114	0.012090	-0.000024
80	0.012364	0.012370	0.000006
90	0.012573	0.012572	-0.000001
100	0.012741	0.012741	0.000000

Table 157 - the fitted results for the IMGC measurements with the 3 mm diameter spot

Index	Chebyshev coefficient
0	9.61662625E-03
1	3.04243861E-03
2	-6.78437027E-04
3	4.50139443E-04
4	-6.96284015E-05
5	-1.65552718E-06
6	-4.03071365E-05

Table 158 - the Chebyshev coefficients for the NPL data with the 6 mm diameter spot

Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
7	0.000519	0.000529	0.000010
9	0.001558	0.001538	-0.000020
10	-	*0.001955*	-
12	0.002670	0.002659	-0.000011
15	0.003417	0.003483	0.000066
18	0.004159	0.004119	-0.000040
20	0.004502	0.004469	-0.000033
25	0.005093	0.005136	0.000043
30	0.005585	0.005568	-0.000017
35	-	*0.005888*	-
40	0.006282	0.006284	0.000002
50	0.007511	0.007511	0.000000

Table 159 - the fitted results for the NPL measurements with the 6 mm diameter spot

Index	Chebyshev coefficient
0	1.36458313E-02
1	3.13670471E-03
2	-1.04870763E-03
3	2.07896491E-04
4	-9.82985263E-05
5	1.51530088E-04
6	-8.38709154E-05
7	1.30494282E-05
8	8.88318760E-05

Table 160 - the Chebyshev coefficients for the IMGC data with the 6 mm diameter spot

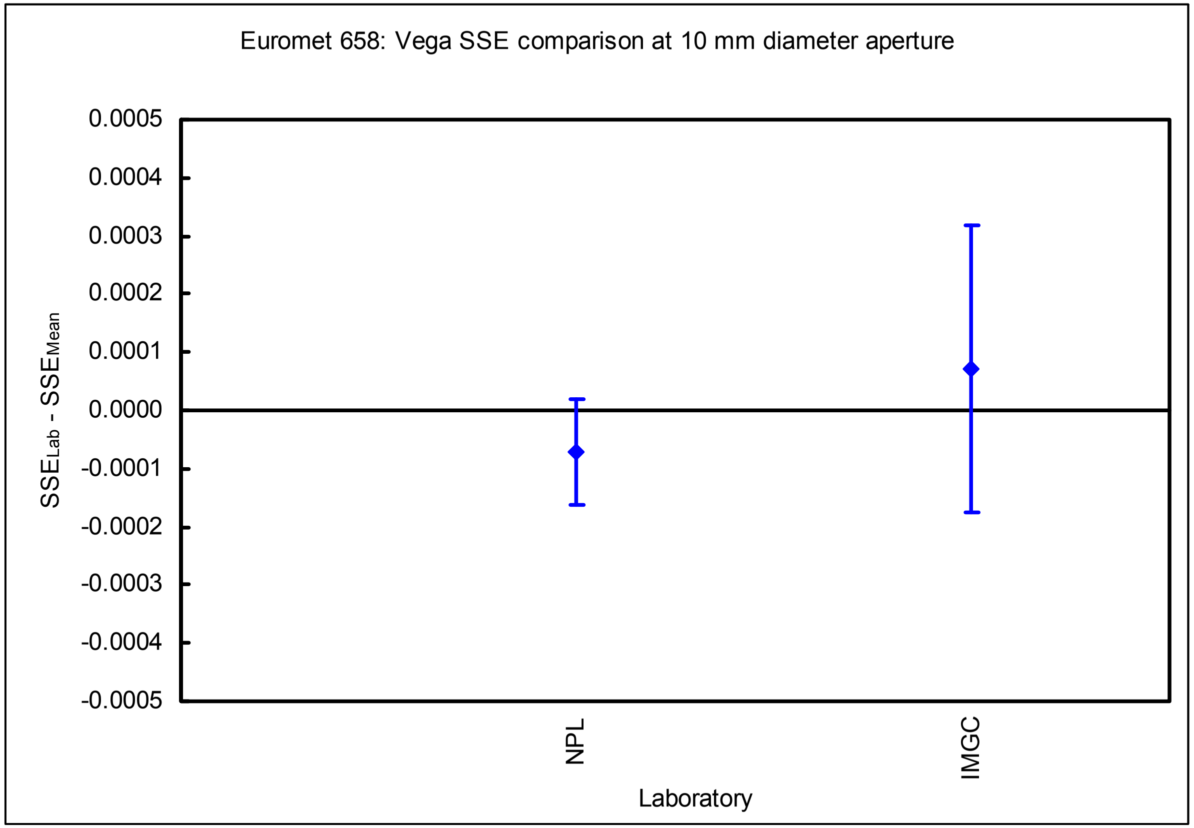
Aperture diameter / mm	SSE (raw data)	SSE (fitted data)	Residual
10	0.002143	0.002172	0.000029
12	0.002800	0.002743	-0.000057
15	0.003544	0.003562	0.000018
18	-	*0.004241*	-
20	0.004562	0.004601	0.000039
25	0.005238	0.005228	-0.000010
30	0.005683	0.005637	-0.000046
35	0.006056	0.006026	-0.000030
40	0.006377	0.006489	0.000112
50	0.007623	0.007527	-0.000096
60	0.008168	0.008230	0.000062
70	0.008536	0.008509	-0.000027
80	0.008788	0.008795	0.000007
90	0.009002	0.009001	-0.000001
100	0.009190	0.009190	0.000000

Table 161 - the fitted results for the IMGC measurements with the 6 mm diameter spot

APPENDIX 5 – THE QDE_{95} AND DOE VALUES FOR THE VEGA SSE RESULTS

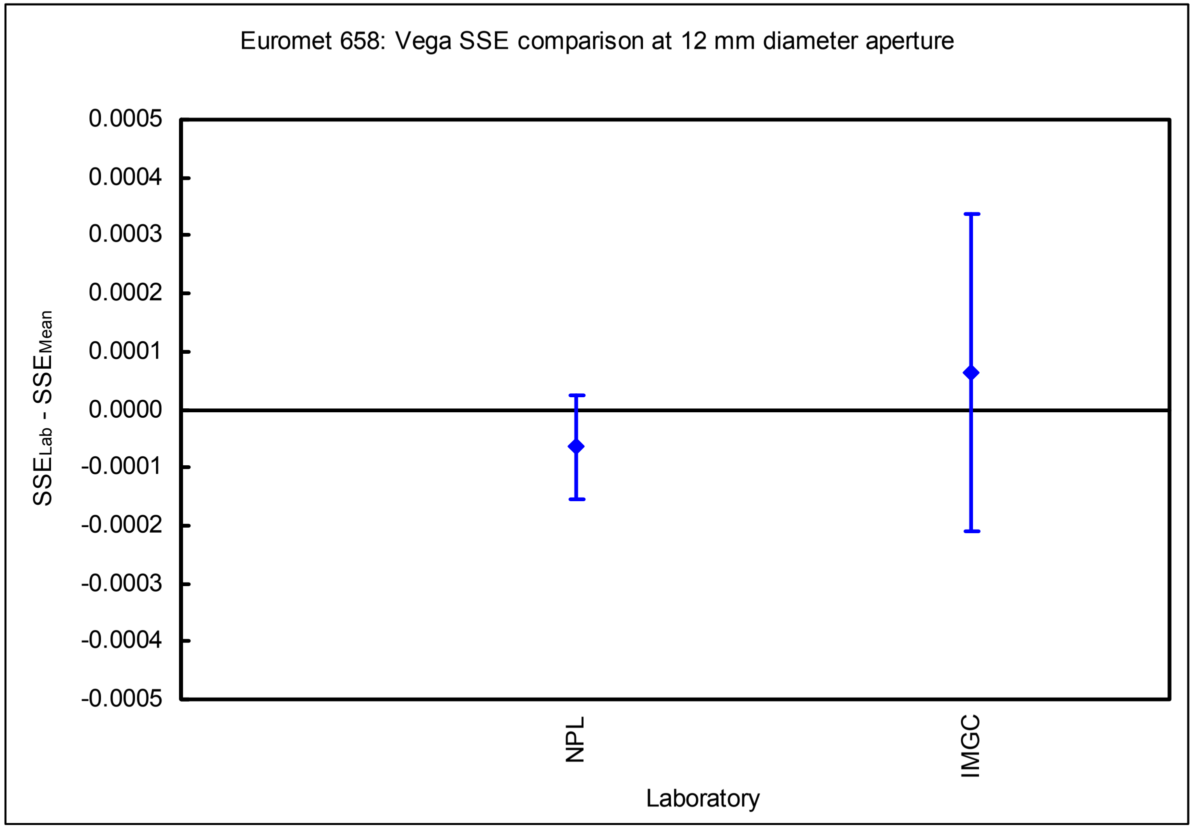
	NPL	IMGC
NPL	-	-0.000145 ± 0.000263
IMGC	*0.000362*	-

Table 162- Vega comparison with the 10 mm diameter aperture and the 3 mm diameter spot



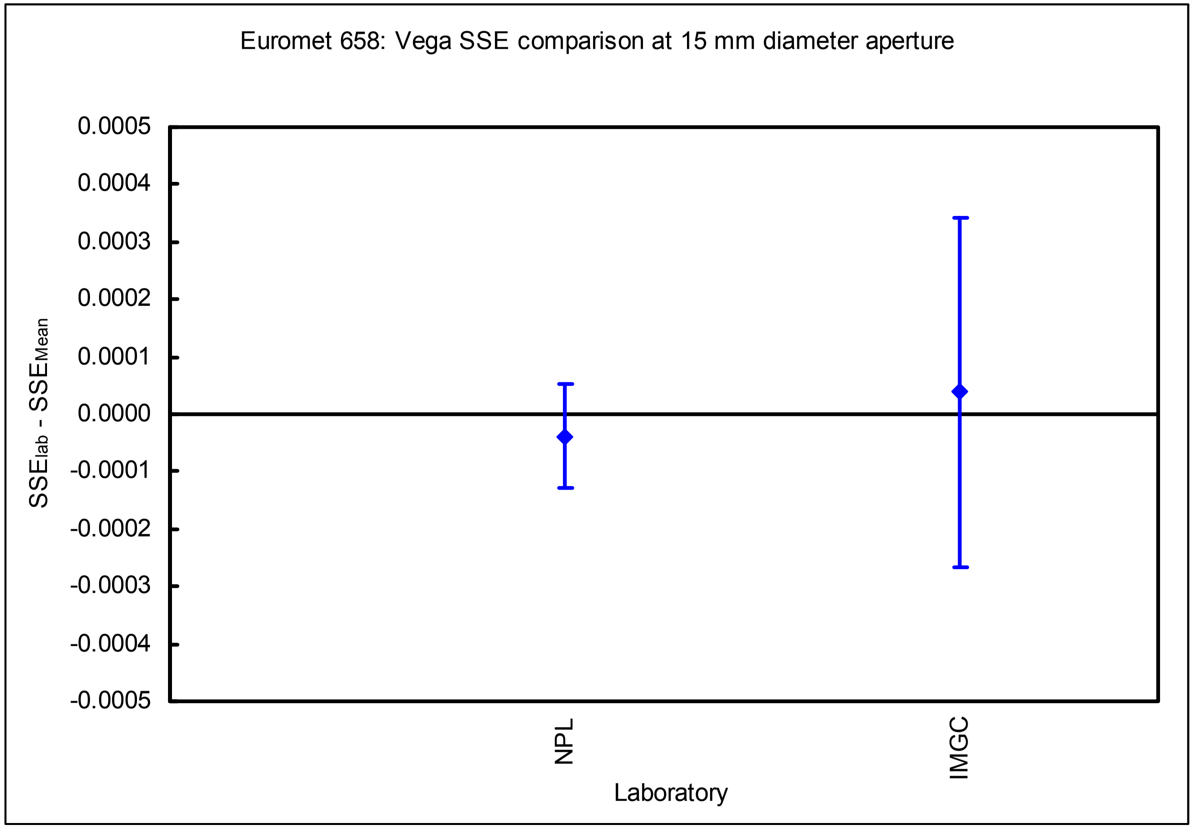
	NPL	IMGC
NPL	-	-0.000129 ± 0.000288
IMGC	*0.000367*	-

Table 163 - Vega comparison with the 12 mm diameter aperture and the 3 mm diameter spot



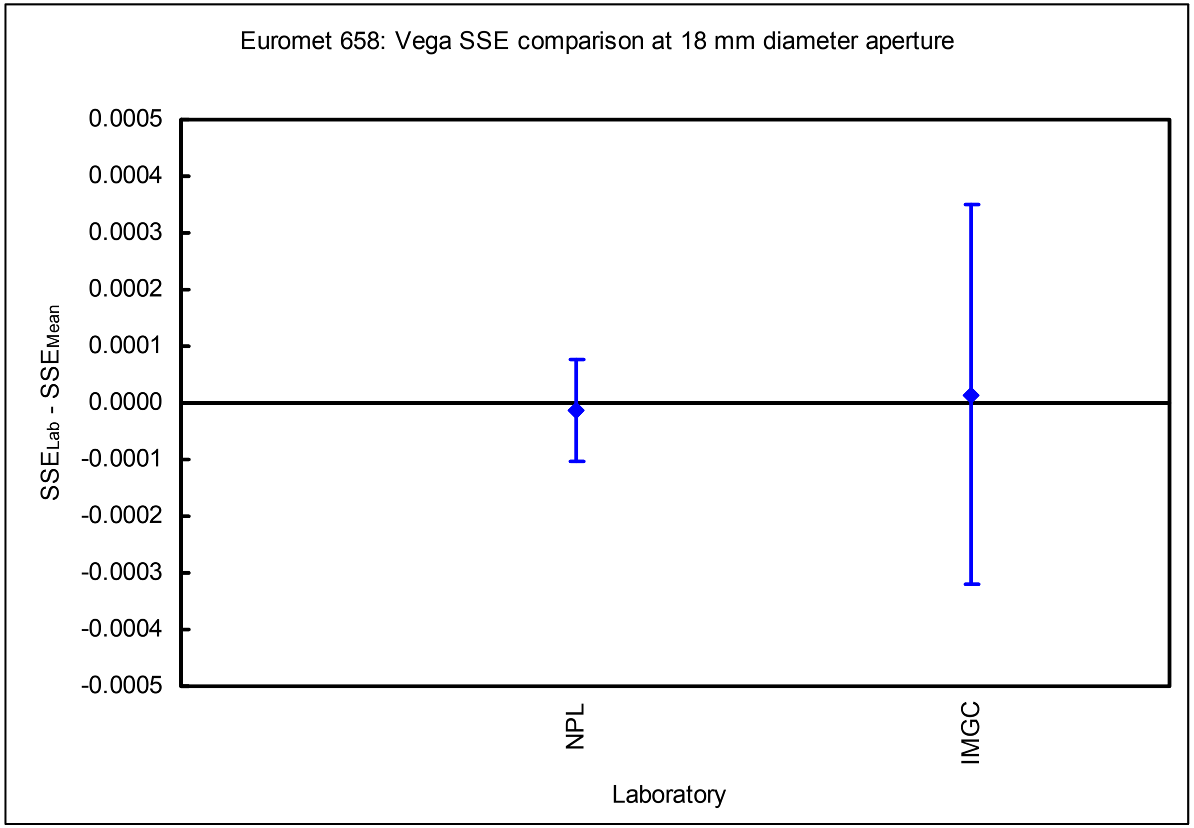
	NPL	IMGC
NPL	-	-0.000076 ± 0.000317
IMGC	*0.000344*	-

Table 164 - Vega comparison with the 15 mm diameter aperture and the 3 mm diameter spot



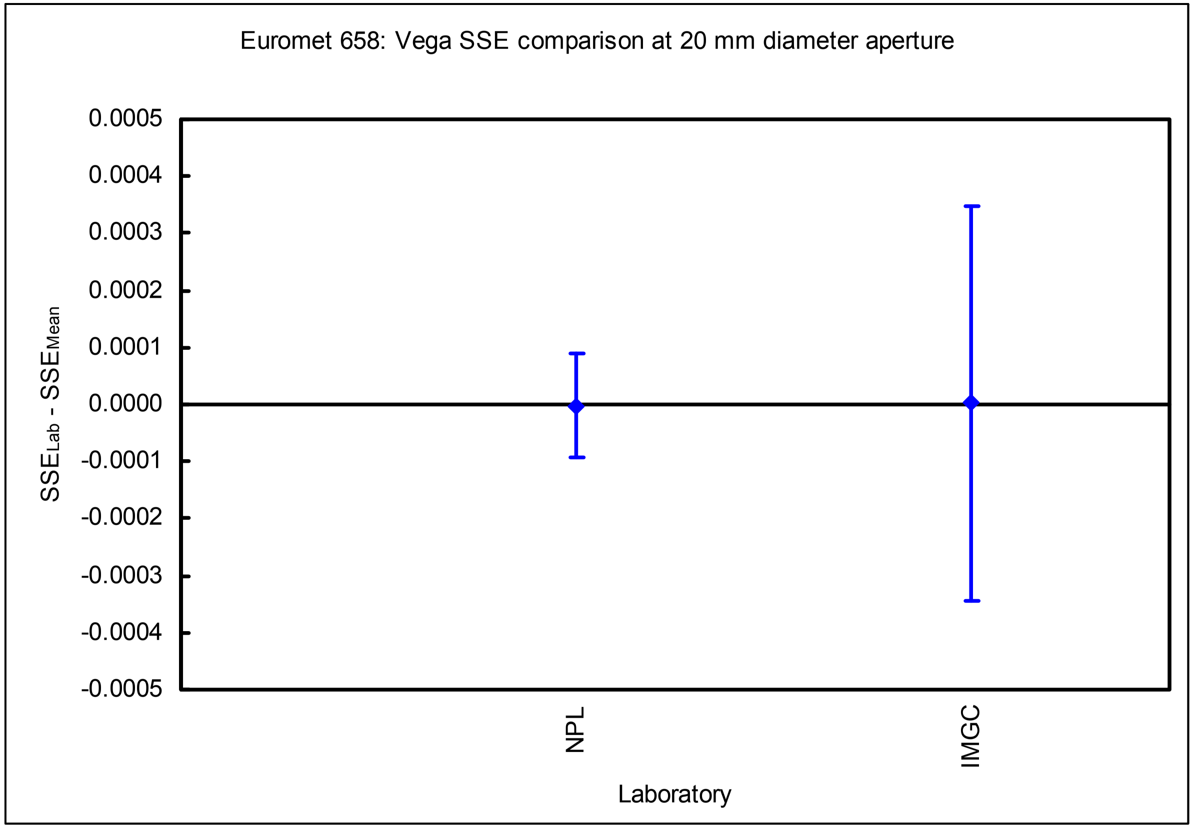
	NPL	IMGC
NPL	-	-0.000029 ± 0.000347
IMGC	*0.000343*	-

Table 165 - Vega comparison with the 18 mm diameter aperture and the 3 mm diameter spot



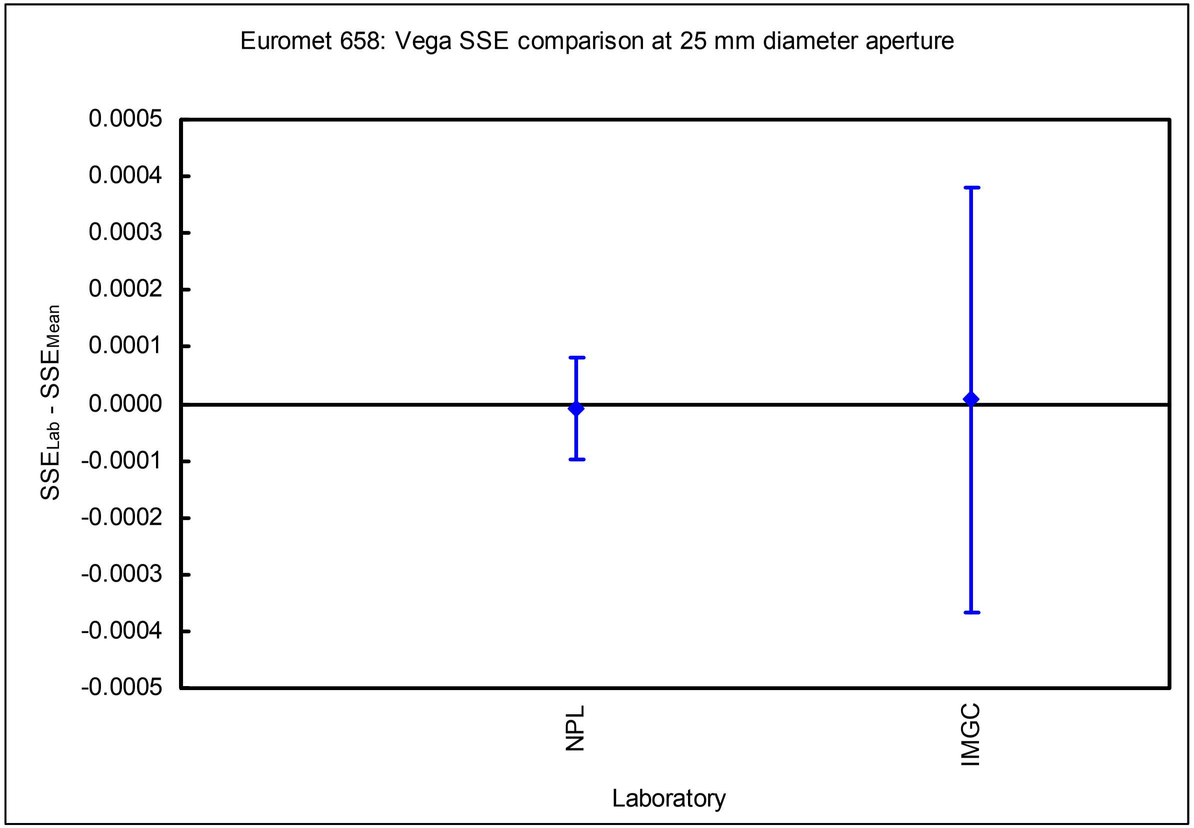
	NPL	IMGC
NPL	-	-0.000004 ± 0.000357
IMGC	*0.000351*	-

Table 166 - Vega comparison with the 20 mm diameter aperture and the 3 mm diameter spot



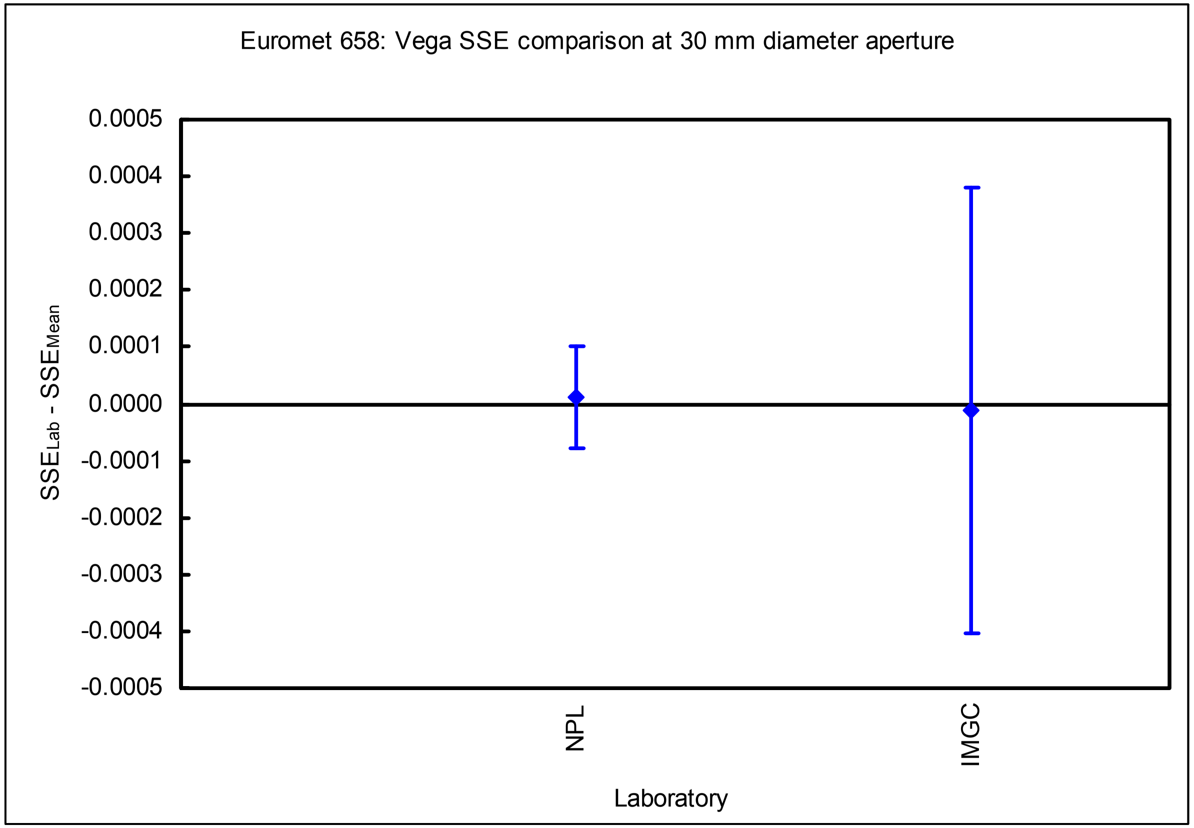
	NPL	IMGC
NPL	-	-0.000014 ± 0.000384
IMGC	*0.000377*	-

Table 167 - Vega comparison with the 25 mm diameter aperture and the 3 mm diameter spot



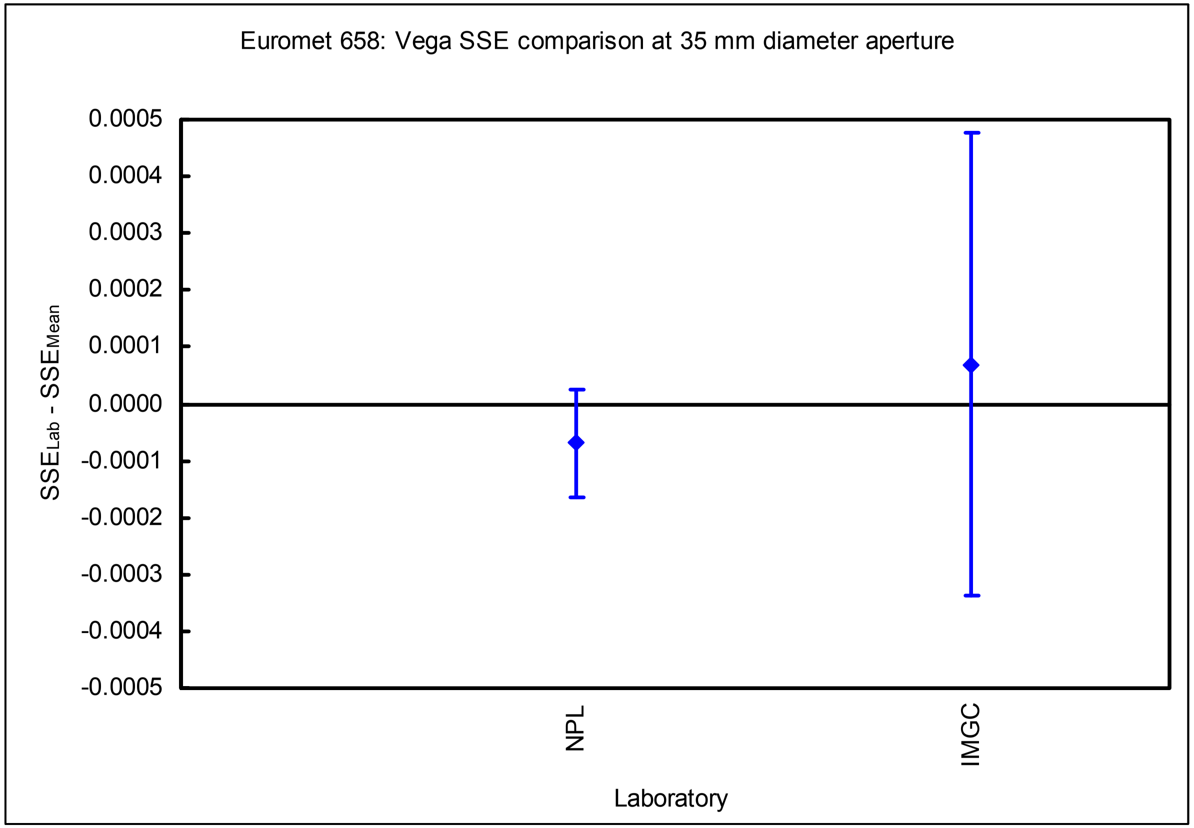
	NPL	IMGC
NPL	-	0.000023 ± 0.000402
IMGC	*0.000395*	-

Table 168 - Vega comparison with the 30 mm diameter aperture and the 3 mm diameter spot



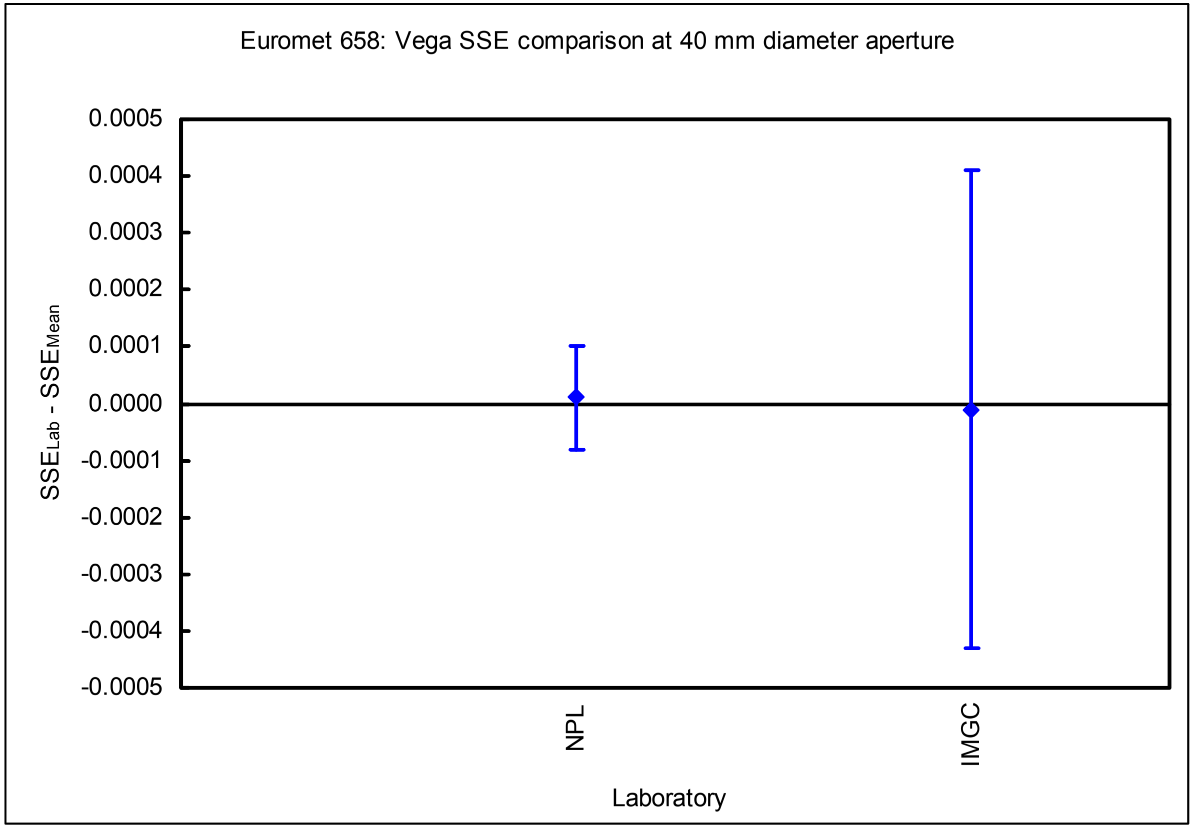
	NPL	IMGC
NPL	-	-0.000138 ± 0.000418
IMGC	*0.000487*	-

Table 169 - Vega comparison with the 35 mm diameter aperture and the 3 mm diameter spot



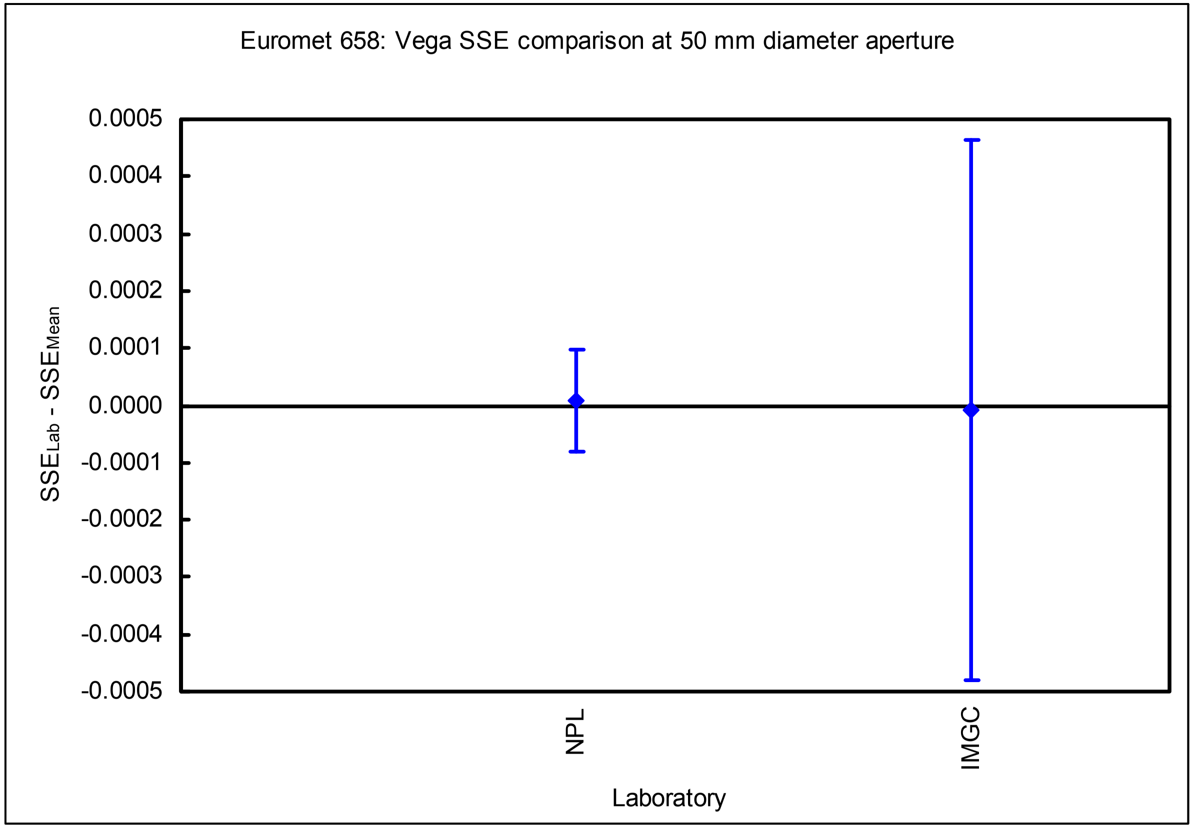
	NPL	IMGC
NPL	-	0.000020 ± 0.000429
IMGC	*0.000422*	-

Table 170 - Vega comparison with the 40 mm diameter aperture and the 3 mm diameter spot



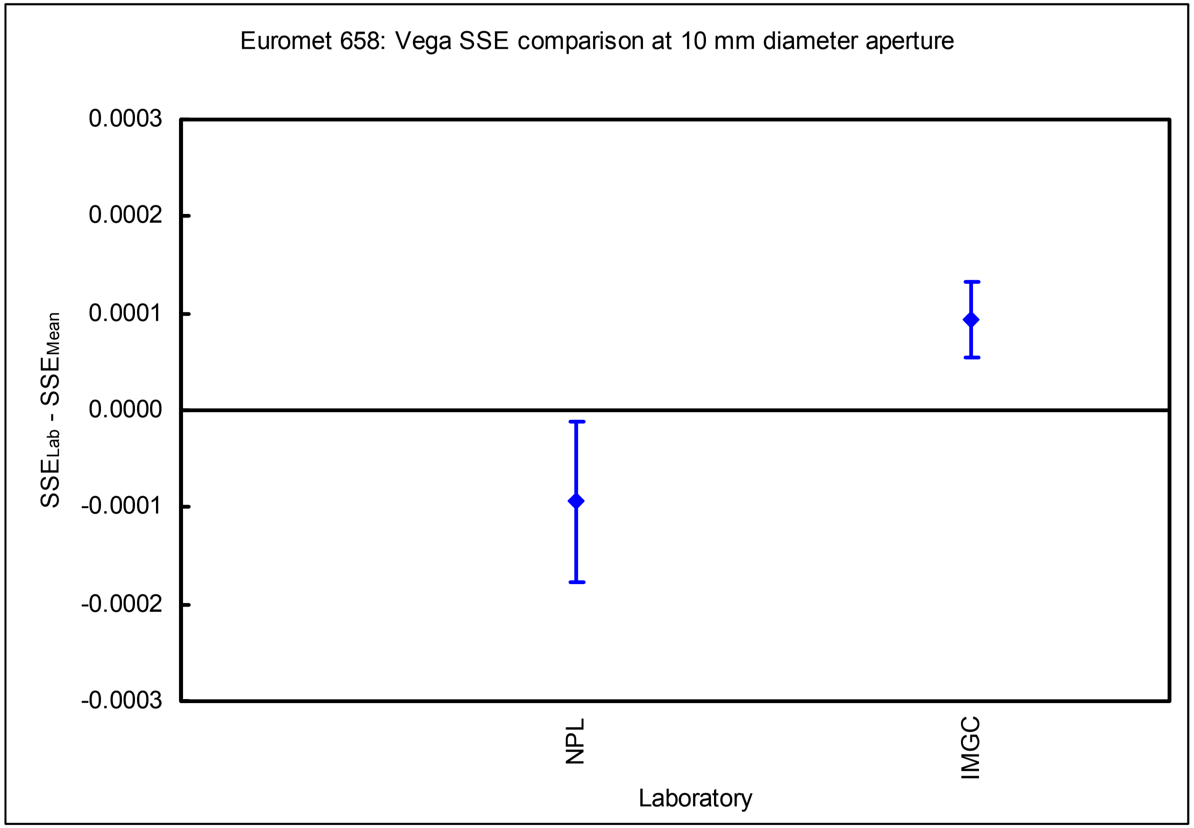
	NPL	IMGC
NPL	-	0.000016 ± 0.000480
IMGC	*0.000471*	-

Table 171 - Vega comparison with the 50 mm diameter aperture and the 3 mm diameter spot



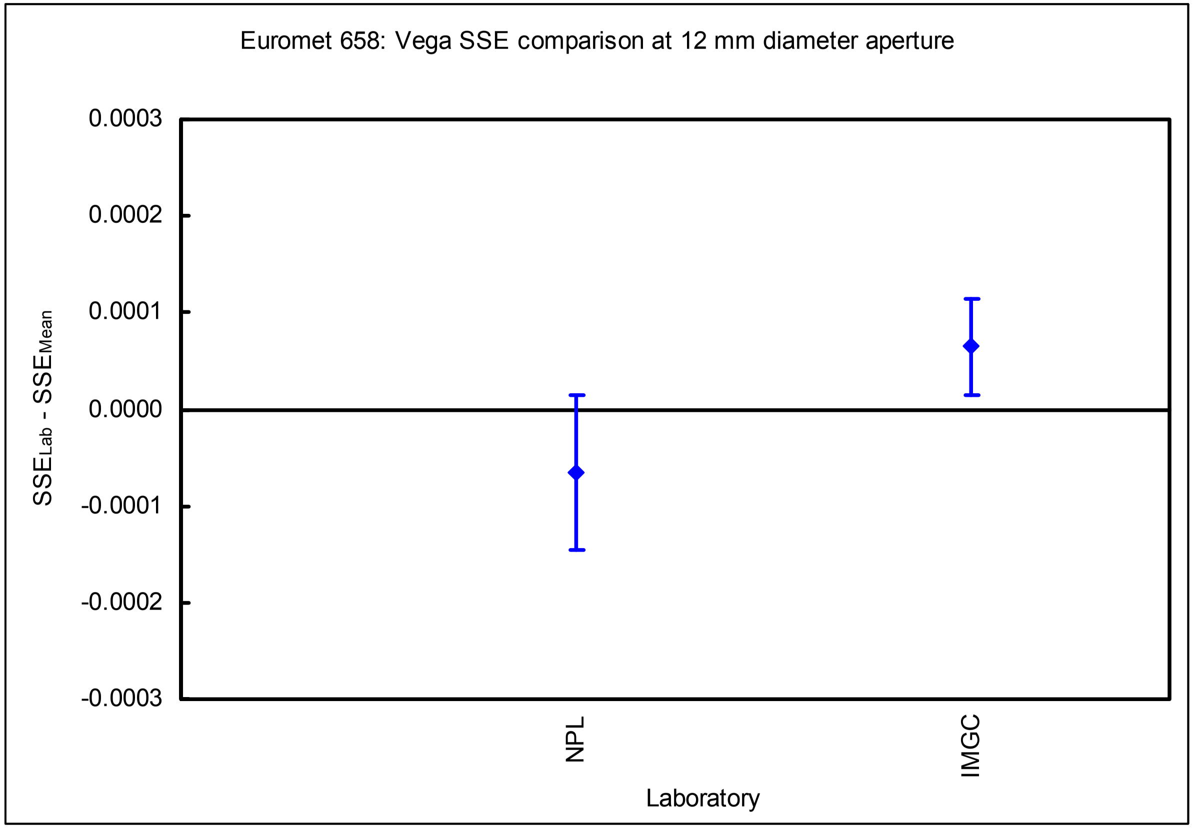
	NPL	IMGC
NPL	-	-0.000188 ± 0.000092
IMGC	*0.000263*	-

Table 172 - Vega comparison with the 10 mm diameter aperture and the 6 mm diameter spot



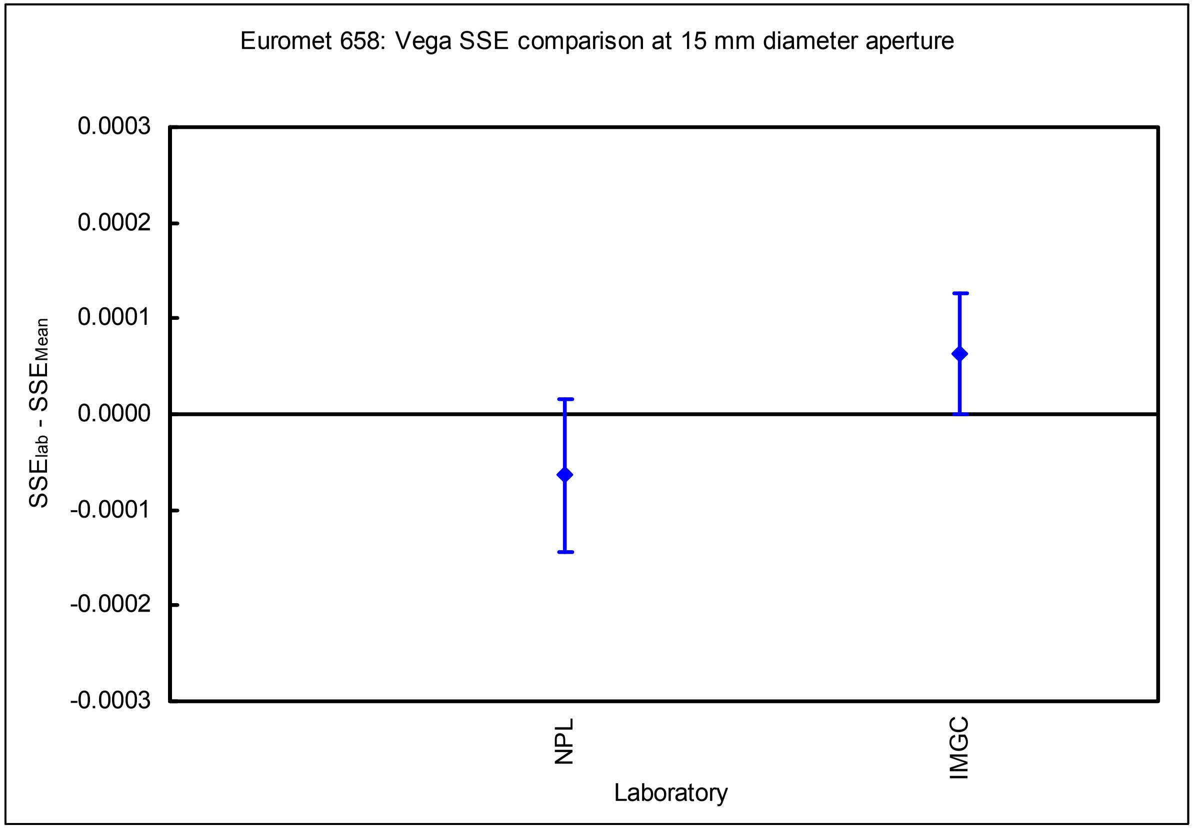
	NPL	IMGC
NPL	-	-0.000130 ± 0.000095
IMGC	*0.000207*	-

Table 173 - Vega comparison with the 12 mm diameter aperture and the 6 mm diameter spot



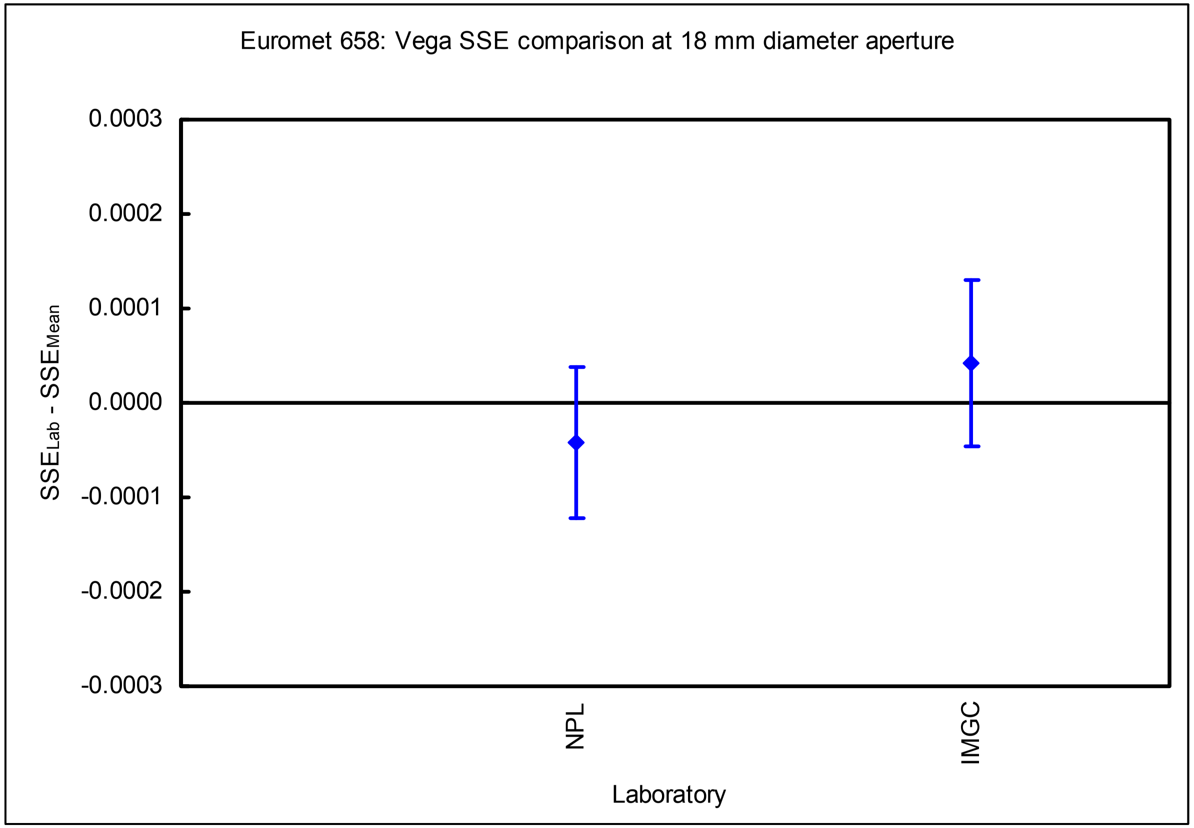
	NPL	IMGC
NPL	-	-0.000127 ± 0.000102
IMGC	*0.000211*	-

Table 174 - Vega comparison with the 15 mm diameter aperture and the 6 mm diameter spot



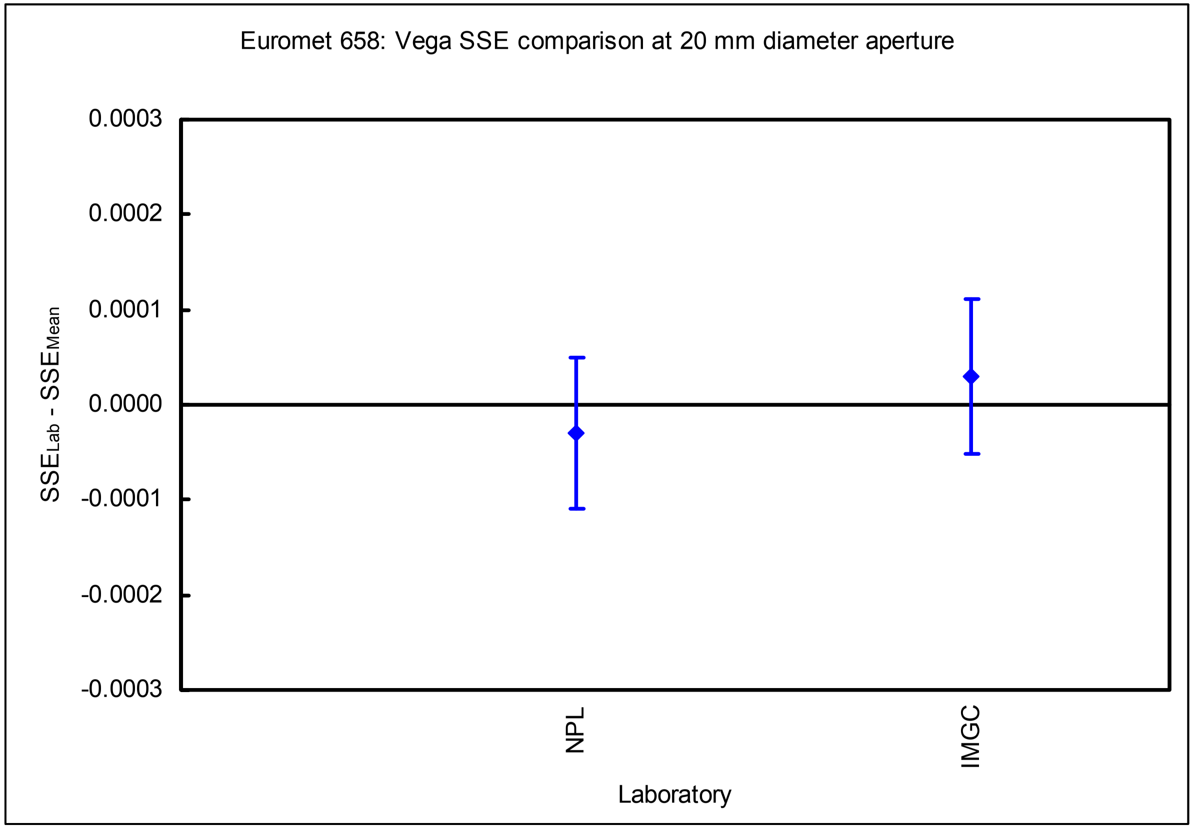
	NPL	IMGC
NPL	-	-0.000083 ± 0.000119
IMGC	*0.000180*	-

Table 175 - Vega comparison with the 18 mm diameter aperture and the 6 mm diameter spot



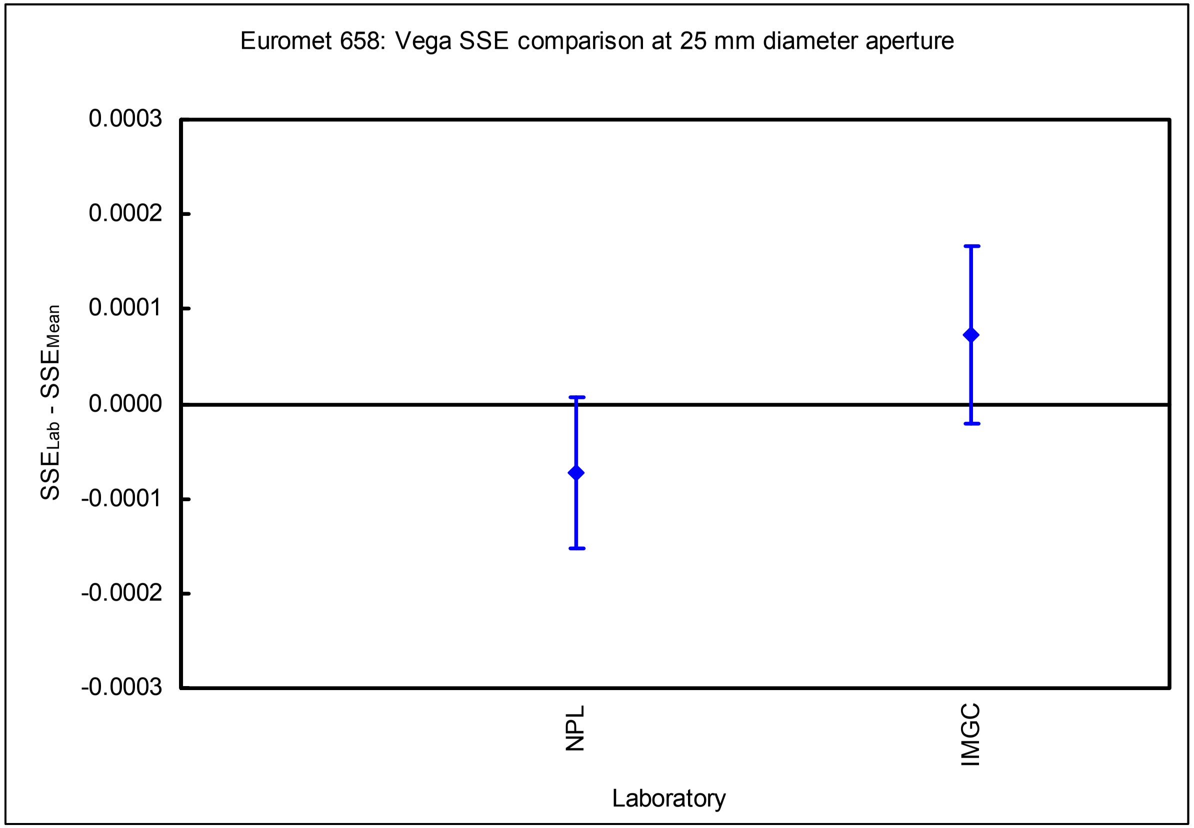
	NPL	IMGC
NPL	-	-0.000060 ± 0.000115
IMGC	*0.000155*	-

Table 176 - Vega comparison with the 20 mm diameter aperture and the 6 mm diameter spot



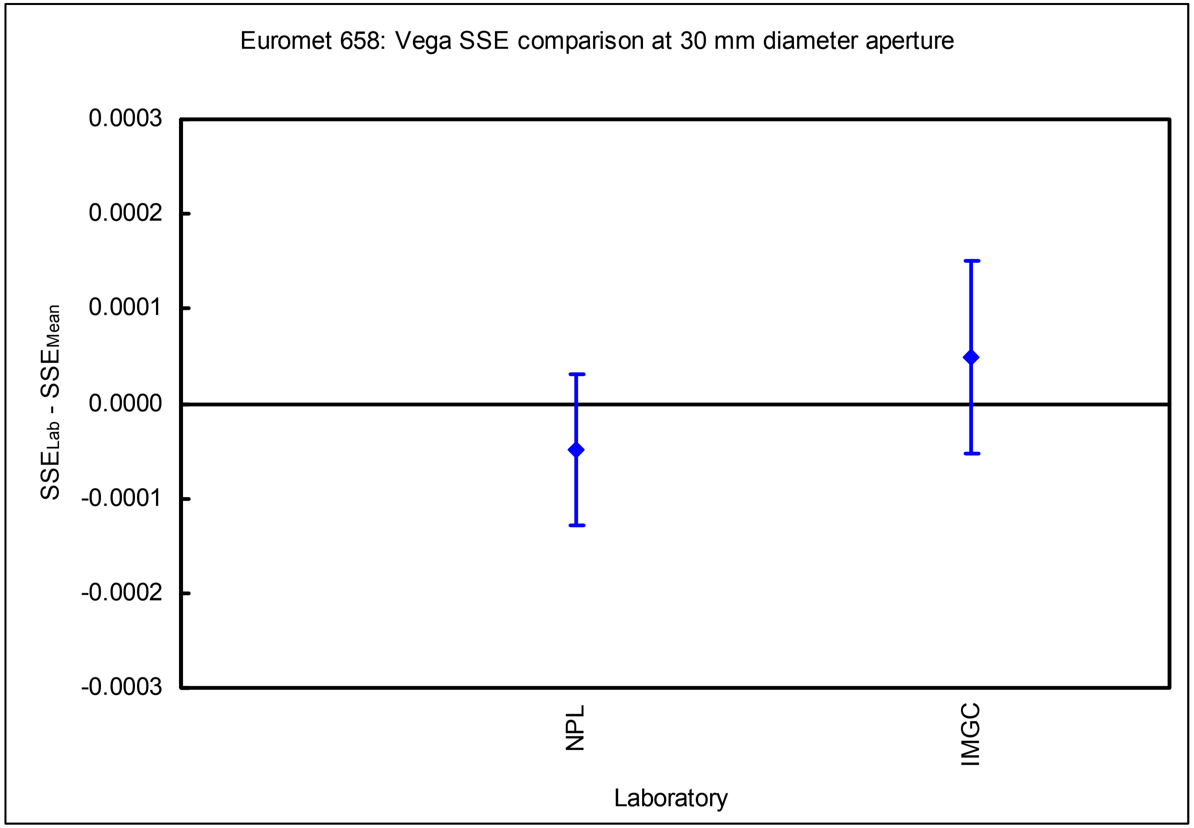
	NPL	IMGC
NPL	-	-0.000145 ± 0.000124
IMGC	*0.000247*	-

Table 177 - Vega comparison with the 25 mm diameter aperture and the 6 mm diameter spot



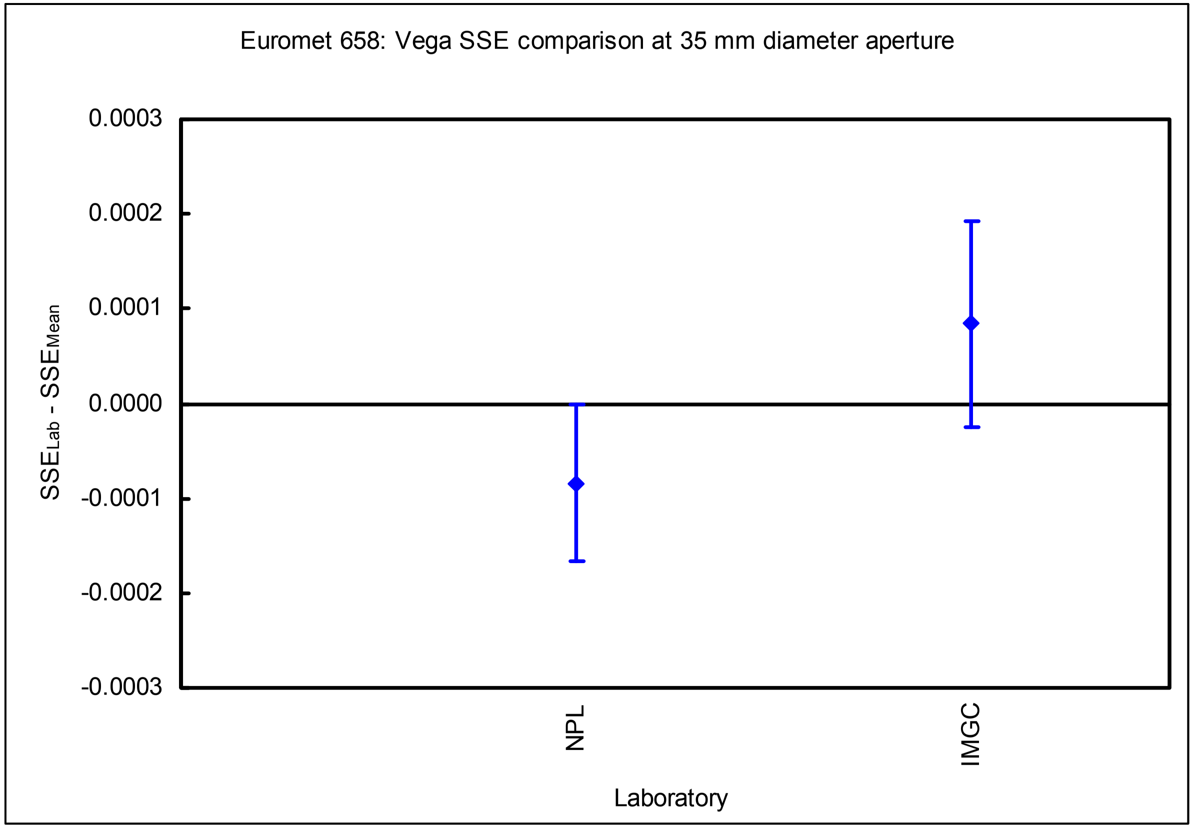
	NPL	IMGC
NPL	-	-0.000098 ± 0.000130
IMGC	*0.000205*	-

Table 178 - Vega comparison with the 30 mm diameter aperture and the 6 mm diameter spot



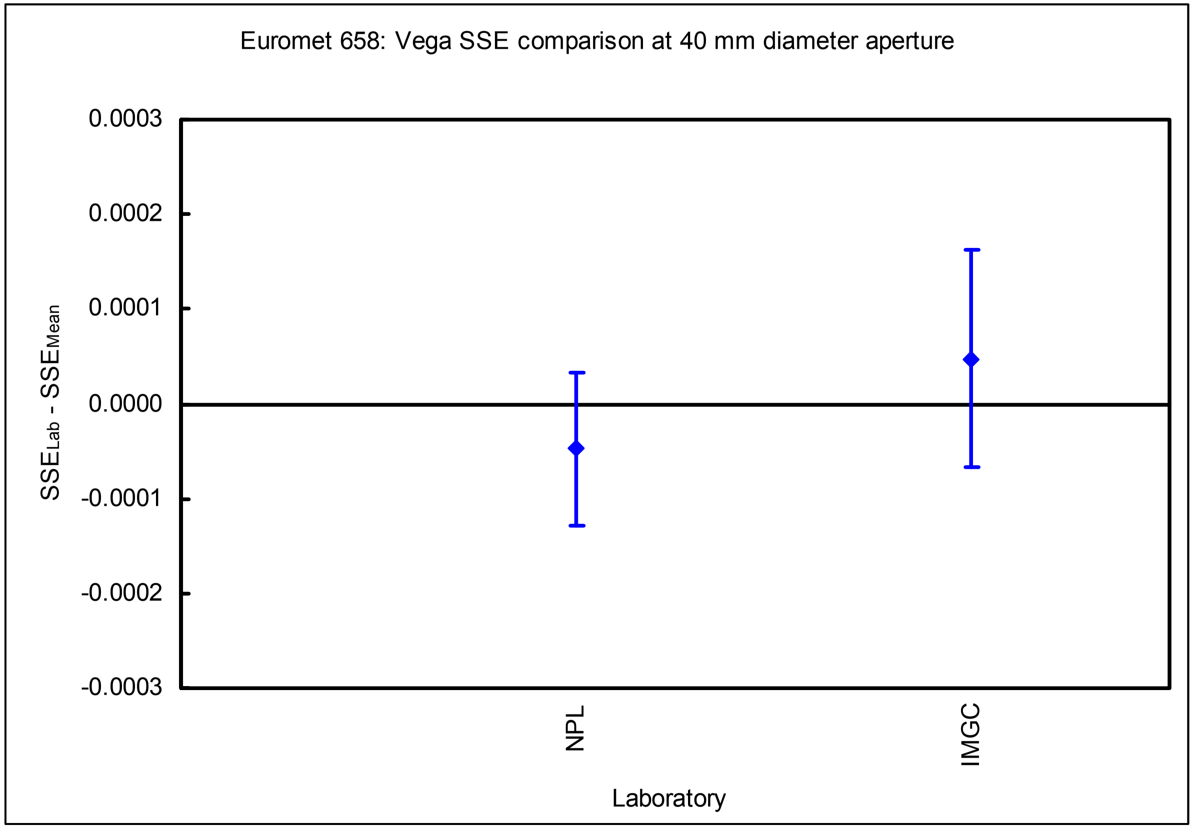
	NPL	IMGC
NPL	-	-0.000168 ± 0.000136
IMGC	*0.000280*	-

Table 179 - Vega comparison with the 35 mm diameter aperture and the 6 mm diameter spot



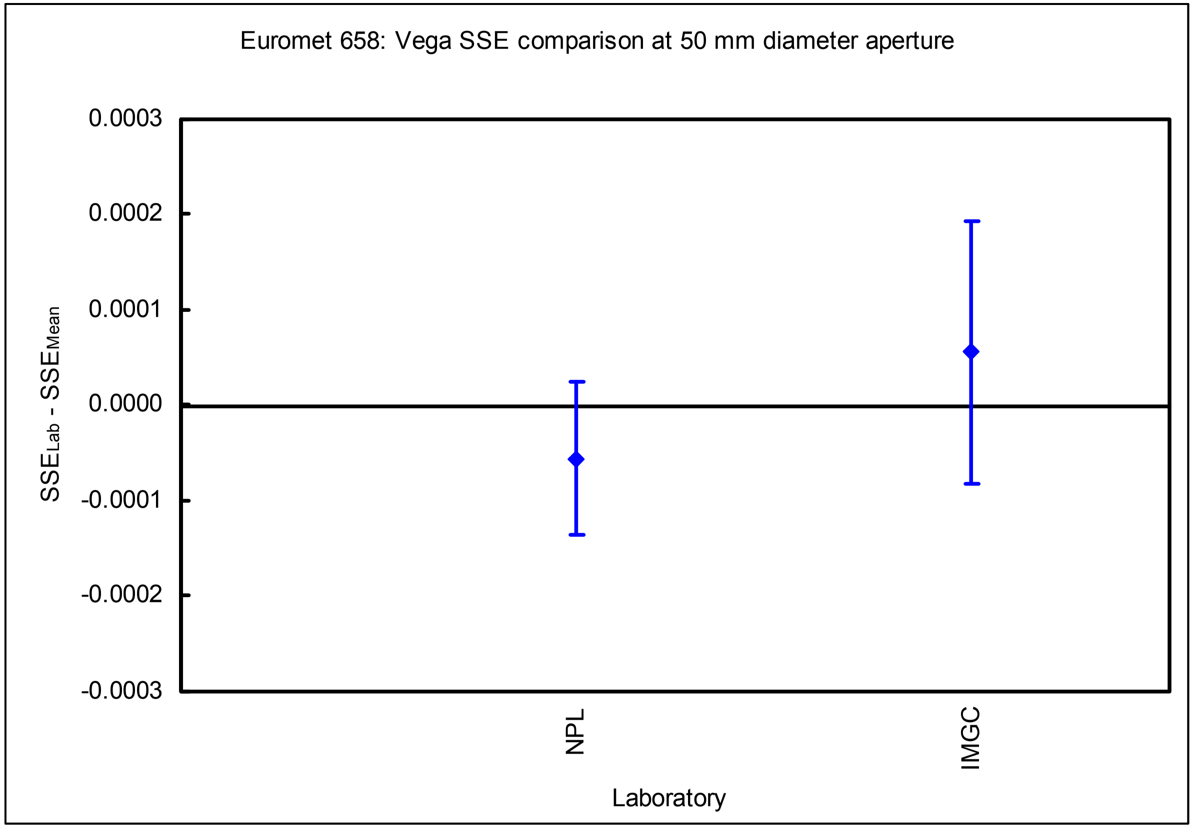
	NPL	IMGC
NPL	-	-0.000095 ± 0.000140
IMGC	*0.000211*	-

Table 180 - Vega comparison with the 40 mm diameter aperture and the 6 mm diameter spot



	NPL	IMGC
NPL	-	-0.000111 ± 0.000159
IMGC	*0.000242*	-

Table 181 - Vega comparison with the 50 mm diameter aperture and the 6 mm diameter spot

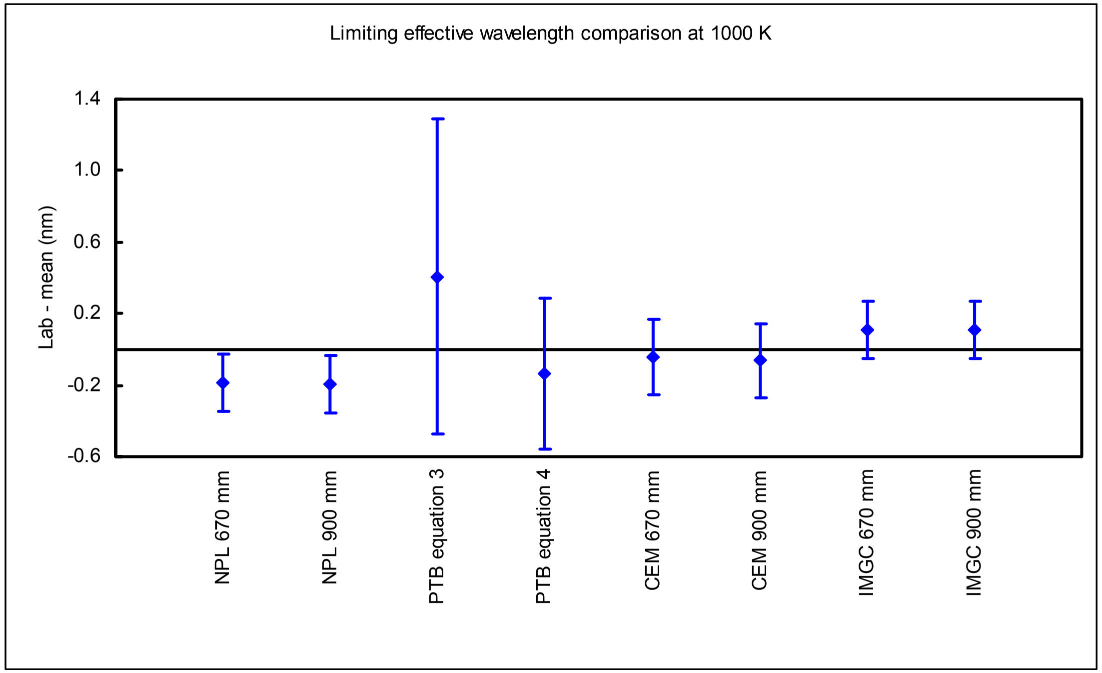


QDE$_{95}$ and DOE values and graphs for the limiting effective wavelength

APPENDIX 6 – THE QDE$_{95}$ AND DOE VALUES FOR THE EFFECTIVE WAVELENGTH RESULTS

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.003 ± 0.226	-0.596 ± 0.894	-0.056 ± 0.449	-0.146 ± 0.264	-0.126 ± 0.264	-0.297 ± 0.226	-0.300 ± 0.226
NPL 900 mm	*0.223*	-	-0.599 ± 0.894	-0.059 ± 0.449	-0.149 ± 0.264	-0.129 ± 0.264	-0.300 ± 0.226	-0.303 ± 0.226
PTB equation 3	*1.332*	*1.335*	-	0.540 ± 0.975	0.450 ± 0.905	0.470 ± 0.905	0.299 ± 0.894	0.296 ± 0.894
PTB equation 4	*0.453*	*0.454*	*1.344*	-	-0.090 ± 0.470	-0.070 ± 0.470	-0.241 ± 0.449	-0.244 ± 0.449
CEM 670 mm	*0.364*	*0.367*	*1.197*	*0.493*	-	0.020 ± 0.297	-0.151 ± 0.264	-0.154 ± 0.264
CEM 900 mm	*0.344*	*0.347*	*1.216*	*0.479*	*0.293*	-	-0.171 ± 0.264	-0.174 ± 0.264
IMGC 670 mm	*0.483*	*0.486*	*1.044*	*0.612*	*0.369*	*0.389*	-	-0.002 ± 0.226
IMGC 900 mm	*0.486*	*0.489*	*1.042*	*0.614*	*0.371*	*0.391*	*0.223*	-

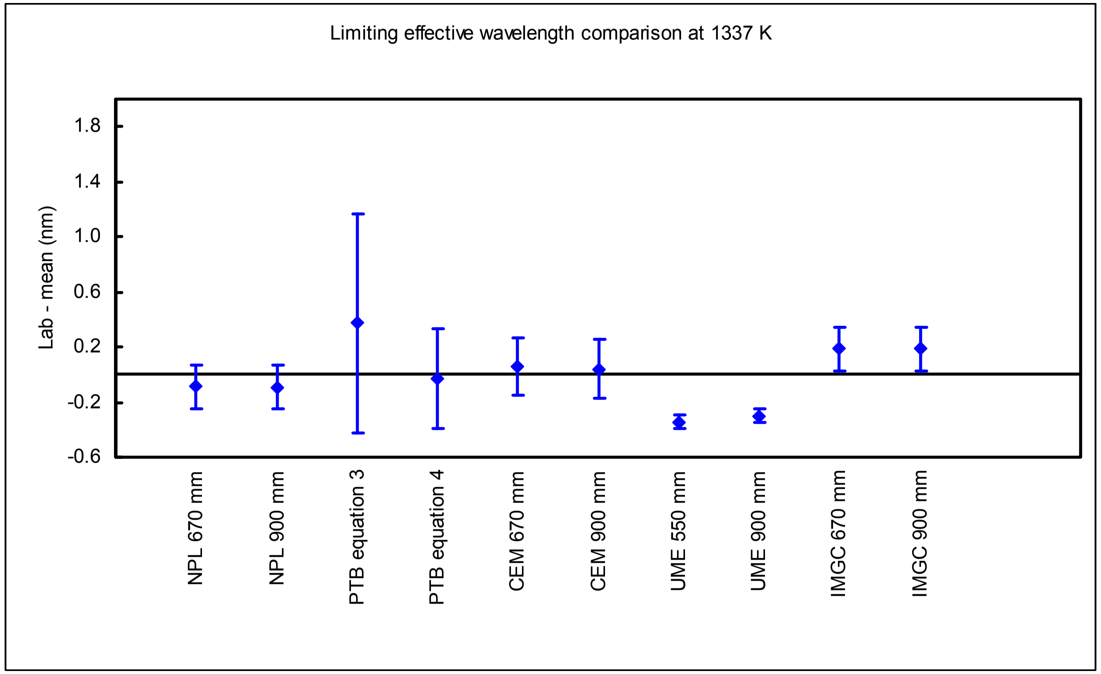
Table 182– DOE and QDE values for the limiting effective wavelength at 1000 K



QDE$_{95}$ and DOE values and graphs for the limiting effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	UME 550 mm	UME 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.004 ± 0.226	-0.458 ± 0.816	-0.058 ± 0.394	-0.148 ± 0.264	-0.128 ± 0.264	0.256 ± 0.167	0.214 ± 0.167	-0.273 ± 0.226	-0.275 ± 0.226
NPL 900 mm	*0.222*	-	-0.462 ± 0.816	-0.062 ± 0.394	-0.152 ± 0.264	-0.132 ± 0.264	0.252 ± 0.167	0.210 ± 0.167	-0.277 ± 0.226	-0.279 ± 0.226
PTB equation 3	*1.130*	*1.134*	-	0.400 ± 0.877	0.310 ± 0.827	0.330 ± 0.827	0.714 ± 0.801	0.672 ± 0.801	0.185 ± 0.816	0.183 ± 0.816
PTB equation 4	*0.402*	*0.404*	*1.125*	-	-0.090 ± 0.417	-0.070 ± 0.417	0.314 ± 0.363	0.272 ± 0.363	-0.215 ± 0.394	-0.217 ± 0.394
CEM 670 mm	*0.366*	*0.370*	*0.997*	*0.445*	-	0.020 ± 0.297	0.404 ± 0.215	0.362 ± 0.215	-0.125 ± 0.264	-0.127 ± 0.264
CEM 900 mm	*0.346*	*0.350*	*1.016*	*0.430*	*0.293*	-	0.384 ± 0.215	0.342 ± 0.215	-0.145 ± 0.264	-0.147 ± 0.264
UME 550 mm	*0.393*	*0.389*	*1.373*	*0.613*	*0.581*	*0.561*	-	-0.042 ± 0.068	-0.529 ± 0.167	-0.531 ± 0.167
UME 900 mm	*0.351*	*0.347*	*1.331*	*0.571*	*0.539*	*0.519*	*0.098*	-	-0.487 ± 0.167	-0.489 ± 0.167
IMGC 670 mm	*0.459*	*0.463*	*0.878*	*0.540*	*0.343*	*0.362*	*0.666*	*0.624*	-	-0.002 ± 0.226
IMGC 900 mm	*0.461*	*0.465*	*0.876*	*0.541*	*0.345*	*0.364*	*0.668*	*0.626*	*0.223*	-

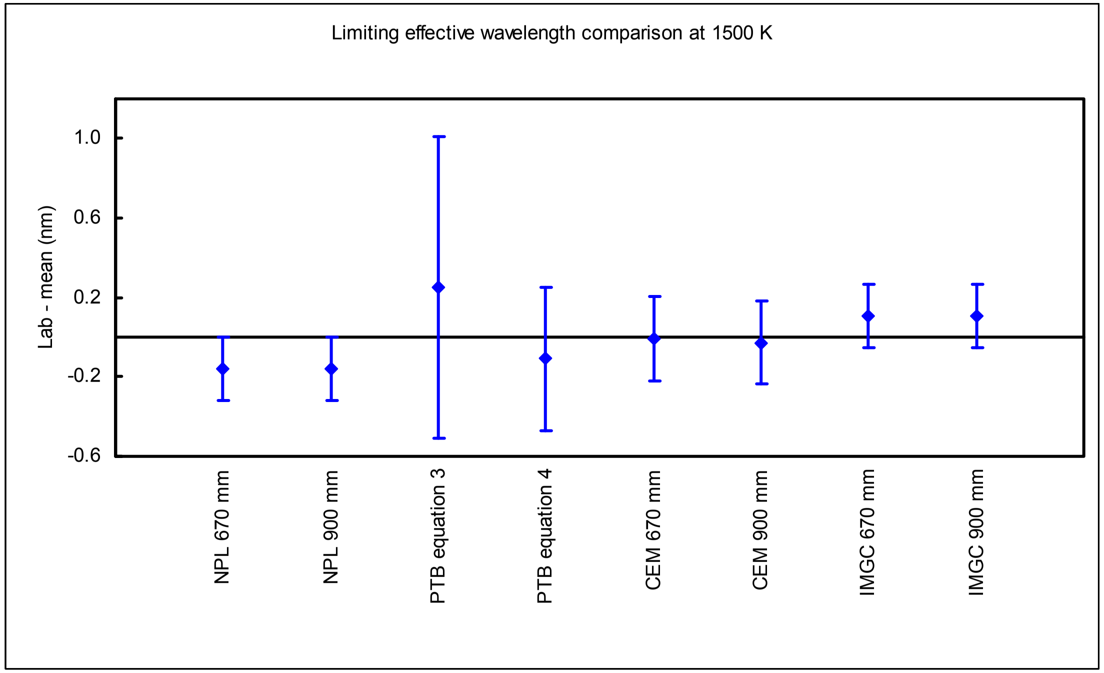
Table 183– DOE and QDE values for the limiting effective wavelength at 1337.3 K



QDE$_{95}$ and DOE values and graphs for the limiting effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.003 ± 0.226	-0.411 ± 0.777	-0.051 ± 0.394	-0.151 ± 0.264	-0.131 ± 0.264	-0.266 ± 0.226	-0.268 ± 0.226
NPL 900 mm	*0.223*	-	-0.414 ± 0.777	-0.054 ± 0.394	-0.154 ± 0.264	-0.134 ± 0.264	-0.269 ± 0.226	-0.271 ± 0.226
PTB equation 3	*1.052*	*1.055*	-	0.360 ± 0.841	0.260 ± 0.788	0.280 ± 0.788	0.145 ± 0.777	0.143 ± 0.777
PTB equation 4	*0.398*	*0.399*	*1.056*	-	-0.100 ± 0.417	-0.080 ± 0.417	-0.215 ± 0.394	-0.217 ± 0.394
CEM 670 mm	*0.369*	*0.372*	*0.918*	*0.453*	-	0.020 ± 0.297	-0.115 ± 0.264	-0.117 ± 0.264
CEM 900 mm	*0.349*	*0.352*	*0.936*	*0.437*	*0.293*	-	-0.135 ± 0.264	-0.137 ± 0.264
IMGC 670 mm	*0.452*	*0.455*	*0.812*	*0.540*	*0.334*	*0.353*	-	-0.002 ± 0.226
IMGC 900 mm	*0.454*	*0.457*	*0.811*	*0.542*	*0.335*	*0.355*	*0.223*	-

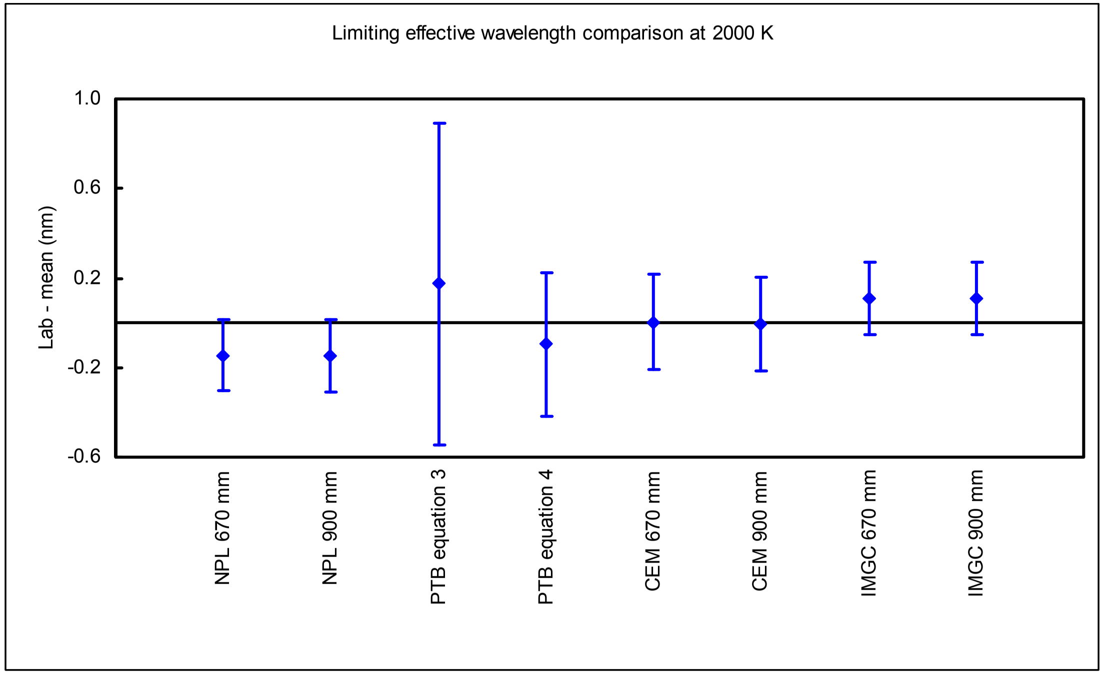
Table 184– DOE and QDE values for the limiting effective wavelength at 1500 K



QDE$_{95}$ and DOE values and graphs for the limiting effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.003 ± 0.226	-0.318 ± 0.738	-0.048 ± 0.358	-0.148 ± 0.264	-0.138 ± 0.264	-0.252 ± 0.226	-0.254 ± 0.226
NPL 900 mm	*0.223*	-	-0.321 ± 0.738	-0.051 ± 0.358	-0.151 ± 0.264	-0.141 ± 0.264	-0.255 ± 0.226	-0.257 ± 0.226
PTB equation 3	*0.928*	*0.931*	-	0.270 ± 0.788	0.170 ± 0.750	0.180 ± 0.750	0.066 ± 0.738	0.064 ± 0.738
PTB equation 4	*0.362*	*0.364*	*0.926*	-	-0.100 ± 0.383	-0.090 ± 0.383	-0.204 ± 0.358	-0.206 ± 0.358
CEM 670 mm	*0.366*	*0.369*	*0.807*	*0.422*	-	0.010 ± 0.297	-0.104 ± 0.264	-0.106 ± 0.264
CEM 900 mm	*0.356*	*0.359*	*0.815*	*0.414*	*0.292*	-	-0.114 ± 0.264	-0.116 ± 0.264
IMGC 670 mm	*0.439*	*0.442*	*0.731*	*0.499*	*0.323*	*0.333*	-	-0.002 ± 0.226
IMGC 900 mm	*0.440*	*0.443*	*0.731*	*0.501*	*0.325*	*0.335*	*0.223*	-

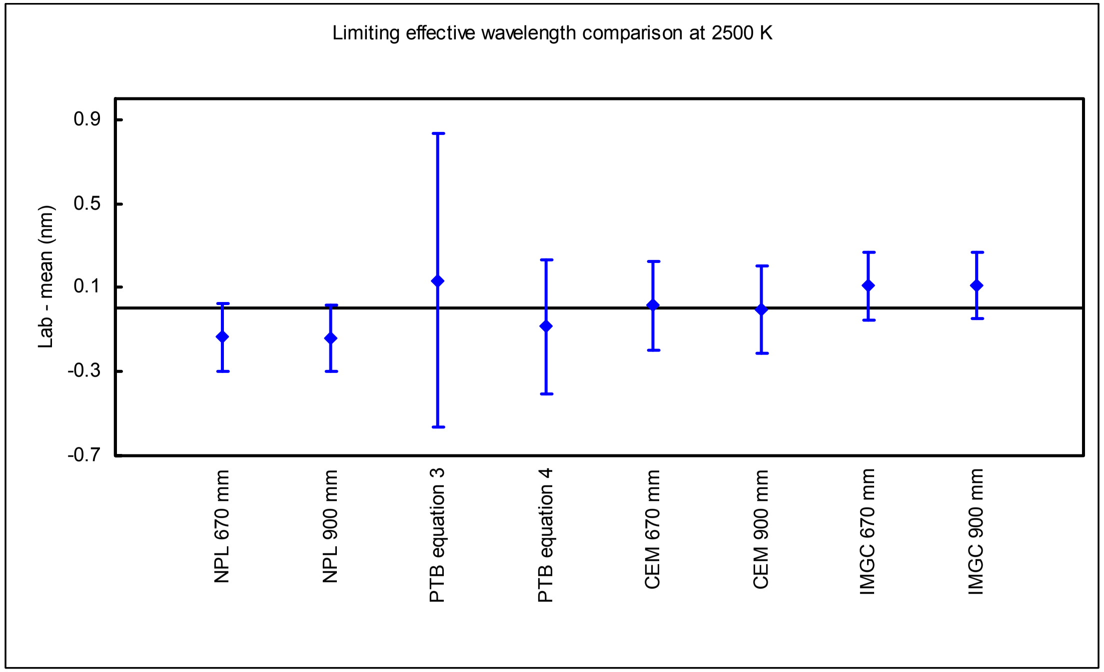
Table 185– DOE and QDE values for the limiting effective wavelength at 2000 K



QDE$_{95}$ and DOE values and graphs for the limiting effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.004 ± 0.226	-0.270 ± 0.718	-0.050 ± 0.358	-0.150 ± 0.264	-0.130 ± 0.264	-0.244 ± 0.226	-0.246 ± 0.226
NPL 900 mm	*0.222*	-	-0.274 ± 0.718	-0.054 ± 0.358	-0.154 ± 0.264	-0.134 ± 0.264	-0.248 ± 0.226	-0.250 ± 0.226
PTB equation 3	*0.866*	*0.870*	-	0.220 ± 0.770	0.120 ± 0.731	0.140 ± 0.731	0.026 ± 0.718	0.024 ± 0.718
PTB equation 4	*0.363*	*0.366*	*0.866*	-	-0.100 ± 0.383	-0.080 ± 0.383	-0.194 ± 0.358	-0.196 ± 0.358
CEM 670 mm	*0.368*	*0.372*	*0.753*	*0.422*	-	0.020 ± 0.297	-0.094 ± 0.264	-0.096 ± 0.264
CEM 900 mm	*0.348*	*0.352*	*0.767*	*0.406*	*0.293*	-	-0.114 ± 0.264	-0.116 ± 0.264
IMGC 670 mm	*0.430*	*0.434*	*0.705*	*0.489*	*0.314*	*0.333*	-	-0.002 ± 0.226
IMGC 900 mm	*0.432*	*0.436*	*0.705*	*0.491*	*0.316*	*0.335*	*0.223*	-

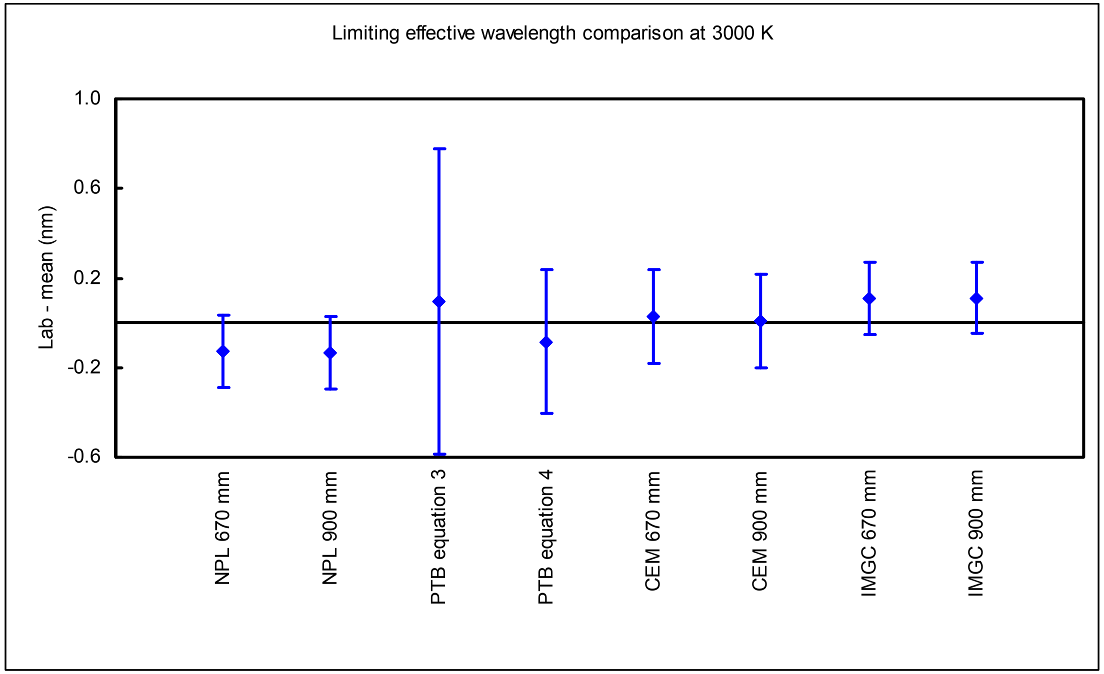
Table 186– DOE and QDE values for the limiting effective wavelength at 2500 K



QDE$_{95}$ and DOE values and graphs for the limiting effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.005 ± 0.226	-0.224 ± 0.699	-0.044 ± 0.358	-0.154 ± 0.264	-0.134 ± 0.264	-0.238 ± 0.226	-0.240 ± 0.226
NPL 900 mm	*0.222*	-	-0.229 ± 0.699	-0.049 ± 0.358	-0.159 ± 0.264	-0.139 ± 0.264	-0.243 ± 0.226	-0.245 ± 0.226
PTB equation 3	*0.807*	*0.812*	-	0.180 ± 0.752	0.070 ± 0.712	0.090 ± 0.712	-0.014 ± 0.699	-0.016 ± 0.699
PTB equation 4	*0.360*	*0.363*	*0.816*	-	-0.110 ± 0.383	-0.090 ± 0.383	-0.194 ± 0.358	-0.196 ± 0.358
CEM 670 mm	*0.372*	*0.376*	*0.708*	*0.431*	-	0.020 ± 0.297	-0.084 ± 0.264	-0.086 ± 0.264
CEM 900 mm	*0.352*	*0.357*	*0.717*	*0.414*	*0.293*	-	-0.104 ± 0.264	-0.106 ± 0.264
IMGC 670 mm	*0.424*	*0.429*	*0.686*	*0.489*	*0.304*	*0.323*	-	-0.002 ± 0.226
IMGC 900 mm	*0.427*	*0.432*	*0.686*	*0.491*	*0.307*	*0.325*	*0.223*	-

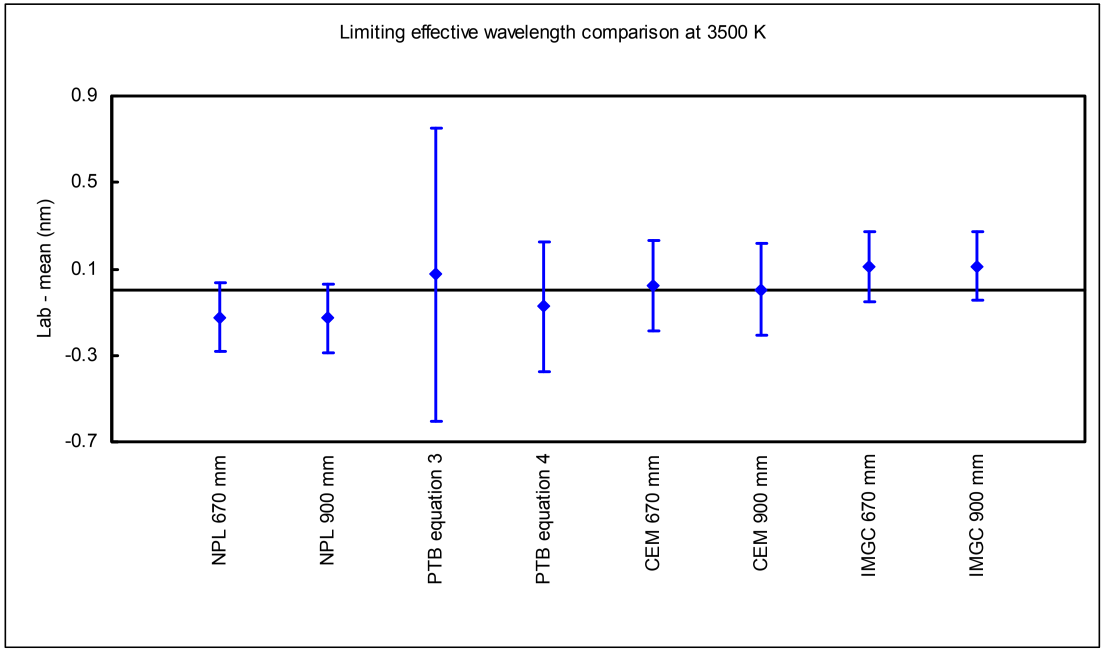
Table 187– DOE and QDE values for the limiting effective wavelength at 3000 K



QDE$_{95}$ and DOE values and graphs for the limiting effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.004 ± 0.226	-0.199 ± 0.699	-0.049 ± 0.340	-0.149 ± 0.264	-0.129 ± 0.264	-0.234 ± 0.226	-0.237 ± 0.226
NPL 900 mm	*0.222*	-	-0.203 ± 0.699	-0.053 ± 0.340	-0.153 ± 0.264	-0.133 ± 0.264	-0.238 ± 0.226	-0.241 ± 0.226
PTB equation 3	*0.785*	*0.789*	-	0.150 ± 0.743	0.050 ± 0.712	0.070 ± 0.712	-0.035 ± 0.699	-0.038 ± 0.699
PTB equation 4	*0.346*	*0.348*	*0.785*	-	-0.100 ± 0.366	-0.080 ± 0.366	-0.185 ± 0.340	-0.188 ± 0.340
CEM 670 mm	*0.367*	*0.371*	*0.702*	*0.408*	-	0.020 ± 0.297	-0.085 ± 0.264	-0.088 ± 0.264
CEM 900 mm	*0.347*	*0.351*	*0.708*	*0.391*	*0.293*	-	-0.106 ± 0.264	-0.108 ± 0.264
IMGC 670 mm	*0.421*	*0.425*	*0.686*	*0.466*	*0.306*	*0.324*	-	-0.003 ± 0.226
IMGC 900 mm	*0.423*	*0.427*	*0.687*	*0.468*	*0.308*	*0.327*	*0.223*	-

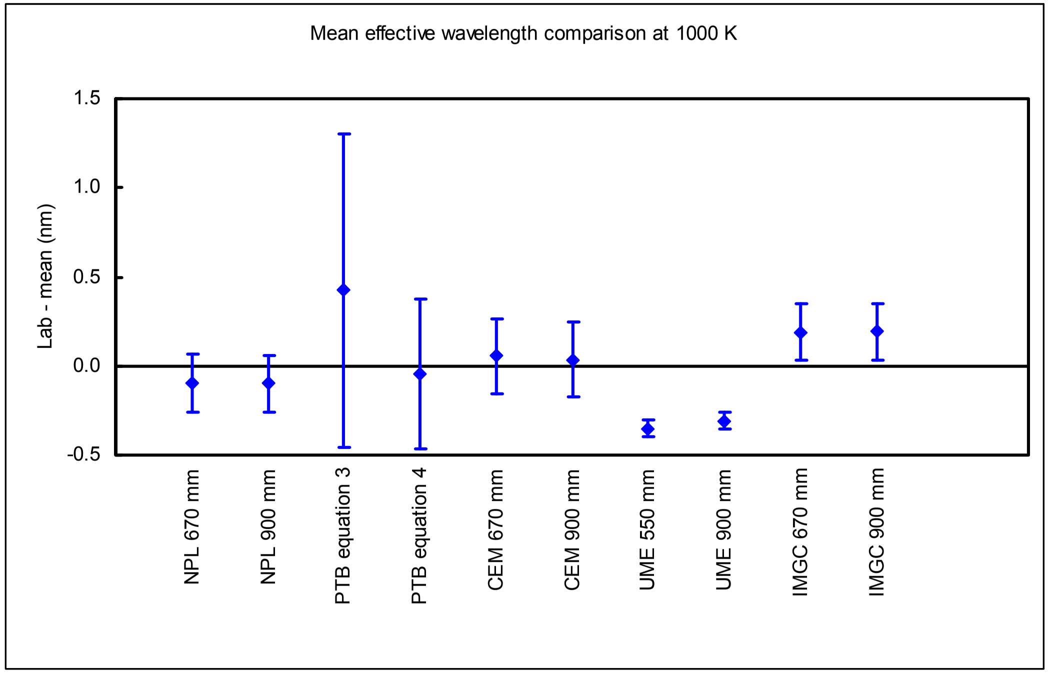
Table 188– DOE and QDE values for the limiting effective wavelength at 3500 K



QDE$_{95}$ and DOE values and graphs for the emissivity values

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	UME 550 mm	UME 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.004 ± 0.226	-0.522 ± 0.894	-0.052 ± 0.449	-0.152 ± 0.264	-0.132 ± 0.264	0.257 ± 0.167	0.213 ± 0.167	-0.285 ± 0.226	-0.287 ± 0.226
NPL 900 mm	*0.222*	-	-0.526 ± 0.894	-0.056 ± 0.449	-0.156 ± 0.264	-0.136 ± 0.264	0.253 ± 0.167	0.209 ± 0.167	-0.289 ± 0.226	-0.291 ± 0.226
PTB equation 3	*1.259*	*1.263*	-	0.470 ± 0.975	0.370 ± 0.905	0.390 ± 0.905	0.779 ± 0.881	0.735 ± 0.881	0.237 ± 0.894	0.235 ± 0.894
PTB equation 4	*0.451*	*0.453*	*1.275*	-	-0.100 ± 0.470	-0.080 ± 0.470	0.309 ± 0.423	0.265 ± 0.423	-0.233 ± 0.449	-0.235 ± 0.449
CEM 670 mm	*0.370*	*0.374*	*1.120*	*0.500*	-	0.020 ± 0.297	0.409 ± 0.215	0.365 ± 0.215	-0.133 ± 0.264	-0.135 ± 0.264
CEM 900 mm	*0.350*	*0.354*	*1.139*	*0.486*	*0.293*	-	0.389 ± 0.215	0.345 ± 0.215	-0.153 ± 0.264	-0.155 ± 0.264
UME 550 mm	*0.394*	*0.390*	*1.504*	*0.657*	*0.586*	*0.566*	-	-0.044 ± 0.068	-0.542 ± 0.167	-0.544 ± 0.167
UME 900 mm	*0.350*	*0.346*	*1.460*	*0.613*	*0.542*	*0.522*	*0.100*	-	-0.498 ± 0.167	-0.500 ± 0.167
IMGC 670 mm	*0.471*	*0.475*	*0.990*	*0.604*	*0.351*	*0.371*	*0.679*	*0.635*	-	-0.002 ± 0.226
IMGC 900 mm	*0.473*	*0.477*	*0.988*	*0.606*	*0.353*	*0.373*	*0.681*	*0.637*	*0.223*	-

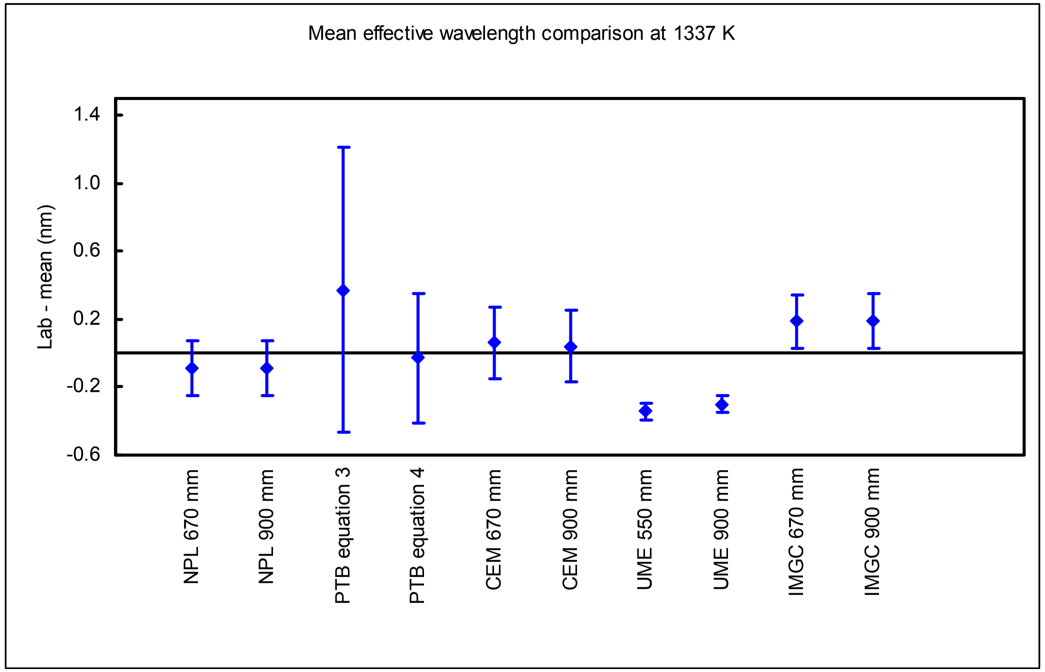
Table 189 – DOE and QDE$_{95}$ values for the mean effective wavelength at 1000K



QDE$_{95}$ and DOE values and graphs for the mean effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	UME 550 mm	UME 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.004 ± 0.226	-0.458 ± 0.855	-0.058 ± 0.412	-0.148 ± 0.264	-0.128 ± 0.264	0.256 ± 0.167	0.214 ± 0.167	-0.273 ± 0.226	-0.275 ± 0.226
NPL 900 mm	*0.222*	-	-0.462 ± 0.855	-0.062 ± 0.412	-0.152 ± 0.264	-0.132 ± 0.264	0.252 ± 0.167	0.210 ± 0.167	-0.277 ± 0.226	-0.279 ± 0.226
PTB equation 3	*1.163*	*1.167*	-	0.400 ± 0.922	0.310 ± 0.866	0.330 ± 0.866	0.714 ± 0.841	0.672 ± 0.841	0.185 ± 0.855	0.183 ± 0.855
PTB equation 4	*0.419*	*0.421*	*1.163*	-	-0.090 ± 0.434	-0.070 ± 0.434	0.314 ± 0.383	0.272 ± 0.383	-0.215 ± 0.412	-0.217 ± 0.412
CEM 670 mm	*0.366*	*0.370*	*1.030*	*0.460*	-	0.020 ± 0.297	0.404 ± 0.215	0.362 ± 0.215	-0.125 ± 0.264	-0.127 ± 0.264
CEM 900 mm	*0.346*	*0.350*	*1.049*	*0.446*	*0.293*	-	0.384 ± 0.215	0.342 ± 0.215	-0.145 ± 0.264	-0.147 ± 0.264
UME 550 mm	*0.393*	*0.389*	*1.406*	*0.629*	*0.581*	*0.561*	-	-0.042 ± 0.068	-0.529 ± 0.167	-0.531 ± 0.167
UME 900 mm	*0.351*	*0.347*	*1.364*	*0.587*	*0.539*	*0.519*	*0.098*	-	-0.487 ± 0.167	-0.489 ± 0.167
IMGC 670 mm	*0.459*	*0.463*	*0.913*	*0.555*	*0.343*	*0.362*	*0.666*	*0.624*	-	-0.002 ± 0.226
IMGC 900 mm	*0.461*	*0.465*	*0.912*	*0.557*	*0.345*	*0.364*	*0.668*	*0.626*	*0.223*	-

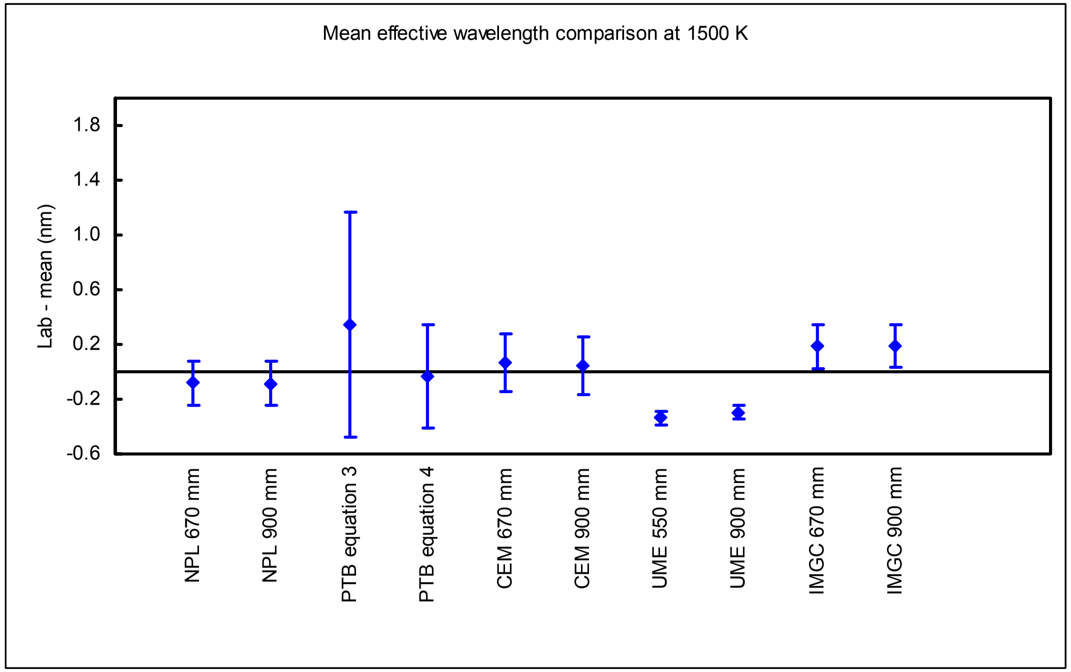
Table 190 - DOE and QDE$_{95}$ values for the mean effective wavelength at 1337K



QDE$_{95}$ and DOE values and graphs for the emissivity values

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	UME 550 mm	UME 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.003 ± 0.226	-0.430 ± 0.835	-0.050 ± 0.412	-0.150 ± 0.264	-0.130 ± 0.264	0.255 ± 0.167	0.214 ± 0.167	-0.270 ± 0.226	-0.272 ± 0.226
NPL 900 mm	*0.223*	-	-0.433 ± 0.835	-0.053 ± 0.412	-0.153 ± 0.264	-0.133 ± 0.264	0.252 ± 0.167	0.211 ± 0.167	-0.273 ± 0.226	-0.275 ± 0.226
PTB equation 3	*1.119*	*1.122*	-	0.380 ± 0.904	0.280 ± 0.846	0.300 ± 0.846	0.685 ± 0.821	0.644 ± 0.821	0.160 ± 0.835	0.158 ± 0.835
PTB equation 4	*0.415*	*0.416*	*1.128*	-	-0.100 ± 0.434	-0.080 ± 0.434	0.305 ± 0.383	0.264 ± 0.383	-0.220 ± 0.412	-0.222 ± 0.412
CEM 670 mm	*0.368*	*0.371*	*0.986*	*0.468*	-	0.020 ± 0.297	0.405 ± 0.215	0.364 ± 0.215	-0.120 ± 0.264	-0.122 ± 0.264
CEM 900 mm	*0.348*	*0.351*	*1.004*	*0.453*	*0.293*	-	0.385 ± 0.215	0.344 ± 0.215	-0.140 ± 0.264	-0.142 ± 0.264
UME 550 mm	*0.392*	*0.389*	*1.361*	*0.620*	*0.582*	*0.562*	-	-0.041 ± 0.068	-0.525 ± 0.167	-0.527 ± 0.167
UME 900 mm	*0.351*	*0.348*	*1.320*	*0.579*	*0.541*	*0.521*	*0.097*	-	-0.484 ± 0.167	-0.486 ± 0.167
IMGC 670 mm	*0.456*	*0.459*	*0.876*	*0.560*	*0.338*	*0.358*	*0.662*	*0.621*	-	-0.002 ± 0.226
IMGC 900 mm	*0.458*	*0.461*	*0.875*	*0.562*	*0.340*	*0.360*	*0.664*	*0.623*	*0.223*	-

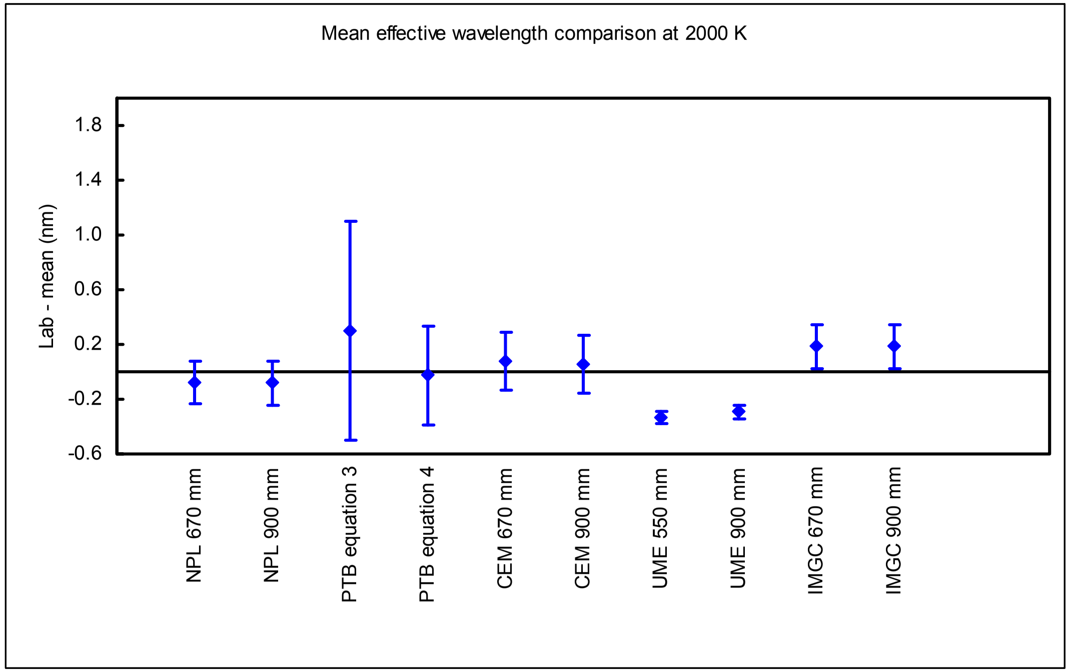
Table 191 - DOE and QDE$_{95}$ values for the mean effective wavelength at 1500K



QDE$_{95}$ and DOE values and graphs for the mean effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	UME 550 mm	UME 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.004 ± 0.226	-0.383 ± 0.816	-0.053 ± 0.394	-0.153 ± 0.264	-0.133 ± 0.264	0.255 ± 0.167	0.215 ± 0.167	-0.263 ± 0.226	-0.264 ± 0.226
NPL 900 mm	*0.222*	-	-0.387 ± 0.816	-0.057 ± 0.394	-0.157 ± 0.264	-0.137 ± 0.264	0.251 ± 0.167	0.211 ± 0.167	-0.267 ± 0.226	-0.268 ± 0.226
PTB equation 3	*1.057*	*1.061*	-	0.330 ± 0.877	0.230 ± 0.827	0.250 ± 0.827	0.638 ± 0.801	0.598 ± 0.801	0.120 ± 0.816	0.119 ± 0.816
PTB equation 4	*0.399*	*0.401*	*1.058*	-	-0.100 ± 0.417	-0.080 ± 0.417	0.308 ± 0.363	0.268 ± 0.363	-0.210 ± 0.394	-0.211 ± 0.394
CEM 670 mm	*0.371*	*0.374*	*0.925*	*0.453*	-	0.020 ± 0.297	0.408 ± 0.215	0.368 ± 0.215	-0.110 ± 0.264	-0.111 ± 0.264
CEM 900 mm	*0.351*	*0.355*	*0.942*	*0.437*	*0.293*	-	0.388 ± 0.215	0.348 ± 0.215	-0.130 ± 0.264	-0.131 ± 0.264
UME 550 mm	*0.392*	*0.388*	*1.297*	*0.607*	*0.585*	*0.565*	-	-0.040 ± 0.068	-0.518 ± 0.167	-0.519 ± 0.167
UME 900 mm	*0.352*	*0.348*	*1.257*	*0.567*	*0.545*	*0.525*	*0.096*	-	-0.478 ± 0.167	-0.479 ± 0.167
IMGC 670 mm	*0.449*	*0.453*	*0.832*	*0.534*	*0.328*	*0.348*	*0.655*	*0.615*	-	-0.002 ± 0.226
IMGC 900 mm	*0.451*	*0.455*	*0.831*	*0.536*	*0.330*	*0.349*	*0.657*	*0.617*	*0.223*	-

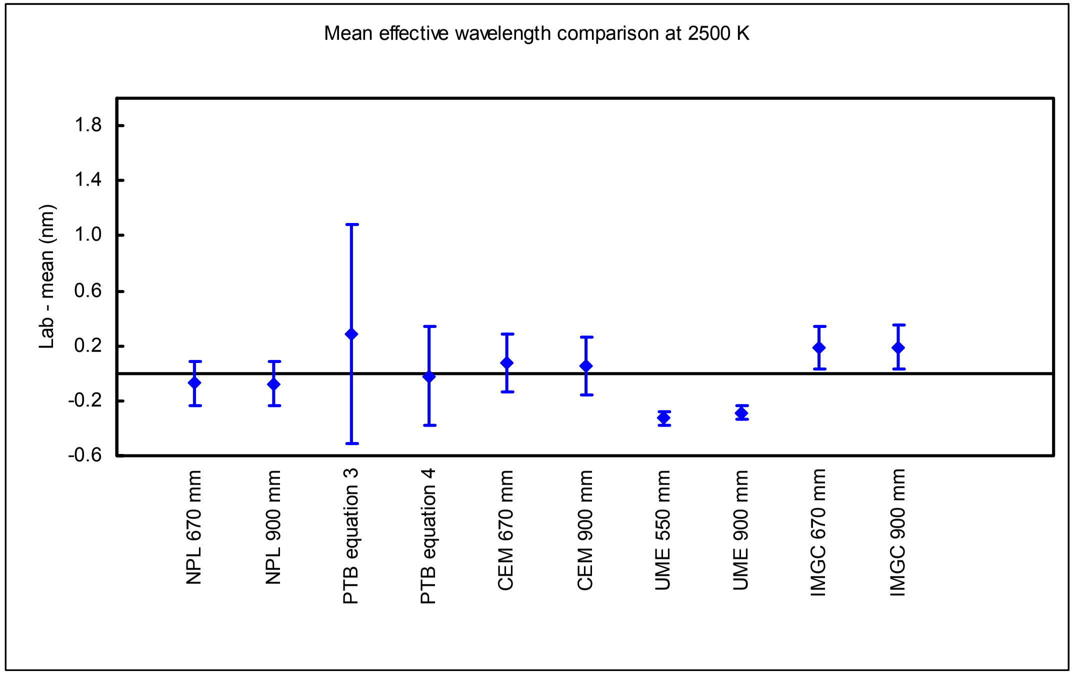
Table 192 - DOE and QDE$_{95}$ values for the mean effective wavelength at 2000K



QDE_{95} and DOE values and graphs for the emissivity values

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	UME 550 mm	UME 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.004 ± 0.226	-0.359 ± 0.816	-0.049 ± 0.394	-0.149 ± 0.264	-0.129 ± 0.264	0.254 ± 0.167	0.215 ± 0.167	-0.258 ± 0.226	-0.260 ± 0.226
NPL 900 mm	*0.222*	-	-0.363 ± 0.816	-0.053 ± 0.394	-0.153 ± 0.264	-0.133 ± 0.264	0.250 ± 0.167	0.211 ± 0.167	-0.262 ± 0.226	-0.264 ± 0.226
PTB equation 3	*1.034*	*1.038*	-	0.310 ± 0.877	0.210 ± 0.827	0.230 ± 0.827	0.613 ± 0.801	0.574 ± 0.801	0.101 ± 0.816	0.099 ± 0.816
PTB equation 4	*0.397*	*0.399*	*1.040*	-	-0.100 ± 0.417	-0.080 ± 0.417	0.303 ± 0.363	0.264 ± 0.363	-0.209 ± 0.394	-0.211 ± 0.394
CEM 670 mm	*0.367*	*0.371*	*0.908*	*0.453*	-	0.020 ± 0.297	0.403 ± 0.215	0.364 ± 0.215	-0.109 ± 0.264	-0.111 ± 0.264
CEM 900 mm	*0.347*	*0.351*	*0.925*	*0.437*	*0.293*	-	0.383 ± 0.215	0.344 ± 0.215	-0.129 ± 0.264	-0.131 ± 0.264
UME 550 mm	*0.391*	*0.387*	*1.272*	*0.602*	*0.580*	*0.560*	-	-0.039 ± 0.068	-0.512 ± 0.167	-0.514 ± 0.167
UME 900 mm	*0.352*	*0.348*	*1.234*	*0.563*	*0.541*	*0.521*	*0.095*	-	-0.473 ± 0.167	-0.475 ± 0.167
IMGC 670 mm	*0.445*	*0.449*	*0.821*	*0.534*	*0.328*	*0.347*	*0.650*	*0.611*	-	-0.002 ± 0.226
IMGC 900 mm	*0.447*	*0.451*	*0.820*	*0.536*	*0.330*	*0.349*	*0.652*	*0.613*	*0.223*	-

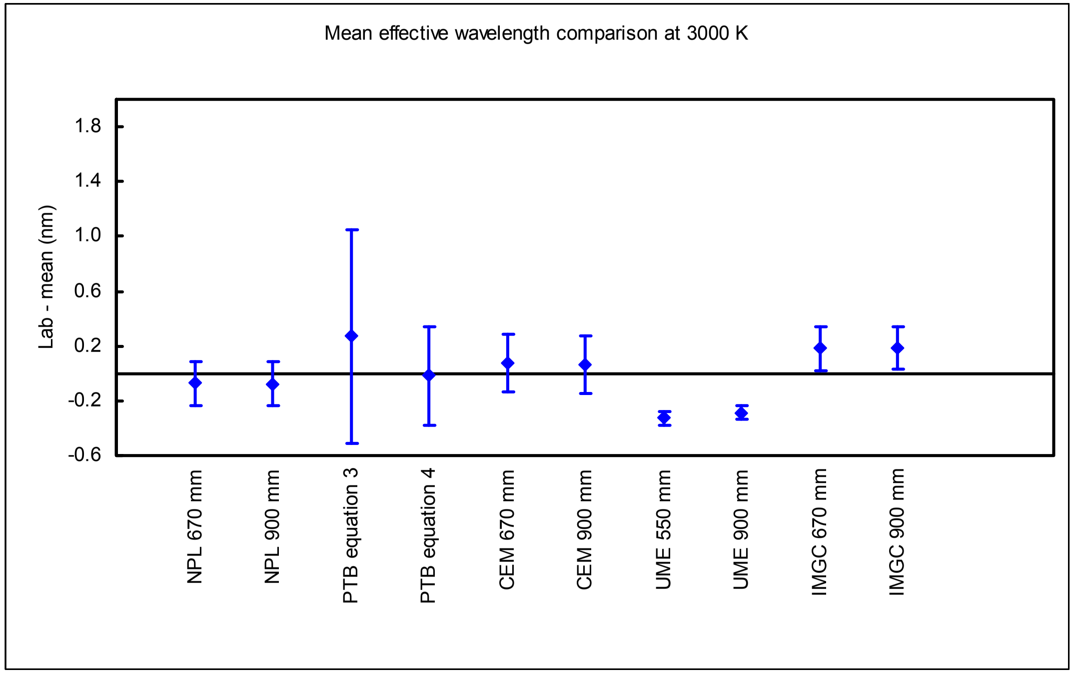
Table 193 - DOE and QDE_{95} values for the mean effective wavelength at 2500K



QDE$_{95}$ and DOE values and graphs for the mean effective wavelength

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	UME 550 mm	UME 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.005 ± 0.226	-0.346 ± 0.796	-0.056 ± 0.394	-0.146 ± 0.264	-0.136 ± 0.264	0.254 ± 0.167	0.216 ± 0.167	-0.255 ± 0.226	-0.258 ± 0.226
NPL 900 mm	*0.222*	-	-0.351 ± 0.796	-0.061 ± 0.394	-0.151 ± 0.264	-0.141 ± 0.264	0.249 ± 0.167	0.211 ± 0.167	-0.260 ± 0.226	-0.263 ± 0.226
PTB equation 3	*1.005*	*1.010*	-	0.290 ± 0.859	0.200 ± 0.808	0.210 ± 0.808	0.600 ± 0.781	0.562 ± 0.781	0.091 ± 0.796	0.088 ± 0.796
PTB equation 4	*0.401*	*0.404*	*1.006*	-	-0.090 ± 0.417	-0.080 ± 0.417	0.310 ± 0.363	0.272 ± 0.363	-0.199 ± 0.394	-0.202 ± 0.394
CEM 670 mm	*0.364*	*0.369*	*0.882*	*0.445*	-	0.010 ± 0.297	0.400 ± 0.215	0.362 ± 0.215	-0.109 ± 0.264	-0.111 ± 0.264
CEM 900 mm	*0.354*	*0.359*	*0.891*	*0.437*	*0.292*	-	0.390 ± 0.215	0.352 ± 0.215	-0.119 ± 0.264	-0.122 ± 0.264
UME 550 mm	*0.391*	*0.386*	*1.243*	*0.609*	*0.577*	*0.567*	-	-0.038 ± 0.068	-0.509 ± 0.167	-0.512 ± 0.167
UME 900 mm	*0.353*	*0.348*	*1.205*	*0.571*	*0.539*	*0.529*	*0.094*	-	-0.471 ± 0.167	-0.474 ± 0.167
IMGC 670 mm	*0.442*	*0.447*	*0.798*	*0.525*	*0.328*	*0.338*	*0.647*	*0.609*	-	-0.002 ± 0.226
IMGC 900 mm	*0.444*	*0.449*	*0.797*	*0.527*	*0.330*	*0.340*	*0.649*	*0.611*	*0.223*	-

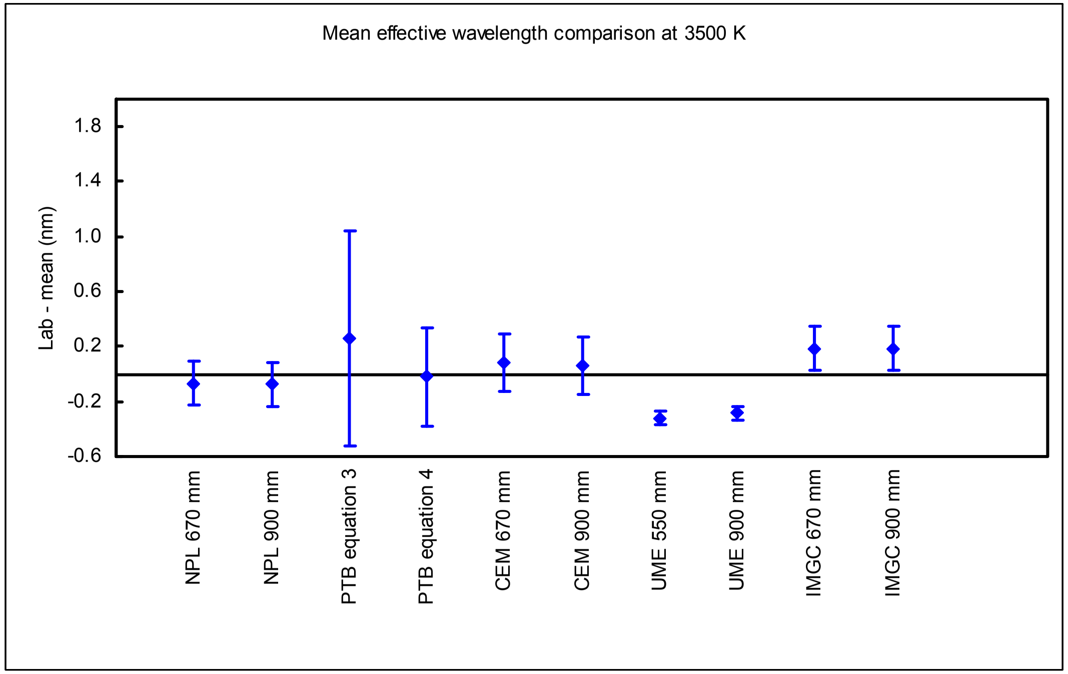
Table 194 - DOE and QDE$_{95}$ values for the mean effective wavelength at 3000K



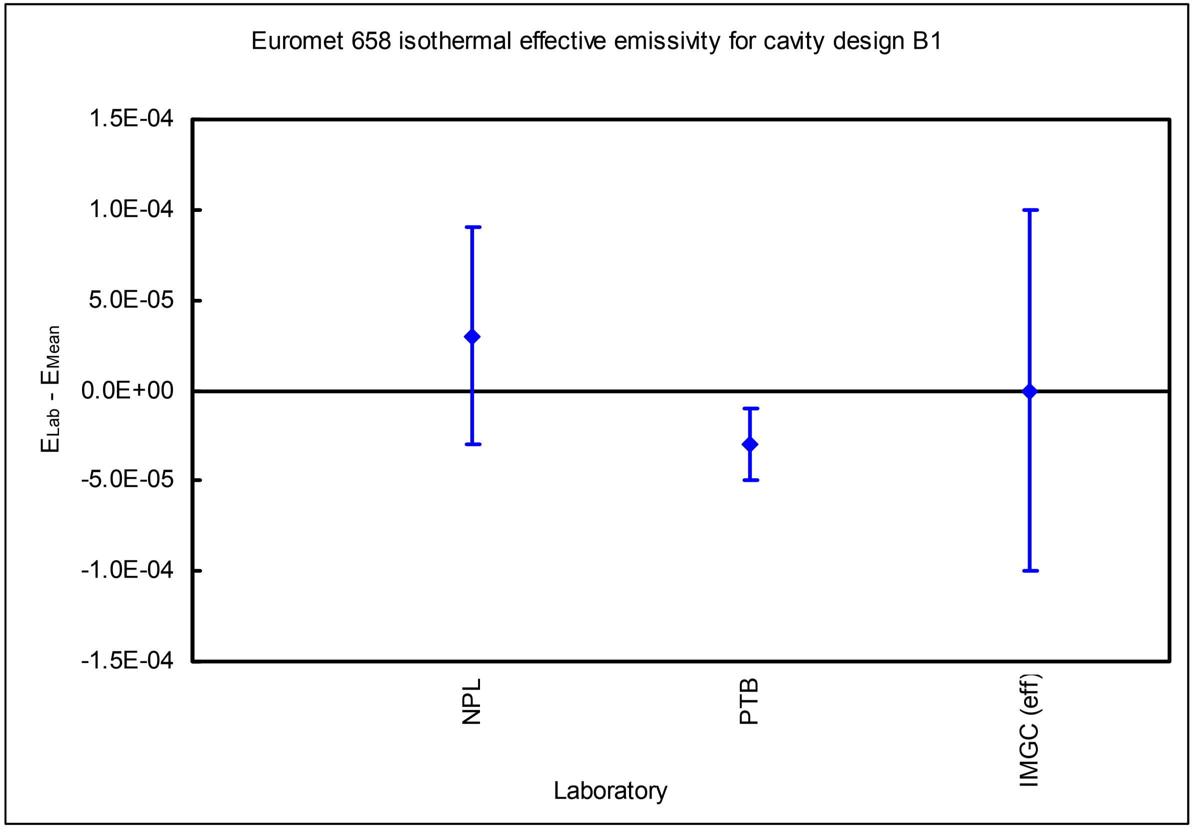
QDE$_{95}$ and DOE values and graphs for the emissivity values

	NPL 670 mm	NPL 900 mm	PTB equation 3	PTB equation 4	CEM 670 mm	CEM 900 mm	UME 550 mm	UME 900 mm	IMGC 670 mm	IMGC 900 mm
NPL 670 mm	-	0.004 ± 0.226	-0.329 ± 0.796	-0.049 ± 0.394	-0.149 ± 0.264	-0.129 ± 0.264	0.253 ± 0.167	0.215 ± 0.167	-0.254 ± 0.226	-0.256 ± 0.226
NPL 900 mm	*0.222*	-	-0.333 ± 0.796	-0.053 ± 0.394	-0.153 ± 0.264	-0.133 ± 0.264	0.249 ± 0.167	0.211 ± 0.167	-0.258 ± 0.226	-0.260 ± 0.226
PTB equation 3	*0.989*	*0.992*	-	0.280 ± 0.859	0.180 ± 0.808	0.200 ± 0.808	0.582 ± 0.781	0.544 ± 0.781	0.075 ± 0.796	0.073 ± 0.796
PTB equation 4	*0.397*	*0.399*	*0.997*	-	-0.100 ± 0.417	-0.080 ± 0.417	0.302 ± 0.363	0.264 ± 0.363	-0.205 ± 0.394	-0.207 ± 0.394
CEM 670 mm	*0.367*	*0.371*	*0.866*	*0.453*	-	0.020 ± 0.297	0.402 ± 0.215	0.364 ± 0.215	-0.105 ± 0.264	-0.107 ± 0.264
CEM 900 mm	*0.347*	*0.351*	*0.882*	*0.437*	*0.293*	-	0.382 ± 0.215	0.344 ± 0.215	-0.125 ± 0.264	-0.127 ± 0.264
UME 550 mm	*0.390*	*0.386*	*1.225*	*0.601*	*0.579*	*0.559*	-	-0.038 ± 0.068	-0.507 ± 0.167	-0.509 ± 0.167
UME 900 mm	*0.352*	*0.348*	*1.187*	*0.563*	*0.541*	*0.521*	*0.094*	-	-0.469 ± 0.167	-0.471 ± 0.167
IMGC 670 mm	*0.440*	*0.444*	*0.791*	*0.530*	*0.324*	*0.343*	*0.644*	*0.606*	-	-0.002 ± 0.226
IMGC 900 mm	*0.442*	*0.446*	*0.790*	*0.532*	*0.326*	*0.345*	*0.647*	*0.609*	*0.223*	-

Table 195 - DOE and QDE$_{95}$ values for the mean effective wavelength at 3500K



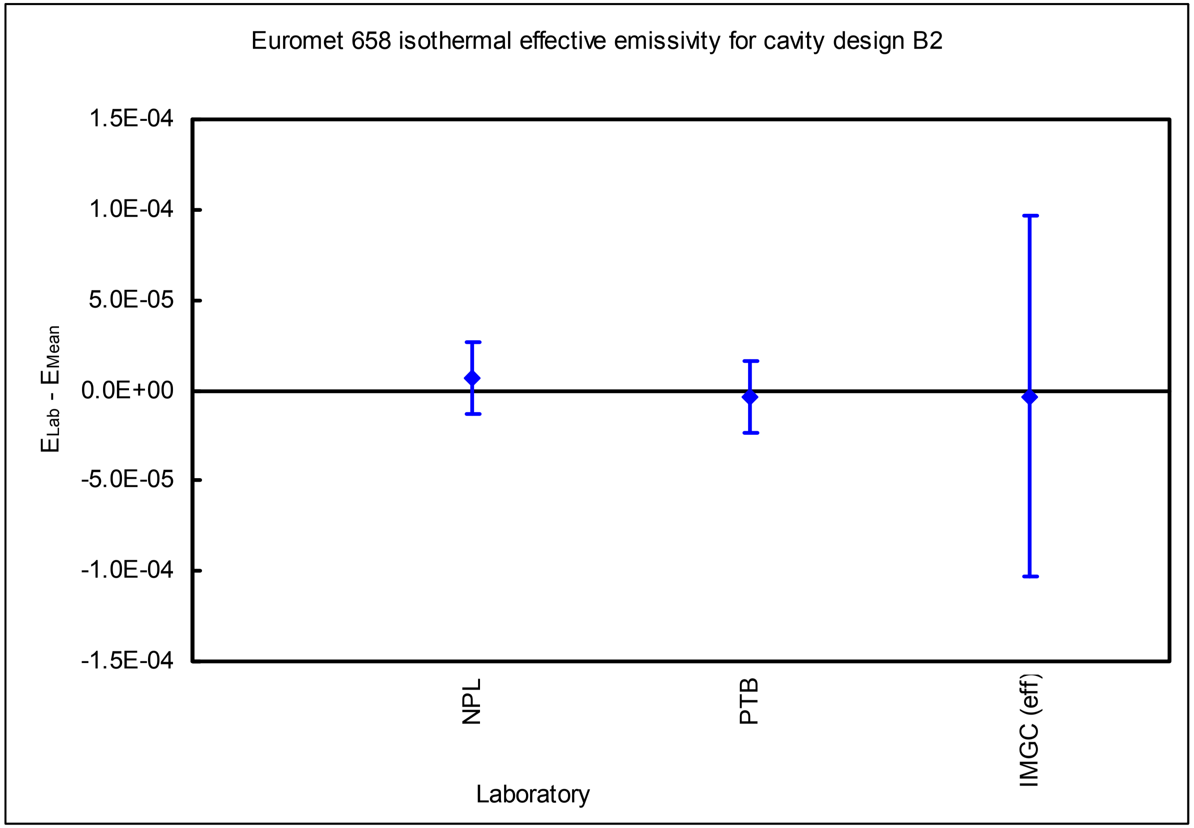
APPENDIX 7 – THE QDE_{95} AND DOE VALUES FOR THE EMISSIVITY RESULTS



	NPL	PTB	IMGC (eff)
NPL	-	0.00006 ± 0.00006	0.00003 ± 0.00012
PTB	*0.00011*	-	-0.00003 ± 0.00010
IMGC (eff)	*0.00013*	*0.00012*	-

Table 196 – DOE and QDE_{95} values for isothermal effective emissivity values for cavity design B1

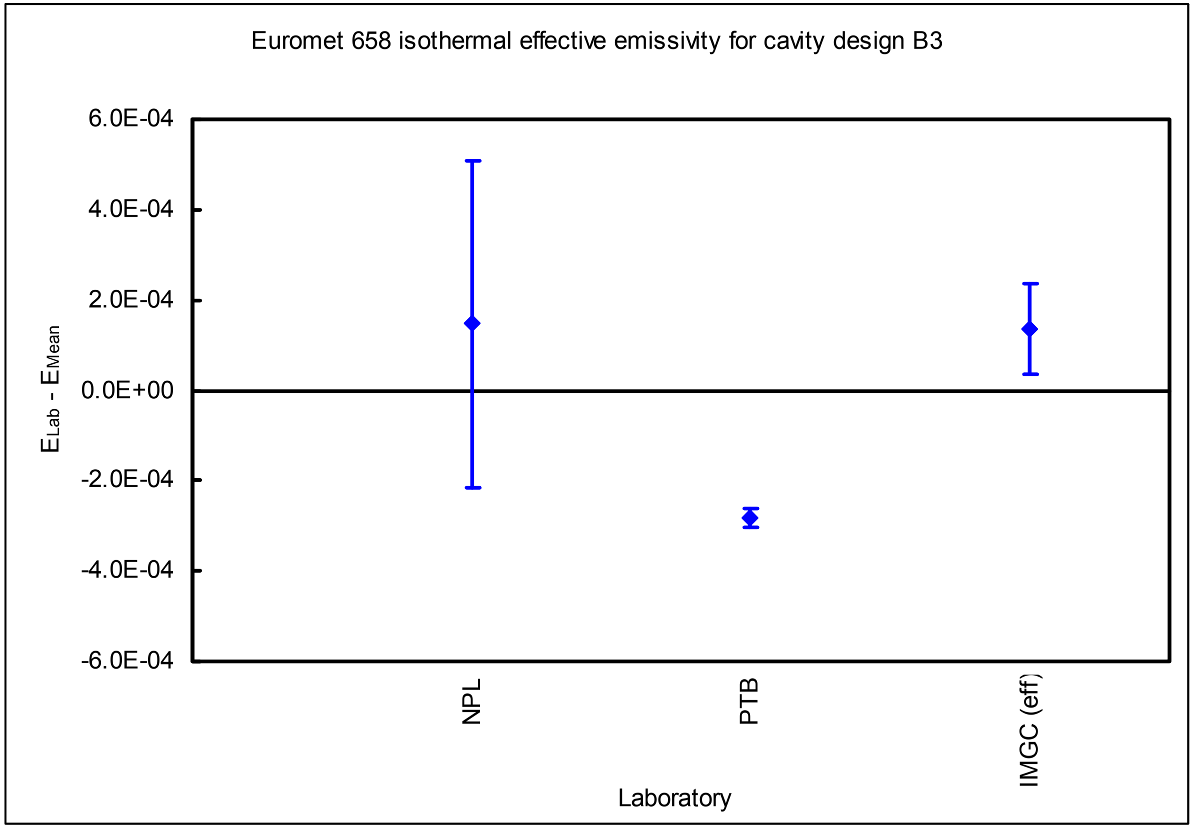
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00001 ± 0.00003	0.00001 ± 0.00010
PTB	*0.00003*	-	0.00000 ± 0.00010
IMGC (eff)	*0.00010*	*0.00010*	-

Table 197 – DOE and QDE$_{95}$ values for isothermal effective emissivity values for cavity design B2

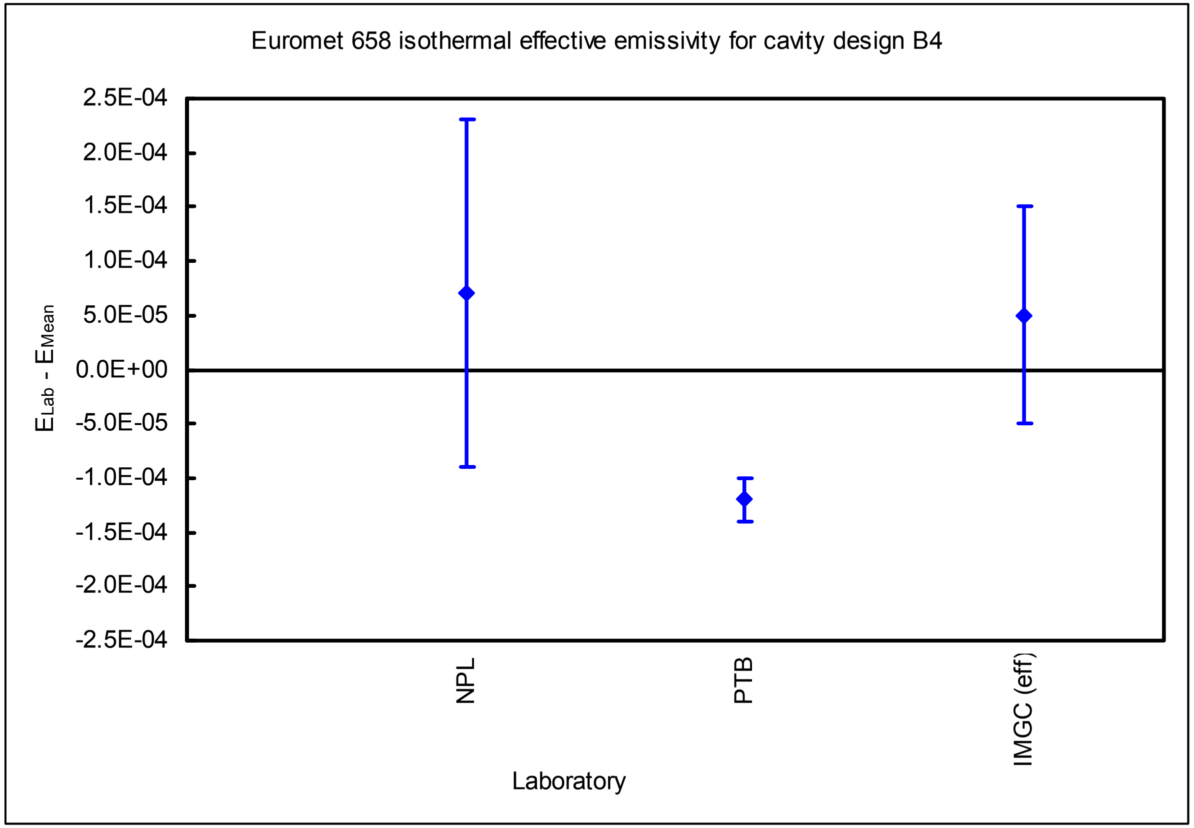
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00043 ± 0.00036	0.00001 ± 0.00037
PTB	*0.00073*	-	-0.00042 ± 0.00010
IMGC (eff)	*0.00037*	*0.00050*	-

Table 198 – DOE and QDE$_{95}$ values for isothermal effective emissivity values for cavity design B3

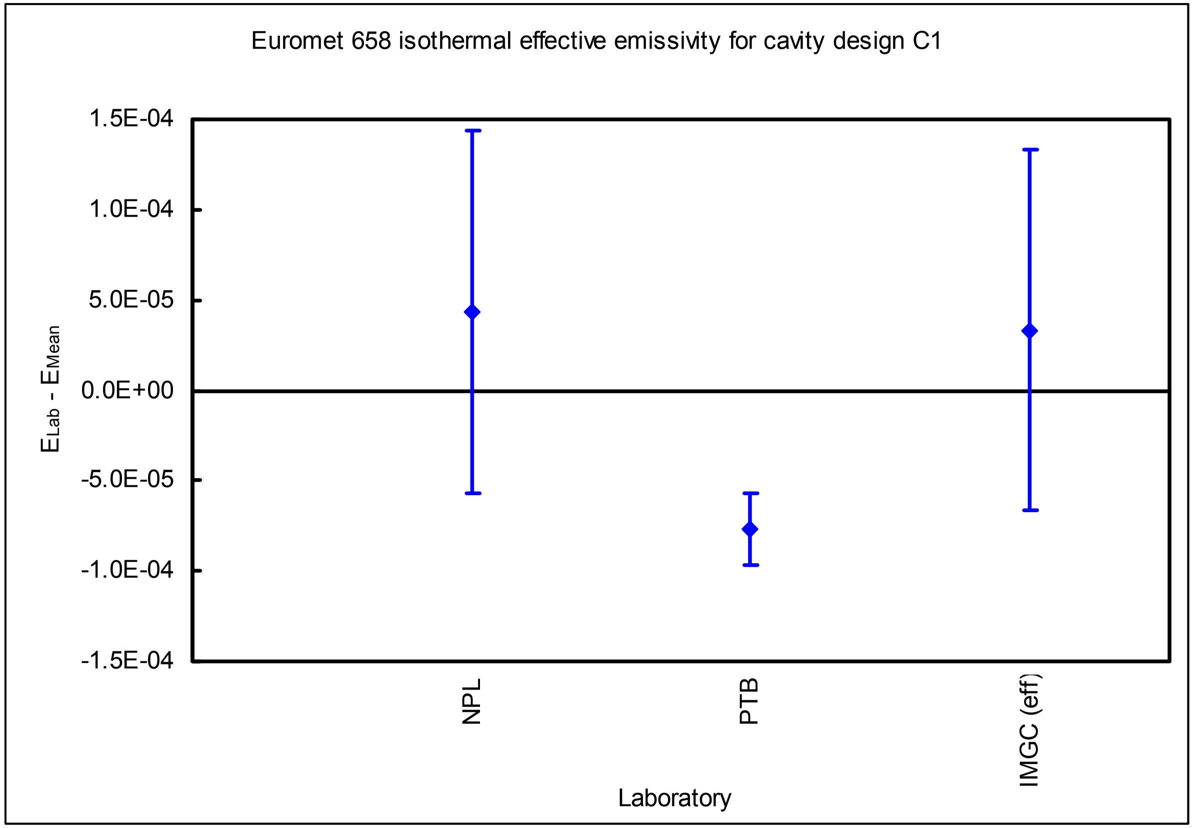
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00019 ± 0.00016	0.00002 ± 0.00019
PTB	*0.00032*	-	-0.00017 ± 0.00010
IMGC (eff)	*0.00019*	*0.00025*	-

Table 199 – DOE and QDE$_{95}$ values for isothermal effective emissivity values for cavity design B4

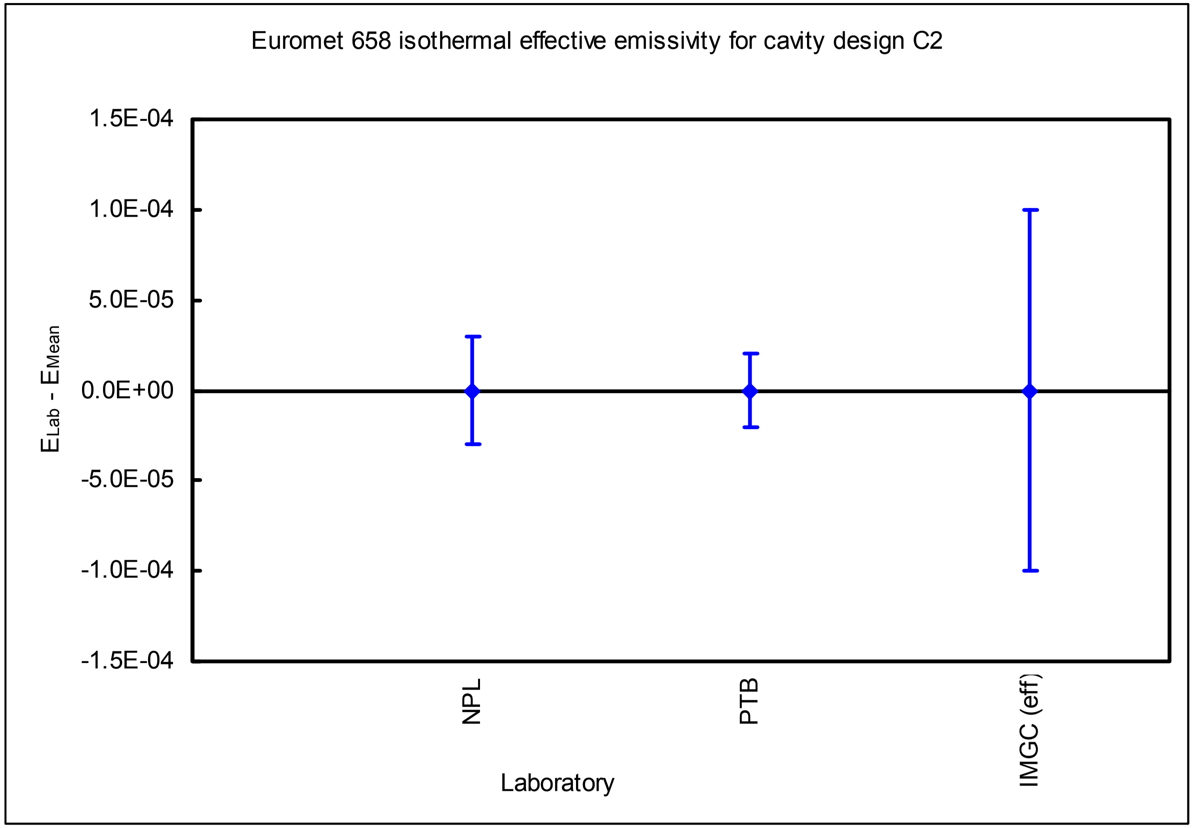
QDE_{95} and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00012 ± 0.00010	0.00001 ± 0.00014
PTB	*0.00020*	-	-0.00011 ± 0.00010
IMGC (eff)	*0.00014*	*0.00019*	-

Table 200 – DOE and QDE_{95} values for isothermal effective emissivity values for cavity design C1

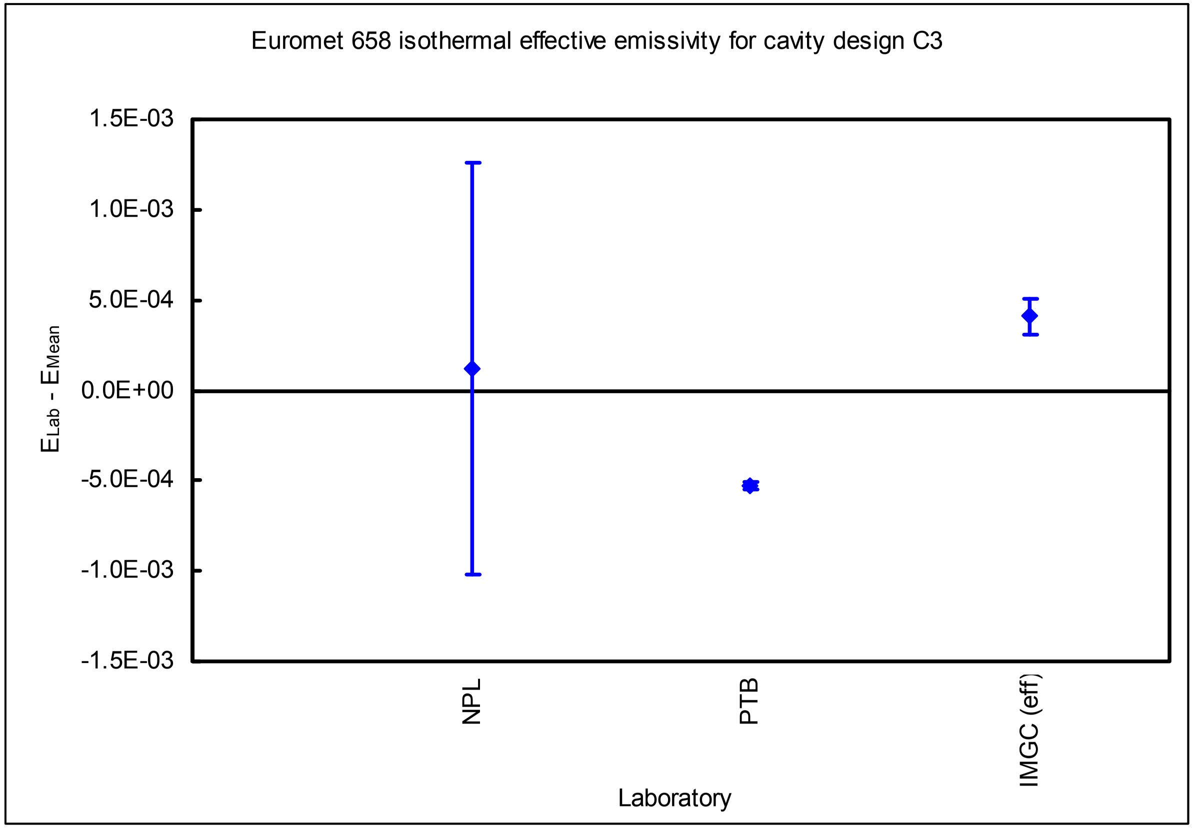
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00000 ± 0.00004	0.00000 ± 0.00010
PTB	*0.00004*	-	0.00000 ± 0.00010
IMGC (eff)	*0.00010*	*0.00010*	-

Table 201 – DOE and QDE$_{95}$ values for isothermal effective emissivity values for cavity design C2

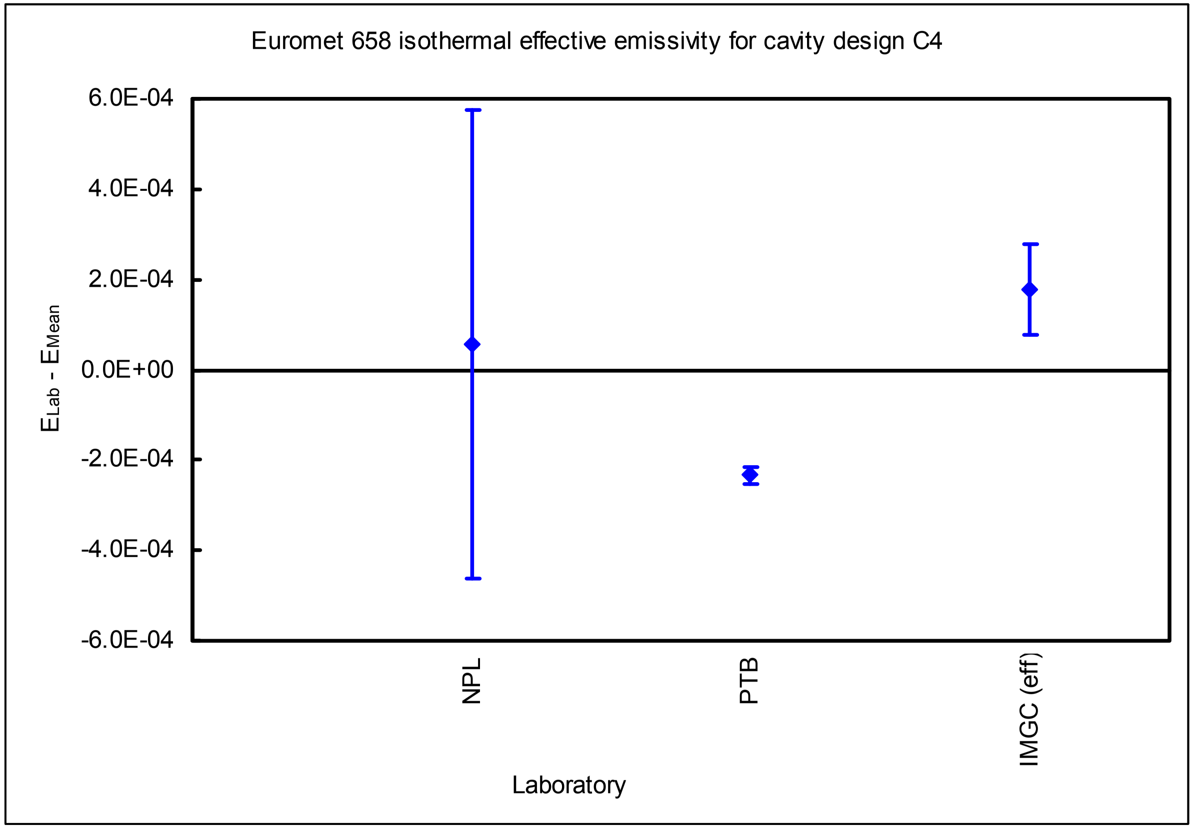
QDE_{95} and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00065 ± 0.00114	-0.00029 ± 0.00114
PTB	*0.00159*	-	-0.00094 ± 0.00010
IMGC (eff)	*0.00126*	*0.00102*	-

Table 202 – DOE and QDE_{95} values for isothermal effective emissivity values for cavity design C3

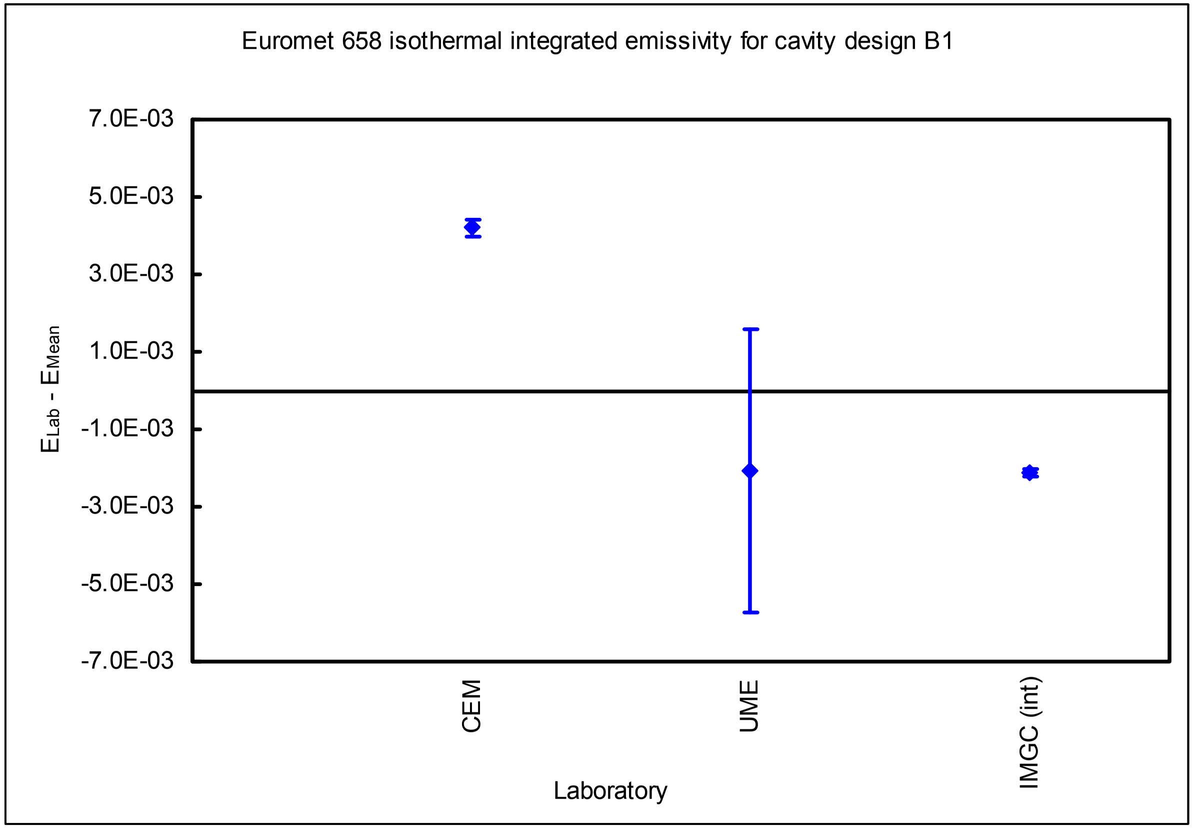
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00029 ± 0.00052	-0.00012 ± 0.00053
PTB	*0.00072*	-	-0.00041 ± 0.00010
IMGC (eff)	*0.00057*	*0.00049*	-

Table 203 – DOE and QDE$_{95}$ values for isothermal effective emissivity values for cavity design C4

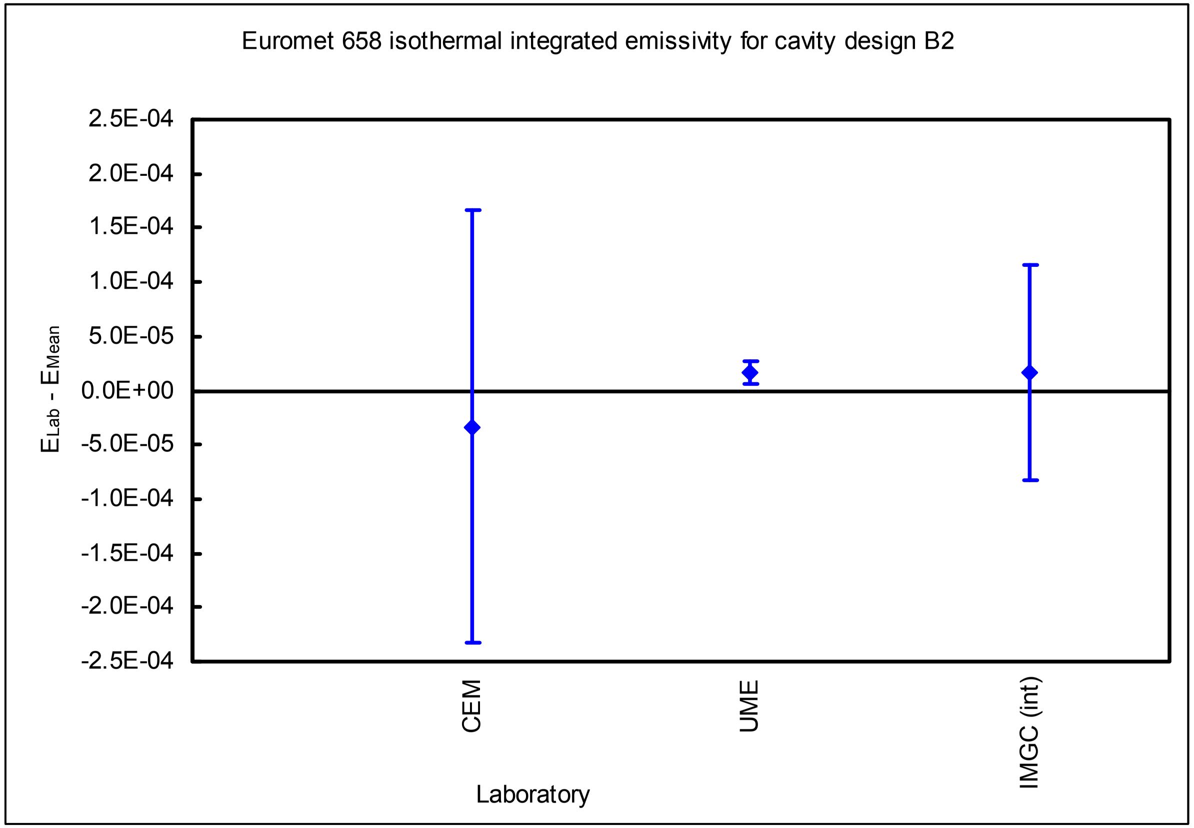
QDE$_{95}$ and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.00629 ± 0.00367	0.00631 ± 0.00022
UME	*0.00930*	-	0.00002 ± 0.00366
IMGC (int)	*0.00649*	*0.00361*	-

Table 204 – DOE and QDE$_{95}$ values for isothermal integrated emissivity values for cavity design B1

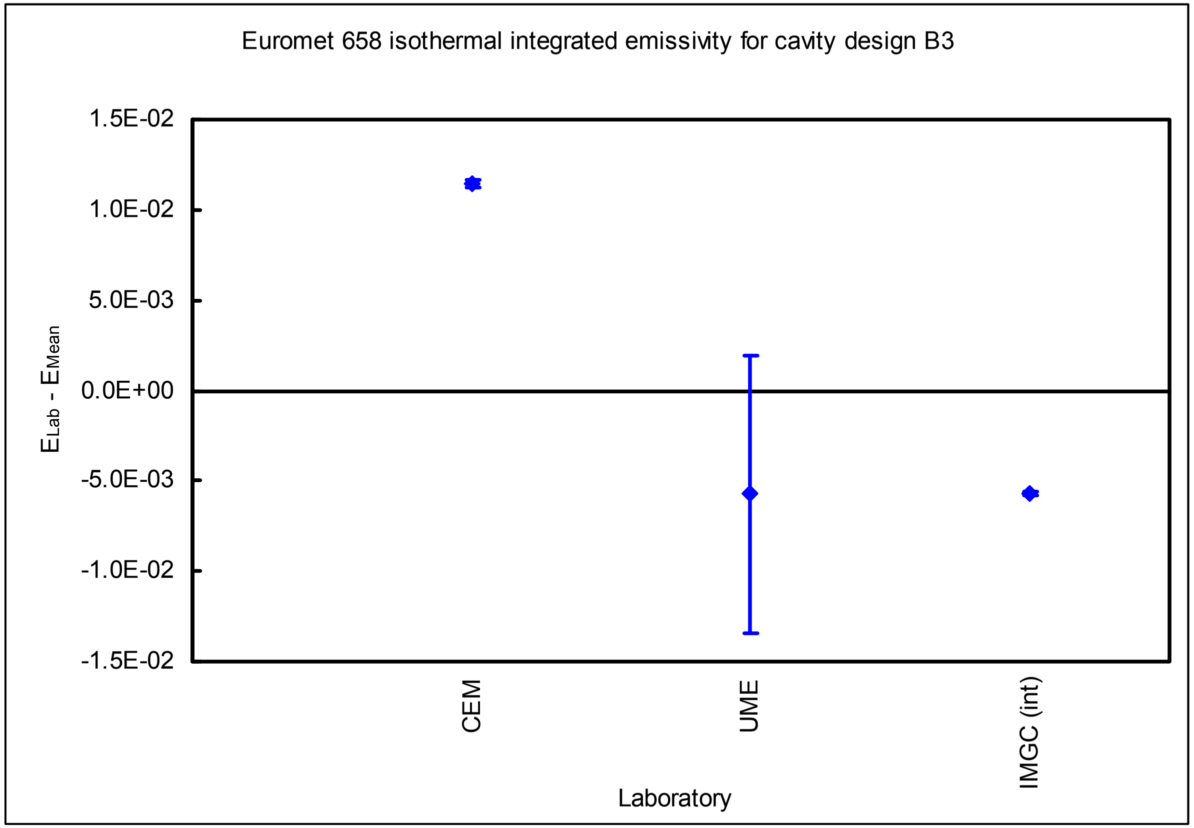
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	-0.00005 ± 0.00020	-0.00005 ± 0.00022
UME	*0.00022*	-	0.00000 ± 0.00010
IMGC (int)	*0.00024*	*0.00010*	-

Table 205 – DOE and QDE_{95} values for isothermal integrated emissivity values for cavity design B2

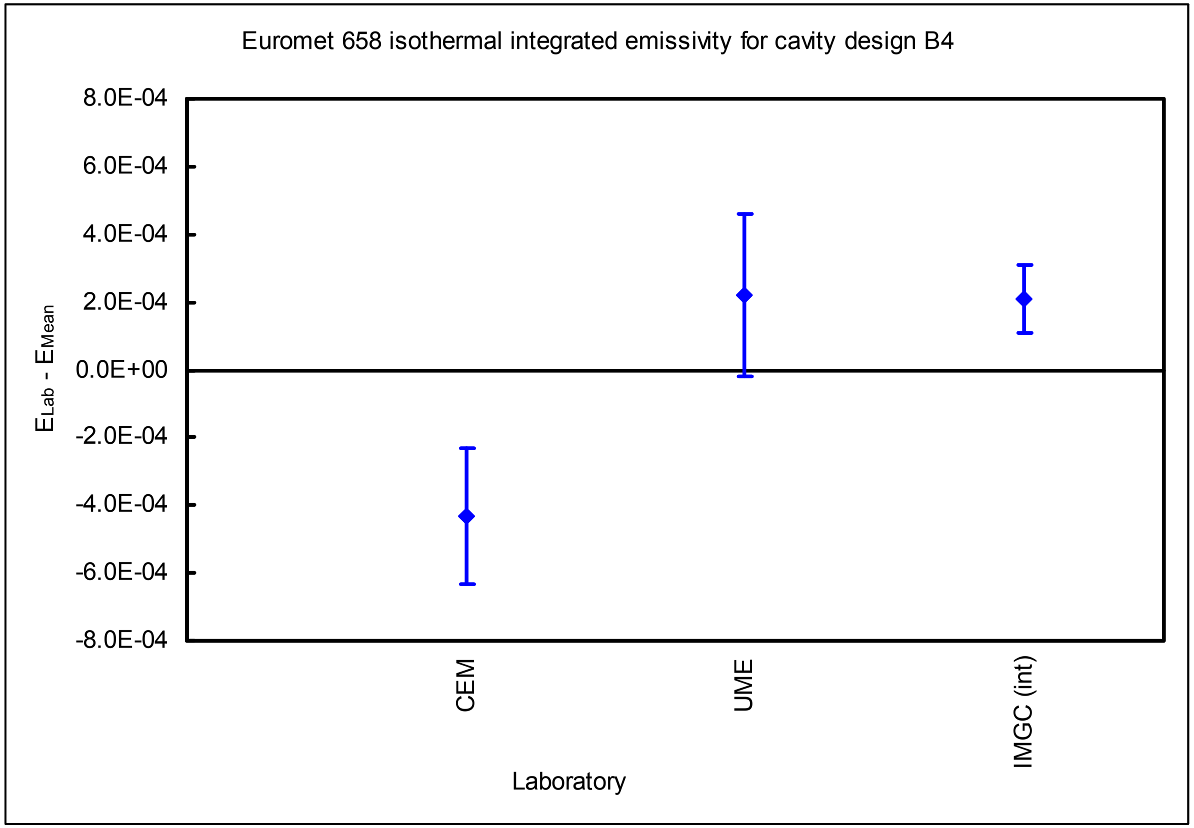
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.01719 ± 0.00770	0.01719 ± 0.00022
UME	*0.02353*	-	0.00000 ± 0.00770
IMGC (int)	*0.01737*	*0.00760*	-

Table 206 – DOE and QDE_{95} values for isothermal integrated emissivity values for cavity design B3

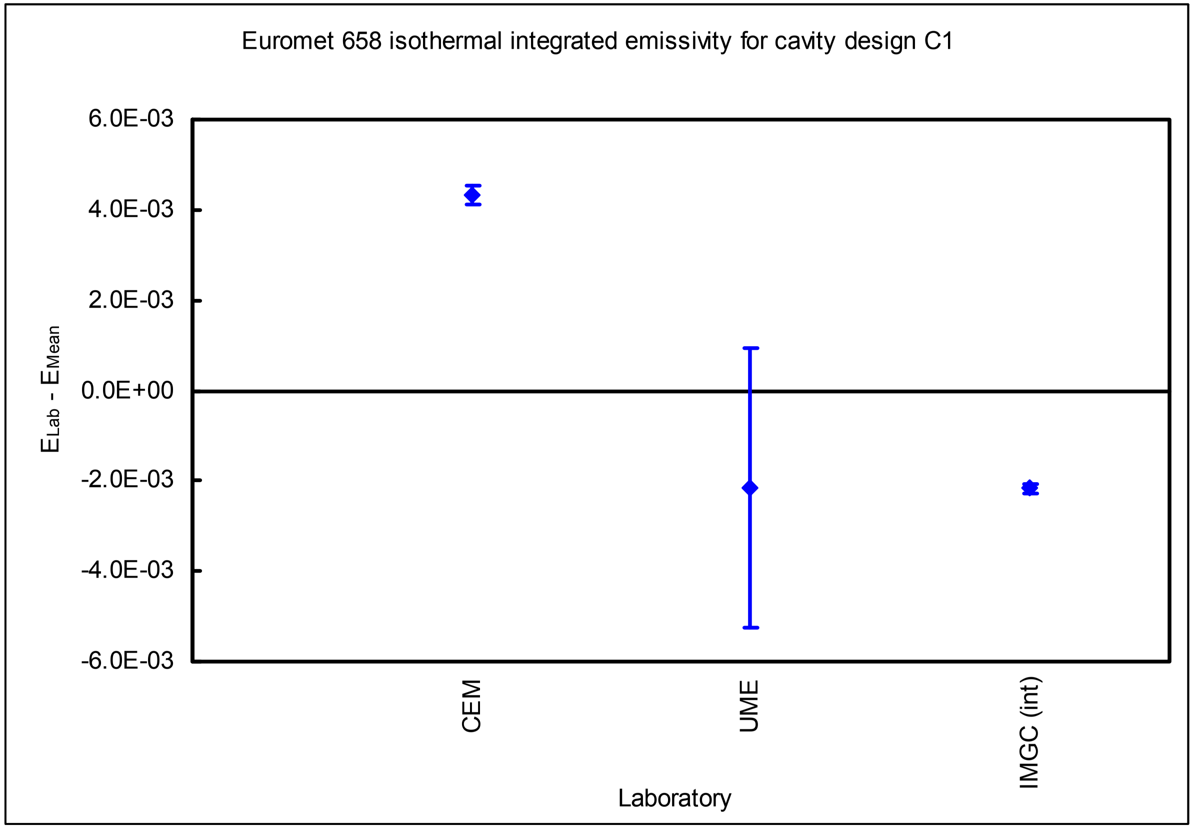
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	-0.00065 ± 0.00031	-0.00064 ± 0.00022
UME	*0.00091*	-	0.00001 ± 0.00026
IMGC (int)	*0.00082*	*0.00026*	-

Table 207 – DOE and QDE_{95} values for isothermal integrated emissivity values for cavity design B4

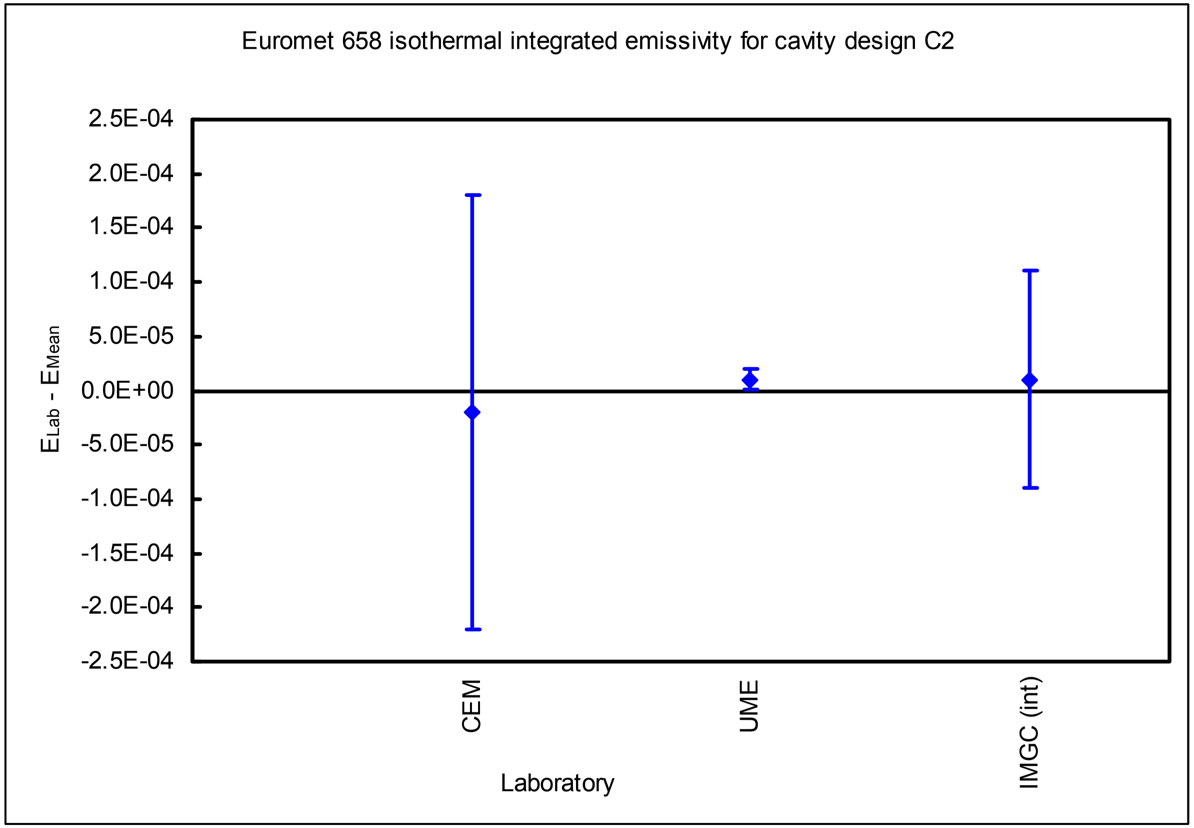
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.00649 ± 0.00311	0.00650 ± 0.00022
UME	*0.00905*	-	0.00001 ± 0.00310
IMGC (int)	*0.00668*	*0.00306*	-

Table 208 – DOE and QDE_{95} values for isothermal integrated emissivity values for cavity design C1

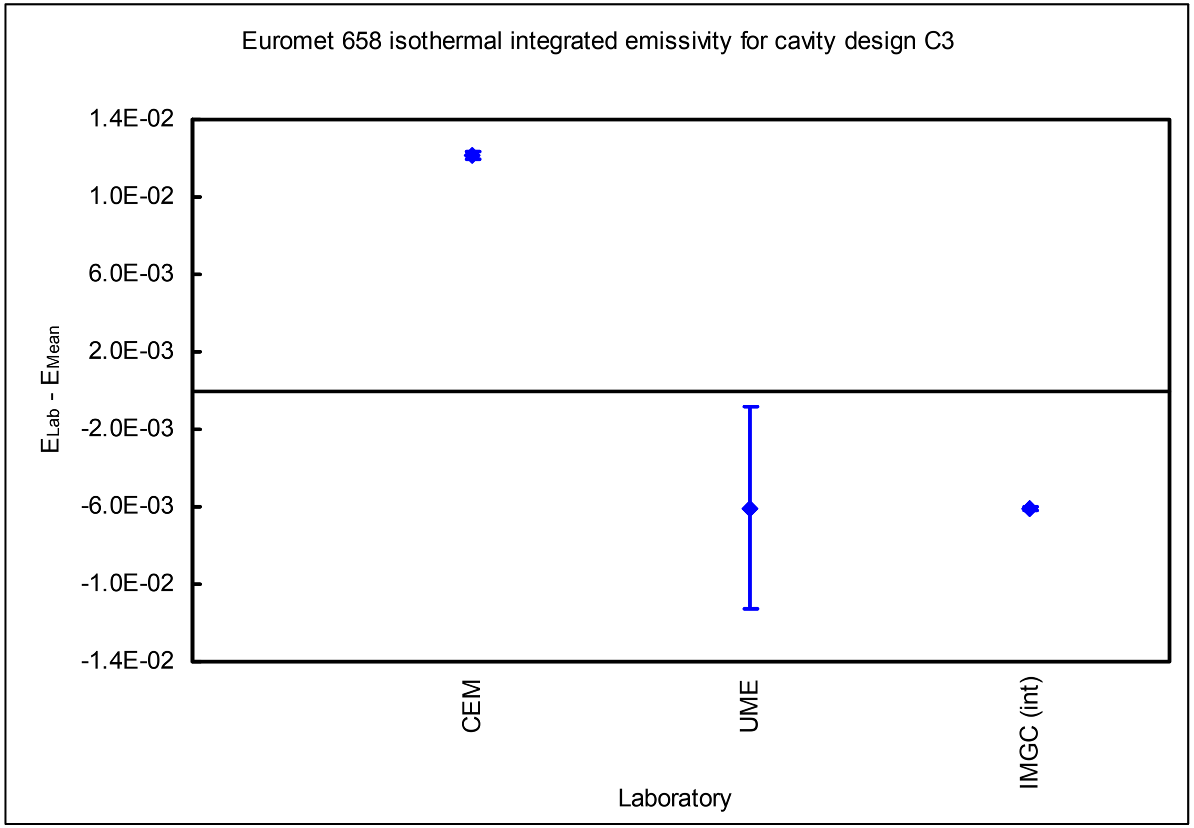
QDE$_{95}$ and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	-0.00003 ± 0.00020	-0.00003 ± 0.00022
UME	*0.00020*	-	0.00000 ± 0.00010
IMGC (int)	*0.00023*	*0.00010*	-

Table 209 – DOE and QDE$_{95}$ values for isothermal integrated emissivity values for cavity design C2

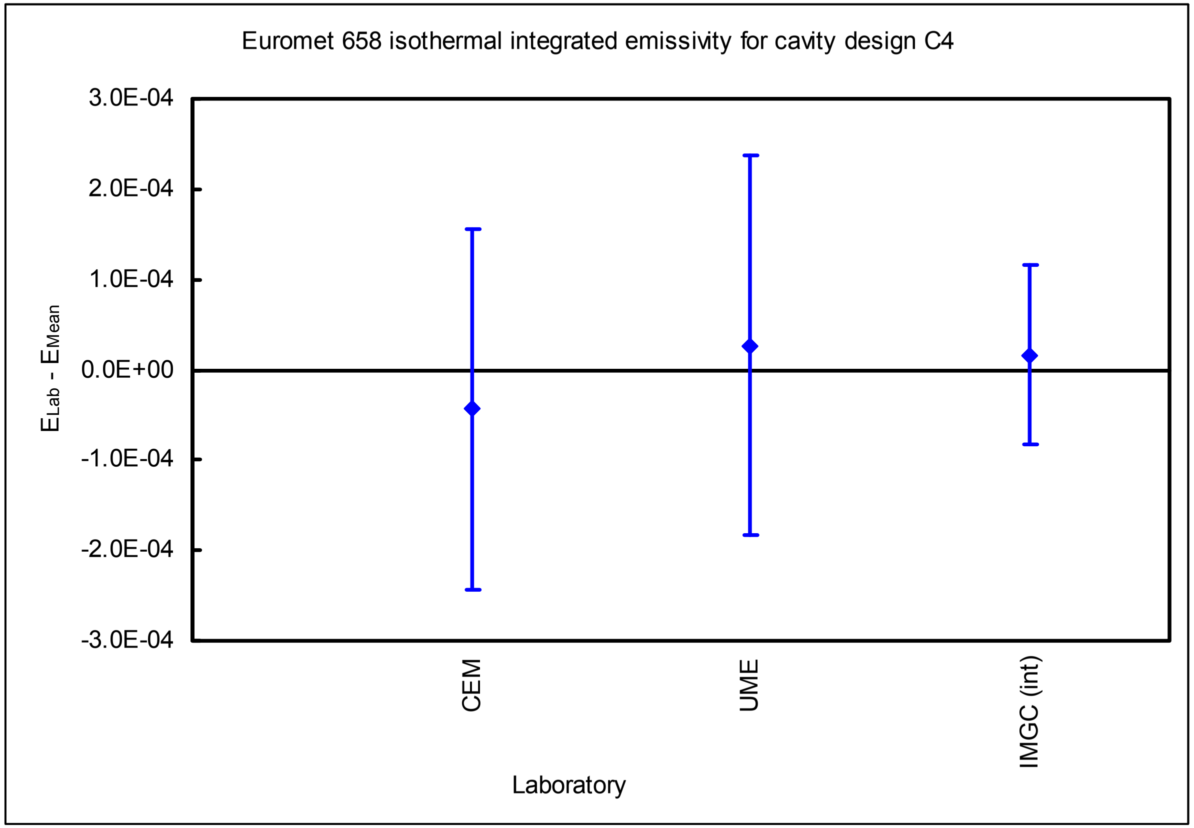
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.01816 ± 0.00523	0.01816 ± 0.00022
UME	*0.02246*	-	0.00000 ± 0.00523
IMGC (int)	*0.01834*	*0.00516*	-

Table 210 – DOE and QDE_{95} values for isothermal integrated emissivity values for cavity design C3

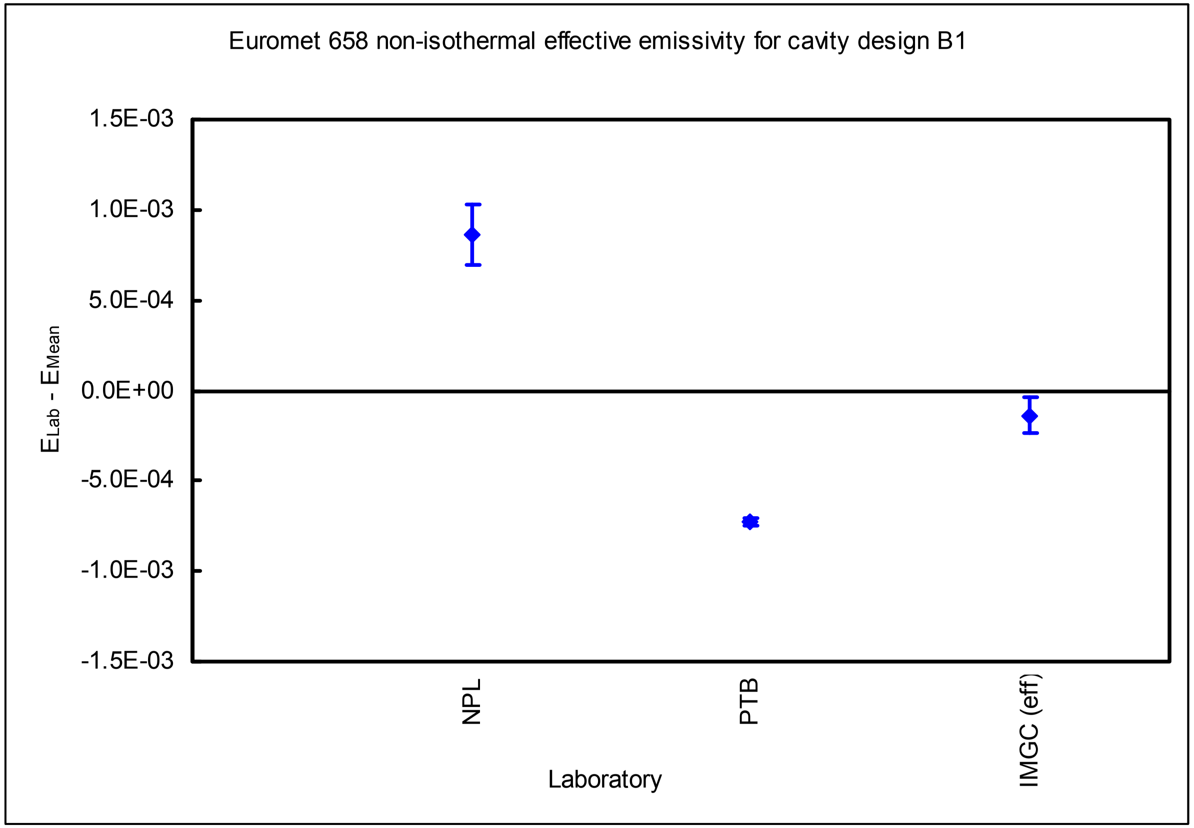
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	-0.00007 ± 0.00029	-0.00006 ± 0.00022
UME	*0.00032*	-	0.00001 ± 0.00023
IMGC (int)	*0.00025*	*0.00023*	-

Table 211 – DOE and QDE_{95} values for isothermal integrated emissivity values for cavity design C4

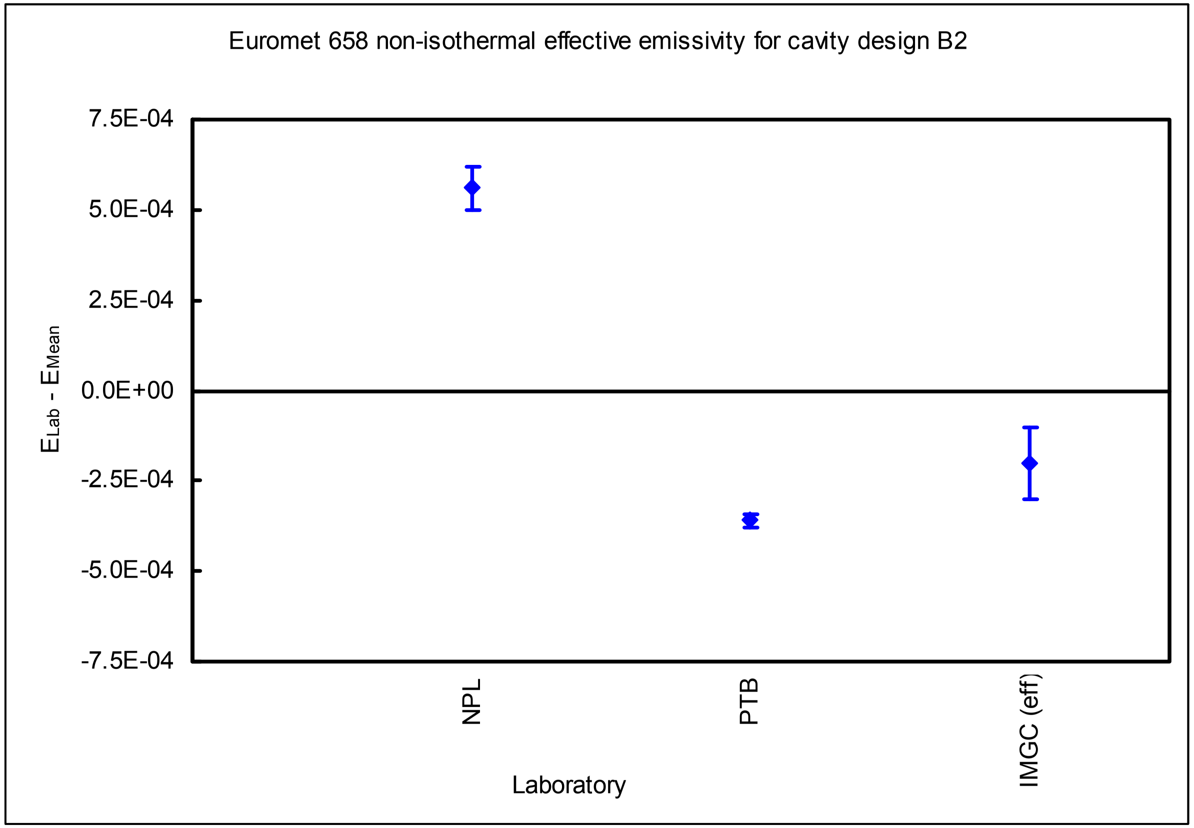
QDE_{95} and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00159 ± 0.00017	0.00100 ± 0.00020
PTB	*0.00173*	-	-0.00059 ± 0.00010
IMGC (eff)	*0.00116*	*0.00067*	-

Table 212 – DOE and QDE_{95} values for non-isothermal effective emissivity values for cavity design B1

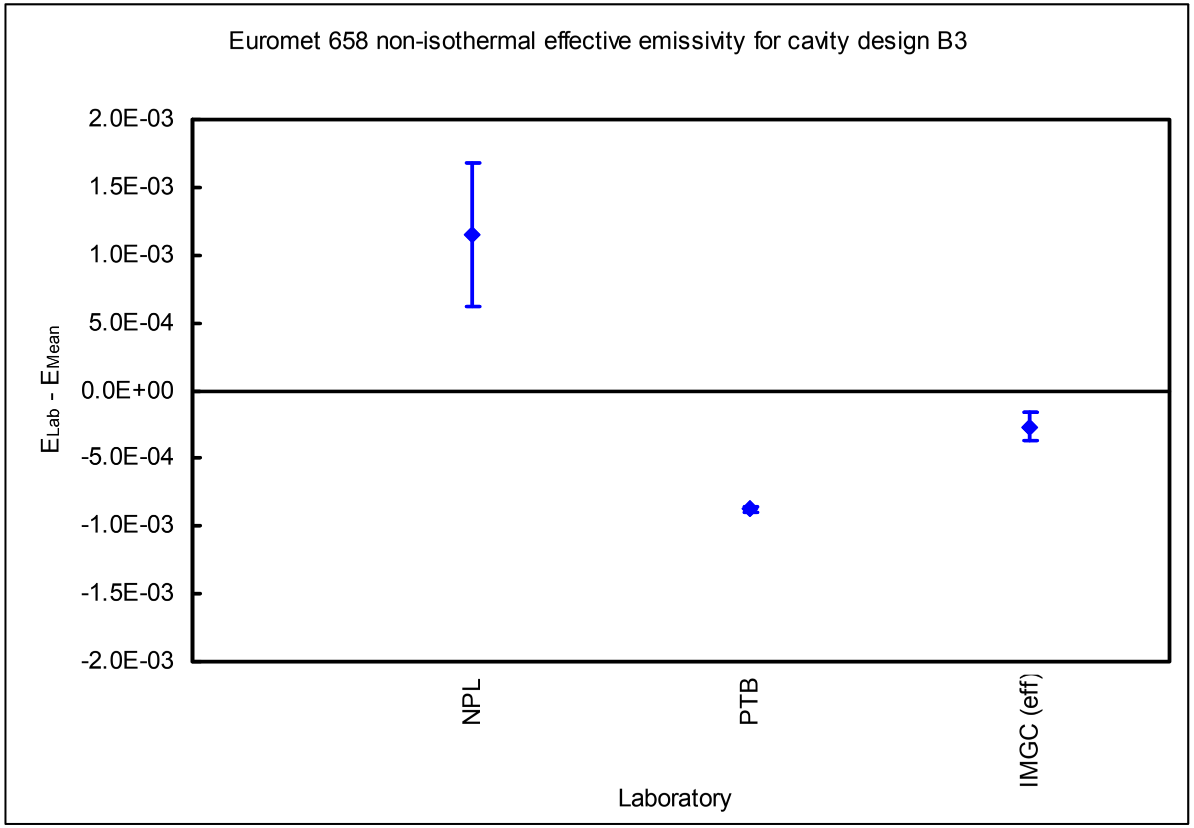
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00092 ± 0.00006	0.00076 ± 0.00012
PTB	*0.00097*	-	-0.00016 ± 0.00010
IMGC (eff)	*0.00086*	*0.00024*	-

Table 213 – DOE and QDE$_{95}$ values for non-isothermal effective emissivity values for cavity design B2

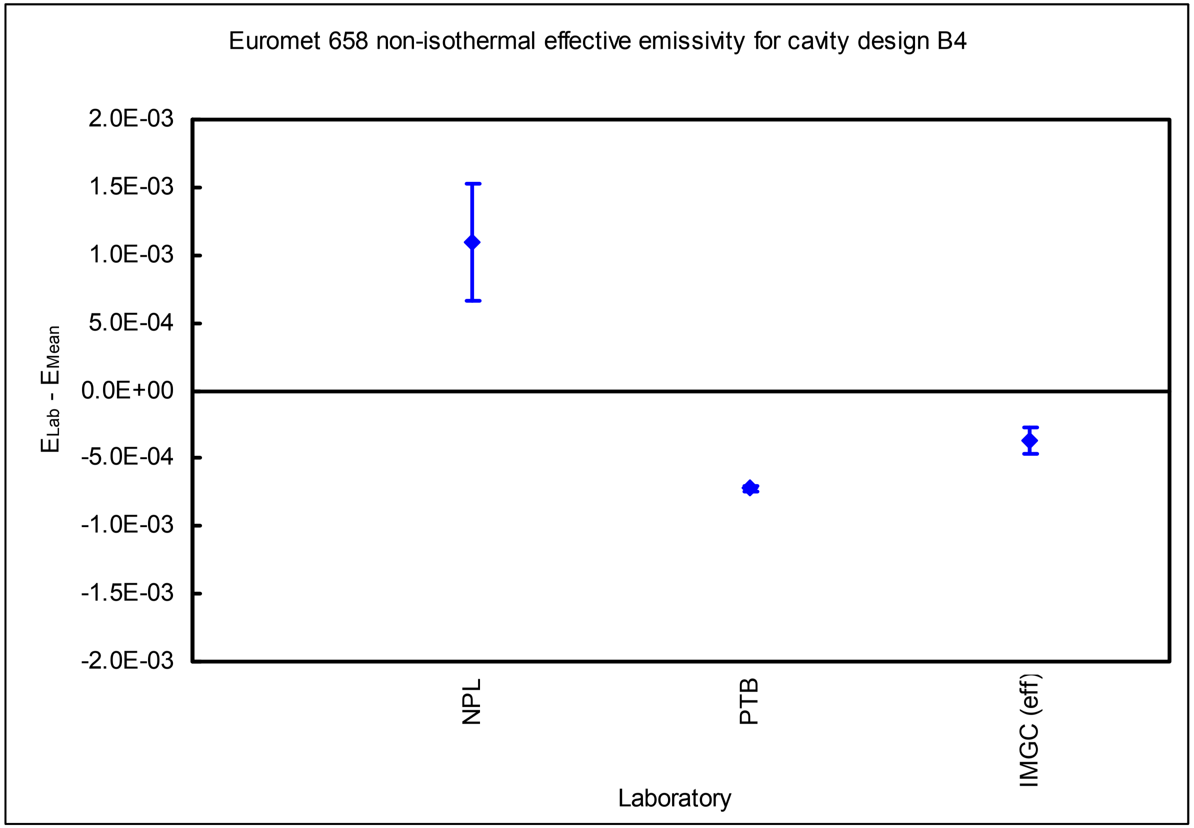
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00202 ± 0.00053	0.00141 ± 0.00054
PTB	*0.00246*	-	-0.00061 ± 0.00010
IMGC (eff)	*0.00185*	*0.00069*	-

Table 214 – DOE and QDE$_{95}$ values for non-isothermal effective emissivity values for cavity design B3

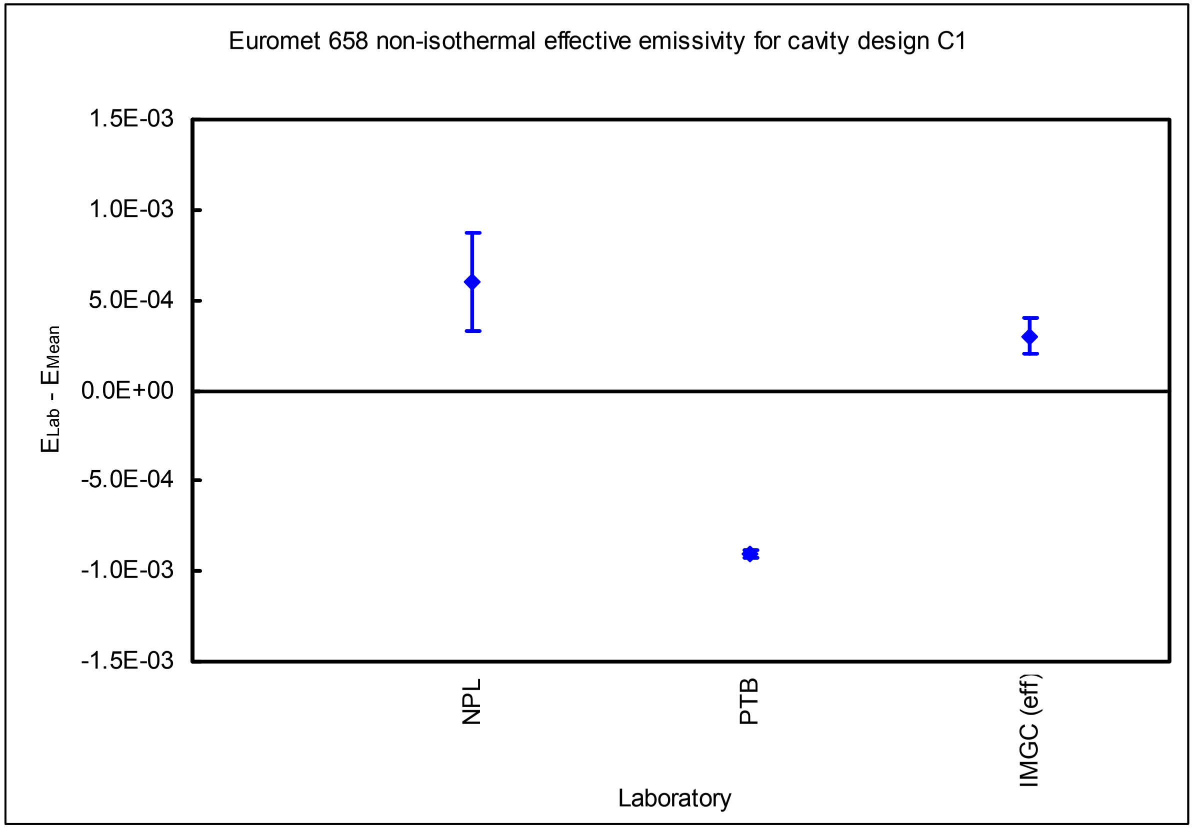
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00181 ± 0.00043	0.00146 ± 0.00044
PTB	*0.00216*	-	-0.00035 ± 0.00010
IMGC (eff)	*0.00182*	*0.00043*	-

Table 215 – DOE and QDE$_{95}$ values for non-isothermal effective emissivity values for cavity design B4

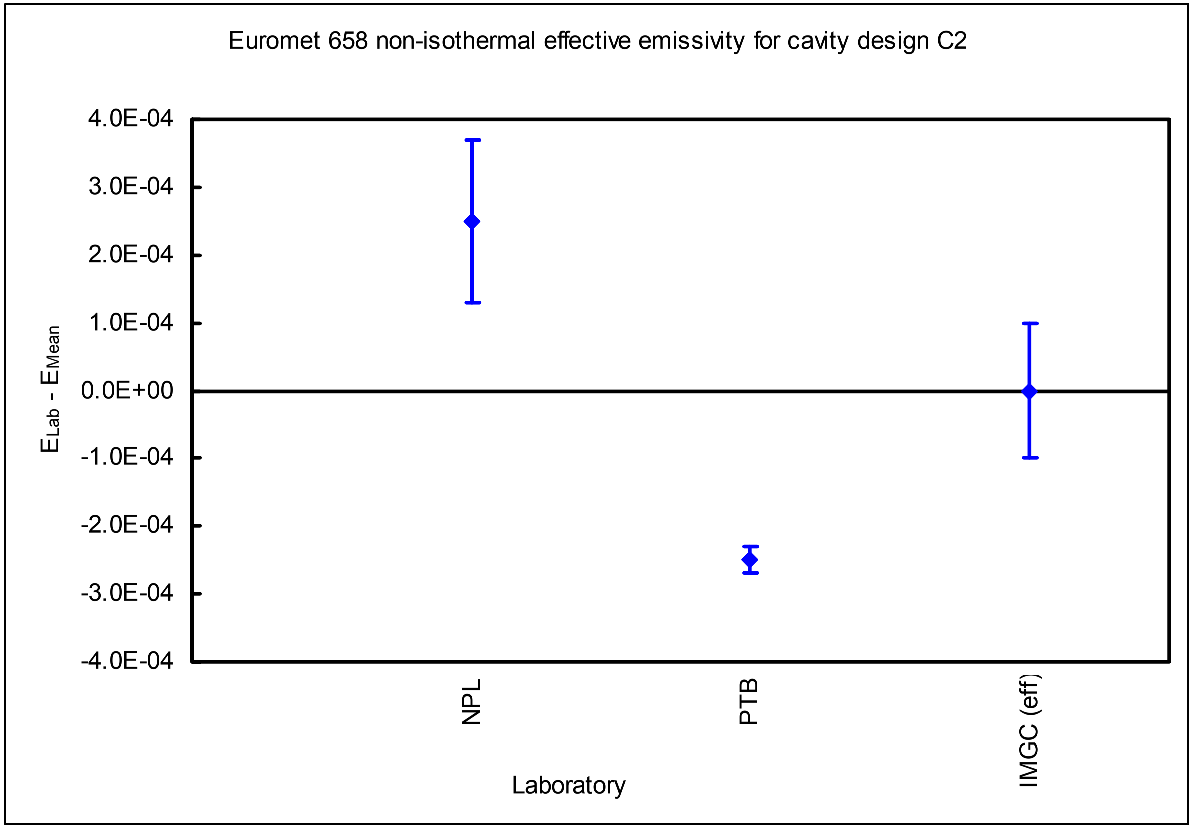
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00150 ± 0.00027	0.00030 ± 0.00029
PTB	*0.00172*	-	-0.00120 ± 0.00010
IMGC (eff)	*0.00054*	*0.00128*	-

Table 216 – DOE and QDE$_{95}$ values for non-isothermal effective emissivity values for cavity design C1

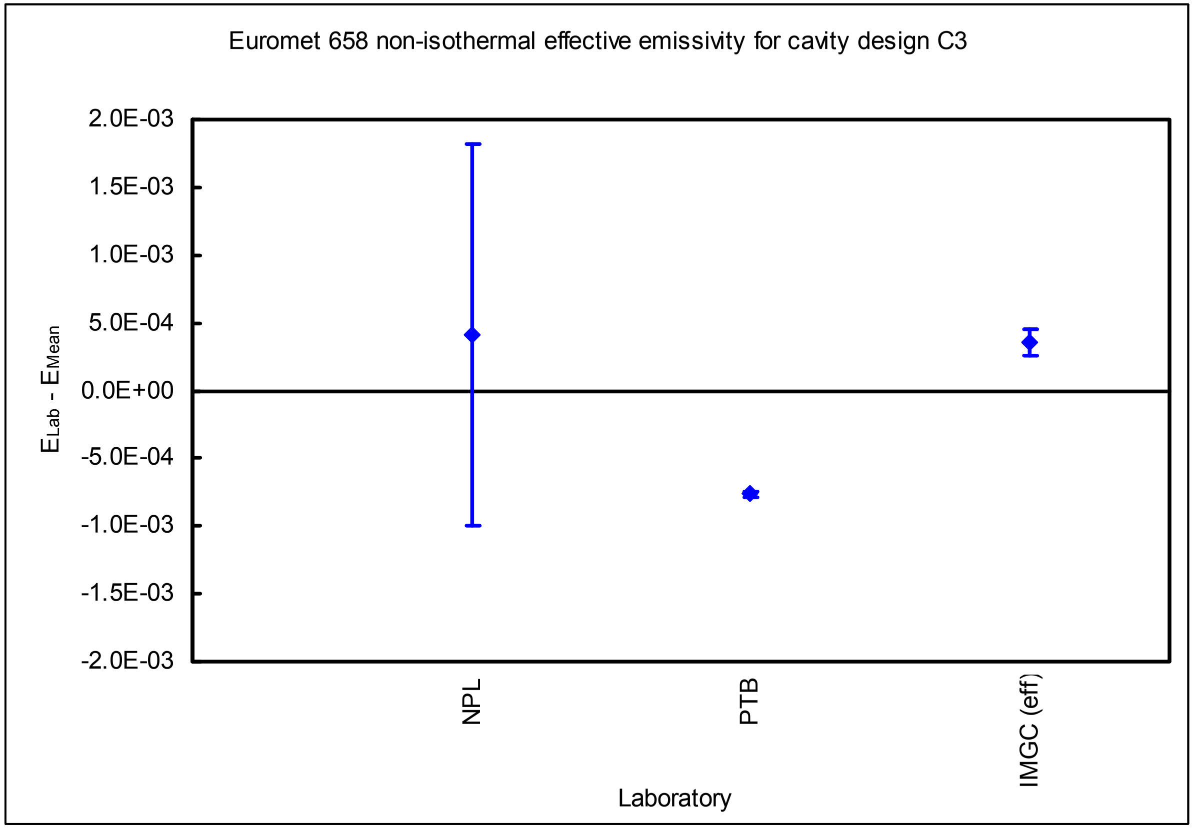
QDE_{95} and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00050 ± 0.00012	0.00025 ± 0.00016
PTB	*0.00060*	-	-0.00025 ± 0.00010
IMGC (eff)	*0.00038*	*0.00033*	-

Table 217 – DOE and QDE_{95} values for non-isothermal effective emissivity values for cavity design C2

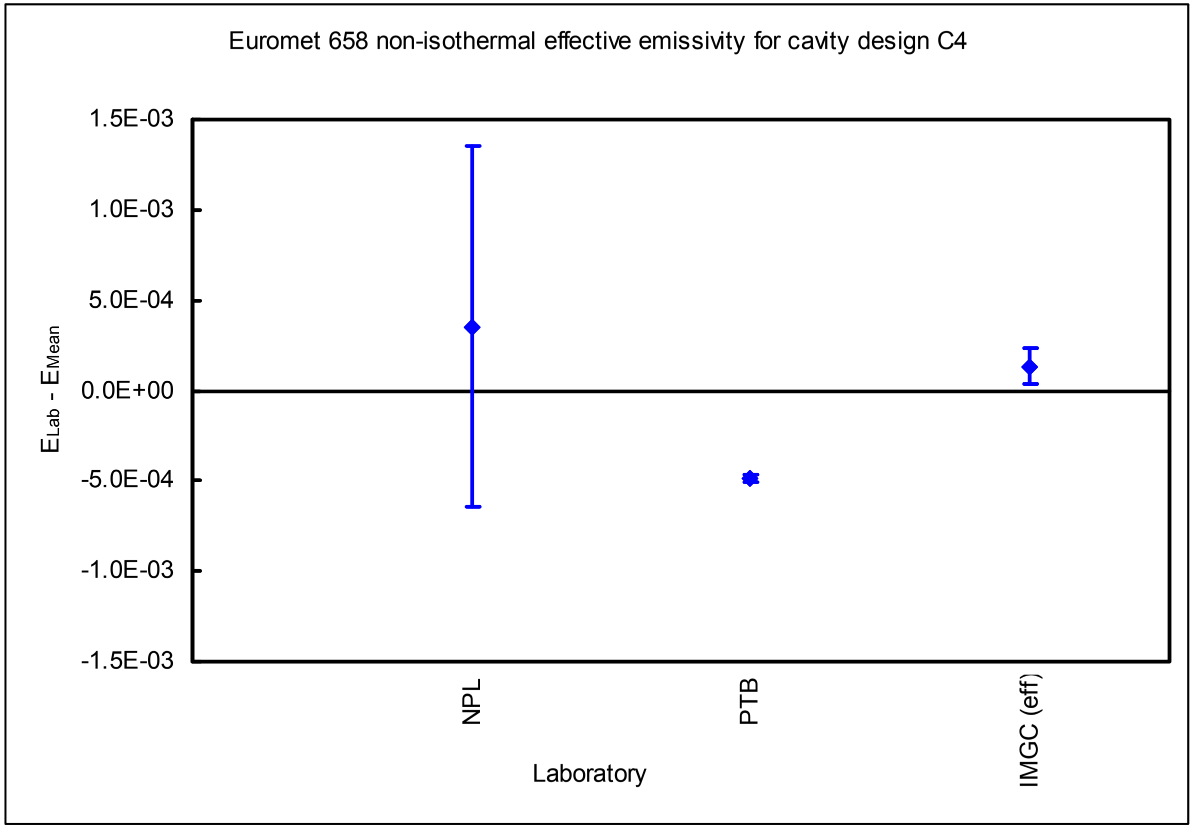
QDE_{95} and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00117 ± 0.00141	0.00005 ± 0.00141
PTB	*0.00233*	-	-0.00112 ± 0.00010
IMGC (eff)	*0.00139*	*0.00120*	-

Table 218 – DOE and QDE_{95} values for non-isothermal effective emissivity values for cavity design C3

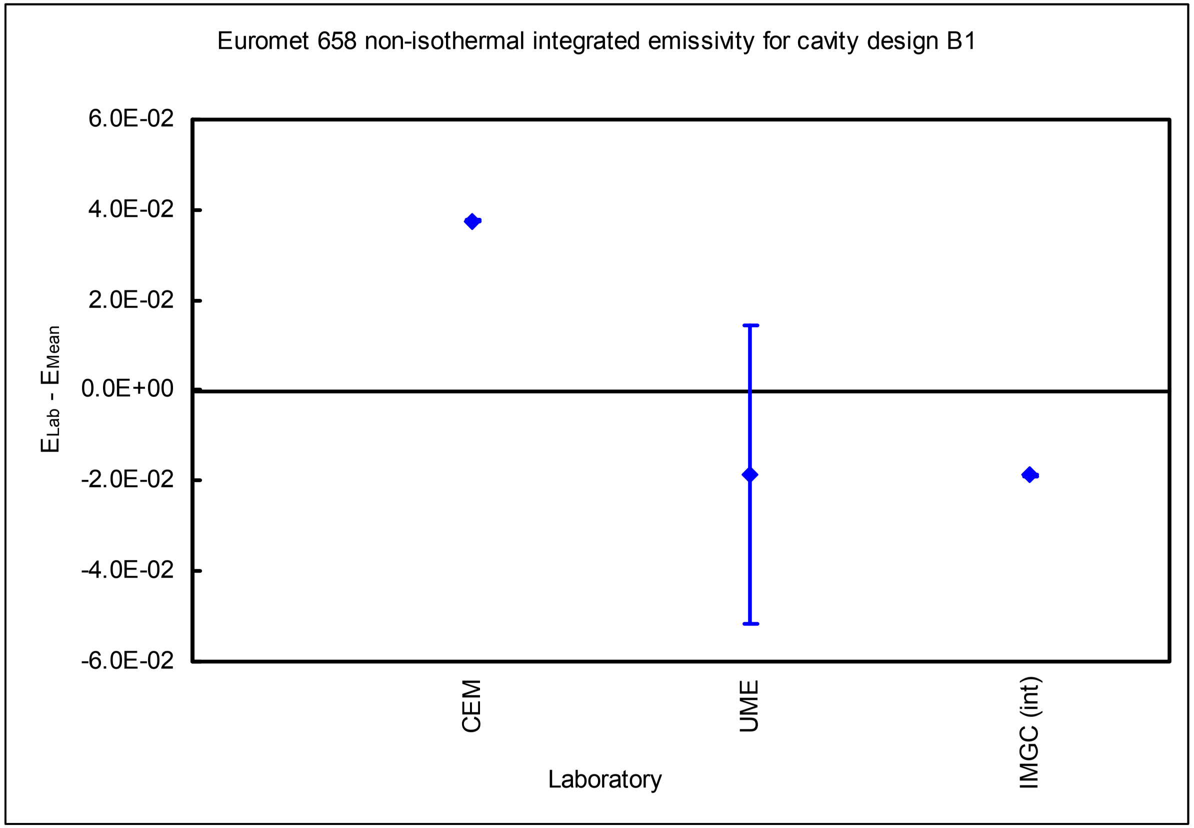
QDE$_{95}$ and DOE values and graphs for the emissivity values



	NPL	PTB	IMGC (eff)
NPL	-	0.00084 ± 0.00100	0.00022 ± 0.00100
PTB	*0.00166*	-	-0.00062 ± 0.00010
IMGC (eff)	*0.00107*	*0.00070*	-

Table 219 – DOE and QDE$_{95}$ values for non-isothermal effective emissivity values for cavity design C4

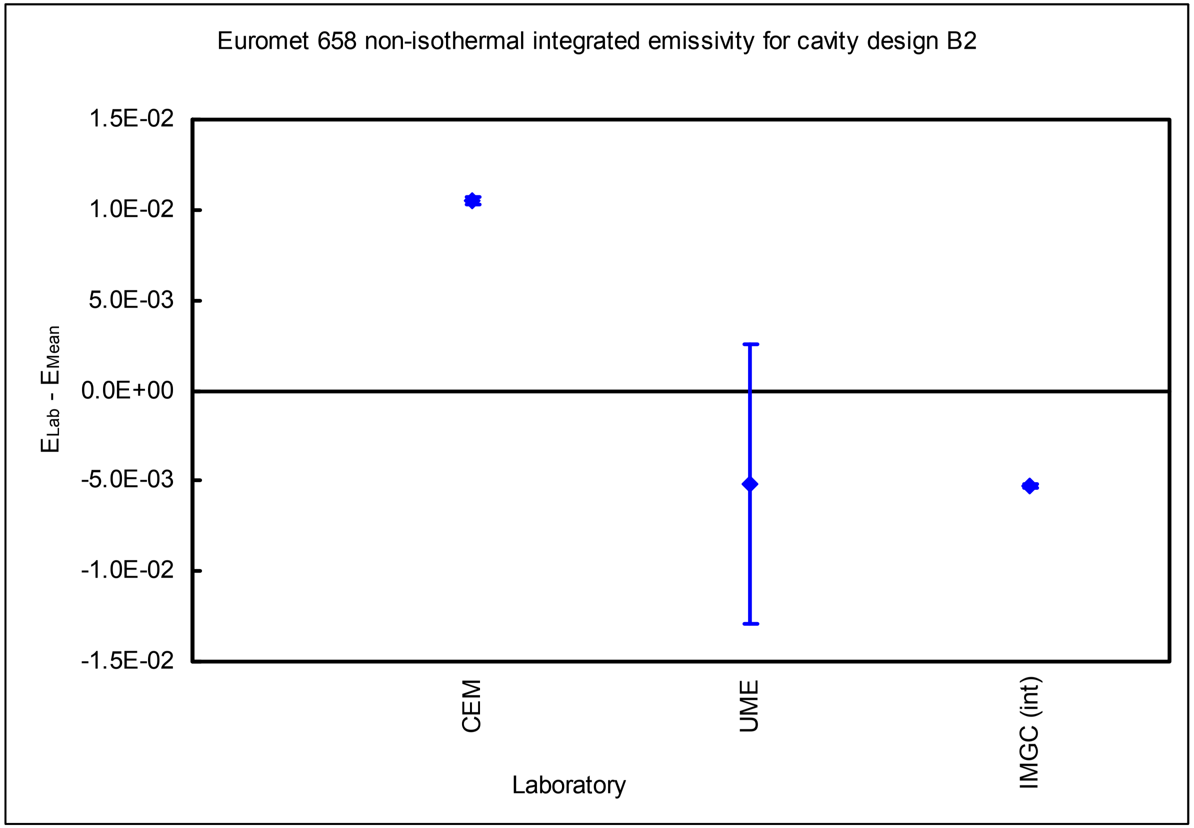
QDE$_{95}$ and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.05615 ± 0.03312	0.05616 ± 0.00022
UME	*0.08339*	-	0.00001 ± 0.03312
IMGC (int)	*0.05634*	*0.03269*	-

Table 220 – DOE and QDE$_{95}$ values for non-isothermal integrated emissivity values for cavity design B1

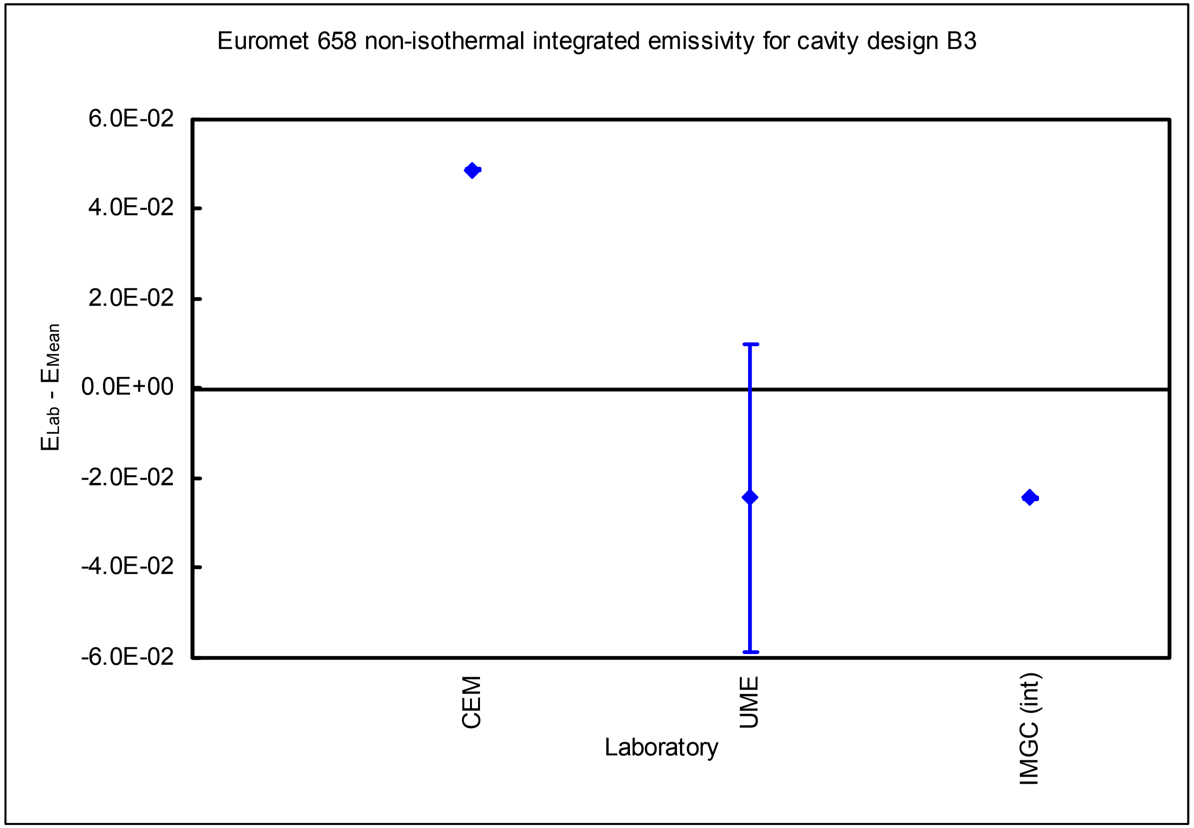
QDE$_{95}$ and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.01565 ± 0.00770	0.01580 ± 0.00022
UME	*0.02199*	-	0.00015 ± 0.00770
IMGC (int)	*0.01598*	*0.00757*	-

Table 221 – DOE and QDE$_{95}$ values for non-isothermal integrated emissivity values for cavity design B2

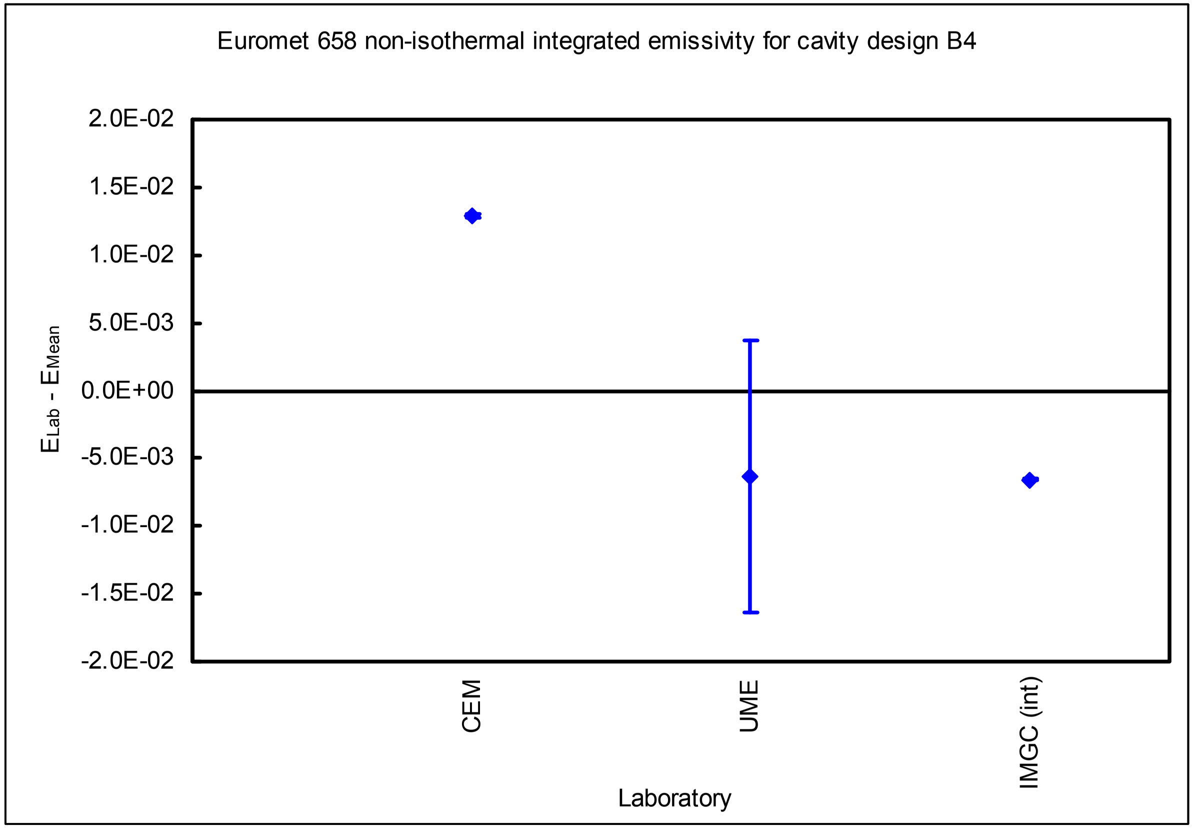
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.07311 ± 0.03433	0.07312 ± 0.00022
UME	*0.10135*	-	0.00001 ± 0.03433
IMGC (int)	*0.07330*	*0.03389*	-

Table 222 – DOE and QDE_{95} values for non-isothermal integrated emissivity values for cavity design B3

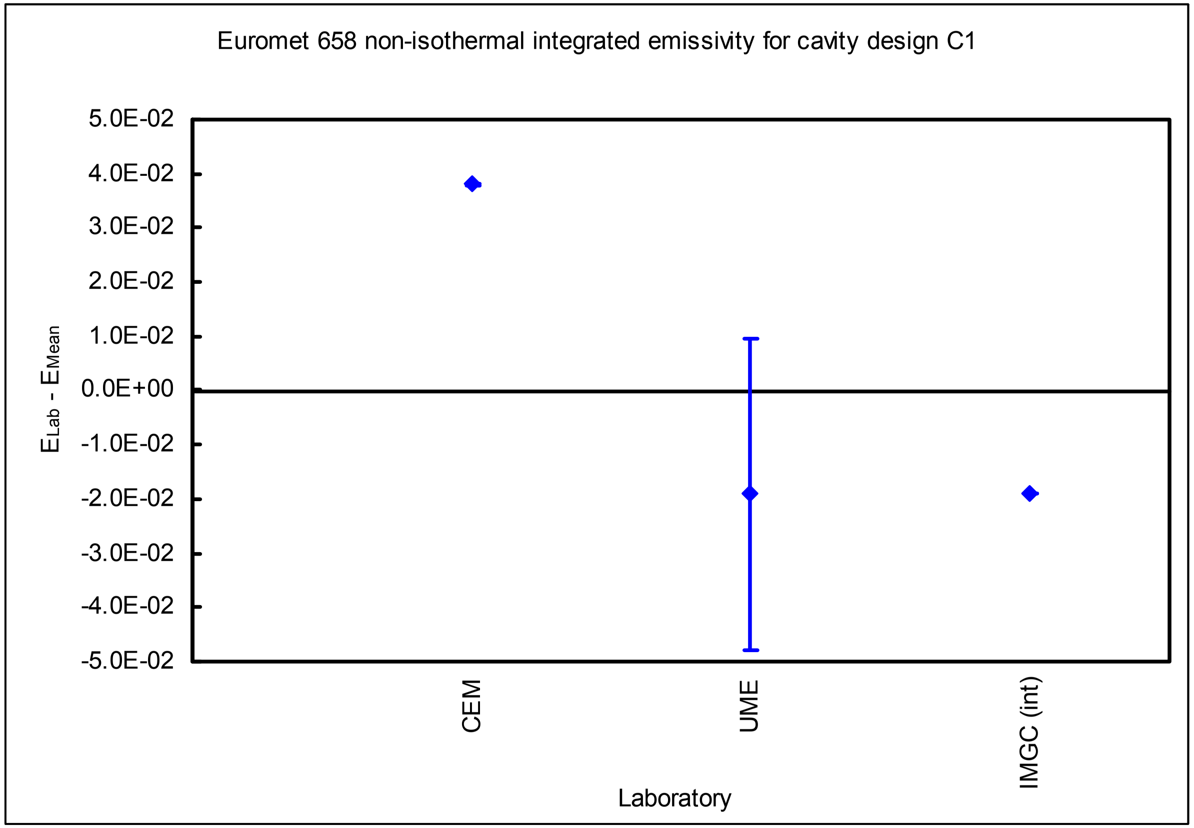
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.01922 ± 0.01008	0.01945 ± 0.00022
UME	*0.02751*	-	0.00023 ± 0.01008
IMGC (int)	*0.01963*	*0.00990*	-

Table 223 – DOE and QDE_{95} values for non-isothermal integrated emissivity values for cavity design B4

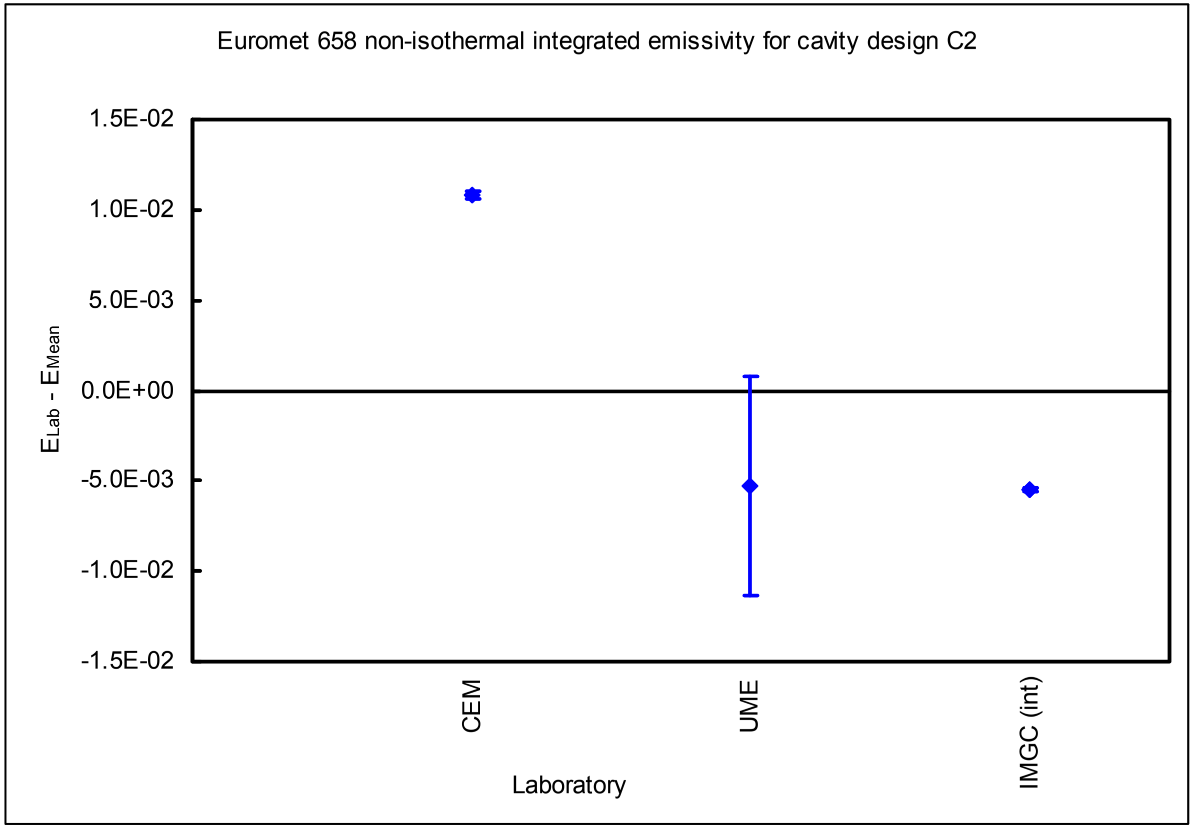
QDE$_{95}$ and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.05708 ± 0.02873	0.05709 ± 0.00022
UME	*0.08071*	-	0.00001 ± 0.02873
IMGC (int)	*0.05727*	*0.02836*	-

Table 224 – DOE and QDE$_{95}$ values for non-isothermal integrated emissivity values for cavity design C1

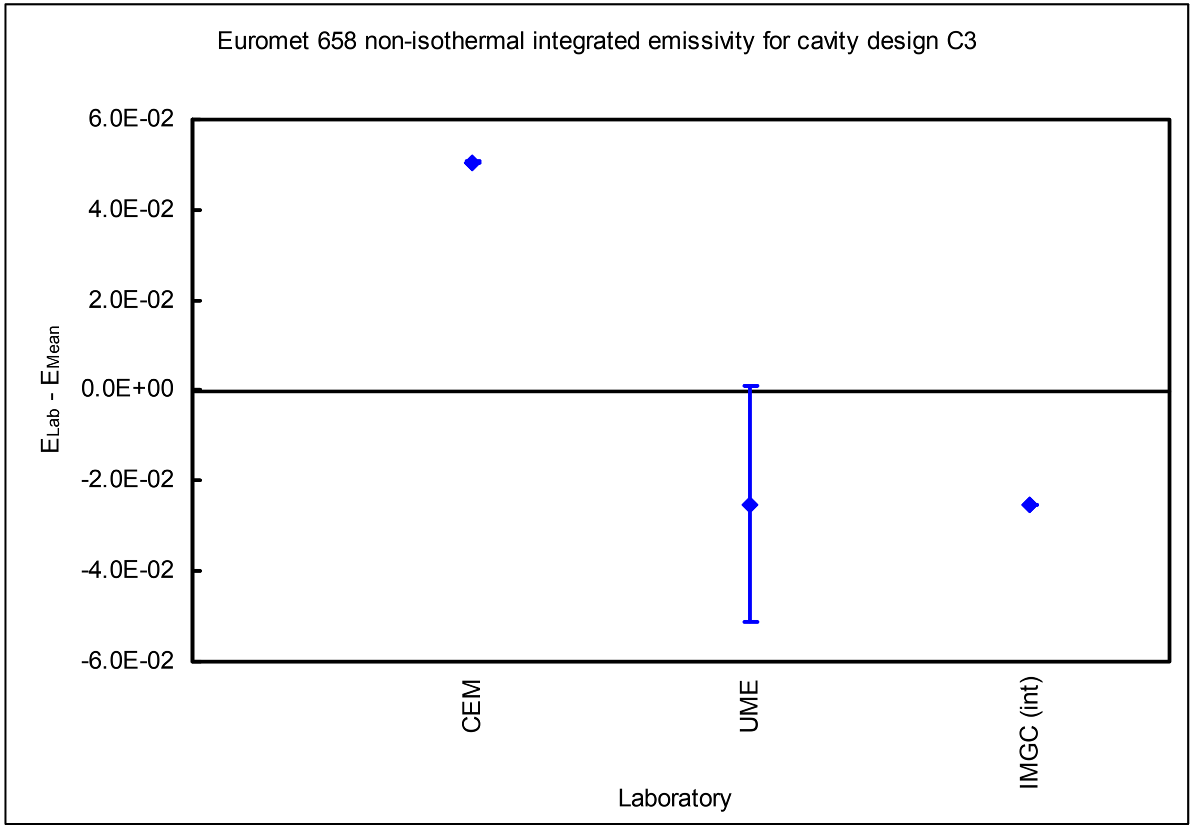
QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.01608 ± 0.00609	0.01629 ± 0.00022
UME	*0.02109*	-	0.00021 ± 0.00609
IMGC (int)	*0.01647*	*0.00598*	-

Table 225 – DOE and QDE_{95} values for non-isothermal integrated emissivity values for cavity design C2

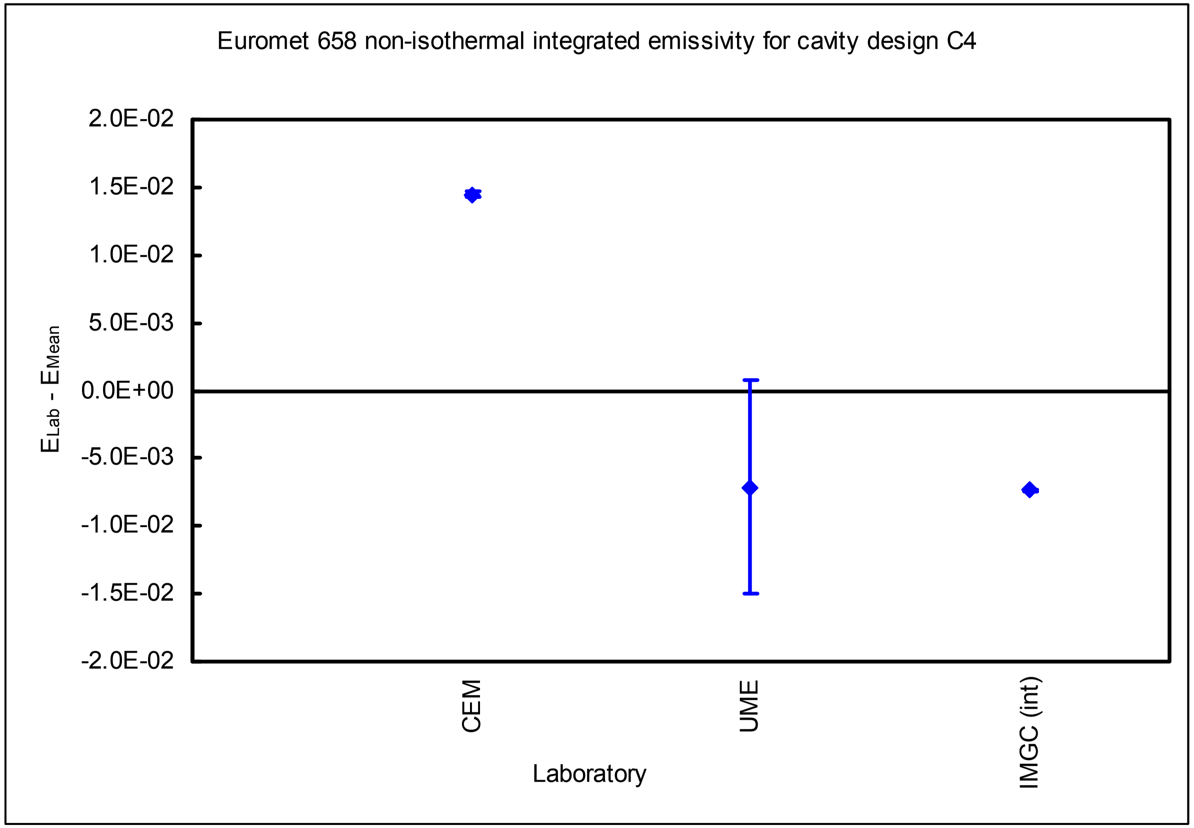
QDE$_{95}$ and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.07565 ± 0.02619	0.07565 ± 0.00022
UME	*0.09719*	-	0.00000 ± 0.02619
IMGC (int)	*0.07583*	*0.02586*	-

Table 226 – DOE and QDE$_{95}$ values for non-isothermal integrated emissivity values for cavity design C3

QDE_{95} and DOE values and graphs for the emissivity values



	CEM	UME	IMGC (int)
CEM	-	0.02159 ± 0.00783	0.02185 ± 0.00022
UME	*0.02803*	-	0.00026 ± 0.00783
IMGC (int)	*0.02203*	*0.00769*	-

Table 227 – DOE and QDE_{95} values for non-isothermal integrated emissivity values for cavity design C4