

# Validation of the spectral radiosity calculation tool LUMOS in regards to the CIE TR 171 test scenarios for lighting simulation software

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*To validate the spectral radiosity simulation program LUMOS, the software is tested against a set of test scenarios, described in the Technical Report 171 of the International Commission on Illumination. Although not all test scenarios are applicable to the LUMOS software, the overall simulation results correspond well to the experimental and analytical reference data, displaying an error of less than 6 % for all but one reference scenarios. This confirms that LUMOS is a suitable tool with the capacity to deliver accurate photometric results.*

## Introduction

LUMOS is a spectral radiosity simulation tool developed in Matlab® [1] for the determination of spectral light distributions in interiors. The program provides a graphical user interface, including an editor, and can simulate artificial lighting, as well as daylight distributions. The artificial lighting simulation mode uses the EULUMDAT [2] file format and an additional spectral power distribution for the luminaires. The daylight simulation mode uses spectral radiance data of a Tregenza hemisphere with 145 sky patches [3]. To validate the photometric simulation results of the software, it is tested against a set of reference scenarios, described in the Technical Report 171 of the International Commission on Illumination (CIE) [4]. The test case numbering in this document corresponds to the reference report.

## Test scenarios

The reference test cases (TC) in CIE 171 were developed to ensure the quality of lighting simulation software for different aspects. The first test scenarios of the CIE 171 are based on experimental measurements. Accordingly, the LUMOS simulation results are expected to lie within the measurement and simulation uncertainty range. The subsequent test scenarios of the CIE 171 are based on analytical considerations on how light distributes. The LUMOS simulation results are compared directly to the analytical references with the relative error expressed as in equation 1 [4].

$$(1) \quad \Delta e = 100 \left( \frac{x}{x_0} - 1 \right) \% \quad \text{with:}$$

$\Delta e$ : relative error in %  
 $x$ : quantity in question  
 $x_0$ : reference value



## Photometric reference data

The luminous flux used during the LUMOS simulations was adapted to the test scenarios. The CIE standard illuminant FL2 [5] was used for spectral power distribution of the luminaires with a spectral range of 380 nm to 780 nm in 10 nm steps. The spectral reflectance values were set uniformly for all wavelengths in 10 nm steps, ranging from 360 nm to 830 nm and the total reflectances were adapted to the individual test case.

The luminaires photometric reference data for test cases 4.1 to 4.6 is provided in CIBSE TM 14 [6] file format. The photometric data was converted to EULUMDAT file format [2], using the LDT-Conv [7] converter. Since the reference luminous intensities  $I_r(\gamma, C)$  are given in cd/1000 lm, each luminaire was adjusted to its correct luminous intensities with the reference total luminous flux  $\Phi_r$  as in equation 2:

$$(2) \quad I(\gamma, C) = \frac{I_r(\gamma, C) \cdot \Phi_r}{1000}$$

The photometric reference data of luminaires two and four for test cases 4.3 and 4.6 had to be corrected due to erroneous conversion. Further photometric data for artificial lighting test scenarios were generated using DIAL's LDT Editor [8].

Daylight radiance distributions were created by first calculating a spectral daylight radiance distribution, using the method of Judd et al. [9] for a correlated colour temperature (CCT) of 6500 K, which is then weighted with the luminance distributions of the CIE standard general skies [10] for Tregenza's 145 sky patches [3].

The transmittance of 6 mm clear glass was calculated for a perpendicular incidence angle, resulting in  $\tau_0 = 0.88$  [11].

## LUMOS characteristics

Some characteristics and limitations of LUMOS are important to note and understand, since they have a direct consequence on the reviewed test scenarios.

1. LUMOS is a radiosity simulation tool that divides all surfaces into triangles. It first calculates the direct lighting for all triangle patch centres and then determines the light reflections from and to all other triangle patch centres. The simulation results therefore strongly depend on patch density and number of internal reflections.
2. Since LUMOS calculates the internal spectral power distribution, the calculation time increases rapidly with patch density, number of internal reflections and spectral resolution. All test cases were simulated with the standard setting of a patch density of five patches per m<sup>2</sup> and three internal reflections, except in test cases with no internal reflections and in TC 5.8.
3. LUMOS determines the irradiance of the defined measurement points and areas after the calculation of the internal reflections. This way—even if no reflections are set—all measurement points always receive the full luminous flux from the surroundings areas. This also means that the measurement point results are the product of one additional reflection compared to the room and object surfaces.
4. LUMOS can only evaluate objects inside a room geometry, hence test cases 5.6.2.1 and 5.6.2.2 were enclosed in a larger room geometry. Test cases 5.6.2.3 and 5.13–5.14 are not applicable.
5. Light beams as used in raytracing software are not yet included in LUMOS, hence test case 5.5 is not applicable.

### TC 4.1: Artificial lighting scenario CFL, grey wall

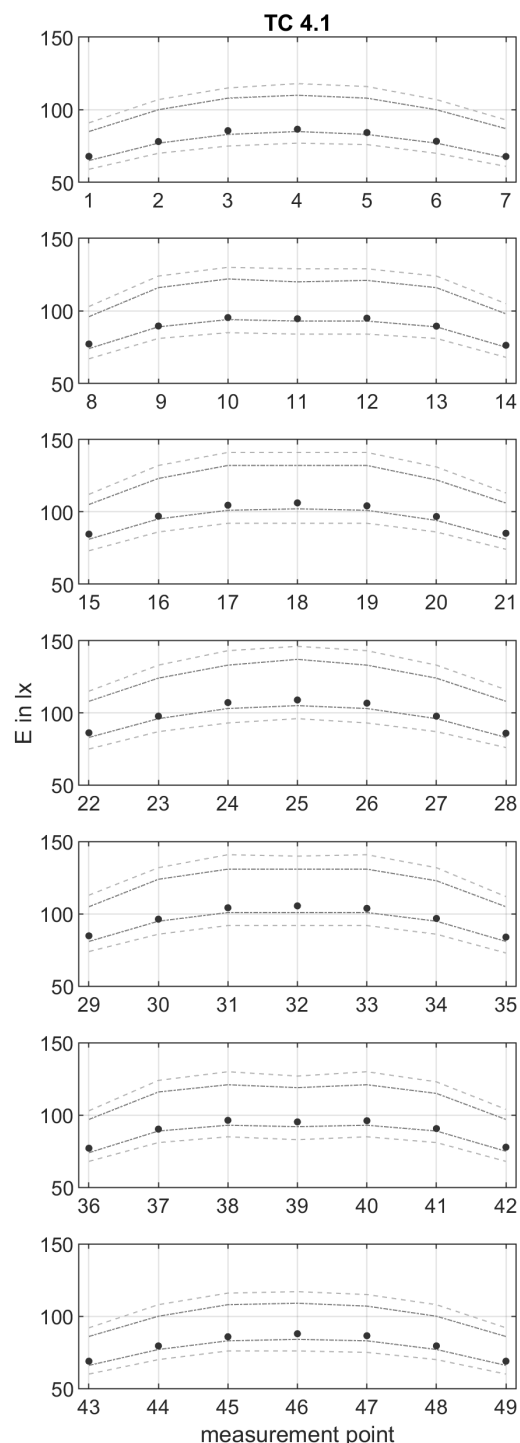
This experimental test case comprises four compact fluorescent reference lamps and surface reflections. The luminaire geometries were neglected as in the reference.

A measurement grid of 7×7 points in 0.80 m height is compared to the experimental reference data.

Table 1 shows the simulation setting and results in three significant digits. Figure 1 illustrates the simulation results in comparison to the reference data. All results lie within the measurement error range.

**Table 1:** TC 4.1 – settings and results

simulation setting							
patch density	5						
reflections	3						
calculation points							
total number of points	49						
within measurement limits	49						
outside measurement limits	0						
outside total error limits	0						
simulated mean room illuminance							
upper limit	112.0 lx						
LUMOS result	89.6 lx						
lower limit	88.0 lx						
simulation results, $E$ in lx							
	1	2	3	4	5	6	7
1	67.9	78.1	85.6	86.6	84.3	78.3	67.8
2	77.2	89.6	95.4	94.6	95.0	89.5	76.3
3	84.5	96.9	105	106	104	96.7	85.1
4	86.2	97.7	107	109	107	97.7	85.9
5	84.9	96.4	104	106	104	96.9	84.0
6	77.1	90.3	96.4	95.3	96.1	90.7	77.8
7	68.9	79.5	85.8	87.9	86.5	79.5	68.9



**Figure 1:** LUMOS simulation results (point) for test case 4.1 with measurement error range (dot-dashed) and total error range (dashed)

### TC 4.2: Artificial lighting scenario opal luminaire, grey wall

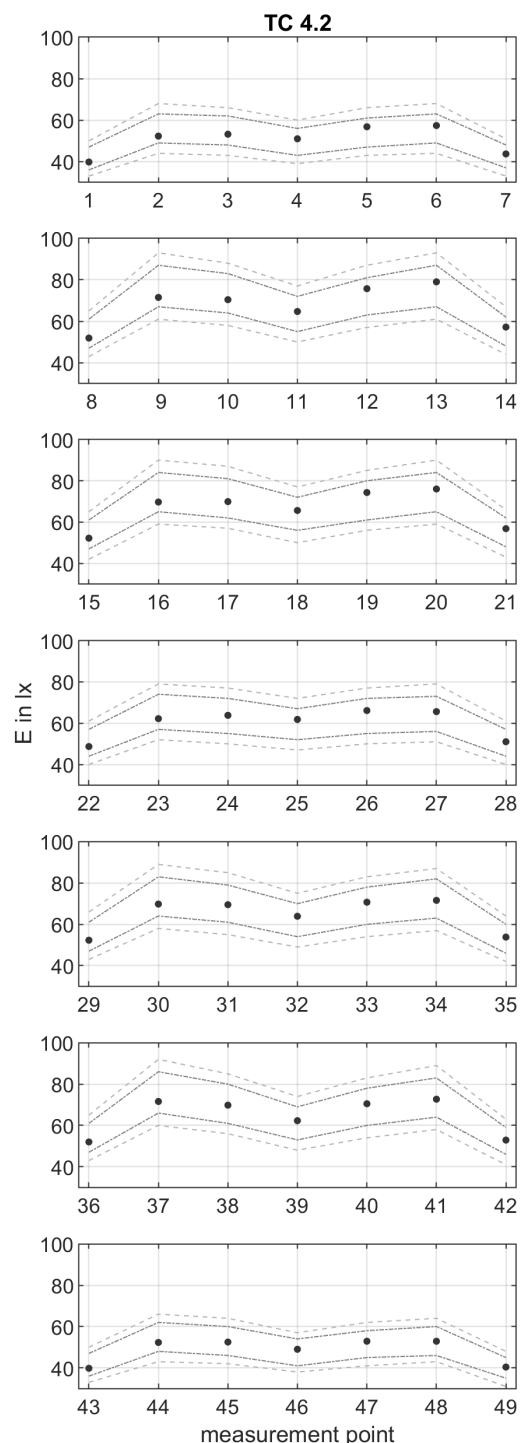
This experimental test case comprises four opal reference luminaires with amalgam compact fluorescent lamps and internal surface reflections.

A measurement grid of 7×7 points in 0.80 m height is compared to the experimental reference data.

Table 2 shows the simulation setting and results in three significant digits. Figure 2 illustrates the simulation results in comparison to the reference data. All results lie within the measurement error range.

**Table 2:** TC 4.2 – settings and results

simulation setting							
patch density	5						
reflections	3						
calculation points							
total number of points	49						
within measurement limits	49						
outside measurement limits	0						
outside total error limits	0						
simulated mean room illuminance							
upper limit	67.5 lx						
LUMOS result	60.2 lx						
lower limit	53.1 lx						
simulation results, $E$ in lx							
	1	2	3	4	5	6	7
1	39.9	52.4	53.3	51.1	56.8	57.5	43.9
2	52.0	71.6	70.5	64.8	75.8	79.1	57.3
3	52.3	69.8	70.0	65.6	74.4	76.1	56.9
4	48.7	62.3	63.9	61.9	66.2	65.6	51.1
5	52.4	69.9	69.6	64.0	70.7	71.7	53.9
6	52.1	71.7	69.9	62.3	70.6	72.8	53.0
7	40.0	52.4	52.6	49.1	53.0	52.9	40.5



**Figure 2:** LUMOS simulation results (point) for test case 4.2 with measurement error range (dot-dashed) and total error range (dashed)

### TC 4.3: Artificial lighting scenario semi-specular reflector, grey wall

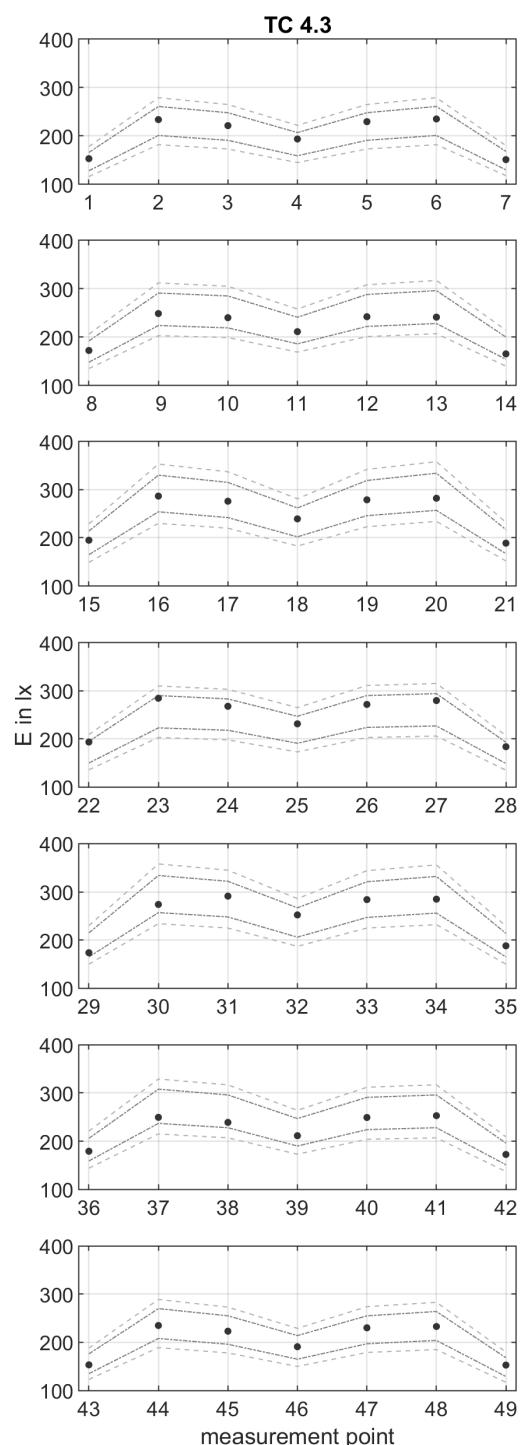
This experimental test case comprises four semi-specular reflector luminaires and internal surface reflections.

A measurement grid of 7×7 points in 0.80 m height is compared to the experimental reference data.

Table 3 shows the simulation setting and results in three significant digits. Figure 3 illustrates the simulation results in comparison to the reference data. All results lie within the measurement error range.

**Table 3:** TC 4.3 – settings and results

simulation setting							
patch density	5						
reflections	3						
calculation points							
total number of points	49						
within measurement limits	49						
outside measurement limits	0						
outside total error limits	0						
simulated mean room illuminance							
upper limit	254.2 lx						
LUMOS result	226.9 lx						
lower limit	199.8 lx						
simulation results, $E$ in lx							
	1	2	3	4	5	6	7
1	153	234	221	194	229	235	151
2	172	249	240	211	242	241	165
3	195	287	276	239	279	282	189
4	194	284	268	231	272	280	184
5	174	274	291	252	284	285	188
6	179	249	239	211	249	253	172
7	153	235	223	191	230	233	153



**Figure 3:** LUMOS simulation results (point) for test case 4.3 with measurement error range (dot-dashed) and total error range (dashed)

### TC 4.4: Artificial lighting scenario CFL, black wall

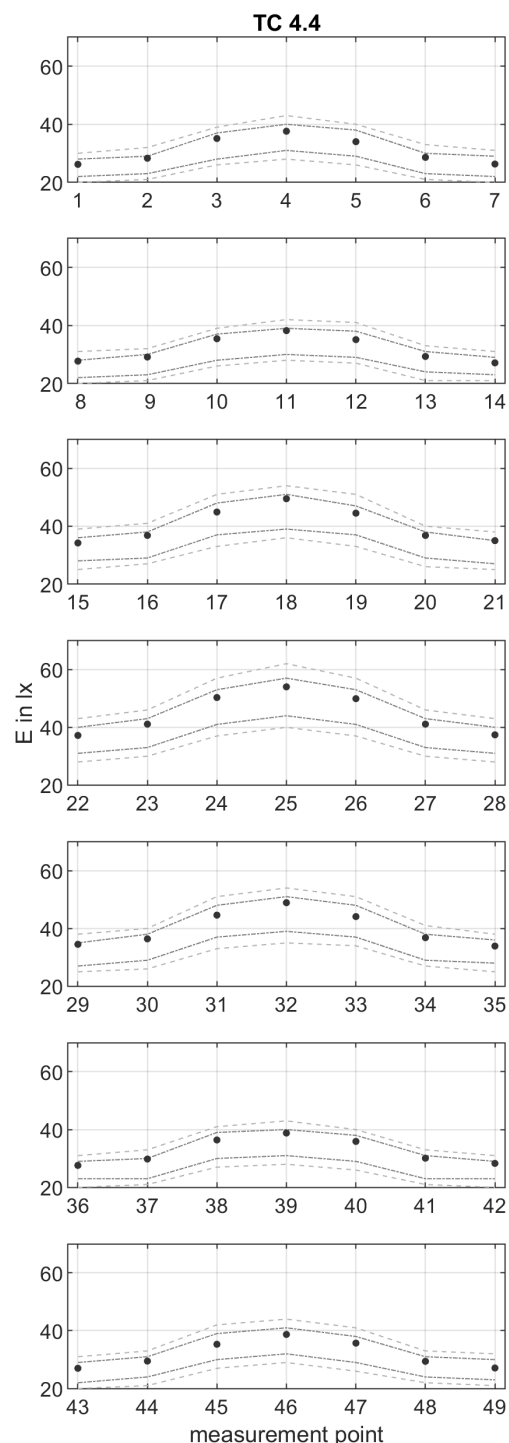
The test case is identical to TC 4.1 but with black surfaces to minimize internal reflections.

A measurement grid of 7×7 points in 0.80 m height is compared to the experimental reference data.

Table 4 shows the simulation setting and results in three significant digits. Figure 4 illustrates the simulation results in comparison to the reference data. All results lie within the measurement error range.

**Table 4:** TC 4.4 – settings and results

simulation setting							
patch density	5						
reflections	3						
calculation points							
total number of points	49						
within measurement limits	49						
outside measurement limits	0						
outside total error limits	0						
simulated mean room illuminance							
upper limit	37.5 lx						
LUMOS result	35.9 lx						
lower limit	29.5 lx						
simulation results, $E$ in lx							
	1	2	3	4	5	6	7
1	26.2	28.3	35.1	37.6	34.0	28.6	26.3
2	27.7	29.1	35.4	38.2	35.1	29.3	27.1
3	34.2	36.8	44.9	49.5	44.5	36.8	35.0
4	37.2	41.1	50.3	54.0	49.9	41.1	37.4
5	34.5	36.4	44.6	48.9	44.1	36.8	33.9
6	27.6	29.8	36.4	38.8	35.9	30.1	28.3
7	27.0	29.5	35.3	38.7	35.7	29.4	27.1



**Figure 4:** LUMOS simulation results (point) for test case 4.4 with measurement error range (dot-dashed) and total error range (dashed)

### TC 4.5: Artificial lighting scenario opal luminaire, black wall

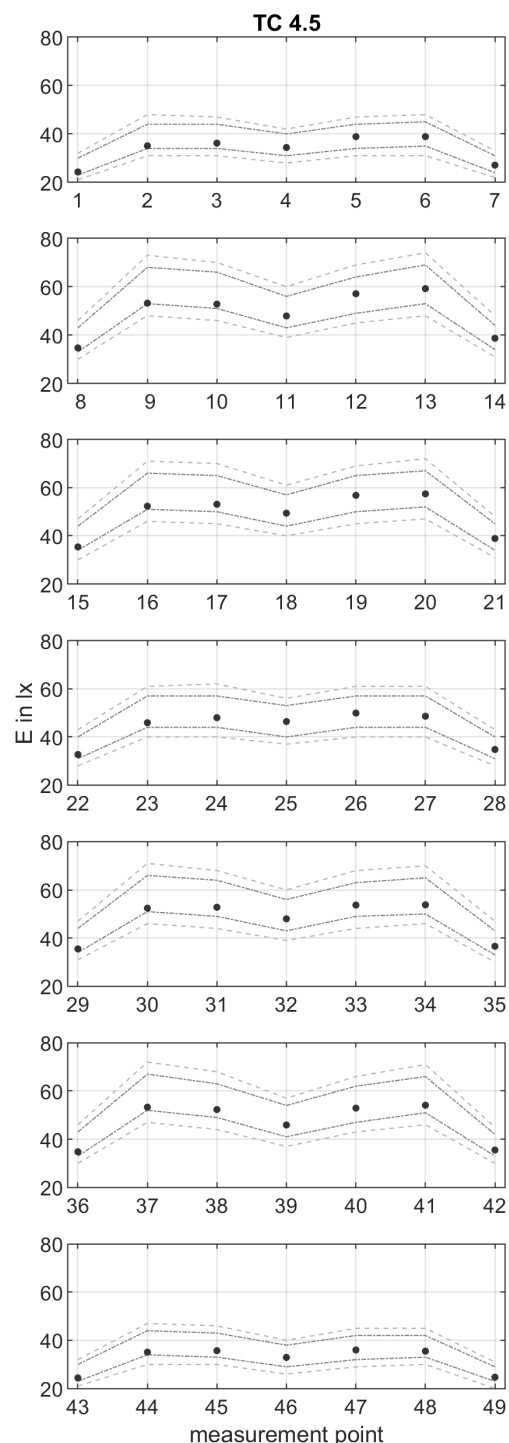
The test case is identical to TC 4.2 but with black surfaces to minimize internal reflections.

A measurement grid of 7×7 points in 0.80 m height is compared to the experimental reference data.

Table 5 shows the simulation setting and results in three significant digits. Figure 5 illustrates the simulation results in comparison to the reference data. All results lie within the measurement error range.

**Table 5:** TC 4.5 – settings and results

simulation setting							
patch density	5						
reflections	3						
calculation points							
total number of points	49						
within measurement limits	49						
outside measurement limits	0						
outside total error limits	0						
simulated mean room illuminance							
upper limit	51.1 lx						
LUMOS result	43.1 lx						
lower limit	40.1 lx						
simulation results, $E$ in lx							
	1	2	3	4	5	6	7
1	24.3	35.1	36.2	34.4	38.9	38.9	27.1
2	34.7	53.2	52.8	47.9	57.1	59.2	38.7
3	35.4	52.3	53.1	49.4	56.8	57.4	38.9
4	32.7	45.9	48.0	46.4	49.9	48.6	34.8
5	35.5	52.4	52.8	48.0	53.7	53.8	36.6
6	34.8	53.3	52.3	45.9	52.9	54.1	35.5
7	24.4	35.1	35.7	32.9	36.0	35.5	24.7



**Figure 5:** LUMOS simulation results (point) for test case 4.5 with measurement error range (dot-dashed) and total error range (dashed)

### TC 4.6: Artificial lighting scenario semi-specular reflector, black wall

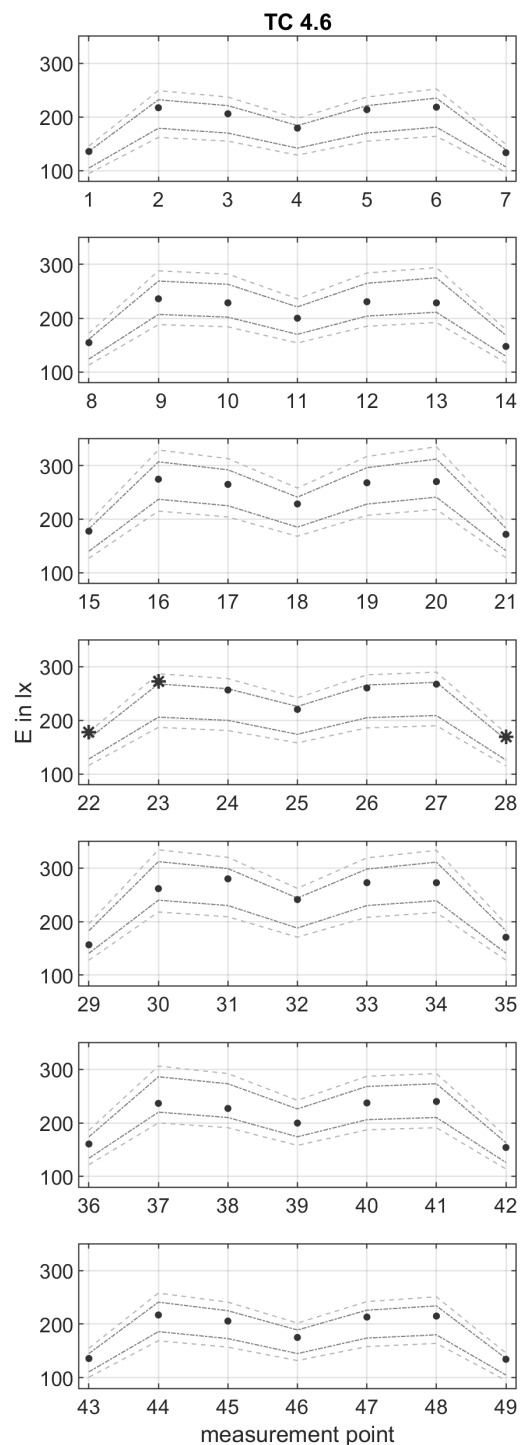
The test case is identical to TC 4.3 but with black surfaces to minimize internal reflections.

A measurement grid of 7×7 points in 0.80 m height is compared to the experimental reference data.

Table 6 shows the simulation setting and results in three significant digits. Figure 6 illustrates the simulation results in comparison to the reference data. Three results lie outside the measurement error (bold/asterisk) but within the total error range.

**Table 6:** TC 4.6 – settings and results

simulation setting							
patch density	5						
reflections	3						
calculation points							
total number of points	49						
within measurement limits	46						
outside measurement limits	3						
outside total error limits	0						
simulated mean room illuminance							
upper limit	228.5 lx						
LUMOS result	212.5 lx						
lower limit	179.5 lx						
simulation results, $E$ in lx							
	1	2	3	4	5	6	7
1	136	217	206	178	211	215	132
2	154	237	230	202	236	235	151
3	177	274	264	228	268	271	172
4	<b>175</b>	<b>269</b>	253	218	258	264	<b>167</b>
5	156	261	279	240	272	272	170
6	161	236	227	200	237	240	154
7	136	217	206	175	213	215	134



**Figure 6:** LUMOS simulation results (point/asterisk) for test case 4.6 with measurement error range (dot-dashed) and total error range (dashed)

## TC 5.2: Simulation of point light sources

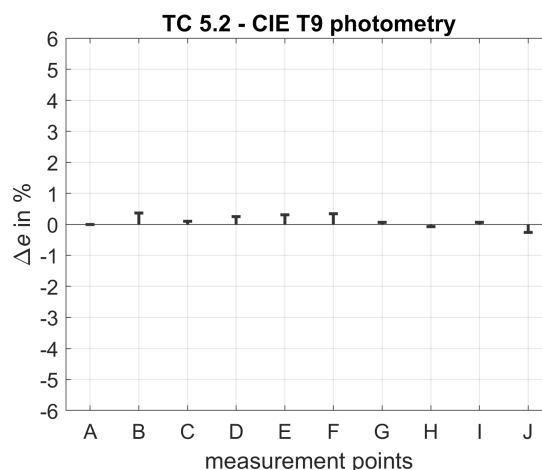
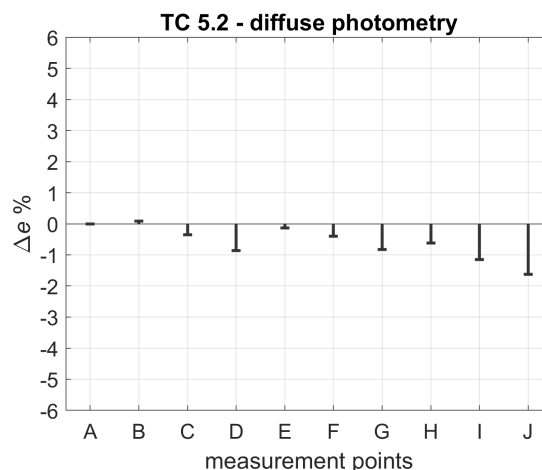
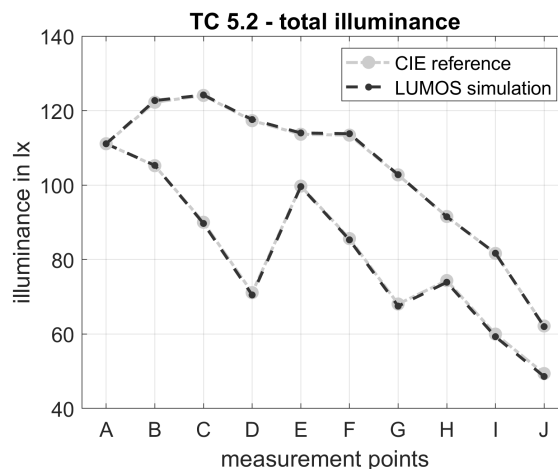
This is a test case for point light sources, using diffuse and asymmetric photometry.

The horizontal illuminances  $E_h$  of ten measurement points are compared to the analytical reference. To avoid clipping errors the measurement points were moved 1 cm inwards.

Table 7 shows the setting, results and relative errors of the simulation. Figure 7 illustrates the total illuminance and relative errors.

**Table 7:** TC 5.2 – settings and results

simulation setting			
patch density		5	
reflections		0	
diffuse photometry results, E in lx			
point	CIE	LUMOS	$\Delta e$ in %
A	111.11	111.1	-0.01
B	105.21	105.3	0.09
C	90.02	89.7	-0.36
D	71.11	70.5	-0.87
E	99.73	99.6	-0.13
F	85.64	85.3	-0.40
G	68.06	67.5	-0.83
H	74.36	73.9	-0.62
I	59.98	59.3	-1.15
J	49.39	48.6	-1.63
CIE T9 photometry results, E in lx			
point	CIE	LUMOS	$\Delta e$ in %
A	111.11	111.1	-0.01
B	122.25	122.7	0.37
C	124.08	124.2	0.10
D	117.31	117.6	0.25
E	113.65	114.0	0.31
F	113.41	113.8	0.34
G	102.74	102.8	0.06
H	91.57	91.5	-0.08
I	81.65	81.7	0.06
J	62.16	62.0	-0.26



**Figure 7:** TC 5.2: Simulation results compared to reference in lx (top), in % – diffuse photometry (middle) and CIE T9 photometry (bottom)

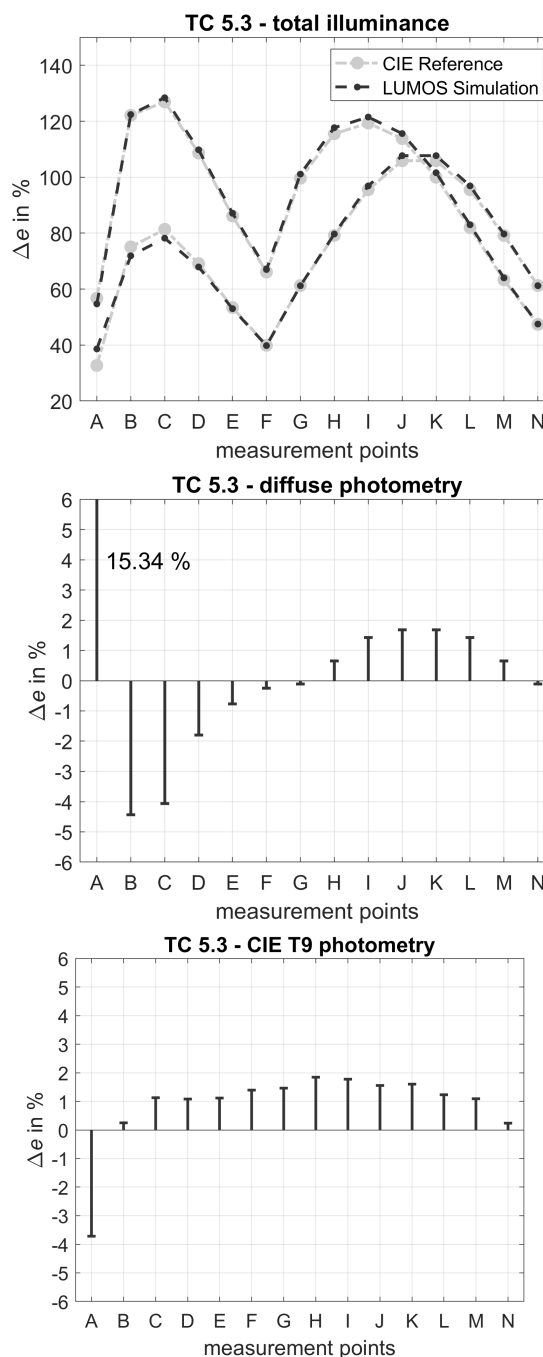
### TC 5.3: Simulation of area light sources

This test case is identical to TC 5.2 but with an area light source. To avoid clipping errors the points were moved 1 cm inwards.

**Table 8:** TC 5.3 – settings and results

simulation setting			
patch density		5	
reflections		0	
diffuse photometry results, E in lx			
point	CIE	LUMOS	$\Delta e$ in %
A	32.68	38.6	<b>15.34</b>
B	75.09	71.9	-4.44
C	81.38	78.2	-4.07
D	69.12	67.9	-1.80
E	53.41	53.0	-0.77
F	39.90	39.8	-0.25
G	61.27	61.2	-0.11
H	79.18	79.7	0.65
I	95.52	96.9	1.42
J	105.89	107.7	1.68
K	105.89	107.7	1.68
L	95.52	96.9	1.42
M	79.18	79.7	0.65
N	61.27	61.2	-0.11
CIE T9 photometry results, E in lx			
point	CIE	LUMOS	$\Delta e$ in %
A	56.73	54.7	-3.71
B	122.10	122.4	0.25
C	126.95	128.4	1.13
D	108.61	109.8	1.08
E	86.13	87.1	1.11
F	66.07	67.0	1.39
G	99.62	101.1	1.46
H	115.53	117.7	1.84
I	119.34	121.5	1.78
J	113.80	115.6	1.56
K	99.97	101.6	1.60
L	81.98	83.0	1.23
M	63.30	64.0	1.09
N	47.39	47.5	0.23

Table 8 shows the setting, results and the relative errors of the simulation. Figure 8 illustrates the total illuminance and relative errors.



**Figure 8:** TC 5.3: Simulation results compared to reference in lx (top), in % – diffuse photometry (middle) and CIE T9 photometry (bottom)

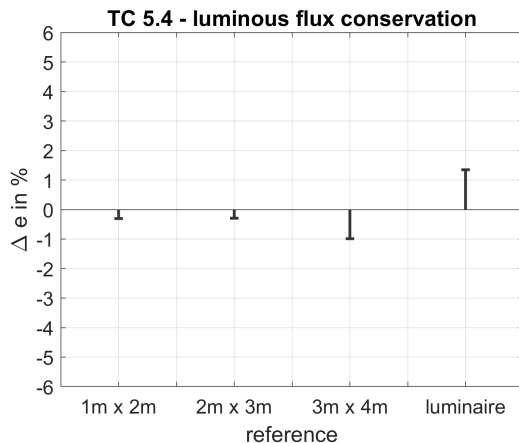
### TC 5.4: Luminous flux conservation

Test scenarios with various wall openings were used, neglecting the wall thickness. A CIE 1 overcast sky served as daylight data. The reference luminaire of test case 4.1 was used in 2 m height as artificial photometry. To avoid clipping errors, the calculation grid points were moved 1 cm inwards.

Table 9 shows the setting and relative error of simulation. Figure 9 illustrates the relative errors.

**Table 9:** TC 5.4 – settings and results

simulation setting		
patch density		5
reflections		0
results		
Reference	opening	$\Delta e$ in %
daylight	2 m × 1 m	-0.32
daylight	3 m × 2 m	-0.30
daylight	4 m × 3 m	-0.99
artificial lighting	–	1.35



**Figure 9:** TC 5.4: LUMOS simulation results compared to reference in %

### TC 5.5: Directional transmittance of clear glass

This test case is not applicable. LUMOS is a radiosity simulation tool that has no ability to create light beams. Nevertheless, the proposed directional reflectance equation in CIE TR 171 [4] by Schlick [12] was implemented in LUMOS, but with a variable spectral transmittance to be provided by the user. Compare also test cases 5.10 and 5.12.

### TC 5.6: Light reflection over diffuse surfaces

These test cases assess the calculation accuracy of diffuse surface reflection of various sizes. The uniform illumination of the reflecting surfaces was achieved by manually editing the surface irradiance and radiance in the debugging mode of Matlab [1].

Since LUMOS can only evaluate objects inside the room geometry, test cases 5.6.1 and 5.6.2 were encapsulated in a larger room geometry. With an area of 500 m × 500 m, test case 5.6.3 is not applicable, due to the large external area and the fact that LUMOS approximates the external ground as an infinite surface.

The reference values are given in percentage of light reflection. The error is therefore given as a difference of reference and LUMOS results:

$$(3) \quad \Delta e = R - R_{ref} \quad \text{with:}$$

$$(4) \quad R = \frac{E_i}{E_{hz} \cdot \rho} \quad \text{with:}$$

- $E_i$  illuminance in point  $i$
- $E_{hz}$  horizontal illuminance of area  $A$
- $\rho$  reflectance value of area  $A$

**TC 5.6.2.1: 50 cm × 50 cm**

Table 10 shows the setting, percentage of reflection and relative errors of the simulation. Figure 10 illustrates the relative errors.

**Table 10:** TC 5.6.2.1 – settings and results

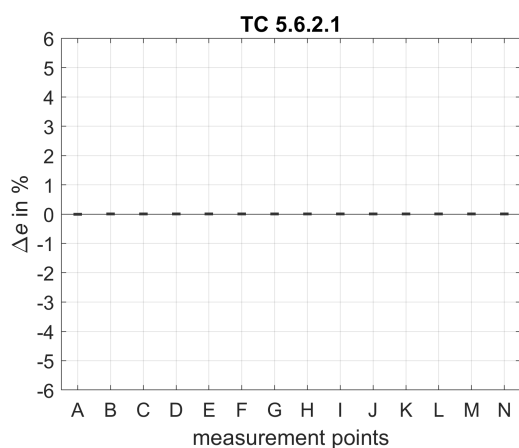
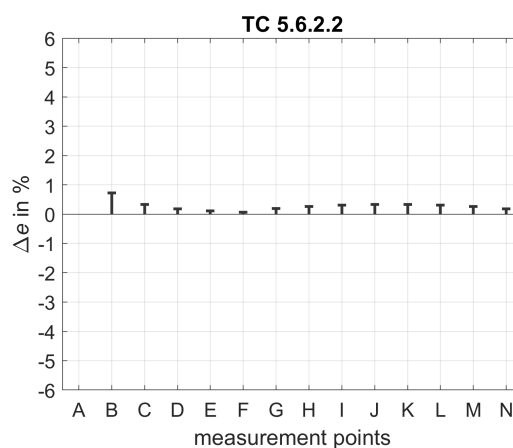
simulation setting			
patch density			5
reflections			0
results, percentage of reflection in %			
point	CIE	LUMOS	$\Delta e$
A	0.246	0.244	-0.002
B	0.580	0.584	0.004
C	0.644	0.651	0.006
D	0.556	0.561	0.005
E	0.433	0.437	0.004
F	0.325	0.327	0.002
G	0.491	0.494	0.003
H	0.639	0.644	0.005
I	0.778	0.786	0.008
J	0.864	0.874	0.010
K	0.864	0.874	0.010
L	0.778	0.787	0.009
M	0.639	0.646	0.007
N	0.491	0.496	0.005

**TC 5.6.2.2: 4 m × 4 m**

Table 11 shows the setting, percentage of reflection and relative errors of the simulation. Figure 11 illustrates the relative errors.

**Table 11:** TC 5.6.2.2 – settings and results

simulation setting			
patch density			5
reflections			0
results, percentage of reflection in %			
point	CIE	LUMOS	$\Delta e$
A	–	–	–
B	35.901	36.619	0.718
C	27.992	28.327	0.325
D	21.639	21.820	0.181
E	16.716	16.829	0.113
F	12.967	13.036	0.069
G	26.80	26.986	0.186
H	30.94	31.204	0.264
I	33.98	34.282	0.302
J	35.57	35.896	0.326
K	35.57	35.896	0.326
L	33.98	34.282	0.302
M	30.94	31.196	0.256
N	26.80	26.978	0.178

**Figure 10:** TC 5.6.2.1: LUMOS simulation results difference in %**Figure 11:** TC 5.6.2.2: LUMOS simulation results difference in %

## TC 5.7: Diffuse reflection with internal obstructions

This test case applies internal obstruction to account for the presence of shading. The uniform illumination of the reflecting surfaces was achieved by manually editing the surface irradiance and radiance in the debugging mode of Matlab [1].

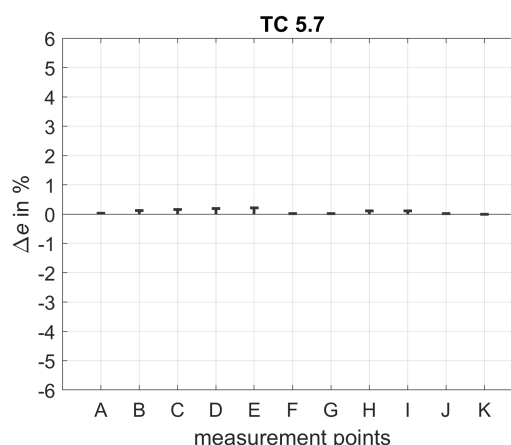
The reference values are given in percentage of light reflection. The error is therefore given as a difference of reference and LUMOS results as in equation 3 and 4.

Table 12 shows the setting, percentage of reflection and relative errors of the simulation. Figure 12 illustrates the relative errors.

The reference data in the original CIE TR 171 [4] document is erroneous [13, 14, 15, 16, 17]. In table 12 the correct values [14] are given next to the original CIE values.

**Table 12:** TC 5.7 – settings and results

simulation setting				
patch density				5
reflections				1
results, percentage of reflection in %				
point	CIE	correct	LUMOS	$\Delta e$
A	20.941	16.071	16.101	0.030
B	21.187	16.330	16.456	0.126
C	19.946	15.399	15.559	0.160
D	17.284	13.322	13.507	0.185
E	14.053	10.317	10.533	0.216
F	9.751	7.079	7.091	0.012
G	4.761	3.382	3.394	0.012
H	5.261	3.629	3.734	0.105
I	4.525	3.013	3.121	0.108
J	0.000	0.000	0.017	0.017
K	0.000	0.000	0.000	0.000



**Figure 12:** TC 5.7: LUMOS simulation results difference in %

## TC 5.8: Internal reflected component calculation for diffuse surfaces

Since this test is designed to assess the inter-reflection accuracy for various reflectance values, the number of reflections must be set accordingly, depending on the internal reflectance value. Instead of the standard setting of three reflections, the number is increased in accordance to equation 5. This way, after  $n$  reflections, a maximum of 1% radiant flux remains for two adjoining surfaces:

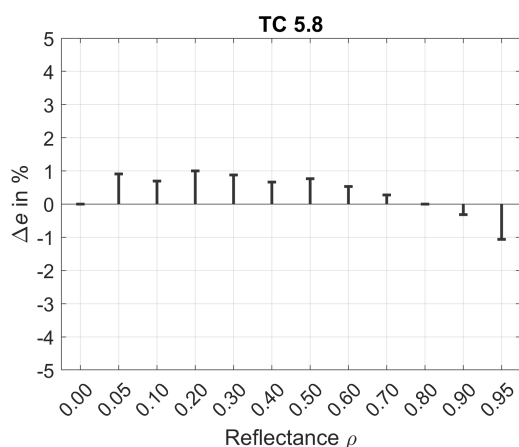
$$(5) \quad n \approx \frac{\log\left(\frac{\Phi_n}{100}\right)}{\log(\rho)} \quad \text{with:}$$

- $n$  number of reflections
- $\Phi_n$  radiant flux at  $n$ th reflection in %
- $\rho$  uniform room reflectance value

Table 13 shows the setting, average indirect illuminance and relative errors of the simulation. Figure 13 illustrates the relative errors.

**Table 13:** TC 5.8 – settings and results

simulation setting				
patch density				5
average indirect illuminance $E$ in lx				
$\rho$	$n$	CIE	LUMOS	$\Delta e$ in %
0.00	0	0.00	0.00	0.00
0.05	2	5.48	5.53	0.91
0.10	2	11.6	11.68	0.69
0.20	3	26.0	26.26	1.00
0.30	4	44.6	44.99	0.87
0.40	5	69.4	69.86	0.66
0.50	7	104	104.80	0.77
0.60	9	156	156.83	0.53
0.70	13	243	243.66	0.27
0.80	21	417	417.02	0.00
0.90	44	937	933.99	-0.32
0.95	90	1979	1957.90	-1.07

**Figure 13:** TC 5.8: LUMOS simulation results difference in %

### TC 5.9: Sky component for a roof unglazed opening and the CIE general sky types

This test case regards two roof unglazed openings and their resulting sky components for CIE standard general skies [10].

Table 14 and 15 show the resulting sky com-

ponents. Figure 14 and 15 illustrate the relative errors of the simulation.

### TC 5.10: Sky component under a roof glazed opening

This test case regards two roof glazed openings and their resulting sky components for CIE standard general skies [10].

Table 16 and 17 show the resulting sky components. Figure 16 and 17 illustrate the relative errors of the simulation.

### TC 5.11: Sky component and external reflected component for a façade unglazed opening

This test case regards two façade unglazed openings and their resulting sky and external reflected components for CIE standard general skies [10].

Table 18 and 19 show the resulting sky and external reflected components. Figure 18 and 19 illustrate the relative errors of the simulation.

### TC 5.12: Sky component and external reflected component for a façade glazed opening

This test case regards two façade glazed openings and their resulting sky and external reflected components for CIE standard general skies [10].

Table 20 and 21 show the resulting sky and external reflected components. Figure 20 and 21 illustrate the relative errors of the simulation.

Although the results demonstrate a small overall error, some data points in TC 5.11 lie approximately 5% below the reference. This indicates that in the results of test case 5.12 these errors are compensated by an opposing error of equivalent magnitude.

### TC 5.13: Sky component and external reflected component for an unglazed façade opening with a continuous external horizontal mask

This test case is not applicable since LUMOS cannot evaluate external objects at the current state.

### TC 5.14: Sky component and external reflected component for an unglazed façade opening with a continuous external vertical mask

This test case is not applicable since LUMOS cannot evaluate external objects at the current state.

## Conclusion

The simulation results of the experimental test cases 4.1 to 4.6 all lie within the total error range of the CIE reference [4]. Only three of the total 294 results lie outside the narrower measurement error range.

Regarding the analytical test cases, most simulation results lie considerably below 6% with only a few reaching an error of about 6%. The sole outlier is test case 5.3 for a diffuse area light source in point A. With a deviation of 15.34% it shows a notable difference to the reference, which in turn represents an extreme case.

The overall good results demonstrate that LUMOS is capable of accurate photometric calculations.

The differences to the reference values are mainly due to the radiosity approach of LUMOS, which leads to three disadvantages:

1. All surfaces are divided into patches, the surface is thus rendered discrete. This espe-

cially concerns window surfaces, since the sky hemisphere is also discretised as a Tregenza hemisphere with 145 patches [3].

2. All surfaces but windows are assumed to be perfectly diffuse and hence are treated as a lambertian light source, neglecting directional influences. This should not affect the analytical test scenarios for which the same assumption applies.

3. The luminous flux exchange between two patches is calculated with the photometric law which is only valid if the distance between the patches is considerably larger than the extension of the patches. If this condition is violated the luminous flux must be corrected by an approximation factor.

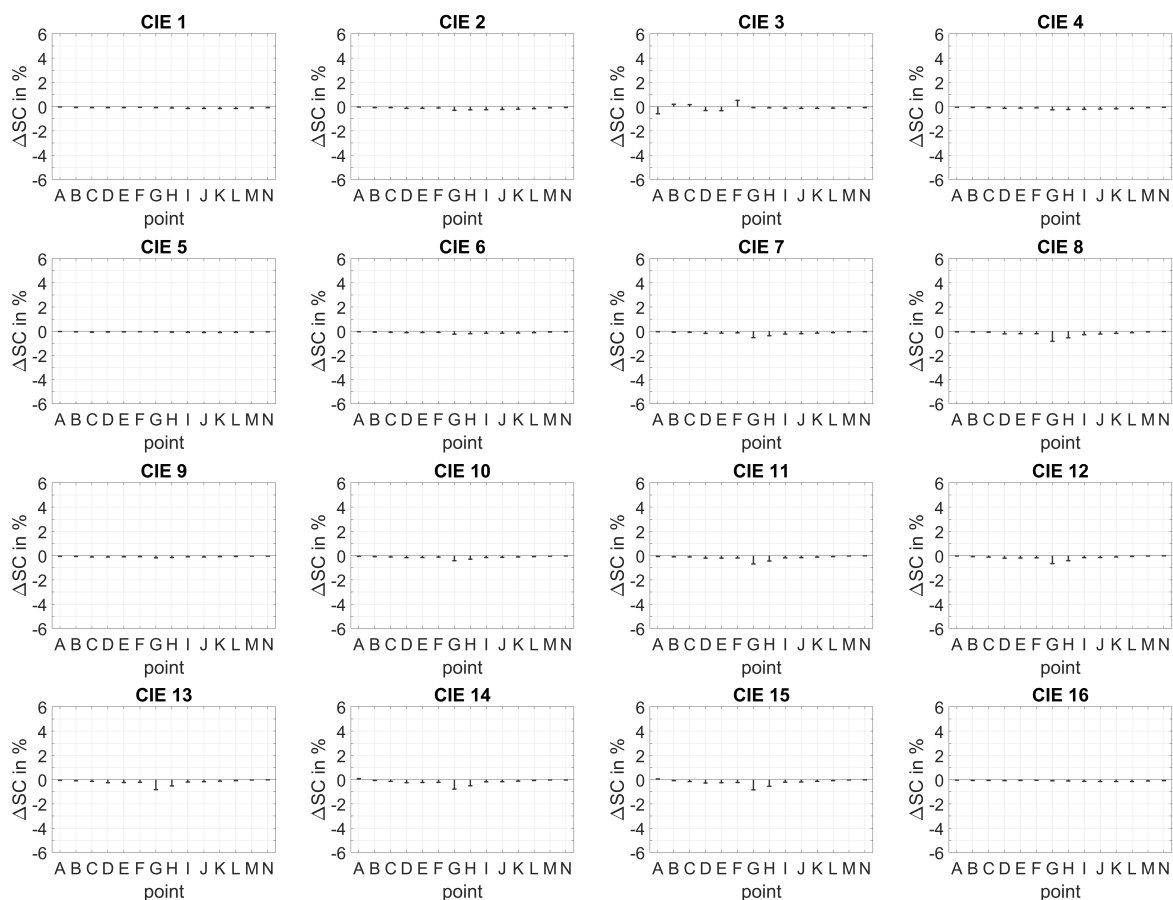
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**Table 14:** TC 5.9.3.1 – 1 m x 1 m opening

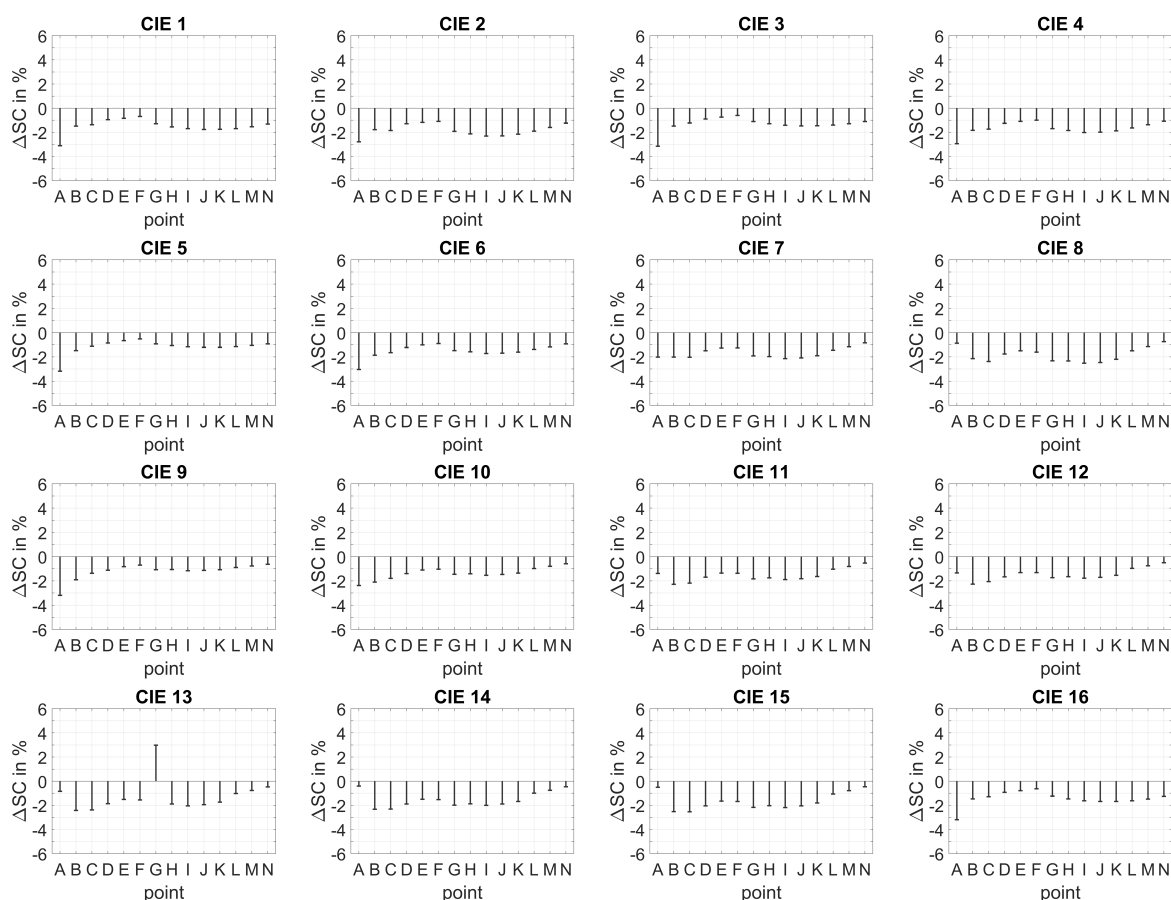
	LUMOS sky component in %															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	0.44	0.37	0.77	0.670	1.02	0.90	0.78	0.67	1.59	1.40	1.23	1.71	1.56	2.30	2.20	0.52
B	1.57	1.64	1.98	2.09	2.33	2.50	2.44	2.35	3.46	3.43	3.36	3.68	3.67	3.94	4.07	1.71
C	2.26	2.78	2.38	2.97	2.51	3.17	3.52	3.78	3.56	4.02	4.38	4.42	4.74	4.74	5.07	2.25
D	2.17	3.01	2.14	3.01	2.13	3.03	3.73	4.33	3.03	3.79	4.48	4.40	4.91	4.80	5.19	2.12
E	1.80	2.76	1.71	2.67	1.64	2.59	3.52	4.39	2.39	3.30	4.18	4.05	4.65	4.48	4.85	1.75
F	1.41	2.33	1.31	2.21	1.23	2.10	3.05	3.97	1.83	2.71	3.60	3.45	4.04	3.86	4.17	1.38
G	2.24	3.70	2.05	3.45	1.89	3.22	4.68	6.10	2.70	4.00	5.32	5.06	5.93	5.64	6.10	2.20
G	2.99	4.73	2.70	4.35	2.44	3.99	5.58	7.10	3.18	4.55	5.91	5.59	6.49	6.14	6.64	2.96
I	3.69	5.21	3.30	4.75	2.95	4.32	5.46	6.49	3.35	4.34	5.26	4.96	5.60	5.28	5.71	3.67
J	4.13	5.13	3.67	4.65	3.26	4.19	4.72	5.14	3.18	3.67	4.07	3.82	4.13	3.88	4.17	4.14
K	4.13	4.52	3.67	4.09	3.26	3.69	3.75	3.75	2.80	2.91	2.97	2.78	2.86	2.69	2.82	4.14
L	3.69	3.59	3.30	3.27	2.95	2.97	2.78	2.59	2.29	2.19	2.08	1.96	1.90	1.79	1.82	3.67
M	2.99	2.66	2.70	2.44	2.44	2.24	1.98	1.75	1.78	1.61	1.45	1.37	1.27	1.20	1.17	2.96
N	2.24	1.83	2.05	1.71	1.89	1.59	1.35	1.14	1.33	1.15	0.99	0.94	0.84	0.80	0.74	2.20



**Figure 14:** TC 5.9.3.1: LUMOS simulation results difference in %, 1 m x 1 m opening

**Table 15: TC 5.9.3.2 – 4 m x 4 m opening**

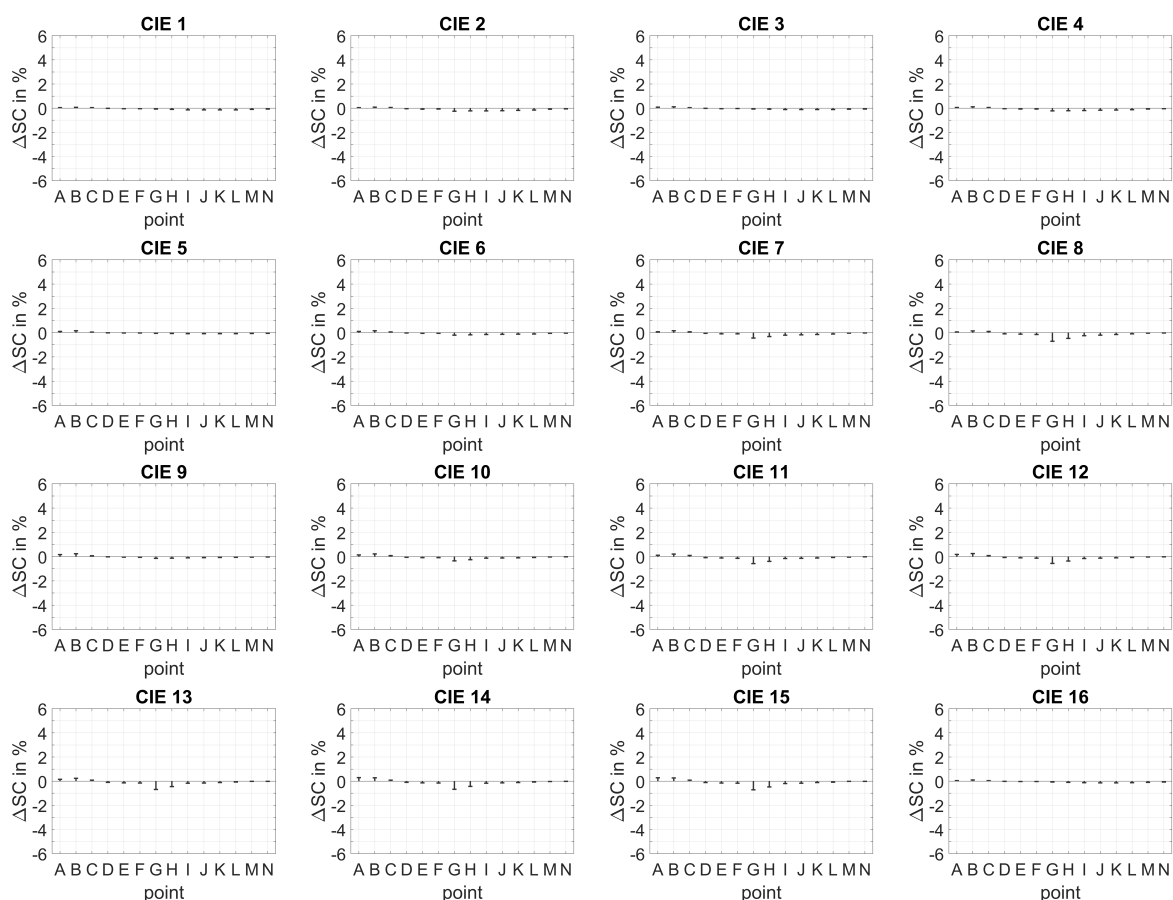
		LUMOS sky component in %															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A		34.7	39.2	39.6	43.9	43.6	47.9	49.8	51.4	58.1	59.5	60.6	65.0	65.8	71.4	72.7	36.1
B		30.2	35.2	32.5	37.8	34.6	40.1	42.9	45.3	45.3	48.3	50.7	52.1	54.1	55.2	57.5	30.8
C		25.5	30.9	26.2	31.9	26.9	32.9	36.5	39.5	35.0	38.8	42.1	42.2	44.8	44.5	47.1	25.5
D		21.1	26.8	20.9	26.8	20.8	26.9	31.1	34.6	26.8	31.2	35.0	34.4	37.4	36.6	39.1	20.9
E		17.1	22.5	16.5	22.1	16.1	21.7	26.0	29.6	20.7	25.0	28.9	28.2	31.0	30.1	32.4	16.7
F		13.7	18.7	13.0	18.0	12.5	17.5	21.5	25.0	16.1	20.1	23.7	22.9	25.6	24.7	26.6	13.4
G		30.6	40.1	28.1	37.5	25.9	35.1	42.2	48.3	29.6	36.4	42.5	40.6	45.1	43.0	46.2	30.1
G		35.8	44.9	32.6	41.7	29.9	38.9	45.4	51.0	32.3	38.6	44.3	42.2	46.4	44.1	47.3	35.3
I		39.6	47.5	36.0	44.1	32.8	40.9	46.4	51.2	33.5	39.0	44.0	41.8	45.4	43.2	46.0	39.1
J		41.6	47.8	37.8	44.2	34.4	40.9	45.0	48.6	33.3	37.5	41.3	39.1	42.0	39.8	42.2	41.1
K		41.6	45.6	37.8	42.1	34.4	38.9	41.2	43.2	31.5	34.1	36.3	34.4	36.2	34.3	36.0	41.1
L		39.6	41.0	36.0	37.9	32.8	35.0	35.4	35.6	28.4	29.2	29.8	28.2	28.9	27.3	28.3	39.1
M		35.8	34.8	32.6	32.2	29.9	29.9	28.6	27.4	24.4	23.8	23.1	21.9	21.6	20.5	20.7	35.3
N		30.6	27.8	28.1	25.9	25.9	24.1	22.0	20.0	20.1	18.6	17.1	16.3	15.5	14.7	14.4	30.1



**Figure 15: TC 5.9.3.2: LUMOS simulation results difference in %, 4 m x 4 m opening**

**Table 16:** TC 5.10.3.1 – 1 m x 1 m opening, clear glass 6 mm

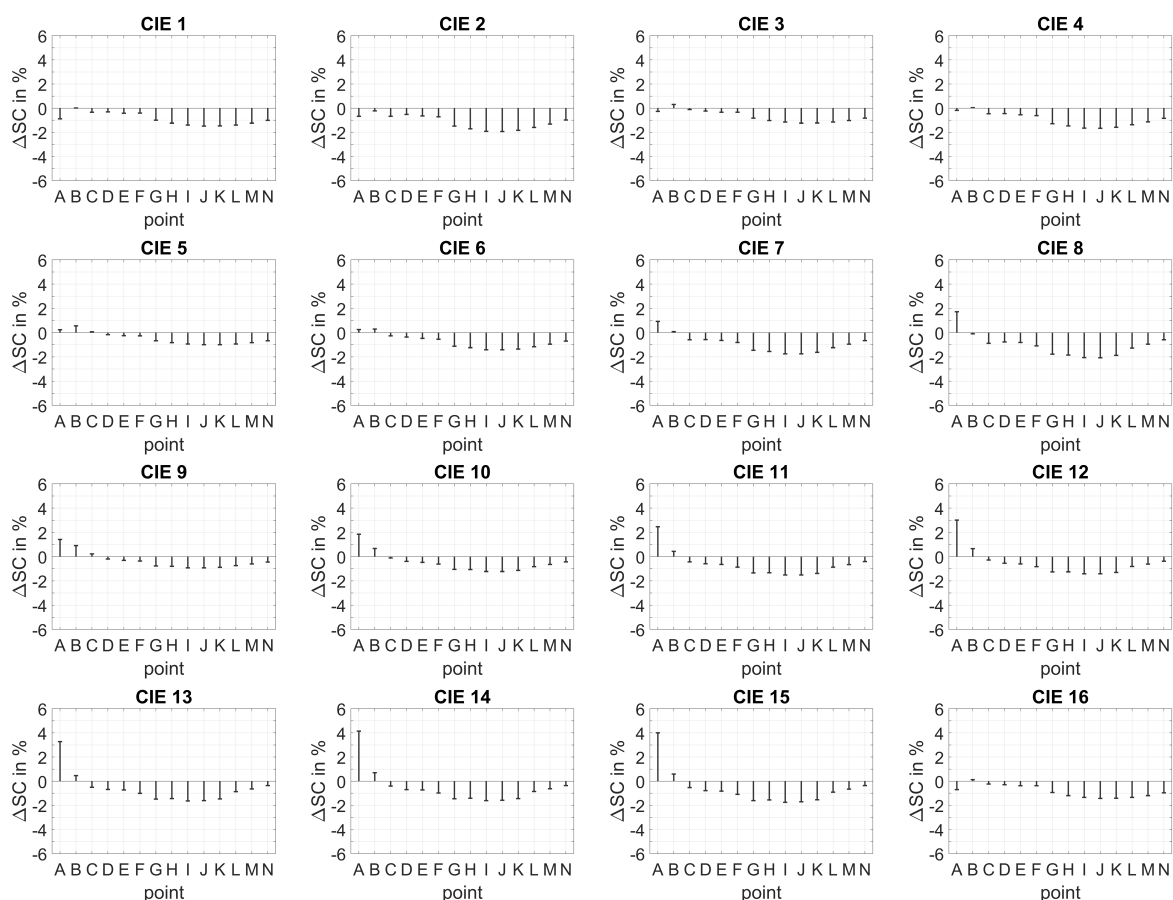
	LUMOS sky component in %															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	0.20	0.17	0.34	0.30	0.46	0.40	0.35	0.30	0.71	0.63	0.55	0.77	0.70	1.03	0.99	0.23
B	1.24	1.30	1.56	1.66	1.84	1.97	1.93	1.87	2.72	2.71	2.66	2.90	2.90	3.11	3.21	1.36
C	1.95	2.39	2.05	2.56	2.16	2.73	3.03	3.26	3.07	3.46	3.77	3.81	4.08	4.08	4.37	1.94
D	1.90	2.63	1.87	2.64	1.86	2.66	3.27	3.80	2.65	3.32	3.92	3.85	4.30	4.20	4.54	1.85
E	1.58	2.42	1.50	2.34	1.44	2.28	3.09	3.86	2.10	2.90	3.68	3.56	4.09	3.94	4.26	1.54
F	1.24	2.05	1.15	1.94	1.08	1.84	2.68	3.49	1.61	2.38	3.17	3.03	3.55	3.40	3.67	1.21
G	1.97	3.25	1.80	3.03	1.66	2.84	4.12	5.37	2.37	3.52	4.68	4.45	5.22	4.96	5.36	1.93
G	2.63	4.16	2.38	3.82	2.15	3.51	4.91	6.25	2.80	4.01	5.20	4.92	5.71	5.40	5.84	2.61
I	3.25	4.59	2.90	4.18	2.59	3.80	4.81	5.71	2.95	3.82	4.63	4.36	4.93	4.65	5.03	3.23
J	3.64	4.52	3.23	4.09	2.87	3.69	4.16	4.52	2.80	3.23	3.58	3.36	3.63	3.42	3.67	3.64
K	3.64	3.98	3.23	3.60	2.87	3.25	3.30	3.30	2.46	2.56	2.61	2.45	2.51	2.36	2.49	3.64
L	3.24	3.16	2.90	2.88	2.59	2.61	2.44	2.28	2.02	1.93	1.83	1.72	1.68	1.58	1.60	3.23
M	2.63	2.34	2.38	2.15	2.15	1.97	1.74	1.54	1.57	1.42	1.27	1.20	1.12	1.06	1.03	2.61
N	1.97	1.61	1.80	1.50	1.66	1.40	1.19	1.00	1.17	1.01	0.87	0.83	0.74	0.70	0.65	1.94



**Figure 16:** TC 5.10.3.1: LUMOS simulation results difference in %, 1 m x 1 m opening

**Table 17:** TC 5.10.3.2 – 4 m x 4 m opening, clear glass 6 mm

	LUMOS sky component in %															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	27.8	32.1	30.6	34.9	32.9	37.3	39.6	41.5	43.3	45.4	47.1	49.3	50.7	53.2	54.8	28.5
B	25.4	29.8	27.0	31.6	28.4	33.3	36.0	38.2	37.1	39.8	42.2	43.0	44.9	45.5	47.6	25.8
C	21.9	26.7	22.4	27.4	23.0	28.2	31.4	34.1	29.8	33.2	36.1	36.1	38.4	38.1	40.4	21.9
D	18.4	23.4	18.2	23.3	18.1	23.4	27.0	30.1	23.2	27.1	30.4	29.9	32.5	31.8	34.0	18.1
E	14.9	19.7	14.4	19.3	14.1	19.0	22.7	25.9	18.1	21.9	25.3	24.6	27.2	26.3	28.3	14.7
F	12.0	16.4	11.4	15.8	10.9	15.4	18.9	22.0	14.1	17.6	20.8	20.1	22.5	21.7	23.4	11.8
G	26.9	35.3	24.7	33.0	22.8	30.9	37.1	42.5	26.1	32.0	37.4	35.7	39.6	37.8	40.7	26.5
G	31.5	39.5	28.7	36.7	26.3	34.2	39.9	44.9	28.4	33.9	39.0	37.1	40.8	38.8	41.6	31.0
I	34.8	41.8	31.7	38.8	28.9	36.0	40.8	45.1	29.5	34.3	38.7	36.7	40.0	38.0	40.5	34.4
J	36.6	42.1	33.2	38.9	30.3	36.0	39.6	42.8	29.3	33.0	36.3	34.4	37.0	35.1	37.1	36.1
K	36.6	40.1	33.2	37.0	30.3	34.2	36.3	38.0	27.7	30.0	32.0	30.3	31.8	30.2	31.7	36.1
L	34.8	36.1	31.7	33.3	28.9	30.8	31.1	31.3	25.0	25.7	26.2	24.8	25.4	24.1	24.9	34.4
M	31.5	30.6	28.7	28.4	26.3	26.3	25.2	24.1	21.5	20.9	20.3	19.2	19.0	18.0	18.3	31.0
N	26.9	24.4	24.7	22.8	22.8	21.2	19.3	17.6	17.6	16.3	15.1	14.3	13.6	12.9	12.7	26.5



**Figure 17:** TC 5.10.3.2: LUMOS simulation results difference in %, 4 m x 4 m opening

**Table 18:** TC 5.11.3.1 – 2 m x 1 m opening

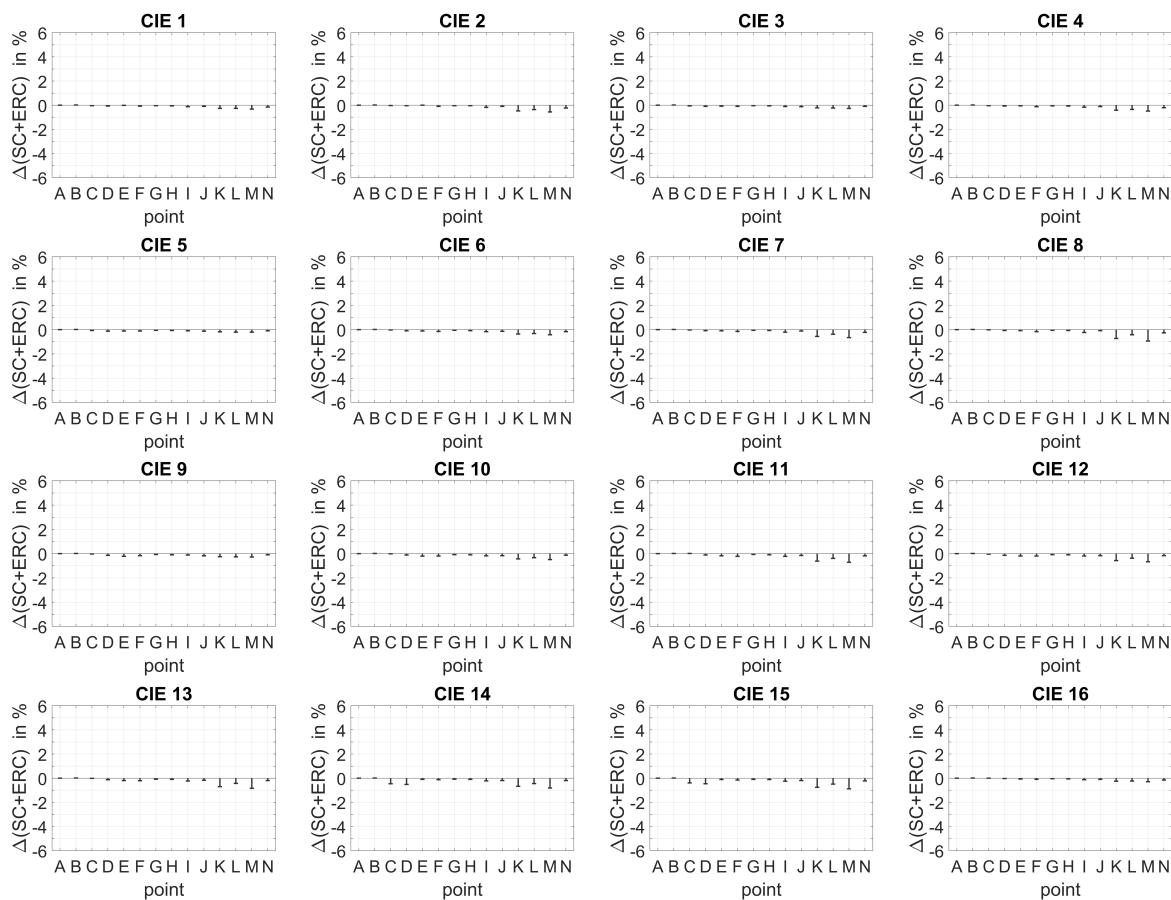
LUMOS sky component + external reflected component in %																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
B	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
C	1.20	1.15	1.50	1.41	1.72	1.62	1.51	1.41	2.24	2.07	1.92	2.35	2.21	2.88	2.78	1.28
D	1.45	1.28	2.32	2.06	2.97	2.67	2.34	2.06	4.47	3.98	3.54	4.79	4.40	6.35	6.08	1.68
E	1.69	1.55	2.67	2.47	3.43	3.21	2.87	2.56	5.29	4.81	4.37	5.61	5.24	7.02	6.85	1.99
F	1.77	1.73	2.48	2.45	3.06	3.07	2.86	2.65	4.65	4.41	4.16	4.81	4.66	5.38	5.43	2.04
G	0.83	0.88	1.04	1.11	1.21	1.31	1.29	1.25	1.80	1.79	1.77	1.92	1.92	2.06	2.13	0.90
H	1.25	1.37	1.48	1.64	1.68	1.89	1.90	1.89	2.45	2.51	2.54	2.70	2.75	2.88	3.01	1.32
I	1.89	2.12	2.15	2.45	2.39	2.76	2.83	2.86	3.43	3.59	3.69	3.86	3.98	4.10	4.32	1.95
J	3.10	3.77	3.28	4.04	3.46	4.32	4.75	5.07	4.87	5.44	5.89	5.96	6.35	6.36	6.79	3.09
K	4.80	6.10	4.89	6.31	5.01	6.55	7.48	8.23	6.94	8.06	9.01	8.97	9.73	9.61	10.3	4.72
L	7.37	10.4	7.10	10.2	6.90	10.0	12.6	15.0	9.47	12.1	14.6	14.2	16.0	15.5	16.7	7.18
M	9.01	13.1	8.35	12.3	7.78	11.7	15.2	18.5	10.0	13.3	16.4	15.7	17.8	17.0	18.4	8.82
N	4.94	6.09	4.46	5.60	4.03	5.14	5.75	6.23	4.09	4.67	5.15	4.86	5.23	4.95	5.30	4.89

LUMOS external reflected component in %									
	G'	H'	I'	J'	K'	L'	M'	N'	
	0.38	0.52	0.75	1.08	1.56	2.15	2.43	1.26	

reference external reflected component in %									
	G'	H'	I'	J'	K'	L'	M'	N'	
	0.38	0.53	0.75	1.08	1.56	2.14	2.40	1.24	



**Figure 18:** TC 5.11.3.1: LUMOS simulation results difference in %, 2 m x 1 m opening

**Table 19: TC 5.11.3.2 – 4 m x 3 m opening**

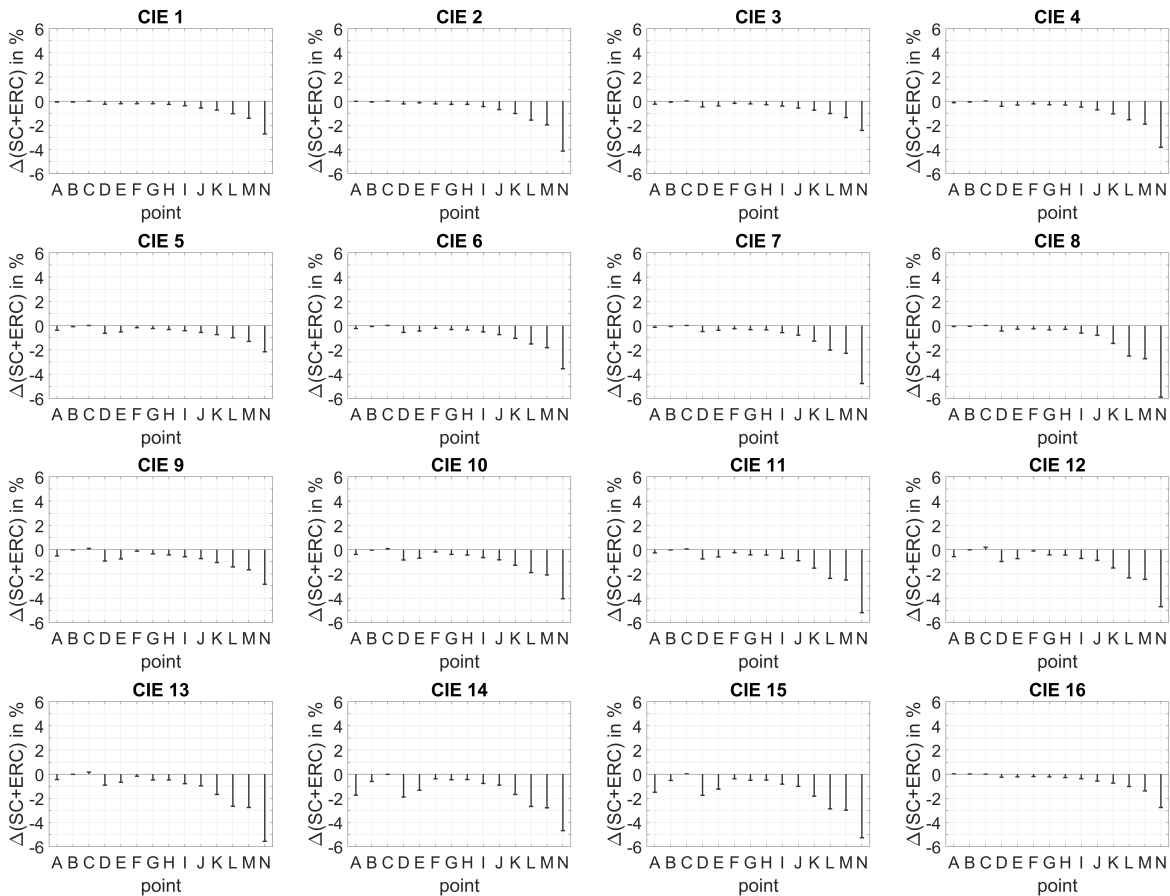
LUMOS sky component + external reflected component in %																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	5.18	5.08	5.68	5.53	6.06	5.87	5.68	5.52	6.90	6.61	6.35	7.05	6.82	7.91	7.75	5.32
B	6.04	5.71	7.67	7.16	8.88	8.27	7.65	7.13	11.6	10.7	9.84	12.1	11.4	14.9	14.4	6.47
C	6.98	6.58	9.34	8.73	11.1	10.4	9.58	8.82	15.3	14.1	13.0	16.0	15.0	19.5	18.9	7.67
D	7.73	7.30	10.6	10.0	12.9	12.2	11.2	10.3	18.3	16.9	15.6	19.0	17.9	22.7	22.2	8.63
E	8.57	8.35	11.6	11.3	14.1	13.8	12.8	11.9	20.4	19.1	17.9	21.4	20.5	25.2	24.9	9.50
F	9.14	9.13	12.4	12.4	15.0	15.0	14.2	13.3	22.2	21.1	19.9	23.6	22.7	27.7	27.5	10.1
G	4.05	4.44	4.86	5.32	5.55	6.11	6.15	6.12	8.01	8.12	8.14	8.83	8.91	9.66	9.98	4.27
H	5.65	6.44	6.55	7.44	7.31	8.33	8.64	8.83	10.5	10.9	11.2	11.9	12.2	13.0	13.5	5.87
I	7.95	9.30	8.93	10.4	9.78	11.4	12.1	12.6	13.8	14.7	15.3	16.1	16.7	17.5	18.3	8.15
J	11.2	13.6	12.3	14.8	13.2	15.9	17.4	18.7	18.4	20.1	21.5	22.3	23.4	24.2	25.4	11.4
K	16.1	20.0	17.1	21.1	18.0	22.2	25.0	27.3	24.6	27.5	30.0	30.6	32.5	33.1	34.8	16.2
L	22.8	28.5	23.7	29.5	24.5	30.5	34.6	38.2	32.5	36.6	40.3	40.7	43.4	43.8	46.1	22.9
M	31.6	39.3	32.3	40.0	32.9	40.6	46.0	50.7	42.1	47.2	51.9	52.0	55.4	55.5	58.4	31.7
N	41.4	48.8	42.3	49.7	43.1	50.5	54.7	58.2	52.4	56.3	59.7	60.4	62.9	63.8	66.4	41.7

LUMOS external reflected component in %									
	G'	H'	I'	J'	K'	L'	M'	N'	
	1.73	2.28	3.05	4.12	5.62	7.64	10.27	13.48	

reference external reflected component in %									
	G'	H'	I'	J'	K'	L'	M'	N'	
	1.74	2.29	3.06	4.14	5.63	7.65	10.27	13.59	



**Figure 19: TC 5.11.3.2: LUMOS simulation results difference in %, 4 m x 3 m opening**

**Table 20:** TC 5.12.3.1 – 2 m x 1 m opening, clear glass 6 mm

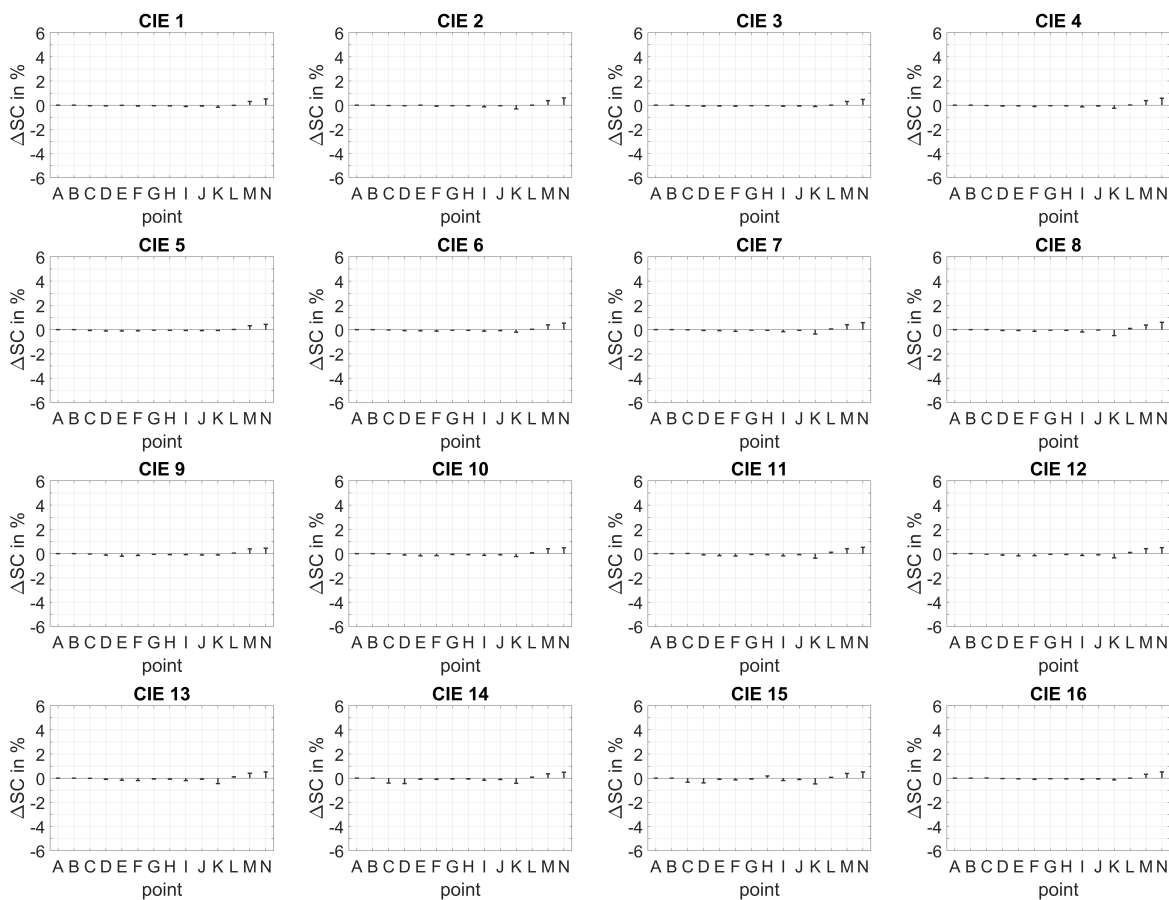
LUMOS sky component + external reflected component in %																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
B	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
C	1.06	1.01	1.32	1.24	1.52	1.42	1.33	1.24	1.97	1.82	1.69	2.06	1.95	2.53	2.45	1.13
D	1.27	1.13	2.04	1.82	2.61	2.35	2.06	1.82	3.94	3.50	3.12	4.22	3.87	5.59	5.35	1.48
E	1.49	1.36	2.35	2.17	3.01	2.82	2.52	2.25	4.66	4.24	3.85	4.93	4.61	6.18	6.03	1.75
F	1.56	1.52	2.18	2.16	2.69	2.70	2.52	2.33	4.09	3.88	3.66	4.24	4.10	4.74	4.78	1.79
G	0.73	0.77	0.91	0.97	1.07	1.15	1.13	1.10	1.58	1.58	1.55	1.69	1.69	1.81	1.87	0.79
H	1.10	1.21	1.30	1.44	1.48	1.66	1.68	1.67	2.16	2.21	2.23	2.38	2.42	2.53	2.65	1.16
I	1.66	1.87	1.89	2.16	2.11	2.43	2.49	2.52	3.02	3.16	3.24	3.40	3.50	3.61	3.80	1.71
J	2.72	3.31	2.88	3.56	3.04	3.80	4.18	4.46	4.28	4.78	5.18	5.24	5.59	5.59	5.98	2.72
K	4.21	5.36	4.30	5.54	4.40	5.75	6.57	7.23	6.10	7.09	7.91	7.88	8.55	8.45	9.07	4.15
L	6.43	9.07	6.19	8.87	6.02	8.73	11.0	13.1	8.26	10.6	12.8	12.4	13.9	13.5	14.6	6.26
M	7.50	10.9	6.95	10.3	6.49	9.72	12.7	15.4	8.36	11.1	13.7	13.1	14.9	14.2	15.4	7.34
N	2.67	3.31	2.41	3.04	2.18	2.79	3.13	3.40	2.22	2.54	2.80	2.65	2.86	2.70	2.89	2.65

LUMOS external reflected component in %									
	G'	H'	I'	J'	K'	L'	M'	N'	
	0.33	0.46	0.66	0.95	1.37	1.88	2.02	0.68	

reference external reflected component in %									
	G'	H'	I'	J'	K'	L'	M'	N'	
	0.33	0.46	0.65	0.94	1.34	1.80	1.85	0.53	



**Figure 20:** TC 5.12.3.1: LUMOS simulation results difference in %, 2 m x 1 m opening

**Table 21:** TC 5.12.3.2 – 4 m x 3 m opening, clear glass 6 mm

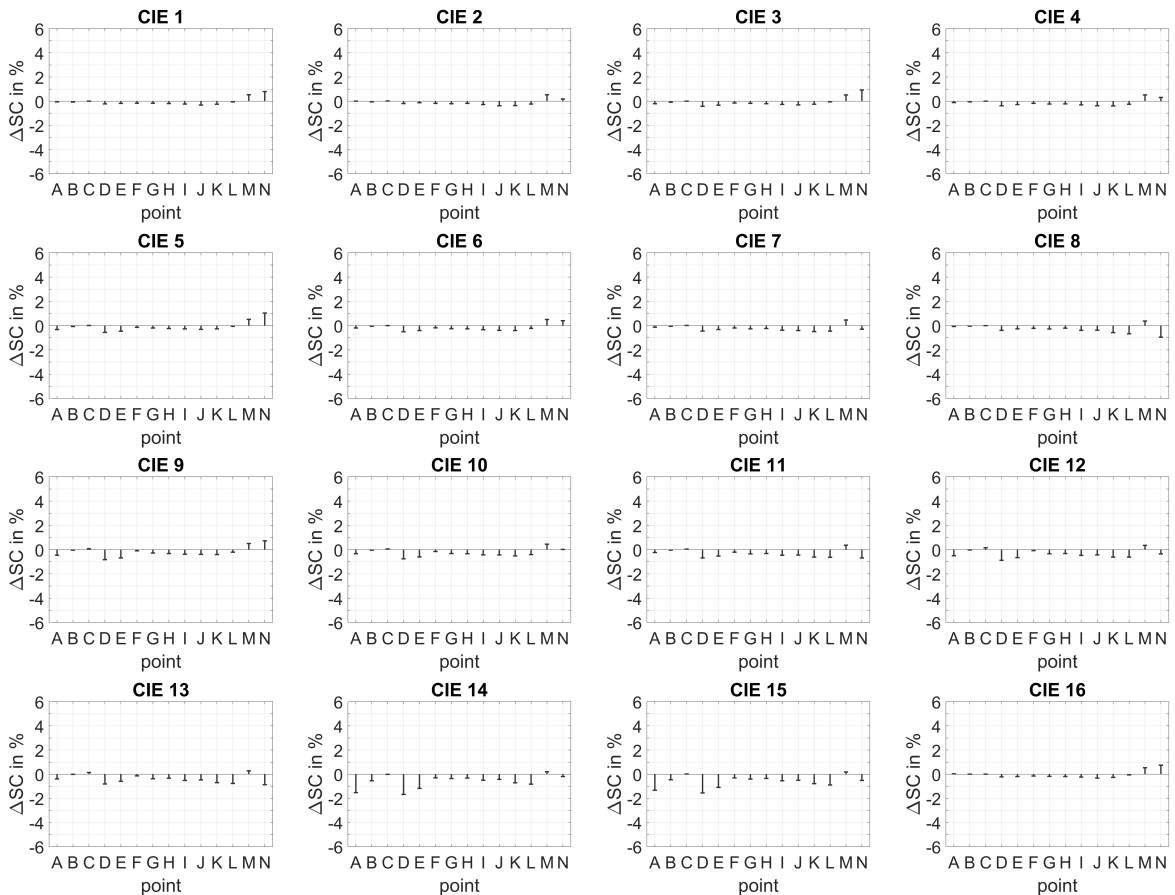
LUMOS sky component + external reflected component in %																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	4.560	4.47	5.00	4.86	5.33	5.16	5.00	4.85	6.07	5.81	5.59	6.21	6.00	6.96	6.82	4.68
B	5.310	5.03	6.75	6.30	7.81	7.28	6.73	6.27	10.2	9.39	8.65	10.7	10.0	13.1	12.7	5.69
C	6.150	5.79	8.22	7.69	9.79	9.19	8.43	7.76	13.5	12.4	11.4	14.1	13.2	17.2	16.6	6.75
D	6.810	6.42	9.34	8.81	11.3	10.7	9.83	9.02	16.1	14.9	13.7	16.7	15.7	20.0	19.5	7.60
E	7.540	7.35	10.2	9.96	12.4	12.1	11.3	10.5	17.9	16.8	15.8	18.8	18.0	22.2	21.9	8.36
F	8.040	8.03	10.9	10.9	13.2	13.2	12.5	11.7	19.5	18.5	17.5	20.7	20.0	24.3	24.2	8.89
G	3.570	3.90	4.28	4.68	4.88	5.38	5.41	5.38	7.05	7.15	7.16	7.77	7.84	8.50	8.78	3.76
G	4.970	5.66	5.76	6.54	6.43	7.33	7.60	7.77	9.19	9.57	9.81	10.5	10.7	11.4	11.9	5.16
I	6.990	8.17	7.85	9.16	8.60	10.1	10.7	11.1	12.1	12.9	13.5	14.1	14.6	15.4	16.0	7.17
J	9.860	11.9	10.8	13.0	11.6	14.0	15.3	16.4	16.2	17.7	18.9	19.6	20.6	21.3	22.3	10.0
K	14.04	17.4	14.9	18.4	15.7	19.4	21.8	23.8	21.5	24.0	26.2	26.7	28.4	28.9	30.4	14.2
L	19.60	24.5	20.4	25.4	21.2	26.2	29.8	32.9	28.1	31.6	34.8	35.1	37.5	37.8	39.8	19.7
M	26.17	32.5	26.9	33.2	27.5	33.8	38.2	42.1	35.3	39.6	43.4	43.6	46.4	46.6	49.0	26.2
N	30.82	36.6	32.0	37.6	32.9	38.6	41.9	44.7	40.9	43.9	46.6	47.4	49.4	50.4	52.4	31.1

LUMOS external reflected component in %									
	G'	H'	I'	J'	K'	L'	M'	N'	
	1.52	2.01	2.68	3.62	4.91	6.60	8.57	10.28	

reference external reflected component in %									
	G'	H'	I'	J'	K'	L'	M'	N'	
	1.52	2.00	2.66	3.57	4.80	6.36	8.09	9.55	



**Figure 21:** TC 5.12.3.2: LUMOS simulation results difference in %, 4 m x 3 m opening