Validation of Radiance against CIE171:2006 and Improved Adaptive Subdivision of Circular Light Sources

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7th International RADIANCE workshop
Fribourg Switzerland
30-31 October 2008

Contents

CIE171:2006: Test Cases to Assess the Accuracy of Lighting Computer Programs

- proposed in 2006 by the International Commission on Illumination (CIE) in Publication 171:2006
- goal: assess accuracy of lighting computer programs and identify weaknesses
- experimental and analytical test cases

$\Rightarrow$ Possibility of comparison with AGI32 results published by Dau Design and Consulting Inc.

Experimental Test Cases

Overview

- based on experimental protocol of CIBSE TM 28/00 (Slater and Graves, 2002)
- real-world test scenes
- different luminaires and surface reflectances
- inaccuracy: dark brown floor (negligible for illuminances)

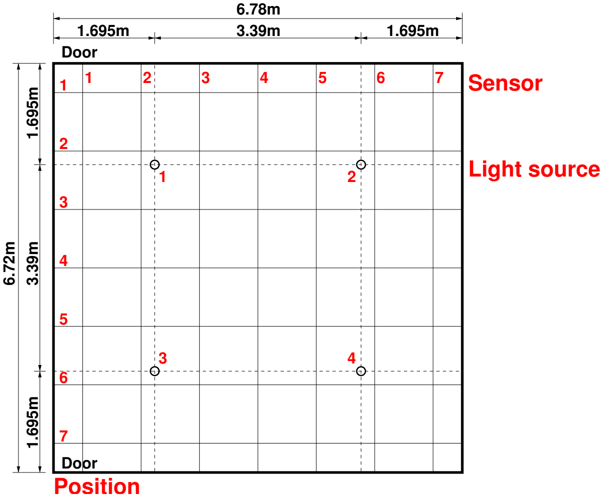
Experimental Test Cases

Measurements

- 49 measurement positions on a regular grid
- measurement plane 0.80m above the floor level
- measured variable: illuminance
- two measurement error bands for point illuminances:
  measurement error (+/- 2 x 6.7%) and
  total error (+/- 2 x 10.5%, including simulation errors)
- room average illuminances:
  total expectation error (measurement +/- 2 x 6.3%)

Experimental Test Cases

Measurement points



Test Case 4.1: grey wall, CFL lamp

Set-up

- ceiling: white acoustic tiles (70% reflectance)
- floor: dark brown (6% reflectance)
- walls: matte grey (41% reflectance)
- luminaires: compact fluorescent lamps modeled as point light sources; output (≈2200 lm each) and photometric data given

Total expectation error upper limit	112.0
Radiance mean room illuminance	88.5
Total expectation error lower limit	88.0

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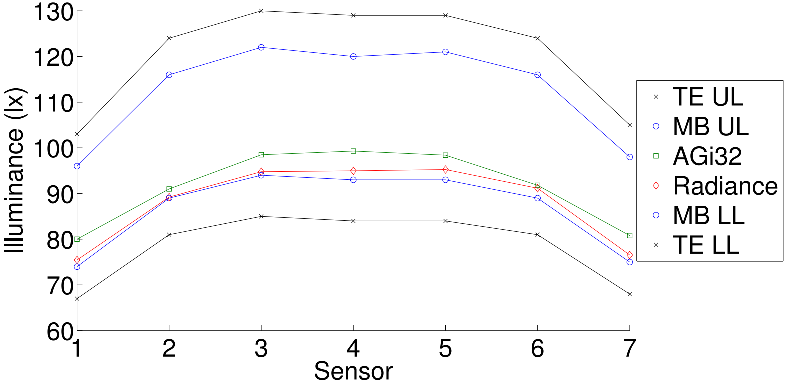
Total expectation error lower limit	88.0

TC 4.1: grey wall, CFL lamp

Results (Position 2)

⇒ all 49 values inside measurement band (AGI32: 49)



Test Case 4.2: grey wall, opal luminaire

Set-up

- ceiling: white acoustic tiles (70% reflectance)
- floor: dark brown (6% reflectance)
- walls: matte grey (52% reflectance)
- light sources: 4 circular luminaires (450mm diameter) with compact fluorescent lamps; output ($\approx$ 1800 lm – 2100 lm each) and photometric data given

Total expectation error upper limit	67.5
Radiance mean room illuminance	51.4
Total expectation error lower limit	53.1

Test Case 4.2: grey wall, opal luminaire

Set-up

- ceiling: white acoustic tiles (70% reflectance)
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Total expectation error upper limit	67.5
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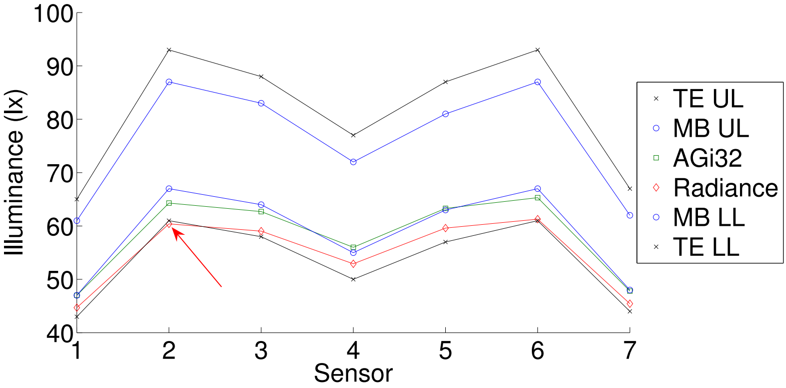
TC 4.2: grey wall, opal luminaire

Results (Position 2)

⇒ 33/49 values (67.35%) below MB LL (AGI32: 12)

⇒ 1 value even outside total error band (AGI32: 0)



Test Case 4.3: grey wall, semi-specular reflector (SSR) luminaire

Set-up

- ceiling: white acoustic tiles (70% reflectance)
- floor: dark brown (6% reflectance)
- walls: matte grey (52% reflectance)
- light sources: 4 square luminaires (600 mm $\times$ 600 mm) with compact fluorescent lamps; output ($\approx$ 4100 lm each) and photometric data given

Total expectation error upper limit	254.2
Radiance mean room illuminance	234.5
Total expectation error lower limit	199.8

Test Case 4.3: grey wall, semi-specular reflector (SSR) luminaire

Set-up

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- floor: dark brown (6% reflectance)
- walls: matte grey (52% reflectance)
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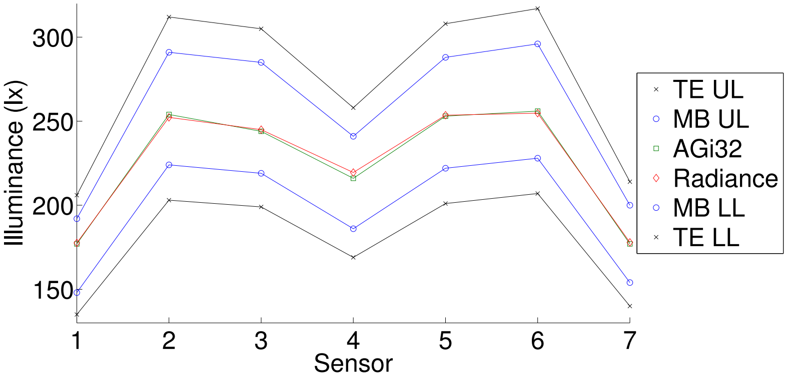
Total expectation error upper limit	254.2
Radiance mean room illuminance	234.5
Total expectation error lower limit	199.8

TC 4.3: grey wall, SSR luminaire

Results (Position 2)

⇒ all 49 values inside measurement band (AGI32: 49)



Test Cases with Analytical References

Overview

- lighting simulations based on theoretical, physical laws

Goals:

- isolate certain aspects of the light propagation
- minimize / eliminate uncertainty in the reference values

Test Case 5.6: Light reflection over diffuse surfaces

Specification

- reflection of light inside a room
- reflection of daylight on the external ground

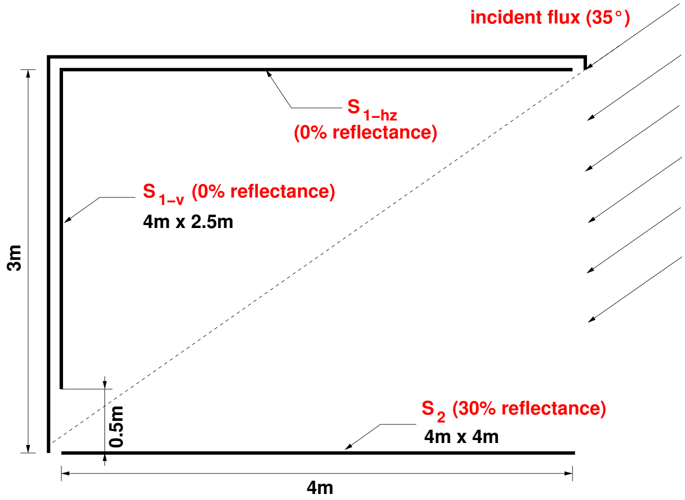
- 4m×4m reflecting surface, 30% reflectance
- measured variable: relative illuminance divided by reflectance

$$E/(E_{hz} \cdot \rho)$$

(equal to configuration factor F_{12} between the measurement point and the reflecting surface S_2)

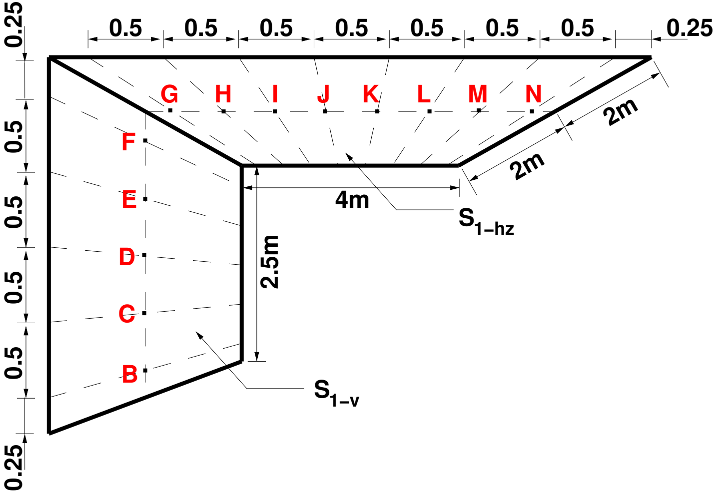
TC 5.6: Light reflection over diffuse surfaces

Test scene descreption



TC 5.6: Light reflection over diffuse surfaces

Measurement points



TC 5.6: Light reflection over diffuse surfaces

Results

	Points of measurement for S_{1-v}				
F_{12}	B	C	D	E	F
CIE Reference	35.901	27.992	21.639	16.716	12.967
Radiance	35.861	27.898	21.573	16.707	12.955

Points of measurement for S_{1-hz}							
G	H	I	J	K	L	M	N
26.80	30.94	33.98	35.57	35.57	33.98	30.94	26.80
26.77	30.91	33.94	35.53	35.53	33.94	30.91	26.77

mean error: 0.137%

Test Case 5.7: Diffuse reflection with internal obstructions

Specification

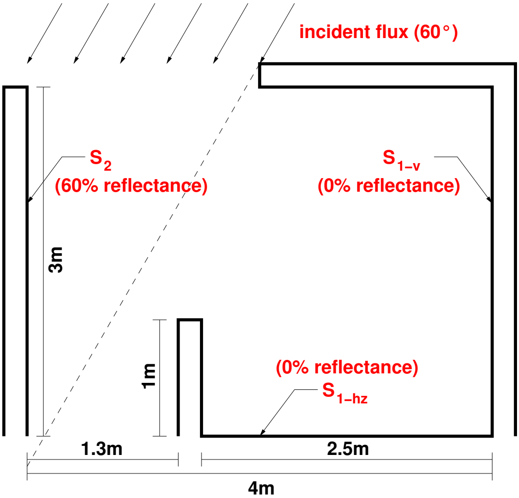
- influence of an obstruction to diffuse reflection
- shading influence of internal furniture
- externally reflected component received from external objects through apertures
- measured variable: relative illuminance divided by reflectance

$$E/(E_{hz} \cdot \rho)$$

  (equal to configuration factor F_{12} between the measurement point and the unobstructed portion of the reflecting surface S_2)

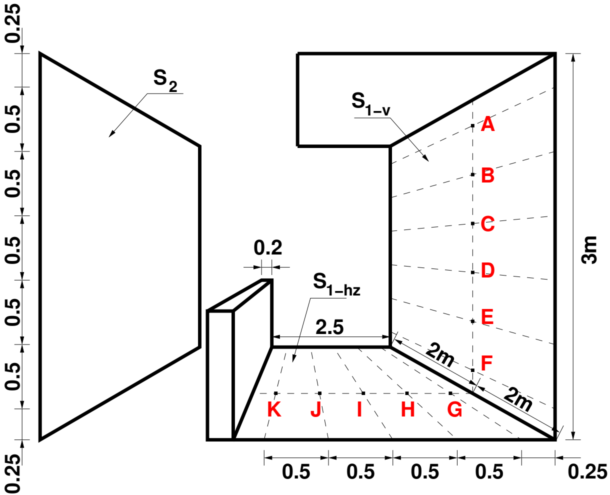
TC 5.7: Diffuse reflection with internal obstructions

Test scene description



TC 5.7: Diffuse reflection with internal obstructions

Measurement points



TC 5.7: Diffuse reflection with internal obstructions

Results

	Points of measurement for S_{1-v}					
F_{12}	A	B	C	D	E	F
CIE Reference	20.941	21.187	19.946	17.284	14.053	9.751
Radiance	16.096	16.359	15.422	13.332	10.310	7.077

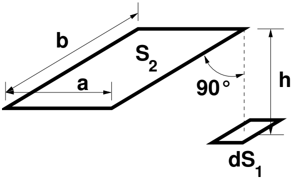
	Points of measurement for S_{1-hz}				
F_{12}	G	H	I	J	K
CIE Reference	4.761	5.261	4.535	0.000	0.000
Radiance	3.366	3.615	3.012	0.000	0.000

mean error: 21.791%

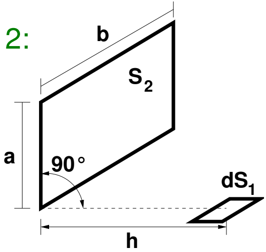
TC 5.7: Diffuse reflection with internal obstructions

Analytical calculation of configuration factors

Case 1:



Case 2:



$$1:\ F_{12} = \frac{1}{2\pi} \cdot \left[\frac{X}{\sqrt{1+X^2}} \cdot \arctan \frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}} \cdot \arctan \frac{X}{\sqrt{1+Y^2}} \right]$$

$$2:\ F_{12} = \frac{1}{2\pi} \cdot \left[\arctan Y - \frac{1}{\sqrt{1+X^2}} \cdot \arctan \frac{Y}{\sqrt{1+X^2}} \right]$$

where $X = \frac{a}{h}$ and $Y = \frac{b}{h}$

TC 5.7: Diffuse reflection with internal obstructions

Results

	Points of measurement for S_{1-v}					
F_{12}	A	B	C	D	E	F
CIE Reference	20.941	21.187	19.946	17.284	14.053	9.751
analytical	16.071	16.330	15.399	13.322	10.317	7.079
Radiance	16.096	16.359	15.422	13.332	10.310	7.077

	Points of measurement for S_{1-hz}				
F_{12}	G	H	I	J	K
CIE Reference	4.761	5.261	4.535	0.000	0.000
analytical	3.382	3.629	3.013	0.000	0.000
Radiance	3.366	3.615	3.012	0.000	0.000

mean error (analytical $\leftrightarrow$ Radiance): 0.142%

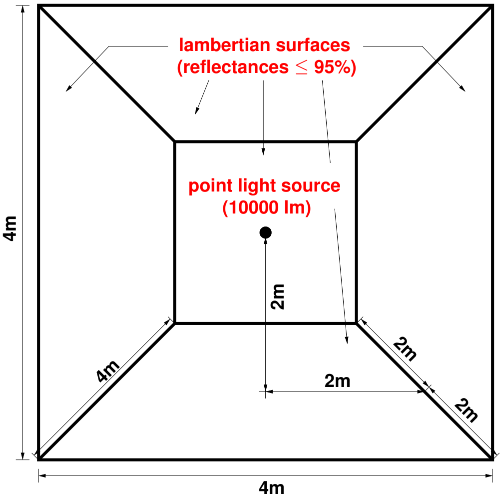
Test Case 5.8: Internal reflected component calculation for diffuse surfaces

Specification

- diffuse interreflections inside a room
- contribution of interreflections to global illumination inside a room
- measured variable: average indirect illuminance E_{av}

TC 5.8: Internal reflected component calculation

Test scene descreption



TC 5.8: Internal reflected component calculation

Results

	Indirect average illuminance variation					
Reflectance	0%	5%	10%	20%	30%	40%
E_{av}(lx) CIE	0.00	5.48	11.6	26.0	44.6	69.4
Radiance	0.00	5.50	11.5	26.0	44.6	69.7

	Indirect average illuminance variation					
Reflectance	50%	60%	70%	80%	90%	95%
E_{av}(lx) CIE	104	156	243	417	937	1979
Radiance	104	157	244	419	884	1472

mean error for reflectances $\leq$ 80%: 0.318%

Validation of Radiance against CIE171:2006

Conclusion

- good results for experimental test cases with point and square light sources (test cases 4.1 and 4.3)
- weakness in modeling circular light sources (test case 4.2)
- error in CIE references for test case 5.7
- proper modeling of diffuse reflection (test cases 5.6, 5.7 and 5.8)
- lambertian surfaces with reflectances > 80% problematic (test case 5.8; slow convergence of Neumann series for the solution of Kajiya's rendering equation used in ray tracing)

Motivation

Experimental test case 4.2:
4 circular luminaires (450mm diameter) with CFLs

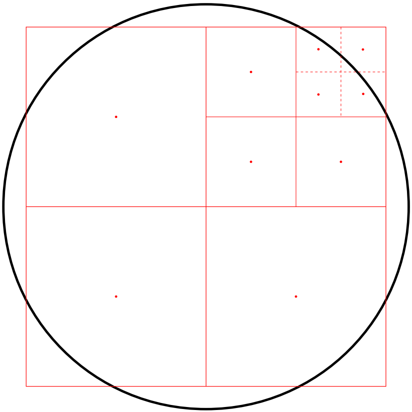
Total expectation error upper limit	67.5
Radiance mean room illuminance	51.4
Total expectation error lower limit	53.1

⇒ 33/49 values (67.35%) below measurement band lower limit
⇒ 1 value even outside total error band

Current Implementation

Radiance:
(Ward and Shakespeare, 1998)

- all flat light sources approximated as rectangles
- circular light source approximated as square
- jittering over full source volume: probability for *aiming failure*: 9.1%
- full subdivision, no jittering: 4 out of 64 rays miss light source



Current Implementation

Subdivision algorithm:

- if fraction (source size $\div$ distance to source) too large (`-ds` option), subdivide along longest axis
- repeat on each subsource until size criterion is satisfied

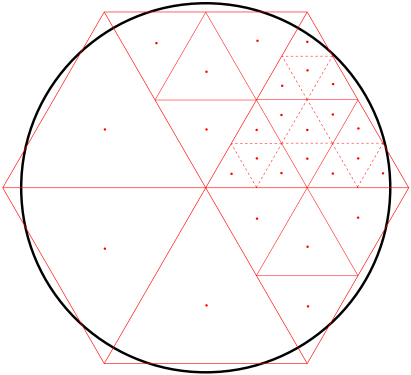
Jittering:

- jitter over rectangular volumes
- degree of jittering controlled by `-dj` option

Triangulation approach

Improved subdivision:

- approximate circular light source as hexagon
- subdivide hexagon into equilateral triangles
- jittering over full source volume: probability for *aiming failure decreases from 9.1% to 3.7%*
- full subdivision, no jittering: all 96 rays hit light source

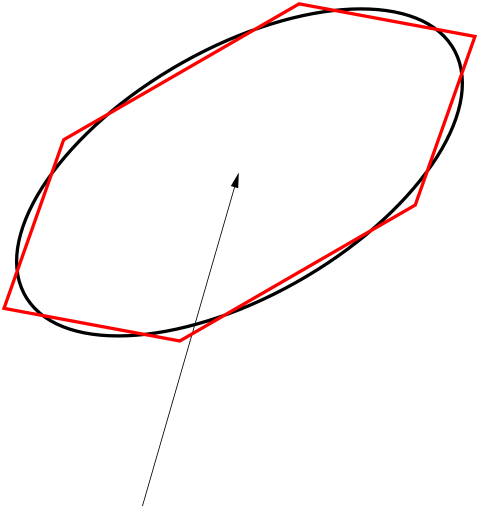


Triangulation approach

Subdivision algorithm:

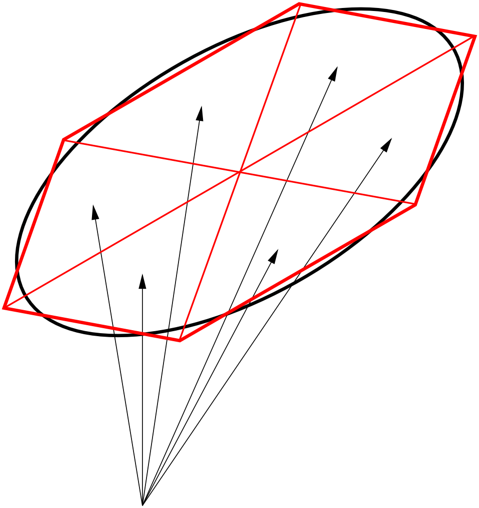
```
RINGPART(srcindex si, ray r)
    initialize;
    if ((source size ÷ distance to source) too small)
        no subdivision;
        return ;
    approximate disk as hexagon;
    subdivide into 6 equilateral triangles;
    for each triangle
        while ((partition size ÷ distance to current partition) too large)
                subdivide into 4 equilateral triangles;
    write partition structure to si;
```

Triangulation approach
Subdivision algorithm

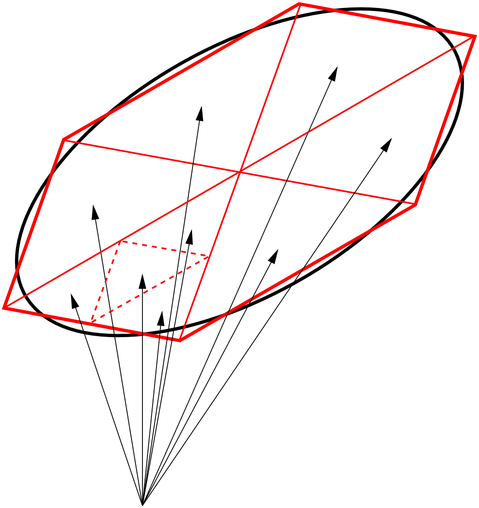


Triangulation approach

Subdivision algorithm



Triangulation approach
Subdivision algorithm



Triangulation approach

Jittering:

- if source is not subdivided: circular jittering (Shirley, Wang and Zimmermann, 1996)
- if source is subdivided: triangular jittering based on barycentric coordinates
- degree of jittering controlled by `-dj` option as in the standard algorithm

Triangulation approach

Implementation:

- definition of macro SRING in *src/rt/source.h*
- additional functions `ringpart`, `flt_tripartit` and `skiptriparts` in *src/rt/srcsamp.c*
  (similar to `flatpart`, `flt_partit` and `skipparts`)
- additional vector operations defined in *src/common/fvect.h*
- minor changes to *src/rt/srcsupp.c*

Triangulation approach – Results

Analytical test: illuminance under a totally diffuse circular light source

Analytical:

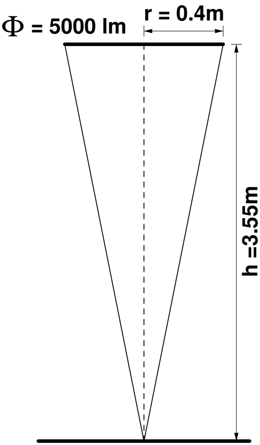
$$E = L_0\pi\frac{r^2}{r^2+h^2} = \frac{\Phi}{\pi(r^2+h^2)} = \mathbf{124.705}\,\text{lux}$$

Radiance:
(64 quads, aiming failure!)

$$E = 117.082\,\text{lux}$$
$$\text{Error} = 6.11\%$$

Triangulation approach
(96 triangles):

$$E = 124.800\,\text{lux}$$
$$\text{Error} = 0.08\%$$



Triangulation approach – Results

TC 4.2: grey wall, opal luminaire

Experimental test case 4.2:

4 circular luminaires (450mm diameter) with CFLs

Simulated mean room illuminance	
Total expectation error upper limit	67.5
Radiance	51.4
Triangulation approach	54.0
Total expectation error lower limit	53.1

$\Rightarrow$ 33/49 values (67.35%) below measurement lower limit

$\Rightarrow$ 1 of those values even outside total error band

$\Rightarrow$ 12/49 values (24.49%) below measurement lower limit (63.64% decrease of values below limit)

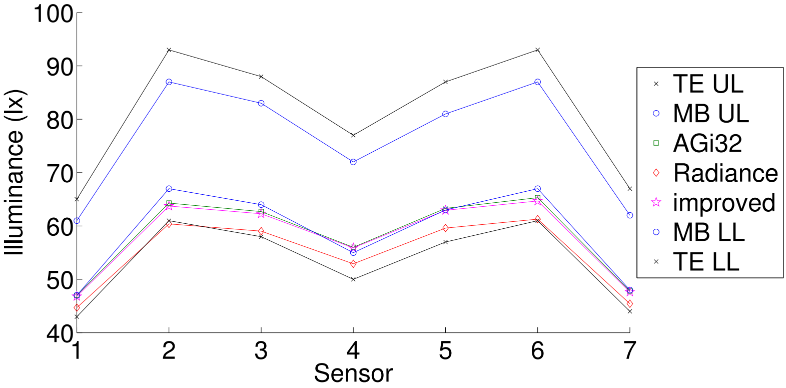
$\Rightarrow$ all 49 calculated values inside total error band

$\Rightarrow$ mean illuminance increase of 5.23%

Triangulation approach – Results

TC 4.2: grey wall, opal luminaire; position 2

⇒ 12/49 values (24.49%) below MB LL (AGI32: 12)
⇒ all 49 values inside total error band (AGI32: 49)



Triangulation approach – Results

Real world test scene – seminar room at Lichtakademie Bartenbach

Triangulation approach – Results

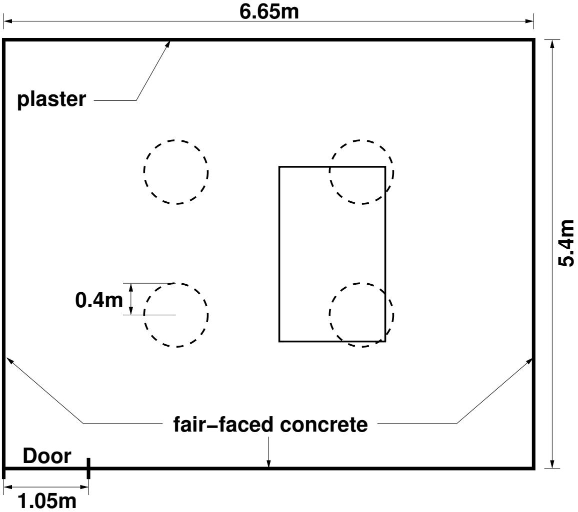
Real world test scene – seminar room at Lichtakademie Bartenbach

Simplified set up

- red linoleum floor, 3 fair-faced concrete walls, 1 plastered wall, plastered ceiling
- 4 light tubes with scattering inserts
- spectral measurements of reflectances and photometric data of light sources done by Bartenbach LichtLabor

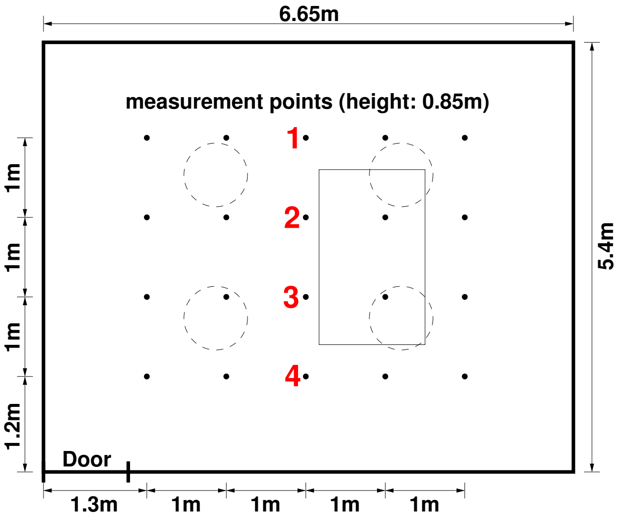
Triangulation approach – Results

Seminar room: simplified set up



Triangulation approach – Results

Seminar room: simplified set up (measurement points)



Triangulation approach – Results

Real worl test scene – seminar room at Lichtakademie Bartenbach

Measurement point	1	2	3	4
Measurement	600.2	844.4	819.4	560.2
Radiance	621.0	776.9	739.7	515.6
Deviance	*3.47%*	*7.99%*	*9.73%*	*7.96%*
Triangulation approach	657.9	825.9	786.8	546.6
Deviance	*9.61%*	*2.19%*	*3.98%*	*2.43%*

- mean decrease in deviance: -2.74%
- mean illuminance increase from Radiance to our triangulation approch: + 6.16%
- probable reason for deviances: imprecise modeling of light tubes with scattering inserts

Improved Adaptive Subdivision of Circular Light Sources

Conclusion

- significant improvement in accuracy
  Analytical test: error decrease from 6.11% to 0.08%
  Test case 4.2: all values inside total error band
  Seminar room: mean deviance decrease of 2.74%
- measured illuminance increase of about 6%
- only slight increase in rendering time (about 0% – 5%)

Acknowledgment

This research was supported by the FIT-IT program of the BMVIT (Bundesministerium für Verkehr, Innovation und Technologie) and the FFG with grant 81600.

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Any questions?