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

David Geisler-Moroder  Arne Dür

Department of Mathematics
University of Innsbruck, Austria

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

1 Validation of Radiance against CIE171:2006
   - Experimental Test Cases
   - Test Cases with Analytical References

2 Improved Adaptive Subdivision of Circular Light Sources
   - Proposed algorithm
   - Validation of our new algorithm
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

⇒ Possibility of comparison with AGI32 results published by Dau Design and Consulting Inc.
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

<table>
<thead>
<tr>
<th>Position</th>
<th>Door</th>
<th>Door</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light source</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Sensor</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Dimensions:
- 6.78m
- 1.695m
- 3.39m
- 1.695m
- 1.695m
- 6.72m
- 3.39m
- 1.695m
- 1.695m
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 ($\approx 2200$ lm each) and photometric data given

<table>
<thead>
<tr>
<th>Total expectation error upper limit</th>
<th>112.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiance mean room illuminance</td>
<td>88.5</td>
</tr>
<tr>
<td>Total expectation error lower limit</td>
<td>88.0</td>
</tr>
</tbody>
</table>
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 ($\approx 2200$ lm each) and photometric data given

<table>
<thead>
<tr>
<th>Total expectation error upper limit</th>
<th>112.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiance mean room illuminance</td>
<td>88.5</td>
</tr>
<tr>
<td>Total expectation error lower limit</td>
<td>88.0</td>
</tr>
</tbody>
</table>
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 ($\approx 1800 \text{ lm} - 2100 \text{ lm each}$) and photometric data given

<table>
<thead>
<tr>
<th>Total expectation error upper limit</th>
<th>67.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiance mean room illuminance</td>
<td>51.4</td>
</tr>
<tr>
<td>Total expectation error lower limit</td>
<td>53.1</td>
</tr>
</tbody>
</table>
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

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total expectation error upper limit</td>
<td>67.5</td>
</tr>
<tr>
<td>Radiance mean room illuminance</td>
<td>51.4</td>
</tr>
<tr>
<td>Total expectation error lower limit</td>
<td>53.1</td>
</tr>
</tbody>
</table>
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 × 600 mm) with compact fluorescent lamps; output (≈ 4100 lm each) and photometric data given

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total expectation error upper limit</td>
<td>254.2</td>
</tr>
<tr>
<td>Radiance mean room illuminance</td>
<td>234.5</td>
</tr>
<tr>
<td>Total expectation error lower limit</td>
<td>199.8</td>
</tr>
</tbody>
</table>
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 × 600 mm) with compact fluorescent lamps; output (≈ 4100 lm each) and photometric data given

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total expectation error upper limit</td>
<td>254.2</td>
</tr>
<tr>
<td>Radiance mean room illuminance</td>
<td>234.5</td>
</tr>
<tr>
<td>Total expectation error lower limit</td>
<td>199.8</td>
</tr>
</tbody>
</table>
TC 4.3: grey wall, SSR luminaire

Results (Position 2)

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

S₁-hz (0% reflectance)
4m x 2.5m

S₁-v (0% reflectance)
4m x 2.5m

S₂ (30% reflectance)
4m x 4m

incident flux (35°)
TC 5.6: Light reflection over diffuse surfaces

Measurement points

D. Geisler-Moroder, A. Dür

CIE171:2006 and Improved Light Source Subdivision
TC 5.6: Light reflection over diffuse surfaces

Results

<table>
<thead>
<tr>
<th>$F_{12}$</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIE Reference</td>
<td>35.901</td>
<td>27.992</td>
<td>21.639</td>
<td>16.716</td>
<td>12.967</td>
</tr>
<tr>
<td>Radiance</td>
<td>35.861</td>
<td>27.898</td>
<td>21.573</td>
<td>16.707</td>
<td>12.955</td>
</tr>
</tbody>
</table>

| Points of measurement for $S_{1-v}$ |

<p>| Points of measurement for $S_{1-hz}$ |</p>
<table>
<thead>
<tr>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.80</td>
<td>30.94</td>
<td>33.98</td>
<td>35.57</td>
<td>35.57</td>
<td>33.98</td>
<td>30.94</td>
<td>26.80</td>
</tr>
<tr>
<td>26.77</td>
<td>30.91</td>
<td>33.94</td>
<td>35.53</td>
<td>35.53</td>
<td>33.94</td>
<td>30.91</td>
<td>26.77</td>
</tr>
</tbody>
</table>

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

Test scene dimensions:
- Length: 4m
- Width: 2.5m
- Height: 3m

Lighting setup:
- Incident flux (60°)

Surfaces:
- $S_2$: 60% reflectance
- $S_{1-v}$: 0% reflectance
- $S_{1-hz}$: 0% reflectance

D. Geisler-Moroder, A. Dür

CIE171:2006 and Improved Light Source Subdivision
TC 5.7: Diffuse reflection with internal obstructions
Measurement points
## TC 5.7: Diffuse reflection with internal obstructions

### Results

#### Points of measurement for $S_{1-v}$

<table>
<thead>
<tr>
<th>$F_{12}$</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
</table>

#### Points of measurement for $S_{1-hz}$

<table>
<thead>
<tr>
<th>$F_{12}$</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIE Reference</td>
<td>4.761</td>
<td>5.261</td>
<td>4.535</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiance</td>
<td>3.366</td>
<td>3.615</td>
<td>3.012</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Mean error: 21.791%
TC 5.7: Diffuse reflection with internal obstructions
Analytical calculation of configuration factors

Case 1:

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

Case 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

<table>
<thead>
<tr>
<th>$F_{12}$</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>$F_{12}$</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIE Reference</td>
<td>4.761</td>
<td>5.261</td>
<td>4.535</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>analytical</td>
<td>3.382</td>
<td>3.629</td>
<td>3.013</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Radiance</td>
<td>3.366</td>
<td>3.615</td>
<td>3.012</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

mean error (analytical ↔ 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 description:

- A point light source (10000 lm) is placed inside a square room with dimensions 4m x 4m x 4m.
- The room is surrounded by lambertian surfaces with reflectances less than or equal to 95%.
- The light source is located at a distance of 2m from the walls.
TC 5.8: Internal reflected component calculation

Results

<table>
<thead>
<tr>
<th>Reflectance</th>
<th>0%</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{av}(lx)$ CIE</td>
<td>0.00</td>
<td>5.48</td>
<td>11.6</td>
<td>26.0</td>
<td>44.6</td>
<td>69.4</td>
</tr>
<tr>
<td>Radiance</td>
<td>0.00</td>
<td>5.50</td>
<td>11.5</td>
<td>26.0</td>
<td>44.6</td>
<td>69.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reflectance</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{av}(lx)$ CIE</td>
<td>104</td>
<td>156</td>
<td>243</td>
<td>417</td>
<td>937</td>
<td>1979</td>
</tr>
<tr>
<td>Radiance</td>
<td>104</td>
<td>157</td>
<td>244</td>
<td>419</td>
<td>884</td>
<td>1472</td>
</tr>
</tbody>
</table>

mean error for reflectances $\leq 80\%$: 0.318%
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)
Experimental test case 4.2:  
4 circular luminaires (450mm diameter) with CFLs

<table>
<thead>
<tr>
<th>Total expectation error upper limit</th>
<th>67.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiance mean room illuminance</td>
<td>51.4</td>
</tr>
<tr>
<td>Total expectation error lower limit</td>
<td>53.1</td>
</tr>
</tbody>
</table>

⇒ 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 ÷ distance to source) too large (\(-ds\) option), subdivide along longest axis
- repeat on each subsouce until size criterion is satisfied

Jittering:
- jitter over rectangular volumes
- degree of jittering controlled by \(-dj\) option
Validation of Radiance against CIE171:2006
Improved Adaptive Subdivision of Circular Light Sources

Validation

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
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 $-d_j$ 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:
\[ E = L_0 \pi \frac{r^2}{r^2 + h^2} = \frac{\Phi}{\pi (r^2 + h^2)} \]
\[ = 124.705 \text{ lux} \]

Radiance:
(64 quads, aiming failure!)
\[ E = 117.082 \text{ lux} \]
Error = 6.11%

Triangulation approach
(96 triangles):
\[ E = 124.800 \text{ lux} \]
Error = 0.08%
Experimental test case 4.2:
4 circular luminaires (450mm diameter) with CFLs

<table>
<thead>
<tr>
<th>Simulated mean room illuminance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total expectation error upper limit</td>
<td>67.5</td>
</tr>
<tr>
<td>Radiance</td>
<td>51.4</td>
</tr>
<tr>
<td>Triangulation approach</td>
<td>54.0</td>
</tr>
<tr>
<td>Total expectation error lower limit</td>
<td>53.1</td>
</tr>
</tbody>
</table>

⇒ 33/49 values (67.35%) below measurement lower limit
⇒ 1 of those values even outside total error band
⇒ 12/49 values (24.49%) below measurement lower limit
   (63.64% decrease of values below limit)
⇒ all 49 calculated values inside total error band
⇒ 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

6.65m

0.4m

1.05m

5.4m

Fair-faced concrete

Plaster

Door

D. Geisler-Moroder, A. Dür

CIE171:2006 and Improved Light Source Subdivision
Triangulation approach – Results
Seminar room: simplified set up (measurement points)

6.65m

measurement points (height: 0.85m)

1.2m

Door

1.3m 1m 1m 1m 1m

1

2

3

4
### Triangulation approach – Results

Real world test scene – seminar room at Lichtakademie Bartenbach

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>600.2</td>
<td>844.4</td>
<td>819.4</td>
<td>560.2</td>
</tr>
<tr>
<td>Radiance</td>
<td>621.0</td>
<td>776.9</td>
<td>739.7</td>
<td>515.6</td>
</tr>
<tr>
<td>Deviance</td>
<td>3.47%</td>
<td>7.99%</td>
<td>9.73%</td>
<td>7.96%</td>
</tr>
<tr>
<td>Triangulation approach</td>
<td>657.9</td>
<td>825.9</td>
<td>786.8</td>
<td>546.6</td>
</tr>
<tr>
<td>Deviance</td>
<td>9.61%</td>
<td>2.19%</td>
<td>3.98%</td>
<td>2.43%</td>
</tr>
</tbody>
</table>

- mean decrease in deviance: **-2.74%**
- mean illuminance increase from Radiance to our triangulation approach: **+ 6.16%**
- probable reason for deviations: imprecise modeling of light tubes with scattering inserts
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%)
This research was supported by the FIT-IT program of the BMVIT (Bundesministerium für Verkehr, Innovation und Technologie) and the FFG with grant 81600.
References

Dau Design and Consulting Inc.:  
*Validation of AGI32 against CIE 171:2006*, 2007

A. Slater and H. Graves:  
*Benchmarking Lighting Design Software*,  
TM 28/00, 33.CIBSE, London, 2002

P. Shirley, C. Wang and K. Zimmermann:  
*Monte Carlo Techniques for Direct Lighting Calculations*,  

G. Ward and R. Shakespeare:  
*Rendering with Radiance*,  
Any questions?