

# Calculation of Luminaires Using Radiance

Krzysztof Wandachowicz

Poznan University of Technology, Institute of Industrial Electrical Engineering  
PL-60-965 Poznań, Poland, ul. Piotrowo 3A,  
e-mail: Krzysztof.Wandachowicz@put.poznan.pl

## Abstract

The paper contains considerations with respect to practical possibility of applying Radiance system to make photometric calculations of lighting fixture system of any configuration. There are described method and the way of making calculations for diffuse, specular and semi-specular luminaires with reflectors and globes. This paper contains also example of calculations of luminance distribution of luminaires and distribution of luminous intensity.

## 1. Luminaire in lighting engineering

Luminaire definition: a complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps and to connect the lamps to the power supply.

Calculation of luminaire means that:

- 1) will be calculated lighting parameters of the luminaire (see below) for given shape of the luminaire and its material properties,
- 2) will be calculated shape of the luminaire for given lighting parameters and material properties.

There is presented in this paper the first of the mentioned above method.

The most important lighting parameters of the luminaires are:

- luminous intensity distribution -  $I_{C,\gamma}$  [cd],
- luminous flux -  $\Phi$  [lm],
- light output ratio (luminaire efficiency) -  $\eta$  [-],
- luminance distribution on the surface of luminaire -  $L$  [ $\text{cd}/\text{m}^2$ ],

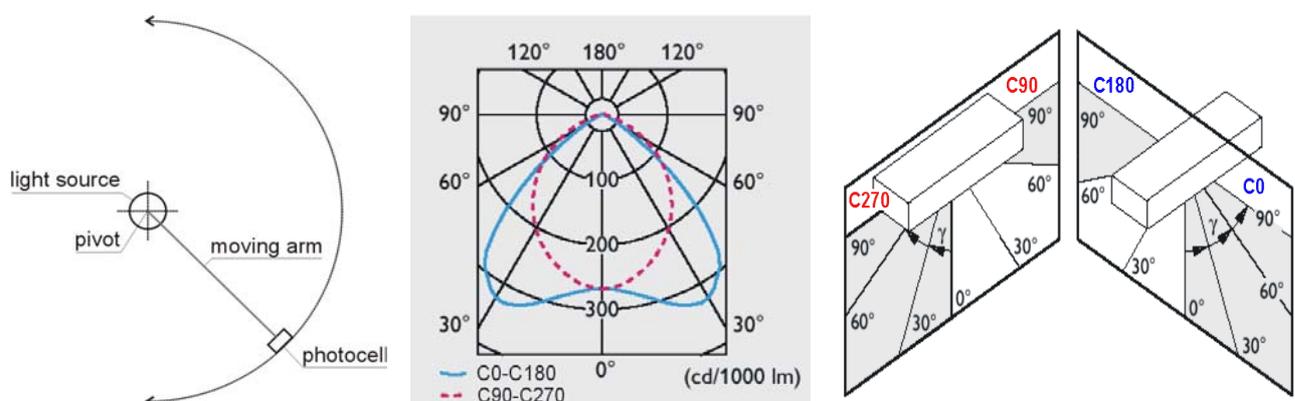


Fig. 1.1 Moving cell photometer, luminous intensity distribution, C-planes.

Luminous intensity distribution (candlepower distribution curve): a curve, generally polar, representing the variation of luminous intensity of a lamp or luminaire in a plane through the light center expressed in candelas or candelas per one thousand lumens of lamp flux. Luminous

intensity distribution can be measured by distribution photometer with moving cell along  $\gamma$  angles for various C-planes (Fig. 1.1).

Luminous flux of the luminaire  $\Phi$  expressed in lumens can be measured directly by the Ulbricht sphere (Fig. 1.2) or can be calculated from luminous intensity distribution of the luminaire  $I_{C,\gamma}$ .



Fig. 1.2 Integrating (Ulbricht) sphere photometer.

Calculation of luminous flux  $\Phi$  means that the small parts of the flux  $\Delta\Phi$  discretized into  $n$  solid angles  $\Delta\omega$  are to add up for  $m$  C-planes:

$$\Phi = \sum_{C_0}^{C_m} \sum_{i=1}^n \Delta\Phi_{\Delta\omega_i} \quad (1)$$

Using definition of luminous intensity  $I_{C,\gamma}$  the luminous flux  $\Delta\Phi$  emitted into solid angle  $\Delta\omega_i$  is given by:

$$\Delta\Phi_{\Delta\omega_i} = I_{C,\gamma(\Delta\omega_i)} \cdot \Delta\omega_i \quad (2)$$

where  $I_{C,\gamma(\Delta\omega_i)}$  is average luminous intensity emitted into solid angle  $\Delta\omega_i$ .

Solid angle  $\Delta\omega_i$  can be represented by the  $\gamma$  angles and calculated as follows:

$$\Delta\omega_i = \frac{\Delta C}{360} \cdot 2 \cdot \pi \cdot [\cos \gamma_i - \cos(\gamma_i + \Delta\gamma)] \quad (3)$$

where  $\Delta C$  is distance between C-planes,  $\Delta\gamma$  is distance between luminous intensities per C-plane.

Luminous intensity is now emitted into solid angle  $\Delta\omega_i$  that is enclosed by  $\gamma$  angles and equation (2) becomes:

$$\Delta\Phi_{\Delta\omega_i} = I_{C,\gamma(\gamma_i \div \gamma_i + \Delta\gamma)} \cdot \Delta\omega_i \quad (4)$$

where  $I_{C,\gamma(\gamma_i \div \gamma_i + \Delta\gamma)}$  is average luminous intensity emitted between  $\gamma_i$  and  $\gamma_i + \Delta\gamma$  angles.

Light output ratio of the luminaire  $\eta$  is the ratio of luminous flux  $\Phi$  emitted by luminaire to that emitted by the lamp or lamps used therein  $\Phi_0$ :

$$\eta = \frac{\Phi}{\Phi_0} \quad (5)$$

Because luminaire can be also source of glare, there is important to know luminance distribution at the surface of luminaire. Luminance of inner surfaces of reflectors and inner and outer surfaces of globes should be measured or calculated.

Optical system elements of luminaires may be globes, reflectors and globes plus reflectors (Fig.1.3).



Fig. 1.3 Luminaires with globe, reflector, globe and reflector.

Materials properties of the globes and reflectors of the luminaires may be diffuse, specular or mixed (Fig. 1.4). Most cases are that materials properties are not ideal diffuse or specular however it is possible to assume that calculations will be made for ideal materials without significant errors.

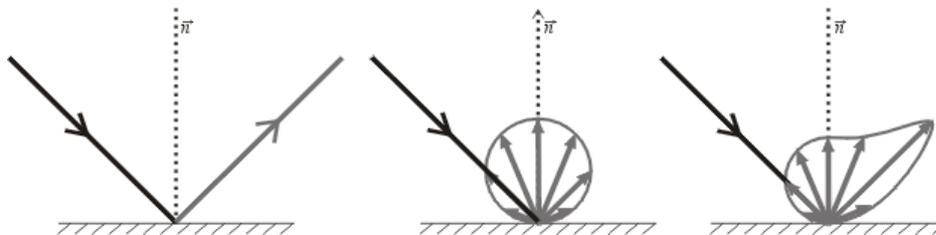


Fig. 1.4 Specular, diffuse and mixed (semi-specular) reflection.

## 2. Calculation of luminaires using Radiance

Necessary for the purpose of computations is proper description of the shapes of the optical system elements of luminaires. In particular, it is necessary to describe the shapes of the following elements:

- reflector,
- globe,
- light source solid (filament, arc tube, bulb),
- bases, sockets, holders and other elements placed in the luminaire.

Description of a luminaire geometry is produced using CAD type software (very useful is Desktop Radiance [1]). From among the available three-dimensional models only the surface models and solid models are applied. By means of surface models (flat surface - *polygon*) it is possible to create elements complicated in terms of shape the surfaces of which (often times curved) are subjected to the process of division into a number of small flat elementary surfaces (Fig. 2.1).

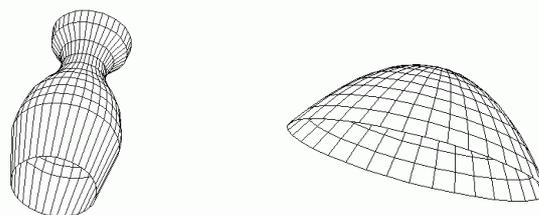


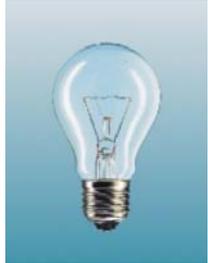
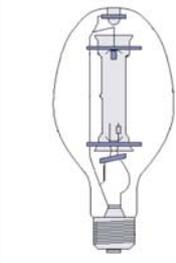
Fig. 2.1 CAD models of globe and reflector with surfaces divided into discrete elements.

Real surfaces of paraboloid reflectors or globes with complicated shapes are then replaced with a surface consisting of a set of discrete flat surfaces. It is also important to describe geometry of other elements placed in the luminaire: bases, sockets, holders etc.

There are used in this method Radiance materials for globes and reflectors that have diffuse, specular and semi-specular properties: *plastic*, *trans* and *mirror* [2, 3].

Description of light properties of the lamps (light sources) can be made in two different ways. First, it is possible to build the real shape of the light source solid (filament, arc tube, bulb) and other element e.g. bulb, cap (base). This method is especially used for lamps with clear bulb (Table 2.1).

Table 2.1 Shapes of the light sources solids.

<i>Picture</i>					
<i>Lamp</i>	Incandescent lamp	Fluorescent lamp	Mercury lamp with clear bulb	Metal halide lamp	High pressure sodium lamp
<i>Light source solid</i>	filament	bulb	arc tube	arc tube	arc tube
<i>Modeling of the shape of the light source solid</i>	very thin cylinders	cylinder	cylinder	sphere, cylinder or disfigured sphere	cylinder

Real shape of the light source solid should be made of small flat elementary surfaces using *polygon* geometry [3]. It is possible for using solid model (*cylinder*, *sphere* [3]) but in this case dimensions of light source do not matter. All rays are traced towards to the center of point source. If it is acceptable for diffuse luminaires that for specular reflectors is not because of great influence of light source dimensions for lighting properties of such luminaires.

Material of the light source solid should be *light* [3] that is the basic material for self-luminous surfaces which emits light in diffuse way. Require luminous flux distribution of the lamp is obtained because of shape of the light source solid and other elements like bulbs (use *glass* material [3]), bases (use diffuse *plastic* material).

Description of the *light* material is as follows [3]:

```
mod light id
0
0
3 RR RG RB
```

where  $R_R$   $R_G$   $R_B$  are radiance values\*. For not coloured sources radiance values are the same for three channels.

\*  $R_R$   $R_G$   $R_B$  are radiance for *R G B* channels. Light sources that are used in this method are not coloured, so radiance values are the same for three channels. Radiance  $R$  can be expressed by luminance  $L$  and multiplier 179 (where  $L=179 \cdot R$ ). It is possible to introduce directly for  $R_R$   $R_G$   $R_B$  luminance value without 179-multiplier. The only thing is that in every places have to input luminance instead of radiance and the product output of *rtrace* process will be luminance or illuminance instead of radiance or irradiance.

Radiance  $R$  is given by:

$$R = \frac{L_s}{179} \quad (6)$$

where  $L_s$  is average luminance of light source solid expressed in candelas per square meters.

Luminance  $L_s$  is a function of luminous flux emitted by the lamp  $\Phi_0$  and area of a surface light source solid  $S_s$  in square meters:

$$L_s = \frac{\Phi_0}{\pi \cdot S_s} \quad (7)$$

When light source solid is made of solid model (*cylinder, sphere*) than area  $S_s$  is calculated directly from well known equations (e.g.  $4 \cdot \pi \cdot r^2$ , where  $r$  is a radius of sphere). For light source solid which is made of small flat surfaces than area  $S_s$  is calculated as a sum of areas of all elementary surfaces.

Example of calculation was made for compact high pressure sodium lamp NAV-TS 150W. Model of the lamp is composed of arc tube (*light material*), bulb (*glass material*) and base (*plastic material*) (Fig. 2.2).

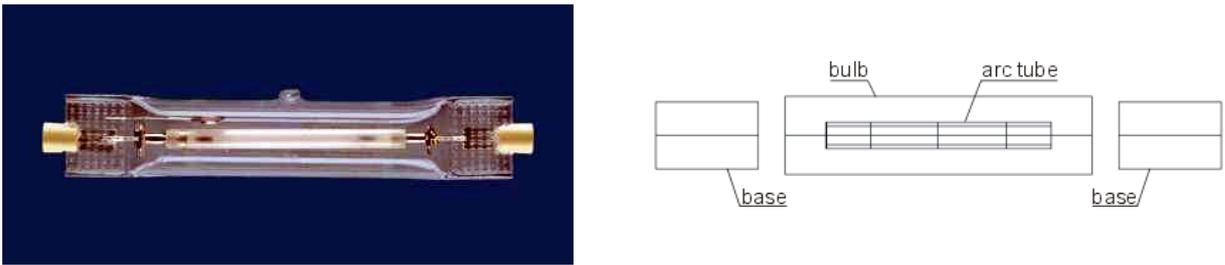


Fig. 2.2 Picture and CAD model of compact high pressure sodium lamp (NAV-TS 150W).

There are four parts along arc tube numbered 1, 2, 3 and 4 from left to right. Because luminance distribution along arc tube of real high pressure sodium lamp is changing, every of these parts have different luminance  $L_s$  (radiance  $R$ ) values. Light source solid (arc tube) should have required luminous flux  $\Phi_0$ . Solving this problem equation (7) becomes:

$$\pi \cdot S_1 \cdot k_1 \cdot L_s + \pi \cdot S_2 \cdot k_2 \cdot L_s + \pi \cdot S_3 \cdot k_3 \cdot L_s + \pi \cdot S_4 \cdot k_4 \cdot L_s = \Phi_0 \quad (8)$$

where  $S_1, S_2, S_3, S_4$  are areas of four parts of arc tube (every part in this example consists of eight small flat elementary surfaces distributed around circle),  $k_1, k_2, k_3, k_4$  are coefficients to scale luminance along arc tube (Table 2.2).

Table 2.2 Values of coefficients to scale luminance along arc tube

Coefficient	$k_1$	$k_2$	$k_3$	$k_4$
Value	0.8	1.0	1.0	0.8

Luminance values  $L_1, L_2, L_3, L_4$  of the four parts of arc tube may be calculated from:

$$\begin{aligned} L_1 &= k_1 \cdot L_s \\ L_2 &= k_2 \cdot L_s \end{aligned} \quad (9)$$

$$L_3 = k_3 \cdot L_s$$

$$L_4 = k_4 \cdot L_s$$

Luminance  $L_s$  can be calculated from equation:

$$L_s = \frac{\Phi_0}{\pi \cdot S_1 \cdot k_1 + \pi \cdot S_2 \cdot k_2 + \pi \cdot S_3 \cdot k_3 + \pi \cdot S_4 \cdot k_4} \quad (10)$$

Bulb as a *cylinder* is made of *glass* material and surrounds arc tube. Luminous flux  $\Phi_0$  was attached to arc tube but complete lamp consists also bulb and base. Luminous flux of complete lamp will be lower than required  $\Phi_0$ . The only solution of this problem is to making preliminary calculations of luminous intensity distribution using Radiance. Luminous flux  $\Phi_0'$  is calculated that is lower than  $\Phi_0$ . The next point is to calculate corrected luminance values  $L_1^{cor}$ ,  $L_2^{cor}$ ,  $L_3^{cor}$ ,  $L_4^{cor}$  of four parts of arc tube:

$$L_1^{cor} = \frac{\Phi_0'}{\Phi_0} \cdot k_1 \cdot L_s \quad (11)$$

$$L_2^{cor} = \frac{\Phi_0'}{\Phi_0} \cdot k_2 \cdot L_s$$

$$L_3^{cor} = \frac{\Phi_0'}{\Phi_0} \cdot k_3 \cdot L_s$$

$$L_4^{cor} = \frac{\Phi_0'}{\Phi_0} \cdot k_4 \cdot L_s$$

After correction new calculations of luminous intensity distribution of NAV-TS 150W lamp was made (Fig. 2.3).

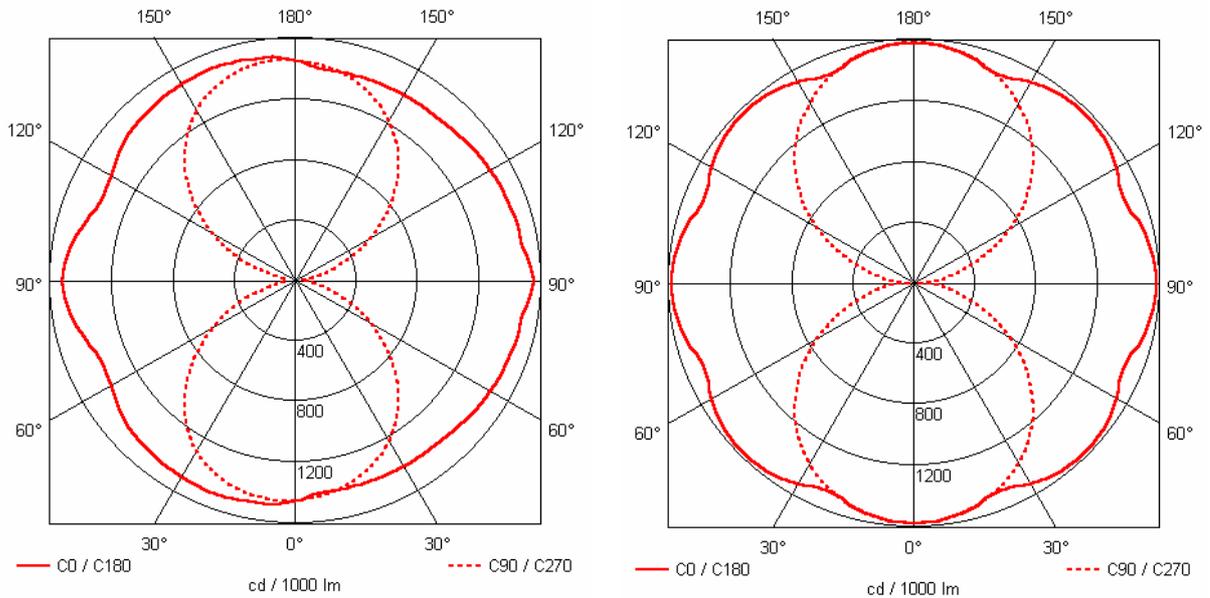


Fig. 2.3 Luminous intensity distribution of compact high pressure sodium lamp (NAV-TS 150W), measured (left) and calculated using Radiance for model of the lamp at Fig. 2.2 (right).

The second way to describe light source properties is to build small sphere with real luminous intensity distribution. The advantage of this method is that there is introduced accurate luminous intensity distribution of light source. Disadvantage is that light source has improper shape and dimensions. This method should be used especially for light sources with large, diffusing bulb.

Light source in Radiance (geometry plus *light* material) has no reflection properties. Reflectance of such object is zero, so light incident on it is absorbed. Real bulb has reflectance that is greater than zero. Putting into luminaire large, diffusing bulb could cause significant error because too much light would be absorbed.

Here is presented example of normal incandescent lamp with clear bulb. Two files should be created:

100Wdesc.rad:

```
# 100W incandescent lamp with clear bulb

void brightdata 100W.dist
5 corr 100Wdist.dat source.cal src_theta src_phi2
0
1 3183

# "3183" is inverse of projected area of light source
# here light source is sphere, radius 0.01 meter
# projected area is  $3.1415 * 0.01 * 0.01 = 0.00031415$ 

100W.dist light 100W_material
0
0
3 1.35 1.35 1.35

# "1.35" is luminous flux of the lamp in thousand of lumens [klm]

100W_material sphere 100W_GLS_clear_bulb
0
0
4 0 0 0 0.01
```

100Wdist.dat:

```
# 100W incandescent lamp with clear bulb
# luminous intensity distribution I(cd/1000lm) divided by 179

# "1" means one dimension array

1
0 180 19

# "19" means the number of gamma angles from 0 to 180

0.407821229
0.418994413
0.424581006
0.430167598
0.441340782
0.446927374
0.452513966
0.452513966
0.458100559
0.458100559
0.463687151
0.463687151
0.469273743
0.469273743
0.463687151
0.452513966
```

0.379888268  
0  
0

When building of geometry and material properties is finished this is a time of making calculations. The goal is to obtain luminous intensity distribution. The illuminance  $E_i$  at point  $i$  is calculated using *rtrace* process (Fig. 2.4):

`rtrace -faa -h -ov -l @parameters.txt luminaire.oct <pointsC0-180.txt> RadianceC0-180.txt`

where *parameters.txt* is a file with the most important parameters of *rtrace* command, *luminaire.oct* is a *octree* file which contains geometry and material properties of luminaire, *pointsC0-180.txt* is input file that contains a list of the points and orientations where illuminance will be calculated (only for plane C0-C180), *RadianceC0-180.txt* is a file with output data (calculated irradiances  $R$  for given points).

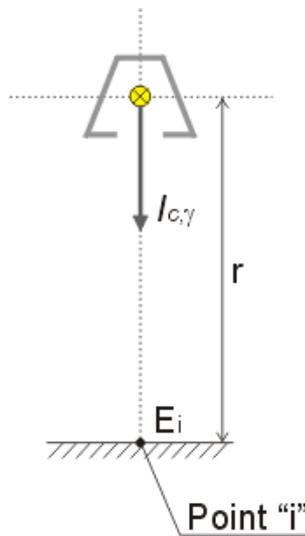


Fig. 2.4 Calculation of illuminance  $E_i$  at point „i” and the luminous intensity  $I_{C,\gamma}$  in direction of point „i”.

Product of *rtrace* process is illuminance at point  $i$ . Illuminance is calculated for points  $i$  that are distributed around circle. Centre of this circle should be located at point 0,0,0 of three-dimensional physical environment in Cartesian world coordinates. At the same 0,0,0 point should be located light centre of luminaire. For luminaires with open globes and/or reflectors with clear glass light centre is geometrical centre of the lamp. Positions of points  $i$  could be the same as positions of photocell moving at the end of photometer around its pivot (Fig. 1.1). Distance between point  $i$  and light centre should be at least five times the maximum dimension of luminaire. This gives results of inverse-square law that are accurate within one percent. It is true only for sources having uniform luminance. For luminaires with narrow luminous distribution (e.g. specular reflectors) this distance can be much more greater. There is presented an example of list points from *pointsC0-180.txt* file for 10 degree distance of  $\Delta\gamma$  (Tab. 2.3):

Table 2.3 List of points and orientations where illuminance will be calculated, distance between point  $i$  and light centre is 5m; x-org, y-org, z-org – coordinates of point  $i$ , x-dir, y-dir, z-dir – direction of normal vector starting from point  $i$ .

$\gamma$	x-org	y-org	z-org	x-dir	y-dir	z-dir
90	5.0000	0.0000	0.0000	-5.0000	0.0000	0.0000
80	4.9240	0.0000	-0.8682	-4.9240	0.0000	0.8682
70	4.6985	0.0000	-1.7101	-4.6985	0.0000	1.7101
60	4.3301	0.0000	-2.5000	-4.3301	0.0000	2.5000

50	3.8302	0.0000	-3.2139	-3.8302	0.0000	3.2139
40	3.2139	0.0000	-3.8302	-3.2139	0.0000	3.8302
30	2.5000	0.0000	-4.3301	-2.5000	0.0000	4.3301
20	1.7101	0.0000	-4.6985	-1.7101	0.0000	4.6985
10	0.8682	0.0000	-4.9240	-0.8682	0.0000	4.9240
0	0.0000	0.0000	-5.0000	0.0000	0.0000	5.0000
-10	-0.8682	0.0000	-4.9240	0.8682	0.0000	4.9240
-20	-1.7101	0.0000	-4.6985	1.7101	0.0000	4.6985
-30	-2.5000	0.0000	-4.3301	2.5000	0.0000	4.3301
-40	-3.2139	0.0000	-3.8302	3.2139	0.0000	3.8302
-50	-3.8302	0.0000	-3.2139	3.8302	0.0000	3.2139
-60	-4.3301	0.0000	-2.5000	4.3301	0.0000	2.5000
-70	-4.6985	0.0000	-1.7101	4.6985	0.0000	1.7101
-80	-4.9240	0.0000	-0.8682	4.9240	0.0000	0.8682
-90	-5.0000	0.0000	0.0000	5.0000	0.0000	0.0000

After calculations of illuminance  $E_i$  for all points  $i$  are finished, luminous intensity of the luminaire  $I_{C,\gamma}$  in a specified direction  $C,\gamma$  is calculated using inverse-square law:

$$I_{C,\gamma} = E_i \cdot r^2 \quad (12)$$

Then from luminous intensity distribution - using equations 1, 3, 4 and 5 – luminous flux and light output ratio are calculated.

### **3. Calculation of diffuse luminaires**

Well known analytical method of calculating diffuse luminaires makes numerous simplifying assumption which are necessary to render the calculations possible. Disadvantages of this method are:

- calculation only for simple shapes of the optical system elements of luminaires,
- the part of the luminaire forming a holder completely absorbs the luminous flux incident on it,
- lamps, sockets and other elements inside a luminaire are not taken into considerations as the participants of the luminous flux concealing and interreflections of the flux,
- the globe or the reflector surface must be uniform in terms of the reflection properties.

There is in the analytical method of calculation diffuse luminaires for given shape and dimensions of the luminaire and given material properties (only diffuse materials) interreflection calculus carry out. For luminaire with reflector or globe the following calculations can be made:

- luminous flux that is transmitted  $\Phi_\tau$ , reflected  $\Phi_\rho$  and that go out luminaire  $\Phi$ ,
- inner and outside luminance of the globe or reflector  $L$ ,
- luminous intensity distribution  $I_{C,\gamma}$ ,
- light output ratio of the luminaire  $\eta$ .

Advantages of calculation of diffuse luminaires using Radiance are:

- calculation for arbitrary shape of the optical system elements of luminaire,
- different parts of the luminaire can have different reflection properties.

The most important features of calculation of diffuse luminaires using Radiance are:

- globes and reflectors are divided into flat elementary surfaces, but dimensions of these surfaces have not to be very small,
- materials for globes and reflectors are *trans* and *plastic*,

- light sources can be modeled as:
  - real shape of the light source solid (filament, arc tube, bulb) and other element (bulb, base), there are used *light* material and *polygon* as a scene description,
  - small sphere with real luminous intensity distribution, there are used *light* material with special function *brightdata* [3] and *sphere* as a scene description,
- the luminaire has proportionally small sizes in relation to the distance at which the measurement point is located; hitting the luminaire with a small amount of rays produces incorrect illuminance values; therefore it is necessary to do additional preliminary calculations to obtain a precise results; the so-called substitute surface is introduced which, in case of the globe, has the shape of a sphere (*sphere* geometry) surrounding the entire luminaire while in case of the reflector it has the shape of a circle or rectangle (*ring* or *polygon* geometry) enclosing the luminaire in the reflector opening (Fig. 3.1),

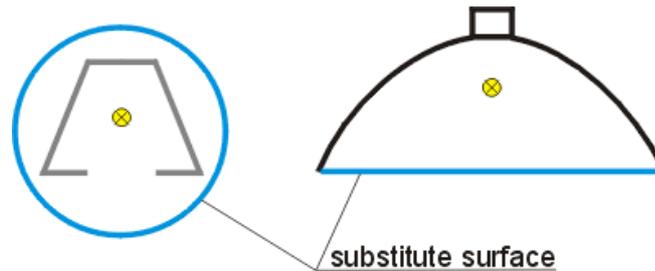


Fig. 3.1 Substitute surfaces: sphere in case of the globe, circle or rectangle in case of the reflector.

- preliminary calculations for substitute surface have to be prepared using *mkillum* process (see below); as a result of this process the luminance distribution  $L_{C,\gamma}$  (or radiance  $R_{C,\gamma}$ ) towards directions  $C,\gamma$  is calculated for the substitute surface which becomes secondary light source;

*mkillum @parameters.txt luminaire.oct <subst-surface.rad> subst-surface-illum.rad*

where *subst-surface.rad* is input file where substitute surface is described. There is an example of this file below:

*subst-surface.rad*:

```
#@mkillum i=void d=1100 s=202 m=illum-1
void sphere illuminator
0
0
4 0 0 0 0.16
```

where  $d=1100$  and  $s=202$  are parameters which represent angular resolution of luminance distribution which will be calculated, parameter  $m=$  allows a specific name the data files (here *illum-1*) that will store values of calculated luminance distribution. Higher  $d$  and  $s$  values give more smooth luminous intensity distribution curve but increase rendering time. For  $d=1100$   $s=202$  it is possible in almost cases to get smooth luminous intensity distribution curve in reasonable time.

Products of *mkillum* process are files *subst-surface-illum.rad* and *illum-1.dat*. First of these files contains information of *brightdata* function and *illum* [3] material of substitute surface. Second file contains an array with radiance distribution  $R_{C,\gamma}$  of substitute surface.

*subst-surface-illum.rad*:

```
# C:\RADIANCE\BIN\MKILLUM.EXE @parameters.txt luminaire.oct
#@mkillum !
# mkillum i=void d=1100 s=202 m=illum-1
```

```

void brightdata illum-1.dist
5 noneg illum-1.dat
  illum.cal il_alt il_azi
0
0

illum-1.dist illum illum-1
0
0
3 6.428704 6.428704 6.428704

illum-1 sphere illuminator
0
0
4
          0          0          0          0.16

```

illum-1.dat (fragment):

```

2
1.010638 -1.010638 96
0.000000 6.283185 149

1.007722e+000 9.795631e-001 1.002144e+000 1.035819e+000 9.966951e-001
9.967660e-001 1.024591e+000 9.907031e-001 9.684063e-001 1.002202e+000
1.002108e+000 9.738895e-001 9.964777e-001 1.030358e+000 9.909344e-001
9.852334e-001 1.002150e+000 9.908960e-001 9.682699e-001 1.002195e+000...

```

- after preliminary calculations the main calculations are executed; illuminances  $E_i$  at points  $i$  are calculated using *rtrace* process:

```
rtrace -faa -h -ov -l @par-diff.txt luminaire-subst.oct <pointsC0-180.txt> RadianceC0-180.txt
```

where *luminaire-subst.oct* is new *octree* file which contain geometry, material properties of luminaire and substitute surface which is described in *subst-surface-illum.rad* file, *par-diff.txt* is a file with the most important parameters of *rtrace* command,

- after calculations of illuminance  $E_i$  for all points  $i$ , luminous intensity of the luminaire  $I_{C,\gamma}$  in a specified direction  $C,\gamma$  is calculated from the inverse-square law, next luminous flux and light output ratio are calculated.

The first verification of correctness of the applied method has been carried out for an ideal spherical globe and open globe with a holder (Fig. 3.2).

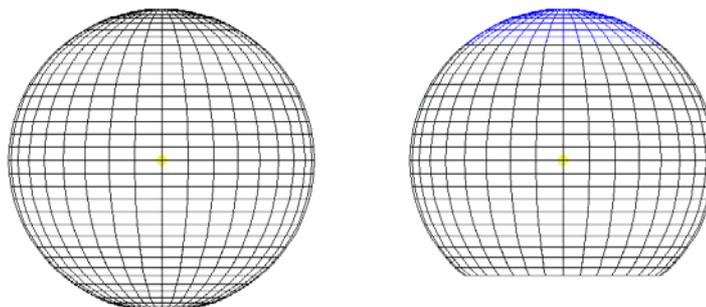


Fig. 3.2 CAD models of ideal spherical globe and open globe with a holder (marked blue).

The globe diameter is 30 cm, and the assumed globe transmittance is 0.6, reflectance is 0.3 and the luminous flux of light source  $\Phi_0 = 1350 \text{ lm}$ . Light source (marked yellow) is built as small sphere with real luminous intensity distribution.

The luminance of the globe surface  $L$ , luminous intensity distribution  $I_{C,\gamma}$ , have been calculated using Radiance. Then the luminous flux of luminaire  $\Phi$  has been calculated using equations 1, 3 and 4. The obtained results (Tab. 3.1) have been compared with the calculations done using the analytical method.

Table 3.1 Luminance of the globe surface  $L$  and the luminous flux of luminaire  $\Phi$  calculated using the analytical method and using Radiance.

		Analytical method	Radiance	Error $\delta$
Luminance of the globe $L$	Ideal spherical globe	<b>1 303</b> [cd/m <sup>2</sup> ]	<b>1 306</b> [cd/m <sup>2</sup> ]	<b>-0.2</b> %
	Open globe with a holder	<b>1 184</b> [cd/m <sup>2</sup> ]	<b>1 187</b> [cd/m <sup>2</sup> ]	<b>-0.3</b> %
Luminous flux of the luminaire $\Phi$	Ideal spherical globe	<b>1 157</b> [lm]	<b>1 166</b> [lm]	<b>-0.8</b> %
	Open globe with a holder	<b>1 011</b> [lm]	<b>997</b> [lm]	<b>1.4</b> %

When analyzing the results it may be concluded that the results obtained by the calculations done using Radiance and calculations done using the analytical method, which is a reference in cases contemplated hereby are almost the same. Therefore, one may presume that a similar degree of preciseness will be possible in case of systems involving more complicated shapes [4].

Another example for which the calculations were done is the diffusing open globe (Fig. 3.3). Models similar in shape and reflection properties to socket and fixings (marked blue) have been placed in the luminaire. The light source (marked yellow) is the incandescent general-purpose lamp with a clear bulb and the power of 100W, which is shown as a sphere with the diameter of 2 cm and which is assigned a real luminous intensity distribution. The luminance distribution on the luminaire globe surface (Fig. 3.4) and luminous intensity distribution (Fig. 3.5) have been calculated.

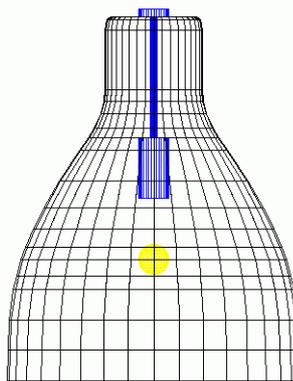


Fig. 3.3 CAD Model of the luminaire with diffusing open globe (transmittance  $\tau = 0.6$ , reflectance  $\rho = 0.3$ ). The objects marked blue colour are holders, the light source as a sphere is marked yellow.

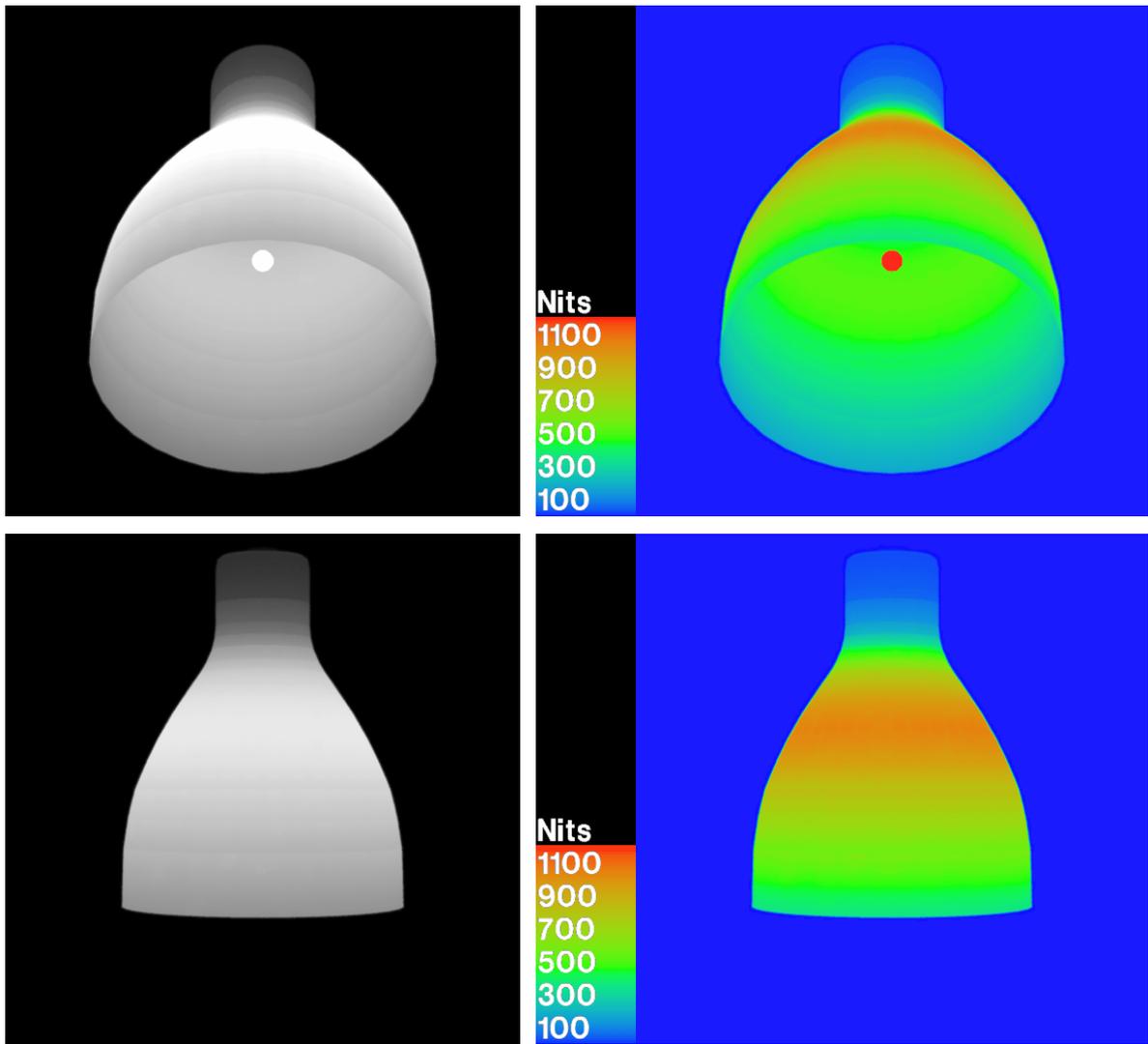


Fig. 3.4 Visualization of the luminance distribution on the surface of diffusing luminaire.

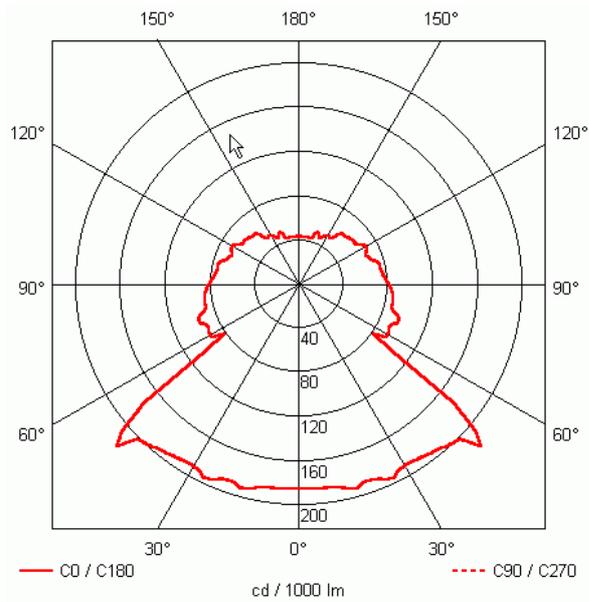


Fig. 3.5 The luminous intensity distribution of luminaire with diffusing globe (Fig. 3.3) calculated using Radiance.

Calculation time was approximate 1 hour. The most important parameter which increase calculation time is  $-ab$ . List of parameters from *par-diff.txt* file, are presented below (Tab. 3.2):

Table 3.2 List of parameters of *rtrace* process.

$-ab$	$-aa$	$-ad$	$-as$	$-ar$	$-av$	$-ds$	$-dj$	$-dt$	$-sj$	$-st$	$-lr$	$-lw$
10	0.2	1024	0	64	0 0 0	0.01	0	0	1	0	12	0

Value of  $-ab$  parameter should be connected directly with value of reflectance of globe or reflector of the luminaire. The higher is reflectance the higher have to be value of  $-ab$ . Calculation of indirect component error was made for closed space as sphere (bubble which is saw from inside) with different reflectance values for different numbers of interreflections (Fig. 3.6). These results can be useful during estimate value of  $-ab$  parameter.

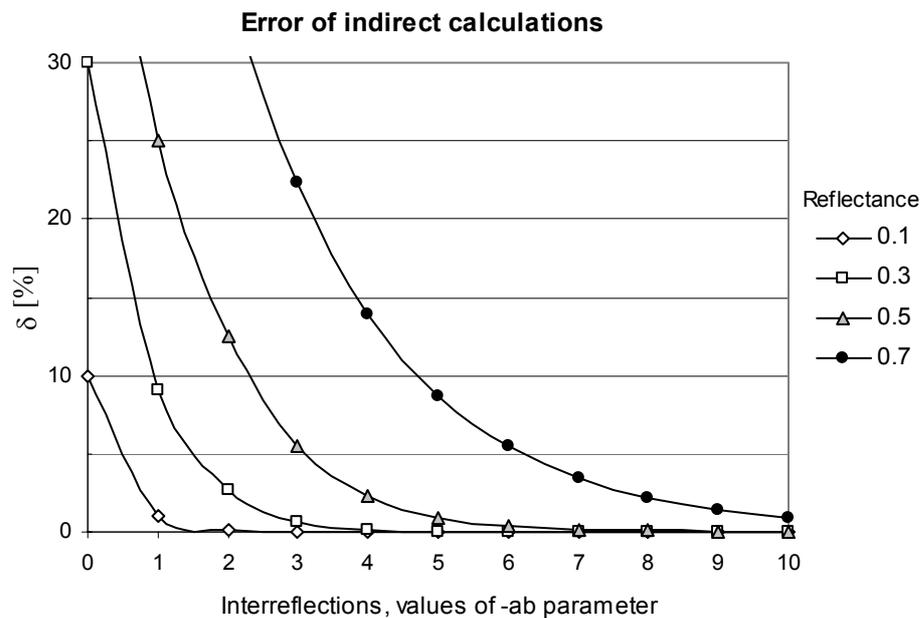


Fig. 3.6 Error of calculation indirect component.

Another example is luminaire with diffuse louvre for compact fluorescent lamp (Fig. 3.7). There are presented picture of luminaire and CAD model of luminaire and also visualizations of luminance distributions (Fig. 3.8).

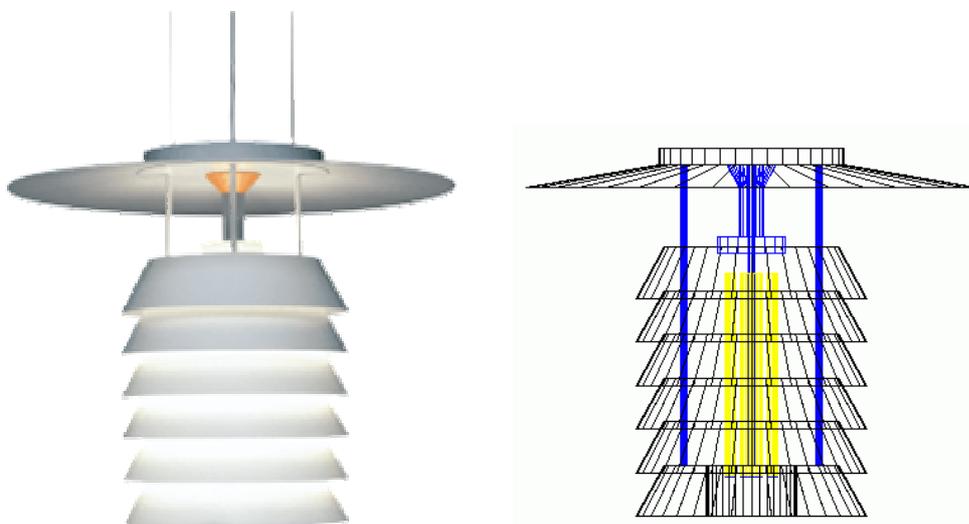


Fig. 3.7 Picture of luminaire, CAD model of luminaire.

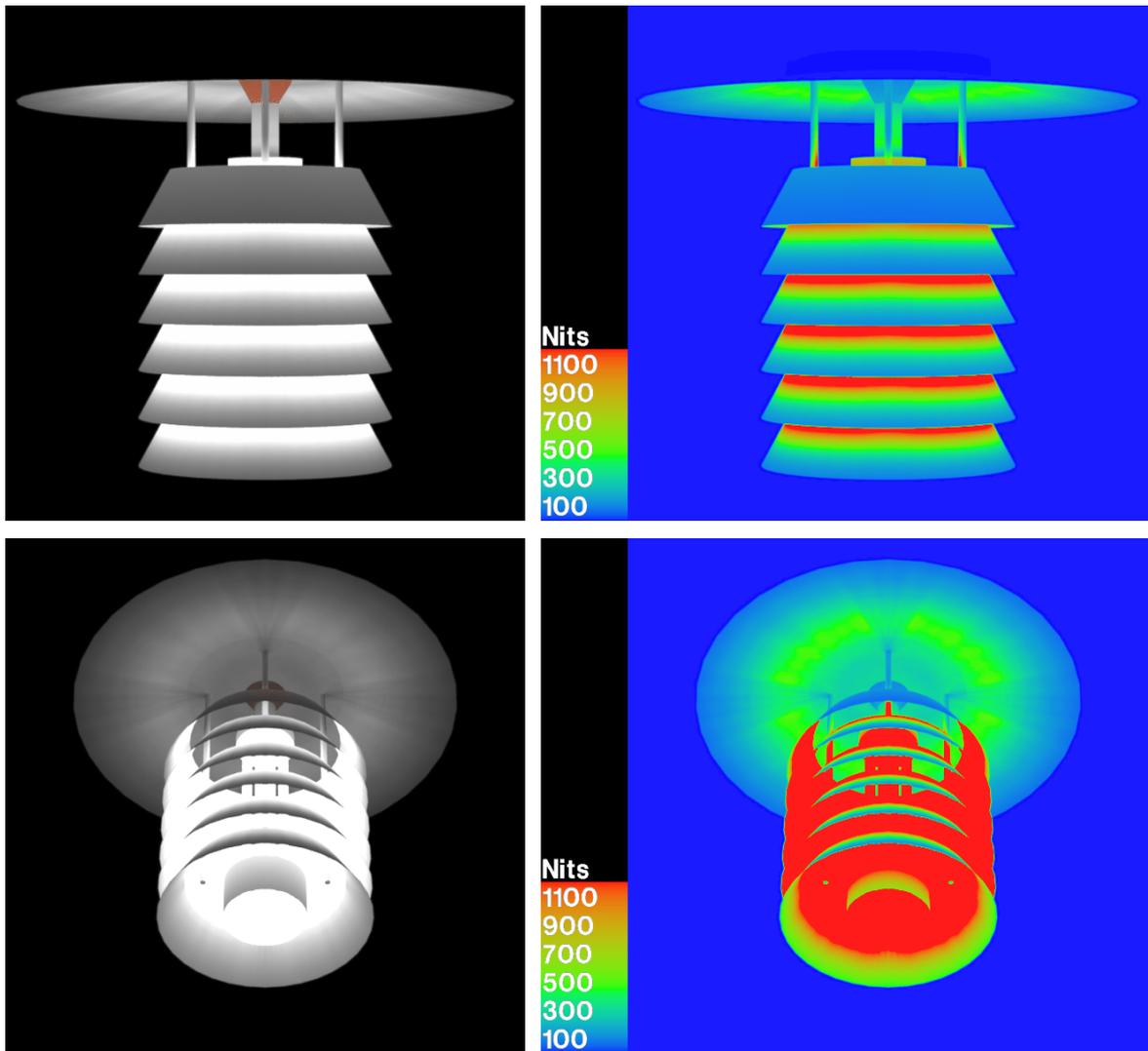


Fig. 3.8 Visualization of the luminance distribution on the surface of diffusing luminaire.

#### **4. Calculation of luminaires with specular reflectors**

Calculations of luminaires with specular reflectors were made only for parabolic reflector with symmetry about the vertical axis. This was done because parabolic reflector can be calculated using analytical method with good accuracy.

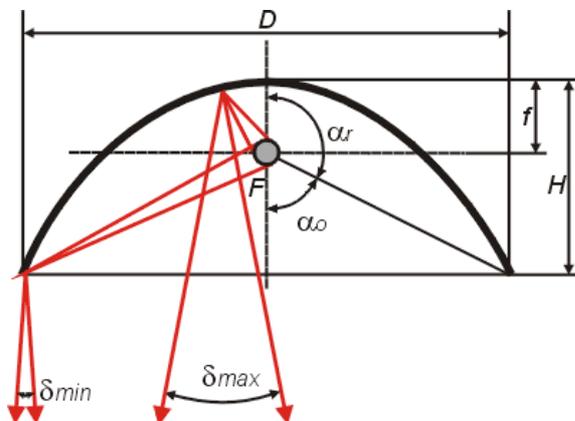


Fig. 4.1 Parabolic mirror reflector.  $F$ - focus,  $f$ - focal length,  $H$ - high of reflector,  $D$ - diameter of reflector,  $\delta_{max}$  and  $\delta_{min}$  - maximum and minimum width of an angle beam,  $\alpha_r$  and  $\alpha_o$  - angles in which luminous flux of a source is emitted to reflector and to reflector opening.

Light rays that are emitted by a point source of light placed at focus of parabolic reflectors are reflected parallel to the axis of reflector. In practice, because the source has finite size, the rays reflected from each point on the reflector diverge slightly. For sphere as a light source width of angle beam is greater in the center of reflector  $\delta_{max}$  and smaller at the edge  $\delta_{min}$  (Fig. 4.1).

Analytical method can be used for calculation maximum value of luminous intensity  $I_{max}$ , values of maximum  $\delta_{max}$  and minimum  $\delta_{min}$  width of angle beam and luminous flux of luminaire  $\Phi$ .

Maximum value of luminous intensity  $I_{max}$  is emitted in the axis direction:

$$I_{max} = S_o \cdot L_s \cdot \rho = \frac{\pi \cdot D^2}{4} \cdot L_s \cdot \rho \quad (13)$$

where  $L_s$  is average luminance of light source solid,  $S_o$  is area of a surface of reflector opening,  $\rho$  is reflector reflectance.

Maximum  $\delta_{max}$  and minimum  $\delta_{min}$  values of width of an angle beam are calculated from the equations:

$$\text{tg} \delta_{min} = \frac{16 \cdot d \cdot f}{D^2 + 16 \cdot f^2}, \quad \text{tg} \delta_{max} = \frac{d}{f} \quad (14)$$

where  $d$  is light source diameter.

Light rays emitted from light source placed at focus are reflected from parabolic mirror reflector and after first reflection are directed to reflector opening. Luminous flux of luminaire  $\Phi$  has two components: luminous flux of a source that is emitted to reflector  $\Phi_r$  and luminous flux of a source that is emitted directly to reflector opening  $\Phi_o$ :

$$\Phi = \Phi_r \cdot \rho + \Phi_o \quad (15)$$

Luminous intensity distribution is calculated using simplifying assumption that says the luminous intensity inside  $\delta_{min}$  is maximum  $I_{max}$  and at the angle  $\delta_{max}$  is zero. Luminous intensity distribution can be drawn only in a simple way (Fig. 4.2).

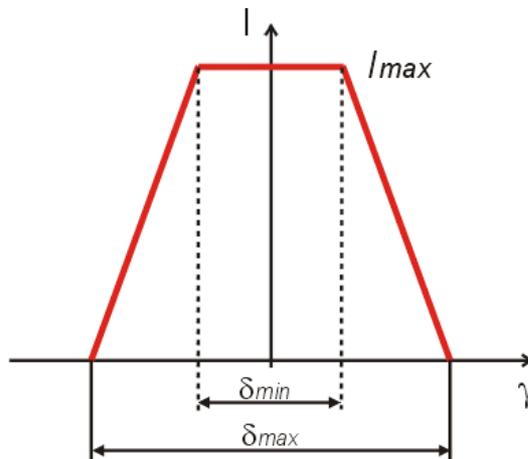


Fig. 4.2 Luminous intensity distribution of parabolic mirror reflector that can be calculated using analytical method.

The most important features of calculation of parabolic mirror reflectors using Radiance are:

- reflector should be divided into very small flat elementary surfaces; the largest dimension of elementary surface have to be smaller than dimension of light source,
- CAD model of reflector contains a lot of elementary surface (Fig. 4.3); it is a problem especially at the top of reflector model because there are met many vertex of elementary surfaces that have triangle shape; it requires to use greater value of *-r* parameter of *oconv* process than default; value of *-r 262144* is enough in most cases,
- it is need to build CAD model of reflector and CAD model of light source with the least of surface number as far as possible, when there are large number of surfaces that system error may occur<sup>†</sup>,

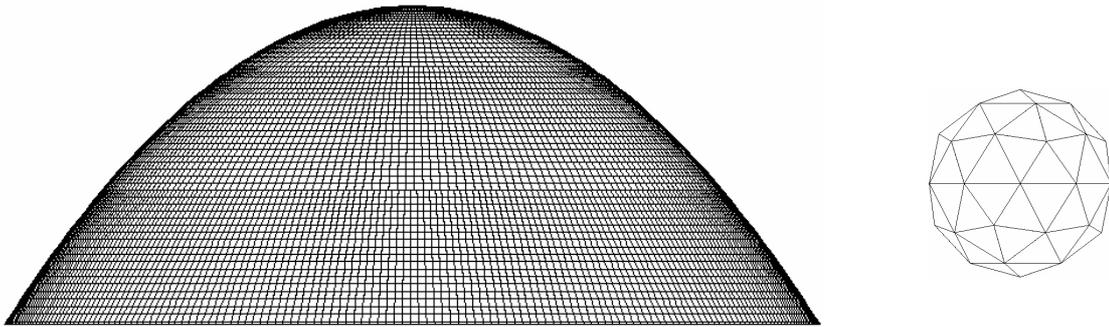


Fig. 4.3 CAD model of reflector, 13230 of elementary surfaces. CAD model of light source, 80 elementary surfaces. Relations between dimensions of reflector and light source are not kept.

- material reflector is *mirror*,
- light sources should be modeled as real shape of the light source solid (filament, arc tube, bulb), there are used *light* material and *polygon* as a scene description,
- there is no needs to use *substitute* surface and *mkillum* process,
- calculations of illuminance  $E_i$  for all point  $i$  are executed using *rtrace* process:

```
rtrace -faa -h -ov -l @par-mirror.txt luminaire.oct <pointsC0-180.txt> RadianceC0-180.txt
```

where *luminaire.oct* is a *octree* file which contains geometry and material properties of luminaire, *par-mirror.txt* is a file with the most important parameters of *rtrace* command,

- when calculations of illuminance  $E_i$  for all points  $i$  are finished, luminous intensity of the luminaire  $I_{C,\gamma}$  in a specified direction  $C,\gamma$  is calculated from the inverse-square law, next luminous flux and light output ratio are calculated,
- parameters set of *rtrace* process are as follows (Tab. 4.1):

Table 4.1 List of parameters of *rtrace* process.

-ab	-aa	-ad	-as	-ar	-av	-ds	-dj	-dt	-dr	-dp	-sj	-st	-lr	-lw
0	0	0	0	0	0 0 0	0.01	0	0	1	0	1	0	12	0

The first verification of correctness of the applied method has been carried out for parabolic reflector of high  $H=17.2cm$ , diameter  $D=43.9cm$ , focal length  $f=7cm$  and for two light sources of diameters  $d_1=1cm$  and  $d_2=4cm$ . Reflector reflectance was 0.9 (*mirror* material) and the luminous flux of light source  $\Phi_0=1000lm$ .

<sup>†</sup> depending on OS (Linux, MS Windows) it can be: *Set overflow in addobject*, *Out of memory in makevsrsc*: *Cannot allocate memory* or *Out of memory in erealloc*.

The luminous intensity distribution  $I_{C,\gamma}$  has been calculated using Radiance (Fig. 4.4 and 4.5) for two light sources of diameters  $d_1 = 1\text{cm}$  and  $d_2 = 4\text{cm}$  and for three distances 5m, 10m and 100m. Calculation time was about few minutes. The luminous flux of luminaire  $\Phi$  using equations 1, 3 and 4 has been calculated for distance of 100m.

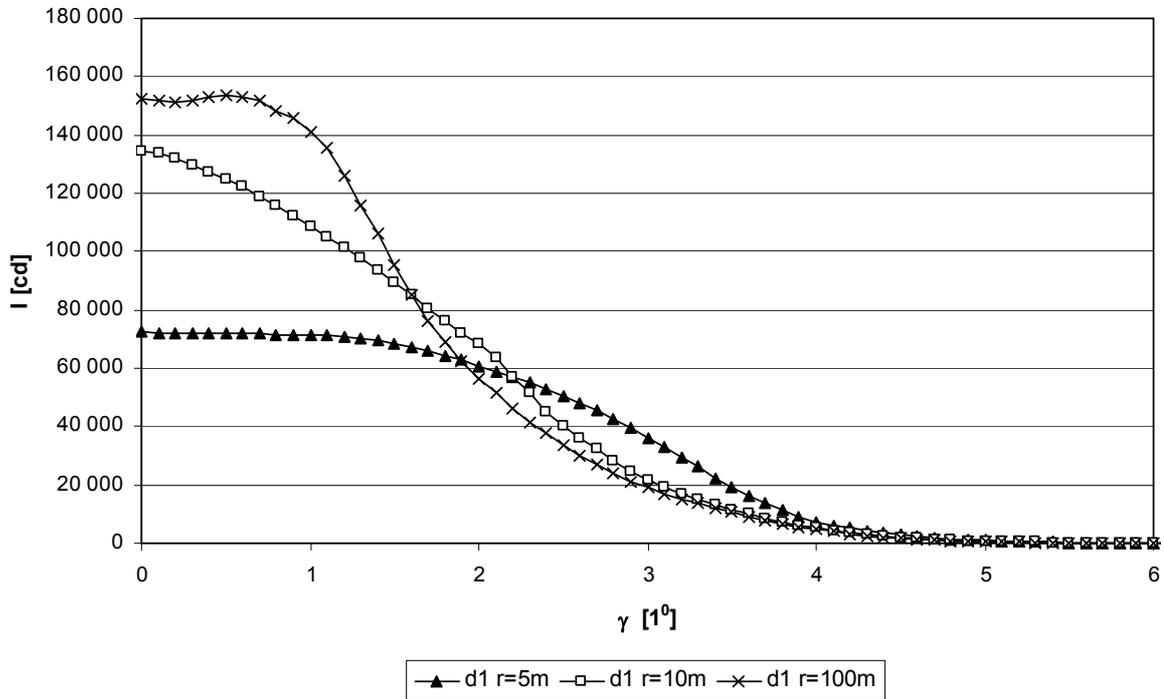


Fig 4.4 Luminous intensity distribution  $I_{C,\gamma}$  of specular reflector with light source of diameter  $d_1 = 1\text{cm}$ . Calculations using Radiance for three distances 5m, 10m and 100m.

Luminous intensity distribution is varied for different distances between light centre of luminaire and test point (Fig. 4.4). It is proper phenomenon because of very narrow distribution of luminous intensity that has luminaire with specular parabolic reflector and light source of relatively small dimensions. Luminous intensity is calculated using inverse-square law. It is defined special distance  $r_s$  where results of inverse-square law are accurate within one percent. For luminaires with uniform distribution this distance is five times the maximum dimension of luminaire. However for luminaires with narrow luminous distribution this distance is much more greater and can be calculated by equation (16).

$$r_s = \frac{2 \cdot D}{d} (f + H) \quad (16)$$

where  $f$ ,  $H$ ,  $D$  and  $d$  are dimensions of parabolic reflector and light source (see Fig. 4.1).

For light source diameter  $d_1 = 1\text{cm}$  this special distance is  $r_s = 21\text{m}$  but for diameter  $d_2 = 4\text{cm}$  only  $r_s = 5\text{m}$ . Luminous intensities that are calculated for distances below special distance  $r_s$  have accuracy lower than one percent. It may say that only calculation that are prepared for distances greater than  $r_s$  are true. In case of light source  $d_1$  true values are obtained for distance 100m.

For light source diameter  $d_2 = 4\text{cm}$  luminous intensity is varied not to much for different distances between light centre of luminaire and test point (Fig. 4.5). Special distance in this case is  $r_s = 5\text{m}$  and this is the reason that results obtained for distances 10m and 100m are almost the same.

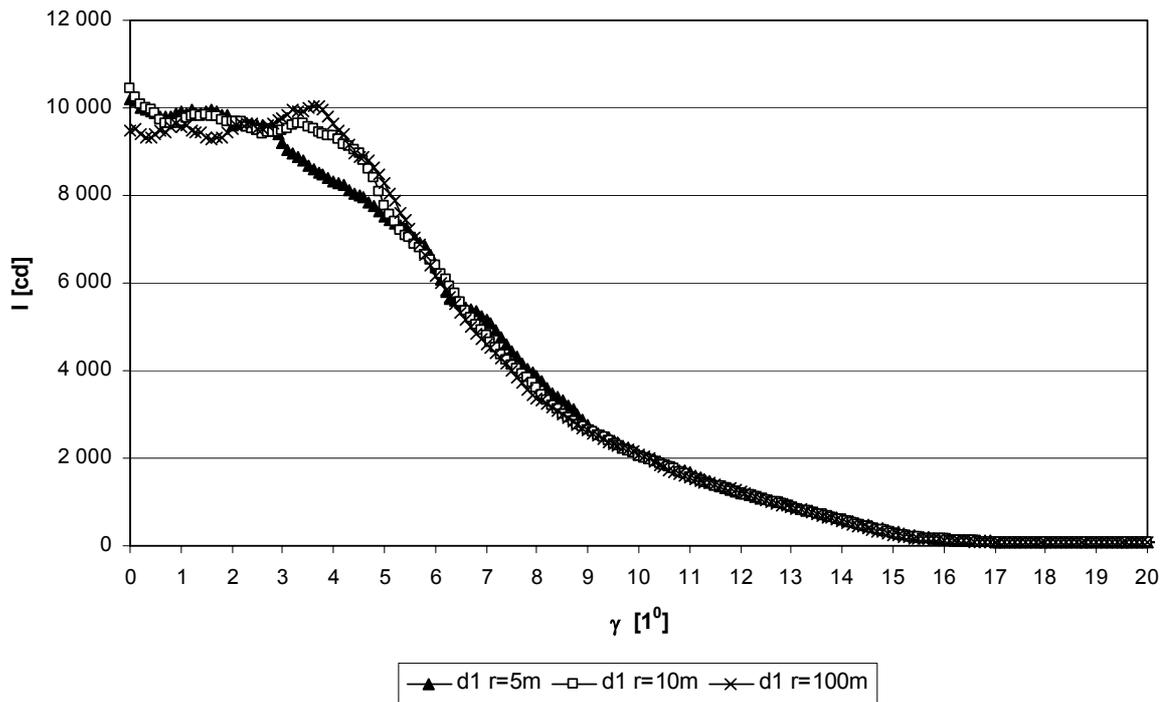


Fig 4.5 Luminous intensity distribution  $I_{C,\gamma}$  of specular reflector with light source of diameter  $d_2 = 4\text{ cm}$ . Calculations using Radiance for three distances 5m, 10m and 100m.

Real luminous intensity distributions of mirror reflectors should be more smooth than calculated using Radiance. The reason of such results is that CAD model of reflector is not ideal. Real reflector has curved surface but CAD model is built of flat surfaces. The only what is possible to do is using flat elementary surfaces that have the same areas and are so small as possible.

The obtained results have been compared with the calculations done using the analytical method (Tab. 4.2).

Table 4.2 Luminous flux of luminaire  $\Phi$ , maximum value of luminous intensity  $I_{max}$ , maximum  $\delta_{max}$  and minimum  $\delta_{min}$  values of width of an angle beams calculated using the analytical method and using Radiance for light sources of diameters  $d_1 = 1\text{ cm}$  and  $d_2 = 4\text{ cm}$ .

	$d_1 = 1\text{ cm}$			$d_2 = 4\text{ cm}$		
	Analytical method	Radiance	Error $\delta$	Analytical method	Radiance	Error $\delta$
$\Phi$	<b>929</b> [lm]	<b>950</b> [lm]	<b>-2.3 %</b>	<b>929</b> [lm]	<b>917</b> [lm]	<b>-1.3 %</b>
$I_{max}$	<b>145 121</b> [cd]	<b>~152 000</b> [cd]	<b>-4.7 %</b>	<b>9 072</b> [cd]	<b>~9 600</b> [cd]	<b>-5.8 %</b>
$\delta_{min}$	<b>2.4</b> [ $1^0$ ]	<b>~1.8</b> [ $1^0$ ]	-	<b>9.4</b> [ $1^0$ ]	<b>~8.2</b> [ $1^0$ ]	-
$\delta_{max}$	<b>8.1</b> [ $1^0$ ]	<b>~9.8</b> [ $1^0$ ]	-	<b>29.7</b> [ $1^0$ ]	<b>~32.2</b> [ $1^0$ ]	-

When analyzing the results it may be concluded that it is possible to obtain right issues using proposed method. Therefore, one may presume that a similar degree of preciseness will be possible in case of systems involving specular reflectors of different shapes.

## 5. Calculations of luminaires with semi-specular reflectors

Calculations using Radiance is possible only for materials that reflection properties are composition of ideal diffuse reflection and ideal specular (mirror) reflection (Fig. 5.1).

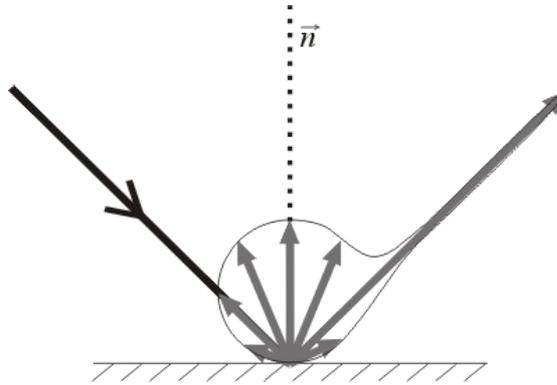


Fig. 5.1 Composition of ideal diffuse and specular reflection.

The most important features of calculation of parabolic semi-specular reflectors using Radiance are:

- because material properties are composition of diffuse and mirror reflection, that problems of calculations are the same that calculations of diffuse and calculations of specular reflectors,
- when CAD model of reflector contains a lot of elementary surface, *-r* parameter of *oconv* process should have greater value than default; value of *-r 262144* is enough in most cases,
- it is need to build CAD model of reflector and CAD model of light source with the least of surface number as far as possible, when there are large number of surfaces that system error may occur<sup>‡</sup>,
- material of reflector is *mirror* that is modified by *plastic* material:

```
void plastic diffuse
0
0
5 0.66 0.66 0.66 0 0
```

```
void mirror semi-diffuse
1 diffuse
0
3 0.2 0.2 0.2
```

- light sources should be modeled as real shape of the light source solid (filament, arc tube, bulb), there are used *light* material and *polygon* as a scene description,
- it is possible to use substitute surface which has the shape of a circle or rectangle (*ring* or *polygon* geometry) enclosing the luminaire in the reflector opening (see Fig. 3.1),
- preliminary calculations for substitute surface have to be prepared using *mkillum* process (see point 3); as a result of this process the luminance distribution  $L_{C,\gamma}$  (or radiance  $R_{C,\gamma}$ ) towards directions  $C,\gamma$  is calculated for the substitute surface which becomes secondary light source;

```
mkillum @ par-spec-dif.txt luminaire.oct <subst-surface.rad> subst-surface-illum.rad
```

where *subst-surface.rad* is input file where substitute surface is described.

- after preliminary calculations the main calculations are executed; illuminances  $E_i$  at points  $i$  are calculated using *rtrace* process:

<sup>‡</sup> depending on OS (Linux, MS Windows) it can be: *Set overflow in addobject*, *Out of memory in makevsrc*: *Cannot allocate memory* or *Out of memory in erealloc*.

`rtrace -faa -h -ov -l @par-spec-dif.txt luminaire-subst.oct <pointsC0-180.txt> RadianceC0-180.txt`

where *luminaire-subst.oct* is new *octree* file which contains geometry, material properties of luminaire and substitute surface which is described in *subst-surface-illum.rad* file, *par-spec-dif.txt* is a file with the most important parameters of *rtrace* command (Tab. 5.1); because calculation time is generally long the list of parameters should be as low as possible,

Table 5.1 List of parameters of *rtrace* process.

-ab	-aa	-ad	-as	-ar	-av	-ds	-dj	-dt	-dr	-dp	-sj	-st	-lr	-lw
5	0.2	512	1024	32	0 0 0	0.01	0	0	2	2048	1	0	12	0

- after calculations of illuminances  $E_i$  for all points  $i$  are finished, luminous intensity of the luminaire  $I_{C,\gamma}$  in a specified direction  $C,\gamma$  is calculated from the inverse-square law, next luminous flux and light output ratio are calculated.

The first verification of correctness of the applied method has been carried out for real reflector (Fig. 5.2 and 5.3) of road-lighting luminaire that has been measured in lighting laboratory.



Fig. 5.2 Compact reflector of road-lighting luminaire.

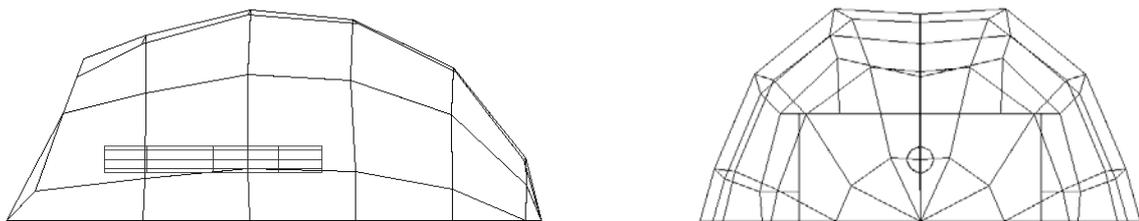


Fig. 5.3 CAD model of reflector of road-lighting luminaire.

This reflector has compact dimensions because it is suitable for compact high intensity discharge lamps especially for compact high pressure sodium lamps (see Fig. 2.2). Reflector is made of one piece of Alanod aluminium *Dessin Stucco G* material. There is used NAV-TS 150W light source that the luminous flux is  $\Phi_0 = 15000lm$ .

The luminous intensity distribution  $I_{C,\gamma}$  has been calculated using Radiance (Fig. 5.4). Calculation time was very long, approximate 150 hours. The luminous intensity distribution  $I_{C,\gamma}$  has been also measured in lighting laboratory (Fig. 5.4). Then the luminous flux of luminaire  $\Phi$  using equations 1, 3 and 4 has been calculated and measured by the integrating (Ulbricht) sphere photometer (Tab. 5.2).

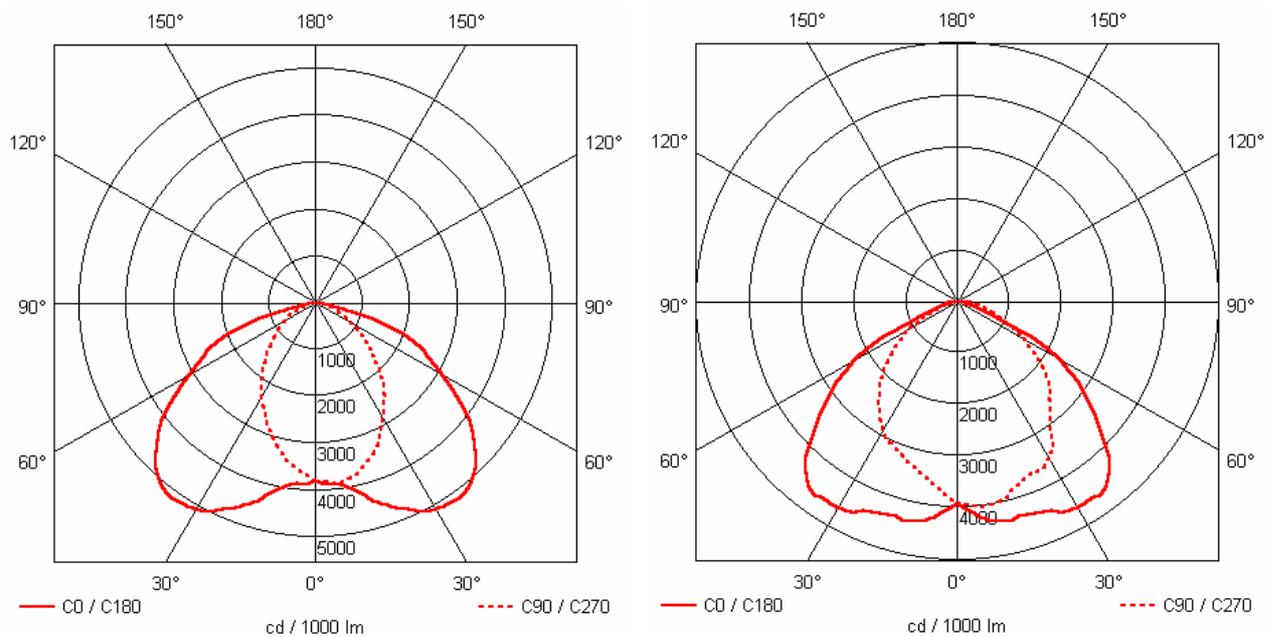


Fig. 5.4 Luminous intensity distribution  $I_{C,\gamma}$  of semi-specular reflector measured in lighting laboratory (left) and calculated using Radiance (right).

Table 5.2 Luminous flux  $\Phi$  and light output ratio  $\eta$  of semi-specular reflector measured in lighting laboratory and calculated using Radiance.

	Measured	Calculated using Radiance	Error $\delta$
$\Phi$	<b>12 435 [lm]</b>	<b>12 137 [lm]</b>	<b>2.4 %</b>
$\eta$	<b>0.83</b>	<b>0.81</b>	

Differences between measurements and calculations may be consequence of not to precise building of CAD model of reflector (Fig. 5.3). It seems that elementary surfaces of reflector should be smaller.

## 6. Summary

The proposed method which uses the backward ray tracing technique and Radiance system makes it possible to calculate luminaires. The main advantages of calculation of luminaires using Radiance are to:

- ensure accurate calculation of luminaires,
- support diffuse, specular and semi-specular properties of materials,
- support complicated geometry,

Presented method of calculation of luminaires have been also developed to introduce Radiance to lighting engineering students. Experiences of last two years indicate that the students reach very interested results. They have classes of design of luminaires. Every student have to prepare project of luminaire. The basic requirement is that they have to prepare calculations using analytical method and using Radiance. There is introduced course in this classes (15 hours) of *Calculation of luminaires using Radiance*. Students have at their disposal many teaching materials. The most important is tutorial *Calculation of luminaires using Radiance and Desktop Radiance* (prepared in polish) [5].

## **References**

- [1] DESKTOP RADIANCE software: <http://radsite.lbl.gov/deskrad/>
- [2] Ward G.L., Shakespeare R. & al.: Rendering with RADIANCE: the Art and Science of Lighting Visualization. Morgan Kaufmann Publishers, San Fransisco, USA, 1998.
- [3] The RADIANCE 3.5 Synthetic Imaging System (reference manual). Building Technologies Department, Lawrence Berkeley Laboratory, 1 Cyclotron Rd., MS 90-3111, Berkeley, CA 94720
- [4] Wandachowicz K.: Calculation of Diffuse Luminaires Using Radiance System and Backward Ray Tracing Method. Lux junior 2003, 6. Forum fur den lichttechnischen Nachwuchs, Arnstadt, 19-21.09.2003.
- [5] Wandachowicz K.: Tutorial: calculation of luminaires using Desktop Radiance and Radiance (in polish): <http://lumen.iee.put.poznan.pl/kw/oprawy/p-opr.html>