

Roadpollution: a software to evaluate and understand light pollution from road lighting installations

Pierantonio Cinzano

Dipartimento di Astronomia, Universita` di Padova, vicolo dell'Osservatorio 5, I-35122 Padova, Italy

Istituto di Scienza e Tecnologia dell'Inquinamento Luminoso (ISTIL), via Roma 13, Thiene, Italy, email:cinzano@lightpollution.it

Key words: atmospheric effects - site testing - light pollution

Abstract: We present Roadpollution, a software to compute main parameters of road lighting design and many useful parameters related to the produced light pollution and the energy waste. The program is not intended to replace road lighting design software but rather to help the evaluation of the light polluting power of an installation designed with them.

Presented to CIE TC4-21, CIE Div. 4 Meeting, Turin, 28 September - 3 October 2003

1. CONTENTS

1.	Contents.....	1
2.	Introduction	3
3.	Installation	4
4.	Input data and files	4
4.1	Input parameters	4
4.2	Input light distribution (Eulumdat files).....	5
5.	Output files	6
6.	Output results.....	7
6.1	Resume of input data	7
6.1.1	Input parameters	7
6.1.2	Input road surface	7

6.1.3	Input luminaire	7
6.2	Luminaire emission data.....	8
6.2.1	Flux factors FF.....	9
6.2.1.1	Downward flux factor DFF %	9
6.2.1.2	Upward flux factor UFF % (UFR, ULR, ULOR_inst) ..	9
6.2.2	Light output ratios LOR	9
6.2.2.1	Light output ratio of the luminaire LORL %	9
6.2.2.2	Downward light output ratio DLOR %.....	9
6.2.2.3	Upward light output ratio ULOR %.....	10
6.3	Grid data	10
6.4	Road lighting parameters.....	11
6.4.1	Maintained luminance, illuminance and uniformity.....	11
6.4.2	Glare	12
6.5	Energy and cost parameters.....	13
6.5.1	Light utilization parameters.....	13
6.5.1.1	Utilization factor.....	13
6.5.1.2	Used fraction of the luminaire flux (utilance)%	13
6.5.1.3	Wasted fraction of the luminaire flux %.....	14
6.5.1.4	Used fraction of the downward flux %.....	14
6.5.1.5	Wasted fraction of the downward flux %	14
6.5.2	Luminaires and lamp flux densities.....	14
6.5.2.1	Luminaires per km.....	14
6.5.2.2	Installed lamp flux per unit length.....	14
6.5.2.3	Installed lamp flux per unit area	15
6.6	Light Pollution: integrated parameters	15
6.6.1	Upward flux factors.....	15
6.6.1.1	Direct upward flux factor UFF % (UFR, ULR, ULOR_inst) 15	
6.6.1.2	Road reflected upward flux ratio RUFR %.....	15
6.6.1.3	Increase of upward flux due to direct emission %.....	16
6.6.1.4	Out-of-road reflected upward flux ratio WUFR%.....	16
6.6.1.5	Increase of upflux due to out-of-road emission %.....	16
6.6.2	Total upward fluxes.....	16
6.6.3	Upward light densities	17
6.6.3.1	Direct unit upward light density DUUD.....	17
6.6.3.2	Road unit upward light density RUUD.....	17
6.6.3.3	Increase of uplight density due to direct emission %... 17	
6.6.3.4	Out-of-road unit upward light density WUUD.....	17
6.6.3.5	Increase of uplight density due to out-of-road emission %	18
6.6.4	Total upward light densities	18
6.7	Light Pollution: direction dependent parameters.....	19

- 6.7.1 Upward intensities 19
 - 6.7.1.1 Average maintained luminance at angle ω 19
 - 6.7.1.2 Upward intensity per unit flux (cd/klm) at low angles 20
 - 6.7.1.3 Average upward intensity per unit flux at low angles . 20
 - 6.7.1.4 Maximum intensities per unit flux..... 21
- 6.7.2 Upward flux factors (rewritten for comparison)..... 21
- 6.7.3 Scattered flux factors 21
 - 6.7.3.1 Road scattered flux factor %..... 22
 - 6.7.3.2 Direct scattered flux factor % 22
 - 6.7.3.3 Increase of scattered light due to direct emission %.... 22
 - 6.7.3.4 Out-of-road scattered flux factor % 22
 - 6.7.3.5 Increase of scattered light due to out-of-road emission %
22
- 6.7.4 Low-angles flux factors 23
 - 6.7.4.1 Low-angles road flux factor % 23
 - 6.7.4.2 Low-angles direct flux factor % 23
 - 6.7.4.3 Increase of low-angles flux due to direct emission % . 23
 - 6.7.4.4 Low-angles out-of-road flux factor % 23
 - 6.7.4.5 Increase of low-angles flux due to out-of-road emission
% 23
- 6.7.5 Low-angles scattered flux factors 24
 - 6.7.5.1 Low-angles road scattered flux factor % 24
 - 6.7.5.2 Low-angles direct scattered flux factor % 24
 - 6.7.5.3 Increase of low-angles scattered flux due to direct
emission % 24
- 6.7.6 Data related to the 3-dimensional plots 25
- 7. Data tables 25
- 8. 3D polar plots of the upward intensity distributions 25
- 9. References 28

2. INTRODUCTION

Roadpollution is a software to compute main parameters of road lighting design together with many useful parameters related to the produced light pollution and the energy wasted. The program is not intended to replace road lighting design software but rather to assist them helping to evaluate the light polluting power of an installation designed with them.

The main elements of the computations are: (a) the road, characterized by the kind of surface and the pavement width; (b) the luminaires, characterized by the lighting system geometry (mounting height, overhang, pole spacing),

their light distribution patterns, the luminous flux emitted by their lamps and the related lumen depreciation factor.

This version of the program works only for straight roads with the same kind of luminaires, installed on the same side of the road. It assumes the road having one carriageway and two lanes. Some parameters are approximate and their computation will be refined in further versions. At the moment the software is in beta 1 test version.

3. INSTALLATION

Roadpollution is compiled for Windows 95, 98, NT, 2000 and XP on PC computers. To install the software, unzip the directory Roadpoll on the hard disk. The program can be run from a command prompt opened in the same directory, typing *roadpoll.exe*, provided that the input files are in the same directory.

4. INPUT DATA AND FILES

4.1 Input parameters

The input parameters must be written with a text editor in a text file called *input_roadpoll.dat*. Input parameters are:

- lamp flux in klm (kilolumen)
- road width in m
- luminaire interdistance in m
- luminaire overhang in m
- luminaire height in m
- lumen depreciation factor
- kind of standard road surface
- name of the file with the photometry of the chosen luminaire

The luminaire overhang, i.e. the distance from the road side, is positive toward the center of the road. The input standard road surface can be any of the C1, C2, R1, R2, R3 standard CIE road surfaces.

As an example, given the input parameters:

- lamp flux (klm) 8.
- road width (m) 7.

luminaire spacing (m) 26.
 luminaire overhang (m) 3.
 luminaire height (m) 7.5
 lumen depreciation 0.8
 surface standard C2
 photometry input file 12877_1.ldt

the input string in the first (single) line of the file *input_roadpoll.dat* must be: 8., 7., 26., 3., 7.5, 0.8, C2, 12877_1.ldt

4.2 Input light distribution (Eulumdat files)

The input luminaire data must be contained in a file in standard European EULUMDAT format, located in the same directory. It would be easy to extend the input to other standard luminaire data file formats, but this is unnecessary because a number of free software allow a quick conversion between them.

Here below a simplified description of Eulumdat data files is presented. More details are given by Ashdown (1999). Frequently Eulumdat files have extension .ldt

- 1 Identification
- 2 Type indicator Ityp (1 - point source with symmetry about the vertical axis; 2 - linear luminaire; 3 - point source with any other symmetry)
- 3 Symmetry indicator Isym (0 - no symmetry; 1 - symmetry about the vertical axis; 2- symmetry to plane C0-C180; 3- symmetry to plane C90-C270; 4- symmetry to plane C0-C180 and to plane C90-C270)
- 4 Number Mc of C-planes between 0 and 360 degrees
- 5 Distance Dc between C-planes
- 6 Number Ng of luminous intensities in each C-plane
- 7 Distance Dg between luminous intensities per C-plane
- 8 Measurement report number
- 9 Luminaire name
- 10 Luminaire number
- 11 File name
- 12 Date/user
- 13 Length/diameter of luminaire (mm)
- 14 Width of luminaire b (mm) (b = 0 for circular luminaire)
- 15 Height of luminaire (mm)
- 16 Length/diameter of luminous area (mm)
- 17 Width of luminous area b1 (mm) (b1 = 0 for circular luminous area of luminaire)

18	Height of luminous area C0-plane (mm)
19	Height of luminous area C90-plane (mm)
20	Height of luminous area C180-plane (mm)
21	Height of luminous area C270-plane (mm)
22	Downward flux fraction DFF (%)
23	Light output ratio luminaire LORL (%)
24	Conversion factor for luminous intensities
25	Tilt of luminaire during measurement
26	Number n of standard sets of lamps
26a	Number of lamps
26b	Type of lamps
26c	Total luminous flux of lamps (lumens)
26d	Color appearance / color temperature of lamps
26e	Color rendering group / color rendering index
26f	Wattage including ballast (watts)
27	Direct ratios DR for room indices $k = 0.6 \dots 5$ (for determination of luminaire numbers according to utilization factor method)
28	Angles C (beginning with 0 degrees)
29	Angles G (beginning with 0 degrees)
30	Luminous intensity distribution (candela / 1000 lumens)

5. OUTPUT FILES

The results of the computation are listed in the file *output_roadpoll_x.dat* and the output data tables are contained in the file *outdat_roadpoll_x.dat*, where *x* is a code giving the run time which defines unambiguously each set of files. The code is *yyyymmddhhmm* where *yyyy* is the year, *mm* the month, *dd* the day, *hh* the hour and *mm* the minutes (e.g. 200209161225). The code is also reported inside the files with added *ss.h* where *ss* are the seconds and *h* the hundredth of second with their decimal.

The upward emission of the lighting installation can be plotted in 3D in polar coordinates applying the procedure *upward.nb* of MATHEMATICA to the files *aaaaa_x.dat*, where *aaaaa* is a code identifying the source: *uplum* for the luminaire, *uproa* for the road, *uptot* for their sum.

6. OUTPUT RESULTS

The results are presented on the screen and in the file *output_roadpoll_x.dat*. Computations are in double precision and variables are written entirely even if the precision of the results is much smaller and still under evaluation. We suggest to consider not more than the first digit after the point.

Here we shortly describe the output lines in *output_roadpoll_x.dat* in the same sequence.

6.1 Resume of input data

At first a resume of the input data is presented.

6.1.1 Input parameters

A resume of the chosen input parameters.

As an example:

```
lamp flux (klm)      8.000000000000000
road width (m)      7.000000000000000
luminaire spacing (m) 26.000000000000000
luminaire overhang (m) 3.000000000000000
luminaire height (m) 7.500000000000000
lumen depreciation 0.8
```

6.1.2 Input road surface

A resume of the chosen kind of standard road surface and the name of the input data file.

As an example:

```
CIE
Standard
C2
Data file
SRT_C2
```

6.1.3 Input luminaire

This sections gives:

1. The chosen luminaire name, the name of the input file with the intensity distribution of the luminaire, the type and symmetry of the

data table (see the eulmdat file format description for details), the number of samples of C and gamma angles and the delta between samples.

2. The conversion factor for luminous intensities when the quantities are given in different unities, and the tilt angle of the luminaire in its measured position.
3. The number of lamp sets (there can be more lamp sets in the same eulmdat file), the kind of lamp and the total luminous flux of the lamp for each lamp set. Note that the flux specified in the input file can be different from the flux of the lamp in order to allow evaluations in case of use of flux reducer.
4. The maximum vertical (gamma) angle above the nadir for which the intensity distribution has been measured. If gamma is lower than 180 degrees some computations cannot be made.

As an example:

```
Siteco
Luminaire input data file 12877_1.1dt
ityp          3
isym          4
C samples      36
C delta       10.000000000000000
Gamma samples  37
Gamma delta    5.000000000000000

Conversion factor for luminous intensities CFLI  1.00
Tilt angle    0.000000000000000E+000

Number of lamp sets          1
type of lamp
HQL
total flux (lm)  13000.000000000000

Maximum measured gamma  180.0000000000000
```

6.2 Luminaire emission data

The parameters on the upward and downward luminous flux emitted by the luminaire and its efficiency are obtained from the DFF and LORL given in the eulmdat file. When the intensity distribution of the luminaire is given up to gamma = 180 degrees, they are also obtained by direct computation to allow a check. Here below a short description of the parameters.

6.2.1 Flux factors FF

6.2.1.1 Downward flux factor DFF %

The downward flux factor DFF % gives the fraction, in percent, of the total flux emitted by the luminaire which is directed downward.

6.2.1.2 Upward flux factor UFF % (UFR, ULR, ULOR_inst)

The upward flux factor UFF % gives the fraction in percent of the total flux emitted by the luminaire which is directly directed upward. It is also called Upward Flux Ratio UFR (e.g. CIE 126) or Upward Emission Ratio R_n (e.g. UNI10819). Sometime it is also inappropriately called ULR or ULOR_inst (see below the ULOR definition). This value is obtained as $UFF=100.-DFF$ or computed by the program by integrating the intensity over the upward hemisphere. The UFF help to identify the luminaires producing an high fraction of polluting flux but frequently its significance is misunderstood: see the section “light pollution: direction dependent parameters” for an explanation and more meaningful parameters.

6.2.2 Light output ratios LOR

6.2.2.1 Light output ratio of the luminaire LORL %

The Light output ratio of the luminaire LORL is the ratio between the flux emitted by the luminaire in any direction (upward and downward) and the luminous flux emitted by the lamp installed in the luminaire. It is expressed in percent. It is also called “efficiency of the luminaire”. It is a misleading parameter because many people think that energy saving requires luminaires with high efficiency whereas, if ever, it requires high downward efficiency (DLOR) luminaires. A luminaire with an high LORL can have a small DLOR and to be a worse one (e.g. a globe can have LORL=80% and DLOR<40%).

6.2.2.2 Downward light output ratio DLOR %

Sometime called “downward efficiency of the luminaire”, DLOR is the fraction of the luminous flux emitted by the lamp going outside the luminaire downward. It is expressed in percent. It shows how much of the lamp flux goes, at least, in the “correct” direction. However DLOR is a misleading parameter too. It does not indicate how much of the downward luminous flux effectively reach the surface which must be lighted and how much goes – on the contrary – outside of it. See the “Utilization factor”, the

“Used fraction of the luminaire flux” and the “Average luminance coefficient” for more significant parameters.

6.2.2.3 Upward light output ratio ULOR %

The Upward light output ratio, sometime called “upward efficiency of the luminaire”, is the fraction of the luminous flux emitted by the lamp going outside the luminaire in upward direction. It is expressed in percent. Sometime it is confused with the UFF, which is obtained dividing ULOR by the LORL. In spite of the appearance, ULOR is an incorrect parameter to recognize more or less polluting luminaires. As a simplified example, consider two luminaires. Let’s assume that the first luminaire has an ULOR two thirds than the second luminaire but also an efficiency (LORL) of two thirds. The first luminaire, having a smaller ULOR, could wrongly appear less polluting. But, if there are no other differences between the luminaires, in order to obtain with the first luminaire the same luminance on the road surface produced by the second one must be used a lamp emitting 1/3 more luminous flux. Then, under the same road luminance the upward flux emitted by the two luminaires is the same in spite of the smaller ULOR of the first one. The UFF does not incurs in this error.

As an example:

```
Downward flux factor DFF % 98.00000000000000
Upward flux factor UFF % (UFR, Rn) 2.00000000000000
Light output ratio of the luminaire LORL % 73.00000000000000
Downward light output ratio DLOR (Down. eff.) % 71.54000000000000
Upward light output ratio ULOR (Upward. eff.) % 1.46000000000000

Downward flux factor DFF (calculated) % 97.7977818205193
Upward flux factor UFF (calculated) % (UFR, Rn) 2.20221817948069
Light output ratio LORL (calculated) % 71.1040367261572
Downward light output ratio DLOR (calculated) % 69.5381707030291
Upward light output ratio ULOR (calculated) % 1.56586602312806
```

6.3 Grid data

The data on the adopted grid, based on the input parameters, and on the positions of the observers for road luminance computation. The grid and the observers positions are set up as required by the Italian standard rule UNI10439.

As an example:

```
luminaire spacing (m) 26.00000000000000
luminaire spacing ratio 3.46666666666667
road width (m) 7.00000000000000
(number of) grid points along X 10
(number of) grid points along Y 10
grid dX (m) 2.60000000000000
```

```

grid dY (m) 0.7000000000000000
(position of the) first/last grid point x=0.0, x= 23.40000000000000
(position of the) first/last grid point y=0.5, y= 6.800000000000000
(position of the) luminaire at x=0, y= 3.000000000000000
(position of the) observer 1 at z=1.5, x=-60.0, y= 1.750000000000000
(position of the) observer 2 at z=1.5, x=-60.0, y= 5.250000000000000

```

6.4 Road lighting parameters

The program computes the main parameters of road lighting design. National standard rules and CIE recommendations suggest the minimum allowed values in dependence of the road kind and the traffic levels.

6.4.1 Maintained luminance, illuminance and uniformity

The program computes the maintained luminance for an observer at infinity and two observers in standard position, i.e. -60 m from the first row, in the center of the right lane (as required by standard rule UNI 10439 and CIE 30) with luminaires at right (observer 1) or at left (observer 2). The program gives the average on the pavement, the root mean square of the differences, the minimum, the maximum, the ratio minimum/average also called overall uniformity and the lengthwise uniformity evaluated along the middle of the right lane. The second number, sometime appearing, give the same quantities as obtained including in the computation the points in correspondence of the subsequent luminaire, like some lighting software erroneously do, in order to allow a comparison with their results. The program also computes the maintained illuminance on the road plane: average, rms, minimum, maximum, min/ave and min/max.

The program computes the average luminance coefficient, i.e. the average luminance per unit illuminance in cd/lm. This coefficient and its inverse, the average illuminance per unit luminance, are useful to evaluate how much the luminaire is capable to produce luminance for a given illuminance. Higher coefficients for the same road, indicates more capable luminaires. However note that it is also necessary that the luminaire be able to produce the higher average illuminance, i.e. to send the greater light flux on the road. In principle, the best luminaire from the efficiency point of view is the luminaire which produces the higher average luminance per unit lamp flux (or even the larger road intensity per unit lamp flux), but in practice the best luminaire from the lighting point of view also depends on the produced uniformity, the glare and other characteristics which cannot be neglected. It has been demonstrated that in many cases a smaller glare threshold index TI allows a better visibility than a larger average luminance.

As an example:

```
observer at infinity
average maintained luminance L_ave: 1.13670402142726
```

```
observer 1
maintained luminance L:
average: 1.04843380069701 1.02367308156671
rms: +- 0.364771255959555
minimum: 0.441843926388382
maximum: 1.92447960706879
overall uniformity U_0 (min/ave): 0.421432355666748
0.431626008678620
lengthwise uniformity U_L: 0.588130928310839
```

```
observer 2
maintained luminance L:
average: 1.05722741298218 1.03221789182912
rms: +- 0.352742621150203
minimum: 0.504492491888136
maximum: 1.92073664895872
overall uniformity U_0 (min/ave): 0.477184459741814
0.488746122191470
lengthwise uniformity U_L: 0.632822439885744
```

```
maintained illuminance E:
average: 13.0379203679477 13.2540310857807
rms: +- 3.03541432643227
minimum : 7.81943528293147
maximum : 18.4646031213945
min/ave: 0.599745593028372 0.589966571854534
min/max: 0.423482445386074
```

```
average luminance coefficient (luminance per unit
illuminance) (cd/lm)
at infinity: 8.718445805373419E-002
observed: 8.041418961834350E-002
```

```
average illuminance per unit luminance K (lx/cd/m^2)
at infinity: 11.4699342328156
observed : 12.4356162108470
```

6.4.2 Glare

The program computes on the grid points the maintained veiling luminance (average, minimum, maximum) of an observer assumed to be 1.5 m over the road surface and looking along the road and 1° below the road plane. It also computes the maximum threshold increment of an observer on the middle of the right lane with luminaires at right (R) and at left (L) (see UNI10439 for the formulas). It also computes on the grid points the

maintained semicilindrical illuminance (average, minimum, maximum) and the disability glare rating index GR (average, minimum, maximum) (AIDI 2001).

As an example:

veiling luminance on the road (cd/m²):

average: 7.000047444690562E-002

minimum: 3.955834974470235E-002

maximum: 0.156932585407483

threshold increment TI% maximum R: 9.04526647990673

threshold increment TI% maximum L: 9.37561404199528

maintained semicilindrical illuminance Esc (lx):

average: 4.93609274279277

minimum: 0.434183652213103

maximum: 12.3267784674263

glare rating index GR:

average: 33.0142061003318

minimum: 27.8323970173582

maximum: 42.1957961487016

6.5 Energy and cost parameters

A number of parameters analyze how much of the luminous flux is properly used. They give a better insight than the DFF and DLOR previously cited. From these parameters is possible to evaluate the quantity of wasted energy and related costs.

6.5.1 Light utilization parameters

6.5.1.1 Utilization factor

The utilization factor gives the ratio between the luminous flux arriving on the road and the luminous flux emitted by the lamp. It is interesting to multiply the utilization factor for 100 to obtain a percent and compare it with light ratios like LORL and DLOR in order to realize how small is the fraction of the lamp flux effectively used in a lighting installation.

6.5.1.2 Used fraction of the luminaire flux (utilance)%

The used fraction of the luminaire flux, sometime called “utilance”, gives the ratio between the flux arriving on the road and the flux emitted by the luminaire (not by the lamp). It is expressed in percent. It is interesting to compare it with the downward light factor DFF. The used fraction of the

luminaire flux is a parameter which must be maximized as much as possible when planning an installation.

6.5.1.3 Wasted fraction of the luminaire flux %

The wasted fraction of the luminaire flux shows how much of the flux emitted by the luminaire is going wasted outside the surface to be lighted, both upward and downward. It is expressed in percent. The wasted energy can be obtained multiplying this fraction by the LORL, the lamp efficacy and the lamp power. This is a parameter to be minimized as much as possible when planning an installation

6.5.1.4 Used fraction of the downward flux %

Only a fraction of the downward flux is really going on the road. The used fraction of the downward flux shows how much of the downward flux is really going to be used. It depends on the quality of both the luminaire and the installation planning. It is expressed in percent.

6.5.1.5 Wasted fraction of the downward flux %

The wasted fraction of the downward flux shows how much of the downward flux is going wasted outside the road, likely producing environmental effects. It is expressed in percent. This is a parameter to be minimized as much as possible when planning an installation.

6.5.2 Luminaires and lamp flux densities

6.5.2.1 Luminaires per km

The number of luminaires installed per kilometer is a parameter related to the cost to buy the luminaires of the installation. However, take note that the cost of the luminaires is only a small fraction of the cost of an installation.

6.5.2.2 Installed lamp flux per unit length

The installed lamp flux per linear kilometer gives the light flux required by the installation to light one km of road in lm/m This parameter is a sort of “efficiency” of the installation and is related to the energy consumption through the lamp efficacy. However it does not allow to compare the energy consumption of installations in road of different width. In this case the installed lamp flux per unit area is the proper parameter.

6.5.2.3 Installed lamp flux per unit area

The installed lamp flux per square kilometer gives the luminous flux required by the installation to light an unit area of the pavement in lm/m^2 . It allow to compare the proper use of the light flux of different installations.

As an example:

```
utilization factor (flux on the road/lamp flux):
0.370765860463512
used fraction of the luminaire flux %: 52.1441366108990
wasted fraction of the luminaire flux %: 47.8558633891010
used fraction of the downward flux %: 53.3183223997811
wasted fraction of the downward flux %: 46.6816776002189

luminaires per km: 38.4615384615385
installed lamp flux per unit length (lm/m):
307.692307692308
installed lamp flux per unit area (lm/m^2):
43.9560439560440
```

6.6 Light Pollution: integrated parameters

The program gives a number of parameters related to the upward light flux integrated on the upward hemisphere.

6.6.1 Upward flux factors

6.6.1.1 Direct upward flux factor UFF % (UFR, ULR, ULOR_inst)

As previously described, the upward flux factor gives the fraction directed upward of the total flux emitted by the luminaire (in percent). It is also called Upward Flux Ratio UFR or Upward Emission Ratio R_n and sometime it is inappropriately called ULR or ULOR_inst (but it must be not confused with ULOR, that is evaluated in respect to the lamp flux and not to the luminaire flux). UFF help to identify luminaires with an high fraction of polluting flux but frequently its meaning is misunderstood. This parameter was already presented in the section "Luminaire emission".

6.6.1.2 Road reflected upward flux ratio RUF_R %

The road reflected upward flux factor gives the fraction in percent of the total flux emitted by the luminaire, which is reflected upward by the road. The program computes two values. The first is a rough estimate obtained assuming an average reflection factor of 10%. The second, much more accurate in case of C2 surfaces, is obtained based on the angular reflectance measured by Gillet (2002) for asphalt.

6.6.1.3 Increase of upward flux due to direct emission %

This parameter gives the per cent increase of the upward flux produced by upward emission of the luminaires over the upward flux produced by the road reflection, based on the angular reflectance measured by Gillet (2002) for asphalt. This parameter shows how much the upward flux produced by the road reflection (which is not avoidable) is increased by the direct upward flux emitted by the chosen luminaires (which is unuseful and eliminable with the use of fully shielded luminaires).

6.6.1.4 Out-of-road reflected upward flux ratio WUFR%

This parameter gives a rough estimate of the upward flux produced by reflection of the light wasted out-of-road. It is given as percent of the total flux emitted by the luminaire and must be minimized as much as possible. The computation assumes an average reflectance of 13.5% by out-of-road surfaces obtained averaging the visual reflectance of some common surfaces (from grass to brick, from concrete to plaster) and assuming that vertical surfaces send upward approximately one half of the reflected light. Due to the range of reflectance of existing materials, this parameter and the other parameters related to the out-of-road surfaces give only a magnitude order for comparison purposes. In particular green vegetation can have a reflectance from half to one third of the previous one, due to chlorophyll absorption at visible wavelength. Reflectances depend on the spectra of the source and the photometric band in which they are measured, therefore they should be always measured in the CIE photopic photometric band and using as light source a typical lamp for road lighting (typically a standard HPS lamp). The use of visual albedo measured for solar light could be source of large errors.

6.6.1.5 Increase of upflux due to out-of-road emission %

This parameter gives a rough estimate of how much the upward flux produced by the road reflection (which is necessary to the lighting process) is increased by the (not-necessary) upward flux produced by reflection of the luminous flux wasted out-of-road. It must be controlled in designing an installation. The parameter is given as percent of the total flux emitted by the luminaire.

6.6.2 Total upward fluxes

The program also computes the total upward fluxes, given as per cent of the flux emitted by the luminaire, obtained as (1) sum of the upward fluxes emitted by the luminaires and reflected by the road and (2) sum of the upward fluxes emitted by the luminaires and reflected by the road and by the

surfaces out-of-road. They are obtained, as before, assuming for the road pavement the angular reflectance measured by Gillet (2002) for asphalt and for the out-of-road surfaces an average upward reflection factor of 13.5% (see the previous comments).

6.6.3 Upward light densities

Upward light densities has been used in some studies. They can be obtained multiplying the related flux factors by the LORL and the installed flux per unit area, i.e. by the flux emitted by the luminaire per unit surface. Area densities in lm/m^2 can be transformed in linear densities in lm/m multiplying by the road width in m. The upward density do not change if the upward flux factor increase but – in the same time - the requested luminance is obtained with a minor flux per unit area. This can be misleading because both the upward flux factor and the installed flux per unit area must be minimized in a good installation.

6.6.3.1 Direct unit upward light density DUUD

The direct unit upright density DUUD in lm/m^2 gives the upward luminous flux produced by direct emission by luminaires per unit square meter of the road pavement.

6.6.3.2 Road unit upward light density RUUD

The road unit upright density RUUD in lm/m^2 gives the upward luminous flux produced by road reflection per unit square meter of the road pavement (estimated based on Gillet 2002).

6.6.3.3 Increase of uplight density due to direct emission %

Like the analogous “increase of upward flux due to direct emission”, this parameter, obtained by the ratio DUUD/RUUD , gives the per cent increase of the upward flux density produced by upward emission of the luminaires over the upward flux density produced by the road reflection. This parameter shows how much the upward light density produced by the road reflection (which is not avoidable) is increased by the direct upward light emitted by the luminaires (which is unuseful and eliminable with the use of fully shielded luminaires).

6.6.3.4 Out-of-road unit upward light density WUUD

The out-of-road unit upright density WUUD in lm/m^2 gives the upward luminous flux produced by reflection by out-of-road surfaces per unit square meter of the road pavement (estimated as before assuming an average reflectance of 13.5% - see the previous discussion).

6.6.3.5 Increase of uplight density due to out-of-road emission %

Like the analogous “increase of upward flux due to direct emission”, this parameter, obtained by the ratio WUUD/RUUD, gives the per cent increase of the upward flux density produced by upward emission of the out-of-road surfaces over the upward flux density produced by the road reflection. This parameter shows how much the upward light density produced by the road reflection (which is not avoidable) is increased by the upward light emitted by the other surfaces (which must be minimized as much as possible).

6.6.4 Total upward light densities

The program also computes the total upward light densities, in lm/m^2 , obtained as (1) sum of the upward light densities emitted by the luminaires and reflected by the road and (2) sum of the upward light densities emitted by the luminaires and reflected by the road and by the surfaces out-of-road. They are obtained, as before, assuming for the road pavement the angular reflectance measured by Gillet (2002) for asphalt and for the out-of-road surfaces an average reflectance of 13.5% (see the previous comments).

As an example:

```

direct upward flux ratio UFR % (Rn%): 2.20221817948069
road reflected upward flux ratio UFR % (Gillet 2002):
3.79557016756868
increase of upflux ratio due to direct emission %:
58.0207474043712
out-of-road reflected upward flux ratio (rho=.135) %:
6.16324210329874
increase of upflux ratio due to out-of-road emission %:
162.379875254598
direct+road upflux ratio % (Gillet 2002): 5.99778834704937
direct + road + out-of-road (rho=.135) upflux ratio %:
12.1610304503481

direct unit uplight density DUUD ( $\text{lm}/\text{m}^2$ ): 0.688292757418929
road unit uplight density RUUD ( $\text{lm}/\text{m}^2$ ) (Gillet 2002):
1.18628729930334
increase of uplight density due to direct emission DUUD/RUUD
(%): 58.0207474043714
out-of-road unit uplight density WUUD ( $\text{lm}/\text{m}^2$ ) (rho=.135 ):
1.92629183676990
increase of uplight density due to out-of-road emission
WUUD/RUUD (%): 162.379875254598
direct+road unit uplight density TUUD ( $\text{lm}/\text{m}^2$ ) (Gillet 2002):
1.87458005672227
direct+road+out-of-road unit uplight density TUUD ( $\text{lm}/\text{m}^2$ )
(rho=.135): 3.80087189349217

```

6.7 Light Pollution: direction dependent parameters

An effective control of light pollution produced by roadway lighting requires that (a) the light necessarily re-emitted by the road pavements be limited as much as possible avoiding overlighting, (b) direct upward light emission by luminaires be negligible in respect to it, (c) the un-necessary light re-emitted by other surfaces be limited as much as possible minimizing the downward light wasted out-of-road and maximizing the “utilance”.

The upward light fluxes, being quantities integrated on the upward hemisphere, are not always good parameters to compare light pollution by roads, by luminaires and by other surfaces, and their effects on the night sky. They are related to the total quantity of light emitted in the atmosphere but not to the light pollution, i.e. on the alterations produced by this light flux (e.g. the artificial night sky brightness). As Cinzano and Diaz Castro (2000) pointed out, the direction of emission of the light is important in determining the quantity of light scattered in the atmosphere (related to the length and position of the light path) and the size of the area that can be polluted, due to the propagation of light and the capability of the light pollution to add up to that produced by the other sources (both related to the geometry of the emission). Given that roads pavements, other surfaces and luminaires have different intensity distributions, the integrated fluxes can be misleading, if the direction of emission is not in some way accounted. In this section the program presents data useful to compare pollution by roads and luminaires accounting for the direction of emission.

6.7.1 Upward intensities

6.7.1.1 Average maintained luminance at angle omega

The program gives the maintained road luminance as observed by an observer at infinity at different azimuth. Omega is the azimuth angle of the observer, defined like the C angle, i.e. zero when the observer is at infinity on the X axis of the grid and increasing counterclockwise.

As an example:

Average maintained luminance at angle omega		
0	cd/m ²	1.13670402142726
10	cd/m ²	0.961828124335278
20	cd/m ²	0.760167741677356
...
350	cd/m ²	0.887837566686457

6.7.1.2 Upward intensity per unit flux (cd/klm) at low angles

The program gives the upward intensity of the road and the luminaire per unit lamp flux (in cd/klm) as observed by an observer at infinity at an azimuth angle ω and an elevation angle α . ω is zero when the observer is at infinity on the X axis of the grid and increases counterclockwise. α is zero when the observer is on the road and 90° when the observer is at the zenith of the luminaire. The program gives also the ratio between the luminaire intensity and the road intensity, which indicates the relative percent increase of the intensity due to the upward light from the luminaire. The results are given only for low α angles, i.e. 0° - 30° , which are of primary interest for the propagation of light pollution at large distances. A good limitation of the effects of light pollution requires that the luminaire intensity be negligible in respect to the road intensity even at low α angles (e.g. $< 5\%$). The intensity of the road at angles $\alpha > 1^\circ$ is obtained from the intensity at $\alpha=1^\circ$, evaluated based on the tables of the luminance coefficient of the standard road surface, assuming the road luminance roughly constant in the range $1^\circ < \alpha < 30^\circ$. This approximation is sufficient to evaluate the magnitude order.

As an example:

Upward intensity per unit lamp flux (cd/klm) at angle α ,
 ω

α (deg)	ω (deg)	road intensity	fixture intensity	ratio%
1	0	0.3610556	9.142256	2532
10	0	3.592436	11.00000	306
20	0	7.075717	9.000000	127
30	0	10.34401	5.000000	48
1	30	0.2068752	7.782140	3761
10	30	2.058369	6.000000	291
20	30	4.054196	4.000000	98
30	30	5.926838	3.000000	50

6.7.1.3 Average upward intensity per unit flux at low angles

The program gives the upward intensity of both the road and the luminaire per unit lamp flux in cd/klm, averaged in azimuth between ω 0° - 360° . It also gives the percent ratio between the luminaire intensity and the road intensity, i.e. the relative increase of the intensity due to the upward light from the luminaire. The results are given only for low α angles, i.e. 0° - 30° , which are of primary interest for the propagation of light pollution at large distances. This parameter allows a comparison of the intensities of the light emitted by luminaires and road surfaces for a sample of randomly oriented road installations of the same kind.

As an example:

Average upward intensity per unit lamp flux at angle α

alpha	average road intensity	fixture intensity	ratio%
1 deg	0.203922510375998	6.26777929229767	3073
10 deg	2.02899081220168	5.444444444444444	268
20 deg	3.99633176529350	3.833333333333333	95
30 deg	5.84224619993833	3.166666666666667	54

6.7.1.4 Maximum intensities per unit flux

The program computes the maximum luminous intensity per unit lamp flux emitted by the luminaire and the associated angles C, gamma. It also estimate the maximum intensity of the road per unit lamp flux (assumed at gamma = 180 degrees). They can be useful for comparison with the previous values.

As an example:

```

maximum luminaire intensity per unit lamp flux at angles
C, gamma
11.00000000000000 cd/klm 0.000000000000000E+000
100.0000000000000
maximum road intensity per unit lamp flux 12 cd/klm at gamma
180 deg

```

6.7.2 Upward flux factors (rewritten for comparison)

The upward flux factors already presented before, obtained by integration of the luminous intensity over the entire upward hemisphere, are rewritten on the screen to allow a quick comparison with subsequent parameters.

As an example:

```

road upward flux factor % (estimated) % 5.15764590585392
direct upward flux factor % 2.20221817948069
increase of upward flux due to direct emission %
42.6981266197661

```

6.7.3 Scattered flux factors

The scattered flux factors are obtained integrating over the upward hemisphere the quantity of light which is scattered by molecules and aerosols along its path in the atmosphere, given the emission intensity and the direction of emission (the elevation angle alpha). The scattered light is evaluated based on the extinction computation in Garstang (1986) assuming the same atmospheric model, standard clean atmosphere, sea level and neglecting Earth curvature. Note that the upward intensity distributions of the road, the surrounding surfaces and the luminaires are different so a comparison of their intensities in the more polluting directions, rather than their fluxes, would be more appropriate.

6.7.3.1 Road scattered flux factor %

The road scattered flux factor gives the fraction, in percent of the total flux emitted by the luminaire, which is reflected upward by the road and scattered by molecules and aerosols along its path in the atmosphere.

6.7.3.2 Direct scattered flux factor %

The direct scattered flux factor gives the fraction, in percent of the total flux emitted by the luminaire, which is directly emitted upward by the luminaire and scattered by molecules and aerosols along its path in the atmosphere.

6.7.3.3 Increase of scattered light due to direct emission %

The increase of scattered light due to direct emission gives the percent increase of the scattered light flux due to the direct upward emission by the luminaires over the scattered flux due to road reflection. This parameter shows how much the scattered light flux produced by the road reflection (which is not avoidable) is increased by the direct upward flux emitted by the luminaires (which is fully eliminable using fully shielded luminaires).

6.7.3.4 Out-of-road scattered flux factor %

The out-of-road scattered flux factor gives the fraction, in percent of the total flux emitted by the luminaire, which is emitted upward by the out-of-road surfaces and scattered by molecules and aerosols along its path in the atmosphere.

6.7.3.5 Increase of scattered light due to out-of-road emission %

The increase of scattered light due to out-of-road emission gives the percent increase of the scattered light flux due to the upward emission by out-of-road surfaces over the scattered flux due to road reflection. This parameter shows how much the scattered light flux produced by the road reflection (which is not avoidable) is increased by the upward flux emitted by the other surfaces (which must be minimized as much as possible).

As an example:

```
road scattered flux factor % (estimated) % 2.02436829129273
direct scattered flux factor % 1.63753331297243
increase of scattered flux due to direct emission %
80.8910769851434
out-of-road scattered flux factor % 2.42393656059585
increase of scattered flux due to out-road emission %
119.737923727701
```

6.7.4 Low-angles flux factors

The directions of primary importance for the propagation of light pollution at great distances are those with alpha $<30-40^\circ$, called here “low alpha angles emission” or “low angles emission”.

6.7.4.1 Low-angles road flux factor %

The low-angles road flux factor gives the fraction in percent of the total flux emitted by the luminaire, which is reflected upward by the road surface in directions with alpha in the range $1^\circ < \alpha < 30^\circ$.

6.7.4.2 Low-angles direct flux factor %

The low-angles direct flux factor gives the fraction in percent of the total flux emitted by the luminaire, which is emitted upward by the luminaire in directions with alpha in the range $1^\circ < \alpha < 30^\circ$.

6.7.4.3 Increase of low-angles flux due to direct emission %

The increase of low-angles flux due to direct emission gives the per cent increase of the flux at low angles due to upward emission by the luminaires over the flux at low angles due to road reflection. In other words, this parameter shows how much the flux at low alpha angles ($0^\circ-40^\circ$) produced by the road reflection (not avoidable) is increased by the direct upward flux emitted by the luminaires (fully eliminable with the use of fully shielded luminaires).

6.7.4.4 Low-angles out-of-road flux factor %

The low-angles out-of-road flux factor gives the fraction in percent of the total flux emitted by the luminaire, which is emitted upward by the out-of-road surfaces in directions with alpha in the range $1^\circ < \alpha < 30^\circ$.

6.7.4.5 Increase of low-angles flux due to out-of-road emission %

The increase of low-angles flux due to out-of-road emission gives the per cent increase of the flux at low angles due to upward emission by the out-of-road surfaces over the flux at low angles due to road reflection. In other words, this parameter shows how much the flux at low alpha angles ($0^\circ-40^\circ$) produced by the road reflection (not avoidable) is increased by the upward flux emitted by the other surfaces (which must be minimized as much as possible).

6.7.5 Low-angles scattered flux factors

The low-angles scattered flux factors are obtained integrating the quantity of light which is scattered by molecules and aerosols along its path in the atmosphere only for directions of emission with α in the range $1^\circ < \alpha < 30^\circ$. These directions, called “low alpha angles emission”, are of primary importance for the propagation of light pollution at great distances.

6.7.5.1 Low-angles road scattered flux factor %

The low angles road scattered flux factor gives the fraction in percent of the total flux emitted by the luminaire, which is reflected upward at low angles ($\alpha=0^\circ-30^\circ$) by the road and scattered by molecules and aerosols along its path in the atmosphere.

6.7.5.2 Low-angles direct scattered flux factor %

The low angles direct scattered flux factor gives the fraction in percent of the total flux emitted by the luminaire, which is directly emitted upward at low angles ($\alpha=0^\circ-30^\circ$) by the luminaire and scattered by molecules and aerosols along its path in the atmosphere.

6.7.5.3 Increase of low-angles scattered flux due to direct emission %

The increase of low angles scattered light due to direct emission gives the percent increase of the scattered light flux due to the direct upward emission at low angles ($\alpha=0^\circ-30^\circ$) by the luminaires over the scattered flux due to road reflection. This parameter shows how much the scattered light flux produced by road reflection (not avoidable) is increased by the direct upward flux emitted at low angles by the luminaires (fully eliminable using fully shielded luminaires).

As an example:

```

low-angles road upward flux factor % 1.30141639040810
low-angles direct upward flux factor % 2.07998150976920
increase of low-angles upward flux due to direct emission %
159.824443974996
low-angles out-road upward flux factor % 1.58723275614815
increase of low-angles upward flux due to out-road emission %
121.961946064812

low-angles road scattered flux factor % 0.771990009630992
low-angles direct scattered flux factor % 1.56072229608294
increase of low-angles scattered flux due to direct emission
% 202.168716772509
low-angles out-road scattered flux factor %
0.953237170797554
increase of low-angles scattered flux due to out-road
emission % 123.477915375252

```


6.7.6 Data related to the 3-dimensional plots

At the end the screen shows some data related to the 3-dimensional plots of the upward intensity distribution of the installation. They are written in *outdat_roadpoll_x.dat*. See the related section for a description.

7. DATA TABLES

Output tables are given in file *outdat_roadpoll_x.dat*.

They are:

- 1) the luminaire intensity (cd/klm) at gamma 30° and 70°,
- 2) the maintained pavement luminance (cd/m²) on the grid as observed by an observer at infinity along the road axis,
- 3) the maintained pavement luminance (cd/m²) as observed by observers at z=1.5, x=-60, on the middle of the two lanes,
- 4) the maintained pavement illuminance (lm/m²),
- 5) the maintained veiling luminance (cd/m²),
- 6) the maintained semicilindrical illuminance (lx),
- 7) the glare index GR,
- 8) the input table of the reduced luminance coefficients of the road surface at each beta and gamma angle
- 9) the input intensity distribution (cd/klm) at each C and gamma angle,
- 10) the estimated intensity distribution of the road (cd/klm) at each C and gamma angle,
- 11) data related to the 3D plots of the intensity distribution (see next section).

8. 3D POLAR PLOTS OF THE UPWARD INTENSITY DISTRIBUTIONS

The upward intensity distribution of the lighting installation can be plotted in 3D in polar coordinates applying the procedure *upward.nb* of MATHEMATICA to the files *aaaaa_x.dat*, where *aaaaa* is a code identifying the source: *uplum* gives the upward intensities per unit lamp flux of the luminaire, *uproa* gives the upward intensities per unit lamp flux of the road, *uptot* gives the total upward intensities per unit lamp flux obtained by their sum. As before, *x* is the code giving the run time which identifies the model.

In order to obtain accurate upward intensities per unit lamp flux of the road at any alpha, omega angles we need its angular reflectance, which depends on the angles alpha, beta, gamma, as commonly defined in lighting

engineering. This quantity so far was not available to the authors. Tables for standard road surfaces typically are given only for $\alpha=1^\circ$. In order to allow a plot of both the upward emission by luminaires and the upward emission by the road, we assumed a model road upward intensity per unit lamp flux. Note that this model is only used for plotting purposes and the quantities given by this program have been obtained more conservatively, as described in the related paragraphs.

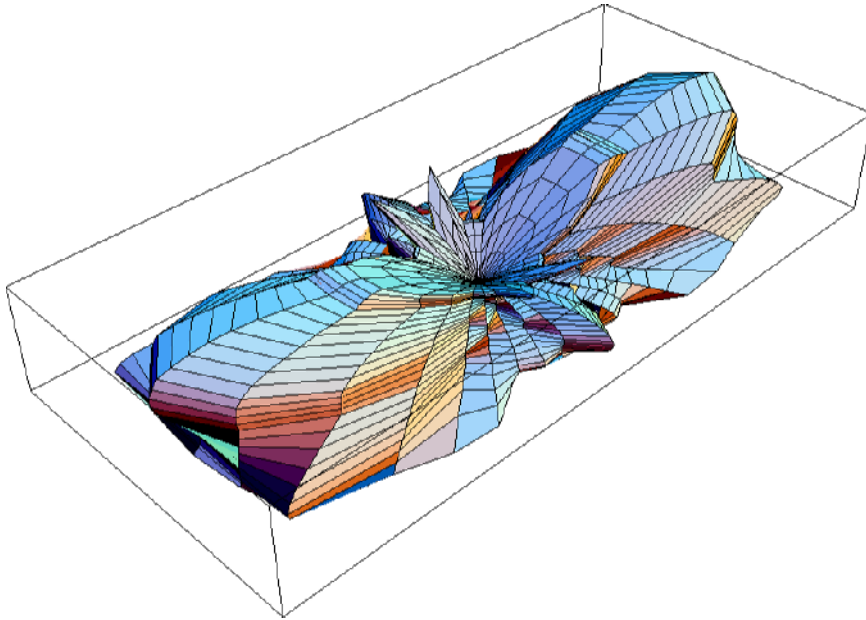
The model assumes that the road emits light both by diffusion and by specular reflection. The diffusion is assumed to be approximately Lambertian. We assumed that the Lambertian intensity distribution fits the intensity per unit lamp flux of the road at $\alpha=1^\circ$ and $C=270^\circ$, obtained by the previous computations. In fact, for $\alpha=1^\circ$ and $C=270^\circ$ the reflection points are well outside the road surface so that the road emission is almost completely due to Lambertian diffusion. Carrous et al. (2001) showed that the luminance factor for some roads can increase even of 15% going from $\alpha=70^\circ$ to $\alpha=20^\circ$ even when light comes with $\gamma=90^\circ$. If the luminance increase when α decreases, we overestimate the intensities at large α angles and the upward flux ratio: in case of a 15% increase the upward flux ratio due to diffusion could be overestimated of roughly 5%. The specular reflection is assumed to produce the same photometric solid of the luminaire but upside down, except that the intensity is zero for α such as that the reflection point is outside the road surface. The reflection factor is assumed to decrease to zero going from $\alpha=0^\circ$ to $\alpha=90^\circ$ with the same slope of the angular reflectance measured by Gillet (2001) which likely decreases with α due to effect of the specular reflection. The scale coefficient is evaluated as the ratio between the upward emission due to specular reflection at $\alpha=1^\circ$, $C=0^\circ$ (obtained as difference between the intensities per unit lamp flux computed at $\alpha=1^\circ$, $C=0^\circ$ and at $\alpha=1^\circ$, $C=270^\circ$, i.e. the pure diffusion) and the reflected luminaire flux in the same direction. We also checked that the integral of the road intensity per unit lamp flux on the upward hemisphere be in agreement with the value obtained based on the angular reflectance measured by Gillet (2001) obtained as described in the previous sections. In conclusion, the model road photometry fits the intensities at $\alpha=1^\circ$ and $C=0^\circ, 270^\circ$ as computed based on CIE standard surfaces and the upward flux ratio as obtained based on the Gillet's angular reflectance.

At the end of the file *outdat_roadpoll_x.dat*, the program writes the range of γ angles for which the photometry is given, usually 90-180, and the upward flux ratios (upward flux per unit flux emitted by the luminaires) produced by the model road by diffusion, by specular reflection and by both of them. This last must agree with the "Road upward flux factor" already seen.

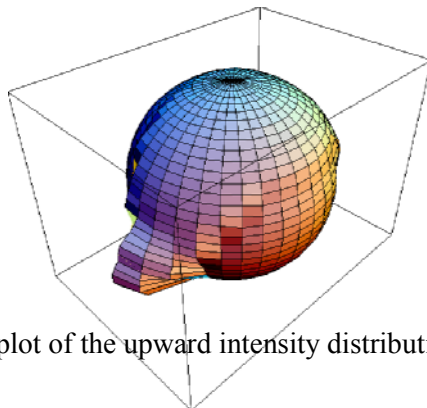
As an example:

3D plot:

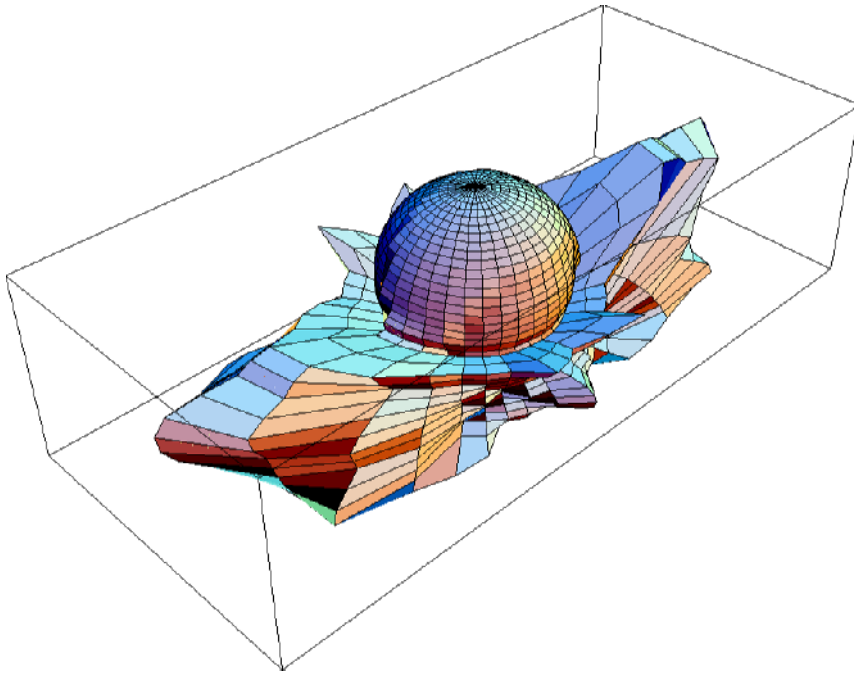
```
First/last gamma angle 90.000000000000 180.000000000000  
model road surface:  
upward road reflected % 0.174946933265858  
upward road diffused % 3.97134572469454  
upward road flux factor % 4.14452142735877  
Raw images writted
```



Example of 3D polar plot of the upward intensity distribution of a luminaire.



Example of 3D polar plot of the upward intensity distribution of a road.



Example of 3D polar plot of the total upward intensity distribution of the luminaire and the road.

9. REFERENCES

- Ashdown I., 1999, in <http://www.helios32.com/Eulumdat.htm>
- AIDI, 1999, *Manuale di Illuminotecnica*, Tecniche Nuove, Milano.
- CIE Publ. 120
- CIE Publ. 30
- CIE Publ. 126
- Cinzano P., Diaz Castro J., 2000, The artificial sky luminance and the emission angles of the upward light flux, in *Measuring and modelling light pollution*, ed. P.Cinzano, Mem. Soc. Astron. It., 71, 251-256.
- Corrons A., Fontecha J.L., Pons A., Campos J., 2001, Reflectancia suelos urbanos, *XXVII Symposium nacional de Iluminacion*, Ponferrada May 24-26 2001.
- Garstang R., 1986, Model for artificial night-sky illumination, *Publ. Astron. Soc. Pacific*, 98, 364-375.
- Gillett M. 2002, Precise evaluation of upward flux from outdoor lighting installations (applied in the case of roadway lighting), *Light Pollution Symposium*, La Serena, March 2002.
- UNI standard rule 10439
- UNI standard rule 10819