Light pollution quantification

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1 Introduction

Many non-astronomers ask, which way of artificial outdoor lighting brings the least light pollution. The answer is very simple: the fully shielded (FS) one, i.e., allowing no direct light over horizon.[1] The same simple criterion reduces glare and most of the light into the windows, into distant areas etc., simply the light pollution in the broadest sense.

This secondary virtue is due to the simple fact that when the light-sending parts of the luminaire have a zero space angle when viewed horizontally (an usual condition to have a fully shielded luminaire), the space angle of the light-sending (emitting, reflecting, refracting, dispersing) parts of it remains small also from views going just slightly upwards, being proportional to the departure from the horizontal direction. Of course, keeping the luminance low within this space angle by a suitable optical construction can help as well, this is where the quality of different fully shielded luminaires appears.

However, the advocates of perpetuating the use of non-FS luminaires claim that using non-FS luminaires helps combating the light pollution. Sounds incredible?

Their argument is that to achieve a sufficient luminance of the road as demanded by some standards, more light is needed using the FS luminaires, hence more light disperses to the atmosphere from the road and the light pollution inevitably rises.

The error in this reasoning is a misperception what the light pollution is. In many cases, it is no measurable quantity. An interpretation, that the luminous flux upward is the measure, is completely unuseful. There are no cases where this quantity would matter. Let us discuss it.

2 Which upward light matters

Are the birds affected by this light? Not very much, what disturbs them most are the bright or even glaring points, i.e., the direct light from the lamps: just FS ones do no harm. Artificial luminance in their field of view may play a role, i.e., mostly again direct light from the lamps, windows or lit facades, but the lit terrain below is irrelevant.

Are the stargazers affected by this light? In some extent yes, but it depends. They do not see this light. What they see, is the light from the sky, going downward. This is

*see also [1]

[1] I've seen a HCO short as well, meaning Horizontal Cut Off

the light pollution in the narrowest old sense: *an artificial increase of the luminance of a cloudless night sky.*

Such an artificially made part of the sky luminance is not simply proportional to the amount of light going upward. A proportionality holds just for one single elevation angle of the upward going radiation. The constant of proportionality depends on the turbidity of the air, and of course, on the elevation angle itself. It quickly declines with the elevation. No wonder, there is less air on the path of the skyward light. As we know, the air is mostly transparent, so most of the upward going radiation never turns back and escapes into the space without doing any harm. This is true for all light going steeply upwards. What matters much more, is the light which goes just very slightly upwards. Almost all of it is dispersed at last, half of it upwards into the space, half of it downwards, contributing to the artificial increase of the sky luminance. Even without computation everybody knows that, when remembers how the setting Sun looks like. Just a very tiny fraction of its light remains undispersed, so little, that it does not heat us at all, and sometimes even so little, that it can be viewed comfortably without any sunglasses.

So, the unwanted increase of the night sky luminance is caused mainly by the artificially produced light going in shalow elevation angles upwards. Counting all the upward light together is like counting all the money together, not regarding if they are liras, marks, dollars or pounds (or euros, pesos, rupies). The exchange rates are to be regarded!

For an air with neither aerosols nor absorption (it does not exist in reality) the fraction of the downward scattered light would be some five per cent per "one air mass" (the same amount would be dispersed upwards). It means, that the light travelling at 30 degrees elevation, going through twice the amount of air as the light going to zenith, would be dispersed downwards from some 10 per cent, 17 per cent would return back to the ground from the light going to 15 degrees, 33 per cent from 6 degrees and 44 per cent from the directions below 3 degrees. So, this almost horizontal light is nine times more polluting, in the terms of the sky luminance, than the vertical one, isn't it?

No, it is not. It's even worse. Such a calculation holds for uniformly populated (or artificially lit) landscape. With villages a couple of kilometres or even more from each other, everybody who is seeking a wonderful natural night would go in the middle between them. There the increase of sky luminance due to the artificially emitted light is even more caused by the low-elevation light from the villages. To the air above such remote places, no other light can get. And as regards observation of aurorae, which are mostly quite low above horizon in our central European latitudes (or comets, which are usually low everywhere), the light caps above villages make the main obstacle, again caused by the shallow elevation light mostly. So does the almost horizontal light twenty or fifty times more harm than the steep-up-going light? Something like that.

Then there is the aerosol content in the atmosphere, always present in some extent, and mostly predominant in the forward scatter of the light, with a steep maximum around the original direction of the light (the Rayleigh scatter on the gases themselves is dumbbell-like shaped, with a minimum perpendicular to the original direction). The light caps above lit areas are caused then mainly by the forward scatter of the low-elevation light on the aerosols. We know such a scatter maximum from our daytime experience as well: this is the reason why the sky around the Sun, even with a rather clean air, is much brighter then elsewhere, often so bright, that it cannot be comfortably viewed even when we shade the Sun itself by our hand.

On the other side, aerosol content diminishes the role of the light going horizontally, making the total scatter including "downscatter" larger at large elevations (for the lowest ones, even the cleanest air scatters almost half of the light downwards, as we know already). So, inside the large lit areas (like urban aglomerations) with badly transparent air it lowers the relative importance of almost horizontal light to perhaps a factor of four instead of nine. There is also some absorption of the light even by the clear air (visible as dark bands in the spectrum of the setting Sun), it reduces the importance of shalow angles even a bit more, but these are per cents rather then a factor of two.

But at the best nights with low turbidity of the air, when the natural sky would sparkle by thousands of stars, the low elevation component is by far the most harmful one everywhere, with an exception of a centre of one single small town in the middle of the ocean (just there the steep light contributes overwhelmingly to the sky luminance directly overhead, it's being of course just one of the many adverse effects of the light pollution).

3 Going quantitatively

This could do perhaps. But some people might like to know how much exactly is the sky luminance increased by each way of artificial lighting of our homes, ways and working places. For an as accurate answer as possible, they have to study the works of Pierantonio Cinzano and his collaborators (starting perhaps from the famous Atlas [3]), or even reproduce their computations with many possible angular distributions of emitted light, of location of the light sources, shapes of the terrain etc. For some Italian situations it has been done already [6]. The angular distribution of the light from real settlements is poorly known, however [2].

In fact, we are not so much interested in just this question. The prevention of all the light pollution is the ultimate goal, not a mere reduction of the luminance of the sky in some places. But let us make a couple of remarks on the luminance of the sky, for those who are still curious.

I have written a programme handling the photometric data on luminaires, the so-called *ies* photometric files.[2] The original goal has been just to get a human-readable table from the standard data. Then I added a computation of further quantities, step after step, and eventually I've included some estimate of the obsolete increase of the sky luminance by the direct light from the luminaires.

The program itself and a lot of it results is available in [8], some old comments on it and this issue in [9].

The model I use is the simplest possible.

The upward light from a lit terrain is considered to be lambertian-distributed, i.e., the luminance of the terrain is the same from any direction and the amount of light is then simply proportional to the cosine of the viewing angle (looking vertically down the angle is zero an the cosine is one). Such a source is called cosine source as well, a graphical representation is a sphere lying on the ground. No real terrain is like that, esp. when illuminated obliquely. There may be also some mirror component, like from an old asphalt road polished by the tyres of millions of cars. If the luminaires produce large luminous intensities far from the nadir, at 75 degrees or even higher, then there is some reflected component at these shallow angles even in the light dispersed from the road. The more when the road is wet. However, lambertian distribution is the simplest model and it would be hardly possible to chose a better one for a general case.

[2]it handles also the *eulumdat* format now

For the computation of dispersed light, all the downward scattered light is taken as a whole and just single scattering is considered in its default variant.

Taking a simplified part of the Pascal code of the programme, the function describing the angular dependence of the scatter (called the indicatrix) can have several shapes, x being the angle of scattering (in degrees):

```
cx:=cos(x);
sx:=sin(x);
y:=sqr(x);
  if Sky=0 then
   if x<=10 then
    y:=7.5*exp(-0.1249*y/(1+0.04996*y))
   else
    if x<=124 then
     y:=1.88*exp(-0.07226*x+0.0002406*y)
    else y:=0.025 + 0.015*sin(2.25*x-369)
  else
   y:=1+cSky[Sky]*(exp(dSky[Sky]*x*pi/180)-exp(dSky[Sky]*pi/2))
      + eSky[Sky]*sqr(cx);
```

where the coefficients are

```
cSky:array[4..6] of real=
(10,16,24);
dSky:array[4..6] of real=
(-3,-3,-2.8);
eSky:array[4..6] of real=
(0.45,0.30,0.15);
```

The amount of total scatter is given by the extinction of direct vertical light, measured conventionally in magnitudes (`ZenExt`, as a default, the programme uses a value of 0.30 mag), for the computation it is necessary to normalise all the values to get the correct extinction.

The first formula (before the last "else" in the piece of code above) is used in the works of Cinzano (e.g., [3]), taken from Garstang [4] and describes just the aerosol part of the scatter (Mie scatter). The gas itself scatters simply half of the scattered light into each half-space, i.e. the scatter is centrally symmetric. The gaseous part is taken as if the vertical extinction caused by it would be always just 0.1 mag, the rest is considered to be the aerosol part: `AerosFr:=(ZenExt-0.1)/ZenExt`.

The other three alternatives are standard CIE skies got from the many measurements of the daytime sky luminance of cloudless skies, as published by Kittler [7], not distinguishing the mechanisms of the scatter. They involve multiple scattering as well.

To speed up the computation, the proportion of the downward-scattered light as a function of the elevation angle h expressed in degrees is approximated by the following functions (these are my formulas, valid for single scattering):

```
case Sky of
 0: FluxX:=(0.08+0.4*exp(-h/24))*AerosFr + 0.5*(1-AerosFr);
 4: FluxX:= 0.342+0.158*exp(-h/27);
 5: FluxX:= 0.275+0.225*exp(-h/27);
 6: FluxX:= 0.184+0.316*exp(-h/29);
```

You can notice that for a horizontal case the downward fraction is almost exactly one half.

What the programme does is just comparing the luminance of the sky caused by the direct light from the luminaire (i.e., an avoidable light, using the proper shielding) and the (unavoidable) light dispersed from the terrain. The terrain is considered lambertian and flat. The first assumption (cosine distribution from the lit surface) can be a good approximation of the reality, whereas the latter is not in many cases. The almost horizontal light from the lit ground is absorbed by trees, houses etc., whereas the lamps on high poles are obstructed far less in most cases. Then the influence of the direct light from the lamps may be still twice larger. On the other side, in tall narrow streets, the horizontal light from lamps may be blocked as well and the influence of the steep light from the pavement may be larger (but anyway, such narrow deep streets contribute to the sky luminance very little).

The exact numbers given by the programme are of a limited value. But one thing is obvious from the results for many luminaires: one per cent of light going almost horizontally from the lamps themselves adds some another thirty per cent to the increase of the sky luminance caused by the lit ground, a very serious penalty! Penalty about three per cent could be perhaps tolerable, if they were some valid reasons to use a non-FS luminaire, but it would demand just 0.1 per cent of light just above horizon. The tolerability would be relative, however, as those three per cent describe just the overall rise of the sky luminance. For the places we'd love to keep near-natural, the influence would be, as shown above, still too large: considering the roughness of the terrain, it may contribute easily more than half of the artificial increase of the sky luminance there, as caused by the outdoor lighting in all the municipalities around.

4 Non-FS luminaires help nobody

The advantage of the non-FS luminaires over the FS ones cited by some lighting experts stems from the fact, that extreme luminous intensities can be reached even at 80 degrees from the nadir with non-FS lamps. Neglecting the horrible glare from such lamps, the simplistic computation of the luminance of the road (with assumptions on its reflectivity which may be far from reality and are never checked) gives a possibility to give these lamps further apart, casting in fact less light on the terrain and getting sometimes lower total upward light fluxes.

This approach makes use of the light reflected from the glossy asphalt road at very low angles – namely, the road standard assumes observation of the road at an angle of just one degree from horizontal! It may be a sound approximation for a highway, but we do not illuminate highways in Czechia very often (fortunately). To compute the lighting tasks this way in a municipality with a legal upper speed limit of 50 km/h seems to be rather queer, luminance in such a very distant point is scarcely the most important value. Making use of the grazing illumination angles means inevitably lots of glare in the same time. It's difficult to quantify, but more fatigue for the drivers is a consensus already and a higher danger of overlooking a traffic signal is obvious. A danger of overlooking a pedestrian when a million times more conspicuous glare bomb is visible near to him, is much more fatal however.

Not just the *light above horizon* causes pollution – it's just that it is agreed to be called pollution by everybody. Even the *not-enough-steep-down light* below horizon is horrible and dangerous pollution, and it is mostly plentiful by those "more efficient" non-FS luminaires, being a synonyme for their "efficiency".

In fact, a responsible lighting project should not be limited to comparing two refractors for the otherwise same luminaire, or just two or three luminaires more. It should take advantage of the free market and choose the best suiting, least-polluting lamps from all the world. Of course just among the FS ones, perhaps with a large and precise reflector system, if the task really demands it, with the least possible amount of light above 80 degrees and usually above 75 degrees already, definitely inside a city at least. In many cases, a very important parameter should be, how well is the light confined to the target property to be illuminated, avoiding illumination of gardens, windows, or sometimes water surfaces (the artificial light damages both marine and freswhater life especially seriously).

Of course, nothing *above* the lamps is illuminated by FS luminaires, but also some things *below* the bulbs should be protected by choosing or adapting the luminaires as needed. When the cone of light is not assymetric in itself enough, a mirror-like Al surface houseside (waterside, ...) helps, adding more light streetside. It's fine that some producers have such option by their fixtures from the beginning already. Of course, for a perfect control of the light cone, the bulb itself might be shielded by small mirrors, avoiding direct light from the bulb going far away from the target area. I hope it will become usual with shallow luminaires in the future – for the deep ones, the cone can be controlled simply by the opening of the fixture.

5 Measures of the light pollution: what to avoid

So, is there a measure of the light pollution? Yes, but not a single one. There are several important measures of pollution, concerning the emissions from the lamps.

First, the amount of light going from the luminaires above horizon, esp. almost horizontally (the quantity given by my programme is a fair approximation, even if understating the damage by near horizontal light), completely evitable by a suitable geometry of the luminaire, confining all the light to the bottom half-space. It needs not be measured in such a case, as the FS-property is visible on the luminaire at the first glance.

Second, the amount of light going, say, over 75 degrees from the nadir, producing glare and compromising visibility and safety.

Third, the amount of direct light going in another inappropriate directions, outside the property to be illuminated.

Fourth, the amount of light going unused from the lit surfaces. This cannot be zero of course. Sometimes the lit surfaces can be dark to lower this amount, e.g., boards with white letters. But generally, the amount of incident light should be kept on the lowest possible levels all the time, always chosing the lower one if in doubt.[3] Avoiding pollution should be a strong motive for that. It may easily mean to have the lights off for most of the time. Motion detectors are a sound option, when they don't start in vain (and when the switched lights are not too strong).

Fifth, some surfaces need not be lit at all at night. *Not to light* is the option most favourable to the environment, most cheap and most responsible in many cases. After all, don't we have small lamps (with very cheap and reliable alkaline accumulators nowadays)

[3]There is an accepted upper limit of an average luminance of any lit surface outdoor, in absence of any safety standars demanding more, namely 1 cd/m^2, this is far enough at night – see e.g. [10].

when the night seems too dark before we adapt to it or when the way goes through a dense forest (and we don't know it and are in a hurry?). Don't we have headlamps in our cars, when riding quickly? There is no obligation to illuminate anything outdoors. Night is a natural phenomenon and our eyes have evolved to work well in such conditions. A street or a road is not a corridor inside a windowless buidling, there is never a true darkness outside. *Not lighting* some areas means to educate people about the advantages of letting some things to nature alone. This pays off in many cases, not just as regards lighting. People have been often afraid of the nature in the past, now they should be afraid of losing their healing contact with it altogether. Night is a possibility to refresh our links with it, with a multitude of gains. Now it is the most endangered part of our world – fortunately, the most easy to rescue as well. Let's do it.

References

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[3] Cinzano, P. – Falchi, F. – Elvidge, C. D. 2000: The first world atlas of the artificial night sky brightness, Monthly Not. of Royal Astron. Soc, 328, 689-707, see also `www.lightpollution.it` (also for further papers of Cinzano)

[4] Garstang, R. H. 1991: ..., Publ. Astr. Soc. Pacific, 103, 1109 (see `physics.colorado.edu/directory/faculty/garstang_r.html` as well)

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[7] Kittler, R. 1993: Relative scattering indicatrix: Derivation from regular radiance/luminance sky scans. Light Res. and Technol., 25, 125-127.

[8] Hollan, J. 2002: `amper.ped.muni.cz/light/ies2`, a programme extracting an information from the ies photometric files and some its results (files and directories).

[9] Hollan, J. 2002: FS fixtures are vital for reducing sky luminance, a letter to the DarkSky-list, `amper.ped.muni.cz/jenik/letters/public/msg00059.html`.

[10] Cielobuio, 2001, Visual Regolamento, in `www.vialattea.net/cielobuio/arc-lrl17.htm`, either `www.vialattea.net/cielobuio/lrl17/visualreg17.htm` or preferrably the typeset pdf version in `www.vialattea.net/cielobuio/lrl17/visualreg17.zip`