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ENERGY SAVING AND ENVIRONMENTAL COMPATIBILITY IN ROAD LIGHTING*

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ABSTRACT

This research was carried out with the cooperation and the financial support of ENEA, the Italian Agency for Energy of the Ministry for the Economic Development.

The paper analyses the conditions for assuring the compatibility of external lighting with the environment and particularly with consumption of energy on one side and the interference with astronomical observations on the other.

The effects of different types of luminaires are described relative to the road illuminated according to illuminance and luminance criteria

The paper demonstrates that illuminated towns seen from far distances, i.e. the main source of disturbance for astronomic observations, behave like single diffusing sources, since the luminaires are hidden in urban "cavities" bordered by buildings.

A model is presented for the analysis of territory around a site, aimed at identifying the possibilities to improve the environmental compatibility of outdoor lighting installations and the possibility of local modification to improve the situation.

Keywords: lighting pollution, sky glow, energy saving, road lighting

1. INTRODUCTION

Compliance with safety standards, like CIE 115 [CIE 2010], and national norms published in many countries, is presumed to assure safety for road users, which is the main scope of public lighting. However, this essential objective should always be associated with the necessity to save energy, not only to minimise operational costs, but also to assure the best environmental compatibility. The required reduction in green house gas emissions by power plants is a worldwide emergency, which also necessitates a reduction in useless spill light, an aim which, as confirmed in this paper, is strictly associated with the consumption of energy.

External lighting is aimed at the safety of the road users at night and at the fruition of the urban nightscape. However, external lighting is always associated with unavoidable side effects and in particular with light pollution, obstructing to the observation of the natural environment and of the night sky. Actually, the light emitted upward by external lighting installations and reflected upwards by the illuminated surfaces is diffused by both air molecules and aerosols from to atmospheric pollution: without the pollution the artificial sky luminance would be a minor problem.

With the aim of limiting those negative effects, in 1997 CIE issued Publication 126 [CIE 1997] prescribing the Upward Light Ratio (ULOR) in four zones E1-E4 according to surroundings (natural, rural, suburban, urban) and to lighting environments (intrinsically dark, low, medium and high district brightness). CIE 126/1997 made no reference to the relations between ULOR and the artificial sky luminance or to a limiting magnitude. No attention was also paid to an issue, which has the

* On basis of report at 27 th CIE session in San-City, South Africa, July 2011

highest level of priority: the minimisation of energy consumptions.

This paper describes how these phenomena can be evaluated and their effects avoided or at least reduced through the results of the research and innovation of lamp and luminaire technology. Actually, the obstacles to the night sky view depend on the light sources, in general the lit towns, whose negative effects on an observation site can be evaluated through the model described in this paper.

Through the cause/effects relationships described in this paper, it is possible to plan actions aimed at the reduction of sky luminance compatible with the best cost/benefit ratio, balancing environmental demands with citizen safety and especially with energy savings.

2. LIMITING MAGNITUDE AND PROPAGATION OF SKY LUMINANCE

For centuries, stars are classified according the magnitude, a quantity linked with their luminous appearance to the naked eye, in increasing logarithmic order for linearly fainter stars.

Actually, a point like star is perceived because of the contrast between its image, created by the luminous flux converging on a receptor of the retina (or on a pixel of a CCD/CMOS matrix), and the luminance of the background, which according to a known theorem, is equal to the luminance of the sky but for the losses of the optical system.

Clearly, if the base luminance of the sky L_B increases to $L_L=L_B+L_A$, the contrast of a star decreases and according to the Sky luminance formula for CIE 126 [SOARDO 2008] [FELLIN 2003], the decrease ΔM_L of the limiting magnitude M_L of an observatory base value M_B due to the base luminance L_B is:

$$\Delta M_L = M_L - M_B = = -2.5 \cdot \log\left(1 + \frac{L_A}{L_B}\right) = -2,5 \cdot \log\left(\frac{L_L}{L_B}\right) \quad (1)$$

and vice versa:

$$\frac{L_L}{L_B} = 10^{-0.4(M_L - M_B)} \quad (2)$$

Astronomers report that the light emitted at low elevations from 0° to 20° over the horizon (90° ≤ γ ≤ 110° in the CIE (C, γ) system) diffuse in the low layers of the atmosphere because of the concentration of aerosols and disturb astronomical observation more than the light emitted at higher elevations where the molecules of the atmosphere diffuse much less than aerosol. For this reason in this paper special attention is paid to both emissions and reflections at elevations 0°-20°.

Several models are available for simulating the propagation of the artificial sky luminance. In this paper, Walker's law is used to calculate artificial sky luminance L_A over a site at a distance D from a light source emitting the luminous flux Φ at 90° ≤ γ ≤ 110° (0° – 20° over the horizon):

$$L_A = H \cdot \Phi \cdot D^{-2,5}, \quad (3)$$

where the coefficient H, in [$m^{0,5} \times sr^{-1}$], is added for dimensional reasons. Walker's law is considered valid at an elevation of 45° in the direction of the source. However, if the aim is the classification of a site according to all the sources around it, L_A in (3) can be at the zenith and supposed to be proportional to the luminance of Walker's law.

Unfortunately, even if theoretical relations have been proposed between the luminous flux emitted upward and the artificial luminance of the sky, it is very difficult if not impossible to calculate the value of this last quantity since it depends on many characteristics of the atmosphere, which depend on local conditions, which can change each day.

3. EMISSIONS AND REFLECTION OF A LIT TOWN

Public lighting installations are concentrated in towns, with an installed luminous flux of 1–1,2 klm per head. Lit towns are thus the main potential sources of upward light and attention should be paid to their photometric behaviour in order to improve their environmental compatibility.

Since the '70 s [WALDRUM 1972], some models have been proposed for the luminous intensity distribution of a lit town, assimilated to a single source Particularly, Garstang [GARSTANG 1986] proposed a diffusing source combined with another asymmetric luminous intensity distribution according to a formula which, with our symbols, can be written as:

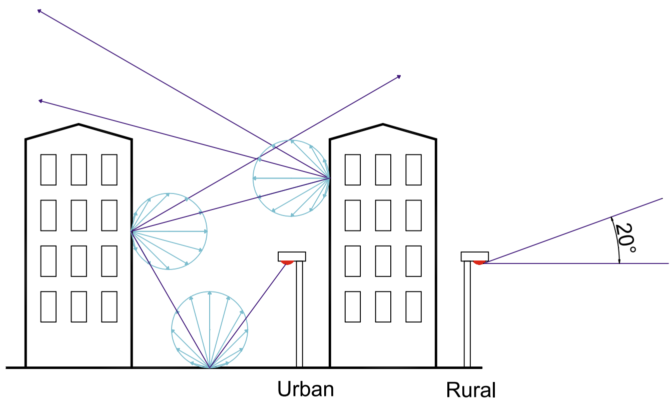

Fig. 1. A town can be assimilated with a set of light sources, with most luminaires hidden into the cavities between the buildings (urban sources) and some others not screened by buildings independently from their position inside or outside the town (rural sources)

$$I(\phi) = \frac{I_M(\phi)}{\Phi_G(\phi)} = \frac{1}{2\pi}\left[2\rho\cos(\phi) + 0{,}554\,ULOR\,\phi^4\right], \quad (4)$$

where *I (φ)* is the luminous intensity distribution of the source, Φ_G the installed luminous flux, *φ* the inclination with reference to the zenith, i.e. the complement to π/2 of the elevation.

The measurements of lit towns by night show that the structure of the Garstang's model with the two terms into the square brackets is correct, even if there is a disagreement in their weight where the luminaires are mainly hidden by the buildings, the lit towns appear to be much more diffusing. This is confirmed by the analysis carried out by Waldrum in 1972 on the disturbances to an observatory by a close village. He found that the public lighting installed in the three streets of the village behaved like diffusers, with the sum of their emissions quite similar to a single diffusing source.

More recent measurements confirm [FELLIN 2003, SOARDO 2005] that illuminated towns behave like single diffusing sources since most luminaires are hidden into cavities bounded by streets and buildings (Fig. 1) and cannot be seen at low elevation angles: in this case the upward emission of these luminaires, called "urban", cannot play any specific role. Only where the luminaires, called "rural", can be seen, a minority case however not to be neglected, their upward emissions should be considered. Fig. 2 shows a scheme of the model considered in this paper with urban and rural luminaires. The two lit towns of Fig. 3 confirm the validity of this model.

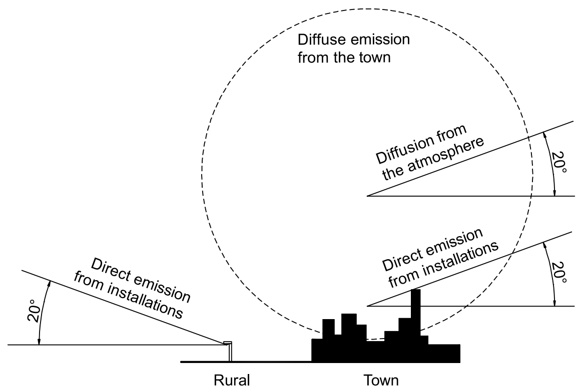

Fig. 2.A single scheme of the light components, which generate the artificial sky luminance

If, and only if, a light source is diffusing, it is possible to calculate its luminance from the installed luminous flux. Table 1 compares the luminance measured for four towns, observed at low elevations from far hills, with the results of calculations. The agreement in the 5th column is very good for an average reflection factor of the illuminated surfaces ρ=0.23, which corresponds to the average reflection factor estimated by an astronomer in a fifth town [MEDUSA 1998]. The low value of the mean of the relative differences between measured and calculated luminance (-0,003) and of its standard deviation (0,051), together with the low standard deviation of the measured reflection factors (0,010) confirm the same diffusing behaviour for all towns with a reflection factor *ρ*=0,23.

4. LUMINAIRES

Many astronomers believe that the increase in sky luminance depends only on the light emitted upward by the luminaires, i.e. their Upward Light

Table 1. Measured and estimated luminances of a lit town seen from a hill

Measured and estimated luminances of a lit town seen from a hill						
Town	Popul. x 10^3	Distance from hill [km]	Reflected lumin. flux [lm/m^2]	Luminance, cd/m^2		Calculated ρ from measures
				Calc. with ρ=0,23	measured at the hill	
Padova	100	15	2,2	0,26	0,25	0,222
Abano	20	6,8	1,8	0,36	0,36	0,23,4
Montegrotto		7,3	2,0	0,40	0,39	0,228
Torino	1000	15	2,1	0,26	0,28	0,248
Treviso	80	-				0,234
Relative difference of measured and calculated luminance				Mean		-0,003
				Std. deviation σ		0,051
Reflection factor ρ				Mean		0,233
				Std. deviation σ		0,010

Fig. 3. On the left is Milan by night from Madonnina on top of the Cathedral: very few luminaires are visible out of at least 15000 installed in this sector of Milan, since they are deeply hidden into urban cavities. On the right is Florence with the well known steeple and cathedral by Giotto and Brunelleschi. Again, practically all the 39000 installed luminaires are hidden into the urban cavities, whose upward diffusing openings are shown by the many small bluish spots

Output Ratio (ULOR). They neglect the upward reflections of illuminated surfaces and require consequently to use only cut-off luminaires installed horizontally. However, the installation in towns of cut-off luminaires is useless and even counterproductive. As pointed out in the literature, since cut-offs requires flat glass luminaires installed horizontally and in a higher number than bowl ones for complying with the safety standards, both installation and energy costs increase by at least 20 % [SOARDO 2002, SOARDO 2005, FELLIN 2003], with a further increase of the light reflected upwards from the lit surfaces (roads, buildings, etc.) and consequently also of sky luminance.

Furthermore, according to the state of the art technology, the lamp is deeply recessed into the reflector in order to maximize the luminous flux collected and reduce consequently energy consumptions. Fig. 4 shows that shallow glasses avoid the internal reflections of flat glasses, increasing their efficiency in this way. The lamp is not visible at low elevations over the horizon: there is no emission upwards but only diffusion when the beam of light crosses the glass.

Calculations and measurements show that in shallow glass luminaires, in spite of their higher ULOR, the reduction of internal reflections (Fig. 5) improve the efficiency and the environmental compatibility.

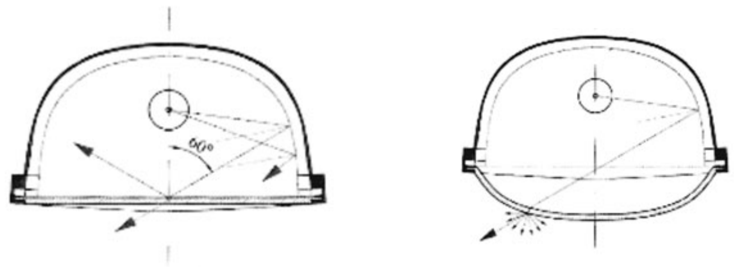

Fig. 4.The internal reflections (left) of flat glass luminaires (cut-off) and the upward light of shallow glass luminaires (right) due to the diffusion of the light crossing the glass with no direct upward emission

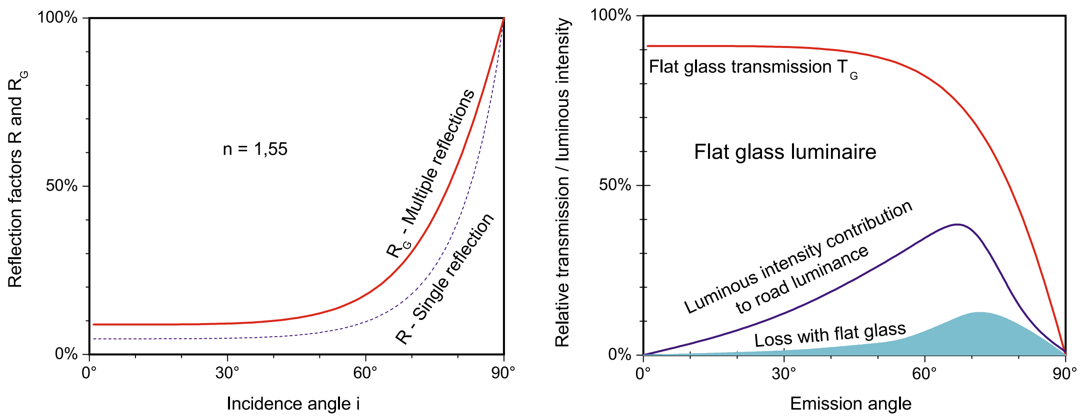

Fig. 5.At the left are single and multiple reflection factors versus incidence angle i. On the right – light transmission through a flat glass and consequent typical losses in road luminance with reference to a bowl luminaire with ULOR = 3 %

However, a suitable limit for ULOR should be prescribed: with ULOR≤3 %, the same value reported by the European Regulation 245 [ED2008], the highest energy efficiency can be reached together with the lowest illuminances, lowest reflections and also the best environmental compatibility: minimum CO_2 emissions and artificial sky luminance.

5. UPWARD LUMINOUS FLUX UPF

A model for the evaluation of the relative upward luminous flux UPF was discussed and partially accepted by CIE [AFE2006]. This model permits to evaluate the Upward luminous flux UPF emitted by the luminaire and diffused by the illuminated surfaces with reference to the luminous flux generated by the light source of the luminaire according to equation (5) below:

$$UPF = E_R \cdot A\left[\frac{ULR}{u} + \rho_1 + \rho_2(\frac{DLR}{u} - 1)\right], \quad (5)$$

where E_R is the illuminance of a sector of the road with area A, ULOR and DLOR are the relative luminous fluxes emitted upward and downward by a luminaire, u is the utilisation factor, while ρ_1 and ρ_2 are the reflection factors of the road and the surroundings, both considered Lambertian as far as the upward diffusions are concerned.

Equation (5) can be used for a lighting installation designed according to illuminance criteria, i.e. classes CE and S of CIE 115. For a road designed according to luminance criteria, according to a suggestion of CIE 144 [CIE 2001], the lighting installation can be characterised through the installation quality factor q_i [SOARDO 2009] defined as:

$$q_i = \frac{L_R}{Q_{0N}\, E_R}, \quad (6)$$

where L_R is the average road luminance and $Q_{0\,N}$ the average luminance coefficient of the road surface prescribed by standards [CIE 2001]. Introducing equation (3) in (5), one obtains:

$$UPF = L_R \cdot A \cdot \left(\frac{1}{q_i \cdot Q_{0i}}\right) \cdot \left[\frac{ULR}{u} + \rho_1 + \rho_2(\frac{DLR}{u} - 1)\right], \quad (7)$$

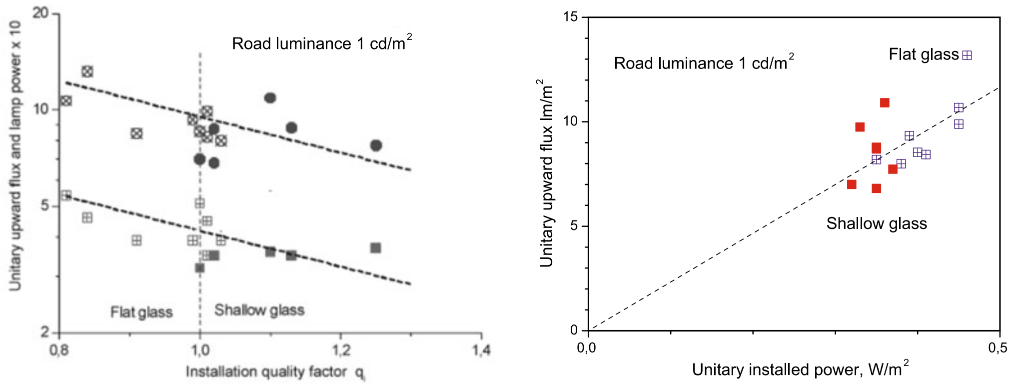

Fig. 6. Unitary upward flux UPF and lamp power versus installation quality factor q_i. The open crossed symbols refer to flat glass luminaires installed horizontally, the full symbols – to shallow glass ones (left); Upward luminous flux UPF versus lamp power: the shallow glass luminaires adsorb less energy. The open crossed symbols refer to horizontal flat glass luminaires, the full symbols – to shallow glass ones (right)

where $Q_{0\ i}$ is the road luminance coefficient of the actual installation, either measured or estimated.

No possibility of reducing UPF in equation (6) and (7) through neither E_R and L_R, which are prescribed by safety standards, nor A, which depends on the installation. In the term in square brackets, which is the same in both formulae, UPF can be reduced with lower values for ULOR and higher for DLOR and u, while ρ_1 and ρ_2 are local parameters normally unchangeable.

Moreover, in equation (7) it is necessary to reduce also the term into round parenthesis maximising q_i, which means reducing the road illuminance necessary to generate the luminance L_R, This can be obtained through luminaires with higher luminous intensities at grazing inclinations. The best conditions can be obtained with shallow glass luminaires, with values of DLOR and u similar to flat glass luminaires and a bit higher ULOR, however, more than compensated by the higher values of q_i. Fig. 6 reports the result of a survey with 16 luminaires, with flat and shallow glass, installed on a two lane road with the lighting class M3 and an average luminance L_R=1 cd/m^2: even if with higher values of ULOR, all shallow glasses perform better for UPF and energy consumptions.

Furthermore, since E_R is proportional to the power of the installed lamps, equation (5) shows that lower lamp powers involve lower UPF and also higher values of q_i in equation (6) and consequently lower UPFs in equation (7). Thus, for all classes of roads, the reduction of energy consumption leads to a better environmental compatibility, as confirmed in Fig. 9 by the survey quoted above.

6. ANALYSIS OF THE TERRITORY

Most of us do not live in a desert. Thus, the choice of a site suitable for astronomic observations or any restriction to public lighting for improving the visibility of the stars need preliminary analysis of the lighting territory around the site with the aim of evaluating the possible benefits and the necessary costs. A model is proposed here for a quick analysis of the territory according to the scheme of Fig. 2 and to the following definitions.

Urban installations. At low elevations, most luminaires are not visible hidden into the town cavities bounded by streets and buildings. Hence, direct emissions from the luminaires have no practical influence on light pollution. The total upward luminous flux Φ_U upward flux due to reflections is $\Phi_U = \rho_{20}\,\Phi_T$, where Φ_T is the installed luminous flux and ρ_{20} is the average reflection factor of lit surfaces equal to 0,20 [SOARDO 2008]. Moreover, because of the cosine shaped luminous intensity distribution, the luminous flux emitted at $90° \leq \gamma \leq 110°$ (0° – 20° elevation) is $\Phi_{20} = e\ \Phi_U$, with e = 0,12 to be added to the multiple diffusions of the atmosphere over the town $\Phi_D = d\ \Phi_U$, with d = 0,15–0,20. In such conditions, the luminance of a lit town can be easily calculated [SOARDO 2008].

Rural installations. Direct emissions are not screened by buildings and at an elevation of 0°-20° ($90° \leq \gamma \leq 110°$), produce a luminous flux equal to $ULOR_{20} \cdot \Phi_U$, to be added to $\Phi_D = d\ \Phi_U$ diffused by the atmosphere.

Combined installations. Any set of lighting installations can be split into urban and rural installa-

$$W_h = \frac{L_{Ah}}{L_A} = \frac{L_{Lh}/L_B - 1}{L_L/L_B - 1} = \frac{\Phi_{Th} \cdot D_h^{-2,5}\left[(d+e)\cdot\rho_h\left(1 - F_h \cdot R_{20h}\right) + F_h \cdot R_{20h}\right]}{\sum_h \Phi_{Th} \cdot D_h^{-2,5}\left[(d+e)\rho_h\left(1 - F_h \cdot R_{20h}\right) + F_h \cdot R_{20h}\right]}, \quad (10)$$

tions, as shown in Fig. 6, where the luminous sources are respectively invisible or visible if observed at elevation angles between 0° and 20°.

The basis for any restriction on both urban and rural lighting installations aimed at protecting a site against light pollution should be a cause/effect analysis of the territory based on the measurement of the local sky luminance $L_L = L_A + L_B$ or of the limiting magnitude M_L at that site and on the influence of each installation h in order to foresee in quantitative terms both the benefits and the costs as a basis for deciding whether to enforce such restriction or not.

An urban installation h is identified with a diffusing source but for a fraction F_h of the luminous flux emitted by the rural installation luminaires visible at low elevations, according to the model described in [SOARDO 2008]. The artificial sky luminance L_{Ah} over a site at a distance D_h from that town, with an installed luminous flux Φ_{Th}, an average reflection factor of the lit surfaces ρ_h and an average upward emission ratio $R_h = \Phi_{20\,h}/\,\Phi_{Th}$ for the fraction F_h of visible luminaires, is given by:

$$\begin{aligned} L_{Ah} &= K \cdot \Phi_{Th} \cdot \\ &\cdot D_h^{-2,5}\left\{\begin{matrix}\left[(d+e)\rho_h(1-F_h)\right]+ \\ \left[F_h\left(R_{20}+(1-R_{20})\rho_h(d+e)\right)\right]\end{matrix}\right\} = \\ &= K \cdot \Phi_{Th} \cdot D_h^{-2,5}\begin{bmatrix}(d+e)\ \rho_h(1-F_h \cdot R_h)+ \\ +F_h \cdot R_h\end{bmatrix}, \end{aligned} \quad (8)$$

where e = 0,06. The coefficient K depends on local environmental conditions and in the upper line the first and the second terms into square brackets identify urban and rural sources. Since L_A is additive:

$$\begin{aligned} L_A &= \sum_n L_{Ah} = K \cdot \sum_n \Phi_{Th} \cdot \\ &\cdot D_h^{-2,5}\begin{bmatrix}(d+e)\rho_h\left(1 - F_h \cdot R_{20h}\right) + \\ + F_h \cdot R_{20h}\end{bmatrix}, \end{aligned} \quad (9)$$

where n is the number of the sources h, F_h is the fraction of rural installations, i.e. 1 for all rural sources and 0 in case of all urban installations. Assuming K constant around a site, the weight W_h of the source h on L_A is equation (10), where L_{Lh} is the local sky luminance due to the source h. From equation (10) the relative contribution L_{Ah} of light source h to the artificial sky luminance L_A is:

$$\frac{L_{Ah}}{L_B} = W_h \cdot \left(\frac{L_L}{L_B} - 1\right). \quad (11)$$

ΔM_L in equation (1) is not a linear function of L_A and it is not the sum of all the ΔM_{Lh} due to each single light source h, i.e. $\Delta M_L \neq \Sigma_h \Delta M_{Lh}$. However, it is possible to estimate the effect of the source h on ΔM_L. A first method evaluates the reduction of the limiting magnitude ΔM_{Lh} over the site due to the source h alone without any other source. Equation (1) can be thus referred to L_{Ah}:

$$\begin{aligned} \Delta M_{Lh} &= -2.5 \cdot \log\left(1 + \frac{L_{Ah}}{L_B}\right) = \\ &= -2,5 \cdot \log\left(1 + W_h\left[\frac{L_L}{L_B} - 1\right]\right) = \\ &-2,5 \cdot \log\left\{1 + W_h\left[10^{-0,4(M_L - M_B)} - 1\right]\right\}, \end{aligned} \quad (12)$$

where W_h can be calculated through equation (10) or (11), L_L or M_L, the sky luminance in terms of mag/arcsec^2 more familiar to astronomers, are measured at the site and L_B or M_B in a close site with similar atmospheric pollution and low artificial sky luminance.

It is to be noted that equation (1) and (9) to (12) depend on either ΔM_L or the ratio L_L/L_B and not on the actual values of magnitudes and luminances separately. Moreover, all equations are valid for any type and mixture of sources: urban, rural, parts of towns and even single luminaires.

7. ANALYSIS OF A SITE

Since it is difficult, if not impossible, to predict the quantitative improvements of the sky luminance

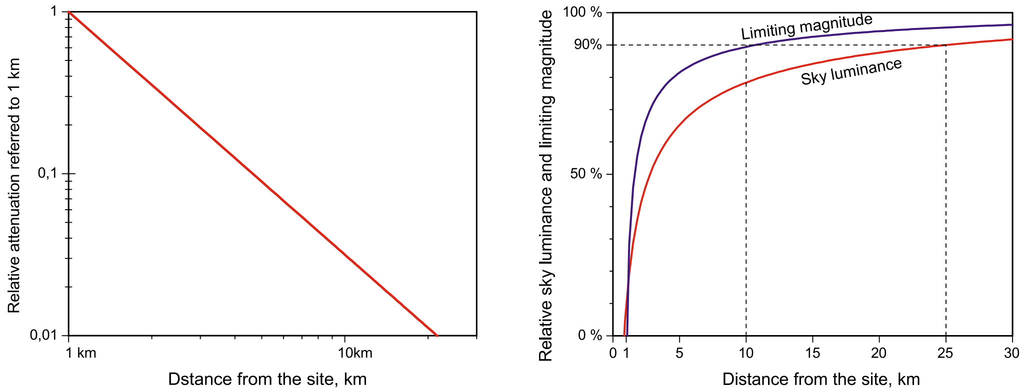

Fig. 7. Relative influence of the light source vs. distance with reference to the same source placed at 1 km form the site (left); relative influence of a uniformly lit territory around a site via distance on sky luminance and limiting magnitude over the site starting at 1 km from the site: the decrease of limiting magnitude reaches 90% of its asymptotic value at 10 km from the site

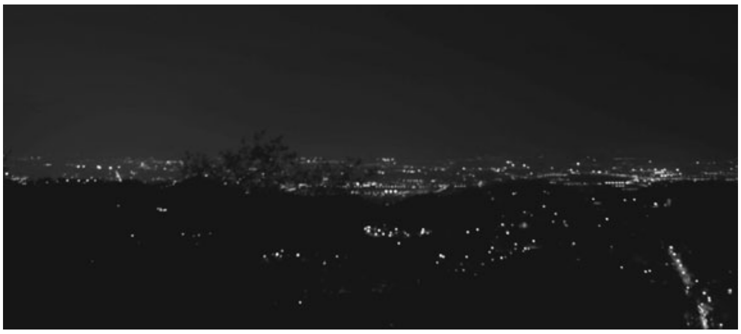

Fig. 8. A view of Turin from the observatory. About 1000 luminaires are visible out of some 50000 installed in the part of the town visible, demonstrating that Turin behaves as a diffusion source

and the consequent costs due to empirical reductions of the upward emissions, it is much easier and efficient to change the focal point from the luminaire to the site. The evaluation proposed here of the weight of each light source is an appropriate way for analysing where sustainable costs produce the best benefits in terms of both sky luminance and energy savings. This analysis should be considered a sort of screening of the light sources surrounding a site aimed at verifying which action is more efficient and on which source, preliminary if necessary to more deep analyses. The analysis of the weight of each light source can be carried out through a dedicated Excel sheet according to what said at § 6, introducing in the sheet the town around the site, with their installed luminous flux and their distance from the site.

This sheet is composed of two parts. In the first all general quantities related to the light sources around a site and to the sky luminance over the sites can be shown with their suggested default values. In the second part below the detailed data about each source must be entered. It is not necessary to extend the analysis to very far distances since according to Walker's law, light attenuation is very quick: Fig. 7 (*left*) shows the relative influence of the light source versus distance with reference to the same source placed at 1 km from the site and (*right*) the relative influence of a uniformly lit territory around a site versus distance on sky luminance and limiting magnitude over the site starting at 1 km from the site: the decrease of limiting magnitude reaches 90% of its asymptotic value at 10 km from the site.

8. A CASE STUDY

As a direct application of this method an exercise was carried out on an observatory, used today mainly for didactics, situated in Pino Torinese on a hill at an elevation of 12 km and about 300 m over the city of Torino. Fig. 8 is a view of Turin from the observatory. Only about 1000 luminaires are visible out of some 50000 installed in the zones of the town visible in Fig 8, demonstrating that Turin behaves as a diffusing source.

Table 2. Luminances over the observatory of Pino Torinese

Analysis of territory Contribution to sky luminance of 72 towns around the site			
Town	Population	Distance from site, km	Contribution to sky luminance, %
Chieri	33 000	5,8	2
Pino Torinese	8 000	0,7	85
Torino	850 000	12,1	7
68 towns	-	≤20	6

The analysis included 72 small towns within a 20 km radius of Turin, i.e. practically the whole disturbing lit area, since, according to the Walker's law the influence of a light source decreases very quickly with distance.

Table 2 reports the weight on sky luminance over the observatory due to 3 towns with a whole weight of 94 %. Distance is more important than luminous flux. Pino Torinese with less than 9000 people contributes more significantly than Turin with its nearly 1 million inhabitants, by 85 % to 7 % respective contribution. Much better to operate on Pino Torinese: a reduction of 50 % of the light levels improves the visibility of the night sky by about 0,6 magnitudes. With on site measurement and the theorethical model implemented it is possible to focus on the most significant contribution and predict the effects on sky glow of the possible choices on the lighting plants.

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