MODELLING LIGHT POLLUTION FROM SEARCHLIGHTS

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ABSTRACT. I analyzed with a simple double scattering model the artificial sky luminance produced by the Light Pollution coming from an advertising searchlight. I evaluated both the artificial luminance produced by direct illuminance of atmospheric particles and molecules on the line-of-sight and that produced by light scattered once. I take in account the height above sea level of the observing site and the orientation of the beam.

1. Introduction

The night sky is a world heritage. The increasing concern of the astronomical community for the growth of the sky brightness due to artificial lighting was expressed in a number of official documents and positions, as the Resolutions of the International Astronomical Union General Assembly (Resolution XVI/9 1976; Resolution XIX/B6 1985; Resolution XX/A2 1988; Resolution 1997) and the positions of many national astronomical societies and organizations (e.g. the American Astronomical Society; the XXXIV Assembly of the Societá Astronomica Italiana). The Commission Internationale de l'Eclairage (CIE) itself undertakes to give consideration to this concern.

Nevertheless, in some countries to the diffuse sky glow produced by outdoor night lighting and big billboards joins the light pollution produced by advertising searchlights. They light directly the sky to get attention of people and to signal the presence of some commercial activity. Not rarely they are installed even in the nearby of an astronomical observatory. Where laws or regulations against light pollution exist, they are prohibited or strictly regulated. As an example, the City of San Diego outdoor lighting control ordinance prohibits operation of searchlights for advertising purposes between 11:00 pm and sunrise, Tucson and Pima County Arizona Outdoor Lighting Control Ordinance (1987) prohibits the use of Laser source light or any similar high intensity light for outdoor advertising or entertainment when projected above the horizontal. Law of the Kingdom of Spain in protection of Canary Island Observatories states that exterior lightings, except those necessary to guarantee aerial navigation, should avoid emission above the horizon. In Italy the Law n.22 1998 of Veneto Region prohibits light beams towards the sky inside 25 km from the protected professional observatories and prescribes that they have to be oriented at least at 90 degrees from the directions of the observatories in the range from 25 km to 50 km. The Law n.17 1998 of regione Valle d'Aosta states that beams oriented upward are prohibited everywhere in side the territory of the Region. Many cities ordinances prohibit advertising searchlights in compliance with Road Code because they can distract car drivers.

The light scattered by searchlights was studied by many authors in order to determine optical characteristics of atmospheric aerosols or the vertical distribution of atmospheric components and from late thirties to the introduction of modern lidar sensing techniques it constituted an important way to study our atmosphere (e.g. Hulburt 1937, 1941, 1946; Johnson et al. 1939; Romantzov and Khvostikov 1946; Mikhailin and Khvostikov 1946; Smirnov 1946; Elterman 1954, 1962, 1964, 1966; Gordon et al. 1975). These authors, nevertheless, were mainly interested to observe the light scattered once by particles inside the beam and considered high order scattering as a disturbance to their determinations. Furthermore, they were interested to measure the brightness only along the axis of the beam and not in the sky near the beam (but see Hulburt 1941). Some theoretical works were also developed (e.g. Hunt 1968; Rybicki 1971; Romanova 1971, 1973).

The Light Pollution produced by light wasted by outdoor night lighting was studied in good detail in the last 25 years. From the theoretical point of view, studies started with the seminal work of Treanor (1973) and evolved in the following years (e.g. Pike 1976; Berry 1976; Yoke *et al.* 1986; Garstang 1984, 1986, 1989a, 1989b, 1989c, 1991a, 1991b, 1991c, 1992, 1993, 1999; Joseph *et al.* 1991). A review is in Garstang (1991a). All these authors studied the artificial sky luminance produced by composed sources like the lighting system of a city or an industrial installation, not the pollution produced by a single fixture. In this paper I apply a simple double-scattering model based partly on the approach of Garstang (1986, 1989a, 1991b) to predict the artificial sky luminance produced by an advertising searchlight in order to determinate its disturbance to the astronomical observations. In section 2 the radiative-transfer model is described and discussed. In section 3 results are presented. Section 4 summarizes the conclusions.

2. Model description.

The beam is assumed to be emitted from a point source C at a height H_C above the sea level and at a distance D from the observing site O at a height H_O above the sea level. In order to became simple the beam is assumed to produce an output flux for unit of solid angle $F(\theta)$, where θ is the angular distance from the axis of the beam, given by:

$$F(\theta) = \frac{P \times \eta}{\Delta} \qquad \theta \leq \theta_0 \qquad\qquad F(\theta) = 0 \qquad \theta > \theta_0 \tag{1}$$

where Δ is the angular area of the beam in units of solid angle (assumed to be little), P is the power of the searchlight and η is the efficiency of the system lamp+fixture in the adopted photometric band. When available, the use of the true distribution of luminous intensity of the luminaire would be preferable. The orientation of the beam axis is determined by its azimut γ_b and its altitude α_b. I modelled the Light Pollution produced by the searchlight using the Garstang (1986) approach and neglecting Earth curvature. The effect of curvature is to produce a more rapid fall-off of sky luminance with distance at large distances but applications in this paper are limited inside 50 km from the observing sites where the effect of curvature is less than 2% (Garstang 1989a).

A telescope of area $\frac{\pi d^2}{4}$ situated in the observing site O collect from within a section $dV = \left(\pi\epsilon^2 u^2 du\right)$ of the cone of angle 2ϵ around the line-of-sight with thickness du at a distance u, a luminous flux $d\Phi$ given by:

$$d\Phi = \frac{\pi d^2}{4}\frac{1}{u^2} M_s(u)\xi_1(u)\left(\pi\epsilon^2 u^2 du\right) \tag{2}$$

where $M_S(u)$ is the luminous flux scattered toward the observer from particles of aerosol and molecules inside a unitary volume at the distance u along the line of sight. $\xi_1(u)$ is the extinction of the light during the path to the telescope:

$$\xi_1(u) = exp\left(-\int_0^u \left(N_m(x\sin\alpha)\sigma_m + N_a(x\sin\alpha)\sigma_a\right) dx \quad cosec\ \alpha\right) \tag{3}$$

where $N_M(h)$ and $N_a(h)$ are the vertical number densities of molecules and aerosols, and σ_m and σ_a are their scattering sections and α is the altitude of the line-of-sight.

The artificial sky luminance b, expressed as total flux for units of area of the telescope and for units of solid angle is found integrating the eq. 2:

$$b = \int_0^\infty M_s(u)\xi_1(u)du \tag{4}$$

The average illuminance of the element of the cone is the sum of the direct illuminance from the source and that produced by the light which reaches the element after some intermediate scattering events, estimated as below. The luminous flux for units of solid angle coming *directly* from the beam and scattered toward the observer from a unitary volume along the line of sight is:

$$M'_S(u) = \left(N_m(u\sin\alpha)\sigma_m(\psi) + N_a(u\sin\alpha)\sigma_a(\psi)\right) \times \left(\frac{F(\theta)}{s^2}\xi_2(s)\right) \tag{5}$$

where the angles ψ, θ and the distance s of the section from the source depend from the distance D, the azimuth and altitude of the line-of-sight (α, γ) and of the beam axis (α_b, γ_b), and the distance u along the line of sight through geometrical relations. The extinction $\xi_2(s)$ between the source site and the considered section is:

$$\xi_2(s) = exp\left(-\int_0^s \left(N_m(x\sin\gamma_b)\sigma_m + N_a(x\sin\gamma_b)\sigma_a\right) dx \quad cosec\ \gamma_b\right) \tag{6}$$

A single scattering model is not sufficient to describe the sky luminance produced by a searchlight. In a real atmosphere several scatterings may occur during the travel of a photon from the source to the telescope. Moreover, it is possible to estimate the sky luminance in directions for which the line-of-sight does not intersect the beam only taking into account at least two scatterings. The optical thickness $\tau = \int kdr$, where k is an attenuation coefficient, determines how important secondary and higher scattering is.

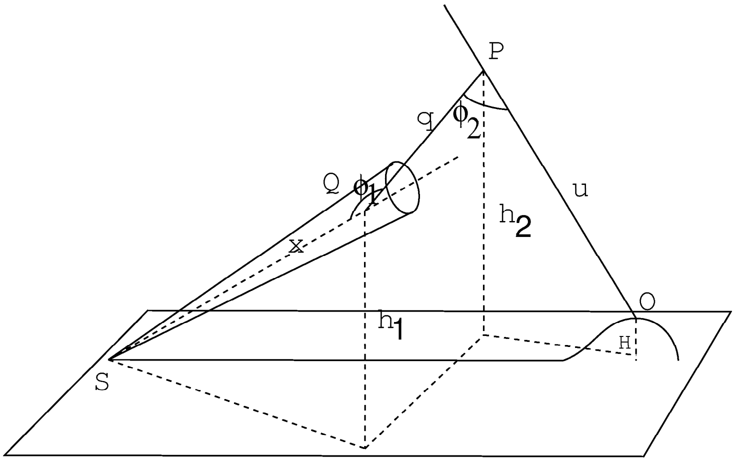

Fig. 1. Geometrical relationships for double scattering.

If $\tau >> 1$ (thick layer) multiple scattering is dominant. The fraction of incident radiation which has been scattered once is $(1 - e^{-\tau})$ and the fraction which it is scattered again is of order $(1 - e^{-\tau})^2$. If $(1 - e^{-\tau})$ is sufficiently small, which happens when τ is small, secondary and higher order scattering can be neglected. In absence of aerosol the optical thickness of the atmosphere at wavelength of 0.55 μm is about 0.1 (Twomey 1977). The aerosol optical thickness can be 0.05 in cleaner regions of the globe, but it can grow to higher values, even in dependence of seasonal changes (Garstang 1988). Then single scattering is the major contributor to scattered radiation but secondary scattering is not negligible. A double scattering model give only an approximation of the searchlight pollution and the error in neglecting third and higher order scattering can be significant for optical thickness higher than about 0.5. In order to take in account at least two scatterings, I computed, for each infinitesimal volume dV along the line of sight, the illumination coming from light scattered there by particles and molecules inside the beam. From it I obtained the luminous flux for units of solid angle scattered toward the observer from a unitary volume along the line of sight and coming from light scattered there from particles and molecules inside the beam:

$$M_S''(u) = \int_x \beta(h_1, \phi_1)\beta(h_2, \phi_2)\xi_a(q)\frac{F(\theta')}{q^2}\xi_b(x)dx \tag{7}$$

where $\beta(h, \phi) = N_m(h)\sigma_m(\phi) + N_a(h)\sigma_a(\phi)$. The angles ϕ_1, ϕ_2, θ', the altitudes h_1, h_2 and the distance q depend from the distance D, the azimuth and altitude of the line-of-sight (α, γ) and of the beam axis (α_b, γ_b), the distance u along the line of sight and the integration variable x through geometrical relations. Figure 1 show the geometrical behaviour. The functions ξ_a and ξ_b are the extinctions of the light respectively between QP and SQ with expressions like (3) and (6).

I adopted the same model for the vertical distribution of molecules and aerosols as Garstang (1986) and the optical characteristics like the angular scattering coefficients

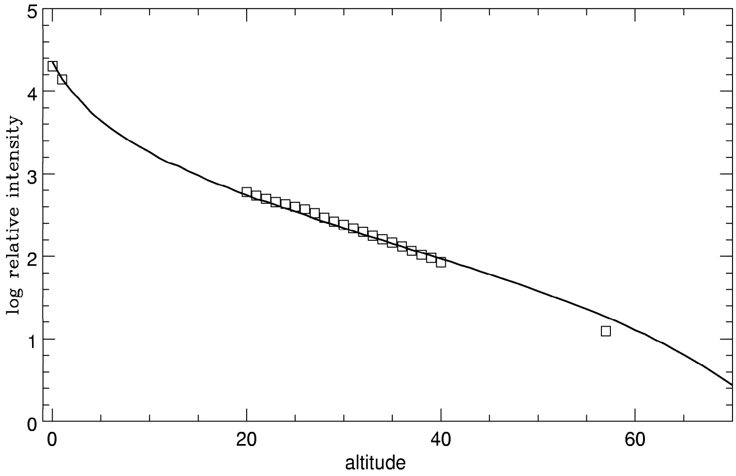

Fig. 2. Comparison between Eltermann(1966) measurement (squares) and model predictions (solid curve).

and scattering sections from Garstang (1986, 1991b), They already were successfully used in models for sky brightness in Italy (Cinzano 1999a,1999b). I calculated the natural night–sky luminance adopting the model described in Garstang (1989a) in the flat-Earth limit. It assumes that 40% of the light comes from the faint star background and a fraction of 60% comes from airglow emission by a van Rhijn layer at a height of 130 km above the ground, as found by Roach and Meinel (1955). The light which reaches the telescope is assumed to be made up of the contribution of the direct transmitted light and the light scattered from the whole sky by molecules and aerosols calculated taking in account double scattering. I assumed the solar activity near the minimum.

Sky brightness in V band can be obtained from sky luminance with Garstang (1986, 1989) formulae. Adopting the proper scattering sections and searchlight efficiency, the sky brightness in other photometric bands can be also computed.

I tested the models with the observations of a searchlight in April 1964 by Elterman (1966) at Sacramento Peak (New Mexico). I adopted $N_a\sigma_a = 9.5\ 10^{-3} km^{-1}$ and $N_m\sigma_m = 8.852\ 10^{-3} km^{-1}$ at the altitude of the beam source (1390 m over the sea level) and an aerosol scale altitude $c = 0.132 km^{-1}$, as inferred by Elterman 's measurements. Dividing the relative intensity measured by Elterman (1966) by the angular area of the searchlight as observed with Elterman 's collector telescope, I obtained a mean luminance distribution with elevation that I compared in figure 2 with the distribution of the luminance predicted by the model along the beam axis. They are in good agreement.

The model of the natural sky luminance was tested by Garstang (1989) comparing his results with measures obtained by Walker (1973) at Junipero Serra Peak. I compared the natural sky luminance predicted by my set of models at Sacramento Peak for the same atmospheric parameters used in Eltermann test with the measurements of Schneeberger

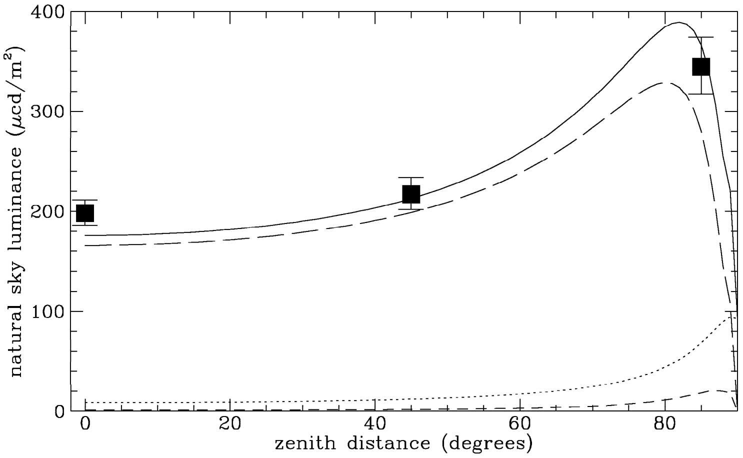

Fig. 3. Natural sky luminance as measured by Schneeberger et al.(1966) at Sacramento Peak(squares) and model predictions (solid curve). Also plotted are the contributions from direct light (long-dashed curve), aerosol scattering (short-dashed curve) and Rayleigh scattering from molecules (dotted curve).

et al.(1979) at zenithal angles 0 °, 45 °, 85 °. I trasformed its sky brightness measurements in V band from magnitudes to cd/m^2 with Garstang (1986) formulae. Results are in good agreement as shown in figure 3. Measures are annual average excluding June (which the authors considered particularly bright) and in Northeast direction (where no light pollution was detected) from table I of Schneeberger et al.(1979). Errorbars are not measurements errors but the standard deviation of the measurements along an year, related also to atmospheric fluctuations. A better fit can be achieved assuming that both natural sky brightness outside the atmosphere and aerosol content are slightly higher.

3. Results.

I computed the artificial sky luminance produced by a searchlight emitting a light flux of 150000 lm. With a mean lamp efficiency of about 90 lumens/watt and a fixture efficiency of the order of 80 percent, this flux would require a lamp with a power of about 2 kw. I assumed a beam aperture semiangle of 2°. High power advertising searchlights with carbon arc lamps have intensities even 8 times stronger than this searchlight (up to 10^9 candlepower). Results can be scaled to other emitted fluxes but other beam apertures require models be recomputed. I assumed a clean atmosphere as defined by Garstang (1986). In order to be simple I also assumed here both source and observer at sea level but other choices are possible.

Figure 4 shows the artificial sky luminance produced by the searchlight at increasing distances. Dotted and dot-dashed curves show respectively the luminance at 30°and 45°elevation for a vertical beam (inclination 90°). Dashed and long-dashed curves show

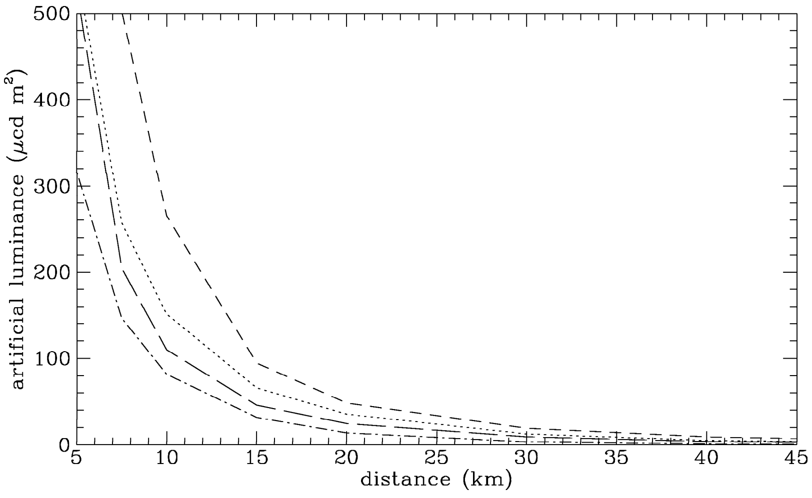

Fig. 4. Artificial sky luminance produced by the searchlight at increasing distances. Dotted and dot-dashed curves show respectively the luminance at 30°and 45°elevation for a vertical beam. Dashed and long-dashed curves show respectively the luminance at 30°and 45°elevation for a beam inclined at 45°toward the observer.

respectively the luminance at 30°and 45°elevation for a beam inclined at 45°toward the observer. The computations were done at distances of 5, 7.5, 10, 15, 20, 30, 40, 50 km and results are interpolated linearly in the figures. The figure shows the dramatic exponential increase of luminance with decreasing distance of the source. Already from this figure readers can notice that a distance of about 25 km is necessary in order that the contribution of this searchlight be lower than 10 percent of natural sky luminance ($\sim$ 200 10^{-6} cd/m^2), which is the limit requested by the recommendation 1 of the IAU Commission 50 (Smith 1979): *the increase in sky brightness at 45° elevation due to artificial light scattered from clear sky should not exceed 10% of the lowest natural level in any part of the spectrum between wavelengths 3000Å and 10000Å.*

However, the disturbance produced by searchlights to astronomical measurements may be even more relevant than the disturbance produced by diffuse glow with the same luminance. Frequently, to call more attention, advertising searchlights orientation has a random motion. This imply not only that the sky area disturbed by the searchlight is more extended than the beam area, but also that the motion of the beam produces a rapid and random varying background luminance. A beam interposing in the telescope field of view would produce a variable increase of photon counts resulting in an additional error on the measurement. Sky limited photometric observations of faint objects can be done down to level of the order of 1/100 of the background sky luminance with errors of 1 percent and probably require a lower limit than 10% on the sky brightness increase produced by the searchlight. The evaluation of this kind of disturbance, together with effects of changes in the spectrum of sky background, is left to subsequent papers.

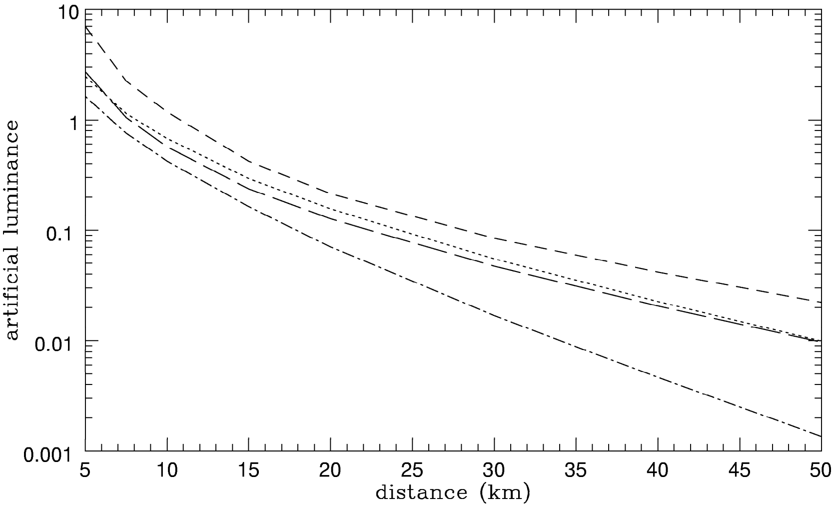

Fig. 5. Artificial luminance produced by the beam in logarithmic scale. Dotted and dot-dashed curves are respectively the luminance at 30°and 45°elevation for a vertical beam. Dashed and long-dashed curves show respectively the luminance at 30°and 45°elevation for a beam inclined at 45°toward the observer.

To these effects must also be added the reflection of the searchlight beam on dense aerosol layers which might be present at random positions and altitudes in dependence of atmospheric conditions. This phenomenon can produce very bright spots and can be another important source of errors which deserves to be studied in detail.

Figure 5 shows the artificial luminance produced by the beam in logarithmic scale. Curves symbology is the same as in figure 4. The figure shows that more than 30 km are necessary in order that over 30°of elevation the artificial luminance does not exceed 1/10 of the natural sky luminance. It can be estimated that more than 60 km are required for this purpose for an high power searchlight with an intensity 8 times higher, but if the beam is vertical only 35 km are necessary. The figure also show that in a moderately polluted site where, as an example, the sky brightness is 3 times the natural value, about 20 km are necessary to avoid a further increase of 10% of the sky luminance in the case of the modelled searchlight but it can be estimeed that about 50 km would be necessary in order to protect the observations from an high power searchlight 8 times more powerful. Only 25 km would be necessary if the beam would be vertical. At least for the considered searchlight powers and beam apertures, these results support the prescription of Law n. 22 1998 of Regione Veneto which prohibite light beams toward the sky inside 25 km from Mount Ekar Observatory and prescribe that they have to be oriented at least at 90 degrees from the direction of the Observatory in the range from 25 km to 50 km.

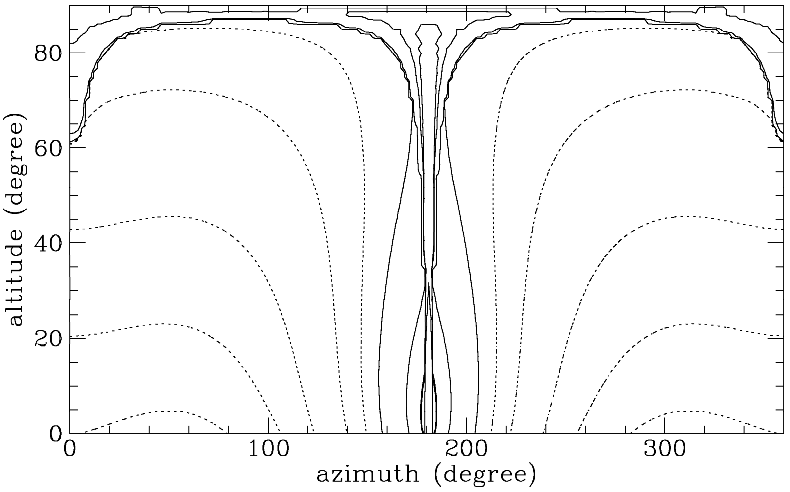

Fig. 6. Artificial sky luminance distribution produced by the searchlight at a distance of 10 km inclined 45°toward the observer. Azimuth 180°is towards the searchlight. Solid isophotes show levels of 2, 10, 50, 57, 200 $\mu cd/m^2$. Dotted isophotes show levels of 0.05, 0.1, .2, .5, 1 $\mu cd/m^2$ which are likely to be important for lower distances and higher powers.

Tab. 1 - Sky luminances along the beam axis

From 0°to 88°zenith distance in step of 2°($\mu cd/m^2$)								
0°	2°	4°	6°	8°	10°	12°	14°	16°
54	55	56	57	58	61	61	60	64
18°	20°	22°	24°	26°	28°	30°	32°	34°
62	64	65	66	70	70	73	73	77
36°	38°	40°	42°	44°	46°	48°	50°	52°
80	85	89	95	100	109	117	131	141
54°	56°	58°	60°	62°	64°	66°	68°	70°
159	176	203	233	274	322	386	493	587
72°	74°	76°	78°	80°	82°	84°	86°	88°
763	997	1262	1938	2664	3731	5887	10548	26100

Figure 6 shows the artificial sky luminance distribution produced by the searchlight at a distance of 10 km when inclined of 45°toward the observer. The effects of second scatter are clearly visible and it can be noted that the area of sky polluted is much larger than the beam area. Solid isophotes show the range under the natural sky luminance, at levels of 2, 10, 50, 57, 200 $\mu cd/m^2$. The level of the natural sky brightness is reached at an elevation of ~32°along the beam. Higher level are reached below this elevation. Dotted isophotes show low levels of 0.05, 0.1, .2, .5, 1 $\mu cd/m^2$ which are likely to be important for lower distances and higher powers. Table 1 shows the sky luminances along the beam axis from 0°to 88°of zenith distance with step of 2°.

The total upward light emission, direct and reflected, from public lighting alone in the italian city of Treviso, computed from a detailed analysis of its fixtures, many of which are flat-glass shelded luminaires poorly polluting, resulted in 90 lm per inhabitant[1] (Medusa 1998). So the upward emission of the considered searchlight (with a power of ~2 kw) is of the order of the upward emission of public lighting of a small town of about 1700 inhabitants.

4. Conclusions

In this paper I apply a simple double-scattering model based partly on the approach of Garstang (1986, 1989a, 1991b) to predict the artificial sky luminance produced by an advertising searchlight in order to determinate its disturbance to the astronomical observations. Main conclusions are:

1. In clear atmospheric conditions, a searchlight emitting 150000 lm with 2°aperture angle and inclined no more than 45°toward the observer produces a sky luminance greater than the 10 percent of the lowest natural level over 45°of elevation (recommendation 1 of the IAU Commission 50 (Smith 1979)) at a distance smaller than 25 km and over 30°at a distance smaller than 30 km.
2. An high power searchlight with an intensity 8 times higher would produce an increase greater than the 10 percent over 30°of elevation at a distance smaller than 60 km.
3. Boundary distance reduces when background sky luminance at the site increases. As an example, if background luminance is three times the natural value, boundary distances to avoid a further increase of 10% of the sky luminance reduces to about 20 km in the case of the modelled searchlight and at about 50 km in the case of an high power searchlight 8 times more powerful.
4. Results support the prescription of Law n. 22 1998 of Regione Veneto, at least for the considered searchlight powers and beam apertures. Higher emitted fluxes or more concentrated beams would require larger protection zones.
5. The polluted area of sky is not restricted to the beam area due to the effects of the second (and higher) scattering.

The effects of (i) the random interposition of the beam on the telescope field of view, (ii) the related changes in the spectrum of sky background, and (iii) the bright spots due at transient denser aerosols layers, deserves further studies to be quantified according to specific kinds of astronomical mesurements.

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[1] The mean total city upward emission per inhabitant in Italy is even more than three times stronger (e.g. Cinzano 1999a,b).

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