From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona

CHRISTIAN B. LUGINBUHL

US Naval Observatory Flagstaff Station, Flagstaff, AZ 86001; cbl@nofs.navy.mil

DAN M. DURISCOE

National Park Service, Bishop, CA 93514; dan_duriscoe@nps.gov

CHADWICK W. MOORE

National Park Service, CIRA, Colorado State University, Fort Collins, CO 80523; moore@cira.colostate.edu,

ANGELA RICHMAN

National Park Service, Curecanti NRA, Gunnison, CO 81230; angie_richman@nps.gov

G. WESLEY LOCKWOOD

Lowell Observatory, Flagstaff, AZ 86001; gwl@lowell.edu

DONALD R. DAVIS

Planetary Science Institute, Tucson, AZ 85719; drd@psi.edu

ABSTRACT. We present panoramic sky brightness measures in the Johnson V band made at the US Naval Observatory Flagstaff Station. We find that these measures show much less sky glow from Flagstaff than expected using the total light output and unshielded fraction determined recently by Luginbuhl et al. and Garstang's 1991 modeling approach. We suggest the difference arises principally from the diminution of upward-directed light after emission from light fixtures and reflection from the ground due to interaction with structures and vegetation. This interaction not only reduces the effective albedo, it also disproportionately reduces flux emitted upward at angles near the horizontal. We explore the size and consequences of this factor in light pollution modeling, and propose a modified upward angular distribution function to account for this effect.

1. INTRODUCTION

Garstang (1986, 1989, 1991) has developed a model useful for predicting sky glow produced by outdoor lighting. This model has become the standard in the field, though it has been elaborated upon to some degree and for particular circumstances by the work of Cinzano (2000), Cinzano et al. (2000), and Cinzano & Diaz Castro (2000). This model has been fundamentally a "sky-down" approach, using measures of sky brightness to deduce the otherwise largely unknown characteristics of on-the-ground lighting. The model has since been used primarily to predict sky glow based on these derived ground "measures." These measures include total lumen outputs (usually combined with population estimates and expressed as lumens per capita), fraction emitted above the horizontal (uplight), and average ground albedo. An uplight intensity versus zenith angle relation, critical to the model, is assumed, based on a combination of Lambertian reflection from the ground and a direct uplight com-

ponent proportional to zenith angle to the fourth power. This composite distribution is assumed not only to represent the intensity of light reflecting from the ground and exiting fixtures in an upward direction, but also to identically represent the distribution of light entering the atmosphere to produce sky glow.

Luginbuhl et al. (2008, hereafter GU1), for purposes of understanding the sources of light that generate artificial sky glow, report on the total light output measured for Flagstaff, Arizona, derived not from sky brightness measures but from a survey of light sources on the ground. They find a lumen output between 3150 and 2520 lm per capita (with sports lighting on and off, respectively), values 2.5 to 3 times those deduced by Garstang in his studies and by other workers using his models (see the review in GU1). In this paper, we show that the GU1 value is also much higher than the light output deduced using measures of sky glow over Flagstaff and Garstang's models. We propose that the source of this discrepancy lies in the assumption that the uplight angular distribution arising from direct fixture

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emanations and ground reflection is the same as that entering the atmosphere to produce sky glow.

In § 2, we describe sky brightness measures made at the Naval Observatory Flagstaff Station, and compare them to a detailed model of sky glow based on the lighting survey described in GU1 using Garstang's approach. Section 3 discusses the interaction of light with objects in the near-ground environment between the time it exits fixtures or reflects off the ground and ultimately propagates unimpeded into the atmosphere. Section 4 presents our summary and conclusions.

2. SKY BRIGHTNESS AND LIGHT OUTPUT OF FLAGSTAFF

2.1. Sky Brightness Observations

The panoramic sky brightness at the US Naval Observatory Flagstaff Station was measured 2004 September 16 between 0714 and 0730 UT (0014 and 0030 MST) using the National Park Service (NPS) camera system and procedures described by Duriscoe et al. (2007). The sky brightness values were calibrated using 148 *Hipparcos* stars with known Johnson V values extracted from the same images from which the sky brightness measures are extracted. Extinction was measured as 0.154 ± 0.002 mag airmass^{-1}. The mosaic image is presented in Figure 1.
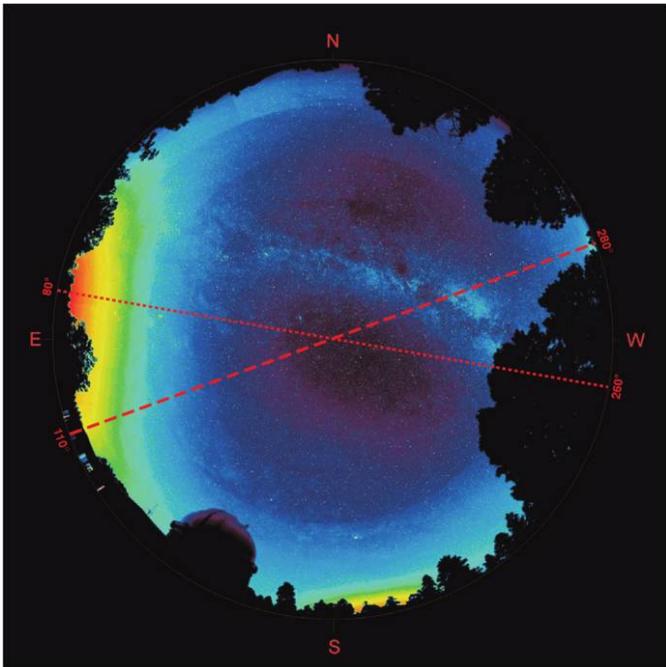

FIG. 1.—False-color "fish-eye" view of the sky over the US Naval Observatory Flagstaff Station, displaying data obtained with the NPS camera system. The dome of the 1.55 mm Kaj Strand telescope is visible, as well as the sky glow from Flagstaff ~8 km to the east and from the Phoenix metropolitan area ~150 km to the south. *Dotted line*: azimuth from which data were extracted for Fig. 3; *dashed line*: azimuth displayed in Fig. 4.

2.2. Sky Brightness Model

Sky brightness predictions were produced beginning with the Flagstaff light output data from GU1, combined with position information from the Flagstaff GIS database. These data included 6310 individual sources representing commercial, industrial, institutional (municipal, schools), roadway, multifamily residential, and sports lighting, as well as approximately 16,000 residences broken down into a 25×20 rectangular grid of points where each point included the light of all residences within each grid cell. Information used for each light source included total flux in lumens, fraction emitted directly upward, and position (latitude, longitude). An additional estimate of the lighting for Bellemont, Arizona was added to the GU1 database (5.2 Mlm, 5% direct uplight), located approximately 11 km at azimuth 300° from the observing site. These light sources serve as input to a program implementing Garstang's (1991) light propagation model that produces the predicted V-band sky brightness as a function of zenith angle at a specified azimuth. The Flagstaff light sources used in the model are shown in Figure 2.

Sky brightness measures from the two azimuths indicated in Figure 1 and Figure 2 were extracted from the observations and compared to models for these azimuths, with results shown in Figures 3 and 4. These azimuths were chosen as they offered the clearest view toward the horizon in the direction of Flagstaff, working around trees located near the observation site. The 110°–290° azimuth offers the additional advantage of a clear western horizon.

The heavy solid lines in Figures 3 and 4 are Garstang models using the total light outputs, uplight fraction, and locations from GU1, supplemented with estimated data for Bellemont, Arizona, as described. The average ground albedo is 0.15, while the parameter K, describing the ratio of aerosol to molecular scattering, is set to 0.31 as determined from the measured

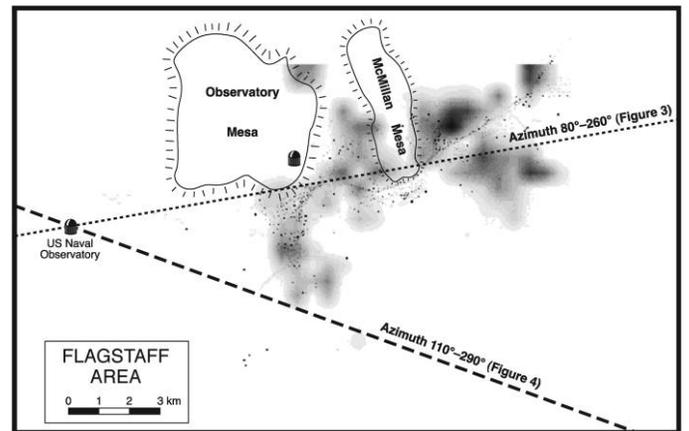
FIG. 2.—Light sources in Flagstaff from the GU1 study. The location of the US Naval Observatory Flagstaff Station is indicated, as well as the azimuths for sky brightness observations displayed in Figs. 3 and 4. *Gray areas*: output from residential lighting; all other lighting is indicated as point sources. The approximate locations and extents of Observatory and McMillan Mesas are indicated.
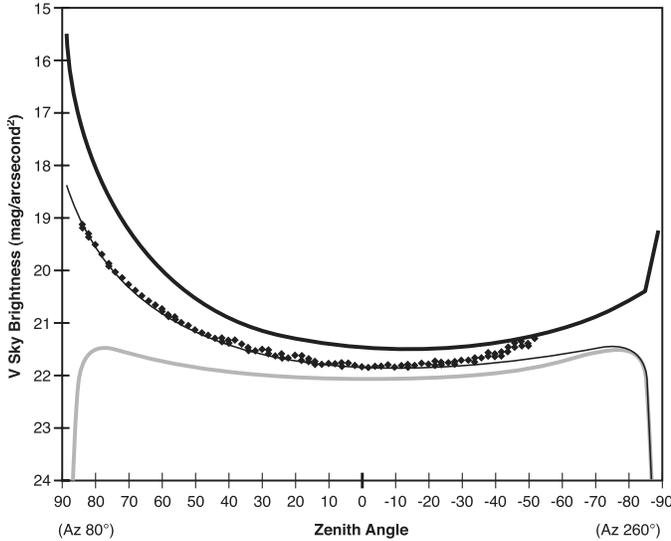
FIG. 3.—Sky brightness observations (*diamonds*) falling within ±2° of azimuth 80°–260°; extracted from the dataset illustrated in Fig. 1. *Gray line*: natural sky brightness, expected at solar minimum with no artificial light sources. *Thick solid line*: standard Garstang model based on the light outputs of GU1. *Thin solid line*: our model discussed in § 3.2.2 (eq. 2), with $\beta = 0$ and $E_b = 0.4$. Observations in zenith angle ranges of −30° to −55° fall in the Milky Way.

extinction coefficient (cf. eq. [6] of Garstang 1991). This model shows a predicted brightness much greater than that observed, from 0.49–0.52 mag too bright at the zenith to 0.85–0.88 mag too bright at zenith angle 45° toward Flagstaff, with increasing divergence at greater zenith angles.
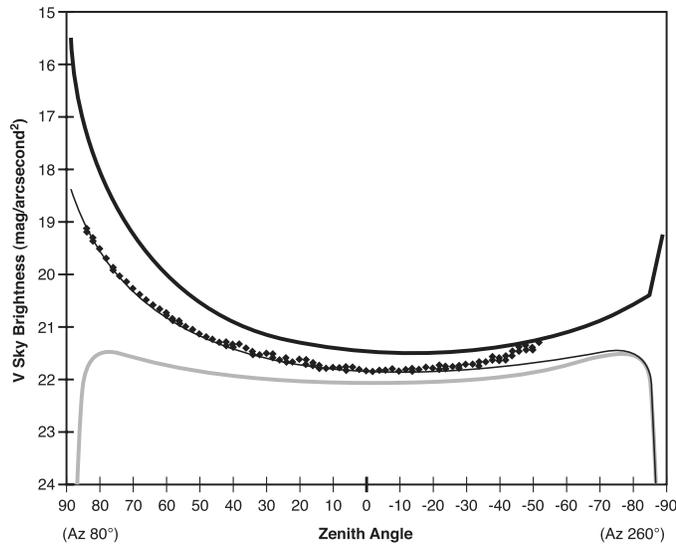

FIG. 4.—As Fig. 3 except for observations falling within ±2° of azimuth 110°–290°. *Thick solid line*: as described for Fig. 3. *Thin solid line*: from the model described in § 3.2.2 (eq. 2), with $\beta = 0$ and $E_b = 0.5$. Contamination from the Milky Way is evident from zenith angles −10° to −60°.

An apparent anomaly is the lack of a turnover in sky brightness toward the western horizon (Figure 4). This effect is likely due to automobile headlights that are directed almost straight toward the observatory from a several-mile section of the eastbound lanes of Interstate 40, which is not accounted for in the lighting database. That automobile headlights can make a significant contribution is clearly visible in time-lapse images taken with a modified NPS camera using a fish-eye lens.

The standard Garstang model, using as input light flux the "ground-up" outputs measured in GU1, clearly predicts a much brighter sky than that measured. In the following section we explore a neglected factor in Garstang's models that could account for this difference.

3. EFFECTS OF THE NEAR-GROUND ENVIRONMENT ON LIGHT PROPAGATION

3.1. Background

The lumen outputs of GU1 represent mean lamp lumens escaping from light fixtures (which they term "effective lumens"), split into downward- and upward-directed components. Other than accounting for simple Lambertian reflection of the downward component from a horizontal ground surface, previous work has not differentiated, or has scarcely differentiated, between these "effective lumen" values and the values escaping upward into the atmosphere to produce sky glow (Garstang 1986, 1989; Cinzano 2000). In a real environment, with not only light sources but structures, vegetation, and terrain that interact with the light after it exits fixtures, accurate prediction of the amount of light escaping into the atmosphere to cause sky glow requires detailed information on the angular distribution of the rays exiting the lighting fixtures; the geometric positions, orientations, and reflective characteristics of any surfaces or objects upon which the light is incident; and the propagative characteristics of the atmosphere as a function of position and altitude.

Workers in this field, beginning with Garstang (1986, 1989, 1991) have treated the latter, principally radiative transfer portion of this problem, including molecular and aerosol scattering and absorption, provisions for absorptive (haze) layers, differing altitudes of light sources (cities) and observation points, Earth curvature, and simple large-scale blocking by terrain features (mountains) between the light source and point of observation. Issues including the angular distribution of emergent light rays, the reflectivity of the ground and other surfaces, and the geometric characteristics of the built and vegetated environment have been less thoroughly treated. All workers beginning with Garstang (1986) have simplified this enormously complex problem.

Garstang assumed an upward-directed angular light distribution that is a composite of a Lambertian distribution arising from light reflected from a horizontal ground surface combined with a ψ^4 component (ψ measured from the zenith and truncated at the horizon), normalized to a total of 10% of the total light flux

in his "standard model," arising from light emitted directly upward from incompletely shielded lighting fixtures. He then generally applied a (scalar) figure of 15% for ground albedo, based on the idea that lights are located predominantly over paved surfaces, and on figures from the engineering literature showing that worn asphalt reflects between 12% and 14% of incident light while worn or dirty concrete reflects between 16% and 18%.

This composite angular distribution (Figure 5), when used in Garstang's atmospheric propagation models, is found to give results in reasonable agreement with available measurements, though critical parameters of the model are determined by essentially the same measurements. Other authors have continued to use this or slightly modified but similar relations (Cinzano 2000), and also find reasonable agreement with measurement.

But Garstang's model makes three assumptions that may not accurately reflect most real outdoor lighting environments. The first assumption is that all downward-directed lighting, no matter the direction relative to nadir, is undiminished by any atmospheric scattering or absorption: he assumed no atmosphere between the light fixtures and the ground. The second assumption was that the ground near the light sources was everywhere flat and horizontal: he assumed that locally the Earth is perfectly smooth. As a consequence of this assumption, he implicitly makes a third assumption, that all rays reflected from the ground or emitted from fixtures directly upward propagate into the atmosphere, unimpeded by any further interaction with surfaces.

The first assumption seems reasonably robust (particularly in light of the discussion below), since light fixtures in general direct the majority of their output not further than about 60° to 70° from nadir in order to bring the light to the ground before excessive dilution by the inverse square law, thus providing a

Fig. 5.—Garstang's "standard model" upward intensity angular distribution function (intensity vs. ψ, *solid line*), consisting of a Lambertian component produced by a relative flux of 0.90 reflecting from a 15% albedo horizontal surface (*dashed line*) and a direct upward component with relative flux of 0.10 and intensity proportional to ψ^4 (*dotted line*).

useful illumination level at the ground. (There are, of course, notorious exceptions.) Such light rays will reach the ground, in general, within two to three mounting heights of the light fixture, and atmospheric effects over such distances can be realistically neglected. Light rays exiting fixtures closer to (but still below) the horizontal, though they would eventually strike the ground on a "smooth Earth," in most real environments would be more likely to strike a structure or vegetation before suffering substantial diminution due to atmospheric effects, an effect discussed further below. Neglecting the scattering and absorption of these light rays will lead to an underestimate of the sky brightness visible to those observers who are located relatively nearby to the fixtures and observing upward with lines of site crossing these rays; the consequence for observers located at even moderate distances (more than a few hundred meters or so) from the light sources is likely to be negligible, due to the near-ground blocking.

But regarding the second, smooth Earth assumption: light rays striking surfaces that are not horizontal leads to an effect that effectively reduces the average albedo, independently of the actual average reflectivity of the surfaces, and alters the angular distribution of the rays escaping into the atmosphere. For a flat horizontal surface, as assumed by Garstang, if the average reflectivity is 15%, then 15% of the flux striking this surface will be reflected back upward and into the sky. But if a portion of the light exiting the fixture strikes a surface oriented perpendicular to the ground (such as the side of a building), then, assuming the surface is Lambertian, only 50% of the reflected light will be directed upward; the remaining 50% will suffer at least another reflection before being directed upward, greatly diminishing its intensity. Compounding this effect, the same structures or vegetation block, to an even greater degree, high zenith angle light paths from the ground to the atmosphere, and to a lesser extent block especially near-horizontal upward paths from fixtures located at some distance above the ground. In heavily built or vegetated environments, this related effect leads to a further substantial reduction in the effective albedo, and most heavily affects rays directed close to the horizontal.

These interactions with the near-ground environment likewise require a reconsideration of Garstang's third assumption, that the angular distribution of light rays entering the atmosphere is described by the Lambertian plus ψ^4 angular distribution of rays emitted directly upward from fixtures. Garstang (1986), in describing his reasoning for the ψ^4 component, admits that the choice is entirely arbitrary, that he used it because it has what he views as the required characteristics of zero emissions directly upward and a rapid increase toward the horizon. He further states "These properties seem to be true for most street lights and for at least some other forms of outdoor lighting." While this reasoning seems appropriate when considering luminaires in isolation, the structure of the environment surrounding the luminaires drastically modifies this distribution of light rays before they ultimately propagate into the atmo-
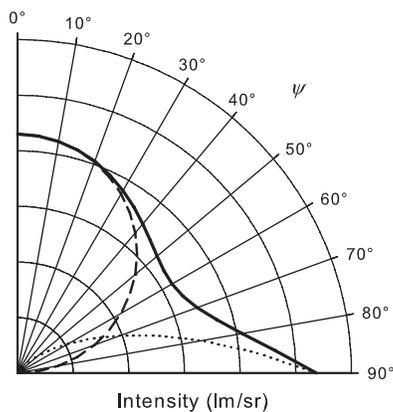
sphere. Indeed, an individual fixture that is visible from all upward angles from the zenith to the horizon, if poorly shielded, will have dramatically increased intensity toward the horizon. But, in fact, the natural and the built environment conspire to block the visibility of most fixtures as viewing angles approach the horizon. This is apparent when one considers the view of a city from some altitude overhead, such as in an airplane, where thousands of lights are visible. But the majority of fixtures become blocked from view by objects in the near-ground environment when viewed from near the horizontal, generally leaving only those nearby visible.

Garstang (1989, p. 322) as well as Cinzano (2000) and Cinzano & Diaz Castro (2000) recognized this problem to a degree. Cinzano also investigated two additional upward angular intensity distribution functions, but these functions are either little different from Garstang's "standard model" or unsupported by any rationale (the "constant intensity" model). Both exhibit strong emission toward the horizon. Falchi & Cinzano (2000) investigated the light output of Italian cities as a function of population, and found evidence that light output per capita tends to decrease for the larger cities. They hypothesized that this effect might be due to a higher concentration of persons per unit area in large cities, and that such densely populated areas may have fewer street lights than lower density areas. This effect, however, may be illustrating the above-mentioned near-ground blocking effect, expected to be dramatic in heavily built areas.

Garstang (1986) indicates that the light output of extended areas surrounding urban centers, developed at low intensity, can be neglected when predicting light outputs contributing to sky glow. Berry (1976), in describing sky brightness measures made within southern Ontario cities, suggests that the light from distant parts of the cities is attenuated more than that originating near the observation point in the inner city, but does not indicate the source of this attenuation. Both of these effects may be hinting at the generally large amount of blocking by vegetation.

Cinzano & Diaz Castro (2000) show that light pollution, assuming the angular distribution function from Garstang (1986), when viewed from some distance from the light pollution source, is much more heavily influenced by light emissions at low angles above the horizontal than by emissions at higher angles. They find that the flux emitted between the horizon and 10° above the horizon has an effect on the zenith sky brightness at a remote site equal to all of the flux emitted between 10° above the horizon and the zenith. It is therefore critical to have more knowledge of the actual amounts of light escaping from cities at angles near the horizontal, information which was not available in the study by Cinzano et al. (2000). The analyses presented here indicate that the upward intensity distribution function assumed by Garstang, and other similar functions heavily weighted toward the horizon, are not likely to represent the actual upward light distribution in most cities.

3.2. Estimating the Effects of the Near-Ground Environment

We examine the nature and magnitude of near-ground interactions by two methods. The first method develops several specific built environments and explores their effect on the propagation of light from specific light fixtures. The second method is an analytic approach that assumes a standard Garstang intensity distribution originating at the ground/light sources but modified by an extinction factor like that applied to model the extinction of starlight produced by the atmosphere, but instead here applying to interaction of light rays with discrete obscuring objects located near the ground.

3.2.1. Interaction of Light with Built Environments

Using the lighting calculation software package AGI32 (ver. 1.96, Lighting Analysts, Inc.), we explored how several built environments affected the total amount and angular distribution of light propagating upward. This program propagates light emerging from light fixtures with defined candlepower distributions through a perfectly transparent atmosphere and traces its interaction with surfaces whose positions, orientations, and reflectances are defined by the user. It assumes Lambertian reflections for all surfaces. The performance of the program was verified by placing a fully shielded fixture (no direct uplight) over a plane with reflectance of 0.15, a smooth Earth model. The intensity of light striking the inside of a nonreflective hemisphere centered at the ground under this fixture was then measured. The program closely reproduced the expected Lambertian distribution and integrated flux determined by the reflectivity of the ground surface (Fig. 6).

Further simulations placed both a fully shielded (0% uplight) and an unshielded light fixture (10% uplight, angular distribution; Fig. 5) on 8 m poles within a rectangular array of buildings,
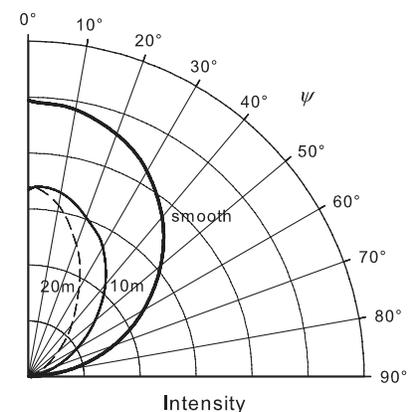
Fig. 6.—Upward intensity distribution (averaged over all azimuths) from the simulations using the fully shielded fixture. *Solid line*: smooth Earth simulation described in the text; *inner curves*: the intensity distribution when the light fixture is immersed in an array of buildings with the indicated heights.

TABLE 1
UPLIGHT FLUXES RELATIVE TO THE SMOOTH EARTH MODEL FOR THE LIGHTING SIMULATIONS

	BUILDING HT (m)	FLUX/FLUX (SMOOTH EARTH)			
		Total	0°–67.5°	67.5°–90°	(0°–67.5°)/(67.5°–90°)
City (shielded fixture)	10	0.51	0.54	0.25	2.2
	20	0.29	0.32	0.07	4.8
City (unshielded fixture)	10	0.65	0.57	0.75	0.76
	20	0.36	0.34	0.37	0.94
Porch light	3	0.91	0.79	1.03	0.77
Wallpack	3	0.93	0.85	1.00	0.85
Canopy (flat lens)	5	0.66			
Canopy (shallow lens)	5	0.54			
Canopy (deep drop)	5	0.47			

either 10 m or 20 m in height.. This we called the "city" model. Figure 6 shows the effective angular intensity distribution for upward-directed and reflected light originating with the shielded fixture, as an example, while Table 1 summarizes the overall flux changes as well as the high- and low-angle changes for all models investigated in this section. The split between high and low angles at 67.5° from the zenith is arbitrary, and reflects the AGI32 setup, which measured intensity at 5° increments, starting at 2.5° degrees above the horizon. Compared to the smooth Earth model, the emergent flux for the shielded fixture is dramatically reduced, to 51% where buildings are 10 m high and 29% in the 20 m city, with reduction between 67.5°–90° even more severe at just 25% and 7%. For the unshielded fixture, the total upward flux is reduced to 65% and 36% of that in the smooth Earth model in the 10 m and 20 m building environments, respectively. Here the reduction in the high-angle flux is somewhat higher than in the lower angles, in contrast to the fully shielded models.

Two models were evaluated to investigate the effect of mounting poorly shielded fixtures on the side of a building with an overhanging roof eave, such as a porch light on a home or a typical "wall pack" on the side of a commercial or industrial building. Each of these fixtures was evaluated in an environment with no structures (smooth Earth) as well as with a 3 m wall directly behind the fixture and with a 1 m overhanging soffit. The fixtures were positioned 2 m over the ground for all models. Here, total uplight is reduced by a much smaller fraction than in the above-described simulations, by just 9% for the porch light fixture and only 7% for the wall pack. Table 1 summarizes the results.

A special case of blocking, especially important due to the large amounts of light commonly involved, is the service station canopy. The effect on the upward emission of light was evaluated using three fixture types typically used on canopies. Again, the effective uplight reduction was calculated using two models for each fixture, one with and one without a canopy. Examples of the fixtures evaluated are shown in Figure 7, and the flux reductions are in Table 1.

The upward flux from these canopy-mounted fixtures is reduced to between one-half and two-thirds of that produced in the smooth Earth environment.

Little weight should be attached to the precise figures deduced from the models in this section, as they are sensitive to the particular fixtures and characteristics of the modeled environment used. Though we feel these are typical, substantial variations are expected in the real environment. We emphasize here only the general magnitude of the effects and the tendency in some common environments for the reductions at high zenith angles to be substantially greater than at low zenith angles.

3.2.2. Near-Ground "Extinction"

Modeling of the near-ground environment using specific descriptions of buildings and vegetation is much too complex and requires too much information for accurate results, in all but the simplest of applications. We move here to a more general approach that can be applied globally, if approximately, to either entire cities or at least large areasor categories of lighting within cities. Recognizing that the likelihood of light rays interacting with objects near the ground is directly related to the distance these rays must travel through the near-ground environment, we modify Garstang's (upward) angular distribution relation with an "extinction" term. This extinction, or "blocking," is produced not by the atmosphere as in classic atmospheric extinction, but by discrete natural and artificial objects, such as vegetation and buildings. The intensity (in lumen sr^{-1}) directed at a given angle ψ relative to the zenith is described by Garstang (1986) as
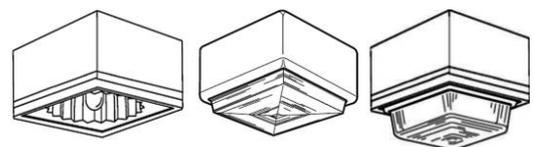

FIG. 7.—Canopy fixture types evaluated. *Left*: flat lens; *center*: shallow drop lens; *right*: deep drop lens.

$$I_g = (1/2\pi)\{2G(1 - F)\cos\psi + 0.554F\psi^4\}, \qquad (1)$$

where G is the scalar reflectivity of the ground and F is the proportion of emergent flux emitted directly from fixtures above the horizontal. Including a "near-ground" extinction factor modifies this relation to

$$I = I_g 10^{-\{0.4E_b \sec(\psi)\}},$$

where E_b is the "blocking" extinction, in magnitudes, at the zenith. (We neglect the difference in height between the ground and the light sources, assuming a single value for E_b applied to all rays). While this relation has the desired property of increased blocking toward the horizon, it may go too far, in that intensity in all cases goes to zero at the horizon. While we desire a relation that decreases the intensity toward the horizon compared to Garstang's approach, we expect that at least most cities do not disappear when viewed from the horizon. To account for the patchiness of blocking caused by the discrete rather than continuous nature of the obscuring objects within the near-ground environment, we include an additional factor that effectively allows an "unblocked" fraction, β, of the flux to suffer no extinction:

$$I_{ge} = I_g\{\beta + (1 - \beta)10^{-\{0.4E_b \sec(\psi)\}}\}. \qquad (2)$$

In place of the somewhat arcane system of magnitudes favored by astronomers, the coefficient E_b can be expressed in terms of the percentage coverage B (the fraction of the ground that would be blocked from direct overhead view by the objects in this obscuring layer), recognizing the relation $(1 - B) = 10^{\{-0.4E_b\}}$

$$I_{ge} = I_g\{\beta + (1 - \beta)10^{\{\log(1-B)\sec(\psi)\}}\}.$$

The needed blocking factor could be estimated from aerial images by measuring that portion of the ground obscured by vegetation and buildings.

We note that this approach assumes that the objects producing this near-ground blocking extinction are purely absorptive; since in general the reflectivity of objects is relatively low, we consider this a useful approximation. Furthermore, we are assuming that the absorption is strictly proportional to path length through the near-ground layer and independent of azimuth. If the objects in the obscuring layer have a preferred shape/orientation (such as trees with a larger vertical extent than horizontal), the obscuration will show a different dependence on zenith angle than the $\sec(\psi)$ assumed here. Further, real azimuthal variations in the blocking extinction and unblocked fraction are expected in complex city environments, which are likely to lead to sometimes considerable azimuthal dependence of sky glow. Figure 8 shows I_{ge} with various values for the zenith extinction, while Table 2 shows the effective diminution in the albedo (reduction in integrated upward flux) as compared to the unmodified Garstang model (which we note is equivalent to $\beta = E_b = 0$ in eq. 2).

As E_b increases from 0.0 to 1.25 (see Table 2), the effective albedo is reduced to less than 40% of the value of Garstang's model for $\beta = 0.20$, and to less than 25% for $\beta = 0.0$. But the amount of reduction is increasingly more severe for the high-angle rays (defined here as those between 67.5° and 90° from zenith; Table 2, columns [5] and [6]). Column (7) in Table 2 indicates the factor by which the low-angle flux reduction exceeds that of the high angle. These values show that the light emitted upward but near the horizontal direction is reduced substantially more than that at higher angles, from ∼2× at $E_b = 0.25$ to a factor of 2–25 for $E_b = 1.25$, with the more severe reductions as β approaches zero. The significance of this
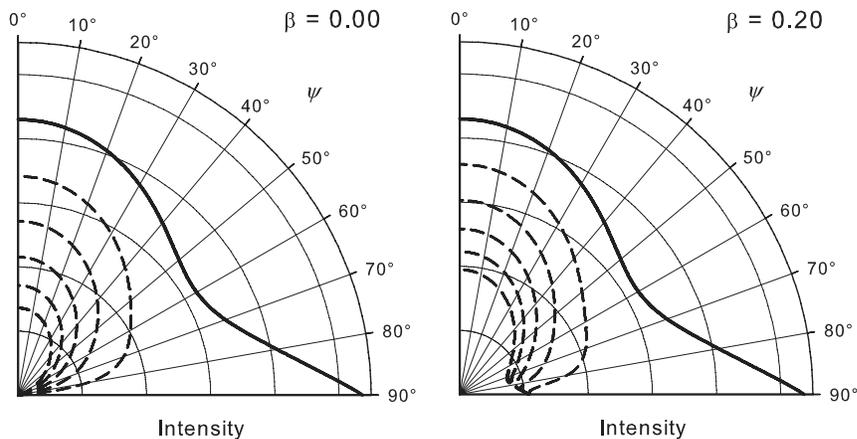

FIG. 8.—Effect of extinction proportional to $\sec(\psi)$ and β on the standard Garstang upward angular distribution. $\beta = 0.00$ and 0.20 are illustrated, as indicated. *Solid line*: the standard Garstang model (I_g, eq. 1); *nested dashed lines*: I_{ge} (eq. 2) with zenith blocking extinction (E_b) values of 0.25, 0.50, 0.75, 1.00, and 1.25.

TABLE 2

UPLIGHT FLUXES RELATIVE TO THE GARSTANG STANDARD MODEL AS A FUNCTION OF FACTORS E_b, B, AND b

			FLUX/FLUX (GARSTANG)			
E_b	B	β	Total	0°–67.5°	67.5°–90°	(0°–67.5°)/(67.5°–90°)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0.00	0.00	0.00	1.00	1.00	1.00	1.0
		0.05	1.00	1.00	1.00	1.0
		0.10	1.00	1.00	1.00	1.0
		0.20	1.00	1.00	1.00	1.0
0.25	0.21	0.00	0.71	0.76	0.30	2.5
		0.05	0.72	0.76	0.34	2.2
		0.10	0.74	0.77	0.37	1.9
		0.20	0.77	0.80	0.44	1.7
0.50	0.37	0.00	0.52	0.56	0.12	4.7
		0.05	0.55	0.58	0.16	3.6
		0.10	0.57	0.60	0.20	2.7
		0.20	0.62	0.65	0.29	2.1
0.75	0.50	0.00	0.39	0.42	0.05	8.4
		0.05	0.42	0.45	0.10	4.5
		0.10	0.45	0.48	0.14	3.1
		0.20	0.51	0.54	0.24	2.2
1.00	0.60	0.00	0.30	0.32	0.02	16
		0.05	0.33	0.35	0.07	5.0
		0.10	0.37	0.39	0.12	3.1
		0.20	0.44	0.46	0.22	2.1
1.25	0.75	0.00	0.23	0.24	0.01	24
		0.05	0.26	0.28	0.06	4.7
		0.10	0.30	0.32	0.11	2.9
		0.20	0.38	0.40	0.21	1.9

disproportionate reduction of flux directed near the horizon will be discussed further below.

3.2.3. Effective Uplight Amount and Distribution Function

Though the specific details of blocking of light rays will vary from city to city, within different areas of cities, and even from light fixture to light fixture, § 3.2.1 and 3.2.2, as well as the comparison of observed and predicted sky brightness described in Section 2, provide general guidance on the effects of near-ground blocking of light. In § 3.2.3.1 we present an analytical model with single values of the four parameters of equation (2) to be applied globally to the light outputs determined in GU1 to produce a greatly improved fit to the observed sky brightness, as described in § 2 and illustrated in Figures 3 and 4.

3.2.3.1. The Global Flagstaff Model

For the factor F in equation (2), we adopt the measured direct uplight fractions for the lighting categories determined in GU1. We use a surface albedo (F) of 0.15 everywhere. We find that the best fits to the observations illustrated in Figures 3 and 4 are obtained with $\beta = 0.0$, and $E_b = 0.4$ or 0.5. We

attribute the poor fit in Figure 4 very near the northwestern horizon (azimuth 290°)both to headlights directed toward the observatory, as noted in § 2, and the probable different values for β and E_b that should be applied to the Bellemont lighting, as there is very little vegetation in this area. (The computer code is not currently adapted to allow different values of these parameters for different light sources.) Though we expected β to be quite low for Flagstaff due to the forested environment, the fact that $\beta = 0.0$ best fits the data probably reflects a contribution from blocking by the terrain itself, which is not modeled here. As viewed from the Naval Observatory, two low hills indicated on Figure 2 (Observatory and McMillan Mesas, with approximate altitude above typical city elevations of 60 m) block much of the city from directly illuminating much of the line of sight at these high zenith angles, thus decreasing the observed sky brightness. This may also be the explanation for the deviation of the observations from the predictions at zenith angles >65° in azimuth 110° (Fig. 4).

4. SUMMARY AND CONCLUSIONS

The total light fluxes estimated to escape into the atmosphere as determined by the lighting inventory approach of GU1, when

provided as input to a Garstang model (1986, 1989, 1991), produce sky glow levels more than twice that observed, with greater deviations shown at higher zenith angles. We conclude that the principal source of this discrepancy is the interaction of the light, after it exits light fixtures, with objects such as buildings and vegetation. From our models and simulations, we conclude that this interaction can produce overall reduction to the light outputs needed to reproduce the observations.

We further find that, in many important lighting situations, light rays emitted upward but near the horizontal direction suffer a reduction two or more times greater than those at higher angles, resulting in an emergent angular intensity distribution much more heavily weighted toward the zenith than Garstang's description. This has the net effect of reducing the light pollution, observed from outside the city, to a degree greater than would be expected based on a simple ratio of the flux reduction obtained from integrating over the entire upward hemisphere. Combining this increased low-angle reduction with the general reduction in the effective albedo caused by these effects may provide the explanation necessary to reconcile the approximately 2500 effective lumens per capita determined by Luginbuhl et al. (2008) with the sky brightness measurements presented here, and with the ~1000 lm per capita used by others in their generally successful efforts at modeling the sky glow produced by outdoor lighting in urban and suburban areas.

However, the nature and details of these effects will vary greatly from city to city, from one portion of a city to another, and from one lighting application to another. In general, the blocking effect of building structures would tend to be largest in areas with buildings taller than typical light poles, in other words in typical downtown districts. The blocking from vegetation would be largest in heavily vegetated areas, particularly with vegetation that reached higher than the average height of lighting fixtures. Blocking by vegetation would be expected to be particularly important in vegetated suburban and residential areas, reducing upward-directed light emissions from these areas to small fractions of what would be expected under the smooth Earth assumption implicit in Garstang's approach.

The net effect of ground-level blocking is to decrease the sky brightness at remote locations, particularly at large zenith angles. A further consequence is that reductions of near-horizon emissions arising directly from fixtures, for example, through light code restrictions requiring more effective shielding, will be less effective than expected at reducing sky glow, though they may still be desirable for reducing glare, light trespass, and other impacts to the immediate environment. The flip side is that the relative importance of reducing near-zenith emission is increased, for example, by reducing overall lighting amounts (and thus the heavily zenith-weighted Lambertian reflection from the ground) and by reducing the use of lighting practices and amounts with substantial direct near-zenith emission, such as bottom-mounted billboard lighting or upward-directed building façade lighting.

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