Modelling differences in Skyglow in rural areas from common luminaire designs

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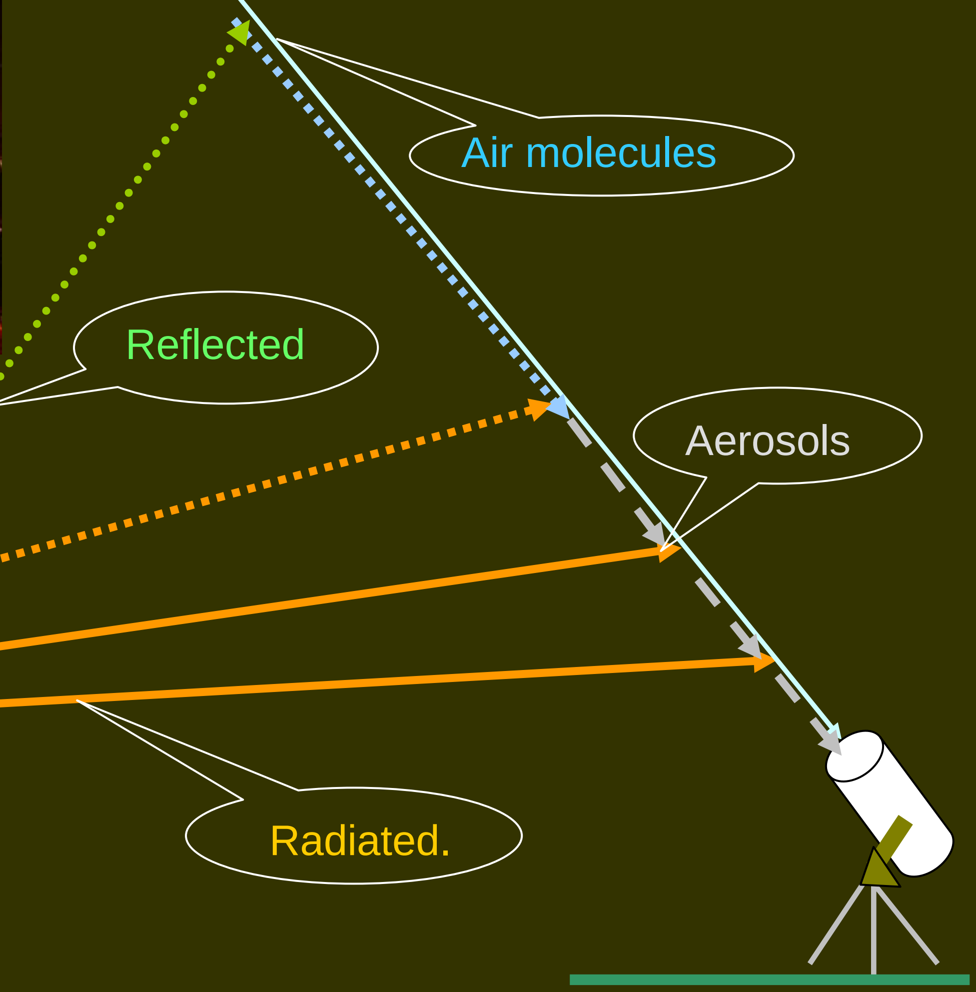
Worcester from Malvern Hills , and 4 years later 2007 (Chris Baddiley)

Photometry of skyglow

Direct and reflected rays diagram



Skyglow is caused by the downward scattering of upward light by air molecules and also aerosols, mostly water droplets and dust. The longer the path length through the lowest part of the atmosphere, the more the scattering. Light that goes straight up is mostly reflected, and has shorter paths through the lower scattering layers. The low angle light is mostly directly radiated, and it is this that causes most of the sky glow well away from the source.

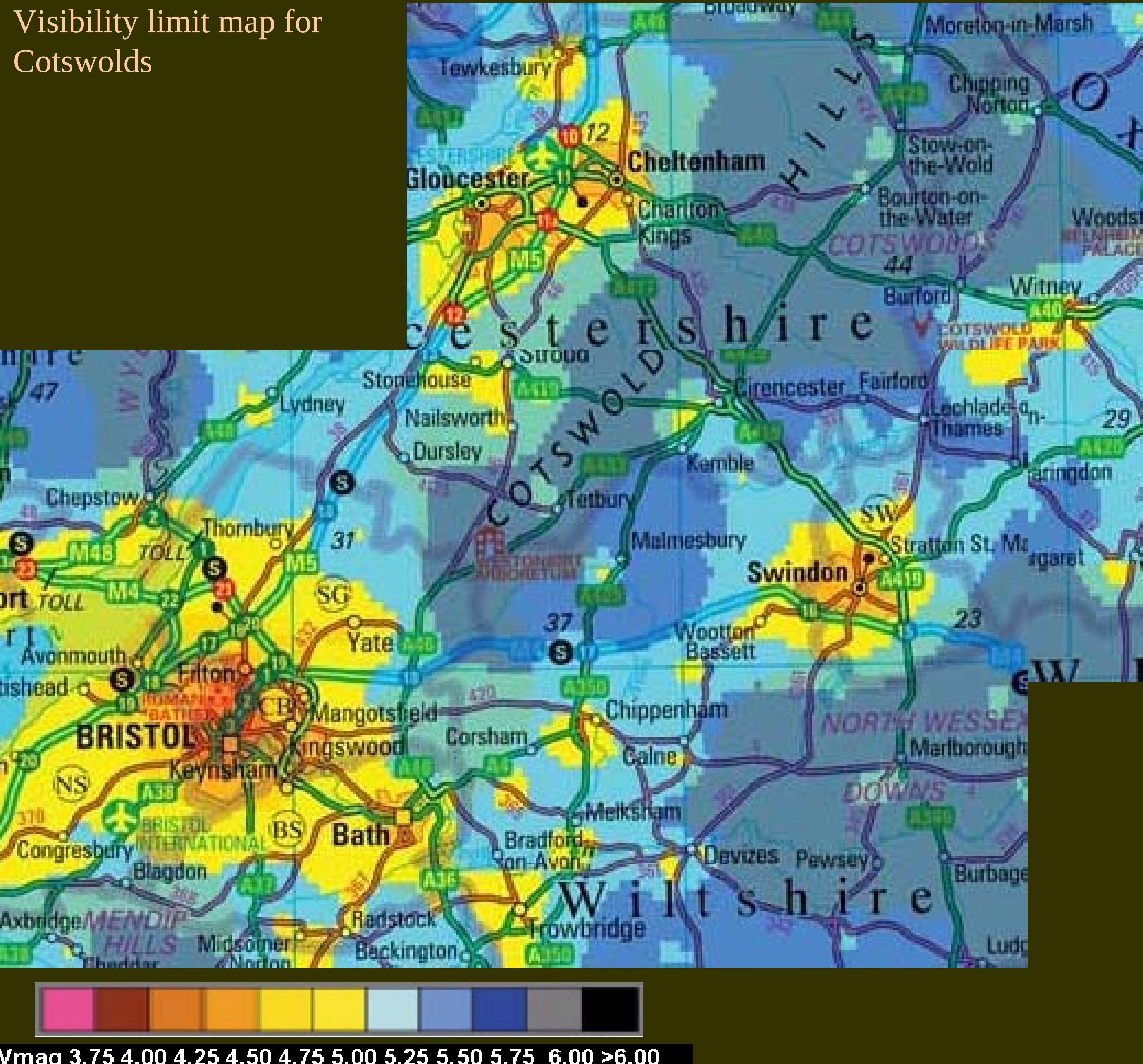
Skyglow in Cotswolds, location SO967102
Western quadrant, composite transfromed to equal area projection, CCD image images (James Weightman) Milky Way, Scutum,

Skyglow in the Cotswolds

Skyglow in Cotswolds, location SO967102. Western quadrant, composite transfromed to equal area projection, CCD image images (James Weightman) Milky Way, Scutum, Sagittarius etc taken last night 2003/8/2 at SO967102 near Cirencester, Glos; Unguided Olympus C5050Z

Even in the countryside, there is no escape ! Note the gradation from the horizon upwards, due to the concentration of scattering aerosols at lower altitudes. The skyglow from very distant sources is still bight.

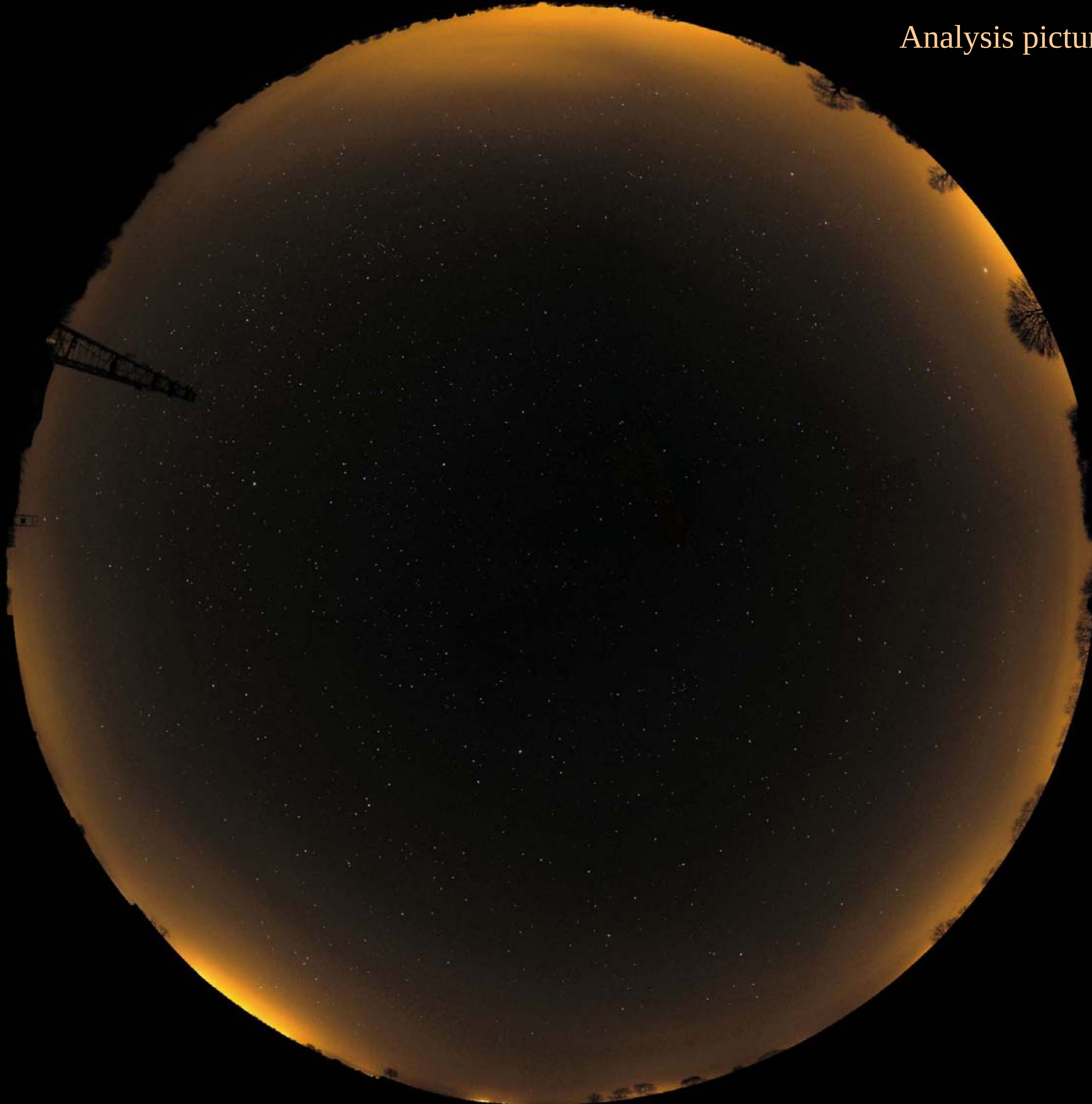
Visibility limit map for Cotswolds



Dark sky areas of the Cotswolds

(P. Cinzano / F Falchi ISTIL-Dipartimento di Astronomia Padova, Italy), Philips – Maps publication for CfDS, 2004 September

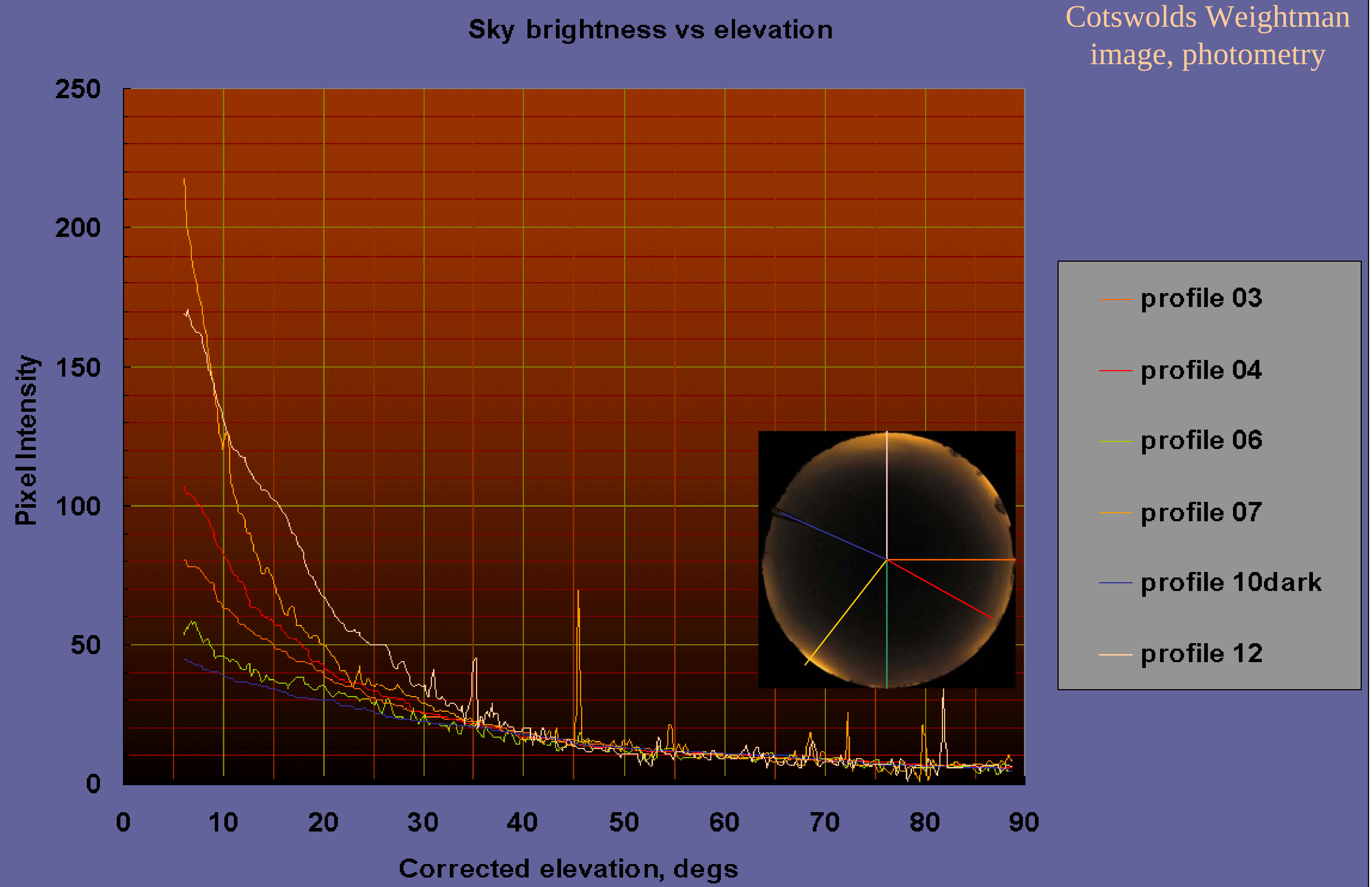
Analysis picture Skyglow in the Cotswolds



CCD composite of 20 x15 second exposures. Cotswold Hills, 6 miles south of Cheltenham. It can be seen, perhaps aided by the rising early morning mist, that a glow can be seen all around the horizon, particularly at 12 o' clock. Location SO967102 (Cheltenham), 7 o'clock (Cirencester). By James Weightman, BAA

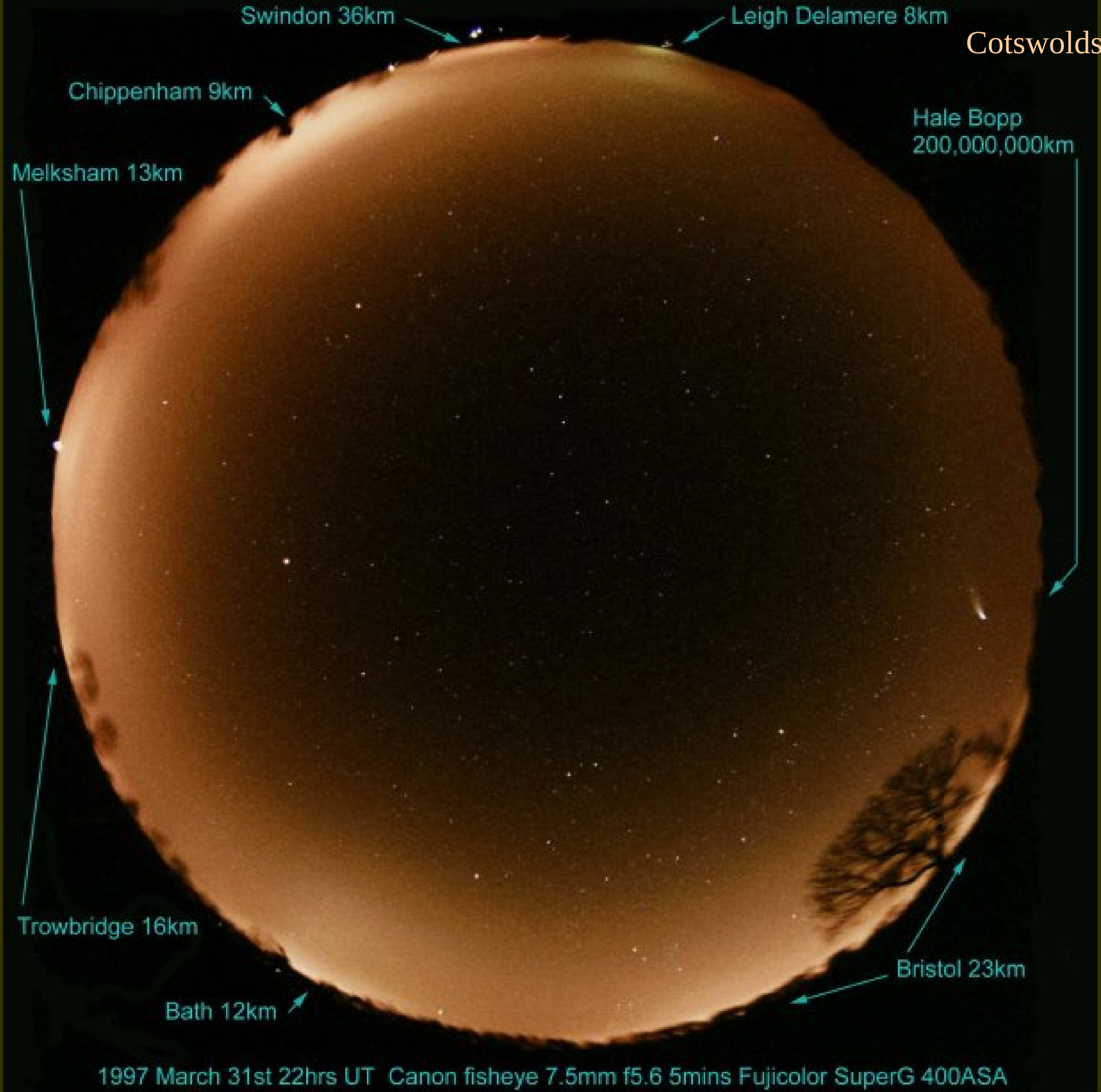
Made from 12 images covering the whole sky taken with wide angle zoom 7 mm fl lens, setting of Casio QV3500 digital camera over a period of approx 15 minutes.

Cotswolds Weightman image, photometry



Intensity profiles of horizon to zenith lines as shown. The towns are from the top

12 o'clock Cheltenham, 7 o'clock Cirencester.

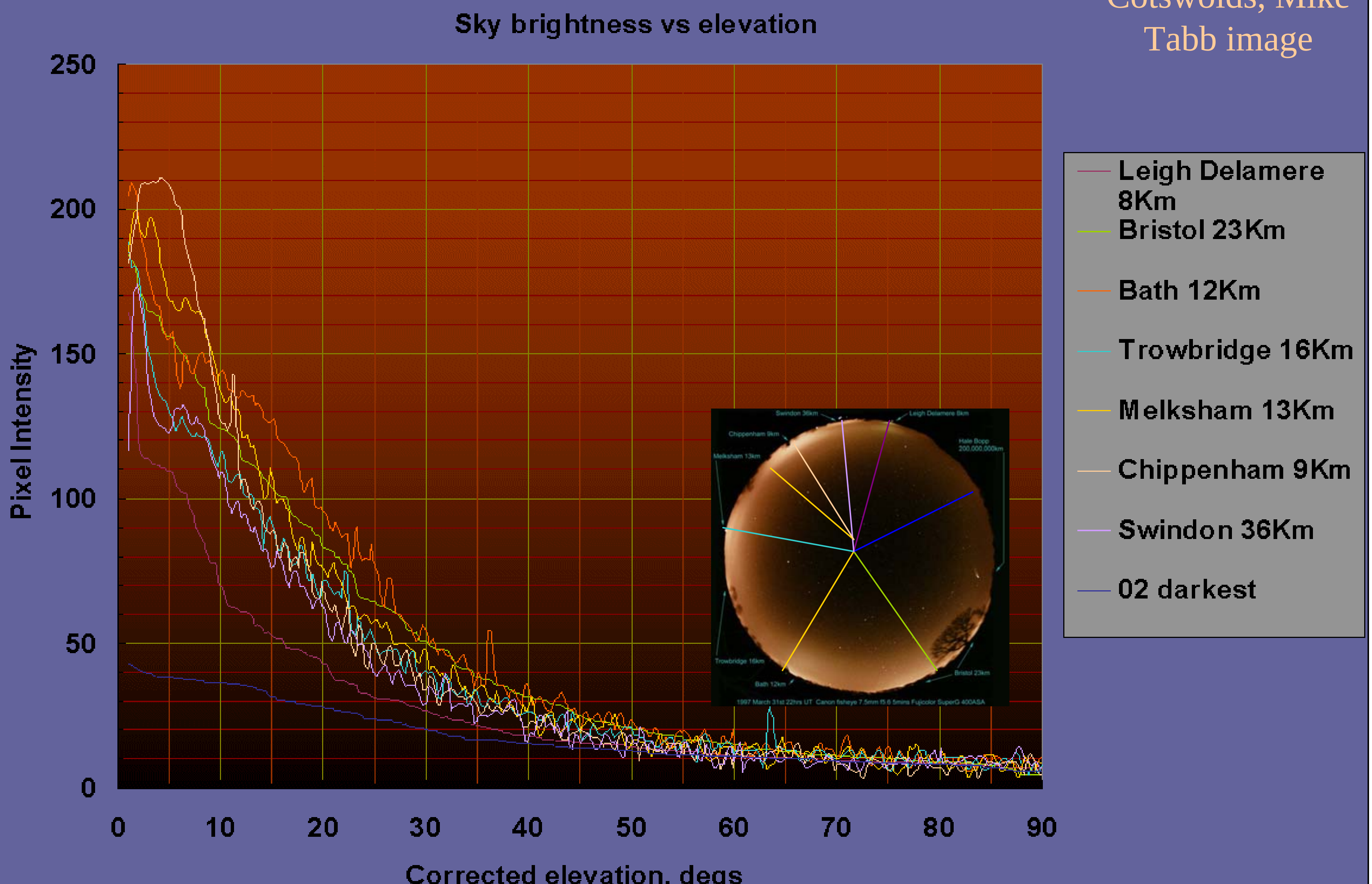


Cotswolds, Mike Tabb image

Sky glow in the countryside, from distant towns from the darkest Cotswolds.

The lens compresses objects to the horizon (see the tree), so the dark hole overhead appears actually smaller than shown. Location ST829 743 (Mike Tabb).
The towns, are clockwise from the top,
Leigh Delamere,
Bristol, Bath,
Trowbridge,
Melksham,
Chippenham,
Swindon

Cotswolds, Mike Tabb image



Intensity profiles of horizon to zenith lines as shown. The towns, are clockwise from the top, Leigh Delamere, Bristol, Bath, Trowbridge, Melksham, Chippenham, Swindon

Rural skyglow estimation summary

	Source to source brightness range	Brightest / darkest horizon	Darkest horizon / Zenith	Brightest horizon / Zenith
Cotswolds Weightman data	2.0	4.8	7.5	36
Cotswolds Tabb data	2.1	4.9	6.3	31
Poole Mizon data	2.4	4.9		
Sky brightness lower limit estimates Cotswolds Skyglow approx. mag 3 /sq deg at 52 deg elevation				

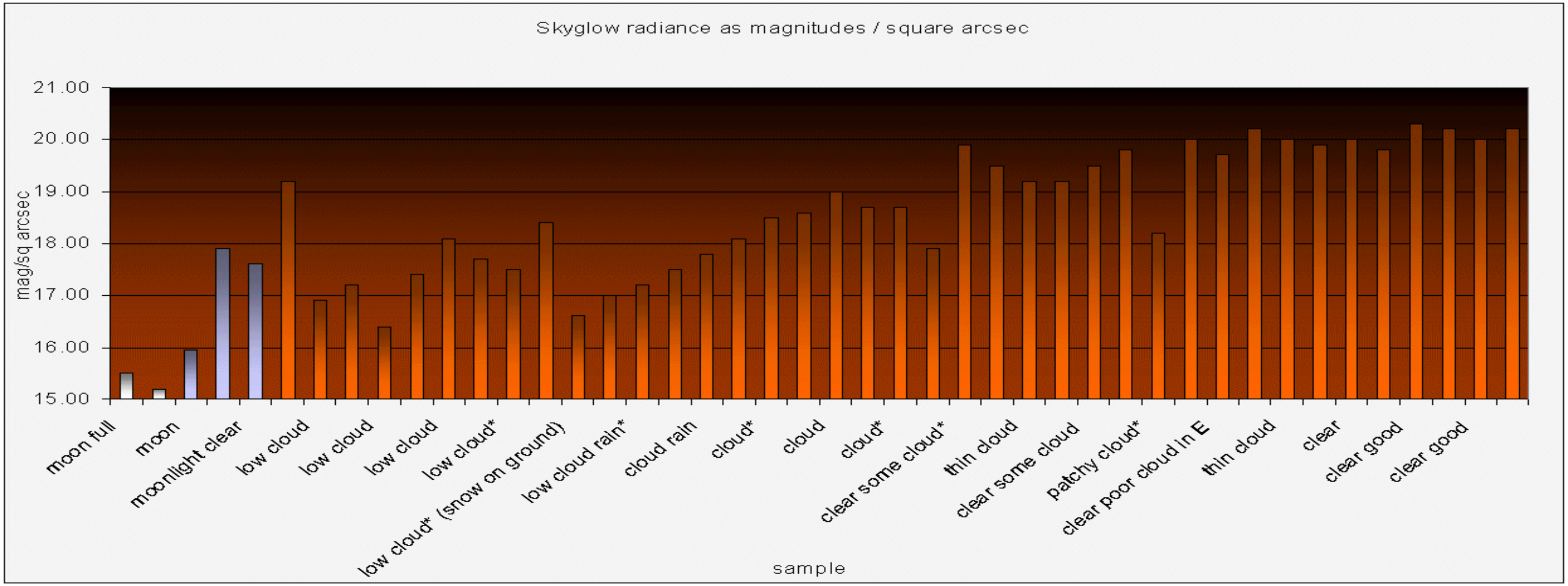
Photometry of Skyglow with weather conditions study

Malvern 2005 October to December

Using the Sky Quality Meter (SQM)

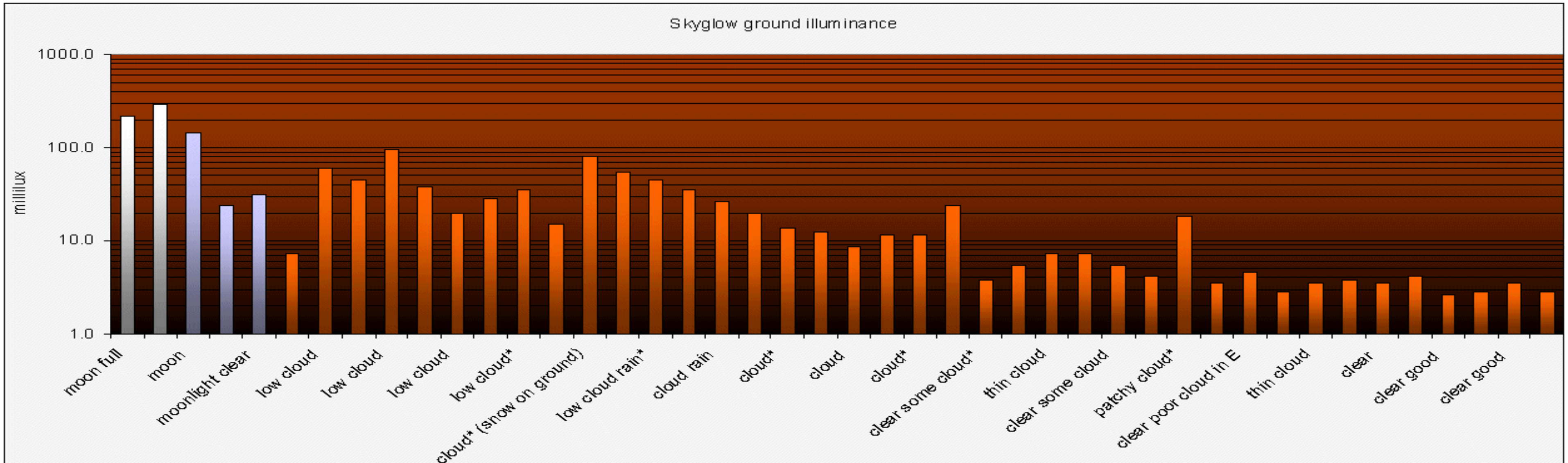
Each data set is the most consistent of a set of three or more readings taken in succession, to the nearest 0.1 mag/sq arcsec. Meter held at about 70 degs elevation. In the SE quadrant was the same reading as vertical.

2003/8/20 at location SO967102 looking south (main glow Swindon 30+ Km SSE); Mars visible left. Sagittarius right. Illumination of clouds from underneath Canon D60 digital SLR + 15mm f/2.8 lens. ISO 800 15 secs. (James Weightman)

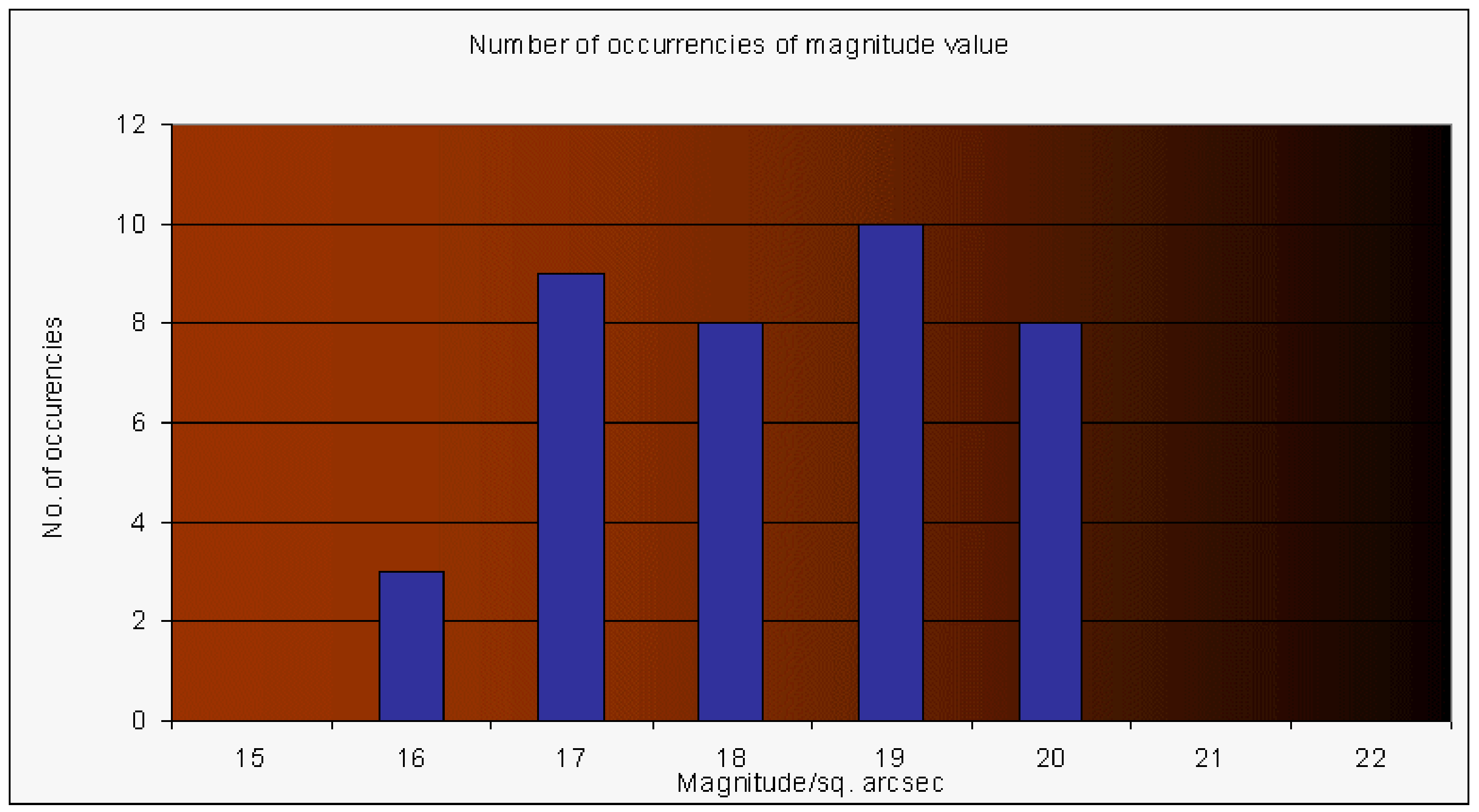


Measured skyglow mags/arcsec2 at 70 degs elevation, SE. vs. weather condition

Measured skyglow equivalent lux at 70 degs elevation, SE. vs. weather condition



Measured skyglow vs. weather condition



Frequency of occurrence of skyglow, value for weather condition, on moonless nights from 2005 October to December (3 months)

Using luminaire photometry files and to mathematical model surface reflection, scatter, and atmospheric scatter.. skyglow

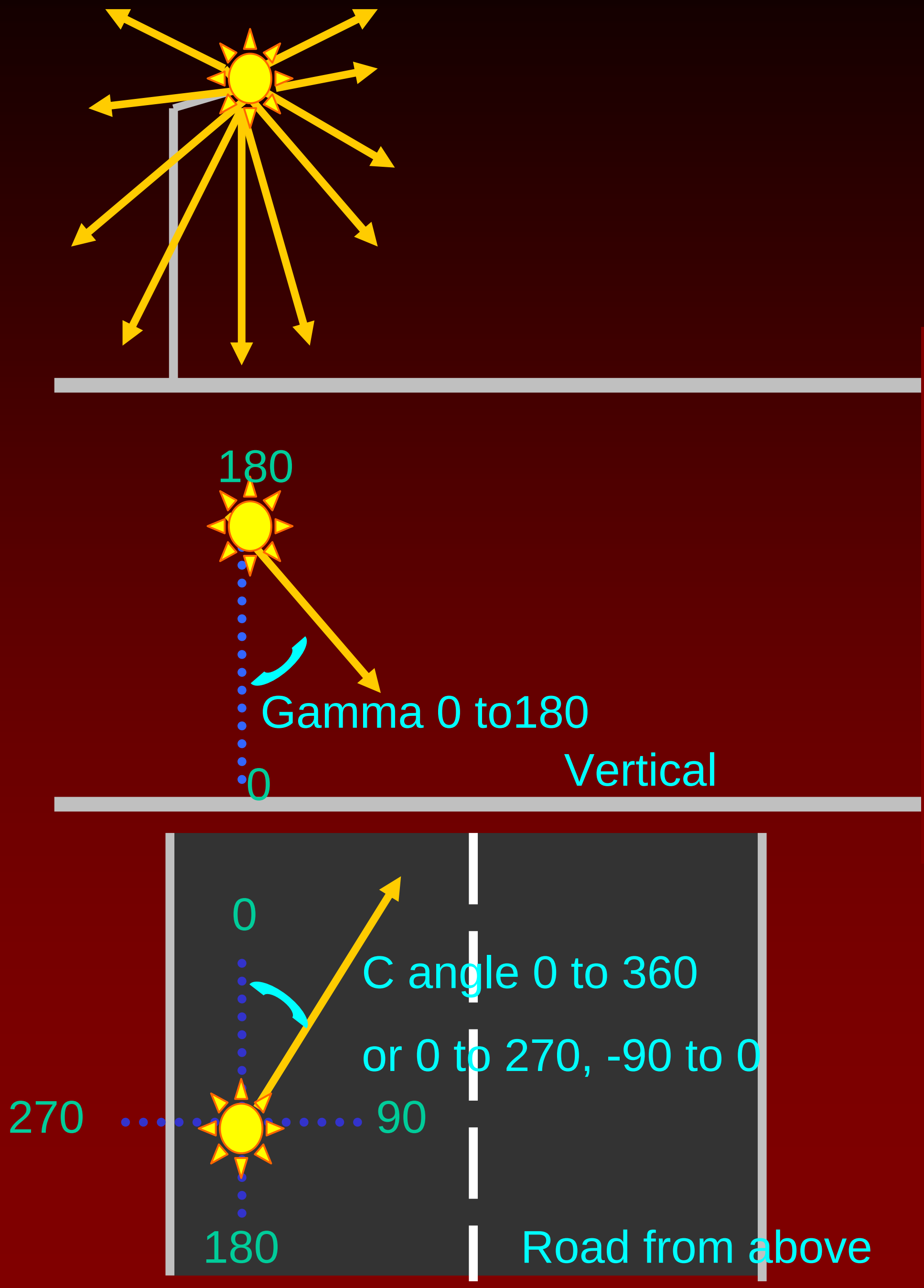
Luminaire polar distributions

Low pressure sodium, SOX

High pressure sodium (SON) wide angle Shallow bowl

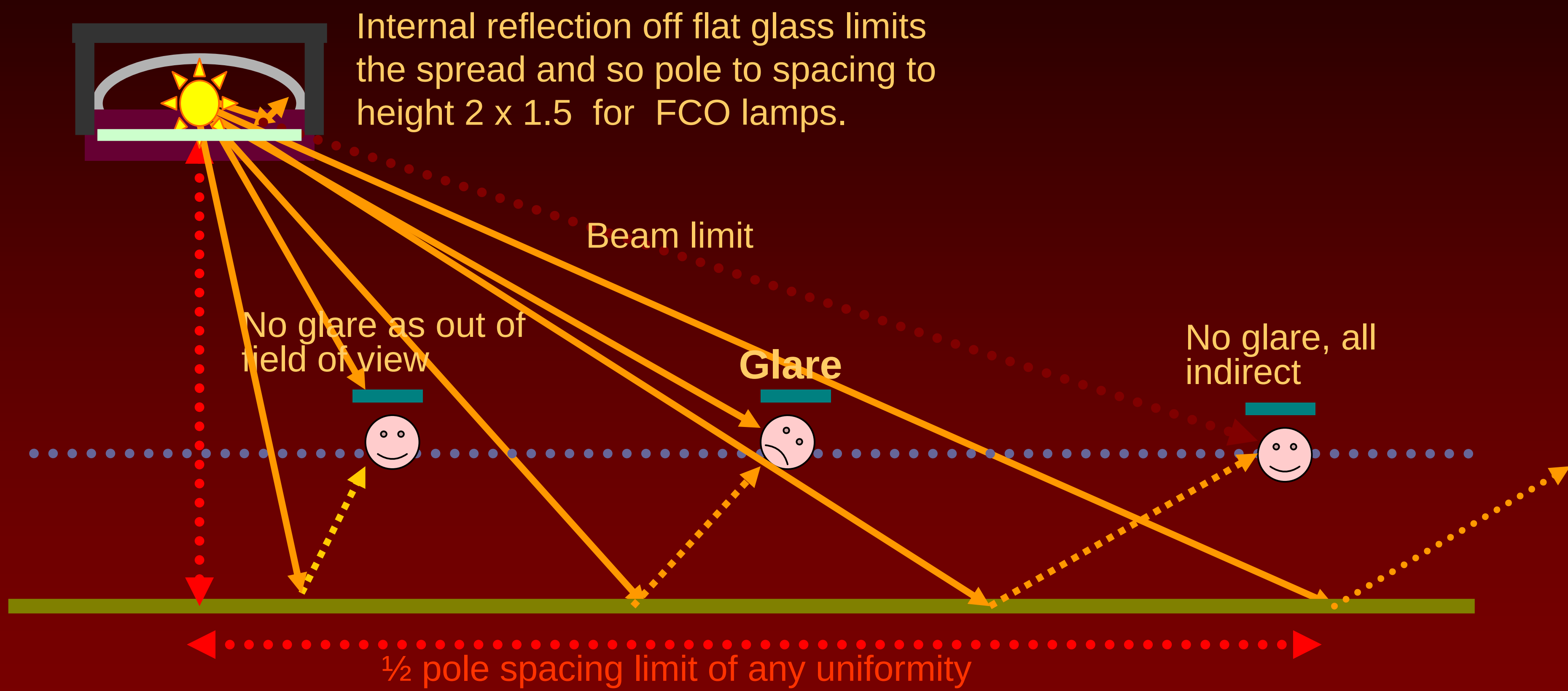
High pressure sodium (SON) Full Horizontal Cutoff (FCO /HCO)

SOX Luminaire polar plots



Polar plot, distance from centre represents luminance in that direction

Limits on FCO spacing, uniformity and zones of glare

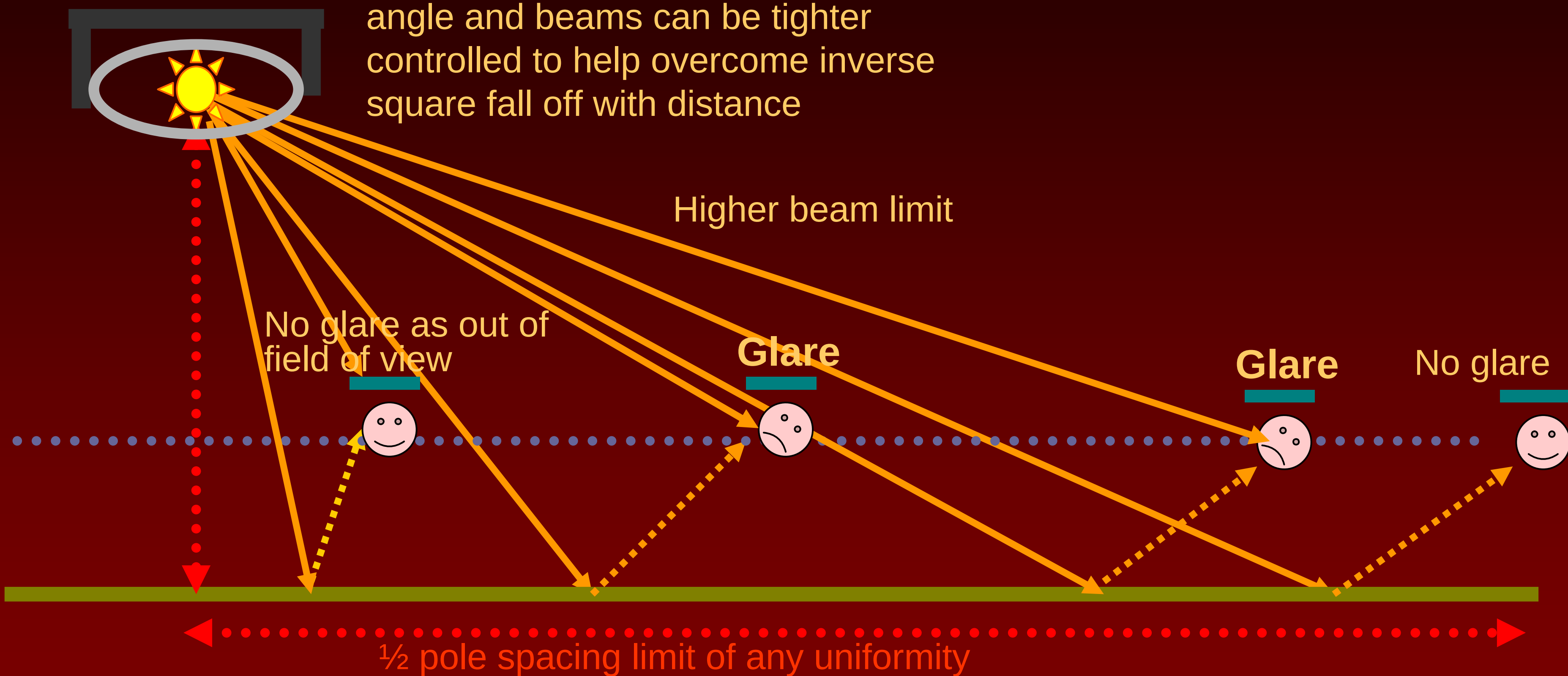


For flat glass, when 1/Tan (incidence angle) = glass refractive index 1.5 the light is reflected back inside 60 degs, this limits the spread and so pole to spacing to height 2 x 1.5 for FCO lamps. Intensity of light falls as inverse square of distance

Diagram shows region of no glare outside of beam visibility, glare as one enters beam, and no glare as beam is too high an angle to be seen in filed of view.

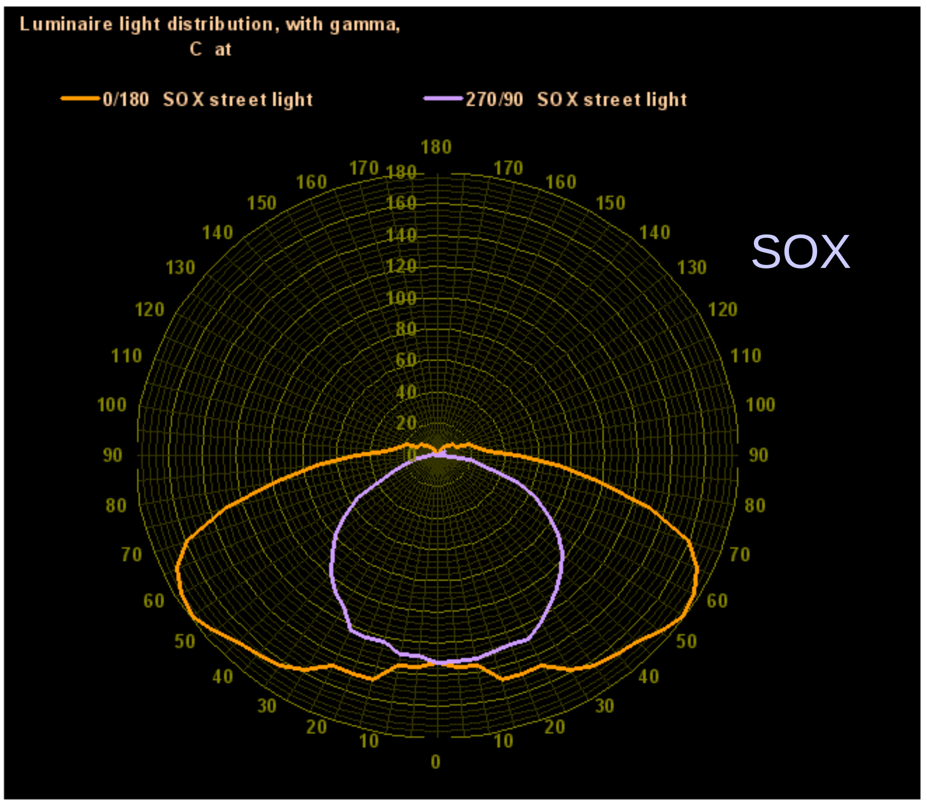
Limits on Cut off shallow bowl further spacing

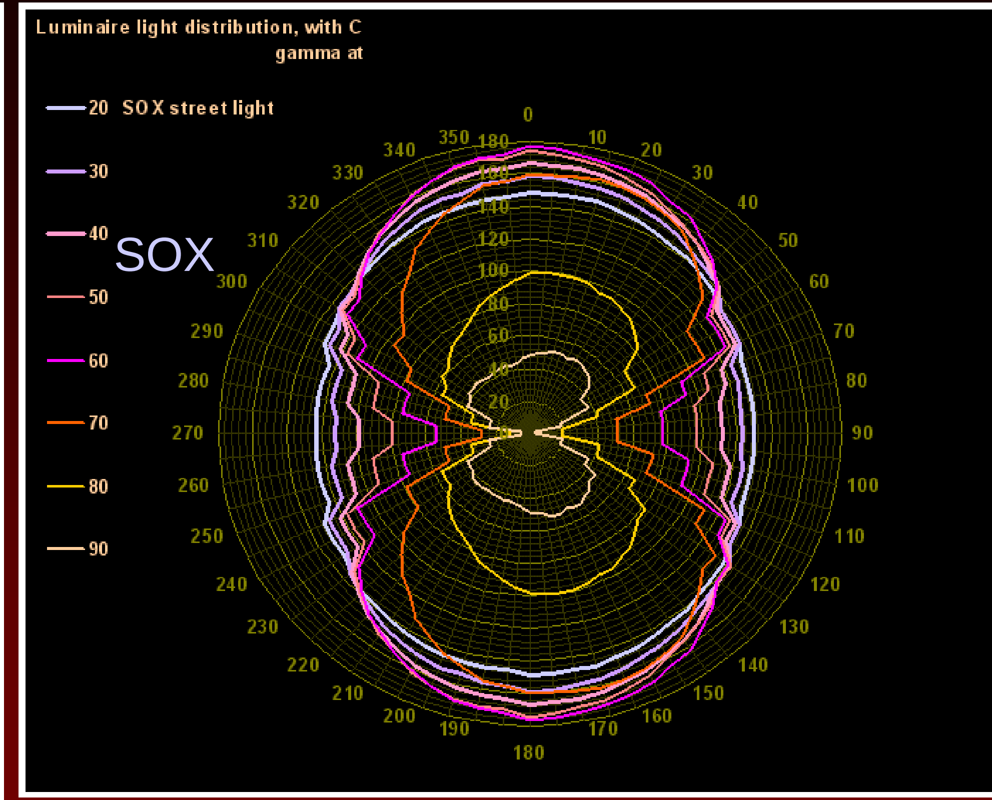
A shallow bowl is less limited in beam angle and beams can be tighter controlled to help overcome inverse square fall off with distance



With a curved bowl this can be greater with further spacing, but then there is more glare at this further spacing and also sideways emissions that are intrusive in open environments.

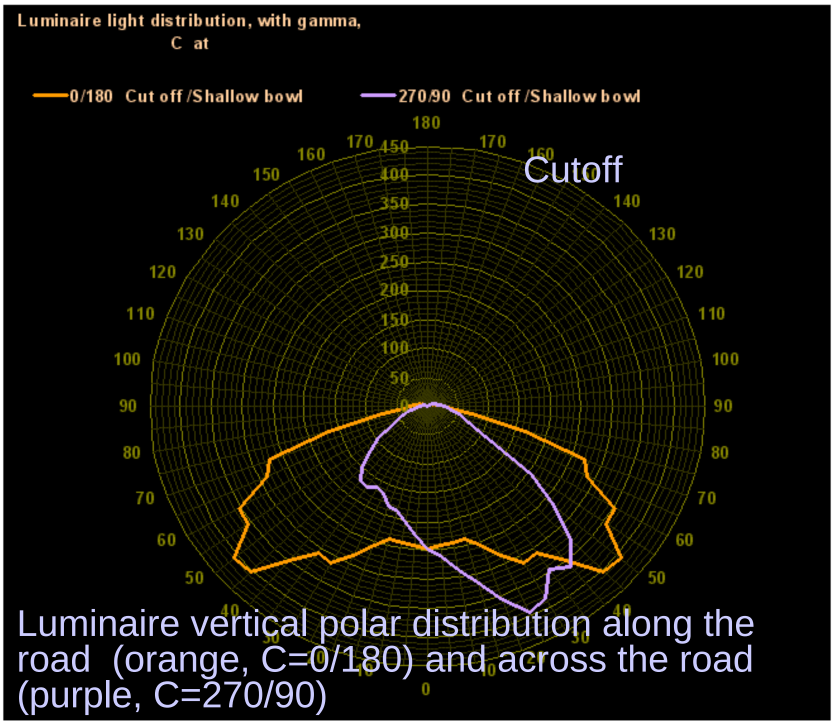
SOX Luminaire polar plots

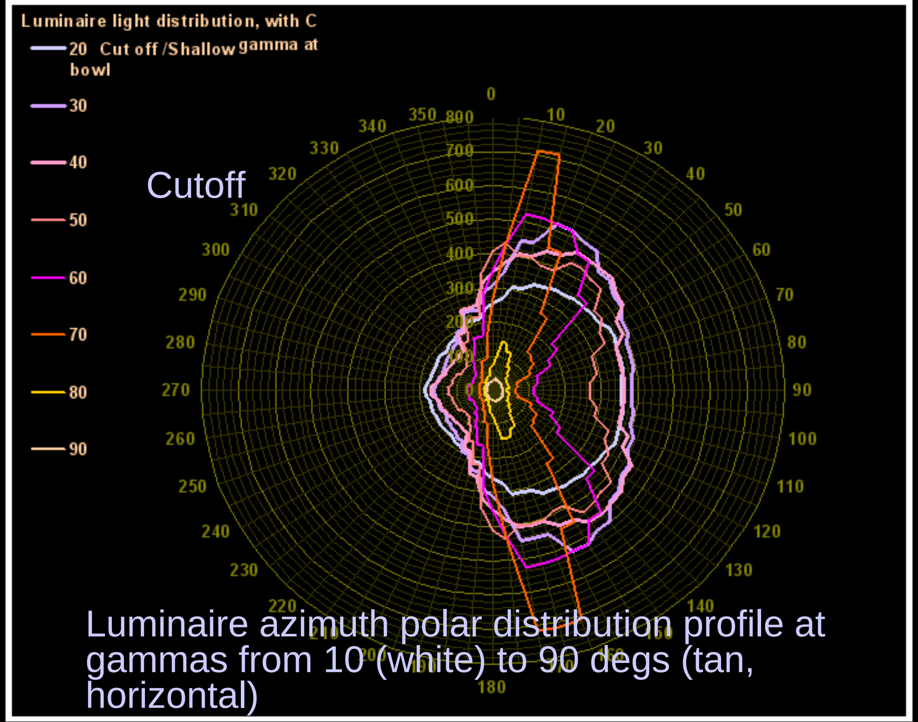


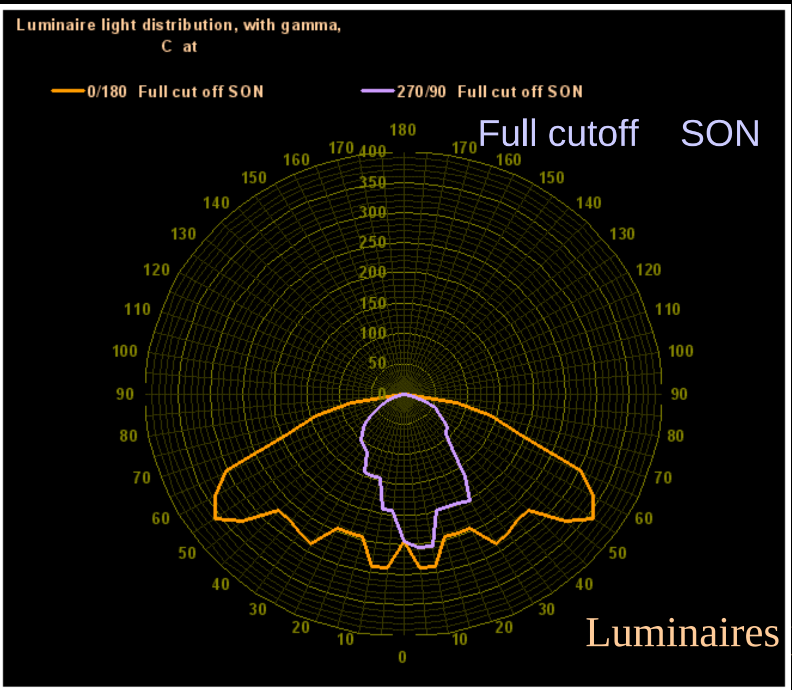


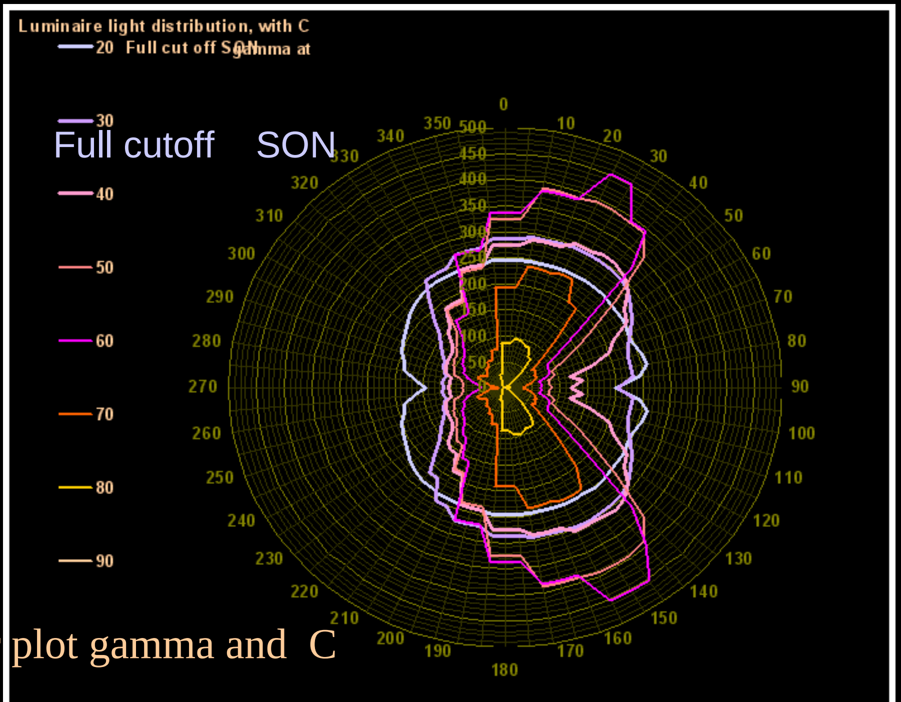
Luminaire vertical polar (all gammas) distribution along the road (orange, C=0/180) and across the road (purple, C=270/90)

Luminaire azimuth (all C angles) polar distribution profile at gammas from 10 (white) to 90 degs (tan, horizontal)

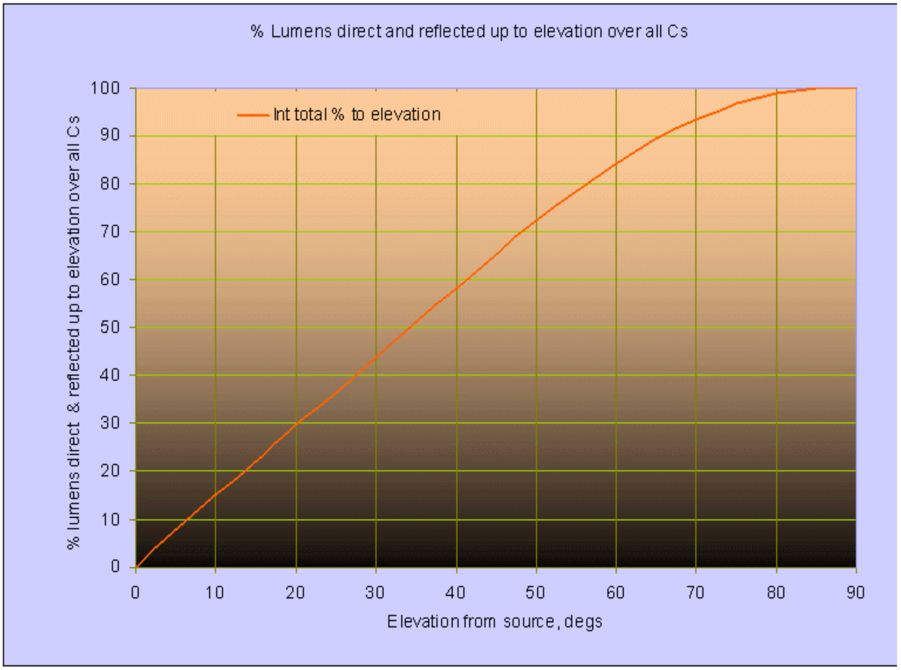


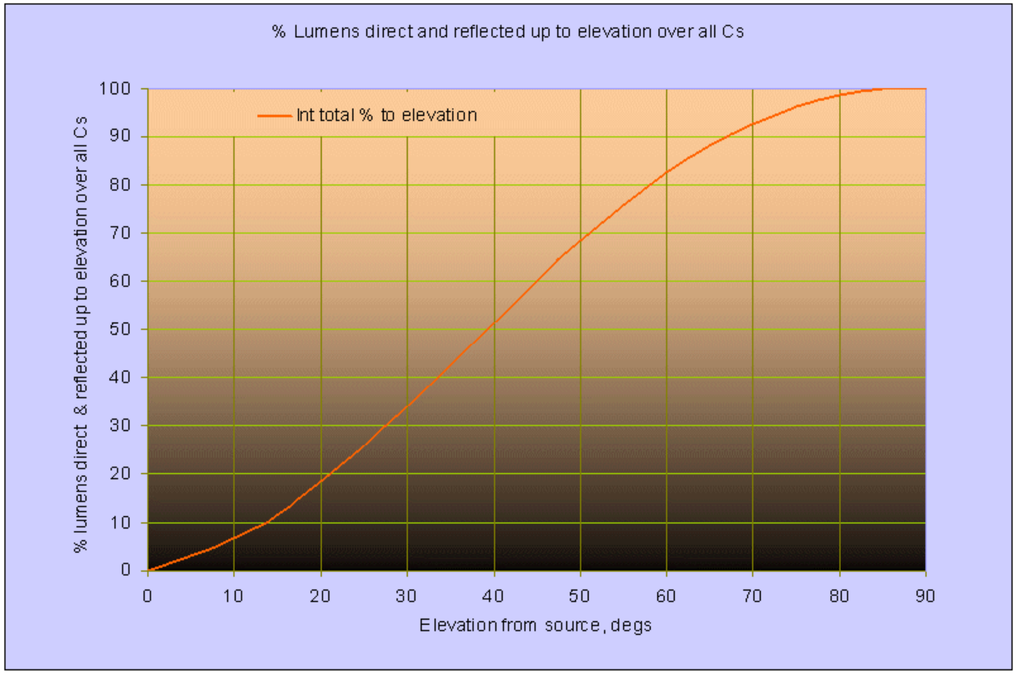






Luminaires polar plot gamma and C



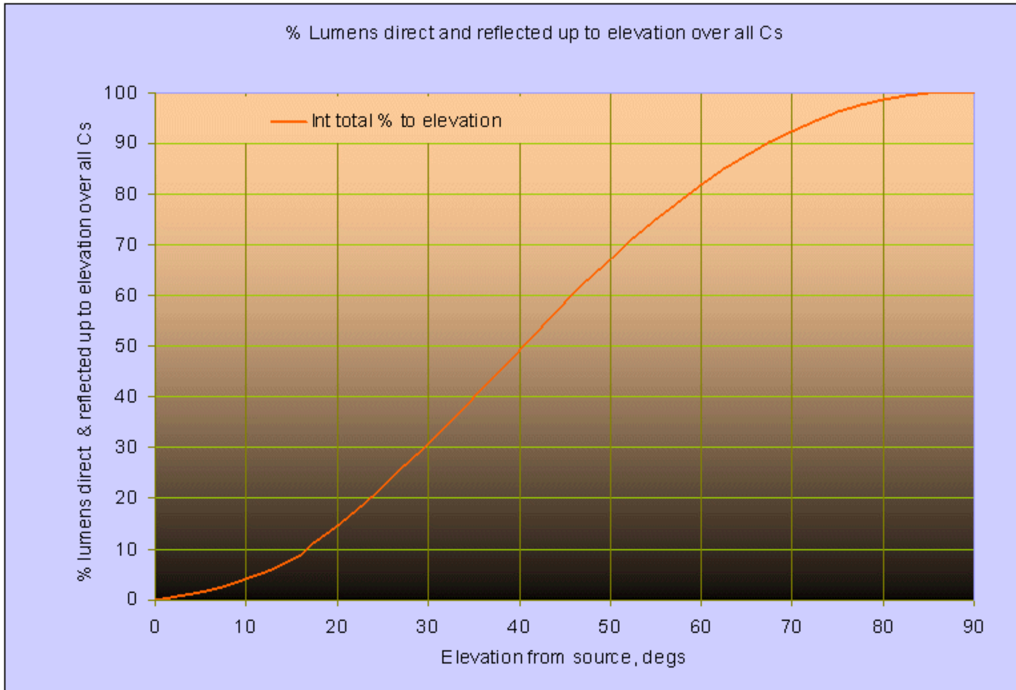


SOX

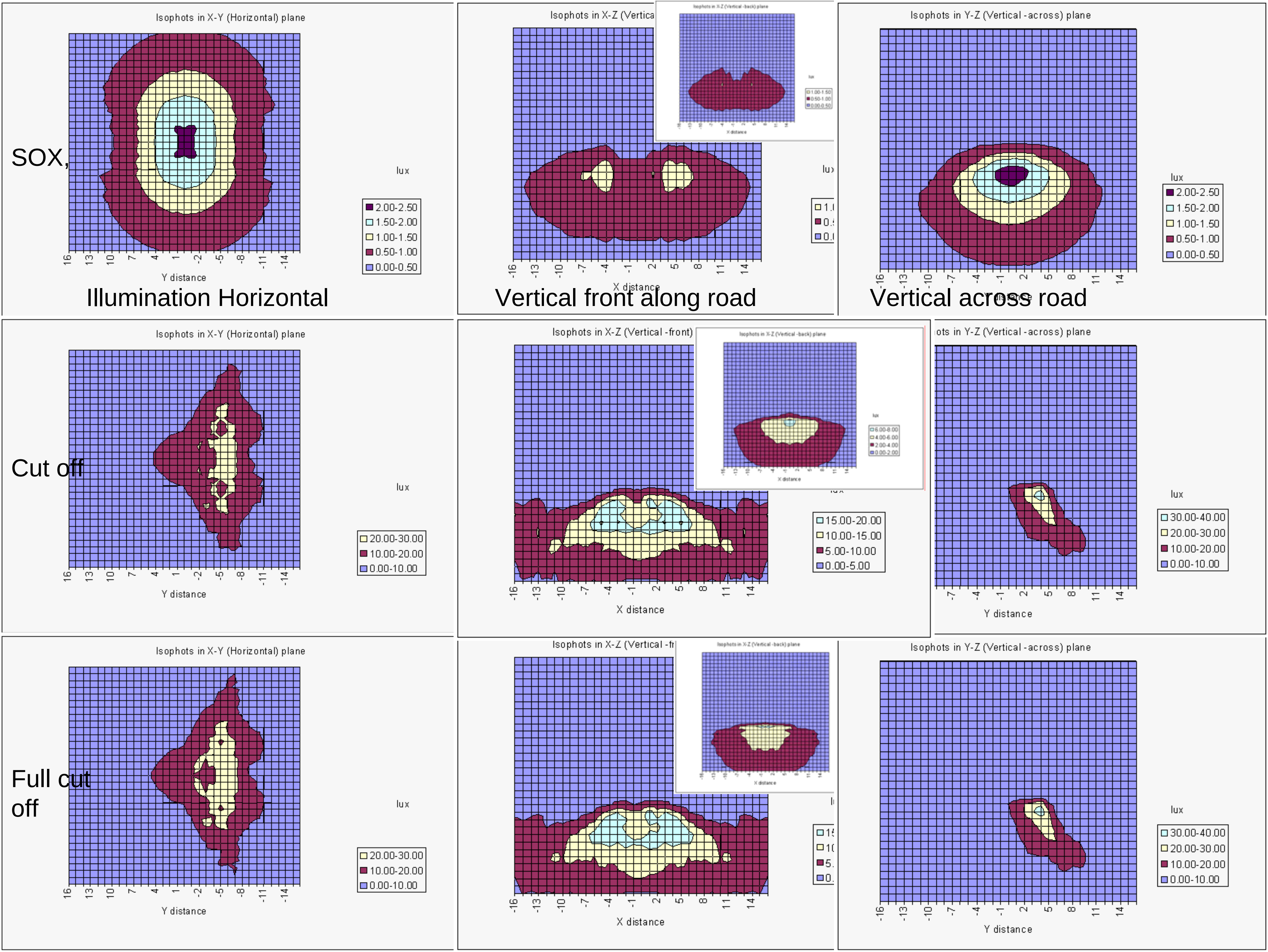
Integrated direct and reflected luminance ratio to total over all C angles up to gamma angle vs gamma angle.

Cutoff (above right) and full cutoff (right) SON

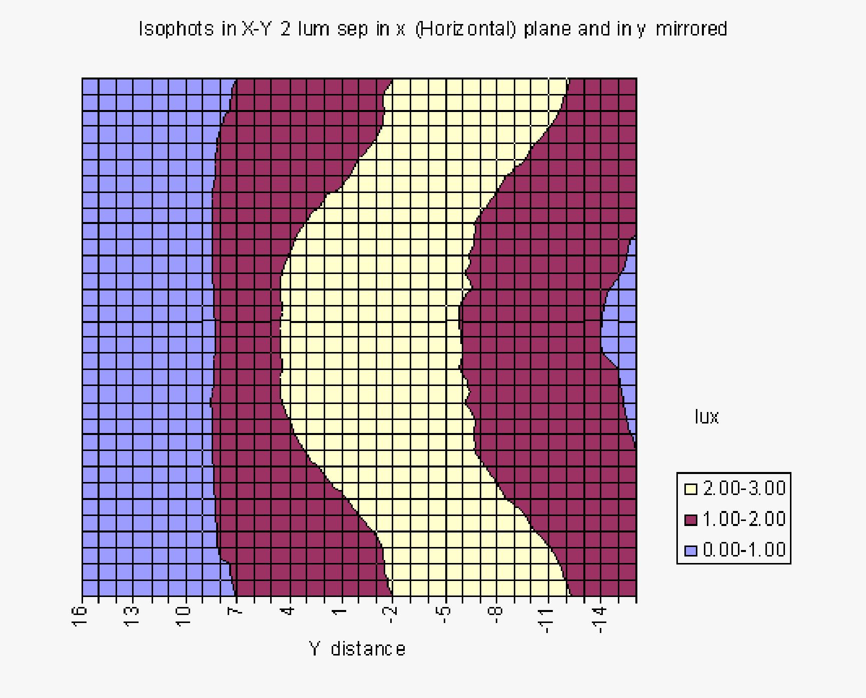
Integrated direct and reflected luminance ratio to total over all C angles up to gamma angle vs gamma angle.

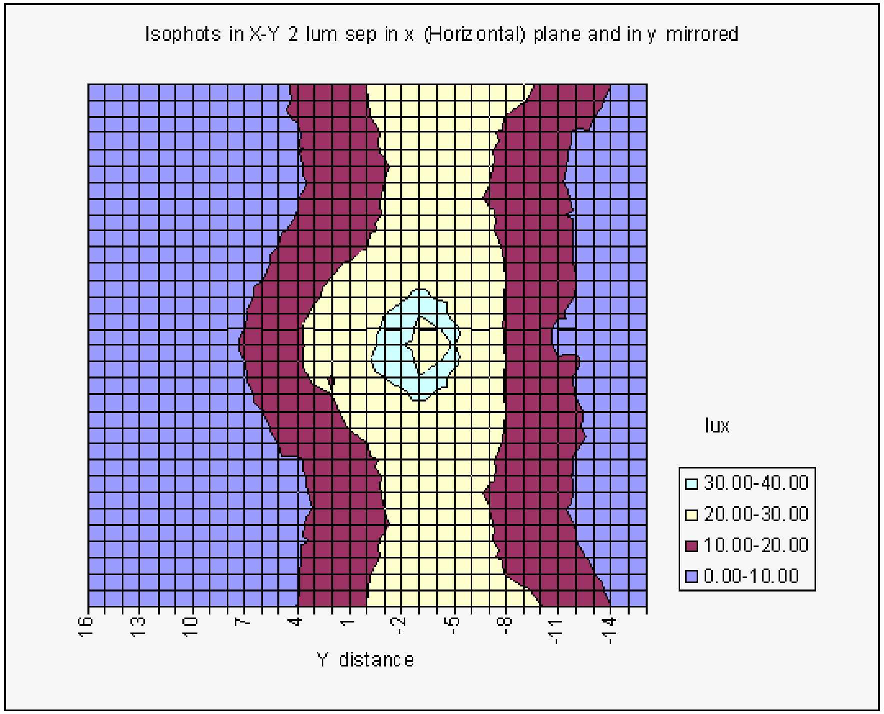


Luminaire surface illuminance in horizontal and vertical planes



SOX,
Illumination Horizontal
Vertical front along road
Vertical across road
Cut off
Full cut off
Isophots in X-Y (Horizontal) plane
Isophots in X-Z (Vertical -front) plane
Isophots in Y-Z (Vertical -across) plane
Isophots in X-Z (Vertical -back) plane
Y distance
X distance
lux
2.00-2.50
1.50-2.00
1.00-1.50
0.50-1.00
0.00-0.50
20.00-30.00
10.00-20.00
0.00-10.00
15.00-20.00
10.00-15.00
5.00-10.00
0.00-5.00
6.00-8.00
4.00-6.00
2.00-4.00
0.00-2.00
30.00-40.00

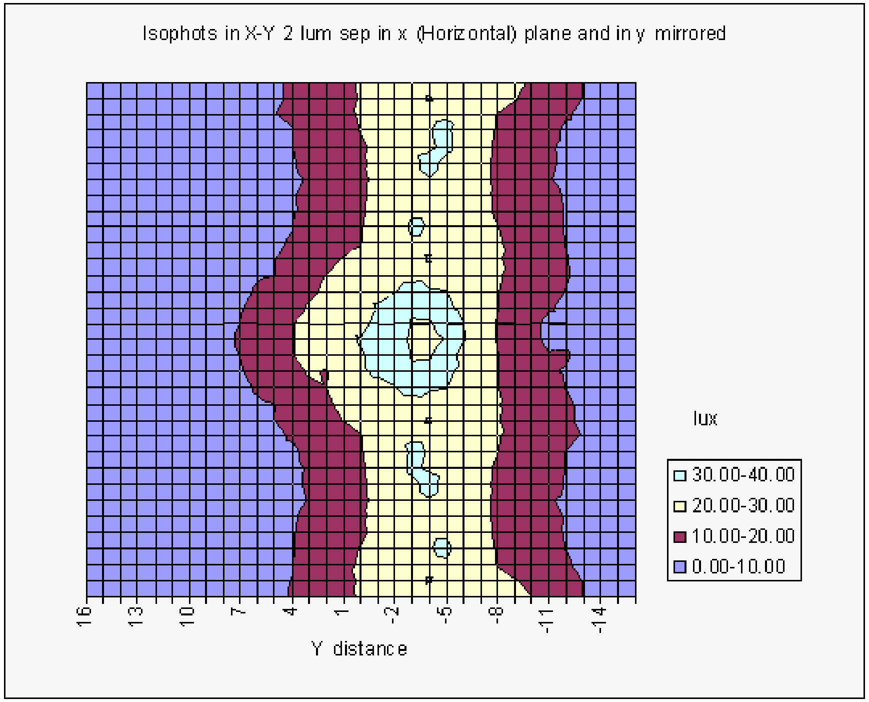




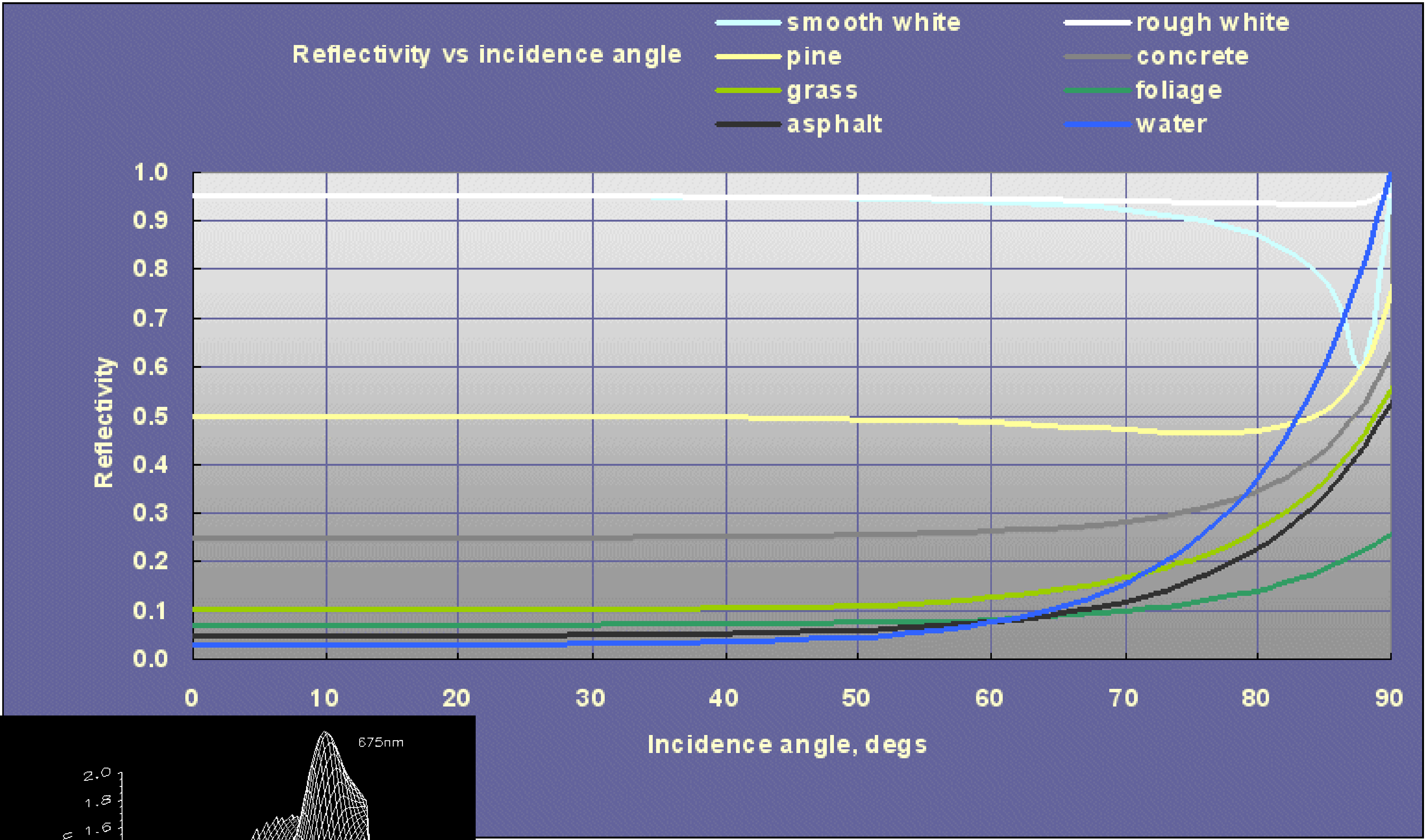
Horizontal surface illumination from SOX and Cut off (above),

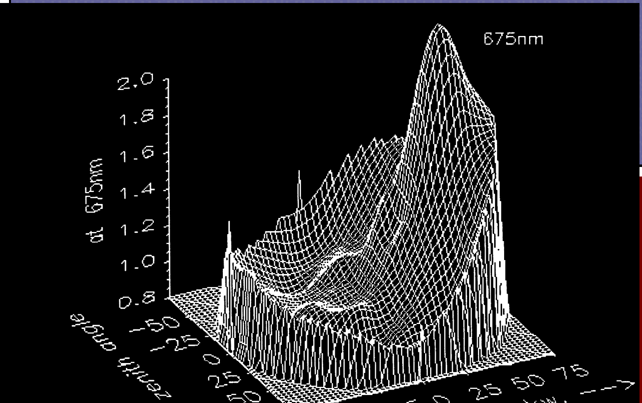
and Full cut off luminaires

Spaced alternate sides of a road.



Surface reflections and Bi-directional Reflectance Distribution Functions (BRDFs)

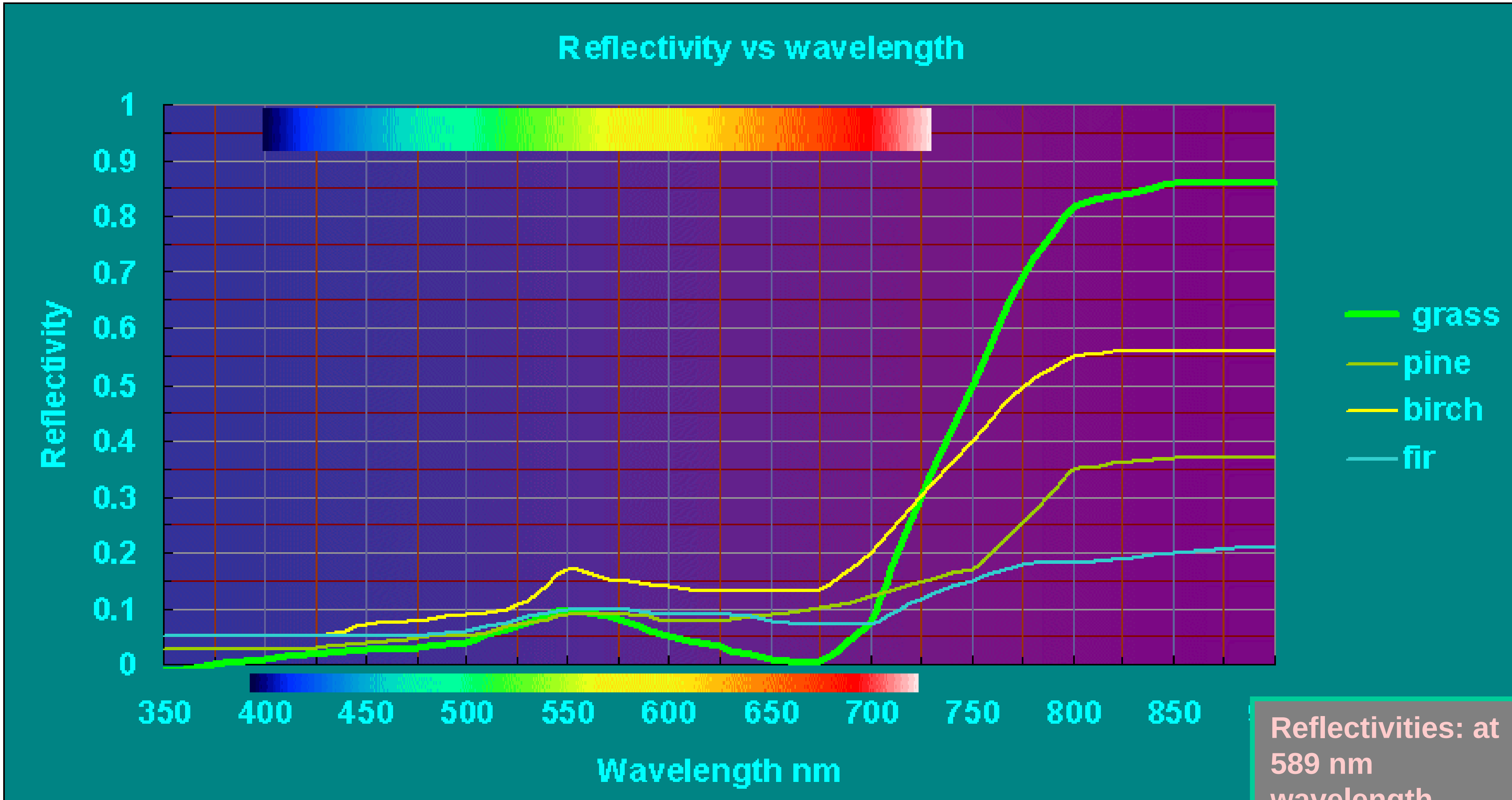




Reflectivity of grass as a function of angle of incidence to normal.

Reflectivity as a function of angle of incidence to normal.

Reflectivites of surfaces increase towards grazing incidence. Smooth surfaces go to unity. The Brewster angle is before this which blocks the horizontally polarised components. Most surfaces, even roughness are very reflective beyond 70 degrees, i.e. below 20 degrees to the horizontal. Low angle light is reflected, smooth ones become a mirror. Grass reflectivity 0.1 Rises to 0.2 at 80 degrees, asphalt goes from 0.04 to 1 at grazing angle, as does water



Reflectivities: at 589 nm wavelength

Soil 0.1

Grass 0.08

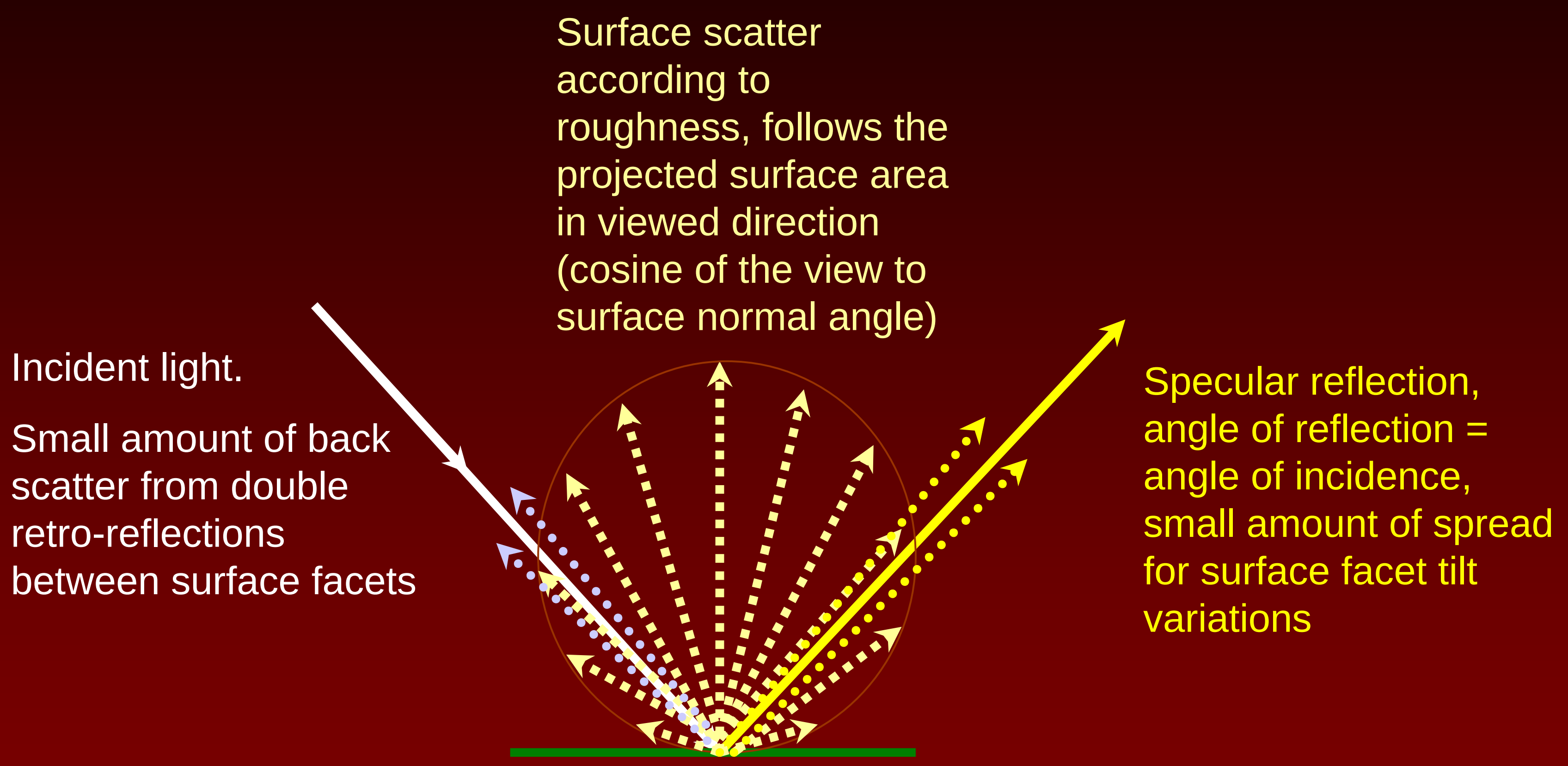
Foliage 0.06

Asphalt 0.04 to 0.08 (dirty)

Concrete 0.25

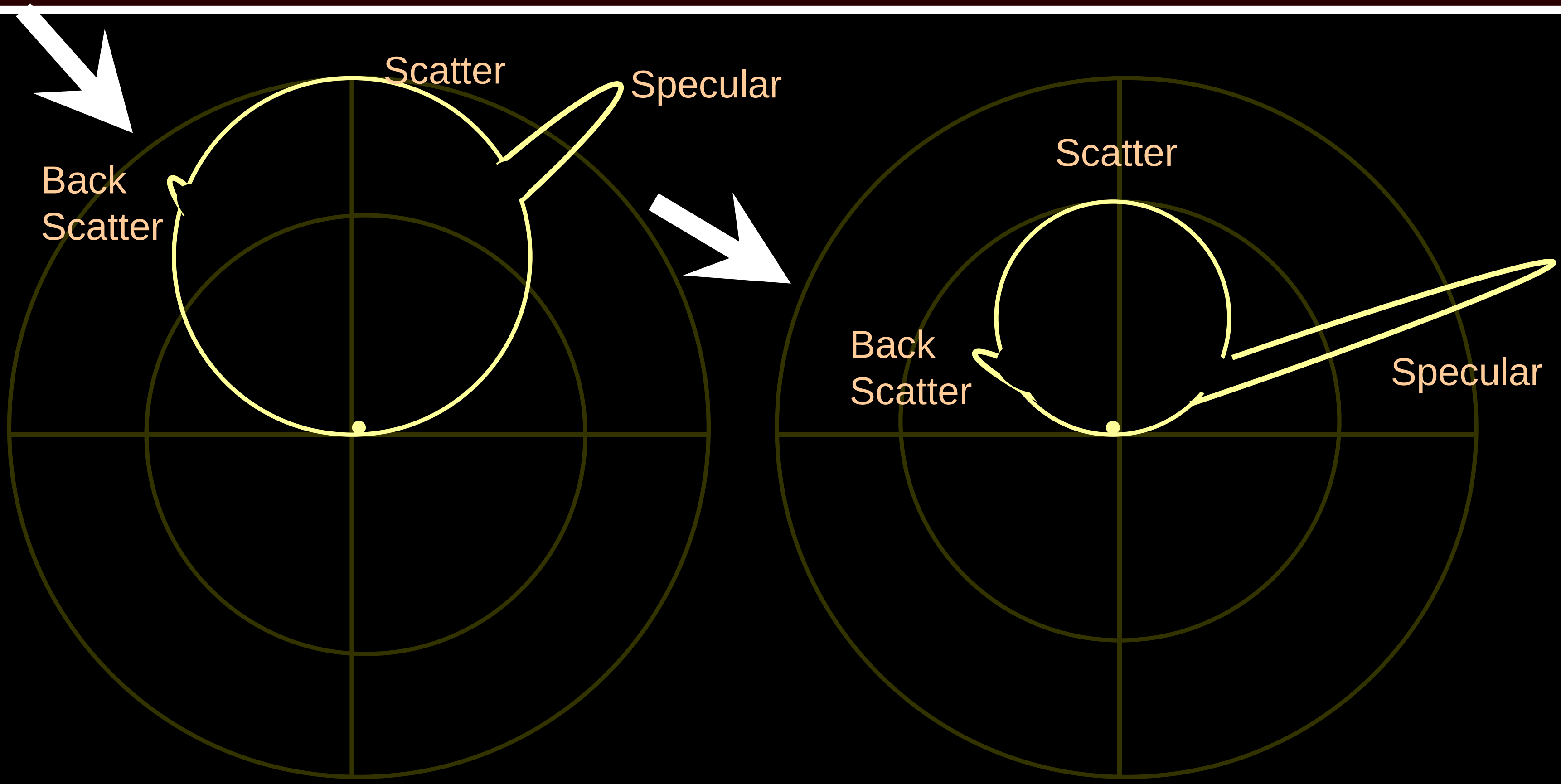
Reflectivities vary with wavelength. Grass is less reflective in yellow. Switching to white light increases its value. The minimum reflectivity is at about 670 nm where light is absorbed by photosynthesis, in common with all vegetation. Reflectivities rise rapidly in the near infrared for thermal rejection.

Surface specular and scatter reflection



Incident light to a surface is reflected and scattered thus :- A small amount of back scatter from double retro-reflections between surface facets. Specular reflection, angle of reflection = angle of incidence, small amount of spread for surface facet tilt variations. Surface scatter according to roughness, follows the projected surface area in viewed direction (cosine of the view to surface normal angle)

Surface specular and scatter reflection
Bi-directional Reflectance Distribution Function (BRDF)



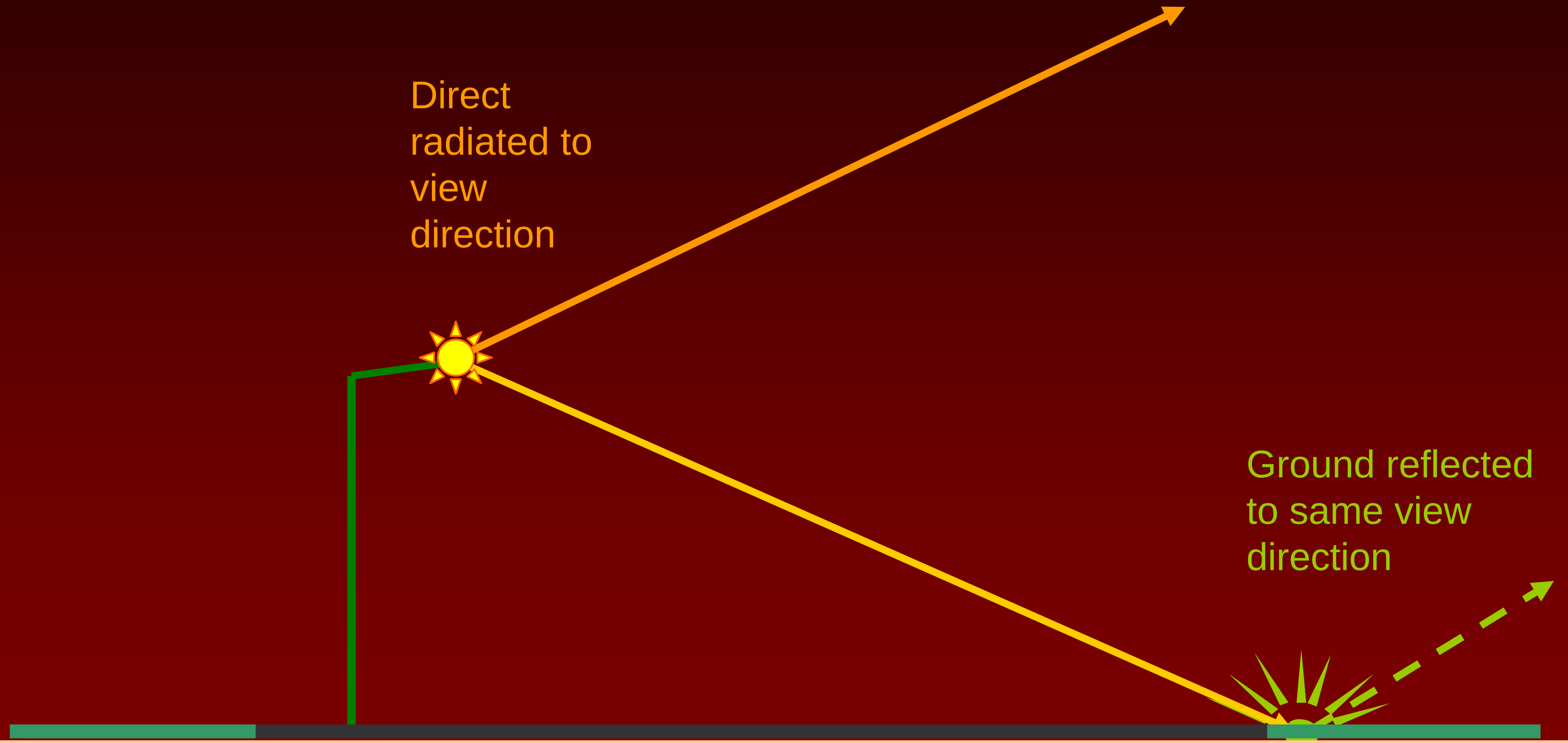
Small incidence to normal angles

Large incidence to normal angles

Bi-directional Reflectance Distribution Function

Showing dependence of scatter on cosine of incidence and cosine of view projection angle, and specular reflection near 1-cosine dependence on incidence angle (near Lambertian), increasing towards grazing.

Direct and surface reflected rays diagram for low above horizontal gamma view, for horizontal surface reflections



At low gamma (elevation) the specular reflection point is on the surrounding surface. The program specifies a normal incidence wavelength dependent reflectivity and roughness factor, for every surface type, and calculates local specular and scatter angular dependent reflectivity. At shallow reflection angles the surface reflectivity is significantly enhanced, according to the degree of smoothness.

Direct and surface reflected rays diagram for high above horizontal gamma view, for horizontal surface reflections

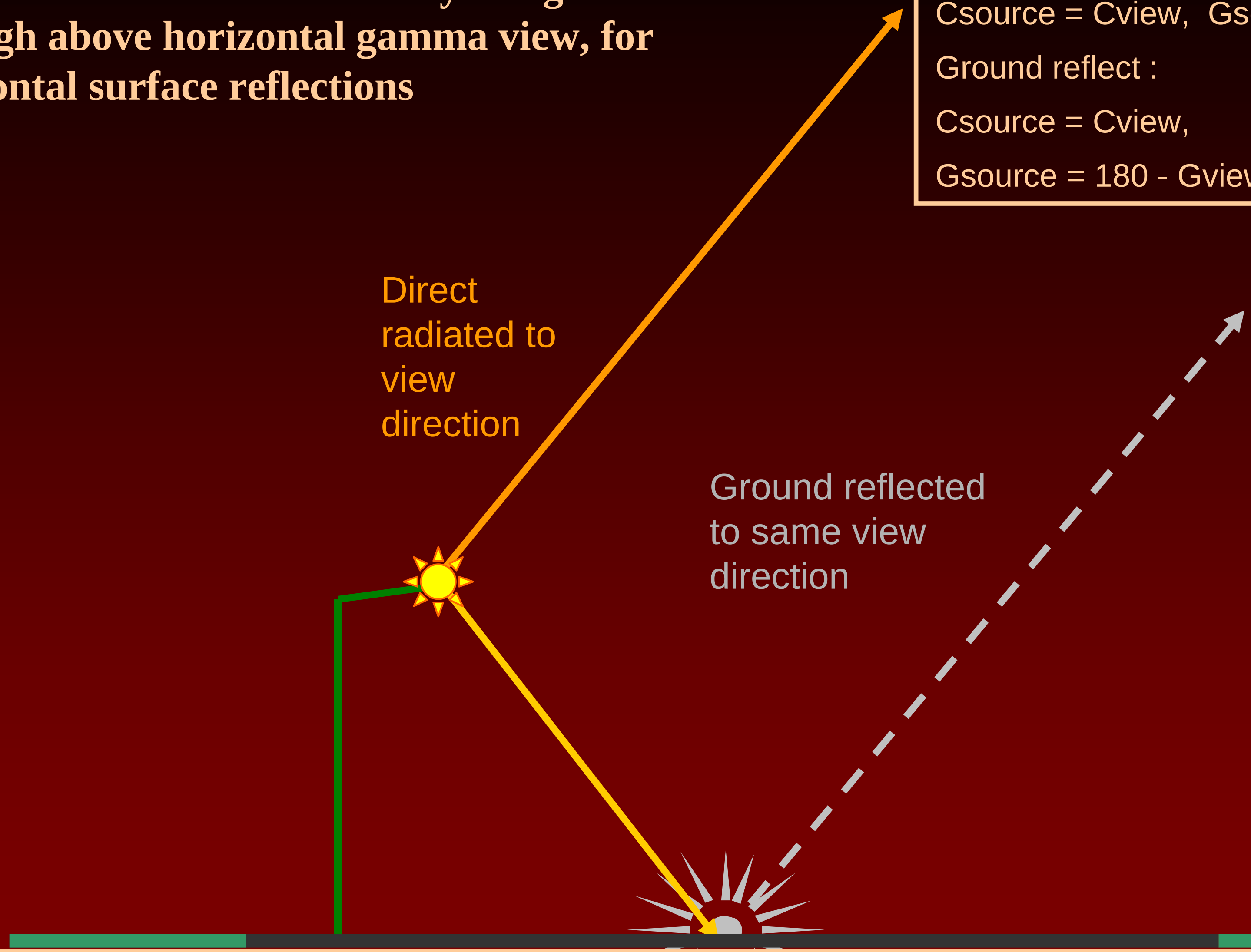
Direct :

Csource = Cview, Gsource = Gview

Ground reflect :

Csource = Cview,

Gsource = 180 - Gview

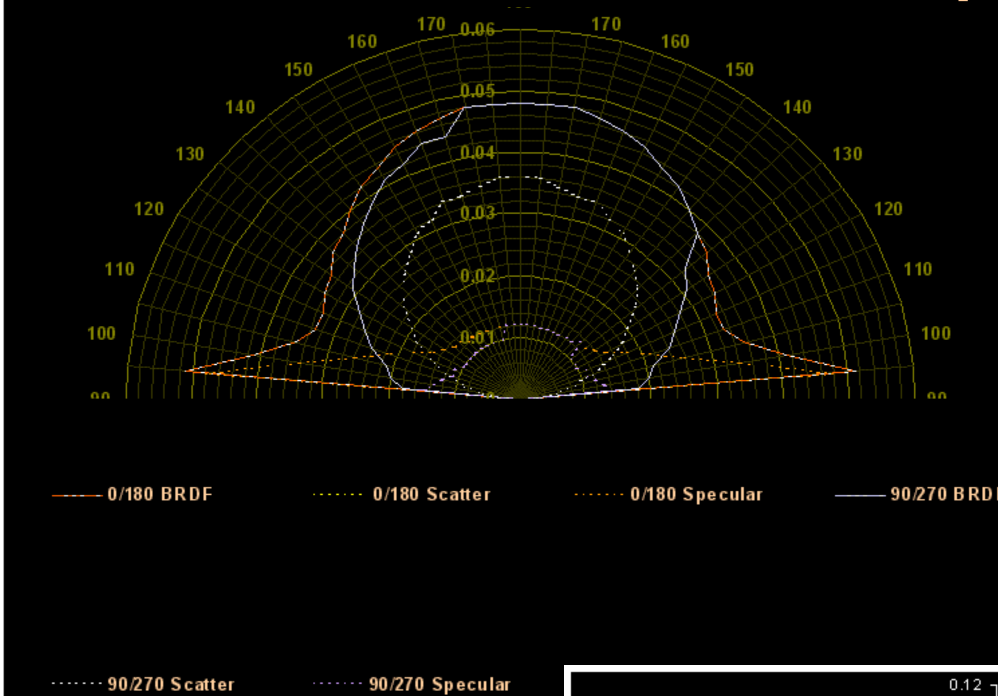


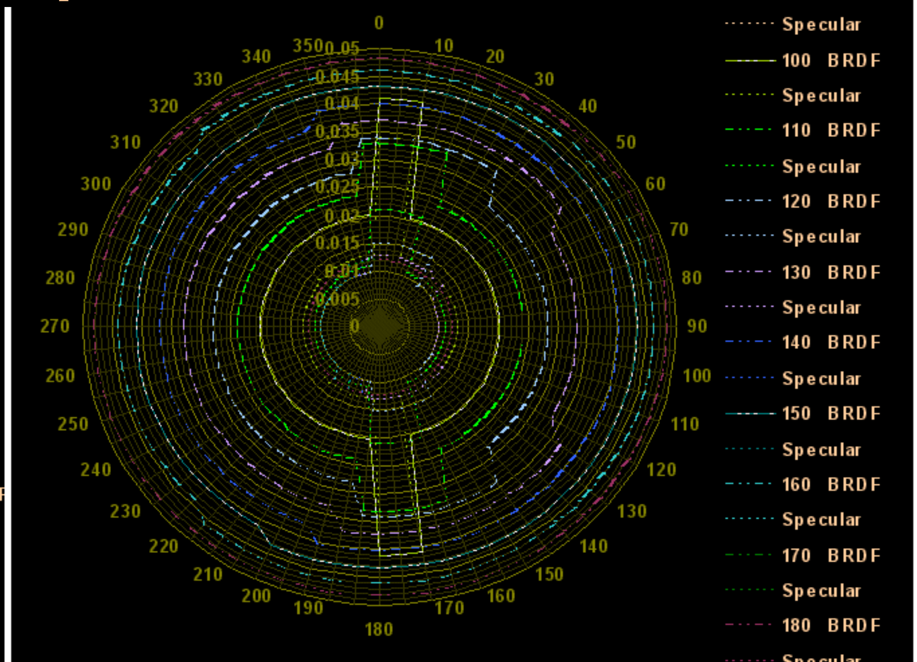
At higher view gamma angles (elevation) the reflection point is on the road surface. The law of reflection applies. The direct specular, and scatter reflected components for each source C and gamma angle, are calculated and stored as view angle addresses. So they are re-grouped (as shown) for all routes to each same view angle.

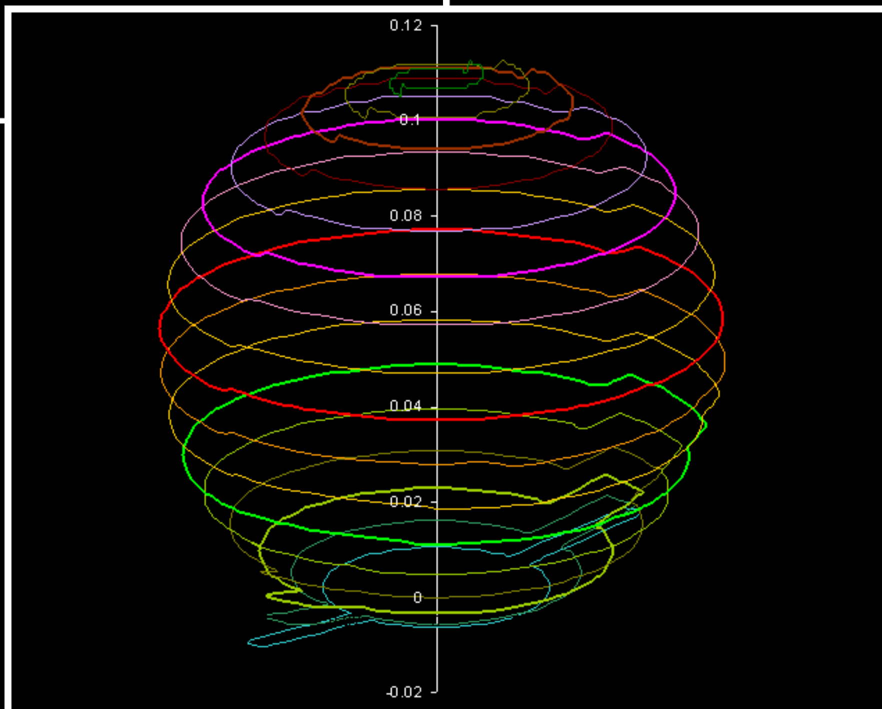
Luminaire upward light polar distributions for horizontal surface reflections

Street lights and reflections at night, Canterbury (John Kemp)

BRDF polar plots







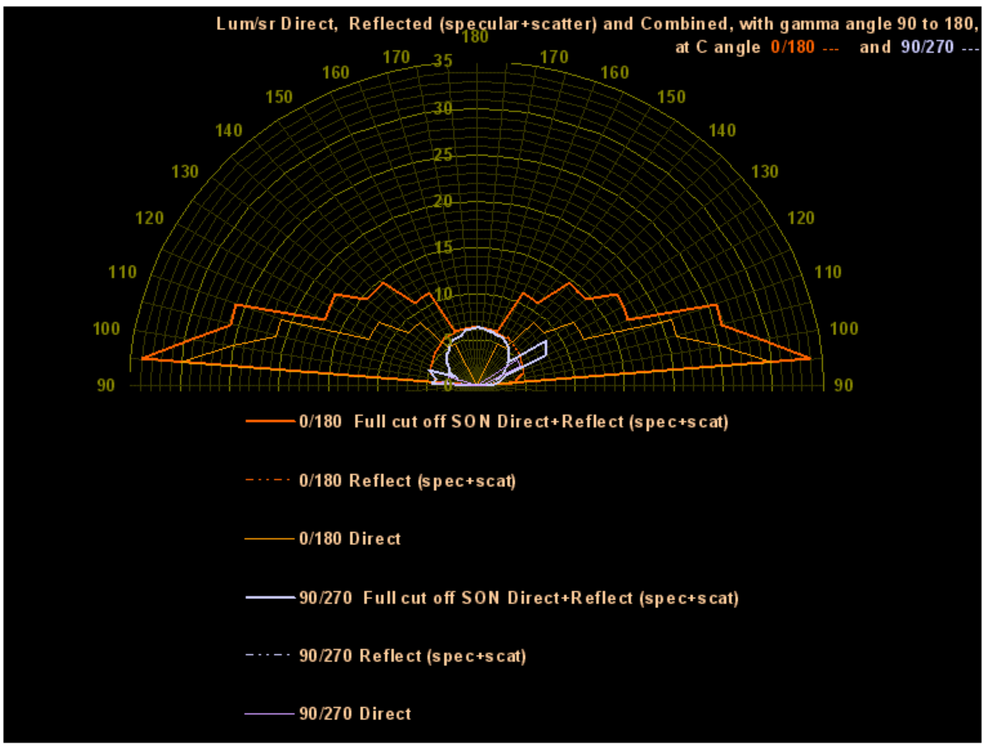
Elevation (gamma angle) polar diagram of Bi directional Reflectivity Distribution Function (BRDF)

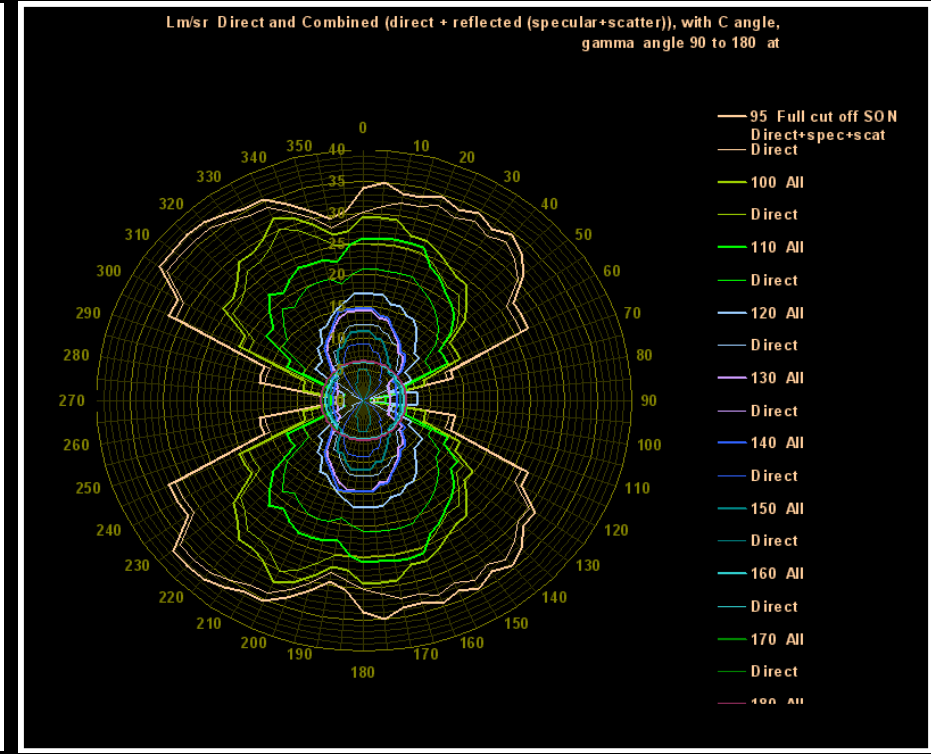
For specular reflectivity, scatter reflectivity, and combination at C angle 0-180 and 90-270 for gamma 90 to 180.

Azimuth (C angle) polar diagram of Bi directional Reflectivity Distribution Function (BRDF)

For specular reflectivity, scatter reflectivity, and combination at at gamma angles of 90,100,110,120,130,140 ,150,160,170,180.

Luminaires reflection and upper radiance polar plots





SOX

SOX

Elevation (gamma) polar diagram

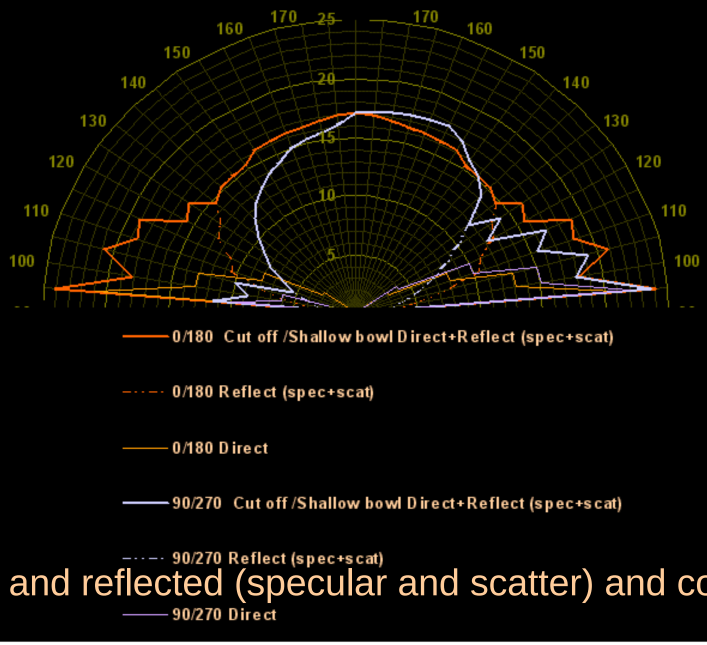
For direct and reflected (specular and scatter) and combination for gamma 90 to 180, at C angle 0-180 and 90-270.

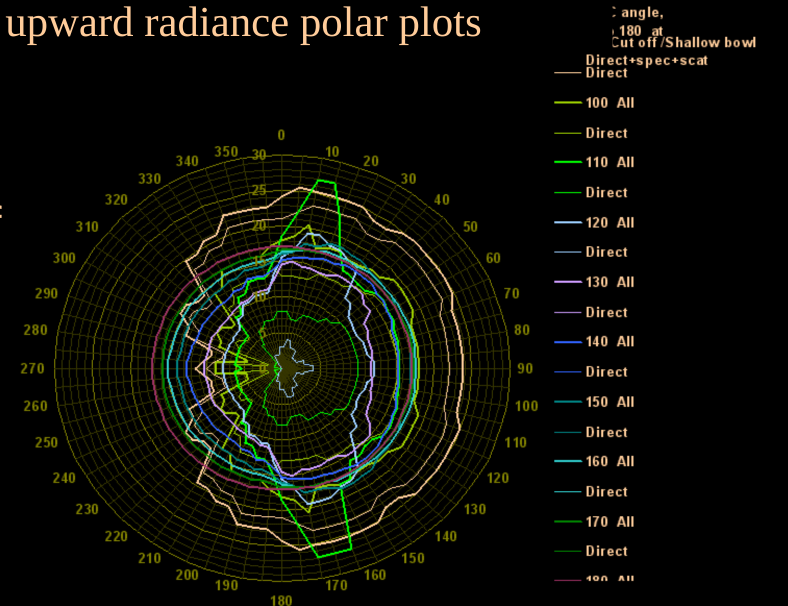
Azimuth (C angle) polar diagram

For direct and combined direct and reflected (specular and scatter), at gamma angles of 90,100,110,120,130,140,150,160,170,180.

Luminaires reflection scatter and direct upward radiance polar plots

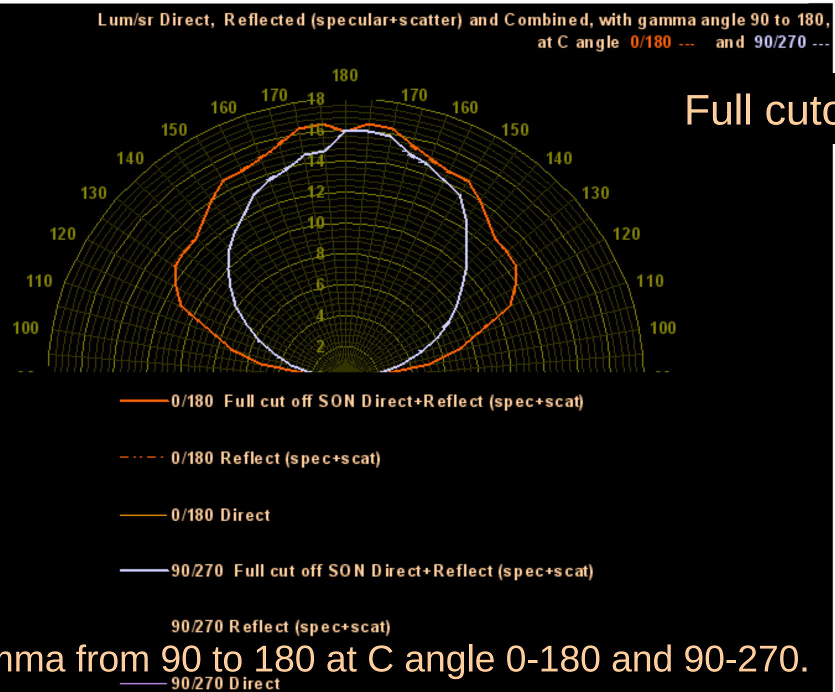
Cut off

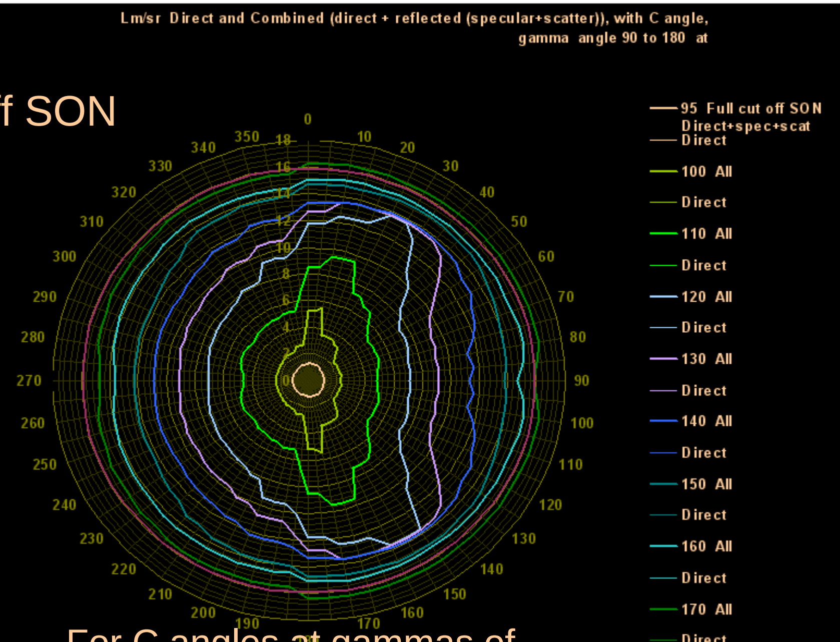




Direct and reflected (specular and scatter) and combination

Full cutoff SON





For gamma from 90 to 180 at C angle 0-180 and 90-270.

For C angles at gammas of 90,100,110,120,130,140,150,160,170,180

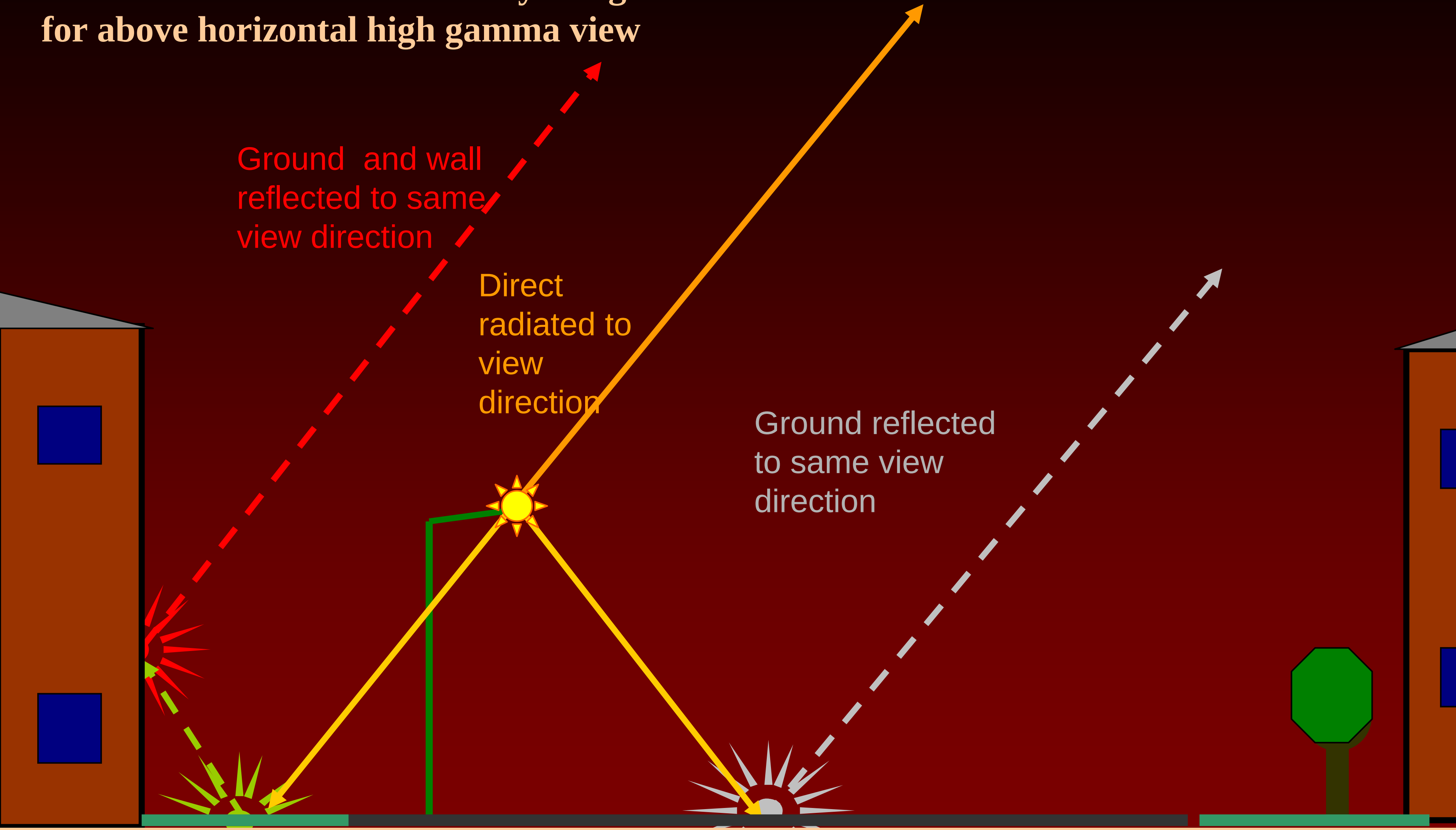
Upward light ratio



Luminaire Type	Upward light ratio (fraction of total above horizontal)	Ground reflection	Upward fraction including ground reflection
Standard SOX	7.8%	6.2%	14%
Cut off SON	3.3%	6.1%	9.4%
Full cut off SON	0%	6.9%	6.9%

Reflections of horizontal and vertical surfaces (built up roads)

Direct and surface reflected rays diagram for above horizontal high gamma view



Direct upward, front ground reflected, and back ground and wall reflected (three routes). Address mapping is used to find all routes from source to view direction. Horizontal reflections are reflected by vertical surfaces back in the opposite direction and back surfaces reflect to forwards directions.

Shown here after the source ray traces have been re-grouped to the same view direction.

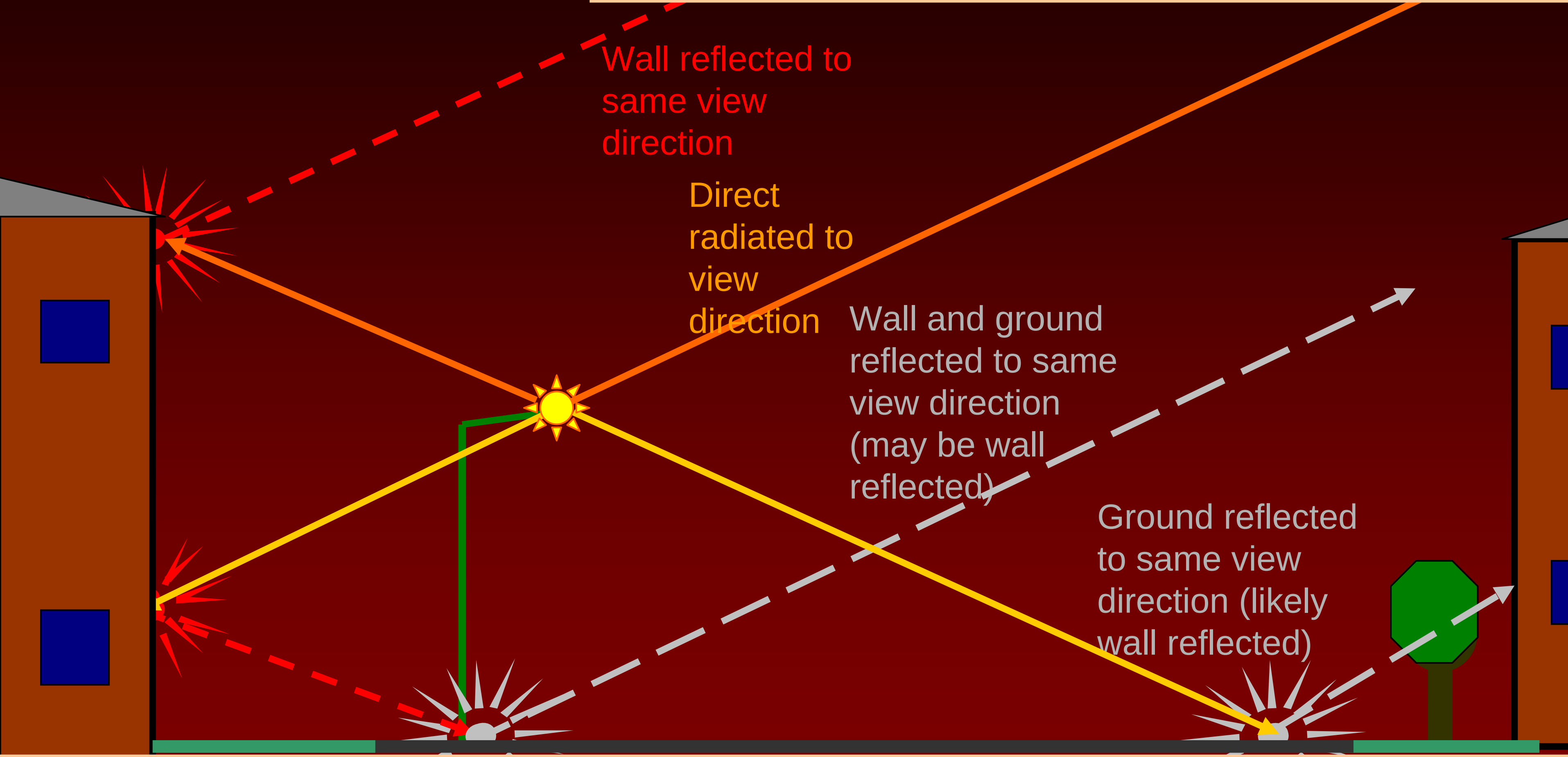
Direct and surface reflected rays diagram for above horizontal low gamma view

Direct : Csource = Cview, Gsource = Gview

Ground reflect : Csource = Cview, Gsource = 180 - Gview

Gnd & wall reflect : Csource = 360 - Cview, Gsource = 180 - Gview

Upper wall reflect : Csource = 360 - Cview, Gsource = Gview



Direct upward, back ground with wall reflected, and upper back wall reflected routes (three routes). Note the front ground reflected one is blocked, and so appears as a back one mapped to the opposite view direction.

Address mapping is used to find all routes from source to view direction. Shown here after the source ray traces have been re-grouped to the same view direction.

Atmospheric scattering

Daylight Rayleigh scattering by air molecules, smaller than the wavelength of light. Equal forward and backward scatter, also sideways, Varies as 1 / wavelength ^{4}

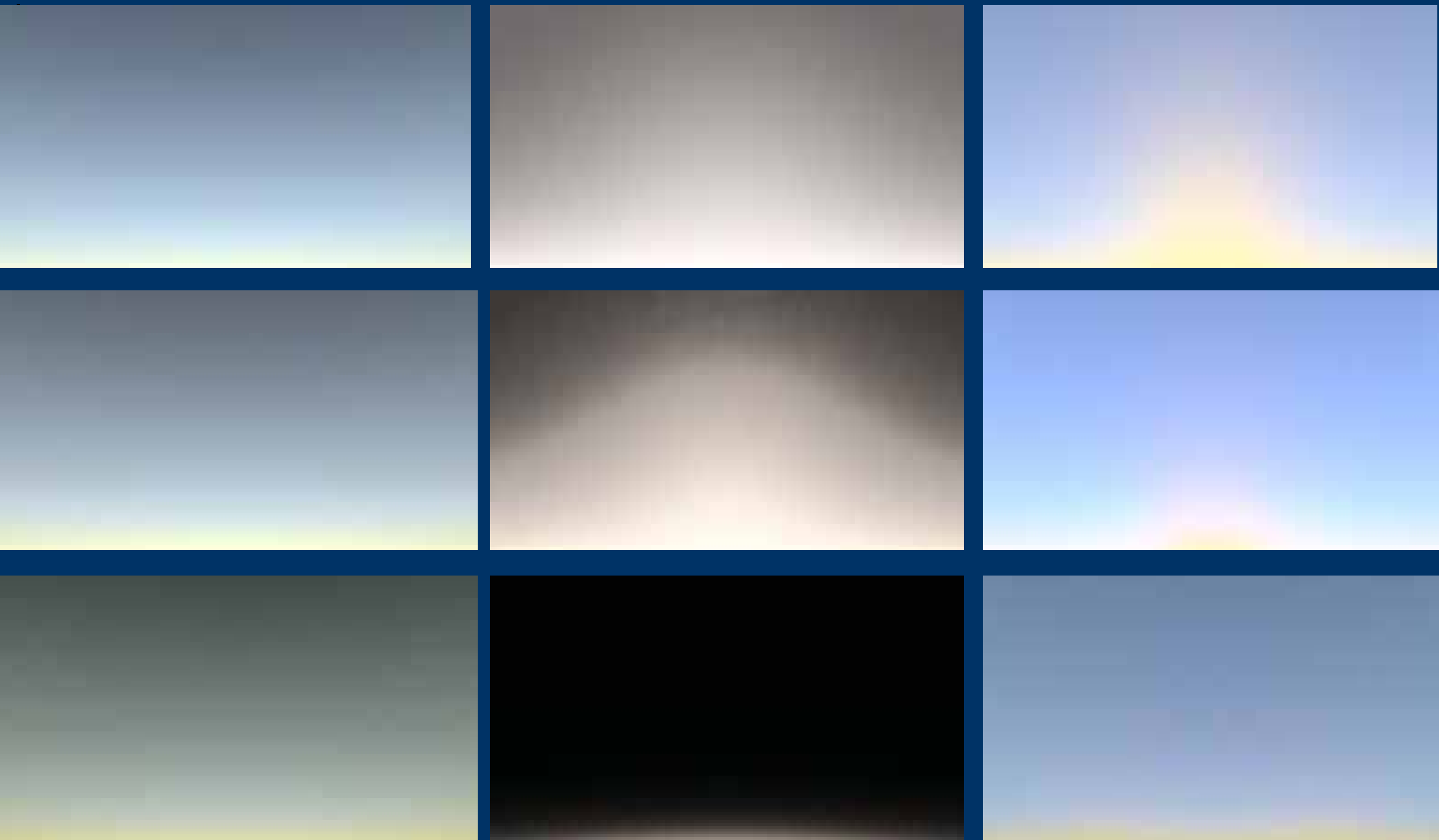
Mie scattering by aerosols.. water droplets and dust, similar or larger than the wavelength of light. No wavelength dependence and very directional.

Note when the Eiffel tower beam is orthogonal, seen by its scatter, it disappears.
(here shown near beam on)

Sunset scatterring simulation

Sky scatter from Sun (sun omitted) with elevation
(//webexhibits.org/causesofcolor/14B.html)

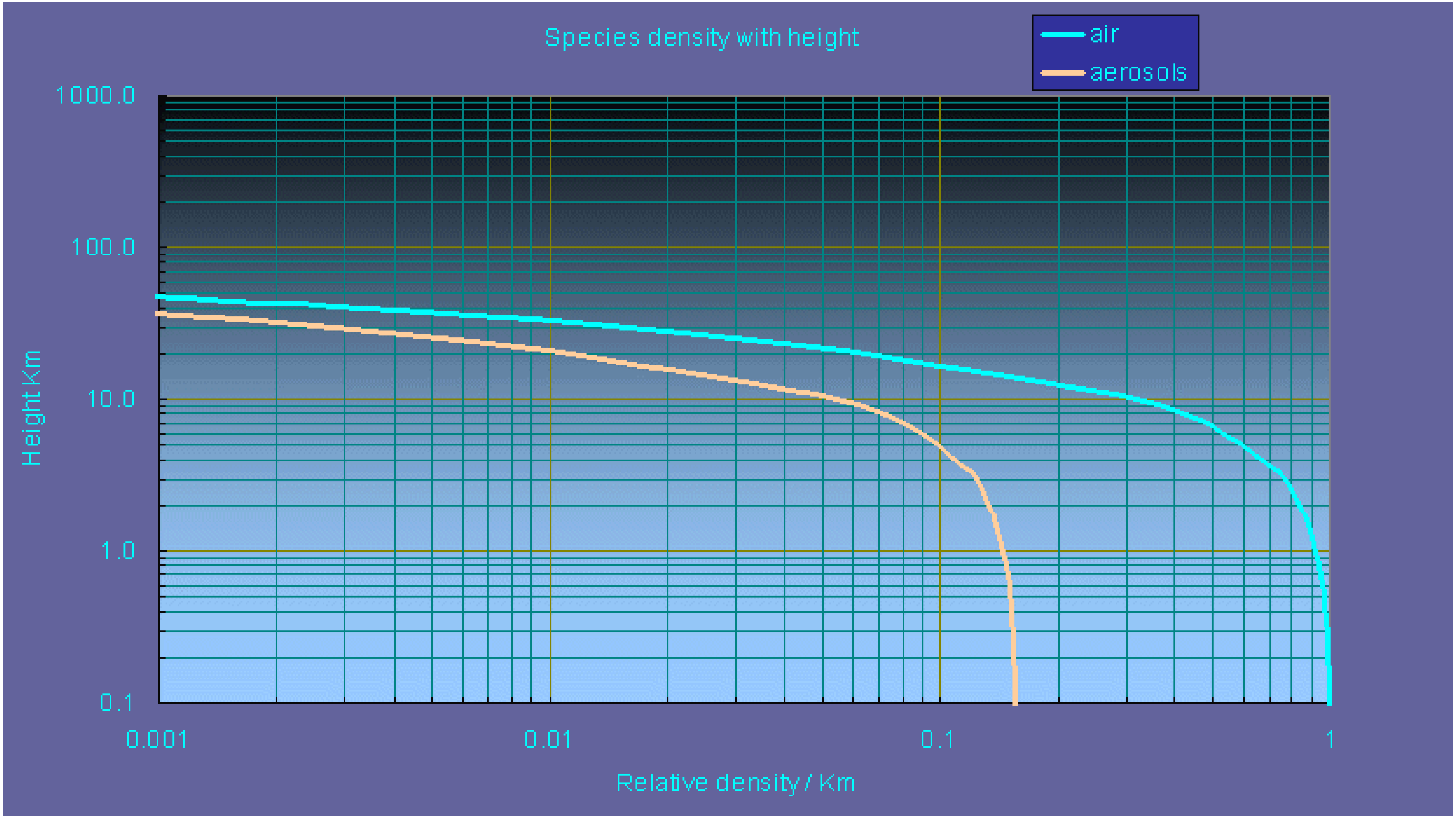
Rayleigh scatter air molecules **Mie scatter from aerosols** **Total Scatter** Sun Elev



0 ^{o}

-2.5 ^{o}

-5 ^{o}

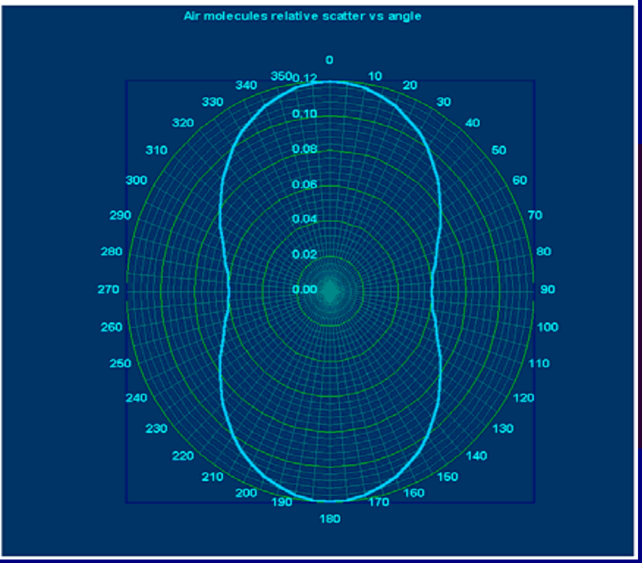


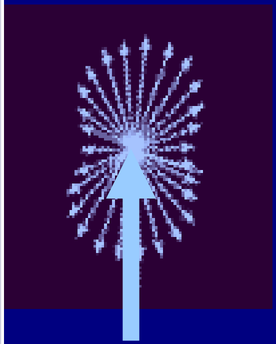
$$\rho_i(y) = \frac{\omega_{0i}(1+\alpha_i)\exp(y/h_i)}{h_i(\alpha+\exp(y/h_i))^2}$$

The variation of density of air molecules and aerosols, as a function of altitude in the atmosphere. At 10 km altitude the density off the air has reduced to 2/3 of its ground value.

The equivalent height of the total atmosphere brought to constant density is only a few km.

Scatter probability





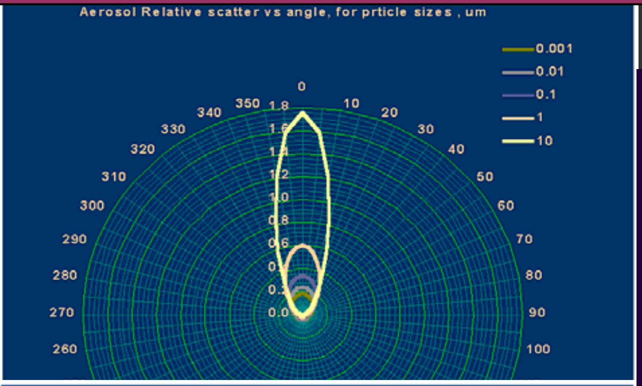
Scatter probability for scatter angle (phase function).

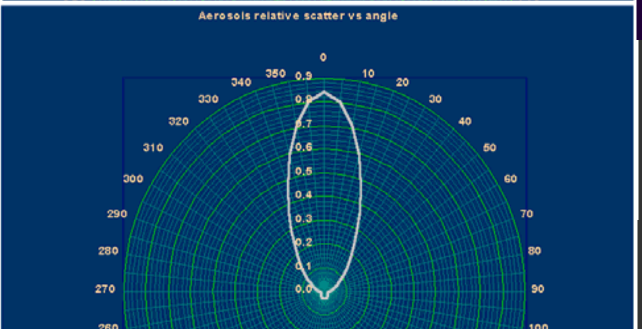
Light from below is scattered in the direction of the grid angles. The distance from the centre curve gives the probability of scatter in that direction. The probability over all angles is set at 1, (100%), and must be multiplied by the scattering density.

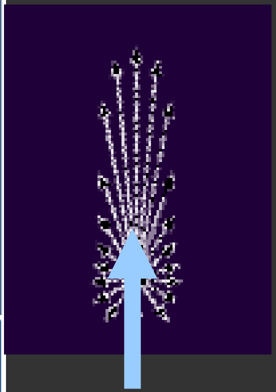
Rayleigh scattering from air molecules.

Equal probability forwards and backwards, 50% of that sideways. Intensity varies as wavelength ^4 (blue biased). It is why the sky is blue by day.

$$P(\psi) = (3/(16\pi)(1+\cos^2\vartheta)$$







Mie scattering from aerosols

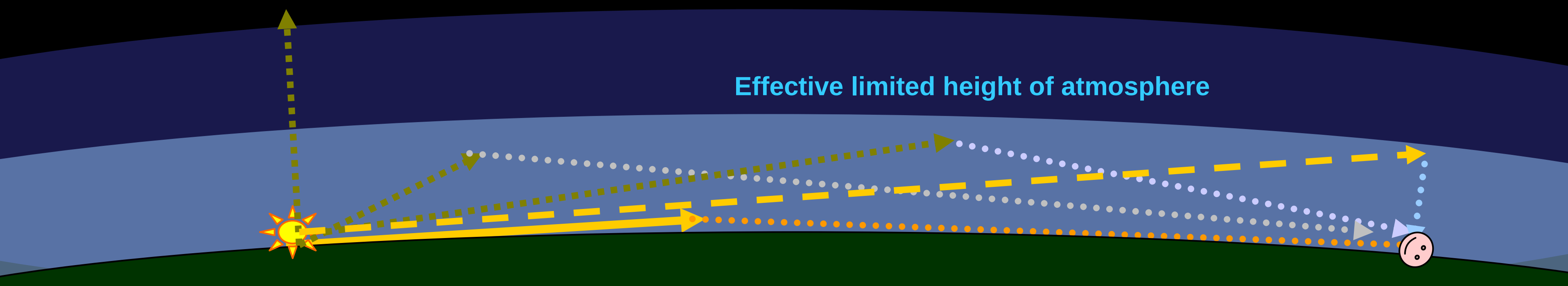
(Heye-Greenstein function with added back scatter).

The forward scatter is very peaked, increasing with particle size from 1nm to 10 microns. There is practically no sideways scatter and back scatter is tiny. No wavelength dependence. It is why clouds and snow are white. The lower scatter probability profile is the one used.

$$P(\vartheta) = (1-g^2)\left[\frac{1}{(1+g^2)-2g\mu)^{3/2}} + f\,\frac{(3\mu^2-1)/2}{(1+g^2)^{3/2}}\right]$$

Path Geometry

Path geometry



Viewing from a distance (10’s of Km) .

Due to the limited height of atmosphere, the path geometry is dominated by shallow angles.

Aerosols scatter efficiently at shallow angles.

While at the zenith of the view location, the scatter is at right angles where aerosols do not scatter, and so scattering is then due to air molecules.

The impact on skyglow in rural areas, of luminaire design…. Results…

Plots of skyglow :-

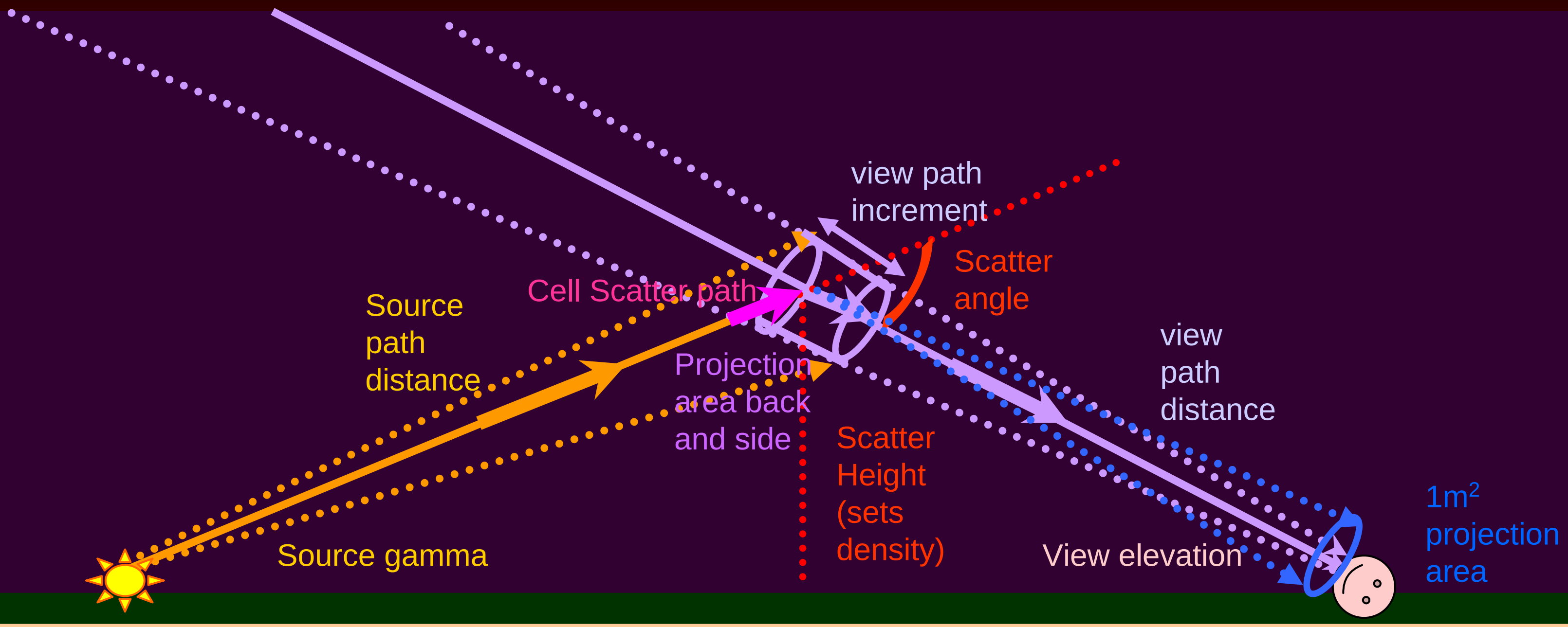
Incremental vs. distance along a given elevation path

Total vs. elevation at a given distance

Total for a given elevation vs. distance

Line of sight cone of view projection to source view path and scatter path increment

Only 2 dimension case shown; it is done in 3D.



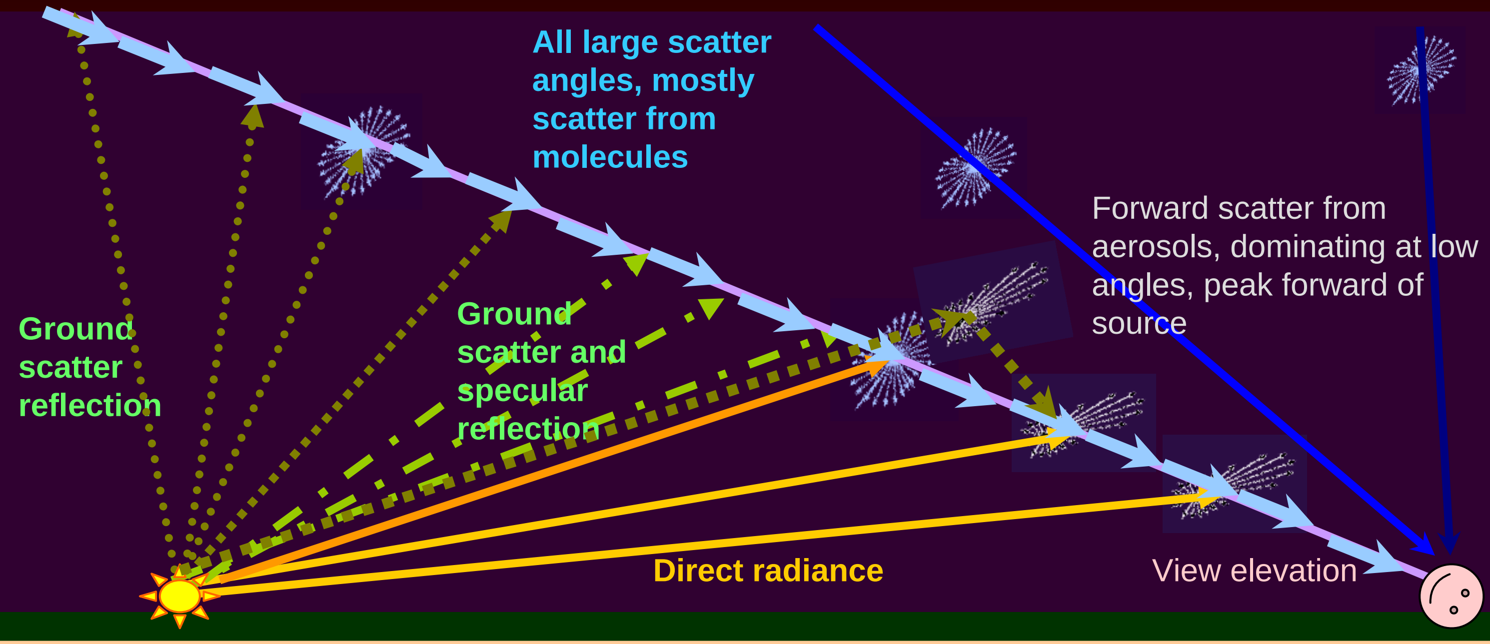
A unit cell in a cone of sky from the viewer is seen to project side and front to the source, according to the scatter point location.

For a given view elevation and azimuth and path distance and source distance ….

all the other distances and angles can be calculated, that is … the source path distance, the scatter point height, the source or reflected gamma and C angle of the light, and the scatter angle. (Also done for curved Earth)

The solid angle subtended by the cell at the source in terms of that for the viewer can be calculated, that times the scatter probability gives the sky luminance for that increment allowing for the source and viewer path extinction. All increments along the viewpath are summed.

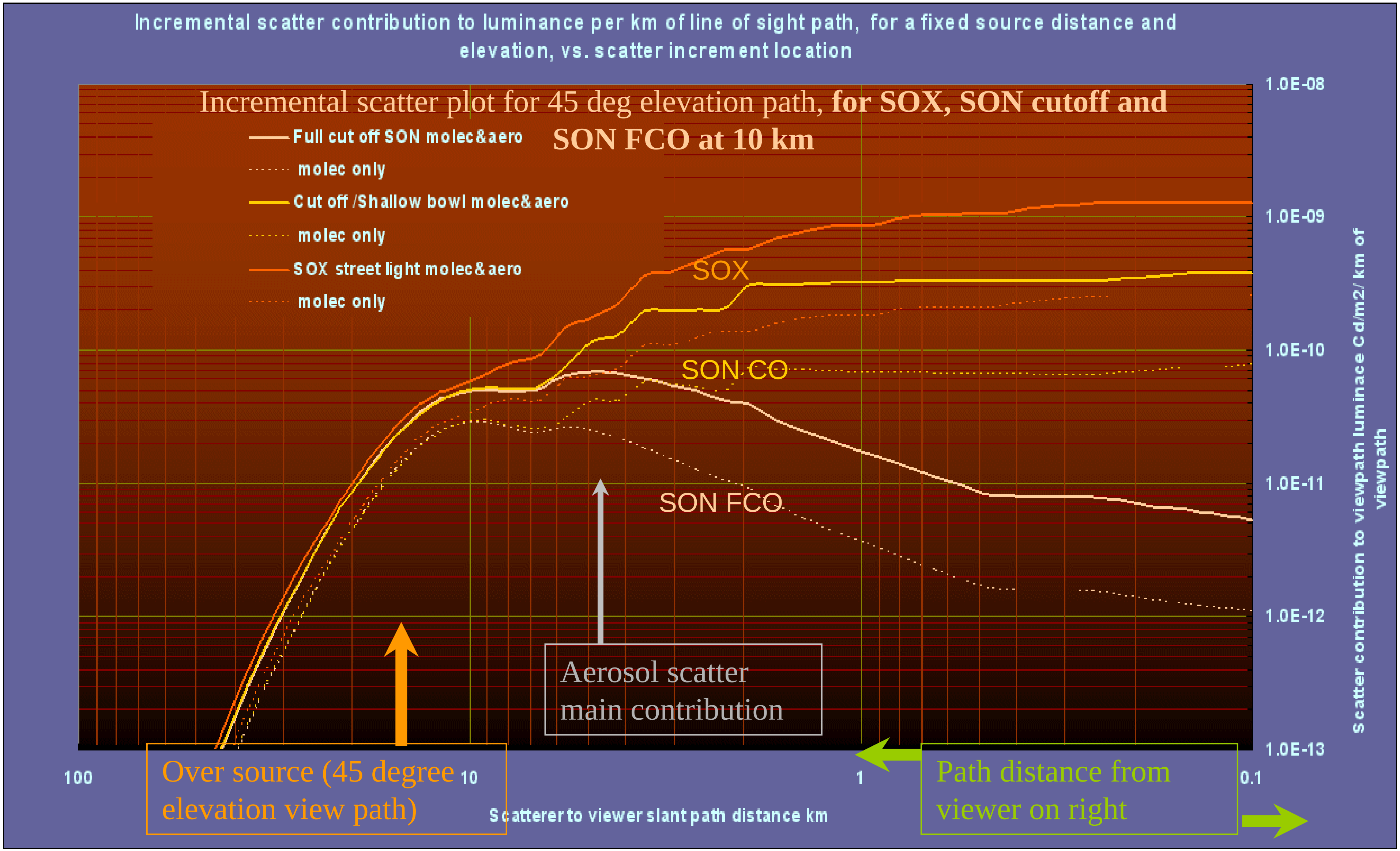
Scatter into line of sight for at an view elevation



Skyglow at an elevation, the sum of all the scattering for all increments along the path.

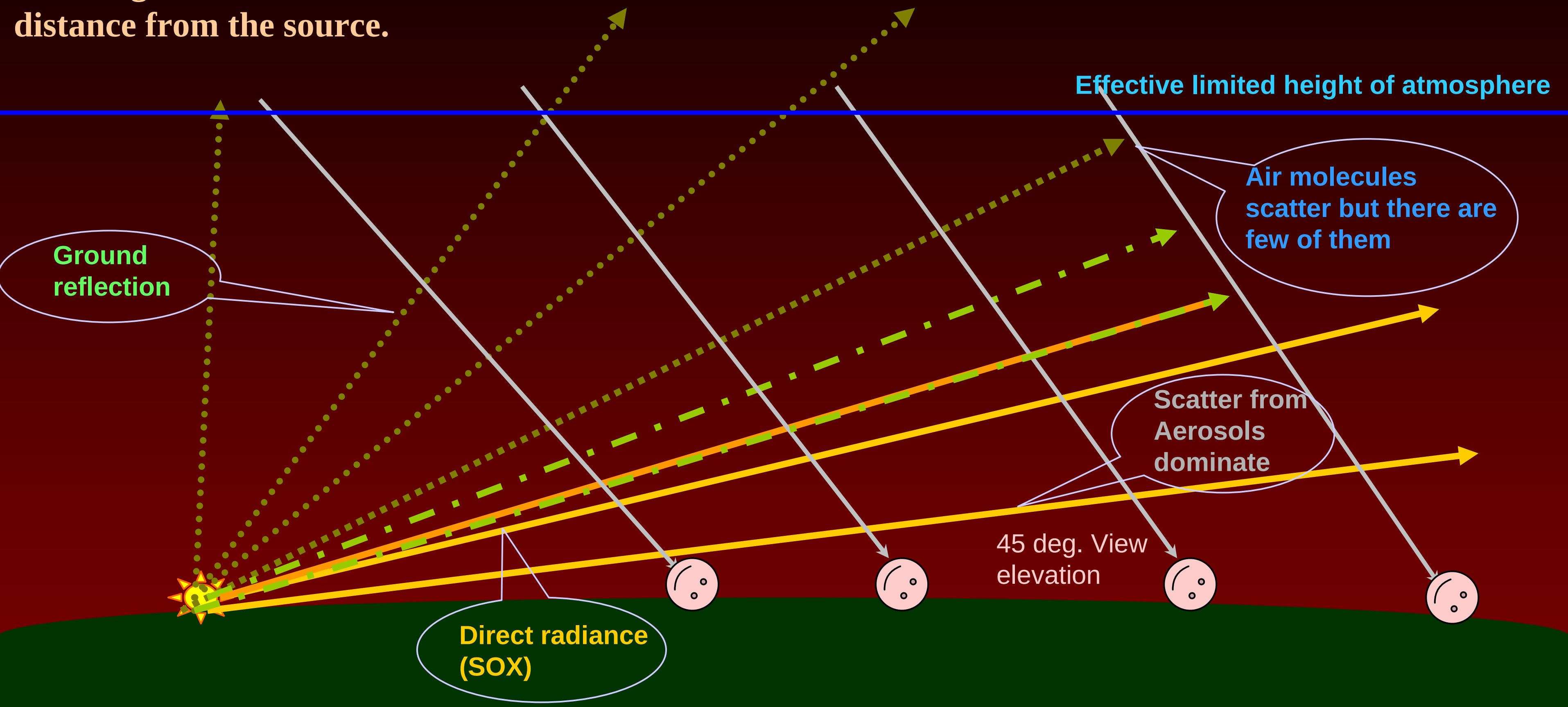
Skyglow at close distance, <2 Km is dominated by ground reflection, but at increasing distance it becomes dominated by low angle light from above the horizontal

Scatter at low angles is from aerosols. Scatter at large angles it is mostly by air molecules, maximally in the blue. Little is from the upper parts of the path, as there the scattering is orthogonal or back scatter and the aerosol density is much lower.

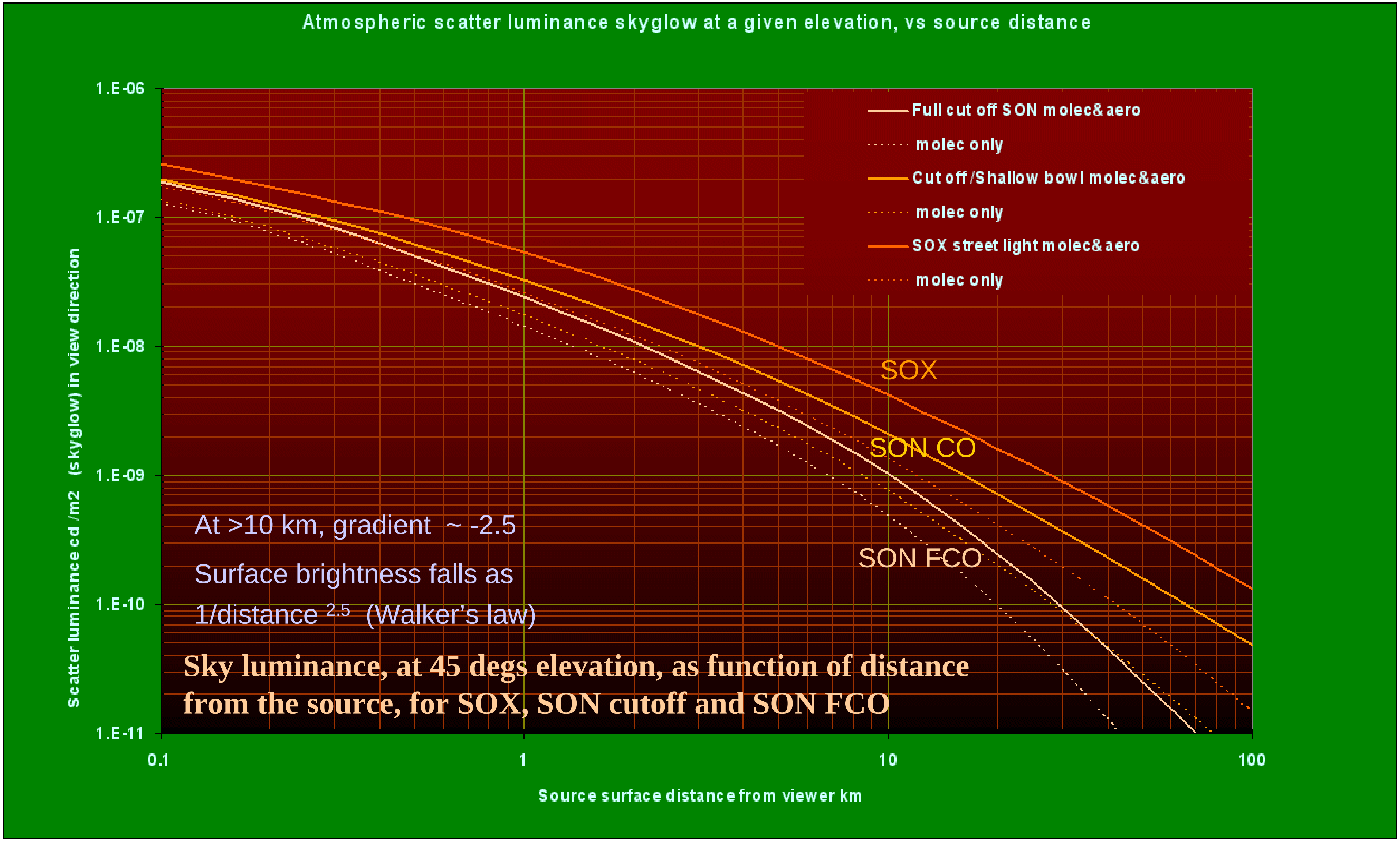


The brightness contribution to a 45 deg elevation view path, scatter at each point along the inclined path in the direction of a source (10 km horizontal, 14 km inclined path). Reflection for grass normal incidence reflectivity 0.1. Luminaires types SOX (orange) and cutoff (light orange) and cutoff SON (pink). Scatter just from molecules (dots) and combined with aerosols (lines). Aerosols dominate at low elevations

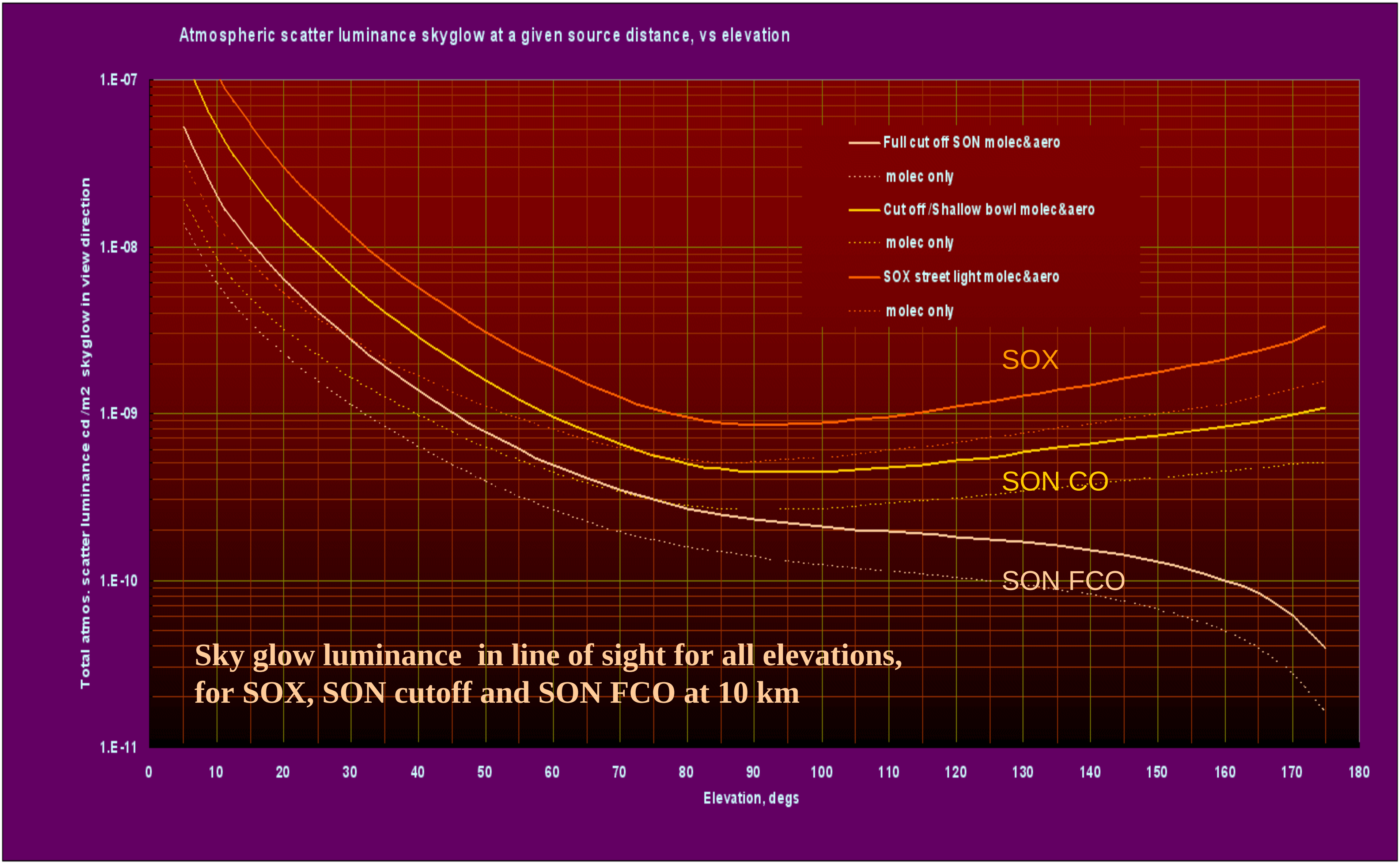
Diagram of scatter into line of sight, at 45 degs elevation, as function of distance from the source.



Skyglow at 45 deg. elevation, as a function of distance from the source.

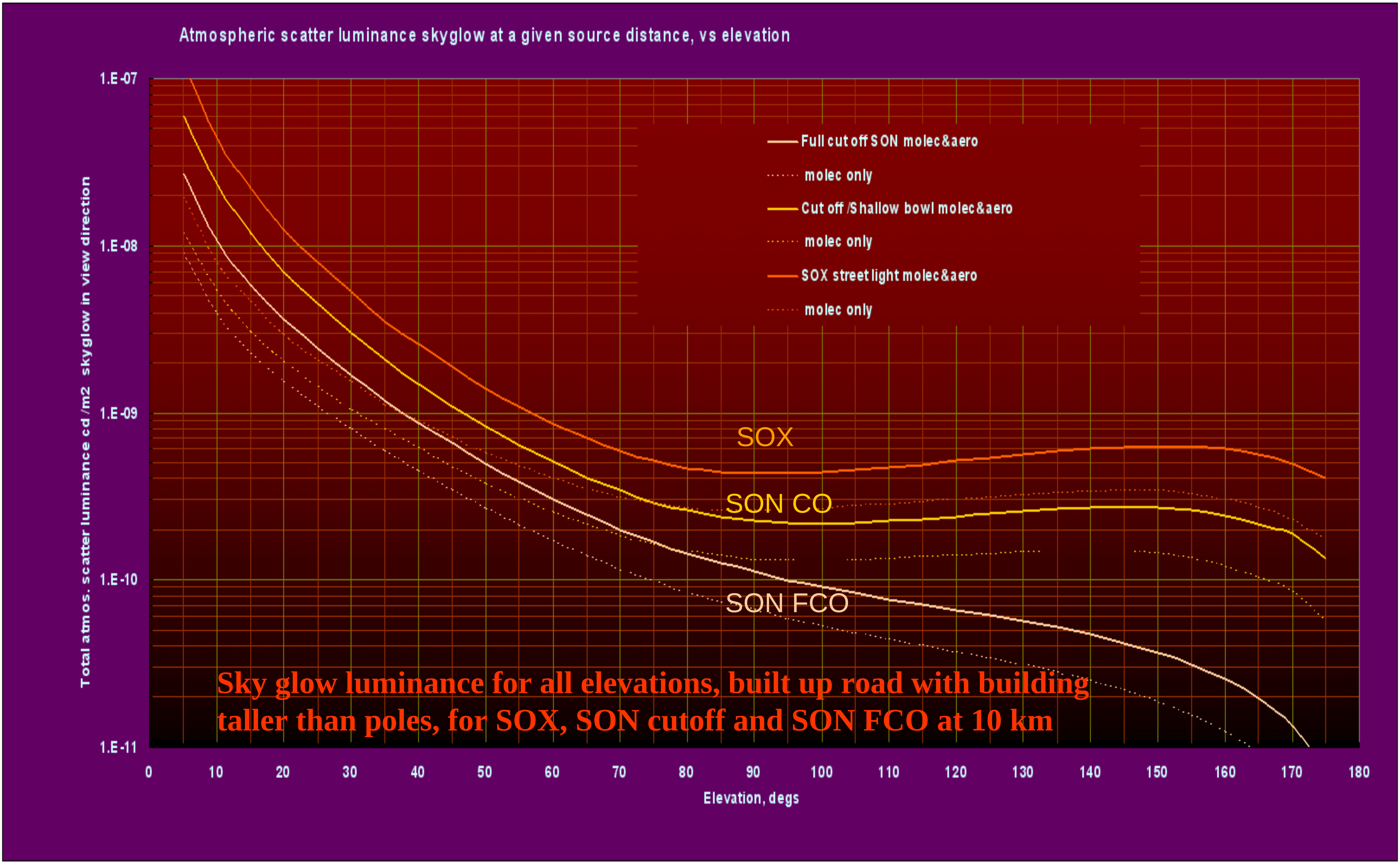


Sky luminance along a 45 degree elevation path in the direction of a source as a function of source distance. Reflection for grass. Luminaires types SOX (orange) and cutoff SON (light orange) and full cutoff (pink). (normal incidence reflectivity 0.1). Scatter just from molecules (dots) and molecules with aerosols (lines) respectively. Walker's law has the brightness fall as 1/distance^2.5 (a constant slope on this plot), but here the slope increases with distance.

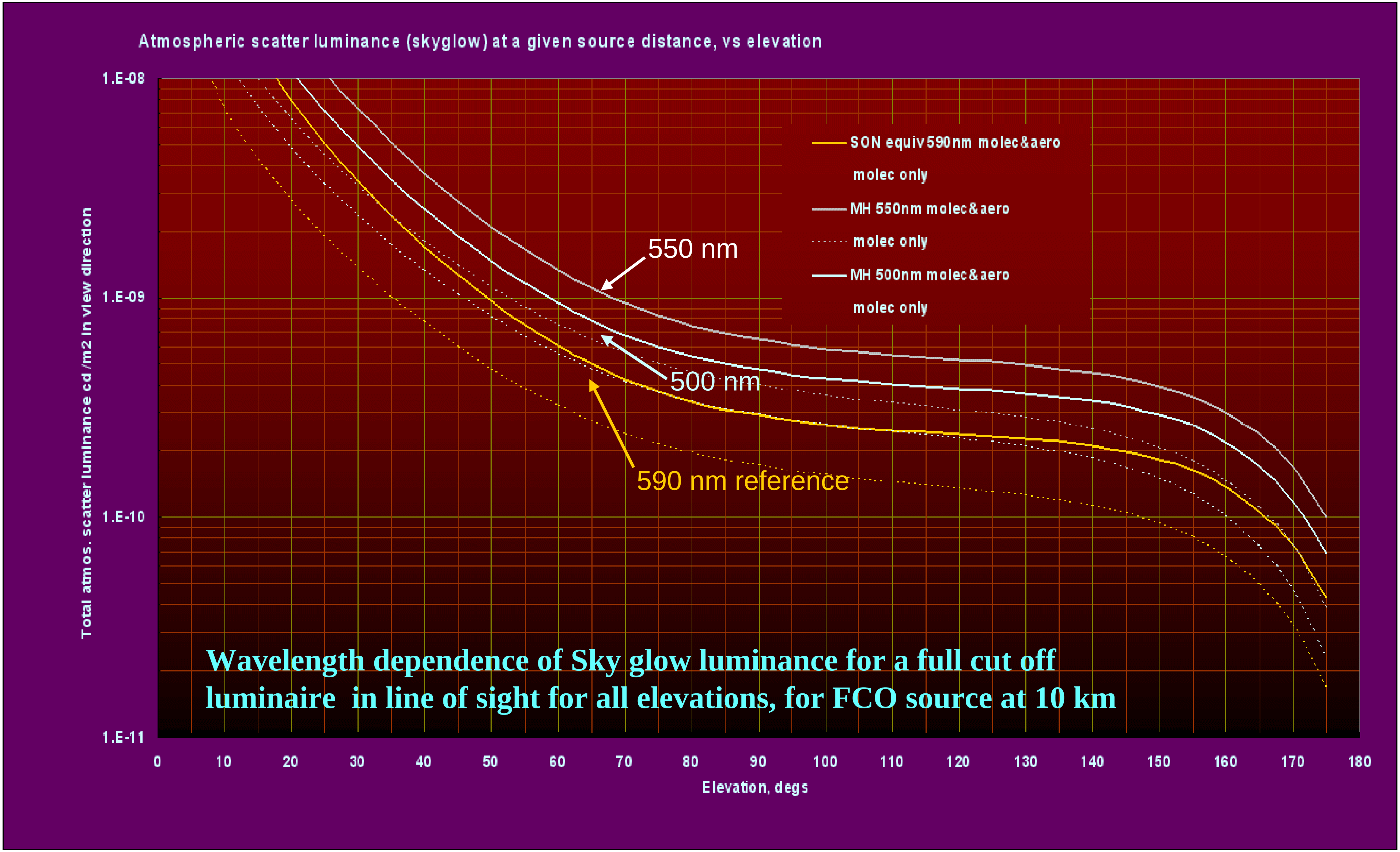


Sky glow luminance from a source 10 km away, for elevations from horizon to horizon.

Luminaires types SOX (orange) and cutoff SON (light orange) and full cutoff (pink). (normal incidence reflectivity 0.1). Scatter just from molecules (dots) and molecules with aerosols (lines) respectively. Aerosols dominate at low elevations.

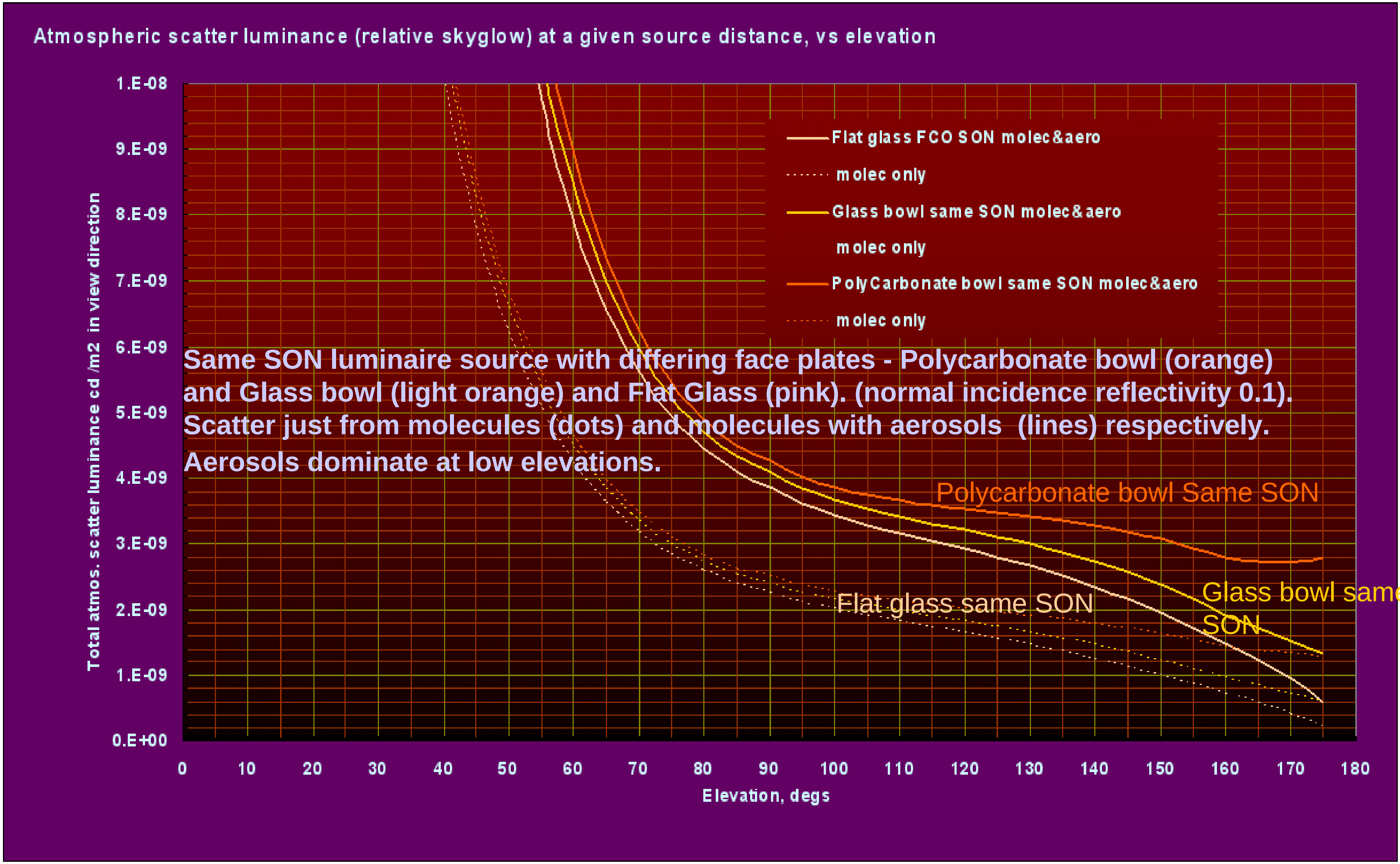


Sky glow luminance is reduced by a factor of 2 due to obstruction by buildings. The vertical surfaces obstruct low angle will reflect mid-angle upward rays further up towards the vertical which has the effect of overall reduction in Skyglow. The differences between the different types of luminaires are still very significant but the upturn form direct components in the away view direction is a little less than without the buildings



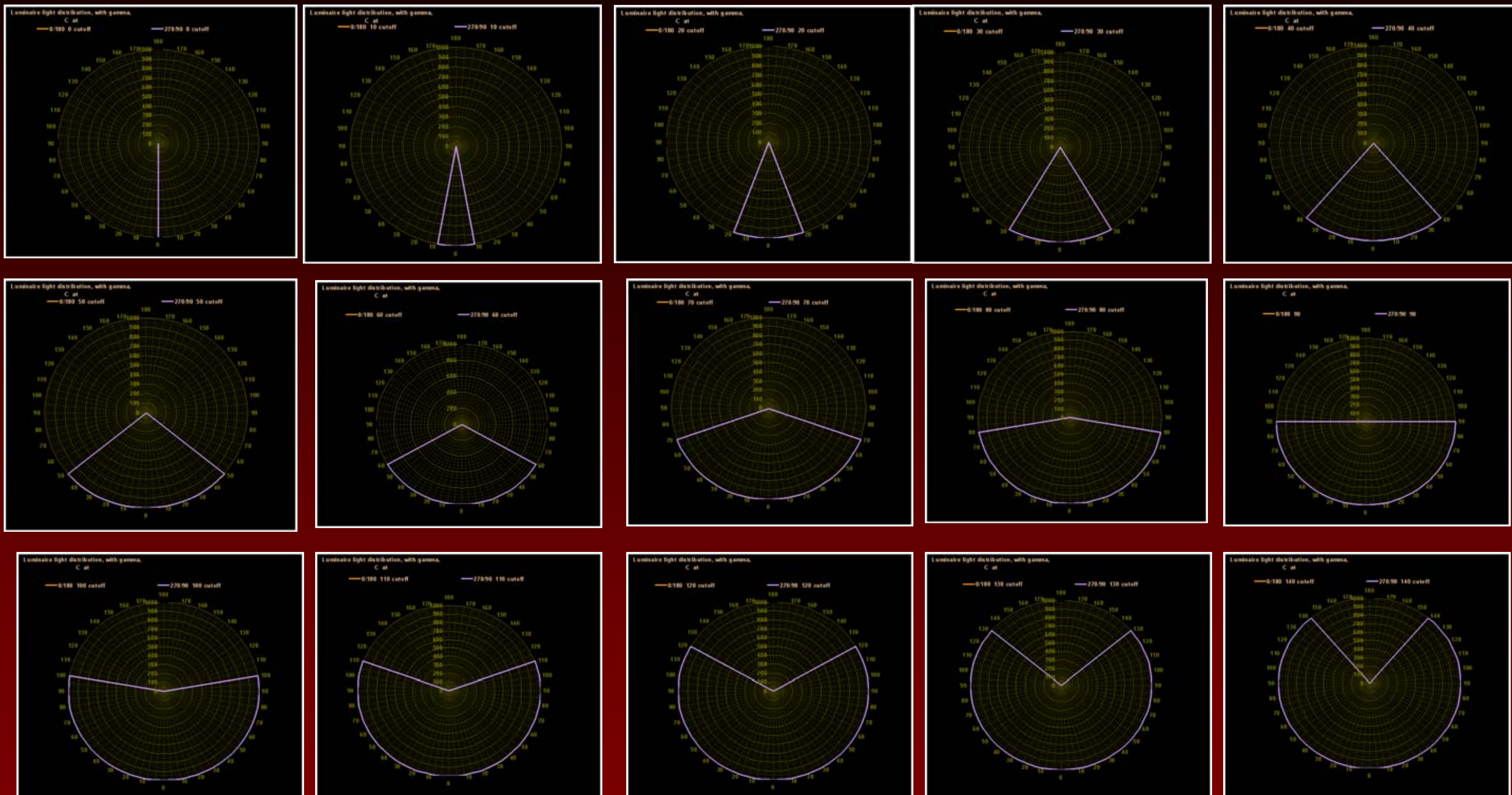
Sky glow luminance from a source 10 km away, for elevations from horizon to horizon.

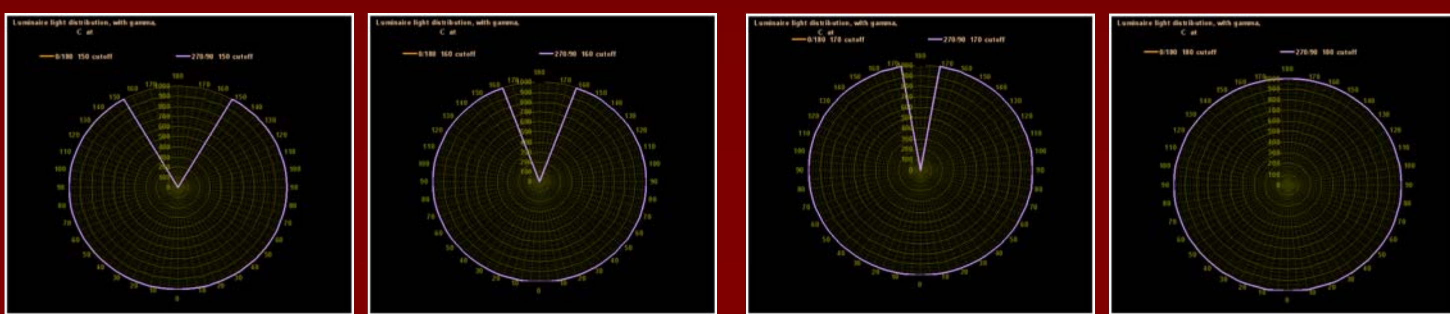
Shows effect of using white light (wavelength peak 550nm, or 500 nm) for an FCO source compared to Sodium D line peak 590 nm. An increase of 100% in scatter from 590 to 550 nm and 60% at 500nm. This is from increased vegetation reflectivity (peaking in green) and greatly increased molecular Rayleigh atmospheric scattering. Note the peak at 550 nm.



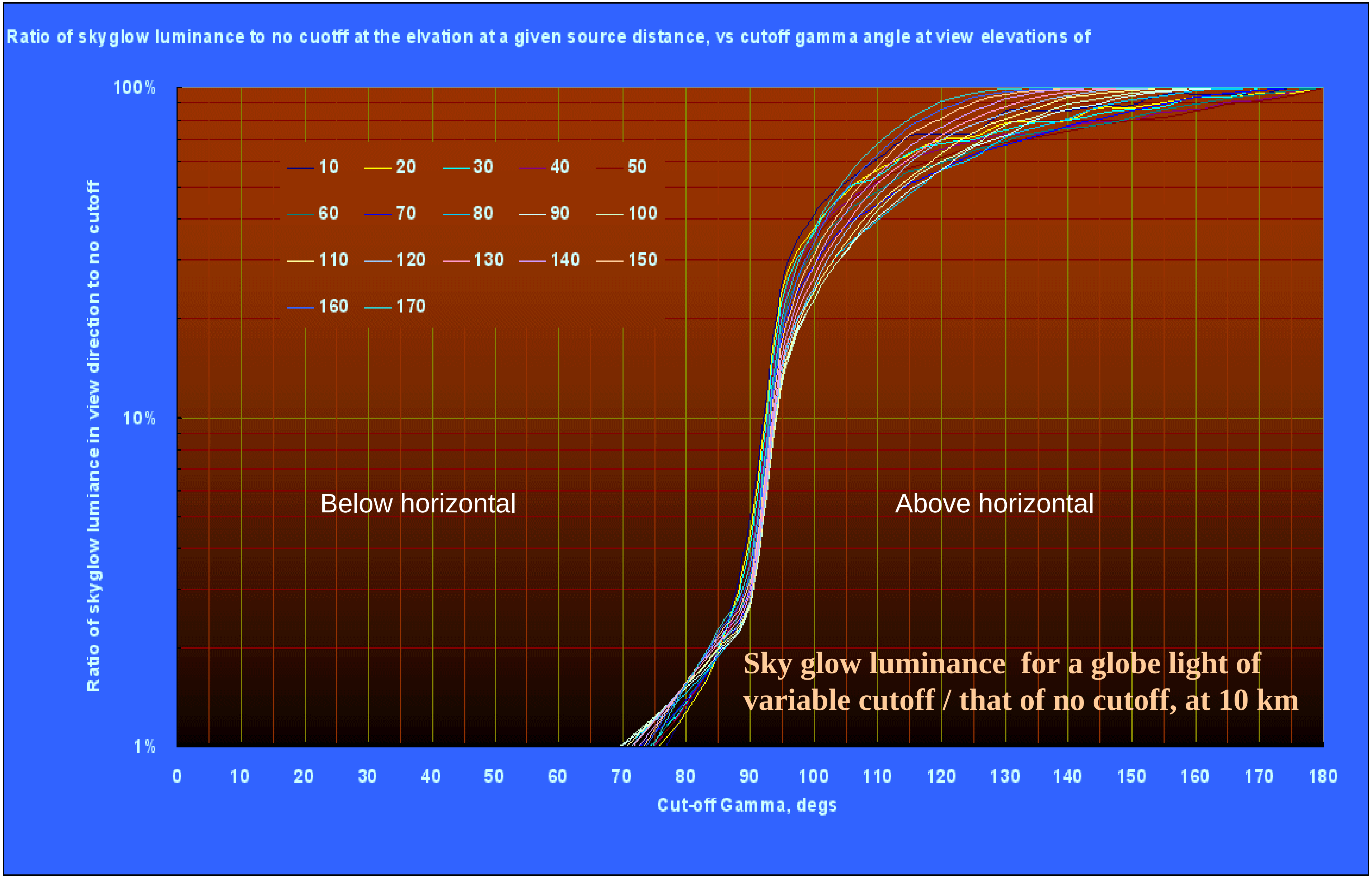
The Milky Way surface luminance was calculated to be about 8.4 x10^-5 cd/m^2. For 10,000 lumianires 1E-9 cd/m^2 becomes 1E-4cd/m^2 which swamps the Milky way, while for FCOs in the away direction it is much lower 1E-5 cd/m2. making the Milky Way visible

Globelight stepped gamma cutoff polar plots





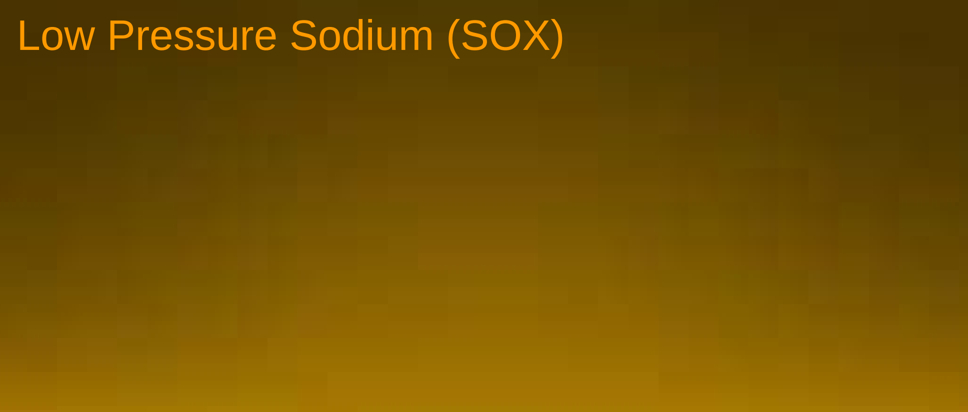
Globe light stepped 0 -180 degree gamma cutoff, vertical polar distribution

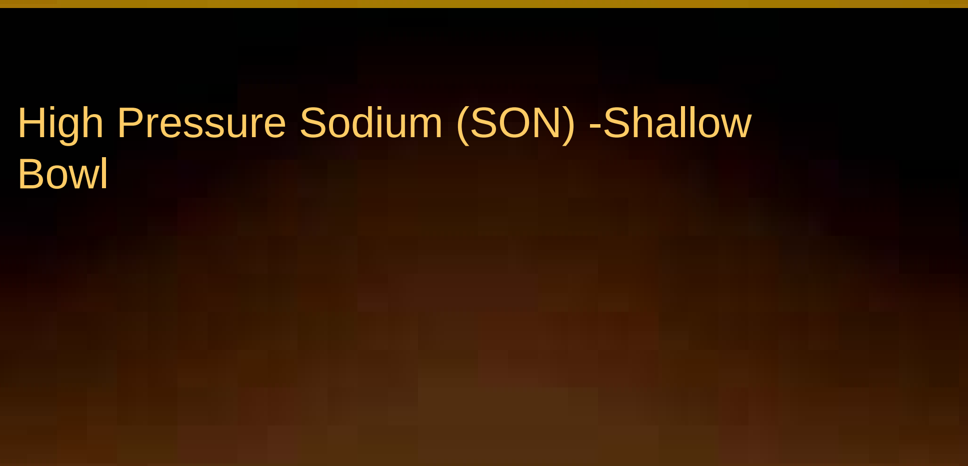


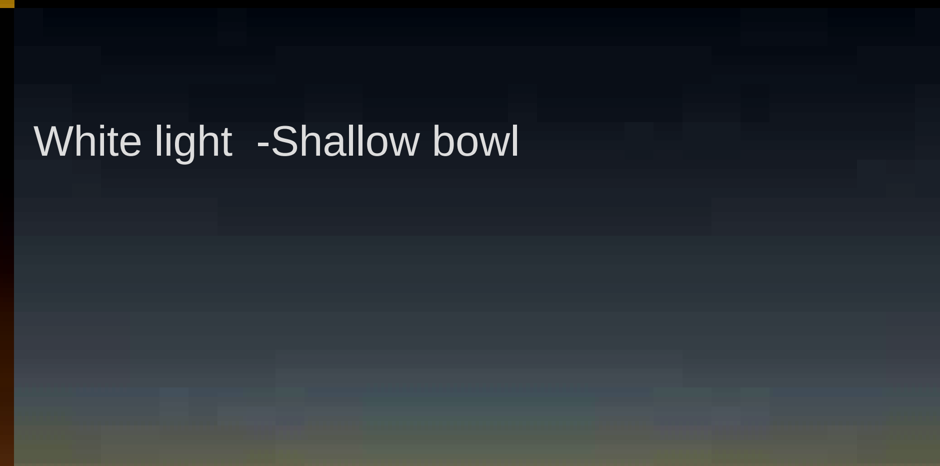
Ratio of skyglow luminance to no cutoff, vs. cutoff gamma angle seen at 10 km, from a globe light with stepped cutoff gamma from 0 to 180 degs, for each elevation. A very sharp increase as cutoff raises above horizontal.

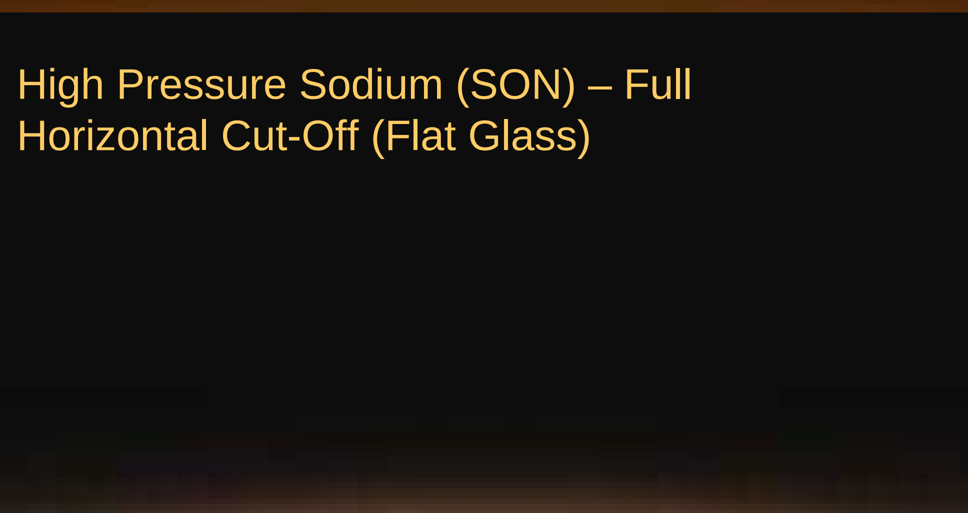
Simulation and Summary

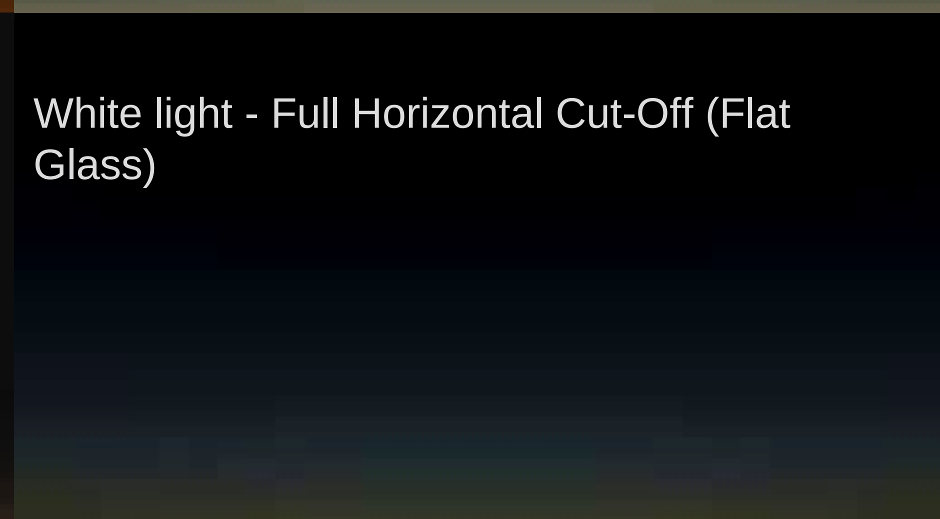
Simulation of Sky Glow of various lighting types











Effect of Luminaire type:- LPS SOX, HPS SON cutoff, SON Flat glass

Luminaire Type	Upward light ratio (fraction of total above horizontal)	Ground reflection	True upward fraction including ground reflection	Relative skyglow at 45 degs, 10 km distance (FCO=100% for same luminance at gamma =30)	Relative skyglow at 135 degs, 10 km distance (FCO=100% for same luminance at gamma =30)
LPS standard SOX	7.8%	6.2%	14%	410%	850%
HPS SON cut off	3.3%	6.1%	9.4%	200%	380%
HPS SON Full cut off	0%	6.9%	6.9%	100%	100%

Effect of changing bowl type:- polycarbonate bowl, curved glass, flat glass

Luminaire Type	Upward light ratio (fraction of total above horizontal)	Ground reflection	True upward fraction including ground reflection	Relative skyglow at 45 degs, 10 km distance (no scaling)	Relative skyglow at 135 degs, 10 km distance (no scaling)
SON poly-carbonate bowl	0.42%	6.8%	7.2%	115%	133%
SON Glass bowl	0.07%	6.8%	6.9%	108%	114%
SON Flat glass	0%	6.8%	6.8%	100%	100%

Effect of changing colour

Luminaire Type	Upward light ratio (fraction of total above horizontal)	Ground reflection	True upward fraction including ground reflection	Relative skyglow at 45 degs, 10 km distance (no scaling)	Relative skyglow at 135 degs, 10 km distance (no scaling)
500 nm FCO	0%	5.8%	5.8%	150%	160%
550nm FCO	0%	11.5%	11.5%	217%	216%
590 nm SON FCO	0%	11.5%	11.5%	100%	100%

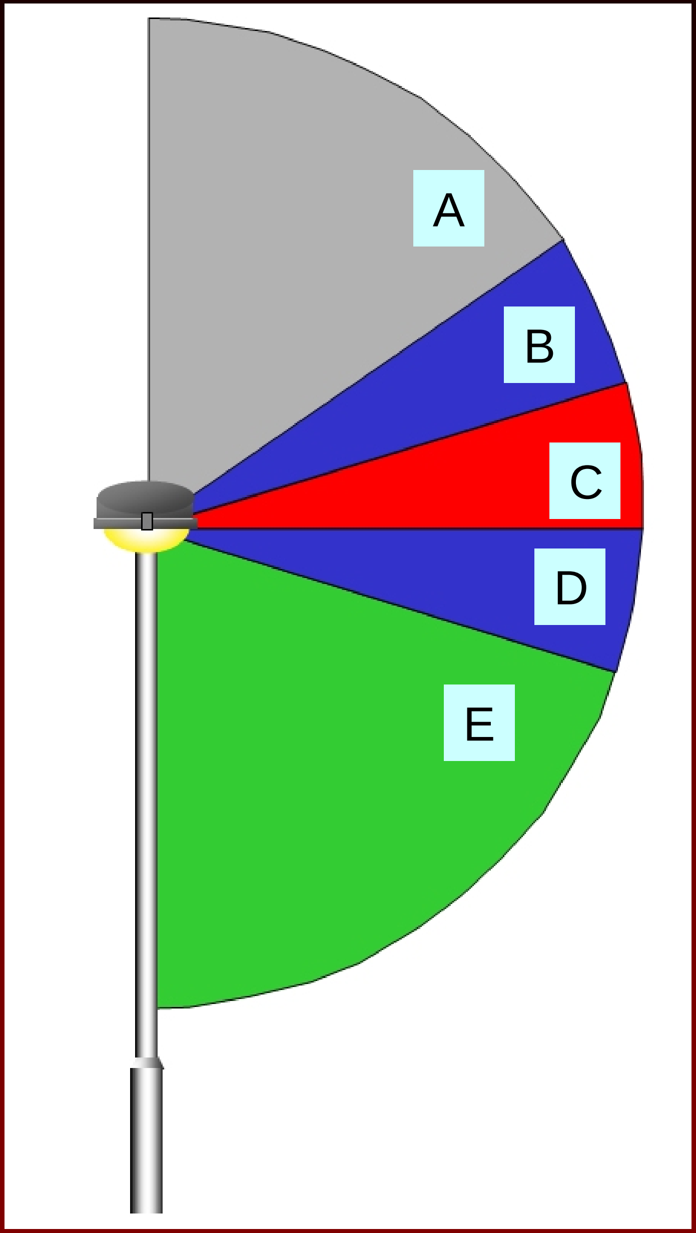


Diagram to show relative impact of a luminaire's output with regards to contribution to skyglow.

A 180-100° Critical area for skyglow from within urban areas but proportionally less impact to rural areas.

B 100-95° Significant contributor to skyglow, especially in rural areas where it is most aerosol dependent. Less likely to be obstructed.

C 99-90° Critical zone for skyglow and obtrusion seen at 10s of km (in rural areas) where it is strongly dependent on aerosol scattering.

D 90-70° Significant contributor to skyglow seen at a distance through reflection but reflected light more likely to be obstructed by buildings, trees and topography.

E 70-0° Ideal light distribution.

Conclusions and advice to minimise skyglow

Sky-glow in rural areas, under good atmospheric conditions.
Summary of findings:-

- Close to towns, ground reflection dominates skyglow.
- At a distance from towns, skyglow is dominated at low to mid elevation angles by direct radiance above the horizontal and reflected below the horizontal.
- The reflected light is mostly from the surrounding surfaces to the roads, - grass in suburban areas.
- Maximum scatter is in front of the source, from enhanced aerosol scatter at shallow angles.
- In moving towards bluer wavelengths, skyglow at high elevations, increases due to the much greater scatter from air molecules. The observer also sees more scotopic matching.
- Shallow bowl luminaires do not convincingly cause less sky glow than full cut-off types, due to lower numbers per given road length. They have a higher beaming angles and side emission and the higher reflectivity of surfaces at these angles enhances this, so causing more skyglow.

Summary

To minimise skyglow in the countryside :-

- **All lighting should be shielded from horizontal view.**
- **The reduction in skyglow by universally adopting full horizontal cutoff lighting in all areas outside of town centres can be a factor of 3 to 5 according to elevation and distance of view.**
- **Shallow bowls can cause more skyglow than equivalent FCOs, and are visually more obtrusive. They should not be used in open areas and should be restricted to town centres.**
- **All measures are needed, such as dimming, as is now being tried, and switching off when not necessary.**
- **Now all to common PFI funded city re-lighting schemes often use shallow bowls, ups the brightness levels and do not allow for future improvements in control. But there is more and more lighting for town centres, new housing and amenities.**
- **Using FCOs alone may not reduce sky glow sufficiently, against the growing amount of lighting in the UK.**