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Technical Information

Optical Performance of a Projector Sector Light

Document

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Content

1 Summary

The technical information describes the optical design of a projector sector light and developes the calculation necessary to estimate the sector angles and the luminous intensity. Results from laboratory tests and some examples are added.

2 Introduction

A projector sectorlight is used to generate high intensity sectors with small horizontal angles and sharp sector boundaries.

The optical design differs significantly from the classical apparatus for Marine Aids to Navigation which generate fan and pencil beam. The calculations for intensity and angular profile are completely different as well.

The optics is discussed with the tools provided by Klein and Furtak [1][2].

3 Optical Principle

A projector can be used to create a sector light in two different ways:

- A single projector with coloured filters for each sector.
- An arrangement of several projectors with different colours or flashes for each sector.

Both applications are described in IALA Guideline 1041 on Sector Lights [3].

An arrangement of projectors is the preferred method when using coloured LEDs.

The single projector consists of at least two lenses (Figure 1).

(a) a projection lens
(b) a condensor lens

The sectors are generated at the field stop. The field stop may contain colour filters. The screen or filters are projected to 'infinity' via the projection lens (blue lines). For maritime application 'infinity' means the waterway, where the mariner can see the sector light.

The condensor lens produces a uniform illumination at the field stop and forms an image of the light source at the projection lens (red lines). The outer rim of the projection lens acts as the aperture stop (clear aperture).

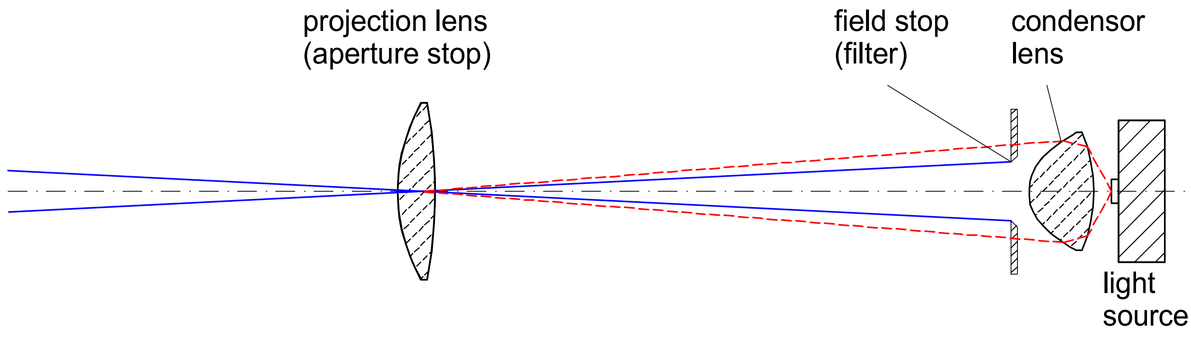

Figure 1: components of a projector

The projection lens can be

- a plano-convex lens,
- a double-convex lens (best form for infinite projection),
- a cemented achromat.

The condensor lens is often

- a plano-convex lens (convex side aspheric),
- a double-convex lens (convex side aspheric).

In some designs more complex lenses are used [4].

4 Sector Projection and Sector Angle

The size of a sector is independent from the light source and the condensor system. It depends on the effective focal length F_P of the projection lens and the lateral extension extension X of the filter or gap at the field stop (Figure 2).

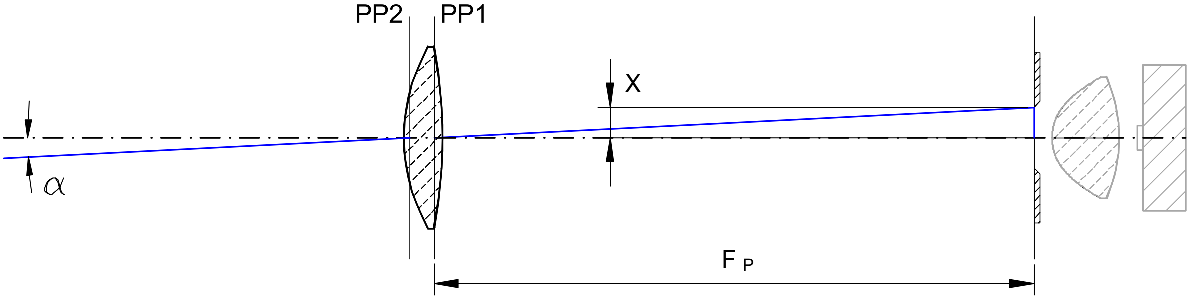

Figure 2: sector size (top view)

Sector angle α measured from optical axis:

$$\tan\alpha = \frac{X}{F_P}$$

Equation 1: Sector angle

- X Lateral extension measured from the optical axis (Y vertical extension)
- F_P Effective focal length of the projection lens (measured from PP1 to field stop)
- PP1 First principal plane
- PP2 Second principle plane

For ordinary projection sector lights the focal length is much larger then the lateral extension $F_P \gg X$ and $\tan\alpha$ can be approximated to $\tan\alpha \approx \alpha$, where α is in radians.

For example a green filter of size X_{green} at the field stop produces a green sector with size $\alpha_{green} \approx \frac{X_{green}}{F_P}$ (α_{green} in radians).

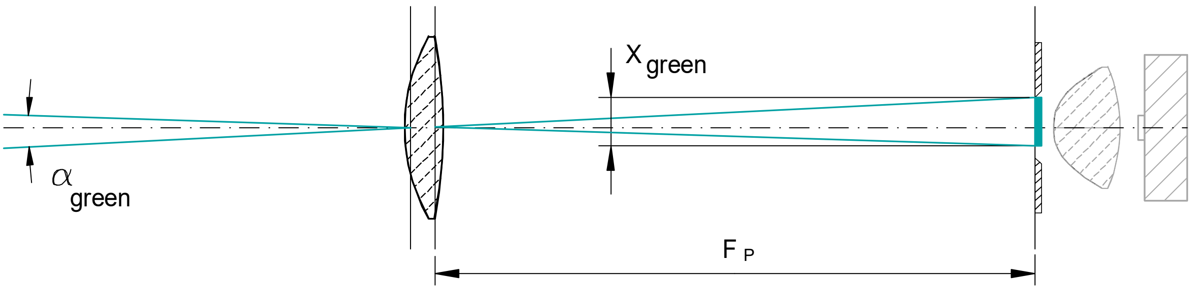

Figure 3: example green sector (top view)

The vertical divergence (vertical sector) of a sector light can be calculated in the same way taking into account the vertical dimension Y of the filter or the field stop.

The intensity in a sector is nearly constant, when the condensor system is well designed.

5 Condensor System and Intensity

The condensor lens forms an image of the light source at the projection lens.The object distance S should be much smaller than the image distance S', to produce a magnified image.

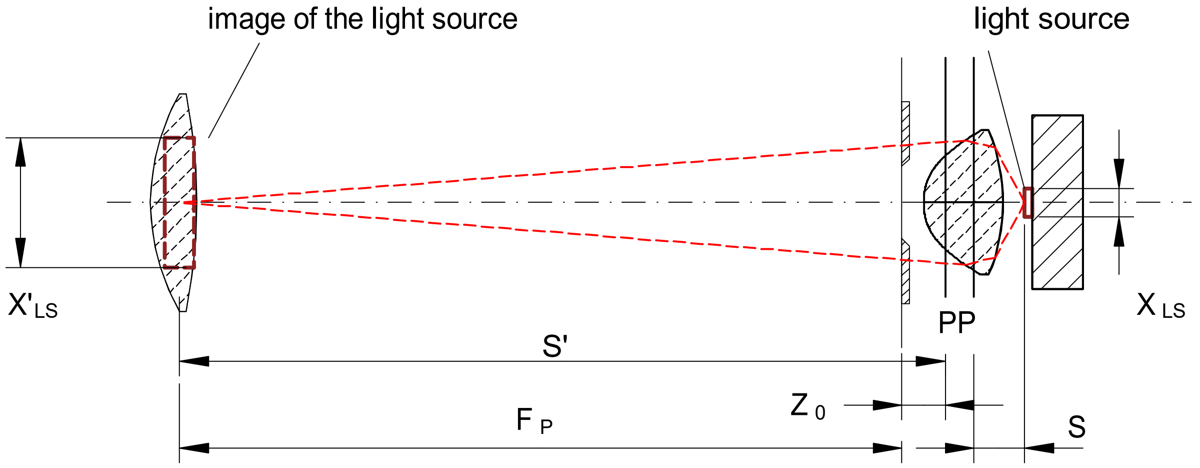

Figure 4: Magnification of the light source (top view)

The magnification of the light source is

$m = \frac{X'_{LS}}{X_{LS}} = \frac{Y'_{LS}}{Y_{LS}} = \frac{S'}{S}$ (magnification of the light source LS, horizontal X, vertical Y)

- X_{LS}, Y_{LS} Lateral extension of the light source
- X'_{LS}, Y'_{LS} Lateral extension of the light source image
- S Object (light source) distance to first principal plane of the condensor lens
- S' Image distance to second principal plane of the condensor lens

This magnification determines the luminous intensity of the sectorlight together with the following rule.

For an optical image formation the luminance of an image L_{image} is the same as for the object L_{object} except for transmission losses [2] [6].

$$L_{image} = T * L_{object}$$

T Transmission of the optical system

There are two different optical arrangements.

Case A: The image fits totally in the projection lens (image not obscured by lens diameter).

Case B: The image covers the lens diameter completely.

Other arrangements should be avoided, because small mechanical misalignment may result in significant changes of intensity.

To simplify the discussion a square light emitting area is regarded here, but the principle is the same for rectangular or circular areas (flat LED).

5.1 Case A / Image fits in projection lens

In this case the magnified image is completely visible through the projection lens. The luminance of the image is $L'_{LS} = T * L_{LS}$.

- L'_{LS} Luminance of the light source image at projector lens
- L_{LS} Luminance of the light source
- T Transmission of the optical system

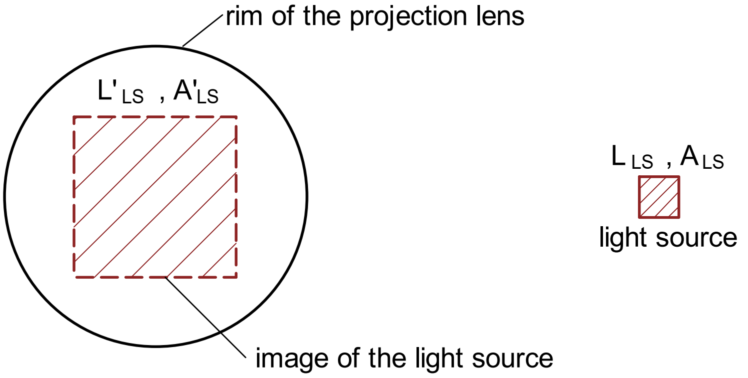

Figure 5: Square light source and its image, **Case A**

The luminous intensity I_{LS} which is emitted form the light source along the optical axis is

$$I_{LS} = L_{LS} * A_{LS}$$

with $A_{LS} = X_{LS} * Y_{LS}$ area of the emitting surface of the light source.

The luminous intensity I_P which is emitted from the projection lens along the optical axis is

$$I_P = L'_{LS} * A'_{LS}$$

with $A'_{LS} = X'_{LS} * Y'_{LS}$ area of magnified image of the emitting surface at projection lens.

The luminous intensity of the sector light (projector) becomes

$$I_P = T * L_{LS} * A'_{LS} = T * \frac{A'_{LS}}{A_{LS}} * I_{LS}.$$

The intensity depends on the intensity of the light source, the magnification of the light emitting area and the overall transmission of the lenses.

As long as the image of the light source fits completey into the rim of the projection lens the magnification of the area A'_{LS} may be expressed with the object and image distance of the condensor.

$$\frac{A'_{LS}}{A_{LS}} = \frac{X'_{LS}}{X_{LS}} * \frac{Y'_{LS}}{Y_{LS}} = \left(\frac{S'}{S}\right)^2$$

The luminous intensity of the projector is then:

$$I_P = T * \left(\frac{S'}{S}\right)^2 * I_{LS}$$

Equation 2: Luminous Intensity of a projection sectorlight, **Case A**

5.2 Case B / Image larger than projection lens

When the image of the light source is larger than the projection lens, the outer part of the image will be obscured by the lens diameter (clear aperture).

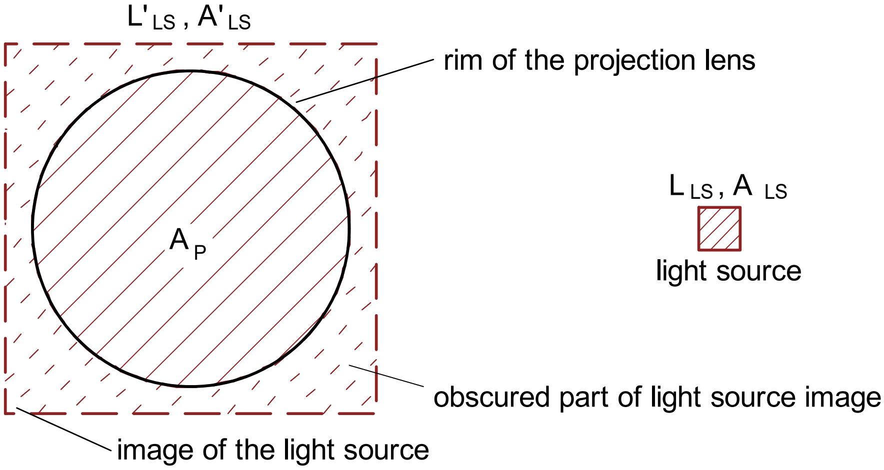

Figure 6: Square light source and its image, **Case B**

In this case the luminous intensity of the sector light becomes

$$I_P = T * A'_{LS} * L_{LS} = T * A_P * \frac{I_{LS}}{A_{LS}} = T * \frac{A_P}{A_{LS}} * I_{LS}$$

This gives the luminous intensity of a projector for case B:

$$I_P = T * \frac{A_P}{A_{LS}} * I_{LS}$$

Equation 2: Luminous Intensity of a projection sectorlight, **Case B**

When the area of the clear aperture is $A_P = \frac{\pi}{4} * {D_P}^2$ (D_p clear lens diameter) the intensity becomes: $I_P = T * \frac{\pi}{4} * {D_P}^2 * \frac{I_{LS}}{A_{LS}}$.

6 Transmission of the Lenses

6.1 Uncoated Lenses

The transmission of a lens depends predominantly on the reflection at the glas surface because the absorption losses can be neclected for optical glas.

The loss caused by reflection of a single glas-air surface is

$$R = \frac{(N-1)^2}{(N+1)^2}$$

where N is the index of refraction of the lens. For a standard glas (e.g. N-BK7) the index is 1.517 and the reflection for each surface becomes $R = 0.042$.

A single lens without anti-reflection coating has two glas-air surfaces, so the transmission is

$$T_{single\ lens} = (1-R) * (1-R) \approx 0.92.$$

For a system containing a single condensor lens and a single projection lens (both uncoated) the transmission becomes $T_{total} = (1-R)^4 \approx 0.84$.

6.2 Anti-reflection Coating

A simple anti-reflection coating can result in a reflection value of about $R = 0.015$. When both the condensor and the projection lens have an anti-reflection coating on both sides the resulting transmission is

$$T_{total} = (1 - R)^4 = (1 - 0.015)^4 \approx 0.94$$

6.3 Compound Lens

The transmission losses of a compound lens are normally published by the manufacturer. It may be necessary to look at each glas-air surface individually. For example a compound projection lens consisting of two single lenses with air gap has four glas-air surfaces. A cemented achromatic lens has no air gap and the intersection between the two lenses can be ignored for loss calculation.

6.4 Colour Filters

When a colour filter with transmission T_{colour} is introduced to create a coloured sector, the luminous intensity in the sector is $I_{P,coloured\ sector} = T_{colour} * I_{P,white}$.

6.5 Appropriate Lens Diameter

The lens diameter of both the projection and the condensor lens depend on the nautical requirements as well.

6.5.1 Projection Lens

When designing a light the goal is often to get the highest luminous intensity. This can be achieved by a large magnification of the light source, which results in a large projection lens diameter. However the market for lenses with large diameter is limited and custom-made lenses are be very expensive. So it is advisable to look for existing lenses.

The largest common lenses are produced for astronomical telescopes (refractors). The maximum diameter is typically about 200 mm with a focal length of 700 to 1800 mm.

6.5.2 Condensor Lens

The diameter of the condensor lens should fully cover the field stop, which itself depends on the required sectors. To avoid problems with misalignment the lens is supposed to be some larger.

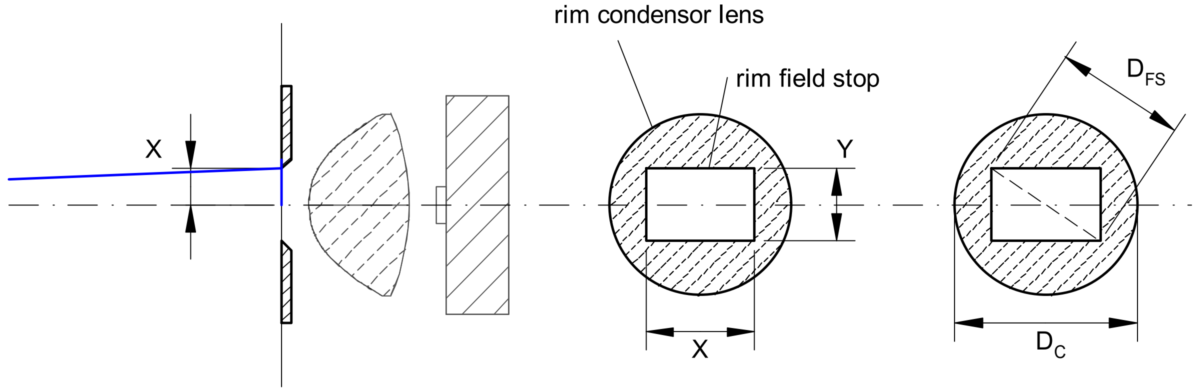

Figure 7: Field stop and lens size

The height Y and width X of the field stop is derived from the required sector size:

$$X \approx \alpha_h * F_P$$

$$Y \approx \alpha_v * F_P$$

All angles are in radians.

With the values of X and Y the diagonal of the field stop will be $D_{FS} = \sqrt{X^2 + Y^2}$.

The diameter of the condensor lens D_C should than be larger than D_{FS}, for example $D_C \geq 1.1 * D_{FS}$.

7 Miscellaneous

7.1 Determing Luminous Intensity from Luminous Flux

The calculation of the projector intensity requires the knowledge of the luminous intensity of the light source. Usually this value cannot be found in the data sheets.

However the main light source for projector sector lights will be a high-power flat LED. It has has no primary lens and radiates light into a hemisphere.

It behaves very close to a Lambertian radiator and is characterized by 'viewing angle' of approx. 120° (Full Width Half Maximum).

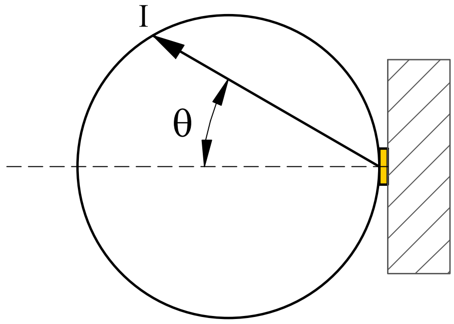

Figure 8: Intensity profile of a Lambertion light source (polar diagram)

The intensity profile depends on the angle θ versus the surface normal according to $I(\theta) = I_{LS} * \cos\theta$ for $\theta = 0 \cdots \frac{\pi}{2}$ and appears as a circle in a polar diagram (Figure 8).

The total luminous flux of the lights source Φ_{ls} is then calculated by an integral in spherical coordinates.

$$\Phi_{LS} = \iint I(\theta) d\Omega = \int_0^{\pi/2} \int_0^{2\pi} I_{LS} * \cos\theta * \sin\theta \, d\varphi \, d\theta = 2\pi * I_{LS} * \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta$$

$$\Phi_{LS} = 2\pi * I_{LS} * \frac{1}{2} \int_0^{\pi/2} \sin 2\theta \, d\theta = \pi * I_{LS} * \left[-\frac{1}{2} * \cos 2\theta \right]_0^{\pi/2} = \pi * I_{LS} * \frac{1}{2}(+1+1) = \pi * I_{LS}$$

$$\boxed{\Phi_{LS} = \pi * I_{LS} \; ^{(*)}}$$

(*) Remark: The equation should not be mixed up with equation $\Phi_{LS} = 4\pi * I_{LS}$, which is valid for a light source which radiates constant intensity over the entire sphere.

The luminous intensity I_{LS} of the light source can be calculated from the luminous flux Φ_{LS}, which is available in the data sheets, with the simple equation $I_{LS} = \frac{\Phi_{LS}}{\pi}$.

7.2 Supplementary Equations

7.2.1 Image distance condensor lens

According to Figure 4 the field stop has a distance Z_0 to the the second principle plane of the condensor. This results in: $F_P + Z_0 = S'$.

7.2.2 Object distance condensor lens

The magnification of the light source can be calculated with the Newtonian Image Equation.

$$\frac{1}{F_C} = \frac{1}{S} + \frac{1}{S'}$$

When F_C and S' are given the object distance S is

$$S = \frac{S' * F_C}{S - F_C}$$

7.2.3 Size of light source image

Assuming that the light source is rectangular and has width X_{LS} and height Y_{LS}, the size of the image at the projection lens is:

Height: $X'_{LS} = m * X_{LS} = \frac{S'}{S} * X_{LS}$ Width: $Y'_{LS} = m * Y_{LS} = \frac{S'}{S} * Y_{LS}$

For case A the image should be completely inside the projection lens (diameter D_P).

<u>Case A:</u> $D'_{LS} = \sqrt{X'_{LS}{}^2 + Y'_{LS}{}^2} < D_P$ or better: $D'_{LS} = \sqrt{X'_{LS}{}^2 + Y'_{LS}{}^2} < 0.9 * D_P$

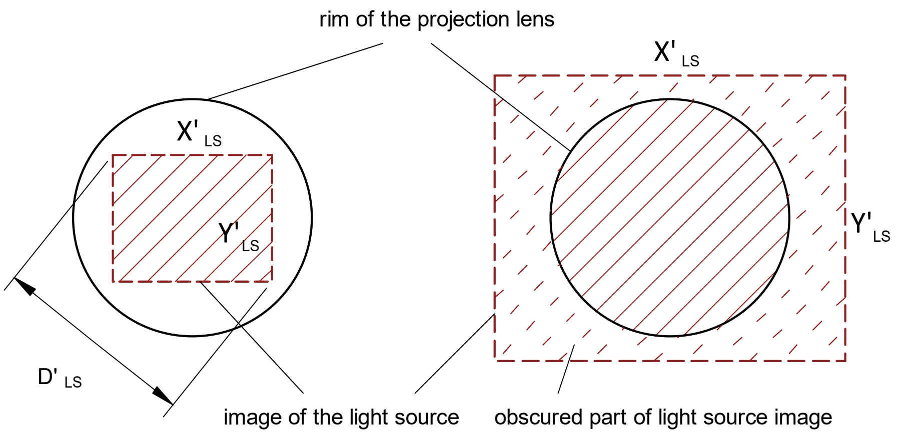

Figure 9: Size of light source image at the projection lens

Case B should only be used for light sources which have a uniform luminance over the light emitting surface. The image of the light source should then cover the lens diameter completely.

<u>Case B:</u> $X'_{LS} > D_P$ and $Y'_{LS} > D_P$ or better: $X'_{LS} > 1.1 * D_P$ and $Y'_{LS} > 1.1 * D_P$

7.3 Use of Telescope Lenses

The lens aberrations of an astronomical telescope are very small because they are designed to meet the Rayleigh criterion [8]. The angular resolving power $\Delta\phi_{telescope}$, which may be interpreted as an angle of uncertainty for a sectorlight, can be calculated with the equation:

$$\Delta\phi_{telescope} = \frac{1.22 * \lambda}{d}$$

with $\Delta\phi_{min}$ in radians and

- λ wavelength,
- d diameter of telescope objective.

For a telescope with a diameter of 150 mm the angular resolution (resolving power) is $\Delta\phi_{telescope} = 4.7 * 10^{-6}\ rad = 0.00027°$.

For a light with very small sectors the angle of uncertainty $\Delta\phi_{sector\ light}$ is about $0.071°$ (see IALA Guideline 1041 on Sector Lights [9]).

The ratio between the precision of a telesope objective and the required precision of a sector light is: $\frac{\Delta\phi_{telescope}}{\Delta\phi_{sector\ lig}} \approx 0.38\ \%$, which means that the precision of any telescope objective is always sufficient for a sector light. Very high correction of lens aberrations is not needed. An achromatic lens is sufficient. An apochromatic lens may be used but will not give significant improvement.

Remark:

The theoretical resolving power of a telescope will not be achieved for a projection sector light for the following reasons:

- The field stop of a sector light is larger than the viewing field of a telescope.
- A sector light works horizontally, where the 'astronomical seeing' is worst.

7.4 Fully Illuminated Lens Diameter

For a projector sectorlight a design according to Case A is recommended. Between the magnified light source image and the lens there is a small gap. This will ensure that the image will rest in the lens even when small mechanical misalignment occur.

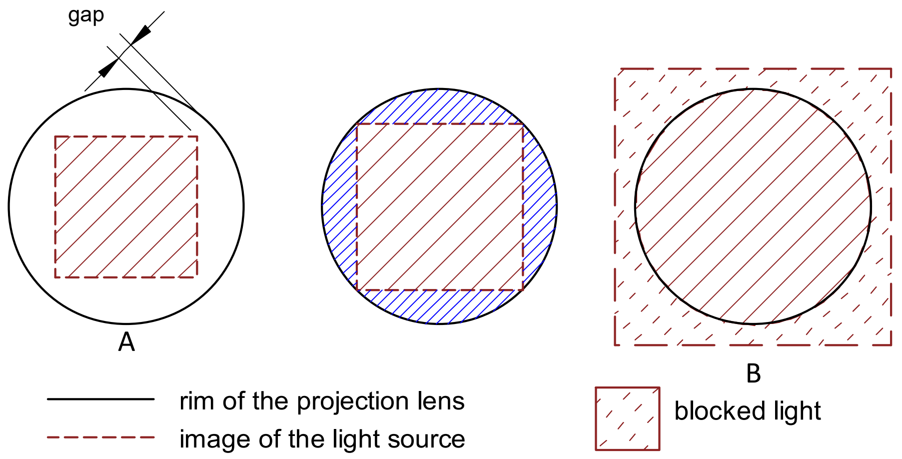

Figure 10: Illumination of projection lens

However to maximize the intensity case B may be used.

In this case it should be considered

- that the light blocked in the lantern results in significant scattered light, which may produce some unintentional false sectors,
- that the outer region of a lens produce more lens aberrations as the inner one.

7.5 Position of Light Source Image

In any case the image of the light source has to be adjusted to a position inside the projection lens. This is because the projection lens acts as the aperture stop. When the image is not in the apertue stop, vignetting will occur. This will result in very poor uniformity of the intensity within the sectors.

7.6 Application with Classical Light Sources

The calculation becomes very simple because of the use of a flat (square) light source, which in practice is repesented by high power LEDs.

However the calculation can be used for traditional lamps as tungsten halogen or metal halide. As the traditional light sources emit light in the whole sphere, the light emitted in the rear direction is collected with a spherical mirror (Figure 11). This produces a second virtual light source (1st lamp image) nearby the real one. Both real and virtual lamp are formed as images at the projection lens via the condensor lens (Figure 12).

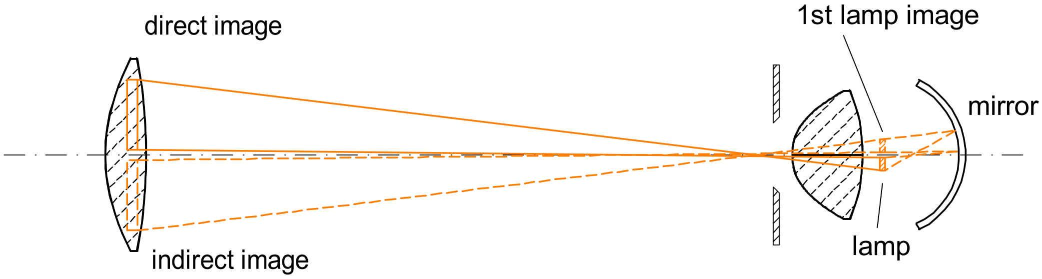

Figure 11: Optical arrangement for traditional light sources

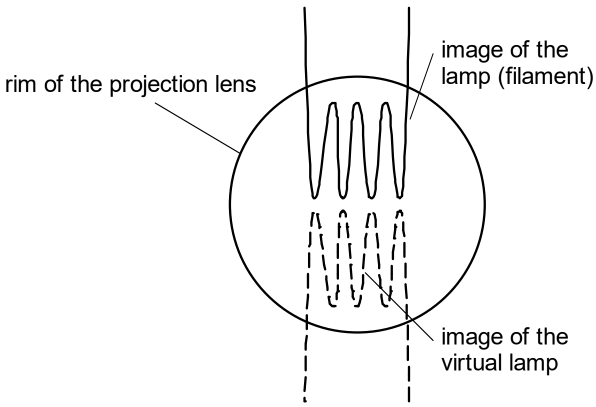

Figure 12: Images of lamp and virtual lamp in the projection lens

An observer in the sector will see both the magnified image of the lamp and the virtual lampe. Because the luminance is not uniform, the resulting luminous intensity is the integral over the aera of the projection lens.

$$I_p = \iint_{A_p} L' \; dx' \, dy'$$

The lateral dimensions at the projection lens correspond directly to the lateral dimension at the position of the light sources.

$$\frac{x'}{x} = \frac{y'}{y} = \frac{S'}{S}$$

$$x' = \frac{S\prime}{S} * x \qquad \Longrightarrow \qquad dx' = \frac{S\prime}{S} * dx$$

$$y' = \frac{S\prime}{S} * y \qquad \Longrightarrow \qquad dy' = \frac{S\prime}{S} * dy$$

With these transformation we substitute the variables in the integral. The area becomes the small area A_{LS} encircling the light sources. For the luminance L' the transmission losses have to be considered: $L' = T * L$.

$$I_P = \iint_{A_{LS}} L' \left(\frac{S'}{S}\right)^2 dx\, dy = \left(\frac{S'}{S}\right)^2 \iint_{A_{LS}} L'\ dx\, dy$$

For traditional lamps the luminance L' is not a constant and the integral can only be calculated when $L'(x, y)$ is known. But in case A, when the light source and its image fit in the projection lens totally, the integral is the luminous intensity of the pure lamp without an optic but reduced for transmission losses.

The luminance has two parts coming from the lamp and its image $L' = L'_{lamp} + L'_{lampimage}$. The transmission losses of the lamp luminance is exactly the same as described above (chapter 6): $L'_{lamp} = T * L_{lamp}$.

The light coming from the spherical mirror has additional losses $T_{lampimage}$, which are caused by the imperfect reflection. In many cases the reflected light has to pass through the light bulb twice. This will add transmission losses as well. When passing through the condensor and projection lens, the transmission is the same for the lamp and its image. As long as the lamp emits symmetrically to the condensor and the mirror it can be assumed that

$$L_{lamp} = L_{lampimage}$$

$$\Longrightarrow$$

$$L' = T * L_{lamp} + T * T_{lampimage} * L_{lamp} = T * \left(1 + T_{lampimage}\right) * L_{lamp}$$

$$\Longrightarrow$$

$$\iint_{A_{LS}} L'\ dx\, dy = T * \left(1 + T_{lampimage}\right) * \iint_{A_{LS}} L_{lamp}\, dx\, dy = T * \left(1 + T_{lampimage}\right) * I_{lamp}$$

$$\Longrightarrow$$

$$\boxed{I_P = \left(\frac{S}{S'}\right)^2 * T * \left(1 + T_{lampimage}\right) * I_{lamp}}$$

With this expression the luminous intensity of the projector I_P can be directly calculated from the luminous intensity of the pure lampe I_{lamp}.

For the transmission T of the projector chapter 6 is valid. The transmission for the lamp image $T_{lampimage}$ can be derived from IALA-Recommendation E-200-5, 5.3.1 to be approx. 0.4. Some measurements in the German light laboratory showed that for modern optical mirrors the transmission may exceed 0.65.

It can be understood that the reflection of modern optical mirrors are much more effective than old lighthouse optics.

7.7 Tests

The formulae have been successfully tested at the German light laboratory in 1995 and 2006. In Figure 13 the luminous intensity of a projector as described in 7.6 is compared to the lamp luminous intensity. The line is the theoretical intensity and the crosses mark the measured values.

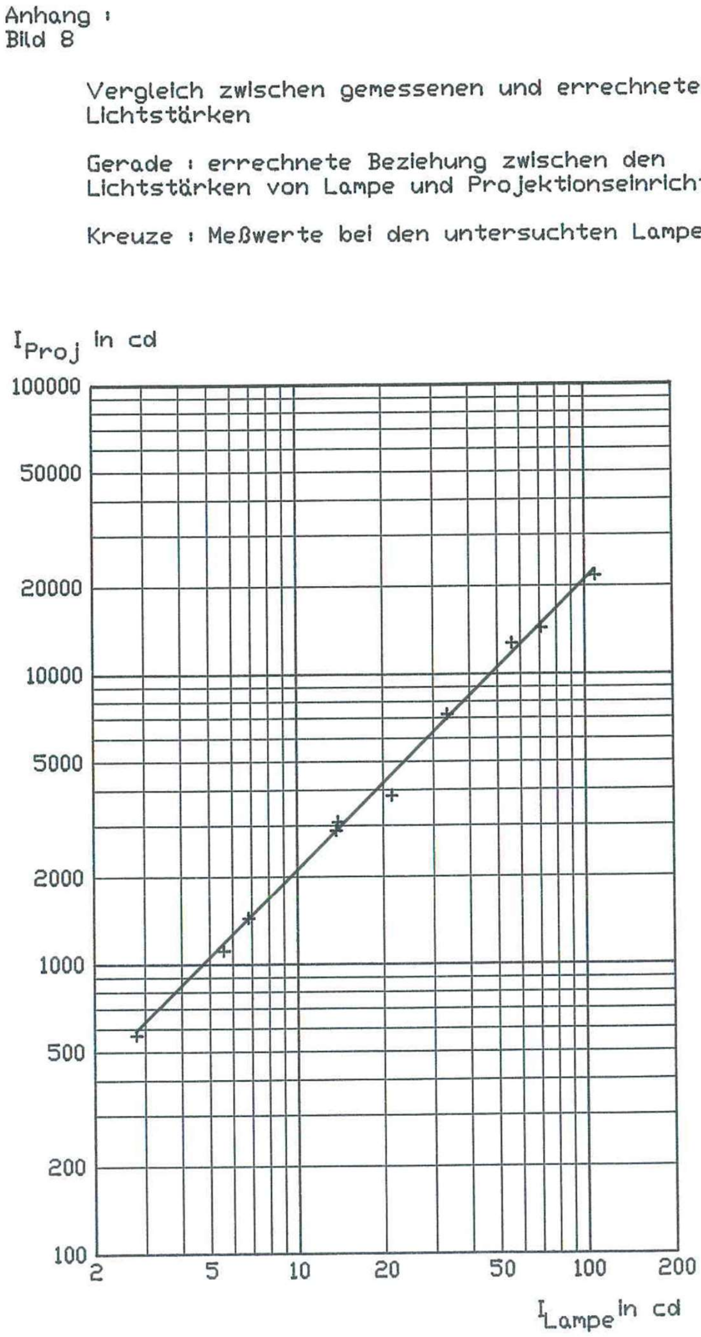

Figure 13: luminous intensity of projector and lamp (test 1995)

The test was repeated with a flat light source in 2006. Here the whole horizontal intensity profile was calculate and measured. Some efforts were made to get a lambertian light source, so the theoretical and measured values move even closer (Figure 14).

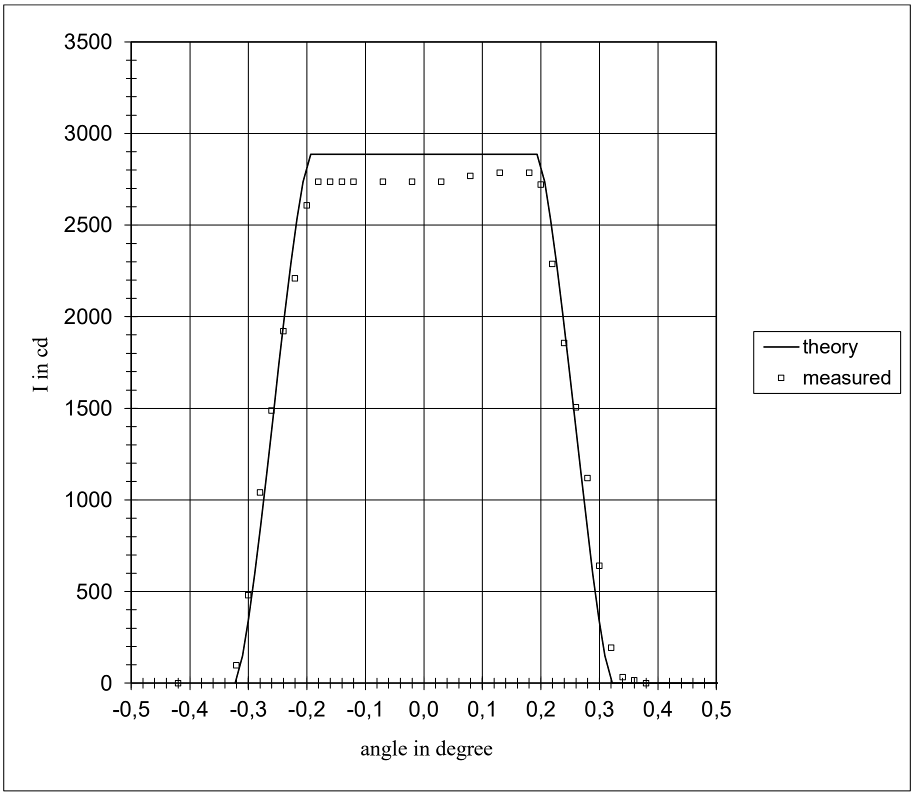

Figure 14: Calculated and measured profile (test 2006)

8 Examples

In the following section three examples are calculated. They do not contain a design methodology.

It is only necessary to calculate the intensity of a single sector for fixed light. When a white sector is devided by colour filters, the transmission of the filter must be multiplied. When a sector shows flashes, effective intensity calculations have to be added.

For the luminous flux of the light source a standard operation mode described by electric current is assumed. When a high power LED-lantern has an excellent heat dissipation the luminous flux may be significantly higher. This is done by some manufacturers.

Projection lenses with large focal length produce a high luminous intensity and show small sectors. A short focal length gives lower intensities but larger sectors.

Input parameters are:

- Light Source (LED): height Y_{LS}, width X_{LS} or area A_{LS}, luminous flux Φ_{LS}
- Projection lens: clear diameter D_P, focal length F_P
- Condensor lens: clear diameter D_C, focal length F_C
- Size of field stop: height Y, width X.

Main results are:

- Luminous intensity of the projector I_P
- Horizontal and vertical angle α_h and α_v

8.1 Medium Intensity

To design a medium intensity sector light a focal length of 500 mm for the projection lens is chosen.

8.1.1 Input

The components are:

- LED: Cree XLamp XM-Le
  $A_{LS} = X_{LS} \times Y_{LS} = 5 \times 5\ mm^2$, $\Phi_{LS} = 1056\ lm$ at $I = 3\ A$
- Projection lens: Edmund PCX #27-507, $D_P = 125\ mm$, $F_P = 500\ mm$
- Condensor lens: Edmund Asphere #46-661, $D_C = 50\ mm$, $F_C = 35.7\ mm$

The field stop has a size of $X = 40\ mm$ and $Y = 10\ mm$.

The distance between second principle plane and field stop is $Z_0 = 20\ mm$.

The lenses have no antireflection (AR) coating.

8.1.2 Result

The minimum condensor lens diameter should be $D_C > \frac{\sqrt{X^2+Y^2}}{0.9} \approx 45.8\ mm$.

The lens chosen has $D_C = 50\ mm$.

Horizontal and vertical angles:	$\alpha_h = 4.57°$ and $\alpha_v = 1.15°$	
Image distance:	$S' = F_P + Z_0 = 520\ mm$	
Object distance:	$S = \frac{520*35.7}{520-35.7} mm = 38.3\ mm$	
Magnification of light source:	$m = \frac{S'}{S} = 13.6$	
Size of the light source image:	$A'_{LS} = 13.6 * 5\ mm \times 13.6 * 5\ mm = 68 \times 68\ mm^2$	
The image fits in projection lens:	$D'_{LS} = \sqrt{68^2 + 68^2}\ mm = 96\ mm < 112.5\ mm = 0.9 * D_P$	

The design is according to case A.

Luminous intensity of the LED:	$I_{LS} = \frac{1}{\pi} * \Phi_{LS} = 336\ cd$	at a current of 3 A
Transmission:	$T = (1 - 0.042)^4 = 0.84$	no AR-coating

Luminous intensity of the projector:

$I_P = T * \left(\frac{S'}{S}\right)^2 * I_{LS} \approx 52\ 000\ cd$ for a maximum sector of $\alpha_h = 4.57°$ at $I = 3\ A$.

8.2 Increased Sector Width

To get a larger sector the focal length of the projection lens is 250 mm.

8.2.1 Input

The components are:

- LED: Cree XLamp XM-Le
  $A_{LS} = X_{LS} \times Y_{LS} = 5 \times 5\ mm^2$, $\Phi_{LS} = 1056\ lm$ at $I = 3\ A$
- Projection lens: Qioptiq Achromat G322311000, $D_P = 50.8\ mm$, $F_P = 250\ mm$
- Condensor lens: Edmund Asphere #15-543, $D_C = 80\ mm$, $F_C = 59\ mm$, AR-coating

The field stop has a size of $X = 70\ mm$ and $Y = 10\ mm$.

The distance between second principle plane and field stop is $Z_0 = 20\ mm.$

Both lenses have antireflection coating.

8.2.2 Result

The minimum condensor lens diameter should be $D_C > \frac{\sqrt{X^2+Y^2}}{0.9} \approx 79\ mm.$

The lens chosen has $D_C = 80\ mm.$

Horizontal and vertical angles:	$\alpha_h = 15.6°$ and $\alpha_v = 2.3°$
Image distance:	$S' = F_P + Z_0 = 270\ mm.$
Object distance:	$S = \frac{270*59}{270-} mm = 75.5\ mm.$
Magnification of light source:	$m = \frac{S\prime}{S} = 3.58$
Size of the light source image:	$A'_{LS} = 3.58 * 5\ mm \times 3.58 * 5\ mm = 17.9 \times 17.9\ mm^2$
The image fits in projection lens:	$D'_{LS} = \sqrt{17.9^2 + 17.9^2}\ mm = 25.3\ mm < 0.9 * D_P$

The design is according to case A.

Luminous intensity of the LED:	$I_{LS} = \frac{1}{\pi} * \Phi_{LS} = 336\ cd$	at a current of 3 A
Transmission:	$T = (1 - 0.015)^4 = 0.94$	AR-coating

Luminous intensity of the projector:

$I_P = T * \left(\frac{S'}{S}\right)^2 * I_{LS} \approx 4\ 040\ cd$ for a maximum sector of $\alpha_h = 15.6°$ at $I = 3\ A.$

8.3 High Intensity

For a high intensity sector light a large telescope lens (clear diameter 210 mm, focal length 1200 mm) is used. The LED has a circular emitting surface. The design is according to case B.

8.3.1 Input

The components are:

- LED: Cree XLamp CMU 1532
  $D_{LS} = 14.5\ mm$, $A_{LS} = \pi \times {R_{LS}}^2 = 165\ mm^2$, $\Phi_{LS} = 9000\ lm$ at $I = 2\ A$
- Projection lens: Tecnosky telescope lens AC210/1200, $D_P = 210\ mm$, $F_P = 1200\ mm$
- Condensor lens: Edmund Asphere #15-541, $D_C = 65\ mm$, $F_C = 50\ mm$, AR-coating

The field stop has a size of $X = 65\ mm$ and $Y = 20\ mm.$

The distance between second principle plane and field stop is $Z_0 = 20\ mm.$

Both lenses have antireflection coating.

8.3.2 Results

The minimum condensor lens diameter should be $D_C > 1.1 * \sqrt{X^2 + Y^2} \approx 74.8\ mm.$

The lens chosen has $D_C = 75\ mm.$

Horizontal and vertical angles:	$\alpha_h = 3.1°$ and $\alpha_v = 0.96°$
Image distance:	$S' = F_P + Z_0 = 1220\ mm.$
Object distance:	$S = \frac{1220*50}{1220-50} mm = 52.1\ mm.$

Magnification of light source: $m = \frac{S\prime}{S} = 23.4$

Size of the light source image: $D'_{LS} = 339.3\ mm$

The image does not fit in projection lens but the entire projection lens diameter is illuminated.

The design is according to case B.

Luminous intensity of the LED: $I_{LS} = \frac{1}{\pi} * \Phi_{LS} = 2865\ cd$ at a current of 2 A

Transmission: $T = (1 - 0.0015)^4 = 0.94$ AR-coating

Luminous intensity of the projector:

$$I_P = T * \frac{\pi}{4} * {D_P}^2 * \frac{I_{LS}}{A_{LS}} = 0.94 * \frac{\pi}{4} * 210^2 * \frac{2865}{165} \approx 566\,000\ cd$$

for a maximum sector of $\alpha_h = 3.1°$ at $I = 2\ A$.

9 References

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[4] Modern Optical Engineering, Warren J. Smith, 1990, Chapter 13.4, Condensor Systems

[5] Handbook of Lens Design, Malacara/ Malacara, 1994, Chapter 17, Projection Systems

[6] Modern Optical Engineering, Warren J. Smith, 1990, Chapter 8.6, The Radiometry of Images

[7] Modern Optical Engineering, Warren J. Smith, 1990, Chapter 7.1 Reflection, Absorption, Dispersion

[8] Optics, Miles V. Klein / Thomas E. Furtak, 1986, Chapter 6.4 D.3, Telescope Resolving Power

[9] IALA Guideline 1041 - Sector Lights, Edition 3.0, Chapter 6, Table 2