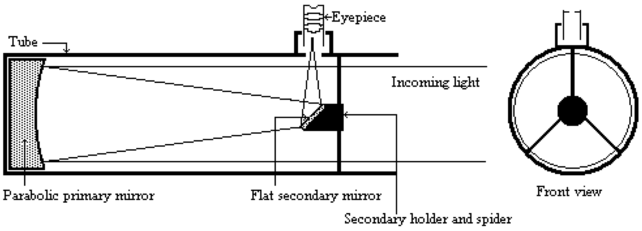
Performance of Optics with Central Obscuration
Technical Notes

Introduction

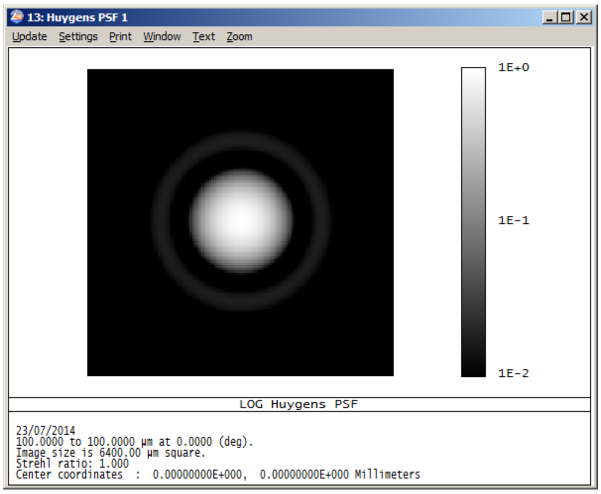
Optical engineers are generally familiar with the performance of diffraction limited systems with circular apertures. However, reflecting telescopes and reflecting microscope objectives have a central obscuration caused by the position of a secondary mirror or by a fold mirror. Diffraction from the central obscuration modifies the image point spread function (PSF) and hence affects the modulation transfer function (MTF). The central obscuration is generally circular. In some of these systems, in particular reflecting microscope objectives, the secondary mirror is carried on a 'spider', the legs of which further affect the PSF and MTF. The effects of the central obscuration do not depend on how they are manufactured or by whom - they are entirely controlled by the relative size of the obscuration, the wavelength in use, and the numerical aperture of the system.

These notes show how these two measures of performance, the PSF and the MTF, are affected by the central obscuration.



The point spread function for an un-oscured circular aperture.

First we look at the image point spread function for a diffraction limited system with a circular aperture - a normal OG for example. (Here we take the commonly accepted definition of a diffraction limited system - one in which the root mean square (RMS) of the wavefront aberration is less than λ/14. This is a system where the aberration is sufficiently small that the image is very close to that of a perfect system).



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23/07/2014
100.0000 to 100.0000 µm at 0.0000 (deg).
Image size is 6400.00 µm square.
Strehl ratio: 1.000
Center coordinates  :  0.00000000E+000,  0.00000000E+000 Millimeters
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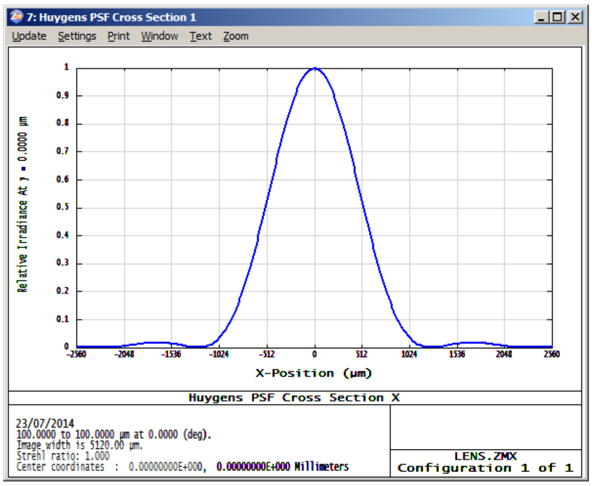
The central area is known as the Airy disc, outside of which is the 'first dark ring' which is followed by the 'first bright ring'. This diagram is limited to an intensity range 0.01 to 1.0. Plotting over a wider density range shows rings of ever decreasing intensity but the range has been limited to keep the diagrams simple.

The scale in this diagram is clearly somewhat 'unusual'! This is because the numerical aperture and wavelength have been scaled in order to normalise the MTF curves (see later) - in other words the limiting spatial frequency is unity (c/mm). This allows the curves to be calibrated by the scale factor...



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23/07/2014
100.0000 to 100.0000 µm at 0.0000 (deg).
Image width is 5120.00 µm.
Strehl ratio: 1.000
Center coordinates  :  0.00000000E+000,  0.00000000E+000 Millimeters
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LENS.ZMX
Configuration 1 of 1
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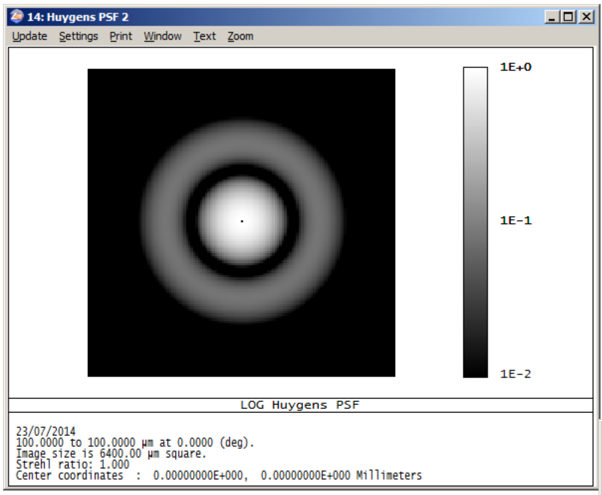
SF = 2 x NA / λ (where NA is the numerical aperture of the image forming beam)

So, to calibrate the curves in this note for your specific system, divide the PSF x-scale or multiply the MTF spatial frequency by this factor. [Note that, in the un-obscured system, the peak intensity in the first ring is approximately 0.0175 (or 1.75%)].

The point spread function for a system with a circular central obscuration.



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23/07/2014
100.0000 to 100.0000 µm at 0.0000 (deg).
Image size is 6400.00 µm square.
Strehl ratio: 1.000
Center coordinates  :  0.00000000E+000,  0.00000000E+000 Millimeters
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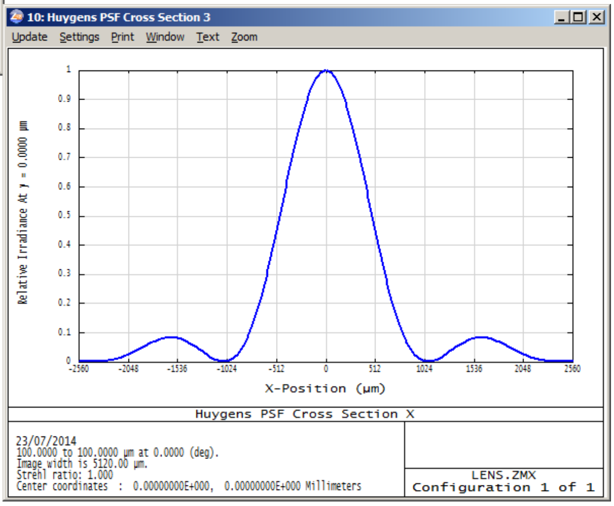
We now look at how the PSF is affected by the addition of a circular obscuration. The diagrams and curves here are limited to a central obscuration of 20% by area. This value has been selected as it is representative of many reflecting microscope objectives (the range is typically between about 15% and 25%).

Clearly there is considerably more energy diffracted into the first bright ring but careful examination of the PSF cross-section plot shows that the Airy disk and the first dark ring are a few percent smaller than those of the unobscured aperture (but not by enough to be exciting!) When this system is used to analyse a point image or to focus, for example, a laser beam to a point, the energy lost to the first bright ring is usually of little consequence from the image diameter point of view. What is affected most by this increase in the intensity of the first bright ring is the contrast in extended images - for example a tissue sample examined under a microscope - more on this later.



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23/07/2014
100.0000 to 100.0000 µm at 0.0000 (deg).
Image width is 5120.00 µm.
Strehl ratio: 1.000
Center coordinates  :  0.00000000E+000,  0.00000000E+000 Millimeters
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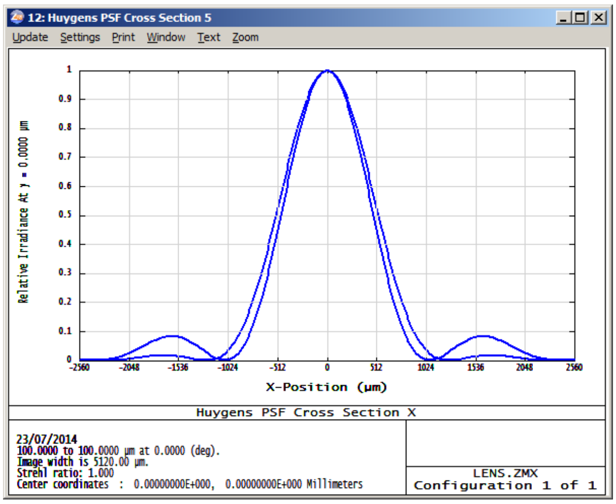

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23/07/2014
100.0000 to 100.0000 µm at 0.0000 (deg).
Image width is 5120.00 µm.
Strehl ratio: 1.000
Center coordinates  :  0.00000000E+000,  0.00000000E+000 Millimeters
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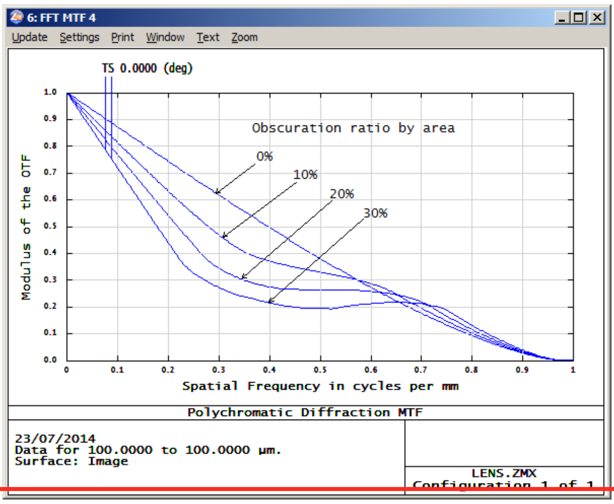
This graph shows the PSF curves for the unobscured and the 20% obscured systems superimposed.

The larger diameter beam with the low intensity first bright ring is that of the un-obscured circular pupil.

The MTF of a system with a central obscuration

The following graph shows the MTF of a system with a central obscuration for several obscuration ratios and compares them with that of an unobscured system. Note that pupils and the central obscurations are circular and the ratio is the obscured pupil area compared to the unobscured area in percentage terms. (Also note that, as explained earlier, the spatial frequency scale has been normalised to unity at the maximum frequency by using a long wavelength and a very small NA – this can be scaled to represent a real system by using the scale factor



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Data for 100.0000 to 100.0000 µm.
Surface: Image
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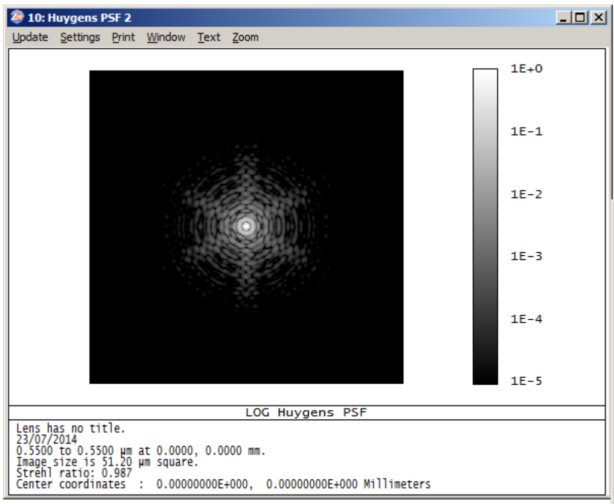
given earlier). It is particularly noticeable that the MTF in the 0.3 to 0.4 normalised spatial frequency is depressed by between about 0.15 and 0.25 in typical reflecting objectives. The effect of this can be seen when viewing extended objects such as tissue samples on a microscope slide – the image will have slightly less contrast than an image seen under a high quality refracting objective. But do note that the ultimate resolution is not affected by the obscuration.

At high spatial frequencies there is a slight enhancement of the MTF compared to that of an unobscured pupil. There is no known use of this phenomenon.

The effect of spider leg diffraction on the image of the point.

Anything placed in the pupil of a lens causes diffraction- the spider legs are no exception!

The Beck Reflecting Objectives are supplied with either 3-leg or 4-leg spiders as required. In general, most customers prefer the 3-leg spider. Although the diffraction pattern (below) looks more complicated, it is in fact less noticeable as the extra diffracted energy caused by the spider is about ¾ that of the 4-leg spider and it is spread over six radials and not four.



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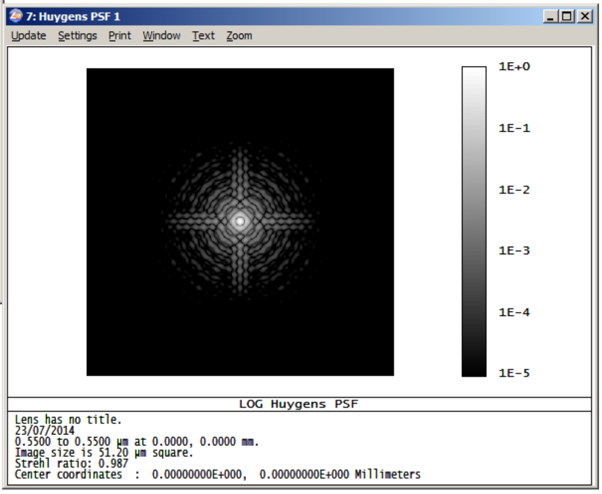
Lens has no title.
23/07/2014
0.5500 to 0.5500 µm at 0.0000, 0.0000 mm.
Image size is 51.20 µm square.
Strehl ratio: 0.987
Center coordinates  :  0.00000000E+000,  0.00000000E+000 Millimeters
```

Diffraction pattern for a 3-leg spider



```
Lens has no title.
23/07/2014
0.5500 to 0.5500 µm at 0.0000, 0.0000 mm.
Image size is 51.20 µm square.
Strehl ratio: 0.987
Center coordinates  :  0.00000000E+000,  0.00000000E+000 Millimeters
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Diffraction pattern for a 4-leg spider

One should not be alarmed by these graphs! The intensity scale has been extended by 5 decades simply to demonstrate their existence – the intensity range is from 100% down to 0.001%. They do, of course, become visible if the viewed point has a high intensity.

Conclusion

Two-mirror reflecting systems provide essential solutions to imaging problems in many circumstances. In astronomy, reflecting telescopes are always used once the aperture becomes larger than about 10 cm as the telescopes are more compact, more economic, and have better image quality than refracting systems.

In the case of reflecting microscope objectives, they have larger working distances than normal objectives and are essential where it is necessary to work over an extended spectral range, whether the spectrum is a wide, continuous spectrum or where it comprises widely spaced spectral lines. They can work from below 200nm to 15µm or more simply by selecting appropriate coatings.

In all of these systems, the effects of the central obscurations and spiders cannot be avoided. However, an understanding of the imaging characteristics described above ensures that you will get the best out of the product.

About Beck Optronic Solutions

Beck has a reputation for excellence in design and manufacture of precision optics that can be traced back over 175 years. Based near London, UK, Beck delivers complex, integrated electro-optic systems for defence and commercial use across the electromagnetic spectrum from UV to LWIR. **For pricing or further information please contact us at:**

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