RESOLUTION OF ICCD CAMERAS

Resolution theoretical background

Spatial resolution is defined as the resolving power to distinguish image details. It is usually defined as a number of line pairs that a camera can resolve per millimeter. Several methods for measuring the resolution of an optical system are in common use: the Modulation Transfer Function (MTF), the Point Spread Function (PSF), the Line Spread Function (LSF) and the Edge Spread Function (ESF)[1]. These methods are all linked together and rely on the characterization of the imaging system as a linear filter, which can be approximated by analytical functions in most cases.

- **Modulation Transfer Function MTF**

The MTF is a quantitative measure of the ability of an optical system to transfer various levels of detail from object to image. It is defined by the ratio of percentage modulation of a sinusoidal signal leaving to that entering the device over the range of frequencies of interest (see **figure 1** below). It is mathematically obtainable from the point spread function (PSF) or line spread function (LSF), which are discussed in a later section, by a Fourier transform. The MTF is usually presented as a graph showing the modulation transfer function versus spatial frequency which is customarily specified in line pairs per millimeter. In the optimal case, the MTF value is 1 meaning that object and image contrast are identical. For a square wave signal, the function is known as the CTF (Contrast Transfer Function)[1][2].

The limiting resolution of an optical system is usually defined as the spatial frequency at which the MTF is 3%. One of the advantages of MTF, which has led to its widespread use for the specification of imaging quality, is that in the case of components in cascade, the total response (MTF) is the product of the response of the individual components. Therefore, as shown in **figure 2**, the overall MTF of an ICCD camera is the product of the MTFs generated by the input lens, the image intensifier (MCP), and the lens- or fibre optic-coupling element.

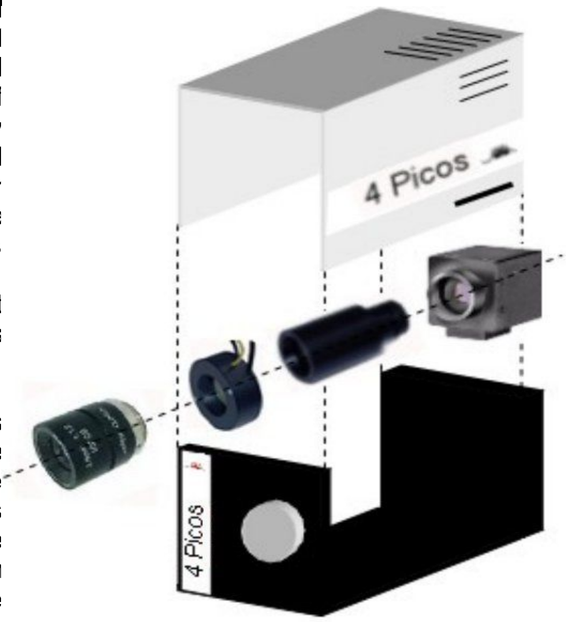

Figure 2. *MTF of an ICCD camera ; MTF_{lens} x MTF_{MCP} x $MTF_{coupling\ lens}$ x MTF_{camera} =* ***MTF_{total}***

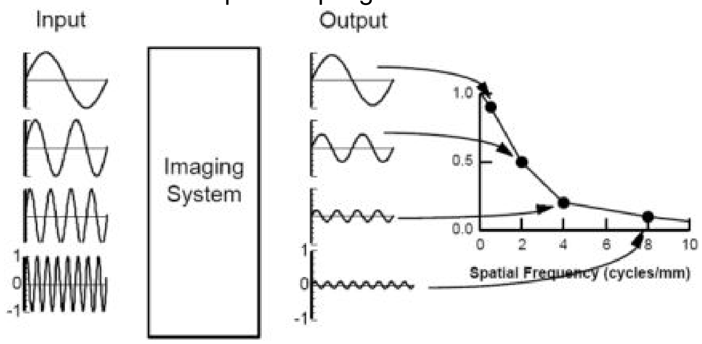

Figure 1. *Conceptual method to measure MTF.*

- **Point spread function PSF**

The image of a perfect point source can never be as precise as the point source itself. Several factors cause a spreading of the radiant energy reaching the image plane of the optical system: dust particles on optical surfaces and scratches in these surfaces, foreign particles (air bubbles, for example) within lens material, irregularities on the edge of the aperture stop, diffraction of the light beam by the aperture stop, and aberrations (including defocusing).

The mathematical function PSF(x,y), called point spread function, gives the flux density as a function of rectangular coordinates on the image plane, the usual origin being the location of the ideal image spot. Obviously, the more concentrated the spot is, the better the resolution. If a profile through the spot is plotted, we obtain a 1-dimensional PSF. Now, the resolution can be defined as the width within which the PSF drops to half the maximal value, called Full Width Half Maximum (FWHM). If the object consists of two ideal points, just a distance FWHM apart, there is a fair chance that they will be separated in the image.

[1]ESF will not be discussed in this article. For further details about this method, please refer to the publications [1], [2] and [3].

- **Line spread function LSF**

The LSF can be transformed to the PSF and vice versa. However, instead of considering the image of a point only, the LSF of a system is the image of an ideal line. Because the line spread function is easier to measure, it is usually preferred over the point spread function in optical analysis. The line spread function LSF(x) is the differential of the edge spread function (ESF) and can also be calculated by taking the modulus of the inverse Fourier transform of the MTF.

As for the PSF, profiles can be drawn orthogonally through the line image, and the full width at half maximum (FWHM) of these profiles define the resolution at a specific point in a specific direction.

Experimental measurements

- **Experimental setup**

All measurements were performed by using an optical bench which was composed of a digital camera (4.65 µm pixel size) combined with several elements such as a custom-made coupling lens, a Sigma lens and a MCP from DEP. For instance, to determine the maximal resolution of the MCP, the Sigma lens was adjusted to reduce the target´s image by two on the MCP. Then, image provided by the MCP was magnified by a factor 3 by inverting the coupling lens. Two types of targets (shown in **figure 2**) were used to determinate the resolution of the camera:

- an optical glass plate comprising 49 groups of opaque patterns (five-bar lines at right angles to each other) with resolution from 1 to 250 lp/mm (**a**)),
- an opaque target comprising 2 adjacent rows of 17 transparent dots and lines and with widths from 3 to 100 µm (**b**)).

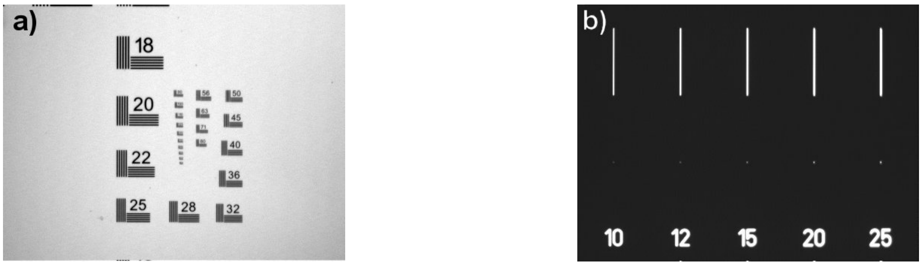

Figure 2. *Targets used to determine the resolution of our ICCD cameras.*

- **Data processing and approximation**

Images were then processed with the 4Spec software in order to evaluate the MTF, LSF and PSF of the camera. Whereas the first target (**a**) shown in **figure 2** allowed to directly calculate the CTF, the second one (**b**) gave the LSF and PSF profiles from which the MTF could be deduced by using the Fourier transform (**equation (1)**)

$$MTF(f) = \int_{-\infty}^{\infty} LSF(x) \times e^{2i\pi fx} dx \qquad (1)$$

It was observed that almost all measured PSF and LSF curves can be very well approximated by Lorentzian or exponential decay functions. These functions were used to calculate the corresponding MTF which was then compared to the directly calculated values. Respectively, CTF measurements were found to be very well fitted by exponential functions of the form **A.exp(-B.f)** where A and B are constants and f is the spatial frequency.

- **Results**

Figure 3 shows some of the performed MTF measurements and the corresponding approximation curves. The MTF of the Sigma lens (upper curve) was deduced from previous measurements through the cascade properties of MTF.

An image intensifier from DEP specified with a maximum resolution of 56 lp/mm was tested. In **figure 3**, the lower experimental curve corresponds to the CTF of the combination “MCP + Sigma lens” and the exponential function of the form ***exp(-0.081 f)*** gives a good approximation of these measured values. This equation results in a resolution at 3% CTF of about 43.2 lp/mm. But by dividing the CTF curve “MCP + Sigma lens” by the CTF curve of the Sigma lens, the CTF of the MCP only can be extracted. The equation ***exp(-0.063 f)*** is a good approximation of this new curve and results in a resolution at 3% CTF of about 55.6 lp/mm which fits very well the specified 56 lp/mm mentionned by DEP.

Furthermore, with a view to measuring the LSF of the combination “MCP + Sigma lens” and to deducing the corresponding FWHM and MTF, pictures of the 3 µm narrow line of the reticle target (see **figure 2.b)**) were taken and analysed. As shown in **figure 4**, the LSF curve was then fitted with a Lorentzian function of the form **(C.a)/(a²+x²)** where C and a are constants and x the pixel number. In this particular case, after making the appropriate unit conversion, a FWHM of about 27.9 µm was found. By applying a Fourier transformation to the fitting Lorentzian function, a MTF equation of the form ***exp(-0.0876 f)*** was obtained which is very close to the directly measured CTF curve (***exp(-0.081 f)***). The slight discrepancy between these two experimental charts is due to the fact that CTF is not strictly the same as MTF. Indeed, the CTF of a fundamental spatial frequency f_f is generally greater than the MTF at this frequency because of extra frequency components that contribute to the measured image modulation depth. Using the Fourier decomposition of square waves, the conversion between CTF and MTF is described by the following equation [3]:

$$CTF(f_f)=\frac{4}{\pi}\{MTF(f=f_f)-MTF\frac{(f=3f_f)}{3}-MTF\frac{(f=5f_f)}{5}-\ldots\} \quad (2)$$

Further analytical studies showed that the multiplication “FWHM [mm] x resolution at 3% MTF [lp/mm]” approaches always **-ln(0.03)/π ≈ 1.116**. This factor allows now to calculate the limit resolution when the FWHM is known and vice versa.

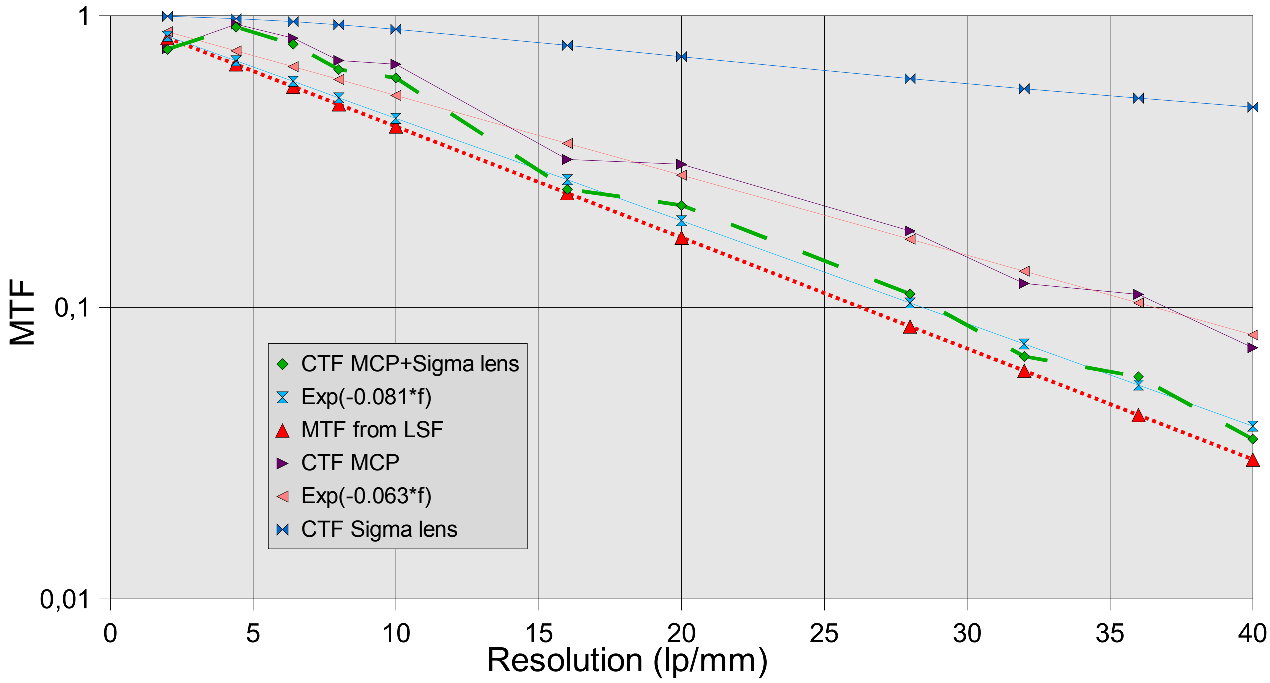

Figure 3. *MTF (or CTF) measurements and approximation with exponential functions.*

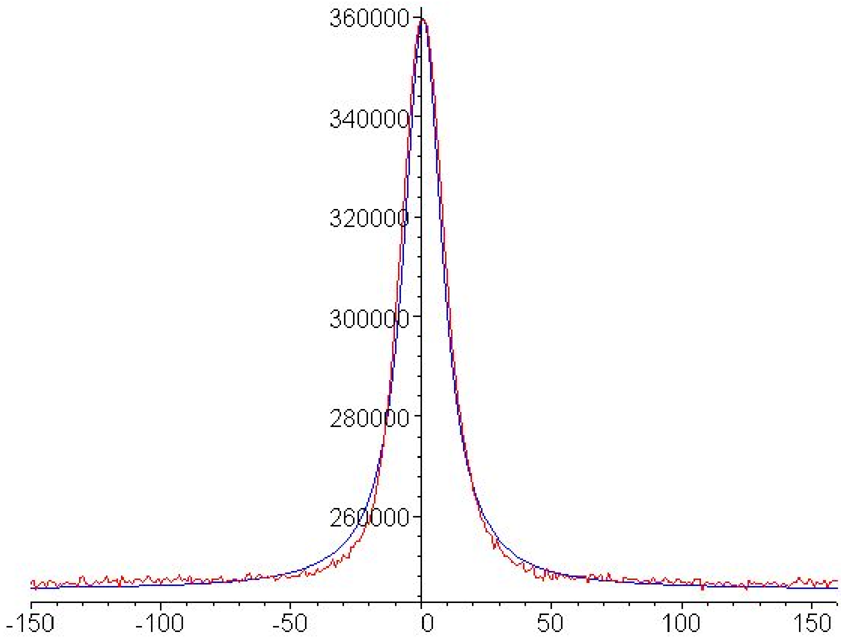

Figure 4. *Measured Line Spread Function (LSF) of a 56 lp/mm MCP and approximation with a Lorentzian function (smooth blue line)*

Conclusions

In this article, notions of MTF, CTF, LSF and PSF were explained. The described experiments illustrated how the resolution of a complex ICCD system can be determined. Several methods of calculation were tested and the corresponding results were compared. MTF calculation via LSF measurement turns out to be very attractive because it only requires to take a single image of a slit, to approximate the corresponding output light distribution curve with a Lorentzian function and to apply a Fourier transformation to this function.

References

1. Charles S. Williams and Orville A. Becklund, *Introduction to the Optical Transfer Function*, SPIE-The International Society for Optical Engineering, Washington, 2002.
2. Illes P. Csorba, The Howard W. Sams Engineering-Reference Book Series, *IMAGE TUBES*, Chapter 6. MTF of Image Intensifier Tubes, 79-94, 1985.
3. Glenn D. Boreman, *Modulation Transfer Function in Optical and Electro-Optical Systems*, SPIE PRESS, Tutorial Texts in Optical Engineering, Volume TT52, Washington, 2001.