Discussion on Optical Resolution

The **resolution** of an optical system is generally determined by two effects: (a) diffraction, and (b) aberrations.

(a) Diffraction – this is where the size of the smallest spot that can be focussed by a lens depends on the ratio of the focal length of the lens, f, to its diameter, D, as follows:

$$f/\# = \frac{f}{D} \tag{1}$$

where f/# is known as the 'f-number' of the lens and will be familiar to those with a photographic interest.

Generally in optical systems where the object is situated near to the focal plane of the lens, such as in a typical optical microscope, then the term Numerical Aperture (NA) is usually used instead of f/#. The relationship between the two terms is as follows:

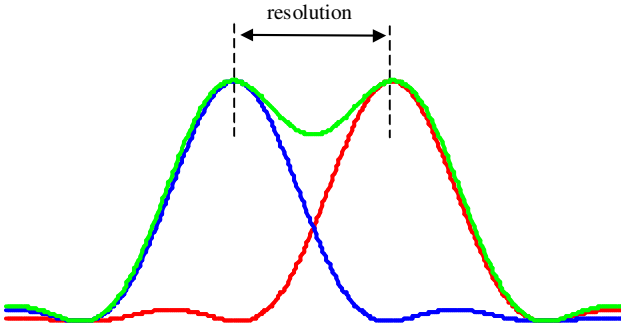
$$NA = \frac{1}{2 \cdot f/\#} \tag{2}$$

Optical resolution is usually determined in terms of the smallest spot of light that can be formed by a lens, known as the 'Airy pattern'. The Rayleigh criterion of resolution states that two adjacent objects can be resolved if the central peak of the Airy pattern of one object coincides with the first minimum of the Airy pattern of the second object. Thus resolution is equal to the radius of what is known as the 'Airy disc' and is defined as follows:

$$\text{Resolution} = \frac{0.61 \cdot \lambda}{NA} \tag{3}$$

where: λ is the wavelength of light.

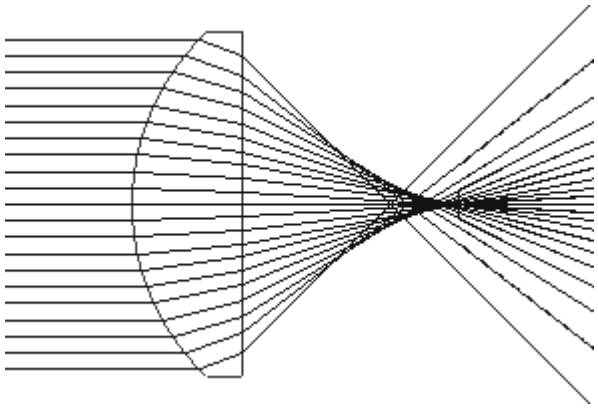
As an illustration, in the diagram below the red and blue curves represent the intensity profiles of the Airy patterns formed by two adjacent objects that are separated by a distance equal to the Rayleigh resolution. The green curve represents the summed intensity of the red and blue curves and the presence of a slight dip in the centre indicates that the two objects are just about resolved.



Thus the expected resolution, from diffraction considerations, may be calculated from (3) by simple reference to the NA of the lens which, in the case of a microscope objective, is normally engraved on the barrel.

(b) Aberrations – It is the aberrations in an optical system, however, that are usually the deciding influence on the actual resolution, or image quality, that can be obtained. In order to achieve the resolution expected from diffraction considerations the optical system must not distort the optical beams, or wavefronts, as they pass through the system. In short, the lenses, mirrors, etc., must be perfect, i.e. aberration-free.

This is a tall order, however, when one considers that the average lens, which is spherical in profile, is in fact not the ideal shape for aberration-free imaging and may contribute a great amount of aberration to the optical beam. The diagram below shows a ray-trace through a plano-convex lens for an object positioned at infinity. It can be seen that the rays travelling at larger angles in the image space to the right of the lens, known as marginal rays, focus at a point closer to the lens than those travelling nearer to the axis of the lens, known as paraxial rays. This resulting 'spherical aberration' causes the focussed spot to be somewhat blurred.



The way to overcome this limitation is to either use a lens element whose surface follows the theoretically optimum shape (known as an 'aspheric') or to use multiple lens elements that are able to correct for each other's deficiencies. This latter solution is employed to great effect in microscope objective lenses where a typical high NA objective may have about ten separate lens elements, which are usually grouped into several subgroups such as achromats or triplets.

The **Depth of Field** of an optical system, sometimes called 'depth of focus', is a measure of how quickly the image becomes de-focussed as it is translated along the optical axis away from the optimum focus position. The depth of field (DOF) in a diffraction-limited system may be determined from the following expression:

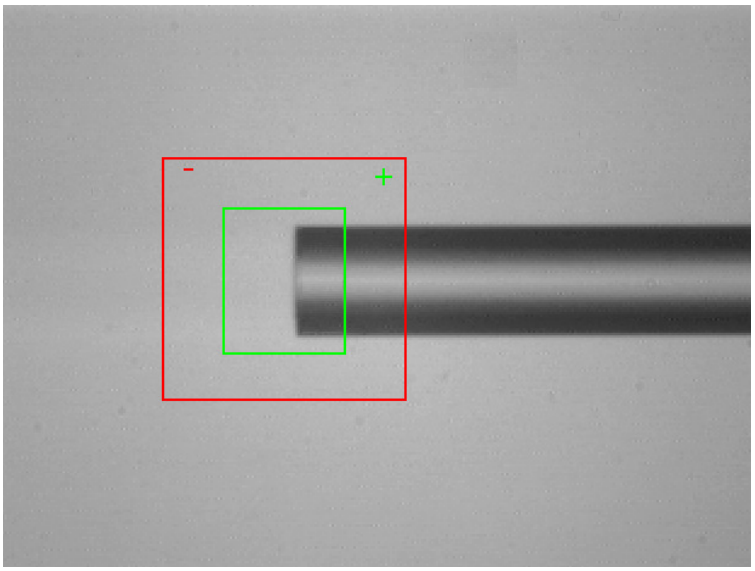
$$\mathrm{DOF} = \frac{\lambda}{2 \cdot \mathrm{NA}^2} \qquad (4)$$

This expression is a fairly good approximation for NAs up to about 0.6 but is a slight overestimation for higher NA systems.

It will be seen from eqns. (3) and (4) that a large DOF is not compatible with a small resolution and so a compromise usually has to be made. For this reason the NA of the illumination in a microscope is normally made adjustable so that the DOF can be optimised to suit the object being viewed, but, of course, at the expense of resolution.

An example of such a compromise is shown in the photograph below where the requirement was to form an image of an optical fibre such that both the cleaved end of the fibre and its sides were sufficiently in focus to allow accurate positioning of the fibre end with the software boxes. If a higher NA lens had been used to form the image then the sides

of the fibre would have indeed been sharper but the end of the fibre would be very blurred due to the reduction in depth of field and so the fibre would be consequently more difficult to align.



The large depth of field allows accurate positioning of the fibre end while good spatial resolution is maintained along the sides of the fibre.