Diffraction-limited photographs

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The optical performance of lenses, even in cheap cameras, is remarkably good these days. We don't have to worry too much about aberrations, even if we 'open up' and use the full lens aperture. Due to the steady progress in lens making over the years, our cameras – certainly the more expensive ones - are being gradually pushed to the diffraction-limited optics situation.

How does diffraction limit the resolution of our pictures? It all depends, of course, on the focal length of the lens (which we usually know) *and* the aperture, or effective lens diameter (which we may be unable to determine).

Fortunately, life turns out to be simple. Let us look at the textbook formula for diffraction through a circular orifice. When trying to image a point source on our film, we find that the radius of the resulting Airy disk is $1{,}22\lambda(f/D)$, with λ the wavelength, f the focal length and D the aperture (the funny numerical factor 1,22 results from integration over rectangular strips).

The nice thing now is that the ratio f/D is the 'F-stop' value, which we recall having used on our non-automatic camera as one of the two parameters determining the exposure. The well-known series of values is 2; 2.8; 4; 5.6; 8; 11; 16; 22, spaced by $\sqrt{2}$, of course, in order to have double exposure between consecutive values.

Now, precisely *how* seriously are we limited by diffraction? Let us take a worst-case scenario, and assume that there is plenty of light such that the F-stop 22 is chosen. The formula for the Airy disk radius yields $r = 15$ μm for the middle of the visible spectrum. In other words: we get a 30 μm diameter spot on the film, rather than a point. If we are using 35 mm film, we may want to enlarge the 24 by 36 mm frame by a factor of 10 in order to have a nice size picture. This means that the diffraction spots become 0,3 mm in diameter, and are no longer negligibly small. The conclusion is that, if we use high-quality optics in our camera, it may be wise to open up the lens much further and use smaller F-stop values.

Now let us compare this to our digital camera: Is it the number of pixels that poses the limit to the resolution, or is it still diffraction? Using the above worst-case scenario with an Airy disk radius of $r = 15$ μm, and assuming the Rayleigh criterion for just-resolvable diffraction patterns (i.e., a spacing by r is adequate to distinguish two adjacent ones from one another), we find that, on a 24 by 36 mm frame, we can store some 1600 x 2400 just-resolvable spots. If we were to image that pattern on our digital camera, and if we assume – somewhat arbitrarily – that the pixel density must equal the density of the just-resolvable spots, we need almost 4 Megapixels. This is just about the performance of a modern standard digital camera. However, if we move from the F = 22 to the other extreme of F = 2, the diffraction limited spot size shrinks by a factor of 10. If the digital camera wants to take advantage of this higher resolution, it has to increase its pixel number by a factor of 100.

So there is still room for improvement in the digital-camera business. ■

◄ Why you shouldn't ask a physicist to take your picture ... (cartoon by W. Drenckhan)