Sharpness Explained - Ian J. Wilson BSc (Hons), PhD (optics)

All photographers have a good qualitative understanding of what 'sharpness' is; after all, it is a technical term that has its origins in photography. It is variously described as 'the quality of details captured in a photograph' or 'the clarity of detail in a photograph' and more precisely:

> *a subjective quality attribute of an image or a lens … sharpness indicates the visually perceived quality of details of an image or details reproduced by a lens. It is associated with both resolution and the contrast of reproduced details [DxOMark].*

Resolution and contrast can be measured, making it possible to formulate a quantitative measure of sharpness. The sharpness of one camera/lens combination can then be compared with another.

You may be surprised to learn that there is no universally accepted scientific definition of sharpness and, at this stage, no settled method for measuring the sharpness of digital camera systems. However, the general outlines of a measurement protocol are emerging and one method has been recently adopted by the DxOMark camera testing website, www.dxomark.com. This is the so-called Perceptual Megapixel concept that *'weights the Modulation Transfer Function (MTF) of the lens with the human visual acuity'*. Unfortunately, DxOMark provide few details and it is not possible to make a rigorous assessment of the efficacy of their method.

The reason why the measurement of sharpness is lagging behind other camera performance indicators is because it depends upon the performance of two systems which are usually designed and optimized separately, namely, the lens and the camera detector system. Until recent times, consumers were content with the notion that if you put a 'good' lens on a 'good' camera body, then the recorded image would be acceptably 'sharp'. However, nowadays, with lots of good lenses and bodies available, people find the choices a bit bewildering and there is a need for a more quantitative approach to matching lenses and camera bodies for specific applications. For bird photography, we generally find the subject is at a distance from the camera and requires the use of a telephoto lens. The bird is usually near the centre of the field of view and lens aberrations in the corners of the field are not of much concern. These qualifications enable the following discussion to be somewhat simplified and permit a rigorous quantitative explanation of sharpness.

Diffraction and Modulation Transfer Function

We begin with the lens and reiterate that it is performance near the centre of the field of view that is important. Then, a simplified form of the Modulation Transfer Function can be used to describe lens performance; one that does not require consideration of the sagittal and tangential response. Furthermore, for well-designed telephoto lenses like those supplied by the leading manufacturers, the residual lens aberrations, except perhaps for the widest aperture, are so small as to be insignificant compared with the effect of the diffraction of light from the edges of the lens aperture. When this is the case, optical designers refer to the performance as 'diffraction limited' and the lens will deliver the best image quality theoretically possible.

Before proceeding to explain what the MTF is, it may be helpful to say a few more words about diffraction from the lens aperture. Diffraction occurs because of the wave nature of light. It is a bit like water-waves passing through a gap in a sea-wall. On the other side of the wall the part of the wave that passed through the centre of the gap will continue on in its original direction but the part of the wave that touched the edge of the opening will spread out in a circular pattern and change direction. The same thing happens with light waves passing through an aperture; a small fraction of the light is diffracted by the edge of the aperture away from the original direction of travel. If a lens is then used to focus the light, most of it will form a nice sharp focus but those rays that have been diffracted will appear as a surrounding blur making the image of a point source appear a little larger than would have been the case if there was no diffraction. The amount of light that is diffracted depends on the circumference of the aperture and the total amount of light reaching the focus depends on the area of the aperture. The fraction of the light that is diffracted is the ratio of circumference to area and therefore proportional to 1/D, the reciprocal of the diameter of the aperture. Eighty-four per cent of the light will be within a focal spot of diameter $2.44 \times \lambda \times f/D = 2.44 \times \lambda \times fNo$, where λ is the wavelength of light and f is the focal length. From this we can see that for a diffraction limited lens, the image of a point source will appear smaller for a large aperture than for a small aperture and this leads to the conclusion that the image quality will be better with a large aperture than with a small aperture. This may be contrary to the experience of photographers who have used lenses with aberration limited performance, in which case the opposite is true, and it is advantageous to use a smaller aperture.

We have now prepared the way for an explanation of the Modulation Transfer Function. It is an unfortunate choice of name that would be less intimidating for non-specialists if it was called the lens frequency response, because it is analogous to the frequency response used to characterize the output of electronic circuits and devices like audio systems. Another less commonly used name is Contrast Transfer Function, which is helpful in that it draws attention to the fact that the MTF is a measure of the fraction of the object contrast transferred by the lens to the image. So how does 'frequency' come into the picture? It is used to describe the 'fineness' of details in the scene; coarse detail is low frequency and fine detail is referred to as high frequency. The MTF is defined as the measure of how well a lens transfers the contrast of spatially varying sinusoidal intensity distributions to the image. In practical terms: how well the lens images light and dark bars when the gradation from light to dark follows a sinusoidal distribution and the bars have a continuum of spacings. A nice way of illustrating this is shown in Figure 1. The top graph depicts the light in the scene shown as a sinusoidal intensity distribution with continuously varying spacing which becomes finer from left to right. This represents a chirped frequency test pattern with contrast = 1. The next graph shows the intensity in the image – note that the contrast of fine detail in the image falls off as the frequency increases. In fact, there is a point beyond which really fine detail is not resolved at all and the contrast becomes zero. The parts of the image where this has happened will appear as featureless monochrome or grey. The bottom graph is the MTF which is a plot of the contrast in the image as the spatial frequency changes from low to high frequency. Note that the lens behaves as a kind of low-pass filter. Some examples of diffraction limited MTFs are shown in Figure 2 which bears out the point made earlier, that the image quality for the larger aperture is better than for the smaller aperture. MTF is a simple concept that is incredibly useful in imaging science and is essential to an understanding of sharpness – more on this anon.

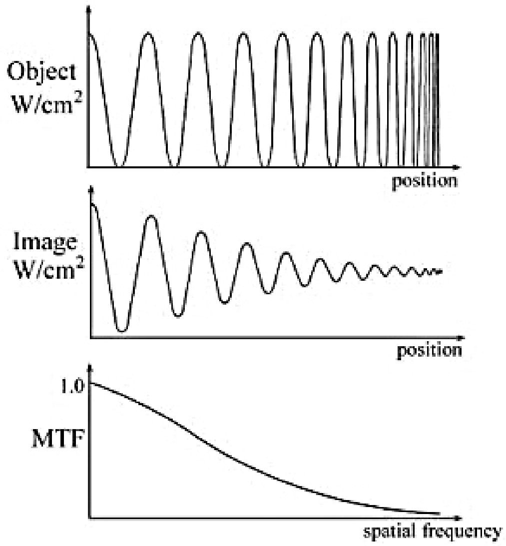


Figure 1. *Illustrating the Modulation Transfer Function concept.*

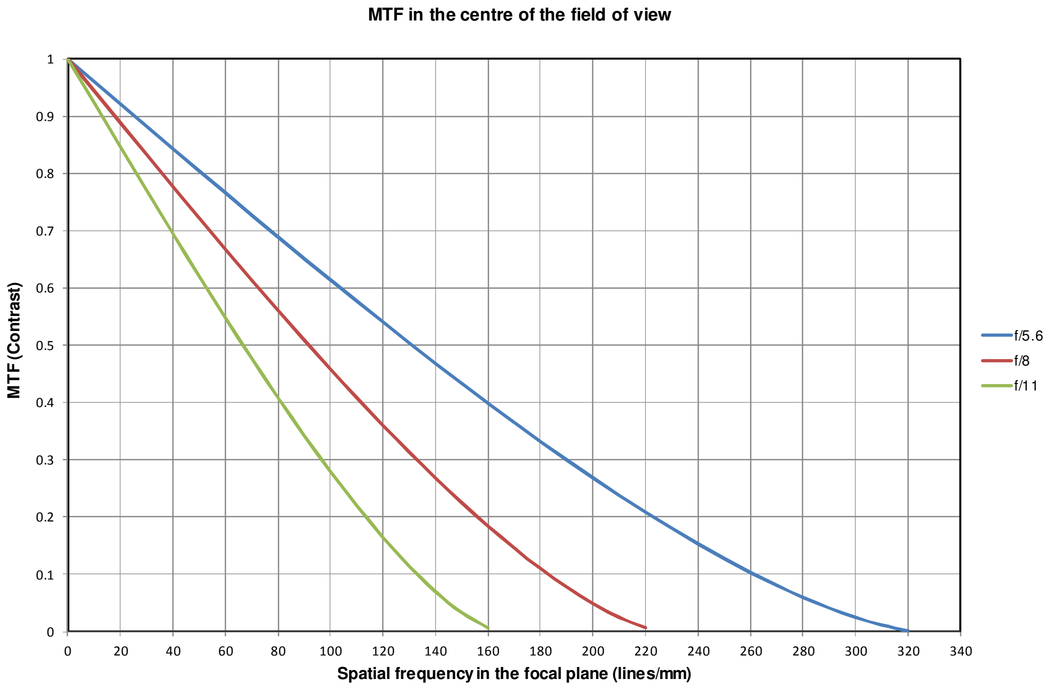


Figure 2. *MTF in the centre of the field of view of a diffraction limited lens – this is the theoretical best performance attainable. An average wavelength for visible light of 0.55 µm (green) was used in the calculation. Fixed focal length super-telephoto lenses made by the leading manufacturers have measured MTFs close to the performance shown.*

Resolution Limit of the Detector System

The other essential system in a digital camera is the detector and signal handling electronics. It is here, in the camera body, that the resolution of the camera is determined by the spacing of the pixels in the detector array. The Sampling Theorem indicates that the detector will only faithfully record details with fineness up to twice the pixel spacing. Finer details will be detected but there is no guarantee that the image will be a faithful representation of the object and spurious artefacts may appear. This is known as aliasing and to reduce the problem, camera makers insert an anti-aliasing filter in front of the detector. It is an optical component that has the effect of blurring detail finer than twice the pixel spacing, thereby limiting the spatial resolution of the detector system. Ideally, the anti-aliasing filter would have a sharp cut-off, called a 'brick wall' filter, as illustrated in Figure 3. The spatial frequency of the cut-off, known as the Nyquist frequency, is half the frequency of the pixel spacing in the detector array. If the lens system is well corrected and has a diffraction limited MTF, then the performance of the camera with a brick-wall filter is the best that is theoretically possible. While a brick-wall anti-aliasing filter is unattainable in practice, it does provide a useful benchmark against which we can compare the performance of real systems. The overall spatial frequency response of real cameras (lens plus detector) can be measured and compared with this theoretical limit.

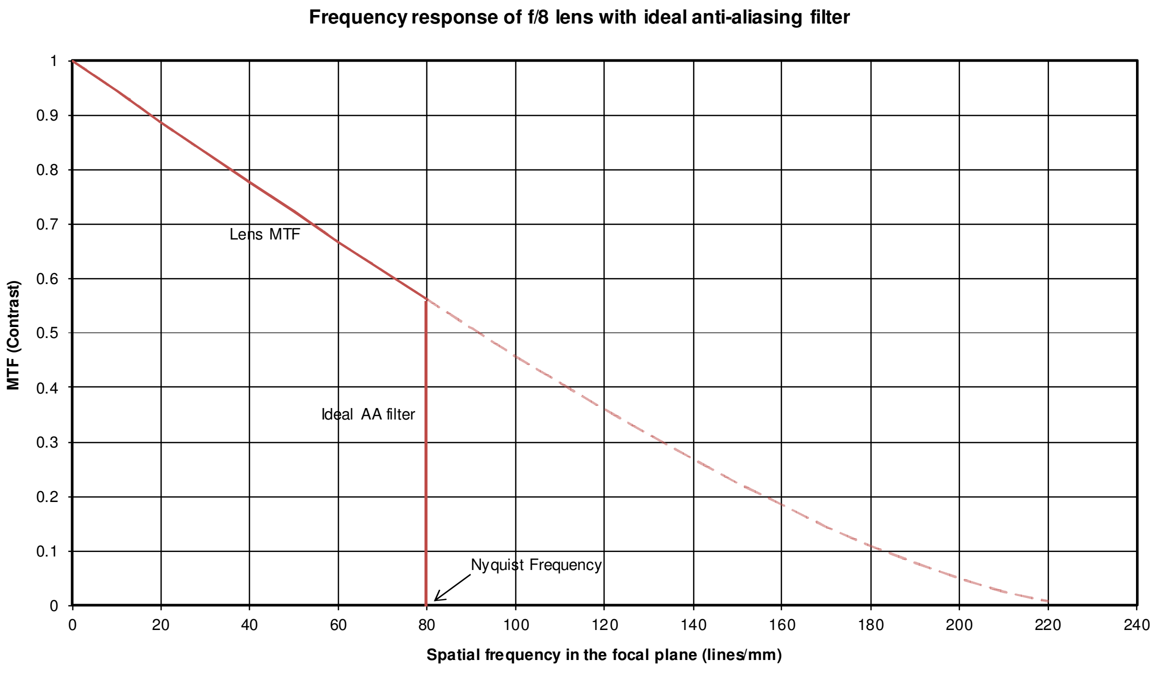


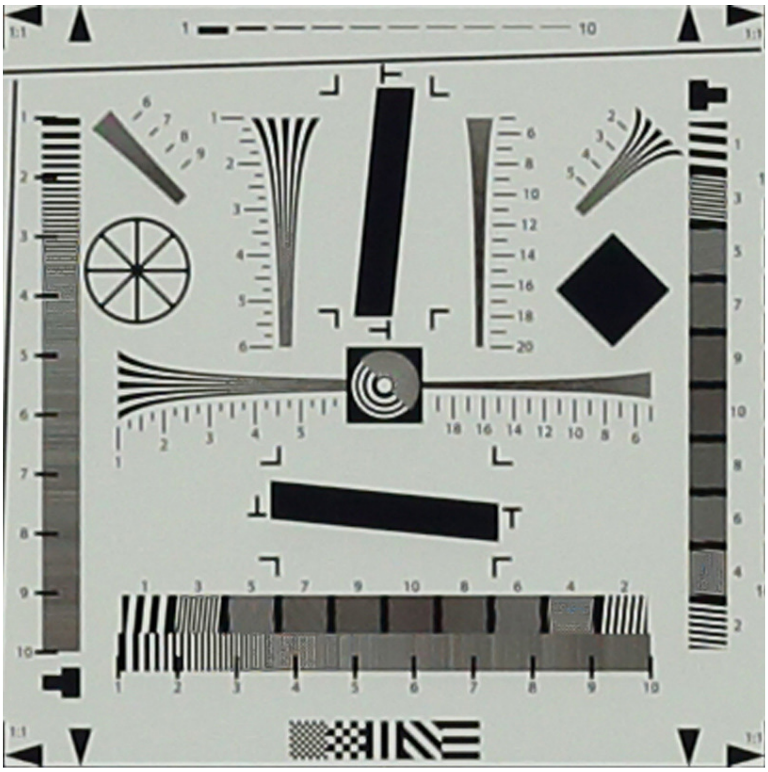
Figure 3. *Frequency response of a diffraction limited f/8 lens and brick-wall anti-aliasing filter. The Nyquist frequency of 80 lines/mm is for a detector pixel spacing of 6.25 µm as in the Canon 5D Mk III. For comparison, the Canon 7D has a Nyquist frequency of 116 lines/mm.*

Sharpness Defined

The overall frequency response of lens and detector system is the key to understanding sharpness. A practical measure of sharpness is the area under the frequency response curve up to the Nyquist frequency – the greater the area, the greater the sharpness. The area under the curve can be calculated using numerical integration (trapezoidal rule) which elegantly shows that the area is approximately equal to the average contrast multiplied by the Nyquist frequency. This result beautifully brings together in a quantitative way the perceived wisdom expressed at the beginning of this article – it shows mathematically that sharpness depends upon the contrast in the image and the resolution limit of the detector system.

SHARPNESS ≈ AVERAGE CONTRAST × NYQUIST FREQUENCY

Contrast is maximized by choosing a diffraction limited lens, such as one of the leading-brand fixed focal length super-telephotos, and in good light, the resolution of a camera having small pixels will be greater than a camera with large pixels. For example, the sharpness of an image from a Canon 7D + 300 mm f/2.8L series lens with the aperture set to say f/8, will be sharper than the image recorded with a Canon 5D Mk III + 300 mm f/2.8 L lens at f/8. The average contrast will be slightly higher with the 5D Mk III but the Nyquist frequency of the 7D is 1.45 times greater than for the 5D Mk III and the 7D combination wins easily (see Figure 4 test images). In poor light, when the 7D is noise limited, the story is different and the 5D Mk III combination is better. We have not taken account of the impact of noise, or in-camera noise reduction and image sharpening, all of which can have an effect on the measured frequency response. Each camera manufacturer has default settings for these parameters but in good light their effect is usually only at the margins compared with the impact of the anti-aliasing filter.



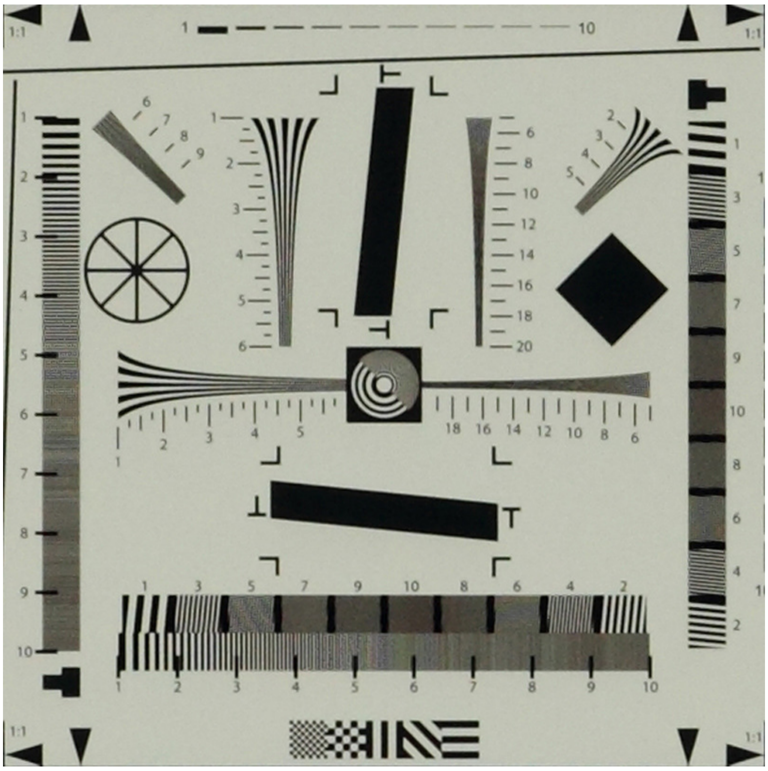


Figure 4. *Test chart images for the Canon 5D Mk III + 300 mm f/2.8L IS II USM (above) and Canon 7D + 300 mm f/2.8L IS II USM (below). In each case, the aperture was set to f/8, ISO 500 and the range was approximately 17 m. The number of pixels and file size is the same for each image. The image recorded by the 7D is noticeably sharper than the image recorded by the 5D Mk III.*

In order to compare the sharpness of cameras having different focal lengths, the frequency response measured at the focal plane needs to be transformed to the frequency response in the field of view. Furthermore, to make this independent of the range to the object, the spatial frequency should be changed to angular frequency in lines or cycles per degree. As an example, consider Figure 5 which shows the overall frequency response of four lens/camera combinations discussed in my article on focal length multipliers (February 2013). The sharpness calculated for each system and for the benchmark case (diffraction limited lens and brick-wall AA filter) is shown in the table below. The results confirm our previous conclusion that, used with care and understanding, focal length multipliers can be very useful in bird photography but they are no match for systems using the prime lens of equivalent focal length.

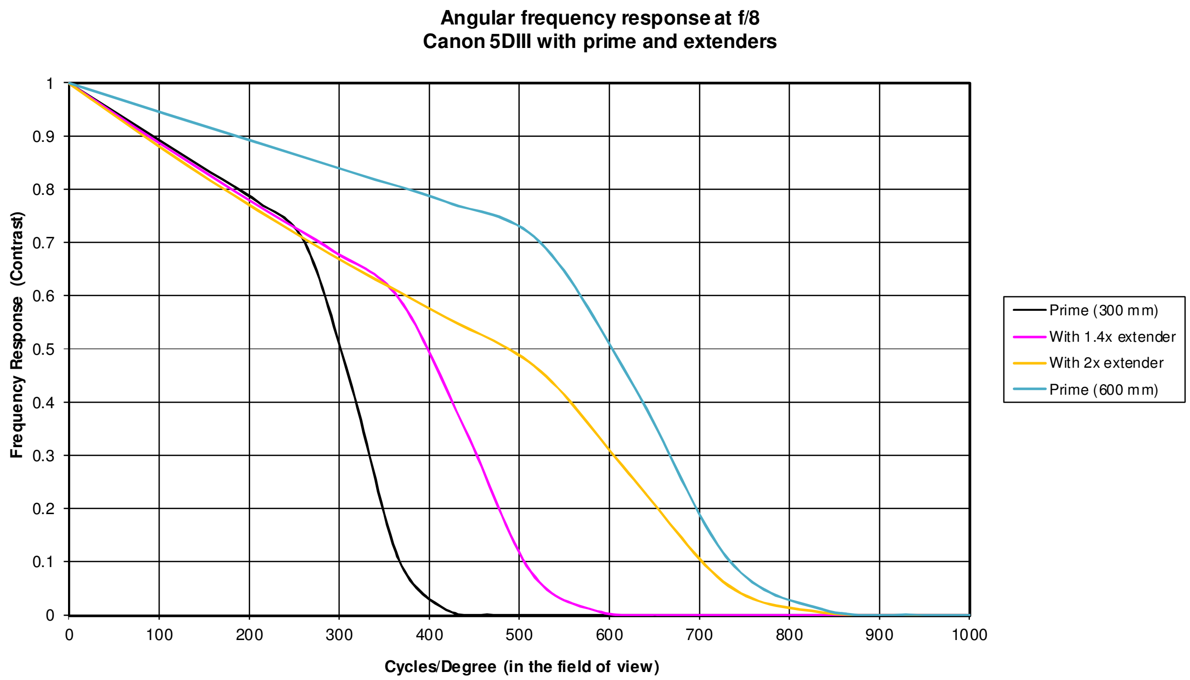


Figure 5. *Overall angular frequency response of 300 mm and 600 mm primes and 300 mm prime with extenders on a Canon 5D Mk III body. Based on MTFs from the centre of the field of view and an average wavelength of 0.55 µm for visible light (green). The sharpness value calculated for each case is shown in the table below.*

Camera System	Sharpness Value (Benchmark Case)	Sharpness Value (Actual)	Percentage of Benchmark
Canon 5DIII + 300 mm f/2.8L Mk II	326	271	83%
Canon 5DIII + 300 mm f/2.8L Mk II + 1.4× Mk III extender	456	347	76%
Canon 5DIII + 300 mm f/2.8L Mk II + 2× Mk III extender	652	432	66%
Canon 5DIII + 600 mm f/4L Mk II	652	542	83%

Sharpness values determined from the frequency responses of the lens and camera combinations shown in Figure 5.

Concluding Remarks

So far we have considered the role of the lens and detector system in determining sharpness. However, there is another important system that could be included in the discussion – the human eye used to view the results of the photographer. The lens of the human eye has an MTF and the eye has an overall Contrast Sensitivity Function that could be convolved with the camera frequency response to arrive at a measure of perceived sharpness. To get a complete picture of perceived sharpness, the optical properties of the eye, the image display medium (print or screen) and typical viewing distance need to be taken into account. This appears to be what DxOMark are trying to do when they calculate the Perceived Megapixel score for sharpness. However, we are not convinced that this added complication is useful, especially as DxOMark do not specify the test and viewing conditions. Their method is also producing some ambiguous results, for example, it indicates that the Canon 5D Mk II with 300 mm f/2.8L series lens should be sharper than the Canon 7D with the same lens when, in good light, the opposite is the case. Averaged over a wide range of lighting conditions the DxOMark score may well be valid but also misleading if their methodology is not well understood.

Finally, we offer a few remarks about the newly available cameras having no anti-aliasing filter. These cameras are marketed as a way of increasing the resolution limit and hence the sharpness of images. This is undoubtedly true and will be especially beneficial when photographing natural landscapes that have little or no periodic image detail. However, when imaging the built environment or natural history subjects with lots of high contrast periodic detail, such as bird feathers, the absence of an anti-aliasing filter is likely to cause severe moiré interference and undesirable aliasing artefacts. These problems can be ameliorated by closing down the lens aperture and taking advantage of the low-pass filter character of its MTF. This is well illustrated in Figure 2. A case in point is the new Nikon D7100 body with a detector pixel spacing of 3.9 µm and a corresponding Nyquist frequency of 128 lines/mm. A good lens used at f/11 on this camera will produce images almost entirely free of aliasing problems but at f/5.6, on subjects having lots of periodic detail, there is bound to be some disappointment. In coming months it will be interesting to see if there is a place for these kinds of cameras in bird photography.

Acknowledgement

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