Out-of-focus point spread functions

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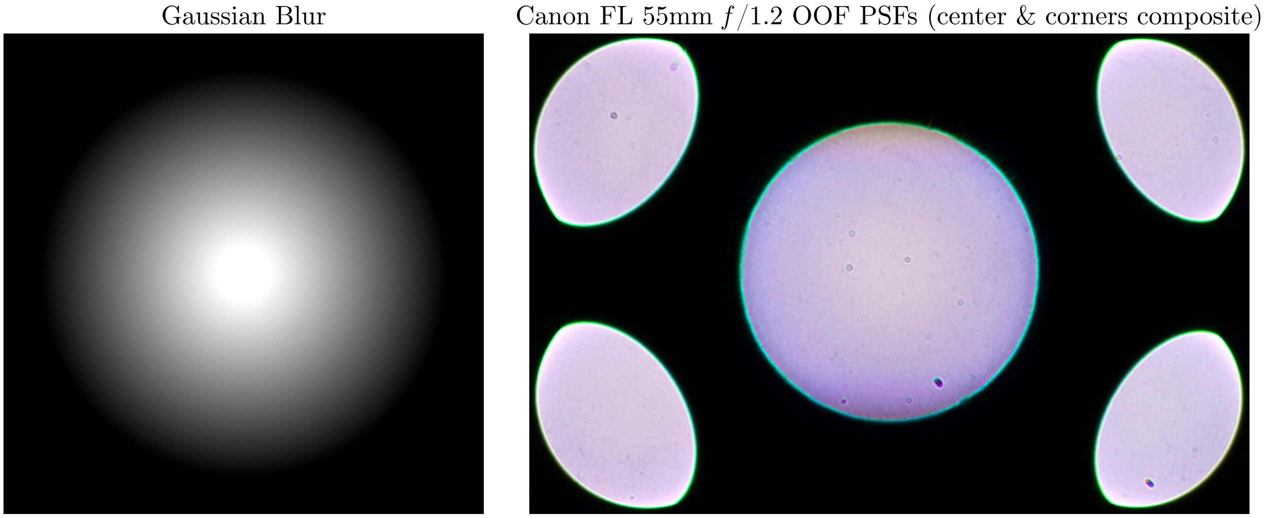
Abstract. *There are many ways in which the performance of a lens can be characterized, most of which measure properties of the in-focus image. The current work instead centers on measuring properties of an out-of-focus (OOF) image. The image created by imaging a point of light is commonly known as the point spread function (PSF). We have found that by measuring the OOF PSF a great deal of otherwise unavailable information about the lens can be obtained.*

The current work presents observations and sample images from measurements made on a collection of over 125 lenses. A variety of the attributes than can be obtained from study of OOF PSFs, and some of their applications, are discussed.



Gaussian Blur

Canon FL 55mm $f/1.2$ OOF PSFs (center & corners composite)

Figure 1. Out-of-focus is not blurry

1. INTRODUCTION

When asked what the image of an *out-of-focus* (OOF) point of light looks like, most people respond that it is blurry – however, that is not what happens. What does happen might not look as pretty or mathematically elegant as people imagine, but carries far more useful information about the lens and the scene. The resulting image is what we have called an OOF *point spread function* (PSF).

Fundamentally, the OOF PSF of a perfect lens would be an evenly-illuminated shape identical to the aperture of the lens – a white disc for a circular aperture. This is caused by the fact that rays entering the lens at different points, literally slightly different view angles, all pass unless they are occluded by the aperture or other obstacles within the lens. Thus, even the OOF PSF of a perfect lens encodes information that can be used to reconstruct multiple views, including stereo images and depth maps.

Of course, no real lens is perfect. Not even quite good lenses, such as the Canon FL 55mm $f/1.2$ whose OOF PSFs measured at the center and full-frame corners of a Sony A7 are shown in Figure 1, come very close to producing an OOF PSF that is a Gaussian blur, nor is it an evenly-lit circular white disc. Imperfect lenses impose many of their characteristics on the OOF PSF, and many of these characteristics can be recovered by examining the OOF PSF or OOF portions – the *bokeh* – of more complex scenes.

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Section 2 discusses the experimental procedure used for measurement of OOF PSFs, which we hope will be adopted by others. The next four sections discuss potential applications of the OOF PSFs. Diagnosing lens defects is discussed in Section 3. Methods by which OOF PSFs can be used to forensically identify the lens used to capture a photograph, or to identify forgery, are discussed in Section 4. Section 5 describes how knowledge of lens OOF PSF also can significantly improve the effectiveness of various methods for recovery and use of depth information. Most of the almost mystical properties people associate with bokeh are, in fact, predictably caused by specific OOF PSF features, as described in Section 6. The final section gives conclusions and information about the OOF PSF repository that we are creating.

2. EXPERIMENTAL PROCEDURE

The work reported in this paper began in Spring 2009, when Professor Dietz advised the undergraduate senior project of Jennifer Danhauer, Joe Lanford, and Ross Levine. Their project used CHDK[1] to enable a Canon PowerShot camera to rapidly capture a sequence of images with different focus distances and then process that data in-camera to produce a depth map image. The processing used fairly state-of-the-art blur measurement techniques, and was effective, but there were strange depth errors echoing the shapes of scene edges. These errors were caused by the sharp edges of the OOF PSF of the camera... and that fact led Dietz to begin collecting lenses to measure what real OOF PSFs looked like.

2.1 The lenses

Over a period of four-years, more than 125 lenses of many types have been collected. Lenses generally are not cheap, but patient searching of eBay and other sources for used lenses has resulted in an average cost of less than $30 per lens. This process does mean that the lenses tested do not include very expensive lenses, such as high-speed super-telephotos, but there are over 25 examples each of wide angles, "fast 50s," telephotos, and zooms. Various specialty lenses also are represented; there are 5 wide angles $f/2$ or faster, 5 dedicated macro lenses, 2 mirror lenses, and even a 135mm $f/1.8$. Focal lengths range from 8mm to 500mm. The oldest lens is well over 100 years old; the newest were manufactured in 2012. There are commercial adapters allowing lenses in a wide variety of mounts to be used on Sony E-mount bodies, and we designed and 3D-printed custom adapters for several other mounts. Thus, most of our measurements have been made using Sony NEX-5, NEX-7, and A7 bodies with lenses spanning many brands including Sony, Minolta, Pentax, Canon, Kiev, Tamron, Sigma, Vivitar, and Spiratone.

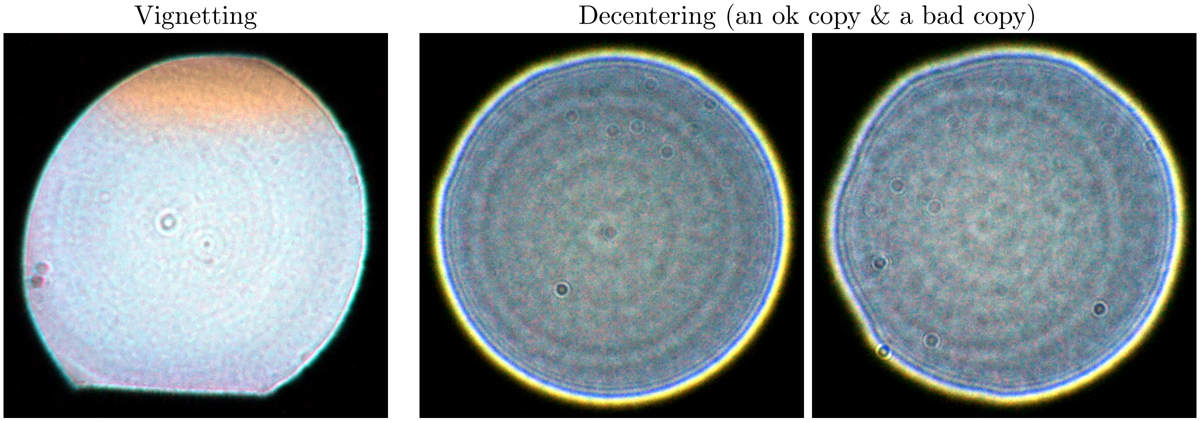
2.2 The test procedure

The OOF PSF is primarily a function of the lens. However, there are various other aspects that can skew the measurements. Thus, it is useful to formalize a test procedure. A more detailed description of the procedure is given at `http://aggregate.org/DIT/OOFPSF` , where the test results also are being made freely available.

The basic concept is simply to photograph a point light source in an otherwise dark and unobstructed room. To measure the background OOF PSF, the lens is manually focused on a target at the smallest integral number of meters distance that the lens can focus on (typically, 2m). The camera position is then shifted to photograph the point light source at a distance of 10m. To measure the foreground OOF PSF, the focus and target positions are swapped and the process repeated.

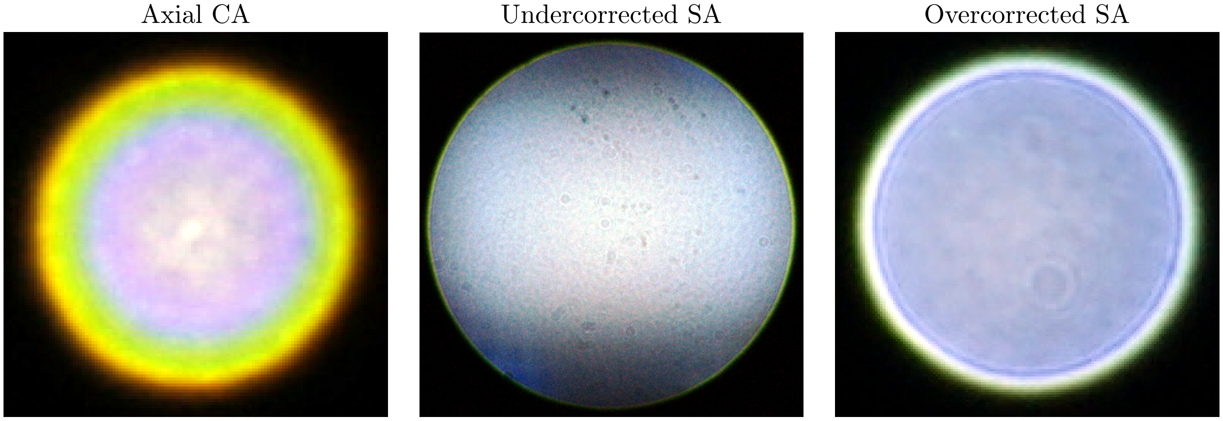
Minimally, the background OOF PSF would be photographed centered on the sensor with the lens wide open. Also capturing the background OOF PSF at one or more corners will record how the PSF is altered by vignetting and aberrations. Capturing the OOF PSF at many positions and various aperture settings, and repeating all measurements for foreground OOF PSF, is very time consuming, but could provide additional useful data. We may employ simple robotic automation to reposition and fire the camera for collection of OOF PSF at a multitude of positions on the sensor, but have not yet captured such extensive data – it did not seem worth the effort with an APS-C crop sensor, and our full-frame A7 did not arrive until December 2013.

A white LED was found to be a sufficiently good approximation to a point light source for background OOF PSF collection, but a foreground light source must be of higher quality. A pinhole or fiber-optic source was found to be acceptable. Rotating an appropriate point light source should produce no change in the measured OOF PSF.



Vignetting

Decentering (an ok copy & a bad copy)



Axial CA

Undercorrected SA

Overcorrected SA

Figure 2. Inherent defects of design or manufacture

The above procedure generally seems to produce sufficiently consistent results, with most variation being due to use of different adapters and camera bodies. Sensors vary in reflectivity and combining these variations with camera/adapter-specific internal light baffles and potentially reflecting surfaces can result in measurable changes in the captured OOF PSF. Fortunately, such issues rarely cause significant changes to the most distinctive features of the measured OOF PSF.

3. LENS DEFECTS

Lenses, especially modern autofocus zooms, are extremely complex electromechanical systems in which a myriad of things can go wrong. OOF PSF measurements are surprisingly effective in diagnosing a variety of optical defects that are difficult to recognize by directly observing either the lens or properties of in-focus images produced by it. OOF PSF measurements also could be used to prove condition of a used lens for sale, which would be a huge improvement over the descriptions and photos usually posted by sellers on eBay.

Defects occurring in lenses can be broadly divided into two categories: defects that are inherent to the lens and those that are acquired by the lens over time and use. Inherent defects generally are caused by poor design or imprecise construction, and often are highly correlated across multiple copies of the same lens. Acquired defects are caused by usage and the passage of time. Although there may be tendencies or patterns to these defects, they are rarely similar across copies of the same lens.

3.1 Defects of design or manufacture

When one thinks of defects inherently occurring in manufactured products, the natural tendency is to think of "sloppy" machining and assembly processes. However, that seems to be the exception rather than the rule for lenses. Most often, the "defects" seem to be traceable to design and manufacturing decisions. For example, one would expect that the amount of optical decentering – the minor misalignment of lens elements – would be randomly distributed around zero. Instead, it seems that multiple copies of the same lens often will have very similar decentering. Perhaps this is due to the common manufacturing practice of designing tooling to "wear through" an allowable tolerance range over a long production run? Whatever the reason, the result is that multiple copies of the same lens are surprisingly similar in the magnitude and direction of their flaws.

Figure 2 shows a sampling of the kinds of distinctive design or manufacturing defects commonly seen in real lens OOF PSFs. Nearly all lenses show vignetting in their off-axis OOF PSF. Typically, the vignetting clips the OOF PSF by an arc with a radius determined by some component of the lens. Some lenses have vignetting that is more complex, clipping by the combination of two or more arcs. The example given here is even more complex, combining a clipping arc with masking caused by a rectangular baffle in the lens mount. The decentering examples are from identical kit zoom lenses. As is common, both are decentered in the same direction, but the earlier one (right side) is clearly worse. Also note the distinctive, yet very similar, interference-pattern texture in both those OOF PSFs: such patterns seem to be especially common in lenses with aspheric elements, and probably arise from surface flaws in the manufacture of those elements. Axial chromatic aberration also is quite common, although the OOF PSF shown here is an extreme example. Spherical aberration is unusual in that many lens designs deliberately introduce it to improve bokeh (see Section 6). Undercorrection produces a bright center while overcorrection produces a bright ring. Note that the undercorrected example also shows a soft rectangular shaping, which is introduced by the rectangular sensor and/or masking in the camera body. The same lens on a different body can generate a somewhat more rotationally-symmetric OOF PSF.

3.2 Acquired defects

Throughout their useful lifespan, most lenses will slowly acquire optical defects. It is interesting, and a happy fact, that most acquired defects have very little impact on the quality of in-focus images. They do directly and adversely impact resale value of the lens, and many also show-up in the OOF PSF and OOF portions of images in general.

The vast majority of lenses employ designs in which the distance between the front surface of the lens and the film plane changes as the lens is focused or zoomed. Even lenses that do not change length still contain internal parts that move relative to each other. This type of movement allows materials to travel into, and within, the lens. This is true even if the lens is not interchangeable, but permanently fixed to the camera body. Lack of sufficient care during cleaning also can cause materials to enter the lens. For example, "wet cleaning" a lens is supposed to be "very slightly damp cleaning" – when a user floods the surface of a lens with cleaning fluid, that fluid can seep inside, potentially carrying more problematic materials.

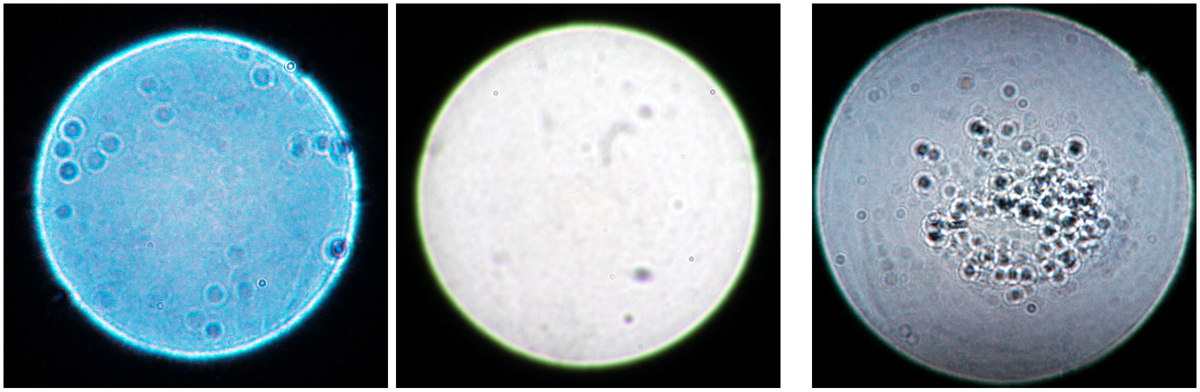
However, not all acquired defects come from outside the lens. Materials used in the construction can decay over time, most literally the slightly radioactive heavy metals that were once commonly used to give glass exotic properties. Radioactive yellowing of lens glass, and repair by UV exposure, is well known. Lubricants can degrade and migrate over time. Similarly, components that were joined together can fall apart.

Not all acquired optical defects are apparent in the OOF PSF. For example, the yellow tint from radioactivity and the diffusion caused by haze are both theoretically detectable, but not obvious. Some of the most important, and most common, acquired defects are obvious in the OOF PSFs of Figure 3.

By far the most common acquired defect found in lenses is fine dust, but even large particles of dust, dirt, and biologicals (e.g., a small bug) commonly find their way onto internal elements of lenses. Depending on object size and which surface is affected, these particles either show-up as shadows or diffraction patterns in the OOF PSF. It is easy to clean these materials from outer surfaces, and some will fall away by themselves under normal use of the lens, but removing them from internal elements generally requires significant disassembly of the lens, which few amateurs will attempt. Even fewer amateurs will succeed – which brings us to the next OOF PSF: an oily fingerprint. It is common that light oils will migrate out of lubricants used for focus helicals, etc., and eventually end-up on aperture blades and/or a lens element. The oil spots produce a subtly different effect in the OOF PSF than dust, but are essentially similar, if somewhat harder to clean.

Perhaps the most feared acquired defect is potentially contagious fungus or mold. Fungus generally will not grow on clean glass, but haze, dust, and dirt can provide sufficient nutrients. The spider-web-like branching

Dust and dirt Oily fingerprint



Fungus infection Nicked element Element separation

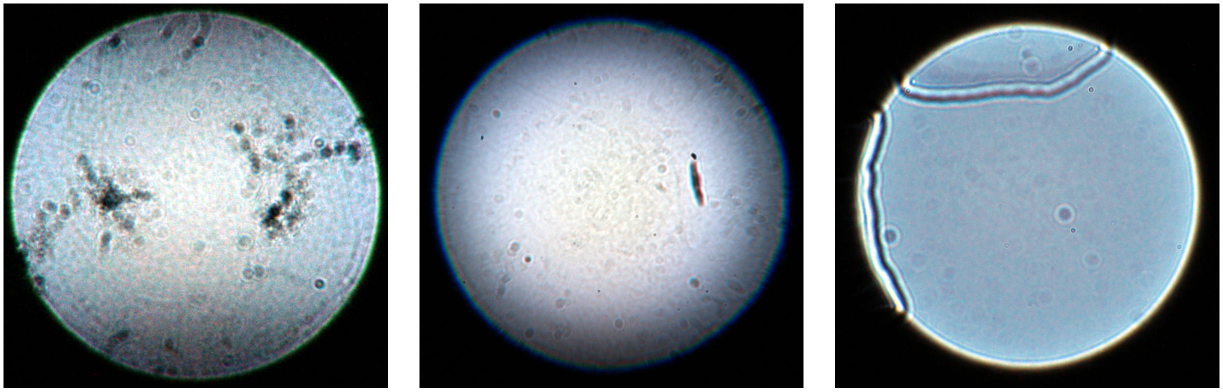


Figure 3. Acquired defects (in order of increasing repair difficulty)

growth pattern of fungus has surprisingly little impact on in-focus image quality and is often difficult to see in direct examination of the lens. The fungus infection shown in the OOF PSF in Figure 3 was minor and very difficult to see by direct examination of the lens using a penlight. Fungus is not much more difficult to remove than haze, but fungus can produce acid that slowly and permanently etches the glass. Thus, the key is catching the infection early, which the OOF PSF can enable.

Minor nicks, scratches, and even cracked elements are not readily repairable, but again have little impact on in-focus image quality until a crack allows portions of the element to shift. Rubbing a black material into scratches is a well-known way to convert a contrast-reducing diffractive defect into a simple light blocking one. In either case, the OOF PSF shows the defect clearly.

The last OOF PSF in Figure 3 shows a less common but very severe defect. Many lenses have elements cemented together; over time, it is possible for the cement to weaken, resulting in an unintended air gap between portions of the cemented elements. This air gap can significantly alter the in-focus properties of the lens. However, the 150mm $f/4.5$ Rodenstock enlarger lens that generated the OOF PSF shown does not yet appear to have any obvious image quality issues; in fact, it is one of the better resolving lenses among the 125+ tested.

In summary, the OOF PSF provides a very sensitive way to detect and monitor the development of acquired defects long before they become significant in-focus image problems.

4. FORENSIC USE

There are a wide range of digital file data and image characteristics that have been used to forensically identify what equipment was used to create a photograph.[3,8] Often, the forensic goal is detection of forgery or tampering rather than blind identification of the camera equipment used, but similar characteristics can serve both purposes.

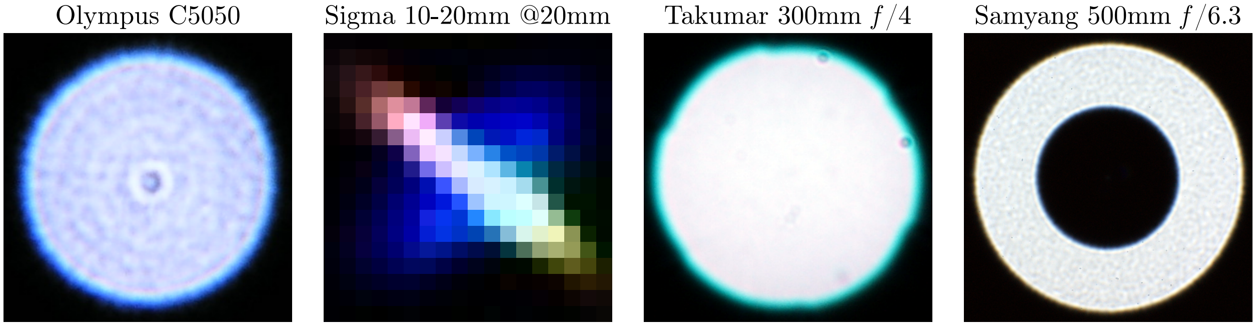


Figure 4. Some OOF PSFs that suggest lens type

It is also useful to note that forensic properties also can be deliberately introduced – for example, to make computer-generated images better integrate with live-action portions of a movie.

The inherent photo-response nonuniformity (PRNU) of sensels due to manufacturing variations directly imposes a sensor "fingerprint" on an image,[4] but there is little mention of a similar type of marker for the lens used. Some lens properties, notably transverse chromatic aberration (which changes magnification of different color channels causing off-axis misalignment), have been applied to detect when an image has been manipulated.[6] However, properties such as chromatic aberration and geometric distortion typically do not uniquely identify a particular lens or even a specific optical formula. General modeling of PSF shapes frequently plays a role in forensic image restoration,[10] to remove motion blur and similar artifacts, but detailed OOF PSF properties do not appear to have been used to identify which lens was used to capture an image.

The primary forensic insight in the current paper is that lens defects that are observable in OOF PSF samples can provide a rich set of features by which a lens "fingerprint" can be recognized. Clearly, the OOF PSF can naturally occur in isolation when the scene imaged contains an OOF point light source set against a featureless background: that is essentially how they are measured. However, it may also be possible to extract features from OOF PSFs in more complex scene contexts. It is further useful to note that rotation of the lens relative to the sensor might not be consistent for some mounts, such as the M42 universal screw thread. Thus, if the lens is not mounted using a rotationally-fixed locking position (as in most bayonet mounts), or if the lens construction is such that elements rotate with changes in focus or zoom, rotation of OOF PSF features also must be considered for forensic matching.

4.1 Design or manufacture properties

While some lenses are constructed in such a way that they have highly distinctive OOF PSF structures, the differences due to design and manufacture choices and flaws usually are not sufficient to identify a particular lens. However, these properties do offer some insight into the general type of lens used. Further, inconsistencies in these properties could be effective in detecting image forgery.

Figure 4 shows some OOF PSFs that strongly suggest the general type of lens that made them. Airy disc-like interference patterns generally come from lenses being used near their diffraction limit, which for small, high-resolution, sensors in compact cameras like the C5050 is true even wide open. Thus, a small, circular, pattern with this type of structure usually comes from a lens designed for a small sensor. Retrofocus wide angles and zoom lenses generally have more complex formulas, so their OOF PSFs often show distinctive aberrations, such as in the tiny off-axis OOF PSF from a Sigma ultra-wide zoom. The coma, astigmatism, etc. often varies significantly with zoom focal length. Near theoretically perfect OOF PSFs are commonly seen for macro lenses, and refractive telephoto lenses like the SMC Takumar 300mm $f/4$ often produce even white discs with color fringing at the edges. Mirror lenses are well-known for their large doughnut-shaped OOF PSF, and are easily identified with high confidence by that feature. As we have discussed earlier, double-Gauss-derived lens designs commonly used for normal lenses usually have undercorrected spherical aberration resulting in OOF PSFs like that shown in Figure 2. In most cases, these rough general attributes of OOF PSFs do not uniquely identify the lens, but still can serve to eliminate many lenses as potential sources of a particular image.

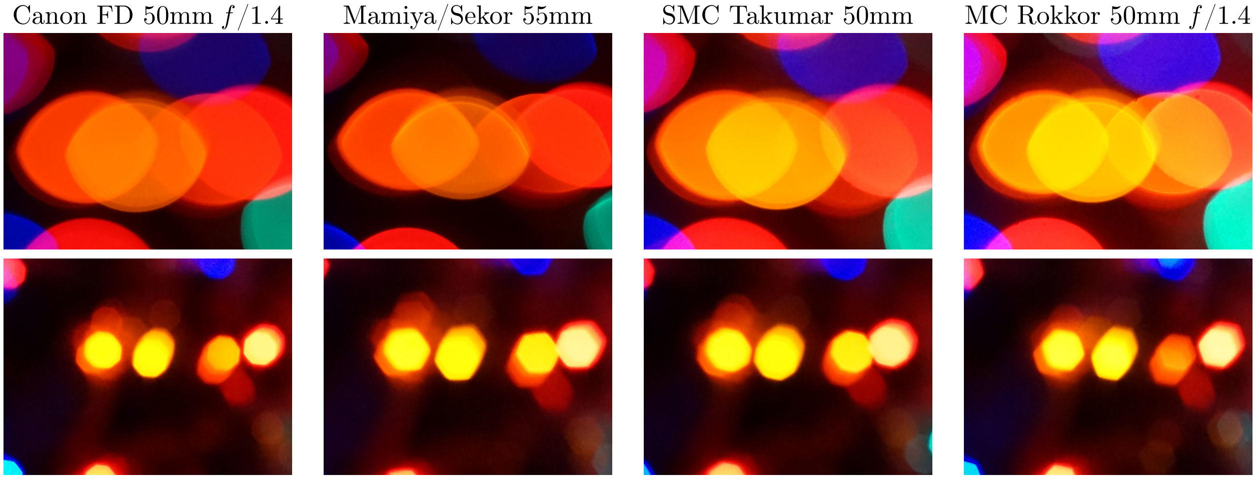


Figure 5. Off-Axis Christmas Tree Lights at $f/1.4$ and $f/5.6$

The bounding shape of the aperture, and how it is clipped off-axis by vignetting, provides a distinctive forensic feature. Vignetting of the OOF PSF is extremely consistent for a particular lens and closely resembles the vignetting of other copies with the same design. Shaping of the aperture by iris blades is less consistent. Although the number of blades and their general shape is consistent across time and copies of a lens, the precise positioning of each blade can vary somewhat between copies and even within the same lens over time. This variation appears to be largely derived from friction between blades, which can change due to wear, humidity, migration of lubricants, etc. Thus, a mismatch in positioning of individual blades is not conclusive, but a match is highly suggestive.

For example, the crops in Figure 5 show an OOF portion of a scene photographed with four different, but very similar, lenses. The Christmas tree lights have bulbs shaped so that each produces many points of light, and the light reflects off tinsel and other decorations on the tree, with overlaps that make it difficult to cleanly isolate a single OOF PSF. Thus, internal structure of the OOF PSF is somewhat obscured. However, the different vignetting arcs in the $f/1.4$ shots and blade count, shape, and rotation in the $f/5.6$ shots might allow these lenses to be distinguished.

Color fringing of the OOF PSF (axial chromatic aberration, also known as “bokeh chromatic aberration”) is also a distinctive forensic feature. Although the color of the fringing is different – approximately opposite – before and after the focus plane, a lens which produces a particular color fringing in its OOF PSF will consistently do so. Figure 6 shows the background and foreground OOF PSF measured for a particular Vivitar 200mm $f/3.5$. Note that we normally emphasize measuring the background OOF PSF because it is usually more important and can be precisely measured with a poorer point light source, but it is also true that a good approximation to the

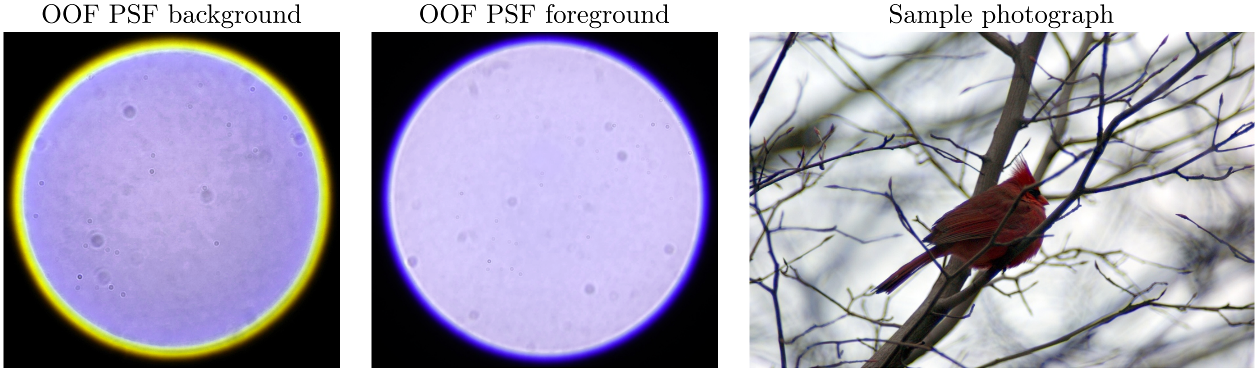


Figure 6. Axial CA of Vivitar 200mm $f/3.5$

foreground OOF PSF can be computationally generated from the background OOF PSF. Perhaps surprisingly, as Figure 6 also shows, this color fringing is easily identifiable even in a photograph for which the OOF PSF is not identifiable in isolation. For example, an OOF bright line essentially generates an image in which a sequence of overlapping OOF PSFs are often not individually distinguishable, yet the line formed by the edge of their union will very clearly carry the axial color. The axial color fringe will have both color and relative size consistent with the independently-measured OOF PSF.

4.2 Acquired defects

The pattern of dust spots and other acquired defect marks in the OOF PSF is essentially unique to a specific lens. If an OOF PSF can be isolated from an image, these patterns can be used; even where an OOF PSF cannot be cleanly isolated, some marks may be evident – as in the f/1.4 crop from the MC Rokkor in Figure 5.

Defects deposited on the external surfaces of the front and rear elements of a lens are accessible to a user, and thus some may be removed by cleaning. However, most internal acquired defects are essentially permanent unless the lens is disassembled for cleaning – an arduous task that is unlikely to be undertaken by most camera users. Additional spots and marks may appear over time. Thus, once a particular pattern has appeared, it can be expected that most of the structure in that pattern will appear in every subsequent capture of an OOF portion of a scene. The existence of multiple marks consistent with the pattern measured for a specific lens identifies that lens as having been used with fingerprint-like certainty.

Apparent absence of these marks is not conclusive if the image might have been captured before the defects were acquired or after they were removed by cleaning. In addition, small scale or overexposure of the OOF PSF in a scene can obscure minor marks. However, if marks of a comparable scale are visible, the image was known to be taken while the lens had the defects, and the marks seen are not consistent with those on the lens, that is strong evidence a different lens was used.

5. RECOVERY OF DEPTH INFORMATION

Directly modeling the optical paths in consumer lenses is not generally practical, as the design specifications are usually not made available. Further, most of these lenses are complex, requiring complex models. However, it is fairly easy to directly model observed variations in OOF PSF with changes in focus depth. Such a model can lead to a variety of applications, including single-shot capture of a depth map or stereo pairs, after-capture refocus, and even potentially faster autofocus algorithms. In essence, if the OOF PSF is sufficiently well known, every lens can be thought of as having a coded aperture.[7]

If a lens is focused on a point light source, the rays from that point coming through the entire area of the aperture should converge to a nearly perfect point on the film plane or sensor. In practice, the in-focus PSF is never a perfect point; in addition to diffraction, for example, aberrations may cause some colors to converge slightly before the sensor plane and others after. However, if the point source is relatively distant from the camera and the lens is well designed and built, the in-focus PSF is small enough to reveal no significant internal structure at the resolution of the sensor. Most of the energy falls on a single sensel or group of sensels directed by an anti-alias filter.

A point light source which is farther away from the camera than the distance the lens is focused on essentially produces a point image in front of the sensor. The rays passing through that point image continue to diverge until they hit the sensor, thus linearly scaling the diameter of the OOF PSF. In fact, once the point is sufficiently OOF to reveal the internal structure of the OOF PSF, that internal structure typically does not significantly change by other than scaling no matter how much farther away the point light source is moved.

The situation in which the point light source is closer to the camera than the distance the lens is focused on behaves in much the same way. The OOF PSF changes primarily by simple scaling as the point source is moved increasingly closer than the depth at which the lens is focused. However, in this case, the sensor intersects the projection before convergence. The result is that a ray coming from the top of the lens hits the top of the OOF PSF, whereas it would hit the bottom of the OOF PSF if the point light source were farther away, thus changing the relative positions of features in the internal structure of the OOF PSF. A simple way to describe the OOF PSF is that it is “turned inside out” as the point source is moved through the distance the lens is focused upon. For example, spherical aberrations flip between undercorrected and overcorrected while axial chromatic aberrations adopt opposing colors. For a lens with significant aberrations, this allows disambiguation between OOF PSFs of the same size before and after the focus distance.

By simple geometric optics,[5] the diameter of an OOF PSF is equal to:

$$ApertureDiameter * RearFocus * (\frac{1}{FocalLength} - \frac{1}{ObjectDistance} - \frac{1}{RearFocus})$$

The sign of the result indicates whether the OOF point is after or before the focus distance. Of course, this formula does not account for vignetting of the OOF PSF, which knowledge of OOF PSF vignetting easily can compensate for. The key concept is that the signed diameter of the OOF PSF is directly tied to the corresponding scene point being at a specific distance from the camera.

A simpler formula can be obtained by observing that if the lens remains focused at a fixed distance, only the *ObjectDistance* of each OOF point changes. Thus, within a single captured image, the formula can be simplified using two experimentally-determined constants:

$$Constant1 - \frac{Constant2}{ObjectDistance}$$

There have been a number of research efforts attempting to determine depth from defocus, typically using differences between two or more differently-focused images to determine the depth at each pixel.[9] However, by knowing precisely what the OOF PSF image is, it becomes possible to directly recognize that pattern within a single image, treating it precisely as a deliberately coded aperture.[7] The more distinctive the OOF PSF, the more effective such an approach will be. It also is possible to independently measure or estimate the OOF PSF image of a lens long after an image has been captured, thus allowing coded aperture approaches to be applied to existing photographs that were taken with known lenses.

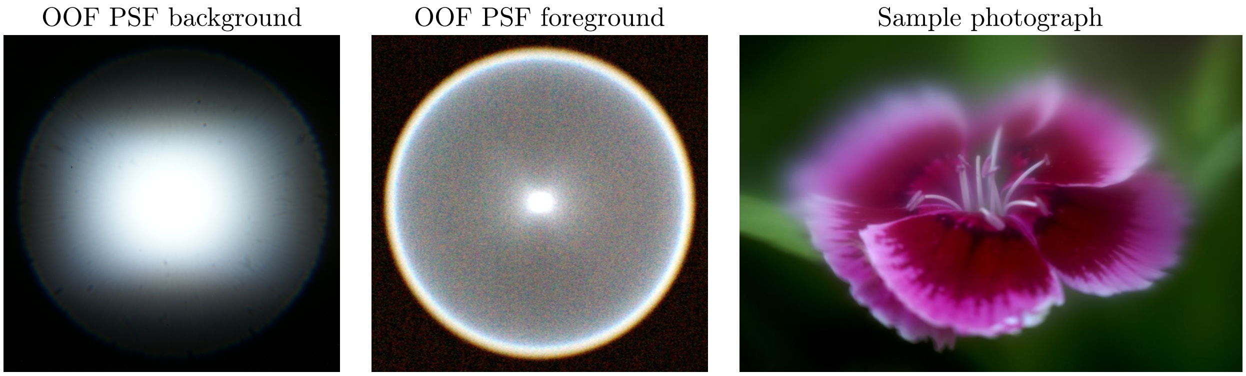
A key problem with most of these approaches, however, is that they use frequency-domain processing that cannot model occlusions within an OOF PSF. A point in the scene which lies within the sensels covered by the OOF PSF of a more distant point occludes that portion of the more distant point's OOF PSF. An OOF portion of a scene is not blurry, but combines light coming from multiple points in the scene as unoccluded PSFs overlap. The ideal solution we are working toward is to directly search for the signed OOF PSF diameter at each pixel, using a painting algorithm to order occlusions while reconstructing the captured image from scaled OOF PSFs. We began experimenting with this approach several years ago, using a genetic algorithm to find a set of signed diameters that will reconstruct the captured image. Very preliminary results were promising, but the problem has thus far proven computationally too intensive to be practical. The discovery of an efficient way to reconstruct full-color stereo pairs from an anaglyph,[2] which can be captured in a single shot by imposing a color filter to shape the OOF PSF, has since taken priority in our research.

6. BOKEH PROPERTIES

Bokeh is the term now commonly used in photography to describe the general properties of the OOF regions of an image. The term does not refer to how much of the image is OOF, nor does it refer to the diameter of the OOF PSFs in the image. Rather, it refers primarily to the smoothness of appearance and freedom from artifacts in OOF regions – OOF blur. As such, bokeh are often viewed as a mystic property of lenses – but measurement of the OOF PSF of many lenses quickly revealed the surprisingly direct relationship between OOF PSF and bokeh.

Good bokeh are bokeh that essentially result from an OOF PSF that gradually darkens from a bright center to a dark edge. A theoretically perfect lens does not generate perfect bokeh. The OOF PSF of a perfect lens would be an evenly-shaded disc, which would still leave sharp edge artifacts in OOF regions. Thus, a perfect lens generates what is known as "neutral" bokeh, which are considered neither particularly good nor bad.

Perfect bokeh actually can be obtained by apodization. For example, imposing a filter that smoothly darkens toward the edges of the aperture will remove any sharp edge artifacts. However, it is very difficult to construct an



OOF PSF background

OOF PSF foreground

Sample photograph

Figure 7. An extreme bokeh example from the Kowa 55mm $f/1.0$

effective apodization filter because any flaws will be emphasized much as the appearance of dust is emphasized in OOF PSFs. The Minolta/Sony 135mm STF (smooth trans focus) lens uses a pair of elements that together form an optical flat, but one of the elements is made of a smoked glass shaped to be thicker at the edges, thus creating virtually perfect bokeh. Ironically, the same apodization that smooths the bokeh also improves sharpness, although the shading of the aperture renders phase-detection autofocus unusable. A more practical alternative is to stack multiple exposures taken with different apertures, another trick developed by Minolta and implemented as "custom mode 25-2" using multiple exposures in the Maxxum 7 film camera. Appropriately adjusting the weighting of different aperture exposures in the stack can shape the OOF PSF using lenses that do not have inherently good bokeh.

For the common case of things behind the focus distance (background) forming the bokeh, designing a lens to deliberately leave spherical aberration undercorrected is the easiest and most common method by which a bright center for the OOF PSF can be achieved. Most "fast 50s" and portrait lenses take this approach. The problem with undercorrected spherical aberration is that on the other side of the focus distance, the OOF PSF will have a dark center and a bright edge – terrible "nisen" bokeh in which OOF lines become sharp double lines. An extreme example of this is the Kowa 55mm $f/1.0$, as shown in Figure 7. This lens was not intended for general use, and can only focus in the macro range with E-mount cameras (making OOF PSF measurement difficult), but the background bokeh are near ideal while the foreground shows nisen double-lines. Spherical aberration also reduces contrast wide open.

There are some lenses which produce better bokeh than their spherical aberration alone would seem to explain: for example, the famous 50mm f/1.4 Takumars. Perhaps these lenses employ some type of vignetting? However they do it, an OOF PSF with a bright center fading to darker edges reliably predicts good bokeh.

Lenses that produce nisen bokeh uniformly are those that have OOF PSFs with bright edges and dark centers. A bright line in a scene becomes two parallel bright lines. Overcorrection of spherical aberration may be the primary cause, although the doughnut-shaped OOF PSF of a mirror lens causes similarly bad bokeh artifacting.

It is interesting to observe that retrofocus wide-angle lenses often have OOF PSFs with both a bright center and a bright outer ring. This may be caused by the fact that retrofocus lenses are really pairing a wide-angle and an inverted telephoto to extend the rear focus of the lens. Bokeh for such lenses seem unpredictable, often very good, but sometimes nisen. In reality, the bokeh are quite predictable. Slightly OOF regions scale the OOF PSF small enough so that the bright ring is not resolved, hence yielding good bokeh. Larger OOF PSF reveal the bright rings and the presence of those rings makes the bright centers seem out of place.

Of course, lenses whose aperture blades impose non-circular shapes, especially asymmetrical shapes, also are generally considered to have bad bokeh. Similarly, heavily textured OOF PSFs also can disturb the smoothness of bokeh. "Swirly" bokeh are primarily the result of heavy vignetting of the OOF PSF off axis, although field curvature also seems to play a role. In any case, the quality of bokeh that will be produced by a lens is easily predicted from the OOF PSFs.

7. CONCLUSION

There are many metrics used to better understand the performance of cameras and lenses or to enable various types of advanced processing. In this paper, we have argued that measurement of OOF PSFs should be one of the standard metrics. OOF PSFs are simple to measure, are uniquely effective in diagnosing various types of lens defects, provide data that is not readily available from other standard metrics, and enable or have the potential to improve a variety of image processing techniques.

In support of our research and as a resource for the community, we have been collecting OOF PSF measurements since 2009 for a wide range of real lenses – over 125 at this writing. We are in the process of establishing a free repository for these measurements at `http://aggregate.org/DIT/OOFPSF` . Using the simple measurement process described in this paper and detailed at that site, we hope that others will contribute OOF PSF data for lenses that have not been available to us, expanding the database.

REFERENCES

1. CHDK Wiki. CHDK Wiki. *http://chdk.wikia.com/wiki/CHDK.*
2. Henry G Dietz. Reprocessing anaglyph images. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 8290, page 26, 2012.
3. Hany Farid. Image forgery detection. *Signal Processing Magazine, IEEE*, 26(2):16–25, 2009.
4. J. Fridrich. Digital image forensics. *Signal Processing Magazine, IEEE*, 26(2):26–37, 2009.
5. Akihiro Horii. *Depth from defocusing.* Citeseer, 1992.
6. Micah K Johnson and Hany Farid. Exposing digital forgeries through chromatic aberration. In *Proceedings of the 8th workshop on Multimedia and security*, pages 48–55. ACM, 2006.
7. Anat Levin, Rob Fergus, Frédo Durand, and William T. Freeman. Image and depth from a conventional camera with a coded aperture. In *SIGGRAPH '07: ACM SIGGRAPH 2007 papers*, page 70, New York, NY, USA, 2007. ACM.
8. HT Sencar and N Memon. Overview of state-of-the-art in digital image forensics. *Algorithms, Architectures and Information Systems Security*, 3:325–348, 2008.
9. Murali Subbarao and Gopal Surya. Depth from defocus: a spatial domain approach. *International Journal of Computer Vision*, 13(3):271–294, 1994.
10. Che-Yen Wen and Chien-Hsiung Lee. Point spread functions and their applications to forensic image restoration. *Forensic Science Journal*, 1:15–26, 2002.