Into the Deep: Adapting ISO Methods for Measuring Depth-of-Field

Don Williams, Image Science Associates, and Peter D. Burns, Burns Digital Imaging

Abstract

Monitoring of imaging performance is well-established and the subject of both imaging standards and guidelines for cultural heritage institutions. To date emphasis has been on the imaging of flat object. As more three-dimensional content is being captured though, performance metrics for this class of materials need to be introduced and considered. Chief among these is depth-of-field (DOF), the distance of acceptable focus along the optical axis in front of the lens. We propose adapting image-resolution tools for arriving at a practical method for measuring depth-of-field. We discuss requirements for test-chart objects and analysis software.

Introduction

To date, imaging performance guidelines for cultural heritage content are usually applied, or should be, to flat 2-D collection objects. As more three-dimensional content is being captured though, performance metrics for this class of materials need to be introduced and considered. Chief among these is depth-of-field (DOF). DOF can be defined as the distance of acceptable focus along the optical axis in front of the lens. So, it can be considered a goodness measure of (object) focus distance. That is, focus distance over the object being imaged. A related term, depth-of-focus, refers to the distance behind the lens.

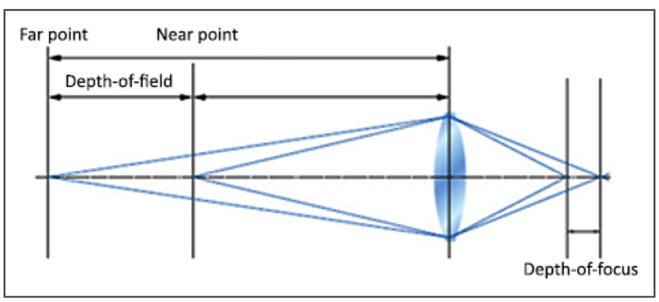

Figure.1: *Depth-of-focus vs. depth-of-field*

We limit our discussion here to depth-of-field. Having quantitative and objective data for DOF can help with more accurate (image) object capture. For example, improved point-cloud mapping, used to estimate object surfaces, and improved camera setups for so-called 2½-D objects, like deeply guttered books or cockled papers. It can even be applied to focus stacking applications if executed correctly.

Focus goodness evaluation can be evaluated under an image (spatial) resolution metric [1, 2] and is standard practice in optical lens design disciplines. In those areas it is better known as through-focus analysis though this is applied behind the lens. Well-established standards for camera /scanner resolution (e.g., ISO 12233) provide accepted methods for doing so via the Spatial Frequency Response (SFR) tools. The method is also used in imaging guidelines for cultural heritage imaging [3, 4]. Indeed, SFR/MTF analysis is the technique used in through focus analysis cited above.

Depth-of-field

Depth-of-field has frequently been discussed in photographic forums. It is one of those subjects that seems to be eternally trendy. Venturing a guess, we suspect this is because no truly analytical and quantitative experimental data to support DOF claims is available to practitioners. Arguably, this is because no easy way to analytically measure DOF has been proposed for field use. We attempt to take the first step in doing so in this paper by adapting SFR/MTF techniques already used in the optical design community. The challenge however is to make it easy and flexible for most studio environments, especially for 3D capture. To make it analytical requires not only tooling and targets but useful software to achieve quantitative results that are resilient and diagnostic. Before proceeding it is worthwhile examining the current discussions around DOF in order to place our proposals in context.

Circles of confusion, f/64, and more

Anyone venturing into the current discussions of DOF will no doubt come across the concept of the 'circle of confusion'. This concept, while scientifically sound, is poorly explained and never brought to a rightful analytical and objective conclusion. What exactly does 'confusion' mean? How can it be quantified and measured? These are the missing components that make DOF a more applicable imaging performance metric today.

The circle of confusion (CoC) concept can easily be extended into existing image performance protocols. It is nothing more than another name for image blur. When images are blurred, confusion or ambiguity exists about the amount of detail contained in the image. Ultimately it is a measure of resolution loss. It is as simple as that. More importantly, there are ISO standards across imaging disciplines, on how to measure image blur and resolution. It is done by measuring the Point Spread (think 'circle') Function (PSF) of imaging systems and in turn the spatial frequency response (SFR) of those systems. That is our objective here; to adapt SFR as a standardized, analytical and diagnostic tool for measuring blur. As indicated earlier, the optical design community already uses SFR for measuring through-focus performance, a very similar metric to DOF.

It is important to note that past uses of CoC have always presumed some human interaction, virtual or otherwise, with the final image [5, 6]. Uses of CoC refer to the perceived blur which presumes some subjective interaction. We depart from that definition in this paper and instead base our proposal on a purely objective metric that makes no assumptions about viewing conditions, F-number, or theoretical thin-lens equations. The amount of blur used to define DOF here is arbitrary but can be standards based for particular applications and object material.

Since SFR (i.e. resolution) is dependent on a variety of optical design parameters, so too is DOF. The one optical variable most associated with DOF is F-number. Generally, the higher the F-number the greater the DOF. Lower F-numbers equate to lower DOF. There is a resolution performance trade-off here that is often overlooked. That is, while higher F-numbers improve DOF, they also lead to lower optimal resolution. Lower F-numbers generally provide greater resolution but the depth over which that resolution (DOF) is maintained is lower. Higher F-numbers often have lower resolution but that resolution is more consistent and stable over a greater object distance or depth.

It is worth noting that historical references to Group f/64 have associated high F-numbers with high resolution as implied by their manifesto (see sidebar). One should not necessarily associate their artistic definition of *clearness* and *definition* with the quantitative form (i.e., resolution) addressed in this paper. It is unfortunate that many do however believe that. Typically, capturing images at f/32 or above will yield very good depth of filed but at the expense of poorer best-resolution. One must consider the extent to which *excellent* focus over a shallow depth is compromised with simply *good* focus over a greater depth.

Group f/64

from Wikipedia.com

Group f/64 displayed the following manifesto at their 1932 exhibit:

"The name of this Group is derived from a diaphragm number of the photographic lens. It signifies to a large extent the qualities of clearness and definition of the photographic image which is an important element in the work of members of this Group

Current Practices

Early work in DOF studies was largely theoretical and based on mathematical models of idealized or very specific optical systems. While academically satisfying and demonstrative, these approaches were not particularly suited to field practice where a wide range of content types and sizes challenged implementing such practices. While today, DOF targets (see Fig. 2) are commercially available, they are crude, limited in size, and constrained in their utility.

With reference to Fig. 2, in order to get reliable DOF assessments the optical axis needs to be aligned with specific angles relative to the target object. These targets only offer subjective DOF solutions that are not objectively quantitative. While the Ronchi ruling features on these targets are suitable for visual DOF evaluation, they lack diagnostic value offered by SFR techniques.

Nevertheless, these targets are good starting points for developing better tools. In the following sections we offer some improvements to the DOF target type shown in Fig. 2, to make them more adaptable to a variety of 3D capture applications.

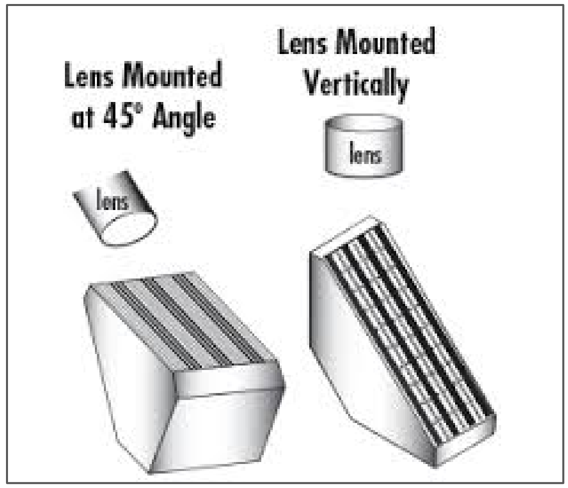

Figure 2: *Illustration of commercially available DOF measurement tool. (Edmund Optics)*

Method

We propose adapting SFR tools for arriving as a practical method for measuring depth-of-field. A pilot study on this was published in 2015 by the authors [7]. Figure 3 shows the tool used in that experiment for DOF evaluation using SFR features. We expand upon that work in this paper. The added effort is to articulate an executable methodology to acquire DOF data: not just a concept that is demonstrable but an approach that easily yields data. We offer other alternative targeting solutions near the end.

Like the tool in Fig. 2, the face of inclined surface has resolution features for determining the amount of blur. Unlike that of Fig. 2 we propose using slanted edge SFR features rather than simple bar targets. The main advantages of the SFR feature use is ISO standard compliance and better objective diagnostic value. Notice that the setup in Fig. 3 allows greater flexibility in camera positioning and target pivoting. Fig.5 shows a perspective view of the setup with annotations.

After capturing an image of the target setup as shown in Fig. 3, aligned rulings on the front and back plates are noted by the user. These ruling marks and the detent location of the baseplate are entered into an algorithm that calculates the near and far distances along with the SFRs for each of the SFR feature on the top plate. The details of calculating the depth distance of each SFR feature is included in the Appendix. The following section illustrates the SFRs calculated from the tools shown in Fig. 3 and Fig. 4.

Figure 3: *Example image capture setup with simple test chart, from Ref. 5.*

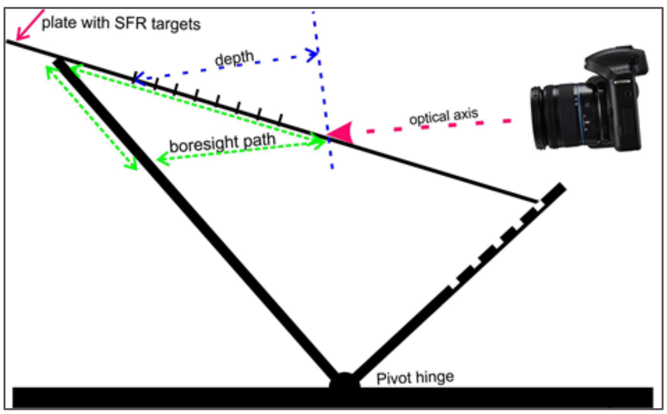

Figure 3: *Graphic illustration of DOF fixture with key features*

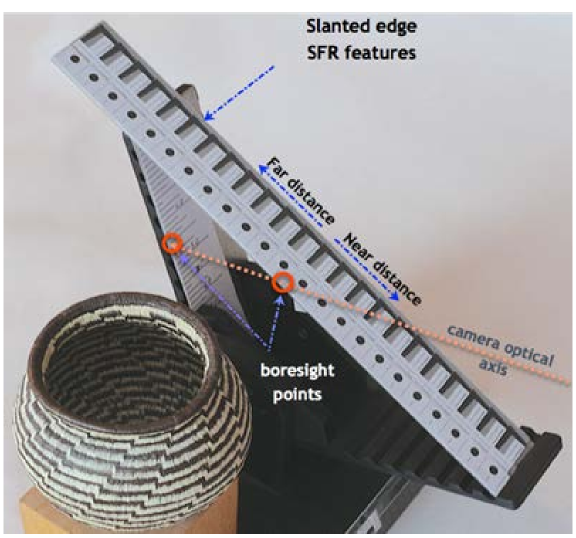

Figure 4: *Annotated illustration of DOF target tool*

DOF Data Extraction

We chose to demonstrate the DOF calculations using a common mid-range F/5 aperture of a DSLR camera. For context we show in Fig. 5 the best focus SFRs for each of several F-numbers for the chosen lens. F/5 and F/8 performance were nearly identical and were similar in both the horizontal and vertical directions. Note too that as the F-number increased, the SFR performance decreased. Figure 6 then shows the SFRs for F/5 at different depth distances relative to best focus (position 0). The numerical increments of the legend are at ½ inch intervals. For example, position $+1 = 0.5\ \text{inch}\ (1.27\ \text{cm.})$ away from the camera along the target.

Notice how the far direction (+1, +2) SFR behavior drops more dramatically than that of the near direction. We plot the frequency axis in terms of cycles/pixel since it normalizes the differences in magnification between far and close distances. The differences can of course be accommodated if absolute frequency data is needed (*i.e.*, cycles/mm).

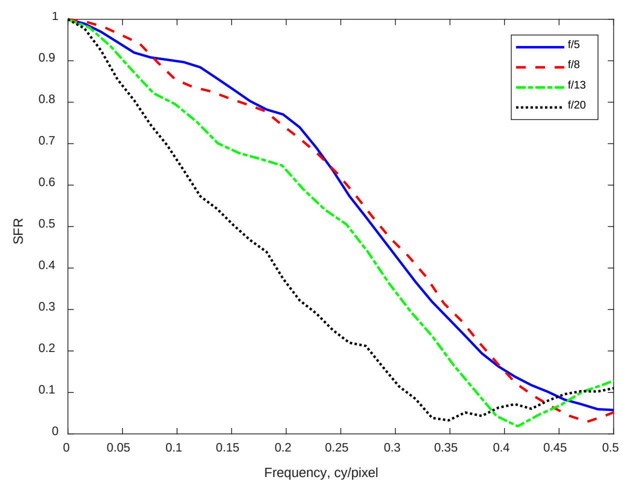

Figure 5: Best focus for several lens F/#

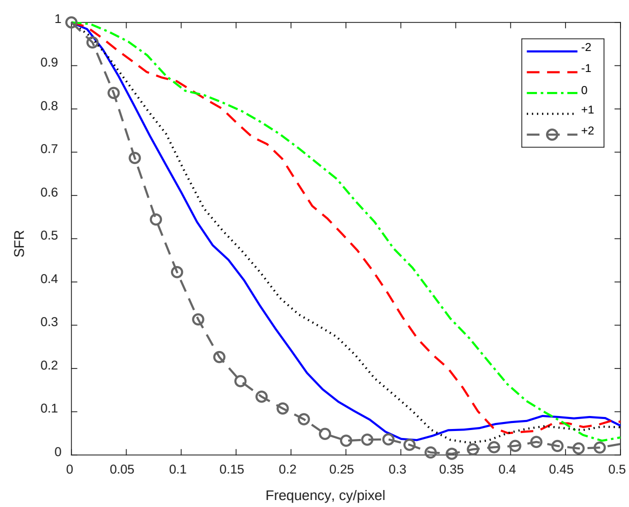

Figure 6: *SFRs for near and far distance from best focus*

For better visualization of these results we include Fig.7. It presents the same data as Fig. 6 but as a contour plot of equal SFR values. Usually the 0.10 value is considered appropriate for defining limiting resolution. Using the peak 0.10 value (0.43 *cy/pixel*) as best focus point, and an 80% DOF criterion (consistent with FADGI 3-star performance)

$$0.80 \text{ x } 0.43 \text{ cy/pixel} = 0.34 \; cy/pixel$$

shown with the vertical line. The associated near and far distances (horizontal lines) are at approximately -2.5 and 1.75 target positions respectively, or a total of 4.25 inches. Depending on the angles shown in Fig. 3 one can then associate this relative target distance with scene or object depth units.

For example, if the boresight path show in Fig. 3 was at 30°, each ½ inch (1.2 cm) target unit would be equivalent to

$$0.50 \; cos(30°) = 0.43 \; inch \; (0.5 \; cm)$$

This in turn would be a total DOF of

$$0.43 \text{ x } 4.25 \; inch = 1.84 \; inch \; (4.7 \; cm)$$

For the F-number used, that would be the total DOF for that lens to object distance used. Longer object distances would have larger DOFs and shorter distances smaller DOF's. With reference to Fig. 7 it is interesting to note that using a SFR blur criteria of 0.30 instead of 0.10 for the peak contour reference, the DOF would be very nearly the same.

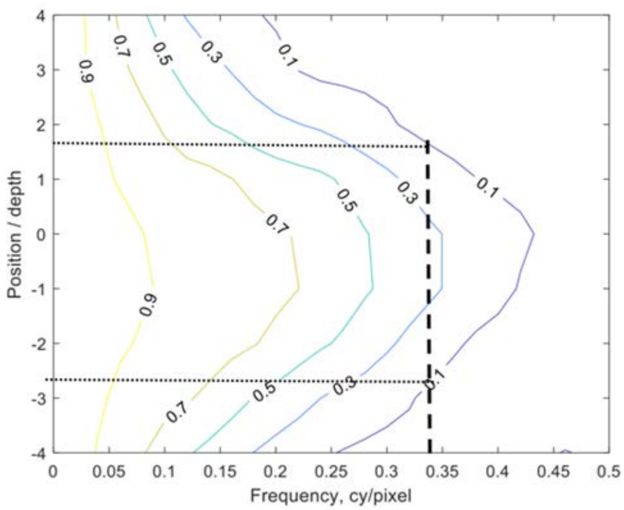

Figure 7: *Iso-SFR contours for F/5 aperture lens setting*

Summary and Conclusions

We have demonstrated how DOF could be objectively established for field and studio use. With a few entries into a software application one could easily calculate the DOF based on well-established and standardized SFR calculations. The ambiguity around CoC can be largely eliminated by using an imaging systems Point Spread Function (i.e., blur) transformation into an objective SFR metric.

While we have concentrated on a basketball-sized (24 cm. diameter) object, one could extend the thinking here to other sizes and modalities, particularly for multiple 3D captures when creating point clouds. Also, shown below (Fig. 8) is an example of a more simplified SFR edge. Rather than individual piecewise slanted edge targets we see a continuous feature. Using this target as shown, we only evaluate the SFR in the horizontal direction (across the vertical edge), but it can be rotated for a vertical SFR.

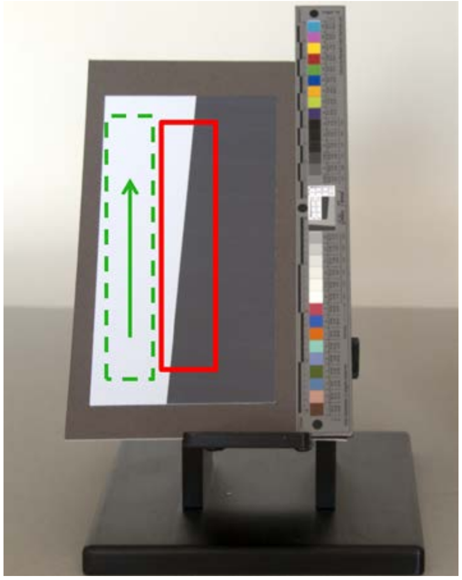

Figure 8: *Example image capture setup with simple test chart, from Ref. 7.*

Acknowledgements

We would like to thank Jon Blundell and Vince Rossi of Smithsonian's Digital Program Office (DPO) for motivating this study as it applies to their 3-D image capture efforts. They provided an opportunity for us to concentrate on a particular application in the broader field of cultural heritage imaging.

References

[1] ISO 12233:2014, Photography -- Electronic still picture imaging -- Resolution and spatial frequency responses, ISO, 2014.

[2] P. D. Burns and D. Williams, Sampling Efficiency in Digital Camera Performance Standards, Proc SPIE 6808, 680805, 2008.

[3] FADGI Still Image Working Group, ed. T Rieger,, US Library of Congress, 2016 http://www.digitizationguidelines.gov/

[4] H. van Dormolen, Metamorfoze Preservation Imaging Guidelines, National Library of the Netherlands (KB), 2012. http://www.metamorfoze.nl/english/digitizatiion

[5] Wikipedia page, Derivation of the DOF Formulae, https://en.wikipedia.org/wiki/Depth_of_field#Derivation_of_the_DOF_Formulae

[6] Wikipedia page, Circle of Confusion, https://en.wikipedia.org/wiki/Circle_of_conf

[7] P. D. Burns and D. Williams, Evaluation of 3D-Projection Image Capture, Proc. Archiving Conf., IS&T, 70-73, 2015.

Author Biographies

Peter Burns is a consultant supporting digital imaging system and service development, and related intellectual property efforts. Previously he worked for Carestream Health, Eastman Kodak and Xerox Corp. He is a frequent conference speaker, and teaches courses on these subjects.

Don Williams is founder of Image Science Associates, a digital imaging consulting and software group. Their work focuses on quantitative performance metrics for digital capture imaging devices, and imaging fidelity issues for the cultural heritage community. He has taught short courses for many years and contributes to several imaging standards activities.

Appendix

The calculations for determining the depth distance for any arbitrary look-angle of the camera is described. Once an image of the SFR targets on the DOF fixture (Fig.9 and Fig. 4) is captured, distances *b* and *c* are determined by noting the aligned distance marks on the SFR target plate and back supporting plate. Angle *A* is adjustable by inserting the bottom of the SFR target plate into precut detents on the bottom plate. These detents are marked with their corresponding angle *A*.

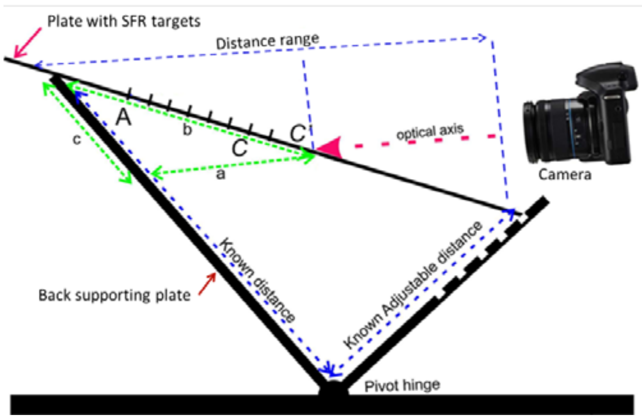

***Figure 9**: Illustration of DOF fixture with SFR plate*

Knowing angle *A*, and distances *b* and *c*, distance *a* can be calculated using the cosine law,

$$a = \sqrt{c^2 + b^2 - 2cbcosA} \quad (1)$$

With the sine law we can then calculate angle *C'* as follows,

$$C' = 90° - arcsin(\frac{c\ sinA}{a}) \quad (2)$$

Using C' one can then calculate the camera-to-target distance for any SFR-target feature over the range of scene depth (distance from the camera). For a given target the SFR can be computed. This can be done for several targets (distances). For this demonstration the distance between each SFR target feature along the plate dimension was 0.5 inches (1.27 cm).

Each distance value would be associated with an SFR target feature and therefore a measured SFR. Total DOF would be calculated by subtracting the near and far depth-values that just exceeded an established SFR blur criterion.