Digital Camera Obscuras

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Abstract

A camera obscura is a darkened chamber in which an image of the scene outside the chamber is projected by a pinhole or other optic onto a screen within the chamber. Early obscuras used pinhole optics, but by the 16^{th} *century obscuras with lenses became popular as aids for drawing or painting scenes with the correct perspective. By the late* 19^{th} *century, the screen had largely been replaced with photo-sensitive materials, and film cameras replaced obscuras. Over the last few decades, digital cameras using electronic sensors have replaced those using film. However, large projections can have significantly different properties from small projections, and it is very difficult to build a large digital image sensor. Thus, there is interest in using a small-sensor digital camera to photograph the large screen of a obscura. For example, it is relatively easy to obtain much shallower depth of field using a large screen, but a small sensor photographing the screen essentially copies that depth of field, so obscuras have often been used as "bokeh adapters" for small-sensor digital cameras.*

The current work is an experimentally-grounded exploration of the issues that arise in construction of digital camera obscuras, their use, and exposure control and post-processing of digital images captured using a small sensor to photograph the image projected on an obscura's screen.

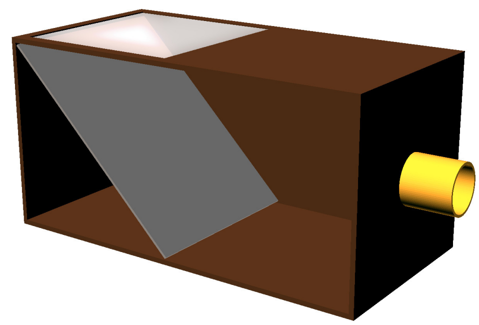

Figure 1. *Camera obscura with 45° mirror and tracing screen on top*

Figure 2. *Faboky* 4×5 *lens BSI digital camera obscura with grip*

Introduction

Long before there were digital sensors or photochemical emulsions, there was the **camera obscura**: a device that projects an image of a brightly lit scene onto a surface from which it may be viewed or copied.

It is likely that camera obscuras were a prehistory discovery rather than an invention. Any darkened interior of a shelter with a small hole to the daylit outside would function as a camera obscura with a pinhole lens projecting an image on an interior surface. A technical explanation of how the rays passing through a pinhole result in an inverted image appears in the writings attributed to Mozi as early as approximately 400 BC. Later works of Euclid, Ibn al-Haytham, and many others continued to evolve understanding of the relevant optical principles, eventually improving image brightness by using a larger aperture with a lens. The term **camera obscura** is generally credited to Johannes Kepler's *Ad Vitellionem Paralipomena* published in 1604.

What is the purpose of a camera obscura? The images produced by early obscuras often were assigned religious significance. Aristotle arguably used a simple obscura to observe solar eclipses and Ibn al-Haytham described this use in detail, a use that survives today. However, the most common modern use of camera obscuras has been to aid in producing permanent pictures. Prehistoric cave paintings have features that suggest they might have been manually copied from a projected image. Since the 16^{th} century, the concept of tracing the projected image to make a permanent picture that faithfully reproduces the scene with correct perspective became increasingly popular, and various innovations aided this type of use.

If the side of the screen that is viewed is considered the front, then we would say that a conventional obscura uses **FSI** (**front side illumination**) because the lens is on the same side of the screen as the viewer. This makes tracing awkward because the artist can cast a shadow on the image, and also tends to require a larger darkened chamber, hindering portability. Thus, using a translucent screen to allow **BSI** (**back side illumination**) was a significant innovation. Another innovation, shown in Figure 1, was the use of a mirror angled to 45° so that the projected image appears upright, although it is still left-right reversed. Fancier mirror systems, such as those in single-lens reflex camera viewfinders, can correct both the top/bottom and left/right orientation. Of course, the biggest innovations were over the last two centuries: replacing the manual tracing of a camera obscura with projecting onto a light-sensitive material, such as film or a sensor, to give us the modern concept of a **camera**.

In this paper, we define a **digital camera obscura** (**DCO**), such as the one shown in Figure 2, as a compound image capture system in which a digital camera is used to photograph the image created by a camera obscura. It would initially seem that such a system is adding unnecessary complexity, but there are potentially important advantages.

In terms of **depth of field** (**DoF**), the range of scene distances that appear simultaneously in acceptable focus, DCOs can behave like larger-format digital cameras, delivering much shallower DoF. In fact, devices for photographing an obscura image have often been referred to as **depth-of-field adapters** or **bokeh adapters**. The relatively small formats used in amateur movie cameras led to a number of DoF adapters accepting lenses originally designed for 36×24mm still cameras using 135 film, the format widely known as **full frame** (**FF**); one example is the Redrock Micro M3[1]. These cinema DoF adapters were followed by simpler DoF adapters for cell phones to also use FF lenses[2][3]. While FF was large for a movie format, 4×5 inch and larger formats were common for film still cameras and that "look" is desired, but digital still camera sensors much larger than FF remain too expensive to manufacture for a mass market. For example, the monochrome LargeSense LS45[4] digital back is 140×120mm and costs $26,000. Beside use of a large-format DoF adapter, the other feasible alternative is a scanning large-format camera[5][6][7], which can cost-effectively simulate a large sensor. Unfortunately, scanning capture time is slow enough to severely limit the types of scenes that can be photographed and make hand-held photography impractical.

Ironically, use of a larger format DCO also helps if the goal is the infinite DoF that can be achieved using a pinhole. Other potential benefits of large-format DCOs include increased total resolution and better handling of very high dynamic range scenes.

The work reported in this paper is highly experimental, largely based on experiences with creation and use of over a dozen separate 3D-printed prototype DCOs with a multitude of modular components. The following section overviews issues of lens choice for an obscura. Details of DCO system design, construction, and performance are significantly different for BSI and FSI obscuras, thus, these are respectively discussed in the next two sections. The digital camera exposure and post-processing issues for both BSI and FSI DCOs are similar, thus they are discussed in single section. The paper ends with a summary of results and conclusions.

Obscura Lenses

There are two main reasons to build a DCO: either to obtain a shallower DoF with a wide view angle or to obtain higher resolution with everything in focus.

Everything In Focus With A Pinhole

Rendering with essentially infinite DoF is accomplished using the simplest type of lens: a pinhole. The author's first two 3D-printed DCOs were BSI pinhole obscuras he created in 2016 to use Canon PowerShot ELPH115IS digital cameras; the second one is shown in Figure 3 and the complete design is freely available as Thingiverse Thing 1515060[8].

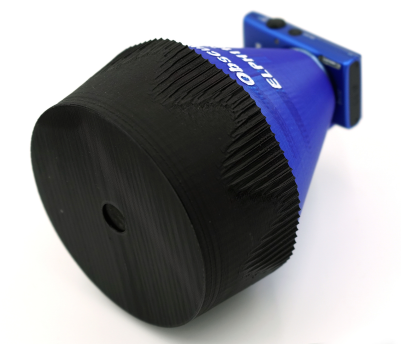

Figure 3. *Obscura ELPH115IS pinhole BSI DCO*

Figure 4. *Faboky zoomable pinhole BSI DCO*

The focal length of a pinhole lens is determined by the distance between the pinhole and the image plane, so by changing that distance, every pinhole essentially becomes a zoom lens. This zooming capability is leveraged in the Faboky pinhole DCO shown in Figure 4.

Pinholes also have the advantage that they have perfectly rectilinear projections even at very short focal lengths whereas most wide-angle lenses have at least a percent or two of distortion, usually barrel distortion bending straight lines outward. However, the disadvantages of using pinholes are significant. Pinhole resolution is limited. To obtain the sharpest possible image, the diameter of the pinhole should be:

$$diameter = constant \times \sqrt{(focal\_length \times wavelength)} \quad (1)$$

There is some debate over the ideal *constant* value, but $\sqrt{2.44} = 1.56$ is the value computed based on Fraunhofer diffraction. Typically, the *wavelength* is assumed to be 0.00055mm (yellow-green). Thus, the formula can be simplified to:

$$diameter = 0.0366 \times \sqrt{(focal\_length)} \quad (2)$$

Note that resolution in line pairs per mm on the image plane is independent of the image format. Thus, a larger image must be captured to obtain higher total resolution.

Pinhole images are very dim. Typical pinhole apertures are well past $f/45$, making long exposures necessary even in bright daylight. In addition, brightness naturally falls off in proportion to $cos^4\beta$ where β is the angle between the axis of the lens and the ray to the point in the image plane, so corners can become very dark. The dim pinhole image makes it critical that the obscura be very light tight. Most 3D-printed plastics are slightly translucent (especially in the near infrared, which might be invisible to humans but can be seen by digital camera sensors), so light-absorbing coatings such as Black 3.0[9] may be needed.

Shallow DoF Lens Options

The other DCO lens option is to use a larger-format lens. Even relatively slow large-format lenses can have highly desirable rendering properties (most of the example images given by LargeSense[4] were shot with slow lenses), but rendering with a very shallow DoF requires a relatively fast lens. The confusing thing about DoF equivalence across image formats is that, if the same lens is used at the same aperture, a smaller format is essentially cropping and thus arguably magnifying the defocus. However, if we keep the field of view the same, larger formats require longer focal lengths and thus give shallower DoF at the same f/number. The **crop factor** in moving from one image format to another is simply the ratio of the diagonals (i.e., diameters of the covering image circles), and the f/number of a lens is the ratio between the $diameter$ of the lens aperture and the $focal\_length$. Thus, if the ratio of image diagonals is r, the larger diagonal image will need a lens with $r\times$ longer focal length, and the f/number can thus be $r\times$ larger to produce the same DoF.

Although there are now multiple FF lenses providing very shallow DoF with apertures as fast as f/0.9, using a larger format allows a simpler lens formula to obtain an equivalent field of view with a much narrower DoF. It is worth noting that an alternative method for computing the f/number, N, of a lens is $N = 1/(2 \times sin(\theta))$ where θ is the opening angle for focused light rays, and this would suggest that constructing a lens with a real aperture faster than f/0.5 is impossible. That formula is an approximation making several assumptions, so faster may be theoretically possible, but only a few commercially produced lenses have been as fast as f/0.7.

In contrast, 4×5 film provides an image area of about 120×95mm or about $13.2\times$ larger area than FF with a 153mm diagonal instead of 43.3mm – so FF is a $3.54\times$ crop of 4×5. For example, a 135mm f/1.7 lens on a 4×5 camera gives the same field of view and DoF as a 38mm f/0.5 lens would deliver on a FF sensor, and even a rather ordinary 135mm f/4.5 lens would give the DoF of a 38mm f/1.3.

Although the market for new large-format lenses is fairly small, such lenses were common for over a century, and many are available used at very modest prices. For example, a typical 135mm f/4.5 lens for 4×5 format is usually under \$100 mounted in a shutter. The same lens intended for an enlarger and thus sold without a shutter is often under \$30 – and an obscura does not need a shutter. There are also ultra-fast large-format lenses made for various special purposes such as photographing CRTs, overhead/episcope projection, and aerial photography. For example, in 2020, the author purchased a set of three large-format Logetar 135mm f/2.2 lenses for less than \$23 including shipping. It is one of these lenses that is shown on Faboky in Figure 2, resulting in a view equivalent to a 32mm f/0.53 lens on a FF camera.

Figure 5. *CHEM BSI DCO equivalent to 46mm f/0.9 FF*

Figure 6. *3-element Fresnel Faboky DCO equivalent to 23mm f/0.13 FF*

Using Excess Coverage

Of course, any lens covering a format larger than your digital camera's sensor provides some benefit in an obscura, so medium-format lenses can still improve upon what a FF camera would normally capture and FF lenses can improve upon smaller formats such as those used in cell phones and compact cameras. However, most lenses can cover a significantly larger image circle than the diagonal of the sensor they were designed for, although image quality may be seriously degraded beyond the specified image circle. For example, most 4×5 lenses can actually cover a circle with a somewhat larger diameter than the 153mm diagonal of 4×5 film; some can cover much more, and were designed that way to allow tilt and shift movements. The popularity of 135 film has meant that the majority of old manual lenses available are intended for use with FF cameras, but the 44×33mm sensor format now commonly being marketed as "medium format" actually has a diagonal of just 55mm, which many FF lenses are able to cover. Arguably, the 44×33mm format is not really medium format, but variable-aspect-ratio 135, allowing cropping to any aspect ratio within the 43.3mm diameter circle needed to cover standard 3:2 FF, from 43.3mm wide to a 1:1 square with 30.6mm sides. Figure 5 shows the author's CHEM DCO, which has a 44×33mm screen and takes advantage of the extra coverage of FF lenses. In this case, the lens mounted is a FF Minolta Rokkor 58mm f/1.2 producing the same field of view and DoF a 46mm f/0.9 lens would provide to a FF sensor.

Figure 7. Image captured using 23mm $f/0.13$ Fresnel Faboky DCO

Using Fresnel and Other Simple Lenses

Because the line-pairs-per-mm resolution requirements on obscura lenses are easily met, it is even viable to use simple optics like Fresnel lenses. A typical \$2 10.25×7 inch PVC Fresnel lens sold as a sheet magnifier is essentially a 0.5mm thick plano-convex element with a focal length of approximately 290mm. Trimming it to a 177.8mm diameter circle results in an $f/1.63$ single-element lens. Stacking multiple Fresnel elements allows building a very poorly corrected lens of correspondingly shorter focal length and lower f/number. In fact, using one to three Fresnel elements, one of the Faboky DCOs becomes the equivalent of, respectively, a FF 70mm $f/0.4$, 35mm $f/0.19$, or 23mm $f/0.13$ lens – as shown in Figure 6.

The image quality of this 23mm $f/0.13$ equivalent lens, as shown in Figure 7, is very poor – much worse than single or double element Fresnels. It also appears to have much more DoF than one would expect due to abberations smearing the focus over a range of depths. However, this DCO has a much smaller FF-equivalent f/number than the possibly fastest FF lens ever built: the Carl Zeiss Super-Q-Gigantar[10] which was built as a non-functional publicity stunt and labeled as 40mm $f/0.33$.

Other Lens Issues

Rather than depending entirely on the inherent rendering characteristics of a lens, it is possible to use an apodizing filter to shape the **out-of-focus point spread function** (**OOF PSF**)[11] or a center filter to darken the center of the image to match the brightness of the corners. Some of the apodizers constructed for the DCOs are shown in Figure 8; the inverse apodizer, if positioned differently, can instead serve as a center filter. The first two types were laser printed on transparency material, the third was 3D printed. Apodizers generally are used to soften the bokeh, but for a DCO (especially one using a Fresnel lens) it can be more desirable to emphasize the edges of the huge OOF PSF, so inverse apodization was expected to be preferable. In practice, the additional optical defects introduced by these imperfect filters generally made their use undesirable.

A lens feature commonly found in large-format cameras is the ability to tilt the lens for Scheimpflug rotation of the plane of focus[12] and/or a shift mechanism for perspective correction. Most obscura designs presented in the current work do not implement these features, but easily could by relatively simple modifications to the lens mounts. Both tilt and shift require that the lens have some additional coverage, so using some coverage to avoid vignetting with tilt and shift effectively would be reducing the coverage available for making the DoF shallower.

It is important to note that in a DCO, no matter what lens is on the obscura, the sensor size and lens of the digital camera photographing the projected image is irrelevant. A compact camera or cell phone with a tiny sensor and lens still copies the effective scene DoF and most other attributes of the projected image.

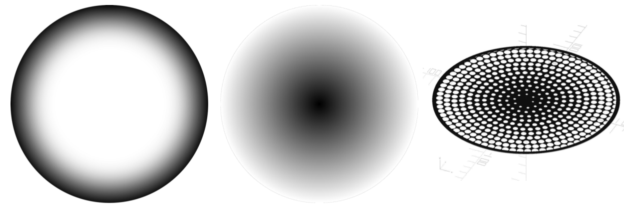

Figure 8. Apodizer, inverse apodizer, and spiral inverse apodizer

Figure 9. 4x5ob, an obscura back for a Burke & James 4×5 camera

Back Side Illuminated (BSI) Obscuras

Although early camera obscuras were nearly all FSI, DoF adapters and DCOs are predominantly BSI: with the obscura lens on the opposite side of the rear-projection screen from the camera. This is because BSI is more convenient to use than FSI.

BSI DCO Prototypes

The author's first two 3D-printed DCOs use pinholes. They were created in 2016[8] and use BSI as seen in Figure 3. Most of the DCOs created over the past year specifically for the research reported in this paper also use BSI.

Least interesting of the new BSI DCOs is **4x5ob**, shown in Figure 9 mounted on a Burke & James 4×5 Press View camera with a Wollensak 101mm $f/4.5$ lens to produce the FF equivalent view of 29mm $f/1.3$. It might seem that making a DCO back compatible with existing 4×5 cameras would be a compelling approach, but the resulting form is awkward to handle and heavy. Without lens and back, the Burke & James camera body shown weighs more than 2000g. Even borrowing the concept of a bel-

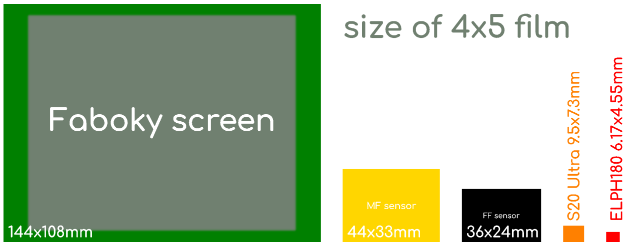

Figure 10. *FF (black) is a* $4.16\times$ *crop of BSI DCO Faboky screen (green)*

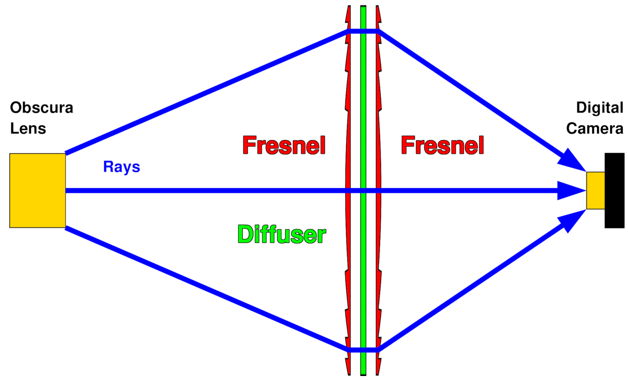

Figure 11. *BSI DCO with Fresnel screen sandwich (not to scale)*

lows proved unwise. Several attempts using soft PLA or TPU to 3D print a bellows for a lighter 3D-printed body failed and any bellows also would require an additional support structure.

The BSI DCOs in Figures 2, 4, and 6 are all versions of **Faboky** (pronounced fah-bow-key). A typical complete configuration of Faboky weighs under 1000g – which is less than half the weight of a Nikon 58mm f/0.95 Noct FF lens alone! Faboky originally was intended to showcase the concept of using a Fresnel magnifier as an ultra-fast large-format lens (as shown in Figure 6), so it originally stood for **Fresnel Apodized Bokeh Obscura from KentuckY**. However, given the pinhole (Figure 4) and conventional large-format lens (Figure 2) versions, perhaps **Flexibly Adaptable Bokeh Obscura from KentuckY** would be a better definition? The ideas behind Faboky grew out of discussions in DPReview's Adapted Lens Talk forum, and the construction details for the open source Faboky are given in an Instructable[13].

Most parts are interchangeable between different versions of Faboky, although the lengths of the main body and focusing thread need to be adjusted to suit the lens being used on the obscura. The threading is particularly significant because it is self-supporting and allows focusing of conventional and Fresnel lenses, or zooming of a pinhole lens, while keeping a light-tight seal. The body diameter was designed to allow the Fresnel lens to be the full width of the Fresnel sheet, yet be small enough to be printable on a typical consumer-level 3D printer; most of the Faboky parts were printed on a $180 Anycubic printer. This size constraint also determined the maximum possible screen diagonal, which was set at 180mm. Since most compact cameras use 4:3 aspect ratio sensors, the screen dimensions were set as 144×108mm, which is somewhat larger than the standard 4×5 inch format, as shown in Figure 10.

The most recent prototype created for this research is also a BSI DCO: **CHEM**, shown in Figure 5, which stands for **Canon Hack Emulating Medium format**. It uses entirely 3D printed parts to mount any FF lens adaptable to Sony E mount to project an image on a 44×33mm "medium format" screen. The projected image is captured using a Canon PowerShot ELPH180 or similar camera capable of being reprogrammed using the **Canon Hack Development Kit** (**CHDK**)[14]. CHEM's full design is freely available as Printables 390482[15], and it is by far the easiest of these BSI DCOs for others to replicate.

BSI DCO Screen Issues

The most challenging aspect of BSI DCO design is selection of an appropriate screen for rear projection. There are many potential screen materials, but none is ideal.

A very transparent screen material, such as ground glass, suffers a variety of problems. Such a screen might be very bright, but does not necessarily form a focus plane for the image; this should not be surprising given that a clear optical flat of glass inserted in an optical path certainly does not behave like a focus plane. The result is that the obscura lens largely behaves like an additional element for the digital camera's lens, and DoF and other properties are not a good approximation to what a larger-format capture would record. Photographers trying to use manual-focus lenses with the optical viewfinders of autofocus film and digital **single-lens reflex** (**SLR**) cameras are familiar with this problem in that the bright, but highly transparent, viewfinder screens commonly used in such cameras make it exceedingly difficult to determine when the image is in focus.

Because the light source (lens exit pupil) can be seen through a somewhat transparent screen, there is often a strong **hot spot** in the image that is much brighter than the rest of the image. In effect, this is the partial superposition of the desired image and the image created by the obscura lens acting as an additional element of the digital camera's lens. The screen needs to be dense enough to block this direct view.

A **rear telecentric** or **image-space telecentric** lens is a lens that has its exit pupil appear infinitely distant, and thus projects light onto the image plane such that the chief rays are all parallel to the optical axis and perpendicular to the image plane. However, most lenses do not have this property. Thus, when a ray from the obscura lens hits the screen, it typically hits at a spatially-varying angle tilting outward. The portion of that ray which is not perfectly diffused will continue to pass through the screen at approximately the same angle. Off-axis rays that pass through generally are not aimed at the digital camera's lens, and thus there is increasing brightness falloff at greater distances off axis in the image. This problem can be partially corrected using lenses: one lens can correct the ray angles to be closer to parallel to the optical axis going into the screen and a second lens could be used to direct the rays exiting the screen so they all point at the digital camera's lens. It is particularly common to see Fresnel lenses used for this purpose. Figure 11 shows how a diffuser (shown in green) that scatters light only a little can be made into a more efficient screen by sandwiching it between two Fresnel lenses (shown in red) of focal lengths selected to align the rays from the obscura lens to pass through the diffuser parallel to the optical axis and then aim the rays toward the digital camera's lens. For example, Perkiscope[16] uses a pair of Fresnel lenses on either side of a diffuser to implement the screen for giant BSI DCO equivalent to a FF 35mm $f/0.3$. This type of screen arrangement is relatively bright and can have good resolution due to low scattering, but often shows artifacting from the Fresnel lenses. There is also the issue that the selection of Fresnel lens focal lengths cheaply available is very limited.

It would seem that a perfect diffuser should make an ideal BSI obscura screen resulting in a relatively evenly lit image, but there are problems with highly-scattering diffusers too. The screen image will be dim. In part, the dimness is due to light scattering evenly in all directions, but more effective diffusers are also generally thicker and more opaque, which means a significant fraction of photons entering are simply absorbed. The scattering also can take paths within the screen material itself, reducing microcontrast and useful resolution of the obscura image.

Perhaps the worst issue with BSI DCO screens is texturing. Most readily available diffusers impose a fairly heavy texture on the rear-projected image. Even the highest-quality finely etched glass has a grain-like texture that is heavy enough to limit resolution of the images. Highly-scattering diffusers tend to have less texturing than low-scattering diffusers, but performance strongly depends on the particular screen being used. There are two main ways to reduce the visibility of such textures:

- A clever way to minimize the appearance of grain-like textures involves moving the screen material during the exposure interval to blur the grain-like pattern. The exact type of motion used can vary; Redrock's Micro M3[1] rotates the screen, but simple vibration can be used. The catch is that the motion must be quite rapid to blur the pattern without artifacting when using a reasonably fast shutter speed, and that becomes very difficult to manage. For example, rotating screens create precessional forces and vibrations can easily cause camera shake that blurs the captured image.
- Unlike film, which provides a new surface for each frame, a speck of dust on a digital sensor can be there for hundreds of exposures. Thus, many digital cameras and image post-processing software packages have support for learning the shading pattern caused by dust and automatically subtracting it from subsequent images. This mechanism, or something very similar to it, can be applied to remove the screen texture from captured images. In theory, this method should be very effective, but in practice even a tiny shift of the screen relative to the camera can make the exact position of texture features move significantly from frame to frame.

Empirical Properties of BSI DCO Screen Materials

Of the many thousands of potentially usable screen materials, several dozen have been tested for BSI DCO use. Representative results testing various BSI screens are shown in Figure 12. For comparison, the upper left image in that figure was created by directly photographing the test scene with a Canon PowerShot ELPH180; the image was cropped to approximate the same framing obtained using an SMC Takumar 50mm $f/1.4$ lens on the CHEM BSI DCO. The other images within that figure used various different screens in CHEM, and are discussed within a brief summary of properties found:

- **White film** (top middle and right images in Figure 12): There are various thin plastic sheet materials, mostly intended for high-quality inkjet printing. The particular material experimented with here is HP High-gloss White Film for Inkjet C3885A, which is 165 gsm 4.7 mil thick polyester, ISO brightness 90, and opacity 89%. We originally purchased this material for printing E-format posters, but long ago discovered that it made an excellent rear-projection screen and, for example, used it in research exhibit at various conferences in the early 2000s. A very heavy diffuser, this material produces even brightness without Fresnel lenses. Texture is also relatively mild. Unfortunately, the high opacity makes the image dim and the heavy scattering limits resolution. Despite the front and back sides of the film having very different surfaces (the front is shiny), it made little difference which side faced the digital camera in the BSI DCO.
- **Chemically etched or ground glass or plastic** (not shown): These materials are frequently used for SLR viewfinder screens and for commercial BSI obscura screens. Most are very light diffusers that produce both serious light falloff and a hot spot unless used in a Fresnel sandwich. Sharpness is fairly good, but is limited by the texture resembling heavy film grain. This texture is very difficult to remove by texture subtraction, but can be reduced by applying various noise reduction algorithms. There typically is also some extension of the DoF. The thickness of some of these materials is sufficient to cause additional artifacting, such as chromatic aberrations or even double images off axis.
- **Tracing paper** (not shown): Most tracing papers are light to moderate diffusers. Although they tend not to produce as serious light falloff and hot spots as ground glass, they tend to have a much coarser and heavier, somewhat splotchy, texture. The texture commonly will include fine fiber lines that make alignment of a texture reference image critical for removal by texture subtraction.
- **Vellum** (middle left image in Figure 12): Classically, vellum referred to animal skins or membranes, i.e., parchment. Modern vellum is instead commonly made of plant materials. Although much like tracing paper, the texture is often smoother and less splotchy with a slightly higher average opacity, thus somewhat easier to correct by texture subtraction.
- **Diffusers** (Roscolux #111, #117, and #102 images in Figure 12): Diffusers are available in a wide variety of structures. Thick glass or plastic diffusers tend to disperse a rear-projected image too much, but theatrical diffusion filters can be quite thin. Some have heavy textures, but Roscolux #116, Tough White Diffusion, provides a high degree of diffusion while keeping both opacity and texturing low. Small samples of this and alternative theatrical filters can be taken from the Roscolux Swatchbook, but it is available in 24"

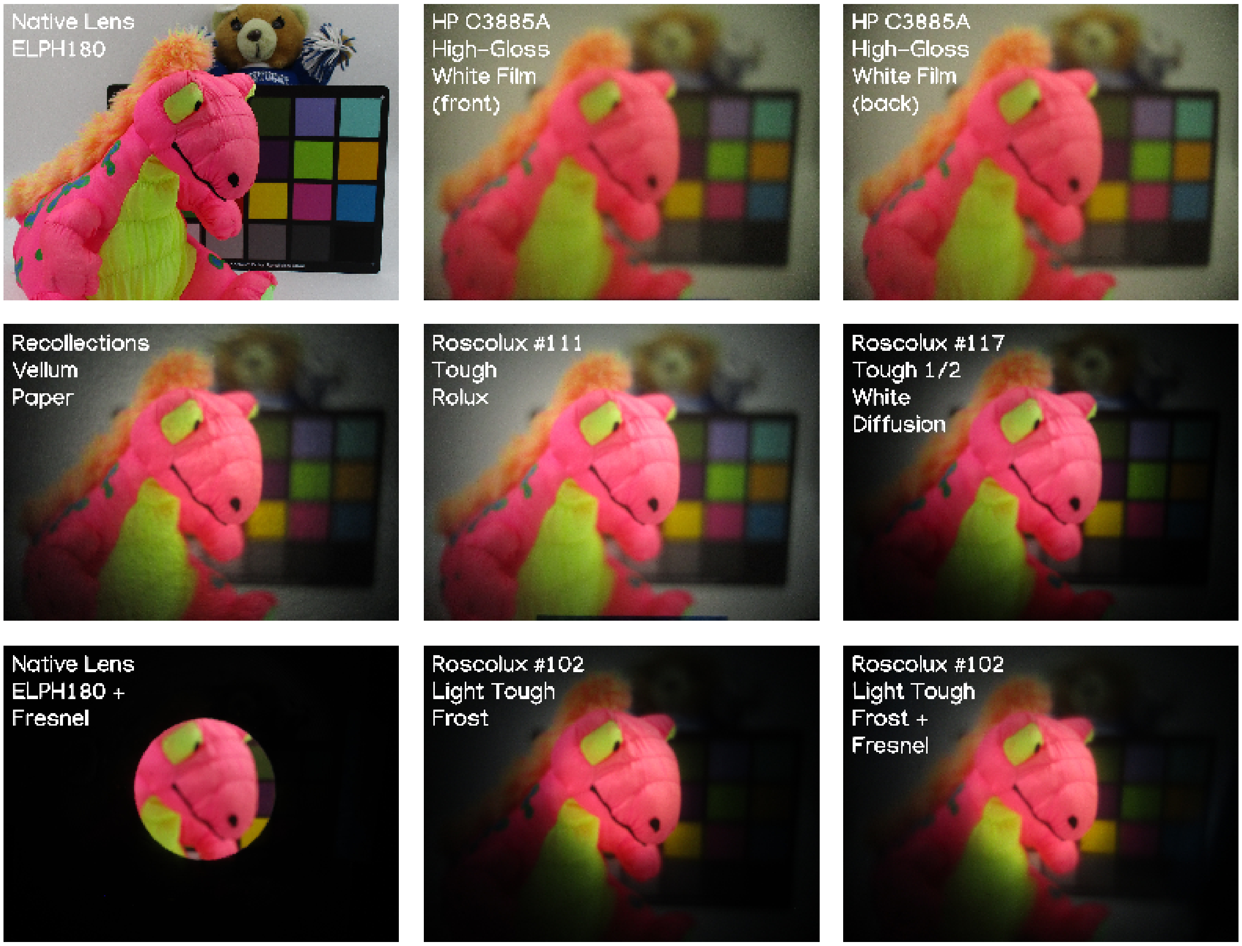

Figure 12. *Test scene BSI DCO images using various screens with ELPH180 on CHEM with SMC Takumar 50mm $f/1.4$*

wide sheets and rolls. Roscolux #111, Tough Rolux, arguably gave the best image quality trade-offs overall, while Roscolux #117 and #102 gave higher contrast and detail at the expense of increased vignetting.

The last row of images in Figure 12 shows the effect of using Fresnel lenses to reduce vignetting. The images show the Fresnel alone, Roscolux #102 screen alone, and the combination of Fresnel and #102 screen. Although the Fresnel lens used is not of the optimal focal length, it does visibly reduce vignetting, just not as dramatically as use of a slightly stronger diffuser (e.g., Roscolux #117) does. Using a heavier diffuser also seems to produce a slightly narrower DoF. Given that and the difficulty of locating Fresnels of the appropriate focal length, accepting a slightly stronger diffuser seems more practical.

Although white film gave the most even exposure of the materials tested, we suggest that vellum or a moderately heavy diffuser generally makes the best screen material for a BSI DCO.

BSI DCO Construction

The design of a BSI DCO housing is fairly straightforward: it is a pair of light-tight chambers with a screen between. However, there are a few details worth mentioning in creating a 3D-printable housing.

The obscura chamber must provide some mechanism for focusing the obscura lens. The most common large-format focusing mechanism involves combining a track on a rigid bed for support with a flexible bellows to provide the light seal, but for 3D printing, it is simpler to combine the support and focus mechanisms into a simple threaded cylinder. In Faboky, the main body is internally threaded and externally presents an Arca Swiss compatible tripod mount. The length of the main body cylinder is an important parameter because, without a more complex structure, the focusing range is limited to run from approximately the length of the tube to twice that length. For example, for a typical 4×5 format lens of approximately 135mm focal length, the rear focus distance at infinity measured from the lens mount is typically around 120mm, so the main body tube should not be longer than 120mm and the maximum rear focus would be close to 240mm.

It is easiest by far if the entire housing can fit within the build volume of a commodity 3D printer. Typical build volumes for resin-based 3D printers might fit all the parts for CHEM, but are are far too small to make parts for large-format obscuras like Faboky. Extrusion-based **Fused Deposition Modeling** (**FDM**)

Figure 13. Faboky mounts for compact cameras and cell phones

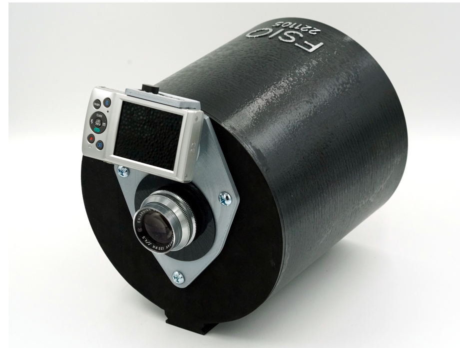

Figure 14. FSIO with Wollensak 135mm $f/4.5$

Figure 15. FSIO showing focus mechanism

printers typically have build volumes of at least an 8-inch cube: about 203mm on a side. In order to be able to make full use of the 7-inch width of the Fresnel magnifier sheets as lenses, Faboky provides a 180mm diameter (7.1 inch) clear internal path and can accommodate a screen diagonal of 190mm. Conveniently, this allows a 4:3 aspect ratio frame of 152×114mm, significantly larger than 4×5 but still able to be covered by most lenses designed for that format. Faboky's outer diameter is 192mm, with the Arca foot extending to 203mm; thus, it can fit on a circular bed of 203mm diameter or, rotated 45°, on a square bed 192×192. Of course, different length tubes can be made for lenses of very different focal lengths, and very long ones become problematic to fit on the bed of a commodity 3D printer, but most can fit a tube of at least 200mm height, which would allow varying rear focus from about 205mm to 390mm.

Given a specific digital camera, the darkened chamber between the digital camera and the screen does not need a focusing mechanism and can be of fixed length. This is because the camera should have focus fixed on the screen, with the captured image frame edges aligned with the edges of the screen. It is relatively easy to make this part of the BSI DCO interchangeable to use various different digital cameras. Two examples of this are shown in Figure 13, with interchangeable digital camera mounts for Faboky to use either a compact camera (Canon PowerShot ELPH180 shown) or a cell phone (Samsung S20 Ultra shown).

Front Side Illuminated (FSI) Obscuras

While BSI DCOs are more convenient both to use and to build, FSI DCOs offer a variety of significant advantages. They behave quite differently in a variety of ways.

The prototype built for testing FSI DCO properties in this research is the 3D-printed **FSIO**, the **Front Side Illuminated Obscura** shown in Figure 14. The main body of FSIO is similar to that of Faboky, but the closed end of the tube mounts both the obscura lens and the digital camera used to record the projected image. The screen in FSIO is on a plate with a threaded edge so focus can be changed by screwing the plate in or out. The circular screen diameter is the same as the diagonal for Faboky, so the Wollensak 135mm $f/4.5$ Enlarging Raptar lens mounted on it behaves as a 32mm $f/1.1$ would on a FF sensor. As seen in Figure 15, the back of the screen plate has a simple reinforcement strut pattern that also serves as a grip for focusing.

An FSI DCO relies on reflected light rather than transmitted light, so any internal structure of the screen will not impose a texture. Front-projection screens don't need to have light penetrate very deeply at all, thus defining a thin and precise focus plane, so scattering within the material can be very low and resolution of the projected image can be high. Unfortunately, some screen materials can show specular reflections, and those flaws cannot easily be corrected – thus glossy screen materials are generally unacceptable. A more subtle issue is that spectral properties of the screen material can alter colors; the SpectrumViz[17] tool presents measured reflection spectra for a large number of printing papers, and the surprisingly large differences between papers are immediately obvious.

Of course, the most awkward aspects of FSI DCO design involve placement of the digital camera. If the obscura lens, which typically has a large diameter, is centered in front of the screen, then the digital camera used to capture the projected images cannot be. There are four ways around this:

- Offset the digital camera and photograph the screen at an angle. This angle will cause perspective distortion similar to pointing a camera up at a tall building. The perspective easily can be corrected in post-processing, but at the cost of some resolution. This approach is used in both Lumigraphe[18] and our FSIO prototype.
- Offset the digital camera, but keep it parallel to the screen and use lens shift to photograph the screen without perspective distortion. Most compact digital cameras do not support lens shift, but Zev Hoover used an Irix shift lens on a

Figure 16. *DCO cameras: Canon PowerShots & Samsung S20 Ultra*

Sony a7s to create an 8×10 FSI DCO[19].

- Use a 45°-mounted semi-transparent half-silvered mirror to redirect the view to a place where the camera does not interfere with the obscura lens. The mirror would be used to allow the camera photographing the screen to be placed at a 90° angle to the obscura lens, which can be accomplished by having the projection from the obscura lens pass through the transparent side of the mirror and be reflected up to the camera by the other side of the mirror. However, an angled thick mirror can be expected to cause ghosting, and very thin mirrors are fragile and difficult to mount. There is also some light loss. It seems this is the only approach that would allow relatively small FSI DCOs to be constructed.
- Use a ring of tiny cameras placed parallel to the screen around the obscura lens. Provided the coverage of a tiny camera can extend over the obscura lens axis, such a ring can be arranged to ensure that stitching captures will cover the full projected image. The complexity of coordinating multiple tiny cameras makes this approach impractical.

Digital camera positioning for FSI DCOs is not merely awkward for construction, but also for use. The Canon PowerShot cameras used with FSIO have neither a rear LCD panel that can be flipped to face the photographer nor a video output that could drive a separate monitor.

Digital Camera Exposure and Processing

Although FF and larger cameras can be used in DCOs, smaller cameras allow a more portable and compact design – and compactness enables use of 3D printing for body components. In addition, the fact that FF cameras generally have interchangeable lenses actually complicates DCO design because different digital camera lens choices can require significantly different camera mounting structures.

The digital cameras used for this research are reasonably compact and have fixed lenses: the CHDK-compatible Canon PowerShot ELPH180, ELPH160, and ELPH115IS and Samsung S20 Ultra cell phone shown in Figure 16. Those PowerShot models are the cheapest available for their delivered image quality. Each had a new cost of around $100 and is widely available used, but low-end ELPH models have been discontinued as the compact camera market contracts, with the ELPH360HS the currently cheapest new option at around $300 (although it was introduced at $210 in 2016). Despite their low cost, the ELPH models are actually better suited than cell phones for still capture use in DCOs because they are smaller and more programmable, which is ironic in that without using CHDK these cameras do not even offer the most basic manual controls. Higher models, such as the $630 G7X Mark II, are also supported by CHDK and offer a larger CMOS sensor and a flip-up display that could be useful for FSI DCOs. Cell phones are far superior in video capabilities; non-"HS" PowerShot ELPH models use CCD sensors that are not capable of better than 720p video, while "HS" and higher models use CMOS sensors handling up to 1080p.

The most basic camera setting requirements for DCOs include:

- Once attached to a BSI DCO, the camera focus should be fixed on the screen. This requires close focusing and the ability to disable autofocus.
- The exposure settings must be sufficient to allow proper exposure of the projected image, which is rarely a problem with most obscura lenses and outdoor scenes, but pinhole projections can be extremely dim. Photographing a full daylight scene with a bright screen, the Faboky pinhole BSI DCO often required a 20 second exposure at ISO 800; the white film screen brought that time to several minutes. Flash also must be disabled.
- For best quality, the ISO should be set to the value that yields the largest possible dynamic range, because correcting vignetting and removing textures tends to reduce dynamic range. On Canon PowerShots, that is generally ISO 100; the number is even lower for most cell phones. Ideally, all captures should record raw image data rather than JPEGs to preserve as much as possible of the dynamic range.

Both CHDK Canon PowerShots and Android cell phones allow the above settings, although Android cell phones do not handle the darkness of pinhole images very well. Beyond basic settings, a sufficiently programmable camera can provide features making DCOs easier to use and more effective:

- A script automating the settings described above is easily implemented using CHDK Lua.
- Exposure bracketing or in-camera multi-shot **high dynamic range** (**HDR**) image capture, potentially with in-camera repair of vignetting and screen texture. Flexible bracketing is built-into CHDK, and CHDK Lua scripts easily (if not quickly) implement multi-shot HDR combining in camera – even with histogram-based automatic selection of the covering exposure set. In-camera repair of vignetting and subtraction of screen texture is feasible, but slow even if implemented as a compiled C module for CHDK.
- Correction of the orientation and/or FSI perspective distortion for the live view is possible, but can be difficult to accomplish without lag. Most cameras have support for tagging captured image files for automatic rotation on viewing, but the hardware-assisted live view stream exposed to CHDK programs does not have this feature. The dual-core 80MHz ARM cores in the ELPH cameras can implement the live view correction, but are not really fast enough to implement a high-quality live view without lag.

Figure 17. *Faboky with 135mm $f/2.2$ lens and cell phone*

Figure 18. *Image captured by the cell phone in Figure 17*

- Obscura focusing aids, such as **peaking** which highlights the contrast of in-focus scene edges in the live view and live view magnification are feasible using a compiled C module for CHDK.

A CHDK Lua script implementing much of the above for the Faboky BSI DCO is `faboky.lua`, documented and posted within the Faboky Instructable[13].

Results and Conclusions

Not surprisingly, across the DCOs constructed for this research work both image quality and ease of use varies significantly.

Figure 17 shows Faboky being used with an S20 Ultra cell phone to photograph the image projected by the 135mm $f/2.2$ lens mentioned earlier. The live view is rotated 180°, but is usable for composing photographs. This photo was captured using a FF camera with a 55mm $f/1.8$ lens with focus relatively close, producing strong background blur. However, the background defocus in the FF-equivalent 32mm $f/0.53$ image captured by the cell phone, shown in Figure 18, is far stronger despite focus being less close. The screen material used for this shot was the white film, which produced an image with even lighting and very little texture. Unfortunately, the image also is not very detailed. In part, this is due to the poor correction of the 135mm $f/2.2$ lens, which shows obvious halos from spherical aberration around the in-focus white elements of the scene.

The S20 Ultra's camera used for this capture has a 108MP sensor, but between the screen and fast lens, the useful resolution obtained here is closer to 1MP. Another example shot with

Figure 19. *ELPH180 capture with same obscura as Figure 17*

Figure 20. *Image captured using ELPH180 with pinhole Faboky*

the same obscura, but hand-held using a 20MP ELPH180, is Figure 19. Measurements of MTF50 screen resolution using MTFmapper[20] found that BSI screens rarely exceeded 4 line pairs per mm, whereas FSI screens were often 10 or better. Under ideal circumstances, Faboky's $144 \times 108mm$ BSI screen area might deliver up to 4-6MP of recoverable resolution, while same-size FSI screens in FSIO could approach native resolution of the ELPH180. The ELPH180's sensor was never a limiting factor in BSI DCO resolution.

Using a 0.4mm diameter pinhole Faboky with the same screen material and capturing a long exposure on an ELPH180 produced the ultrawide image shown in Figure 20. Although nothing is very sharp, sharpness from infinity to the wildcat's nose inches from the camera is essentially the same. Pinhole resolution appears to be limited by the BSI screen used.

In conclusion, the 3D-printed DCOs described here are very inexpensive, lightweight, and are practical even for hand-held use. BSI DCOs are easier to use than FSI DCOs, but resolution, vignetting, and texturing of captured images all tend to be poorer for BSI DCOs and depend critically on the choice of screen. The primary benefit in using a DCO thus lies in the artistic use of rendering characteristics like DoF equivalent to a near-impossible full-frame lens combining a wide view with very shallow depth of field, such as a 32mm $f/0.53$; such ultra-fast lenses are not particularly sharp, so the limited resolution is less of a concern.

Links to detailed plans and other materials for building and using the DCOs discussed in this paper are available at:

`http://aggregate.org/DIT/DCO/`

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