Front converter lenses for smart phones

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ABSTRACT

Front converters for the iPhone 6, from six different vendors, are examined in detail. Telephoto, wide angle, and fisheye converters are examined. System performance is measured, and the measured lens designs are presented. Great variety is found in both design type and performance; little correlation is found between performance and design type.

Keywords: Lens design, Photography

1. INTRODUCTION

Front converter lenses are afocal attachments to the object side of photographic lenses; they are used to modify the field of view of a prime lens. Historically, front converter lenses found wide acceptance because they economically added functionality to photographers' large investment in fixed focal length lenses.[1] Front converters also allowed a quick change in field of view without removing the lens or changing focus. Front converters have also been used as anamorphic attachments for cinematography. However, most functions of front converters were better achieved using zoom lenses, so front converters fell out of favor as the performance of zoom lenses improved.

In recent years, however, the wide adoption of smart phones that include high quality cameras has re-opened the market for front converter lenses. As with front converters from years ago, these new lens attachments add functionality to owners' large investment in smart phones, which generally have fixed focal length lenses. At least 10 firms offer front adapter lenses for smart phones, offering wide-angle, telephoto, macro, and fisheye attachments.

This paper will evaluate products for the iPhone 6 from six vendors: Zeiss ExoLens, Schneider iPro, olloclip, Moment, Imvio, and Manfrotto. The results are anonymized, presented as vendors A-F. Telephoto, wide angle, and fisheye lenses are evaluated. This evaluation consists of first measuring performance then disassembling to find the lenses design form. The converters represented a wide range in price, but this data is not presented because there it is impossible to get information on cost.

2. MEASURING PERFORMANCE

Quantitative evaluation of image quality is a field of its own[2], and is well beyond the scope of this paper. In this paper, only two measurements will be used for evaluations of image quality: 1) width of the edge spread function and 2) chromatic aberration. Width of the edge spread function is chosen over the more-typical MTF because several of the converters have image quality that is so poor that MTF calculations break down.

Image quality is measured using the SRFplus chart from Imatest.[3] This chart contains a 7x9 array of rotated squares, each providing four high-contrast slanted edges. Imatest software is used to find the slant edges and calculate a 4x oversampled edge spread function (ESF) for each slanted edge. From this ESF, Imatest is used to characterize the edge sharpness as the difference in pixels between 10-90% levels in the black & white ESF; similarly, chromatic aberration is characterized by the area in pixels between the red, green, and blue color planes' ESF. All of these calculations are based on the JPEG output from the camera.

This measurement technique makes no attempt to isolate optical performance from the camera system performance. The JPEG images that serve as the raw data include effects from image sharpening, noise reduction, demosaicing, distortion correction, digital correction of chromatic aberration, just to name a few of the advanced image processing techniques used to make photographs look pleasing. However, this practice is reasonable for three reasons. First, all converter lenses are evaluated in the same experimental setup, including illumination, chart, phone, and software. Second, all judgements are to be interpreted as relative, not absolute; in other words, the calculated edge

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spread function from the jpeg file might have little relation to the physical edge spread function formed by the lens, even though it seems related to the perceived image quality. Third, this kind of evaluation is similar to how the user experiences his lens.

Reducing comparisons of optical performance to comparisons of ESF and chromatic aberration is also fraught with difficulties. From images of the SFRplus chart, Imatest software readily evaluates other important measures of image quality such as distortion, vingetting, oversharpening, and noise. These factors are neglected in this analysis because they provided no differentiation among the lenses. For example, lenses with objectionable distortion also had objectionable ESF or chromatic aberration.

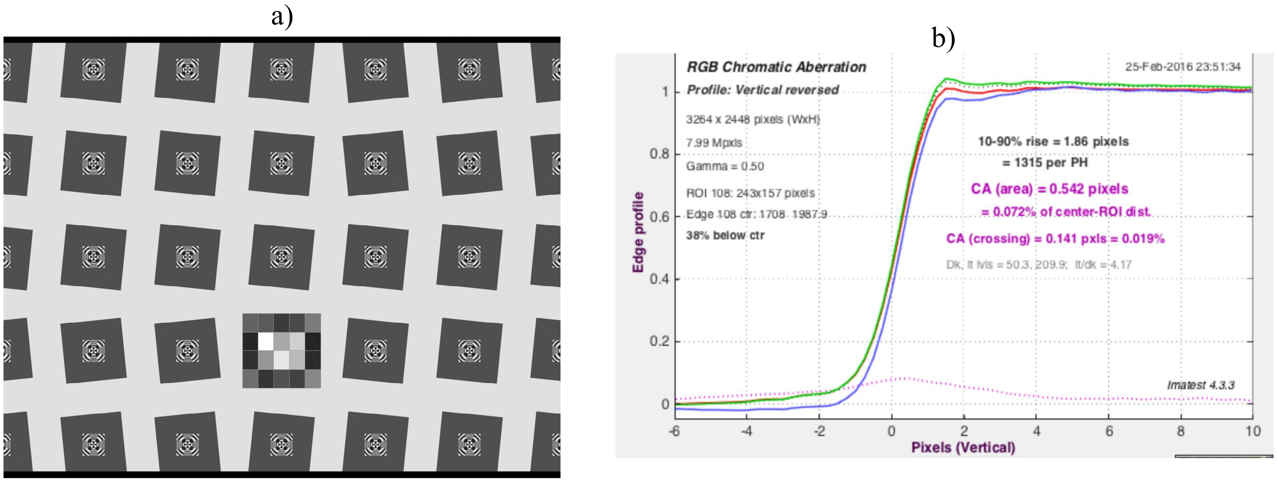

Figure 1: Basis for testing front converters on the iPhone 6. Figure 1a shows a sample of the SFRplus test chart, which contains dozens of slanted edges. Figure 1b shows the output from Imatest's calculation for the edge spread function of one of these slanted edges.

3. DISASSEMBLY AND MODELING

After measurement of the SFRplus chart, all lenses were disassembled to gain insight into design forms. Radii of lens elements were measured using an inexpensive spherometer. Thicknesses and spacings of lens elements were measured using an inexpensive drop gauge. Diameters of lens elements were measured using inexpensive calipers.

These values were entered into a lens design program with a glass selection option and a simple merit function, with glass choices constrained glass choices to well-behaved, relatively inexpensive glasses.

The resultant lens models are thought to provide insight to the design space. However, the resultant lens models are insufficient for fabrication. One important omission is aspheres. The simple measurement techniques used couldn't distinguish weak aspheres, yet the high-volume nature of these lenses suggests that aspheres are often used. Lenses were qualitatively inspected for aspheric departures, but only one surface had such obvious departure from sphere.

4. iPHONE ALONE

The measurements described in this paper were made throughout 2016. Each time a measurement was made with a front converter lens, a measurement was also made on the iPhone alone. A representative sample of these iPhone measurements is shown in Figure 2. The measured performance compares well to the iPhone's diffraction limit at f/2.2, which is about 1.2 pixels. Because all measurements were made with the same iPhone, variations in the measurements should correspond to the repeatability of the measurement technique. Similarly, the values of the measurements represent a performance floor for the iPhone with a front converter.

Ideally, modeling of the iPhone with front converters would also include a model for the iPhone lens. Unfortunately, no such model seems to be available although paraxial properties are published: efl = 4.18mm, f/2.2, image 1/2 diagonal = 3mm. Additional insight can be gleaned from patent literature, which contains a wide variety of prescriptions for lenses for smart phones. For example, U.S. Patent 8,934,179 has paraxial properties that match the paraxial properties of iPhone 5, has an application date that seems to align with a likely development time for the iPhone 5, and is assigned to a firm that is reported to be a supplier for the iPhone 5. A schematic of this lens is shown in Figure 3. This patent design shows many characteristics that are common for smartphone lenses. Most importantly, it contains many gross aspheres, prohibiting balancing of aberrations by a front converter. Also, aberrations are very well controlled; there are no meaningful aberrations to balance with a front converter. Finally, both the aperture stop and the principal planes are near the front of the lens. Therefore, all system modeling treats the iPhone as a paraxial lens.

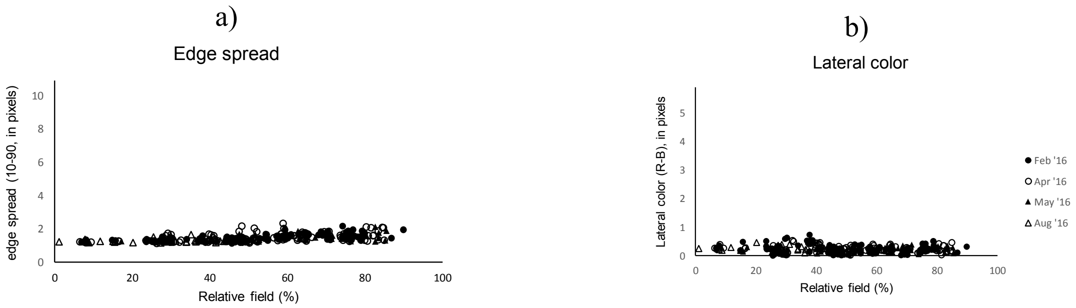

Figure 2: Measurement results for the iPhone 6 alone, showing the excellent imaging for the iPhone 6 camera. The measured width of the ESF compares will with the diffraction-limited ESF of about 1.2 pixels.

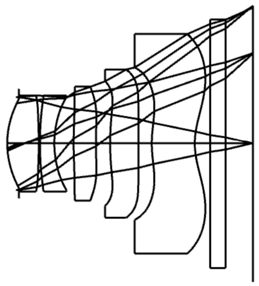

Figure 3: Schematic for U.S. Patent 8,934,179, a design for smart phones that matches the paraxial values for the iPhone 5.

5. TELEPHOTO CONVERTERS

Figure 4 shows measurements of the iPhone 6 with telephoto front converters. All measured converters were nominally 2X. Four of the five converters show meaningful degradation in ESF with field. This degradation is fairly quadratic, with little spread across the field; this behavior suggests that field curvature limits performance.

A useful benchmark for the performance of these telephoto converters is a digital zoom. The performance of a digital zoom is about 2X the values of the plots shown in Figure 2; for simplicity, this benchmark is about a 3 pixel ESF and about 1 pixel chromatic aberration. Only one converter, from Vendor F, clearly exceeds this benchmark. The converter from Vendor E exceeds the benchmark to about 60% of the field. The offerings of from vendors C & D meet this benchmark only over 30% of the field.

Schematics of some of these converters are shown in Figure 5. The designs from Vendors C & E seem to be of the same design family. Figure 6 shows the Seidel term for field curvature, W220, is balanced similarly for these similar designs.

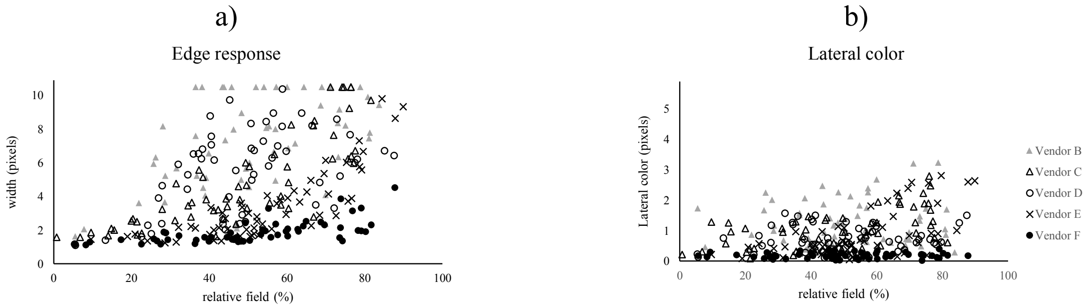

Figure 4: Measurements of telephoto front converters on the iPhone 6. Figure 4a shows the width of the edge spread function, defined at the 10 and 90% points; Figure 4b shows the chromatic aberration, defined as the integral between the red, green, and blue planes. Only the converter from Vendor F clearly exceeds the performance of the benchmark - a digital zoom of the iPhone data shown in Figure 2. Note that ESF values wider than 10 pixels are plotted as equal to 10 pixels,

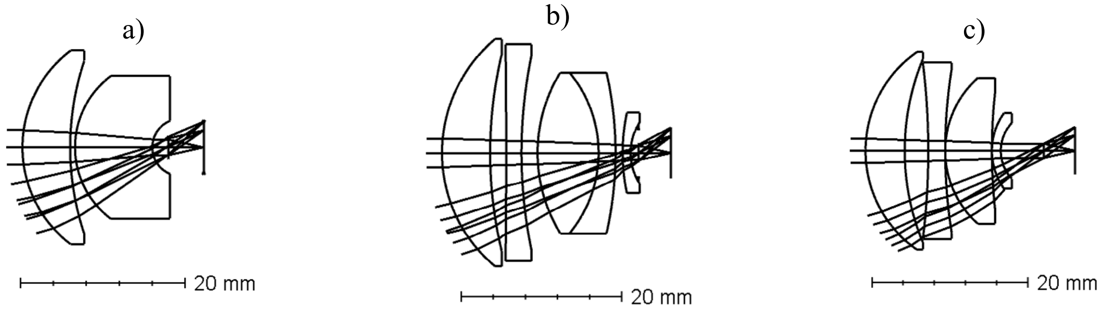

Figure 5: Schematics of the telephoto front converters. Figure 5a shows the schematic for Vendor B, . Figure 5b shows the schematic for Vendor C, Figure 5c shows the schematic for Vendor E, The lenses from vendors C & E seem to be from the same design family.

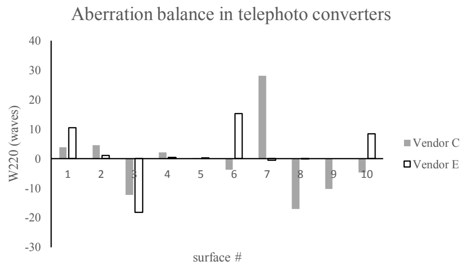

Figure 6: Aberration balancing in the telephoto front converters from vendors C & E. Field curvature is balanced similarly for these similar design forms.

6. WIDE ANGLE CONVERTERS

Figure 7 shows measurements of the iPhone 6 with wide front converters. The nominal magnification was between 0.5X and 0.6X. As with the telephoto converters, four of the five converters show meaningful degradation in ESF with field. Similarly, this degradation is fairly quadratic, with little spread across the field; this behavior suggests that field curvature limits performance.

A useful benchmark for the performance of these wide angle converters is a high-quality photographic system - Panasonic Lumix DMC G5 camera with a Panasonic Leica DG Summilux 25mm f/1.4 ASPH. Lens. This benchmark, digitally cropped on-camera to 8 megapixels to match the iPhone, shows similar degradation with field as the iPhone with the wide converters from vendors C, D, & E. The edge spread function increases quadratically with field, with little spread, indicating that field curvature is the dominant aberration. The converter from vendor A has meaningfully more degradation with field; the converter from vendor F has significantly less.

Schematics of some of these converters are shown in Figure 8. The wide variation in converter size is evident. The lens from Vendor C appears similar to the lens from Vendor E, but with a split front element; otherwise, little similarity in design types is evident. Figure 9 shows the Seidel terms for field curvature, W220, for the best-performing lenses; no pattern is evident. Note that the wide angle teleconverter from Vendor C shows good performance despite its Seidel sum; this mismatch is probably because this lens has an obvious asphere, whose effects aren't modeled here.

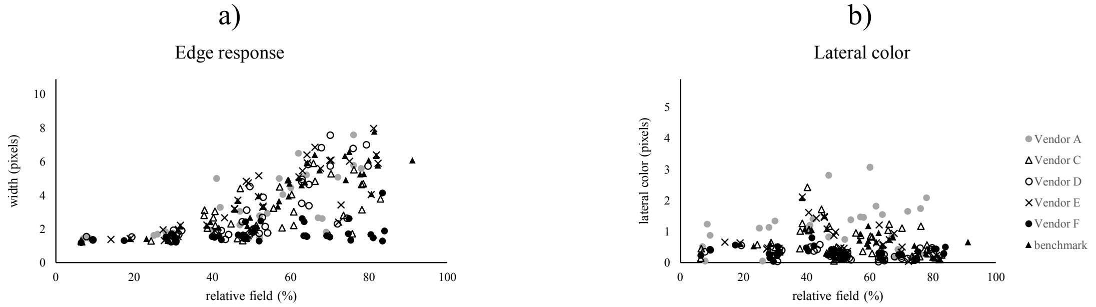

Figure 7: Measurements of wide front converters on the iPhone 6. Figure 7a shows the width of the edge spread function, defined at the 10 and 90% points; Figure 7b shows the chromatic aberration, defined as the integral between the red, green, and blue planes. With the exception of the lens from Vendor A, the lenses compare well to the benchmark, a high-quality dedicated photography system.

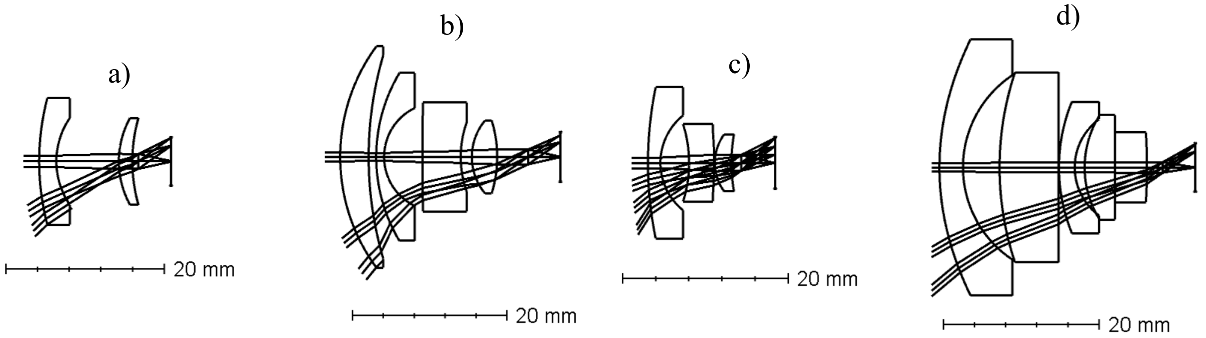

Figure 8: Schematics of the wide angle front converters. Figure 8a shows the schematic for Vendor A, . Figure 8b shows the schematic for Vendor C, Figure 8c shows the schematic for Vendor E, Figure 8d shows the schematic for Vendor F,

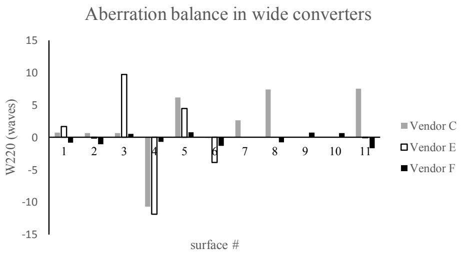

Figure 9: Aberration balancing in the wide angle front converters from vendors C, E, and F. Field curvature is balanced similarly for these similar design forms.

7. FISHEYE CONVERTERS

All fisheye converters reached +-90 deg. coverage, although some reached this value on the short axis of the sensor, and some reached it near the diagonal. As with the other tests, the object was the SFR chart. This test object is a poor choice for a fisheye converter[4] because a fisheye lens is unlikely to be designed for a planar object. Finding a reasonable object distance also presents difficulties; filling the entire sensor requires placing the lens unreasonably close to the object. A distance of 200mm, about 50X the focal length, was chosen for all tests so the full 90 deg. coverage is not evaluated. All showed degradation of performance with field; the spread of values for ESF suggests that astigmatism contributes to this degradation..

Figure 10 shows measurements of the iPhone 6 with fisheye converters. Chromatic aberration is much larger than for the other front converters. The converters from Vendors A and B show a large amount of chromatic aberration, which was objectionable to the authors' eyes.

A useful benchmark for the performance of these converters is a high-quality photographic system - Panasonic Lumix DMC G5 camera with a Panasonic Lumix G Fisheye 8mm f/3.5 Lens. This benchmark, digitally cropped on-camera to an 8 megapixel image size to match the iPhone, shows similar degradation with field as the iPhone with the fisheye converter from vendors E. The converters from vendors A and B have meaningfully more degradation with field; the converter from vendor D has significantly less..

Schematics of some of these fisheye converters are shown in Figure 11. The lenses all seem to be from a similar design family. The wide variation in performance suggests that important design variables are not captured here; such design variable might include glass choice, aspheres, or tolerances. Although Seidel terms are a poor predicter of fisheye performance, the Seidel terms for field curvature, W220, are shown in Figure 12 for completeness.

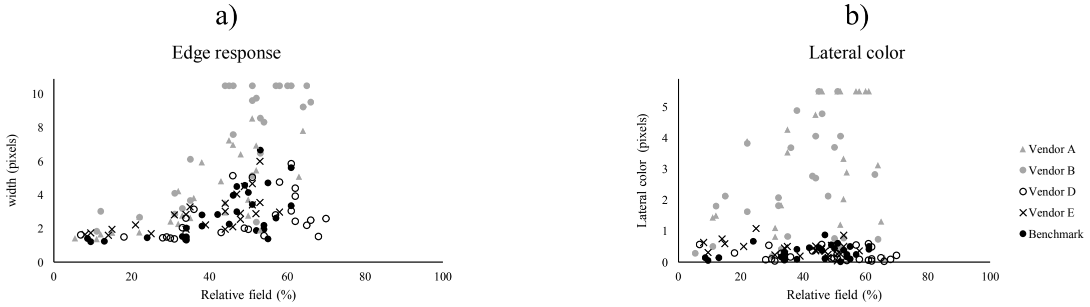

Figure 10: Measurements of fisheye front converters on the iPhone 6. Figure 10a shows the width of the edge spread function, defined at the 10 and 90% points; Figure 10b shows the chromatic aberration, defined as the integral between the red, green, and blue planes. The lenses from Vendor A and B perform much worse than the benchmark, a high-quality, dedicated photographic system. ESF values over 10 pixels are plotted as equal to 10 pixels; lateral color values over 5 pixels are plotted as equal to 5 pixels.

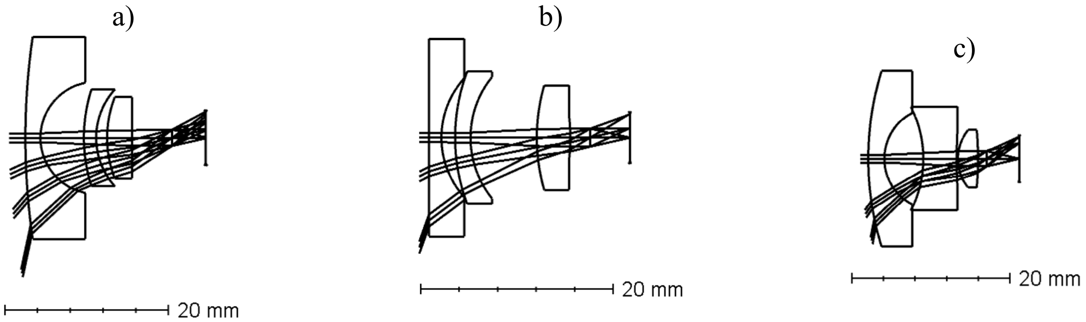

Figure 11: Schematics of the fisheye front converters. Figure 8a shows the schematic for Vendor A, . Figure 8b shows the schematic for Vendor B, Figure 8c shows the schematic for Vendor E,

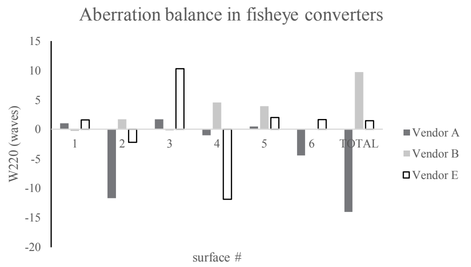

Figure 12: Aberration balancing in the fisheye front converters from vendors C & E.

8. CONCLUSIONS

Front converters can be a useful addition to smart phones, adding flexibility to the camera's field of view. The imaging performance of these front converters often compares well to that of dedicated photography systems. Performance of the front converters has little correlation with size.

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