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Mixing and matching sensor format with lens coverage

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Abstract

The 36x24mm 135 film format was most popular for high-end consumer cameras for decades, but the difficulty of making large sensors made smaller formats more common in digital cameras. The result is a variety of sensor formats – and lenses designed to cover each. However, mirrorless bodies allow mounting lenses designed for various non-native formats. One would expect lenses to work best using the sensors they were designed for, but there are many potentially good reasons to use lenses designed for one format on a sensor of another format. This paper explores how lens behavior changes as lenses are used on non-native sensor formats, either directly or with the addition of optical elements that have the side-effect of adjusting coverage: rear-mounted focal reducers and tele-converters.

Introduction

The 36x24mm format was almost universally accepted for film, but digital sensors have not seen the same level of format standardization. APS-C, Micro Four Thirds[8], and even 1" sensor formats are all common. This has led to pragmatic issues involving what happens to image quality of existing lenses when one switches to a different sensor format.

Adding optical elements to change magnification of a lens has always been assumed to reduce image quality, but *does it really reduce image quality if that change is being made to better match the lens projection to the sensor format*? The Speed Booster focal reducer claimed that it actually can increase image quality while providing a larger effective aperture[1]. Although the practice is far less well known, it is similarly possible to use a larger-format tele-converter to expand the coverage of a lens to that format; the effective aperture is made smaller, but do the additional pixels result in better image quality than if the sensor data is simply cropped to the native coverage of the lens?

It is theoretically possible to make new lens designs optimized for each sensor, but using existing lenses is far more cost effective and may be more flexible. The question is how to get the desired attributes by wisely pairing lens and sensor. For example, Figures 1 and 2 show the result of pairing an Opteka 6.5mm rectangular APS-C fisheye lens with a 1.5X teleconverter to cover a full-frame sensor. The same lens also can produce an unclipped circular image on a full-frame sensor using a focal reducer. This paper describes viable alternatives and attempts to establish baseline expectations for how such combinations can be expected to perform.

While it is obvious that the short flange-to-sensor distance of Sony E-mount and other mirrorless bodies allows lenses to be mounted despite the fact they were intended for a different sensor size, the full range of potentially worthwhile adaptations has not been enumerated – let alone characterized in terms of the expected impact on image quality. Nearly all published data have been limited to evaluating resolution of full-frame lenses used directly on both full frame and APS-C crop sensors, with just a few empirical evaluations made of vignetting when lenses are used on sensors larger than their intended target. In contrast, the current work considers various combinations of lenses not just directly mounted on different format sensors, but also mounted using focal reducers or teleconverters.

This work began with a very narrow and informal article the author posted at DPReview in December 2013[7]. The current work is still highly pragmatic and empirical, with little theoretical contribution. However, it is much broader in scope and is not based on subjective human impressions of general image quality. Expectations for the various combinations possible are characterized by direct measurement of specific image properties.

Figure 1. *APS-C rectangular fisheye on full frame via 1.5x teleconverter*

Figure 2. *300x200 pixel crop from Figure 1*

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Lenses mentioned in this paper

Lens Make, Designation	Format	Focal Length		*f*/number		Notes
Opteka Fish-Eye CS	APS-C	6.5		3.5		removable shade Samyang 8mm?
Sigma DC HSM	APS-C	8	16	4.5	5.6	zoom
Sigma EX DC	APS-C	10	20	4	5.6	zoom
Spiratone YS	FF	18		3.5		
Sony AF DT (SAL-1870)	APS-C	18	70	3.5	5.6	zoom
Mir 20	FF	20		3.5		KMZ
Spiratone Plura-Coat	FF	24		2.8		
Vivitar Auto Wide-Angle	FF	28		2.5		Kiron
Super-Takumar	FF	28		3.5		
Super-Multi-Coated Takumar	FF	35		2		
Super-Takumar	FF	50		1.4		
Auto Mamiya/Sekor	FF	55		1.4		
Sony AF DT (SAL-55200)	APS-C	55	200	4	5.6	zoom
Zenit MC Helios 44M-7	FF	58		2		

What Combinations Are Feasible?

There are thousands of lenses easily available at modest prices and there are hundreds of digital camera bodies upon which any of those lenses theoretically could be used. However, not all of those combinations are feasible, and even fewer combinations yield photographically useful lens properties at a lower cost than a functionally-similar native lens. The following subsections describe the sensor formats, lenses, and adapters for which results are reported in the current work.

Formats

As cameras moved from film to electronic sensors, the cost of making sensors as large as popular film formats would have been prohibitive, so smaller sensors became the norm and lenses were designed for these smaller formats.

Before digital cameras, the dominant film format for interchangeable-lens cameras was 135 cartridge, or “35mm” full-frame. The official image area is 36x24mm, but it was common that the actual usable image area was slightly smaller to allow for slide mounting. In 1996, the Advanced Photo System (APS) 240 film cartridge was introduced as new standard. It allowed users to select which of three image formats to use for each image: H for "High Definition" (30.2x16.7 mm), C for "Classic" (25.1x16.7 mm), or P for "Panoramic" (30.2x9.5 mm). Although APS film never became very popular, the C format was a standard, smaller, format with the same 3:2 aspect ratio as 135 full-frame, so it became the basis for the APS-C format which has dominated digital interchangeable-lens cameras. Most camera brands call roughly 23.7x15.6mm APS-C, while Canon uses 22.3x14.9mm. Compared to the 43.3mm diagonal of full-frame, APS C is 30.1mm, digital APS-C is 28.4mm, and Canon’s version is 26.8mm. This means APS-C is a 1.52x crop of full-frame and Canon’s version is a 1.61x crop.

The catch is that just over the past couple of years, it has become economical to make full-frame sensors. Thus, cross-format interest centers on mixing APS-C and full-frame lenses and bodies. The current work considers both these formats, and also considers a 24x24mm crop of a full-frame sensor – photographers often request a square format.

Conveniently, Sony E-mount mirrorless bodies not only have a short flange distance that makes mounting non-native lenses relatively easy, but also come in both 1.5x crop APS-C and full-frame models with the same 6000x4000 pixel resolution (24MP). In contrast, the APS-C crop of the A7’s sensor is just 3936x2624 pixels (10MP). The APS-C model used for the experiments reported here is a NEX-7; the full-frame model is the A7. The generally similar attributes of these cameras facilitates per-pixel comparisons of measured image properties.

Lenses

According to CIPA[4], the number of interchangeable lenses shipped in 2014 was 5,860,050 targeting full-frame bodies and 17,067,842 for smaller sensors (largely APS-C). Still, the majority of lenses people have around, or can buy used via garage sales or eBay, were designed for full-frame (film) bodies. As of November 28, 2015, KEH (a major seller of used lenses) listed 106 APS-C format and 786 full-frame used lenses for sale on their WWW site. Clearly, lenses for both formats are common.

Many of the full-frame lenses available are several decades old. While that does not necessarily harm optical performance, it does mean they could not take advantage of advances like improved coatings and cheap aspherical elements, which are particularly useful in creating high-quality ultrawide lenses and zooms. In contrast, such features are heavily employed in APS-C lenses. Table 1 lists the nine full-frame and five APS-C lenses used for the experiments reported in this paper. These lenses were selected from over 140 as being representative of the lens types most likely to be of interest for mixing formats.

Adapters

Many APS-C bodies use a mount that also is used for full-frame bodies of that brand, but the community-maintained list

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Adapter/Converter Optics mentioned in this paper

Adapter or Converter	Format	Magnification		Notes
		Market	Actual	
Metabones Speed Booster ULTRA	APS-C	0.71	0.71	can correct data
Zhongyi Lens Turbo	APS-C	0.726	0.73	
Zhongyi Lens Turbo II	APS-C	0.726	0.74	rectangular masking
glassless adapters	FF	-	1.00	
Kenko alpha-AF 1.4x Teleplus MC4 DGX	FF	1.4	1.39	8-pin data corrected
Rokunar 1.4x M/AF Tele-converter	FF	1.4	1.45	5-pin data corrected, "no lens" on E-mount
Kenko Mx-AF 1.5x Teleplus SHQ	FF	1.5	1.39	8-pin pass-through
Kenko N-AFd 1.5x Teleplus SHQ	FF	1.5	1.56	Nikon F mount

of lens mounts at Wikipedia[12] names over 90 different types. Oleson[9] does not list as many mount types, but provides photos to help people identify some of the more popular mounts.There are two fundamentally different ways to mount a non-native-mount lens on a camera body:

1. Convert the lens by removing the original mount and replacing it with the desired mount, which may be a complex and irreversible process
2. Adapt the lens by attaching it to an adapter that accepts the lens mount on one side and offers the desired lens mount on the other side

Some third-party lens makers have offered a mount conversion service for their lenses, but generally only conversions between the mounts they offer each lens in as a new product are available. There also are conversion services and kits for various other lens and body mount combinations; among the best known is Leitax for converting Leica lenses to Pentax DSLR mounts. Some conversions require significant surgery to the lens, ranging from removal or grinding-down of mechanical parts to shifting of the lens assembly to move the infinity focus position. Independent of how desirable conversion might be, lens mount conversion adds cost to each lens processed. Thus, an adapter that can be shared by multiple lenses is much more cost effective and is the only method considered in the current work.

There are effectively four different types of adapters that can be placed between a lens and the sensor:

1. Glassless adapters that have no significant optical properties
2. Teleconverters[10] that incorporate optical elements to extend focal length without changing the aperture diameter
3. Glass adapters that incorporate optical elements to extend the focal length slightly to increase rear focus distance – a special case of teleconverters
4. Focal Reducers[2] that incorporate optical elements to reduce focal length without changing the aperture diameter

For the most commonly available and obviously useful combinations of lens mount and camera mount, it is farly easy to find commercially-available glassless adapters. An extensive list of high-end adapters are sold by CameraQuest[3]. However, searching eBay quickly reveals that many different types of low-cost lens adapters are now being made in Asia, some with selling prices under $10. Consumer-level 3D-printing technology provides a cost-competitive way to make adapters for lens and body combinations that have never been commercially available. For example, Thing 137540[5] is an adapter we designed and 3D-printed to allow the Mir 20 lens, in Kiev 10/15 mount, to be used for the experiments reported here.

The adapters with optical components not only provide mechanical mounting, but also allow the lens coverage to be changed. A focal reducer reduces coverage, in effect increasing the field of view for a smaller format, which has the happy side effect of also decreasing the effective f/number. A teleconverter does the opposite, increasing coverage while narrowing the field of view for the original format of the lens... and teleconverters have a reputation for harming image quality in the process. However, here a teleconverter from a larger format is being used with a sensor in the larger format; thus, although lens resolution may be stretched, the larger pixels of the larger sensor might not see this as a drop in resolution. Of course, it would be convenient for the magnifications to precisely compensate for the format size difference, but as Table 2 shows, magifications often do not even match the values advertised. It is also worthy of note that of the teleconverters listed here, only the Kenko 1.4x correctly modifies the lens data transmitted through the adapter.

Results

There are many ways to measure optical performance of a lens. However, the goal in the current work is not quantitatively measuring performance, but characterizing the changes that can be expected to occur when lenses are adapted for use in other than their native format. For this reason, although the measurements used are conventional, the forms in which the results are presented is not.

One of the most fundamental metrics is resolution, often measured as MTF50: the Modulation Transfer Function for 50% contrast. Various tools allow MTF50 measurements to be made at various positions in the field by analysis of an image captured of a test target photographed under reasonably well-controlled conditions[6]. The free software tool MTF mapper[11] was used for all MTF50 measurements reported in this paper. Provided with that tool are SVG slanted-edge target designs; the stan-

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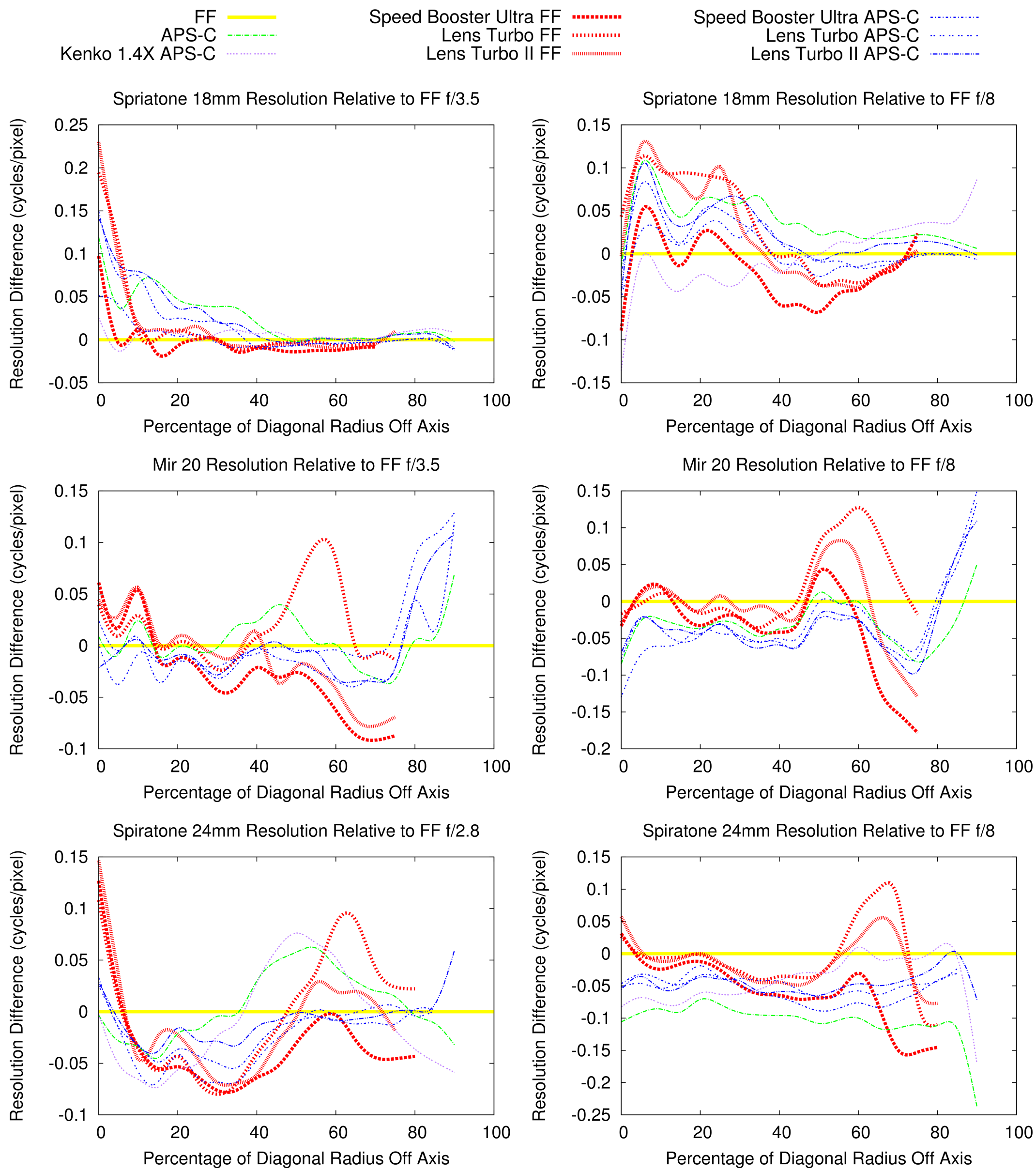

Figure 3. *Ultrawide full-frame lens MTF50 resolution tests*

dard MTF mapping target provided with that package was inket-printed on heavy semi-gloss E-format paper, pinned to a wall, and evenly lit without glare. The mirrorless camera under test was mounted to a heavy tripod and fired using the self timer with the electronic first curtain enabled, thus ensuring no vibration-causing shutter movement. Focus was fully manual even for the lenses supporting autofocus, using peaking with magnified live view. The live view also was used to confirm alignment of the camera with the target, with the intent of compensating for any minor tilt that might be introduced by an adapter. All images were captured as simultaneous raw and JPEG, with all image adjustments (e.g., lens distortion correction) disabled. To minimize noise, all images were shot at base ISO, which is ISO100 for both cameras used. The exposures were made in aperture-priority ("A") mode, with exposure compensation set to +1 EV to compensate for the high percentage of white area in the target.

MTF mapper not only provides a variety of methods for summarizing and visualizing the results of the MTF50 analysis, but also text files giving the raw analysis data about each individual edges detected in the image. The analysis reported here is all derived from the `edge_mtf_values.txt` file, which lists the computed cycles-per-pixel MTF50 resolution and spatial coordinates of each edge.

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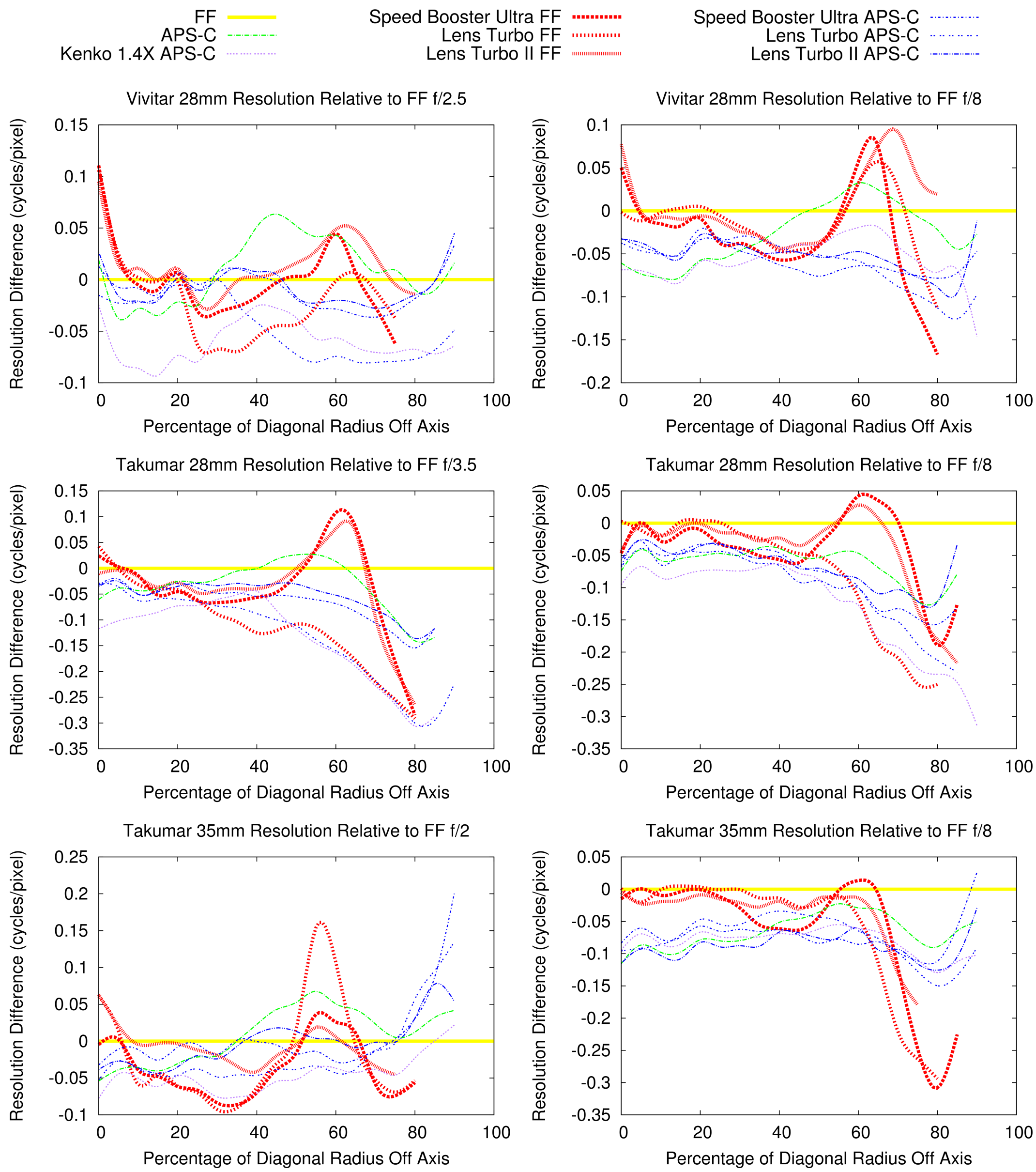

Figure 4. *Wide full-frame lens MTF50 resolution tests*

To determine how resolution is impacted by pairings of adapters and formats, the raw edge data for an image was used to produce MTF50 values for each 5% step moving from the center of the image (0%) to the corner (100%). MTF mapper measurements have good repeatability, but this was further enhanced by median filtering the values for each 5% interval. There is still significant variation near 0% and near 100% because very few edges were in those regions. Note that the APS-C and FF bodies used offer the same 6000x4000 pixel count, so cycles-per-pixel MTF50 values can be directly compared across these two formats. Because the interesting issue is how the adapter and format change the resolution, the data was plotted relative to the native resolution, not as absolute values.

Full-Frame Lens Resolution

Figures 3, 4, and 5 show the MTF50 performance of various full-frame lenses. The MTF50 cycles-per-pixel values for various configurations are plotted relative to the (native) full-frame values. The configurations include three different focal reducers on both full-frame and APS-C sensors, use directly on an APS-C sensor, and use of a 1.4X teleconverter on and APS-C sensor. The focal reducers are really intended to map a full-frame lens view onto an APS-C sensor, providing nearly the same angle on view as when used directly on a full-frame body, and also re-

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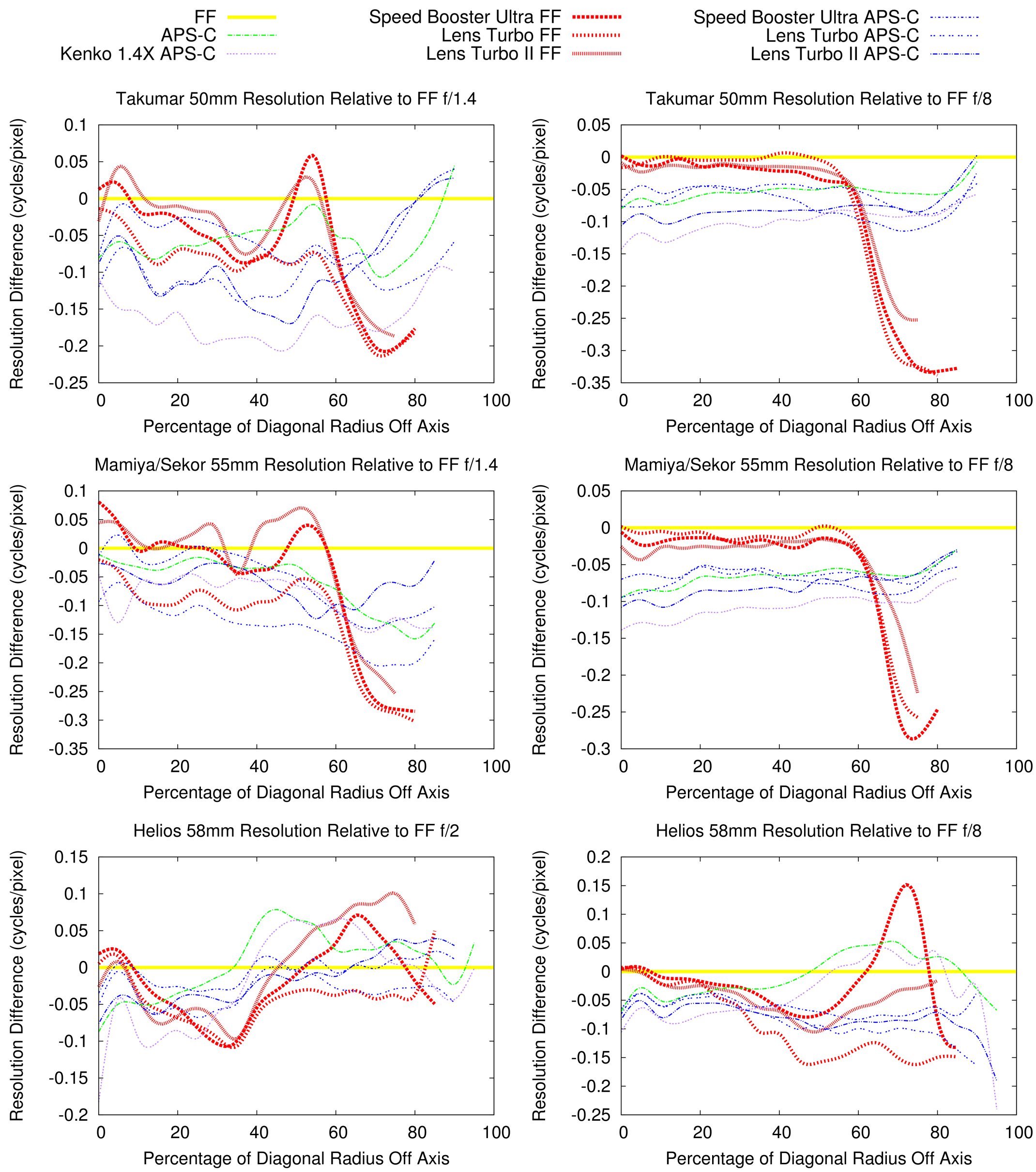

Figure 5. *Normal full-frame lens MTF50 resolution Tests*

ducing the f/number by about 1 stop. Focal reducers generally vignette when used with a full-frame sensor, but they still can be useful as a method to provide a square, rather than 3:2, aspect ratio image with approximately the same view angle. Of course, direct use on an APS-C body is presumed to reap the benefits of using the central "sweet spot" of the lens, where image quality is less impacted by aberrations. Finally, the 1.4X teleconverter on an APS-C sensor gives about a 2X crop overall, which is roughly equivalent to the crop factor that would be seen directly using a Micro Four Thirds[8] sensor. All the measurements were done both with the lens wide open (to show the full impact on aberrations; on the left side of the figures) and stopped down to the aperture marked f/8 (generally stopped down enough to be near optimal performance for the lens; on the right side of the figures).

Three ultrawide full-frame lenses are evaluated in Figure 3. It is immediately obvious that there is no clear winner for the best resolution. However, the variation on the 20mm and 24mm lenses is quite small; all configurations are usable. The 18mm lens is a bit of a different story: like many older ultrawide lenses, it resolves quite poorly toward the full-frame edges. That fact gives benefit to either cropping to the center or using a focal reducer to compress the natural resolution of the lens. In other words, most non-native uses of the 18mm lens actually produce better resolution than using it in the native way.

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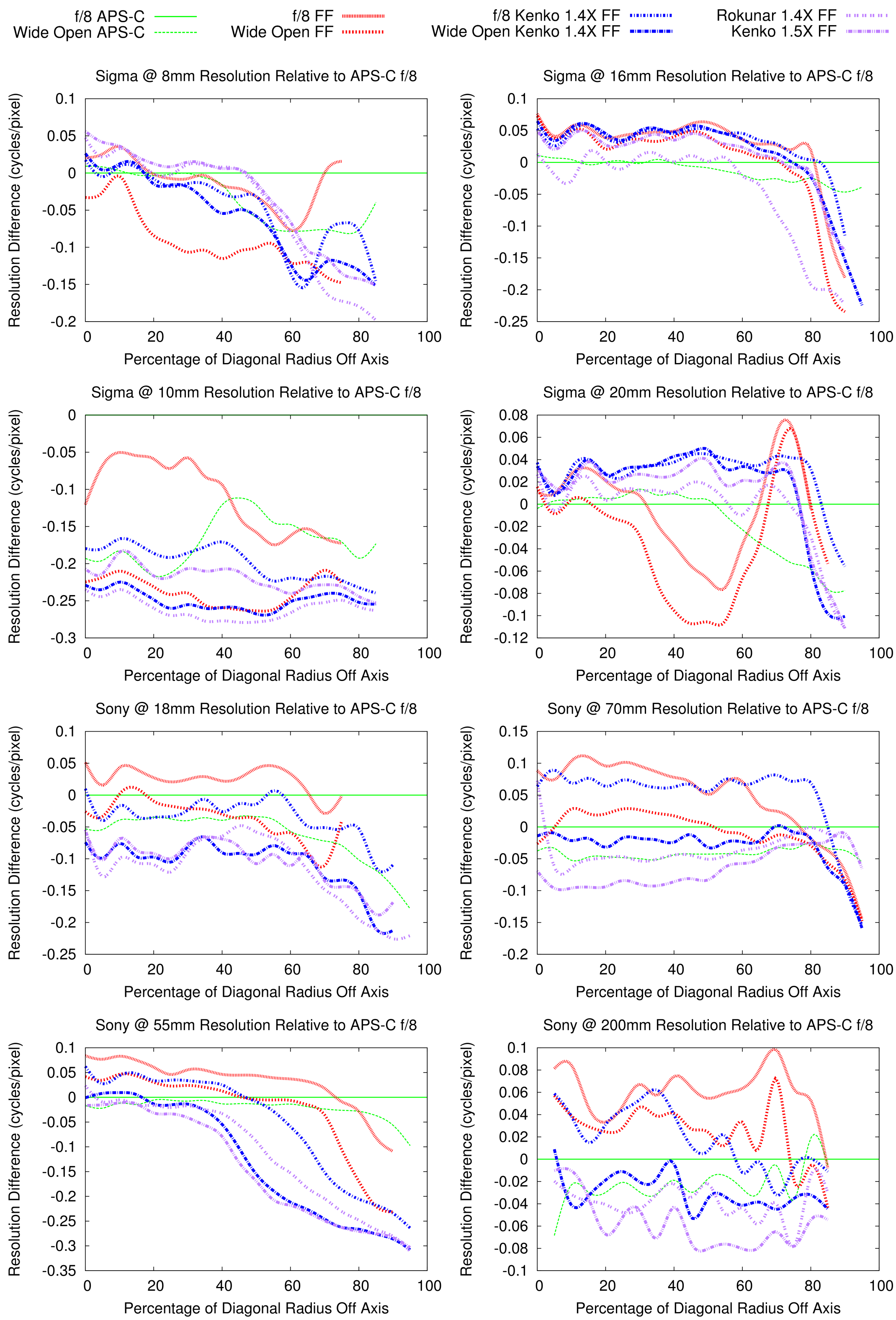

Figure 6. *APS-C lens MTF50 resolution tests*

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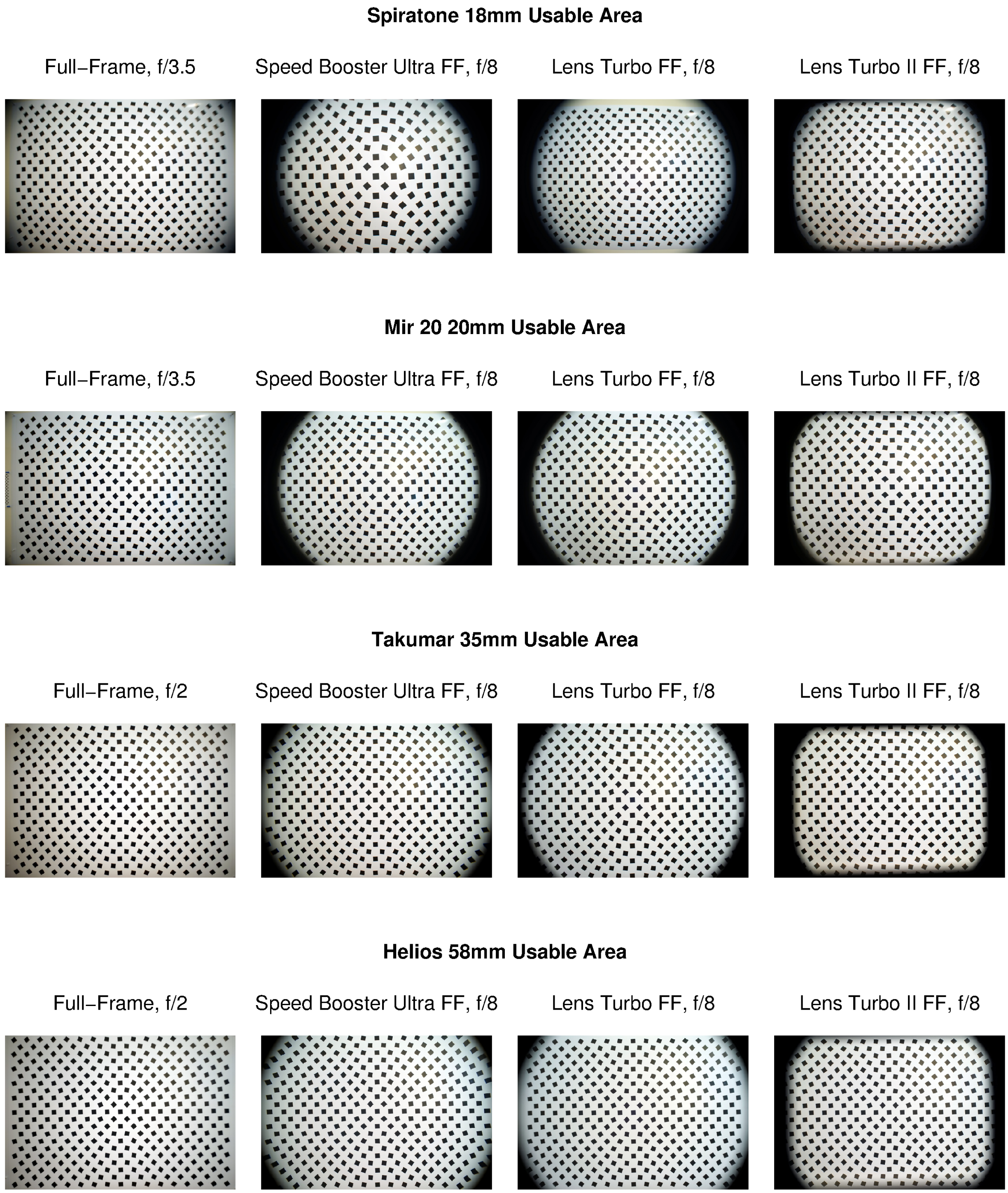

Figure 7. *Four full-frame lens usable area tests*

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Performance of less-extreme wide-angle lenses is explored in Figure 4. For these 28mm and 35mm lenses, the focal reducers used on full-frame sensors suffer very sharp fall-off in resolution, but that happens only as the lens begins to vignette – which would not be relevant if we are using the focal reducer on full-frame to obtain a wide-angle square image. The various APS-C configurations generally do a little worse, but not much worse. Again, these are generally usable configurations.

Figure 5 shows similar data for three normal lenses. Normal lenses are notoriously good optics, and the data shows that it is difficult to beat native full-frame performance, especially stopped down. However, again it is clear that most configurations are usable.

It is interesting to note that focal reducers on APS-C have been claimed to often improve center sharpness as compared to directly using a full-frame lens on an APS-C sensor[1]. That claim is justified by some of the measurements, but the difference is usually small and not always favoring the focal reducer. This is somewhat surprising, as an improvement in apparent sharpness is very commonly noted. Of course, use of a focal reducer also reduces the number of pixels covered by scene texture elements, and the higher frequency of the texture may well produce an impression of increased sharpness even if slanted-edge MTF50 measurements do not find higher cycles-per-pixel values.

APS-C Lens Resolution

The use of full-frame lenses on APS-C sensors was common from the advent of the format. Since the introduction of the original Speed Booster in 2013[1], focal reducers have become a well-accepted tool for users of cameras with APS-C sensors. However, the use of teleconverters to map APS-C lenses into full-frame sensors is only now becoming a topic of discussion. The obvious reason that this is now on people's minds is that it is only in the past year or so that cameras using full-frame sensors have become price-competitive with high-end cameras using APS-C sensors: as users upgrade camera bodies, they do not like having to buy new lenses. Beyond that, teleconverters have been known for decades as a cheap, low-quality, way to increase the effective focal length of lenses. People who are upgrading to full-frame bodies in search of better image quality are naturally hesitant to believe that placing their APS-C lens on a teleconverter will produce better image quality. There is also the issue that teleconverters increase the f/number: a 1.4X teleconverter requires about 1 stop of additional exposure.

To determine the impact on resolution, various APS-C lenses were tested both wide-open and at f/8 directly mounted on APS-C and full-frame bodies, and on full-frame bodies using various focal reducers. The direct mounting of an APS-C lens on a full-frame body is likely to produce vignetting and other problems off-axis past the APS-C crop region, but perhaps bad image quality is not as likely as one would expect. Although coverage of a fixed-focal-length lens does not need to be significantly larger than the format for which it was designed, the most popular APS-C lenses are zooms, and to get the necessary coverage at one focal length often implies greater coverage at another focal length. In practice, it is not uncommon for an APS-C zoom to cover a full-frame sensor at some combinations of focal length and aperture setting; e.g., the Sigma 8-16mm zoom tested here just barely covers a full-frame sensor at 16mm. Coverage should not be a problem with a 1.5X teleconverter. However, each of the three teleconverters implemented the electronic lens protocol differently, and only the Kenko 1.4x allowed control of the lens aperture when mounted on a Sony A7 body using an LA-EA3 glassless A-mount adapter.

Figure 6 gives relative resolution measurements for four APS-C zoom lenses, each of which is tested at both its minimum and maximum focal length setting. Immediately, the graph of the Sigma 10-20mm zoom at 10mm stands out: any type of full-frame use was worse than native APS-C! This was caused by a defective focus mechanism that did not allow focusing quite close enough for the test chart. Even at 10mm, it does not take a lot of defocus to destroy MTF50 performance for all but the native f/8 shot, where depth-of-field largely hides the error. All the other graphs tell a much happier story, with adapted resolution often *better* than native across most of the sensor. Empirically, this also appears to be true of the Sigma 10-20mm at 10mm when the scene is distant enough for this defective lens to focus on. This lens actually is very usable as a full-frame ultrawide via a teleconverter.

Full-Frame Lens Usable Area

For space reasons, only four of the full-frame lens usable area test images are shown in Figure 7. Fundamentally, the biggest issue is vignetting.

Using some lenses, such as the Spiratone 18mm, near wide-open on a full-frame sensor reveals a disturbing level of corner shading even in direct native use. It is largely a matter of the rate of shading becoming too steep near the corner; a smoother transition would be much less obvious. For example, the shading of the Takumar 35mm, and even of Helios 58mm, is not really much different from that of the Mir 20 over most of the frame, but the very dark extreme corners of the Mir 20 are much more problematic. In fact, postprocessing to brighten the corners of the Spiratone or Mir lenses is would consume at least two stops worth of dynamic range. Fortunately, especially for the Mir 20, a tiny bit of cropping easily removes the offending darkness. Interestingly, the slight crop implied by use of a focal reducer on APS-C (0.73x*1.5x = 1.1x) is often sufficient to remove the tiny region of overly dark corner so that vignetting is less than for native full-frame use.

Using a focal reducer with a native full-frame lens suffers sufficient vignetting caused by the focal reducer so that none of the combinations can even support a 24x24mm square crop format. However, the 24x24mm square (about 78% of the full-frame diagonal) would actually deliver a slightly wider view angle than the native 36x24mm image; cropping to a square with the native view angle appears to be possible in all cases.

In general, note that the MTF50 resolution (see Figures 3, 4, and 5) usually does not dive before vignetting becomes critical. If corners are soft, it is likely they also were soft for the lens by itself.

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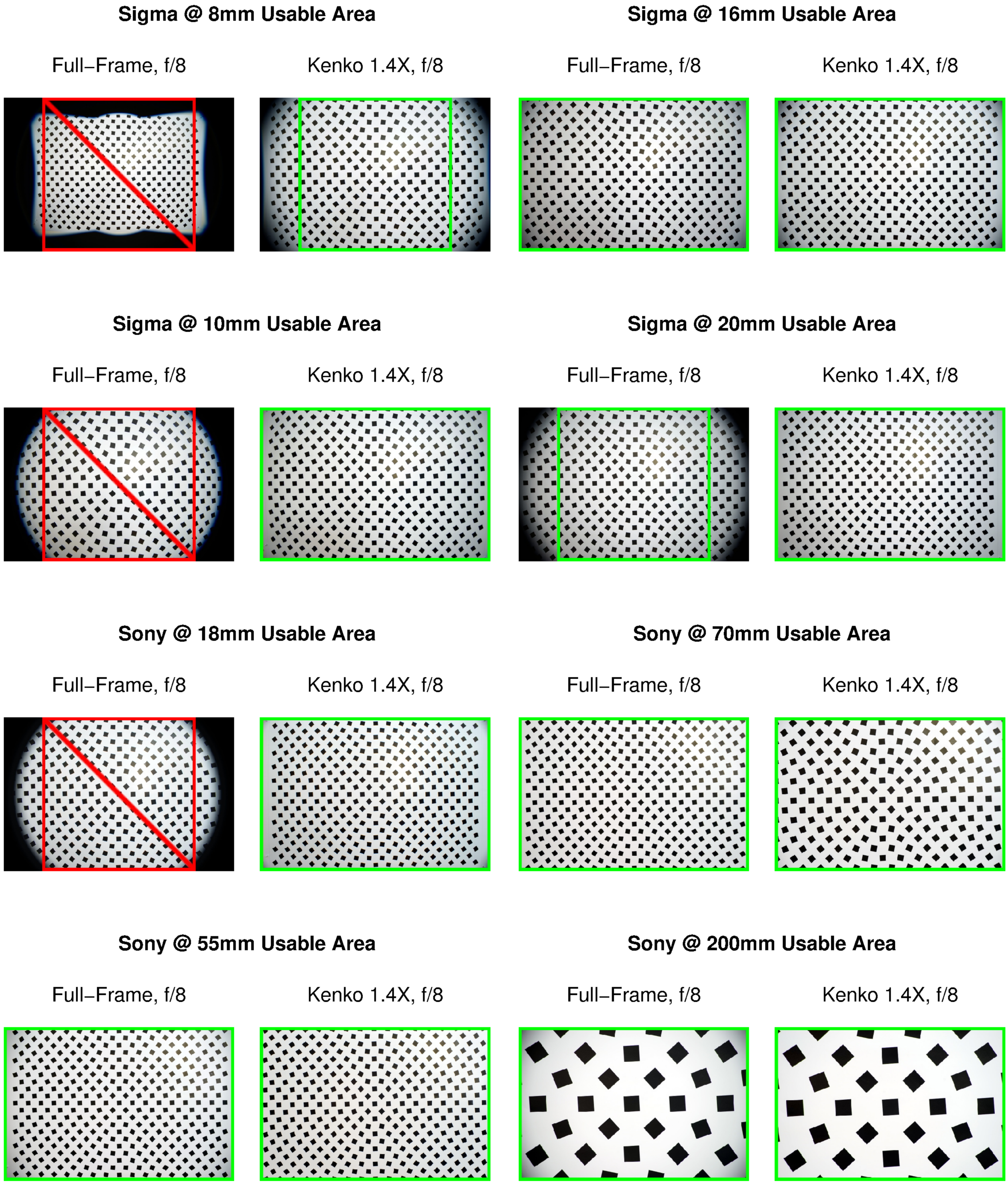

Figure 8. *APS-C lens usable area tests*

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Figure 9. *APS-C 10-20mm @ 10mm on native APS-C*

Figure 10. *APS-C 10-20mm @ 10mm on full frame via 1.4x teleconverter*

APS-C Lens Usable Area

Perhaps the biggest surprise in the current work is the excellent performance of APS-C lenses used on full-frame sensors with a teleconverter, as seen in Figure 8 (in which the largest standard format coverage is marked). Vignetting, which was a common plague among the full-frame lenses used on full-frame sensors, was not a severe issue. Perhaps this is because the image circle for APS-C lenses tends to be somewhat larger than the native format would require? These four lenses are all zooms, and ensuring that a zoom lens covers its native format at all settings often implies extra coverage at some settings.

Even without a teleconverter, it is common that directly-mounted APS-C lenses can cover a full-frame sensor under some combination of aperture and zoom settings. Mounted on a teleconverter, every APS-C lens tested was capable of covering at least a 24x24mm square crop of a full-frame sensor. Also note that Figure 6 clearly shows resolution is often maintained to and beyond the 78% diagonal coverage a square crop requires.

Conclusion

This paper has presented strong evidence that, although optical performance varies widely with particular lens, adapter, and format combinations, non-native use of lenses is often able to result in image quality that is comparable to or better than native – as seen in Figures 9 and 10. Although resolution varied significantly, the biggest consistent image quality issue is usually vignetting. On average, full-frame formats tended to resolve a little better than APS-C, but they also suffered more vignetting.

The claim that focal reducers often improve central resolution[1] was supportable, but not by a large margin nor in every case. A similar claim could be made about telecoverters as format changers, which is surprising given the common belief that teleconverters degrade image quality (based on their use with the lens native format sensor). Some methods using APS-C lenses on full-frame sensors did not quite allow square 24x24mm crops, but full-frame coverage was usually viable.

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Author Biography

Henry (Hank) Dietz earned his PhD at Polytechnic University and joined the faculty at Purdue University's School of Electrical and Computer Engineering in 1986. Since 1999, he has been the Hardymon Chair in Networking at the University of Kentucky. Although best known for his work in compilers and parallel supercomputing using Linux PCs, he also works to improve cameras as computing systems.