

The Perfect Focal Reducer

Brian Caldwell, Caldwell Photographic Inc.

Perfect?

It turns out that it's easy to model a truly perfect focal reducer in lens design software by using something called a "paraxial lens". Think of it as a lens that zero thickness and no aberrations of any kind. So, basically you put a paraxial lens behind any lens of your choice, and you've created a lens system with a perfect focal reducer.

Of course, this is all virtual software stuff, kind of like playing a video game, but it allows you to do a full set of image quality evaluations, including MTF. And it's a very handy way of creating an aberration-free system to serve as a benchmark for evaluating "real" focal reducer designs.

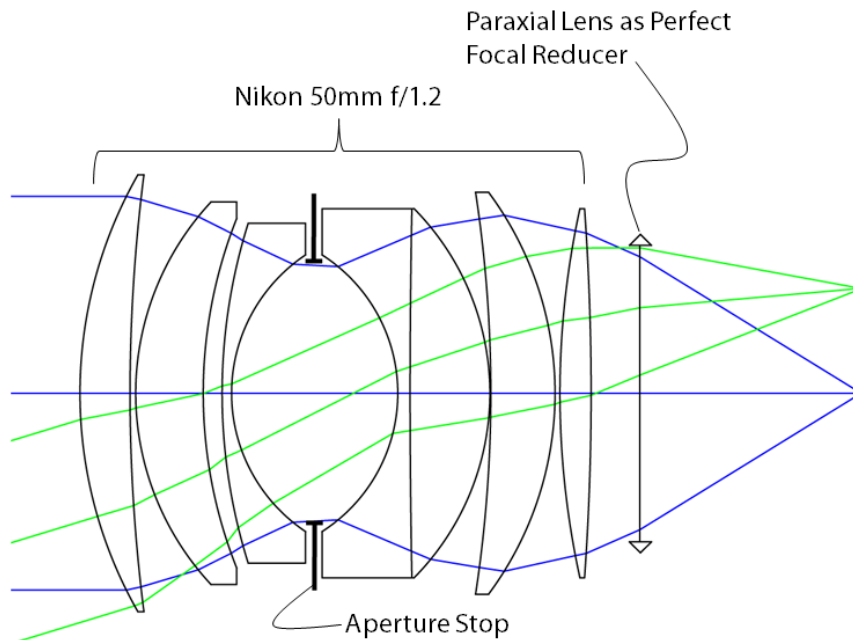


Figure 1: Layout of 50mm f/1.2 Nikkor lens plus perfect 0.71x focal reducer modeled as a positive paraxial lens. The combination yields a system having a focal length of 35.5mm and an aperture of f/0.9.

Figure 1 above shows a fast (f/1.2) 50mm Nikon lens (U.S. Patent 4,621,909 example #3) combined with a perfect paraxial focal reducer having a magnification of 0.71x. The combination is a 35.5mm f/0.9 lens with very high performance, as shown in Figure 2 below.

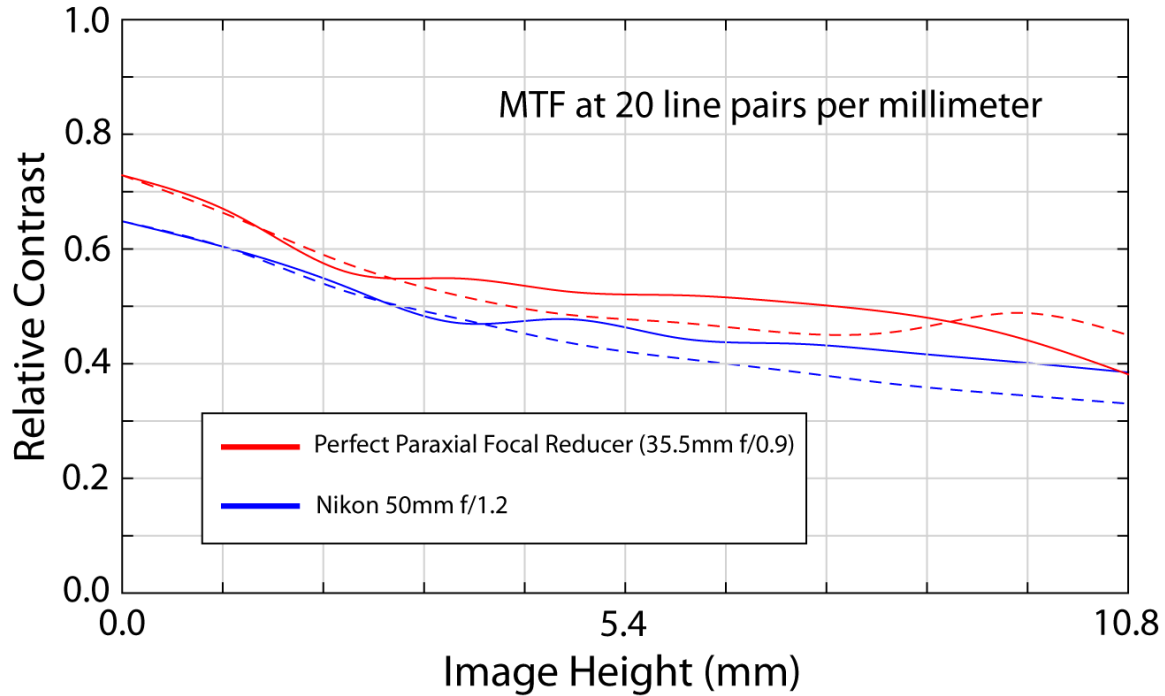


Figure 2: MTF vs. Image Height at 20 lp/mm for the Nikon 50mm f/1.2 at f/1.2 (blue lines) and combined with a perfect paraxial focal reducer (35.5mm f/0.9 at f/0.9) (red lines). Tangential data is given by dashed lines, and sagittal data is given by solid lines.

Figure 2 shows two important things: first, that a perfect focal reducer increases MTF at a given spatial frequency; and second, that the focal reducer shrinks the image circle of the master lens so that the outer parts of the field show up at a smaller image height. This can be seen by comparing details of the MTF curves, such as where the sagittal and tangential curves cross each other, etc..

Reality

OK, it's very nice to show how a perfect focal reducer behaves. But everyone knows that a real focal reducer can't possibly be as good as a perfect one. Right?

WRONG! Figure 3 is identical to Figure 2 except that a third set of MTF curves have been added, corresponding to combining the Nikkor 50mm f/1.2 patent design with a new Micro Four Thirds Speed Booster, called Ultra-m43, clearly showing that the actual real-world design (shown in Figure 4) is actually better than the "perfect" paraxial focal reducer.

You might expect that the perfect paraxial focal reducer would serve as an upper limit of performance achievable in a real-world design, but this is clearly not the case. What's going on here is that aberrations in the focal reducer are actually partially cancelling those in the master lens rather than simply multiplying them by 0.71x. This is similar to what happens when you add lens elements to a design in order to improve performance.

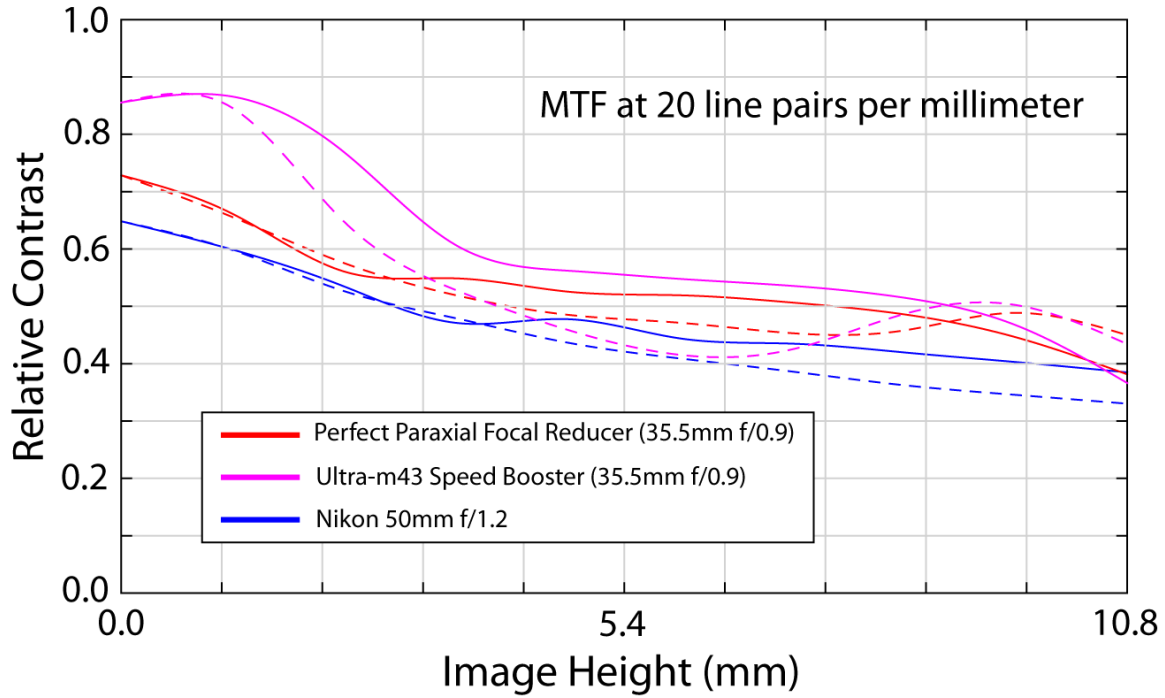


Figure 3: MTF vs. Image Height at 20 lp/mm for the 50mm f/1.2 Nikon patent design (U.S. Patent 4,621,909 example #3) (blue lines); combined with a perfect 0.71x paraxial focal reducer (red lines); and combined with the Ultra-m43 Speed Booster (magenta lines). Tangential data is given by dashed lines, and sagittal data is given by solid lines.

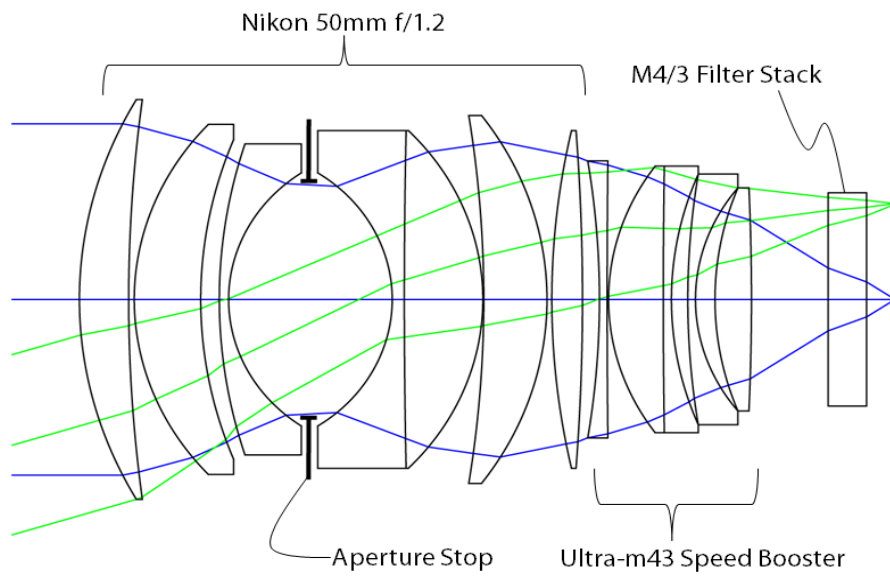


Figure 4: Layout of 50mm f/1.2 Nikon patent design combined with Ultra-m43 Speed Booster.

But was that Really Reality?

(And, Can You Really Improve a Zeiss Otus?)

After all, this is all pretty “theoretical”, using patent designs and all. Well, as far as *I’m* concerned its real enough for that particular master lens design. But then, as a lens designer I tend to be convinced by pure design arguments. However, I do like to make measurements with actual lenses too.

So, for example, how would an actual prototype of my new Ultra-m43 Speed Booster behave with what is arguably the best-performing high speed lens available: the Zeiss 55mm f/1.4 Otus? Fortunately, I was able to study this exact combination during a recent pilgrimage to Roger Cicala’s amazing optics lab at Lens Rentals in Memphis, Tennessee.

First things first, let’s compare the MTF for the Zeiss Otus to the Ultra-m43 Speed Booster:

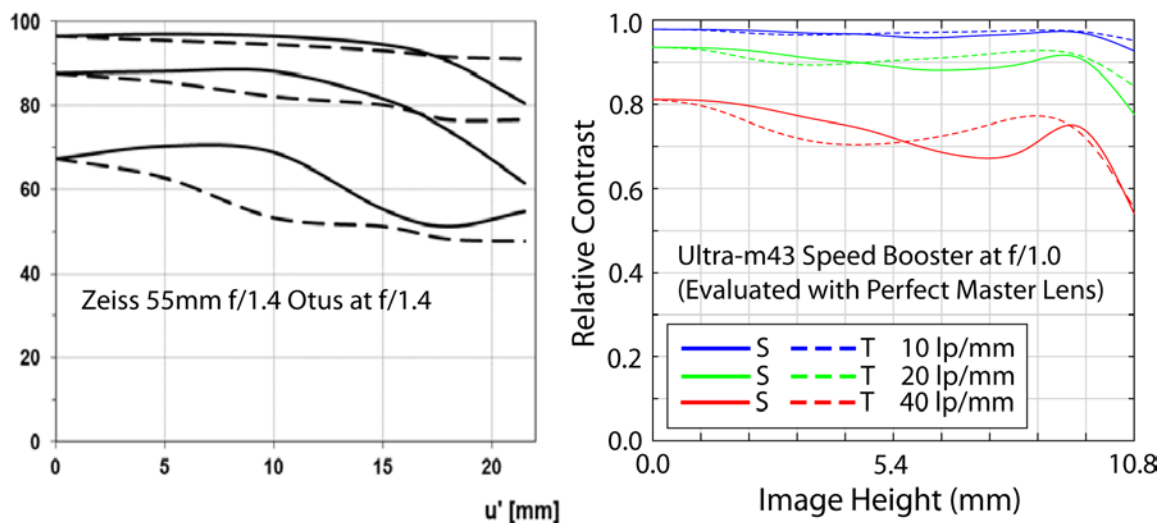


Figure 5: MTF curves at 10, 20, and 40 lp/mm for the Zeiss Otus at f/1.4 and for the Ultra-m43 Speed Booster at f/1.0

As good as the Zeiss Otus is, the Ultra-m43 Speed Booster is better, even though the Speed Booster is evaluated at f/1.0 and the Otus is evaluated at only f/1.4. But there’s a reason I wanted to compare them this way: since the Ultra-m43 Speed Booster is significantly better than the Zeiss you might expect (or at least hope) that when combining the new Speed Booster with the Otus that you will obtain an ultra high speed 39mm f/1.0 lens that actually performs better on micro 4/3 format at f/1.0 than the mighty Otus does at f/1.4.

And sure enough, that’s exactly what happens. Figure 6 below shows a pair of actual MTF measurements (not calculations). One made with the Otus by itself at f/1.4, and one made with the same Otus plus Ultra-m43 Speed Booster at f/1.0. In both cases a 4mm glass plate was positioned near the image plane to accurately model the effect of the filter stack found in micro-4/3 cameras. So what we see here is a small but measureable MTF improvement even as the aperture is increased by a full stop to f/1.0 and the field of view is significantly widened. So, yes, you really can improve a Zeiss Otus – if you use the right focal reducer! The 39mm f/1.0 combination of the Zeiss Otus with the Ultra-m43 Speed Booster may in fact be the highest-performing f/1 photographic lens *ever*.

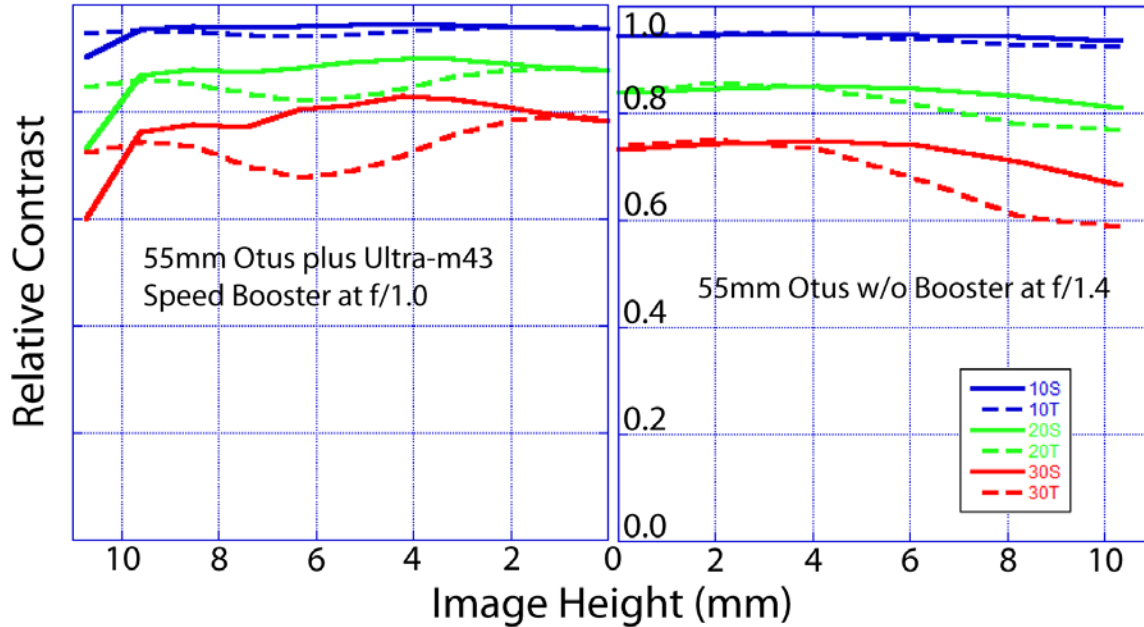


Figure 6: Measured MTF for 55mm Zeiss Otus without Speed Booster at f/1.4 (right side plots) and for 55mm Zeiss Otus with Ultra-m43 Speed Booster at f/1.0 (i.e., 39mm f/1.0) (left side plots). Measurements made with Trioptics ImageMaster HR, courtesy Roger Cicala.

Additional Pearl of Optical Wisdom #1

Comparison to Scaled Lens

Scaling is something lens designers can do to a design to quickly change its focal length. All you have to do is multiply the radii of curvature and thicknesses by the same number. For example, if the number is two you double the focal length and image circle diameter. Scaling of aspheric surfaces is a little more complicated, but it's all taken care of by design software so that it can be done in a split second.

Figure 7 below shows what a 50mm f/1.2 lens looks like before and after scaling by a factor of 0.71x. Note that the angle of the blue marginal ray is the same as it intersects the image plane for both the scaled and unscaled lenses. In other words, after you scale a 50mm f/1.2 lens by 0.71x to form a 35.5mm lens *the aperture is still f/1.2*.

So, how does a scaled lens compare to a lens that has been transformed by means of a focal reducer? Not surprisingly, scaling a lens to a shorter focal length will improve the MTF because aberrations are also reduced by the scaling process. But adding a focal reducer to a lens does a similar thing. In fact, the effect on aberrations is almost identical, as can be seen in Figure 8. But wait a minute – the MTF curves practically overlay each other even though the focal-reduced lens is evaluated at f/0.9 and the scaled lens is evaluated at f/1.2! So yes, it's true – focal reducers really are one of the great free lunches in optical design. Adding a focal reducer is *better* than simply scaling a lens because you gain aperture without losing image quality.

Of course, this is mostly of interest to lens designers because scaling a lens in reality to produce an actual physical lens is a very costly and time consuming process. But nonetheless it's a little-known fact that deserves wider appreciation. And after all, ordinary photographers *do* have access to high quality focal reducers.

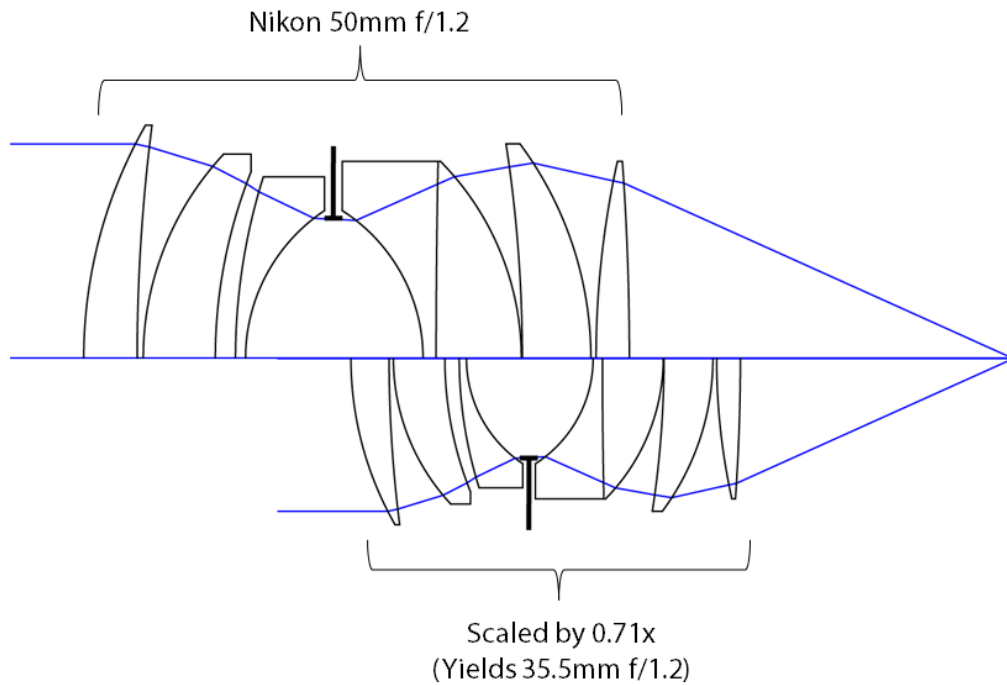


Figure 7: Layout of unscaled and scaled 50mm f/1.2 lens. The scaling factor is 0.71.

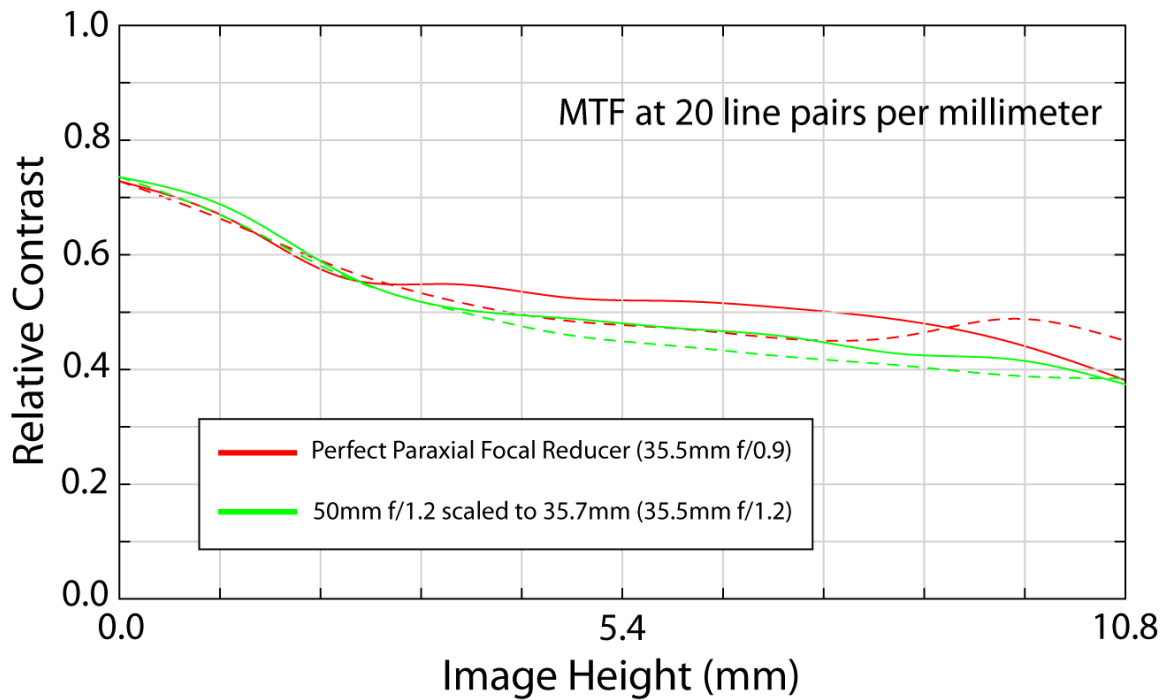


Figure 8: MTF for 50mm f/1.2 lens scaled to 35.5mm f/1.2 and 50mm f/1.2 lens converted to 35.5mm f/0.9 lens by means of a perfect paraxial focal reducer.

Additional Pearl of Optical Wisdom #2 Comparison to Perfect Front Wide Adapter

Front-mounted wide converters, sometimes called afocal wide converters, have been used for many decades, and are still in wide use today. They are especially popular for use with small format video cameras and consumer digicams. Even the ultra high end anamorphic lenses used in cinematography are a special type of front mounted wide converter that use cylindrical lens elements.

The problem with front mounted wide converters is that they generally have low image quality unless they are optimized to work with one particular objective lens, or a narrow range of objective lenses. Distortion and lateral color are particularly difficult to correct. Focusing can cause difficulty because the front converter can interfere with the floating element optical correction found in high quality objectives. Better quality front converters are also quite large, especially if they must work with wide angle objectives.

However, it is possible to design a perfect front wide adapter by the use of two paraxial lenses (a negative one followed by a positive one) as shown in Figure 9.

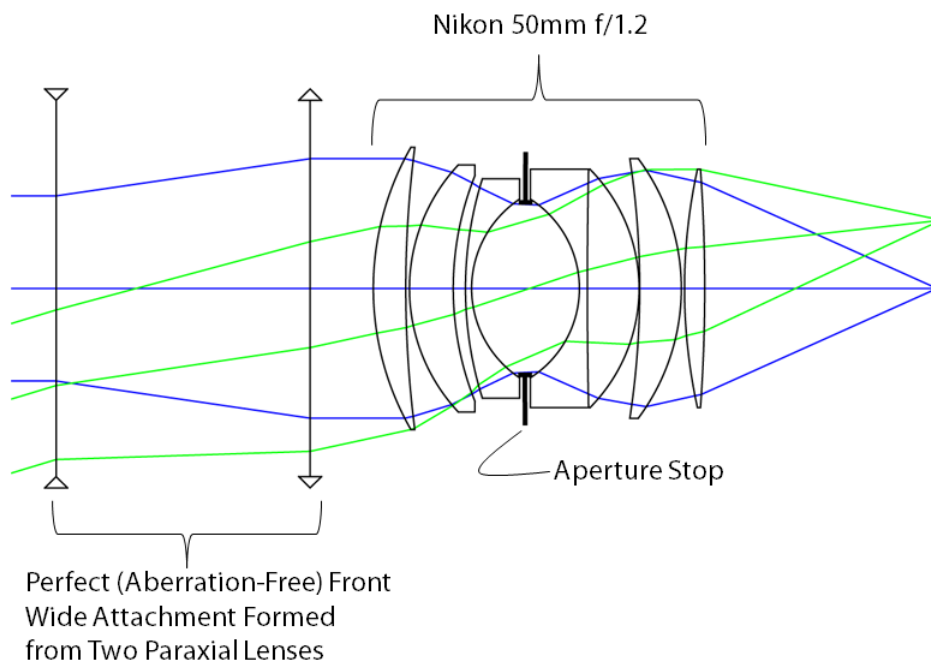


Figure 9: Layout of a 50mm f/1.2 lens converted to 35.5mm f/1.2 by means of a front-mounted wide converter.

Essentially what a perfect front wide attachment does is to increase the field of view and decrease the focal length without changing anything about the rear-mounted master lens. As a result, the relative aperture is unchanged. In fact the aberrations are completely unchanged because there is no change in vignetting or chief ray angle (i.e., the degree of telecentricity). As can be seen below in Figure 10, the

MTF of a lens with and without a perfect front wide attachment is absolutely identical – so much so that you can't tell that there are two sets of curves because they overlay perfectly.

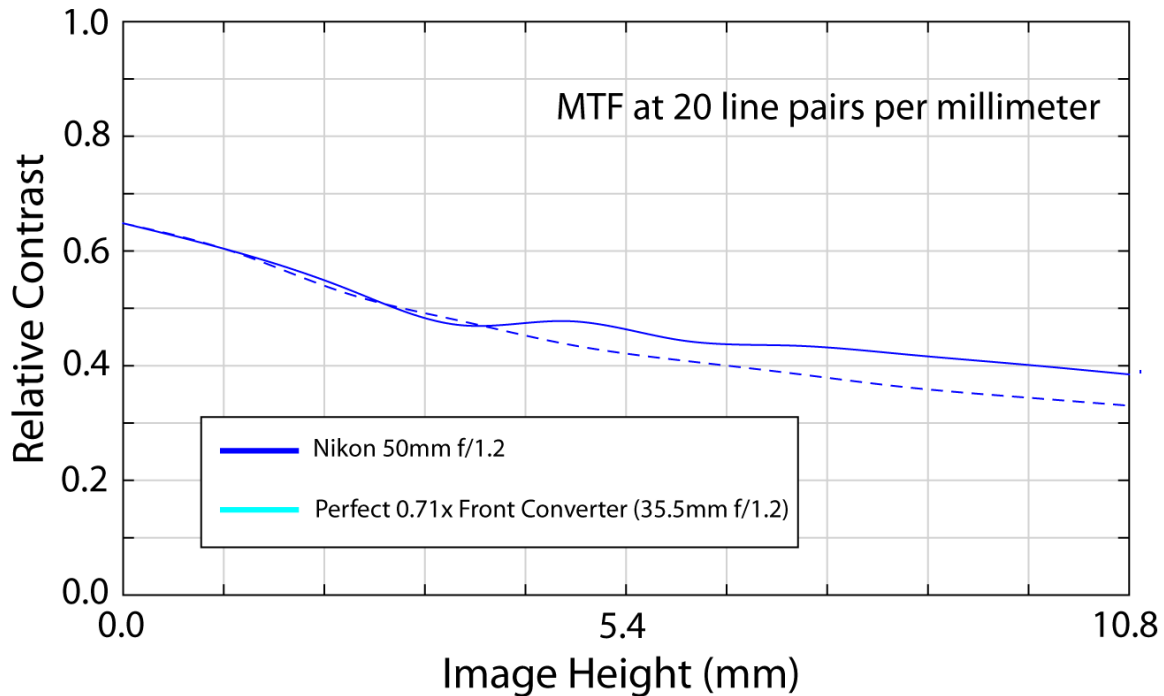


Figure 10: MTF for 50mm lens with (light blue lines) and without (dark blue lines) a perfect paraxial front-mounted wide attachment. There really are two sets of curves here, but they are completely identical, thus the light blue curves are completely hidden by the dark blue curves.

The important thing to realize here is that even if you can use an absolutely perfect front wide attachment you can't improve the MTF of the master lens. This is unlike scaling or the use of a high quality rear-mounted focal reducer, where the MTF is increased even at large apertures, and, most importantly, even in the real world using a well-designed and manufactured focal reducer like the Ultra-m43. Additionally, the front converter can't speed up the lens the way a focal reducer does, and it also adds size and weight. In practice, front attachments also tend to have lots of aberration, so they will generally cause a significant drop in lens performance.

Summary

Paraxial lenses are a useful design device for analyzing the basic properties of various schemes for reducing the focal length of a lens because they introduce no aberrations. A perfect rear focal reducer improves MTF and increases the speed of a system. Scaling a lens to a shorter focal length improves MTF but leaves the aperture unchanged. A perfect front-mounted wide attachment leaves both MTF and aperture unchanged but adds bulk.

Amazingly, actual focal reducer designs like the Ultra-m43 can exceed the performance of a perfect paraxial focal reducer. The excellence of such a design has been shown by using the Zeiss Otus as a master lens and doing actual MTF measurements with a prototype Ultra-m43 focal reducer.



Brian Caldwell

Brian Caldwell is a lens designer and optical engineer with 30 years of experience, and has 500+ design projects and 100+ manufactured products to his credit. Brian founded Caldwell Photographic in 2001 to do independent consulting, and to develop and manufacture optical products. He is best known for his work with Wilfried Bittner to develop the 60mm UV-VIS-IR Apo lens licensed for manufacture by Jenoptik Optical Systems, and also the various Speed Booster products.