QUICK START GUIDE 2.0
Design a Tessar-style Lens with E x H reTORT Ray Tracer
Estimated Time to Invest: 30 minutes

<u>**Purpose**</u>: Design a classic Tessar-style lens as one means of quickly gaining familiarity and skill with the reTORT ray tracer for optical system design. This builds on Quick Start Guide 1.0 which focused on gaining quick familiarity with reTORT's basic navigation at a very low investment of precious time and brings the reader to a high level of competence in using reTORT as a design and analysis tool. Future Quick Start Guides will build further on advanced features of reTORT and its accompanying computational framework, GEMSIF.

<u>**Scope**</u>: Normally, there would be specifications and objectives for the design and use, and ray tracing would be preceded by sketches and calculations to determine initial conditions and intermediate objectives. As the reader is an optical design engineer or researcher, this Guide focuses strictly on the mechanics of using reTORT and those steps common to the use of any design tool are skipped. Instead, we will adopt initial conditions from our past experience and demonstrate the iterative design process and simplicity provided by reTORT. Normally, as the design proceeds, the designer would also identify and resolve aberrations. This guide will touch on that but the full topic of aberrations will be the focus of a future guide.

We're going to follow an example from "Pencil of Rays" and aim toward his 76.93mm back focal length but rather than let diameters vary, stick with the original concept of substantially equal diameter elements. We also don't have the Pencil of Rays materials at hand and will drop in our own set, not trying to match his values. We're not aiming for any particular design f-stop and will focus on those physical values in the calculation of FL and stop aperture rather than the optically-derived value of EFL and pupil size. In this way, we hope to enhance learning of beginning designers while the more experienced designers can surely relate to those other values. We're going to leave you with much you can do to improve the design further.

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1.0 The Classic Tessar-Style Lens (informative, not part of the design exercise)

Tessar is a registered trademark of Carl Zeiss AG. It was invented by Paul Rudolph and granted German patent 142,294 and US patent 721,240, among others. It has remained a steadfast design in the optical industry, particularly for its inherent nature of mitigating astigmatism and spherical and chromatic aberrations, that is, when its principles are applied properly. We are not professing to perfect this design in this guide but rather our intent is to focus on using the Tessar-style as a good tool for gaining familiarity with optical design using the reTORT ray tracer.

Borrowing from the patent, the Tessar-style has four elements as shown below. The first and fourth are meant to be positive lenses usually of a crown glass, while the second and third are negative lenses, usually of a flint glass. The third and fourth lenses are cemented to form a doublet. The stop is located in the approximate center of the lens.
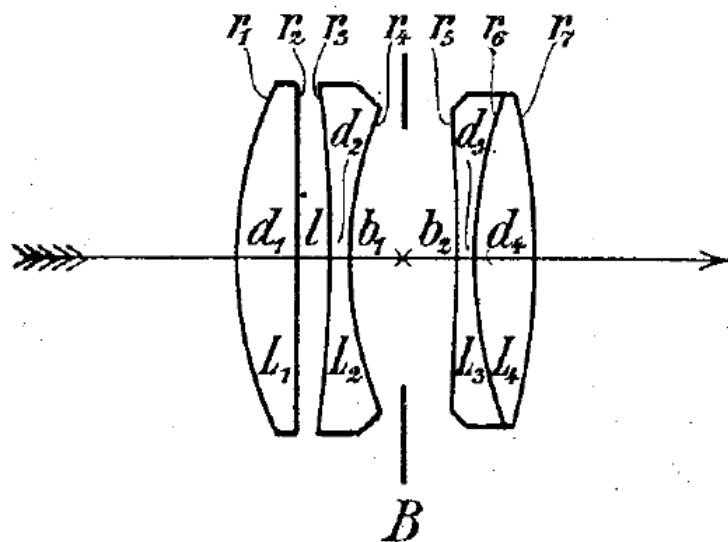

The last is not actually a condition cited in the patent but we have found it a useful initial condition, though usually altered through the design process. The two outer lenses are usually higher refractive index than the two inner, although the difference in "n" of the two elements of the cemented doublet is the most important relationship. But again, these are good starting conditions but can be applied in the reverse and result in a Tessar-style lens of equal performance. You'll find that Abbe numbers are worth paying attention to, sometimes more important than refractive indices.

Most Tessar-style designs observed have four elements of equal or near equal diameter. Again, not essential and dependent on the design objectives. For example, for one of our Customers,

we utilized the Tessar as a component within a more complex system. In this case, not a typical photographic lens, we designed the Tessar component using our "solved diameters" feature. This feature yields the diameter of each element designated as a solved diameter as part of the optimization process. Solved diameters are indicated by setting the diameter parameter of those diameters to be "solved" to "0 mm" or if you prefer, "0 in". This is used within our global CMAES optimization and solved within bounds that meet the system design criteria, if any apply.

In this case, all the diameters were set to 0, to be solved, except the stop.
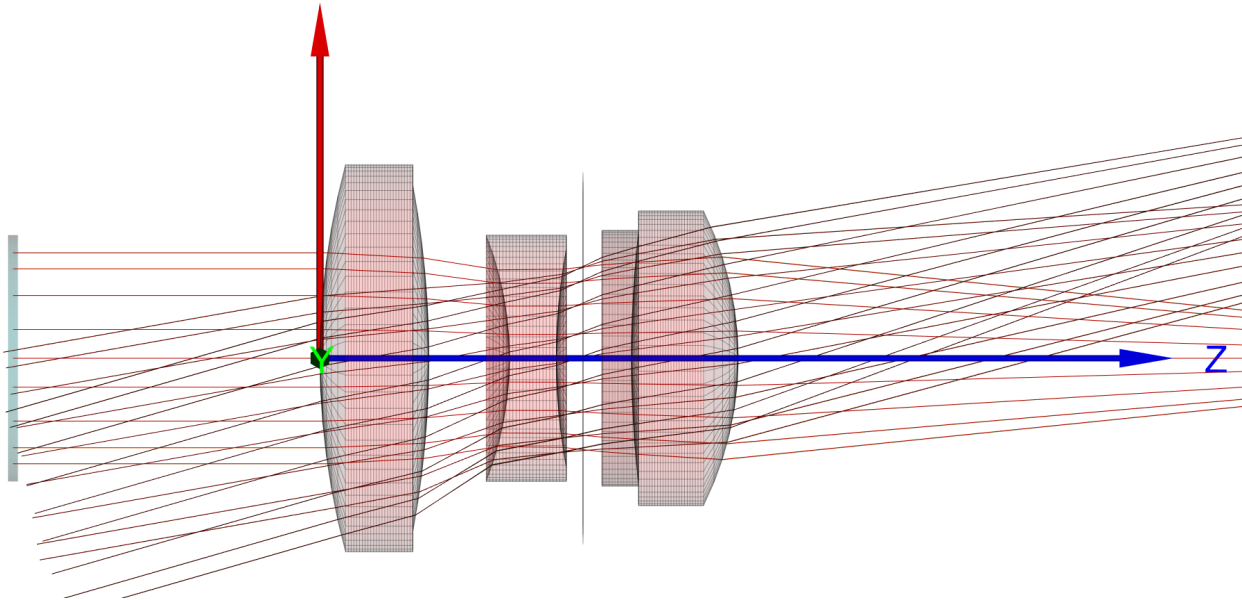
While not meeting all the essential initial conditions cited by the patent, this still meets the essence of a Tessar-style per the original design.

With the luxury of solved diameters, this Tessar-style on its own had just barely acceptable MTF at all angles, for this design, from 0 to 16 degrees off axis. But of course in this situation, this was only one portion of a more complex system.

In not specifying design goals at the start, we're going to play this design by ear as we go along. So, in this exercise, we'll be discovering the design path together with you. We may come back later and try the solved diameters again to see if using this feature offers any improvement to our resulting design.

In the MTF plots you'll find in this guide, as the legend is not strictly necessary, we're going to usually place it to demarcate the "very poor" region of performance below 50% and 10 lp/mm.

Meridonal MTF Trace
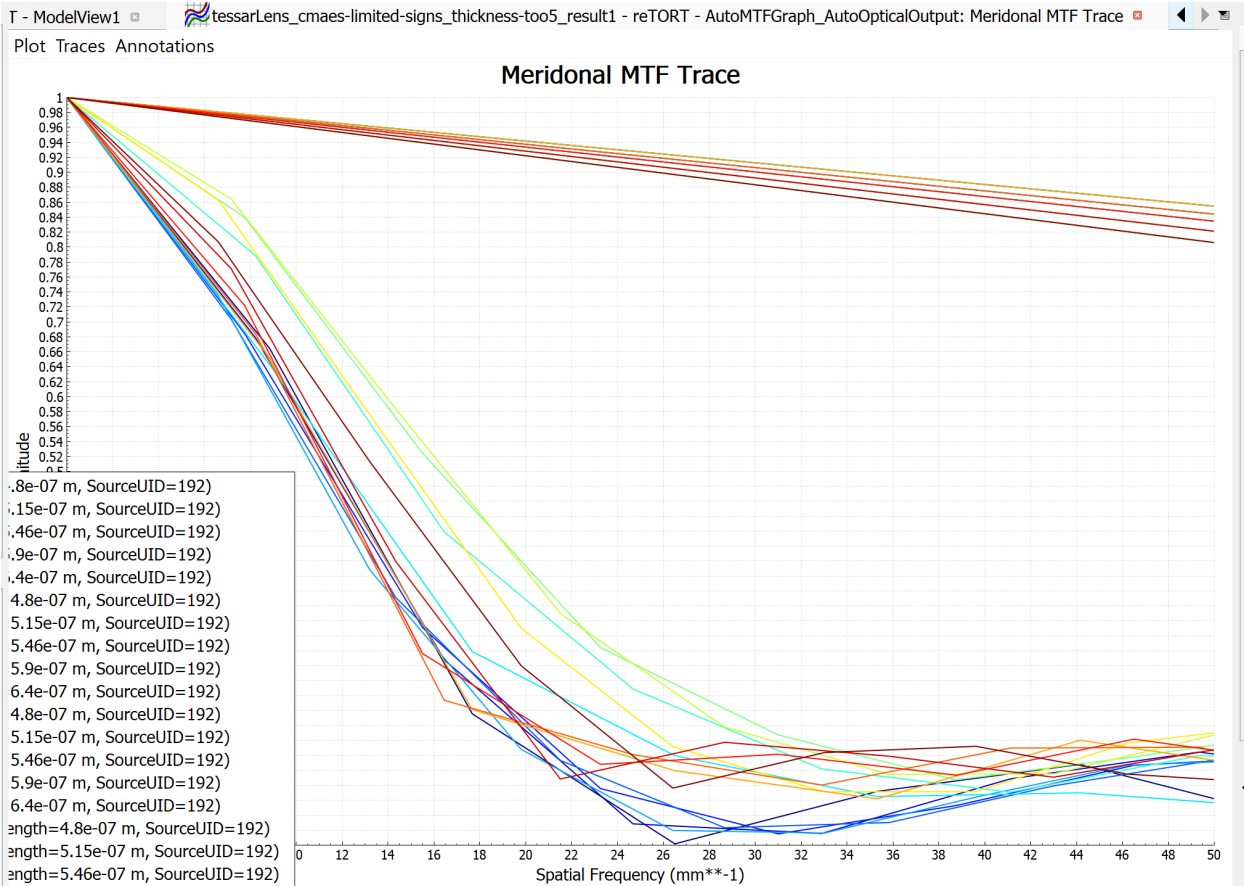
RMS spot sizes for all design angles and all design wavelengths from 480 to 640nm were uniformly 45 to 50 microns which was the principal target of this design. On it' own, a very barely acceptable lens but, as a part of a more complex system, it fit its purpose at the time.

We're going to borrow the initial material choices from this design. We'll get to that in section 3.0.

2.0 Tips and Comments about Using reTORT/GEMSIF and this Guide

1. The most important parts of lens design are the performance goals and pre-planning of the design by doing initial calculations, particularly to set initial conditions. In this guide, given that the reader is likely an optical designer or experienced physicist, we are doing neither but rather establishing some initial conditions from experience, a bit at random to see how it turns out, and allowing reTORT to calculate others. In general, this will bring you up to speed on using reTORT but leave much for you to discover about improving this design.

2. The E x H CMAES implementation is very fast and serves as our major method of optimization, when using the wizard especially. If values are expected to change significantly, we may run only 100 evaluations to start. Normally, we'll run 1000. When refining a design to find the absolute minimum, we'll run 10000 which generally takes from 15 to 20 minutes, and even as many as 40,000. A rule of thumb to start is a 1:1 ratio of evaluations to generations for 1000 and fewer evaluations, and a 5:1 ratio at 5000 and greater evaluations.

3. DLS can also be used to optimize and refine a design. As a personal preference, I lean toward running DLS to set my initial conditions and, in intermediary steps, to restart optimization and observe the gradients before switching back to CMAES.

4. When running DLS without bounds for initialization, I turn on all global thickness bounds on the optimization wizard goals tab, with one exception. Normally, I will only run DLS without bounds enforced at the start of a design for initialization.

5. The exception to #4 above is the coefficients of asymmetric surfaces. Asymmetric surfaces are rigorously rendered and each ray-surface intersection is analyzed with each sampling to assure accuracy of ray tracing and assure no impossible surfaces, such as overlapping, are present. This in effect creates bounds for the polynomial coefficients. In this case, I will run DLS without enforcing bounds for asymmetric aspheres as there are in fact bounds enforced whether the option is checked or not.

6. When running any optimization, DLS or CMAES with bounds enforced, I always turn on the minimum edge thickness global bound on the goals tab. This again does not apply to asymmetric aspheres and you will see a message that edge thickness bounds are disabled when an asymmetric asphere is present.

7. CMAES should always run with bounds enforced as it is a global method and requires defining the search space.

8. You can gather that bounds are important. But you never want to needlessly over-constrain, only when you've hit a limit that you want to preserve. Otherwise, it's good practice to leave at least 2 to 3 mm on both sides of a current value, larger in areas where your analysis shows you want to promote larger movement.

9. Whenever changing parameter bounds, I will run DLS first with bounds enforced until I see the gradient is flattening. This usually provides a good starting point for CMAES. You should find that while DLS has flattened, the E x H CMAES implementation can find a much better solution.

10. To run a simulation, and before each optimization, while not absolutely necessary it is good practice to follow these steps, available in the icons below the main menu and by right clicking on reTORT in the hierarchy: Clear All Data>Validate All>Run All. Assure you see this message in the status box before running an optimization:

ⓘ Simulation completed successfully [5160.438000 ms].

11. For systems with many elements, it is often more efficient to optimize parts of the system rather than all parameters. Experience helps in choosing this sequence according to the most critical aspects of the design. Another strategy is to also optimize only curvatures first and thicknesses later. You will learn what suits your own design methods best. reTORT and GEMSIF are very flexible and adaptable.

12. Develop your own rules as you go along to match your design methodology.

13. Always pay attention to the status dock, I keep it directly below the workspace, It will warn you of problem situations and save you valuable time.

14. Save interim satisfactory designs with descriptive names, You can always come back to that branch of your work and take it in a different direction. GEMSIF will also Auto-save on a regular basis.

15. When you cannot find a function, follow the Model Hierarchy, it follows a typical analysis, starting with the Optical Source and ending with Results and Views.

16. When you cannot find a property, click on the Model Hierarchy among the functions in which you're interested and then scan the Property Editor window that opens, you'll soon learn where to quickly find every bit of design data.

17. Make use of the Parameters Dock to leverage your time by defining additional parameters that can be used by multiple functions.

18. Until you become expert in reTORT and GEMSIF, when you have questions, always click on the function in which you're interested and look to the documentation dock in the lower right for further definition. Usually, your curiosity will be satisfied by the first paragraph you see.

3.0 Tessar-style Design Exercise – Initial Conditions for a 75mm lens

Not working from design objectives, we're going to take initial conditions from our past experience. The principal choices for the four elements are going to be:

Element #	Material	Nominal n value	Abbe number
1	Hikari SK15	1.62299	58
2	Schott F5	1.60342	38
3	Schott K10	1.50137	56
4	Hikari SK15	1.62299	58

The Pencil of Rays elements varied from almost 30mm diameter for the first element on the source side down to about 15mm.

We're going to set a uniform element diameter of 30mm and a stop aperture of 15mm. We'll follow the Pencil of Rays FL of 76.9mm by setting an initial value of 75mm. We'll optimize this at the end to get a more precise number suitable for mechanical design purposes.

An advantage of reTORT is that you can enter data in any units. Units can even be mixed and matched for different fields. reTORT will convert everything to metric for its own computations but maintain your units for reporting. The n value difference for the doublet is important as is the low Abbe number for element 2. However, we'll see if the almost equivalent Abbe numbers of the doublet cause any problems in our design. We'll set the clear aperture margin uniformly at 5mm.

We'll set the curvatures of both sides of elements 2 and 4 to be equal but opposite by using the pickup function. This is a starting point and may be released as our design progresses. For element 2, we know by experience we want the source side to be a smaller radius than the image side, so we're going to offset the image side by adding +0.2 to the source side curvature.

pickup(AutoElement_LensStack1_Index3_Surface_Radius, -1, 0.2 in**-1)

Similarly for element 4, surface Index8 will be equal but opposite to Index7, at least to start:

pickup(AutoElement_LensStack1_Index7_Surface_Radius, -1, 0 mm**-1)

where the -1 indicates a radius opposite to that of Iindex3 and the last term is an offset which here is set to zero.

We'll set initial conditions for curvatures and thicknesses by inserting even numbers, with curvatures correctly signed for a traditional Tessar-style and both curvatures and thicknesses in similar even numbers with the objective of visually seeing the stop close to the center of the system.

Our lens stack and starting model view, with ray bundles of five wavelengths at three angles, now look like:

Surfaces

|	Type	Material	Thickness	Radius	Diameter	Clear Aperture Margin
1	Surface	mat___HIKARI__SK15	0.25 in	1.33333333333333 in	30 mm	5 mm
2	Surface	air	0.25 in	0 mm	30 mm	5 mm
3	Surface	mat___SCHOTT__F5	0.07 in	-3.33333333333333 in	30 mm	5 mm
4	Surface	air	0.25 in	2 in	30 mm	5 mm
5	Stop	air	0.2 in	0 mm	15 mm	0 mm
6	Surface	mat___SCHOTT__K10	0.04 in	-66666.6666666667 in	30 mm	5 mm
7	Surface	mat___HIKARI__SK15	0.35 in	1.33333333333333 in	30 mm	5 mm
8	Surface	air	75 mm	-1.33333333333333 in	30 mm	5 mm
9	Image Plane	air	---	0 mm	1e+15 m	0 mm
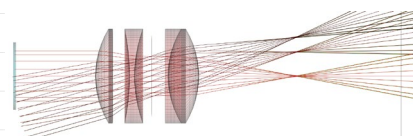
Let's now check and make any adjustments to our output metrics.

In the model hierarchy, navigate to Results>RayResult1>Outputs.

Click on AutoOpticalOutput, or right click and click properties, to check outputs to be computed with each simulation. Click on the double gear in the upper right for advanced properties to see all available choices. Most are checked by default and we're going to add a few more as well as set our focus calculation method to be on the image plane:
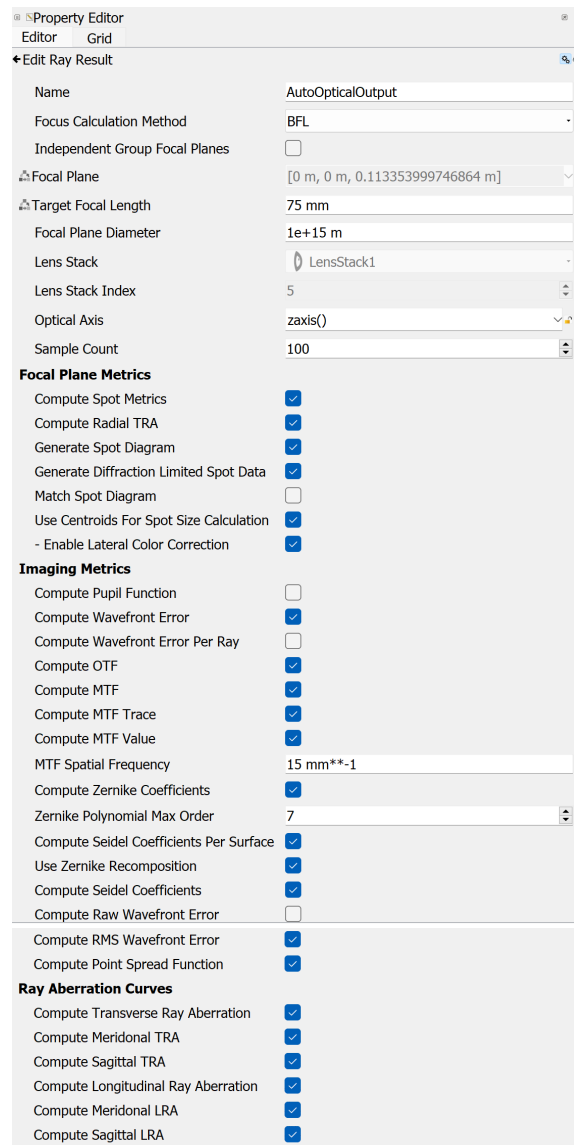
We're calculating at the defined image plane, the sensor in a photographic lens case, and want most of the values to be computed.

Let's do the exact same for OpticalOutput1, directly below the previous selection, which will look much the same and so not repeated here. We're also going to check off "Compute Raw Wavefront Error".

We can set the rest of the initial conditions in the property editor of each surface, in the parameters dock or in the optimization wizard. It all depends on your preference and how much you wish to modify. Each serves its purpose and a change in one appears in all at the same time.

We've run one quick DLS without bounds enforced and our starting conditions in the optimization wizard show only one parameter falling out of bounds, needing correction.

		Parameter	Current	Min Value	Max Value
☑	⚙	LensStack1 Index1 Surface Curvature	0.749999999992947 in**-1	0.45 in**-1	0.9 in**-1
☑	⚙	LensStack1 Index1 Thickness	0.249999999998914 in	0.2 in	0.5 in
☐	⚙	LensStack1 Index2 Surface Curvature	0 mm**-1	-2.7972027972028 in**-1	2.7972027972028 in**-1
☑	⚙	LensStack1 Index2 Thickness	0.249999999999891 in	0.08 in	0.25 in
☑	⚙	LensStack1 Index3 Surface Curvature	-0.300000000003259 in**-1	-0.8 in**-1	-0.05 in**-1
☑	⚙	LensStack1 Index3 Thickness	0.0699999999991634 in	0.04 in	0.25 in
☑	PU	LensStack1 Index4 Surface Curvature	0.500000000003259 in**-1	0.25 in**-1	1 in**-1
☑	⚙	LensStack1 Index4 Thickness	0.250000000000004 in	0.25 in	0.55 in
☐	⚙	LensStack1 Index5 Surface Curvature	0 mm**-1	-2.7972027972028 in**-1	2.7972027972028 in**-1
☑	⚙	LensStack1 Index5 Thickness	0.200000000000014 in	0.2 in	0.6 in
☑	⚙	LensStack1 Index6 Surface Curvature	-0.118450838609111 in**-1	-0.1 in**-1	0 in**-1
☑	⚙	LensStack1 Index6 Thickness	0.0400016877399109 in	0.04 in	0.25 in
☑	⚙	LensStack1 Index7 Surface Curvature	0.653758183691182 in**-1	0.2 in**-1	0.75 in**-1
☑	⚙	LensStack1 Index7 Thickness	0.393700790003235 in	0.25 in	0.55 in
☑	PU	LensStack1 Index8 Surface Curvature	-0.653758183691182 in**-1	-0.75 in**-1	-0.2 in**-1
☑	⚙	LensStack1 Index8 Thickness	75 mm	73 mm	77 mm

Some ranges are invalid. Make sure Min < Max and Current is between Min and Max.

☑ Enforce Global Bounds   ☐ Enforce Local Bounds

Run Global	Run Local

In the goals tab, we used all of the global thickness constraints available in the goals tab under secondary goals. When we run a global optimization using CMAES, we will normally release the max bounds and the min lens edge thickness and control these within the individual Index bounds on the parameters tab. Except for the minimum edge thickness goal which we normally engage.
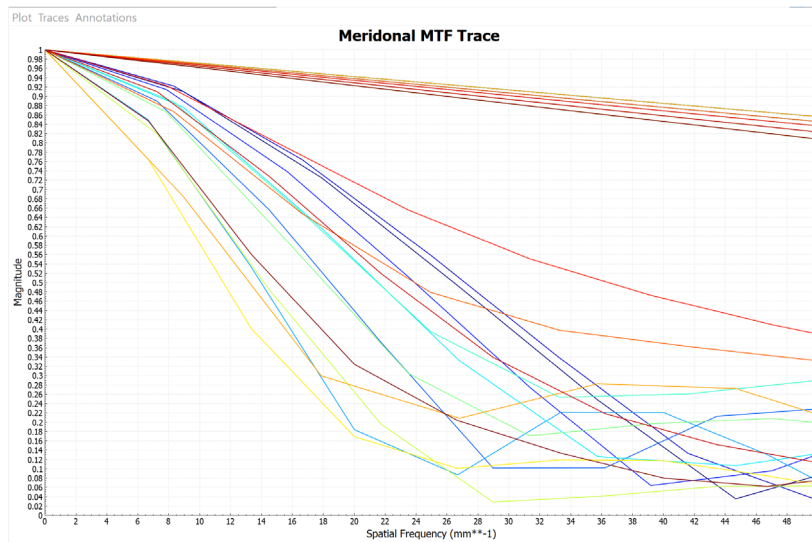
Other than that, we will use our best practices above in Section 2.0.

Using those rules, we determined through sensitivity analysis that the conditions we set up performed better at a FL of 100mm+, our best case targeting a 75mm FL was:
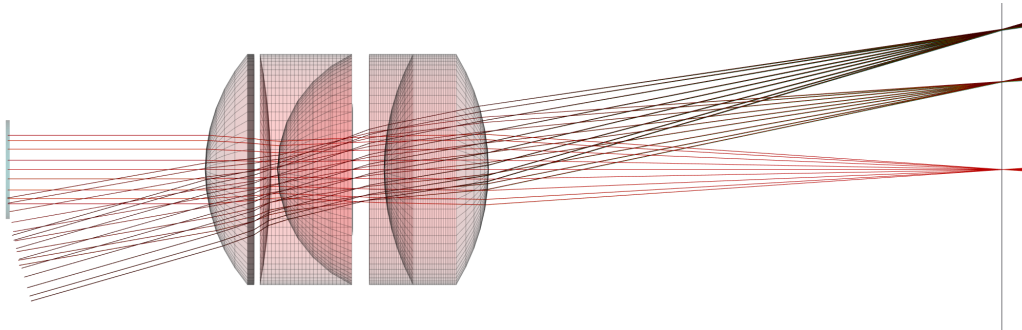
MTF is acceptable but not exceptional, in fact marginal for a few combinations of theta and wavelength, without a clear trend.
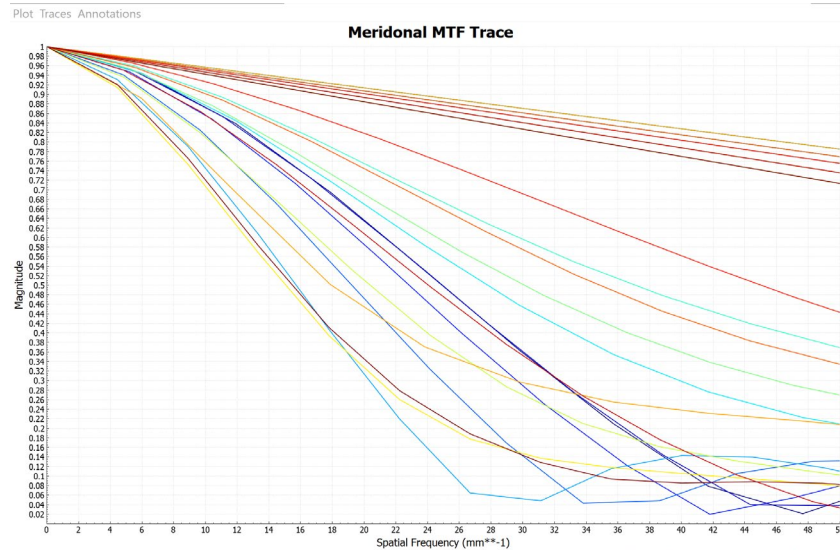

Spot sizes are also adequate but not stunning:

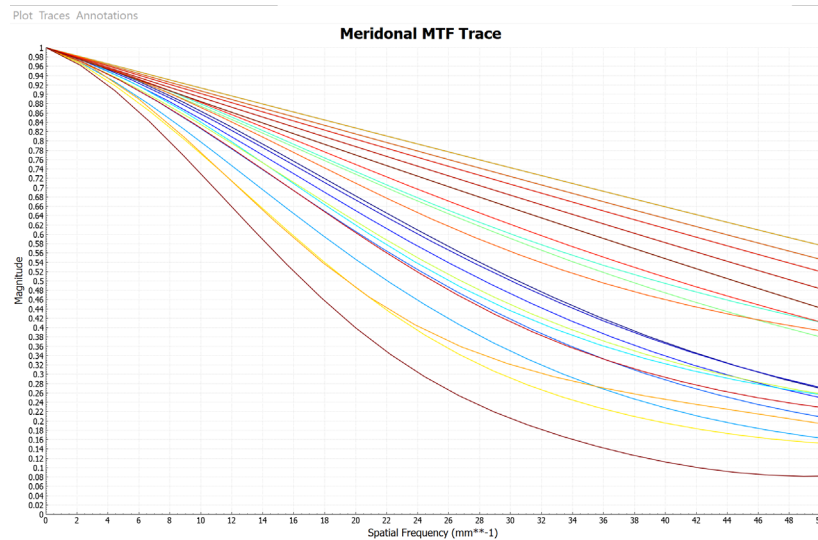| Theta (degrees)	RMS Spot Size (microns)
0 (On Axis)	23
10	32
16	34

Wavelength (nm)	RMS Spot Size (microns)
480	27
515	28
546	28
590	30
640	34

As we stop the lens down, though, MTF incrementally improves, first at 10mm stop aperture:

Then at 5mm:

When we stop down a design to check it's performance at different stop apertures, after changing the diameter of the stop in the lens stack, it's good practice to change the beam diameter of the BeamSource in its property editor. This is simply to initialize it as we'll reset the beam diameter to be based on the entrance pupil. Go to reTORT>Sources/BeamSource1, right click and select properties to open the property editor. Unclick "Select Diameter based on Pupil", change the beam diameter to the new value, and then reenable "Select Diameter based on Pupil".

reTORT tells us the EFL is 77mm and the entrance pupil diameter is 16mm so at f4.8, it's falling right in the middle of the nearest standard f-stops of f/4 and f/5.6.

What if our FL target was 100mm+?

4.0 Reoptimize to Achieve FL ~ 100mm

The prior design is sound but not well performing. We will use that as a base in this new analysis but change the FL to 100mm +/-5mm. We would normally use bounds of only +/-2 to 3mm but in this case, have no target and no idea of where this particular design will yield its best performance.

When we make this change, remember to go to Results>RayResult1>Outputs>AutoOpticalOutput and then also OpticalOutput1 and change the Target Focal Length from 75mm to 100mm. Our Focus Calculation Method is set on Image Plane so temporarily set that to BFL, make the change from 75 to 100 or whatever it is in your case, and then return the Focus Calculation Method to Image Plane.

We optimize according to our rules as before. First we will run DLS enforcing bounds until the rate of change slows. This is usually only 2 or 3 cycles of 100 evaluations. We will monitor our bounds and alter them as needed while running CMAES. In this case, we were stabilized very quickly and then ran 30,000 evaluations.

This yielded a FL of 103.7mm, EFL of 126mm, which seems unusually large, and entrance pupil size of 19mm.

Recall this is just an exercise. I'm not sure where we would make use of this lens design with such a large focal length. Other than an exercise like this, the design goals need to fit a particular application need.
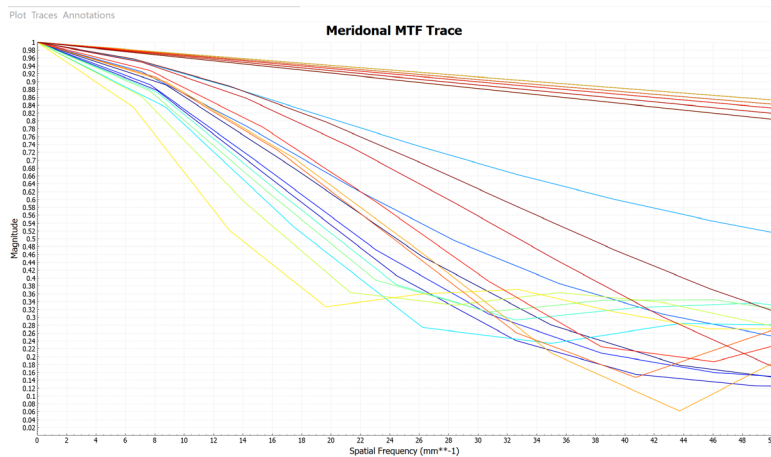
The model view resulting:
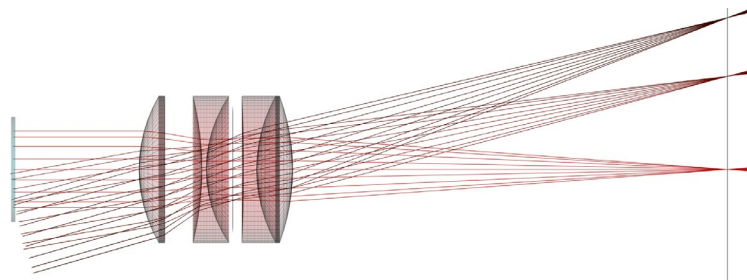
MTF is good with all but the 480nm wavelength at 10 degrees off axis falling below the others. We've seen slight evidence in dispersion in some of our intermediary results as well but nothing that was worrying.

Meridonal MTF Trace
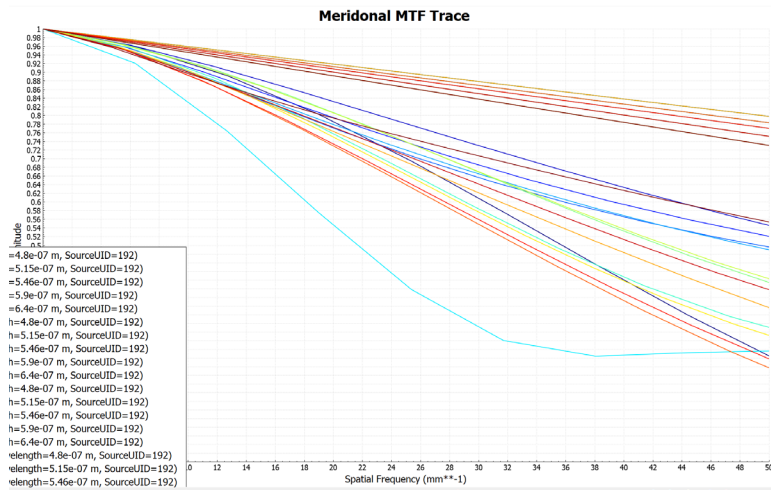
As expected, stopped down to 10mm, we see the typical improvement:

Meridonal MTF Trace

Spot sizes are also improved, cut in half from the 75mm example:

Theta (degrees)	RMS Spot Size (microns)
0 (On Axis)	13
10	19
16	19

Wavelength (nm)	RMS Spot Size (microns)
480	17
515	16
546	17
590	18
640	18

5.0 Substitute Higher n, moderate V, Materials in 75mm Design

Especially for the doublet. Another choice could be to use high Abbe materials. This would be the case if we saw more difference in MTF and spot size as a function of wavelength. But in fact, despite using dispersive materials, we are seeing very minor wavelength dependency. We may try this later but our current material change will focus on the refractive indices.

Our greatest effect should be in modifying the doublet. We search for a pair of materials with a large difference in n values but very close Abbe numbers. The higher n value material will be for the symmetric positive element 4, the lower for the negative element 3.

On the source side of the stop, we'll maintain the slight difference in n values as previously with the higher refractive index used in the positive element 1. Our choice for negative element 2 has a much lower Abbe number. We hadn't considered Abbe numbers in our search and will have to watch this carefully as it could be problematic.

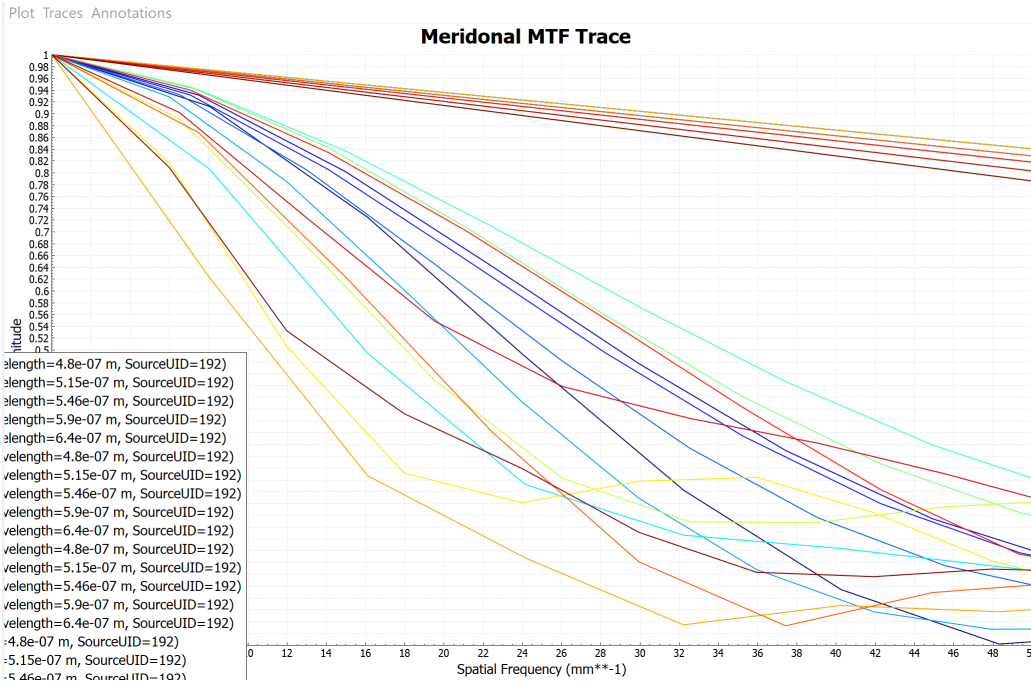We'll apply this change first to our barely acceptable 75mm design.

We would normally substitute new materials gradually but for this exercise, at this point, we have selected a completely new substitute panel based upon their representative n values:

Element #	Material	Nominal n value	Abbe number
1	Ohara LAH66	1.7725	49
2	Ohara TIH10	1.7283	28
3	Ohara FTM16	1.5927	35
4	Sumita LaSFn21	1.8500	40

The result is a small improvement over the initial 75mm design, although it's a question whether the improvement is worth the added cost of materials.
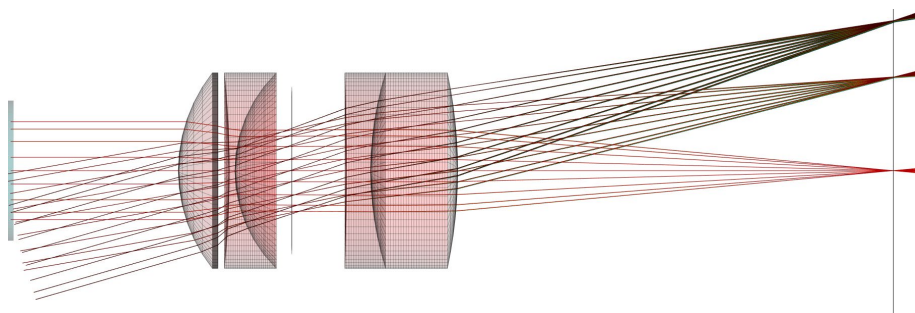
Although not a strong improvement in MTF,

Meridonal MTF Trace

Plot Traces Annotations

X-axis: Spatial Frequency (mm**-1)

Legend (partial, cut off):
elength=4.8e-07 m, SourceUID=192)
elength=5.15e-07 m, SourceUID=192)
elength=5.46e-07 m, SourceUID=192)
elength=5.9e-07 m, SourceUID=192)
elength=6.4e-07 m, SourceUID=192)
velength=4.8e-07 m, SourceUID=192)
velength=5.15e-07 m, SourceUID=192)
velength=5.46e-07 m, SourceUID=192)
velength=5.9e-07 m, SourceUID=192)
velength=6.4e-07 m, SourceUID=192)
velength=4.8e-07 m, SourceUID=192)
velength=5.15e-07 m, SourceUID=192)
velength=5.46e-07 m, SourceUID=192)
velength=5.9e-07 m, SourceUID=192)
velength=6.4e-07 m, SourceUID=192)
=4.8e-07 m, SourceUID=192)
=5.15e-07 m, SourceUID=192)
=5.46e-07 m, SourceUID=192)

RMS spot sizes have not been significantly reduced, and actually increase substantially at the highest off-axis beam source angles.

Our conclusion, this is not a good approach to improving the 75mm design. But that's the reality of optical design, we try a theory and either continue with it to the end, more often modify it, and sometimes abandon a direction completely.

6.0 Improve the 75mm design using Solved Diameters?

As mentioned earlier, rather than specifying surface diameters, reTORT provides the capability to solve for those diameters through optimization to meet a set of performance criteria.

We'll start with our final 75mm design.

To solve for the diameters, we set those diameters we desire to solve, it does not need to be all the surfaces, you can solve for only select diameters, but we simply set them to zero. Note that we still want to specify the clear aperture margin which we'll maintain at 5mm. This amount will be additive to each solved diameter.

Here then is our lens stack with the FL reset to 75mm, to which we'll add bounds of +/-3mm.

Surfaces

	Type	Material	Thickness	Radius	Diameter	Clear Aperture Margin
1	Surface	mat___HIKARI__SK15	0.284062210504427 in	1.09245665978568 in	0 mm	5 mm
2	Surface	air	0.133130174285968 in	0 mm	0 mm	5 mm
3	Surface	mat___SCHOTT__F5	0.040013155862692 in	-3.27341905897652 in	0 mm	5 mm
4	Surface	air	0.4 in	0.869600833801765 in	0 mm	5 mm
5	Stop	air	0.113432936305168 in	0 mm	15 mm	0 mm
6	Surface	mat___SCHOTT__K10	0.0684907796869075 in	-49472.6385881562 in	0 mm	5 mm
7	Surface	mat___HIKARI__SK15	0.417239563595283 in	1.22214486492203 in	0 mm	5 mm
8	Surface	air	75 mm	-1.5209022013473 in	0 mm	5 mm
9	Image Plane	air	---	0 mm	1e+15 m	0 mm

reTORT is pretty bright. We've adjusted an existing solution and so, wherever reTORT sees the diameter replaced by 0mm, it's going to provide an initial condition for each of those diameters. Therefore, before even running our first simulation, our model view has changed.
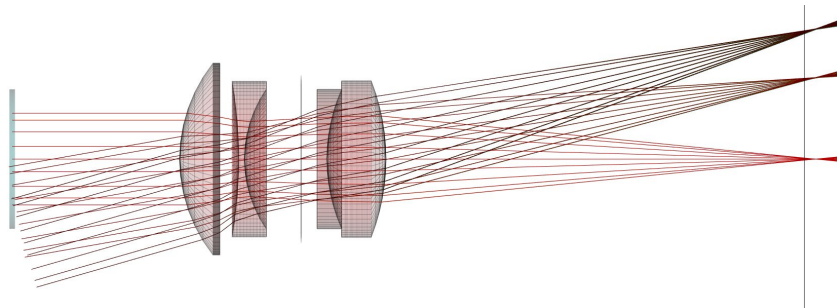

For the record, here is the parameters tab of the optimization wizard with which we'll be starting:

reTORT gives us a very good start and after further initialization using two runs of DLS of 100 evaluations each, our maximum spot size at the image plane is already down to 41 microns before starting to run our star optimizer, CMAES.
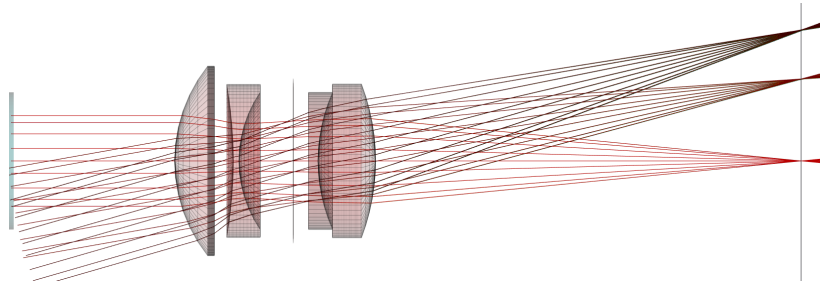
CMAES was run for 30,000 cycles, the MTF is acceptable and more so, all five 16 degree off-axis lines show that this result has very good edge contrast, from 24 to 32 lp/mm at the 70% level.
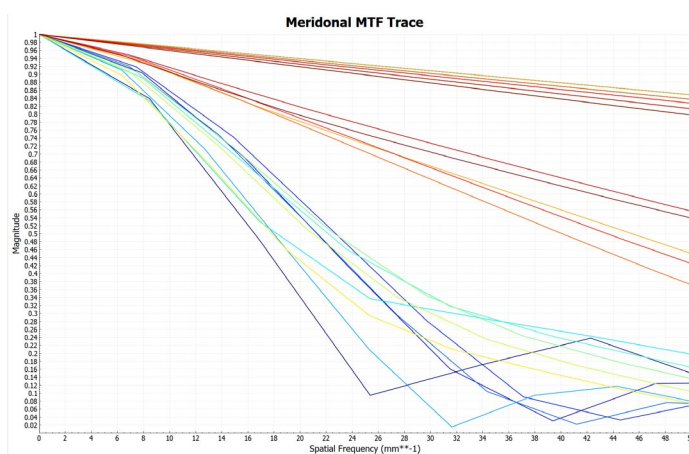
The final model view for this design:
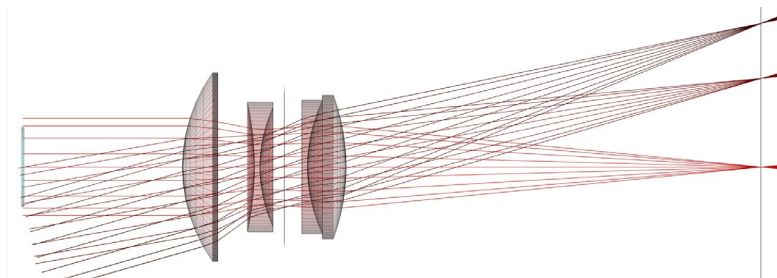
The spot sizes are uniform throughout, although not as small as we would like to complete this design:

| Theta (degrees)	RMS Spot Size (microns)
0 (On Axis)	25
10	26
16	28

Wavelength (nm)	RMS Spot Size (microns)
480	27
515	25
546	25
590	26
640	28

This result has an EFL of 95mm and entrance pupil of 19mm, equivalent to f/5, not terribly good for low light conditions but otherwise good performance

We inserted the solved diameters into the lens stack, all except Surface8 which is causing the abrupt transition from the third element. As element 3 is smaller in this solution, it will never come into play but we want to arrive at that through reTORT's strict computations.
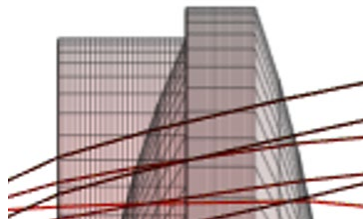
We maintain Surface8 as a solved diameter and reoptimize resulting in the same results and the following model view, confirming the Surface8 diameter = Surface7 diameter.
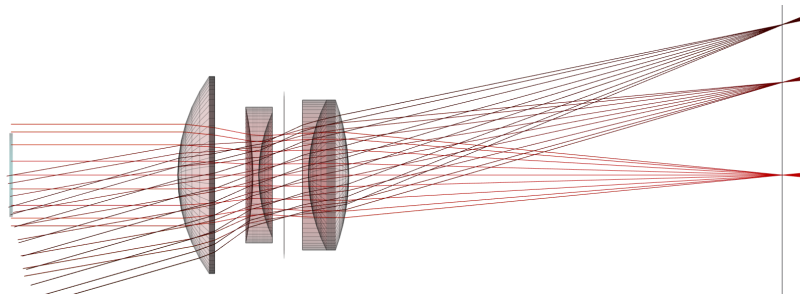
The lens stack w/ the diameters as determined by reTORT's solved diameters method then:

Surfaces

	Type	Material	Thickness	Radius	Diameter	Clear Aperture Margin
1	Surface	mat___HIKARI__SK15	0.262007437967585 in	1.20247923445749 in	30.40940185 mm	5 mm
2	Surface	air	0.271321156663182 in	0 mm	28.36907768 mm	5 mm
3	Surface	mat___SCHOTT__F5	0.0400328143835752 in	-2.25549128869819 in	19.43854329 mm	5 mm
4	Surface	air	0.180193891115709 in	1.05411155637558 in	17.46431479 mm	5 mm
5	Stop	air	0.131869359550534 in	0 mm	15 mm	0 mm
6	Surface	mat___SCHOTT__K10	0.0400403945364604 in	-133.00740163521 in	20.13922001 mm	5 mm
7	Surface	mat___HIKARI__SK15	0.286706356440019 in	1.15891525645774 in	21.99148889 mm	5 mm
8	Surface	air	78 mm	-1.55392151752592 in	21.99148889 mm	5 mm
9	Image Plane	air	---	0 mm	1e+15 m	0 mm

The distance to the image plane has been pushing it's upper bound. As we saw earlier, this design wants to have a larger distance from the back surface to the image plane, perhaps, as before, closer to 100mm.

But let's look at how this lens design performs as it's stepped down. First, at a 10mm.

On-axis MTF is still acceptable but a little worse while the 16 degree off-axis still approaches it's theoretical maximum levels. The 10 degree performance remains between.
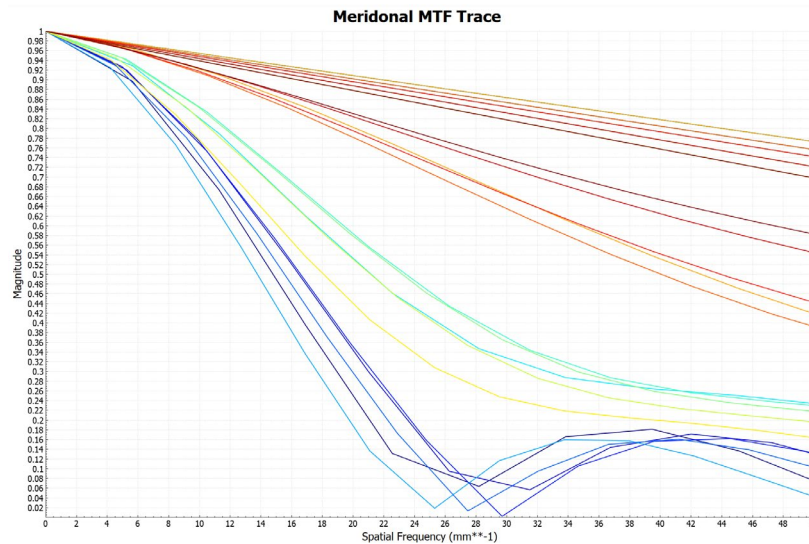
Let's also look at the spot sizes.

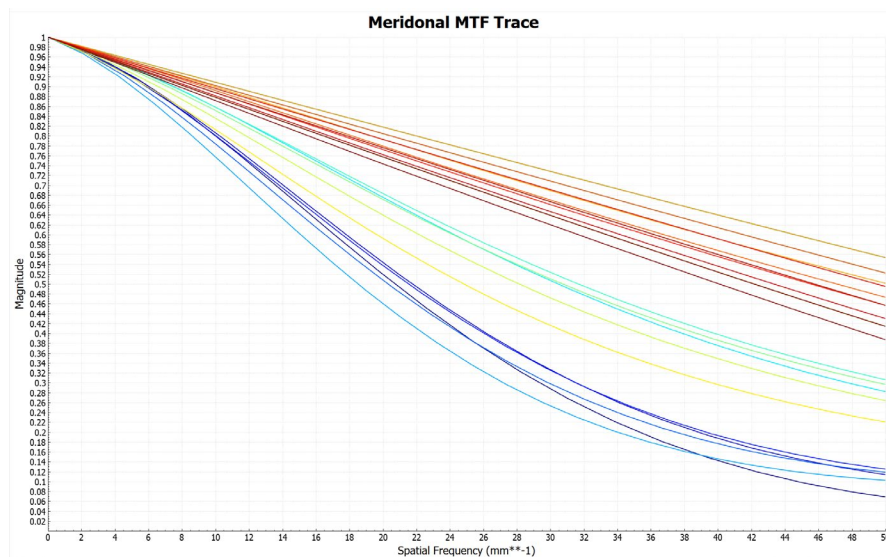We see again the superior performance of the 16 degree off-axis.

Theta (degrees)	RMS Spot Size (microns)
0 (On Axis)	31
10	22
16	13

Wavelength (nm)	RMS Spot Size (microns)
480	22
515	21
546	21
590	22
640	24

Let's look at stopping down to 5mm.

We see further improvement across the board relative to theoretical when stopped down to 5mm, the best performance still at the edges.

The spot sizes show excellent performance at the edges, much better than on-axis. This design could be improved further on-axis.
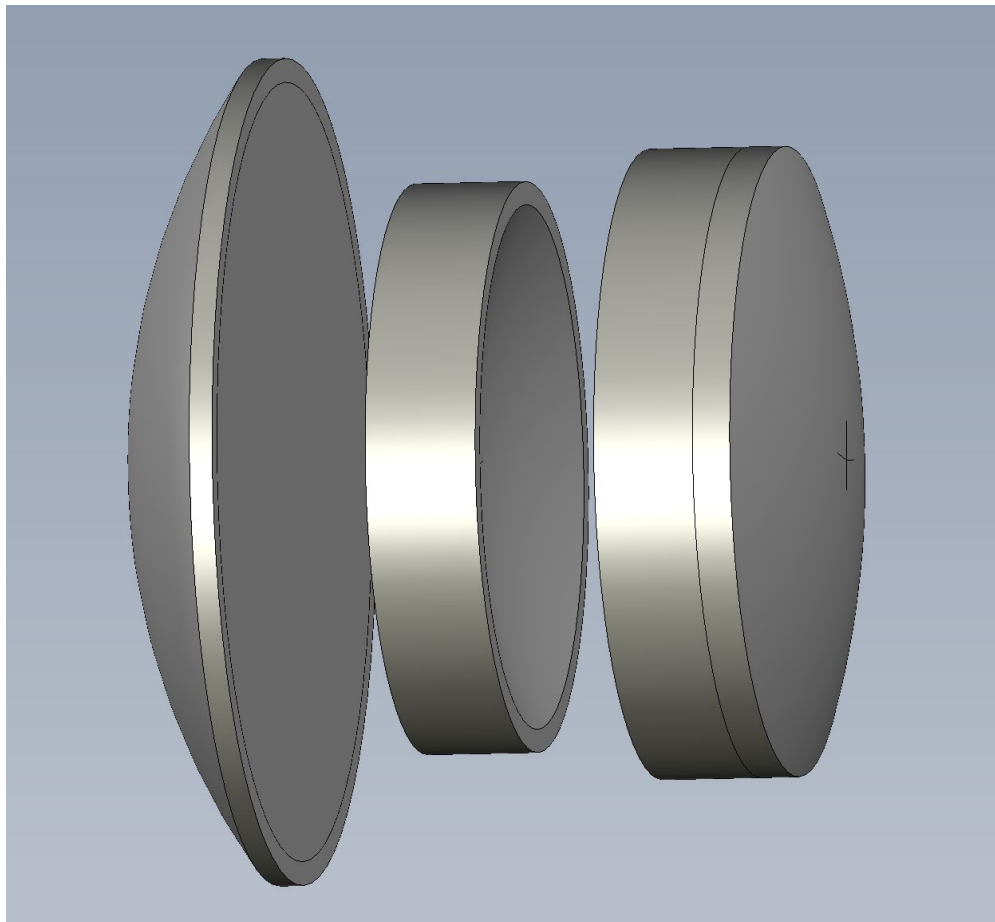
Theta (degrees)	RMS Spot Size (microns)
0 (On Axis)	23
10	14
16	4

Wavelength (nm)	RMS Spot Size (microns)
480	14
515	13
546	13
590	14
640	15

Spot sizes are uniform by wavelength.

7.0 Export to CAD

Download to IGES, STEP or STL files.

8.0 Conclusions and Observations

In this guide, we've set out certain good practices to use in designing optical systems with reTORT. We fully expect the designer to further develop these to suit their own style and types of systems they're working with. In this case, this is a very simple, axially symmetric design for the purposes of quickly getting up to speed with using reTORT effectively.

We've taken the user through several scenarios with our "imaginary" Tessar-style lens. There are many other ways to take this design and many other tools to use, the most popular for this style of lens, the further substitution of materials. There is plenty of room to further improve these designs and we leave that to the reader to take further if they should choose. Or to take what you've learned here and use reTORT on another design of your choice.

We've also demonstrated the power of reTORT's solved diameter method. This is a method that can quickly lead to a viable design. But even more so, it will be a viable design that can be modified further as you test sensitivity of critical aspects of the design under different input conditions.

Happy designing!