Some lens design methods

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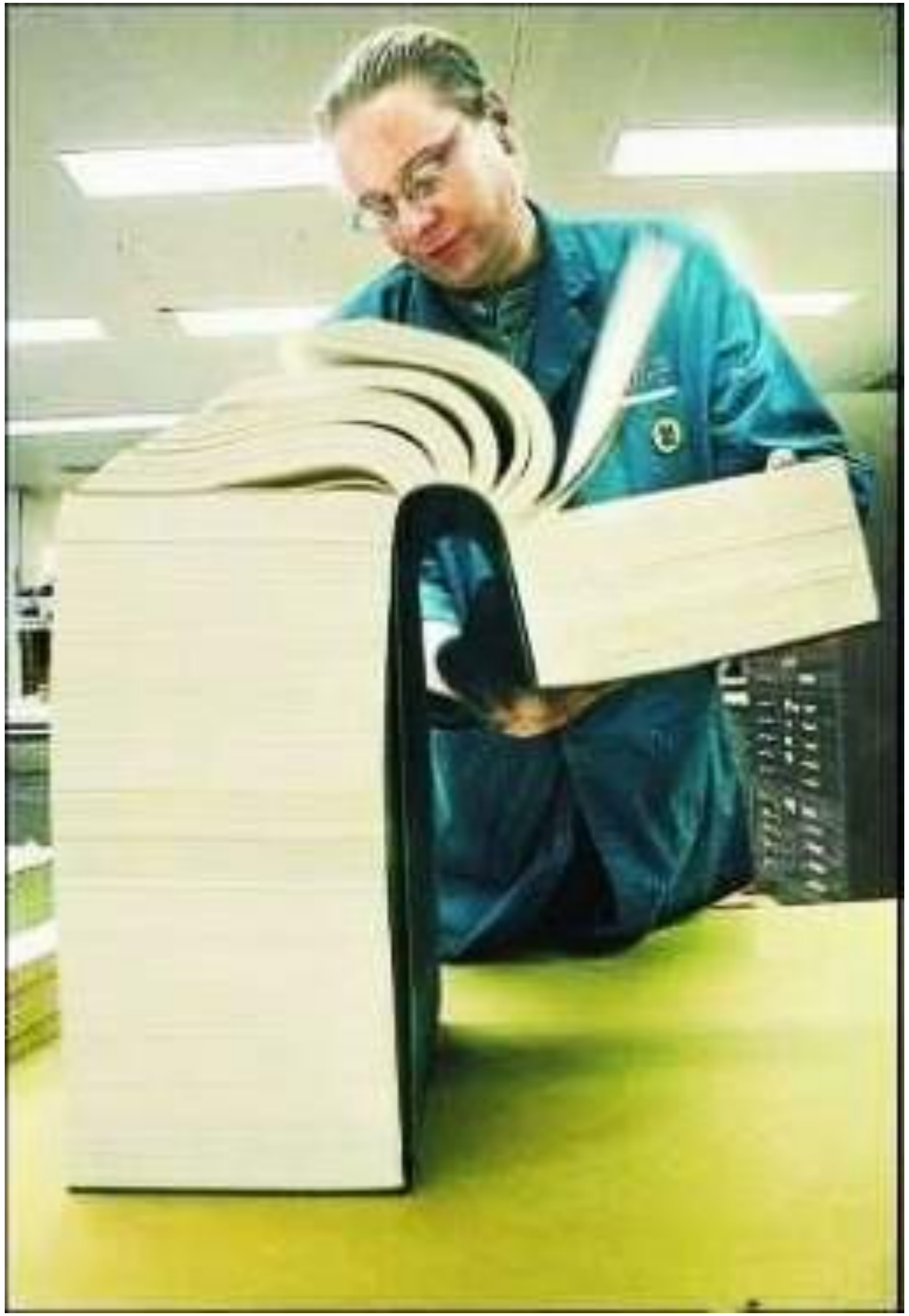
Where do we find our ideas about <u>how</u> to do optical design?



You probably won’t find a simple answer in your CODE V, etc. manual

How can we come up with new design forms?

What design tools do we have?

Answer – **your brain**

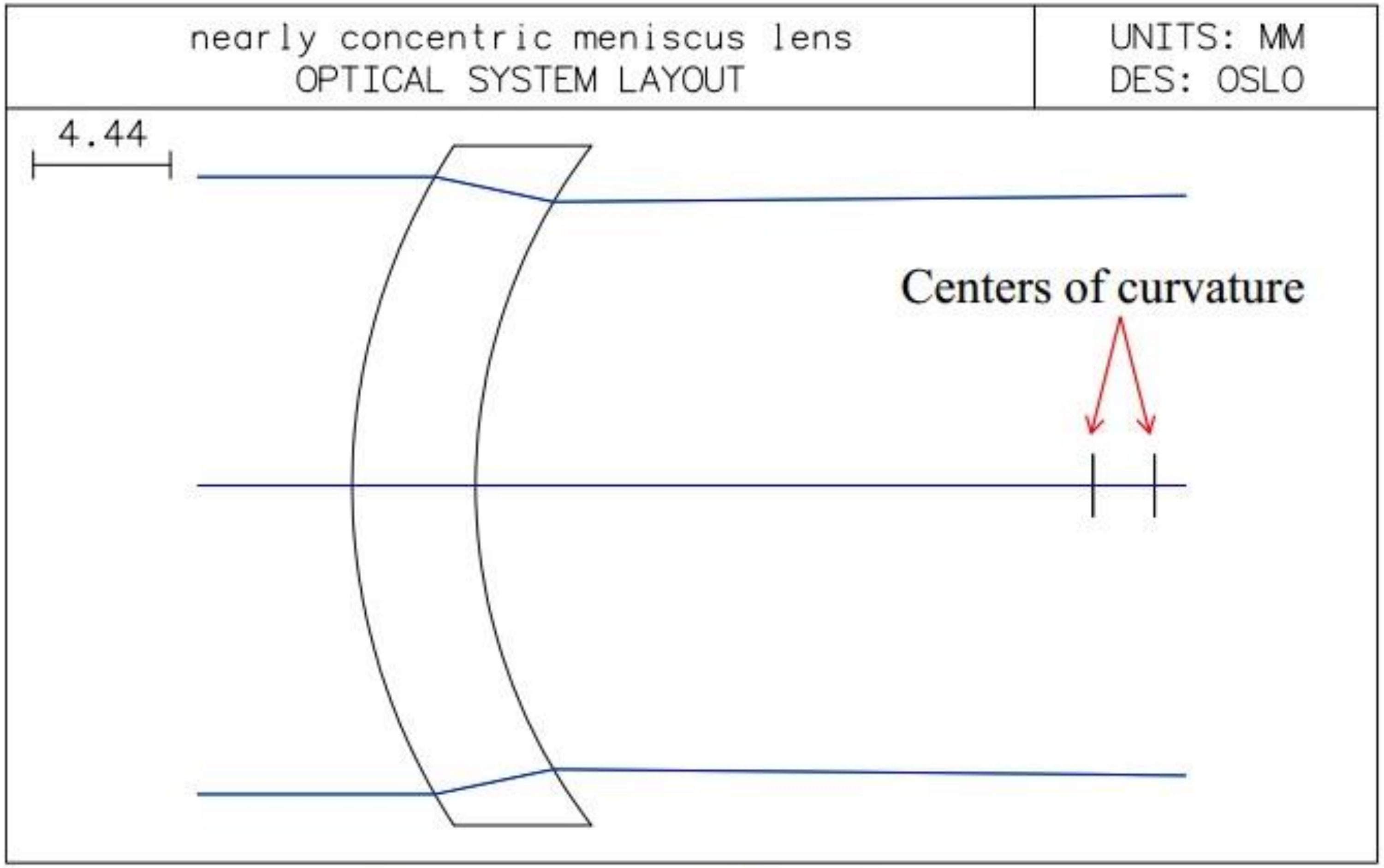
Your Brain

- Free
- Good for 16 hours a day
- User-Friendly
- Familiar Language
- Portable
- Time-Sharing Capability
- Color Monitor
- No Ads

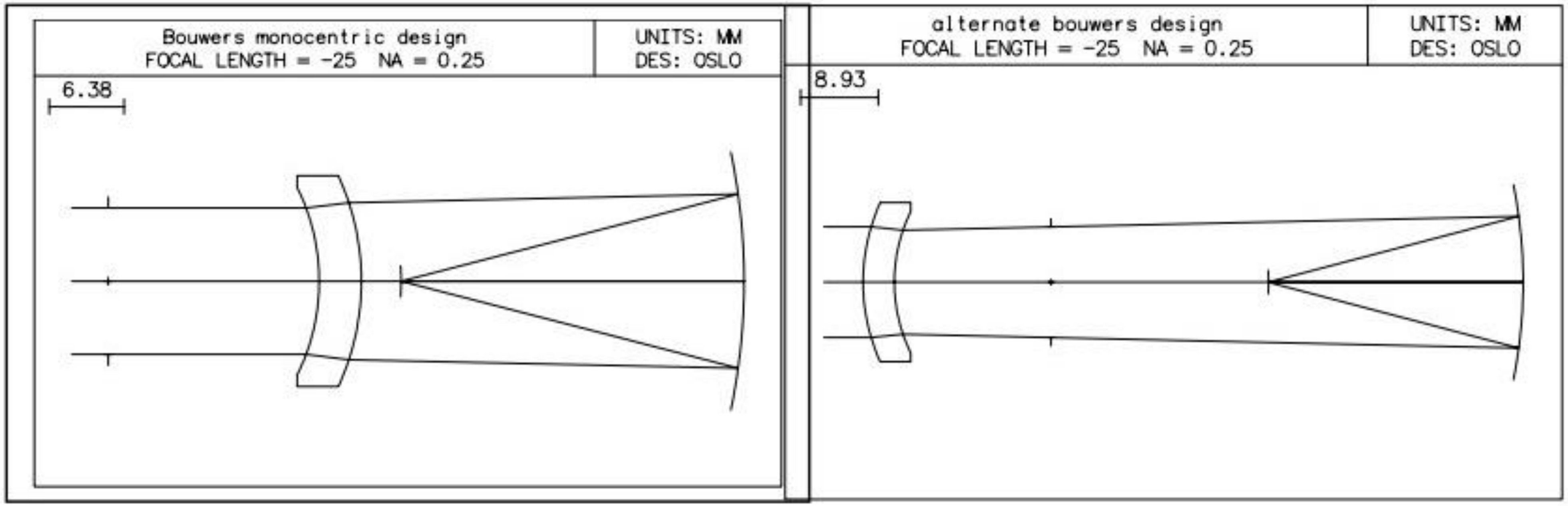
Although computers have revolutionized optical design there is still a big need for creative thinking by the designer, using your own personal mental PC

Experienced designers have a toolbox of design methods and "tricks" that they use when developing and optimizing a new design. The goal here today is <u>not</u> that you learn these or even remember them, but that you see what it might be like to be a professional lens designer. It can be a lot of fun. We will now look at some examples.

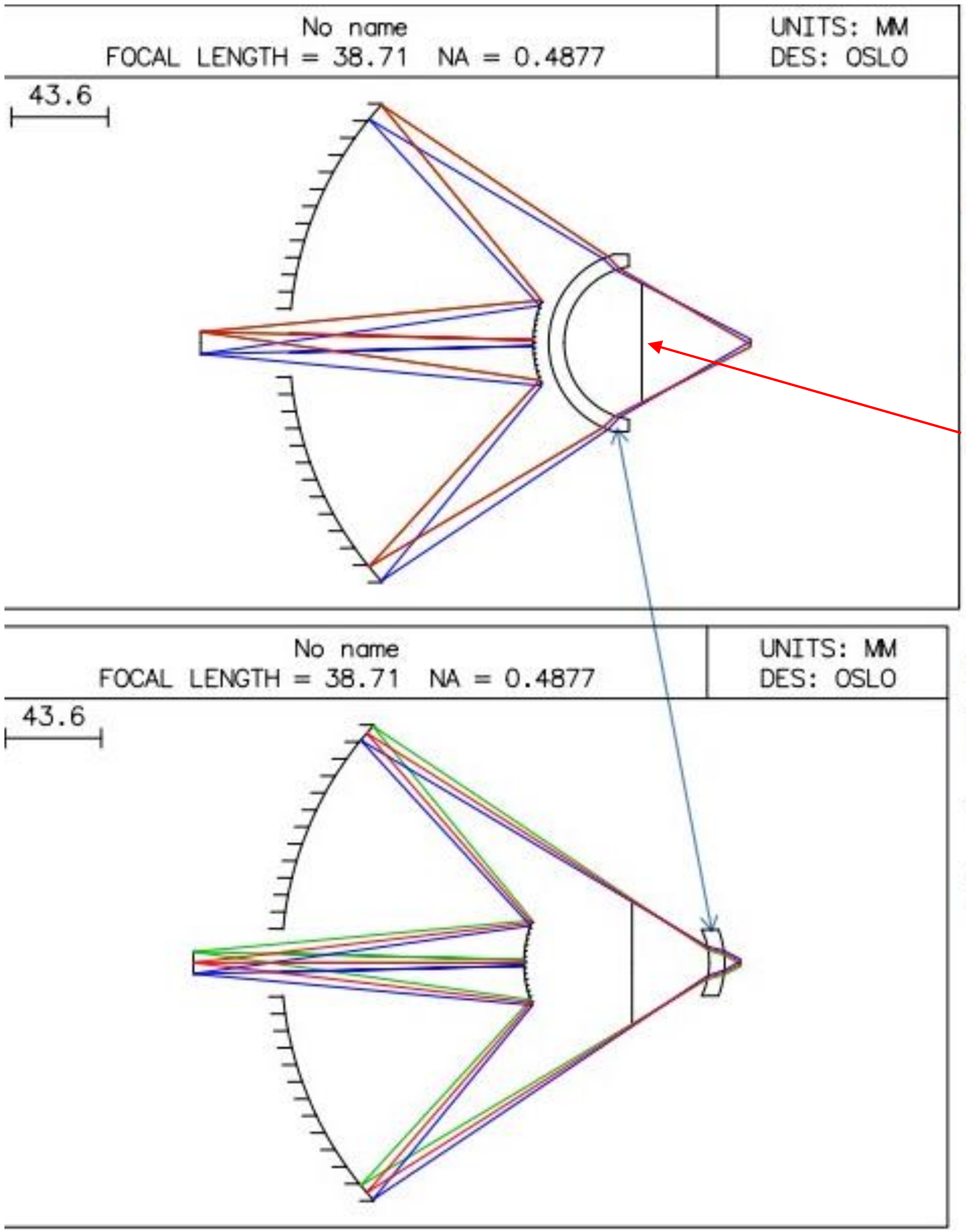
Designing with meniscus nearly concentric lenses



A nearly concentric lens acts as if it is located near the two centers of curvature – both with respect to first order optics and also aberrations. It acts like a weak power (at the first order level) aspheric Schmidt plate located near the centers of curvature, with considerable spherical aberration.



Here are two monocentric (exactly concentric) designs with exactly identical aberrations, to all orders. If you flip a monocentric lens over to the other side of its common center of curvature nothing changes about the system's aberrations. Here the monocentric meniscus lens corrects for the spherical aberration of the mirror. Since that mirror also shares the same common center of curvature in this Bouwers design, there is no 3rd order coma or astigmatism.

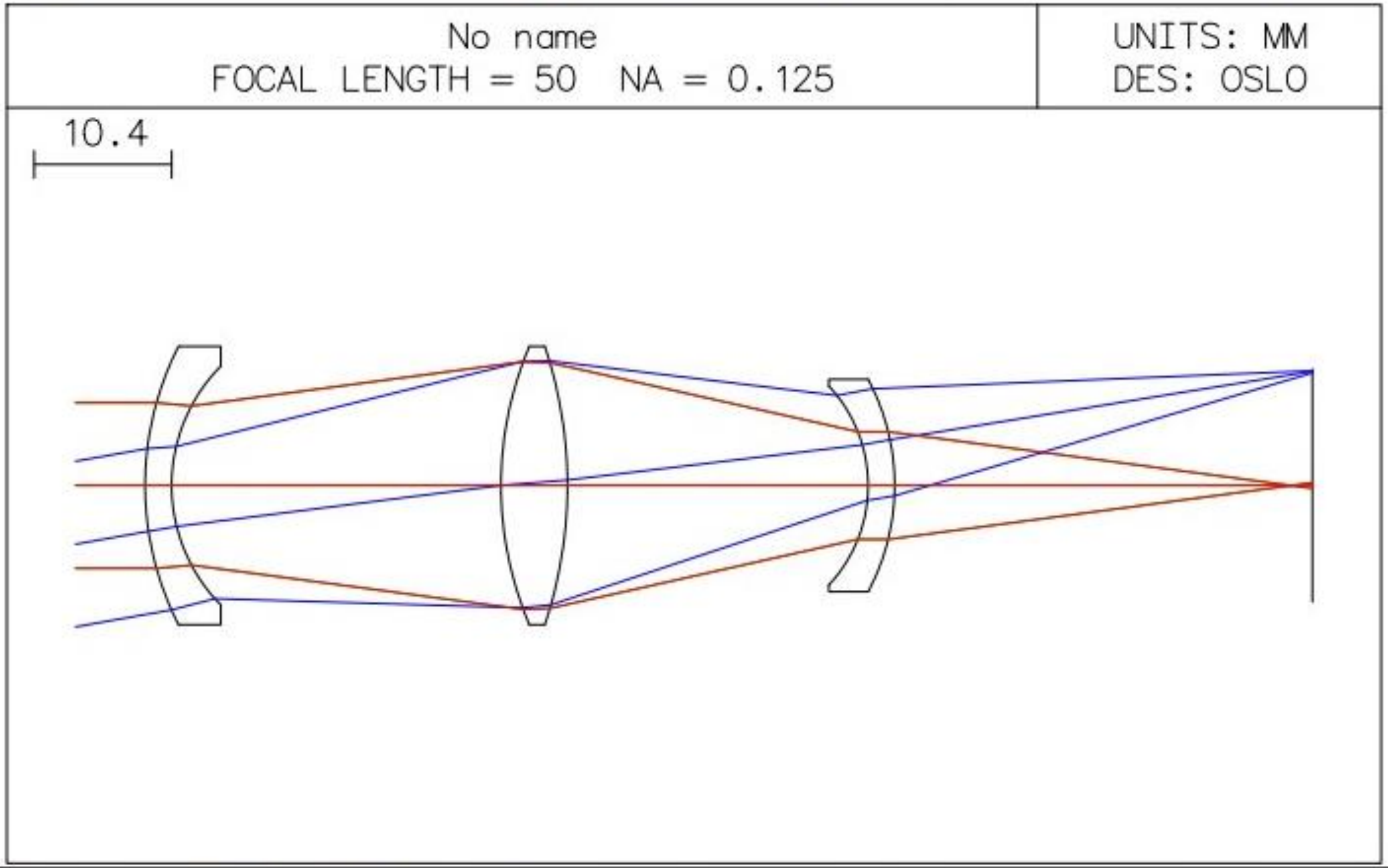


Concentric lens in front of aperture stop has an exact concentric equivalent behind the aperture stop.

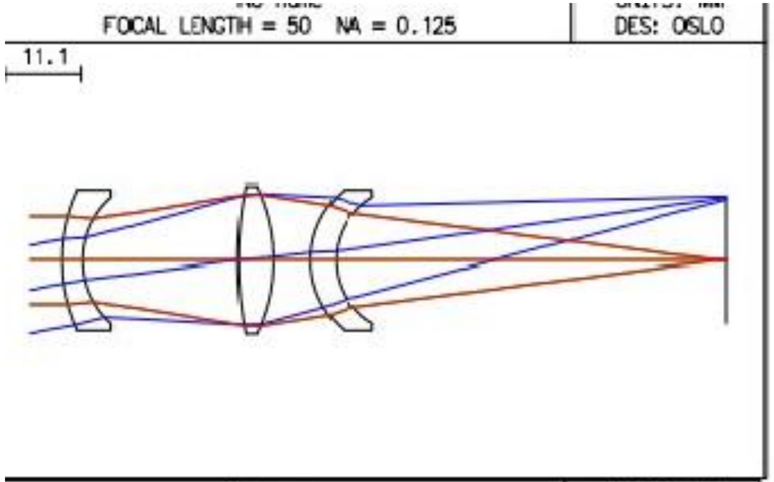
Exactly the same aberrations to all orders, but one lens version is very much smaller than the other one.

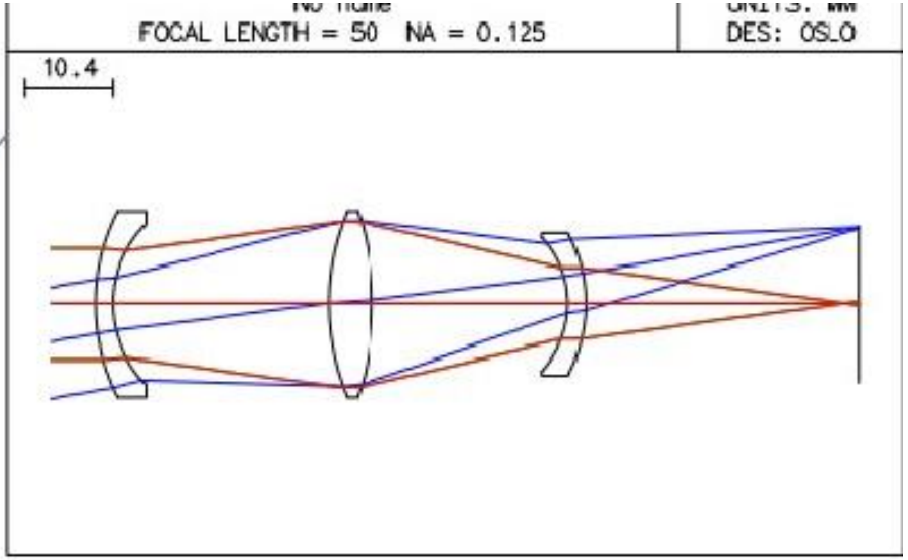
This property of monocentric or nearly monocentric lenses is very useful to know about and to use.

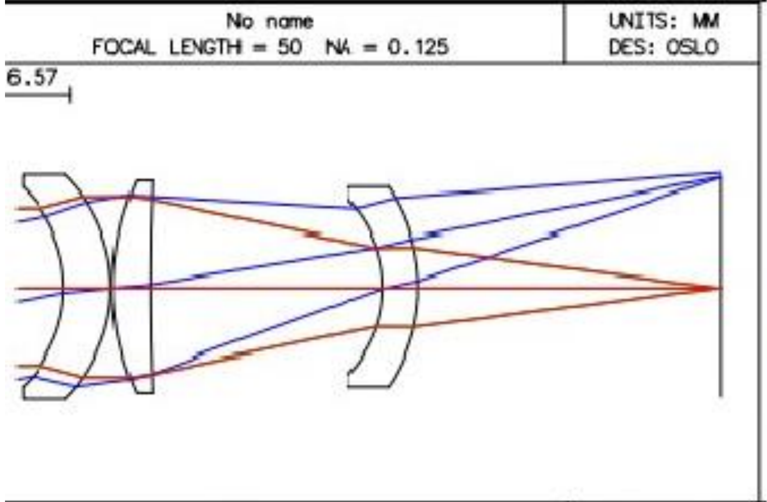
A nearly concentric meniscus can often be flipped over to the other side of its centers of curvature to give a new design version. Here is a design corrected for all five 3rd-order aberrations. The two outer lenses are not very close to being concentric. But we will try flipping them over in the opposite direction, one at a time.

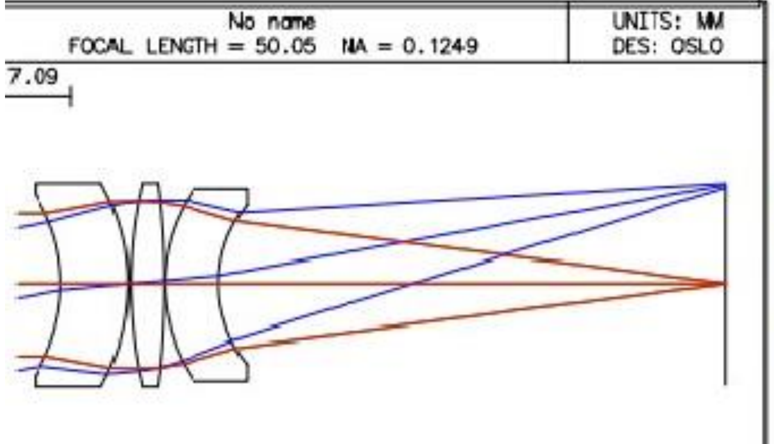


If there is space available to do it you can usually make a new well-corrected design by flipping a nearly monocentric (concentric) lens over to the other side of its nearly common centers of curvature and then reoptimizing.



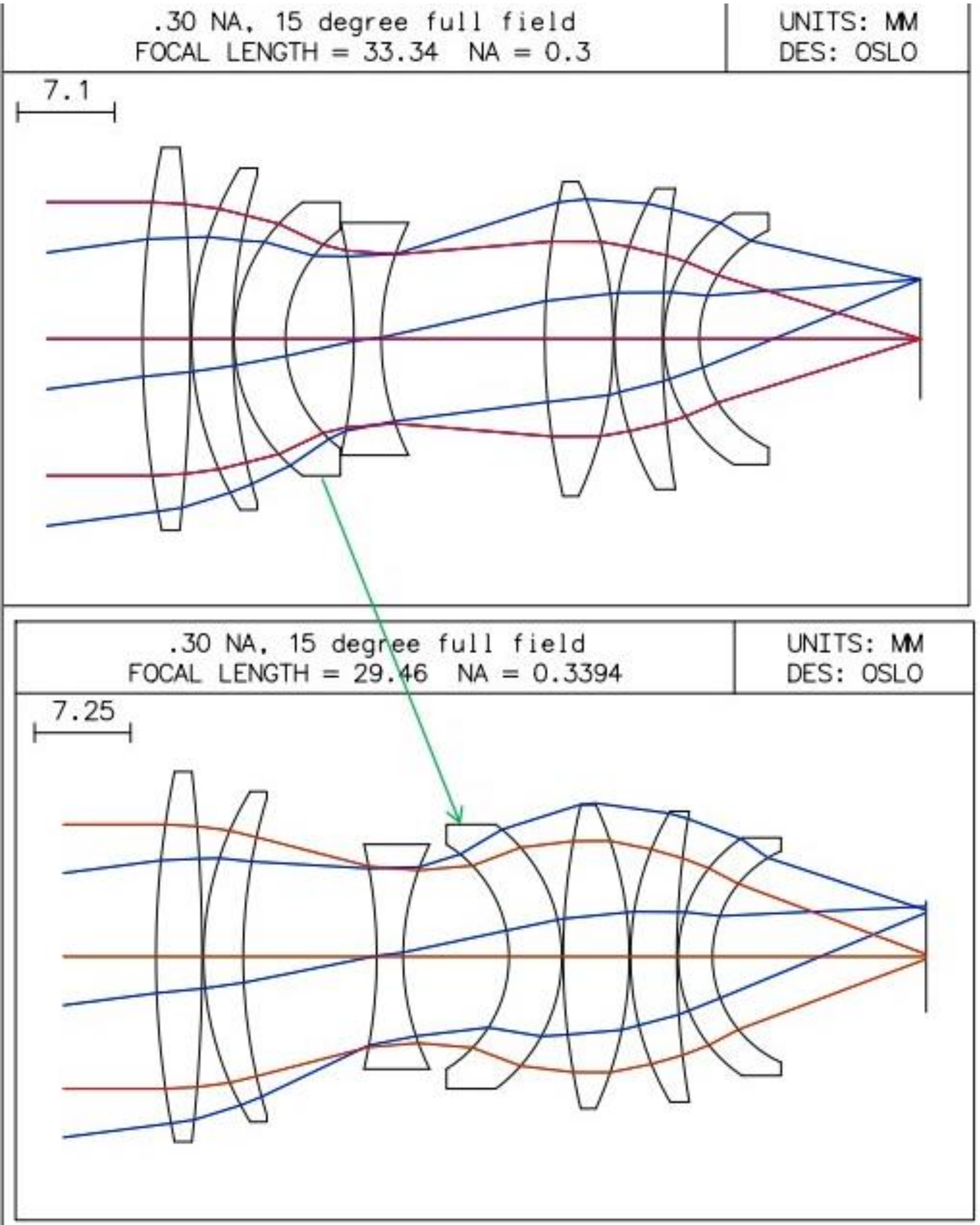






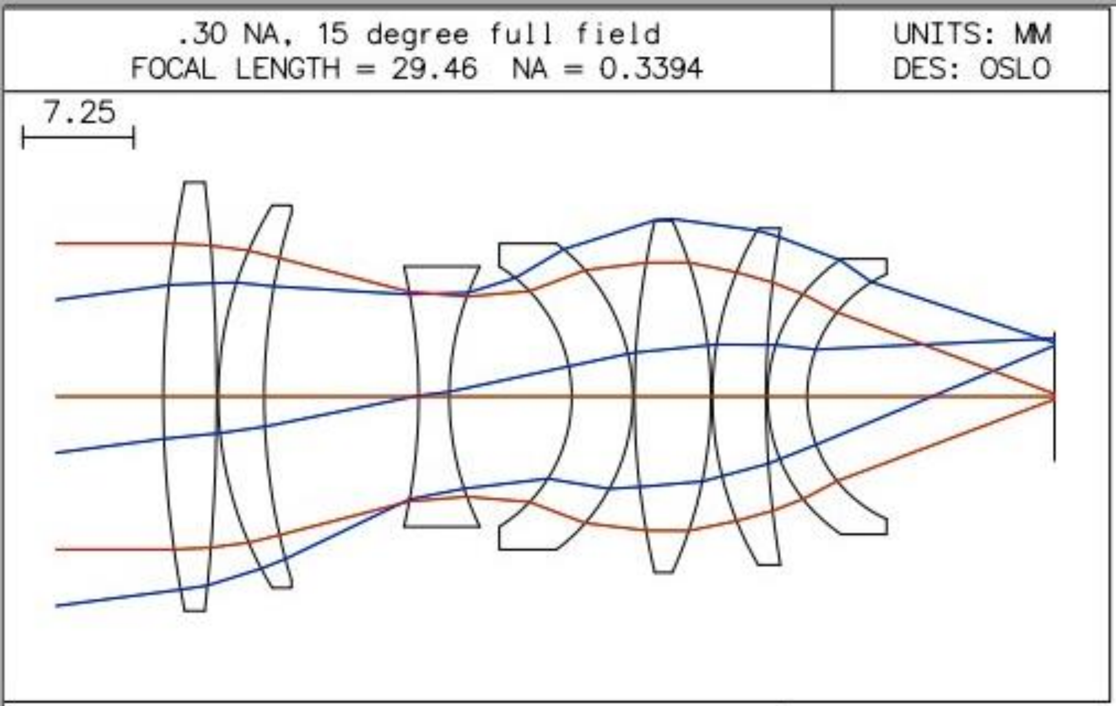
The three designs on the left are all corrected for all the 3rd order aberrations. Each design was the result of flipping one or both of the outer lenses in the design above over to the other side of its average center of curvature and then reoptimizing. Lens thickness is important for the three designs on the left but not for the one at the top here.

The designs will differ in their higher order aberrations and in their length.

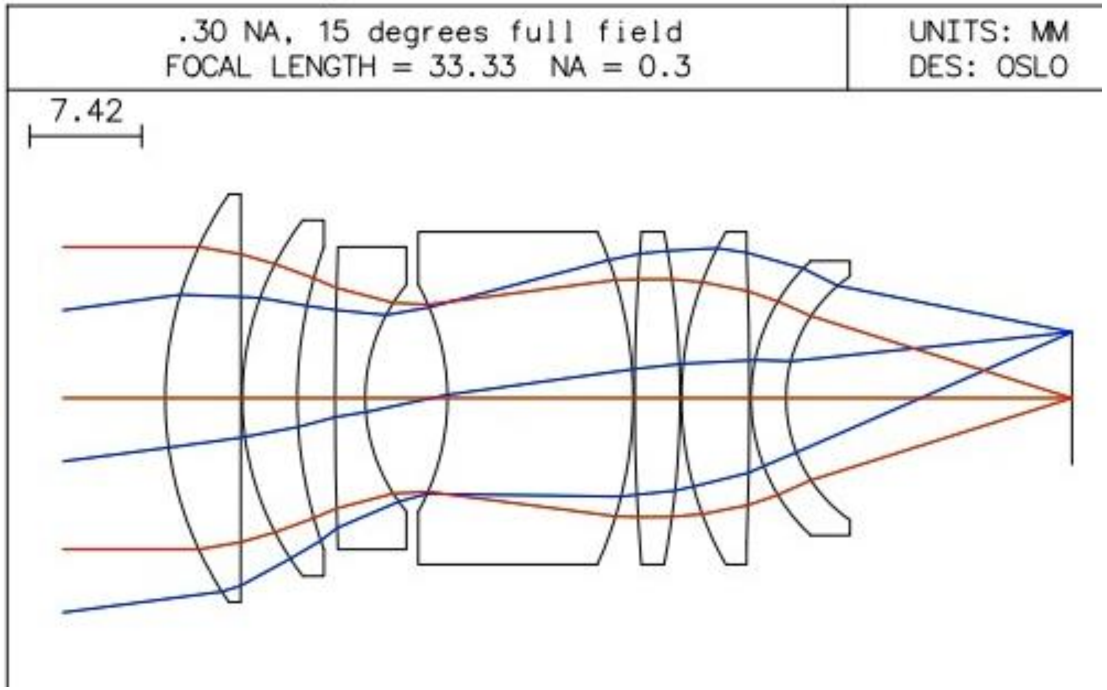


Flip nearly concentric lens over to other side of its centers of curvature to get an alternate design. Then reoptimize. Of the two designs one will be better than the other. There is no way to tell in advance which will be better.

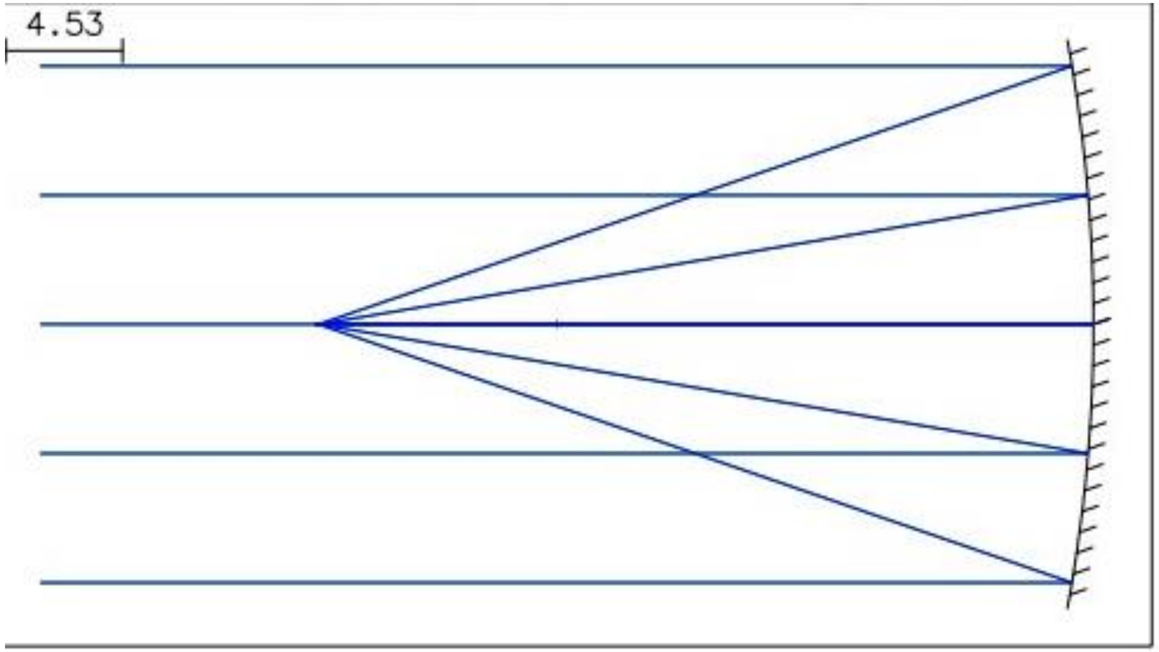
<ins>Not yet reoptimized</ins>



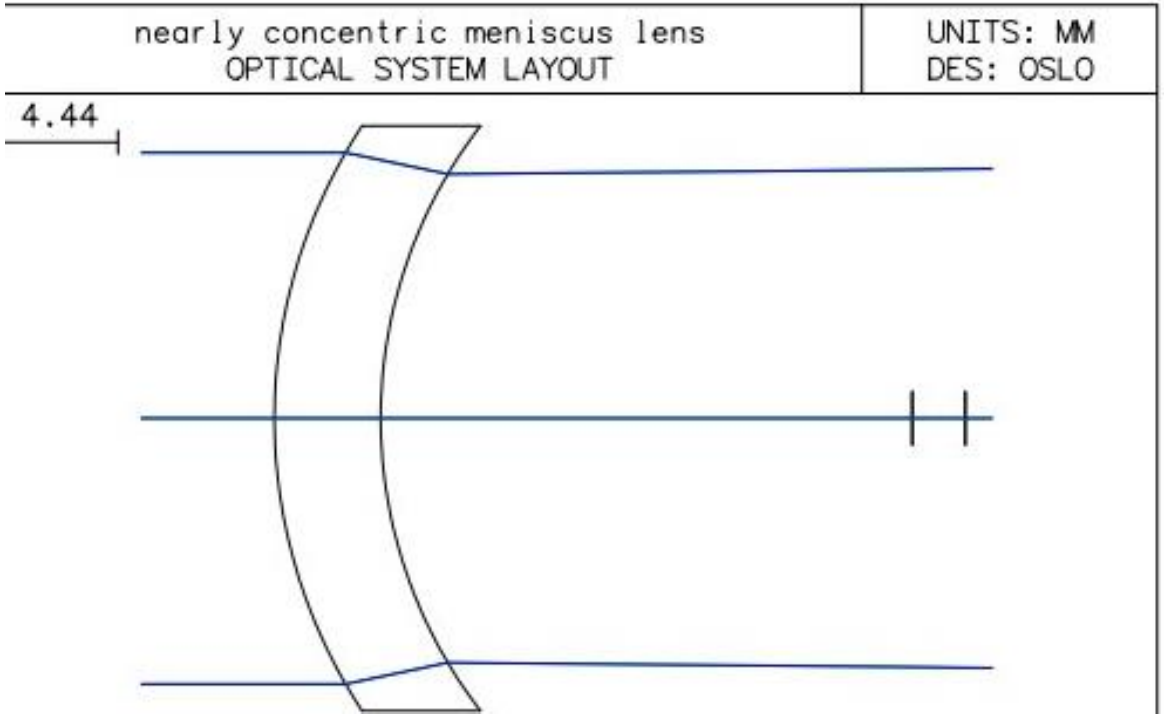
Reoptimized design



Design with meniscus lens in front is .054 waves r.m.s. OPD at edge of field. Bottom design is .038 waves r.m.s OPD = the better design

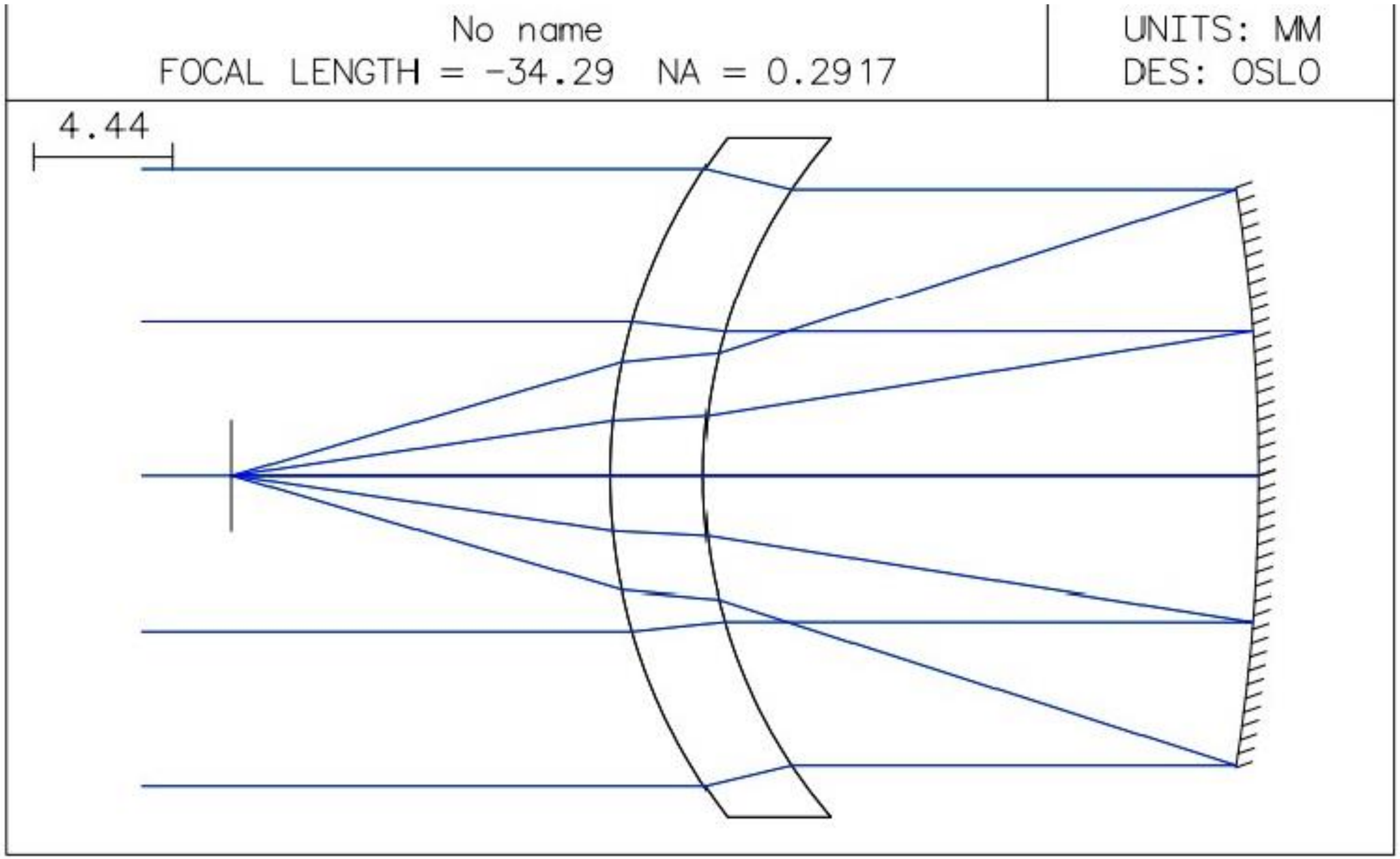


Parabolic mirror has no spherical aberration but has coma and also astigmatism (if stop is in contact). It is equivalent to a spherical mirror + aspheric.

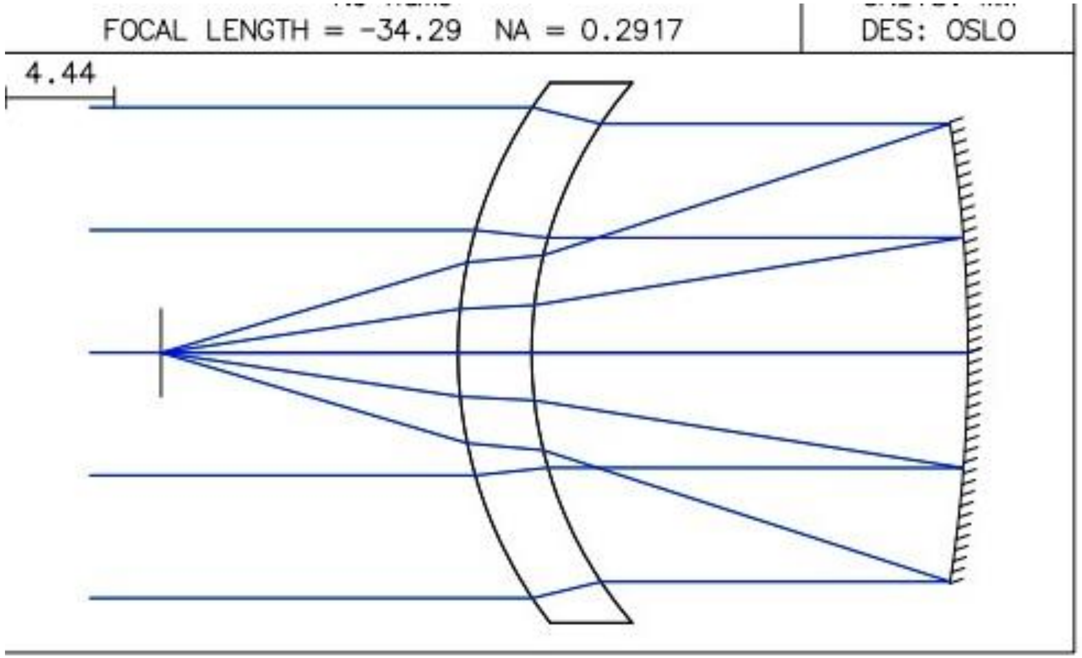


Nearly concentric lens acts like an aspheric Schmidt plate located near its centers of curvature.

So combine the two to get a parabola simulator with a spherical mirror.

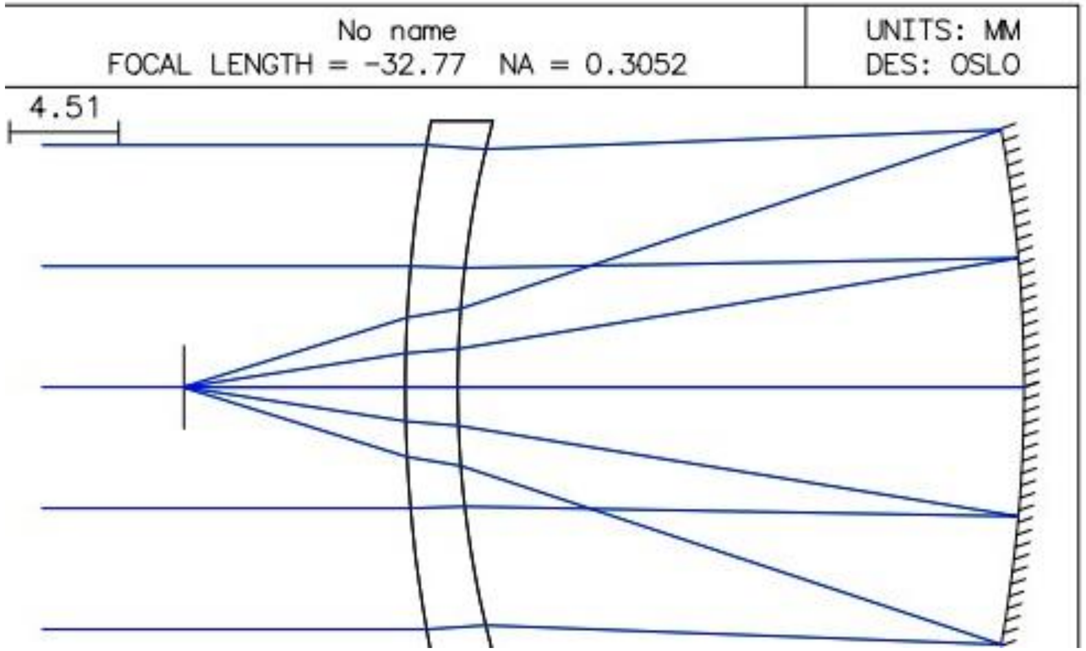


It takes a double pass through the lens to get enough spherical aberration to correct for the spherical mirror. This design has the **same** 3rd order coma and astigmatism as a parabolic mirror. It makes a parabolic mirror simulator. 5th order spherical aberration is also corrected in this design here. Axial color can also be self-corrected in this single lens.



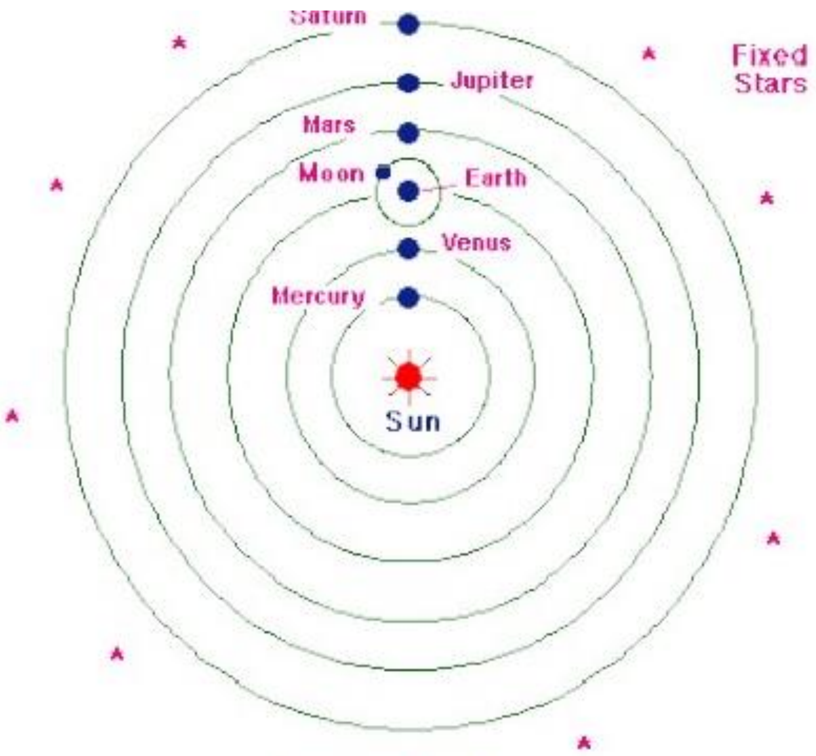
It is surprising that even in this very simple design there are two separate solutions. The one on the bottom is also a 3rd order parabolic mirror simulator but it cannot be corrected for 5th-order spherical aberration.

A lens designer can know a collection of "tricks", like this property of nearly concentric lenses, and use them in a wide variety of situations. The more "tricks" you know the better you are able to think of new design types with no calculations, just by thinking about it.

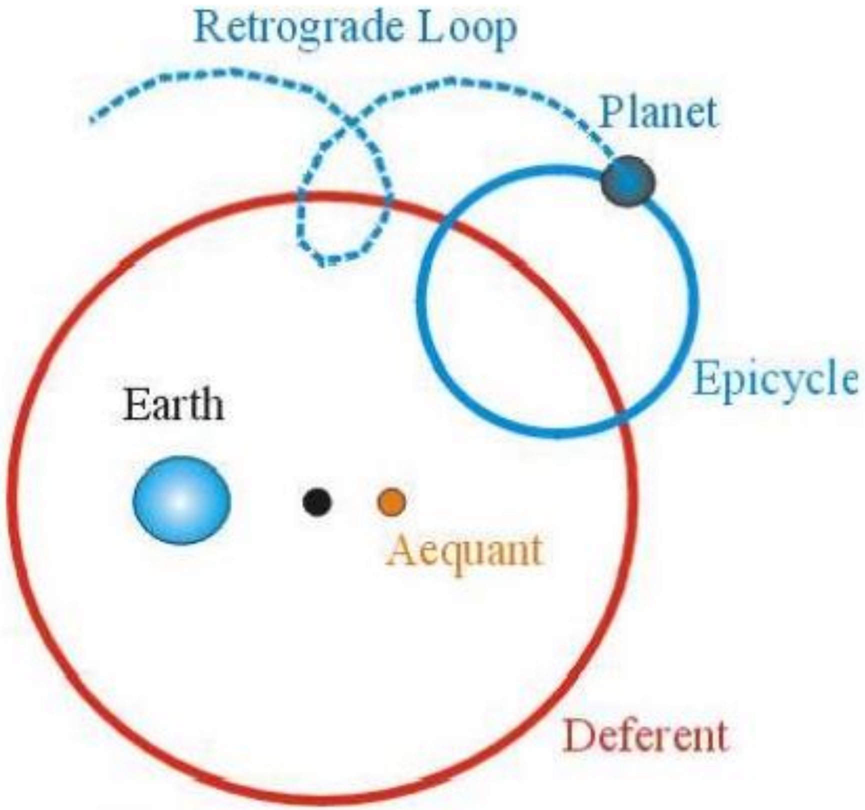


This same design type can also be used to simulate the spherical aberration, coma, and astigmatism of an elliptical or hyperbolic mirror.

<u>Using stop shift theory as an aid in lens design</u>



Copernicus



Ptolemy system

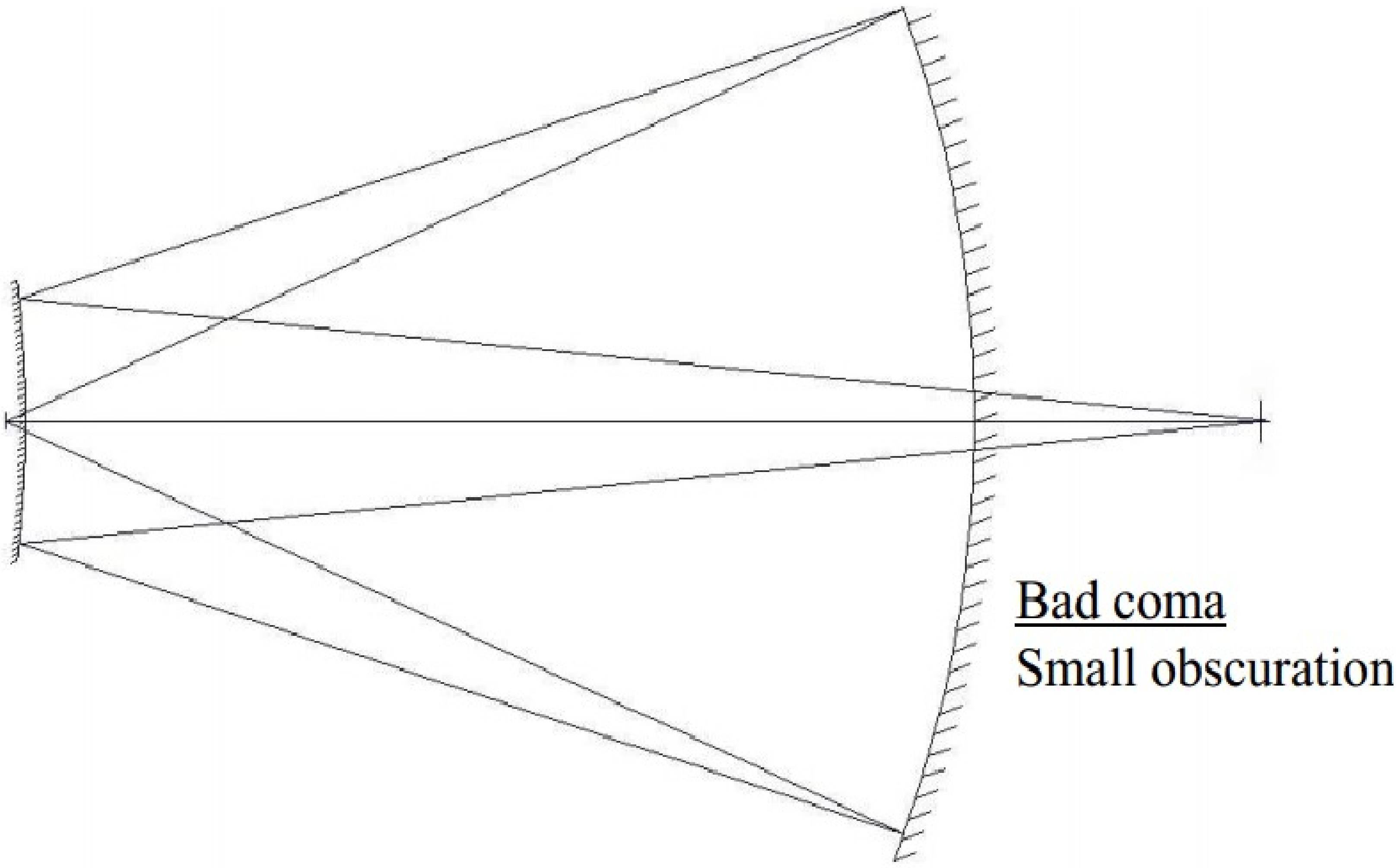
The view of Copernicus, that the sun is the center of the solar system, is widely considered to be the correct view and the very complicated system of Ptolemy, with epicycles and with the earth the center of the solar system, is considered wrong. But neither is right or wrong, if they correctly predict the apparent motions of the planets. One system is much simpler and easier to understand. Stop shift, especially temporary shift, helps understanding in optical design through simplicity – just like Copernicus.

- The use of first and 3rd order stop shift theory can lead to new types of designs and a better understanding of existing designs.

- No computations are necessary to benefit from stop-shift theory – it just involves a few basic principles and some temporary changes in aperture stop position.

- Experiments can be carried out in your head. Computer calculations only happen after you are done with the conceptual work.

A 1.0X catadioptric relay system developed using stop shift theory



Spherical mirrors, same radius, corrected for 3rd order spherical aberration

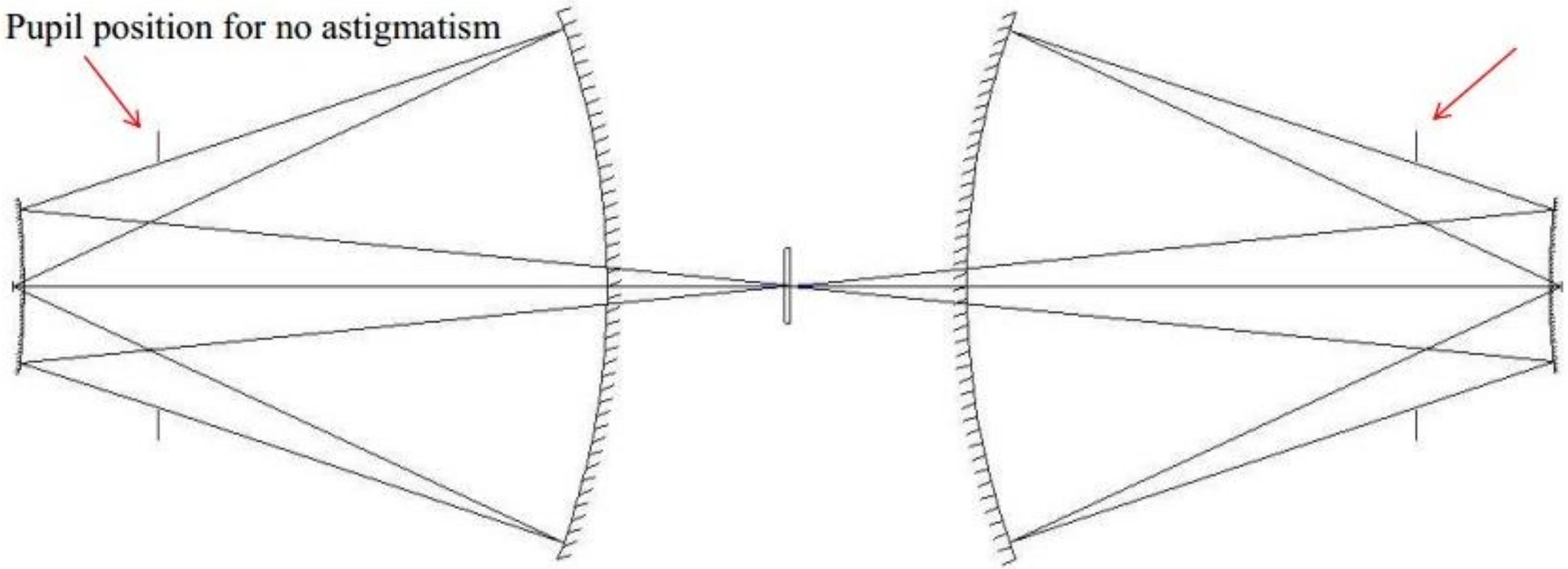
A good designer knows a collection of odd facts where each seems pretty useless by itself but they can then be used as some building blocks to make some new designs, just by thinking.

- If a design has spherical aberration then coma is linear with stop position and astigmatism is quadratic with stop position

- If spherical aberration is corrected then coma is constant with stop position and astigmatism is linear with stop position. Then, for non-zero coma, there is always a stop position that corrects for astigmatism.

- If both spherical aberration and coma are corrected then astigmatism is a constant

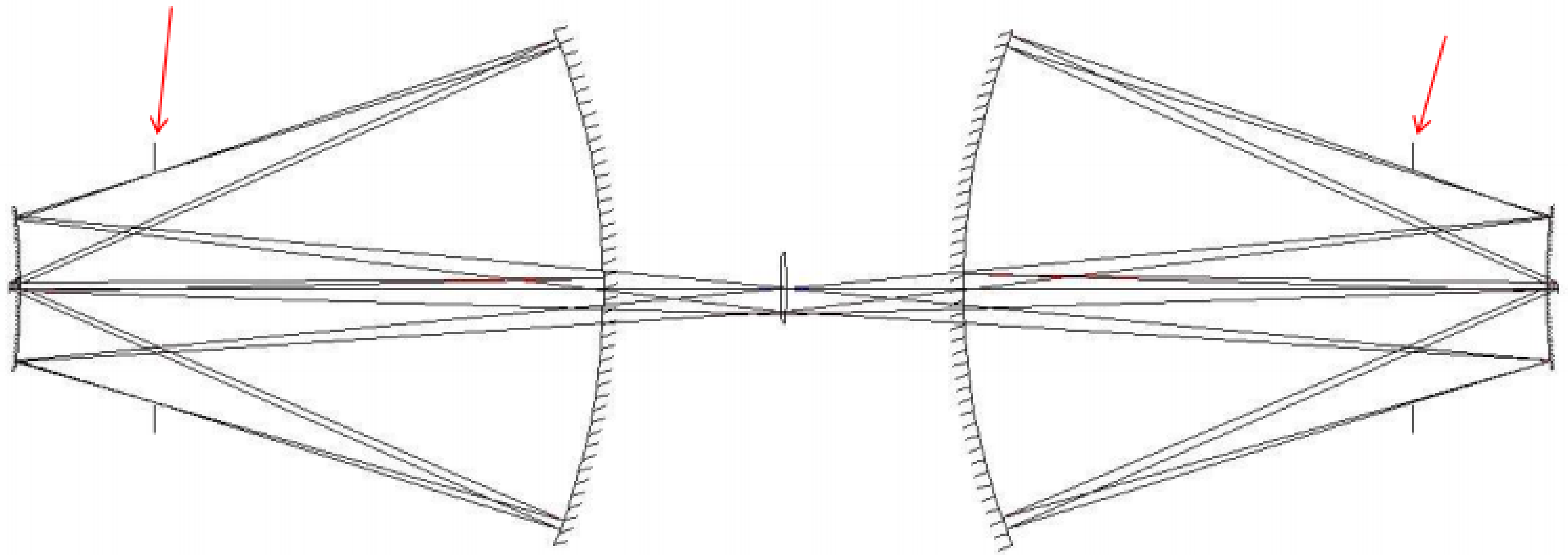
This is our two spherical mirror design – corrected for spherical aberration but not for coma



Two symmetrical systems make coma cancel, give a 1.0X magnification aplanat

Each half has a stop position which eliminates astigmatism, since each half has coma. But pupil can't be in both places at the same time.

The coma here cancels by symmetry – one of a designer's "tricks", so now we have a 1.0X relay corrected for both spherical aberration and coma = an aplanatic design.

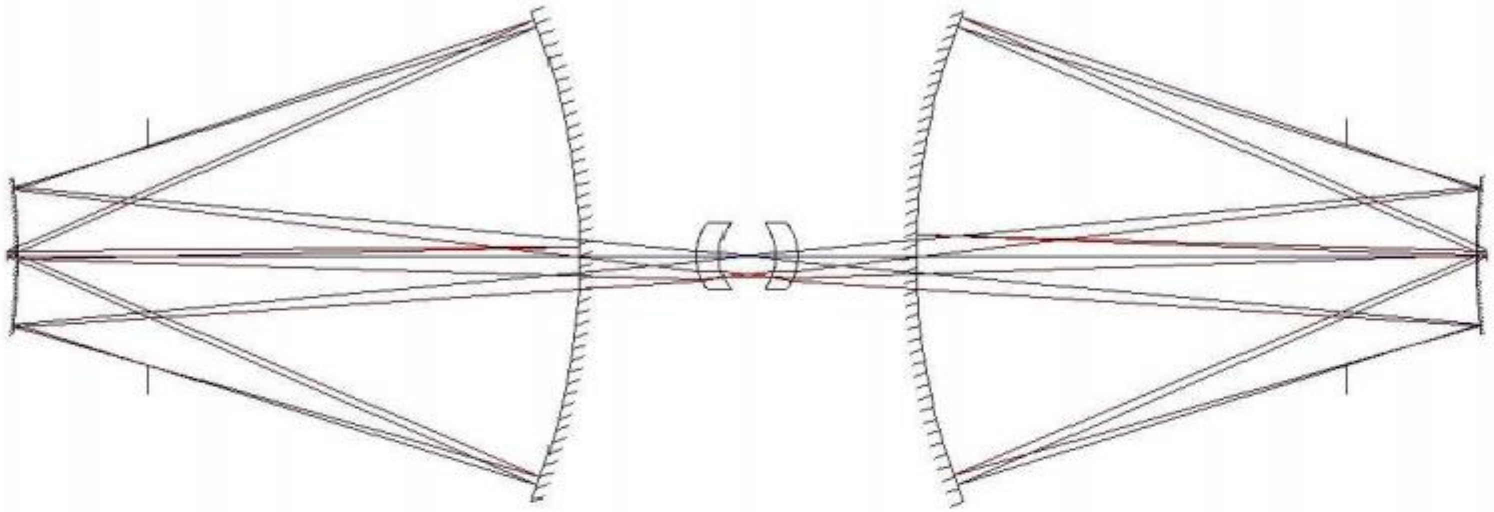


Astigmatism-correcting pupil positions are imaged onto each other by positive power field lens.

System is then corrected for spherical aberration, coma, and astigmatism, but there is Petzval from field lens.

A thin field lens at an image has no spherical aberration, coma, or astigmatism and is very useful for imaging pupils inside the design to be in desired locations.

Another useful designer "trick"



Thick meniscus field lens pair has positive power but no Petzval or axial or lateral color

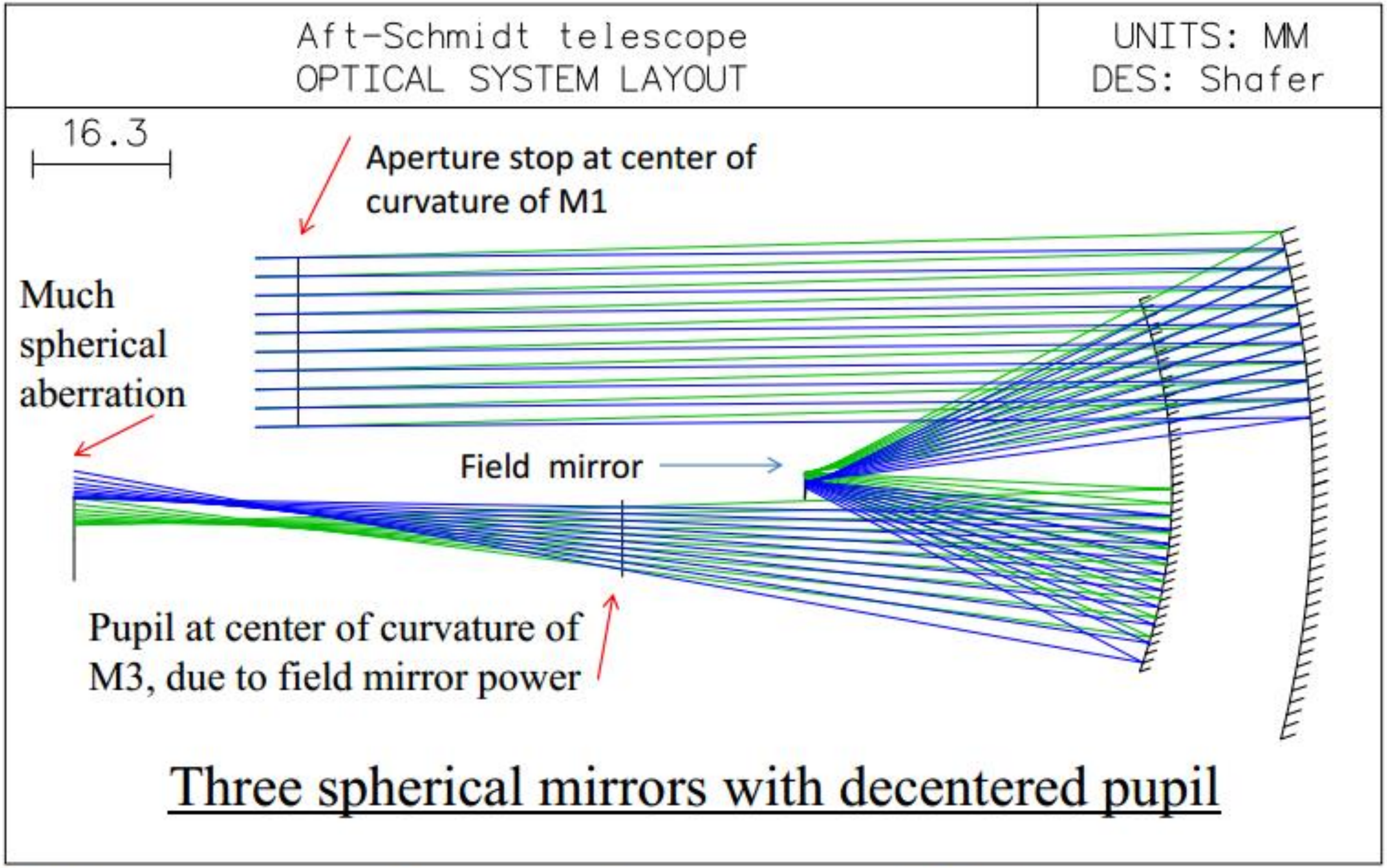
Result is corrected for all 5 Seidel aberrations, plus axial and lateral color. This shows how a simple building block of two spherical mirrors was turned into something quite useful.

Plus, how stop shift theory is useful for thinking of a new design.

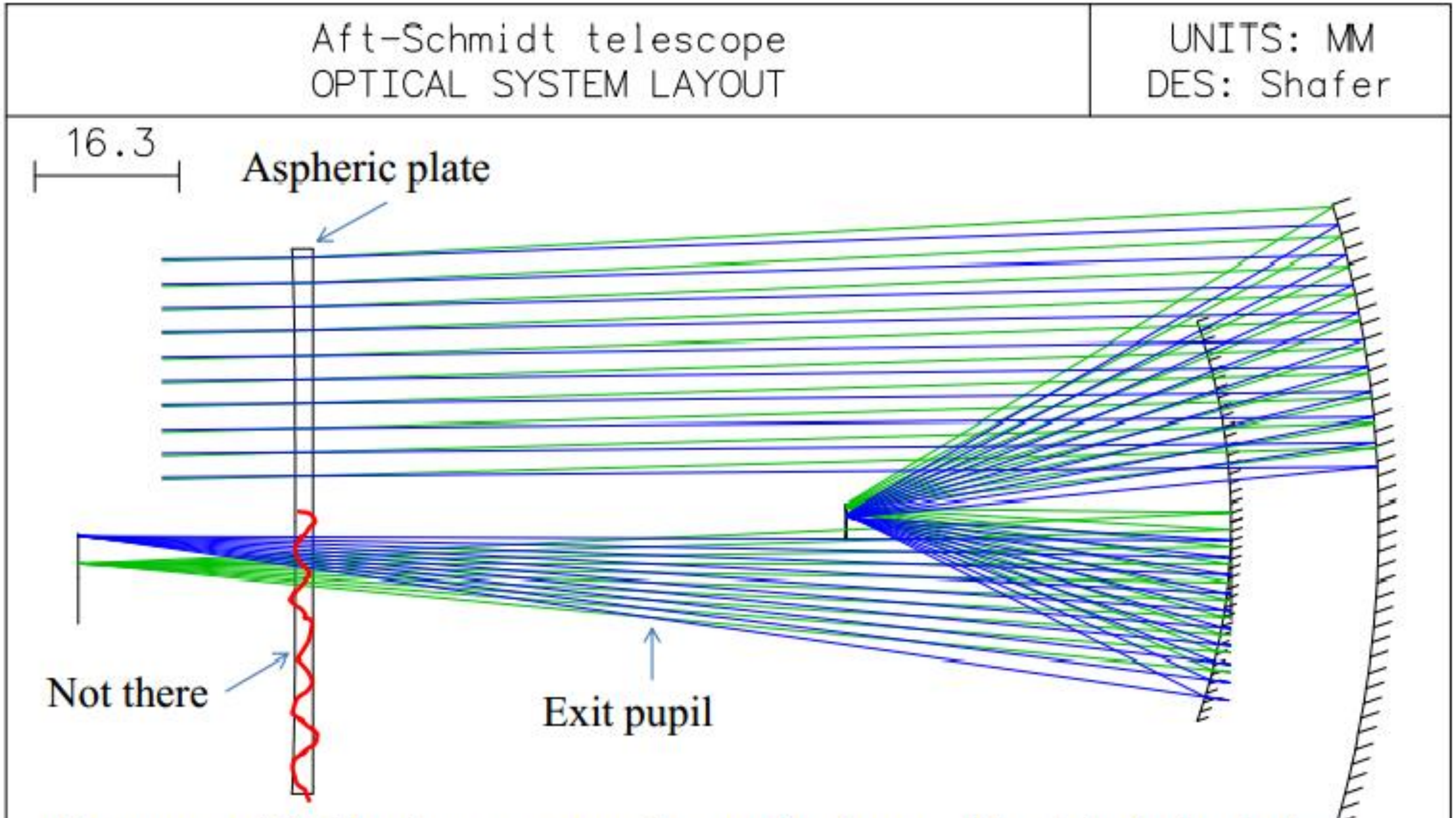
We have thought of this new design and know it will work well without any computer calculations. Now it is time to computer-optimize it and see how good the higher-order aberrations are.

We don’t want a field lens right at an image, where lens defects – scratches, pits, dust, etc. will be right in focus so we spit the positive field lens into two identical thick meniscus lenses on either side of the intermediate image but a little away from it. A thick meniscus lens with the same radius on both sides has positive power and no Petzval curvature, another useful designer “trick”. We need the positive power, as before, to image the pupils to give astigmatism correction. The ray heights on the lenses are very small and any aberrations from them are easily corrected by slightly changing the mirrors. By symmetry coma, distortion and lateral color cancel. Axial color from the lenses can be corrected by a small change in their radii and thickness.

Another field lens (lens close to an image) type of design

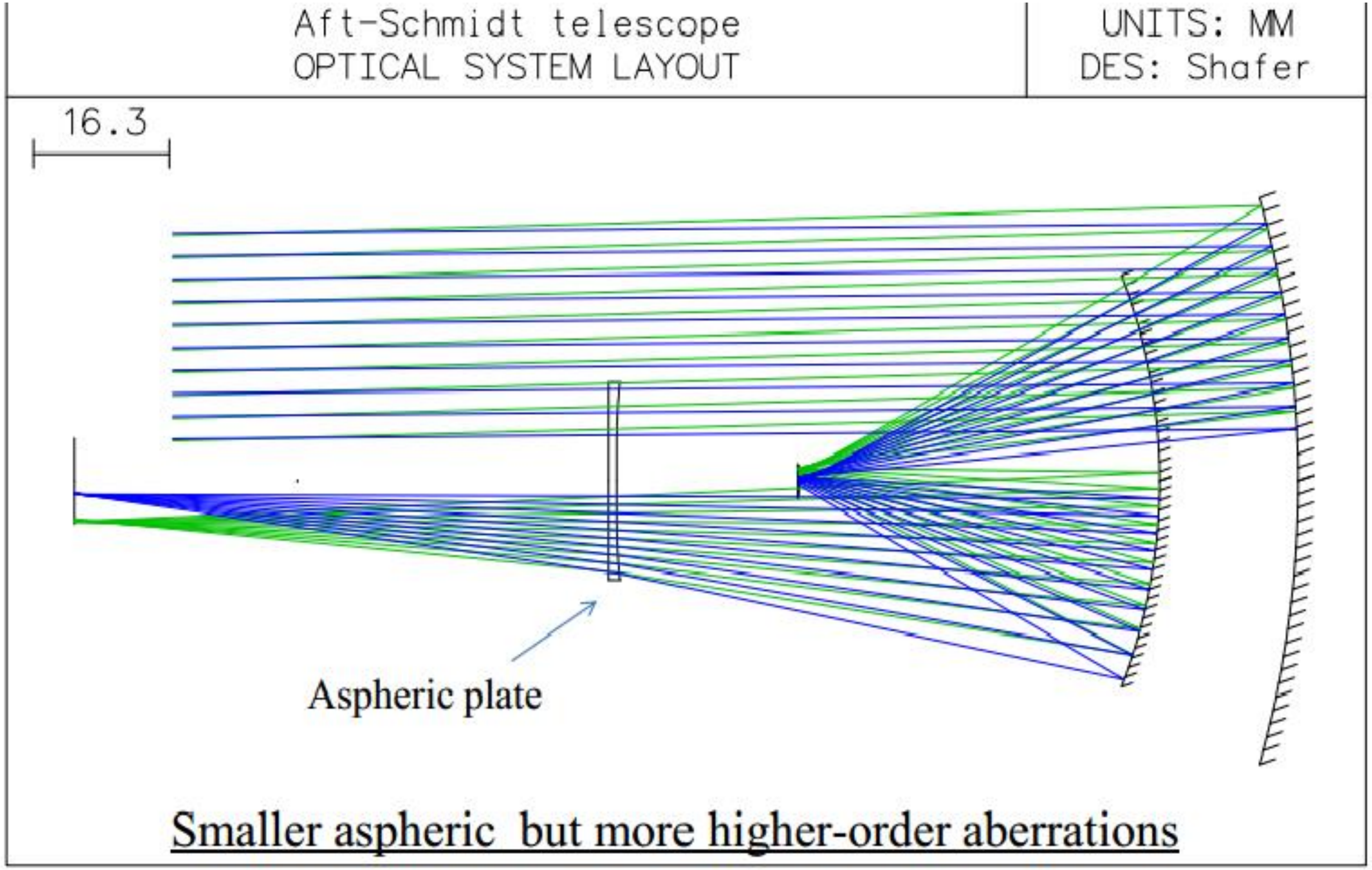


Field mirror images M1 center of curvature onto M3 center of curvature

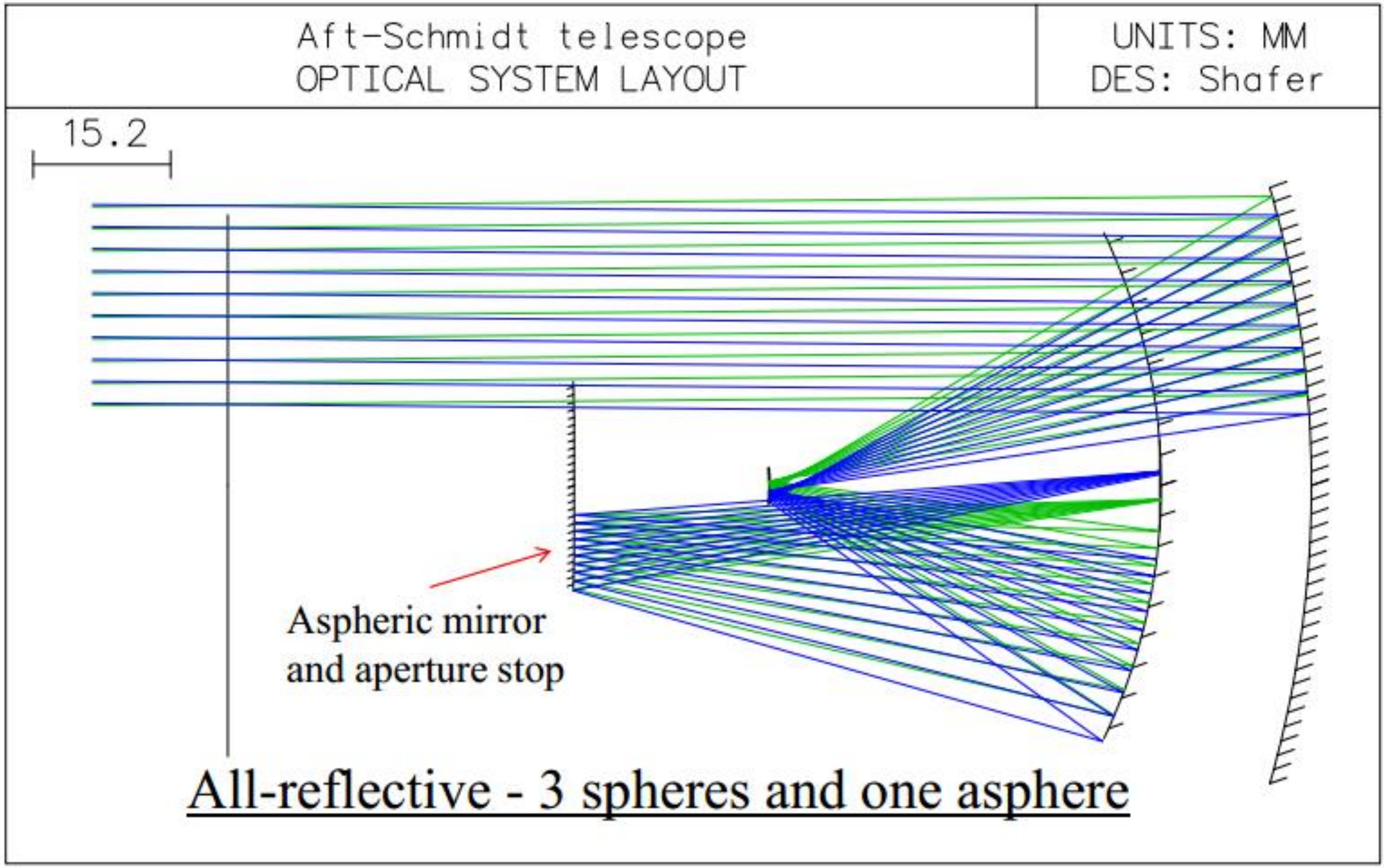


Because of field mirror power the aspheric acts like it is in both the aperture stop and the exit pupil, at the centers of curvature of M1 and M3

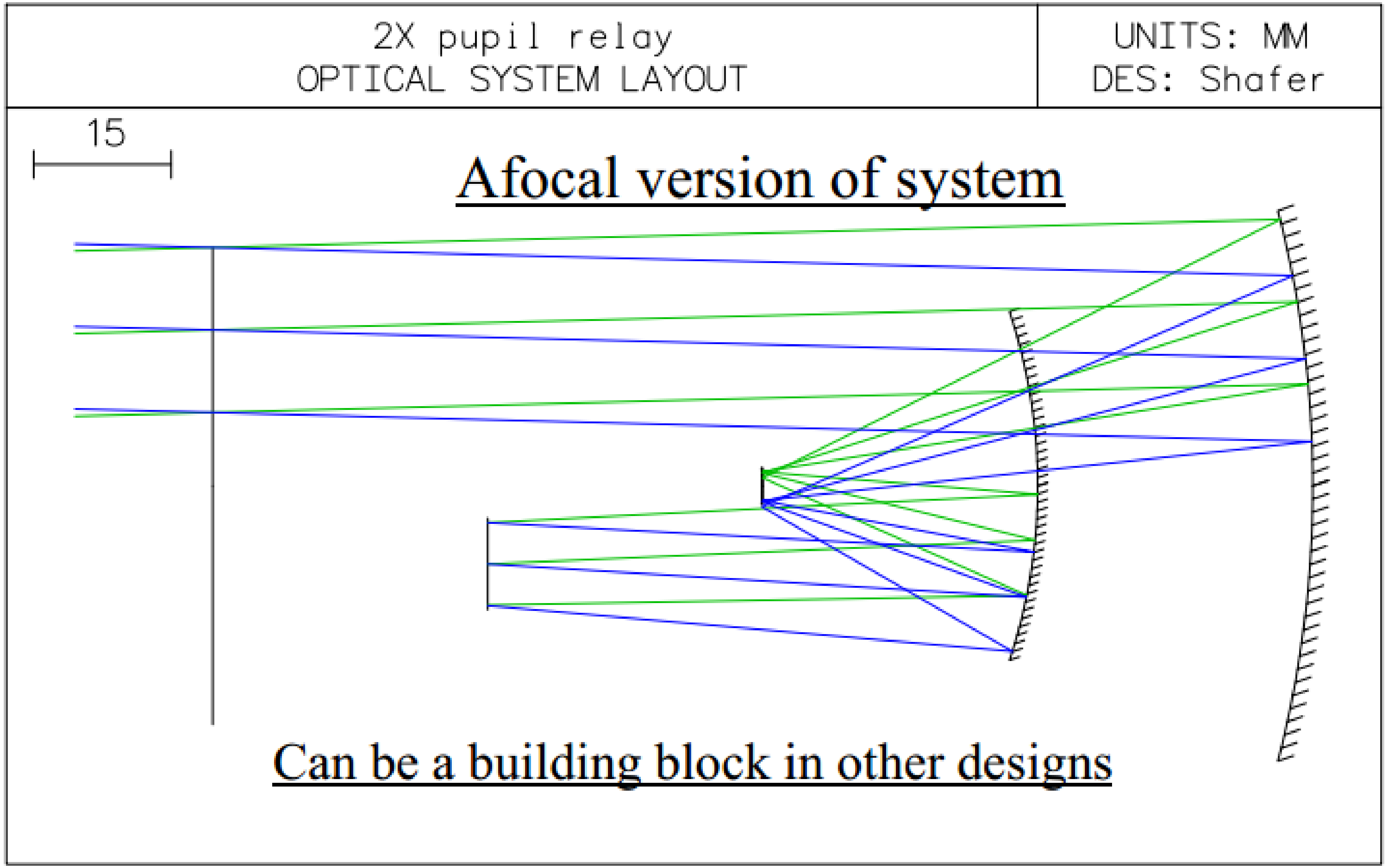
<u>Design is good for rectangular strip fields</u>



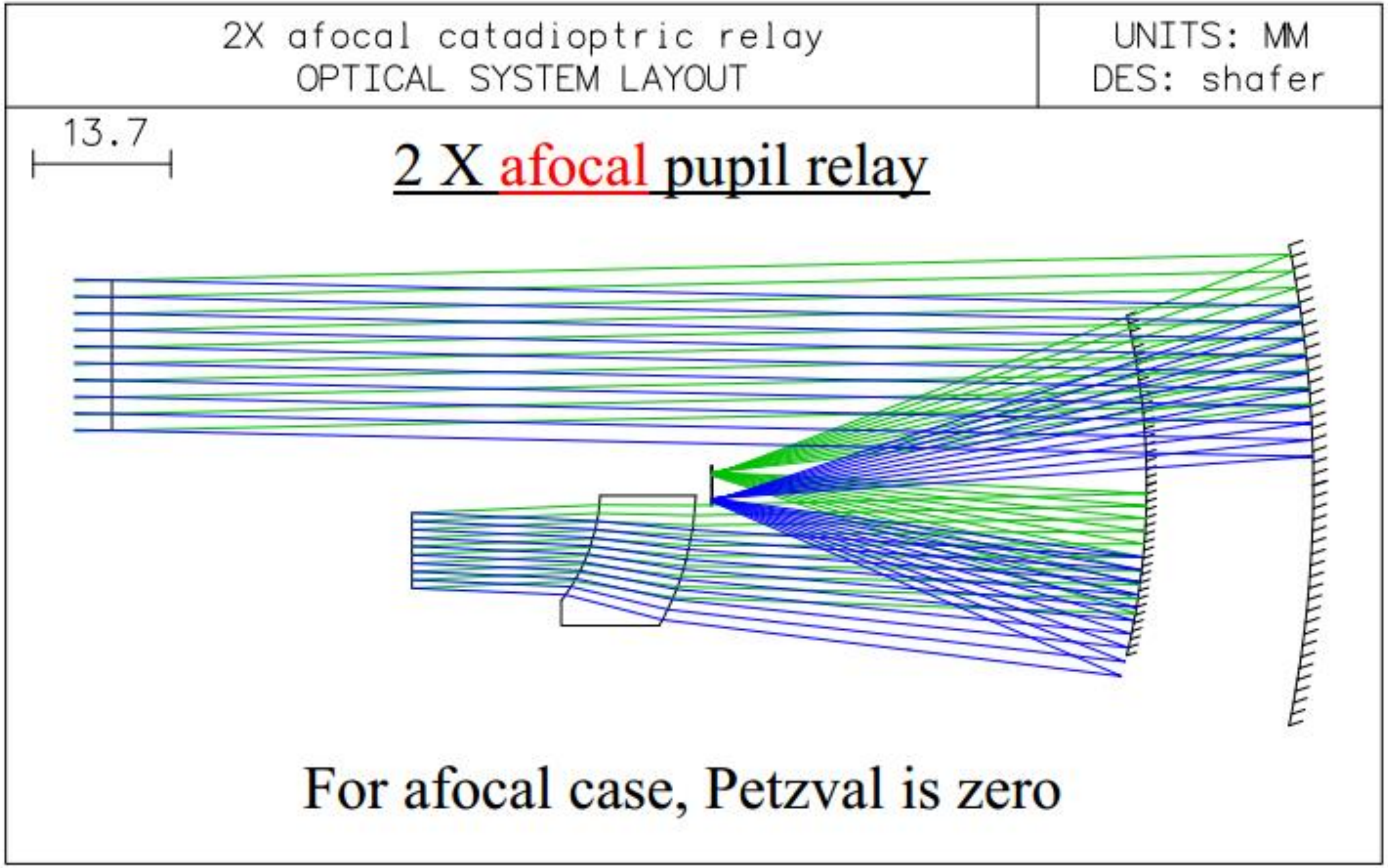
Aspheric acts like it is at the centers of curvature of both M1 and M3, due to power of field mirror



In all of these designs the image is curved

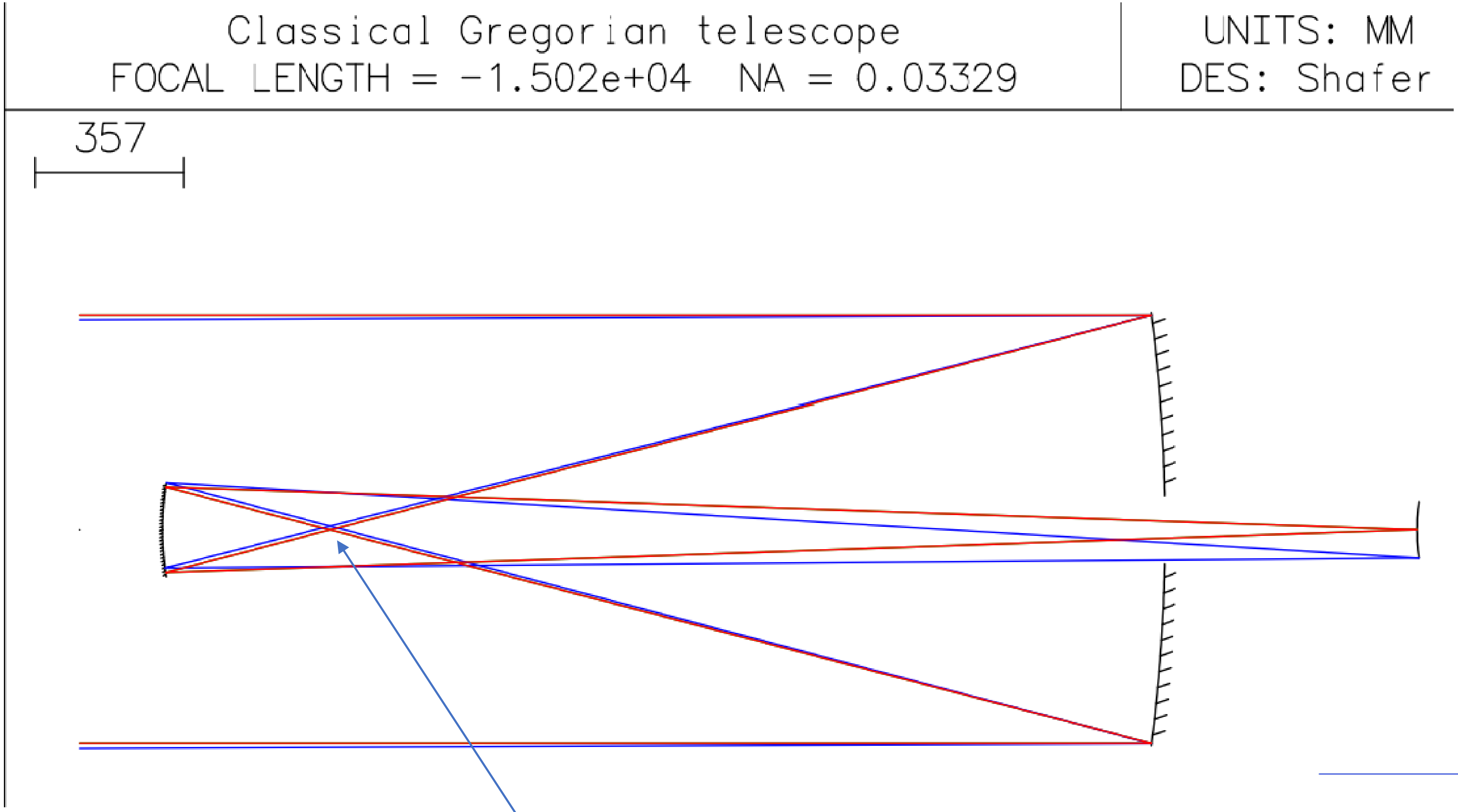


Best for rectangular fields, with long direction in X field direction.

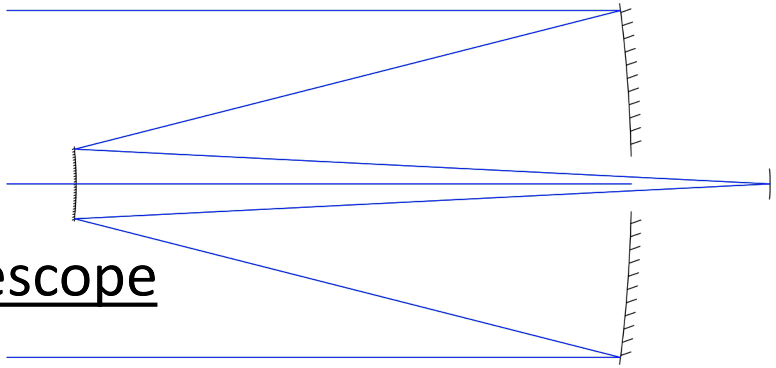


Aspheric plate at either pupil or a concentric Bouwers lens in either place does the spherical aberration correction

Gregorian telescope with a field lens

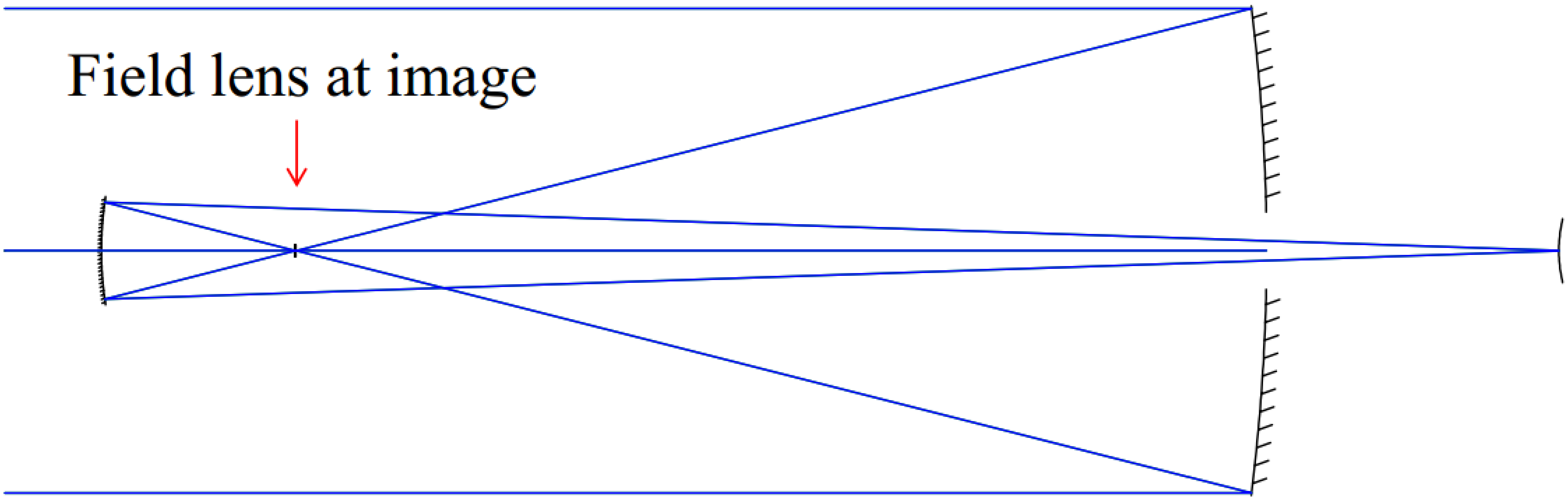


Gregorian telescope has intermediate image



Classical Cassegrain telescope

Now suppose we add a tiny thin field lens right at the intermediate image. It will have no spherical aberration, coma, or astigmatism if it is right at the image



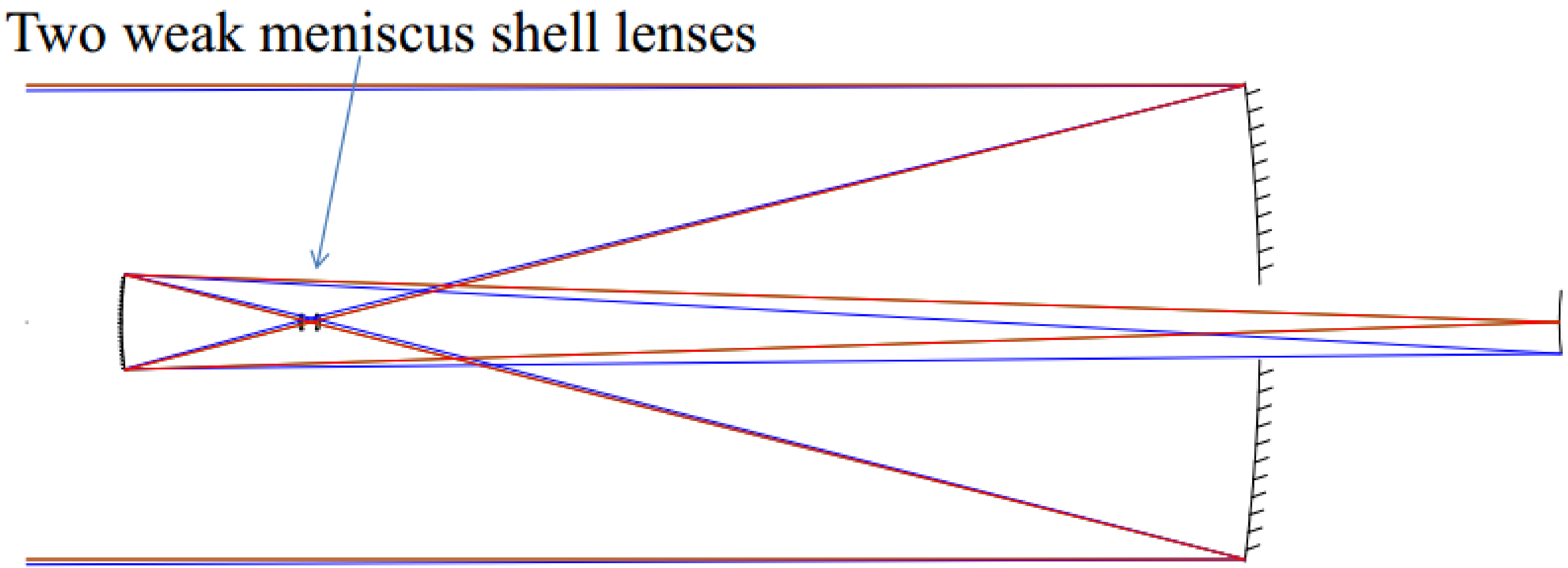
The power of this field lens gives independent control of where the pupil is for the two mirrors. That extra variable, of the field lens power, plus the two conic surfaces on the mirrors as variables, allows us to correct for spherical aberration, coma, and astigmatism

- The required field lens power for this solution is very weak and the mirror conics hardly change at all. The primary mirror conic is still very close to a parabola.

- Using a field lens at an intermediate image to give independent control of the pupil position before and after the intermediate image is a very powerful design tool and it affects all the system aberrations even though it has very little of its own aberrations.

- If the field lens is moved a little away from the intermediate image there is still an anastigmatic solution possible and it changes a little the primary mirror conic that is needed.

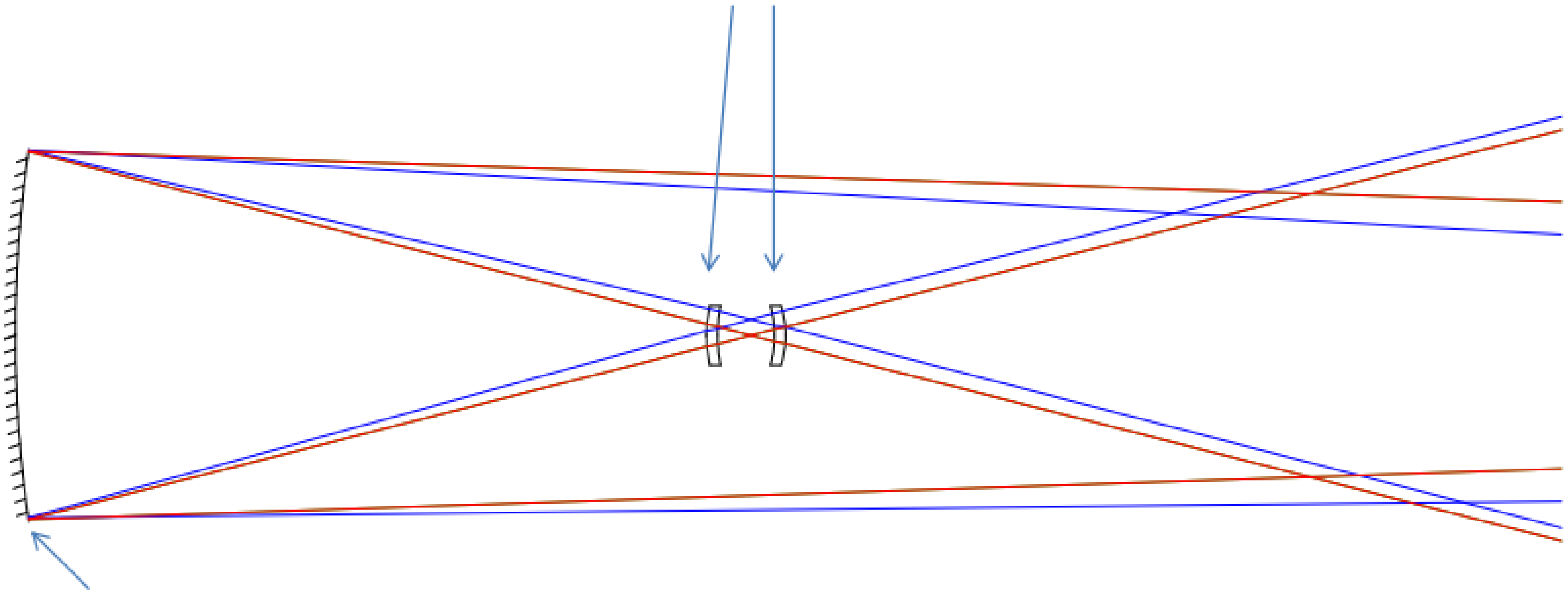
- There is then a solution where the primary becomes an exact parabola. Then this solution can be used with existing observatory parabolas, like at Mt. Wilson and Mt. Palomar.



When the field lens is moved away a little from the intermediate image, to give the exact parabola solution, the lens acquires a small amount of axial and lateral color

That color is corrected by splitting it into two lenses on either side of the intermediate image and making them weak meniscus lenses curved about the image.

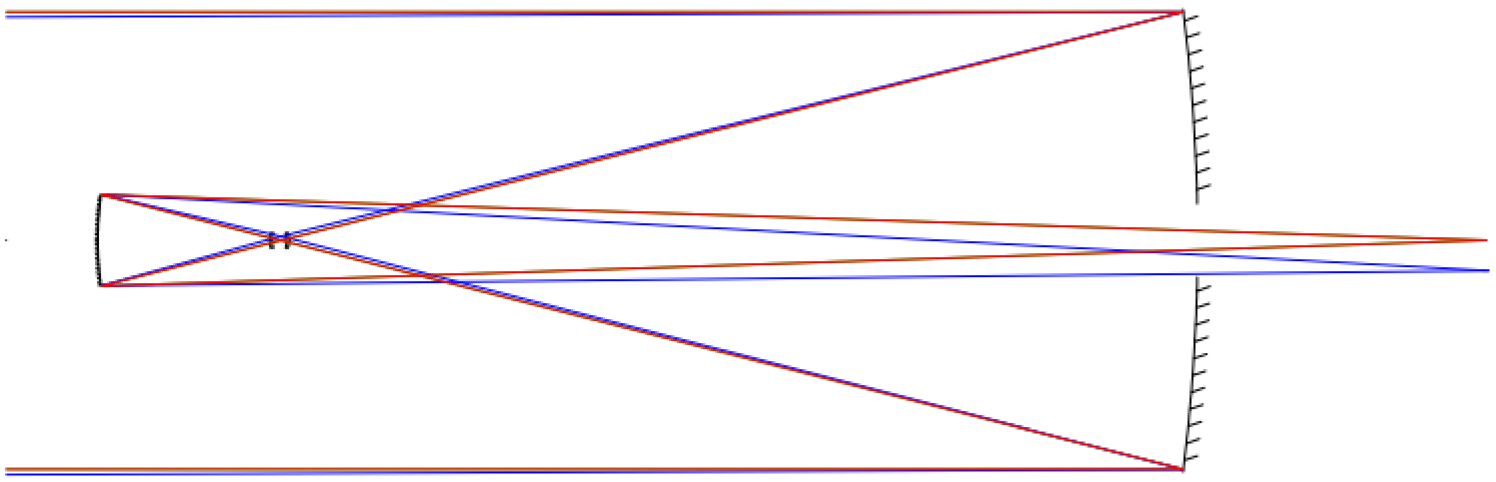
Two weak meniscus lenses on either side of image



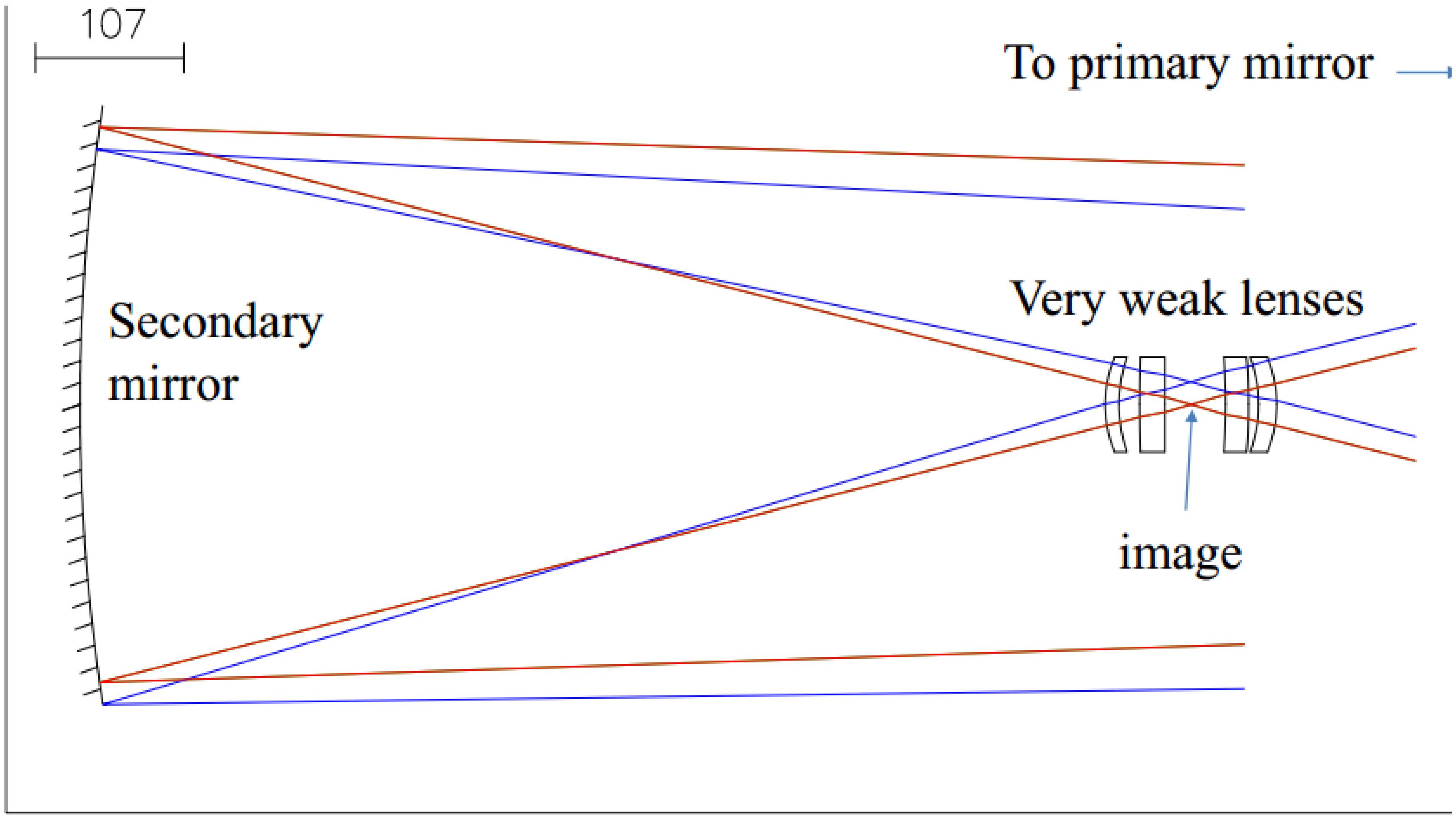
Secondary mirror

By curving the lenses about the image they can correct for both of their axial and lateral color with the same glass type. Here I used BK7 glass. The lenses do not add any to the axial obscuration.

The result is an f/15 design with a 1.0 meter diameter f/2 parabola, an elliptical secondary mirror and two weak BK7 lenses 30 mm in diameter.



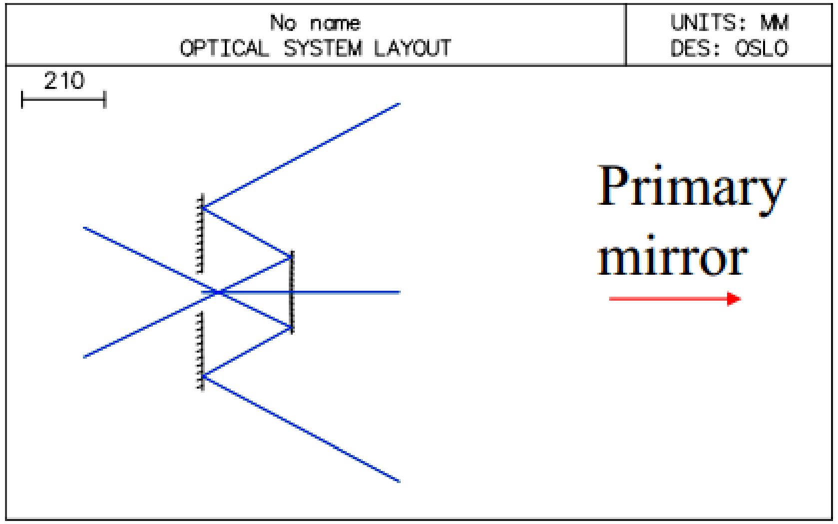
On a curved image (radius 470 mm) the polychromatic (.486u- .656u) wavefront at the edge of +/- .25 degree field is .019 waves r.m.s. If it is reoptimized for a flat image the polychromatic value is .043 waves r.m.s. at the edge of the field.

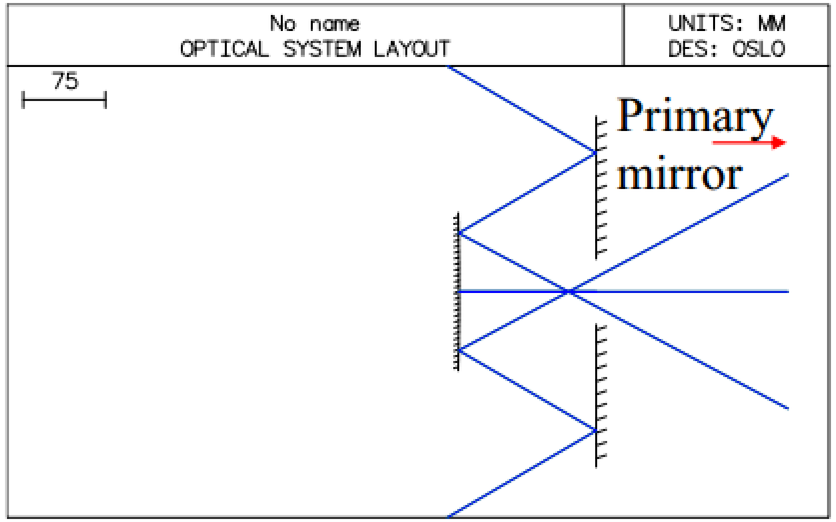


Design has a 2.0 meter diameter f/2 primary parabola, elliptical secondary, 4 BK7 lenses and a polychromatic (.365u - .656u) wavefront of .030 waves r.m.s. at the edge of a +/- .25 degree field on a flat image.

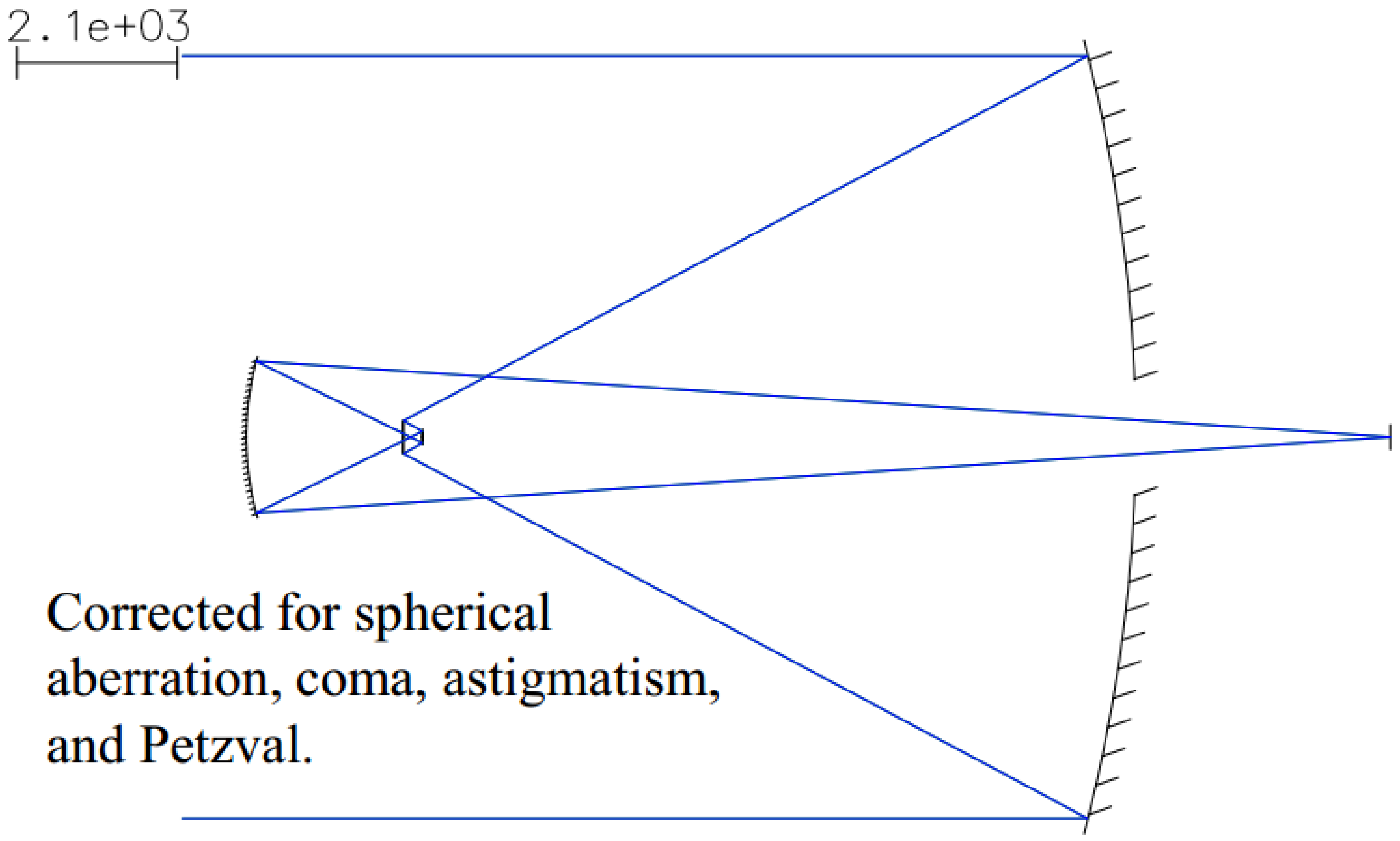
Here is a more complex design for a larger parabola, like the Mt. Palomar one.

A purely reflective solution to the field lens region has two solutions, with two small aspheric mirrors.

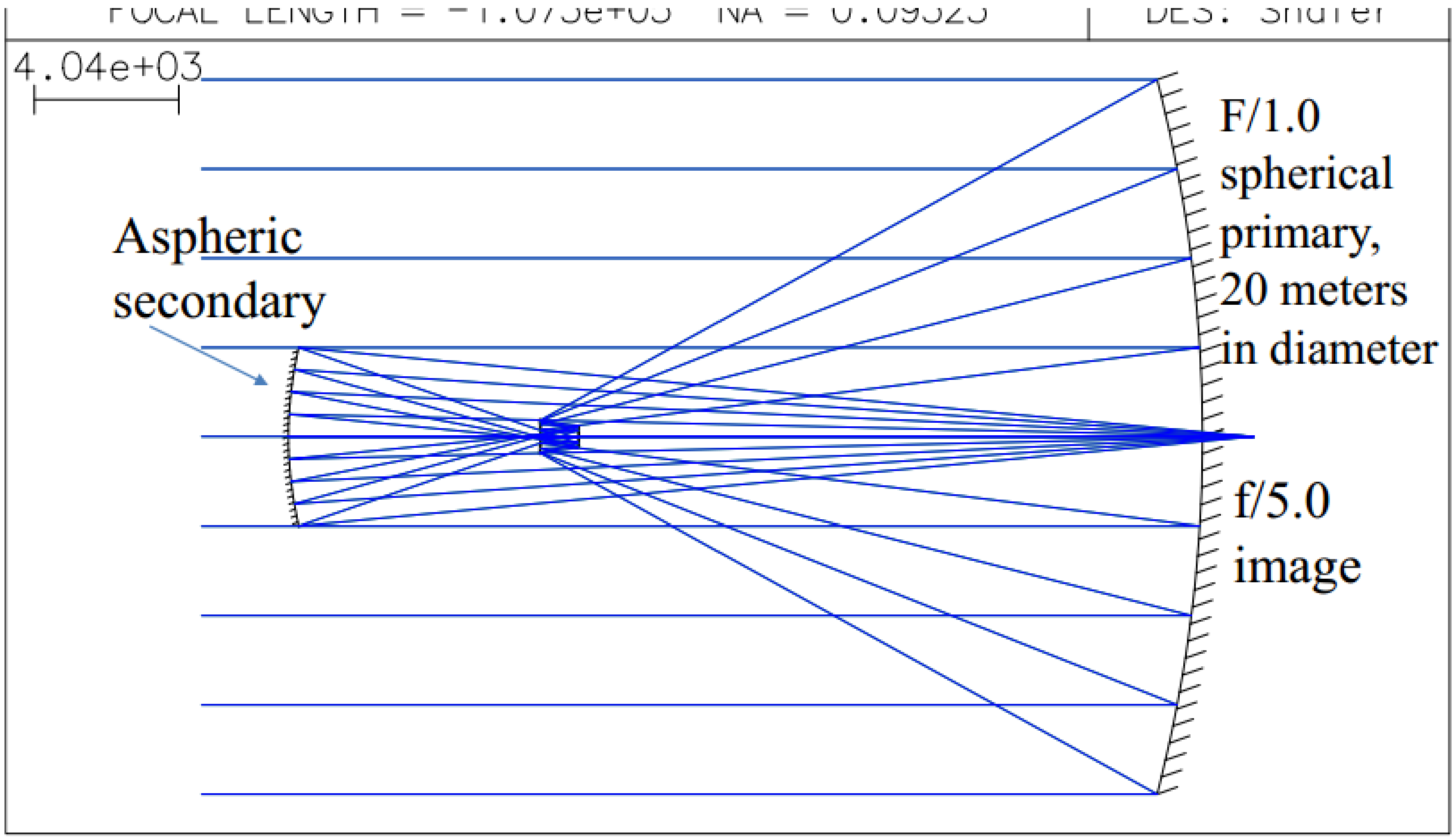




With this in place we have an all-reflective design that works well for all wavelengths. For a 10 meter diameter f/1.0 parabolic primary and a conic secondary mirror and these two small aspheric field mirrors we get a design that is diffraction-limited in the visible over a ¼ degree diameter field on a flat image.

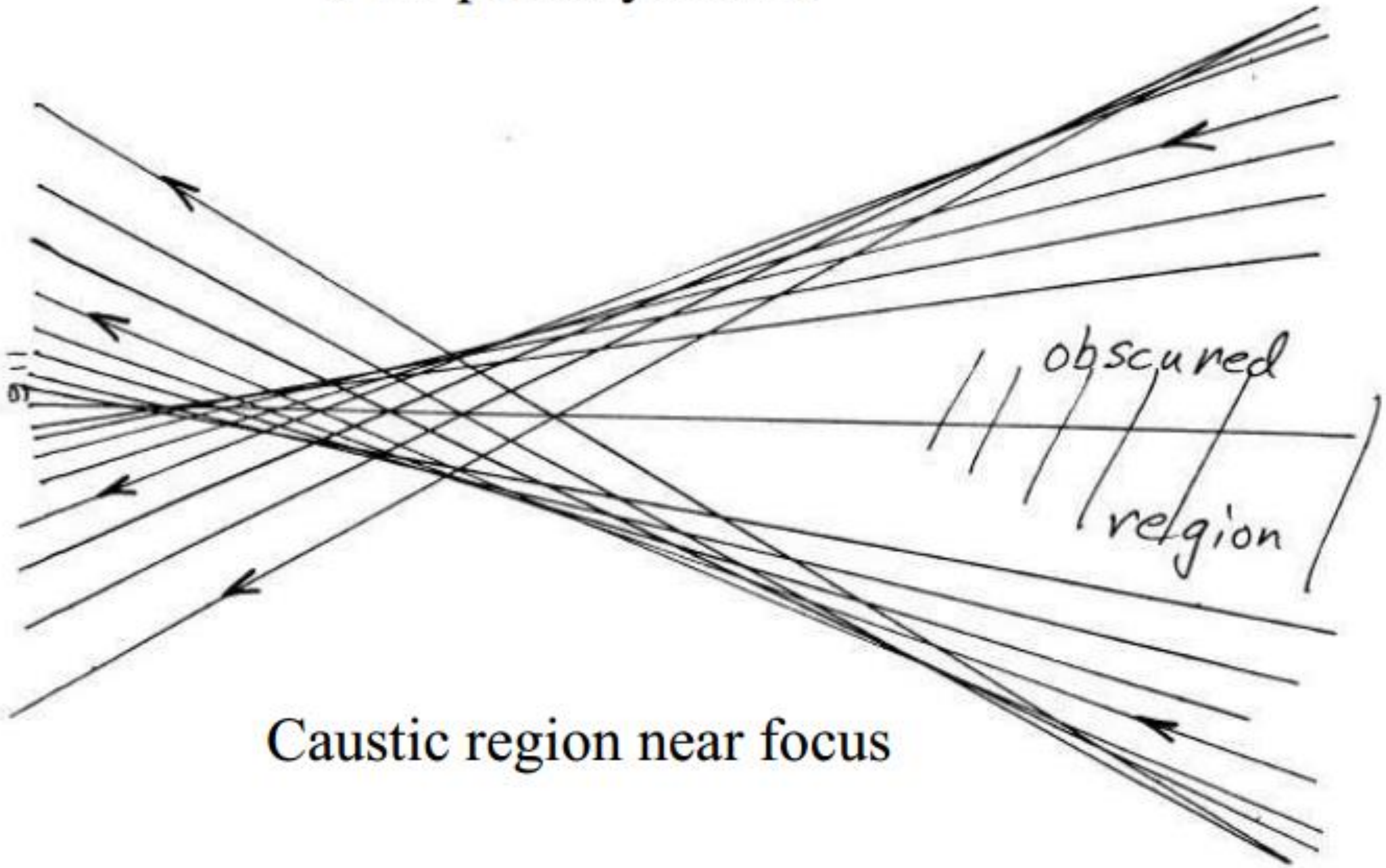


10 meter diameter f/1.0 parabolic primary, elliptical secondary, two small aspheric field mirrors.



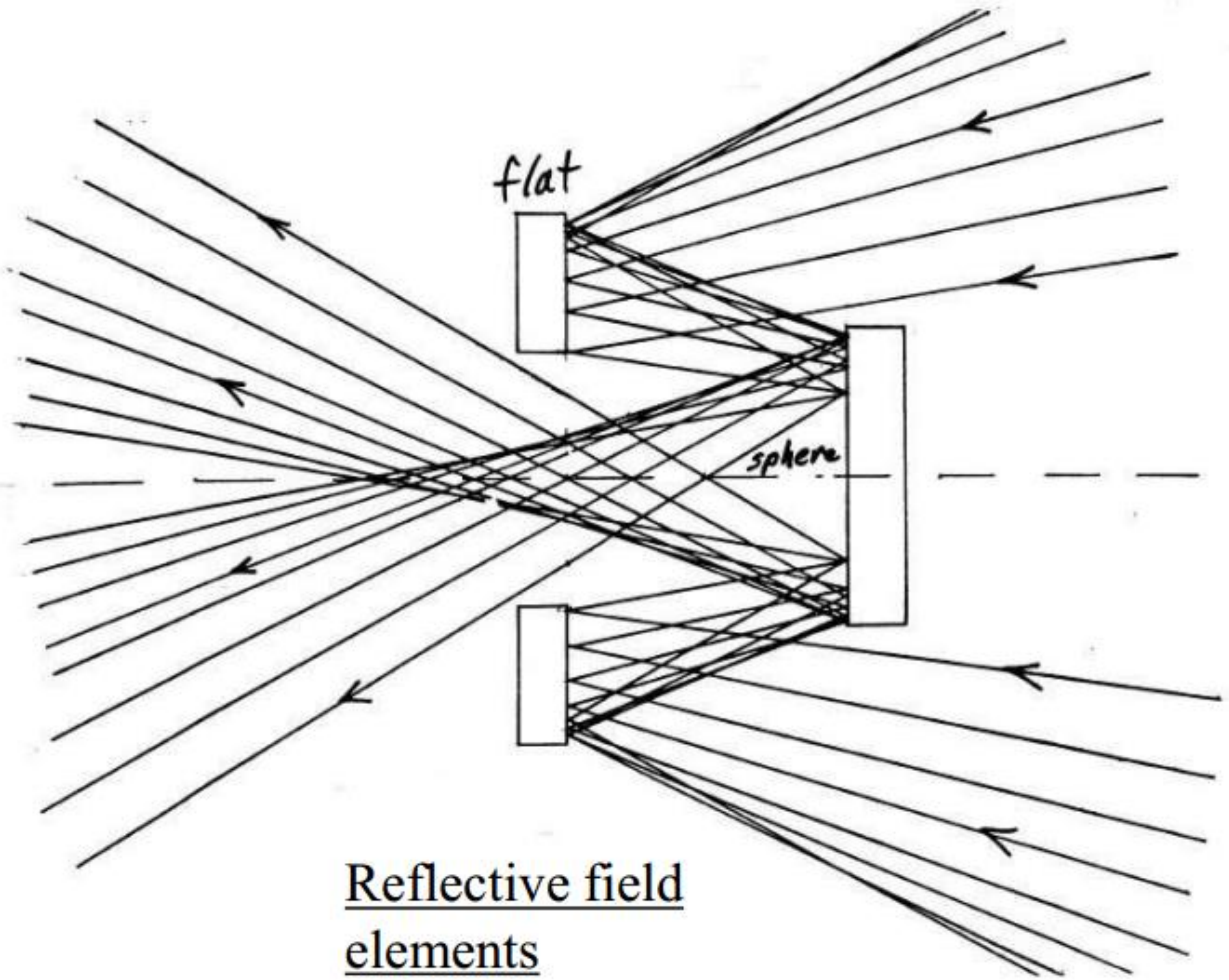
The same type of system can work with a spherical primary mirror but with a much smaller field size.

f/1.0 primary mirror →



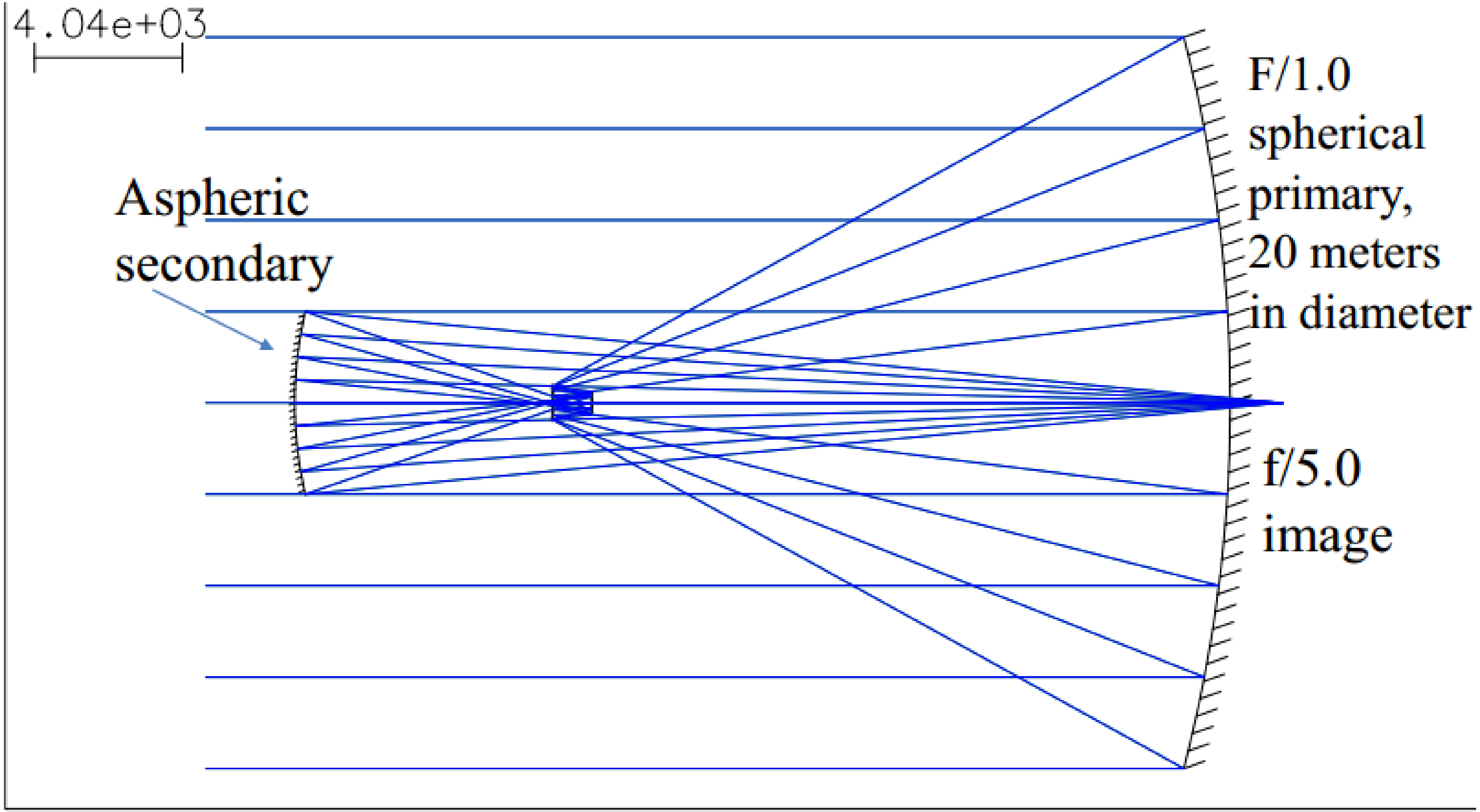
Caustic region near focus

The best focus on-axis spot size from a 20 meter diameter f/1.0 spherical mirror is 180 mm in diameter!



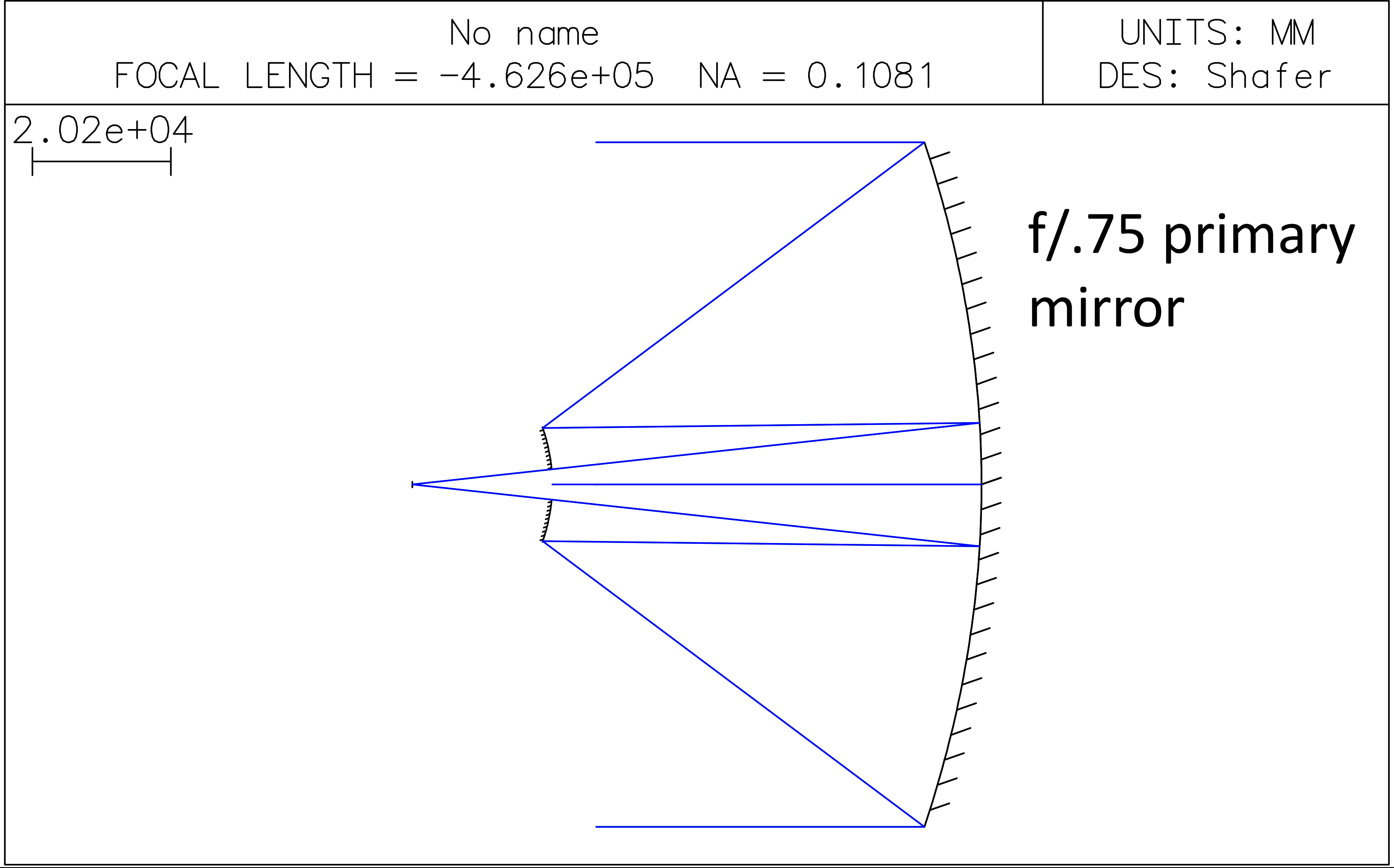
Reflective field elements

The field mirrors obscuration can be 25% of the pupil diameter with this f/1.0 spherical mirror focus.

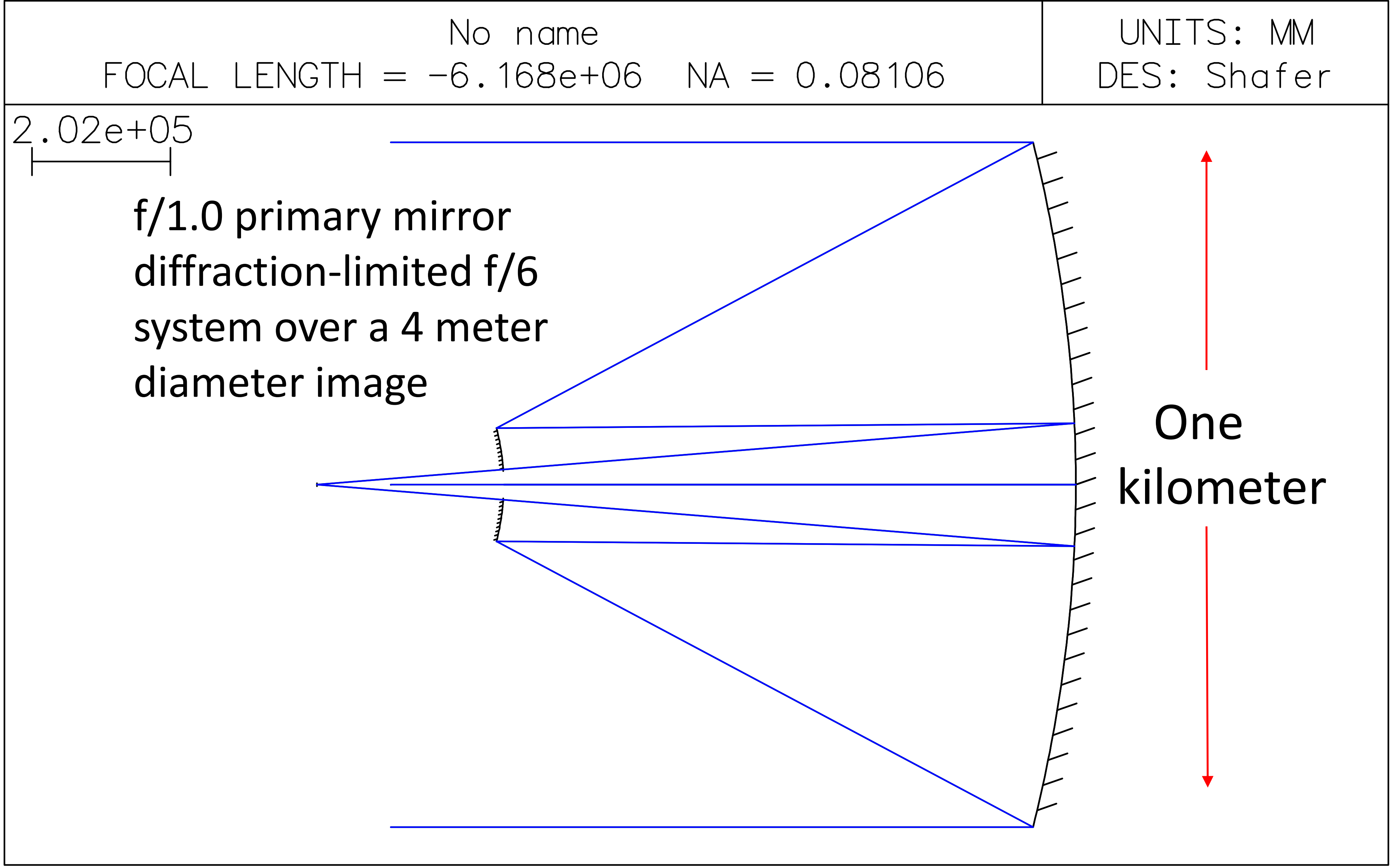


By letting the field mirrors both be curved and aspheric we can get a design that is diffraction-limited at .5u over a 1/20 degree field diameter, or a 100 mm flat image diameter at the final f/5.4 focus.

A whole new group of designs can be developed, all based on the use of a single key optical design “trick” of a field lens near an intermediate image. You can see how a new design can evolve around a simple starting point idea or structure. And this is all “human” based lens design where the fun part, and most important part, comes before we do any computer optimization.



Recently I have discovered an amazing design, of just two conic surfaces with three reflections between them. With a 100 meter diameter f/.75 primary mirror and a f/4.6 system it is diffraction-limited at .5000u over a .10 degree diameter curved field, giving a 800 mm diameter image. Both mirrors are very close to being parabolas. The obscuration due to the hole in the secondary mirror is about 8% area. The big weakness is it can't be baffled well. If the primary is slowed down to f/1.0 then the design can be scaled up by 10X to give a **kilometer-scope,** with a kilometer diameter f/1.0 primary and diffraction-limited correction over a 4 meter diameter curved image. Yikes!!

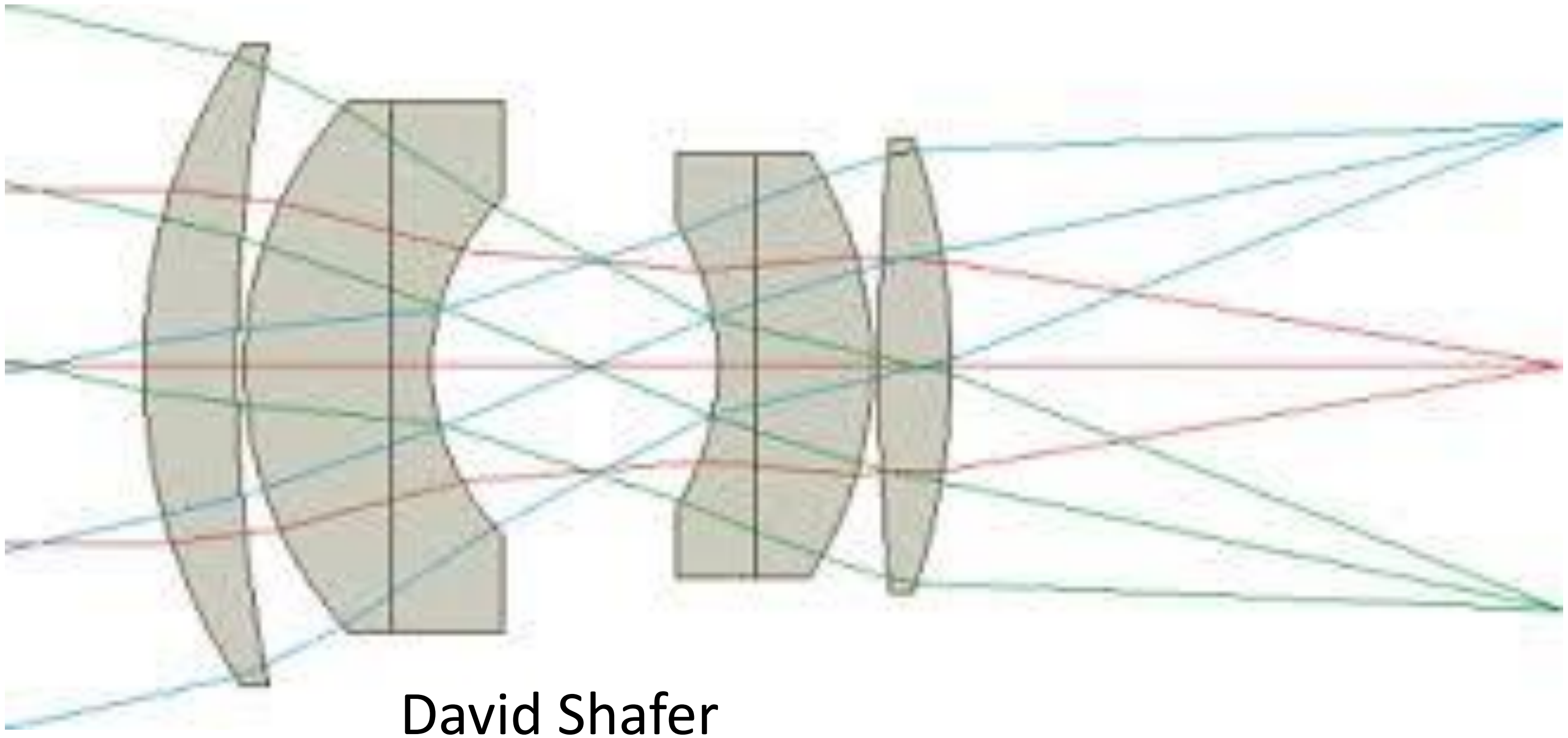


The Kilometer-Scope!!

Now we will use several design principles and "tricks" together to show how a Double-Gauss type of lens could have been designed before there were any computers. One of my general design principles that I always use is to try to separate and de-couple as much as possible different design tasks so that they can be done <u>sequentially</u> and not simultaneously. Before computers that approach would be very important, as a way to reduce the computational burden. These days it is a way to aid in understanding and gives better control of the design process. As one example, I always do a monochromatic design before even looking at color correction.

We want to avoid piling up too many tasks that need to be done at the same time.

Designing a Double-Gauss lens, the Hard Way



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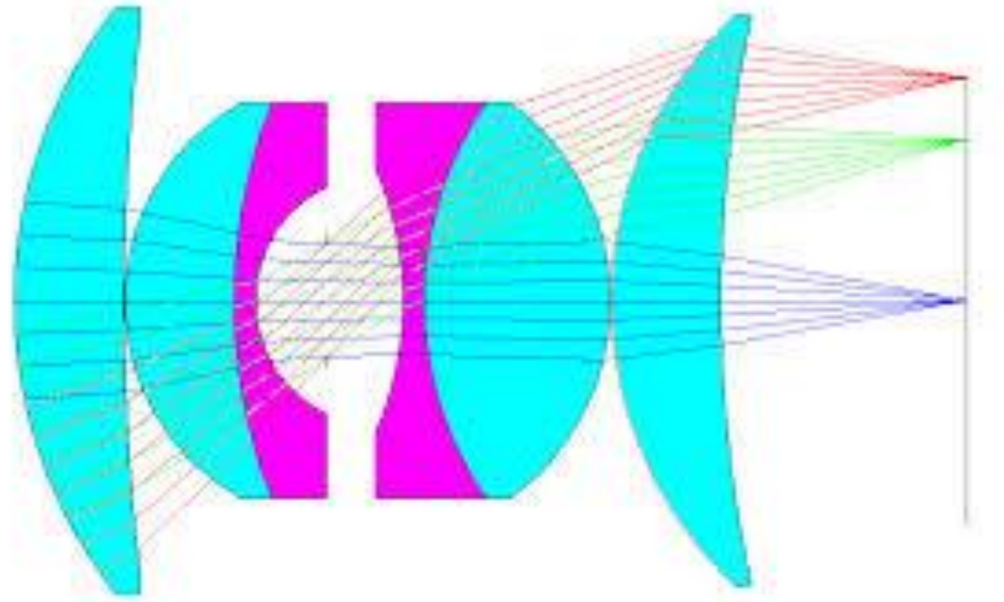
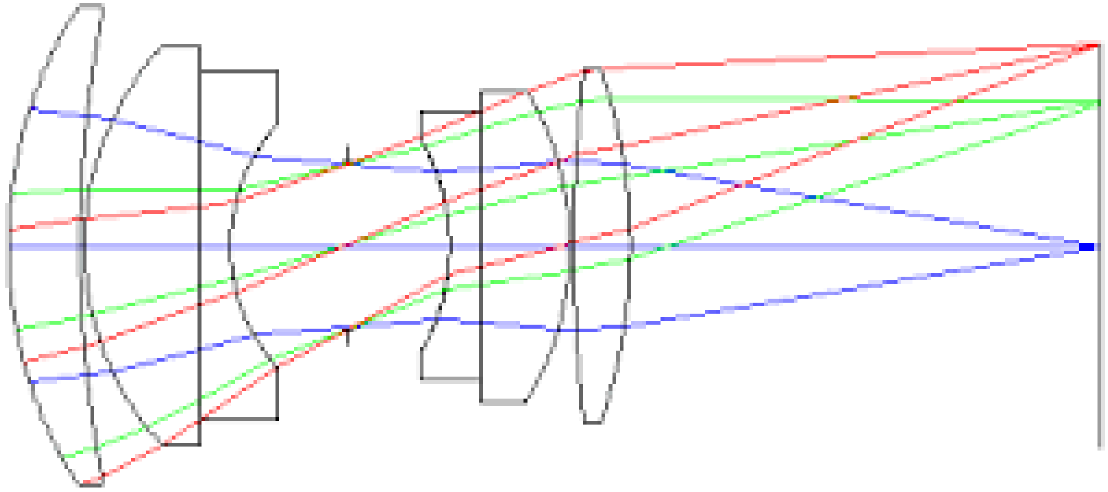
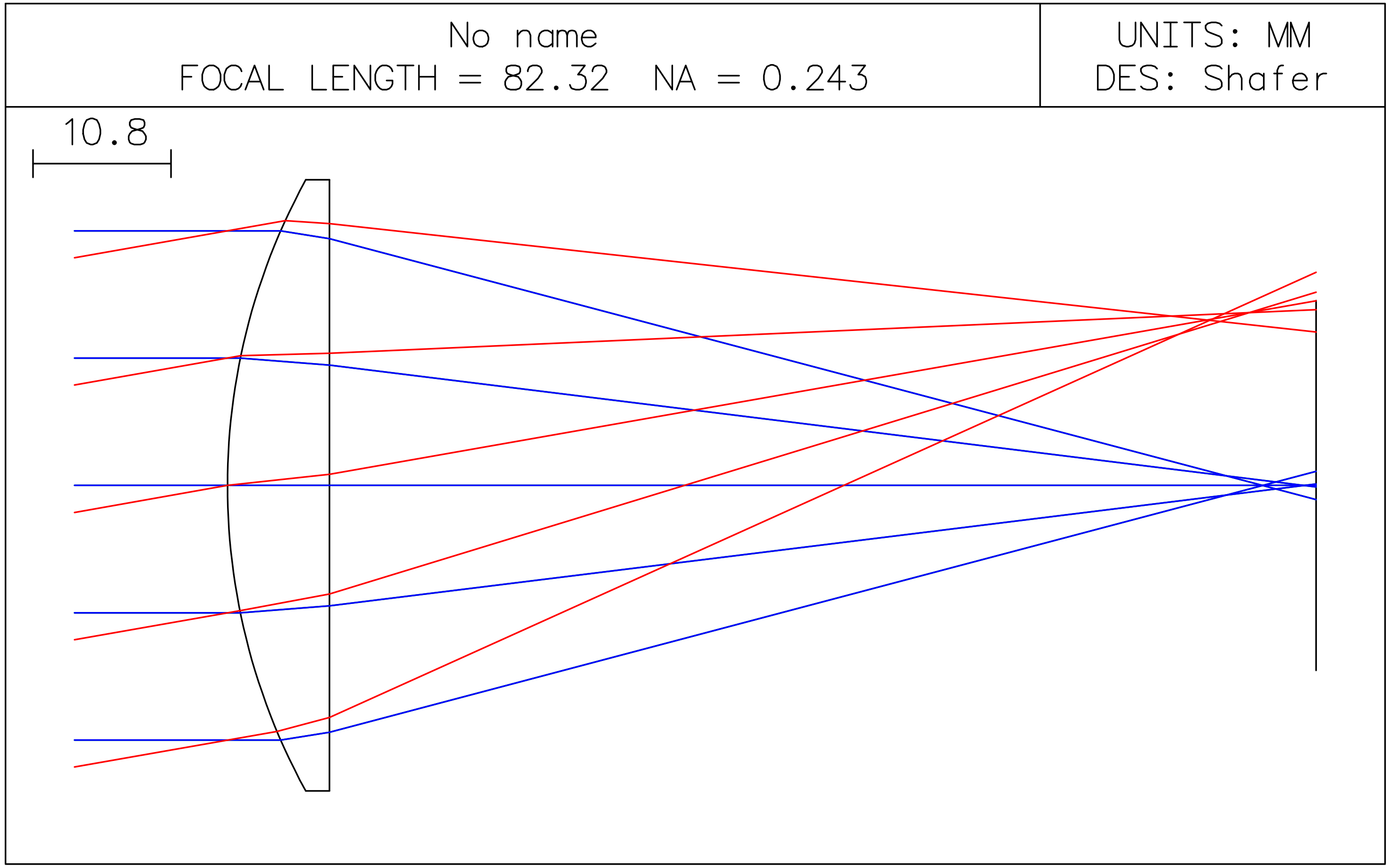




The Double-Gauss type of design is very flexible and can give good performance in a wide variety of combinations of field angle and f# speed. These days you can start a new design from a gazillion Double-Gauss design patents or just enter some design data that give a drawing that looks like a Double-Gauss and then computer optimize.

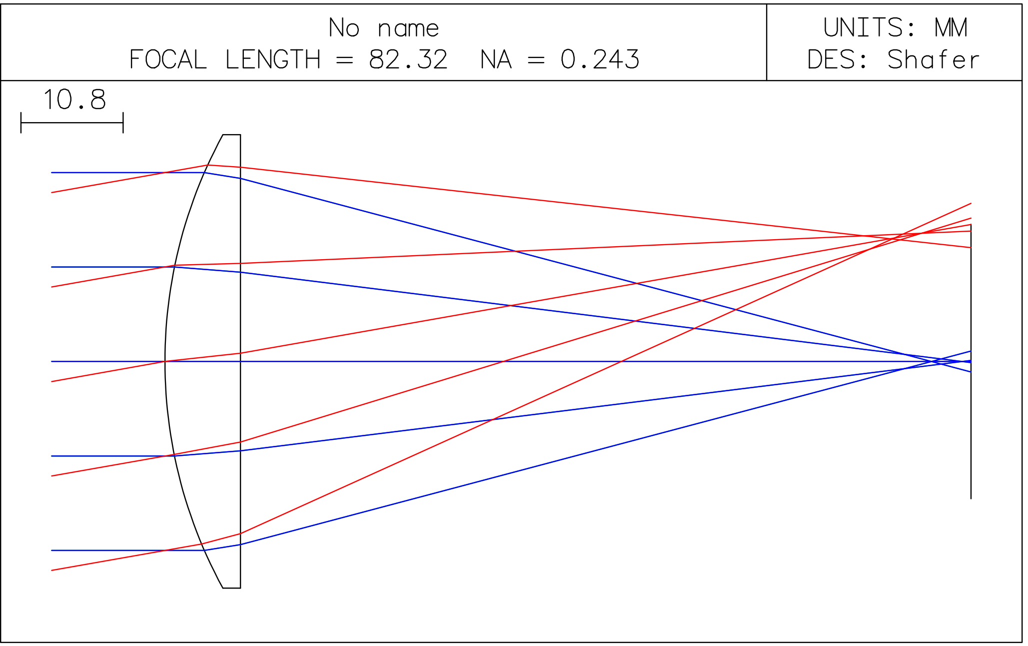
Back in the days before computers a very different style of lens design was necessary. People had to use some aberration theory and insights and did not do more than 2X 2 matrix optimization – by hand.

Let us see what that may have been like, but use a computer to do the required simple calculations, as if we were doing it by hand calculations. We will first do a monochromatic design and then add color correction.

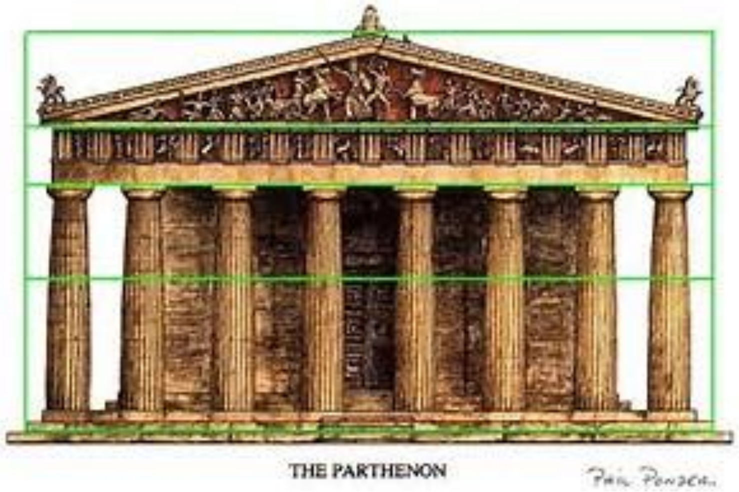


Let's start with a plano-convex lens, with front radius of 50 mm, 40 mm aperture and a glass like Schott SK16, with an index close to 1.62 and low dispersion. We will be doing just a 3rd –order aberration design to get our starting point for computer optimization – or, in the old days, for some very tedious hand raytracing calculations.

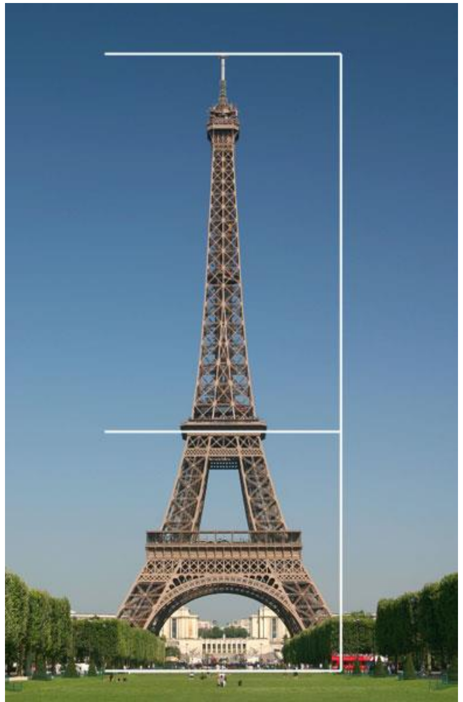
The aperture stop is on the front lens (for now). Since we will be correcting the 3rd-order aberrations to zero, the field angle and f# speed then don't enter in and have no effect. So we pick something that makes the lens drawings look good. After we get our 3rd- order solution we can then choose the field angle and f# of interest, for ray optimizing.

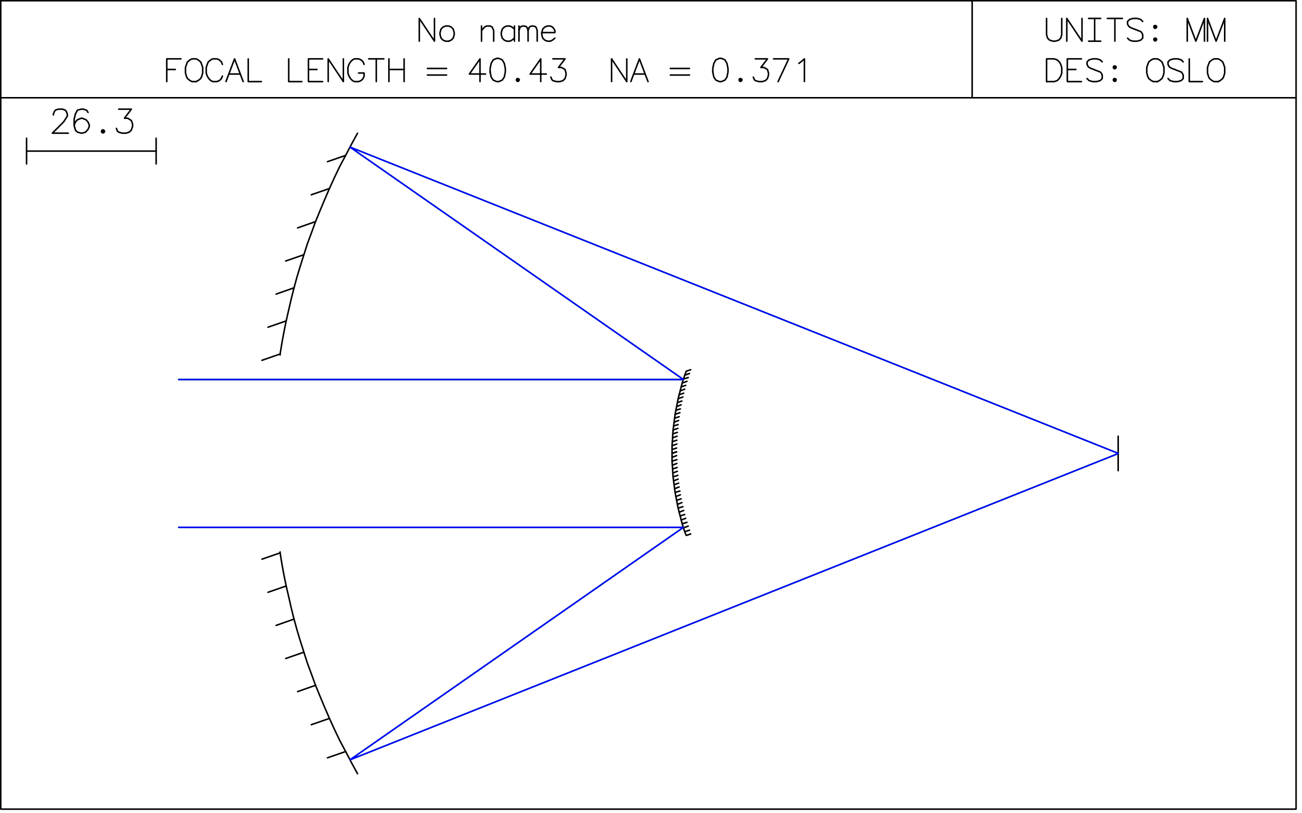


To correct the coma of a single lens with aperture stop in contact, let us look a little more closely at it. Coma of a lens with the stop in contact varies linearly with the bending of the lens. For a thin lens (zero thickness) with the stop in contact the index of refraction that makes 3rd order coma zero for a plano-convex lens is 1.618034……. And this number is the famous Golden Mean or Golden Ratio from classical times. A simple algebraic equation links together lens bending, index and coma so it is easy to handle, pre-computer.



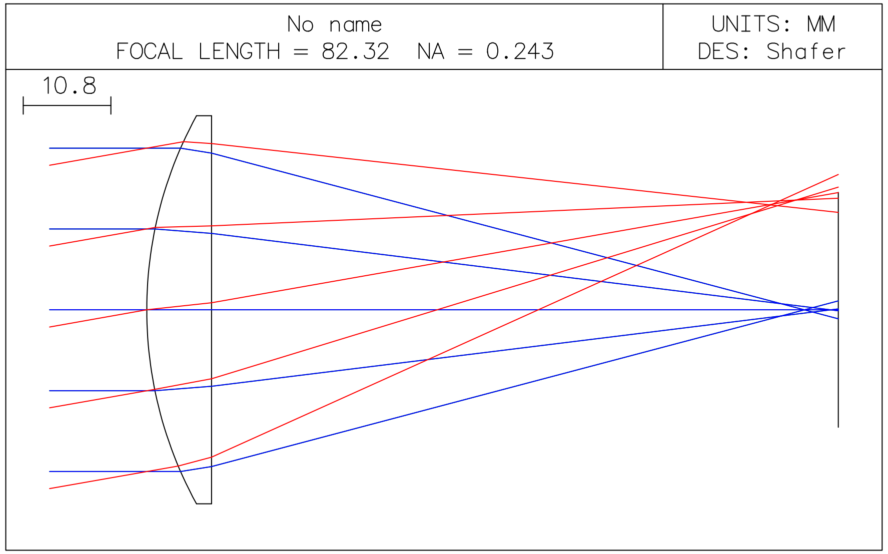
The Golden Mean occurs constantly in nature and in art and architecture. And also in optics



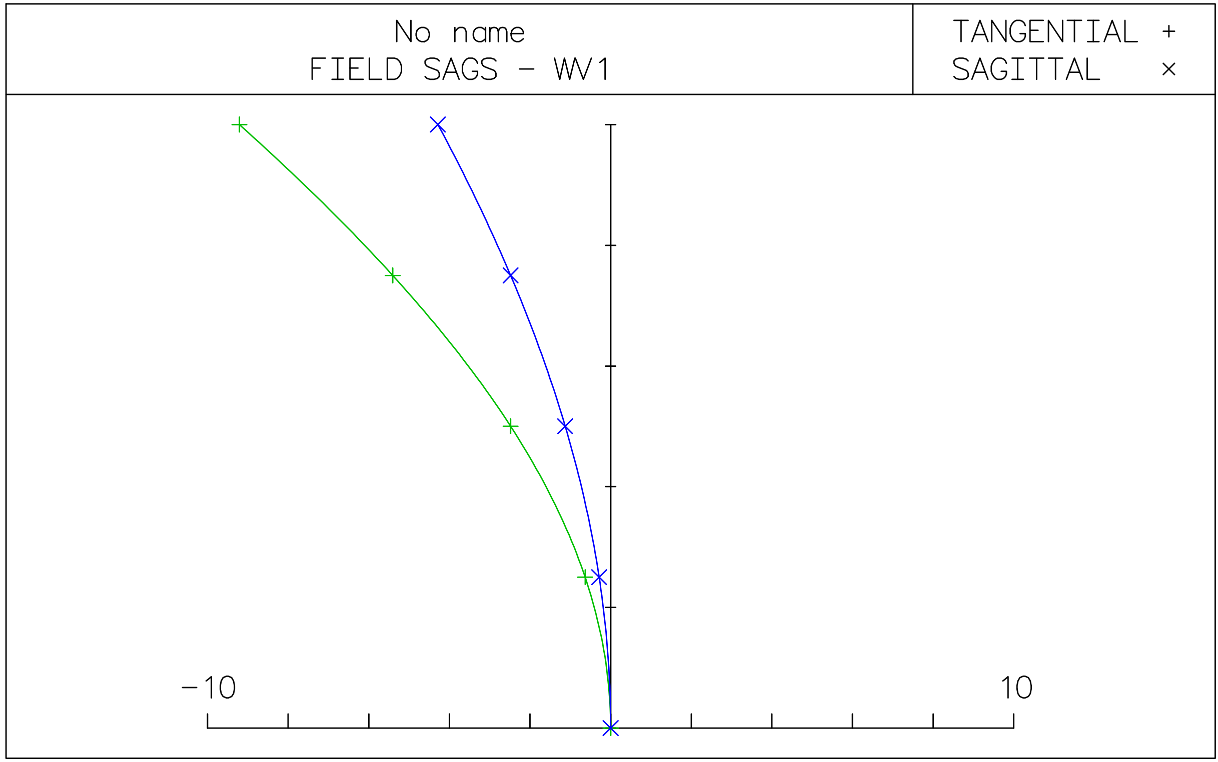


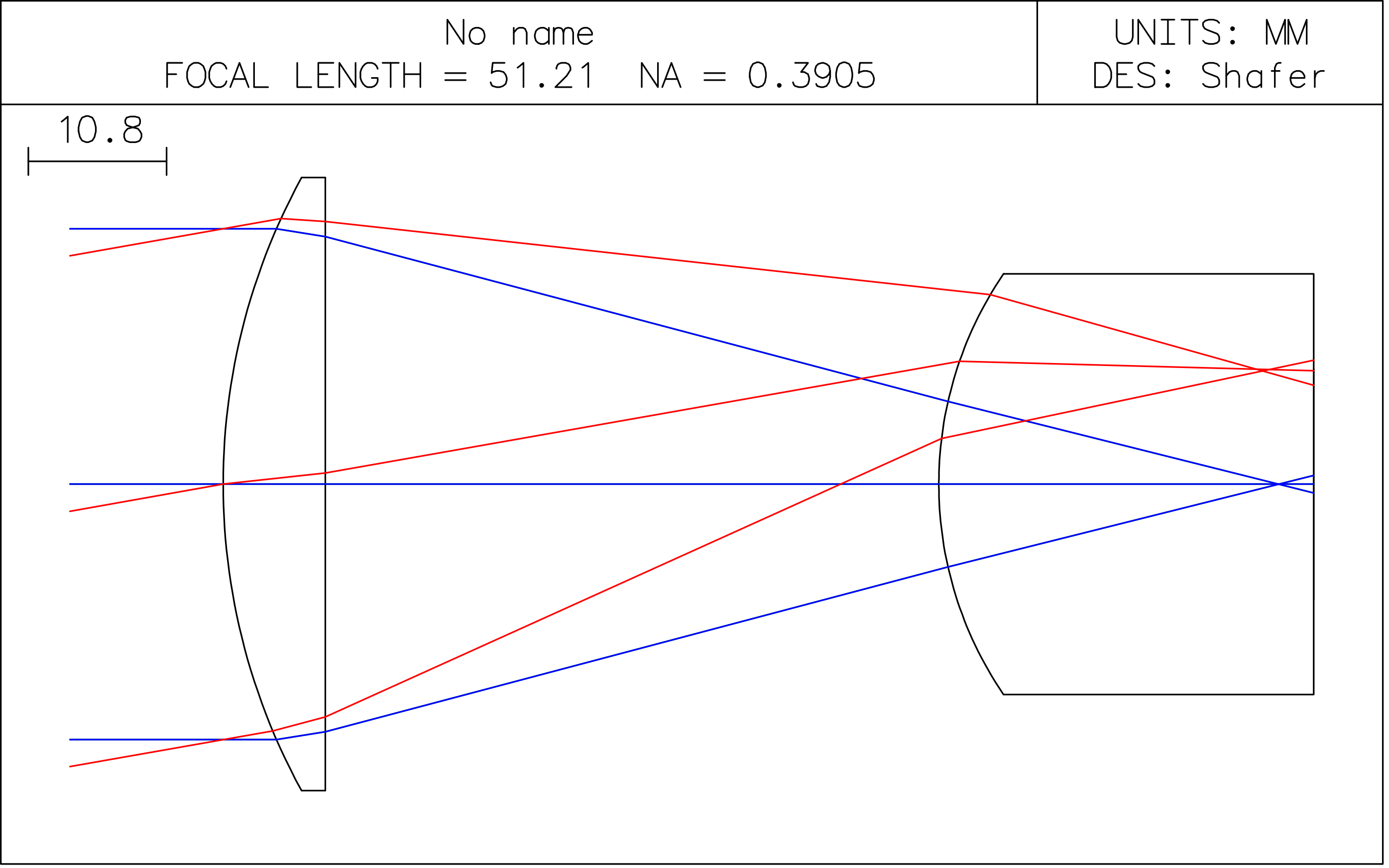
Another case where the Golden Mean occurs in optics is the concentric spherical mirrors design, where for collimated input the radii ratio of the two mirrors that corrects for 3rd order spherical aberration is 1.618034…

There are other examples in optics.



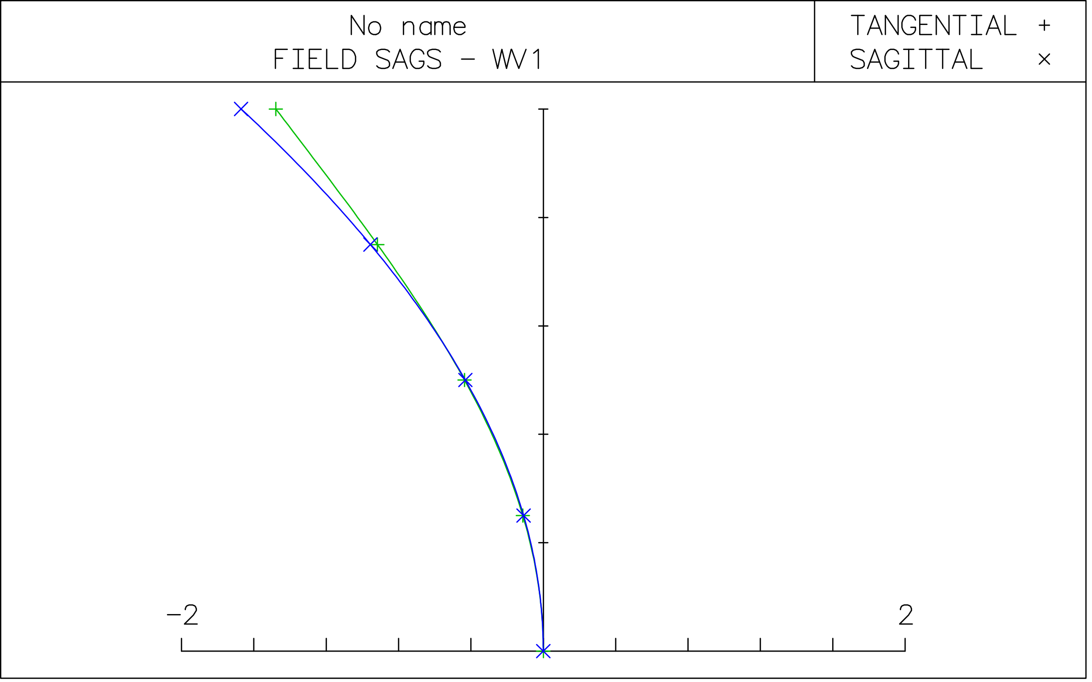
The astigmatism field curves for this single lens with stop in contact look like this.



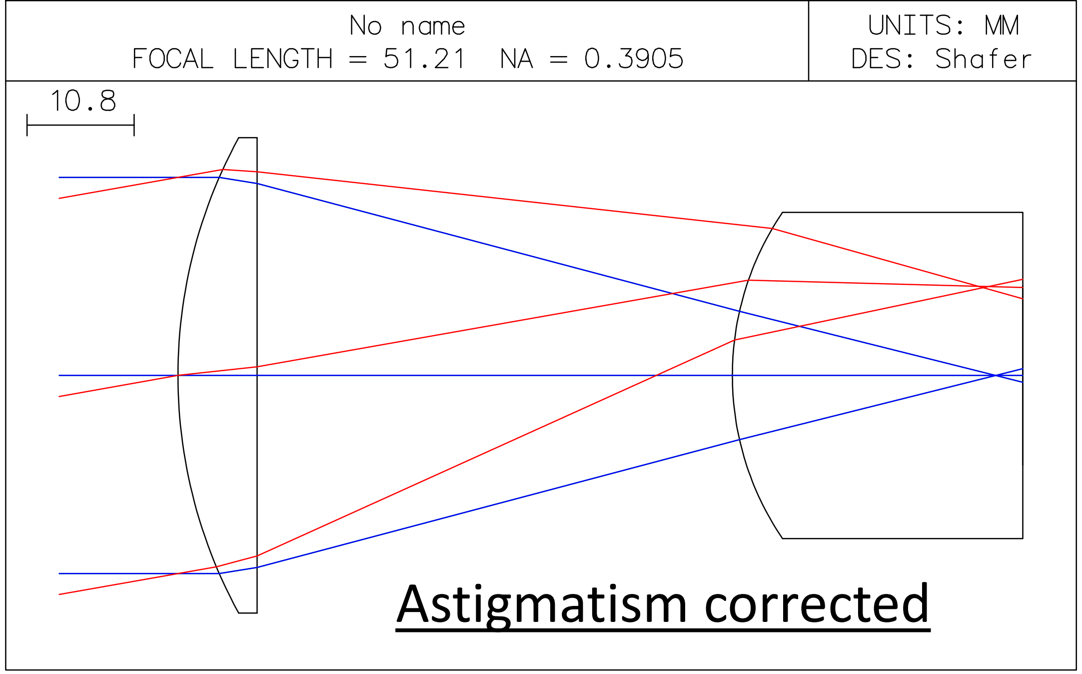


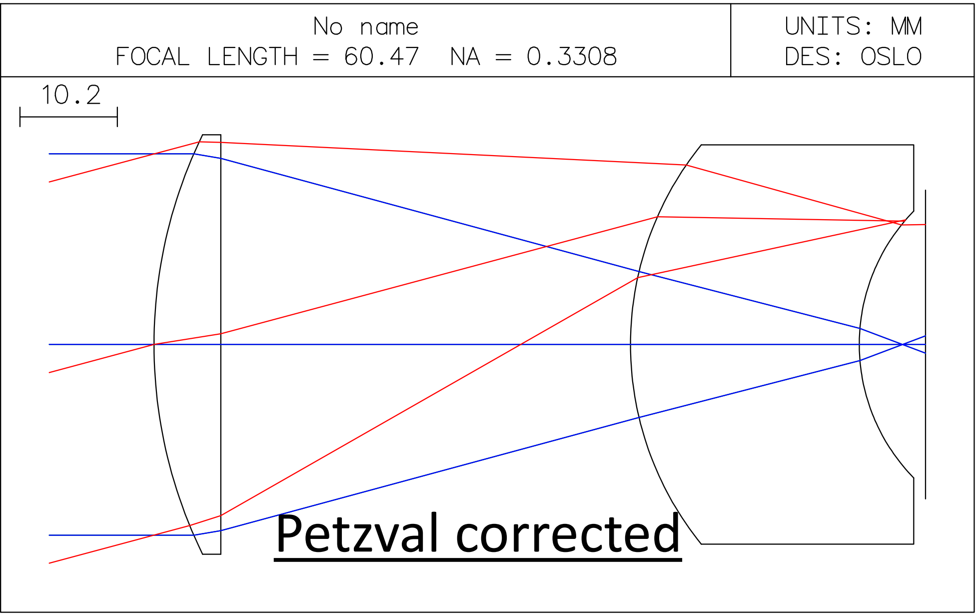
The front lens has spherical aberration, coma, astigmatism and Petzval curvature. With the aperture stop at the front lens and a refractive index of about 1.62 (SK16 glass) the lens bending that makes coma go to zero is almost exactly the plano-convex case shown here. Then we add a thick lens that is concentric about the image for its front face and flat for its back face, right against the image. It is also SK16 glass.

We know that a surface concentric about the image has no spherical aberration or coma but it does have astigmatism and Petzval. Its astigmatism is opposite in sign to that of the front lens. So we do a few trials and find that the second lens's front radius should be about 33 mm to cancel the astigmatism of the first lens. So now this two lens system is corrected for coma and astigmatism but still has spherical aberration (from the first lens) and Petzval curvature. The second lens is 33 mm thick, up to the image. The formula for 3rd-order astigmatism of a surface curved concentric about the image is very simple and easy to handle in pre-computer days.

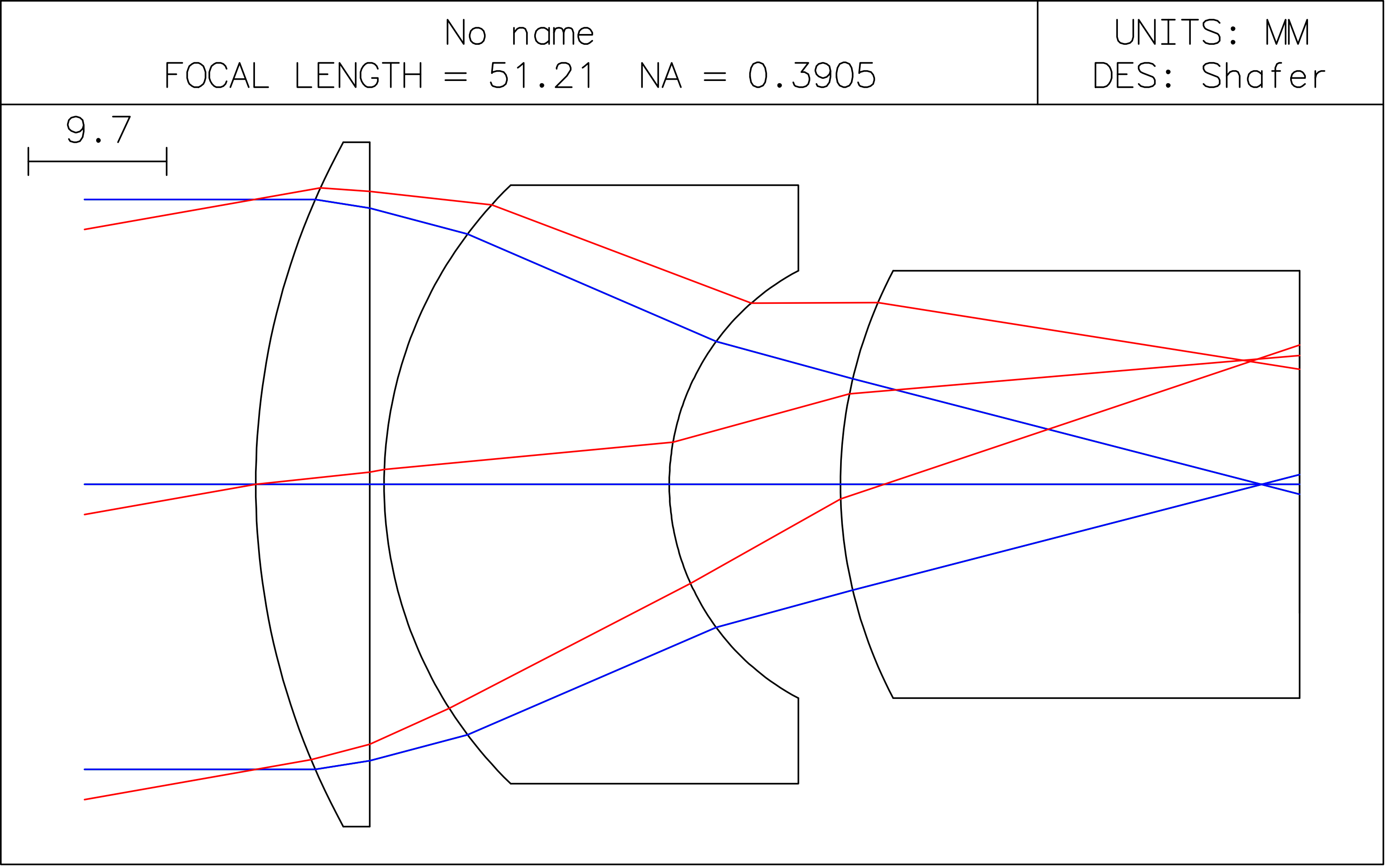


Field curves with astigmatism corrected



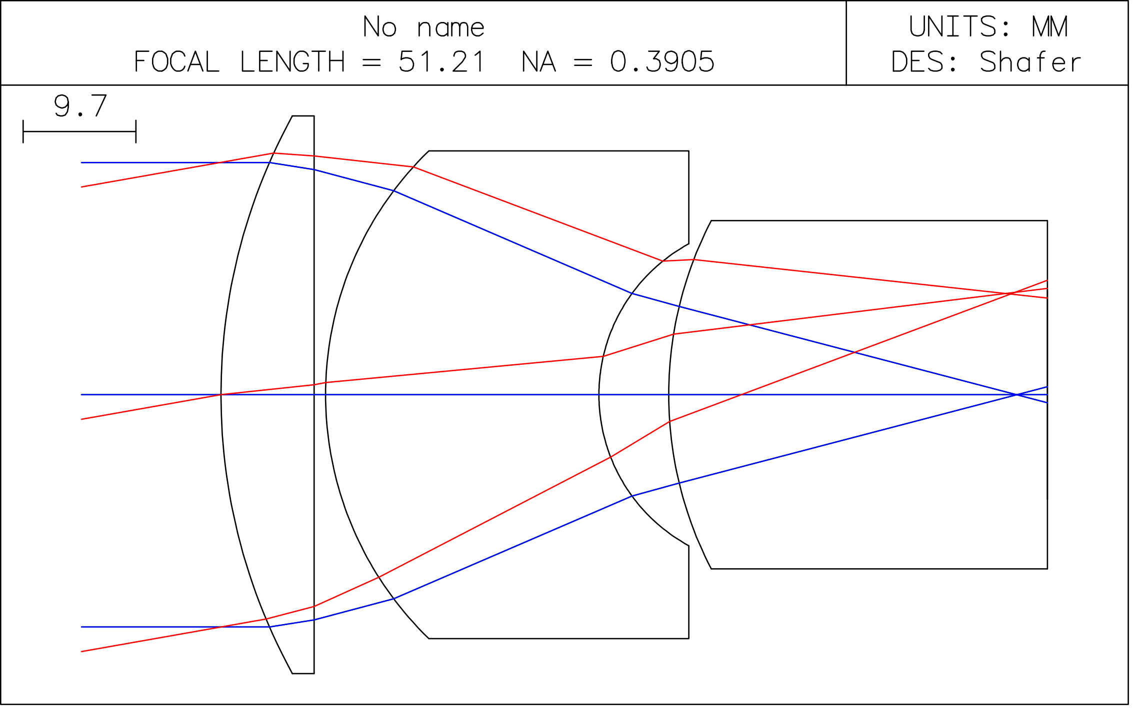


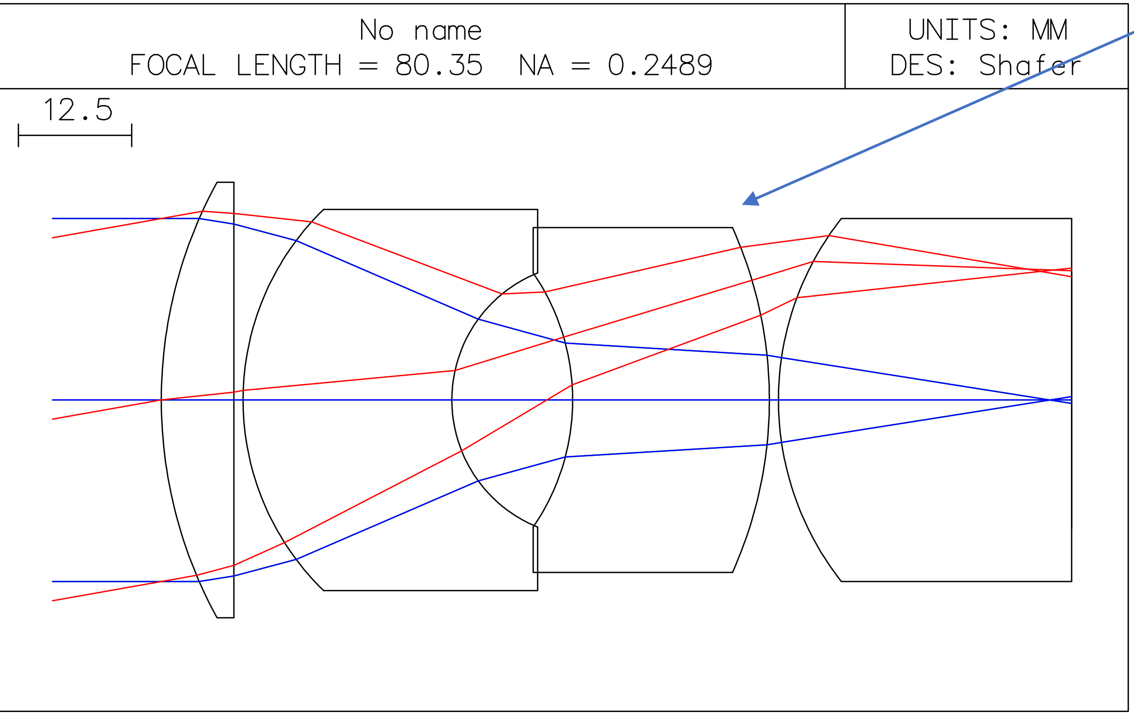
The Petzval curvature of the image could now be corrected by moving the flat lens surface in contact with the image away from the image and putting a strong concave curve on that surface. A radius of 20 mm there would correct the Petzval of the design to zero. But that strong surface, no longer right at the image, would also add in a <u>large</u> amount of astigmatism, some coma, and give TIR for larger field angles. We will not do that.



Next we add a meniscus lens right after the first lens. Both of its surfaces are aplanatic about the axial ray, coming from the first lens. An aplanatic surface has no spherical aberration, coma, or astigmatism, but does have Petzval curvature. Since both surfaces are aplanatic it has no net affect on the axial ray angle – the first aplanatic surface speeds up the axial ray cone angle and the second aplanatic surface slows it down by the same amount.

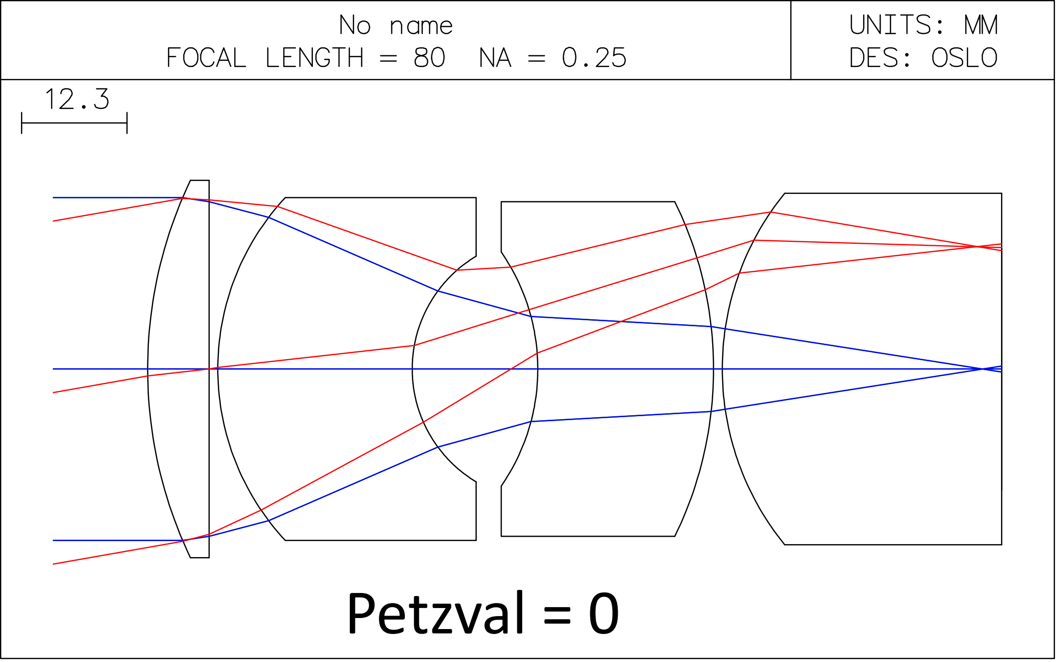
The purpose of this meniscus lens is to largely correct the design for Petzval curvature. Its negative power is just what is needed to get a flat image and it does this without any spherical aberration, coma, or astigmatism of its own. The first and third lenses here have a combined Petzval radius of 52 mm. After adding the aplanatic second lens that becomes 100 mm.



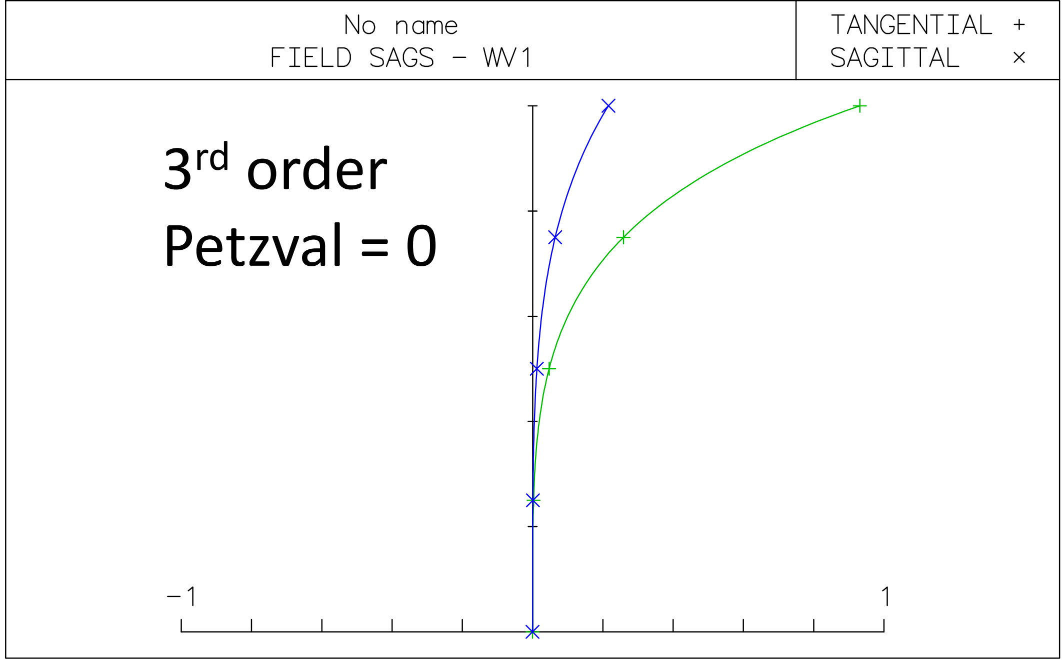


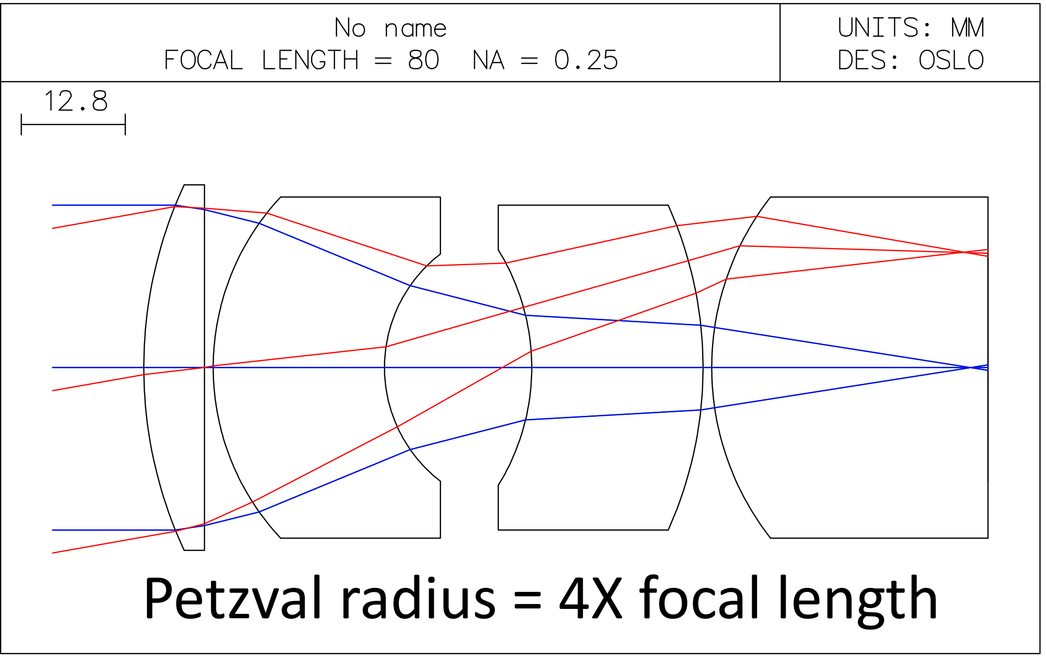
The thickness of that second lens, with its two aplanatic surfaces, can be chosen to have different values providing different amounts of Petzval correction. But if its thickness is made to go all the way up to the front of the back lens it's still not enough Petzval correction to correct Petzval to zero. Here in the picture the Petzval image curvature is 150 mm radius – the best that you can do. The surface next to the image could be curved to do some Petzval correction but that is not the plan here.

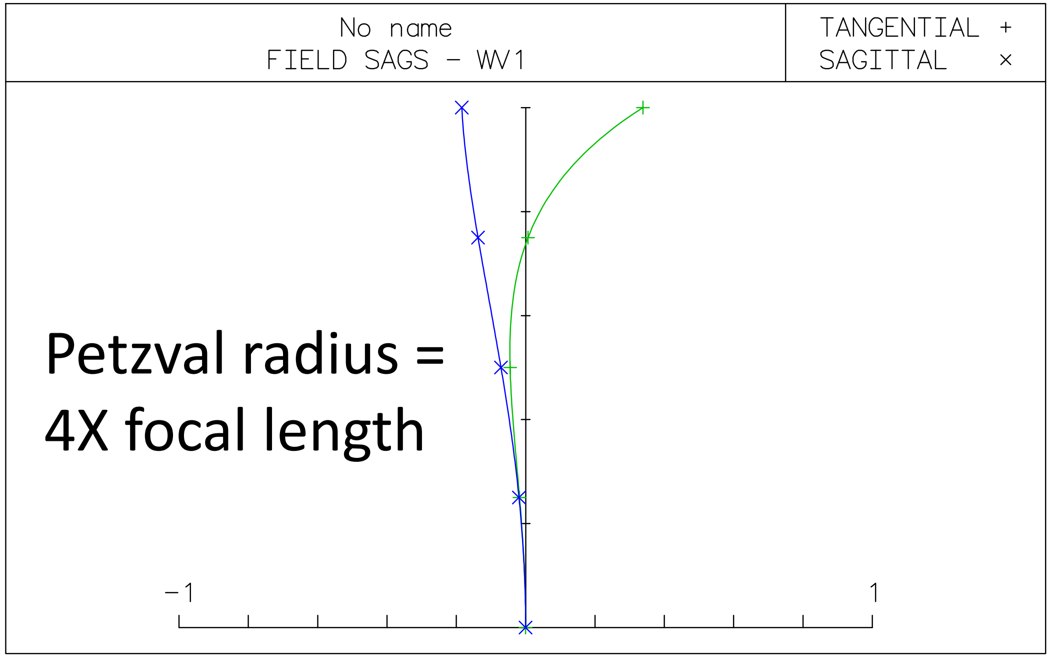
A new lens is added that has both of its surfaces concentric about the chief ray. The chief ray angle is changed by the back surface of the second lens. The new lens with both surfaces concentric about that chief ray has no coma or astigmatism but does have spherical aberration and Petzval curvature. By doing some trials with the thicknesses of the second <u>and</u> third lenses we get the design shown, which has zero Petzval. Now we are left with only spherical aberration to be corrected (and then color next)

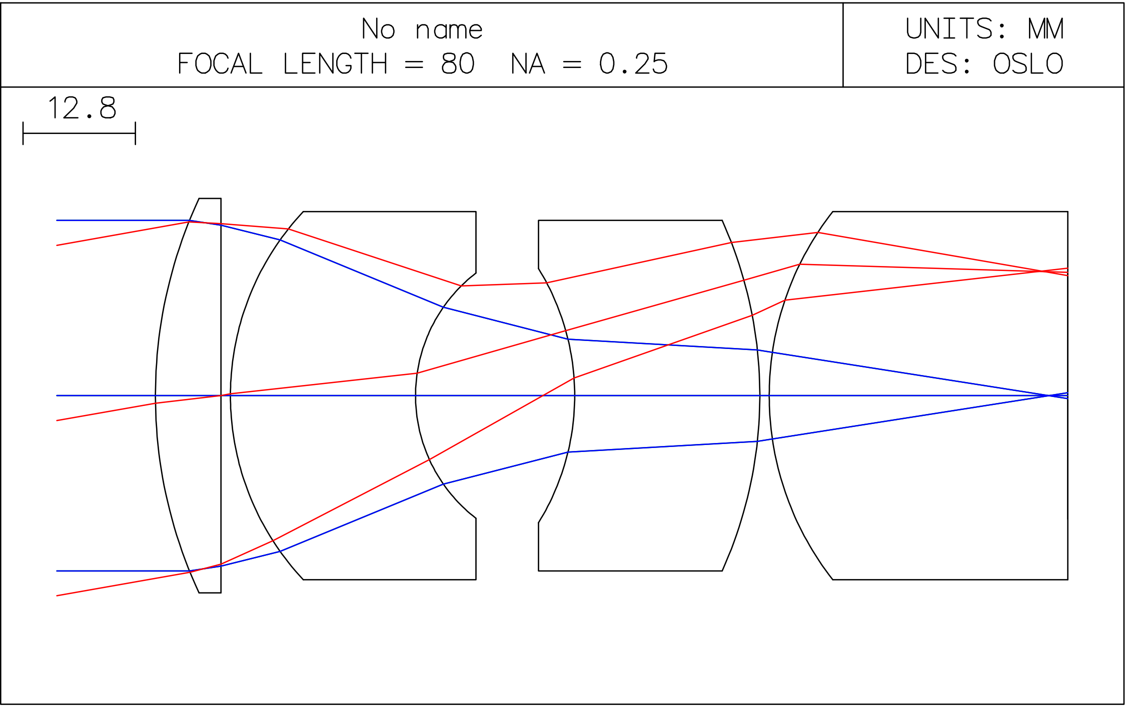


Experienced designers, pre-computer, knew that correcting Petzval to zero gives too much higher-order Petzval and astigmatism. So they usually corrected the Petzval radius to be 3 or 4X the system focal length. We do that here too.





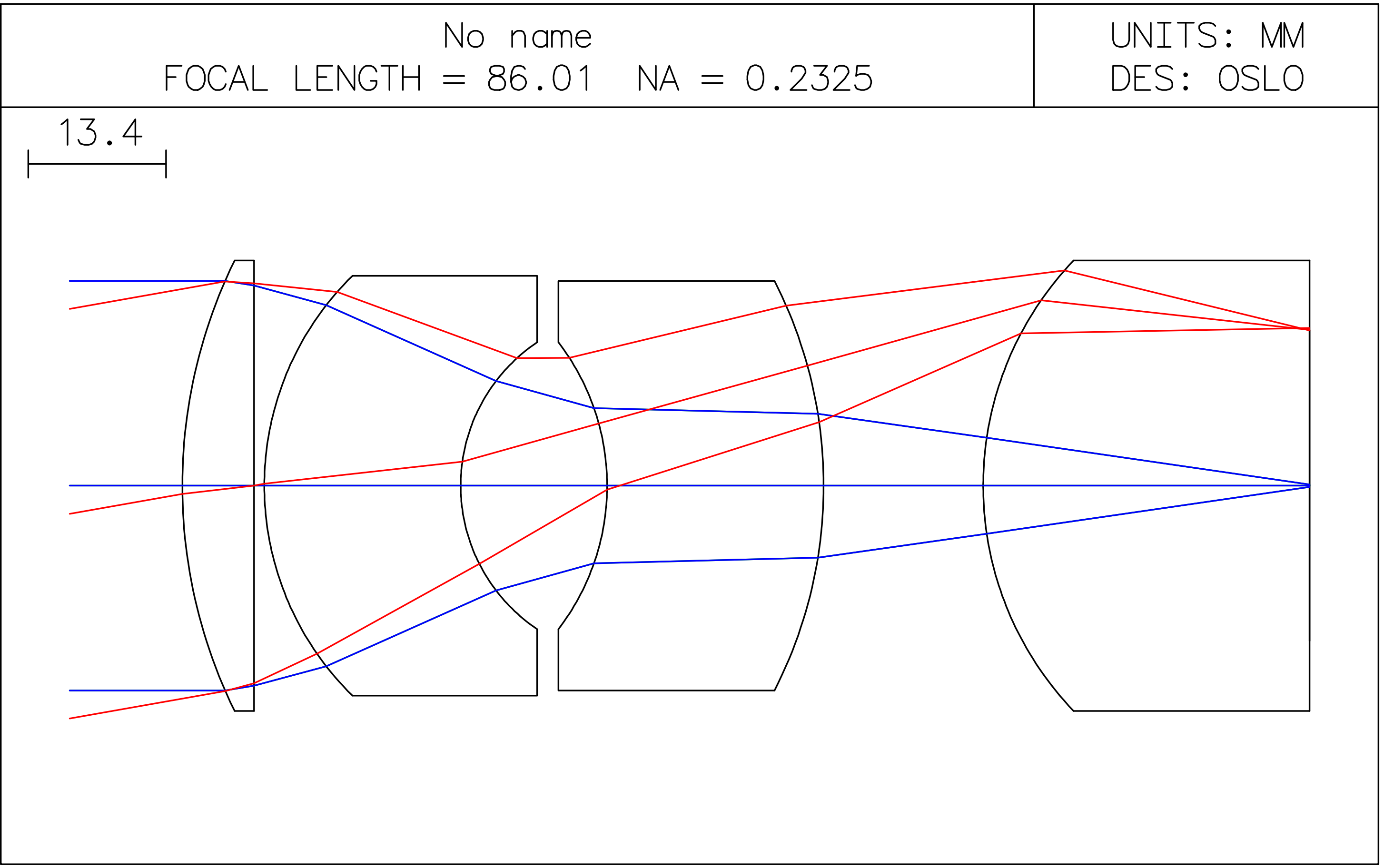




The third lens does not have enough spherical aberration to correct that of the front lens, But we can move that third lens to the left some, while keeping it concentric about the chief ray. That makes for a stronger front surface and more spherical aberration. Let's keep the thickness of that lens unchanged as we move it.

Let us recap where we are now. The front lens, with the aperture stop there, has a bending shape that is corrected for coma. It has spherical aberration, astigmatism and Petzval curvature. The last lens here corrects for astigmatism without adding any spherical aberration or coma, because of its front surface concentric about the image. The second and third lens are double aplanatic, about the axial ray, and double concentric, about the chief ray. So they do not add any coma or astigmatism, but this pair of lenses does correct the system for Petzval, not to zero but to 4X the focal length.

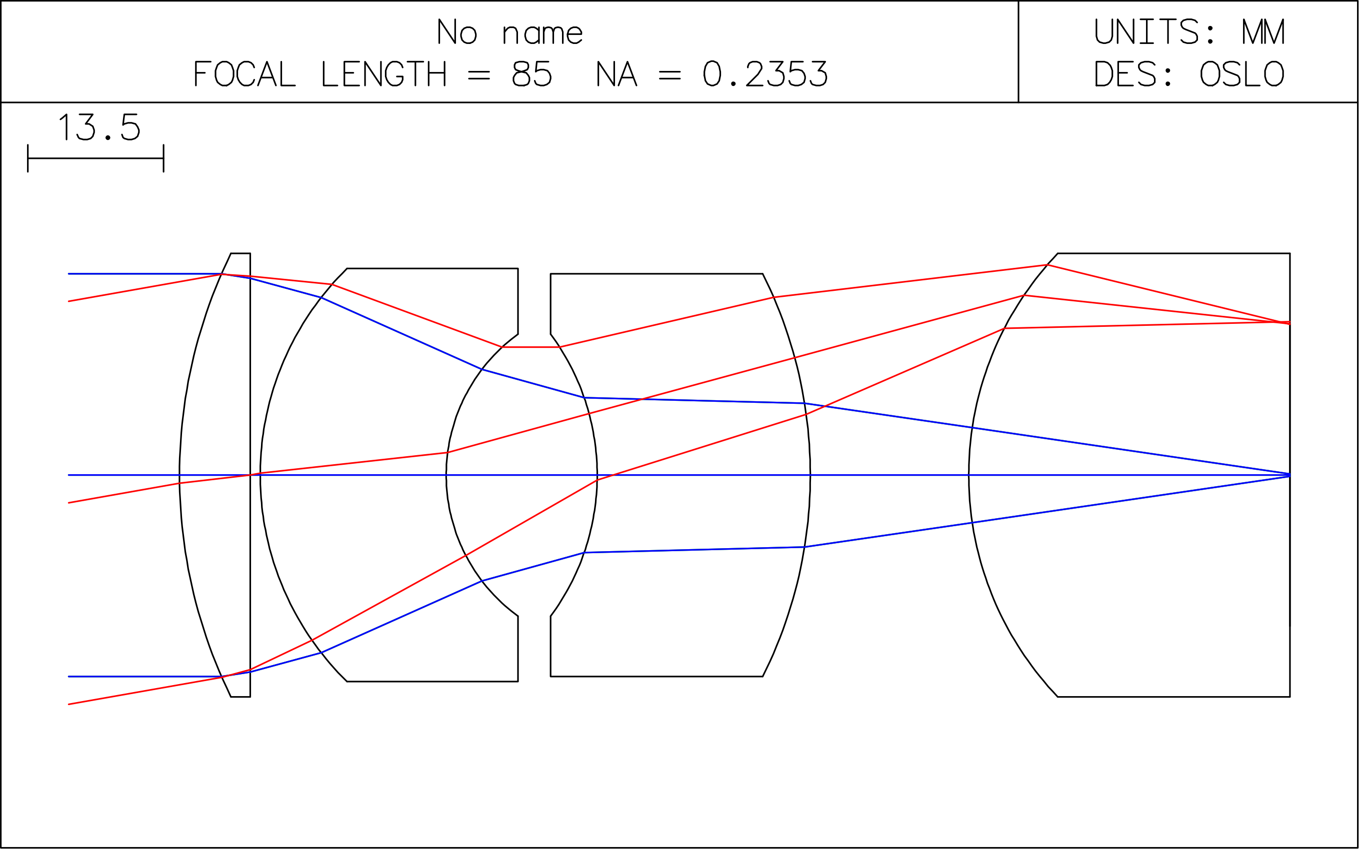
The next step is to correct for spherical aberration. The spherical aberration of the front positive lens and of the negative third lens concentric about the chief ray, are of opposite signs.



We move the third lens to the left, keeping it concentric about the chief ray, until we get enough spherical aberration to correct for the spherical aberration of the first lens. The first and second lens do not change at all and we keep the thickness of the third lens unchanged as we move it to the left.

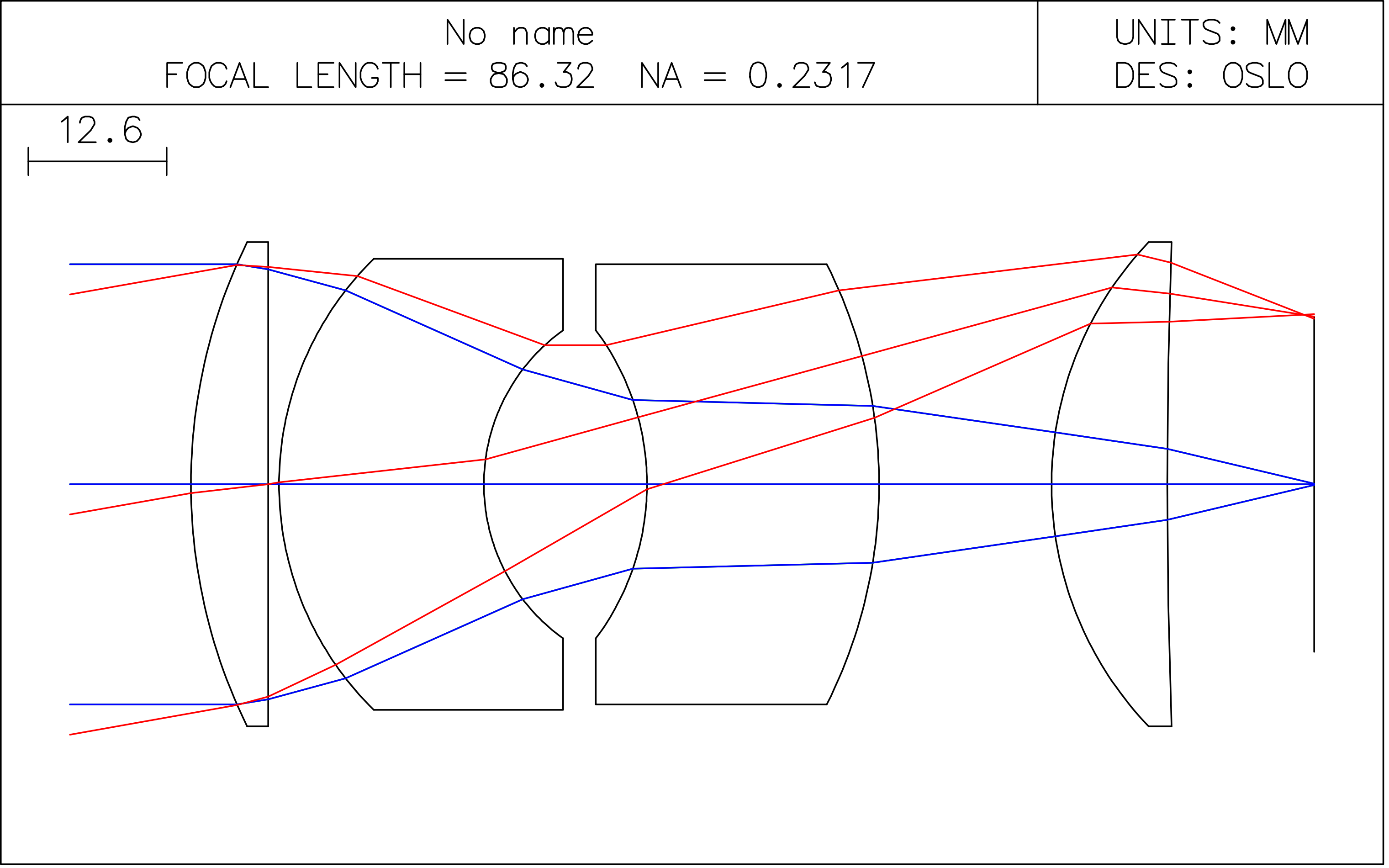
The formula for 3rd order spherical aberration of the two surfaces of the third lens, and of the first lens, are manageable and we are doing this design exercise here without tracing a single real ray.

After we get the third lens to correct the spherical aberration of the first lens we move the last lens, which is unchanged, to stay concentric about the image. With this new design the Petzval correction has been changed a little, since the third lens has changed.



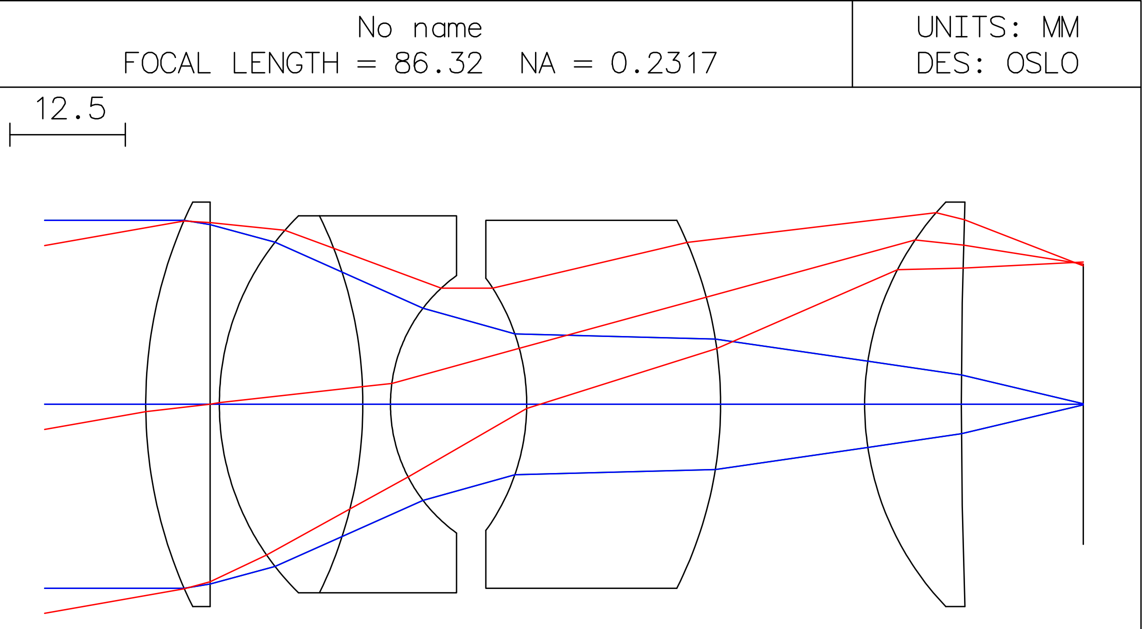
To restore the Petzval correction to what we want we reduce the thickness of the aplanatic/aplanatic second lens by a small amount – just ½ mm – and resolve for the concentric third lens that corrects for spherical aberration. The result is a monochromatic design, shown here, with corrected spherical aberration, coma, astigmatism and optimized Petzval. There are a lot of hand calculations required and that was the life of designers, before computers. But here we have reduced the amount of work by using aplanatic surfaces and surfaces concentric about the image or the chief ray.

The next step is to move the last lens surface away from its contact with the image. As we do that the rest of the design is not touched. The last surface is made concentric about the paraxial chief ray (which is nearly telecentric) so that last surface then has no coma or astigmatism. This is shown next.



The last lens surface has a very weak radius, concentric about the paraxial chief ray. It has no 3rd order coma or astigmatism and the very small amount of 3rd order spherical aberration it has is not worth changing the third lens for in order to correct it.

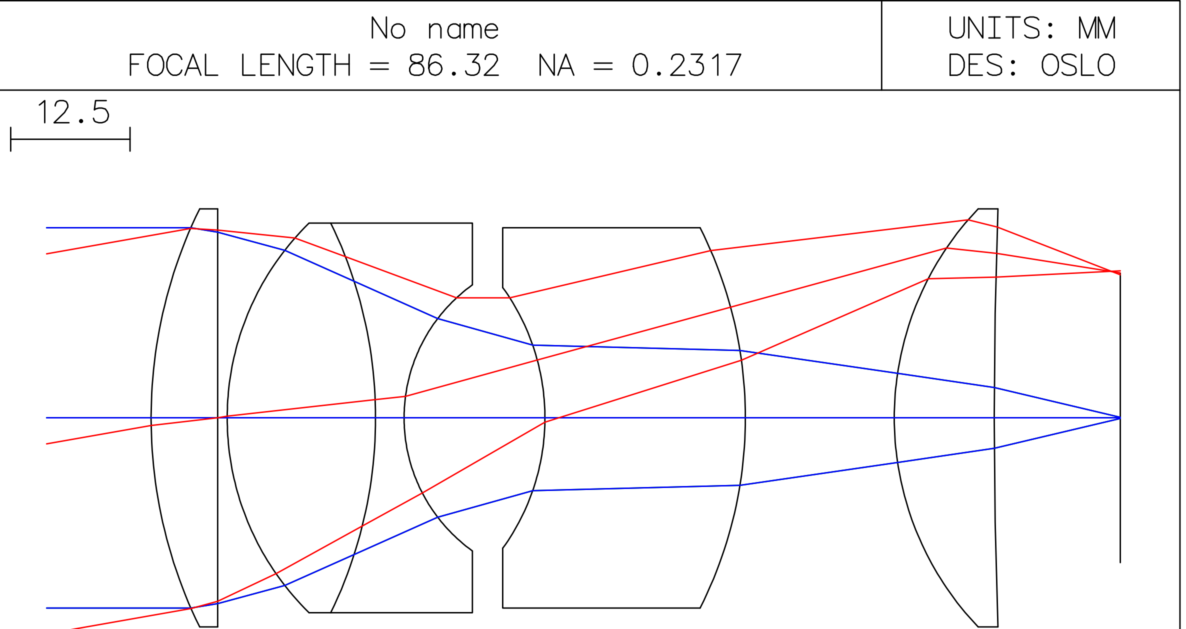
Now we will do color correction. What we want is to be able to do that without disturbing at all the design that we have achieved so far, after a lot of hand calculations. The key to being able to do that is the way the glass type choices are handled.



Glass order = SK16, SK16, F2, F2, SK16

Now we do color correction. We made the glass type used so far be Schott SK16. There is a reason for that. This crown glass has almost exactly the same index of refraction as the flint glass Schott F2, which is much more dispersive. That means that we can now add a "buried surface" or two inside the lenses and use the F2 glass to correct for axial and lateral color. The "buried surface" will have essentially no index difference across it for the central wavelength and therefore will not upset the aplanatic and concentric conditions for the other surfaces.

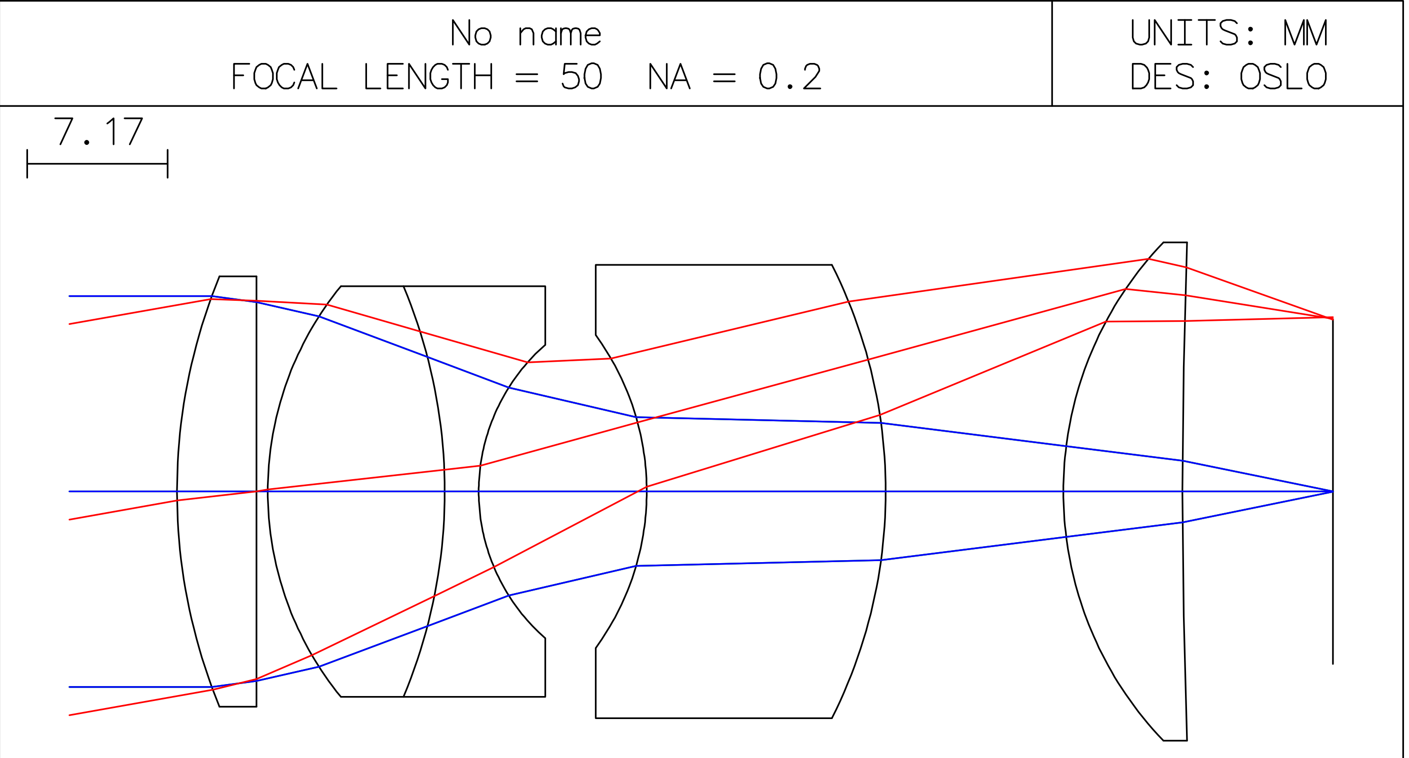
In most Double-Gauss designs there are two cemented doublets for the two meniscus lenses because it takes two separated flint lenses to correct for both axial and lateral color. In this design here only one flint lens is needed because of the almost telephoto first-order optics and both axial and lateral color can be corrected by a single flint lens in the right position. But here we have also made the third lens be F2 glass in order to reduce the power needed of the color correcting "buried surface" in the cemented doublet.



Glass order = SK16, SK16, F2, F2, SK16

In the old days experienced designers would know that you don't want to correct the paraxial axial color to zero because it has to be balanced off against chromatic variation of spherical aberration. Here we made the paraxial axial color be nearly zero. The beauty of this design approach for color correction is that we can change the radius of the "buried surface" in the cemented double of SK16 and F2 glass without having any effect on the rest of the design, since those two glasses have almost exactly the same index at the central wavelength.

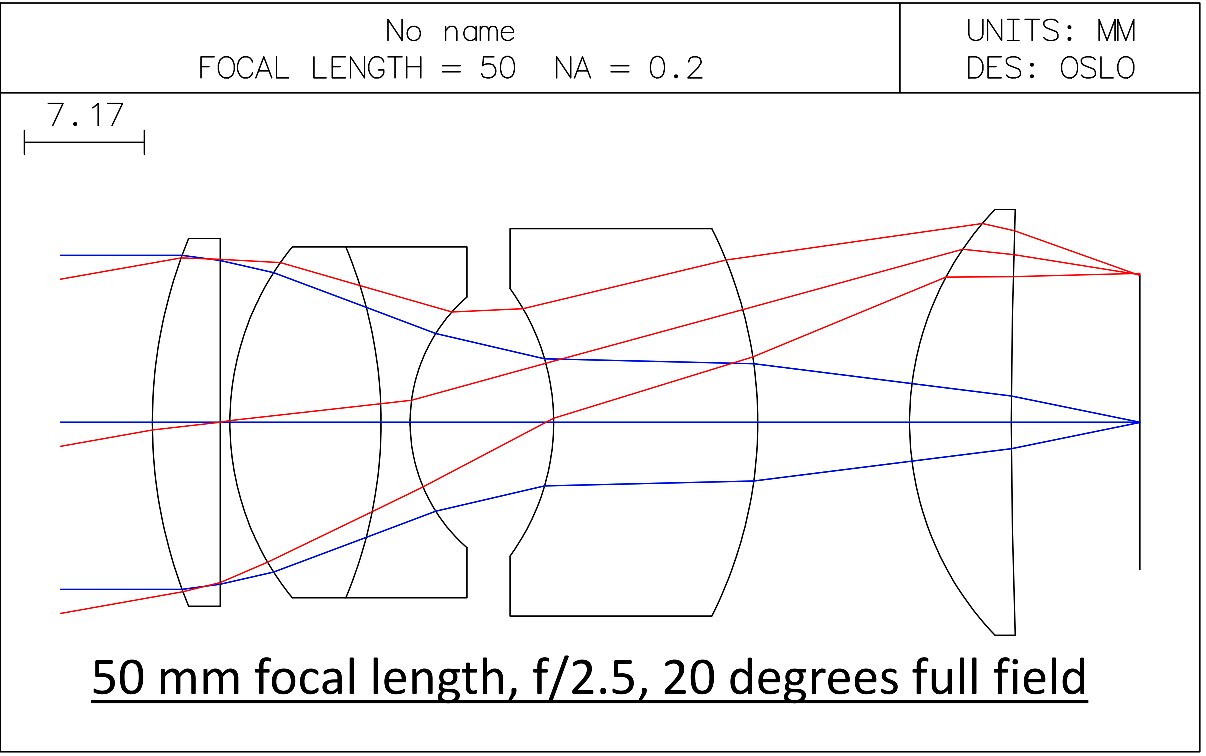
So far this has been a paraxial and 3rd order design and so the field angle and f# have been irrelevant up until now. If 3rd order spherical aberration = 0 then it is 0 for any f# value. Now let us scale our design to a focal length of 50 mm and evaluate it for a speed of f/2.5 and a full field angle of 20 degrees. That is shown next.

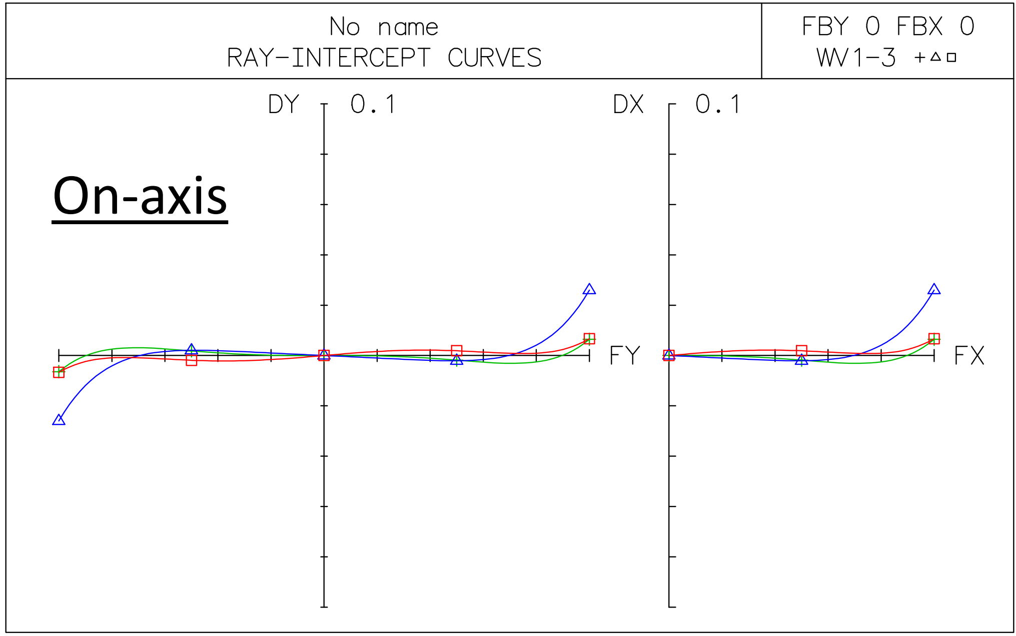


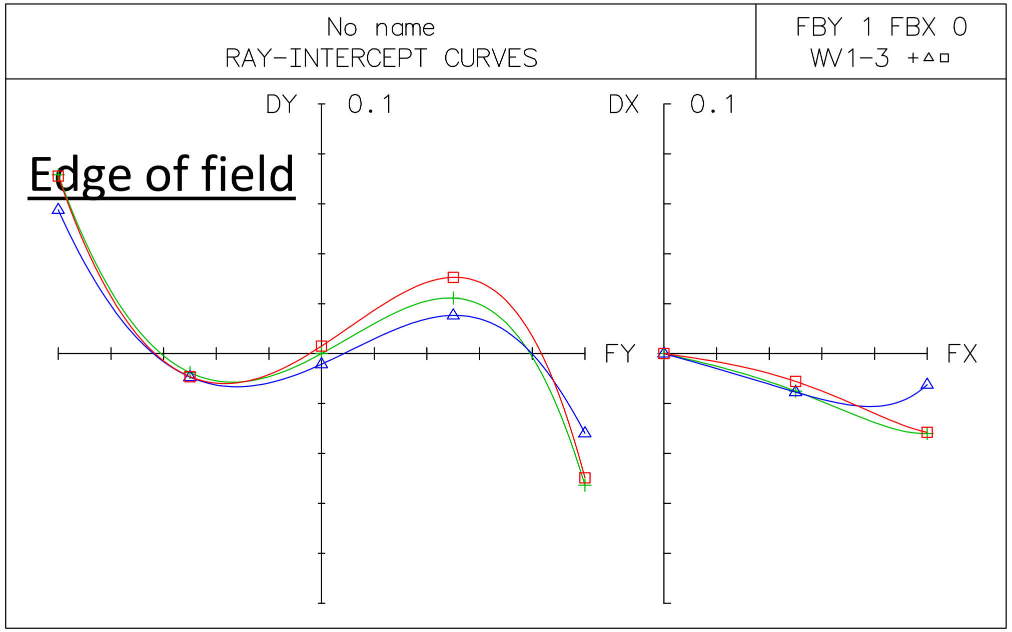
50 mm focal length, f/2.5, 20 degree full field

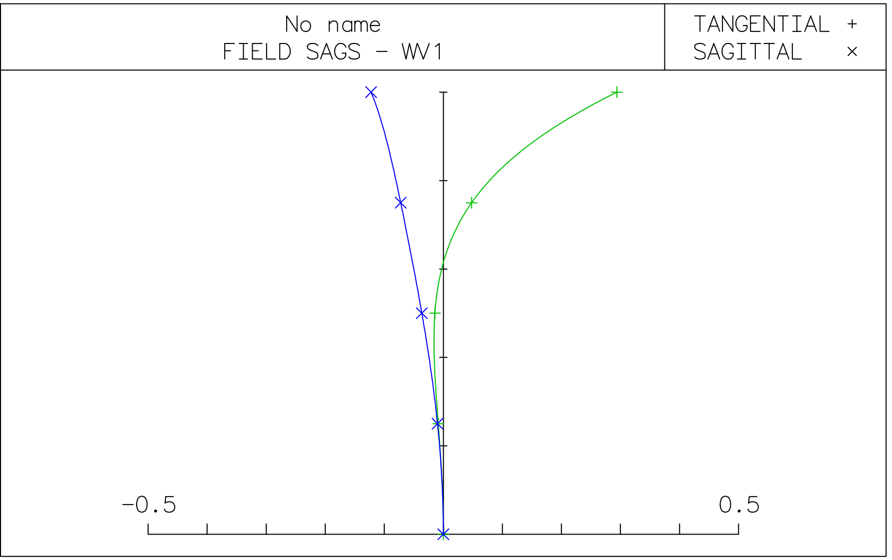
By tracing a single axial real ray and then working with only the concentric lens some trials would allow the 3rd and higher order spherical aberration to be balanced against each other. By working with just the "buried surface" radius and just one additional real ray axial color could be balanced against spherochromatism. Playing with just the aplanatic/aplanatic lens would allow 3rd-order Petzval to be balanced against higher-order field curvature, using Coddington equations.

Now let's us see what we have produced here. Not a single ray was traced. Only paraxial and 3rd order aberrations were considered. No aberration balancing was done of lower order against higher order. No attempt has been made to find the aperture stop position that gives the best higher-order aberration. Axial color has not been balanced against spherochromatism. But in the old days, pre-computer, this would be a good starting point for hand tracing a few real rays and trying to do some of the aberration balancing that is needed. With just two or three rays and doing some one or two variable optimizations much could be done, back then.



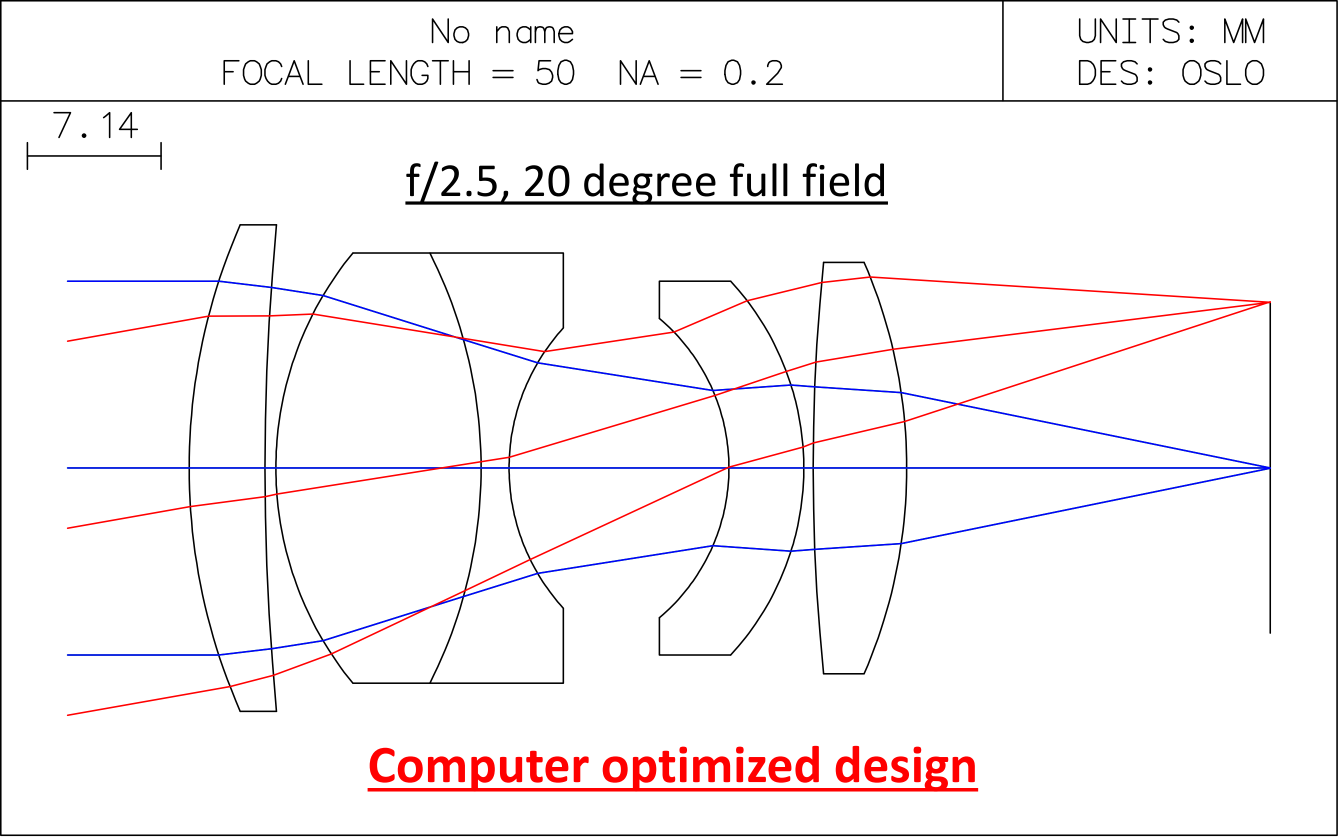




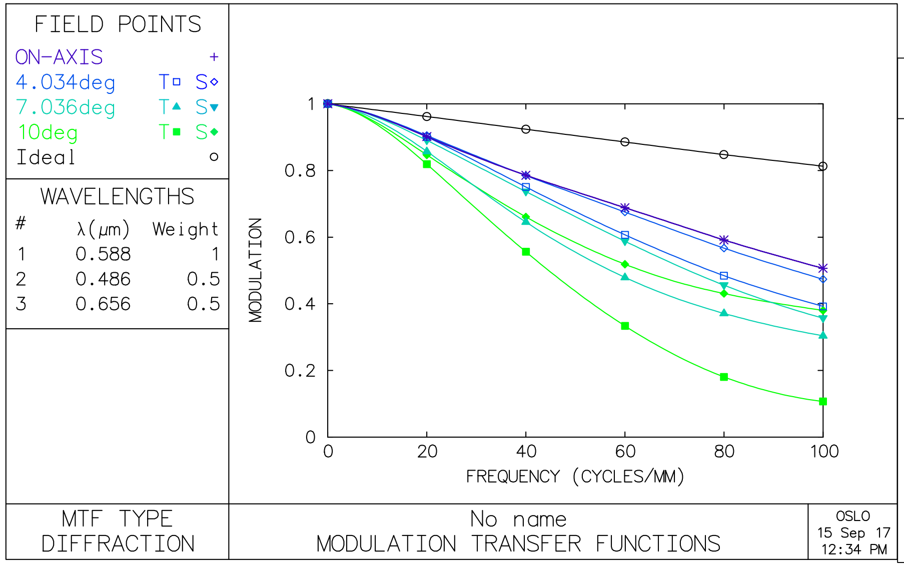


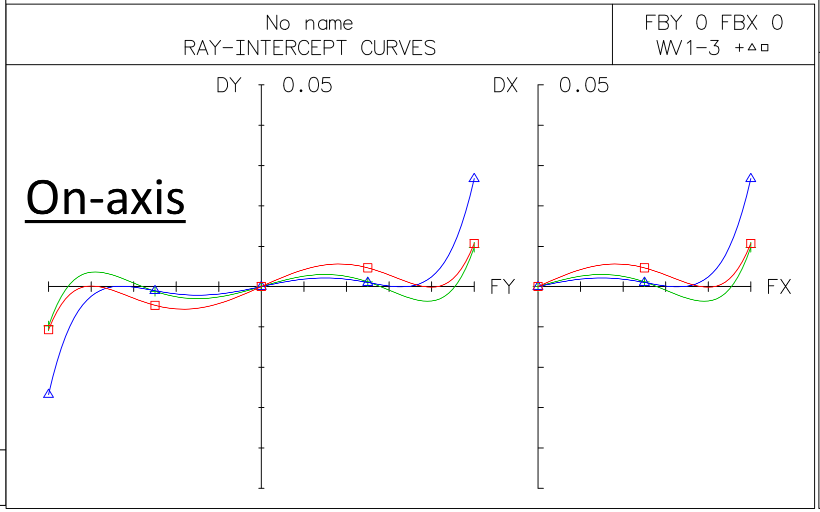
This is the ray trace results of our design, with no aberration balancing or any real rays traced during the design evolution

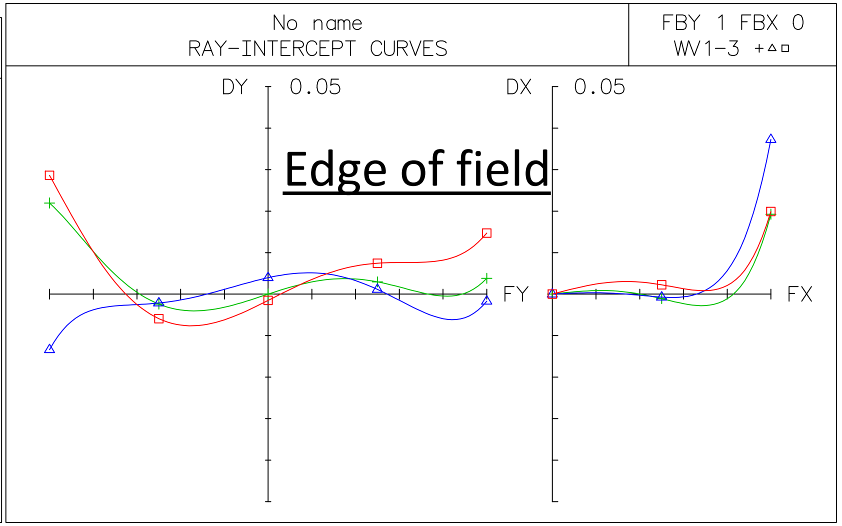
Remember, **none** of these ray traces would be seen at all during the design evolution. We did not trace any real rays

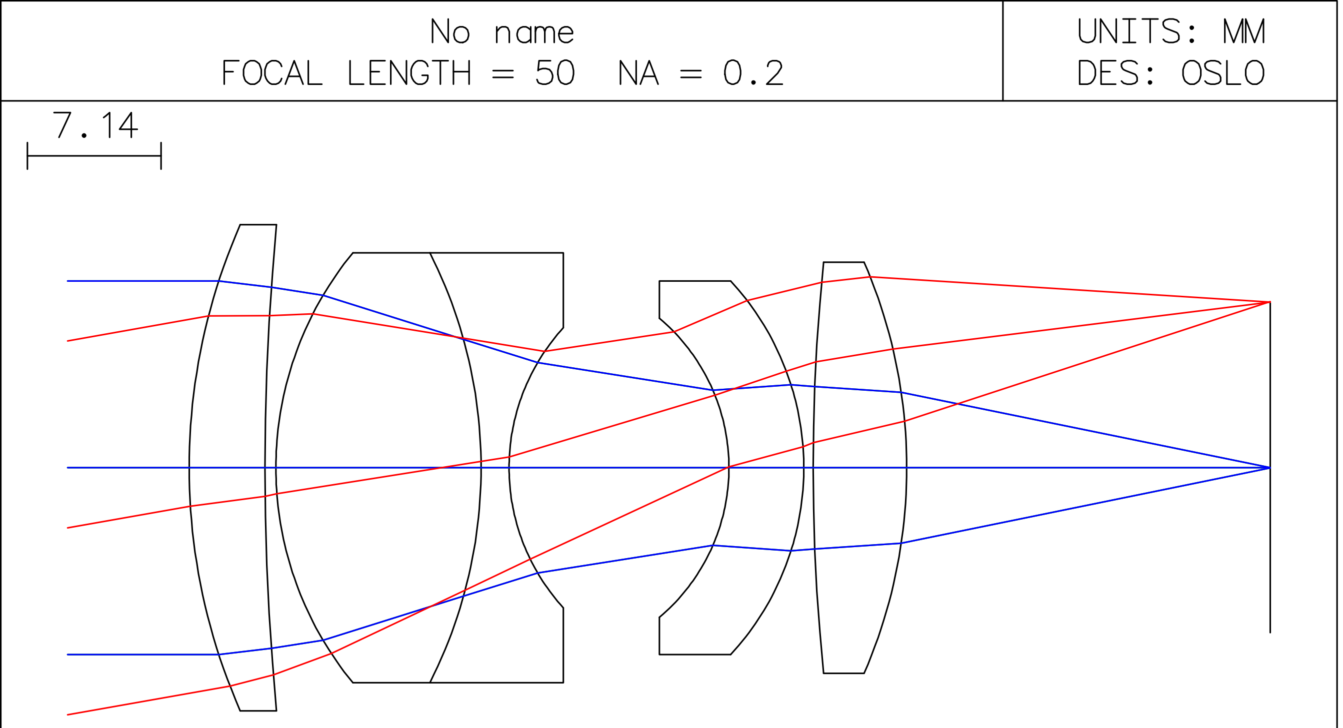


We will not do here the further optimization that would be done next, just described, using just 2 or 3 real rays and the Coddington equations, while doing simple 1X1 or 2X2 matrix calculations to calculate changes needed in the design. But that is what they did pre-computer. We will now jump right into modern computer optimization of the design, with very many real rays at several wavelenghs and vary all the radii and thicknesses and airspaces with no constraints on them, such as the aplanatic/aplanatic and concentric surfaces used here. Here are the results, with 2X smaller scale. The stop position was shifted was best results. There is no vignetting.

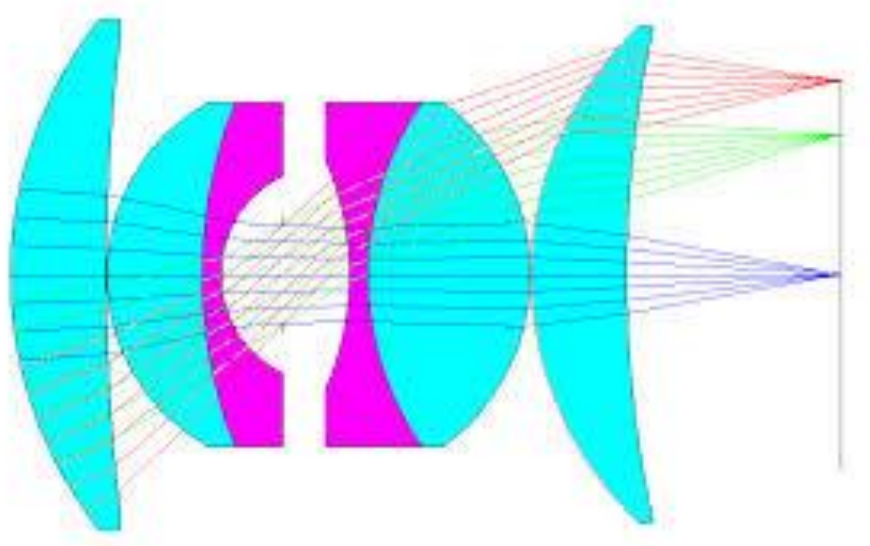








Our local minimum solution



The Double-Gauss form has many local minima and this design is stuck in a very short version of the normal Double-Gauss design. Much better performance will result if the design is coaxed or forced out of this minimum, mostly by having a shorter central airspace and a longer back focus due to a stronger back meniscus lens. Then the central airspace is nearly collimated like in this design. Then two flint glass lenses are needed to correct both axial and lateral color. By having crown and flint glasses have different index values, instead of the same that I used (SK16 and F2), extra aberration control is gained by the "buried surfaces"

So, in summary, a design technique is described here that would have been used, in whole or in part, in the old days before computer aided design. The pre-computer calculations were so tedious and time consuming that any idea that would reduce it was quickly adopted. The use of surfaces that were aplanatic or concentric about the image or chief ray would save effort because of their aberration behavior – as demonstrated here. It also allowed parts of the design to be worked on while not disturbing the correction of other parts – like the use of no index of refraction break across a "buried surface". Or here, where an aplanatic/aplanatic lens can be changed to affect the Petzval curvature without changing the spherical aberration, coma, or astigmatism. These techniques allowed for some simple one or two variables hand optimization.

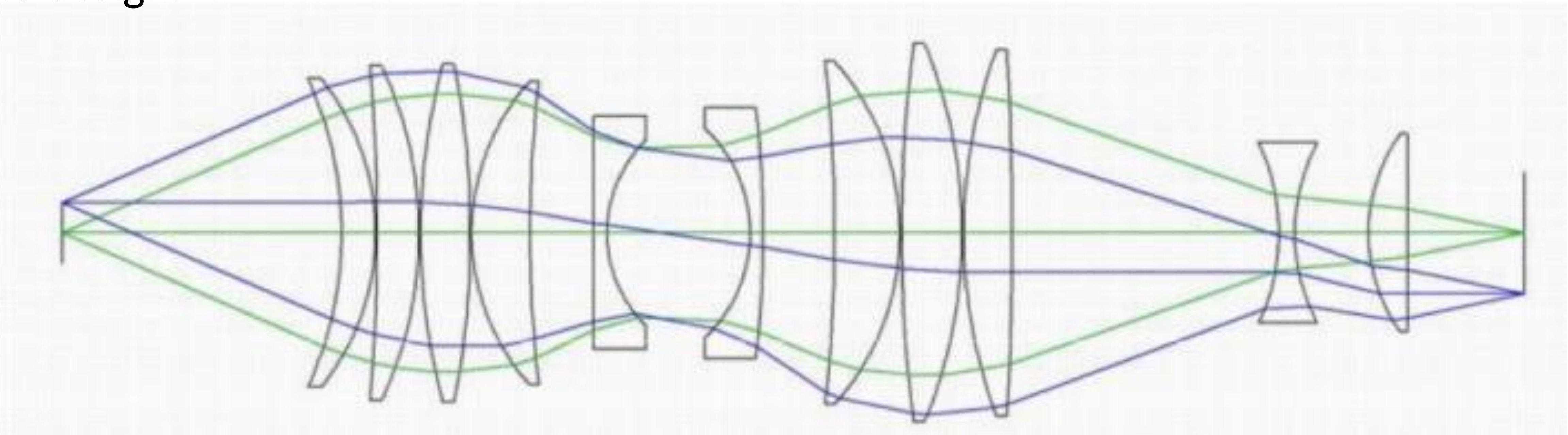
Of course nobody in their right mind would do things this way today, when immense computer power can be brought to bear on the design process. But it is instructive to see how people in the old days were forced by necessity to think and to understand aberration theory in order to make the design process manageable. Now, we don't have to do that. Something has been gained and something has been lost.

Use of temporary aspherics in the Design Process

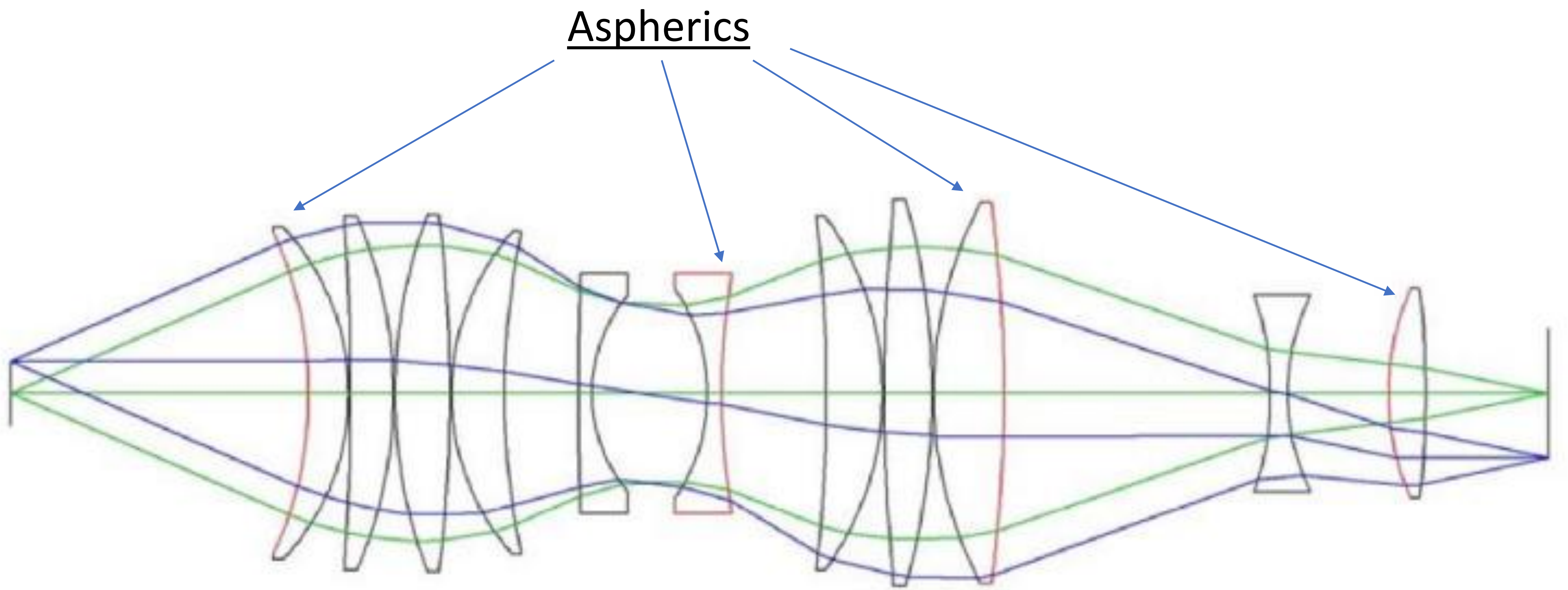
- This means using aspheric surfaces during the design's evolution but then removing them all before the final design.

- Aspherics can allow a design to move into a new solution region that is difficult to find without the aspherics.   Aspherics can easily correct aberrations that may take several extra lenses to do without the aspherics. But once the design is in the new solution region it may no longer need the aspherics.

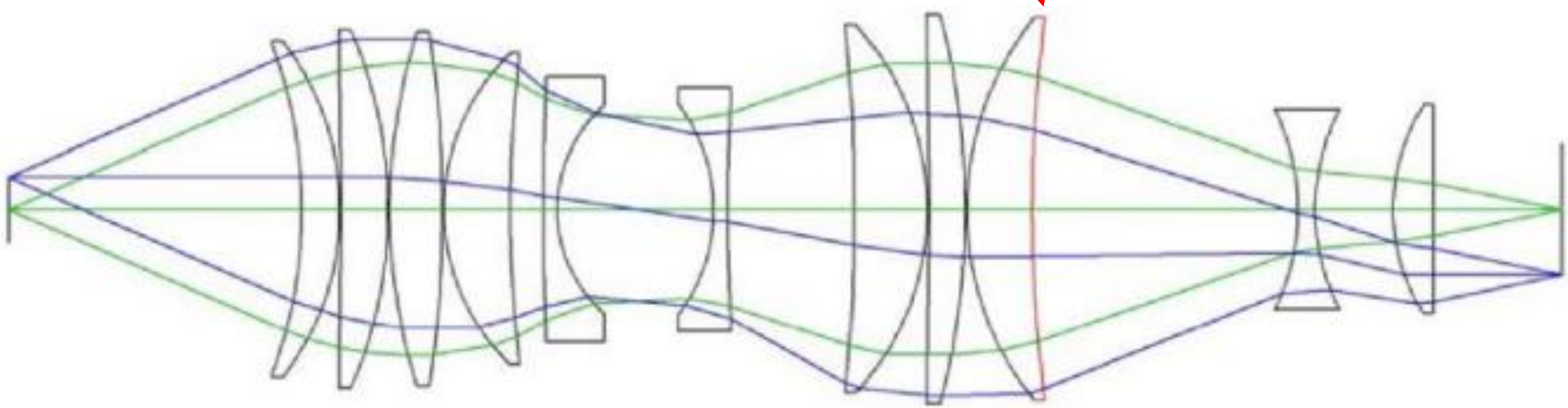
Suppose that you have a design and the performance is not as good as you would like.   You would like to add a lens or two to get more design variables and improve the performance but you don’t know where to do it to get the best effect. A good solution to this is to use the designer “trick” of temporary use of aspherics in the design.   Here is what we do. First we make 3 or 4 of the lens surfaces aspheric and add low-order asphericity to the design variables. We choose locations for the aspherics to be at both ends of the design as well as one or two in the middle area. Then we reoptimize the design.



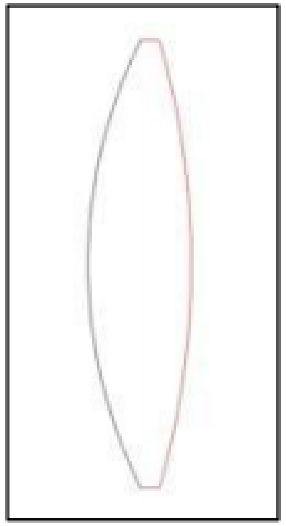
Usually only one of the aspheric locations chosen will have much effect and the others will have little effect. Here, with 4 aspherics spread throughout the design, we got a big improvement in the image quality. If we had not, then this first-order configuration is near the limit of what it can do and a different design type must be used. But here the design got very much better. Now we have to find out which one of the aspherics is the important one.



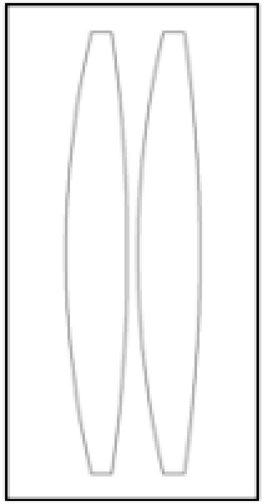
We take our very good improved design and one by one try to remove the aspherics and reoptimize. We find that the two aspherics on either end of the design can be removed with almost no change in the reoptimized design. Of the two aspherics in the middle we find that only this one is important. With that one we get almost all the performance improvement that 4 aspherics gave.

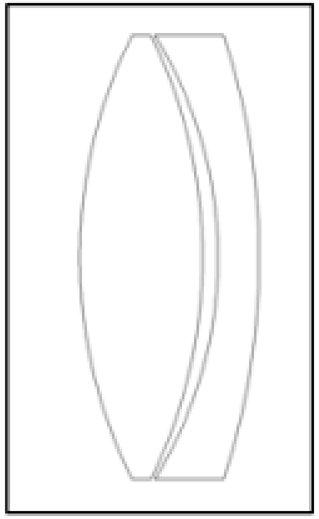


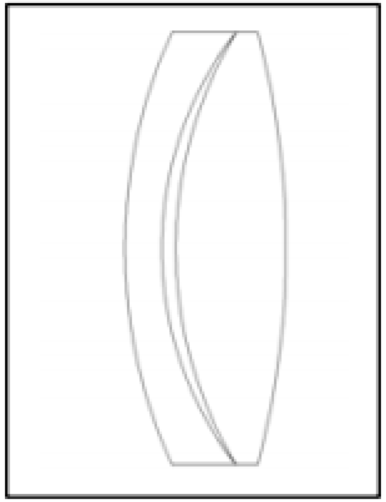
Now we will try to replace the one aspheric surface with a spherical surfaces doublet lens that has the same aberrations. There are several possibilities and some will have better higher-order aberrations than other ones. Next I will show how to find a doublet replacement for an aspheric surface

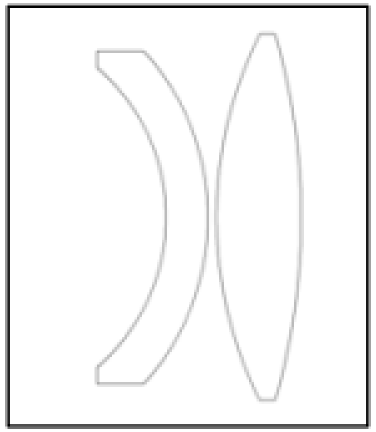


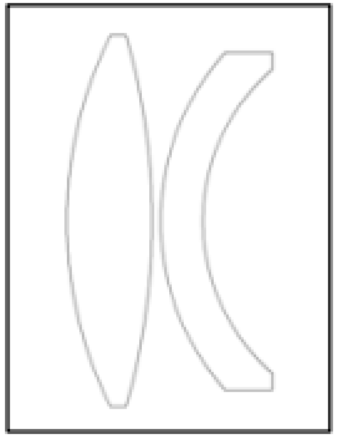
Original aspheric lens









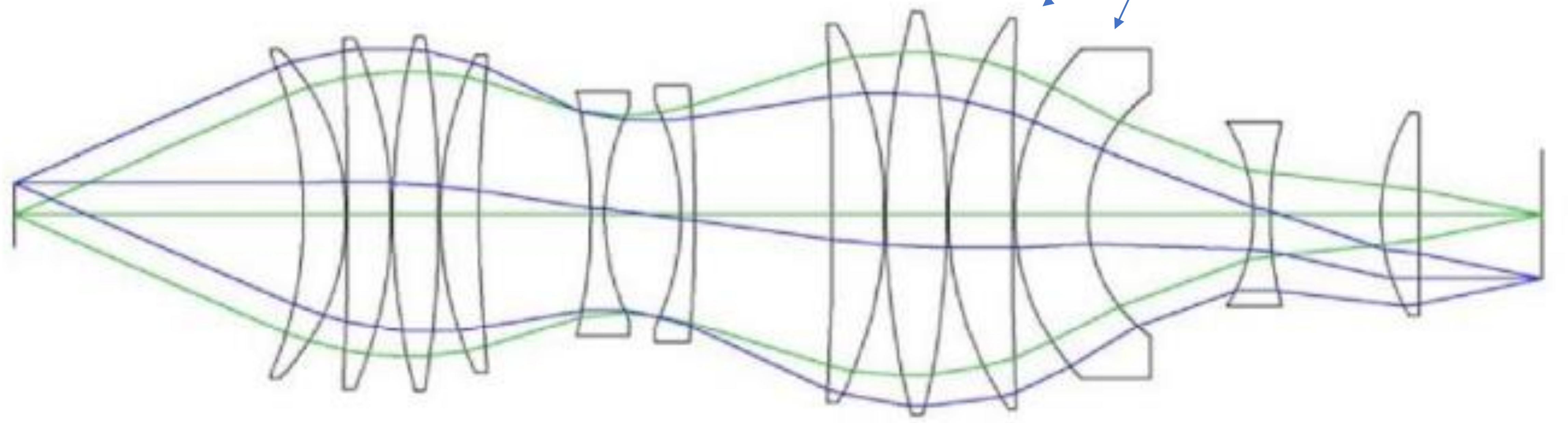


Possible spherical surfaces doublet replacements for the aspheric

So a long process just shown resulted with a design with much better performance with an extra lens. We have shown here a systematic way of finding out where to add a lens to get the best performance improvement

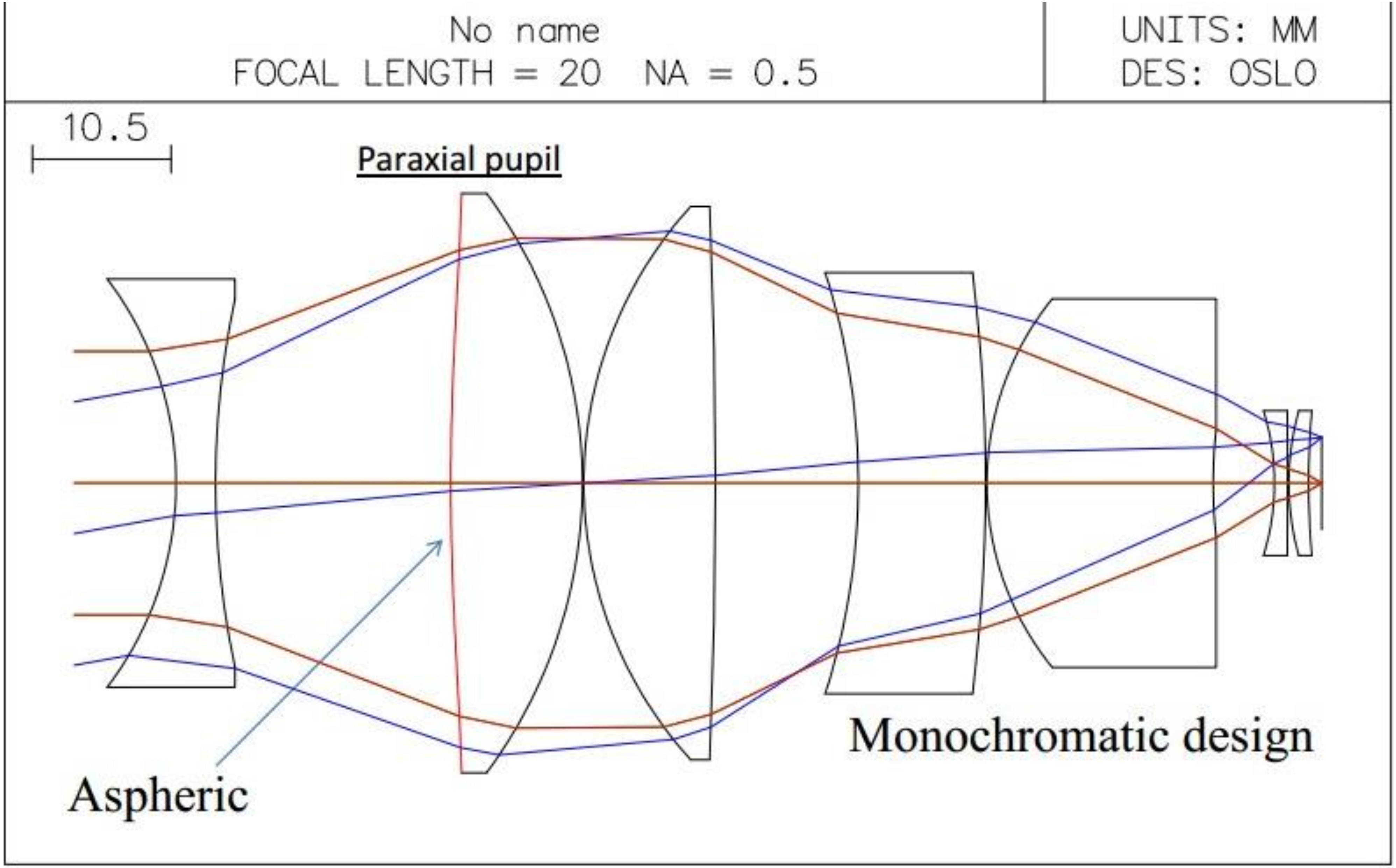
Some design programs have automated this and try different places to add a lens to a design.

Doublet lens with no aspheric that replaces the aspheric single lens that was here.

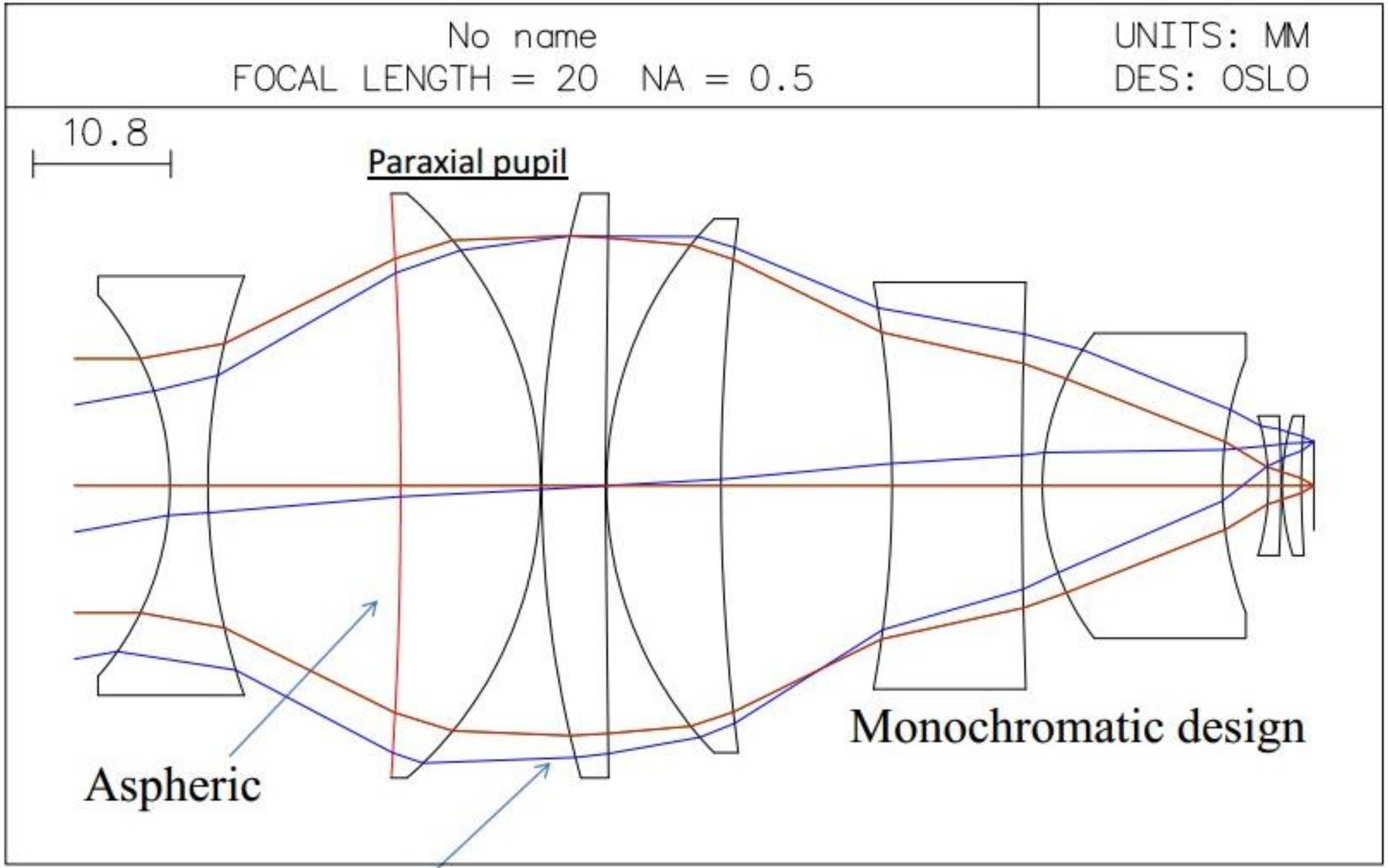


Removing an aspheric from a design

Still with me?

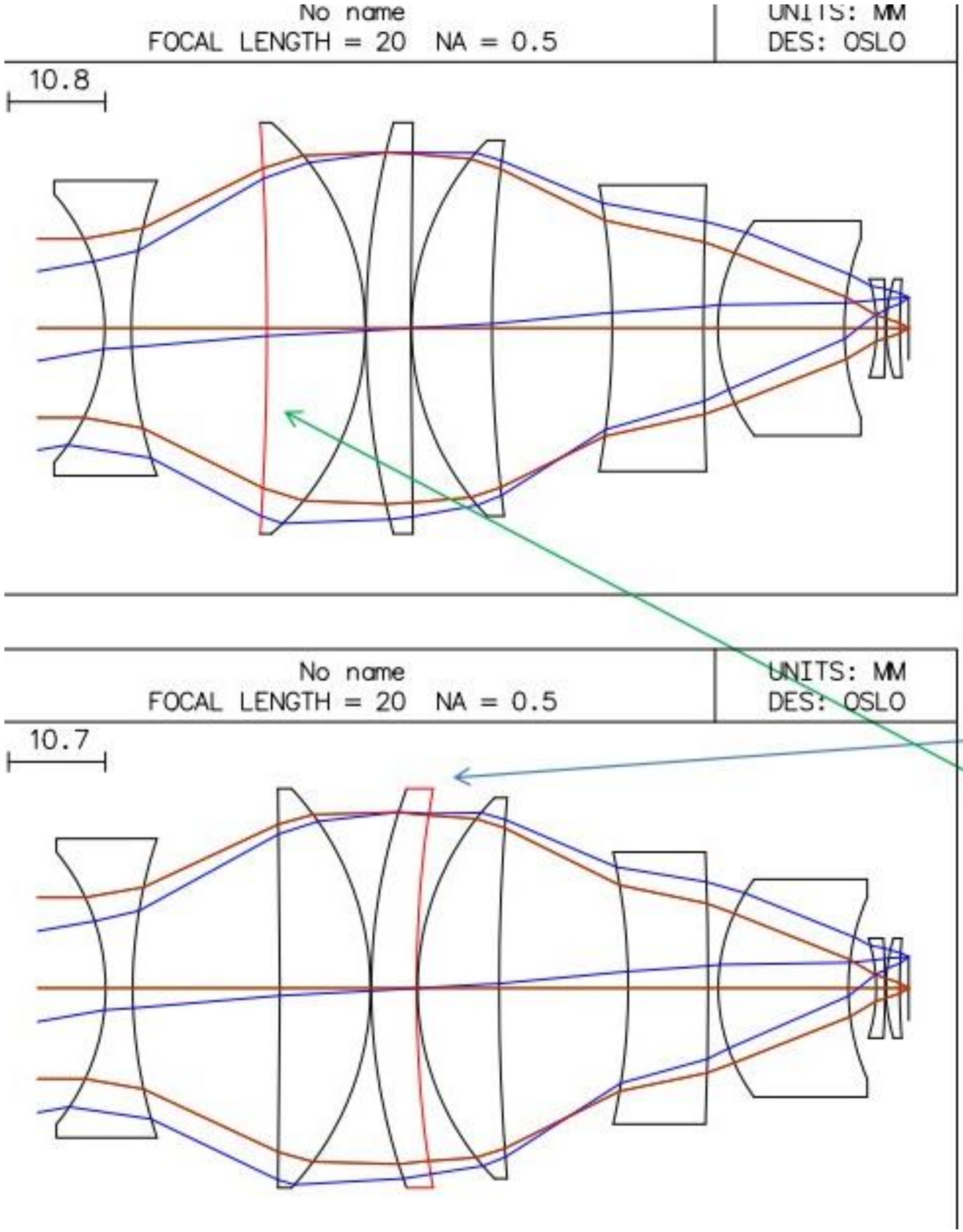


20 degree field diameter, f/1.0, .015 waves r.m.s. OPD at edge of field, with a strong aspheric



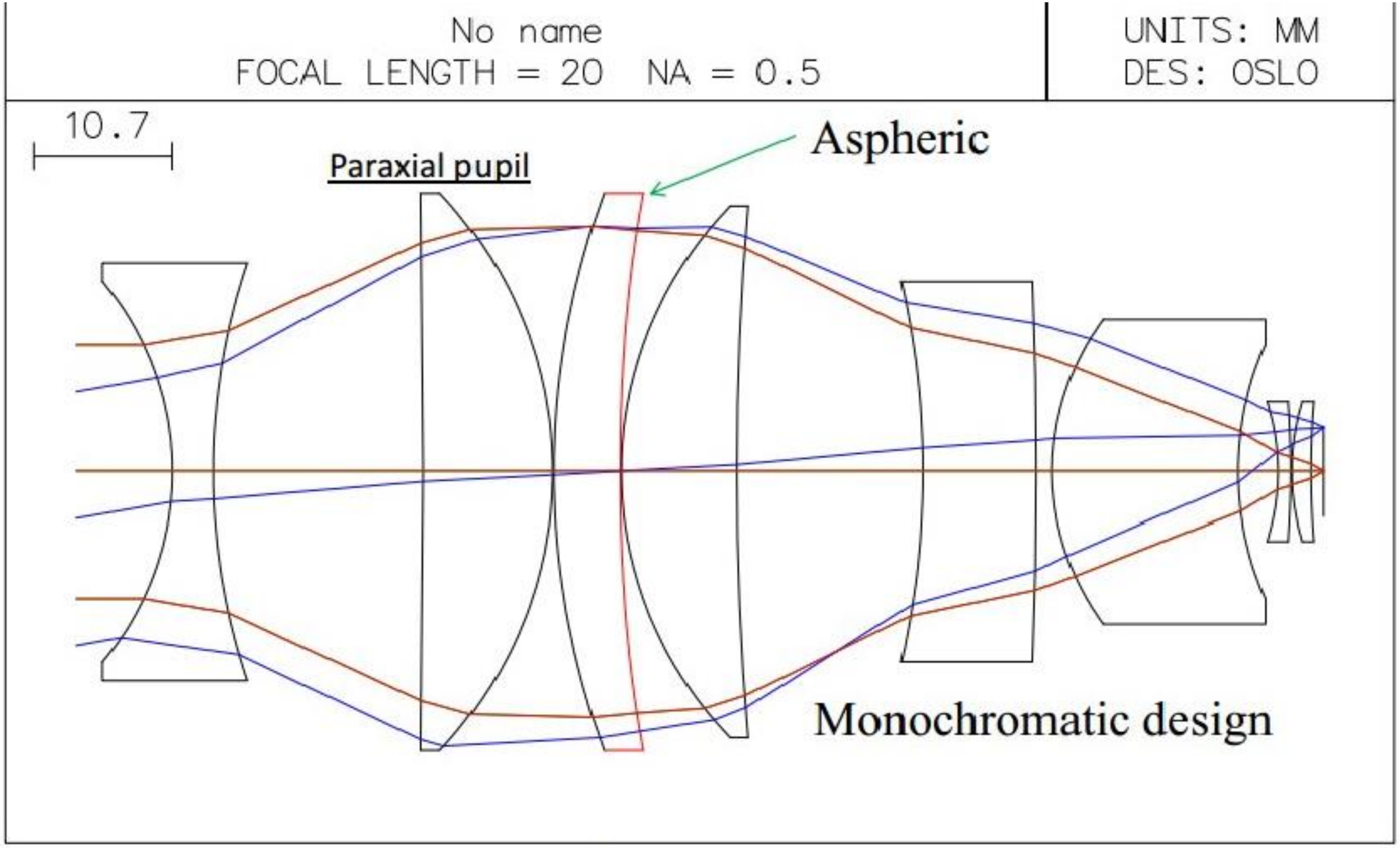
Extra lens allows aspheric to be weakened a lot, even though it does not want to have much power

Adding a lens or lenses near the aspheric surface gives more design variables in that location within the design and then can allow the aspheric to be removed.



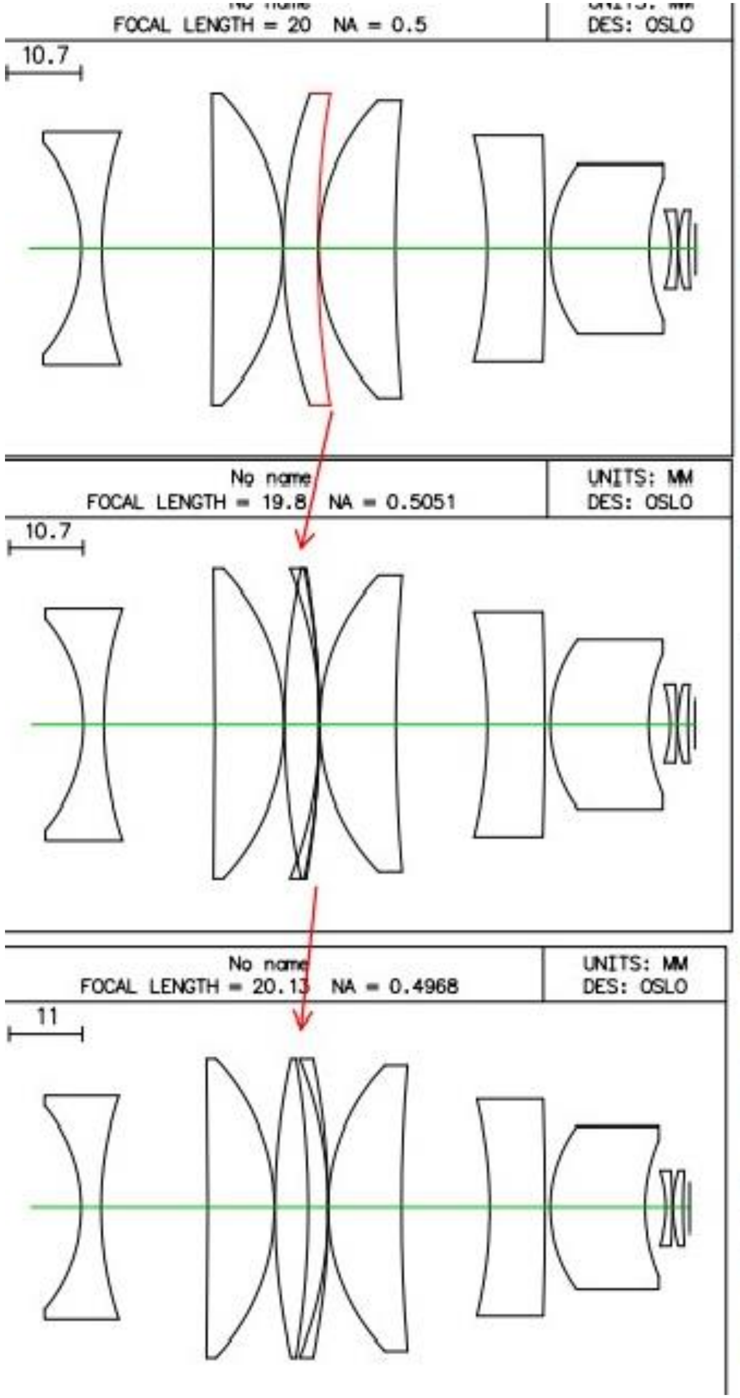
Aspherics are usually easiest to remove if the higher-order terms are small. This is often the case if the aspheric incidence angles are small. So it is a good idea to optimize the design with a preferred location of the aspheric. Here instead of here. The locations are quite close to each other but one has low incidence angles and that aspheric has much smaller higher-order terms than in the other location.

A small change in the position of the aspheric within the design can make a very considerable difference in how hard it is to remove it



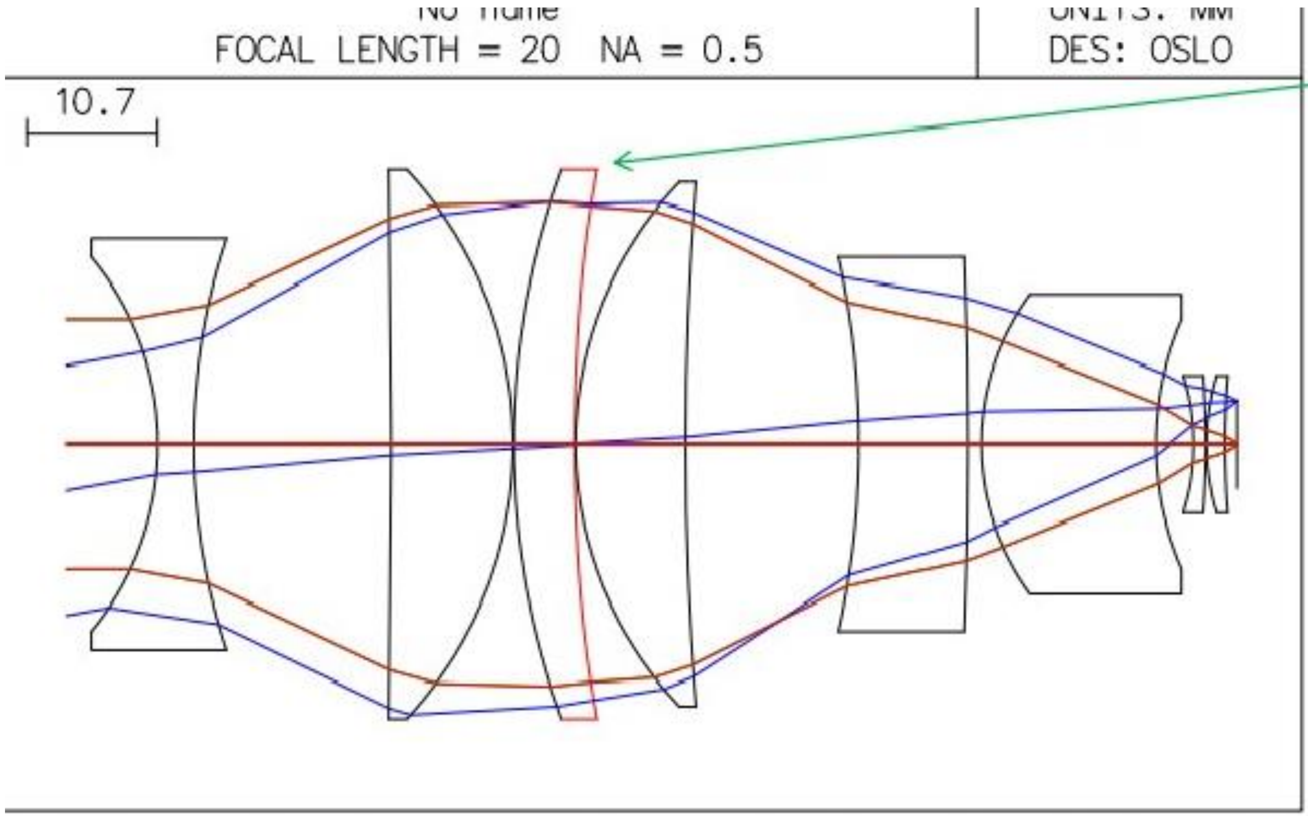
Aspheric was moved to a different lens, with low incidence angles. Result is very small 6th order aspheric term, but +/- 20u aspheric deformation from best fit sphere = a strong aspheric.

We will replace the aspheric surface with a doublet lens in the same location and with the same aberrations. That is done by changing **only** the region right next to the aspheric surface, while freezing the rest of the design. Once an equivalent doublet has been found, that is substituted for the aspheric and then the rest of the design is un-frozen and everything is varied and reoptimized.



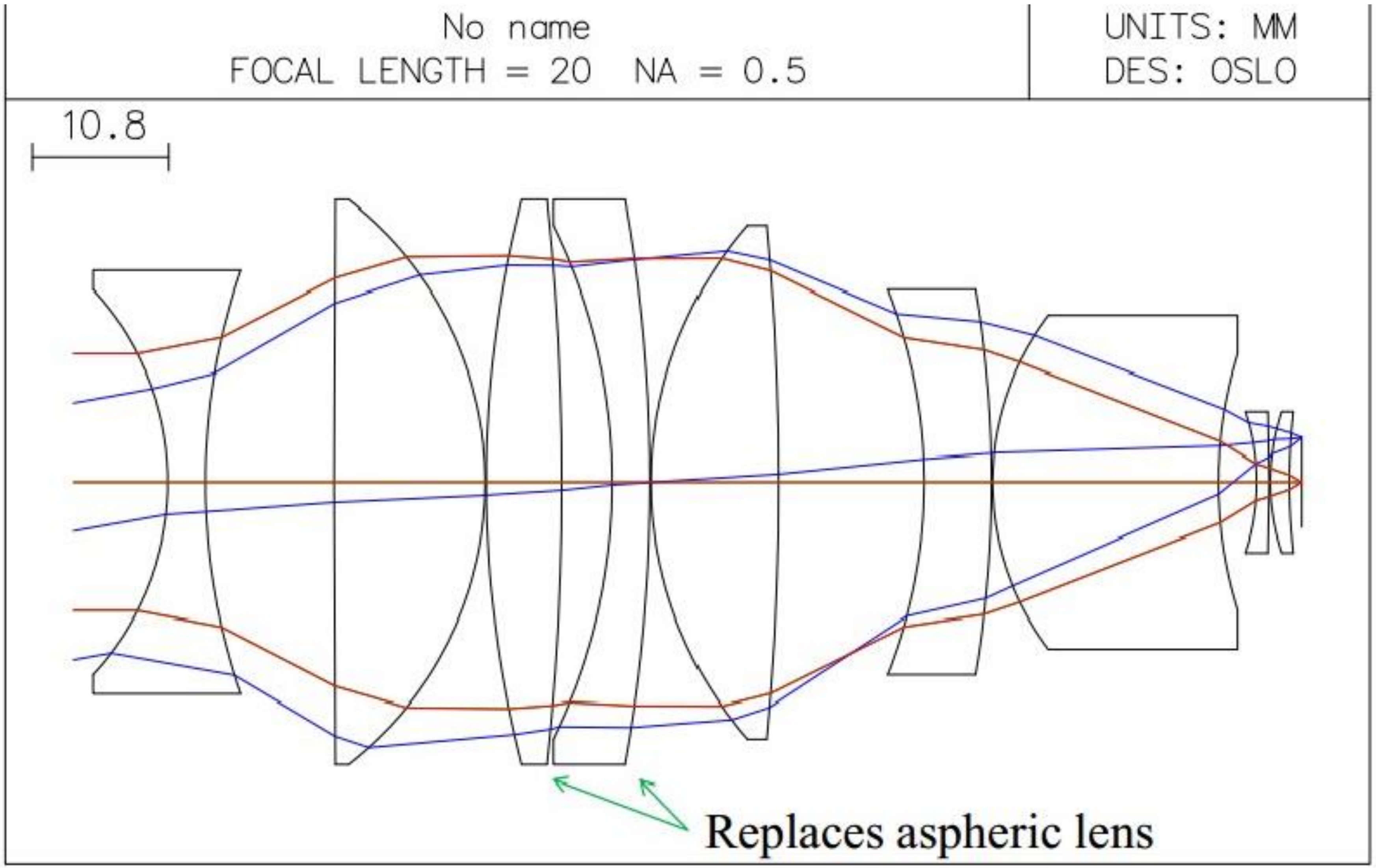
To remove aspheric first add a zero thickness parallel plate right against the aspheric surface. Then remove the aspheric from the surface. Then do an optimization run where the only variables are the curvatures of the parallel plate and those of the lens that it is next to = 4 variables. The only aberrations to be corrected are 3rd order spherical aberration, 3rd order coma, the paraxial focus, and 5th-order spherical aberration. It may take several tries before you find a good solution because there will be several local minima, mostly bad ones. There will probably not be an exact solution. Then this change is put back into the original design and the whole system reoptimized.

The multiple solutions will include positive/negative doublets, negative/positive doublets, some with a strong meniscus lens, and some with two positive lenses. Different starting points can lead to different solutions. You want what gives the best 3rd and 5th order equivalent to the aspheric being replaced.

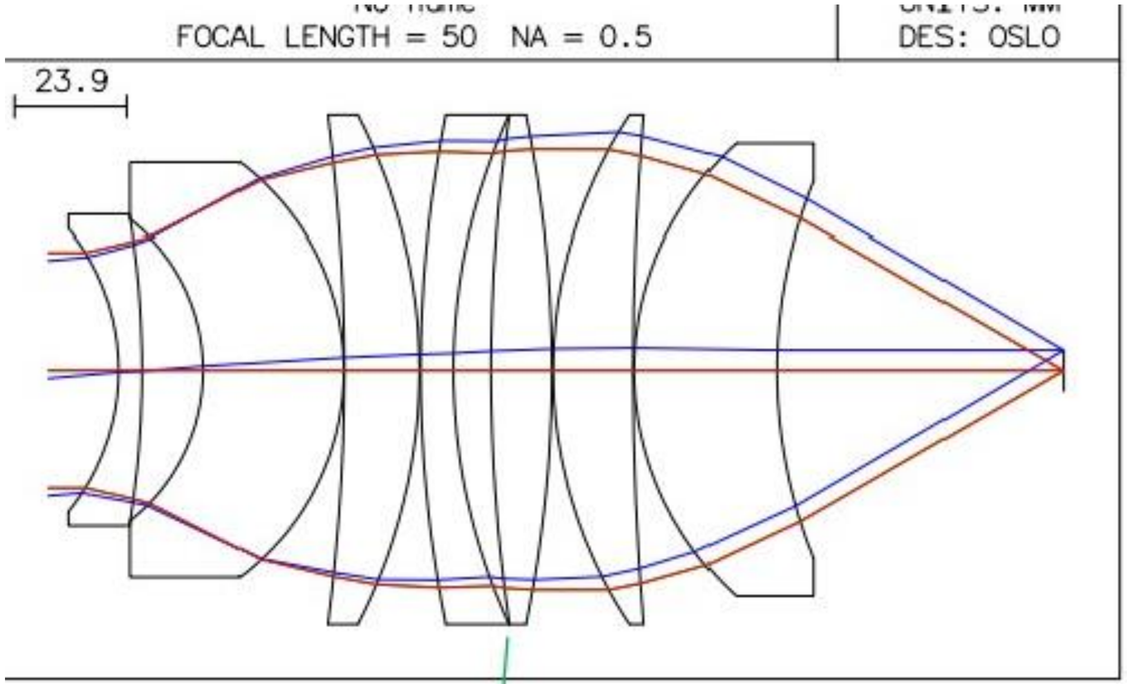


If the aspheric lens is thin then both of its curvatures should be varied in this very simple optimization, along with the parallel plate curvatures. If the aspheric lens is thick then you need to add two parallel plates right against the aspheric surface

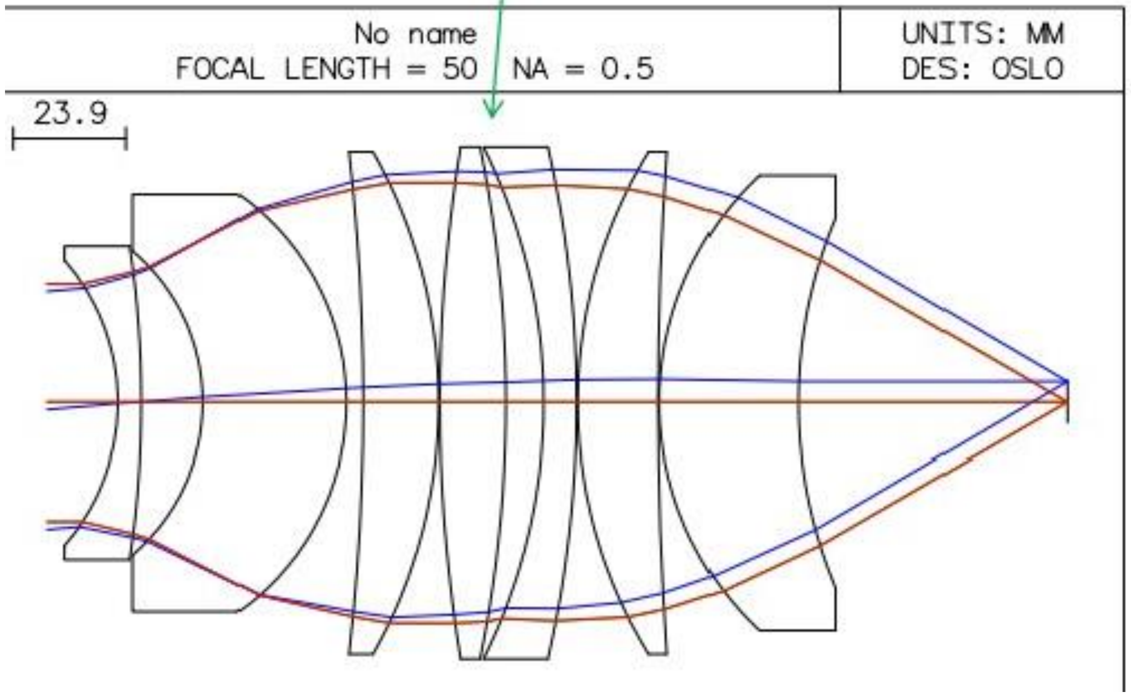
The goal is to replace the aspheric with spherical surfaces that are as close as possible to that location. Then it is easy to insert the resulting solution, of some surfaces without an aspheric, back into the original design without disturbing the first-order optics. Then everything is varied and optimized. Don't forget to remove the aspheric from the variable list.



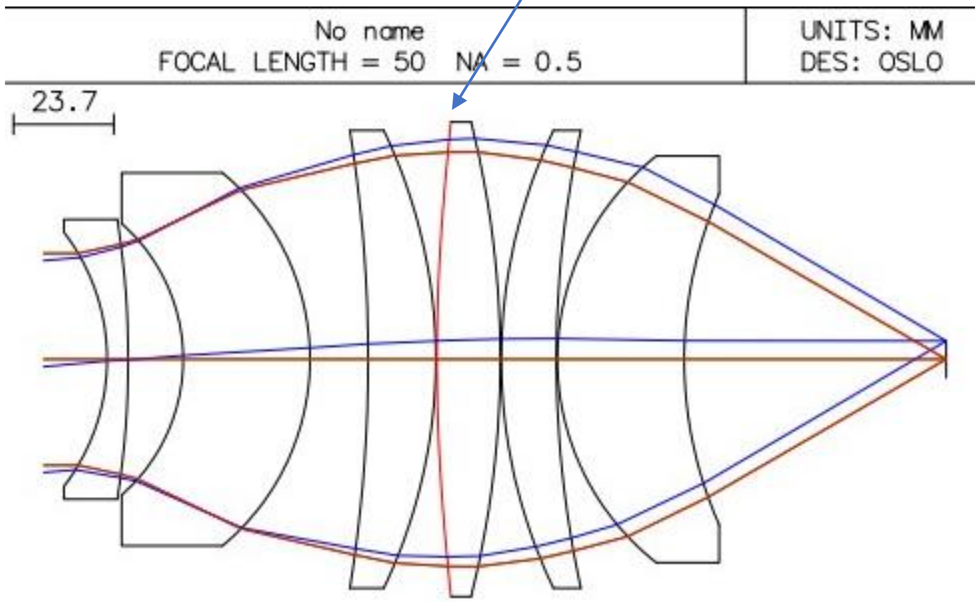
No aspheric, f/1.0, 20 degrees full field, .02 wave r.m.s. at edge of field



Two alternate solutions to replace the aspheric, with very similar performance.

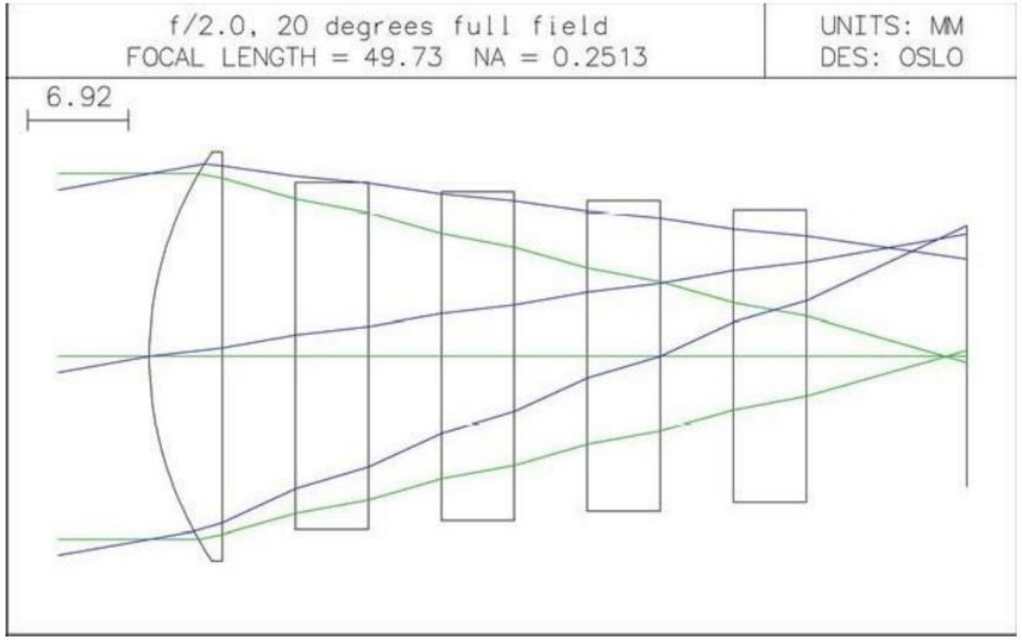


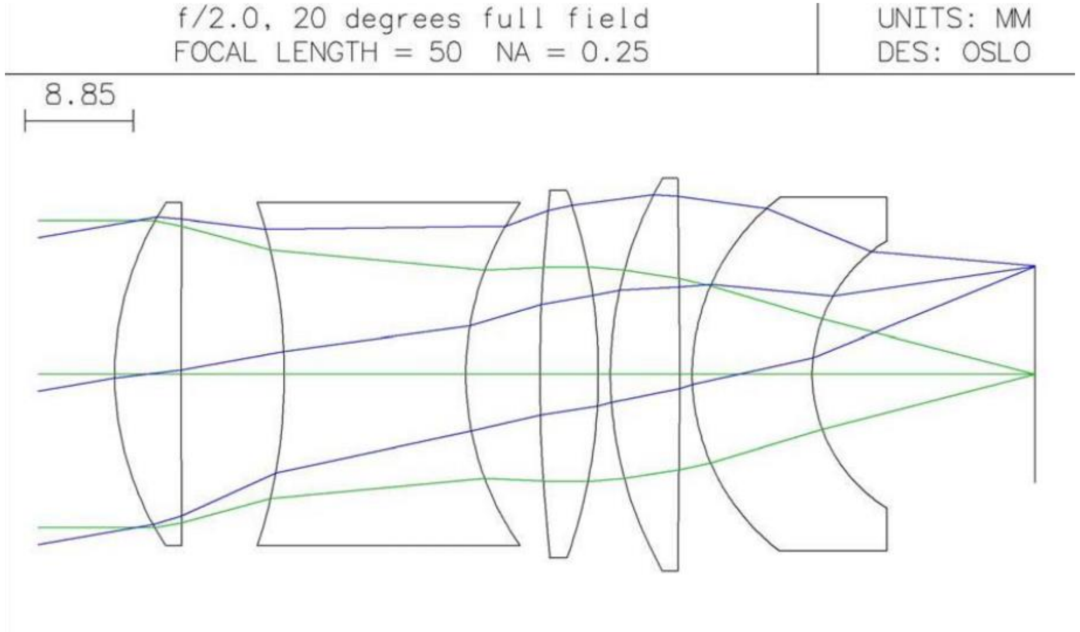
A different design example. An aspheric in the middle of the design is replaced by a doublet and there are two similar solutions found for the aspheric replacement

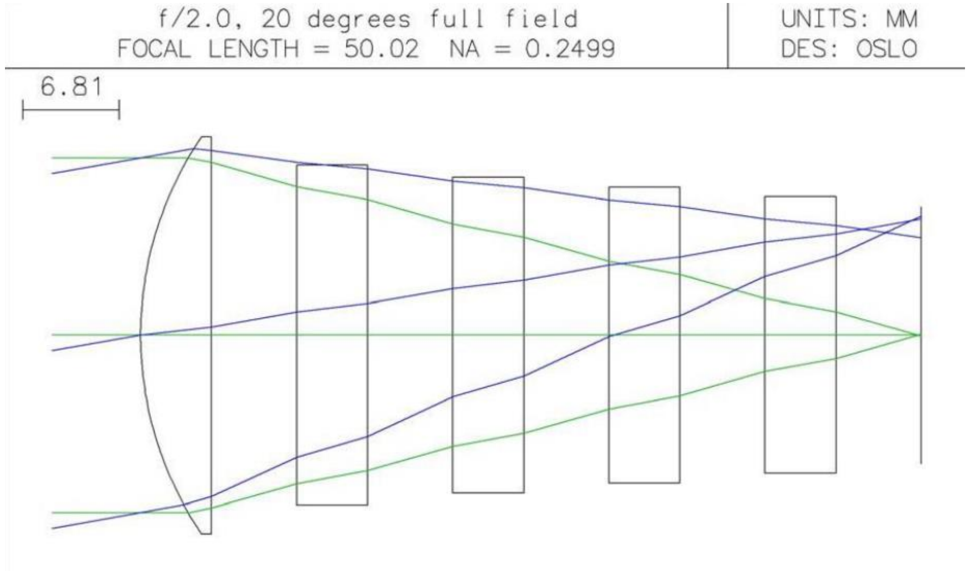


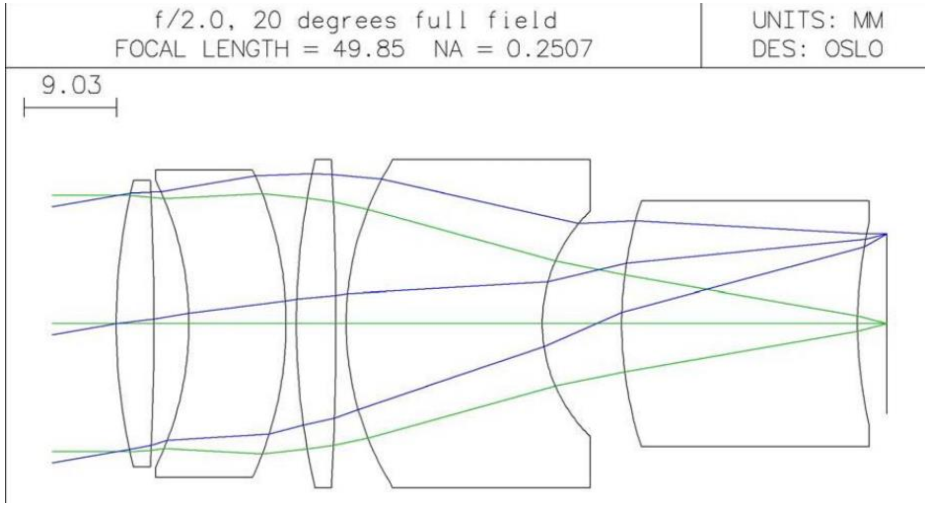
Brixner Parallel Plate Design Method

This design method starts with all or mostly parallel plates and computer optimizes to specs set by designer, like focal length, back focal length, distortion, etc. Results are highly dependent on initial conditions. No human direction required.

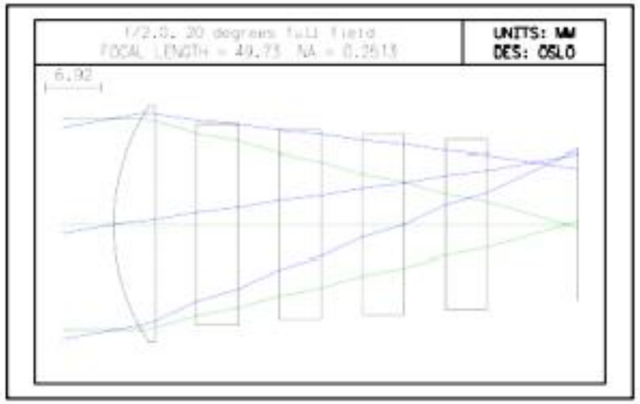


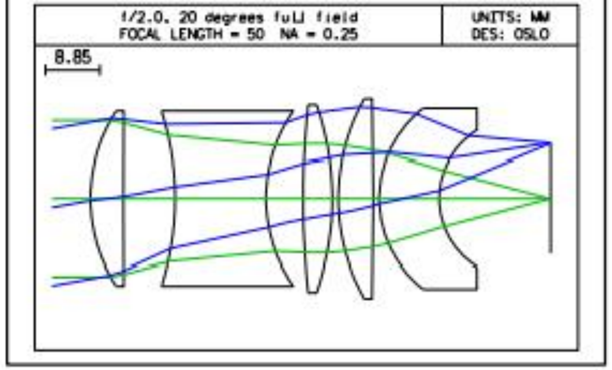




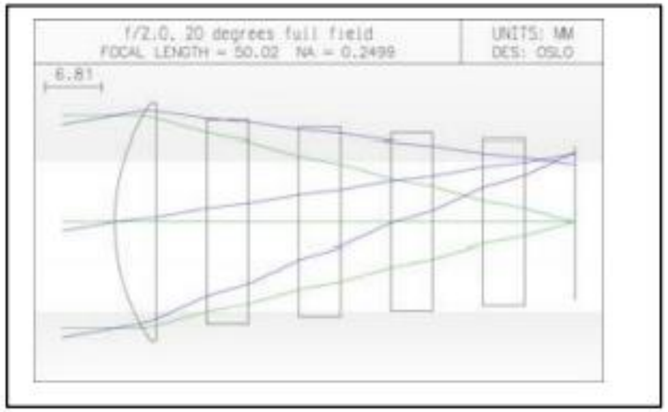


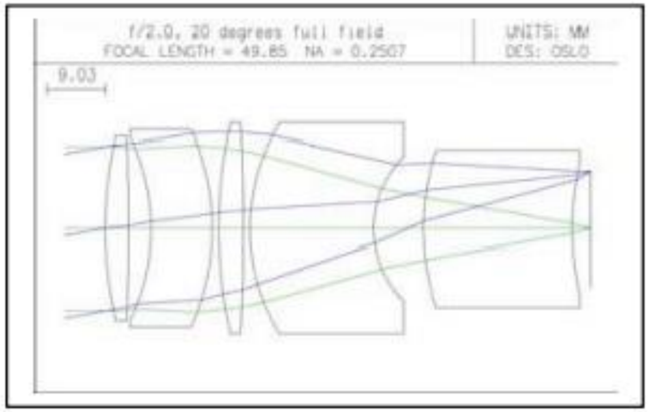
Airspaces here are a little different in starting point





Stop position was not varied





Best design of these three examples, where only change in starting system is airspaces of parallel plates