Some optical design techniques

and general methods

From my 56 years in Optical design

Dave Shafer
June 2022

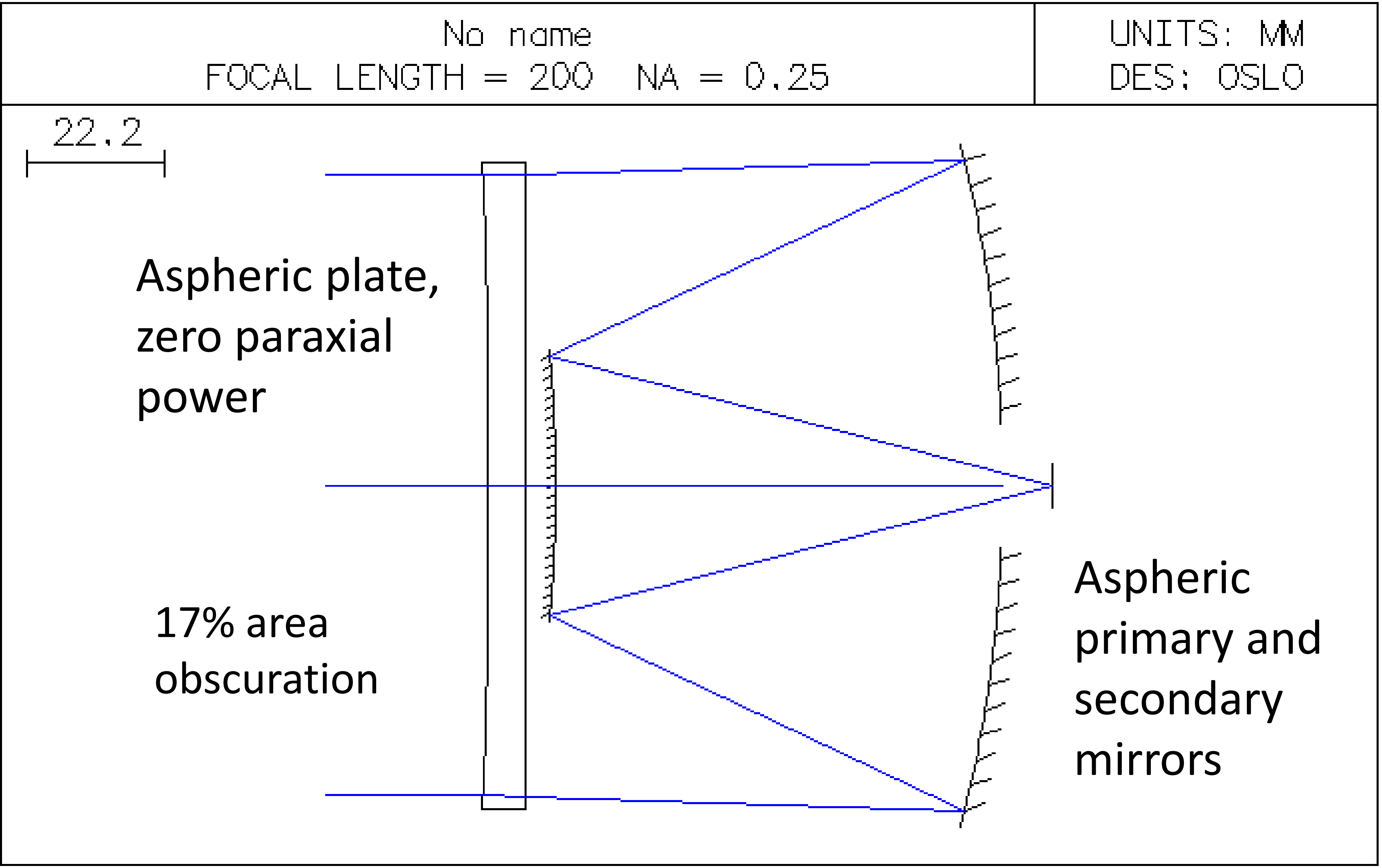
#1

Even very simple designs often have more than one possible version, so investigate to see which is the best one.

Example – there are always two different bending shapes of a single lens that have the same amount of 3rd order spherical aberration, but they differ in the 5th order. See which is the best choice in the design it is part of.

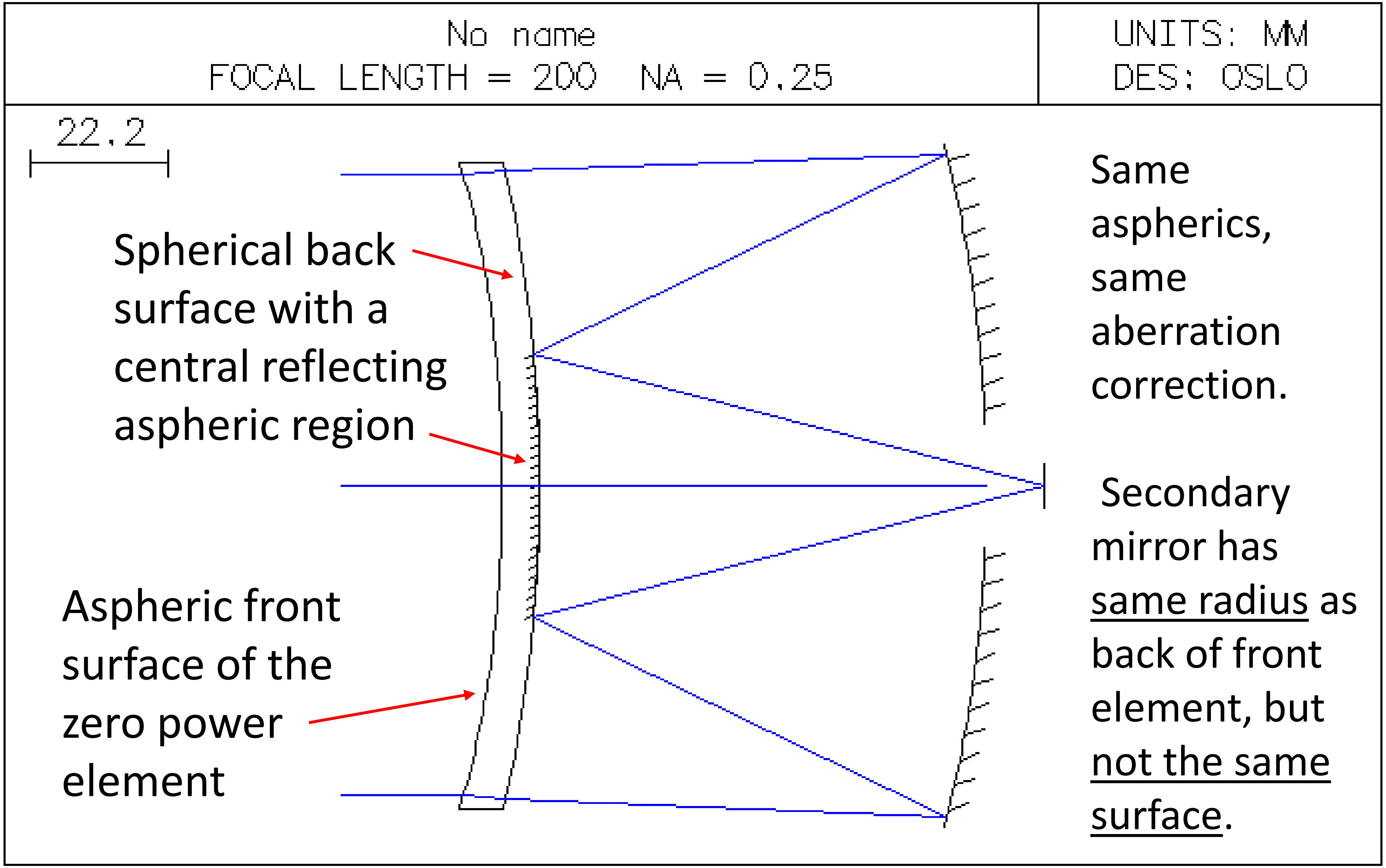
Another example

A high performance two element catadioptric optical design



Typical Schmidt-Cassegrain design.

Three aspherics and equal mirror radii gives correction for spherical aberration, coma, astigmatism and Petzval



Curve the front zero power element

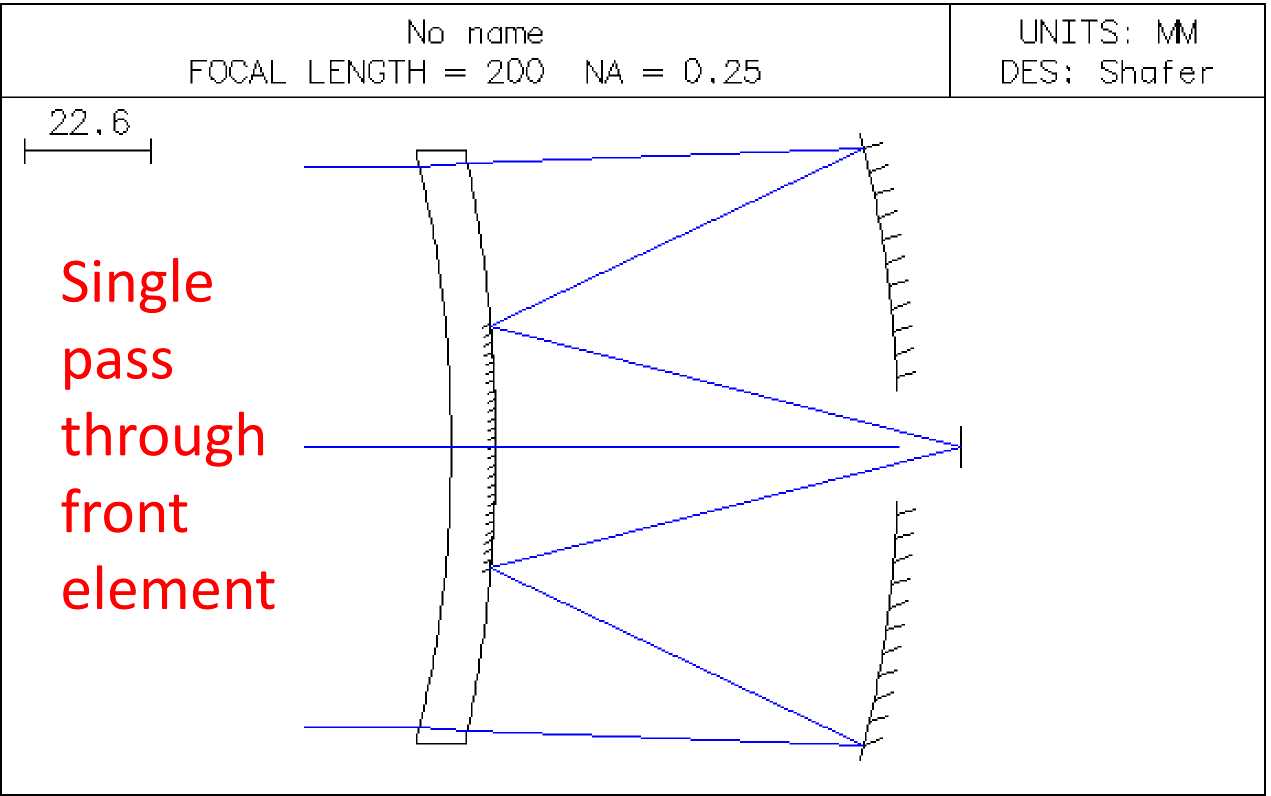
There are 4 possibilities for a design with three aspherics

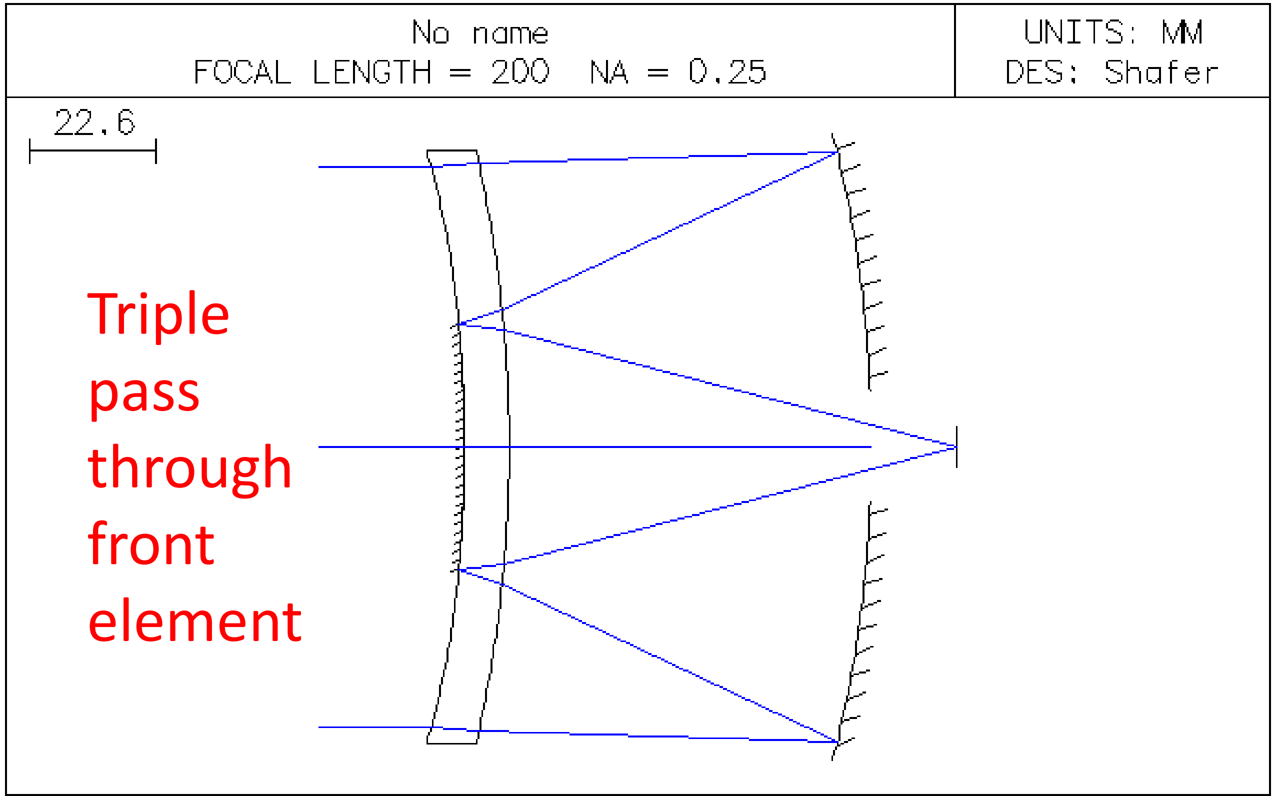
Case #1 – front surface of front lens = aspheric, back surface is spherical with aspheric middle portion

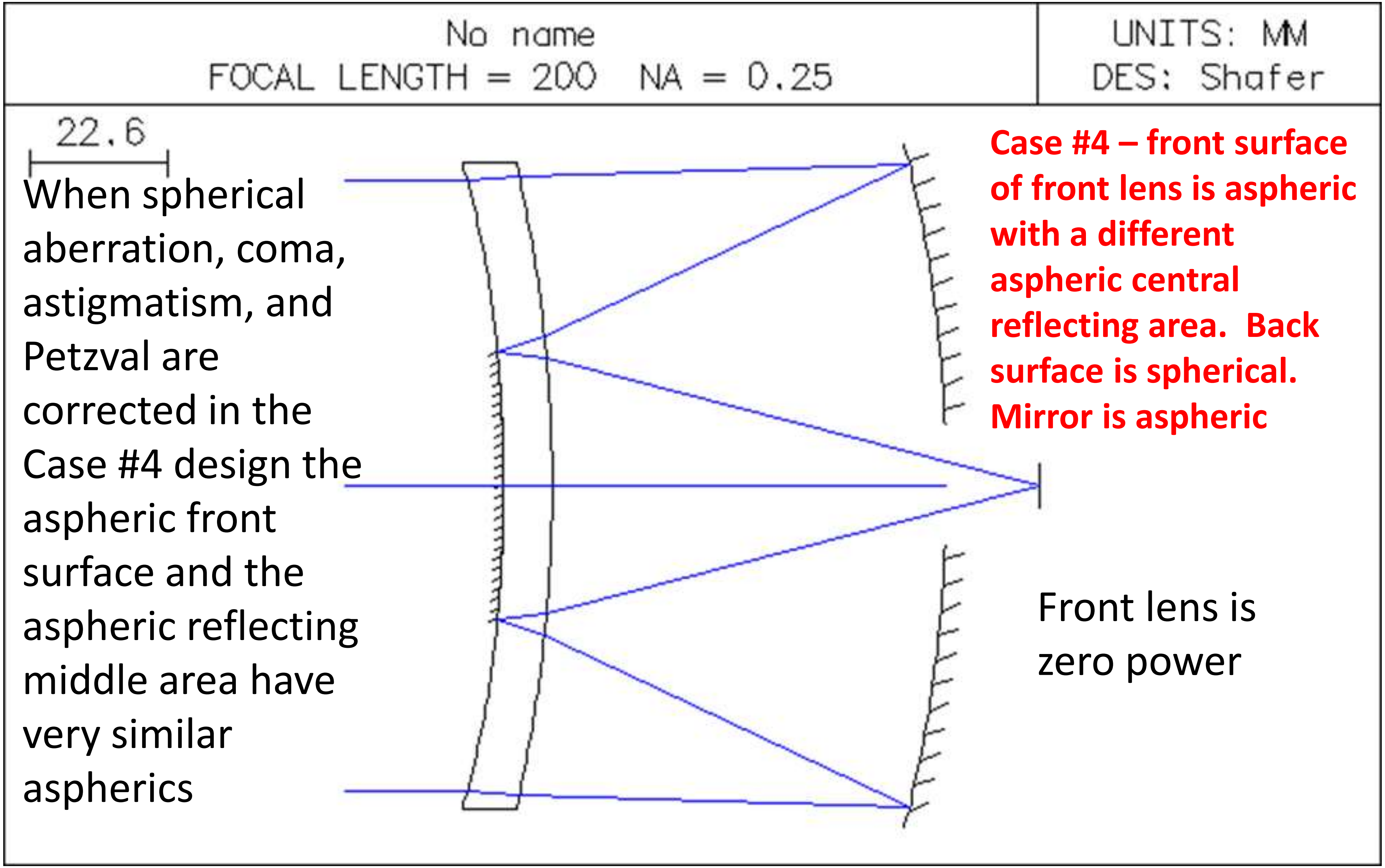
Case #2 – front surface of front lens is spherical, back surface is aspheric with a different aspheric middle portion

Case #3 – front surface of front lens is spherical with a central reflecting aspheric region. Back surface is aspheric

Case #4 – front surface of front lens is aspheric with a different aspheric central reflecting area. Back surface is spherical



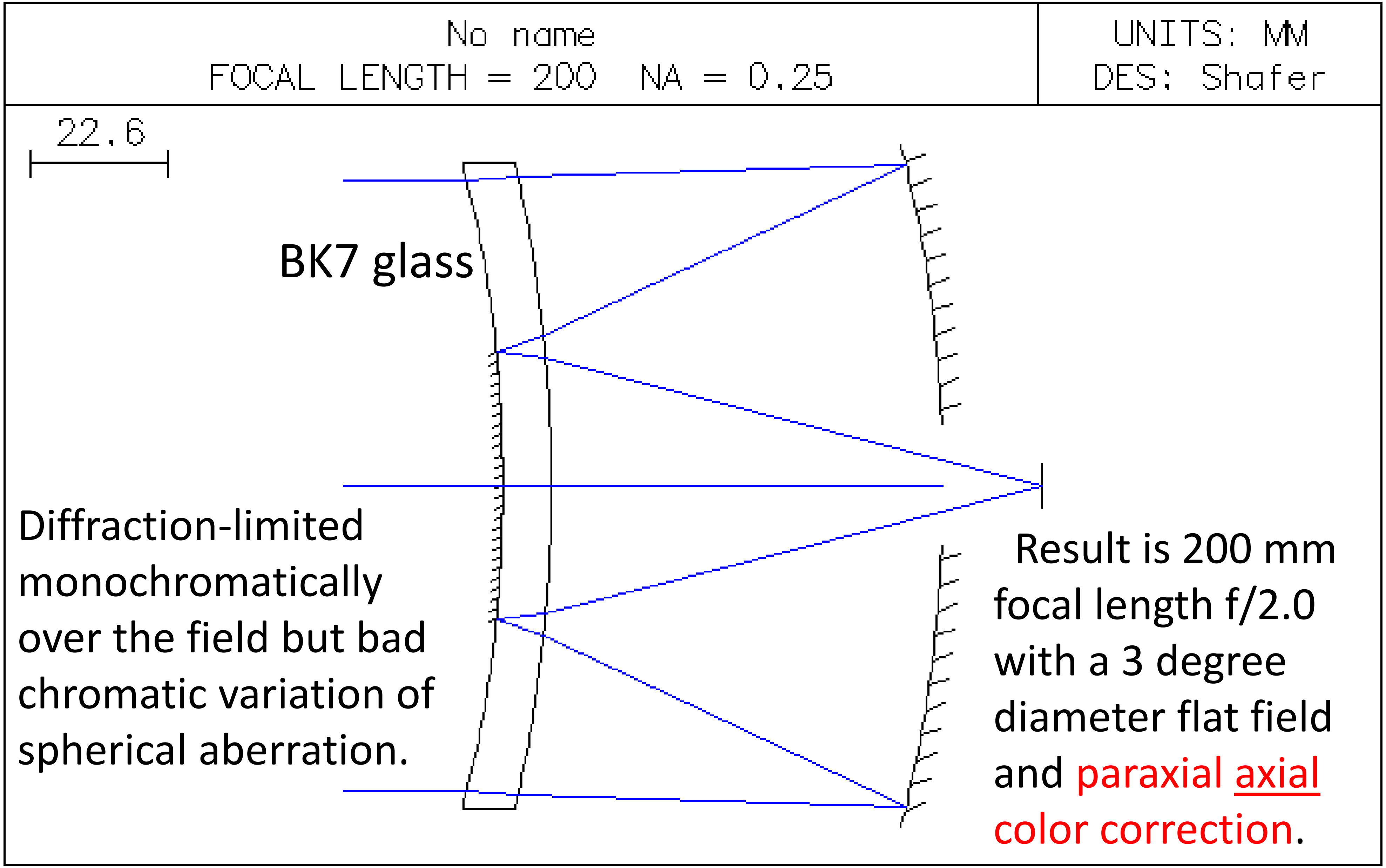




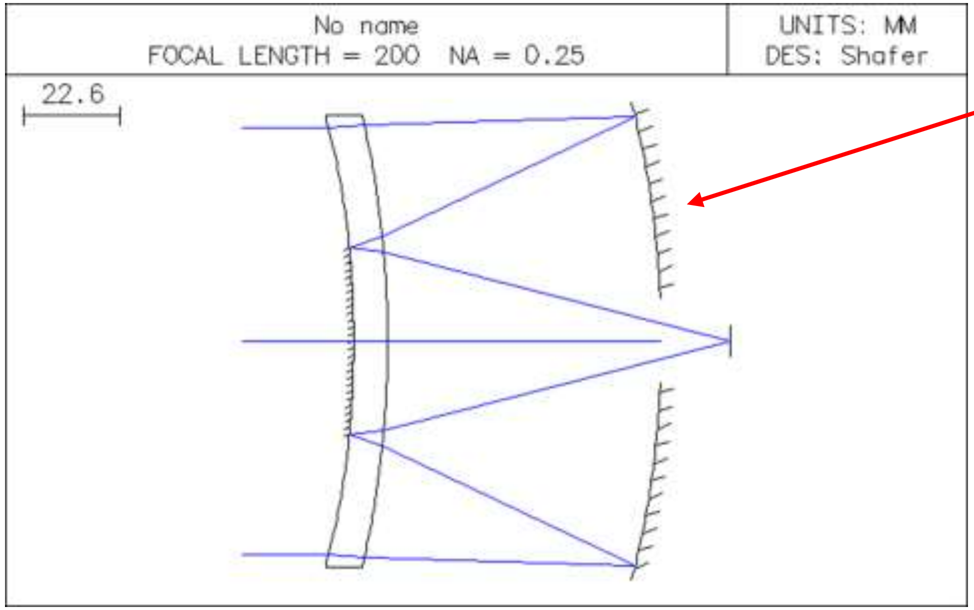
When spherical aberration, coma, astigmatism, and Petzval are corrected in the Case #4 design the aspheric front surface and the aspheric reflecting middle area have very similar aspherics

Case #4 – front surface of front lens is aspheric with a different aspheric central reflecting area. Back surface is spherical. Mirror is aspheric

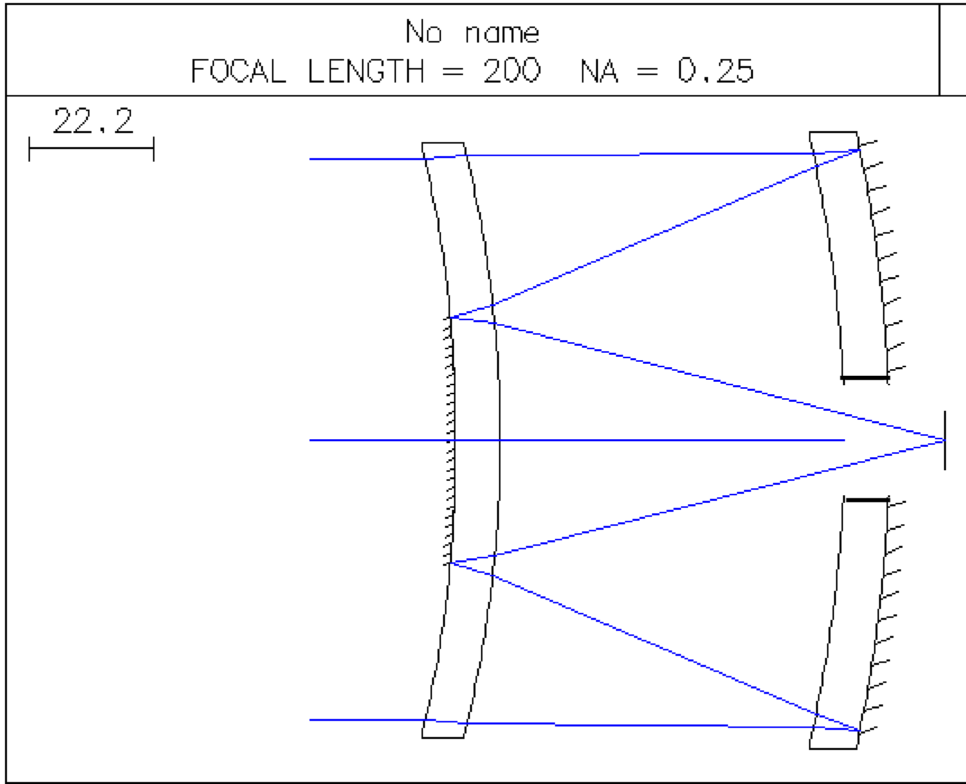
Front lens is zero power



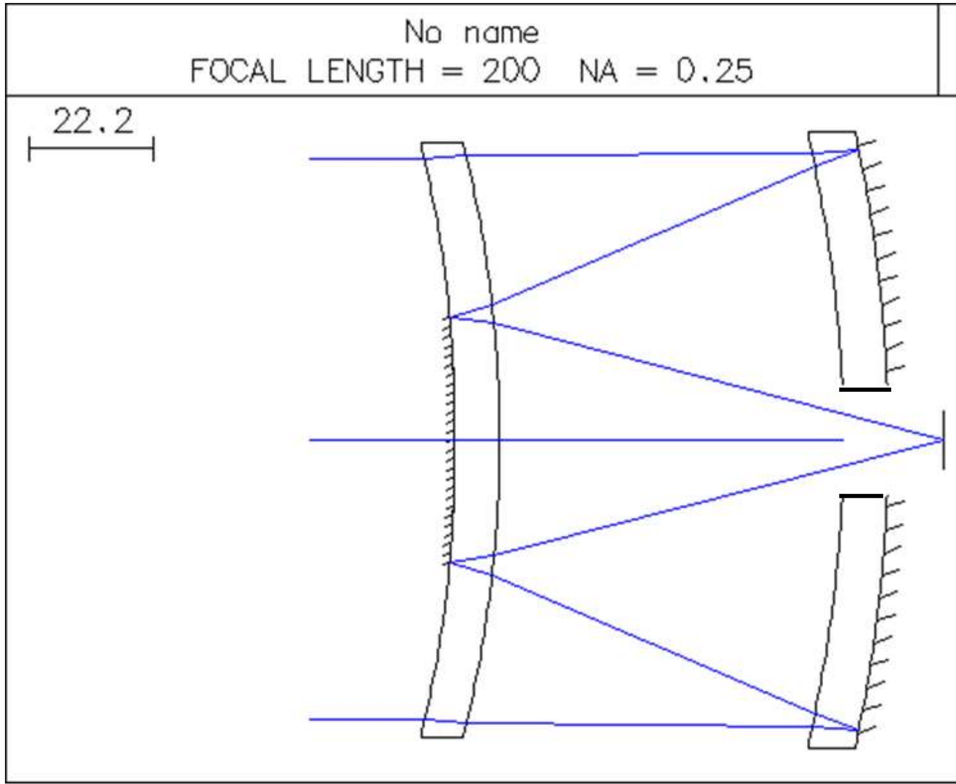
By a small change in the first order parameters the front surface aspheric and the middle region aspheric on the front surface can be made the same, as well as having the exact same curvature. The result is a well corrected design with only two separate aspherics



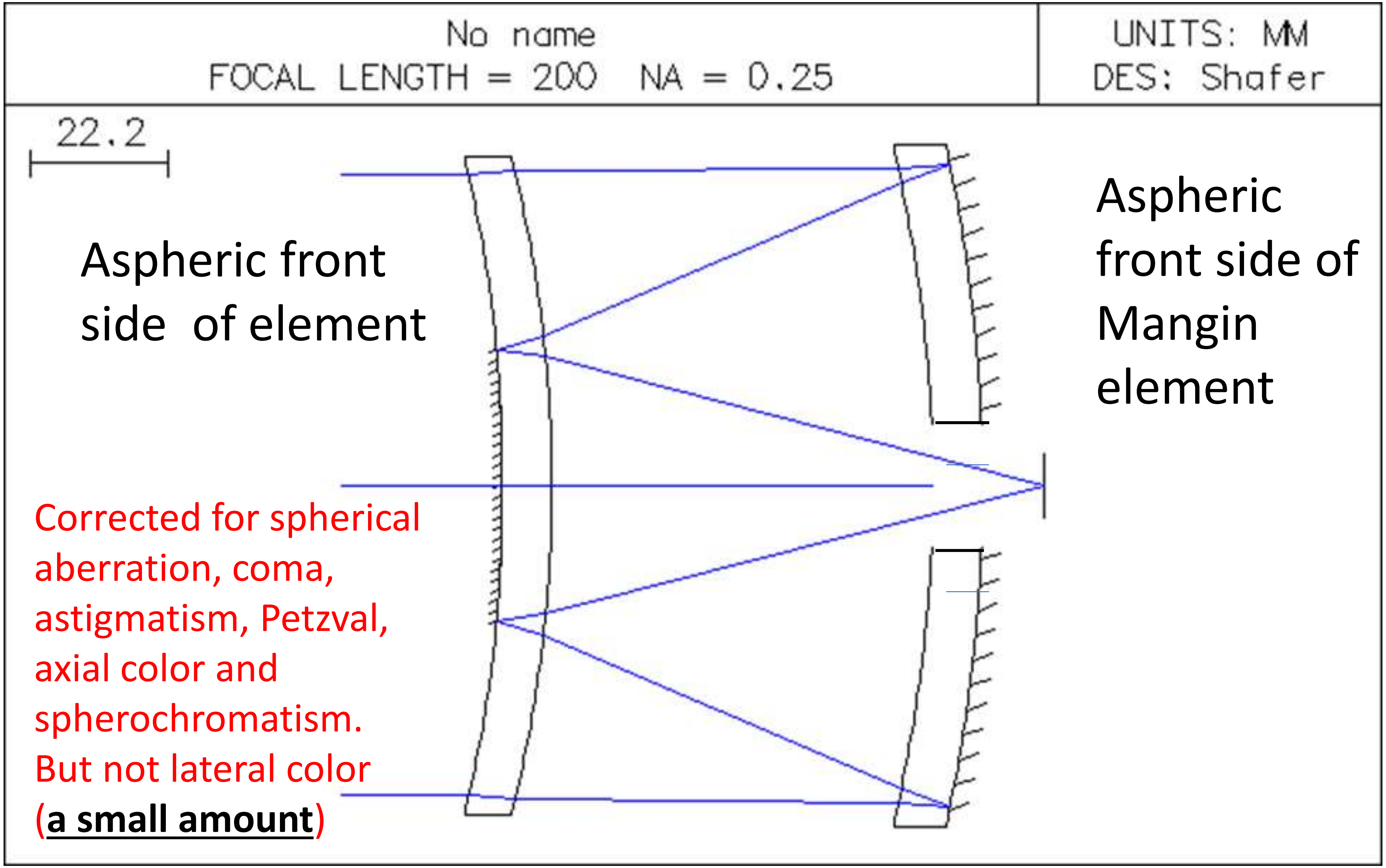
The aspheric mirror can be replaced with a Mangin mirror element to get an extra design variable and that can be used to correct the design's chromatic variation of spherical aberration. The Mangin element has essentially the same radius on both sides as does the front lens so axial color is zero. The aspheric might go on the front or the back of the element.



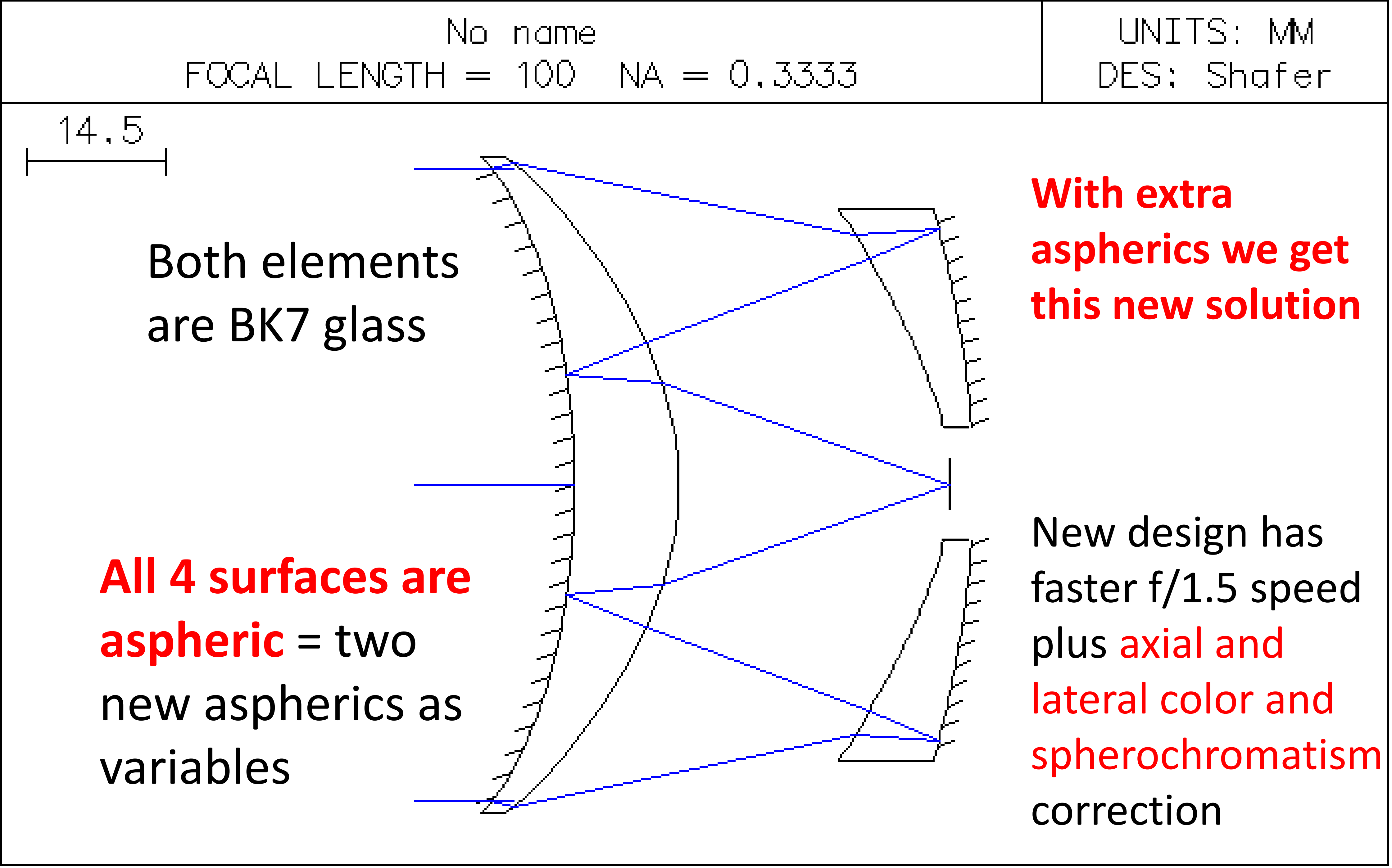
Aspheric on back side of Mangin element. Sphero-chromatism can't be corrected



Aspheric on front side of Mangin element. Sphero-chromatism of design can be corrected.



f/2.0 design with 3 degree field diameter and diffraction-limited monochromatically over field. Axial color and sphero-chromatism is corrected but there is still **lateral color**. How to correct without adding any elements?

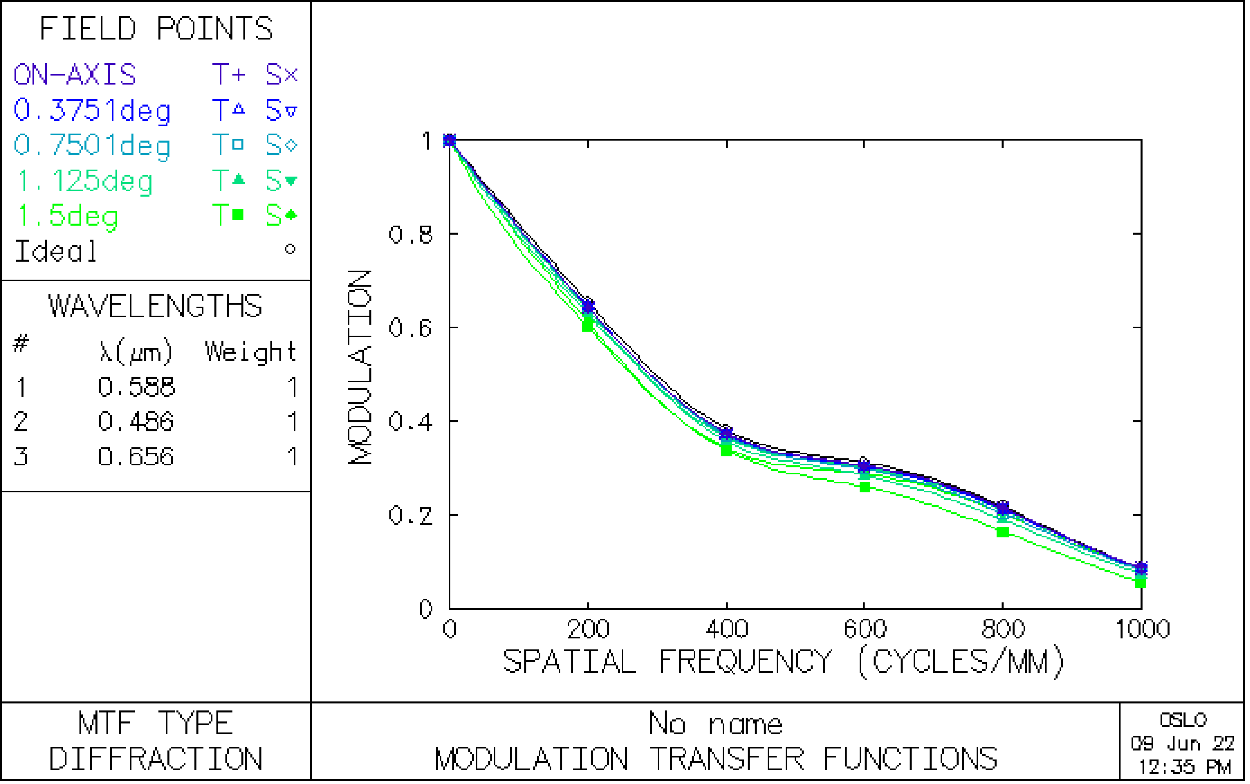


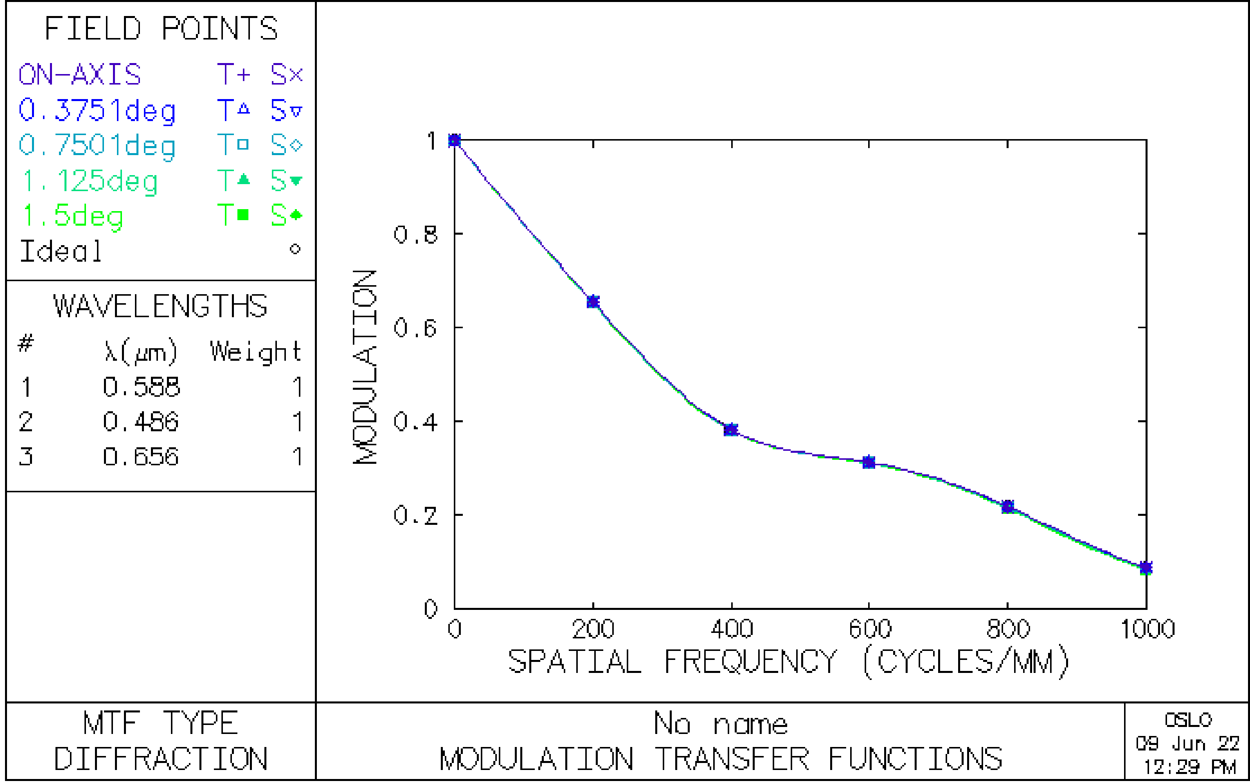
With extra aspherics we get this new solution

Both elements are BK7 glass

All 4 surfaces are aspheric = two new aspherics as variables

New design has faster f/1.5 speed plus axial and lateral color and spherochromatism correction



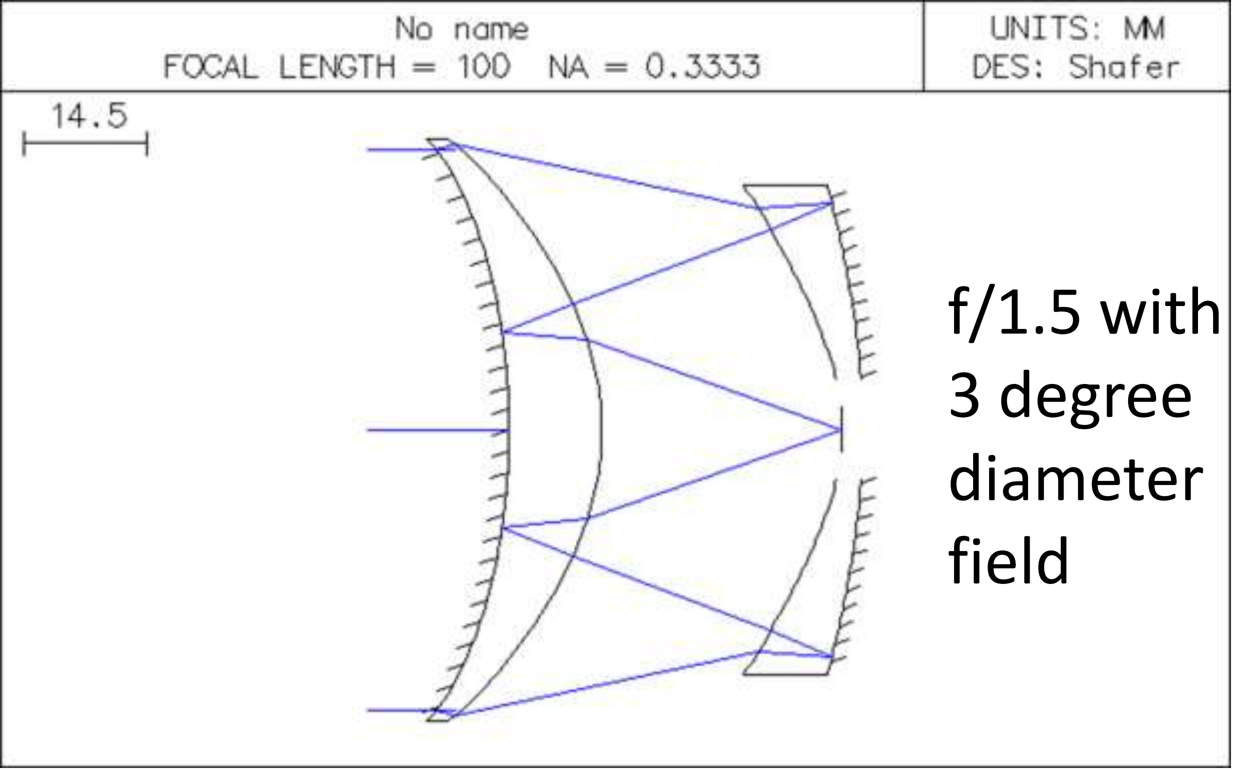


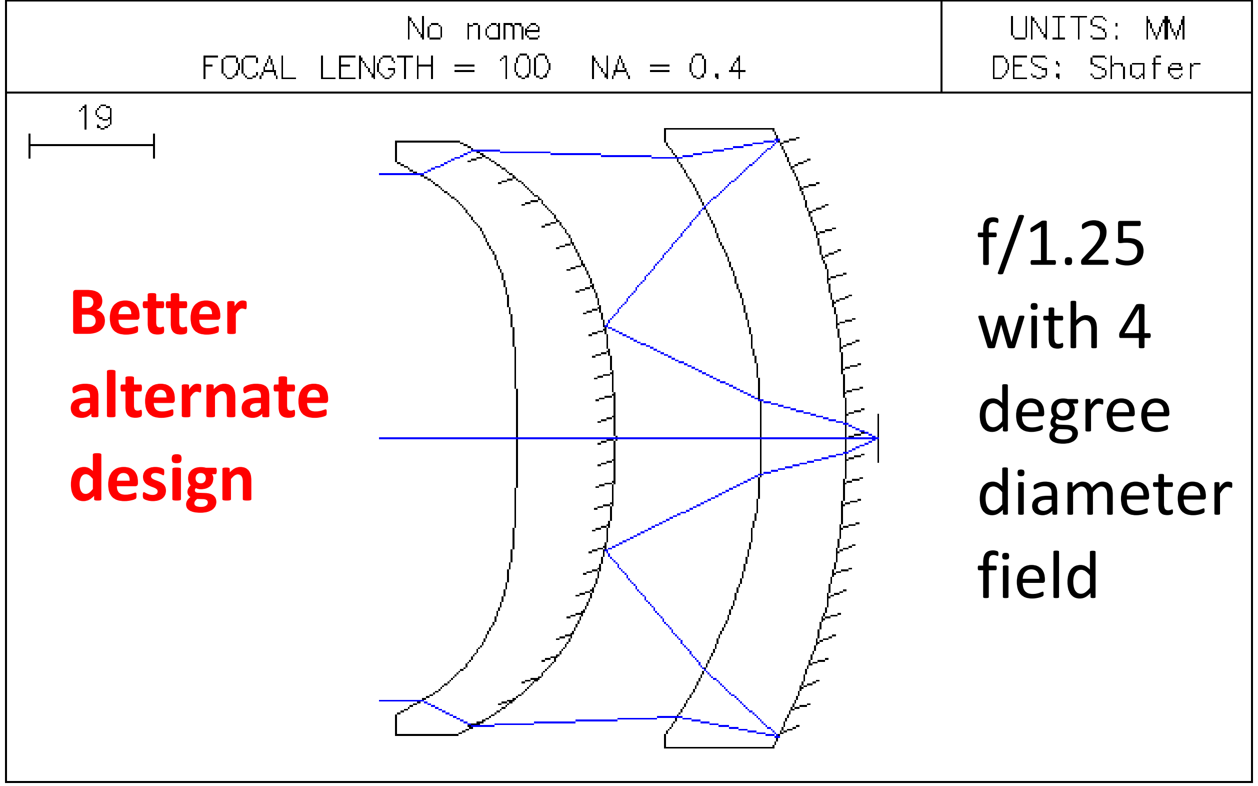
Actual 100 mm focal length f/1.5 design with 3 degree diameter field and 35% obscuration

<u>35% diameter obscuration</u>

Perfect system with 35% obscuration

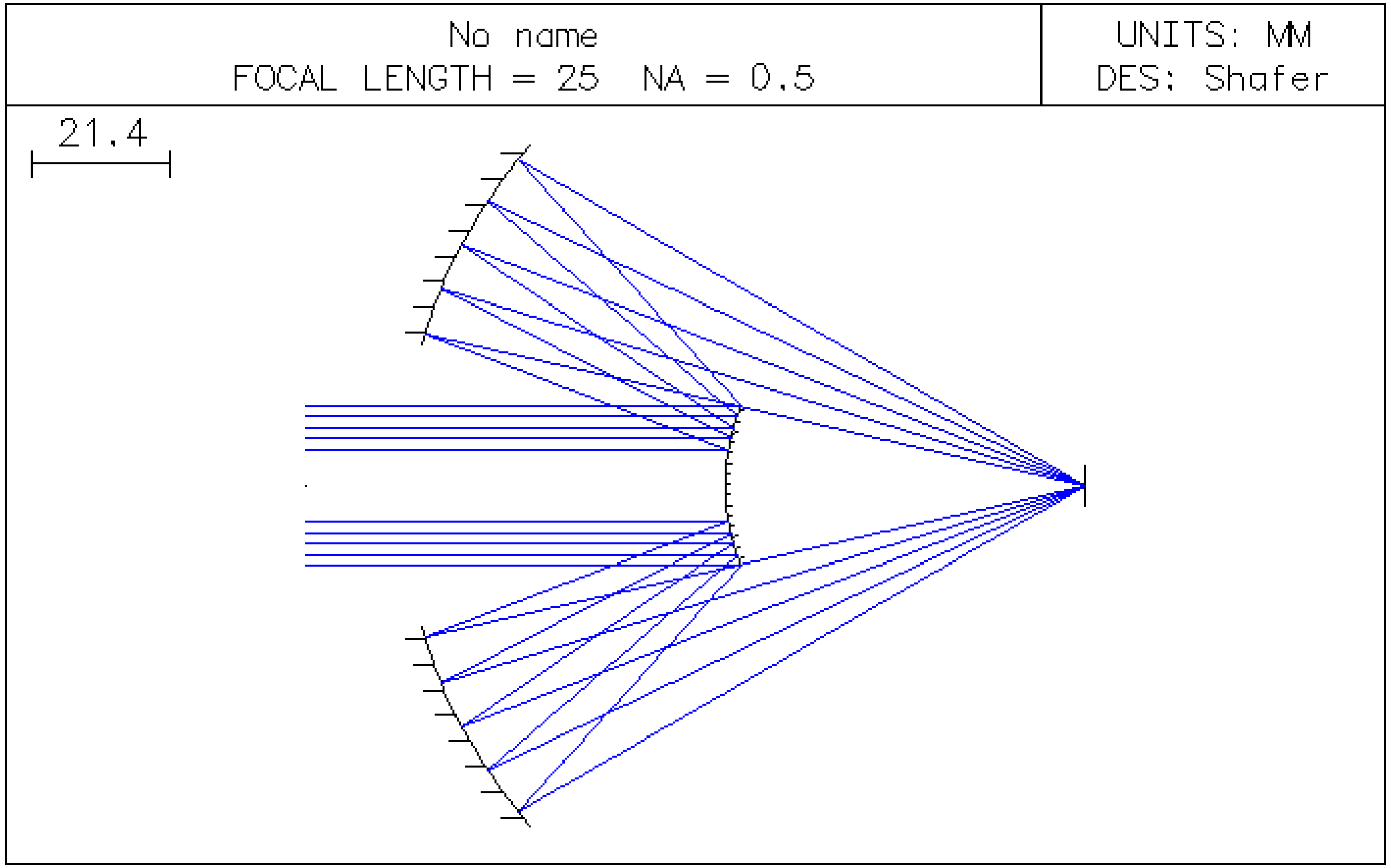
So now we are finished, right? Wrong! There is a better alternate solution that was found after this one was found.





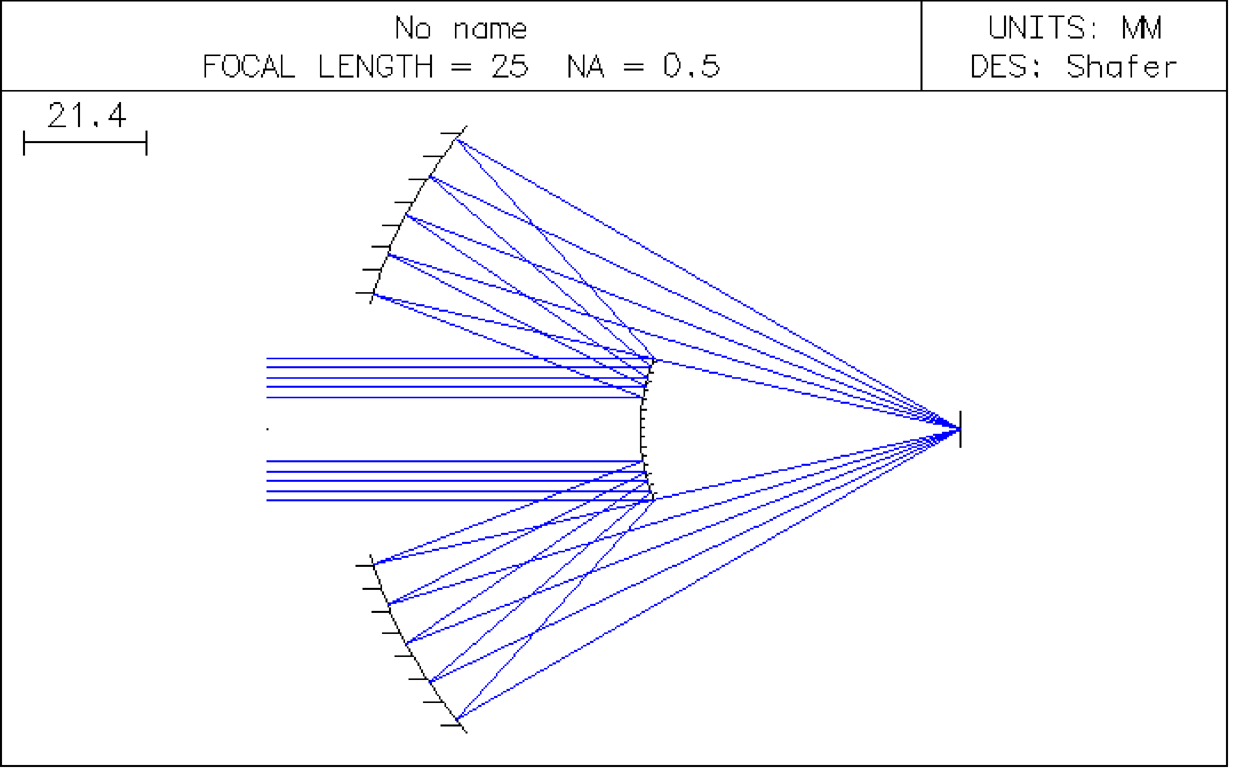
Both designs are just two BK7 elements with 4 aspherics and good color correction but the one on the right is much better. They both evolved from different starting points with the one on the left having a triple pass through the front element while the one on the right has a single pass through that front element.

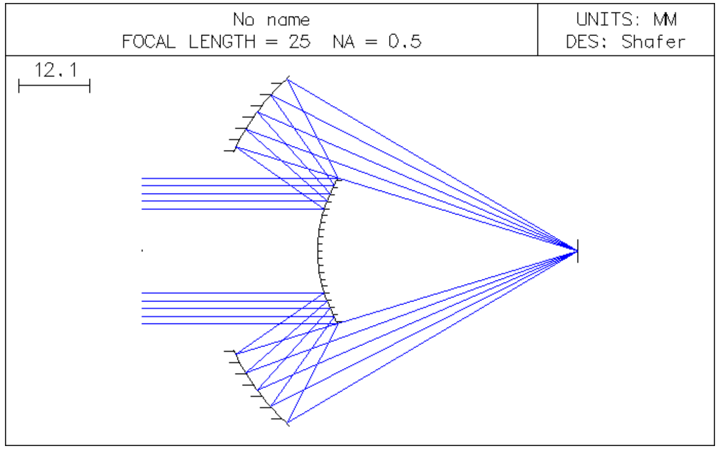
This shows how even a very simple design can have several good solutions and one will be the best one. But you have to go looking for it.



Another example

Suppose you want to focus a collimated beam of light and want the design to have a broad spectral band and be simple and inexpensive. You could use the Schwarzschild design of two concentric spherical mirrors, which is well-corrected for spherical aberration, and also coma and astigmatism. But the concave mirror is large and the diameter obscuration is 45%.



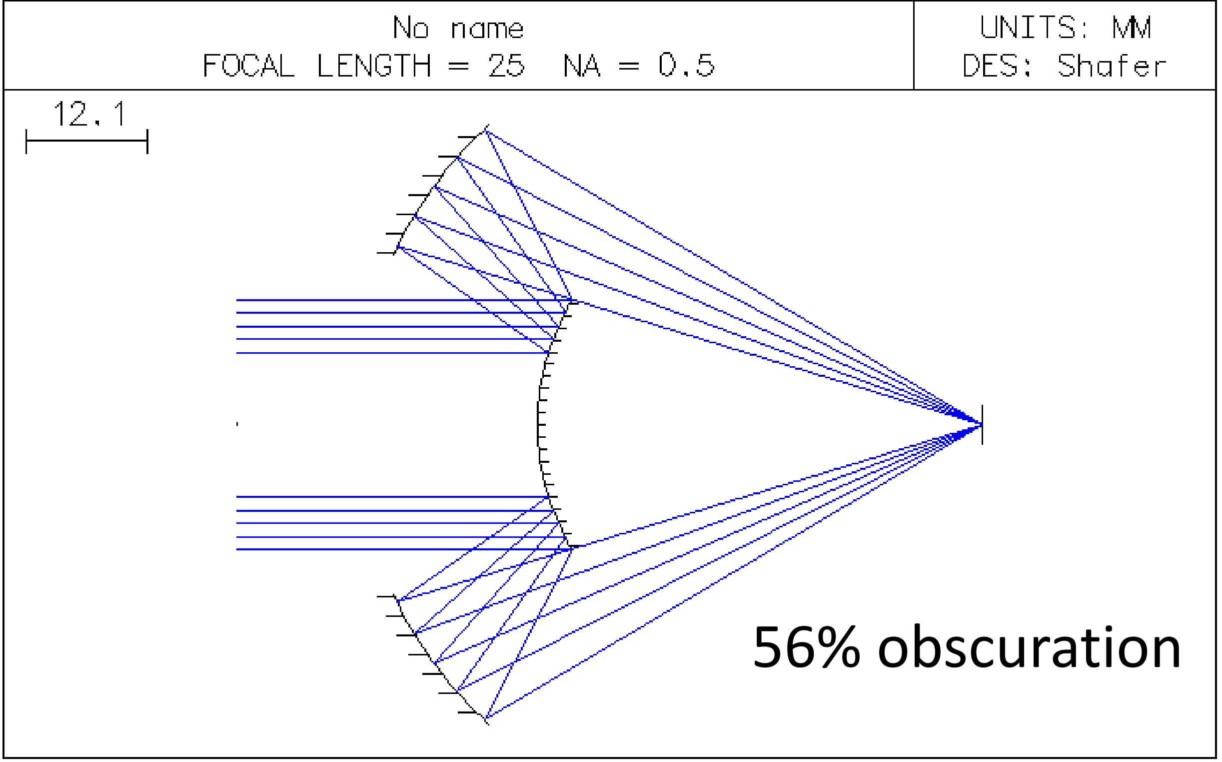


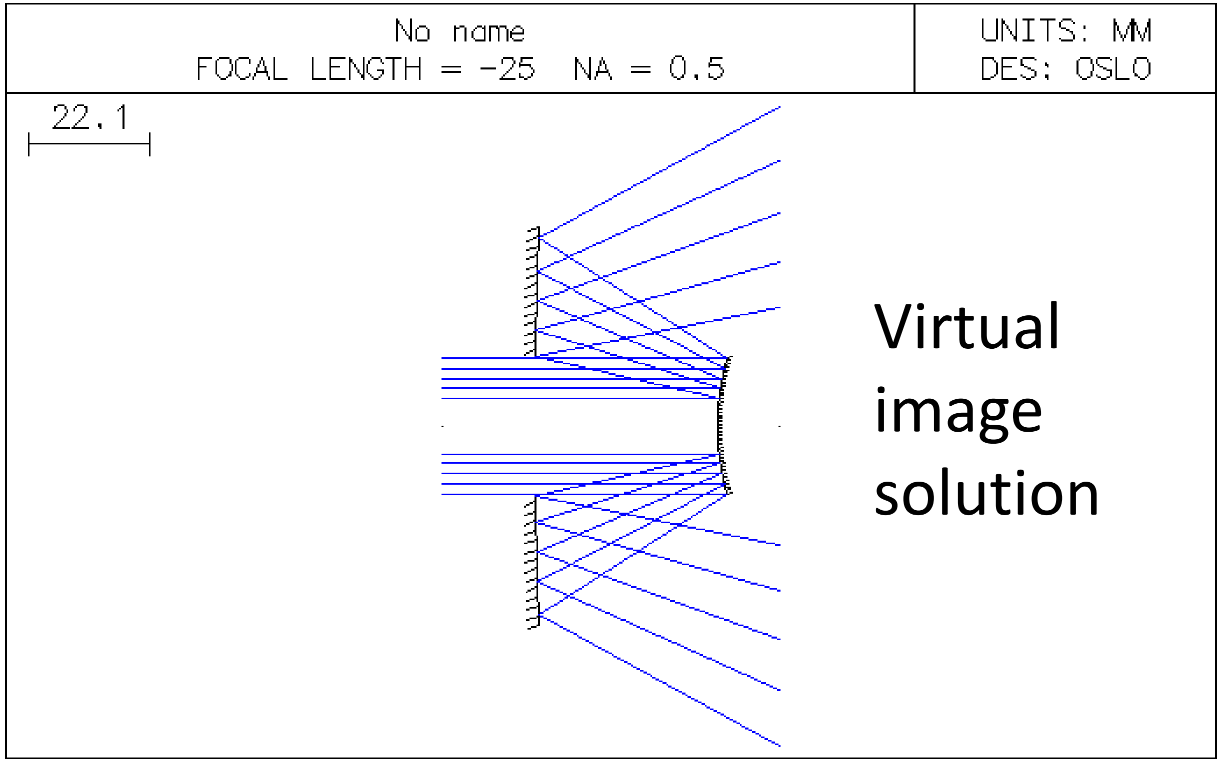
Same scale for 25 mm f.l and f/1.0

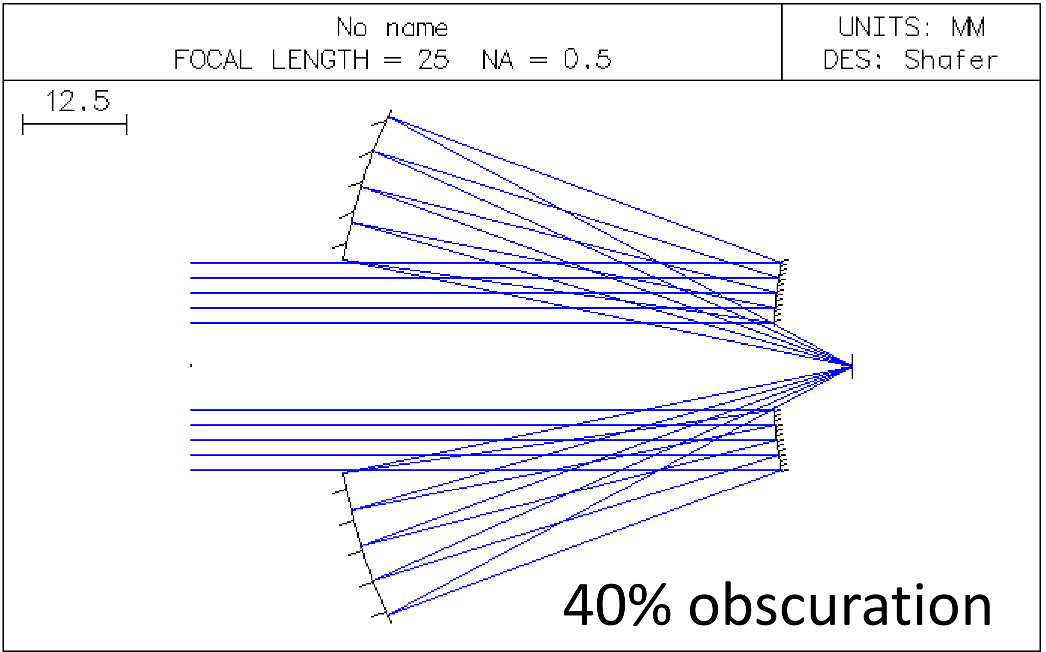
Large mirror is <u>4.24X</u> entering beam diameter. <u>45%</u> obscuration.

Large mirror is <u>2.5X</u> entering beam diameter. <u>56%</u> obscuration. Coma not corrected.

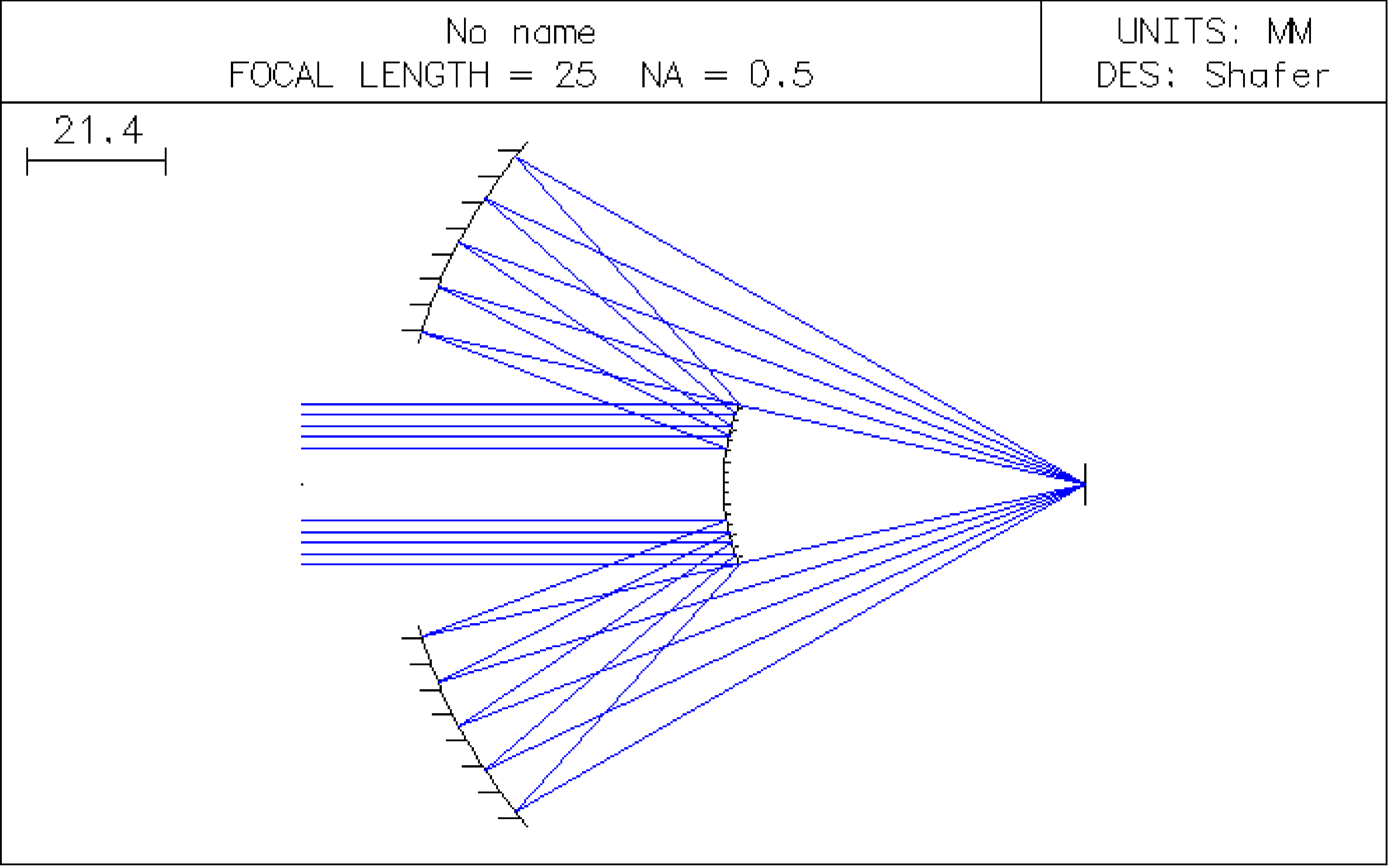
Concave mirror is moved closer to convex mirror to give smaller size. Then concave radius is solved to correct for spherical aberration. Result has larger obscuration. There is only one variable – the concave mirror radius – and only one aberration – spherical aberration – so there is only one solution right? Wrong! There are 3!!



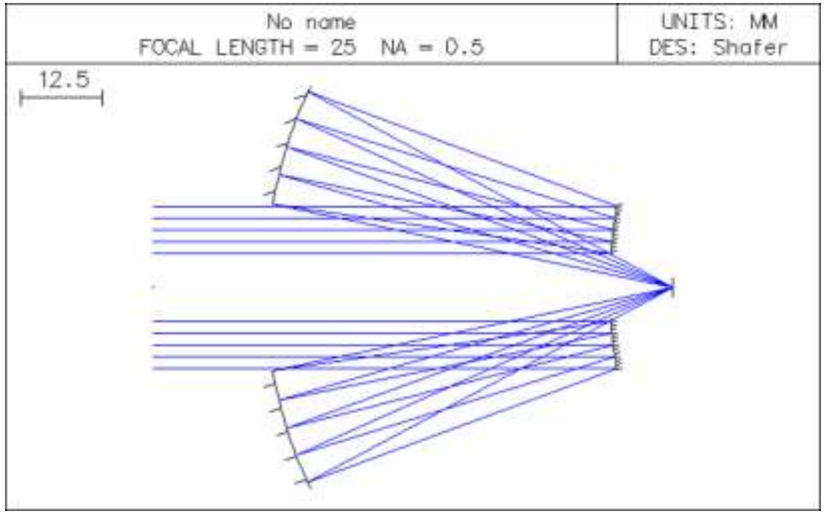




Three different solutions for the concave mirror that correct for spherical aberration. This is a 1 X 1 optimization matrix and yet there are these multiple solutions. But only the Schwartzschild design with a much bigger concave mirror also has coma correction.



Most compact solution of the 3 solutions with 2.5X concave mirror size



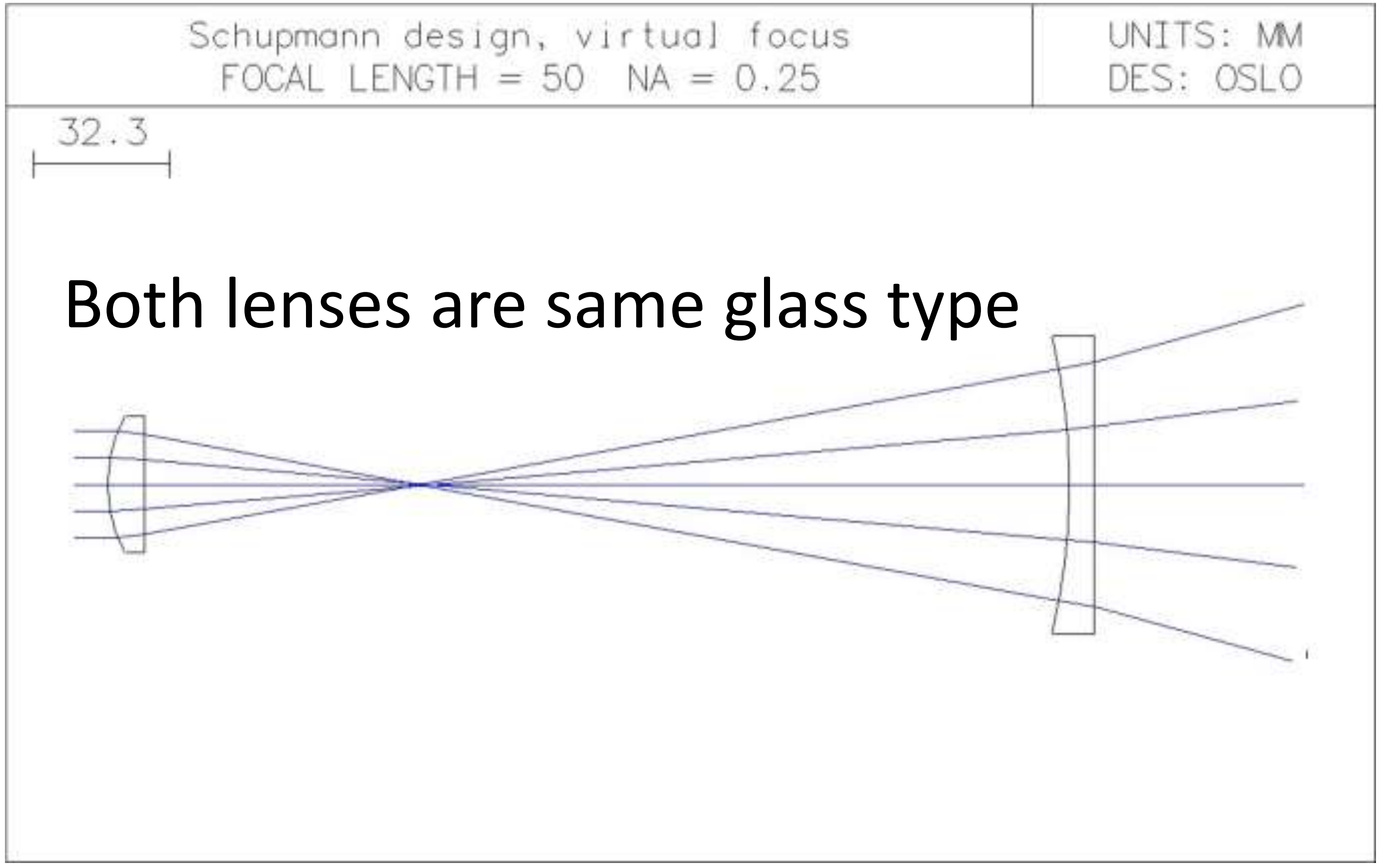
Schwartzschild concentric design with concave mirror 4.24X larger than entering beam

Same focal length

#2

Simple systems with useful properties can be combined to make new types of designs.

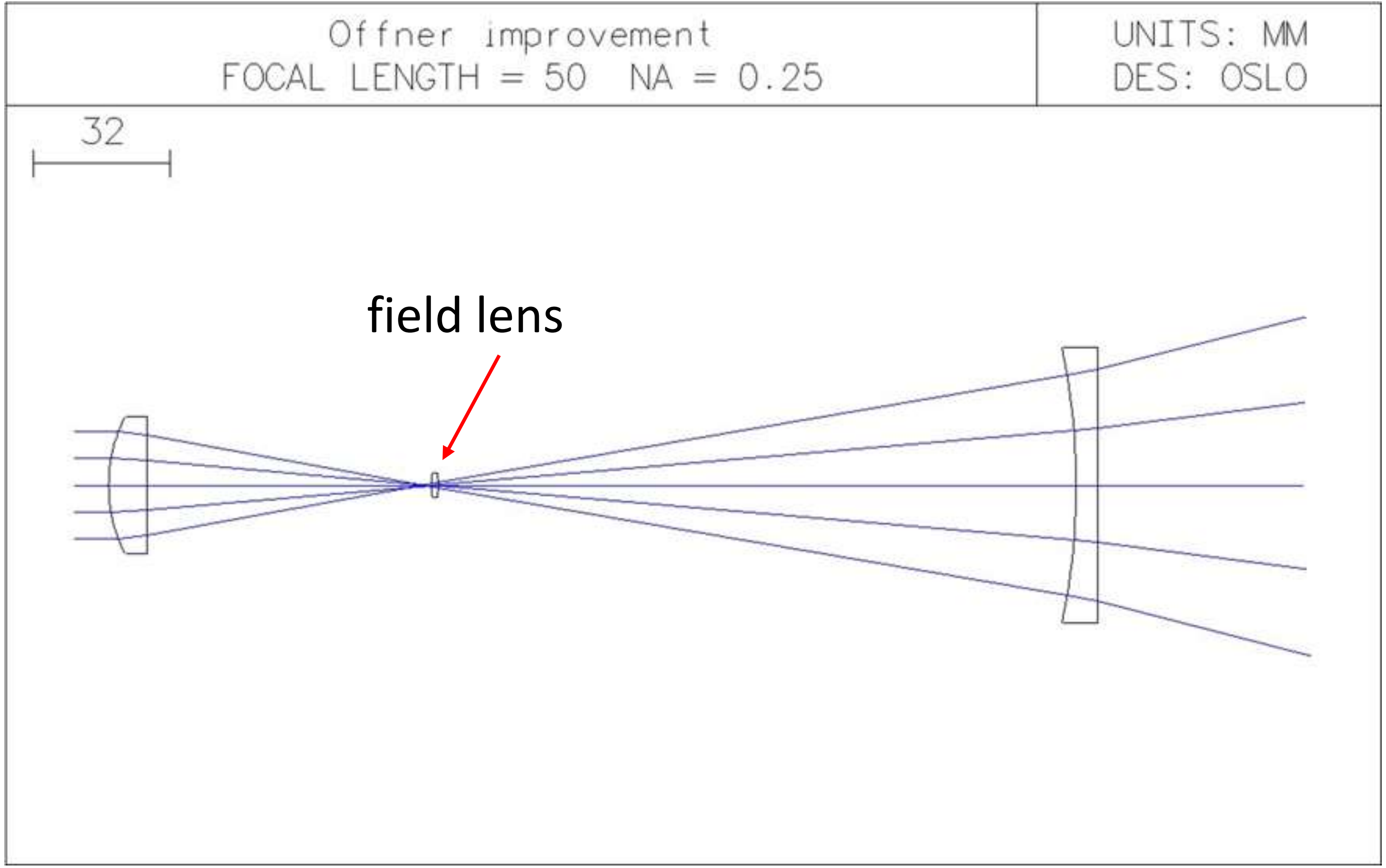
Example – the CMO design



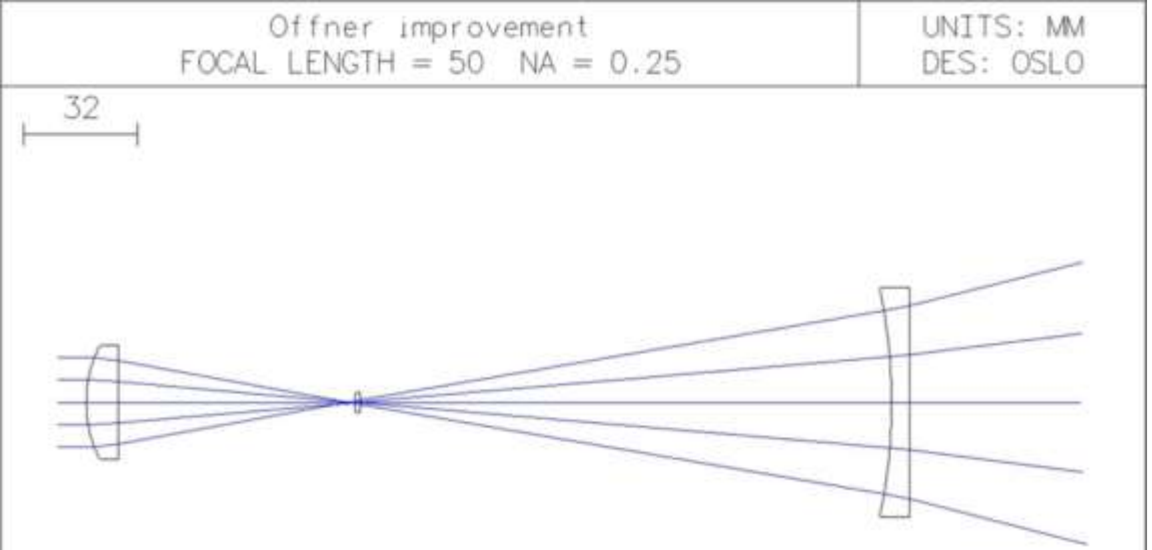
This simple design is not useful by itself, since it does not form a real image, but a virtual one. But it is a good building block in more complex designs.

Schupmann design with virtual focus

Axial color is linear with lens power, quadratic with beam diameter, so axial color here cancels between the lenses, one small with strong power and one large with weak power.



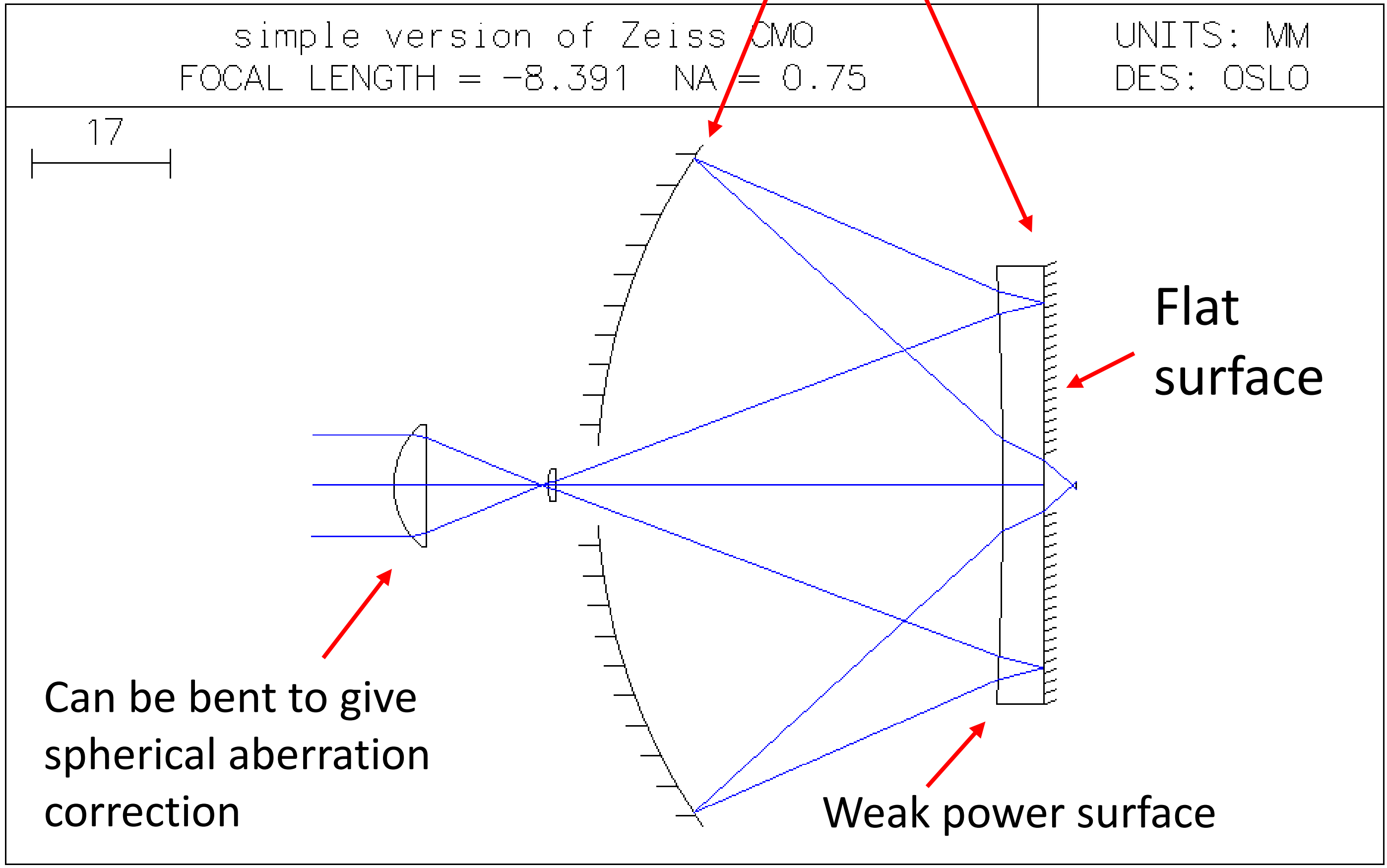
Offner improvement – a field lens at the intermediate focus.
The field lens images the other two lenses onto each other.
That corrects the design for lateral color. Why?



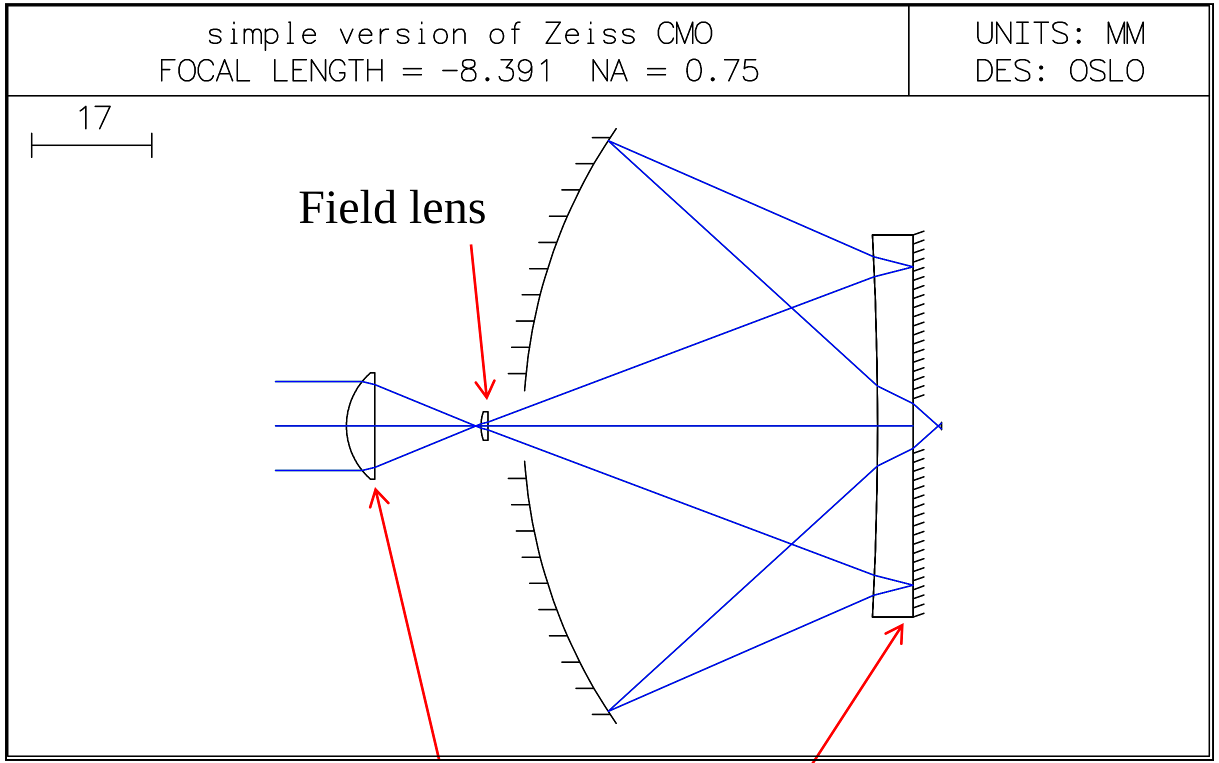
Virtual image design

Virtual image from Schupmann design is made into a **real** image by adding two mirror surface reflections here.

Concave mirror reflection speeds up real image f# by about 2X to give a faster speed design, yet adds no color. New design has small obscuration near final image due to hole in flat reflecting surface.



Low-order theory of design

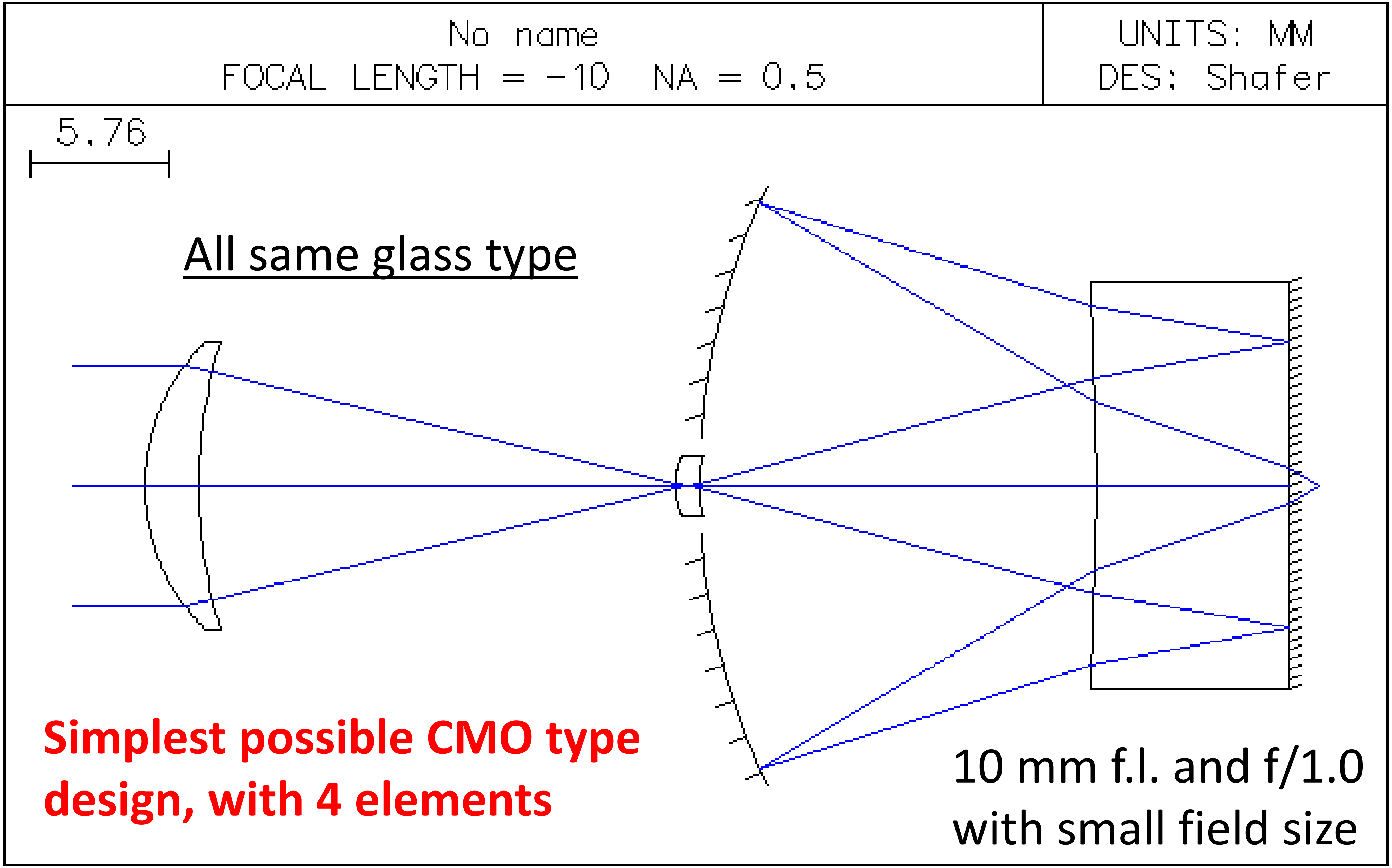


1) Put stop on first lens, then choose power of field lens to image it onto the lens/mirror element. Stop is then effectively at both places.
2) Then neither of those elements has lateral color. Power of lens/mirror element corrects axial color.
3) Field lens imaging and only one glass type corrects for secondary axial color too (Offner theory).
4) Then can put the stop anywhere.

- A key point – the aperture stop was only temporarily located at a place where the theory is simple to understand and the aberration correction method becomes obvious.

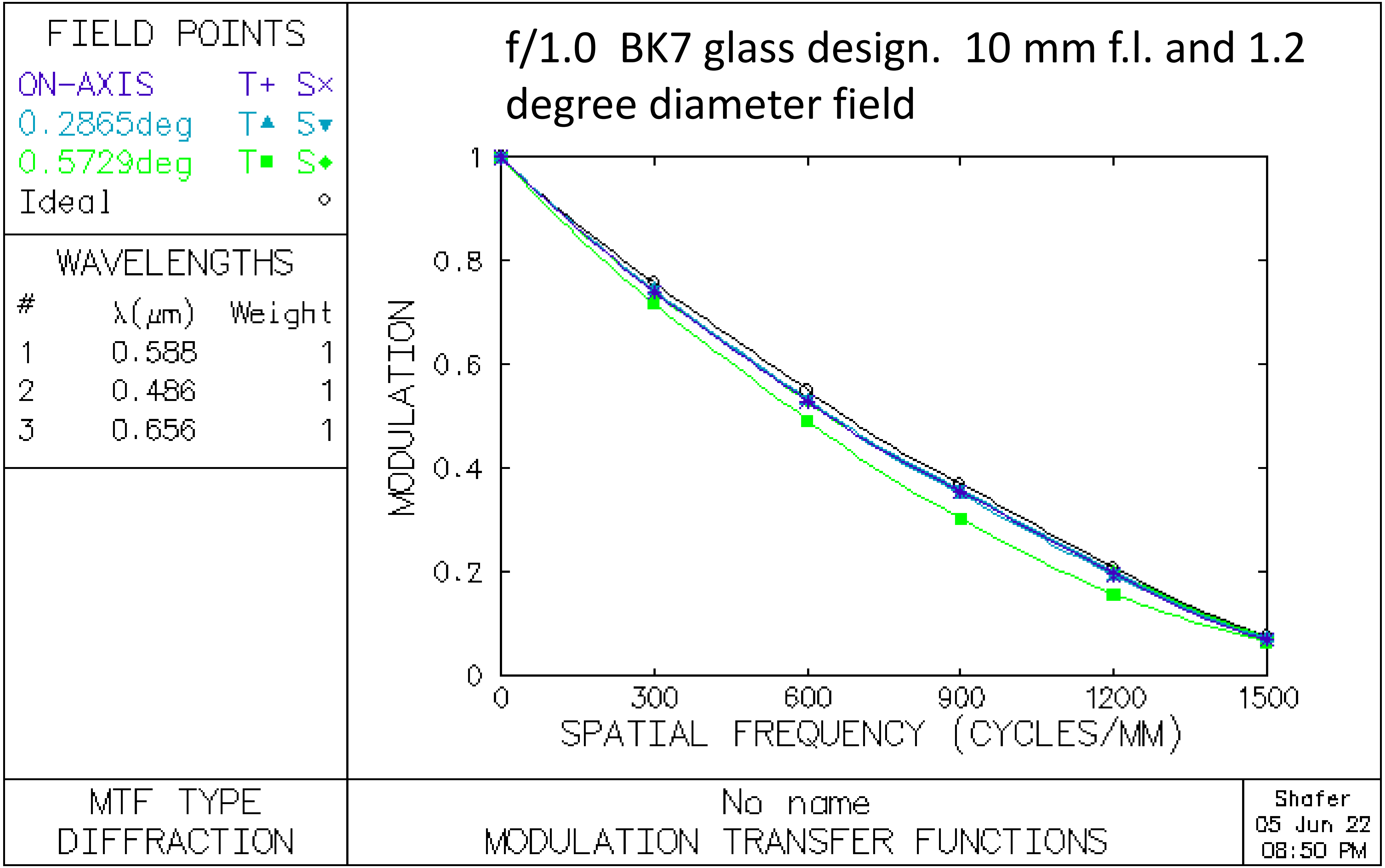
- Then later the stop is moved to where it needs to be – like in order to have a telecentric system.

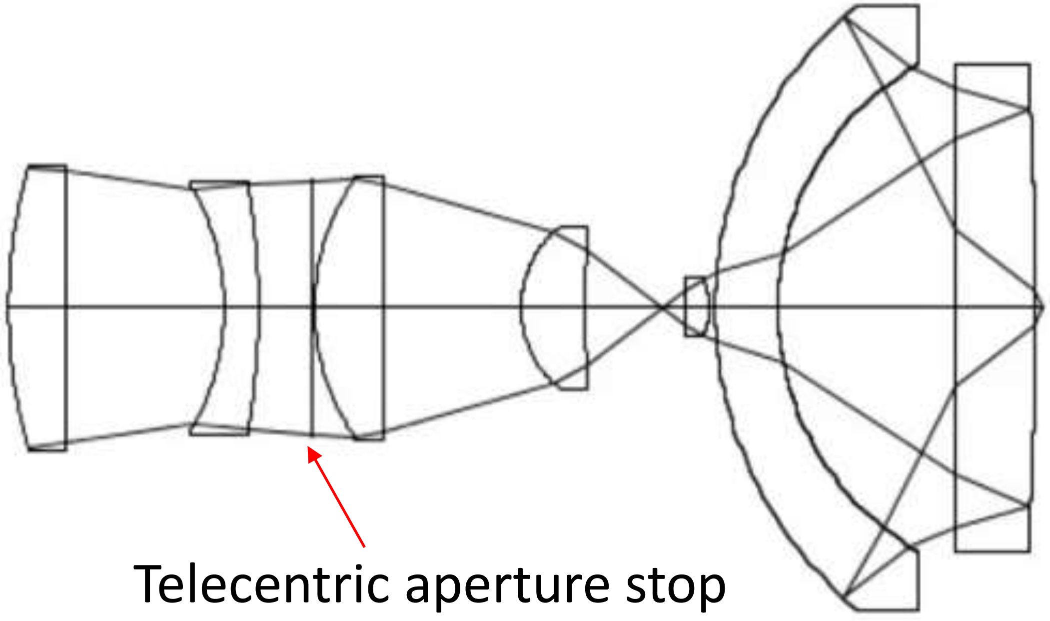
- Once the aberrations are well-corrected they do not change (at the lower-order levels) when the stop is moved.



No name
FOCAL LENGTH = -10 NA = 0.5
UNITS: MM
DES: Shafer
5.76
All same glass type
Simplest possible CMO type design, with 4 elements
10 mm f.l. and f/1.0 with small field size

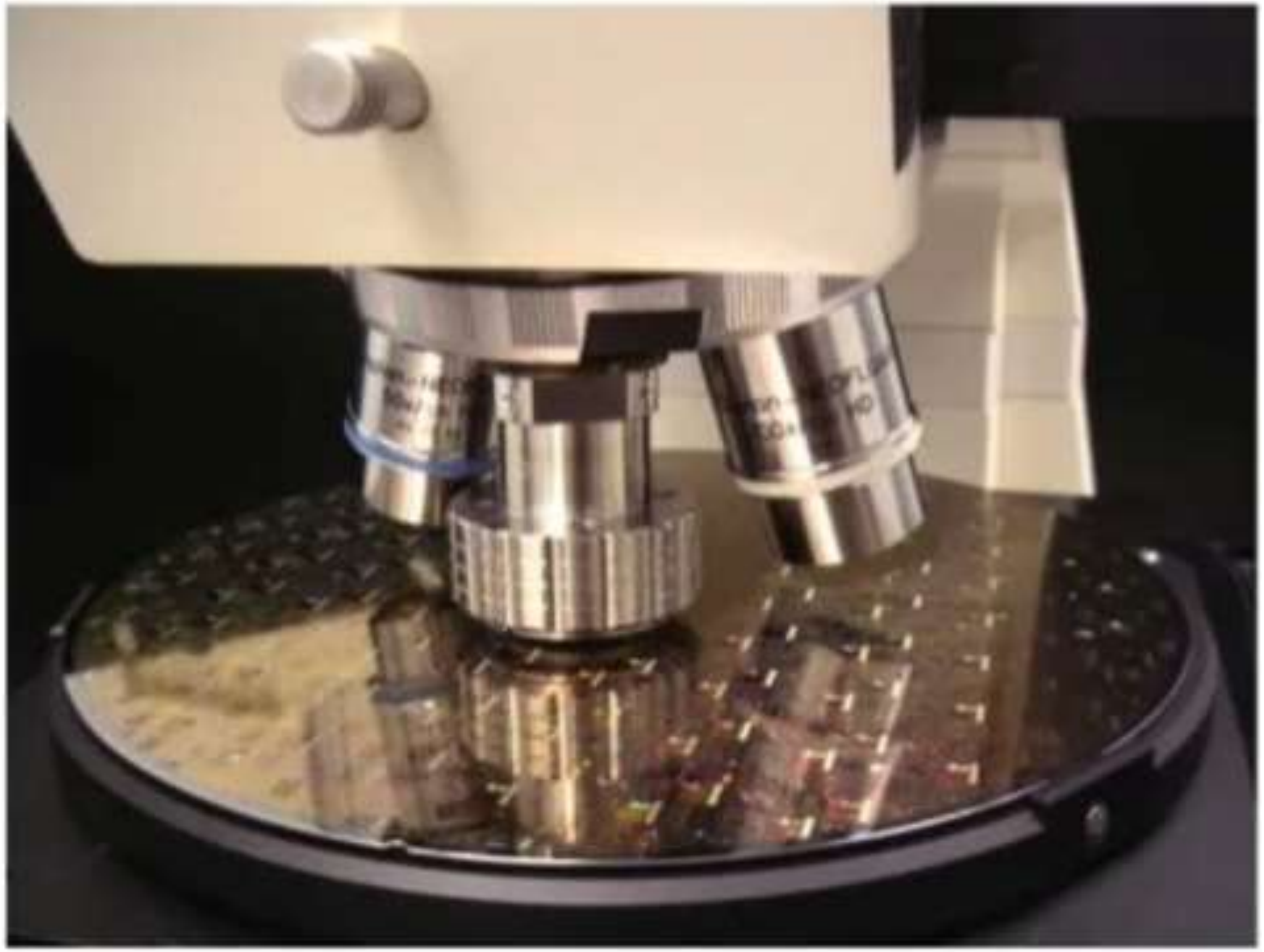
f/1.0 BK7 glass design. 10 mm f.l. and 1.2 degree diameter field





An example 7 element design corrected from 266-800nm. The diameter of the largest catadioptric element is 25mm. This design has an NA of 0.9 at the object with a field size of 0.13mm. The obscuration is 1.5% of the area.

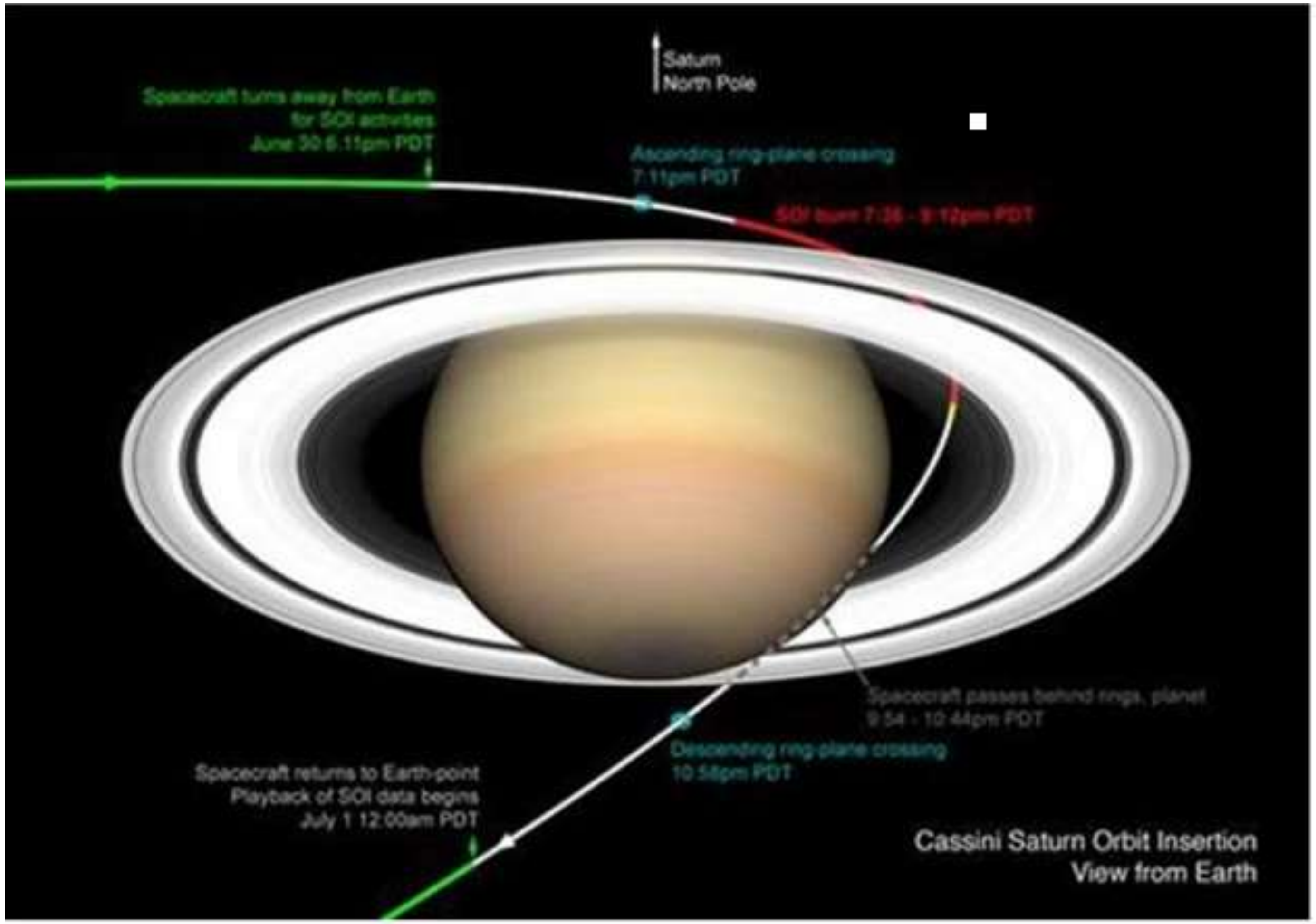
High NA well-corrected for an enormous spectral region, .266u to .800u and yet all same glass



Olympus-made prototype in use.

Student microscope

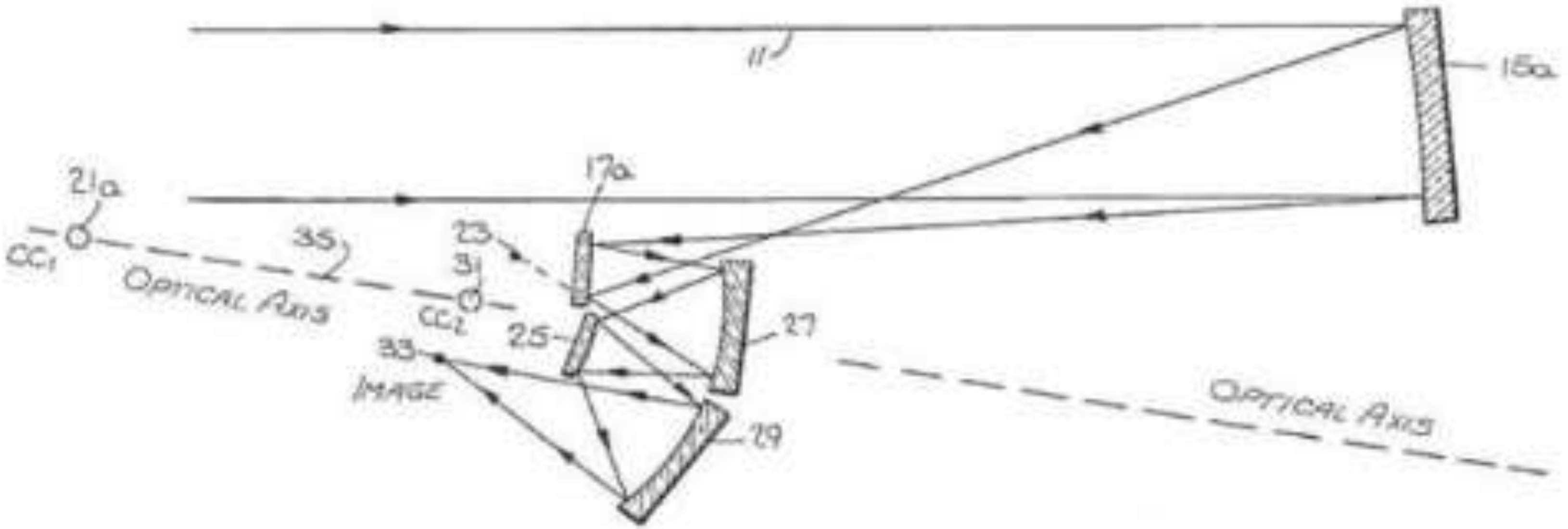
Another example



One of my first patents, in 1977, was for an unusual kind of telescope that only has spherical mirrors.

Many years later one of these unusual telescopes was sent on the Cassini space craft to Saturn.

The Cassini mission to Saturn wanted a telescope on-board that was 1) all-reflective, 2) easy to make and align with no aspherics, 3) unobscured, 4) well-corrected over a large field size, and 5) able to become a spectrograph with no extra elements

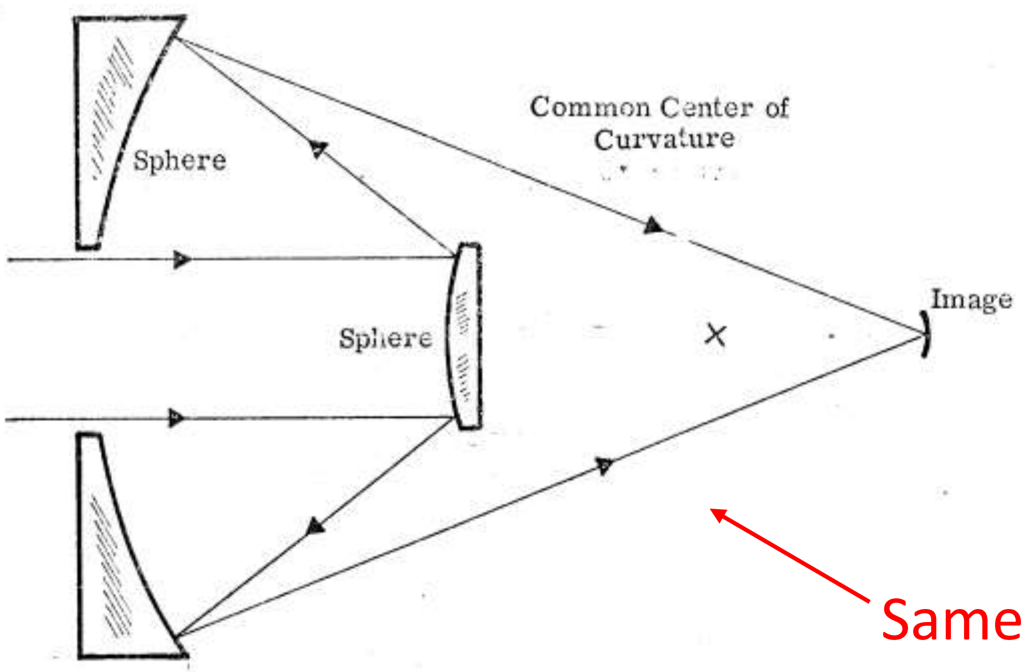


This drawing from my patent, not to scale, shows the design. What is very unusual is that all the mirrors have their centers of curvature on a single optical axis, unlike other tilted mirrors designs. Also the convex mirror "25" in the drawing is the aperture stop. If this is made a grating surface then the final image is a sharp in-focus spectrum.

Three of these telescope/spectrometers were sent out over the years on three different missions – to Saturn, to the asteroid Vesta and the planetoid Ceres, and to land on a comet.

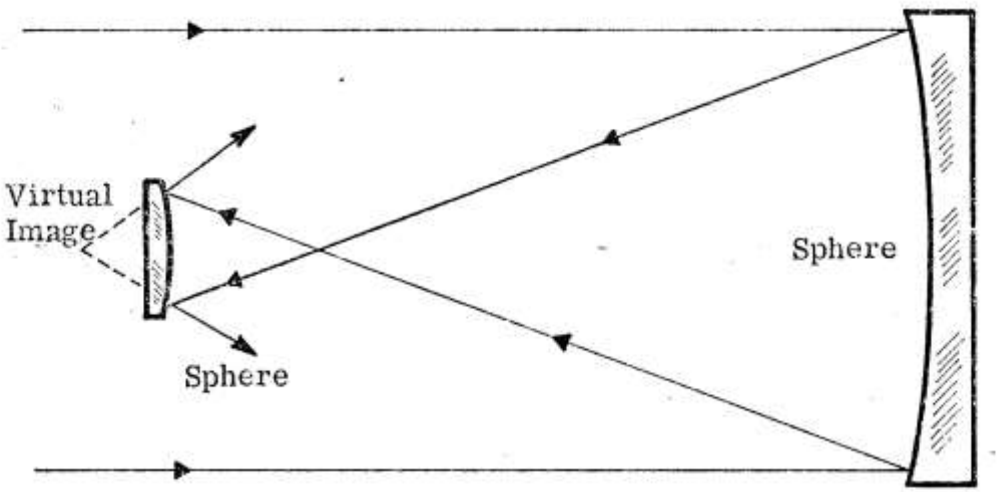
What is the theory behind this design?

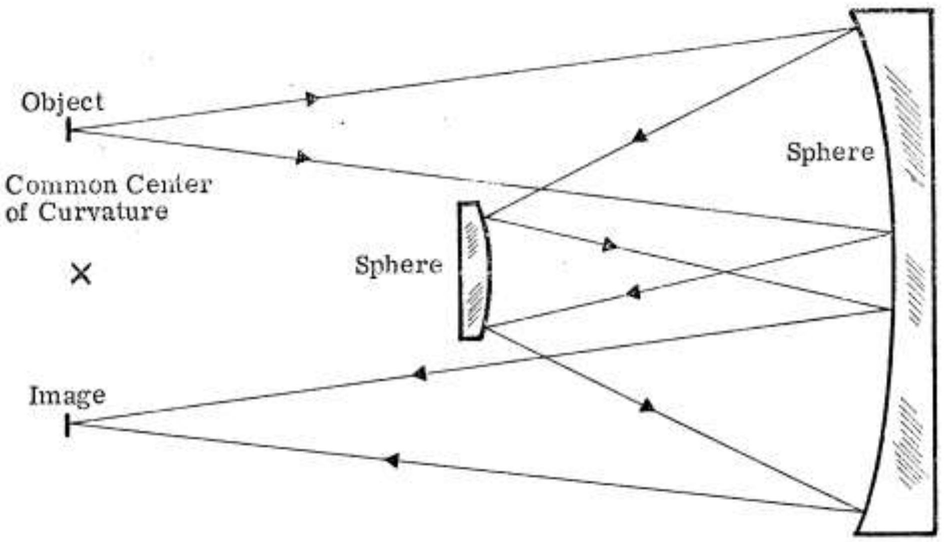
Two concentric spherical mirrors can be corrected for spherical aberration, coma, and astigmatism – with a curved image.

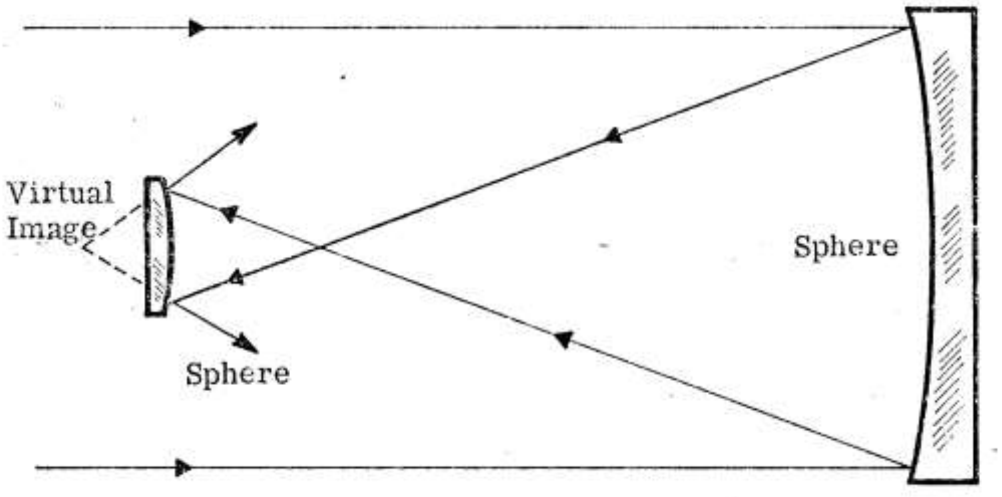


Same design used backwards

Every concentric system has <u>exactly</u> the same aberrations when used backwards – a peculiar and interesting fact

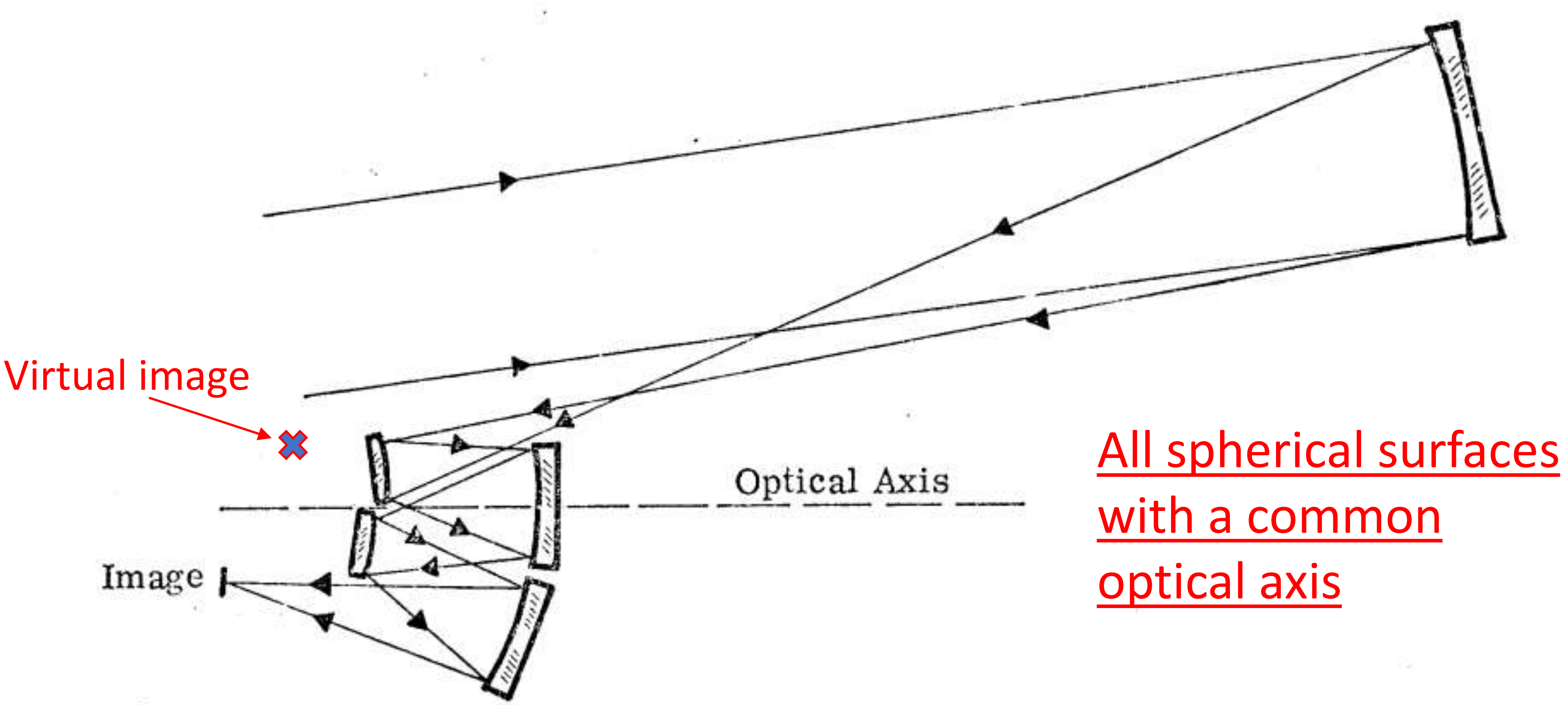




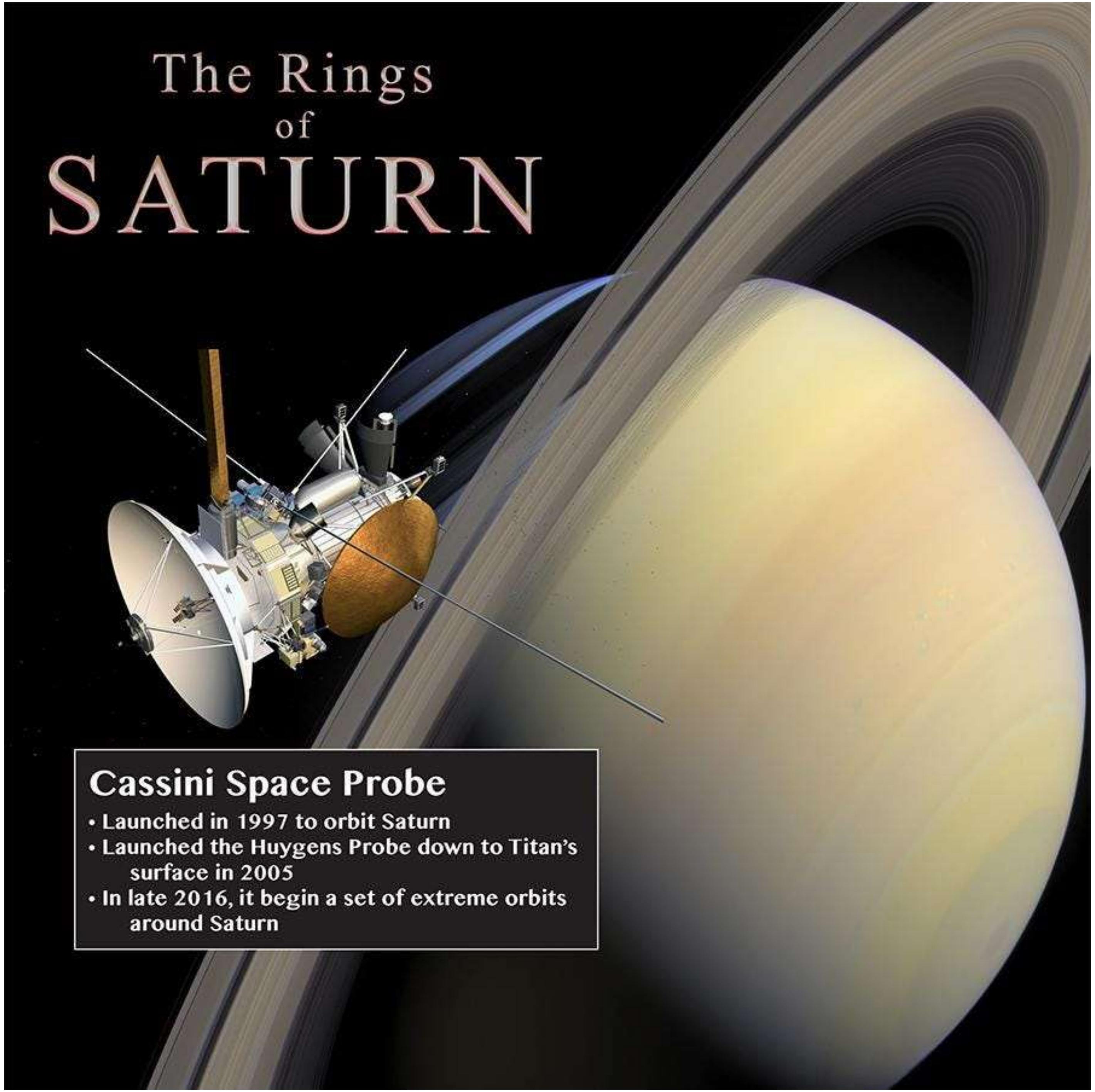


Offner 1X relay design is well corrected for all 3rd-order aberrations

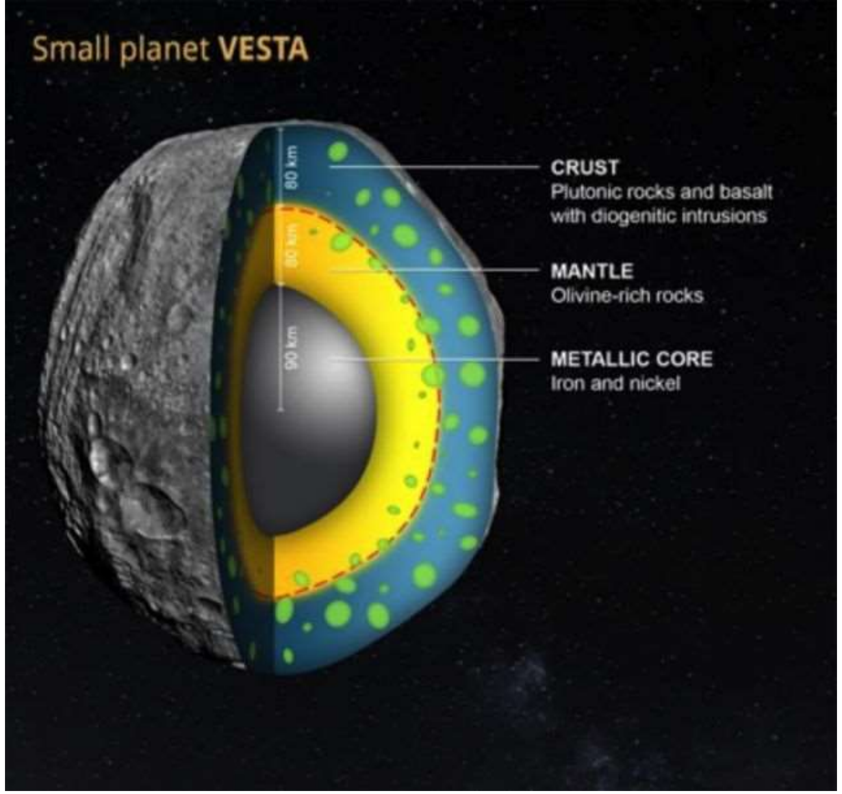
Insight – use this to relay the well corrected virtual image to a well corrected real image



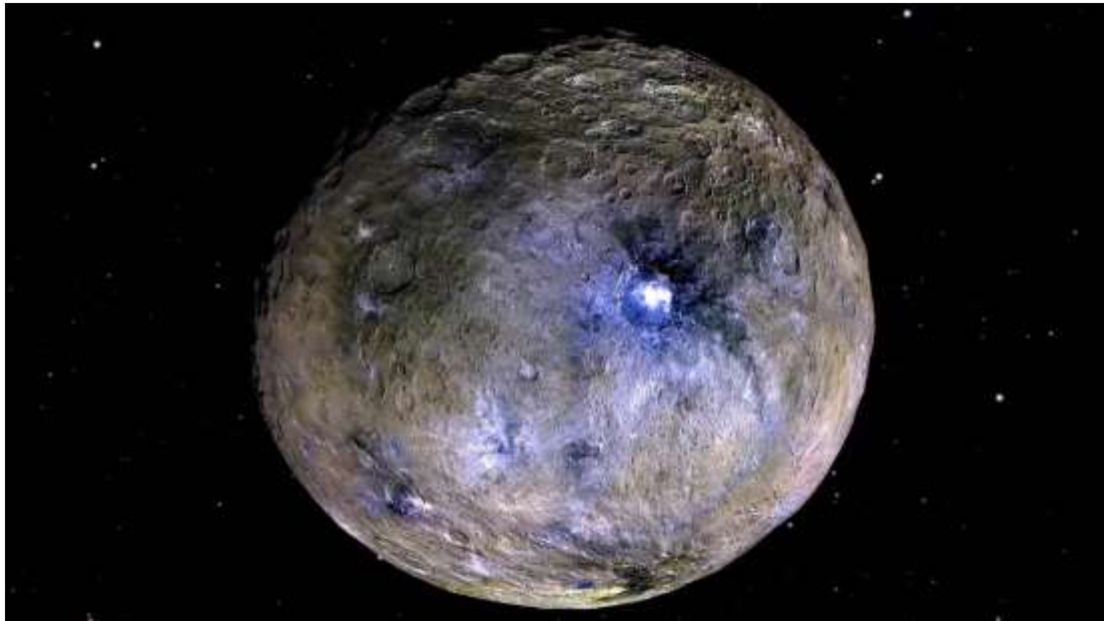
By putting the field of view to one side of the optical axis we can get an unobscured design. By reoptimizing with all the mirror radii as variables we can correct for Petzval as well as spherical aberration, coma, astigmatism and even distortion.


The Rings of SATURN
Cassini Space Probe
• Launched in 1997 to orbit Saturn
• Launched the Huygens Probe down to Titan's surface in 2005
• In late 2016, it begin a set of extreme orbits around Saturn

Vesta

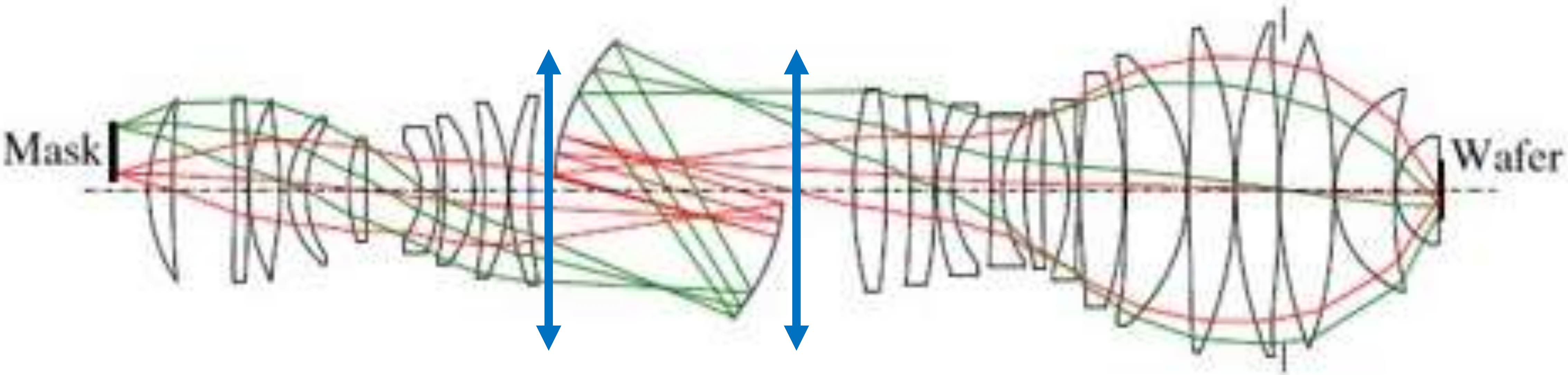

Small planet VESTA
CRUST
Plutonic rocks and basalt with diogenitic intrusions
MANTLE
Olivine-rich rocks
METALLIC CORE
Iron and nickel

Ceres

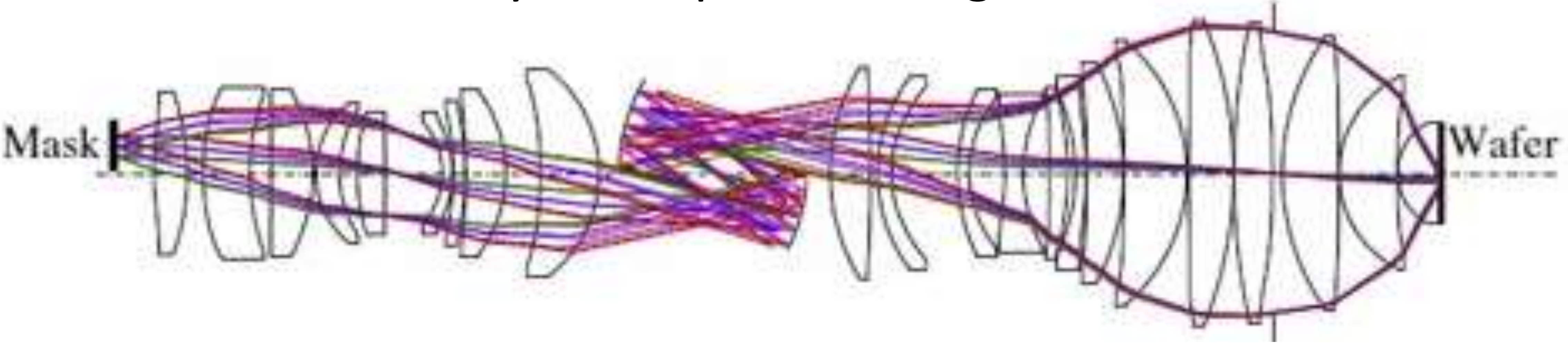


Rosetta spacecraft sends lander to the surface of a comet

One more example - a 1.35 NA Chinese immersion design



3 **separately** optimized (on a curved image) sections. Then the 3 are joined and the whole system optimized together. Result is below here.



#3

Stop shift theory is very useful when creating new designs

<u>Example</u>

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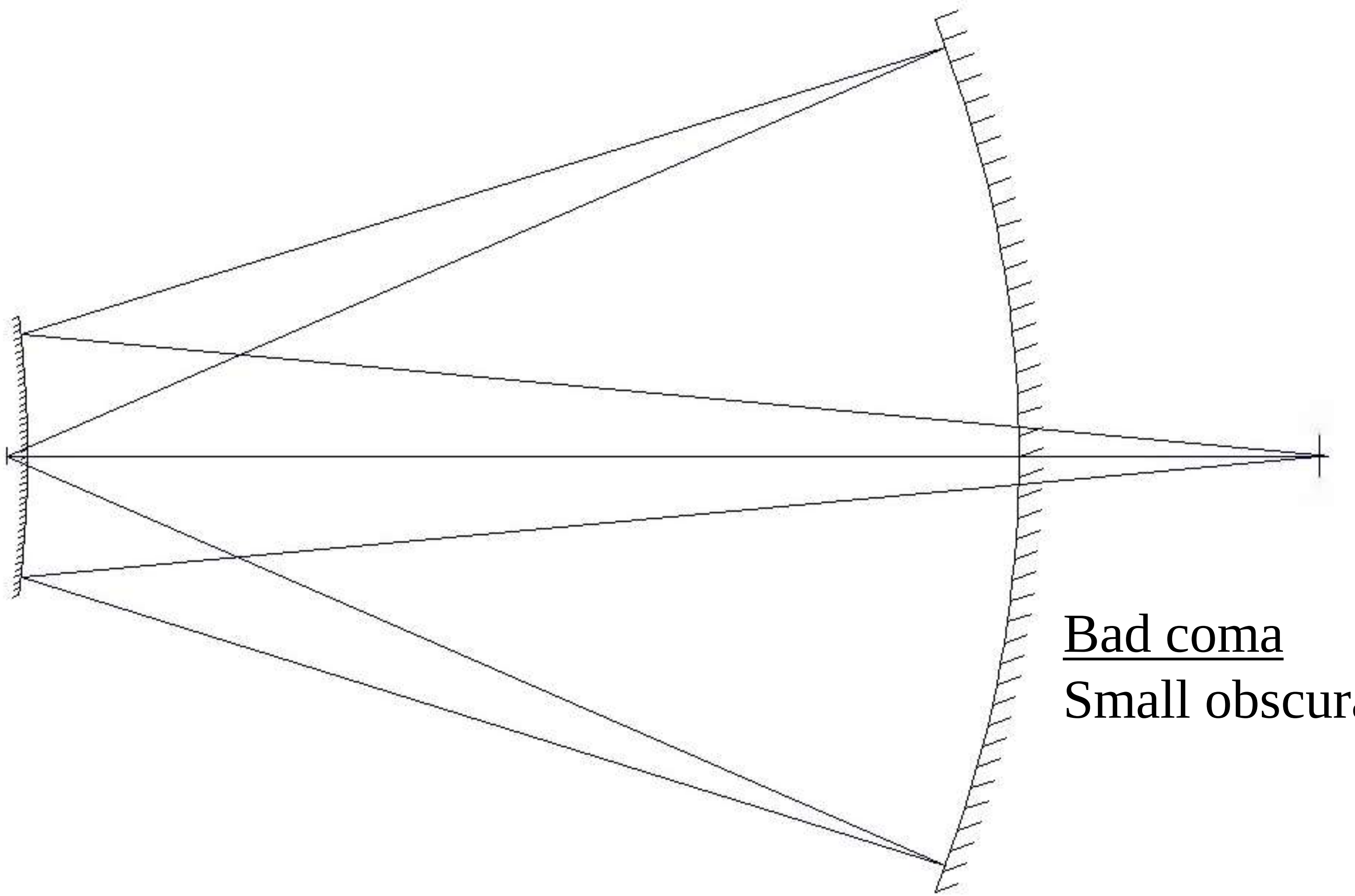
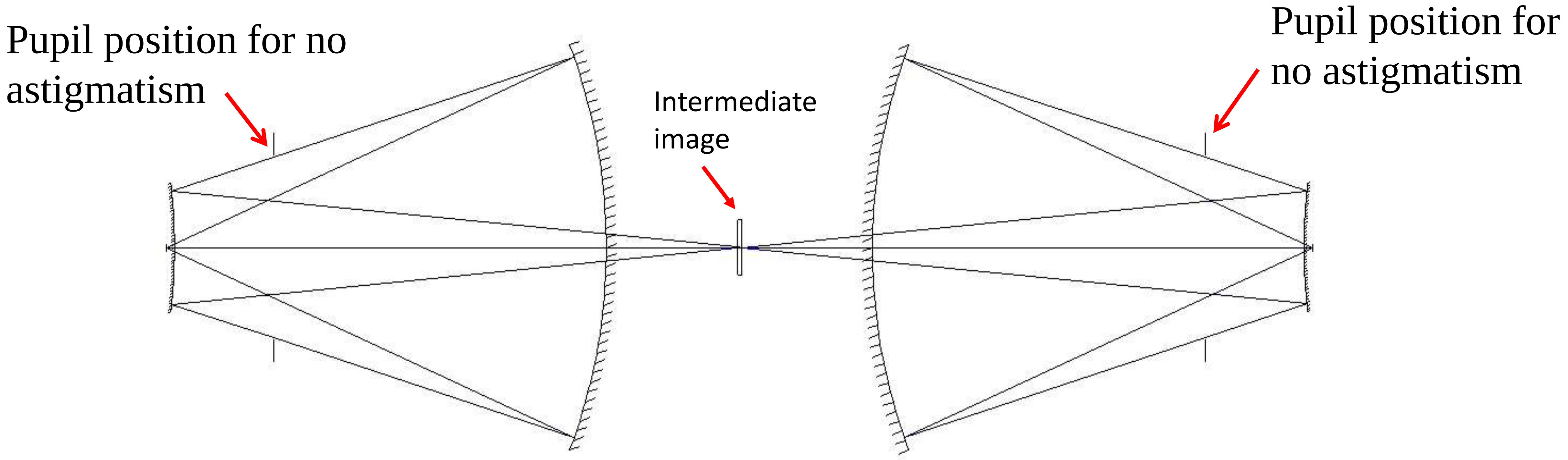
A 1.0X catadioptric relay system developed using stop shift theory



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

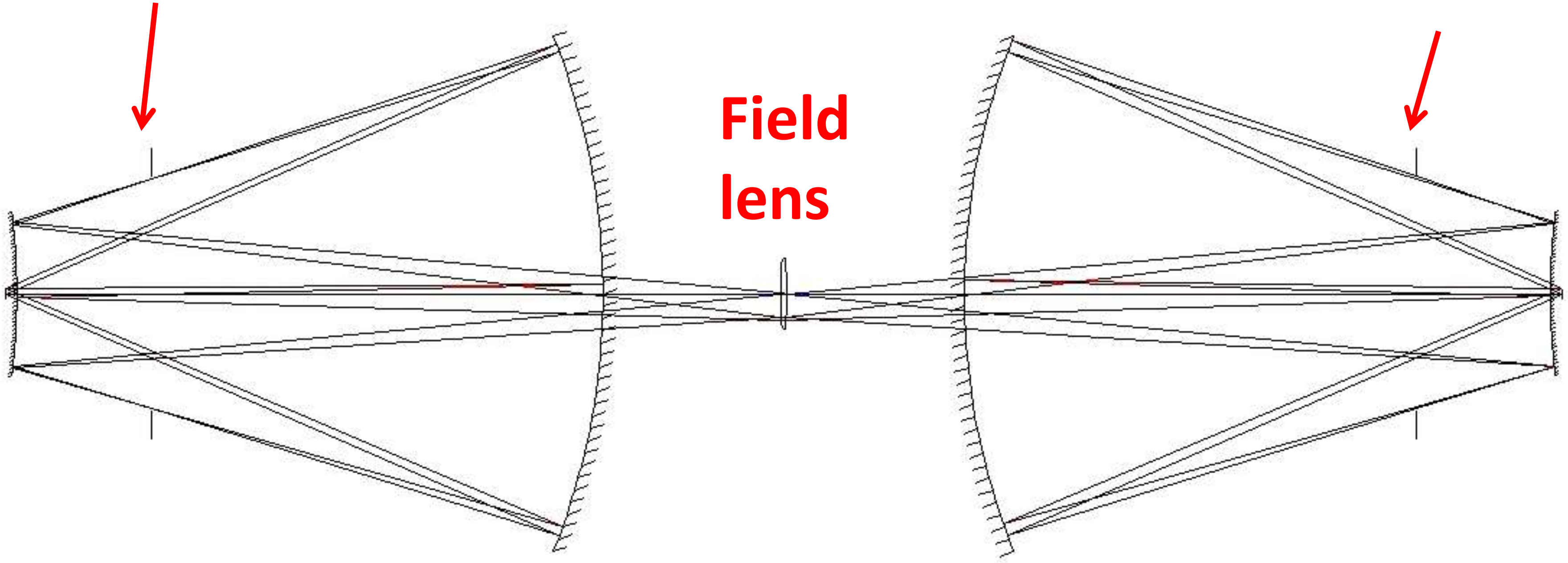
- If a design has spherical aberration then coma is linear with stop position and astigmatism is quadratic with stop position

- 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.



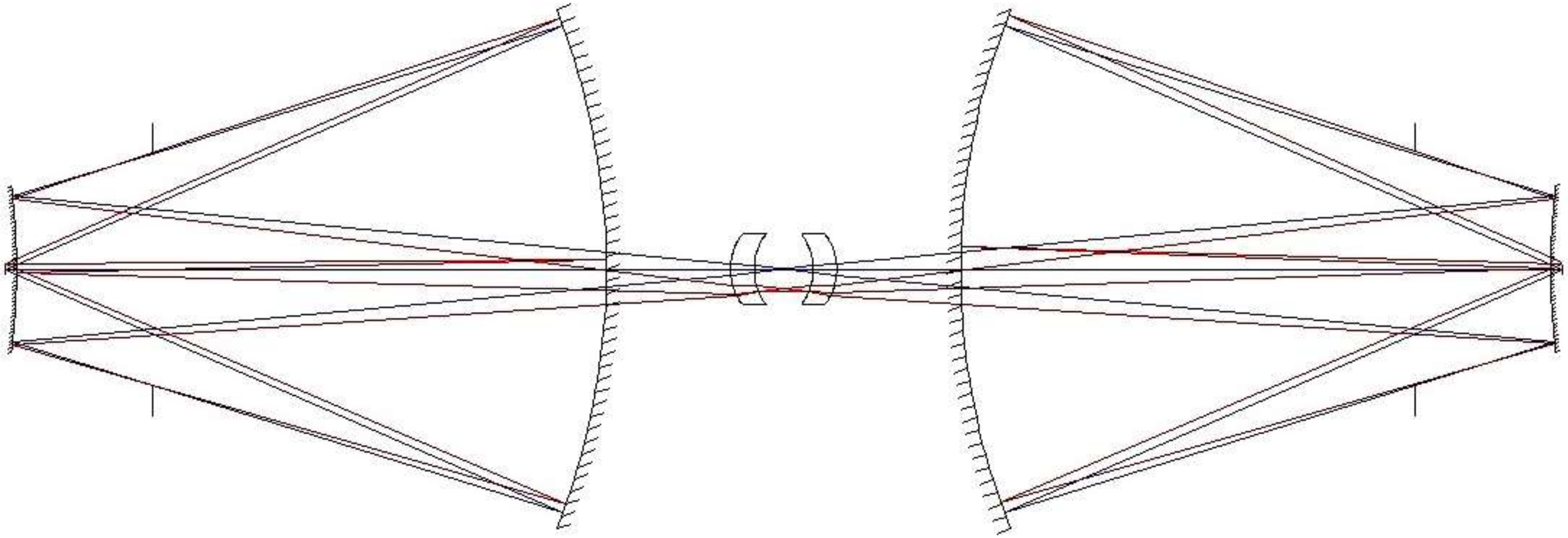
Two symmetrical systems make coma cancel, give a 1.0X magnification aplanat

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.



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

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



<u>Thick meniscus field lens pair has positive power but no Petzval or axial or lateral color</u>

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.

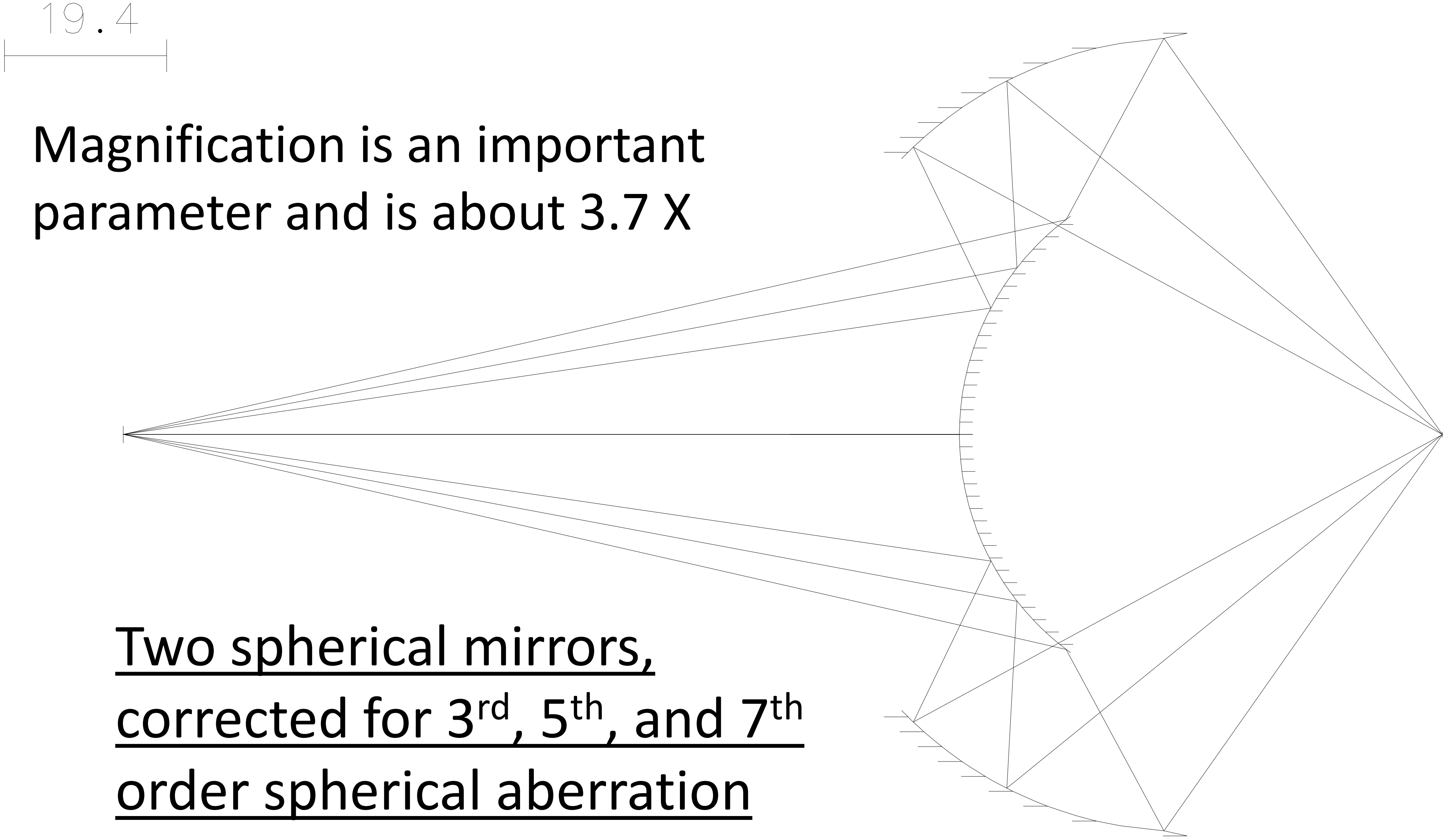
Plus, how stop shift theory is useful for thinking of a new design.

A brief digression

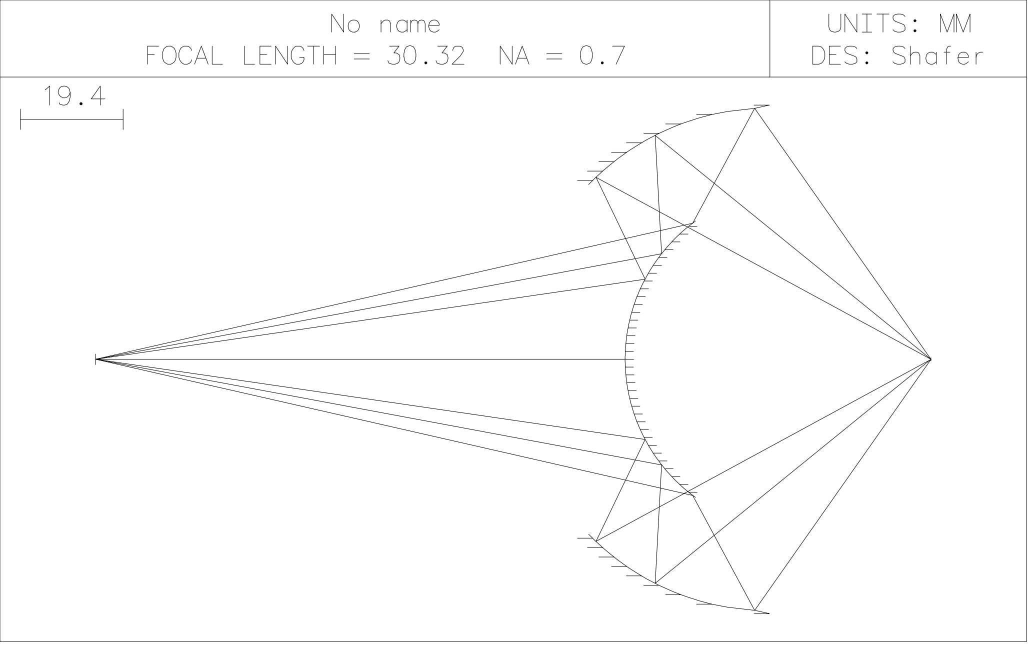
No name
FOCAL LENGTH = 30.32 NA = 0.7

UNITS: MM
DES: Shafer

Magnification is an important parameter and is about 3.7 X



<u>Two spherical mirrors, corrected for 3rd, 5th, and 7th order spherical aberration</u>

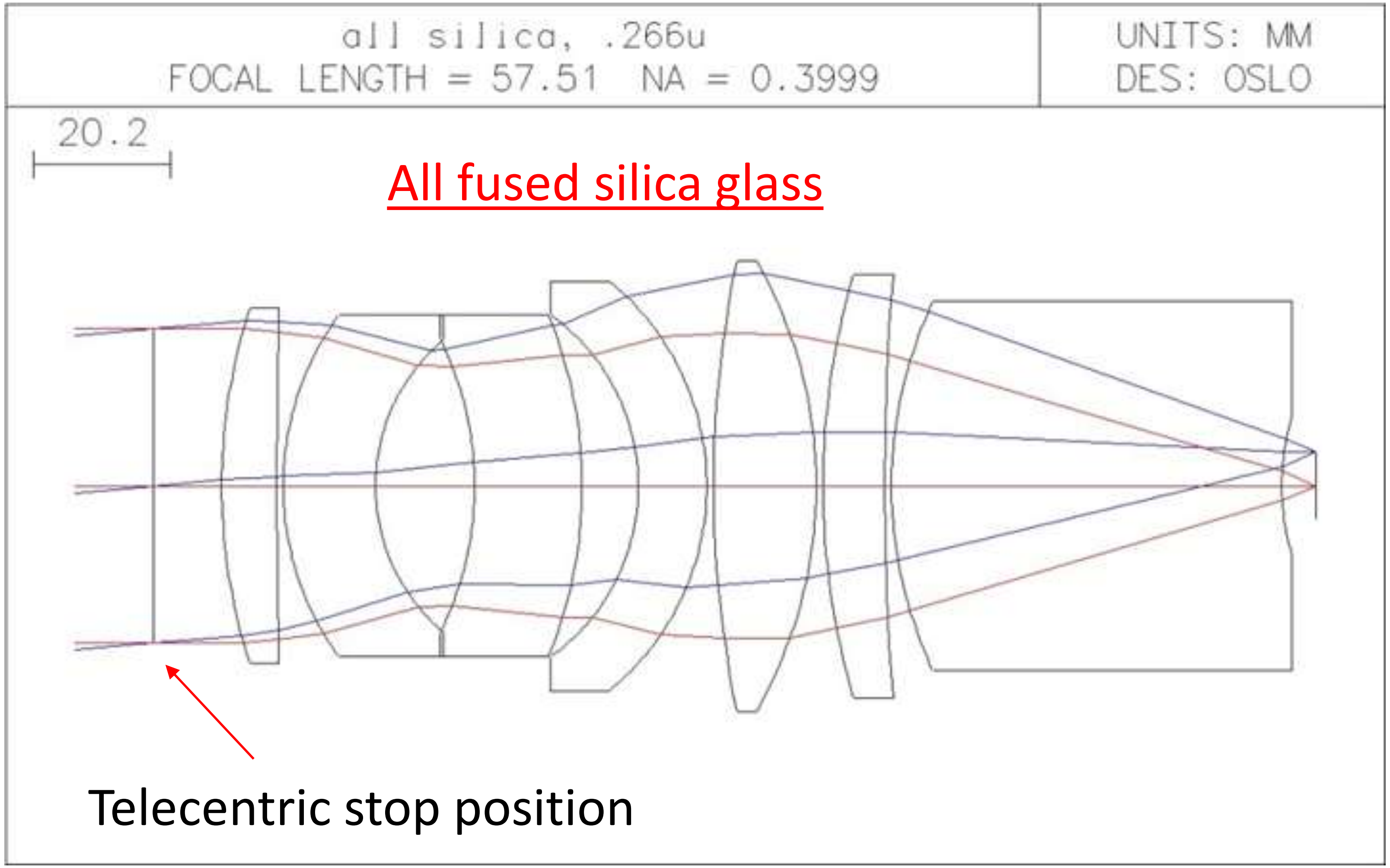


This is a design challenge for both human and AI enhanced computer designers. It is very hard to find this design unless you are right on top of it. Yet it is just two spherical surfaces.

It is a good test of design programs.

This design is almost impossible to find, even with a picture like this. The reason is that in this design both of the spherical mirrors have a very large amount of spherical aberration, of opposite signs and they cancel almost exactly to high orders – if you have this exact configuration. If you have a design starting point that is close to the good solution, but not right at it, the cancellation is not complete. The computer will “see” that the easiest way to reduce that difference of the two large numbers is to minimize both numbers. So it immediately heads for the two trivial 1.0X solutions of a flat mirror and a mirror concentric about the rays, where both mirrors have zero aberration.

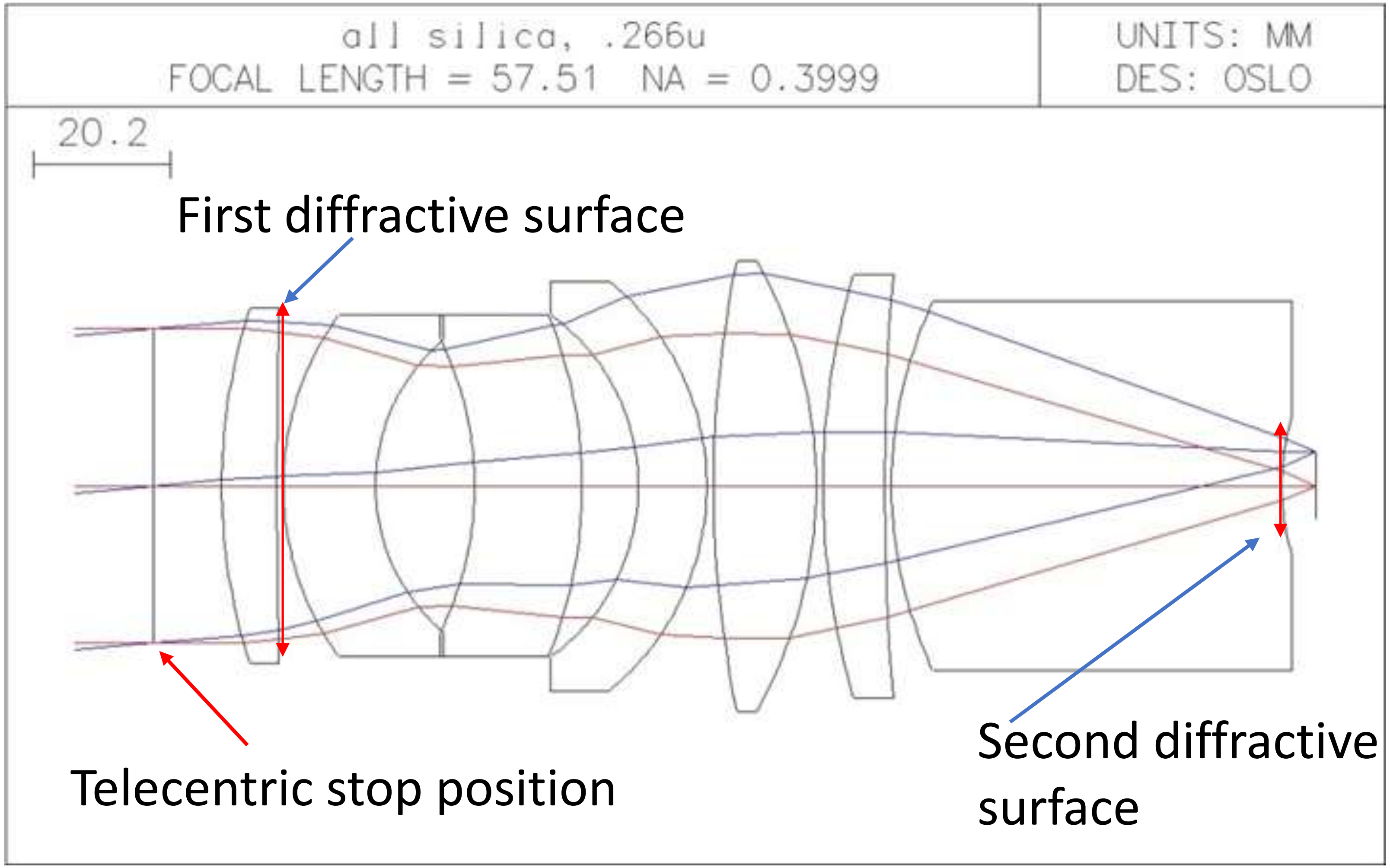
Another example of using stop shift theory



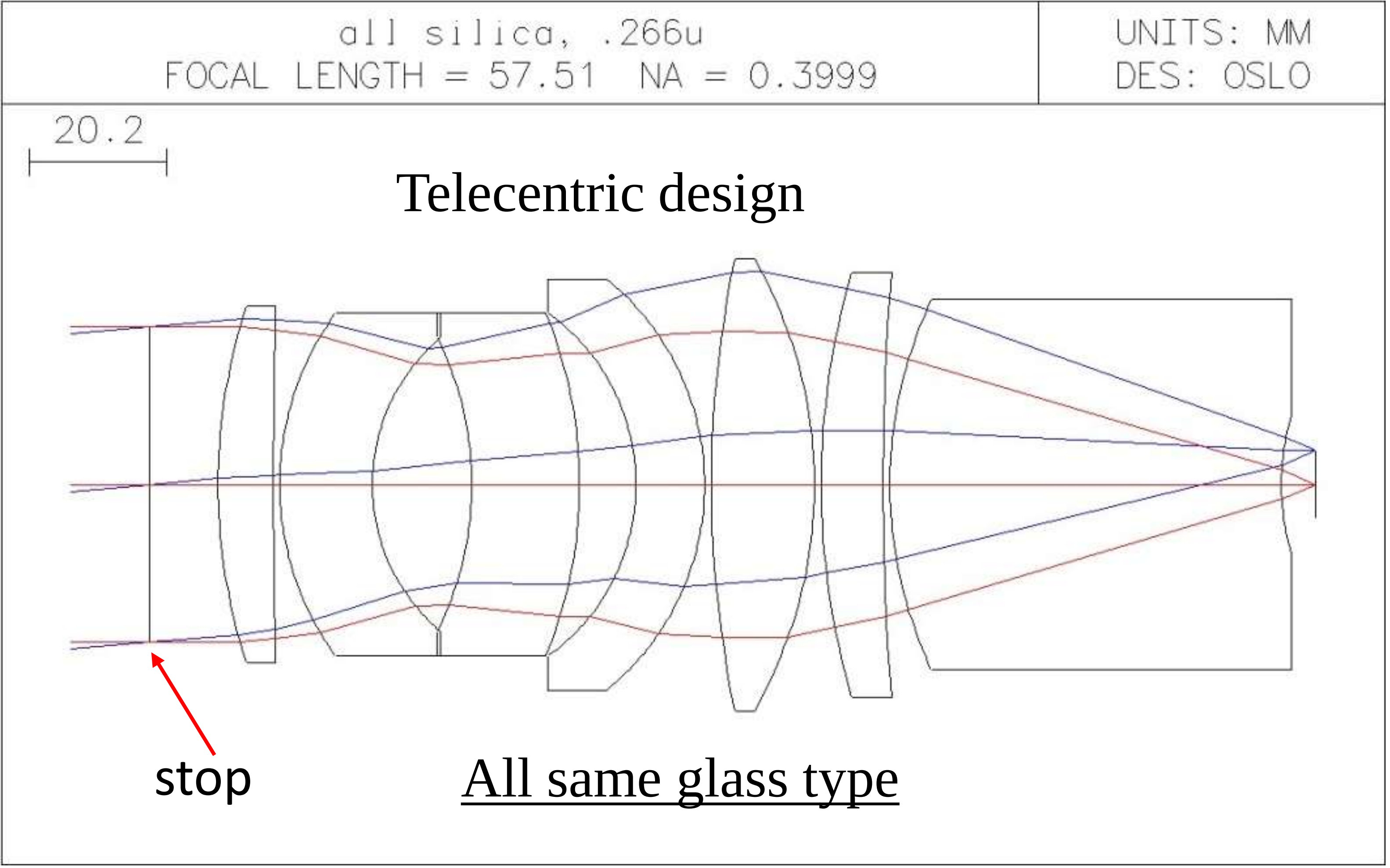
Here is a monochromatic deep UV design that is well corrected at .266u

Suppose we want to correct it for axial and lateral color. We could add some calcium fluoride lenses to correct for color but their small dispersion difference with silica requires strong and thick lenses. Instead we will consider using diffractive surfaces, which are highly dispersive. But they have some scattering transmission losses.

Another example of using stop shift theory

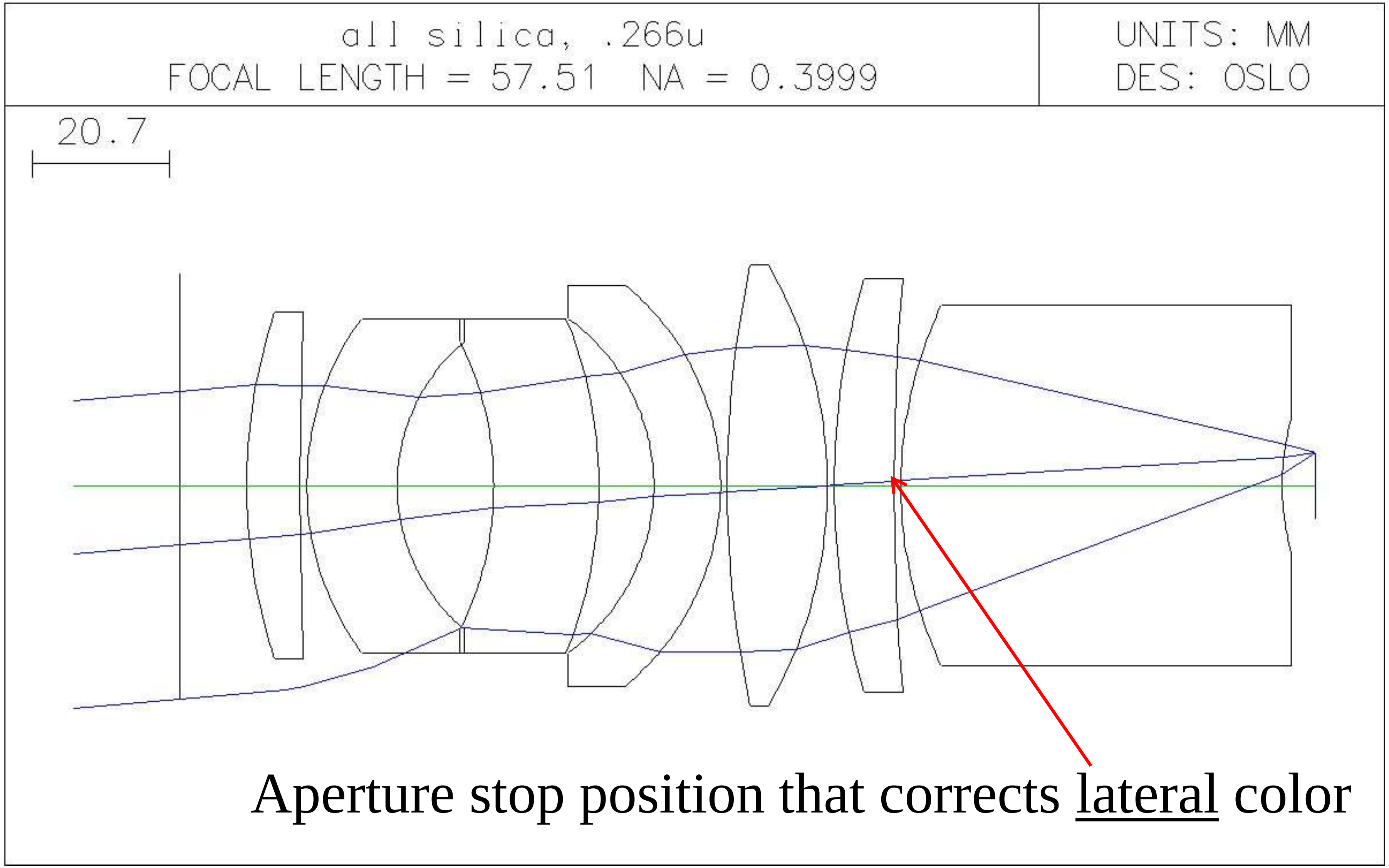


Two widely separated diffractive surfaces with appropriate powers can correct both axial and lateral color of this design. There are many possible positions in the design which work well. Here I show a random example. But costs and extra scattering would make it better to use just one diffractive surface. How then could both axial and lateral color be corrected? I'm glad you asked.

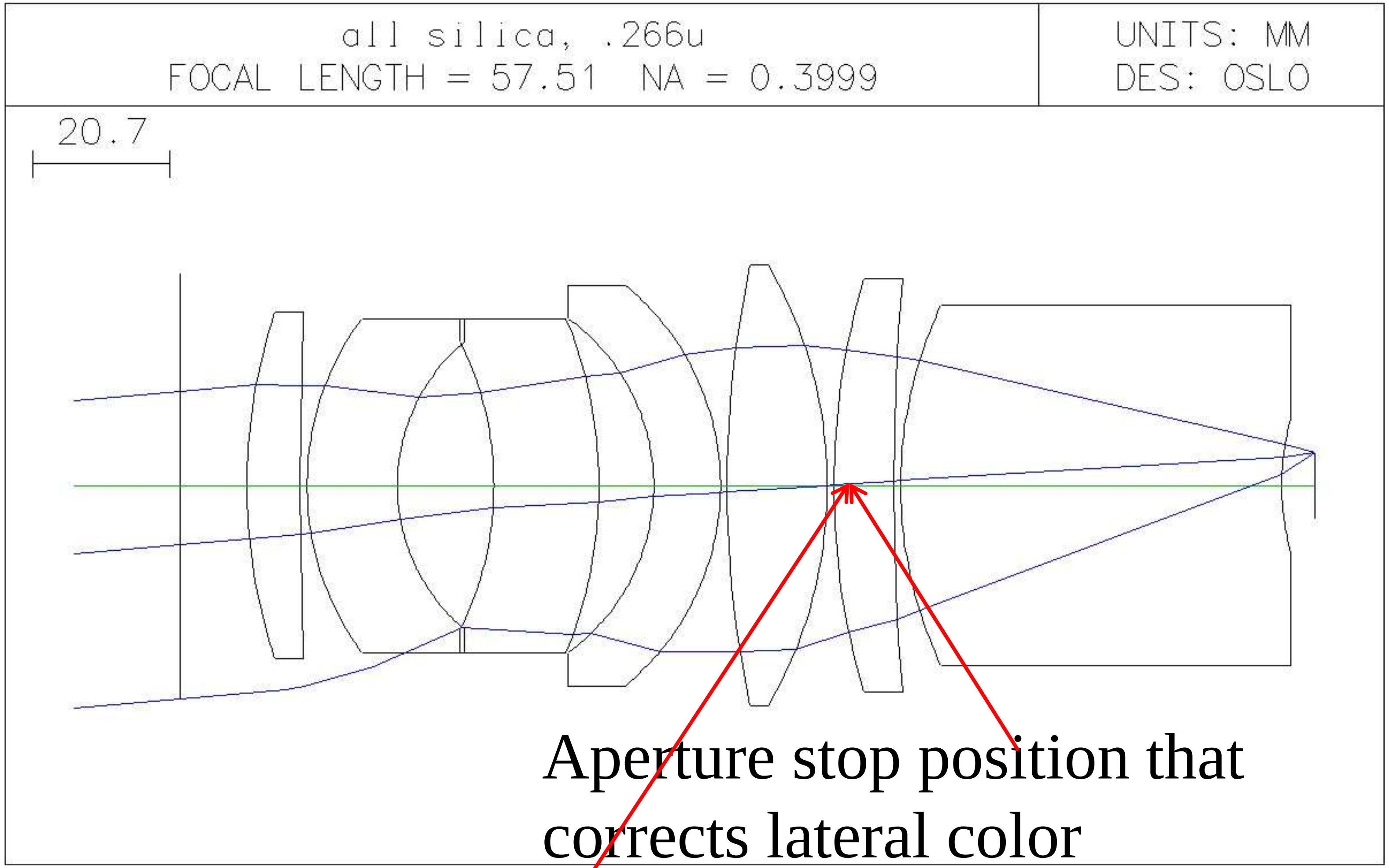


- Lateral color depends on aperture stop position, since axial color is not corrected.
- Move the stop around and find out what <u>temporary</u> position makes **<u>lateral</u>** color be zero.
- Then correct **<u>axial</u>** color at that location. Let's try using a diffractive surface.

<u>Here is the plan</u>

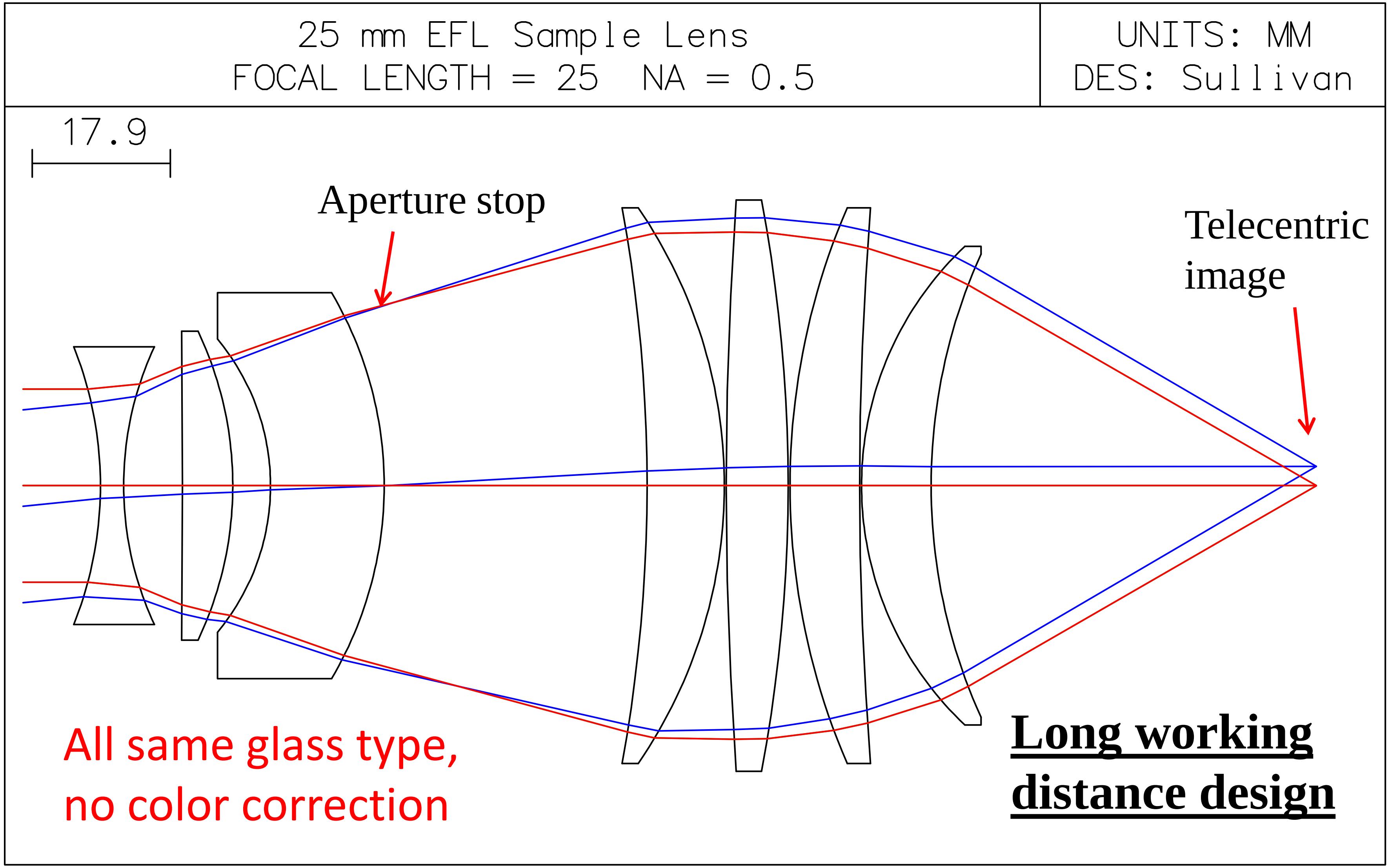


We move the stop position back and forth until we get **lateral** color = zero



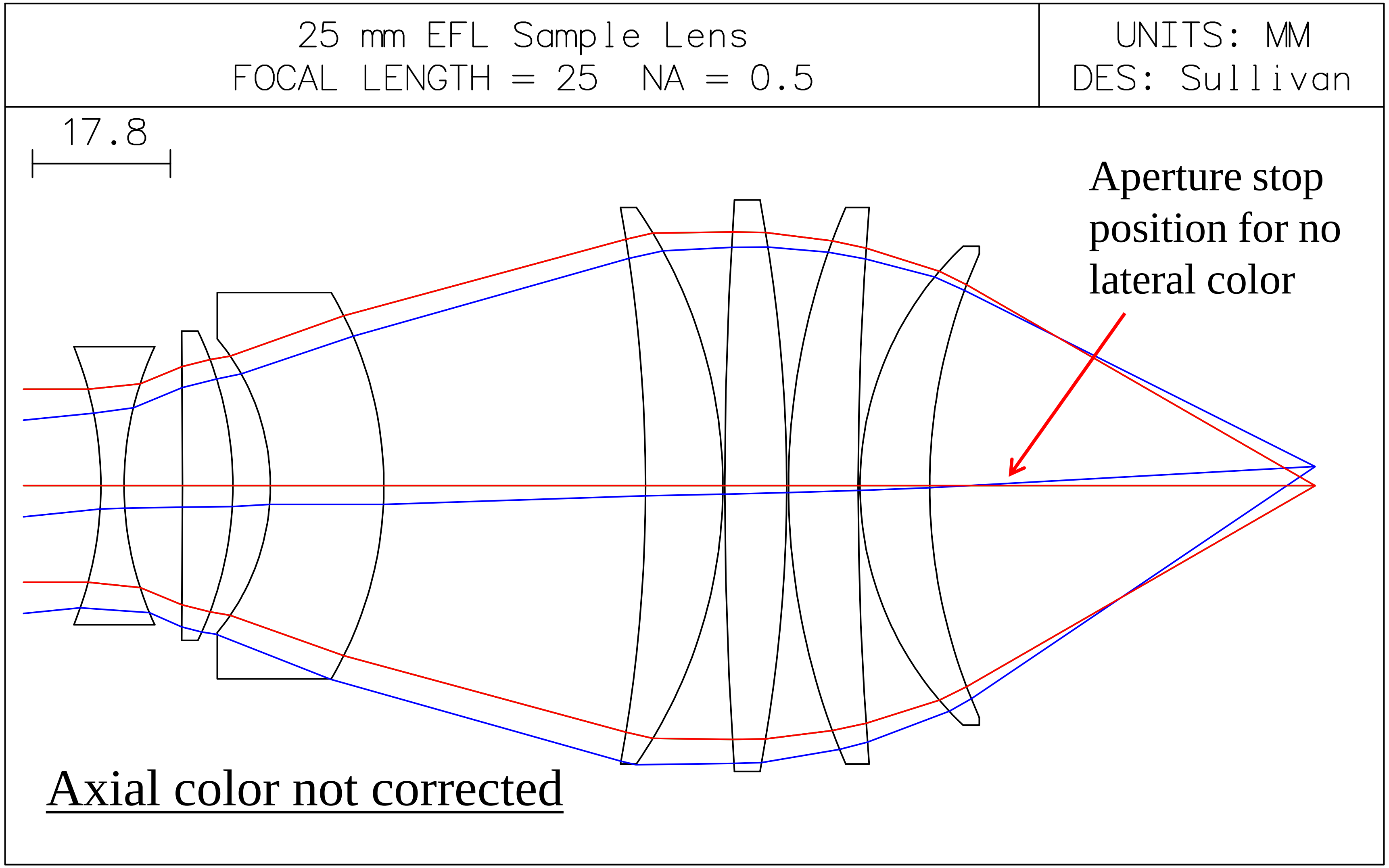
If we correct axial color here, with a diffractive surface, then both axial and lateral color will be corrected. Then we can move the stop back to where we want it, and **both color types will still be corrected**.

- This same design method indicates where to add lenses (instead of diffractive surfaces) for color correction
- It minimizes the number of extra lenses needed for color correction
- But it may indicate adding color correcting lenses where we don’t want them, because of space constraints
- Then we rely on conventional color correcting techniques

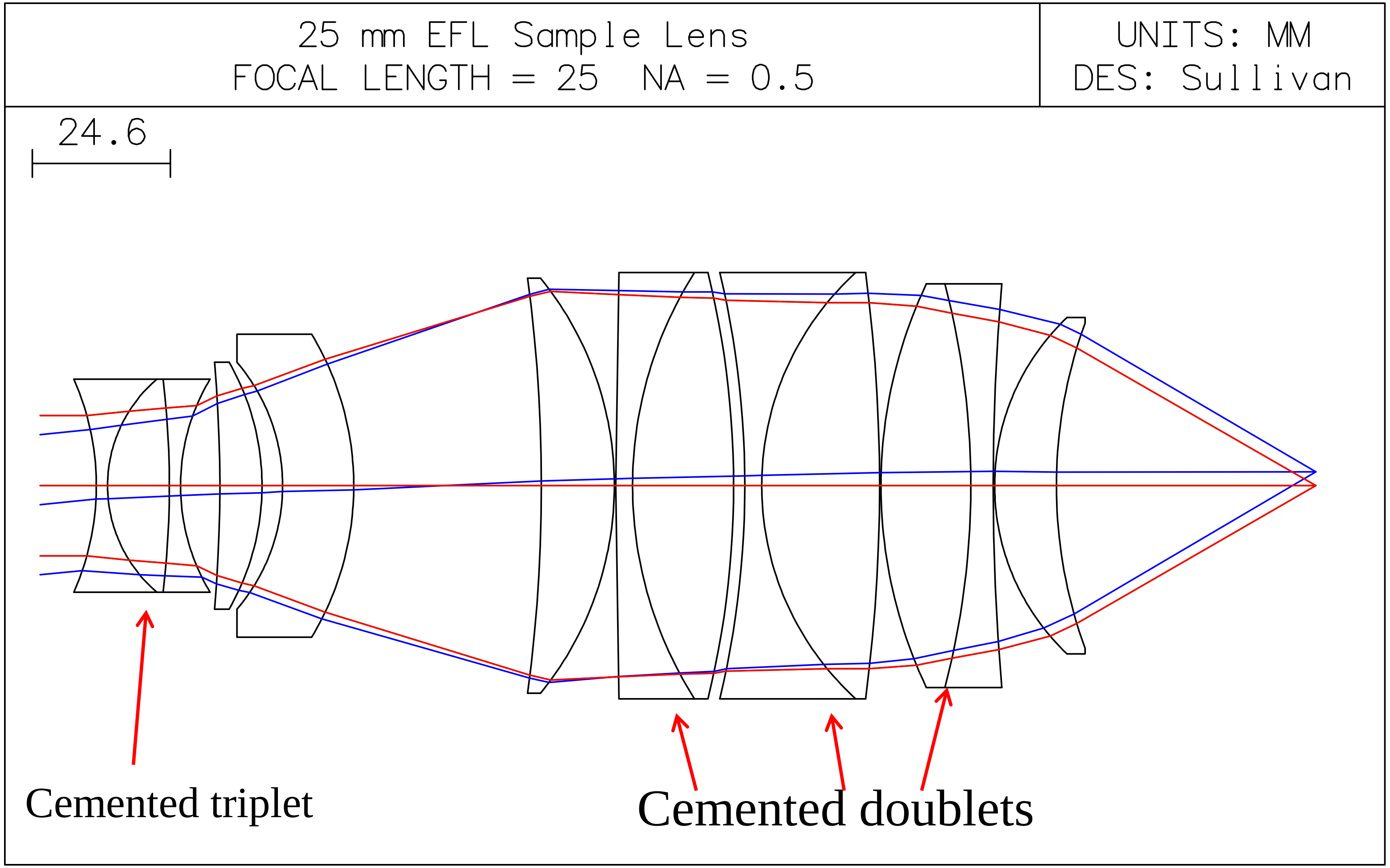


Diffraction-limited monochromatic f/1.0 design with 5.0 mm field diameter

Here is another example



Aperture stop position for no lateral color may not be in a desirable, place - as in this long working distance design. We don't want to put axial color correcting lenses there, in the long working distance space.



In these cases you have to use two separated groups of color correcting lenses, instead of just one, for axial and lateral color correction. That makes for a more complex design like here where I show a deep UV design using silica and calcium fluoride lenses.

Conclusion

- Stop shift theory gives insight into the aberration theory of a design and also suggests new design possibilities

- Temporary stop shift is a powerful design tool and does not usually require changing the actual final position of the stop, which may be set by the telecentric condition or other constraints

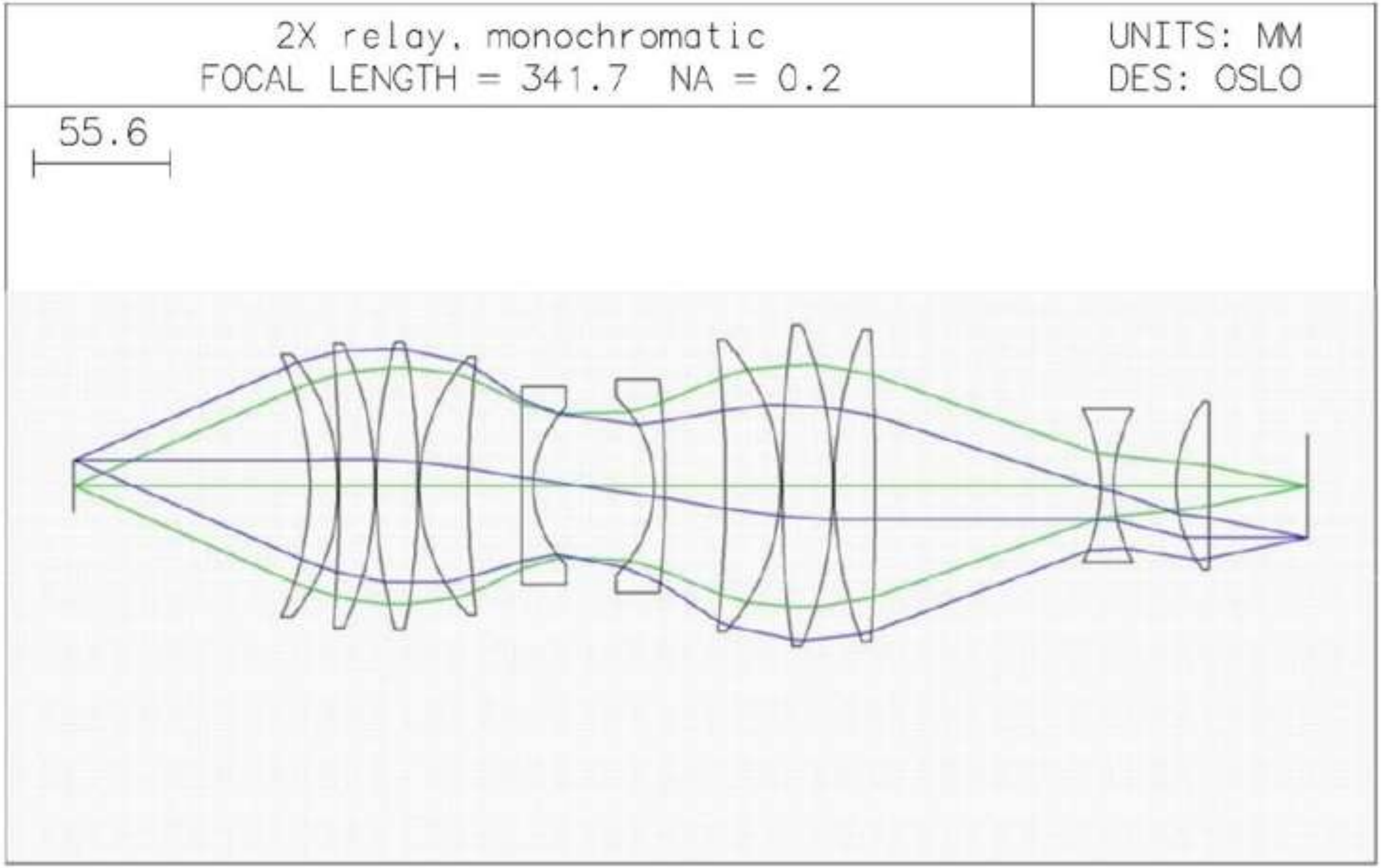
#4

Temporary use of aspherics during design optimization is a very powerful way to find new designs and improve existing ones.

Example – a 2X monochromatic lens relay

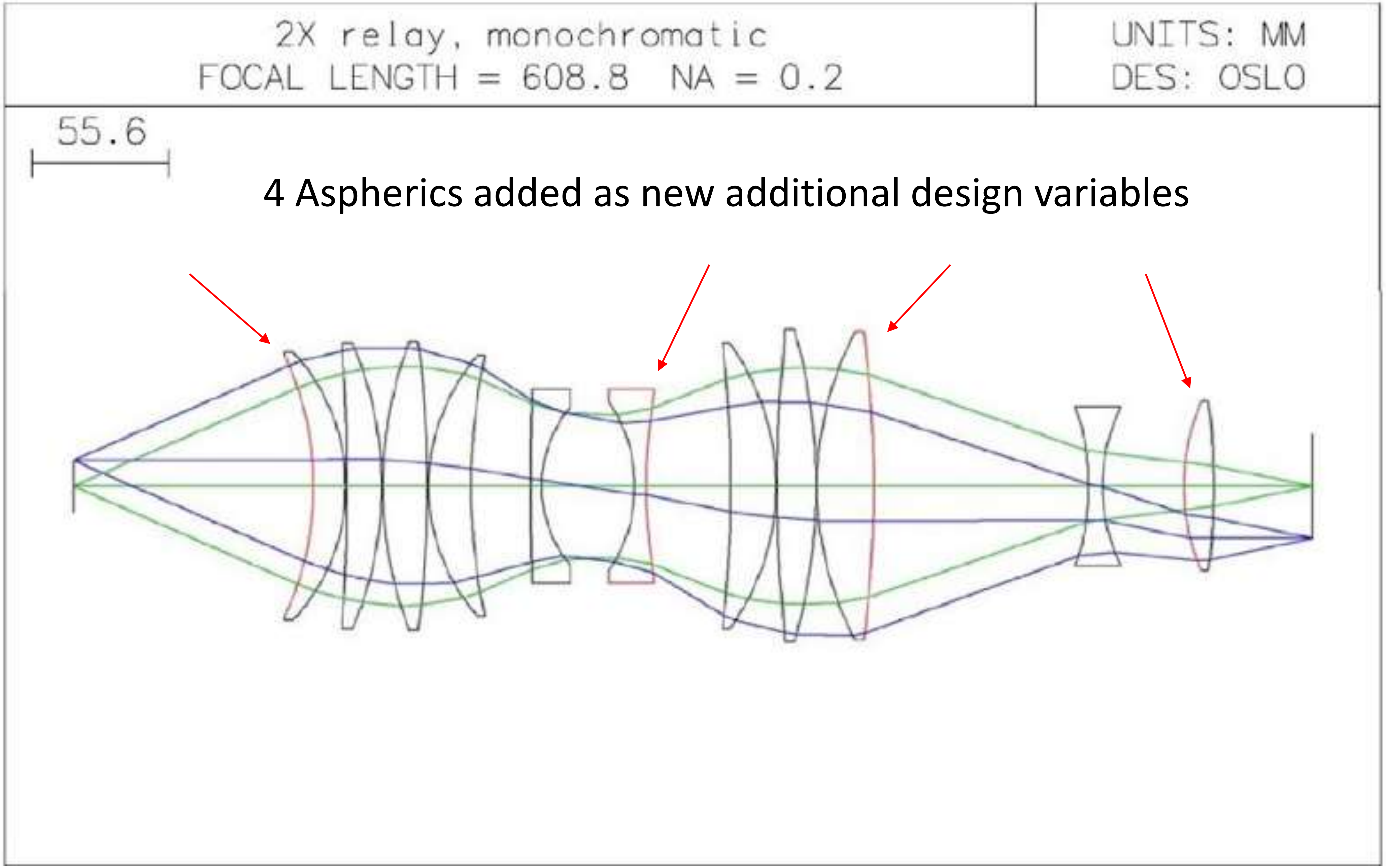
What is the quickest way to go from New York to Munich? By plane, of course. Try to get to the departure gate on time. But you don't need a plane when you are within New York City or when you are within Munich. You only need it to go from one place to the other. In a similar way the use of aspheric surfaces during the design process can ease the path of a design from one solution region to a better one, and yet once there the aspherics can then often be removed as no longer needed, by a certain method.

Even simple designs can have multiple good solution regions and complex designs have very many more. Usually good solutions are separated from nearby other good solutions by regions of bad correction and it is hard for optical design programs to move through the bad regions – especially if you start in a good region where the design would have to get worse first before it then gets better in a nearby good solution. Design programs are set up to optimize a design, always making it better, not let it first get worse on a route to a better solution. Adding aspheric surfaces to a design can allow it to more freely move around in solution space because they **simulate** adding several new lenses to a design, giving lots more variables to work with. But the aspherics might only be needed as a temporary aid to the optimization process and can then usually be removed once a new good solution has been found.

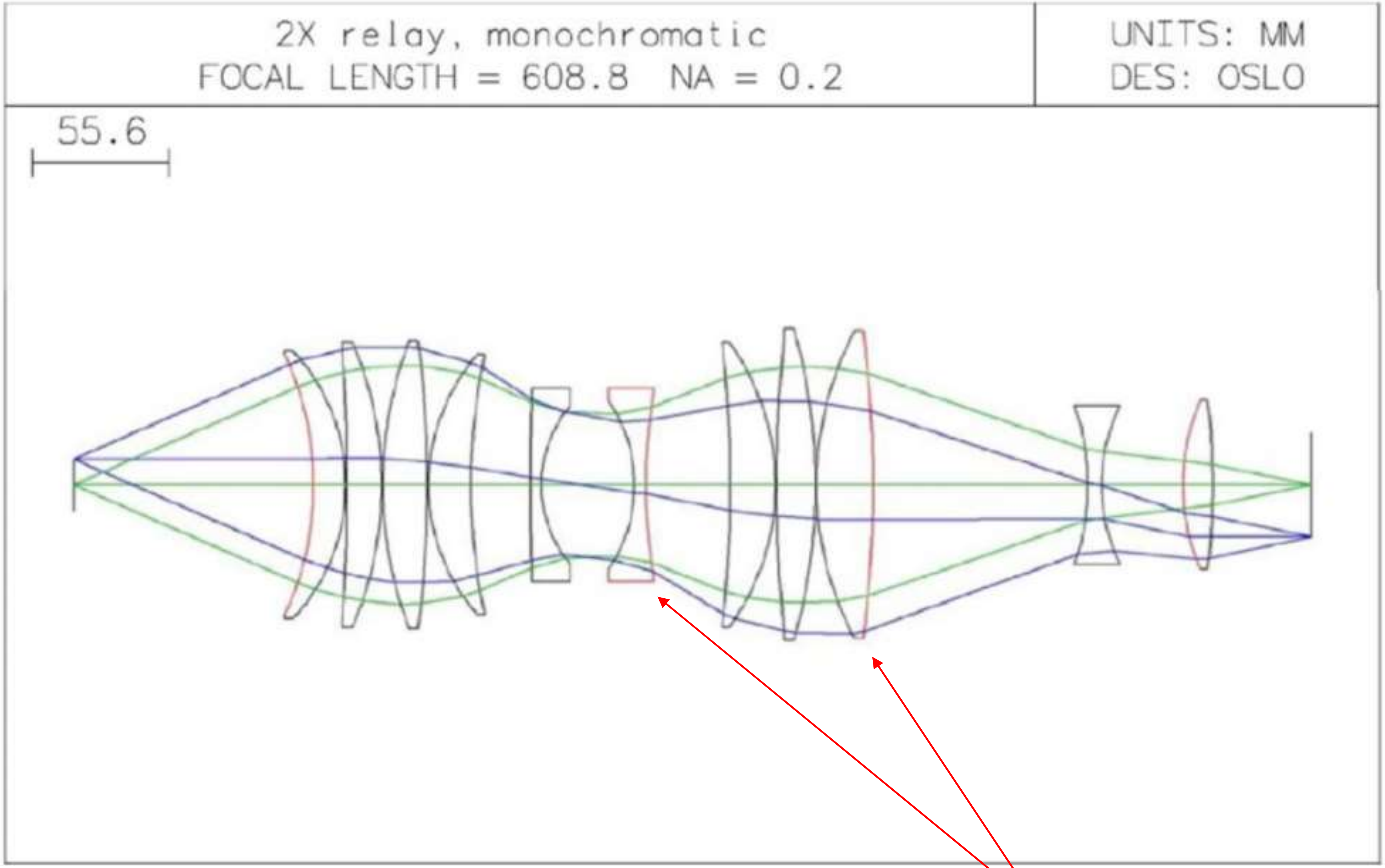


Here is a well optimized good existing design that we want to make better, with better image quality. Making a spherical lens surface be aspheric is often equivalent to adding two new lenses to the design, giving a lot more means to correct aberrations and find a better solution region. Let's add to this design aspheric surfaces at the front and back of the design and 2 more in the middle and then reoptimize. That is <u>equivalent</u> to adding many new lenses to the design.

The design's wavefront is .042 waves r.m.s. or better over its image size but we want better to allow for tolerances in making it.

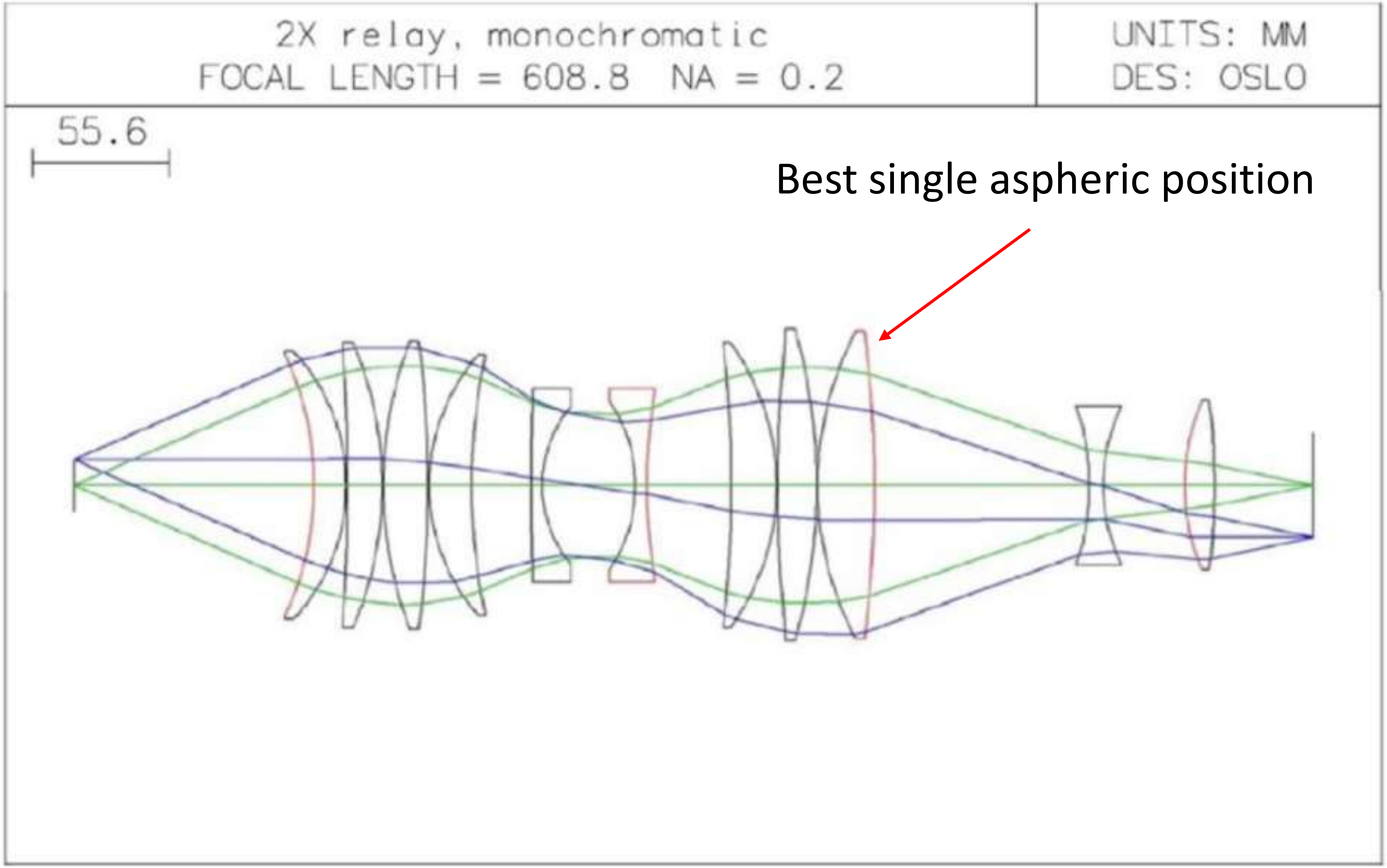


With these 4 aspherics added at the front, back and middle of the design we then reoptimize using the aspheric coefficients as new variables in the optimization. The worst image quality over the field then drops down to .014 waves r.m.s., or **3X better** than before. The design still looks the same.



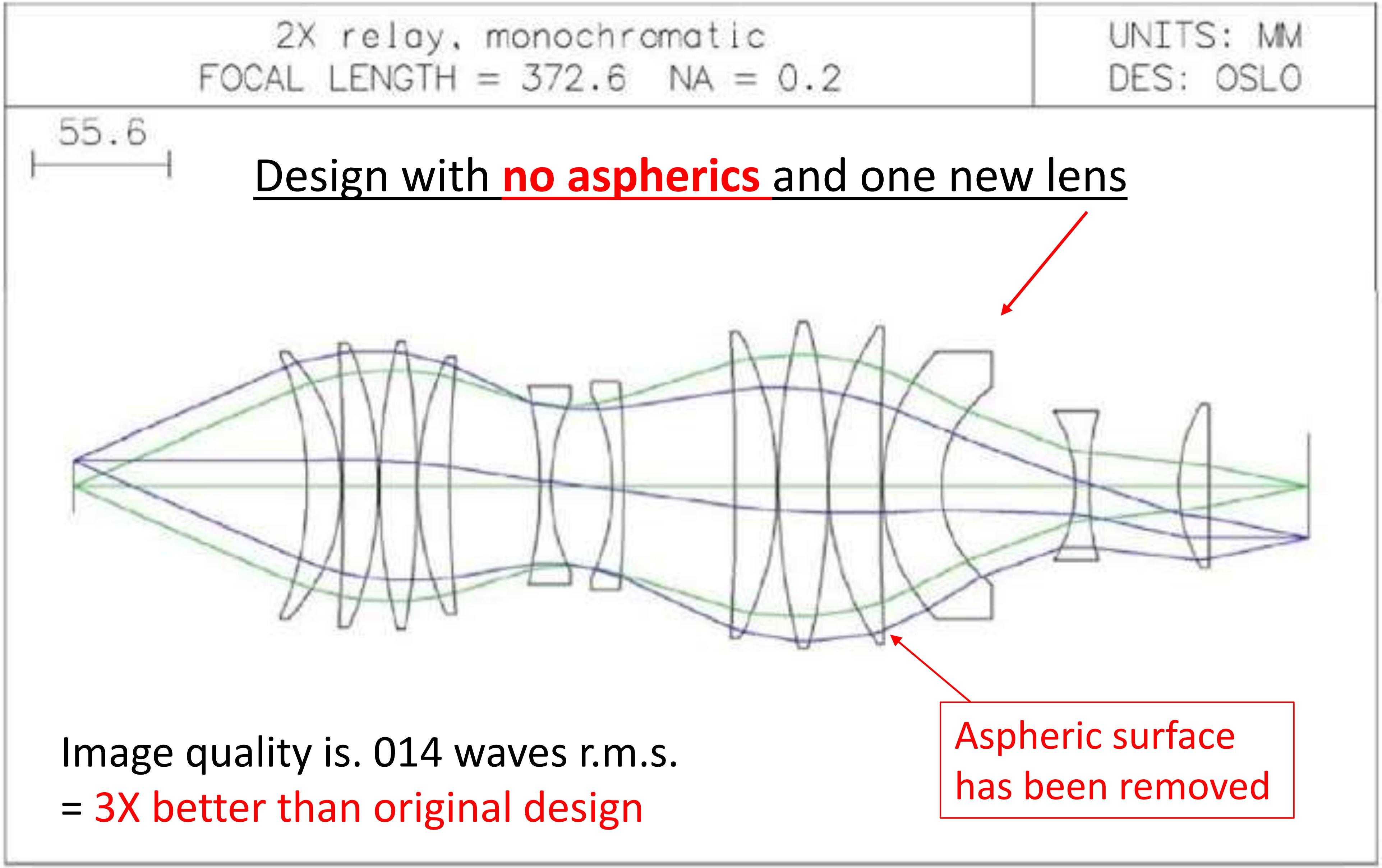
So all the improvement in the design is due to the two middle aspherics, not the two end ones, which can be removed.

Then we try **not** using the aspheric in the front of the design but just the two middle ones and the back one and find that reoptimization gives just as good as before – about .014 waves r.m.s. image quality over the field. The same good result happens if you keep the first 3 aspherics and leave out the last one. So there is not any point in splitting lenses in the front or back sides of the original all spherical surface design. This experiment here has shown us that.



Then we find that either of the two middle aspherics can give almost all the performance improvement. The aspheric indicated here is the better of the two and with just this one aspheric in the design the correction is .016 waves r.m.s. over the field instead of .014 waves r.m.s. with all four aspherics and .042 with none.

This is typical – most designs have just **one** part of the design where an aspheric or splitting lenses is very beneficial. But we don't know where that position is. This process just shown allows us to easily find out where.

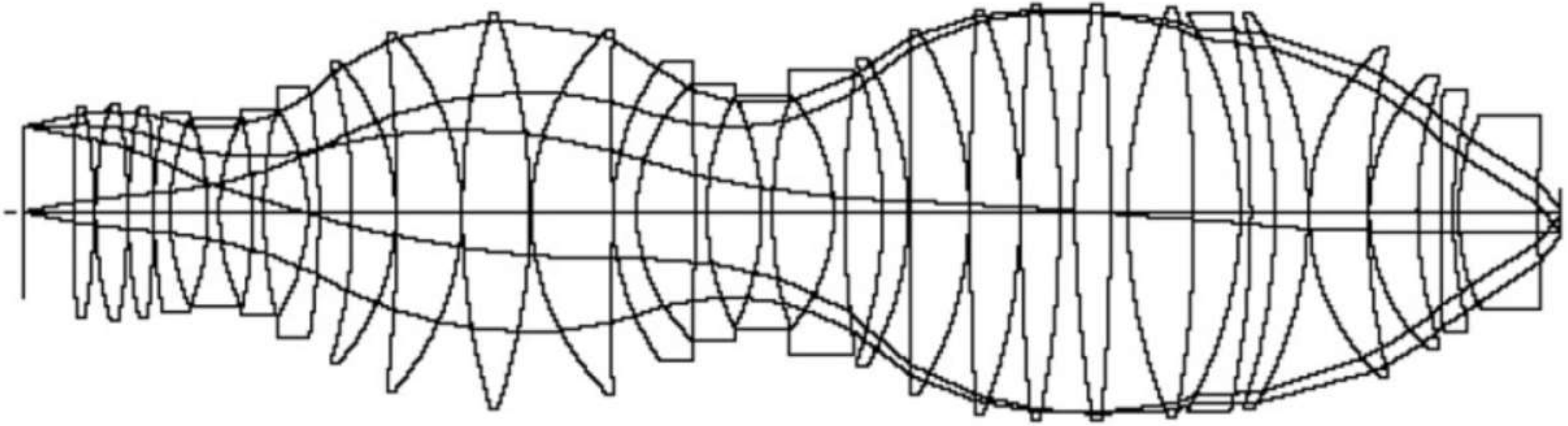


Design with **no aspherics** and one new lens

Aspheric surface has been removed

Image quality is. 014 waves r.m.s.
= 3X better than original design

There is a method for deciding how to replace a lens with one aspheric surface with two equivalent spherical lenses and there is not time here to go into it. The point is that there is such a method and the result here is that aspherics have been used to locate where in the design it is best to add/split a lens to get the most benefit to the design.



This same process of using 3 or 4 aspherics spread out through the length of the design can be used with very complicated designs like this to easily and quickly find out what part of the design would best benefit from an extra lens or two. And it can do that **without** having to first actually do the lens splitting or adding of a lens(s). This use of aspherics during optimization even correctly predicts **beforehand** how much improvement there will be in performance (wavefront correction over the field) **after** all the aspherics have been removed and equivalent extra lens(s) added. Very useful!

Having a good tool kit of different design methods and aberration theory can be a big help in creating new designs and understanding existing ones.

My time is up.
Any questions?