Color Correction

Multiple Ways to Look At IT

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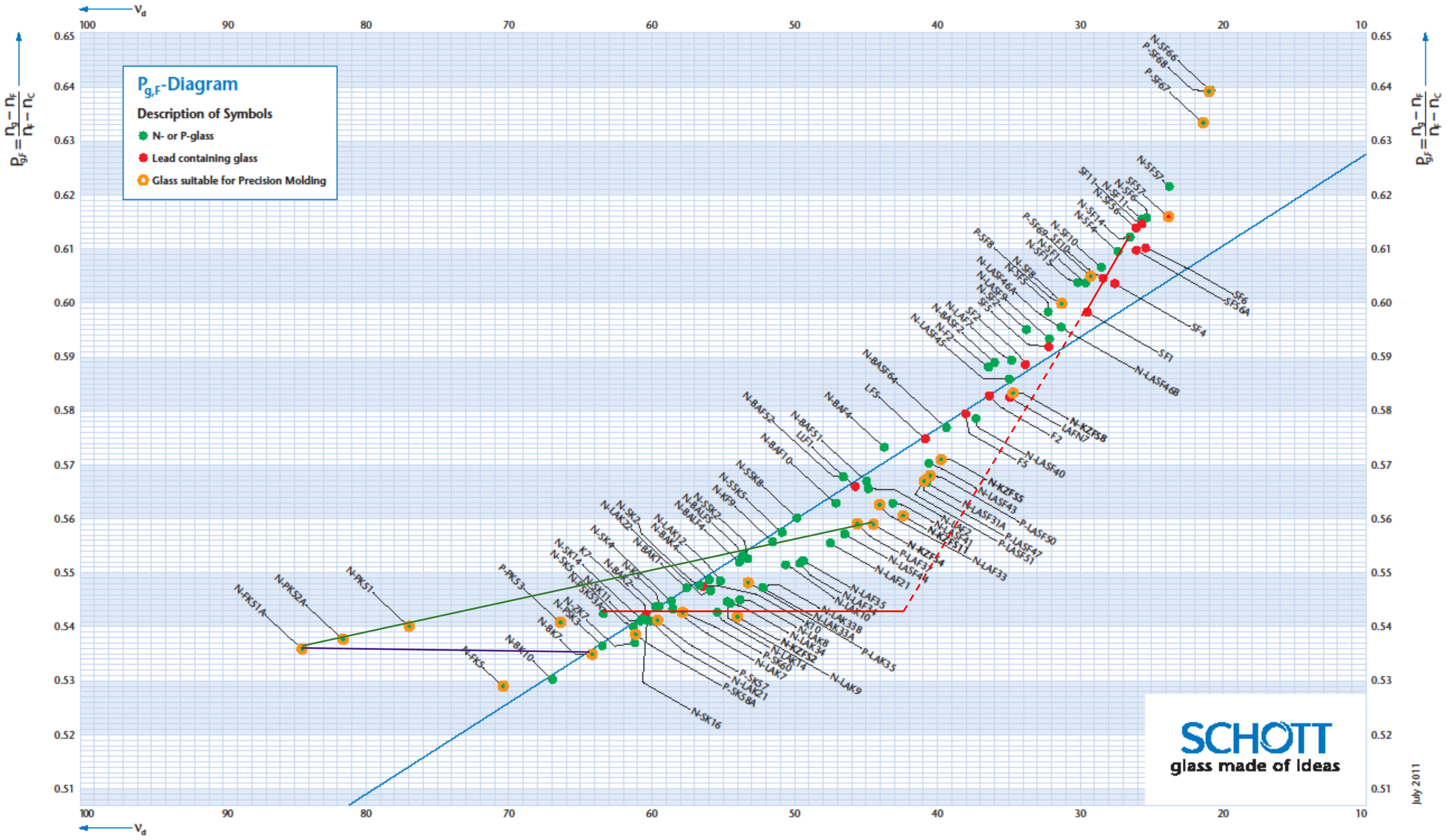
Classical Approach: n, V, P

It's all about choosing the right glasses… Or is it?

The P vs. V Map



$P_{g,F}$-Diagram
Description of Symbols
N- or P-glass
Lead containing glass
Glass suitable for Precision Molding
SCHOTT
glass made of ideas
July 2011

Abbe Number

$$V = \frac{n_d - 1}{n_F - n_C}$$

$V \approx$ 64 for NBK7

$V \approx$ 30 for NSF1

What is the physical significance of ν?

$$n_F - n_C = \frac{n_d - 1}{V}$$

…And?

Primary Color of a Singlet in Air

Power of a singlet in air:

$$\phi_\lambda = (c_1 - c_2)(n_\lambda - 1)$$

$$\Delta_{FC}\phi \equiv \phi_F - \phi_C$$

$$\Delta_{F,C}\phi = (c_1 - c_2)[(n_F - n_C)]$$

$$\Delta_{FC}\phi = (c_1 - c_2)\left[\frac{n_d - 1}{V}\right]$$

$$\Delta_{FC}\phi = \frac{\phi}{V}$$

Primary color ($\Delta_{FC}\phi$) of a singlet:

1/64th of ϕ for NBK7

1/30th of ϕ for NSF1

Partial Dispersion

$$P_{d,C} = \frac{n_d - n_C}{n_F - n_C}$$

$P_{d,C} \approx$ 0.3076 for NBK7

$P_{d,C} \approx$ 0.2895 for NSF1

What is the physical significance of $P_{d,F}$?

$P_{d,C} = \frac{n_d - n_C}{n_F - n_C} =$ The fraction of the dispersion that occurs between the d-line and the C-line

Primary Color Correction for a Thin Doublet
Correct $\Delta_{FC}\phi$

- For a thin lens:

$$\Delta_{FC}\phi = \frac{\phi}{V}$$

- For a thin doublet

$$\phi = \phi_1 + \phi_2$$

$$\Delta_{FC}\phi = \frac{\phi_1}{V_1} + \frac{\phi_2}{V_2}$$

- Want

$$\frac{\phi_1}{V_1} + \frac{\phi_2}{V_2} = 0$$

$$\phi_1 = \left(\frac{V_1}{V_1 - V_2}\right)\phi$$ (≈ 1.9 ϕ, for NBK7 and NSF1)

$$\phi_2 = \left(\frac{-V_2}{V_1 - V_2}\right)\phi$$ (≈ -0.9 ϕ, for NBK7 and NSF1)

Primary Color Correction for a Thin Doublet Correct $\Delta_{FC}\phi$

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(≈ -0.9 ϕ, for NBK7 and NSF1)

NOTE:
ΔV in the denominator
Keep ΔV large to avoid strong powers

Secondary Color for a Thin Achromat

$$\Delta_{dC}\phi_1 = (\Delta_{FC}\phi_1)P_{d,C,1}$$

Sec. Color for Singlet 1

$$\Delta_{dC}\phi_2 = (\Delta_{FC}\phi_2)P_{d,C,2}$$

Sec. Color for Singlet 2

$$\Delta_{dC}\phi = \Delta_{dC}\phi_1 + \Delta_{dC}\phi_2$$

Sec. Color for Doublet

$$\Delta_{dC}\phi = \frac{\phi_1 P_{d,C,1}}{V_1} + \frac{\phi_2 P_{d,C,2}}{V_2}$$

$$P_{d,C} \approx 0.274 + 0.0005V$$

"Normal glass line"

$$\Delta_{dC}\phi = \frac{\phi_1(0.274 + 0.0005V_1)}{V_1} + \frac{\phi_2(0.274 + 0.0005V_2)}{V_2}$$

$$\Delta_{dC}\phi = 0.274\left(\frac{\phi_1}{V_1} + \frac{\phi_2}{V_2}\right) + 0.0005(\phi_1 + \phi_2)$$

Secondary Color for a Thin Achromat

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Sec. Color for Singlet 1

$$\Delta_{dC}\phi_2 = (\Delta_{FC}\phi_2)P_{d,C,2}$$

Sec. Color for Singlet 2

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(Sum = Zero, for Achromat)

Secondary Color for a Thin Achromat

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(Sum = Zero, for Achromat)

$$\boxed{\boldsymbol{\Delta_{dC}\phi = \phi/2000}}$$

Rule of Thumb for "Normal" Achromat

Rule of Thumb For Secondary Color (For a Thin Doublet)

- Secondary color is about 1/2000th of the focal length
- This is a VERY useful rule of thumb to keep in mind!
- Example:
  - Customer has a 1080p format sensor (1920 x 1080 pixels)
  - He asks for lateral color < 1/4th of a pixel
  - Even if axial color is (somehow) perfectly corrected, **lateral color is proportional to $\Delta_\lambda \phi$**
  - The customer is asking for lateral color to be corrected to 1 part in 7680.
  - *This far exceeds what can be expected with an ordinary achromat*

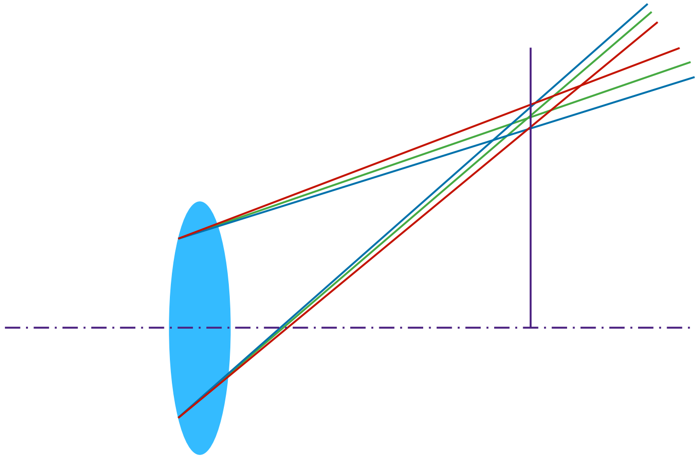
- The above rule of thumb is for a THIN achromat, i.e., no air space
- As we will see, systems that are not thin doublets but have substantial spaces (e.g., telephoto, retrofocus, etc.) are usually WORSE than 1 part in 2000

Chromatic Difference of Magnification

(The old-timers' word for lateral color)

Lateral Color (defined one way)

- "Longitudinal color" or "Axial color" is $\Delta_\lambda(BFD)$
- "Lateral color" is sometimes defined as $\Delta_\lambda\left(\bar{y}_{image\ plane}\right)$
  - This definition depends on the choice of the image plane
  - This definition depends on the stop location
  - If longitudinal color is present, then a stop can be chosen so that the "lateral color" is eliminated (even though the Red, Green, and Blue images are different sizes!)



All three blur circles are co-aligned, so there isn't a "lateral" effect on the image.

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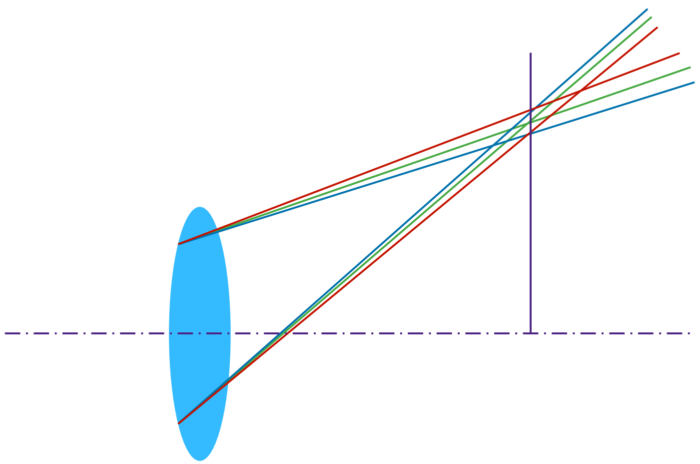
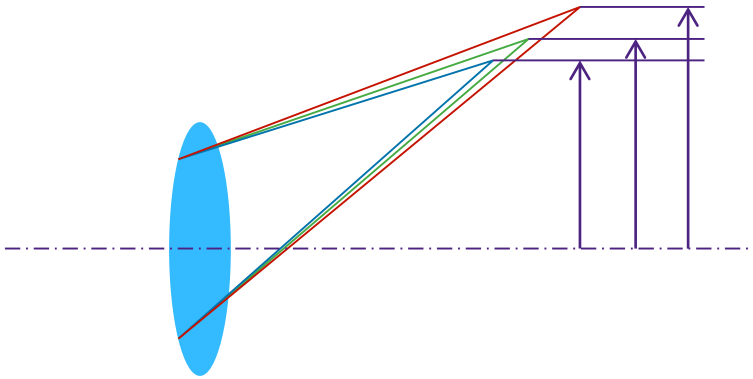


All three blur circles are co-aligned, so there isn't a "lateral" effect on the image.

BUT: this only works if there is axial color, i.e., the system is bad.

Lateral Color (Chromatic Difference Of Magnification)

- We can also define "Lateral color" is sometimes defined as $\Delta_\lambda\left(\bar{y}_{at\ the\ image\ for\ each\ specific\ color}\right)$
  - Chromatic Difference of Magnification
  - Chromatic Difference of Focal Length
  - Chromatic Difference of Power
  - Independent of the choice of the image plane
  - Independent of the stop location



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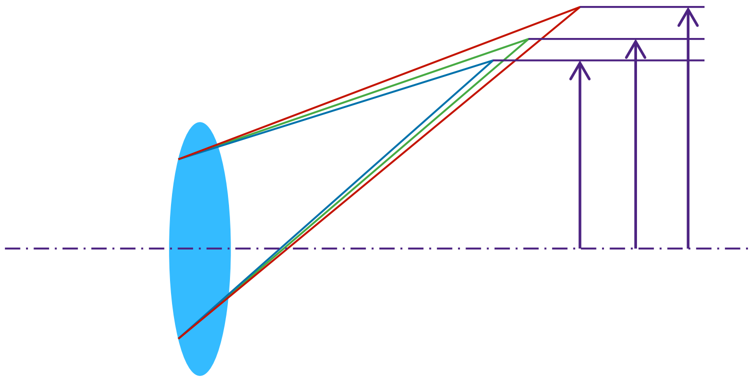
  - Chromatic Difference of Magnification $\Delta_\lambda(mag)$
  - Chromatic Difference of Focal Length $\Delta_\lambda(f)$
  - Chromatic Difference of Power $\Delta_\lambda(\phi)$
  - Independent of the choice of the image plane
  - Independent of the stop location

For the purpose of optical design, this is usually a much more useful concept

In most designs, longitudinal color will be corrected in the end, so it doesn’t hurt to start thinking about $\Delta_\lambda\ (\phi)$ from the very beginning



Lateral or Longitudinal?

- Although quantities like $\Delta_\lambda(f)$ or $\Delta_\lambda(\phi)$ may SEEM like longitudinal quantities, the correlate better to *lateral* color than to *longitudinal* color!
- A system with a non-zero value of $\Delta_\lambda(f)$ has zero axial color if the chromatic variation of the principal plane locations is just right.
- On the other hand, a system with a non-zero value of $\Delta_\lambda(f)$ *must* have a chromatic variation of the image size!

Glass Selection Considerations

(Things to watch out for)

Spherochromatism

- Variation of Spherical Aberration with aperture
- Glass Choices that work well at F/10 may not be optimal at F/2.8!
  - In fact, such glass choices are more often than not, highly problematic
  - Choosing glasses for a low P difference usually means that ΔV is small
  - Small ΔV implies stronger elements, i.e., more spherical and more spherochromatism
- The same is usually true for three-glass apochromats

Sensitivity to Thermal Shock

- The FK and PK glasses are extremely sensitive to thermal shock
  - Some fabricators have worked out procedures for dealing with this
  - Others haven't:
    - "Oh, that's the glass that breaks when you touch it! We can't work with that glass, you'll have to redesign the system."
  - Think about the application: will the sensitive glasses be exposed to sudden changes in temperature?

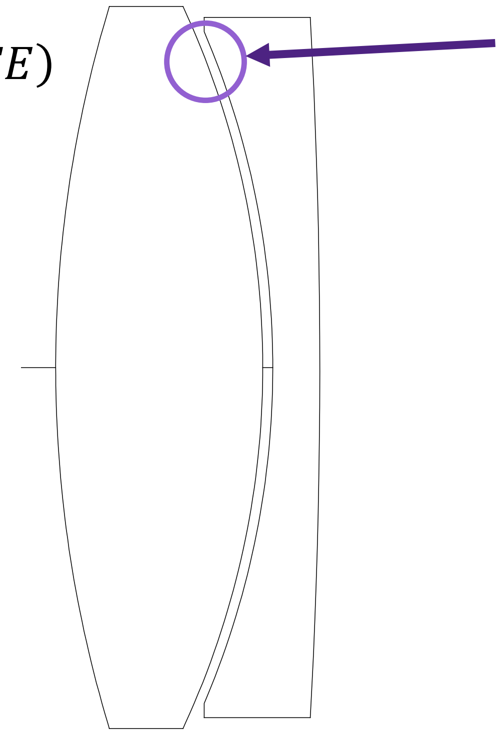
Thermal Expansion Mismatch

- Be careful about thermal expansion mismatch in cemented doublets
  - The FK and PK glasses have very high Coefficients of Thermal Expansion (CTEs)… be careful what you cement them to!

Thermal Expansion Mismatch in Cemented Elements

- How much mismatch is allowed between the Coefficients of Thermal Expansion (CTEs) in a cemented doublet?

Radial Shear = $(Semi\ Diameter) * \Delta T * \Delta(CTE)$



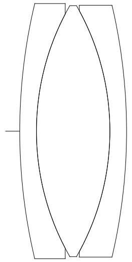
How much shear is generated here because the crown element expands more than the flint?

Will the cement fail (de-laminate) because of the shear stress?

Will it pull the glass apart?

Default Thermal Shear Limit in Glass Expert (CODE V)

- The Default Setting in Glass Expert is intended to help, *but does not guarantee that you will not have problems.*
- By default, Glass Expert will avoid cement layers with radial shear of more than 0.1 μm per degree Celsius. (The 0.1 value can be changed by the user)
  - Over a ±50ºC Temperature range, this allows a maximum shear of 5 μm.
  - Note that this is not simply a limit on Δ(CTE); it also takes the diameter into account, with smaller elements being allowed larger Δ(CTE) values.
- Will the cement layer tolerate 5 μm of shear? It's complicated!
  - If it is an "ordinary-looking" doublet with a relatively thin flint element, the shear stress causes the doublet to bend, and neither the glass nor the cement fails
  - If the two elements are unusually thick, then they are too stiff to bend, and a failure is likely!
  - We have seen a "Hastings Triplet" fail, for similar reasons



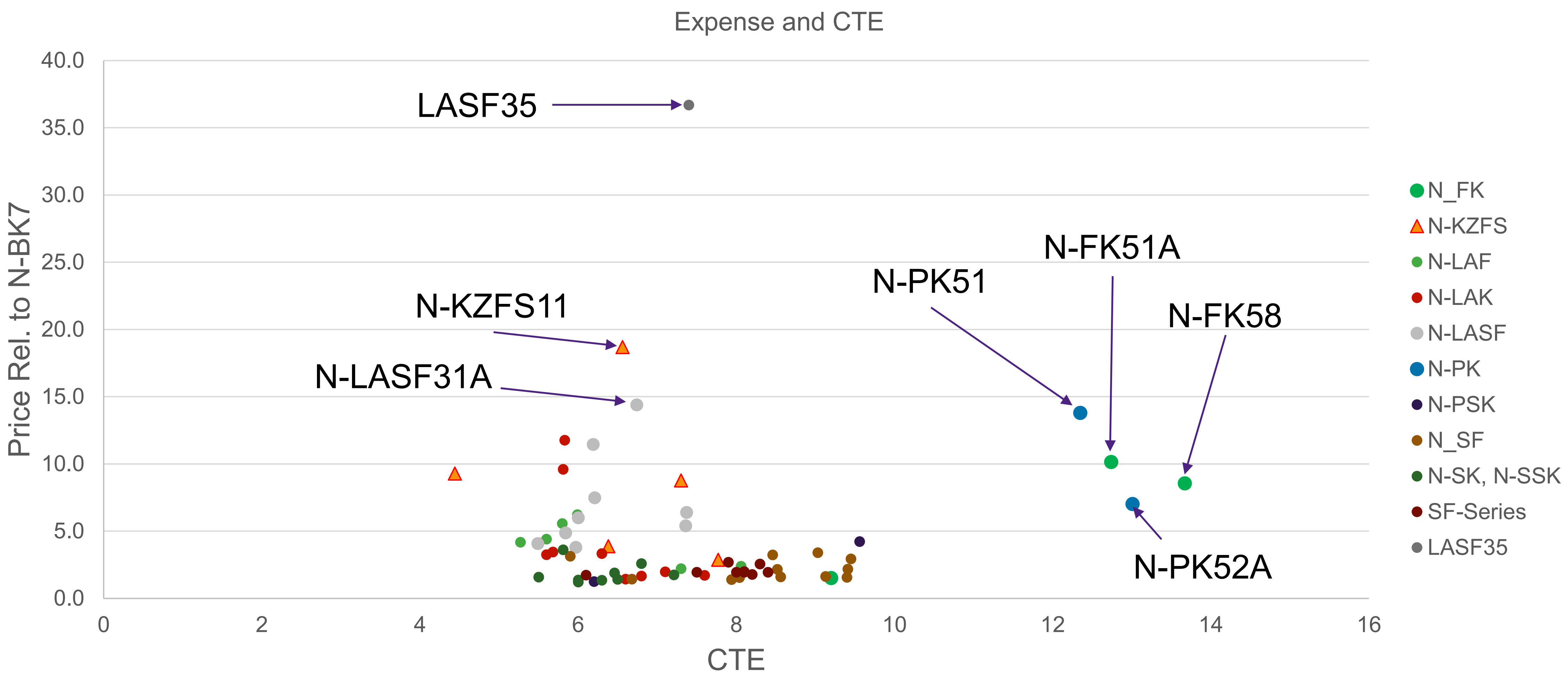
Glass Expert CTE Checking

- It is important to realize that Glass Expert only limits the CTE mismatch *when it makes a glass substitution.*
- If the initial lens has a CTE mismatch problem, and Glass Expert does not make a substitution for either glass, then the output lens will still have a CTE mismatch problem!

Always ensure that the starting lens for Glass Expert meets the CTE mismatch criterion you have entered.

If the starting lens does not meet the criterion, the ending lens might also not meet it.

Expensive and High CTE Glasses



The Schuppmann System

A one-glass Achromat…

A great way to study color aberrations

Solving the Equations for Achromatism (of Power) for Two Separated Elements

- Primary color is corrected if:

$$\frac{y_1^2\phi_1}{V_1} + \frac{y_2^2\phi_2}{V_2} = 0$$

- Secondary color is corrected if:

$$\frac{y_1^2\phi_1 P_1}{V_1} + \frac{y_2^2\phi_2 P_2}{V_2} = 0$$

(Reference: almost ANY textbook, e.g., Kingslake, Kidger, etc.)

Look for a One-Glass Solution for Primary Color

For a one-glass system:

$$V_2 = V_1 = V$$

$$P_2 = P_1 = P$$

Primary color is corrected if:

$$\frac{y_1^2\phi_1}{V} + \frac{y_2^2\phi_2}{V} = \left(\frac{1}{V}\right)(y_1^2\phi_1 + y_2^2\phi_2) = 0$$

The solution occurs when:

$$(y_1^2\phi_1 + y_2^2\phi_2) = 0$$

Or:

$$\phi_2 = -\left(\frac{y_1}{y_2}\right)^2 \phi_1$$

(Note: this is independent of V, so it is the same solution regardless of glass type!)

What About Secondary Color?

Secondary Color is corrected when:

$$\frac{y_1^2\phi_1 P_1}{V_1} + \frac{y_2^2\phi_2 P_2}{V_2} = 0$$

For a one-glass achromat, this is:

$$\frac{y_1^2\phi_1 P}{V} + \frac{y_2^2\phi_2 P}{V} = \left(\frac{P}{V}\right)(y_1^2\phi_1 + y_2^2\phi_2) = 0$$

The solution is:

$$(y_1^2\phi_1 + y_2^2\phi_2) = 0$$

Or:

$$\phi_2 = -\left(\frac{y_1}{y_2}\right)^2 \phi_1$$

This is the same as the solution for primary color !

Primary and Secondary Colors Are Both Corrected!

- The equations say that if we correct for primary color, then secondary color is automatically corrected!
- This happens because both V and P factor out of the equations, because it is a one-glass system.
- Once V and P are factored out of the equations, the solution holds for ANY glass!
  - The equation can be solved for any glass, and the solution is the same for all glasses
  - The only requirement is that the two elements be made of the same glass!
  - Note that because of the factoring, the solution for secondary color is <u>*exact.*</u>

A Schuppmann System with Truly Thin Elements

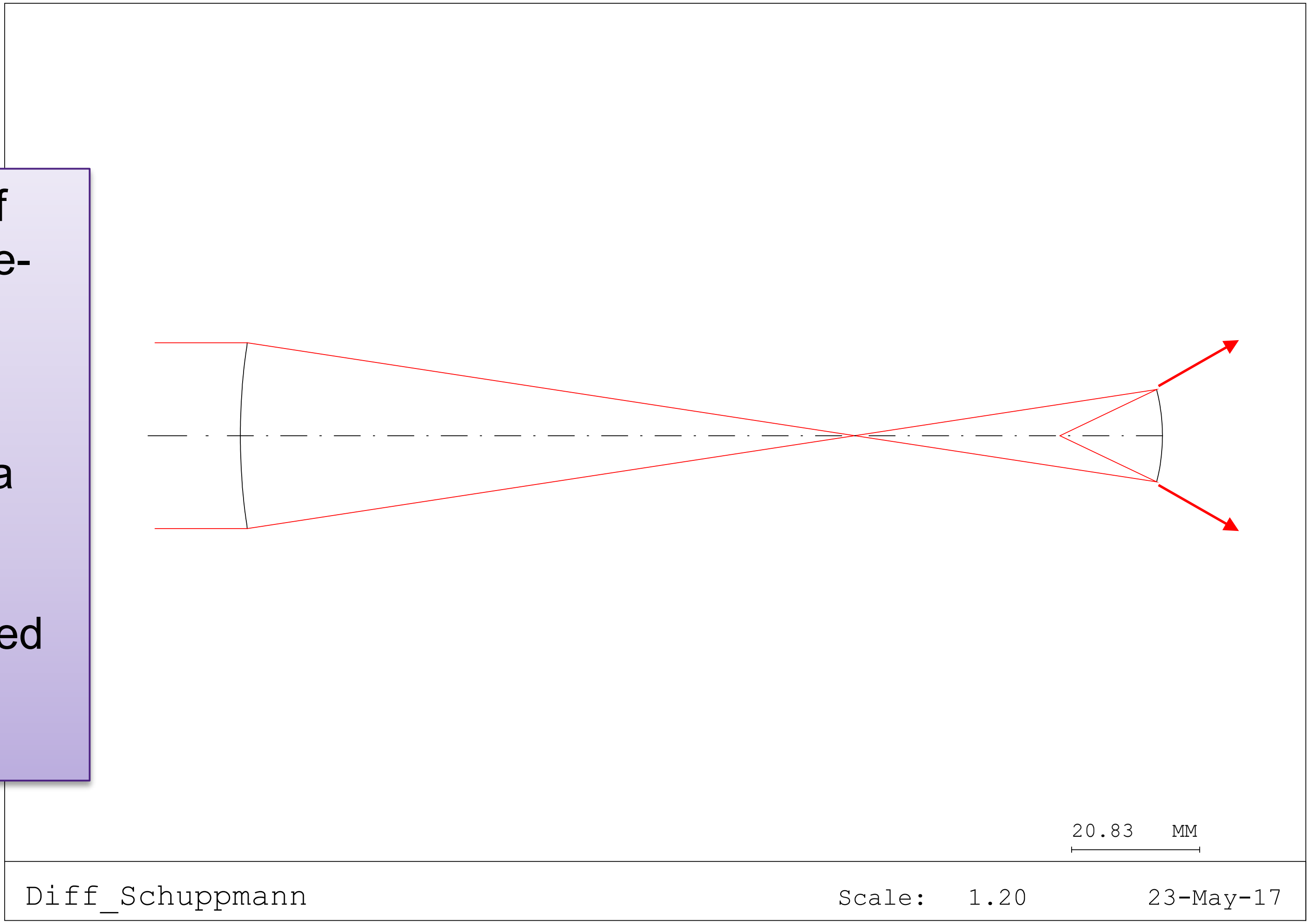
- The color equations are for thin, separated elements
- To investigate the chromatic properties using elements that are truly thin, we will use *diffractive* elements rather than glass elements.
  - The same equations still hold, provided that we are considering the same orders from the two elements
  - This is a good test because the individual elements create a LOT of color!

A Diffractive Schuppmann System

There is a family of solutions to the one-glass achromat equation.

All solutions have a virtual image.

(It is often mis-stated that they all have negative power.)



In this case, we have modeled the diffractives as holograms, that self-correct for spherical aberration.

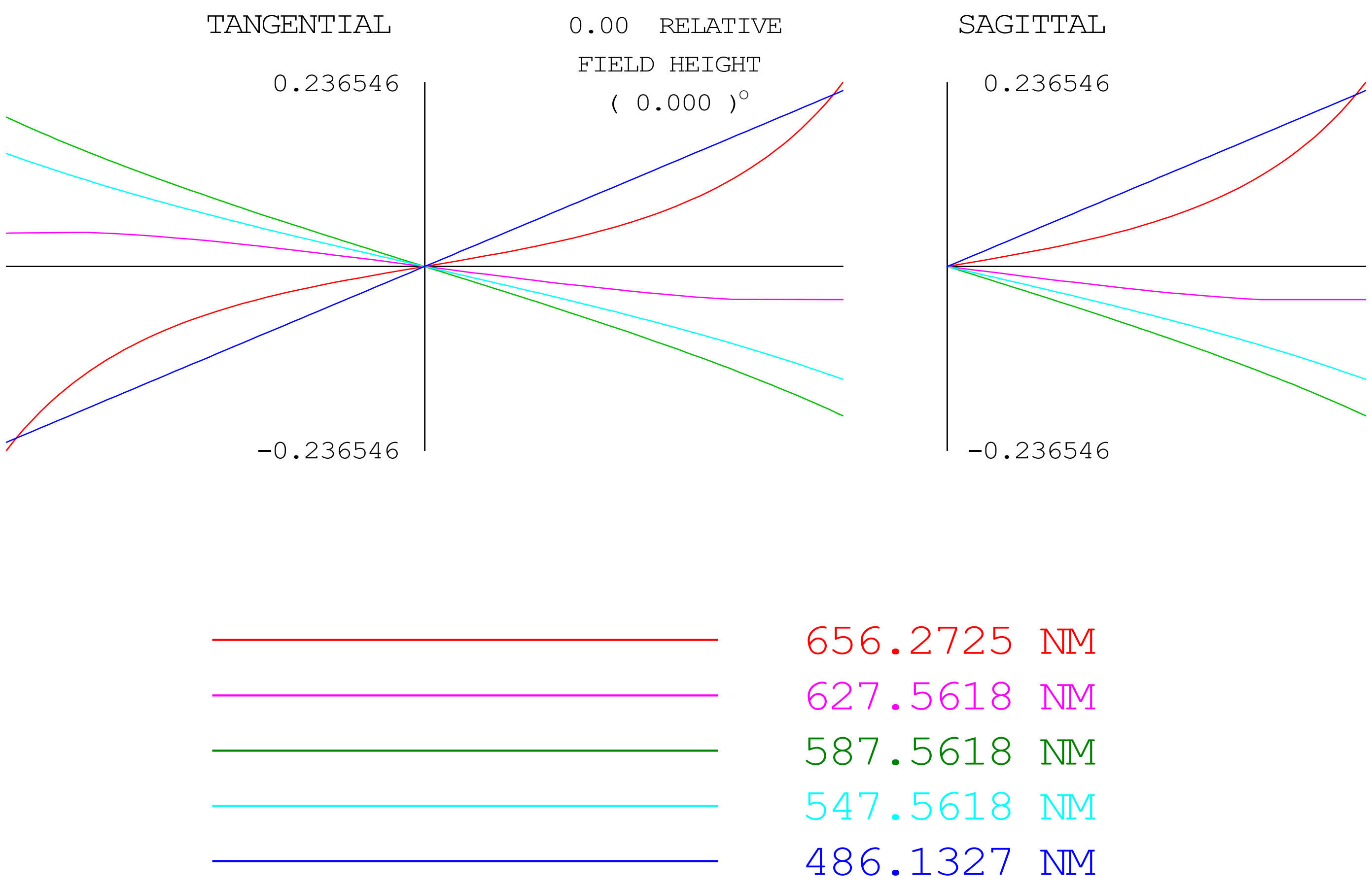
We have curved the substrates to satisfy the Abbe sine condition (zero coma).

Ray Fans, On-Axis Secondary Color

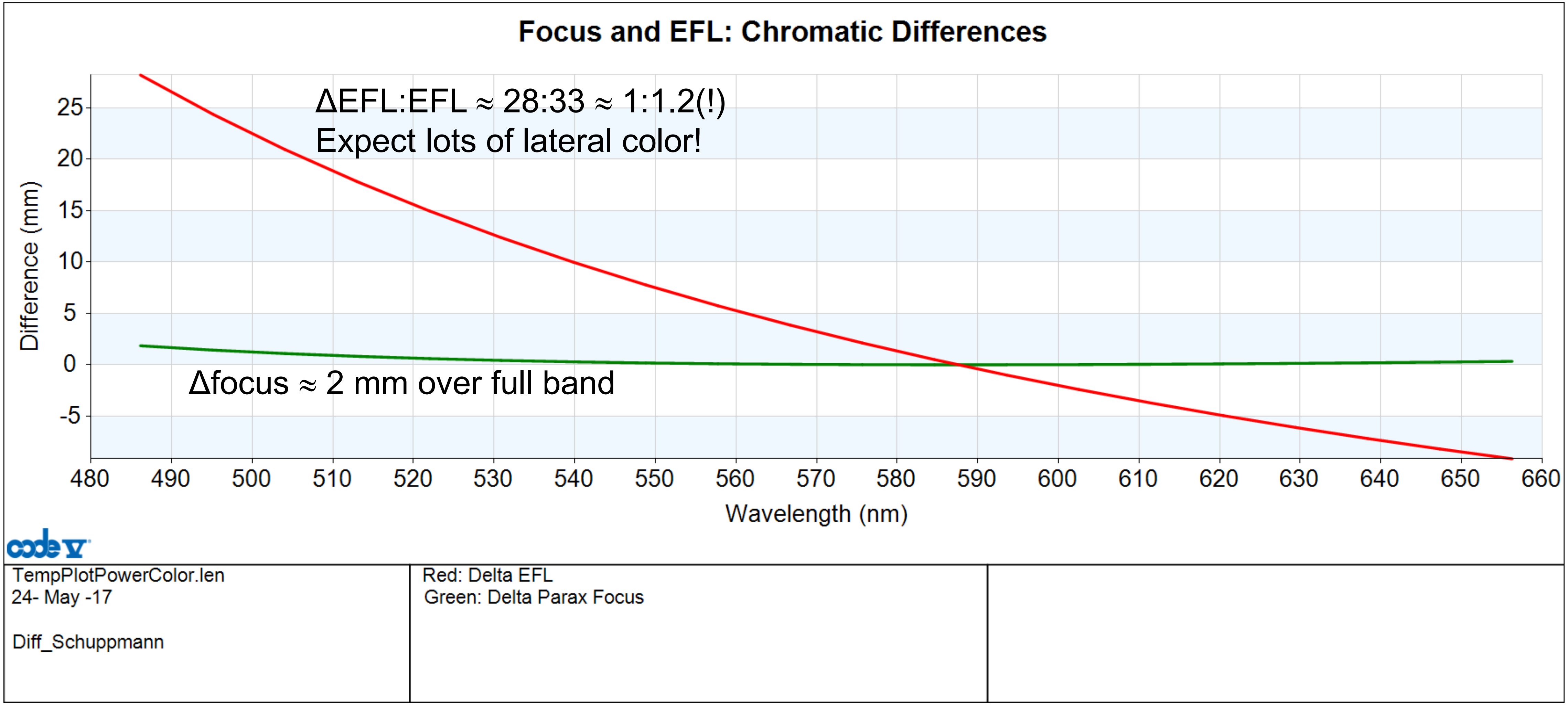
Red and Blue are similarly focused (with some spherochromatism), Green is focused differently

Primary color is corrected, but a substantial amount of secondary color is present.

RMS Spot Dia. = 238 um



Chromatic Differences of EFL and Focus



Why Is There ANY Secondary Color?

- We noted earlier that if the equation for primary color correction is met, then the equation for secondary color is met… *exactly*!
- The equations tell us we should not see ANY secondary color
- By extension, we don't expect to see any color of ANY order
  - We expect the equations for tertiary and quaternary color to be like those for secondary color, with factors (call them T and Q) that can be factored out of the equation
  - In that case, the solution for primary color is a solution for ALL ORDERS of color

- The above is not the case!

- What is wrong with the equations?

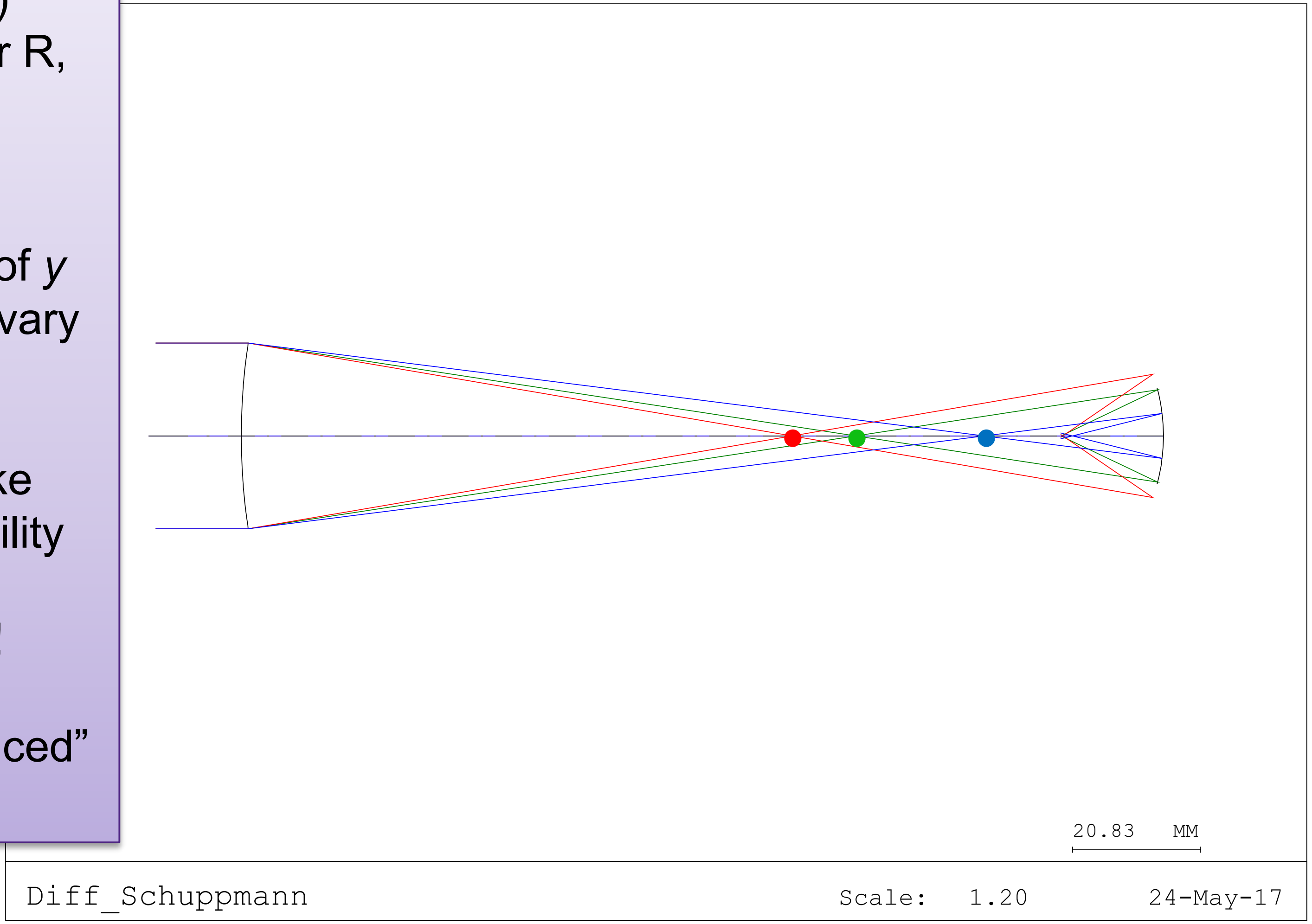
Schuppmann System with R, G, B Wavelengths Shown

We see the (separated) intermediate images for R, G, and B.

As a result of that separation, the values of *y* at the second element vary with wavelength.

The equations don't take into account the possibility that the *y*-values might depend on wavelength!

(They are blind to "induced" color aberrations.)

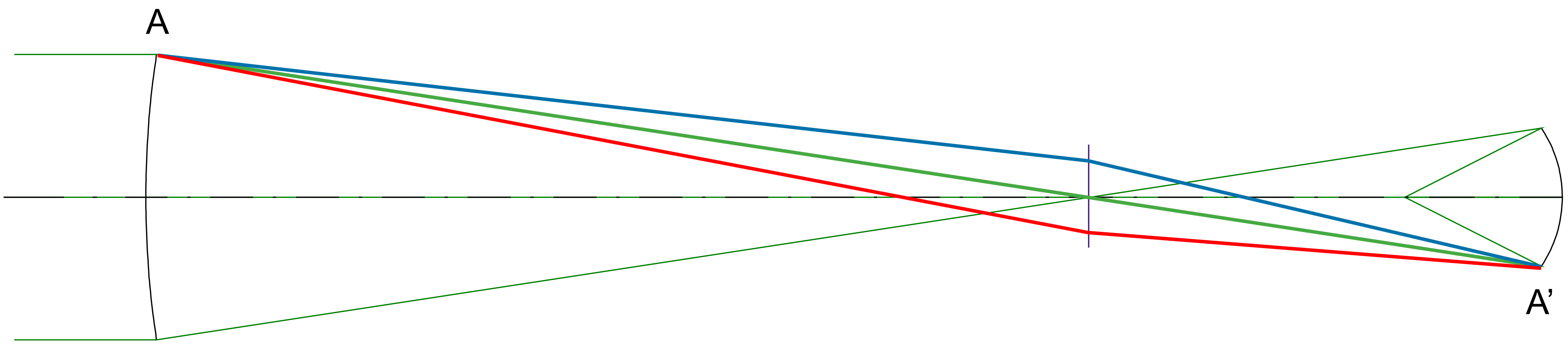


Fixing “The Problem”

- We can make the equations more accurate by explicitly taking the wavelength dependence of the y-values into account
  - That is, taking the induced color aberrations into account
- We can “fix” the system by inserting a field lens at the (green) internal image, to re-image the blue and red rays back together at the third element

Schuppmann, with Diffractive Field Lens

Schuppmann, with Diffractive Field Lens



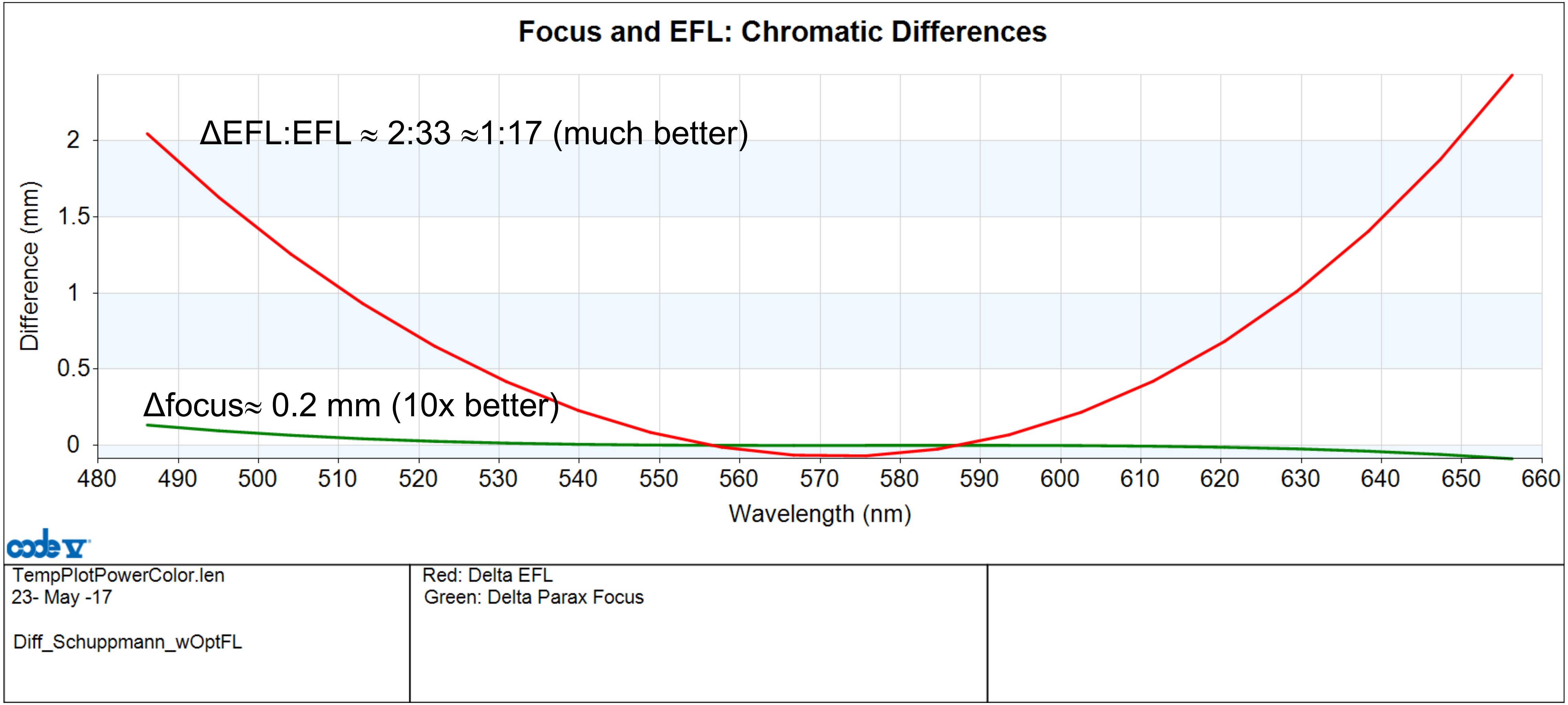
The field lens images Point A onto Point A’, thereby bringing the various colors back together again.

The field Lens itself does not introduce color aberration into the main image, since y = 0 at the internal image.

(The imaging of A onto A’ does suffer chromatic aberration… we will see that it makes a difference.)

Chromatic Differences of EFL and Focus

Diffractive Schuppmann with (Diffractive) Field Lens



Ray Fans

Diffractive Schuppmann with (Diffractive) Field Lens

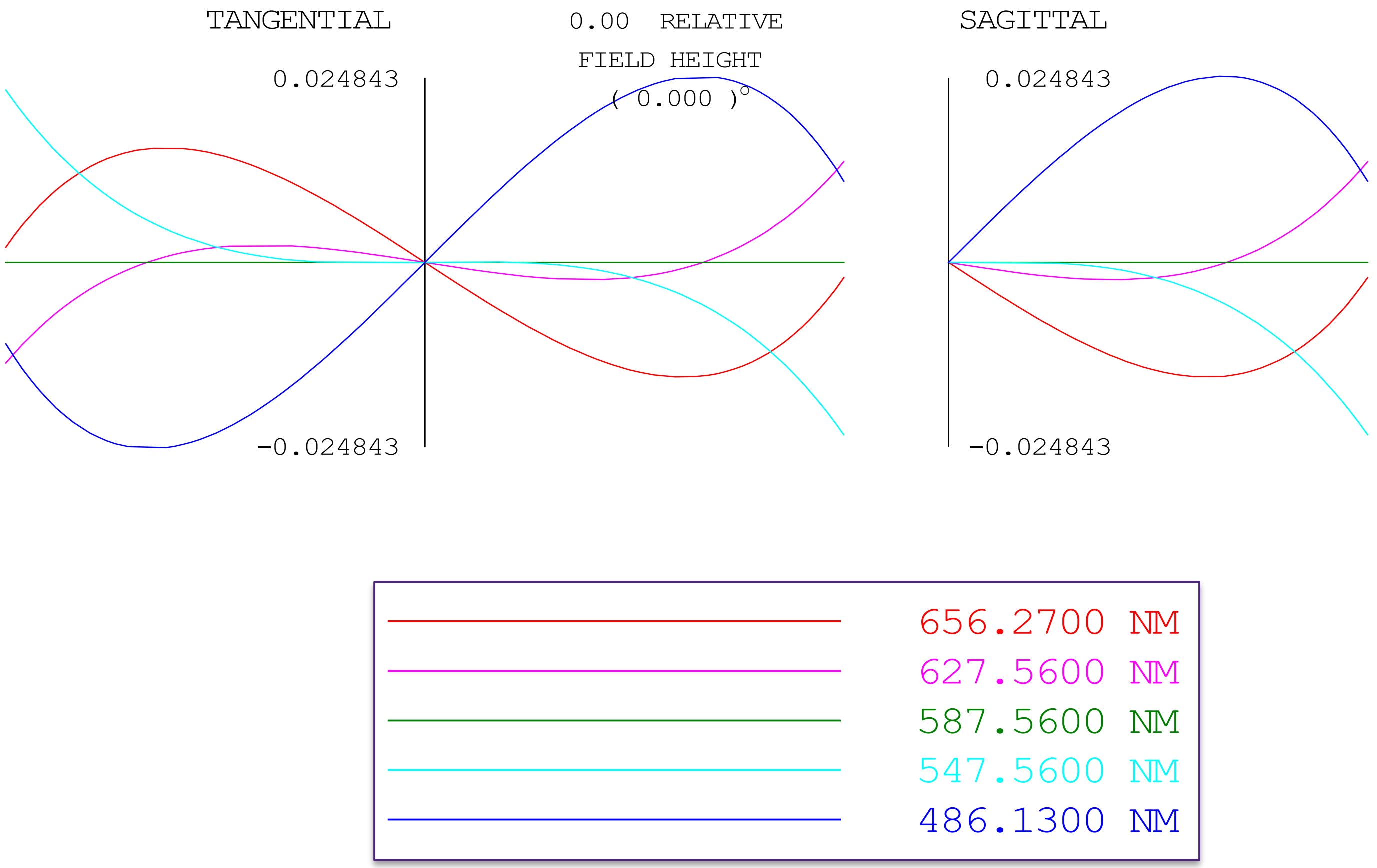
Chromatic focus error greatly reduced.

Spherochromatism now dominant.

Central 3 wavelengths nearly at a common paraxial focus.

Extreme wavelengths still slightly out of focus.

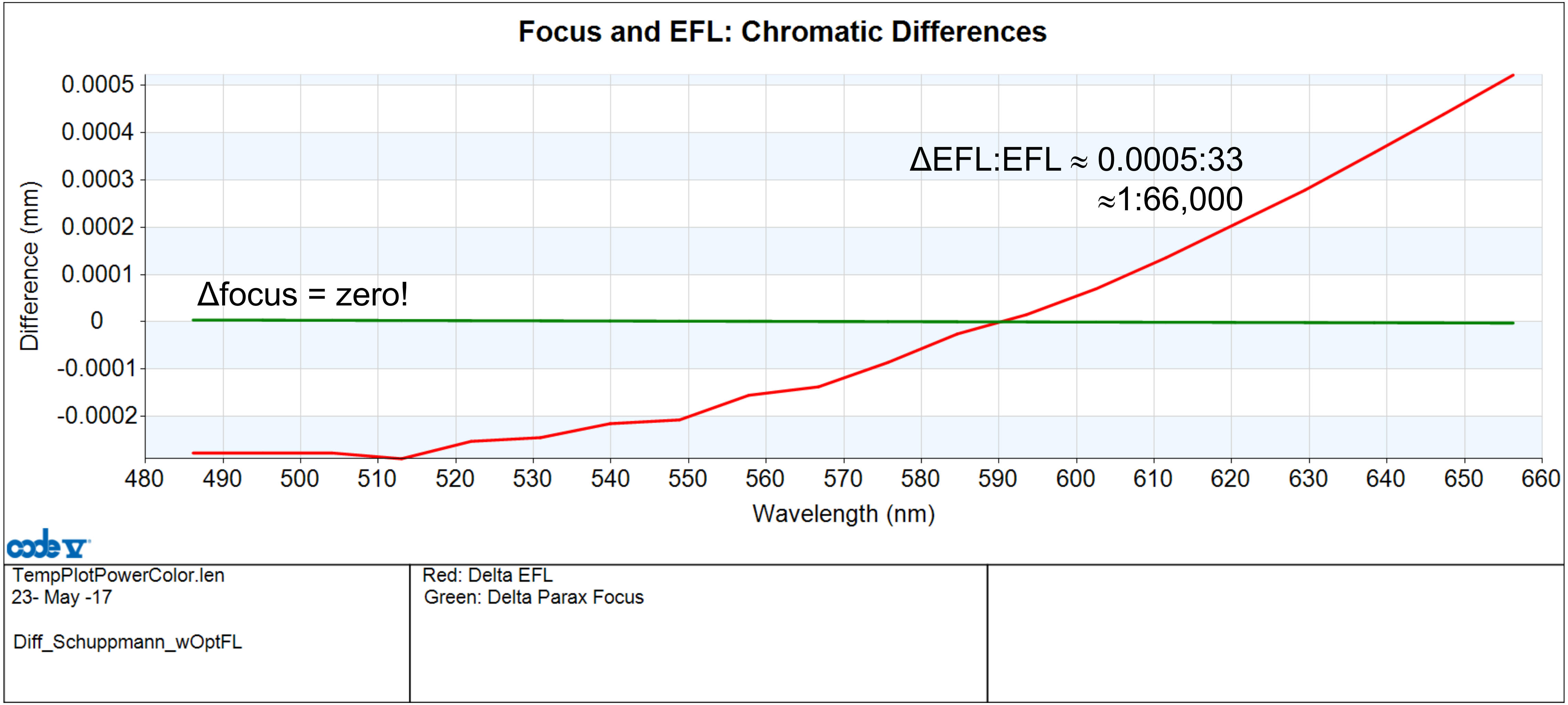
RMS Spot Dia. = 23 um



Schuppmann, with Lens Module Field Lens

- Using a diffractive field lens improves the color correction, but it is still not perfect.
- This is because the diffractive field lens suffers chromatic aberration itself, and cannot bring the rays perfectly back together at the last element.
- If we use a CODE V lens module to create the field lens, the color correction becomes perfect.

Schuppmann, with Lens Module Field Lens



Conclusion:

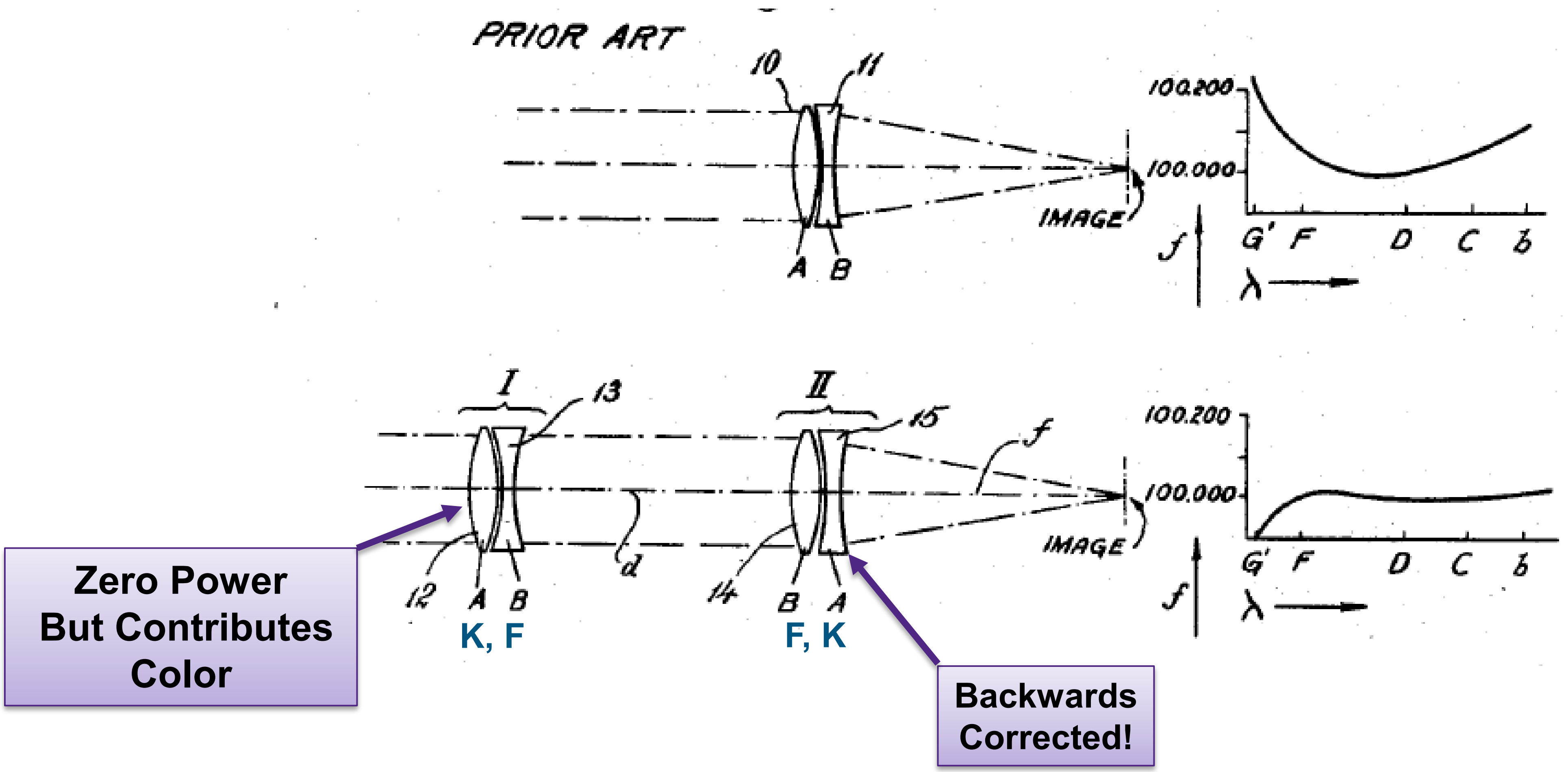
- The Schuppmann system appeared to violate the equation for correction of secondary color, because the colors separated from each other
- This makes perfect sense:
  - At the rear element, the beam diameters for blue and red are different, and the y-values are different
  - We should expect that the chromatic aberration, in the neighborhood of blue, would be different than the chromatic aberration in the neighborhood of red. This is a way of describing secondary color
- Secondary chromatic aberration is "induced" at the rear element because of uncorrected primary color in the front element
- ***The chromatic splitting of rays induces secondary color in elements downstream***
- We reduced this effect by using a lens module to bring the colors back together again

- More important: ***we can make use of induced secondary color to correct the residual secondary color of a system!***

McCarthy's 1955 Patent

First Reference to Induced Chromatic Aberrations in the Literature

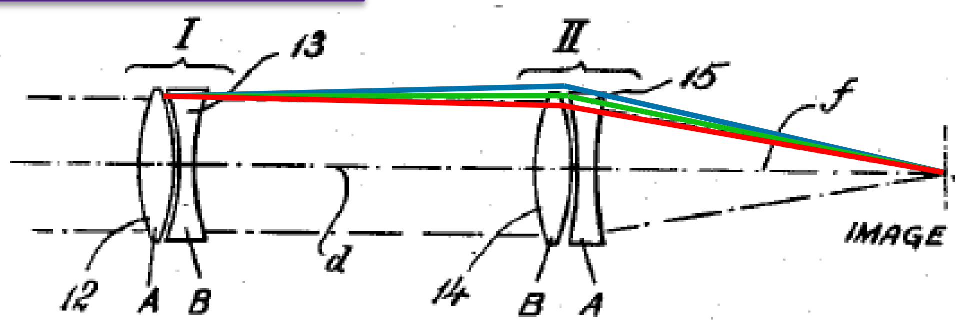
Induction of Secondary Color
US Patent #2,698,555, E. L. McCarthy (1955)



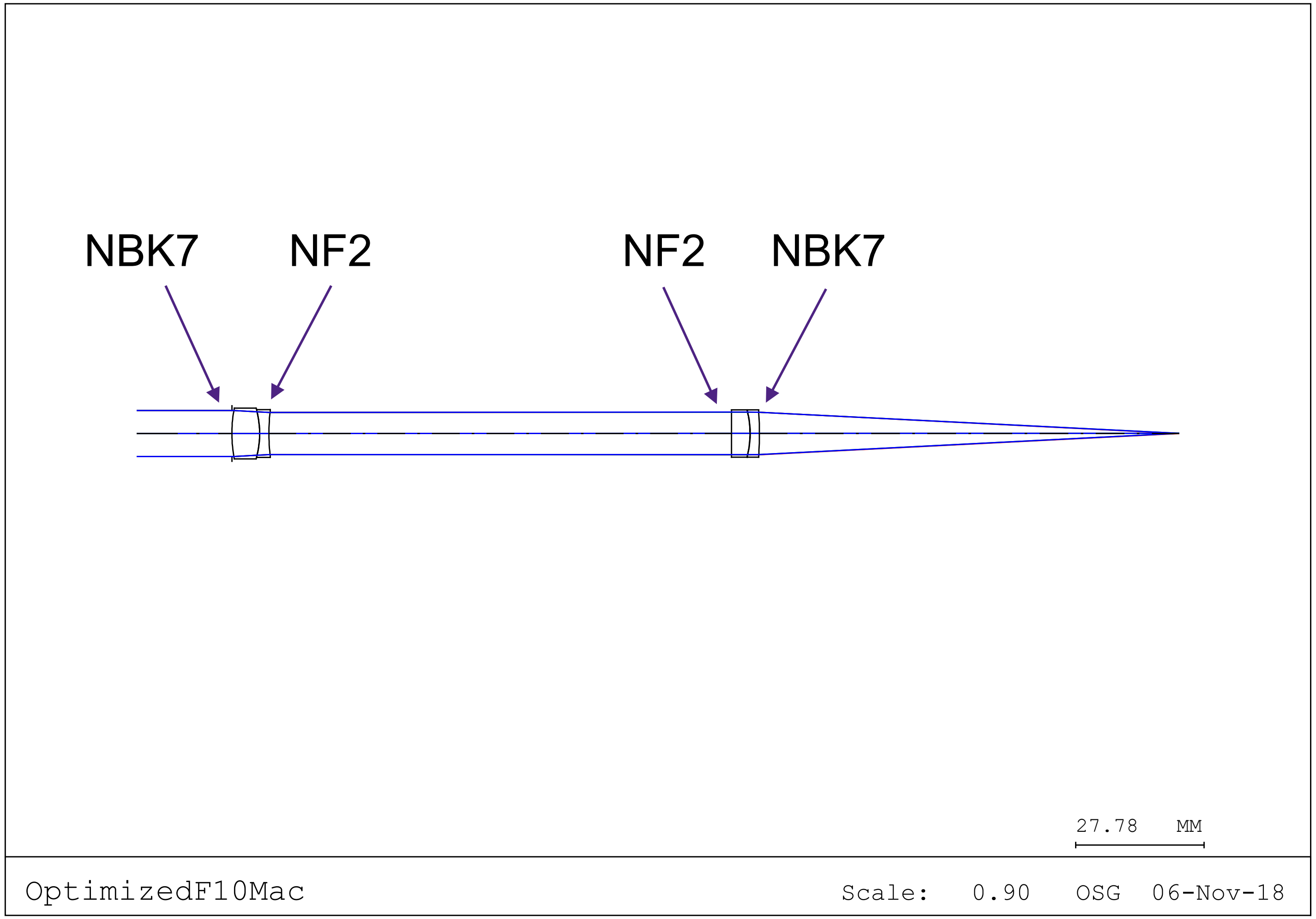
Induction of Secondary Color
US Patent #2,698,555, E. L. McCarthy (1955)

First Doublet Disperses the Beam… Causes Ray Separation at the Second Doublet

Second Doublet Puts The Colors Back Together Again



Optmized F/10 McCarthy Concept

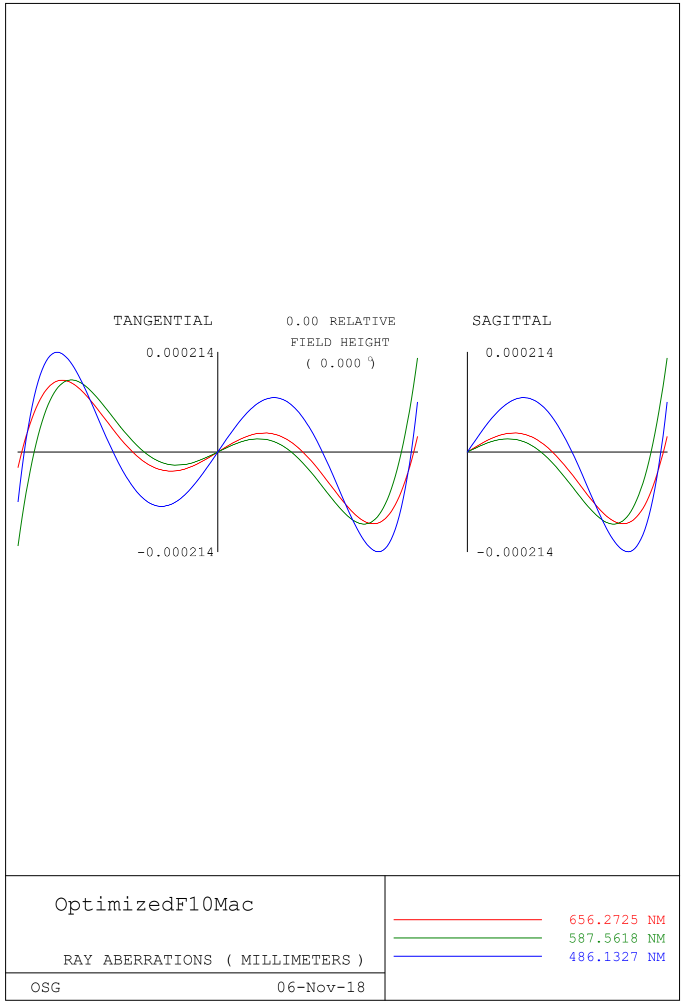


Optimized F/10 McCarthy Concept

Scale = ±0.2 μm !

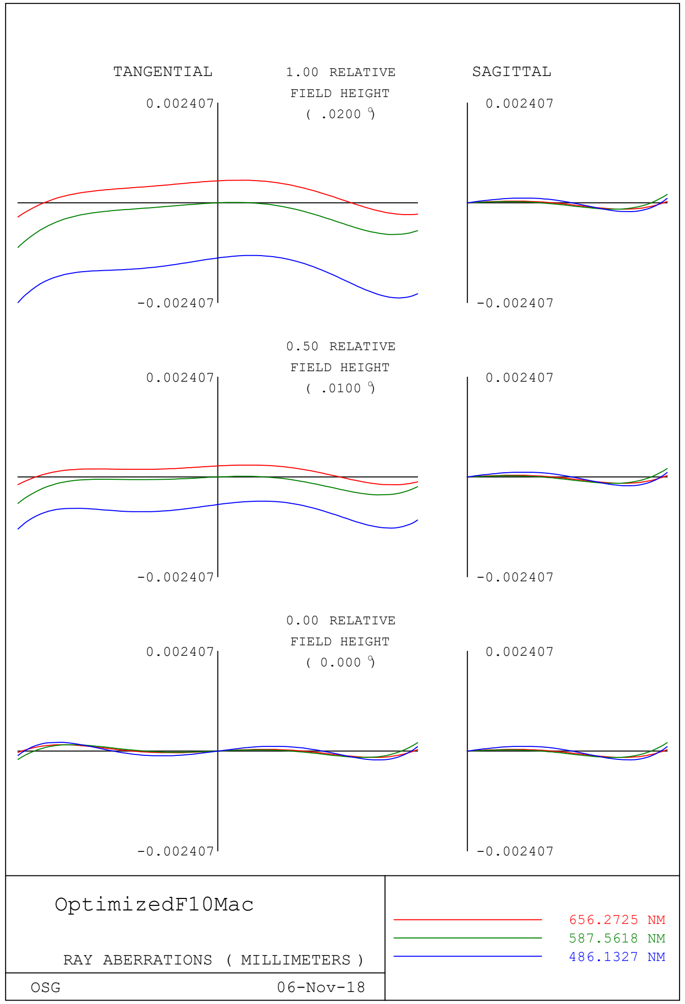
RMS WFE = 0.001λ

BUT…



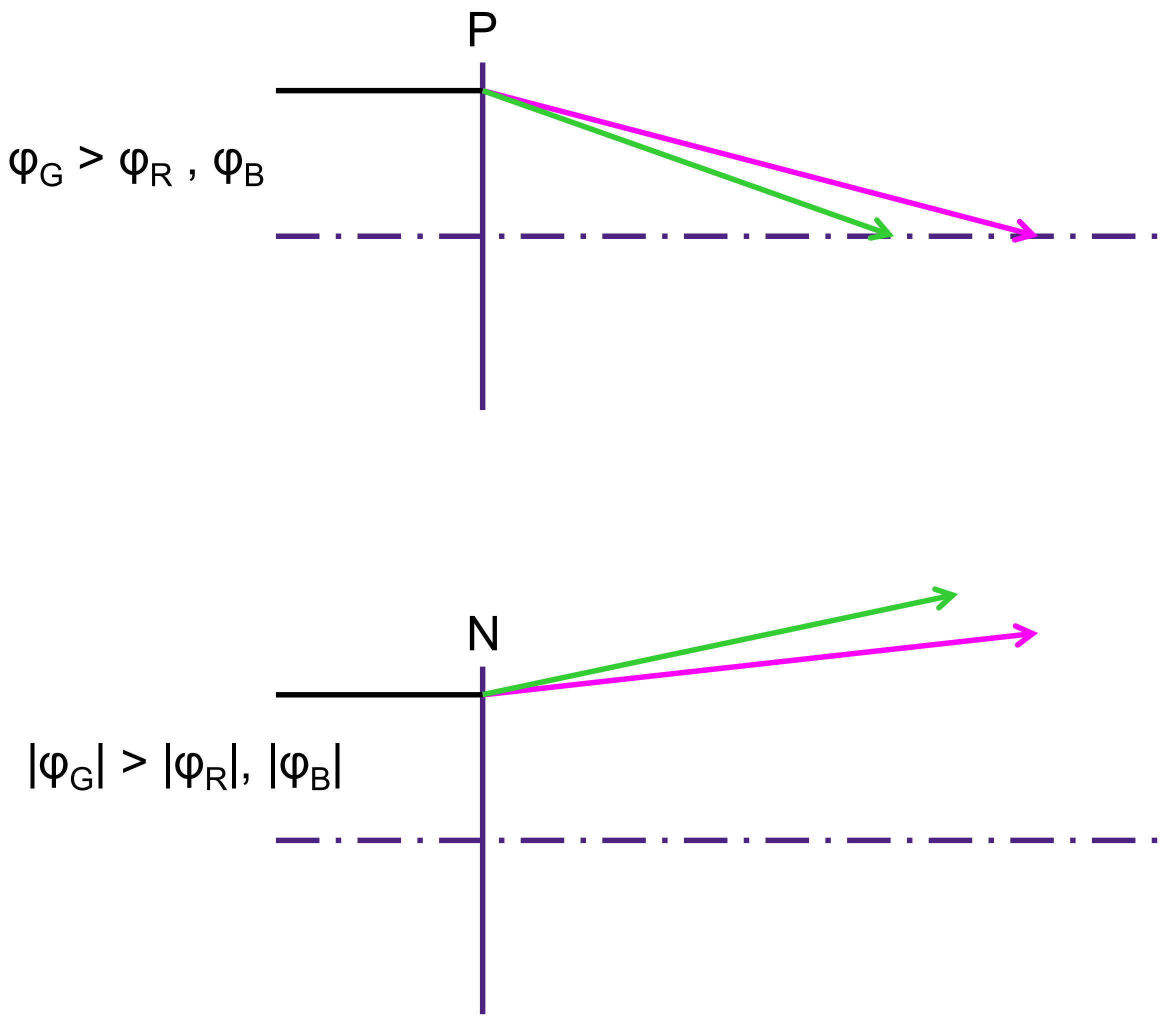
Optmized F/10 McCarthy Concept

Dominated by lateral color at even 0.02º field!

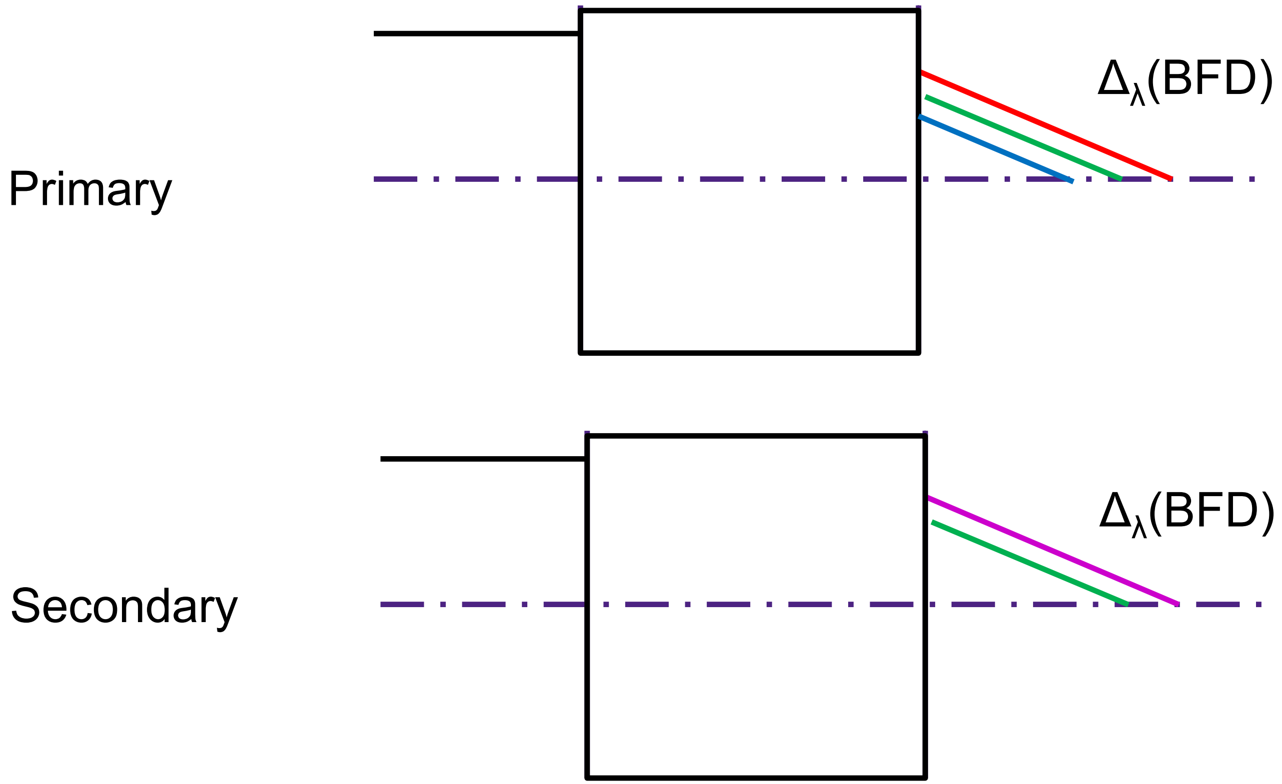


Configuration Considerations

Schematic Depiction of Secondary Color
(For a Thin Achromat)

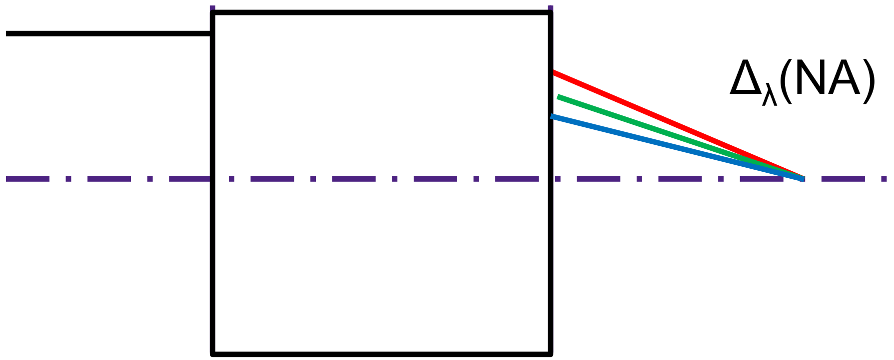


Pure Axial Color
(For a Thick System)

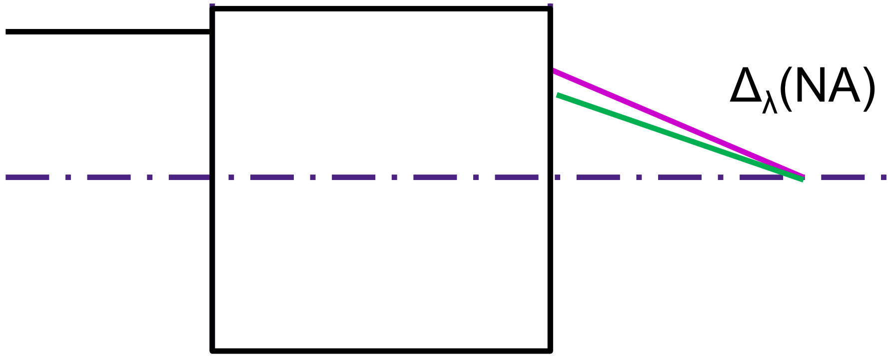


Lateral Color
(Chromatic Difference of Magnification)

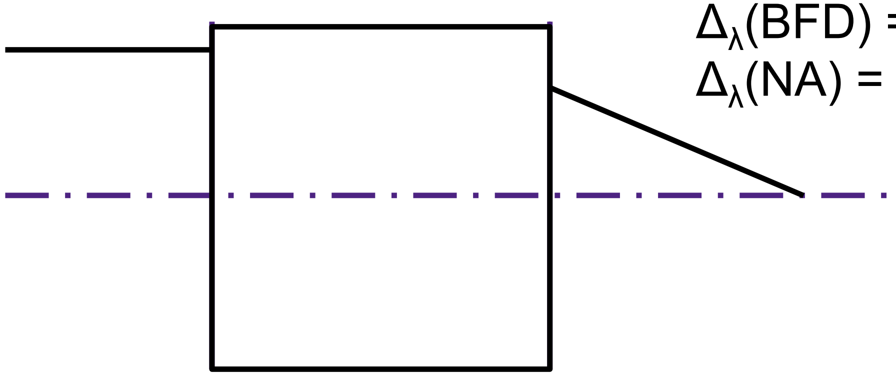
Primary



Secondary



Absence of Chromatic Aberration

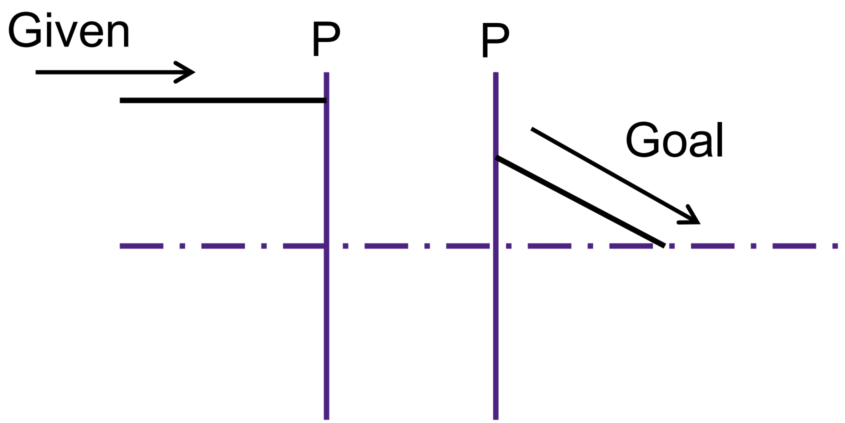


- Marginal rays for all colors must arrive at the same image point at the same angle.
- That means the marginal rays must arrive at the last surface (or group) at the same point, and leave with the same angle

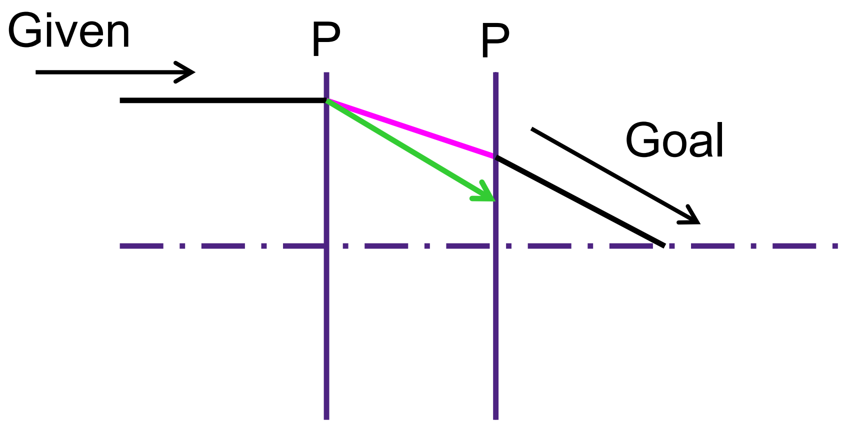
Configurations of Separated Thin Achromats

Which ones are easily corrected for secondary color?

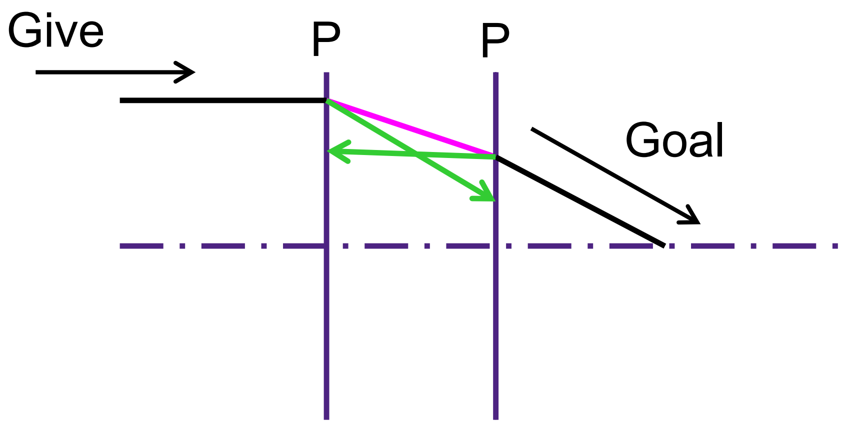
Petzval System

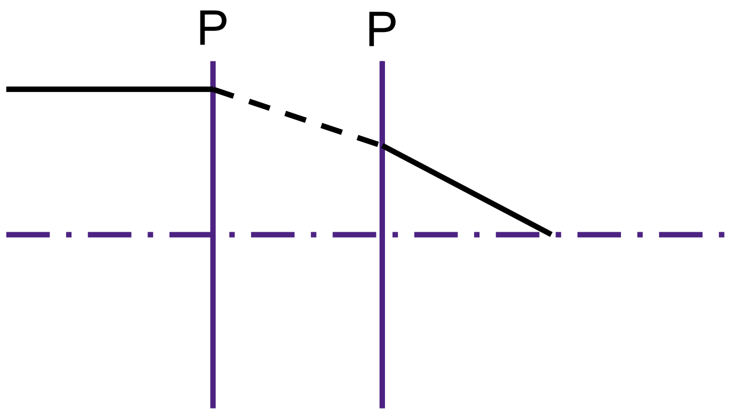


Petzval System



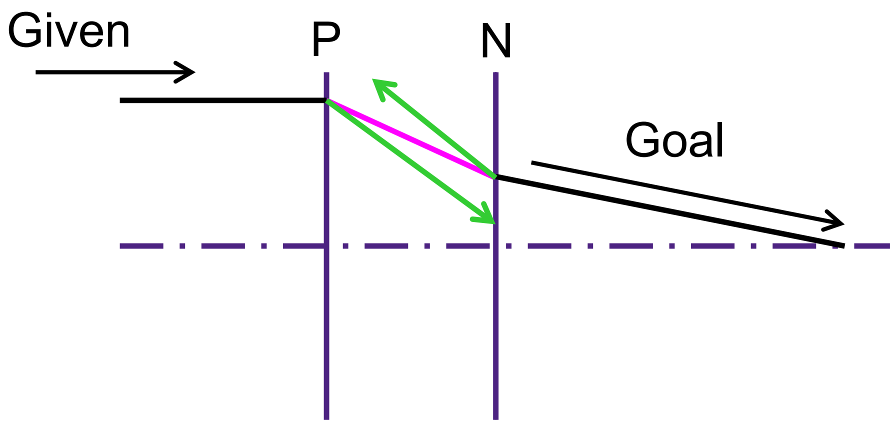
Petzval System

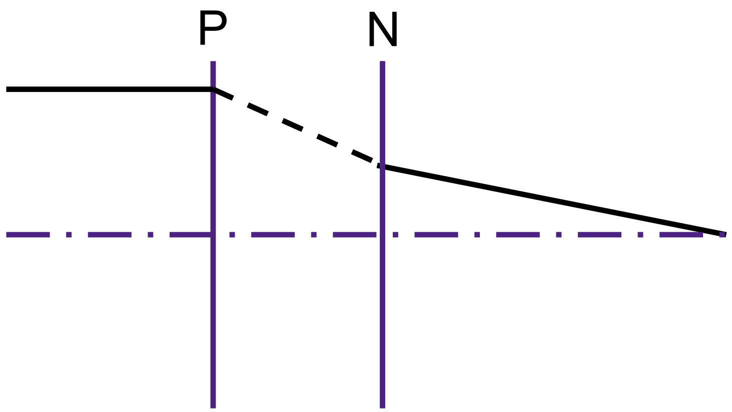




The only way this system can be corrected for secondary color is for the two groups to be independently corrected for secondary color

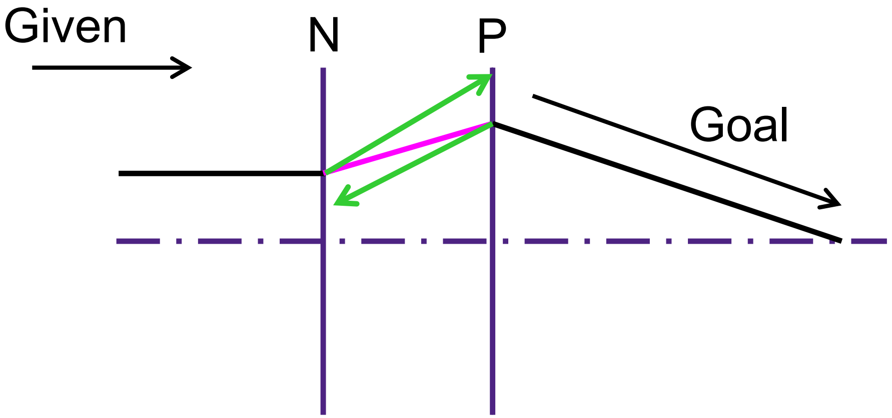
Telephoto System

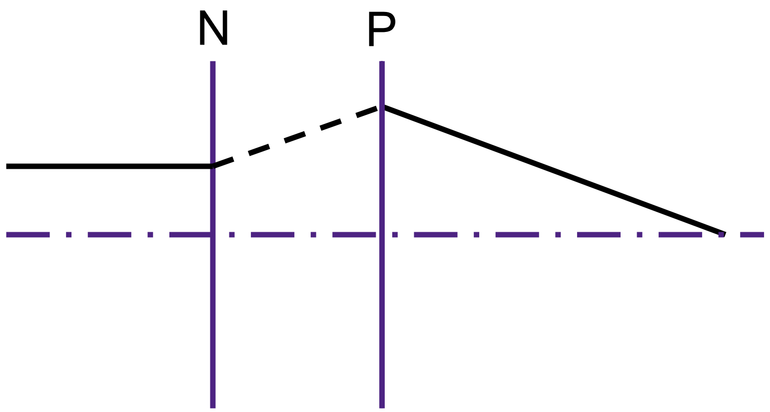




Both groups must be independently corrected for secondary color

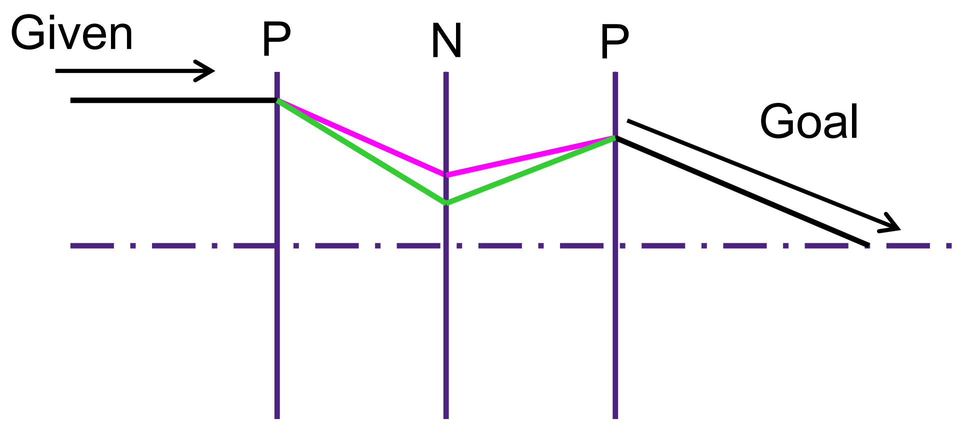
Retrofocus System





Both groups must be independently corrected for secondary color

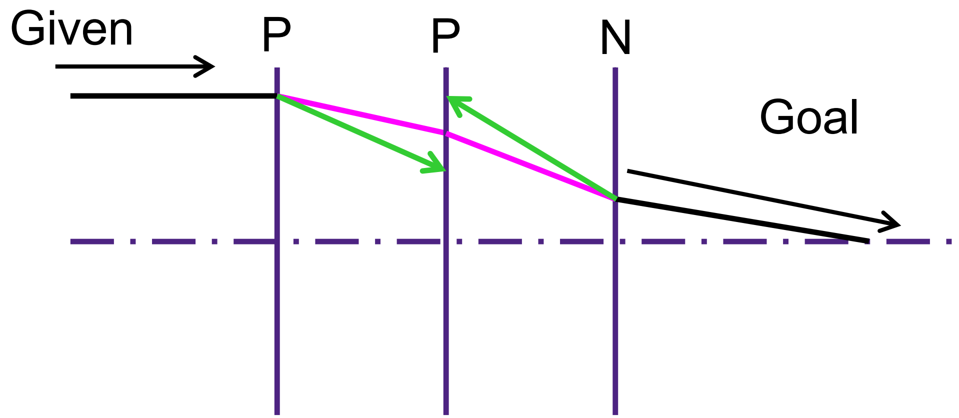
Cooke Triplet System



In this case, it appears possible for the negative achromat to correct for the secondary color caused by the outer, positive achromats.

We can at least say that the SIGN of the secondary color of the middle achromat is correct!

PPN Triplet



In this case, all three achromats must be independently corrected for secondary color.

Conclusion

- Certain systems (telephoto, retrofocus) appear to be difficult to correct for secondary color (at least if the individual groups are achromatic)…
- While other system types (e.g., the Cooke triplet) appear easier to correct
- **Correctability of secondary color is very much configuration dependent!**
- **This is a good opportunity to use GS to find the good configurations!**

- Note: There is no requirement that every group be independently achromatic

Some Comments on Lateral Color Specs

Do the specs make sense?

Does the Spec for Lateral Color Make Sense?

- Rule of thumb: correcting lateral color to less than 1:2000 (or even 1:1000) can be tricky
- Does the customer's spec make sense?
  - Warren Smith: "*Always* challenge your customer's specifications."

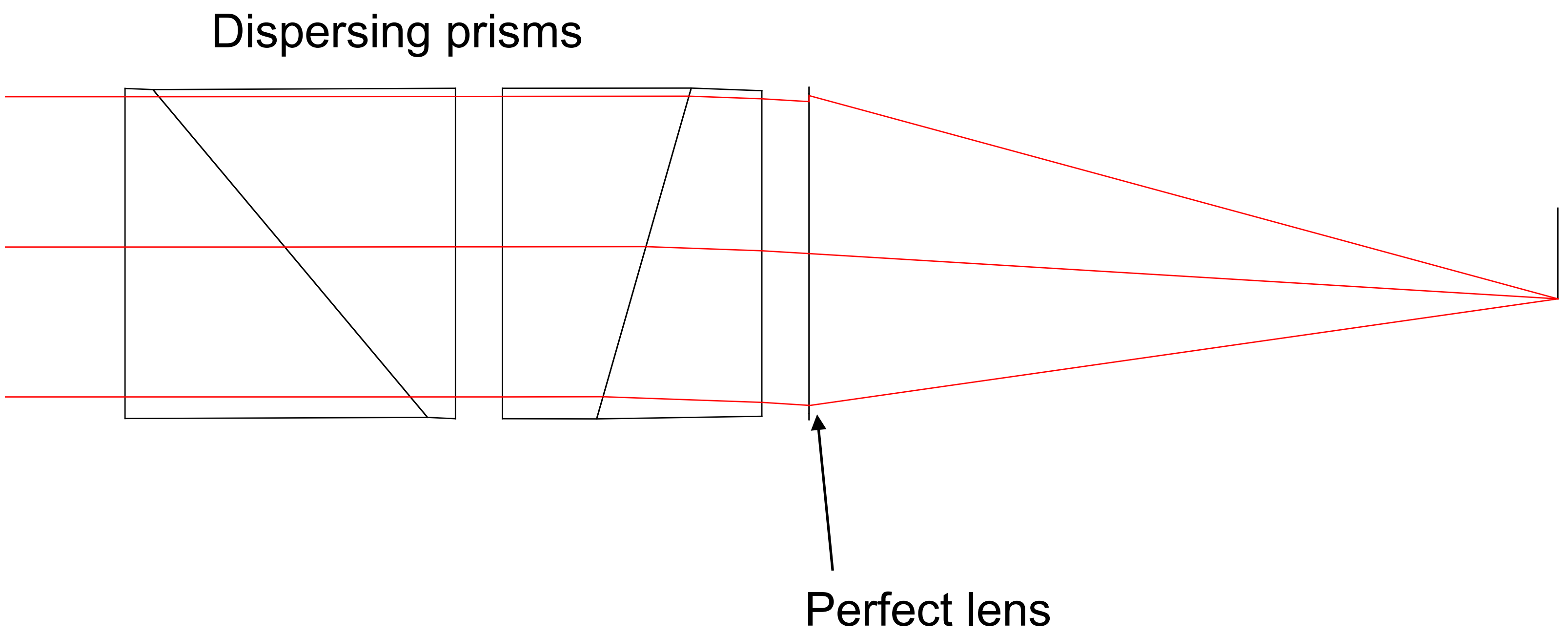
- The customer should have a good justification for asking for:
  - Lateral color < 1 pixel (particularly if the pixels aren't going to be resolvable by the viewer)
  - Lateral color < 1 Airy Disk radius
  - Lateral color < 1 arcmin in a visual system

- Note that once the lateral color spec is smaller than the system resolution, its meaning becomes blurred

- Some crazy requests we have encountered:
  - Lateral color < 0.1 pixel
  - Lateral color < 0.05 Airy Disk radius
  - Lateral color *well* below the resolution of the eye

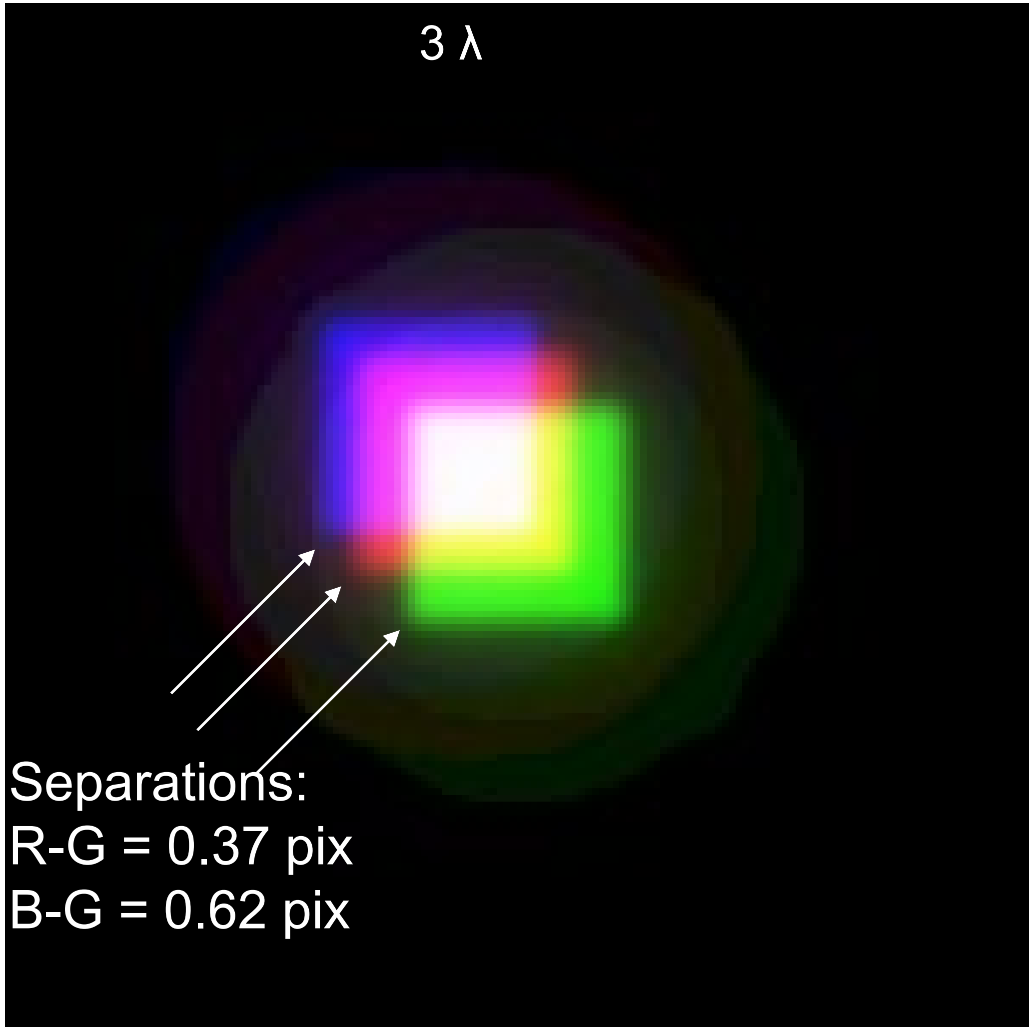
- In all cases, the customer had a good reason, but we made them explain it to us!

A System for Investigating Pure Lateral Color



Using two prisms allows us to adjust the primary color and the secondary color separately

Pixel Simulations with Pure Lateral Color
Simulate (with IMS) the Corner Pixel of a Display



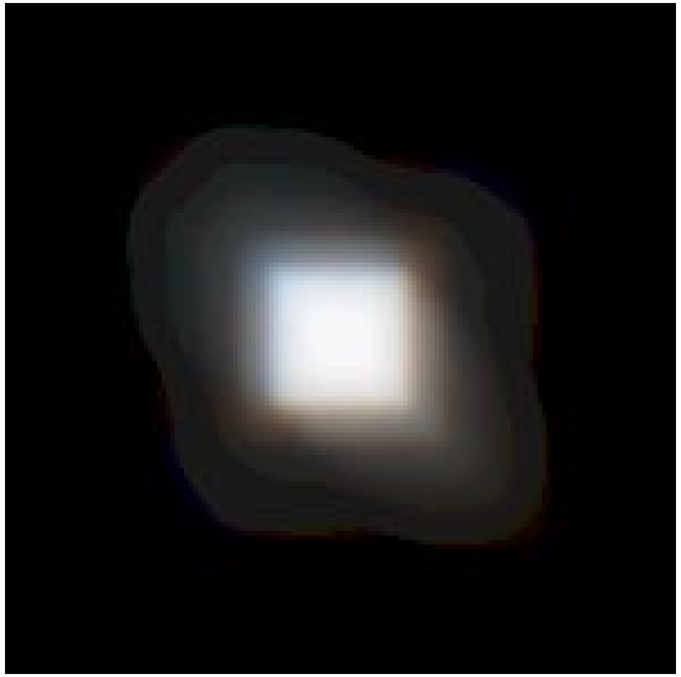
A Real System, Designed for Very Low Visibility of Secondary Color

The customer wanted the lateral color to “not be visible” for cosmetic reasons.

Initially they tried to specify a small value for lateral color; unfortunately, even very small amounts of lateral color are visible, as color changes around the boundary of the white pixel.

Quantifying this is a question of chromaticity, not microns

From the designer’s point of view, what is necessary is not only that the lateral color be very small, but that the chromatic variation of aberrations also be small.



Using Induced Aberrations to Reduce Secondary Color

How to do it

How dangerous is it?

Sensitivity

- Designs whose elements have large individual aberrations that balance each other tend to be sensitive to tolerances
  - Errors is radius, thickness and index disturb the numerical balance of the aberrations
  - Misalignments of the elements cause the aberration fields to be misaligned
    - Misaligned spherical aberration causes coma on axis
    - Misaligned longitudinal color causes lateral color on axis
- As a general rule, it is advisable to avoid designs with large individual element contributions
  - (But sometimes it cannot be avoided)

Questions:

- How dangerous is using separated, intentionally uncorrected elements to correct secondary color?

- Which of the following is better, *after tolerances are considered*?
  - A design with secondary color extremely well corrected using uncorrected individual elements
    - Extremely well corrected for secondary color
    - But tolerance sensitive
  - A design with every element turned into an achromatic doublet
    - Such a design has NO induced secondary color
    - But it has intrinsic secondary color of the individual achromats
    - This design should be less tolerance sensitive

A Realistic Projector Design Problem
(Based Loosely on a Recent Project)

- Resolution Goal : "High Definition (HD) Quality"
  - 1280 x 1024 pixels at a minimum
  - Lateral color < 1/10th of a pixel (!)
  - 60 degree full Field of View
  - Long back focal distance (retrofocus design type)
  - F/2.5
  - Temperature range: ±50° C
- Note that the 1/10th pixel goal requires ΔF:F to be 1:12,800
- An ordinary achromat has ΔF:F of 1 : 2,000
  - Can do better with special glasses, if they don't break
- Retrofocus systems are worse than single achromats, by as much as a factor of 2!

Design Specifications

- Spectrum: d, F, C wavelengths
- Focal Length 40 mm
- 60 degree full field diameter
  - Covers diagonal of 24 x 36 film format
- Image Clearance > 55 mm
- Diameters < 160 mm
- Distortion < 1%
- Chief ray angle < 7 degrees
- Illuminance at corner ≈ 70%
- Materials: Any Schott Glass allowed, provided:
  - Thermally induced shear at edge of the part < 5 um over 50°C
  - Transmission > 80% at the blue end

Design Comparison

- First design: NO induced chromatic aberration
  - Turn every element into an achromat
  - No induced secondary color (hope for less sensitivity)
  - No induced secondary color (cannot correct the intrinsic secondary color of the achromats)
- Second design: Same number of doublets, but no requirement that the doublets be individually achromatized
  - Allows induced secondary color to balance intrinsic secondary color
  - Expect better as-designed performance
  - Expect higher sensitivity to tolerances
- Which design is better, as-built?

ΔF:F

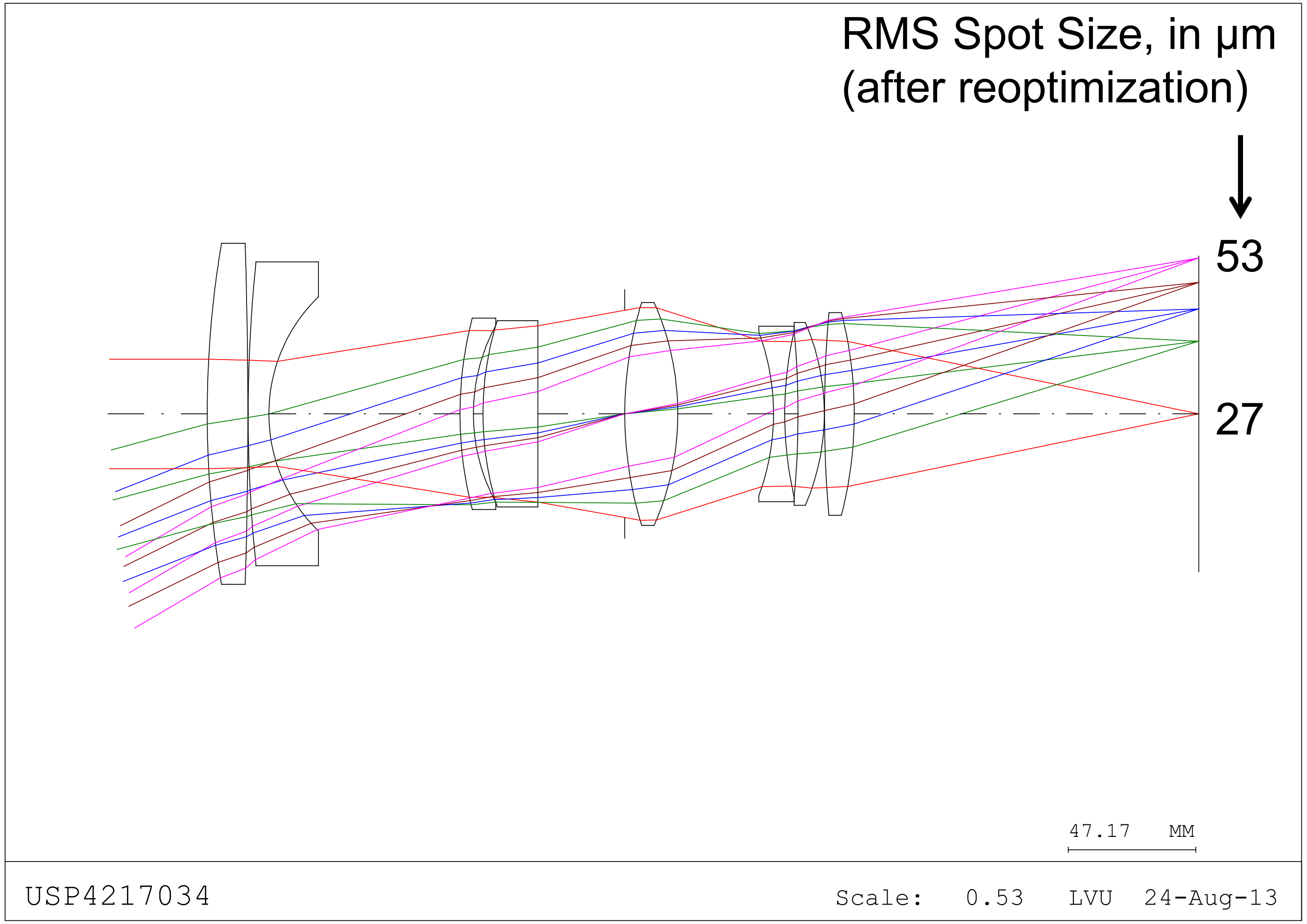
- ΔF:F is a useful performance metric
- Define ΔF as (EFLmax – EFLmin)
- Define F as (EFL @ W2)

- Note that this definition uses the worse of Primary Color and Secondary Color

Wide Angle Starting Point

T. Sugiyama, US Patent 4,217,034 (1980, **8 singlets)**

ΔF:F = 1:679



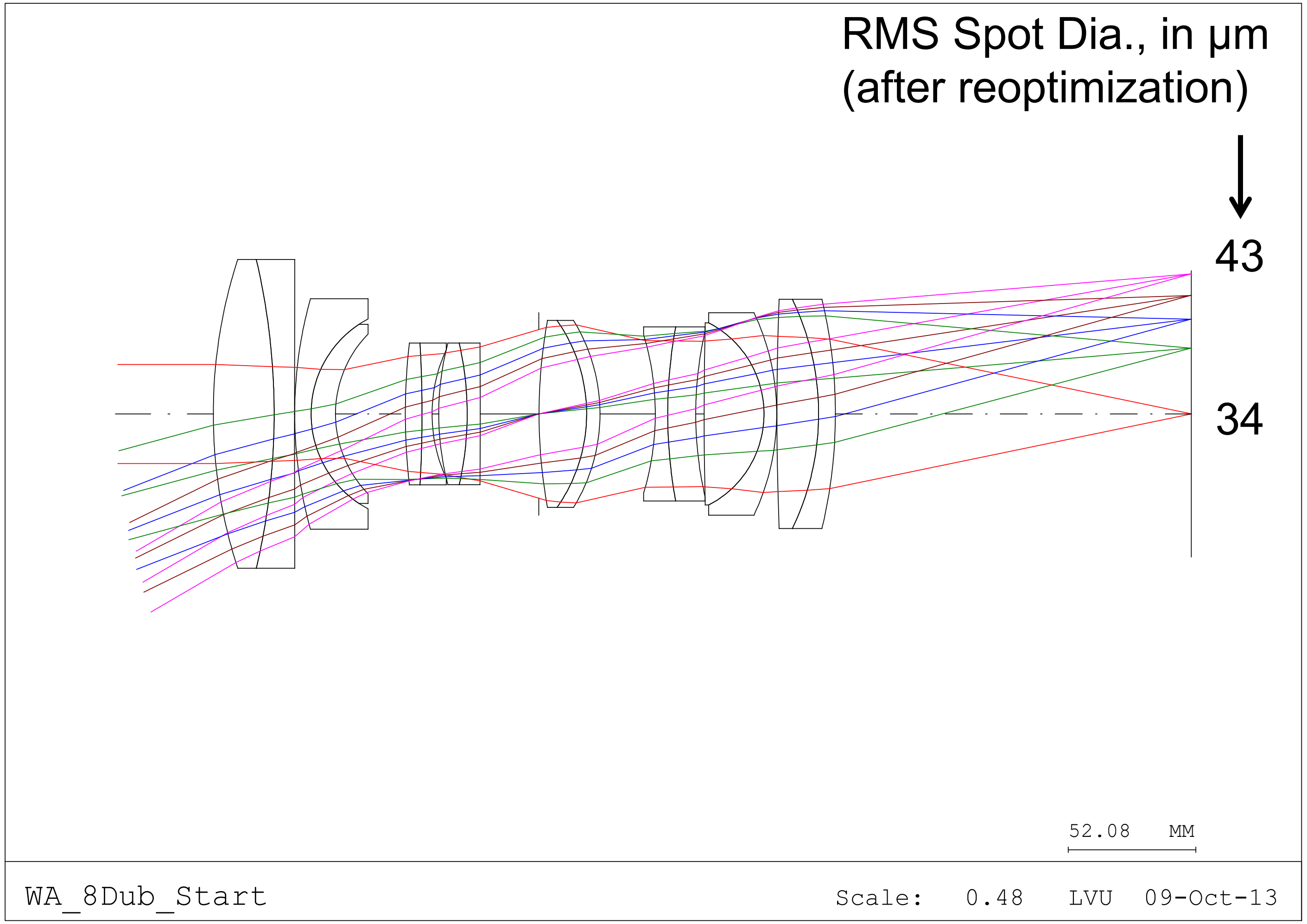
Design Approach

- In both cases:
  - Replace all singlets with doublets
  - Use Global Synthesis to find the best solution using variable glass types
    - Glasses constrained (by default) to lie on the “normal glass line”
    - Apply weighted constraints on SN2, to reduce tolerance sensitivity
  - Replace the fictitious glasses with the nearest “real” glasses and optimize locally
  - Use Glass Expert to improve the glass choice
    - Glass substitutions subject to realistic constraints on thermal mismatch and transmission
    - Apply weighted constraints on SN2, to control tolerance sensitivity
- The only difference:
  - In the first case, the doublets are required to be individually achromatic
  - In the second case, we drop this requirement

Replace Singlets with Doublets

Re-Optimize Locally

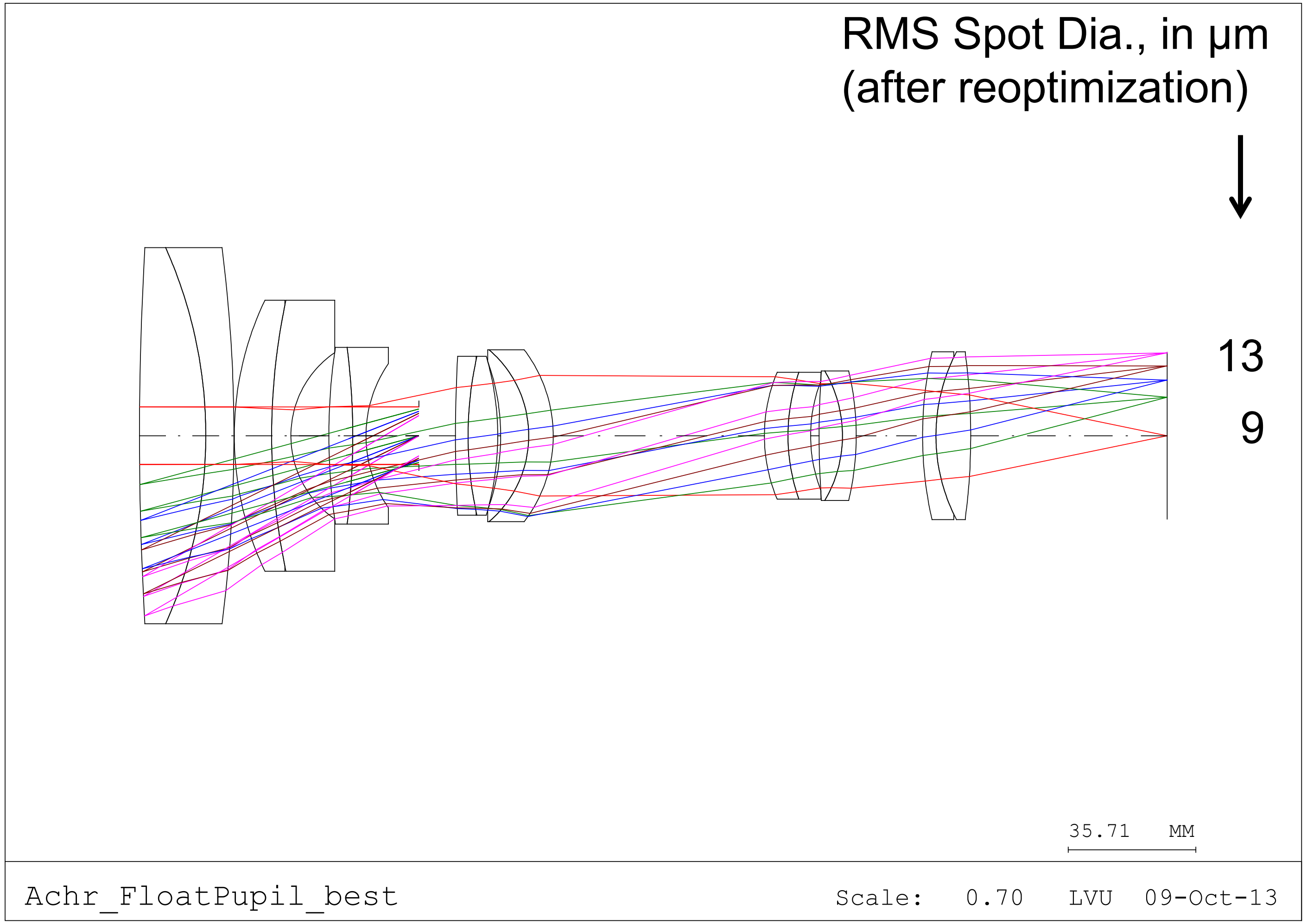
ΔF:F = 1: 659



Allow the Pupil to Float, Re-Optimize with GS

Doublets Constrained to Be Achromatic

ΔF:F = 1:900

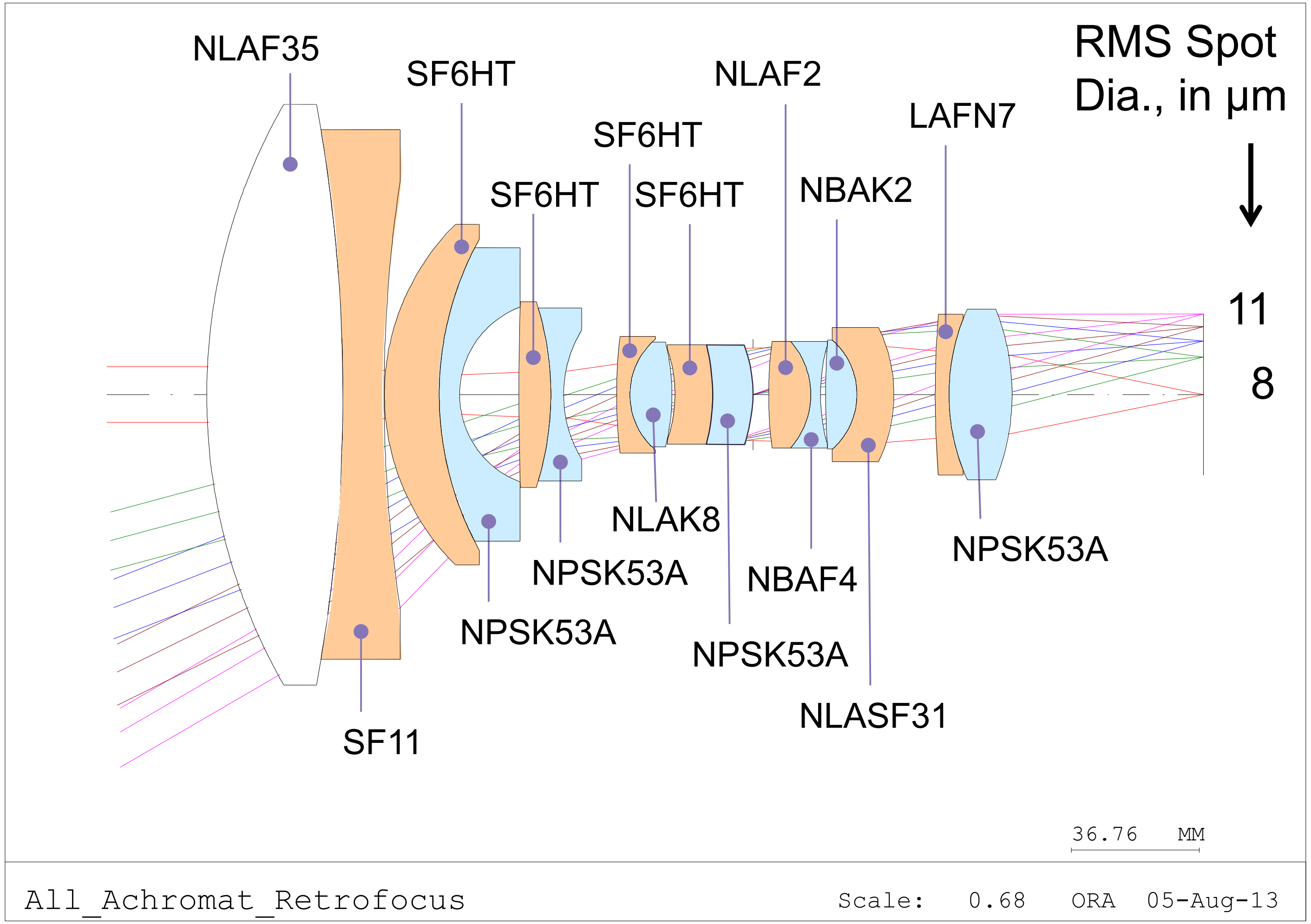


Last Steps: Glass Expert and Freeze the Stop

- Replace fictitious glasses with real glasses using Glass Fit
- Re-optimize locally (Doublets constrained to be achromatic)
- Use Glass Expert to improve the glass choice
- Materials: Any Schott glass allowed, provided:
  - Thermally induced shear at edge of the part < 5 um over 50 degrees C
  - Transmission > 80% at the blue end
- Insert a real stop
- Re-optimize (Doublets constrained to be achromatic)
- Set apertures for approximately 70% illuminance at the corner of the field

First Solution: 8 Achromats

ΔF:F = 1:1,045

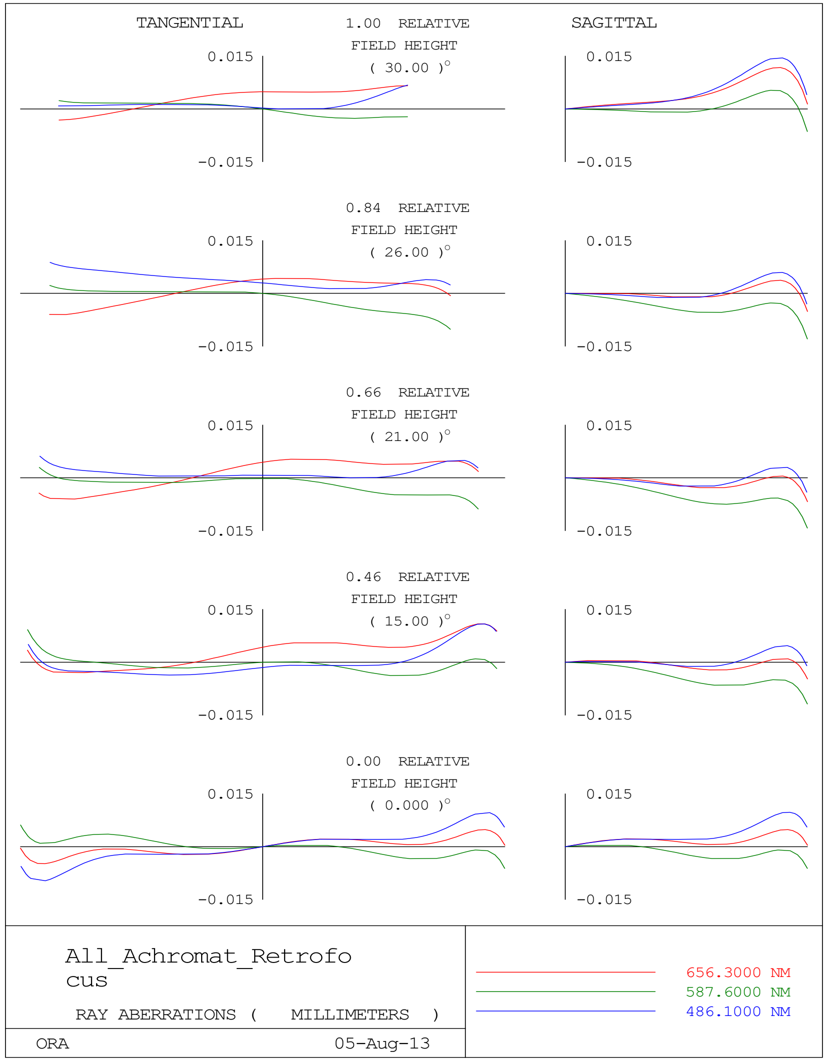


Ray Fans

8 Achromats

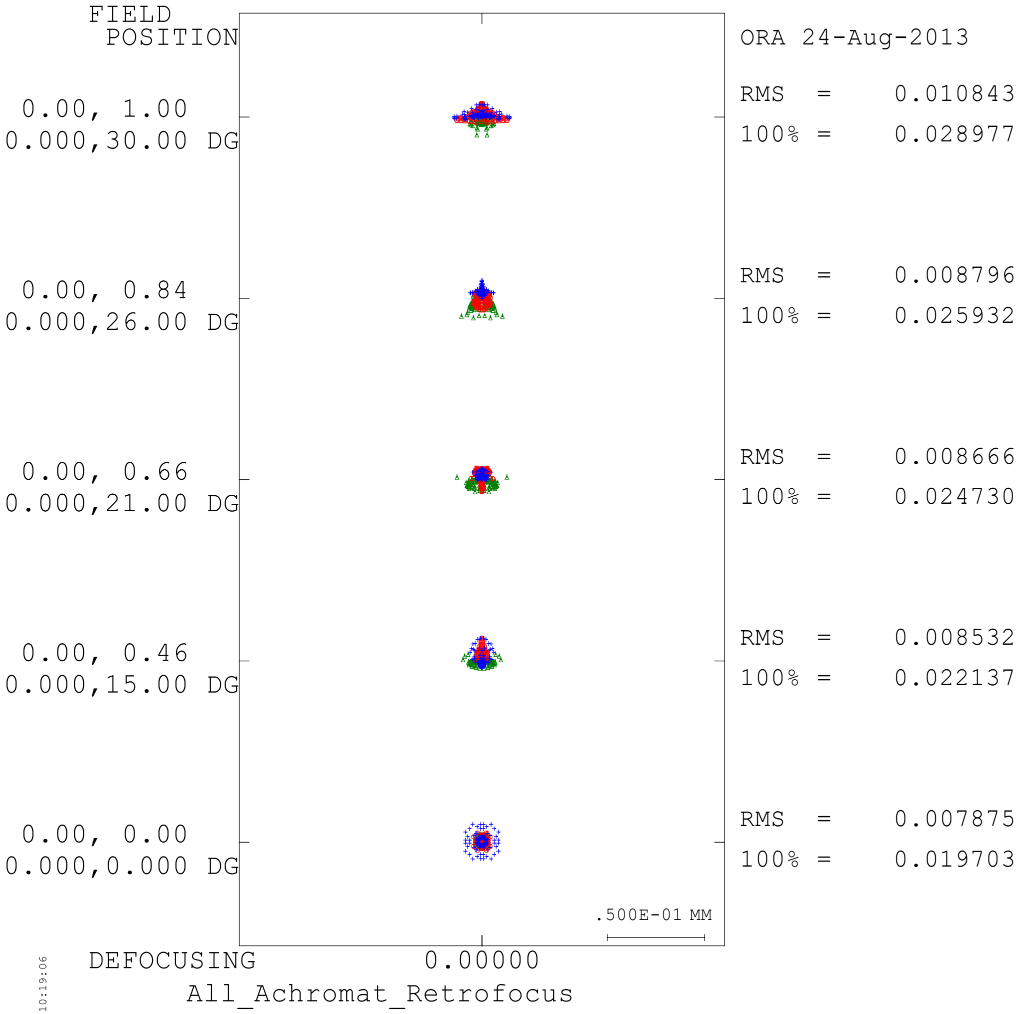
Scale: ±15 μm

Performance limited by secondary color and secondary chromatic variation of aberration

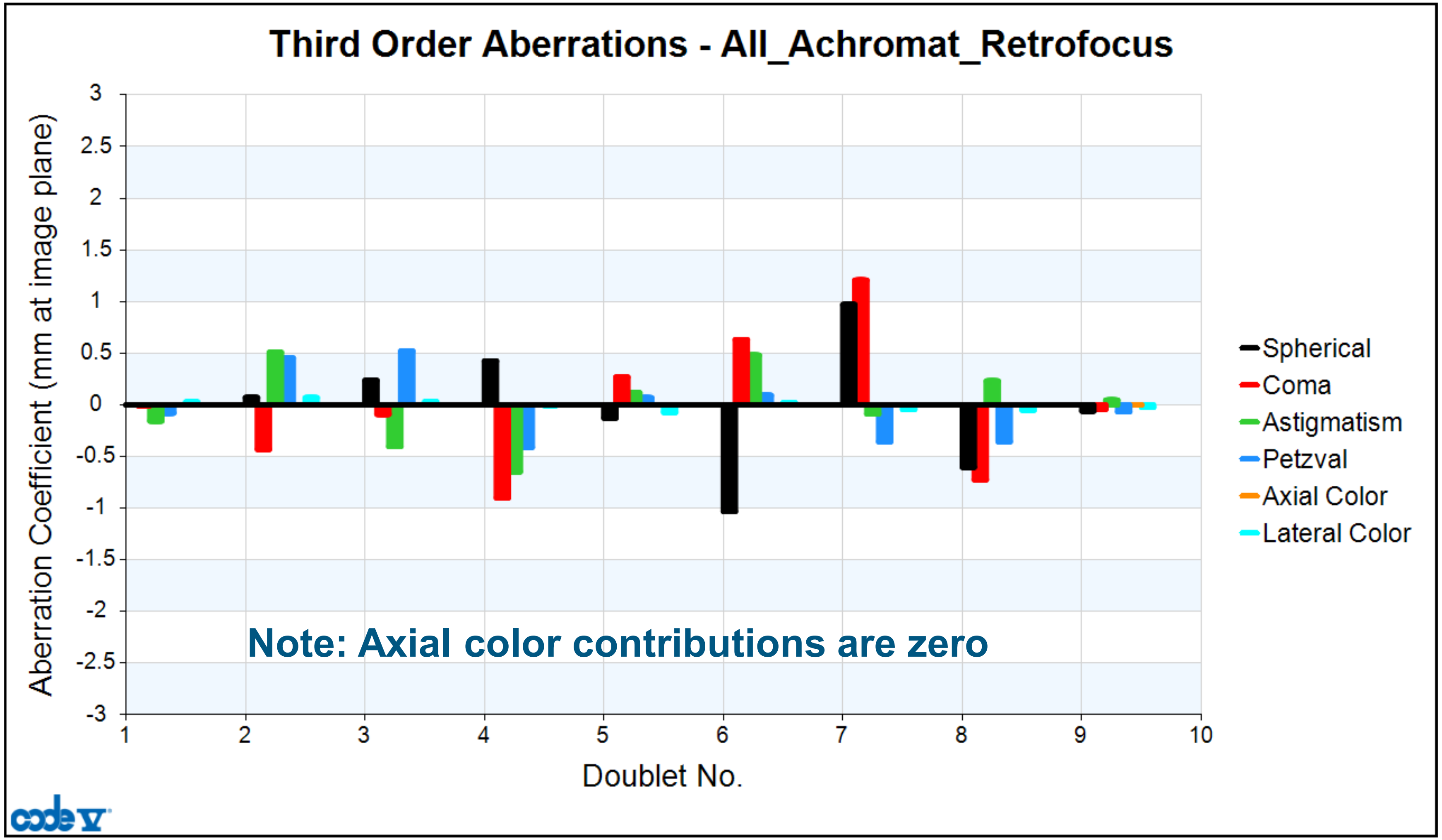


Spot Diagrams

8 Achromats

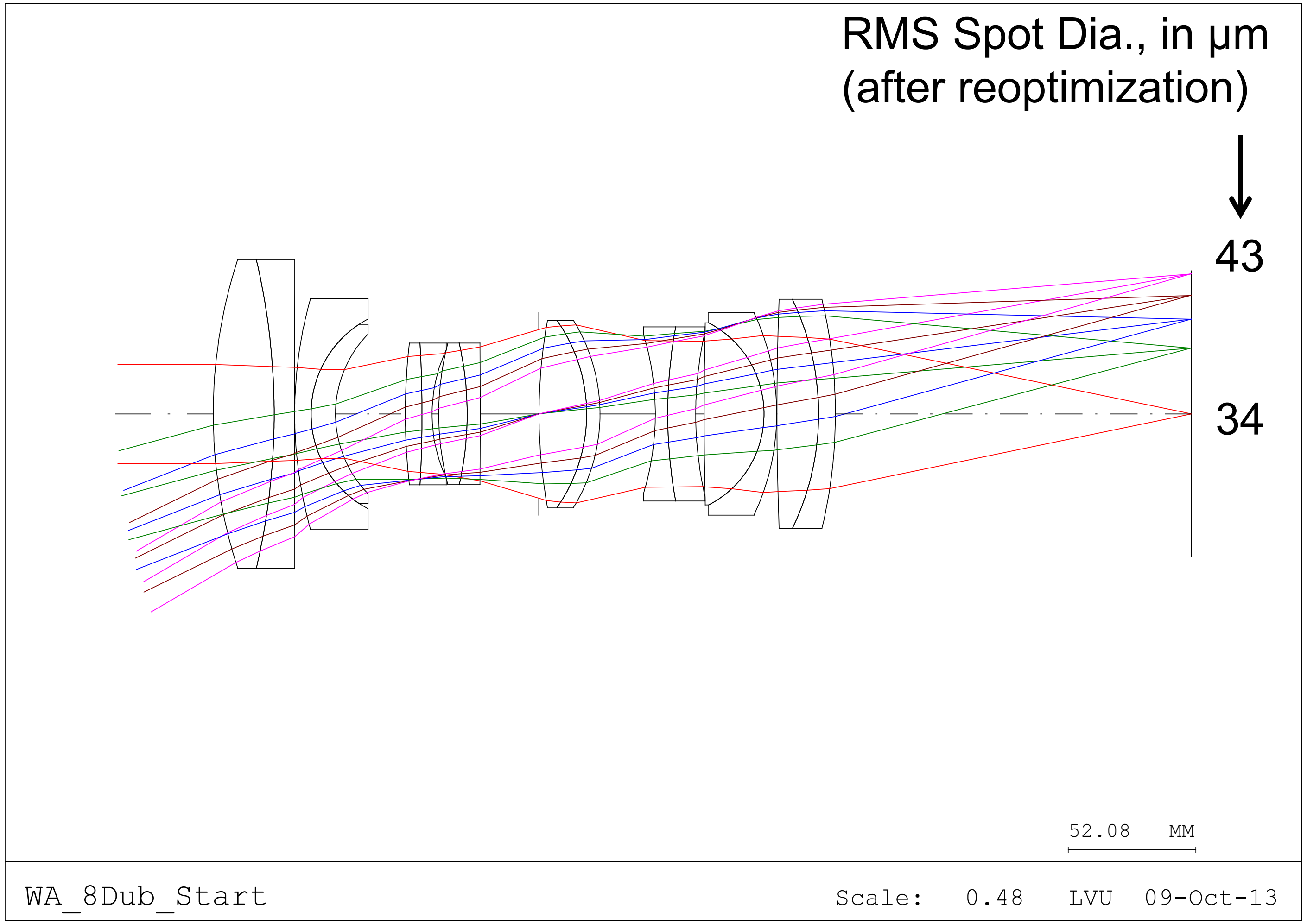


Doublet-by-Doublet Aberration Contributions
(8 Achromats)



Return to 8-Doublet Starting Point

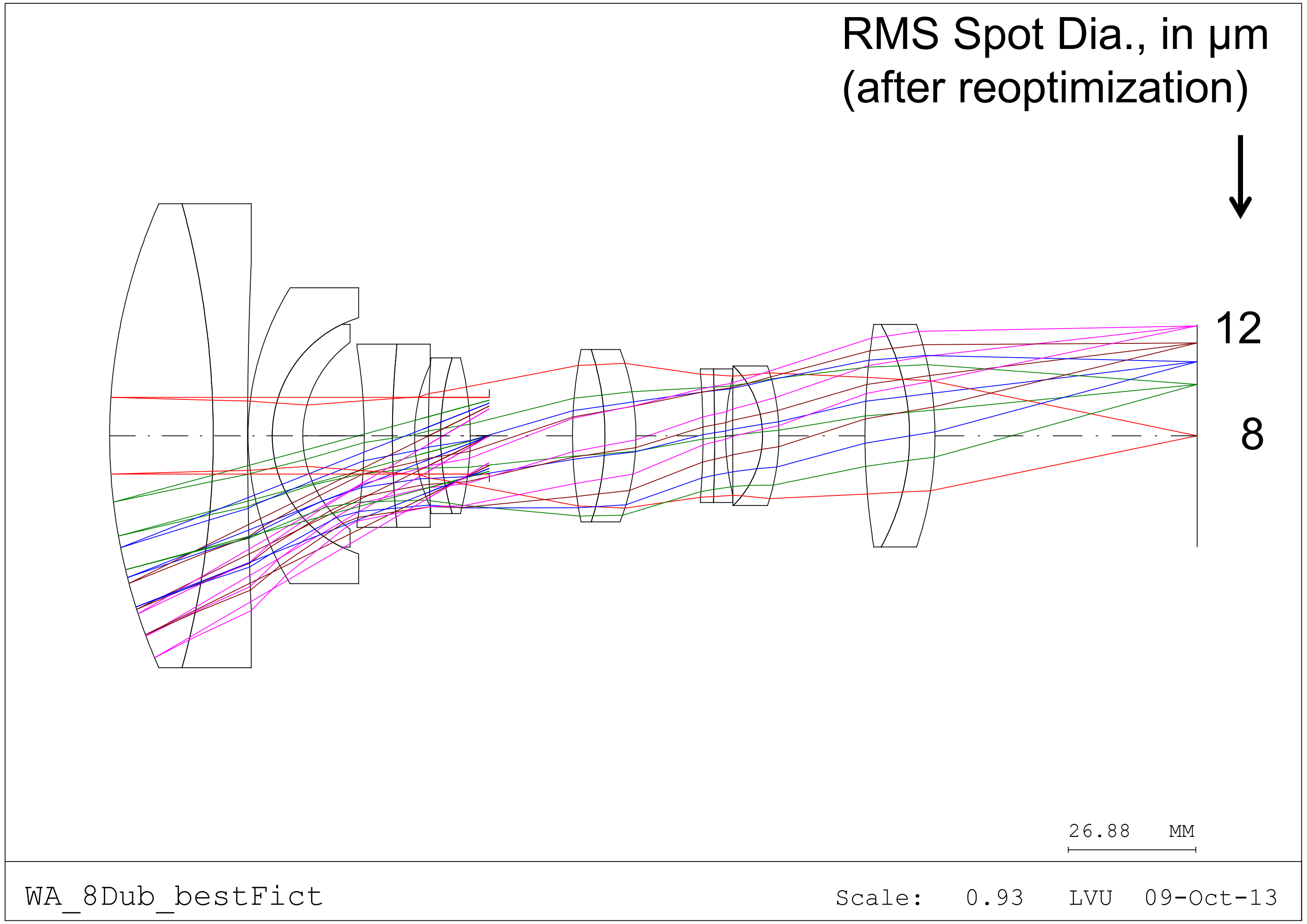
ΔF:F = 1: 659



Global Synthesis, Fictitious Glasses

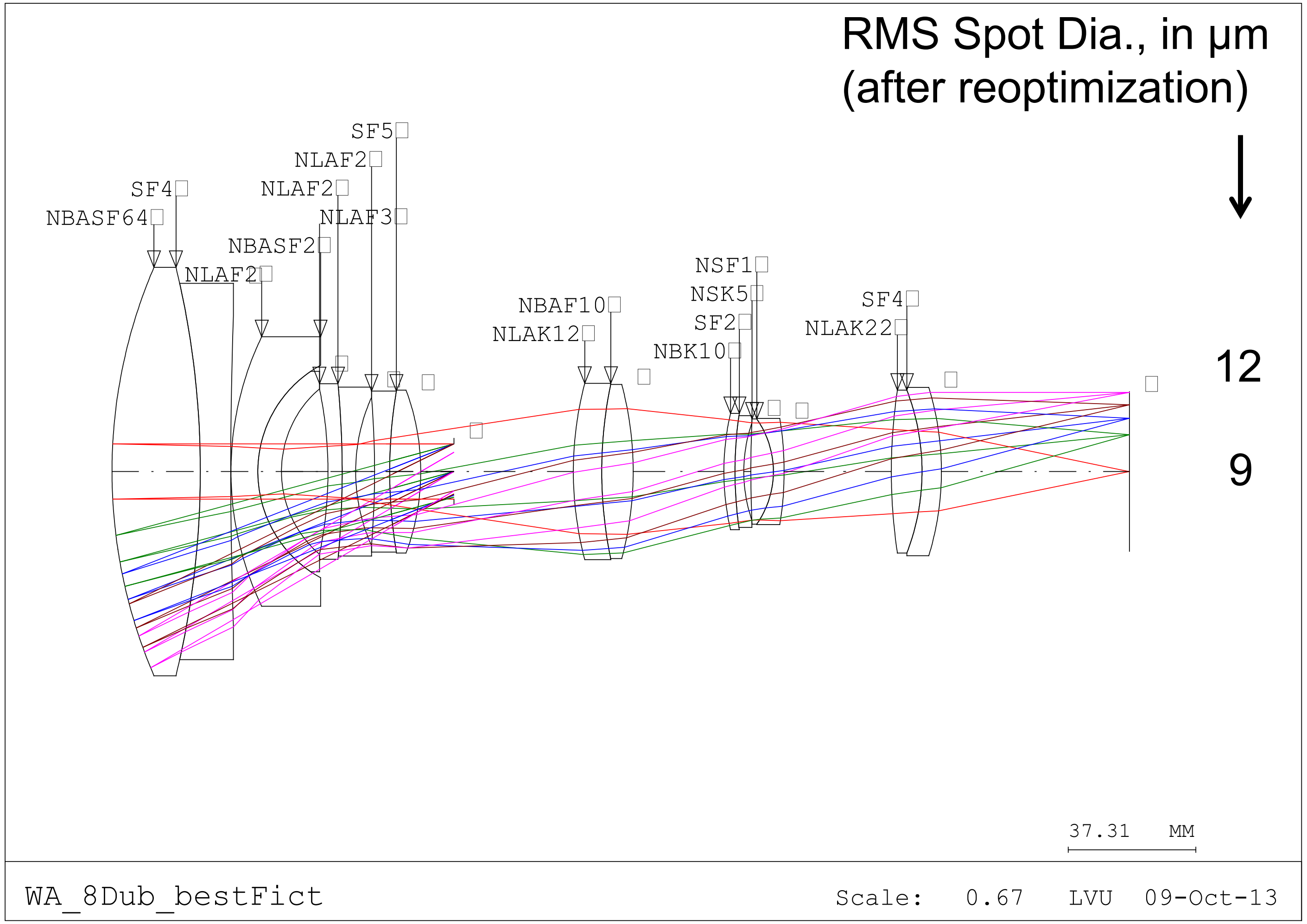
(Doublets No Longer Required to Be Achromatic)

ΔF:F = 1: 1285



Convert to Nearest Real Glass, Re-Optimize

ΔF:F = 1: 1547



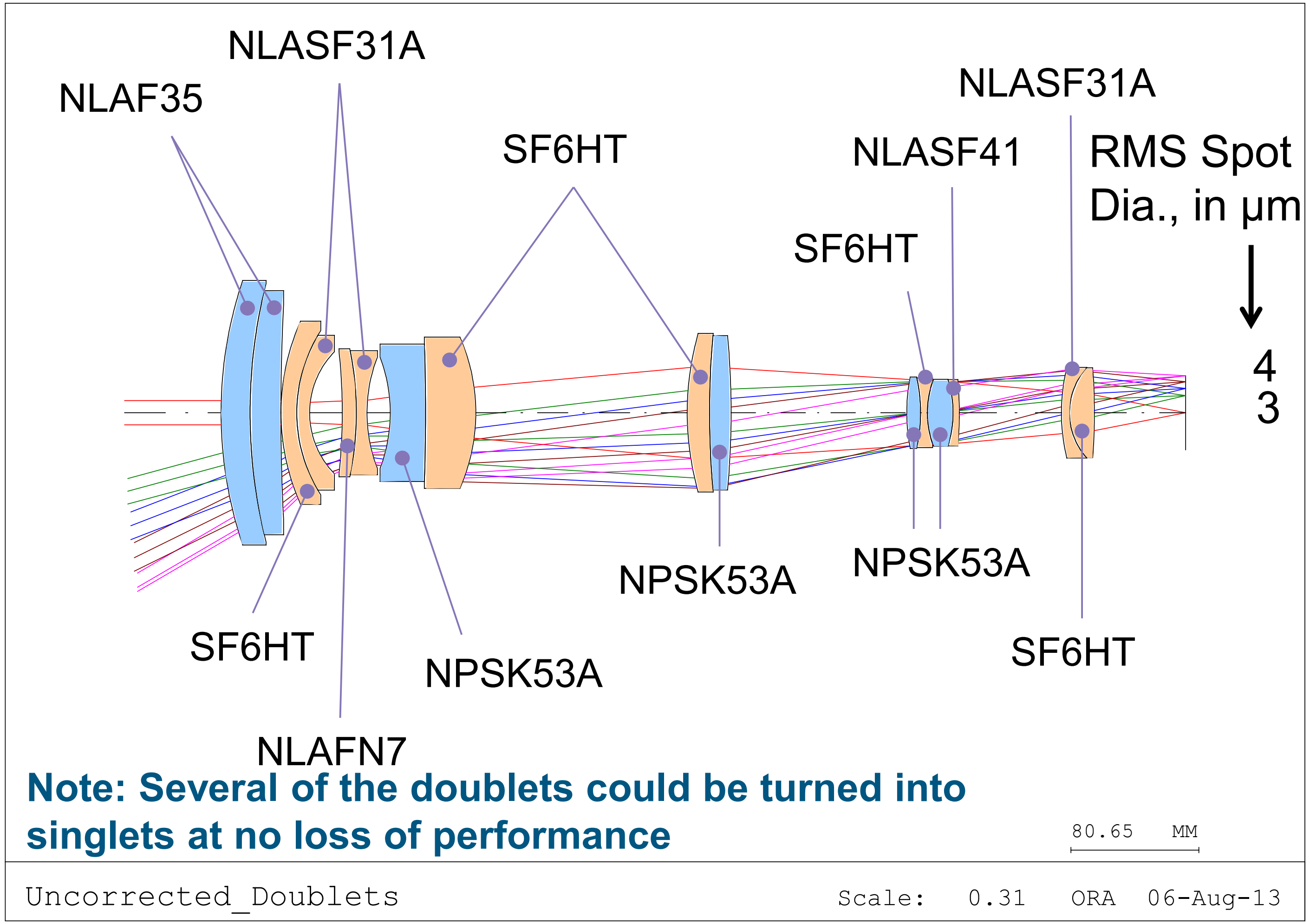
Last Steps: Glass Expert and Freeze the Stop

- Use Glass Expert to look for real glasses that improve performance
- Materials: Any Schott glass allowed, provided:
  - Thermally induced shear at edge of the part < 5 um over 50 degrees C
  - Transmission > 80% at the blue end
- Insert a real stop,
- Re-optimize
- Set apertures for approximately 70% illuminance at the corner of the field

Second Design

8 Doublets (not Achromatic)

ΔF:F = 1: 4535



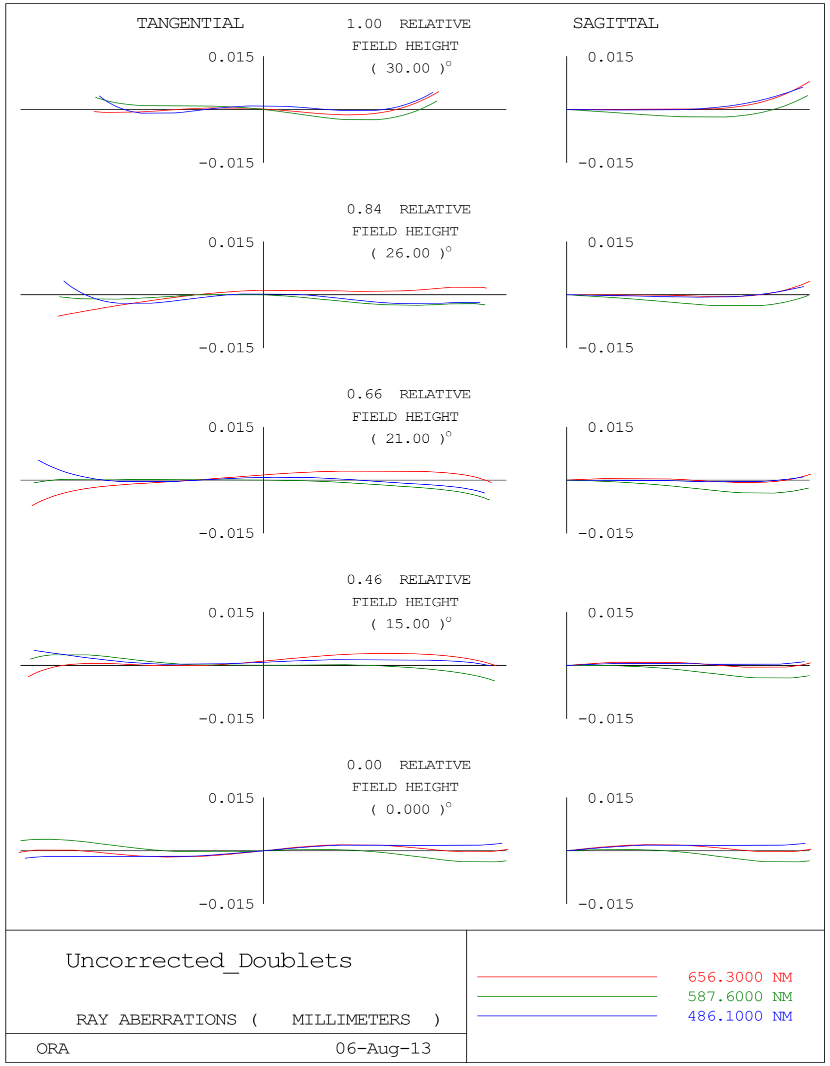
Note: Several of the doublets could be turned into singlets at no loss of performance

Ray Fans

8 Doublets

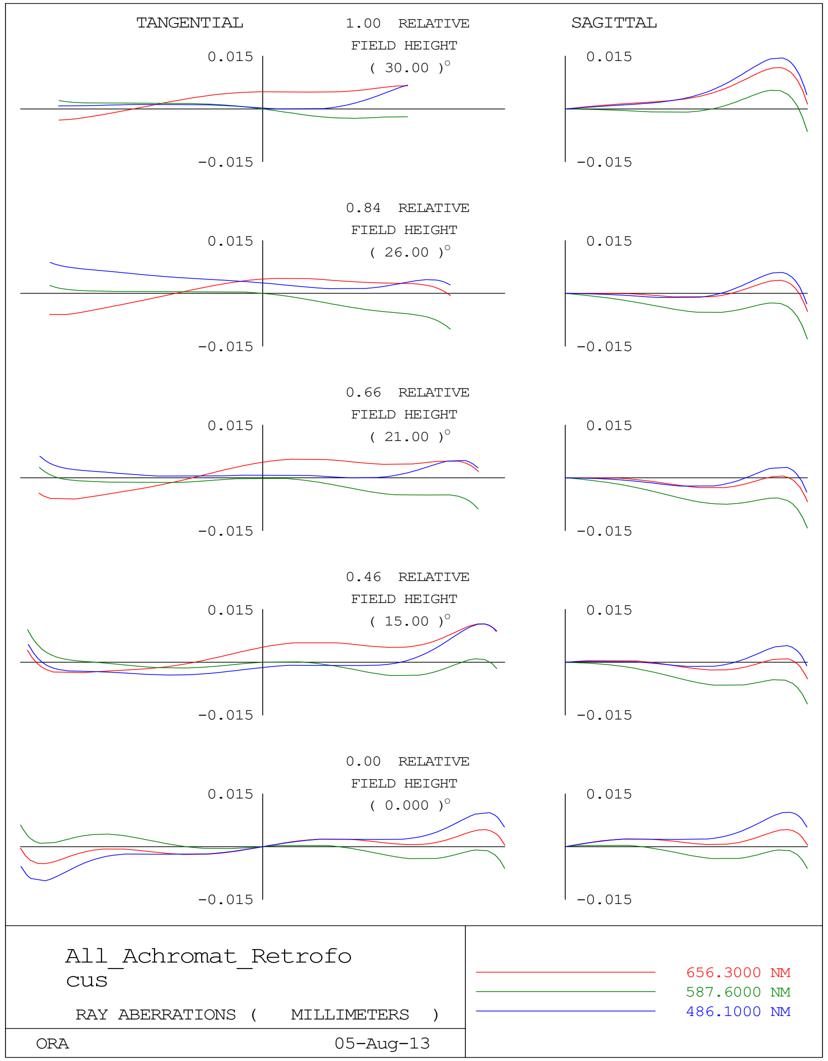
Scale: ±15 µm

Significantly better!



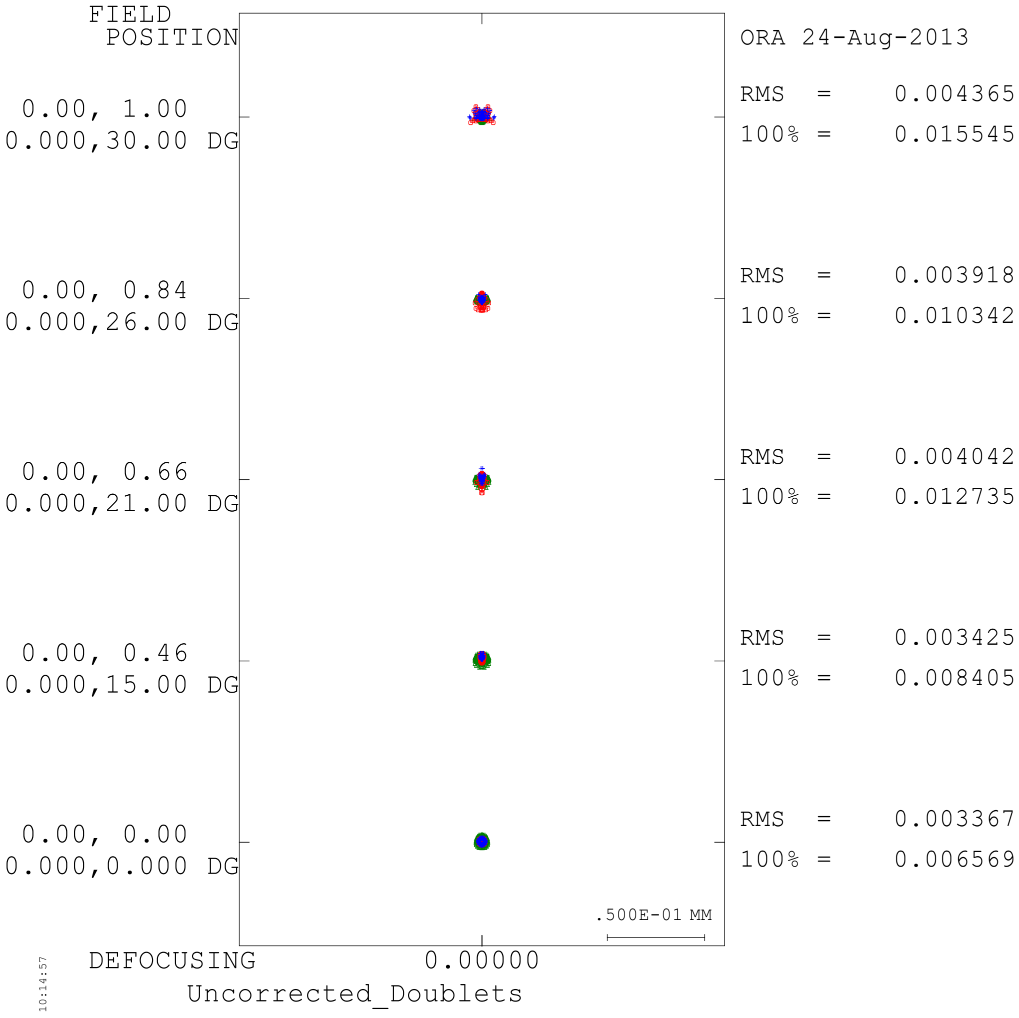
Ray Fans
(All-Achromat Design, for Comparison)

Scale: ±15 µm

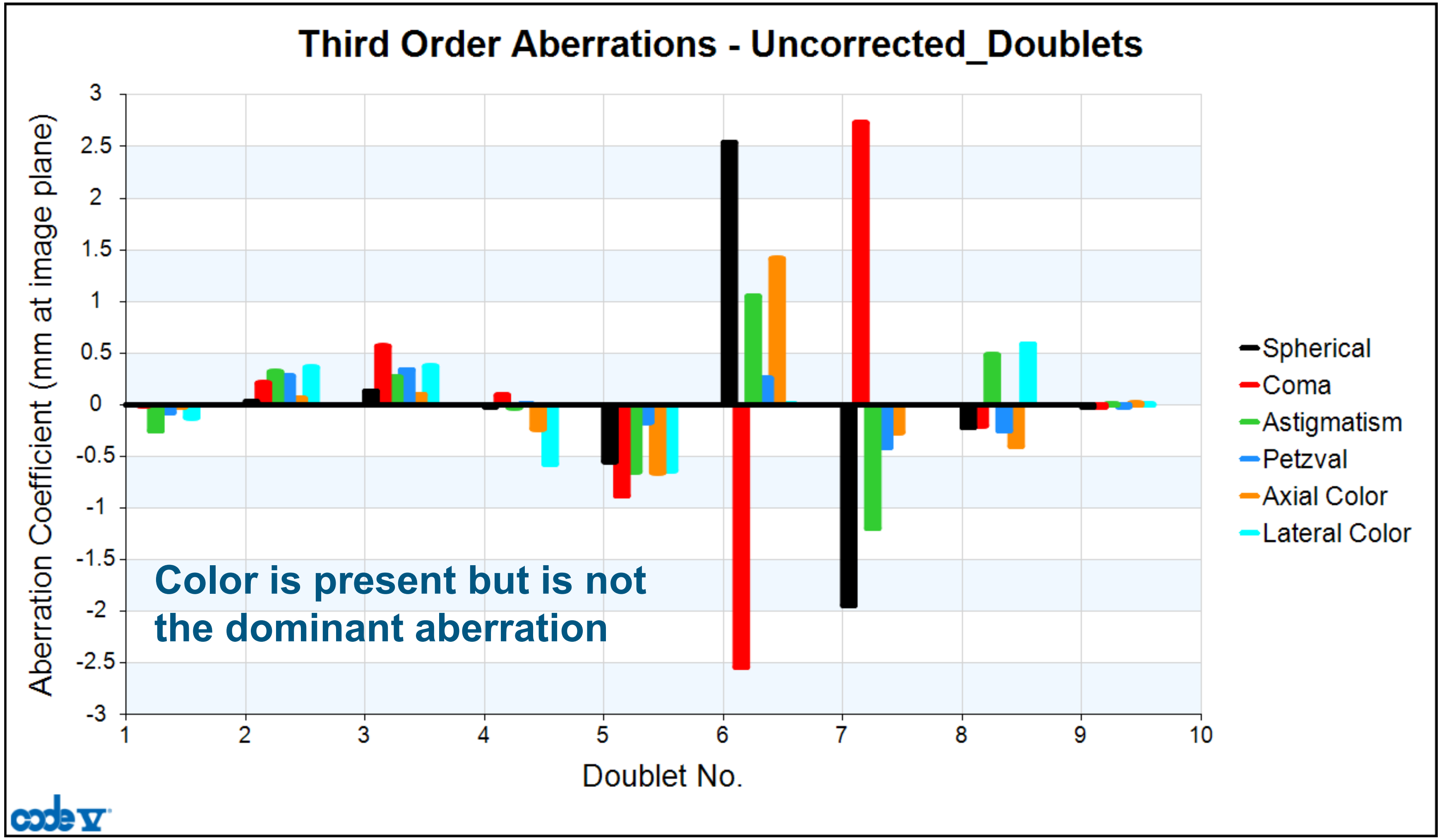


Spot Diagrams

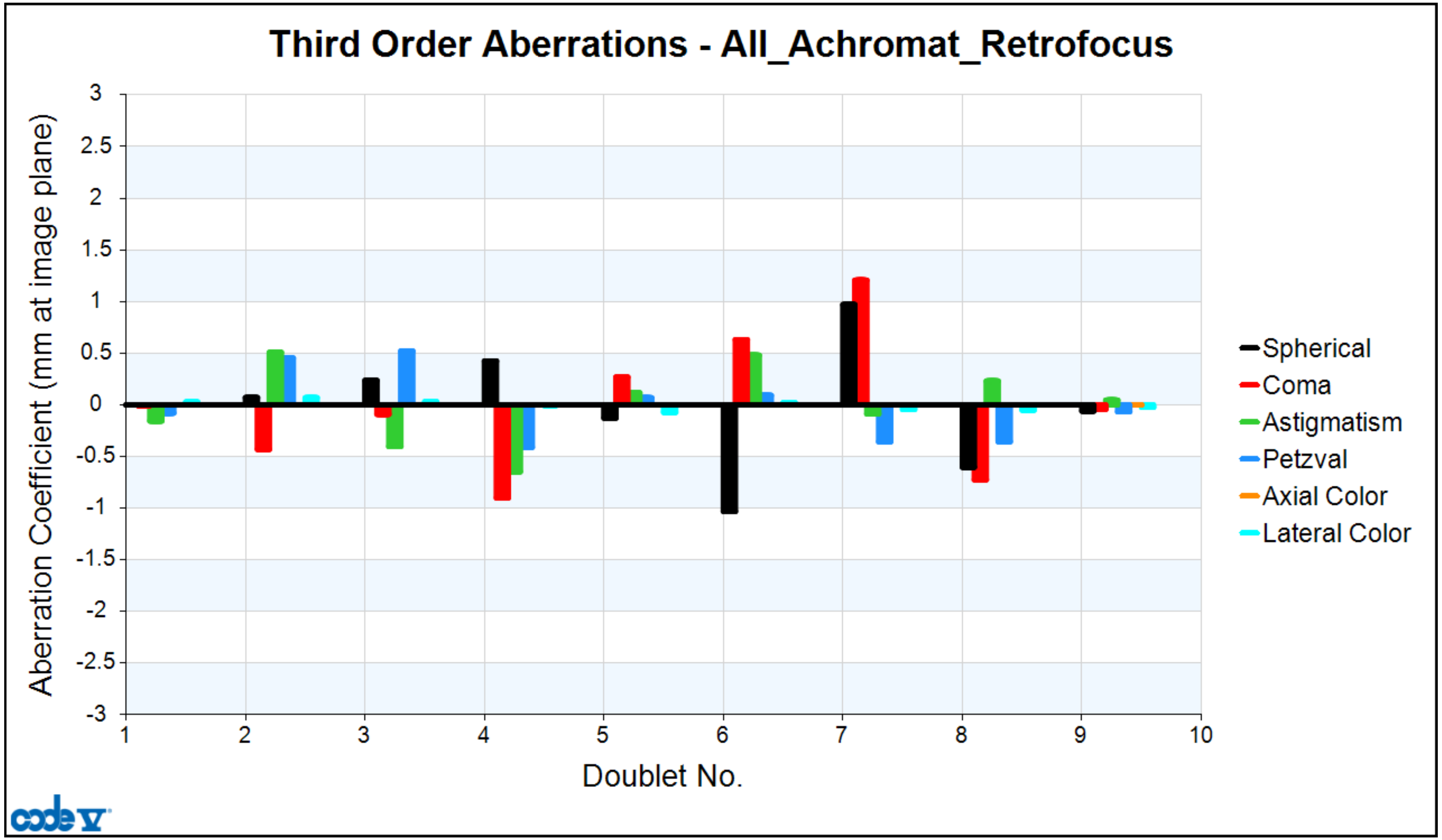
8 Doublets



Doublet-by-Doublet Aberration Contributions
(8 Doublets, not Achromatized)



Doublet-by-Doublet Aberration Contributions
(8 Achromats, for Comparison)



As-Built Performance Comparison

- For a meaningful comparison, the tolerances must be selected carefully
  - For extremely tight tolerances (practically indistinguishable from zero), the tolerance sensitivity does not matter, and the system with the better as-designed performance wins
  - For extremely loose tolerances, the tolerance-induced aberrations overwhelm the as-designed performance, and the system with the lower tolerance sensitivity wins
  - A meaningful comparison can only be obtained using realistic tolerances
- We defined "realistic" tolerances as meaning those that caused a 30% increase in RMS wavefront error *in the all-achromat design*
  - Starting with loose, "drop-in" level tolerances, we identified and tightened tolerance types until we reduced the increase in RMS wavefront to 30%
  - For simplicity, we applied all tolerances of a given type (radii, decenters, etc.) uniformly across all surfaces
- Tolerances for the 8-doublet design were identical to those for the all-achromat design

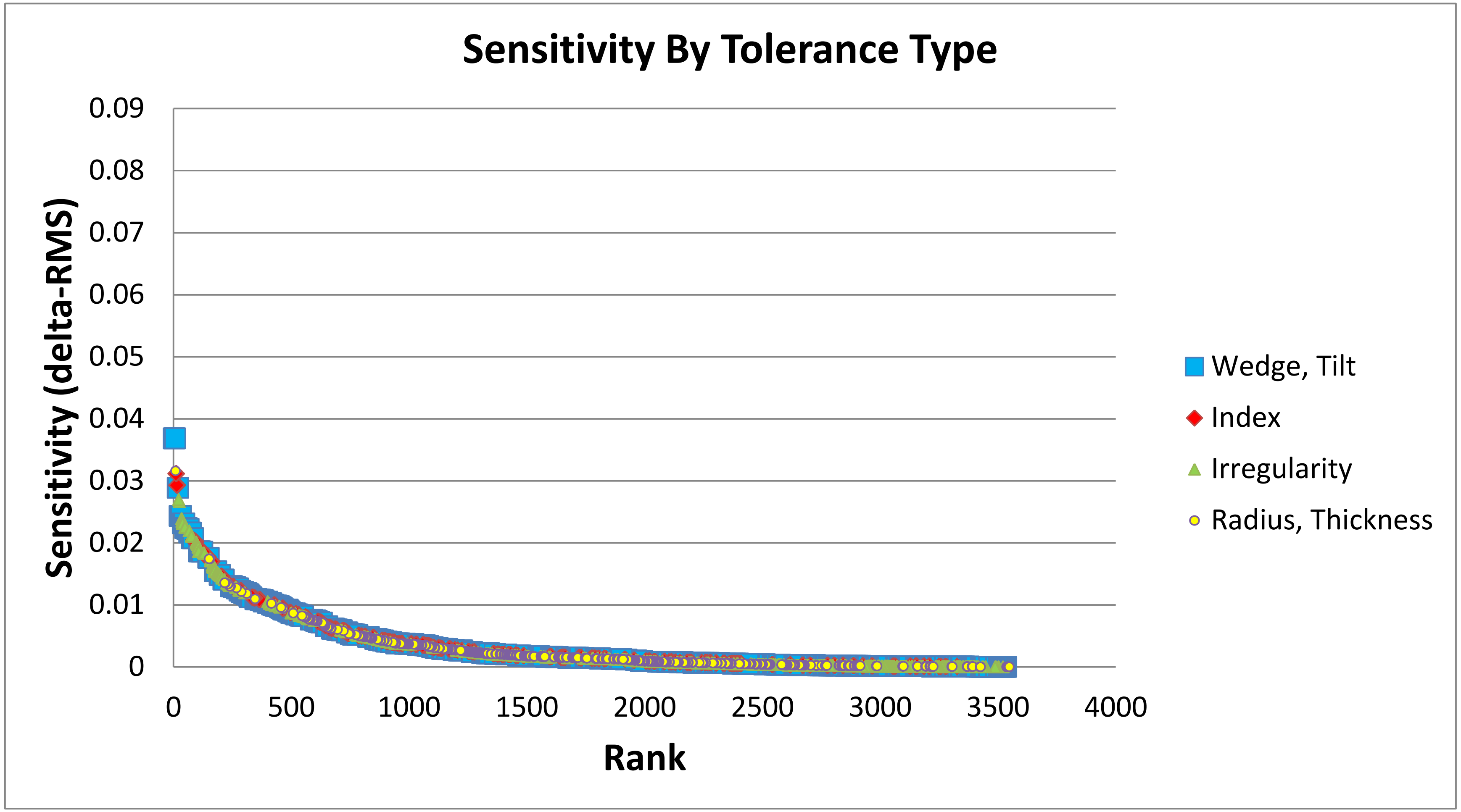
Tolerance List

- Radius errors: ±3 fringes at 0.6328 nm
- Surface irregularity: ±0.5 fringes at 0.6328 nm
- Glass thickness errors: ±0.025 mm
- Air space errors: ±0.025 mm
- Refractive index errors ±0.0002 (Schott "Step 1")
- Abbe errors: ±0.002 (Schott "Step 1")
- Wedge errors: ±0.005 mm Total Indicated Runout (applies to both singlets and doublets)
- Element tilt: ±0.005 mm Total Indicated Runout
- Element decenters: ±0.030 mm

- The only compensator we considered with these tolerances was refocus of the image plane.

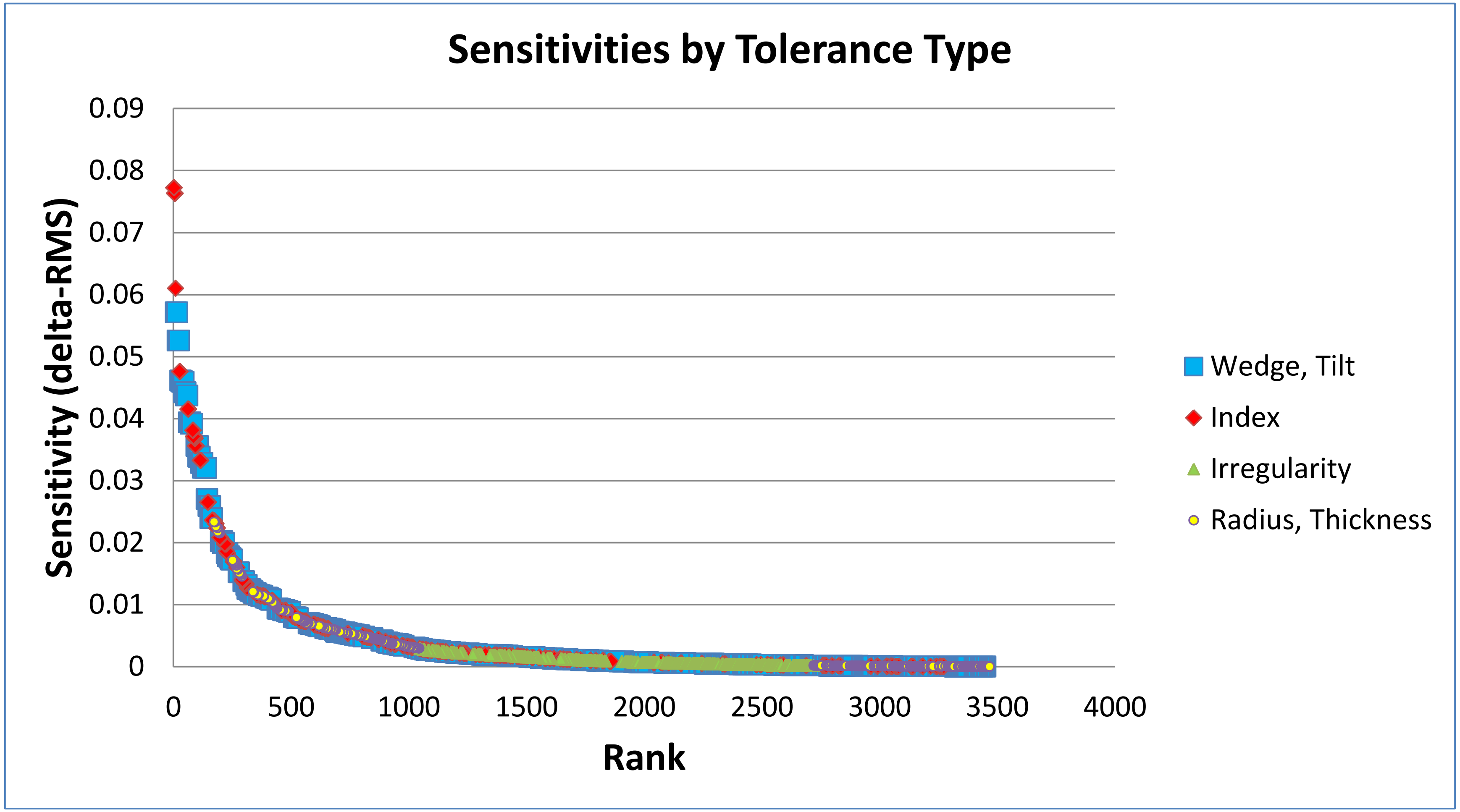
Sensitivities by Tolerance Type

8-Achromat Design



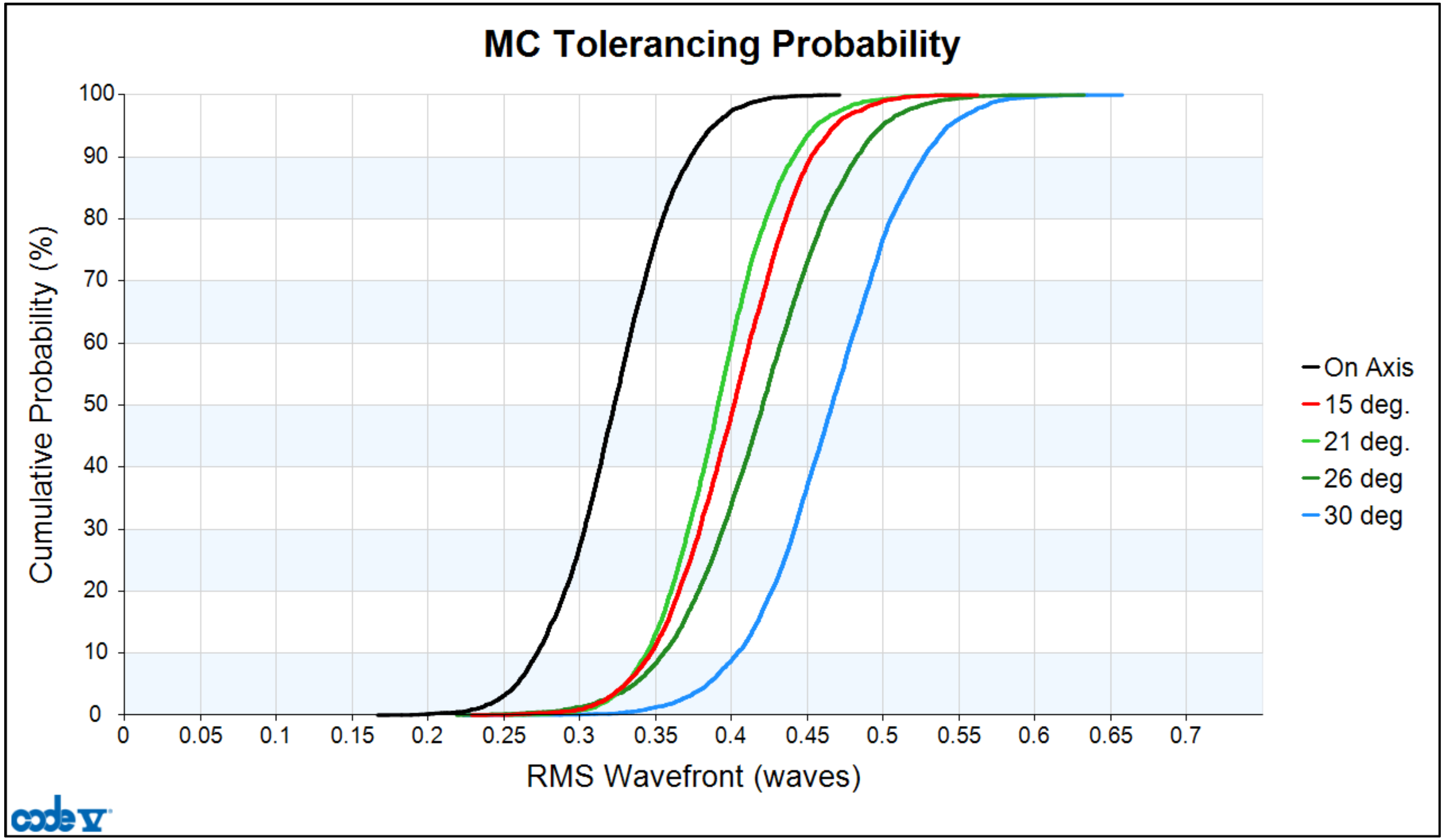
Sensitivities by Tolerance Type

8-Doublet Design



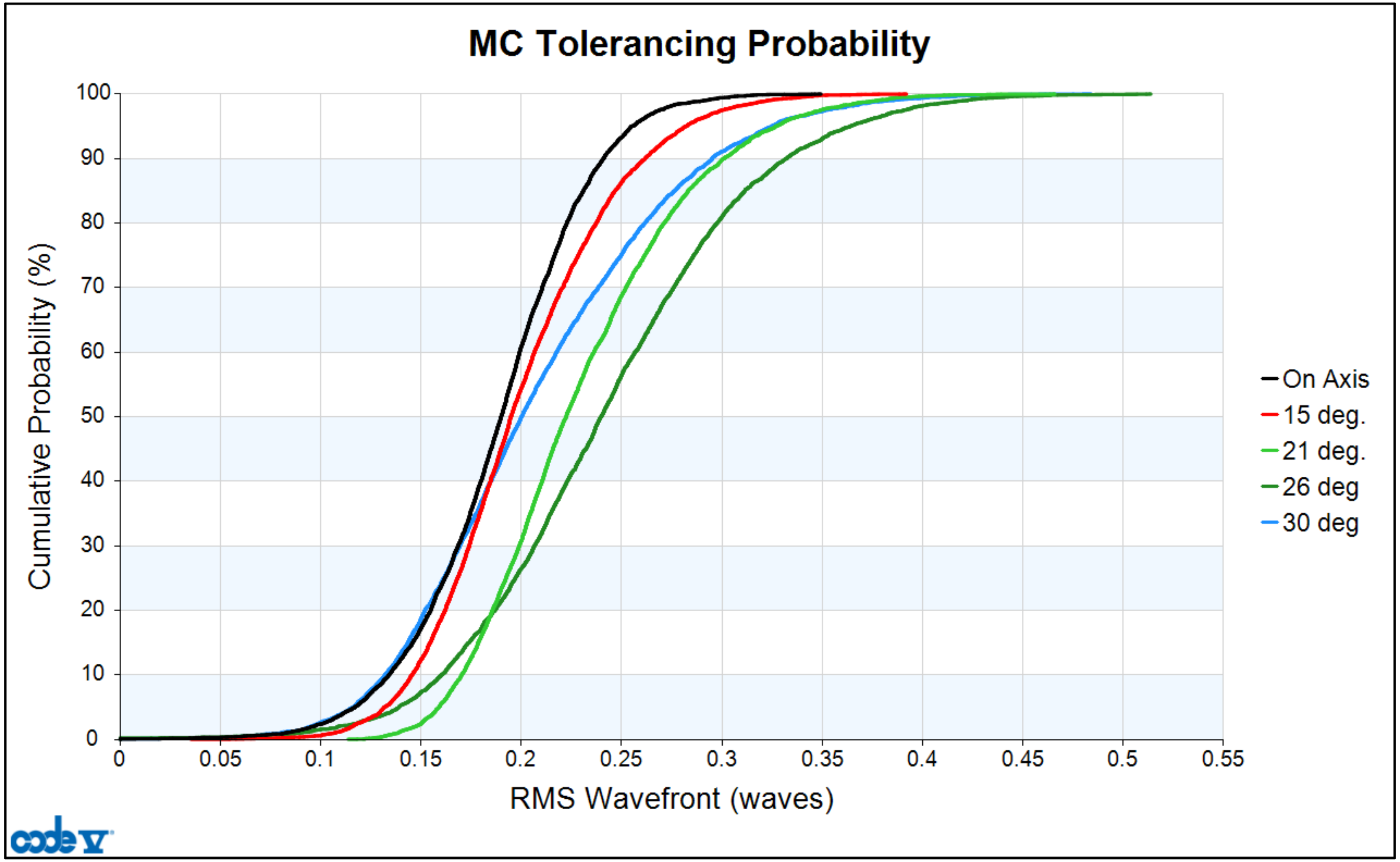
Cumulative Probability Distributions

8-Achromat Design



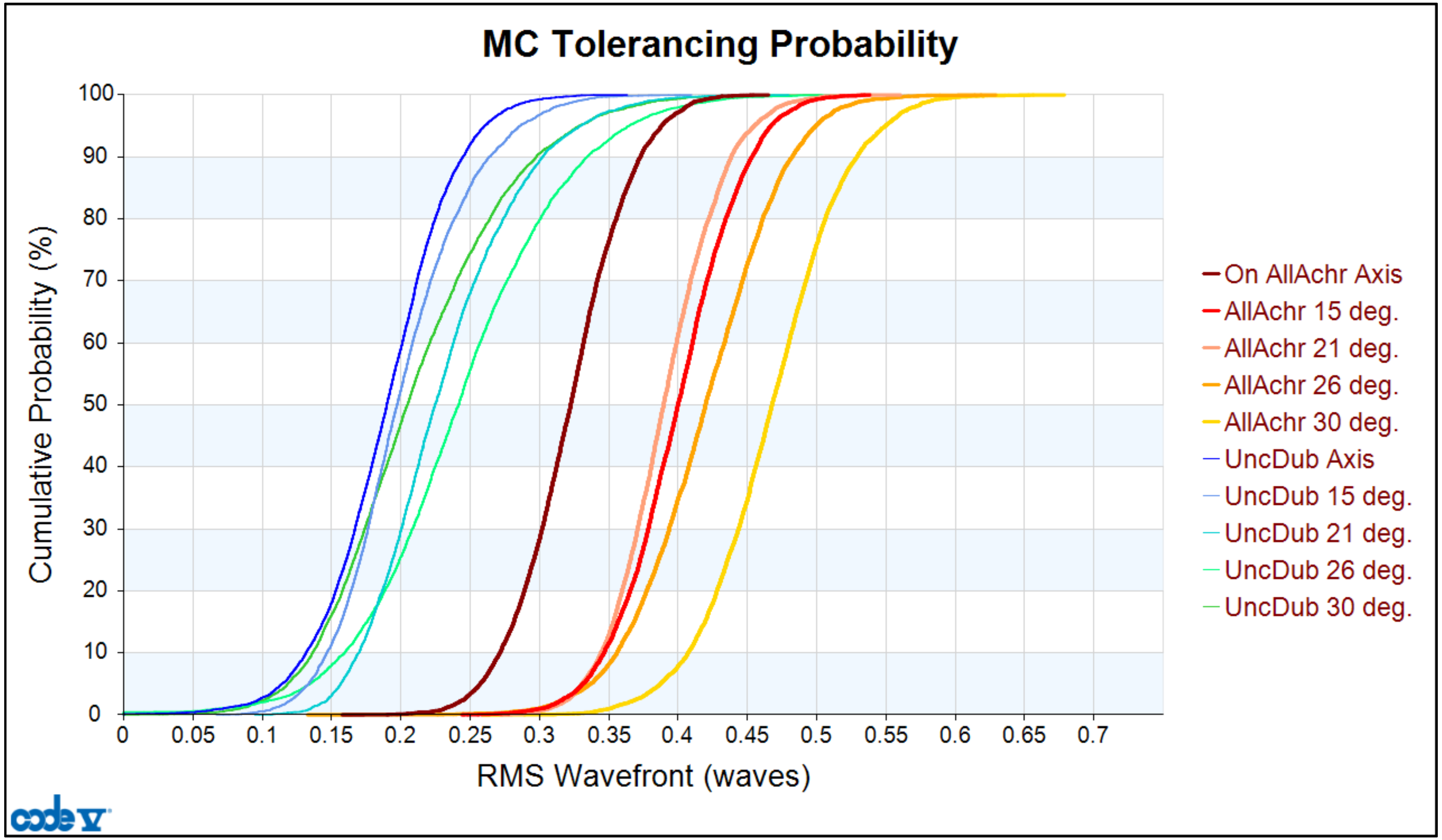
Cumulative Probability Distributions

8-Doublet Design



Cumulative Probability Distributions

Both Designs



Conclusions

- The induction of secondary color is a powerful design tool
- It tends to increase the tolerance sensitivity of the system
- In the system studied, the design that used uncorrected, separated elements to correct secondary was so much better, that with reasonable tolerances, it still had better performance than the all achromat design
- Recommended procedure:
  - Optimize with Global Synthesis and Fictitious Glasses
    - Use WTC constraints on SN2 to minimize sensitivity
    - Use ATC, ATE constraints to keep the design realistic
  - Use Glass Fit to Replace Fictitious Glasses with Real Glasses
    - Replace them all at once (don’t bother to re-optimize between replacements)
    - Check to be sure there are no CTE violations; change glasses if needed
  - Use Glass Expert to improve the glass choices
    - Use WTC constraints on SN2 to minimize sensitivity
    - Use ATC, ATE constraints to keep the design realistic
  - Consider re-optimizing locally with SAB

Thank You