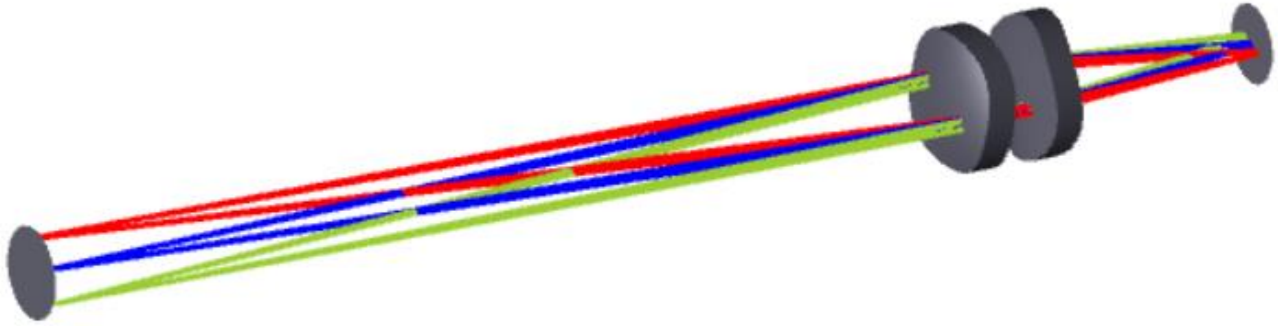
Variable Focus Machine Vision Lens Without Moving Parts:

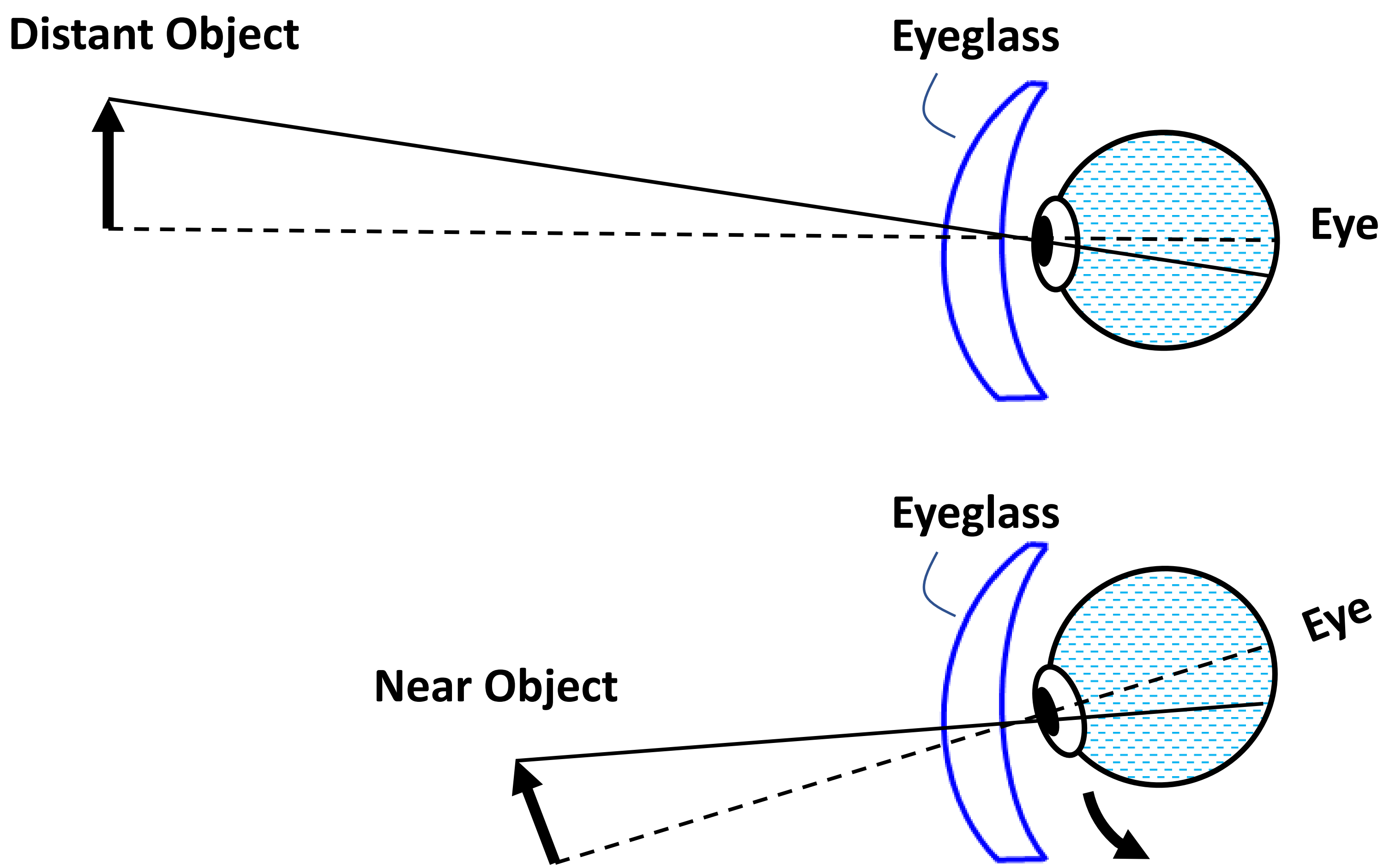
Freeform Progressive Eyeglasses for Non-Humans

RONIAN SIEW

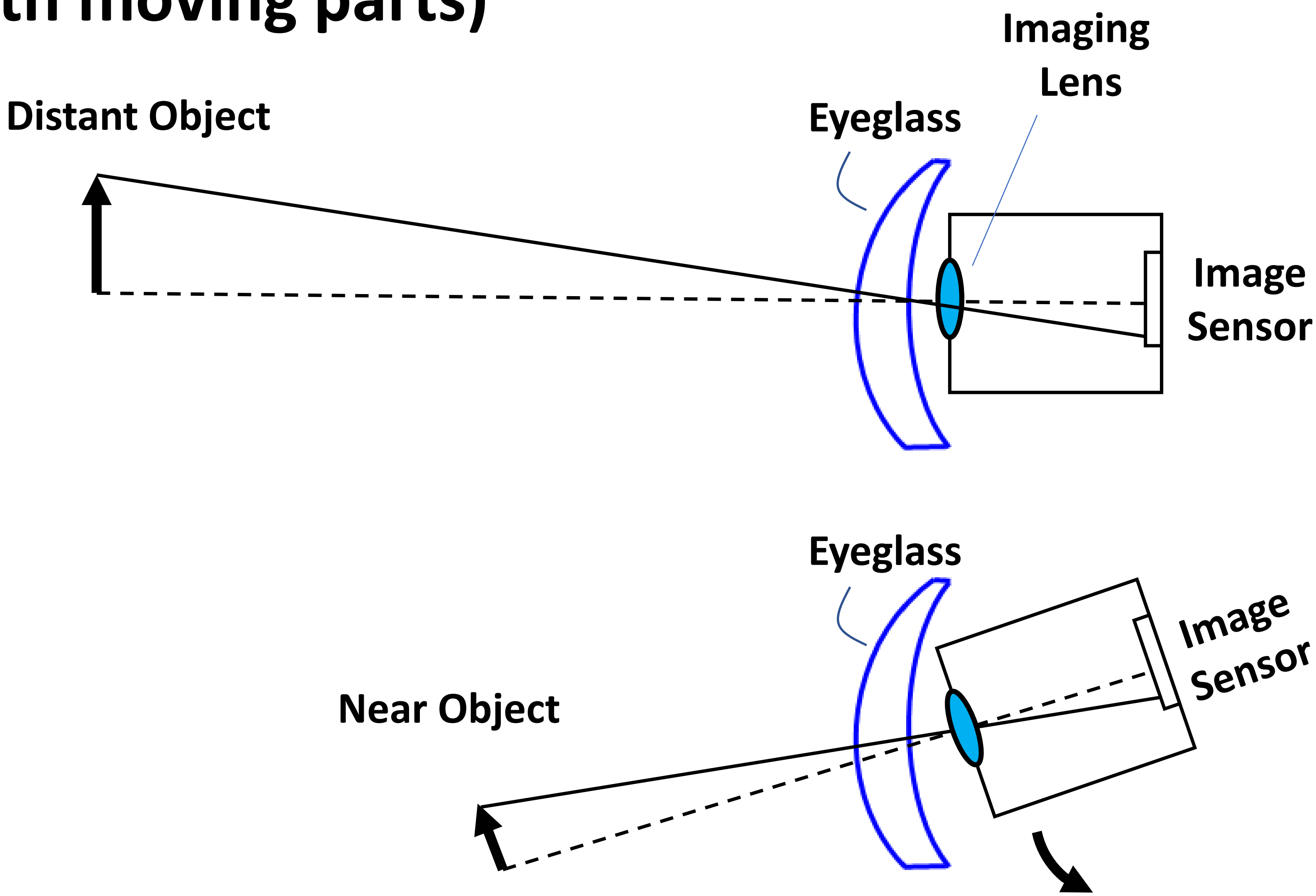


(Prepared for the OSA Applied Optics and Imaging Congress, Online, June 25th, 2020)

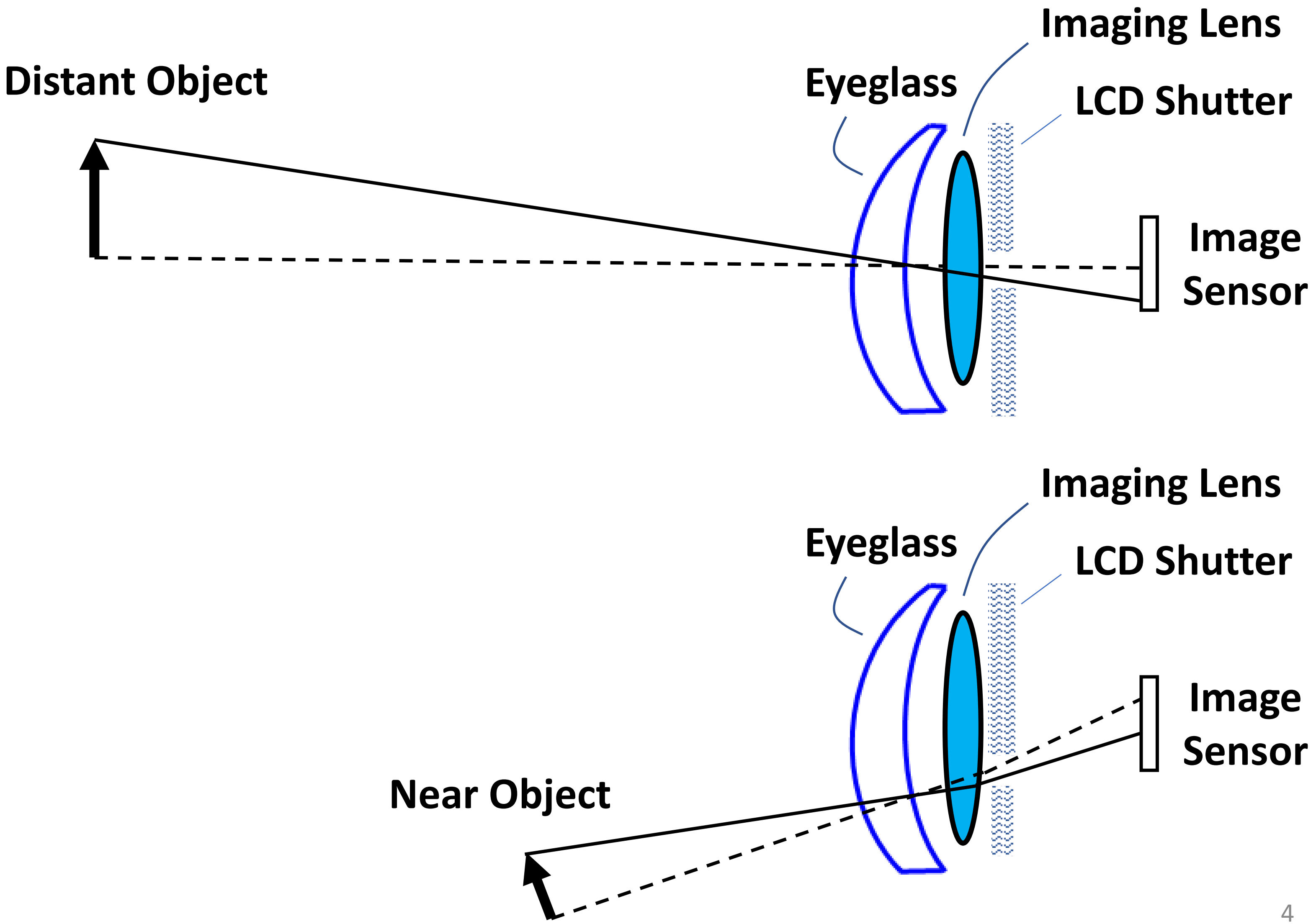
Progressive eyeglasses for humans



Progressive eyeglasses for a non-human (with moving parts)



Progressive eyeglasses for a non-human (***<u>without</u>*** moving parts)

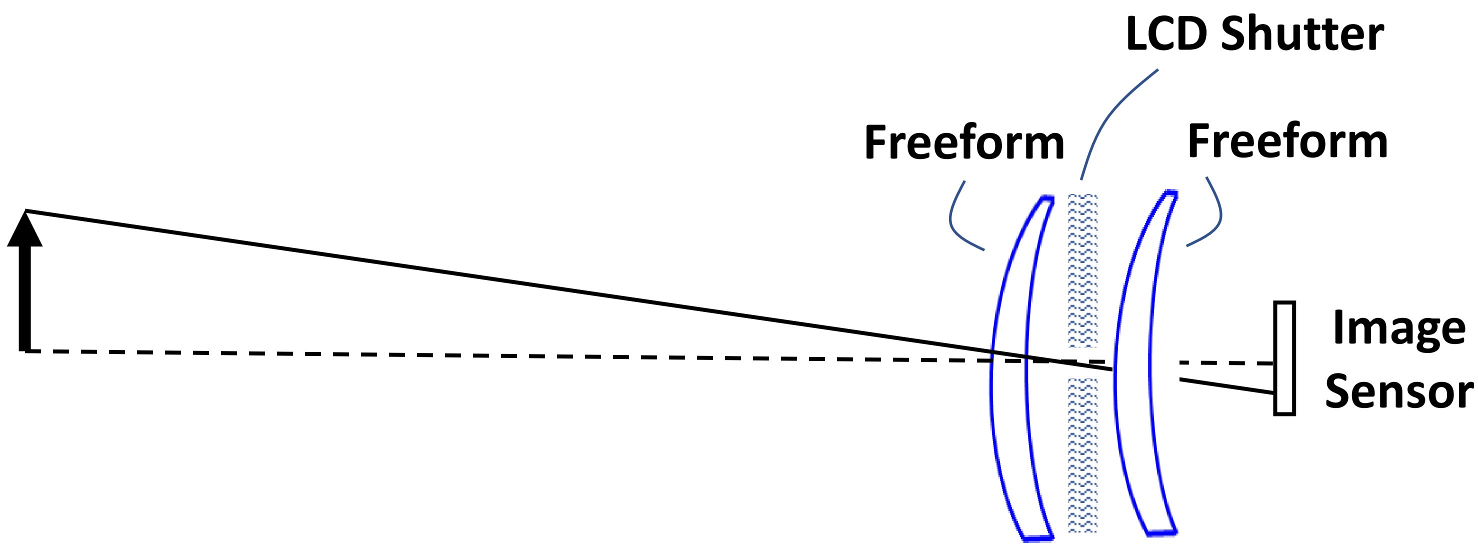


PRIOR ART: ***Discrete*** focal lengths

[1] K. E. Kuijk, "Optical Imaging System Having an Electronically Variable Focal Length and Optical Image Sensor Provided with such a System," U.S. Patent No. 4,927,241, (May 22, 1990).

[2] T. Gustafsson and S. Zyra, "Lens with Variable Focal Length," WIPO Patent Application No. WO/1998/027448, (Dec. 17, 1997).

CURRENT WORK: *Continuous* focal lengths by applying freeform surfaces



Lens prescription for the freeform system

Surf	Radius	Thickness	Material	Semi-Dia	Conic	Coeff. A
OBJ	Infinity	250.00	-	-	-	-
1	Infinity	5.00	-	-	-	-
2	58.638	6.00	N-LAK22	18.00	-6.956	-6.33402E-04
3	-127.173	4.00	N-SF6	18.00	-	-
4	772.599	5.00	-	18.00	-1042.18	-4.34842E-04
STOP	Infinity	5.00	-	1.50	-	-
6	57.595	6.00	N-LAK22	18.00	-1.121	5.63615E-04
7	-132.628	4.00	N-SF6	18.00	-	-
8	606.761	57.38	-	18.00	-3.257E+30	6.26372E-04
IMG	Infinity	0.00	-	8.00	-	-

NOTES:

1. Length dimensions are in mm
2. Set wavelengths at 450 nm, 550 nm, and 650 nm (weight = 1 each)
3. Set the field points at +/- 2.5 deg., so the full field of view is 5 degrees
4. Don't forget to aim the chief ray into the entrance pupil

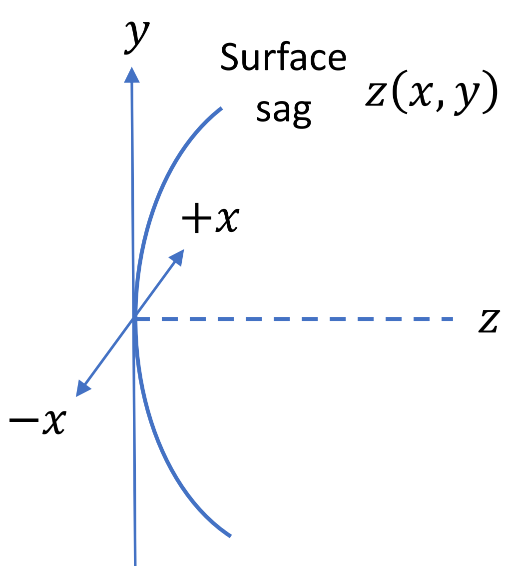
The coefficient "A" and conic are defined by the following formula for surface sag

c = 1/Radius

Surface Sag ***Coefficient A***

$$z(x,y) = \frac{c(x^2+y^2)}{1+\sqrt{1-(1+k)c^2[x^2+y^2]}} + Ayx^2$$

Conic

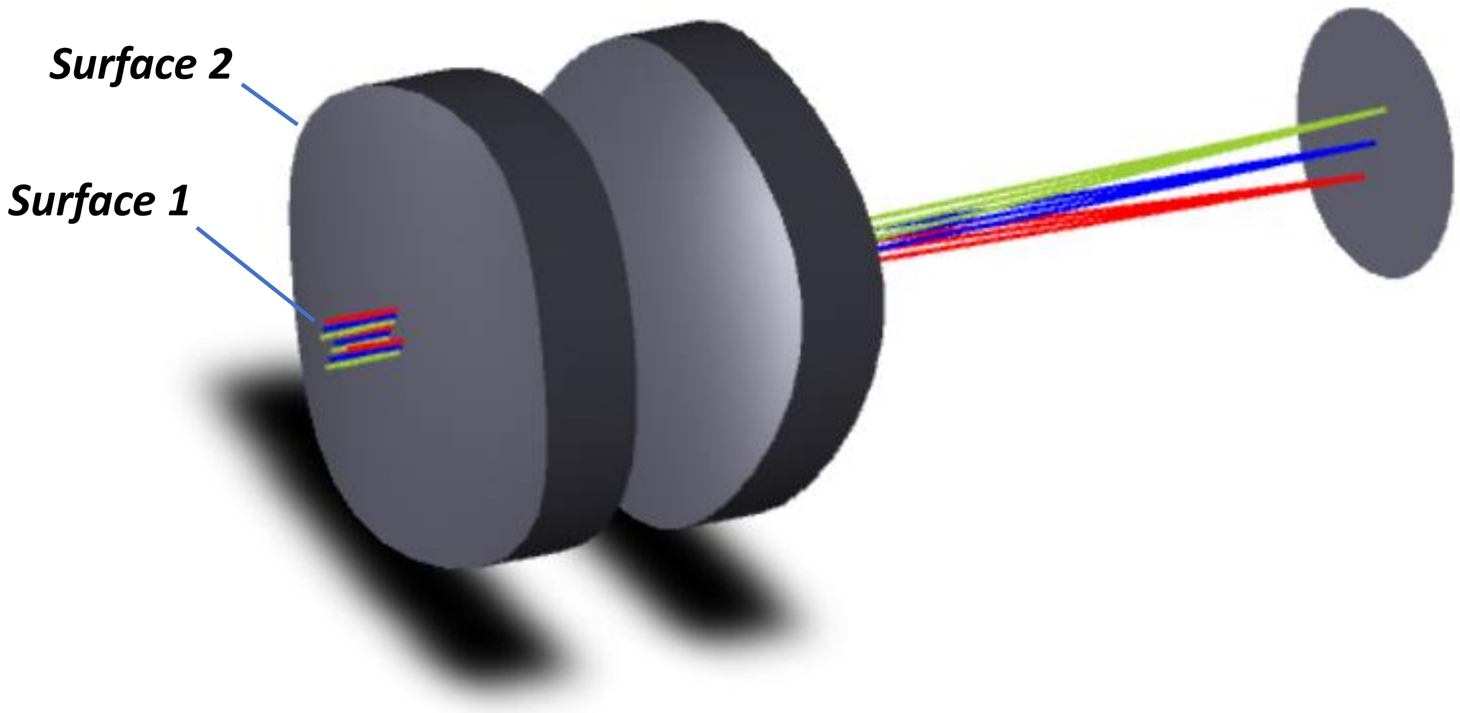


NOTE !

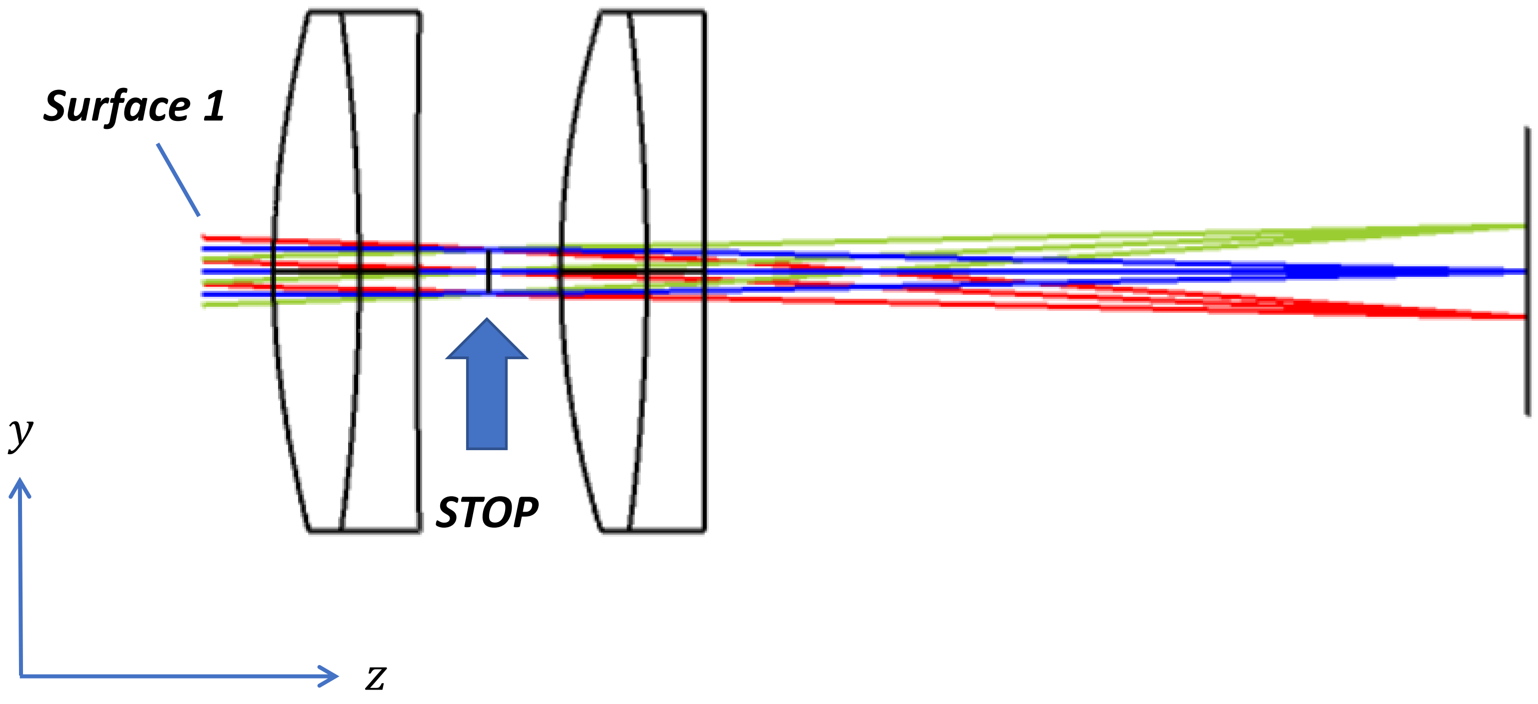
- In Zemax® OpticStudio® (which I am using), this is an "Extended Asphere" surface type
- This sag profile only applies to the +y direction of the lens system

Applying field heights at +/- 2.5 degrees, the 3D model of the lens system looks like this

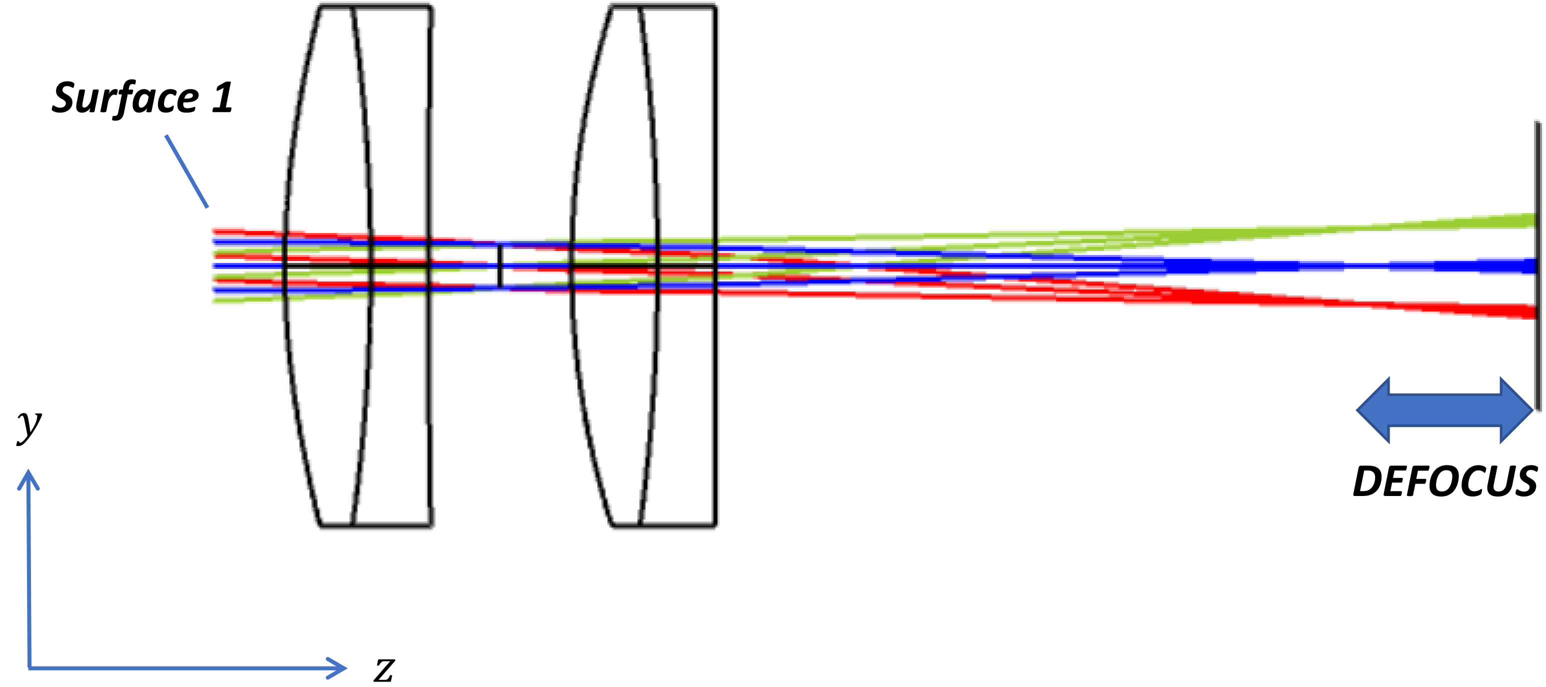
Note: Layout rays are shown at wavelength of 550 nm only



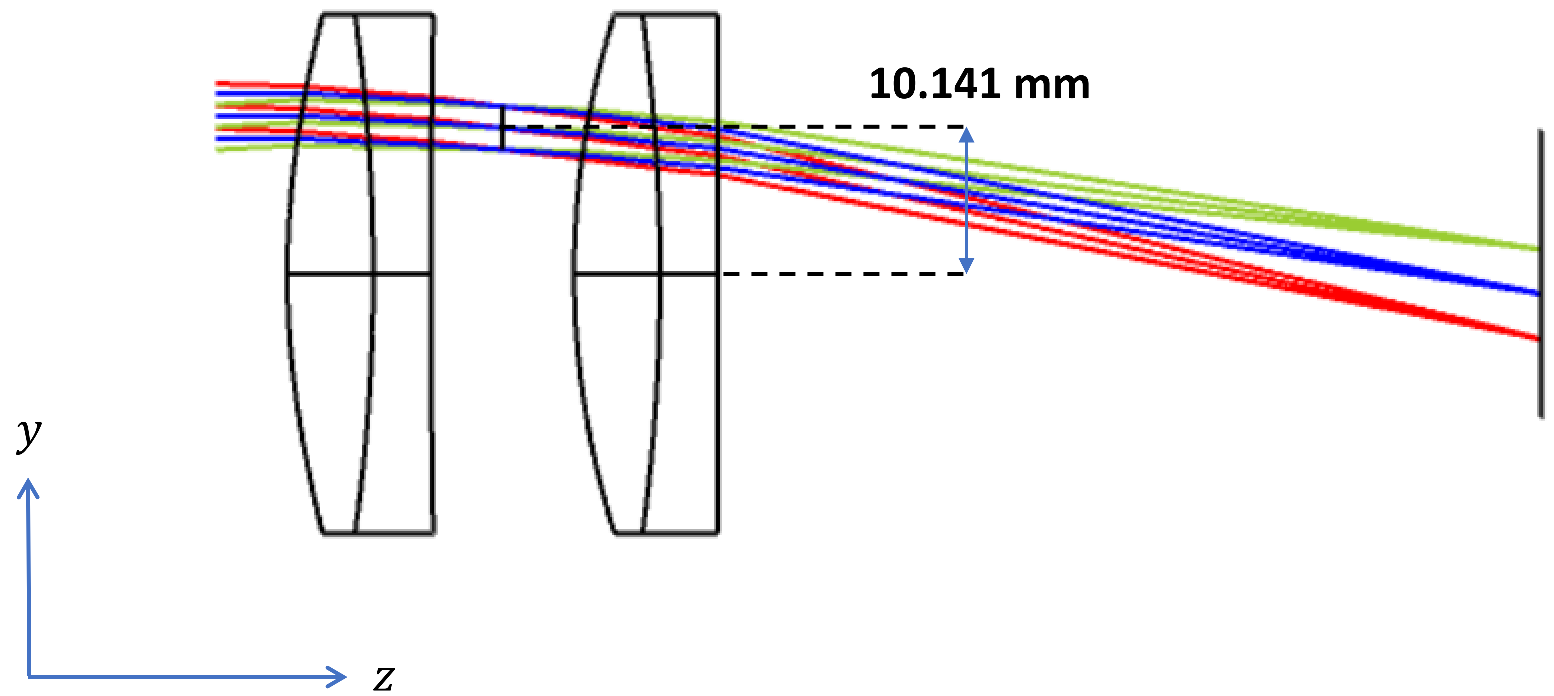
It looks like this in the y-z plane (cross-section)



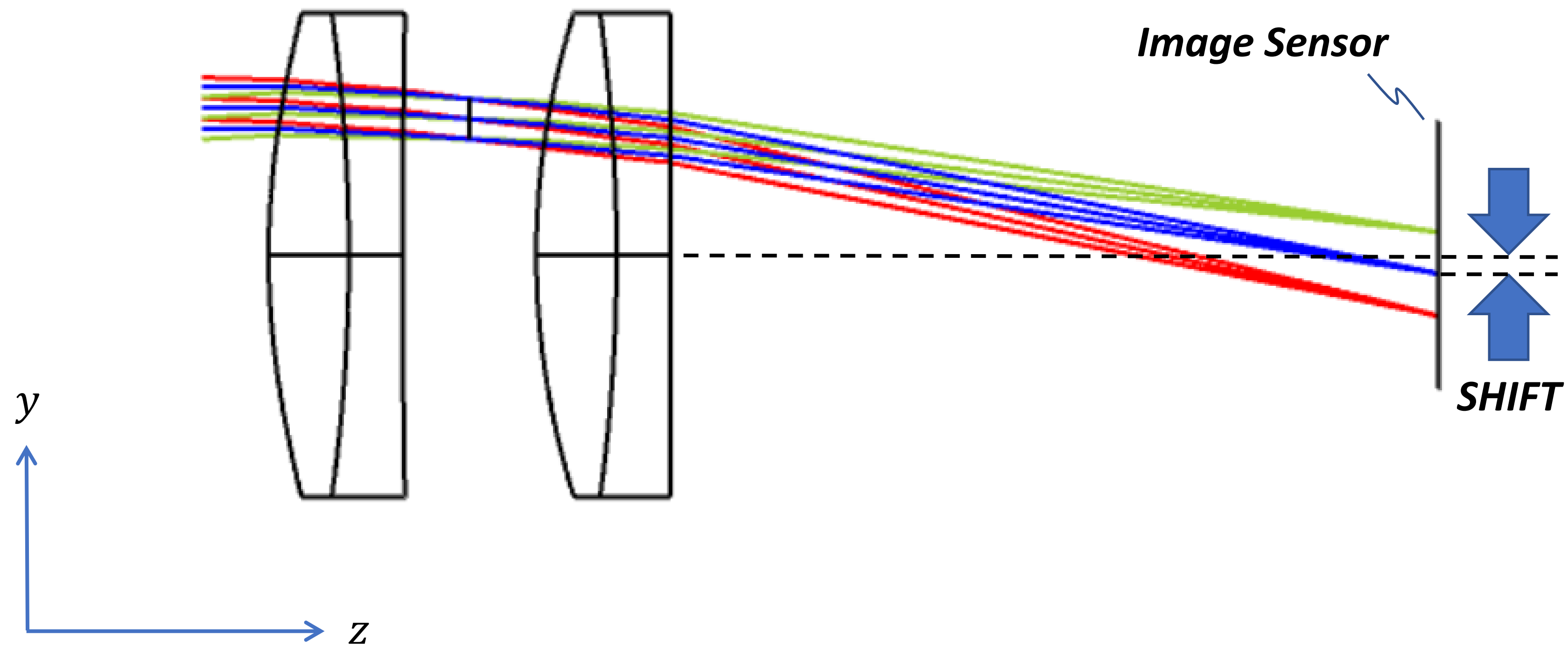
Now, set the object distance to 1000 mm from surface 1, and the image will be defocused



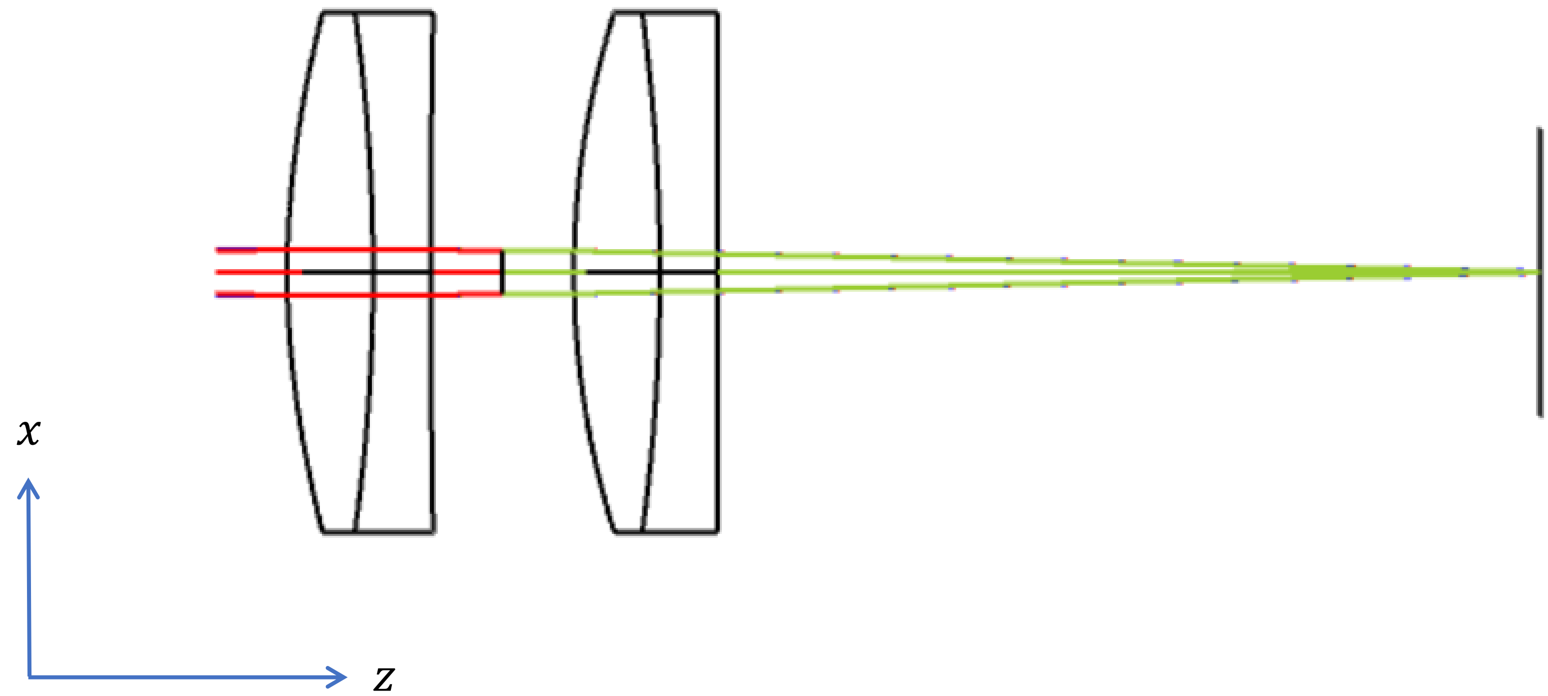
Now, shift the stop by 10.141 mm above the optic axis, and the image is back in focus



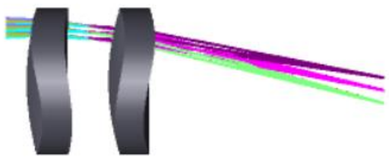
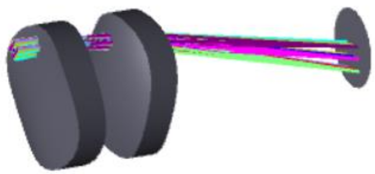
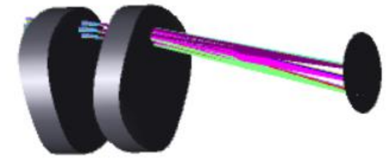
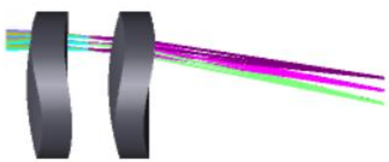
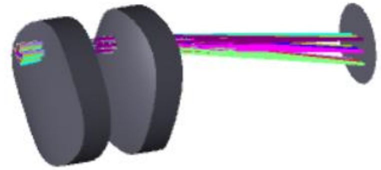
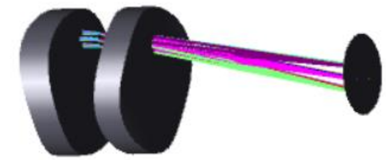
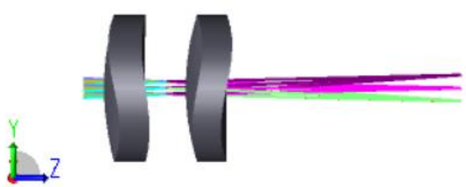
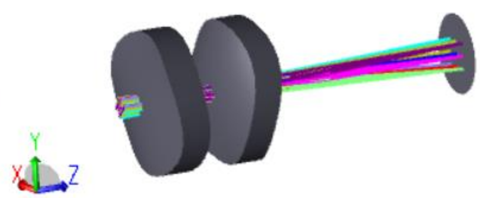
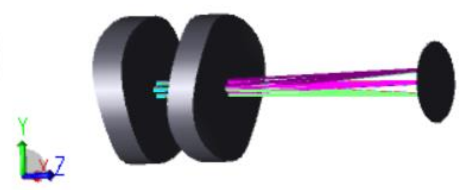
There is a shift in image height, but it can perhaps be calibrated-out computationally



Rotate 90^0 about the z-axis and see that it's also focused for the sagittal rays



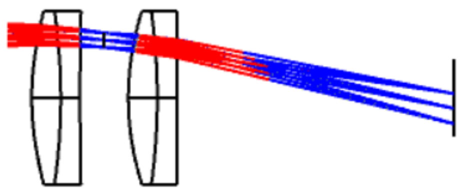
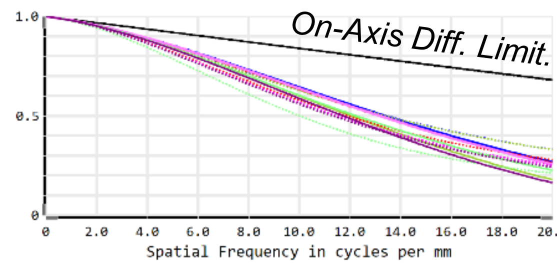
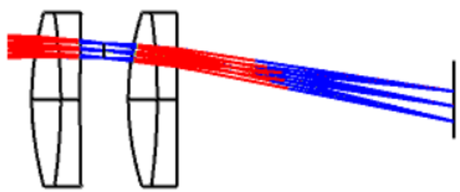
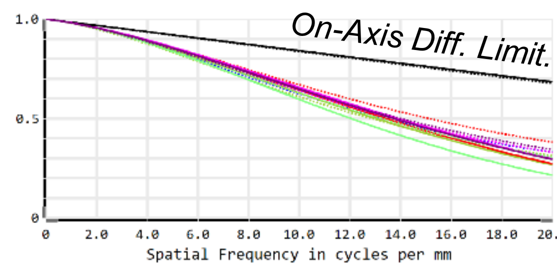
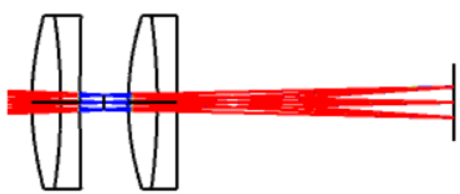
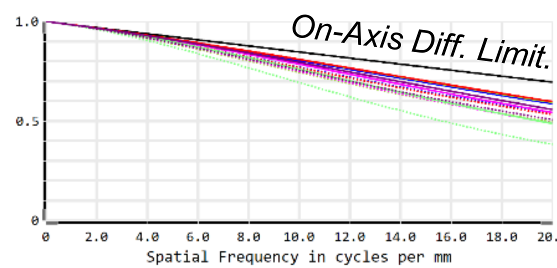
Perspective views of the lens system for three object distances at nine field points*

Obj. Dist.	Layout (side view)	Layout (Front Diagonal)	Layout (Back Diagonal)
100,000 mm			
1000 mm			
250 mm			

* Nine angular field points (θ_x, θ_y) at: (0^0, 0^0), (0^0, $+2.5^0$), (0^0, -2.5^0), ($+2.5^0$, 0^0), (-2.5^0, 0^0), ($+2.5^0$, $+2.5^0$), ($+2.5^0$, -2.5^0), (-2.5^0, -2.5^0), (-2.5^0, $+2.5^0$)

** Stop height is at 0 mm, 10.141 mm, and 12 mm at object distance 250 mm, 1000 mm, and 10^5 mm, respectively

Check polychromatic MTF at 450, 550, and 650 nm (weight = 1 at each wavelength*)

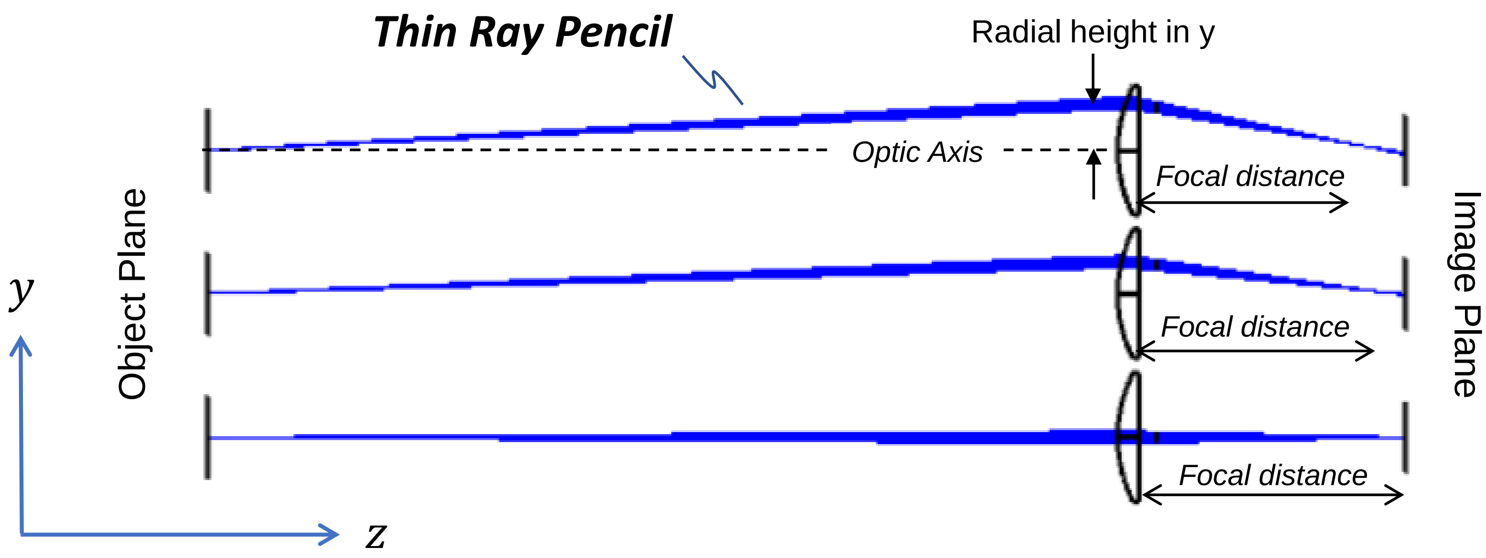
Obj. Dist.	Layout (y-z plane)	MTF
100,000 mm		
1000 mm		
250 mm		

20 lp/mm

* The rays look “colored” because the layout consists of all three wavelengths overlapping

Design Theory

For thin ray “pencils”, Coddington’s equations (sometimes also called “Thomas Young’s astigmatic formulas”) tell us that spherical surfaces possess natural focal length for tangential and sagittal rays, as a function of radial height above the optic axis



Design Theory

For any rotationally symmetric surface, paraxial focal power is always given by a sag that's quadratic with radial height. For a plano-convex lens, if the convex surface is made aspheric, it can be shown* that, for an appropriate choice of the conic constant, the focal length for a thin pencil of tangential rays can be controlled with radial height:

$$\frac{1}{f(y)} = \underbrace{(n-1)\frac{1}{R(y)}} = (n-1)\frac{2cy^2}{1+\sqrt{1-(1+k)c^2y^2}}$$

Effective focal length of a plano-convex "sub-aperture lens" for a thin ray pencil, where the local base radius for the ray pencil has been made variable with radial height y

* R. Siew, "Progressive lens approach to variable focus without moving parts in electronic imaging systems," Inopticalsolutions open access technical note (Jan, 2018); DOI: https://dx.doi.org/10.6084/m9.figshare.5786733

Design Theory

- To correct the astigmatism in the thin ray pencil, an additional term – quadratic in x but linear in y – may be applied to the surface

Provides power control for sagittal rays

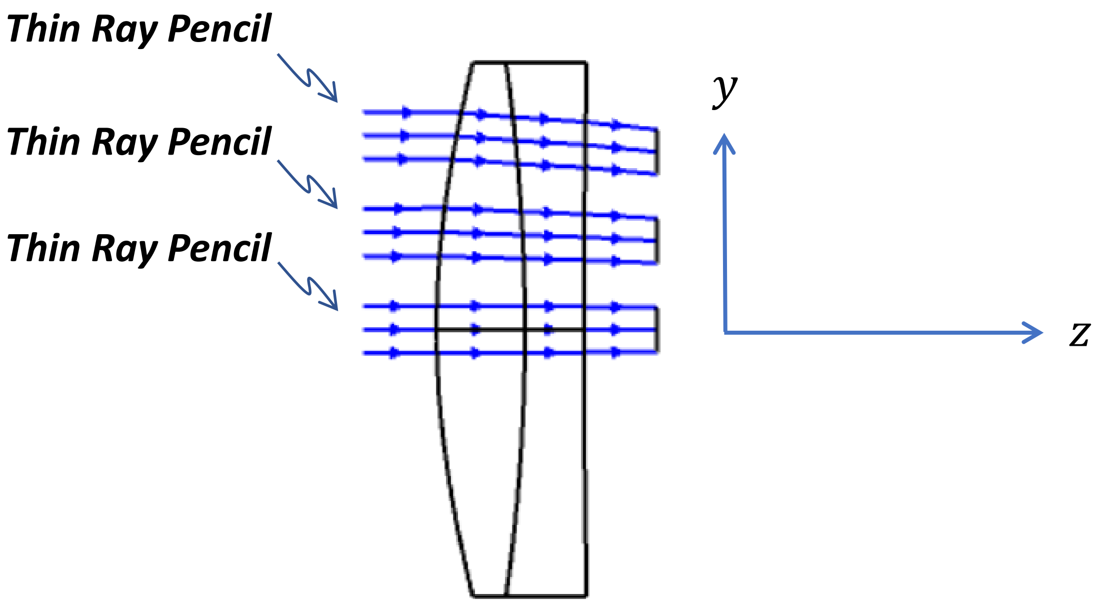
$$\frac{1}{f(x,y)} = \frac{2c(n-1)(x^2+y^2)}{1+\sqrt{1-(1+k)c^2(x^2+y^2)}} + Ayx^2$$

Provides power control for tangential rays for $x = 0$

Design Theory

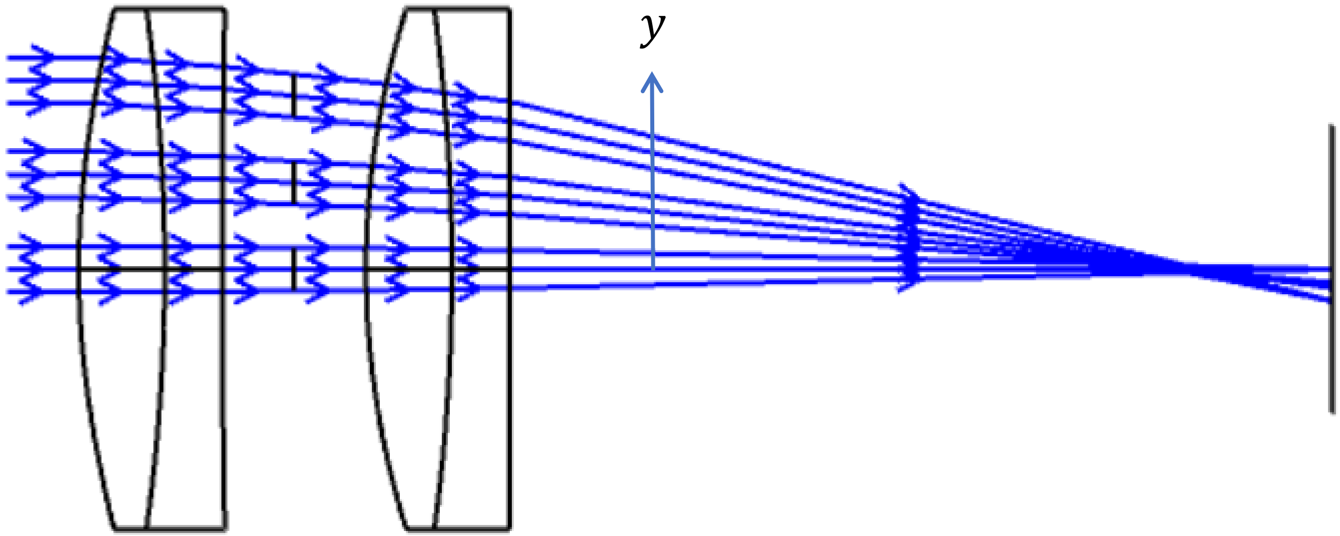
- To correct primary color, ray pencils at any radial height y must "see" an achromatic doublet satisfying the usual power relations (this is why two conics per doublet were used in the lens prescription):

$$\phi_1(y) = \frac{\phi(y)}{1 - \frac{V_2}{V_1}} \qquad \phi_2(y) = \frac{\phi(y)}{1 - \frac{V_1}{V_2}}$$

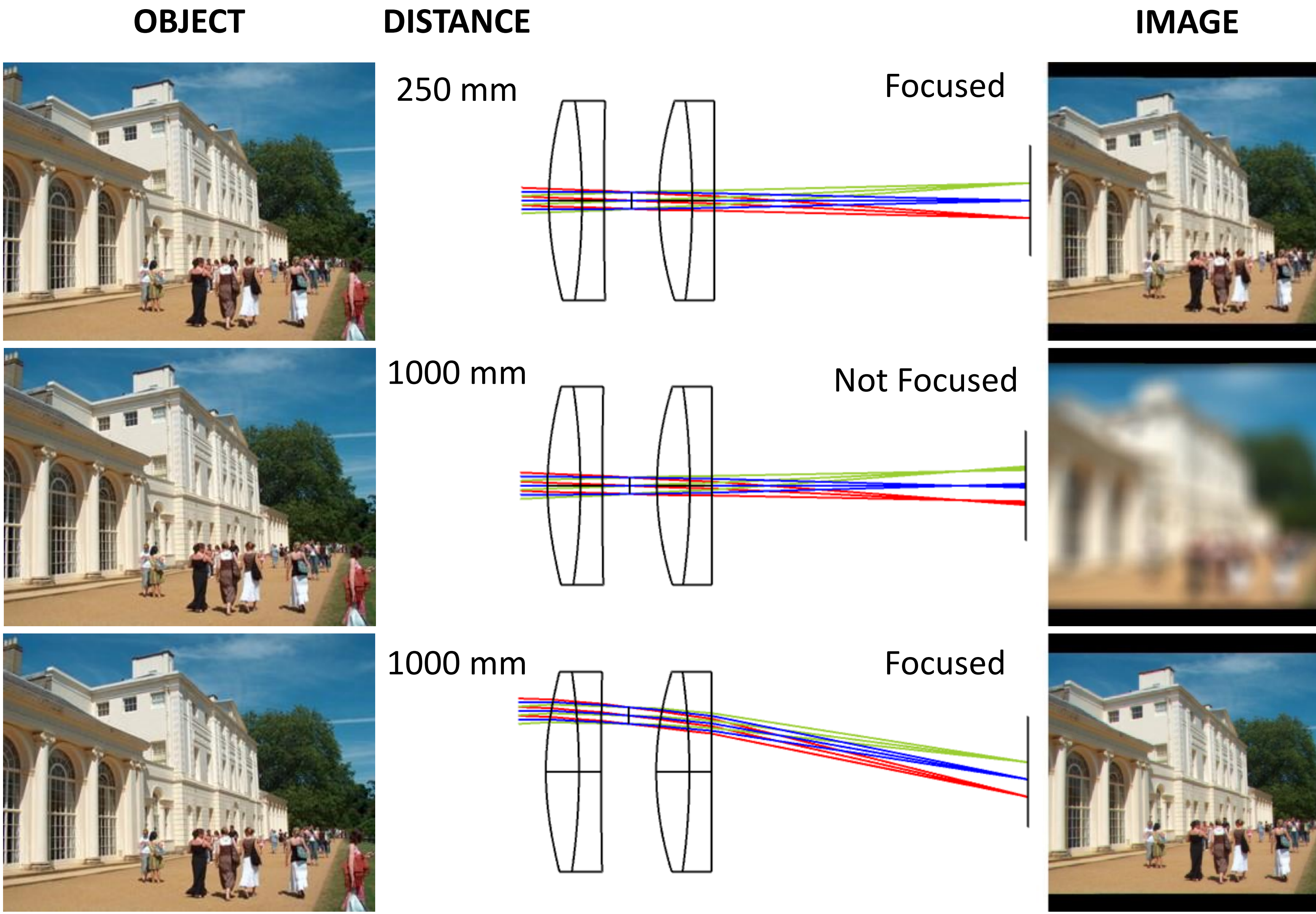


Design Theory

- Why two doublets? Simple – I had to split the powers of the first doublet so that surface curvatures are reduced, yielding a ***freeform progressive*** Petzval system, optimized across three stop positions in y



Simulated Image (assume 100% contrast LCD)



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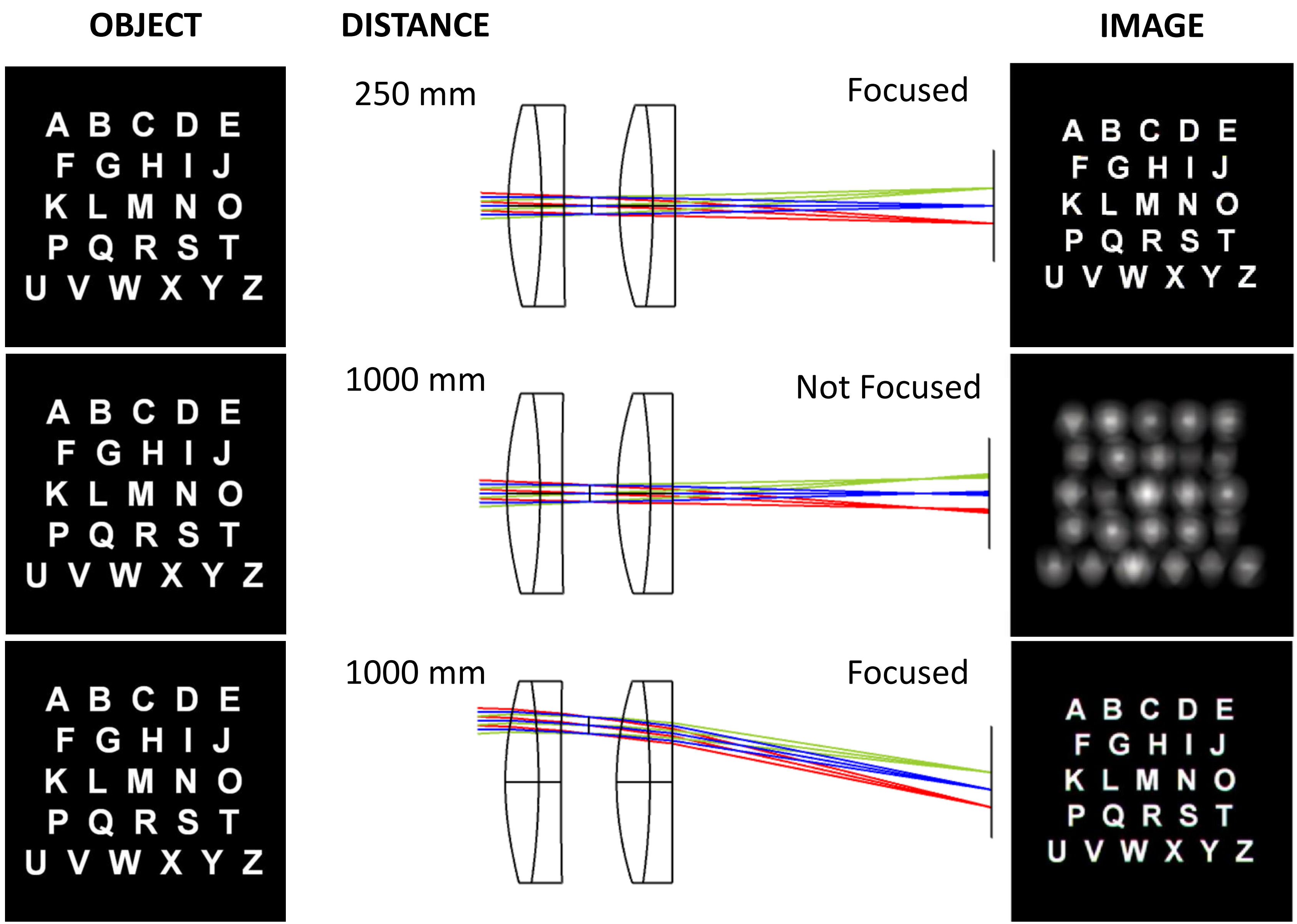
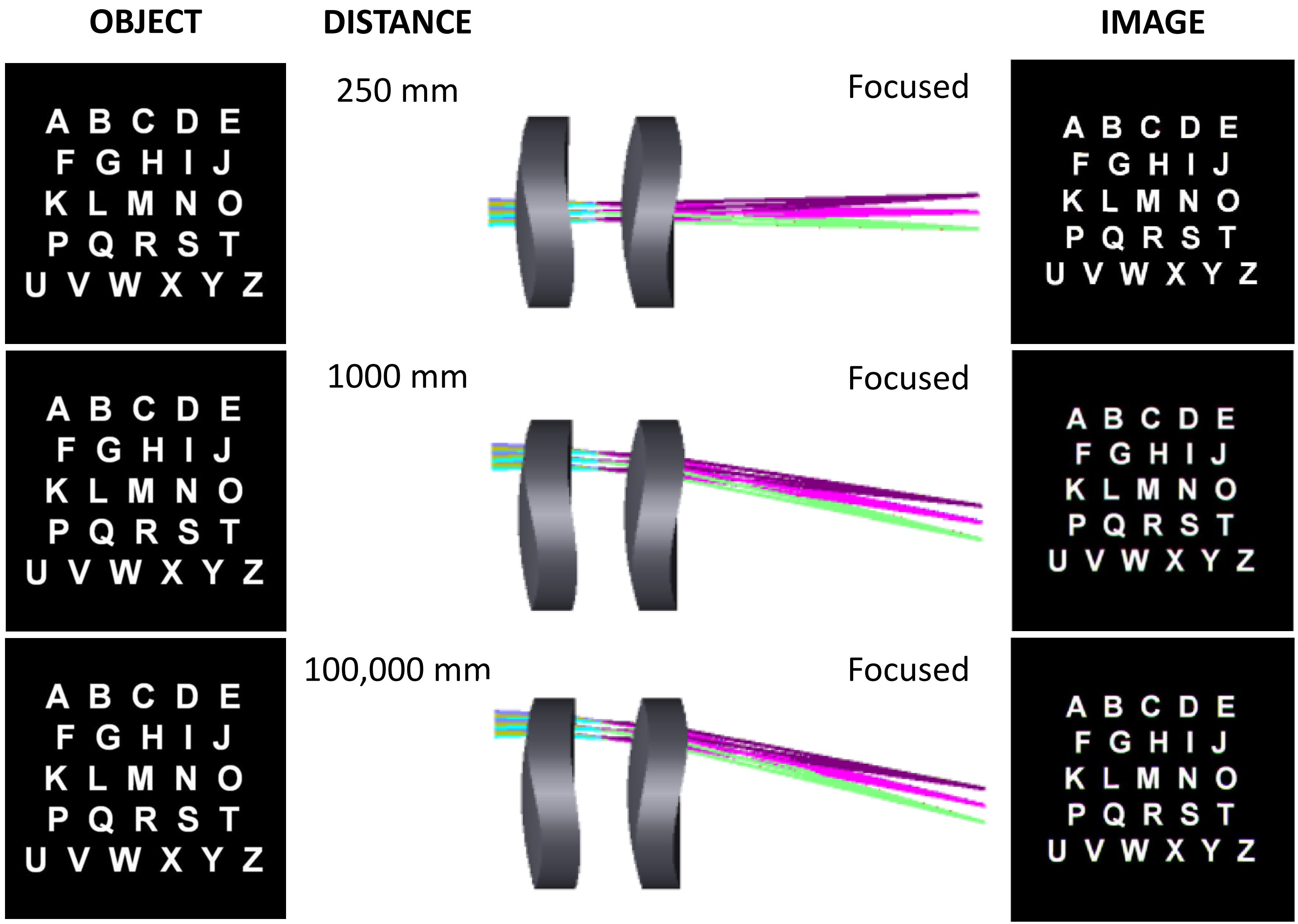
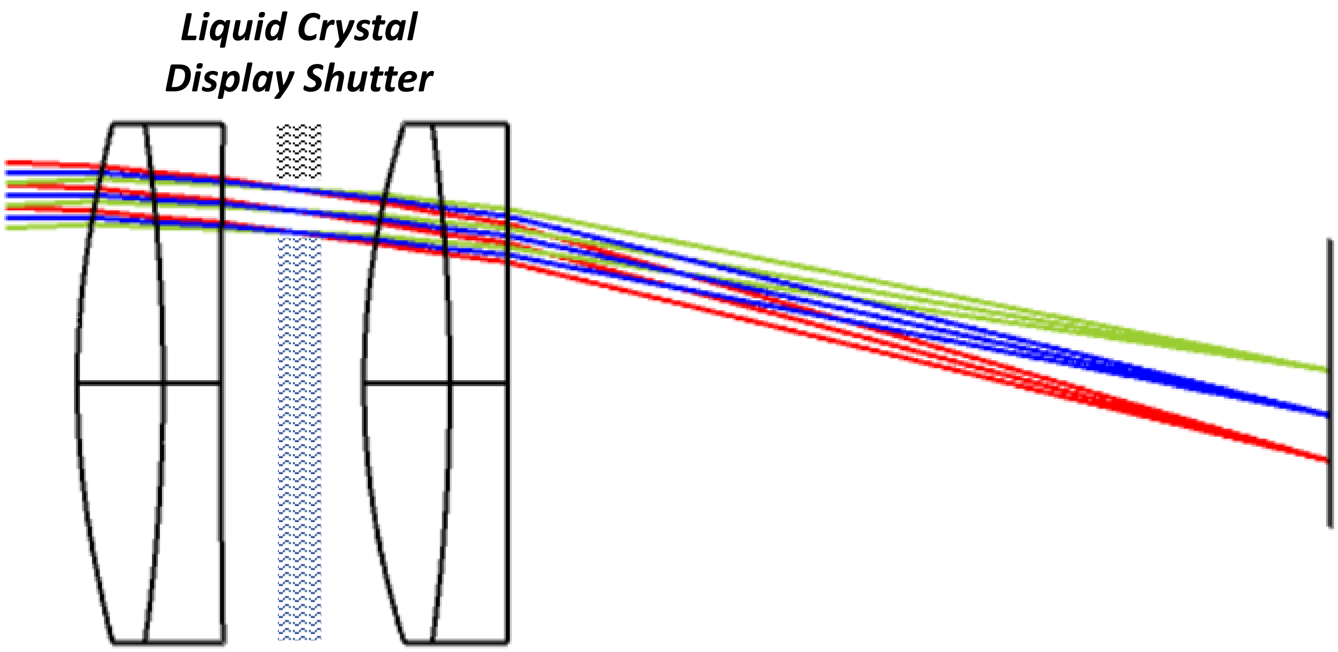


Simulated Image (assume 100% contrast LCD)



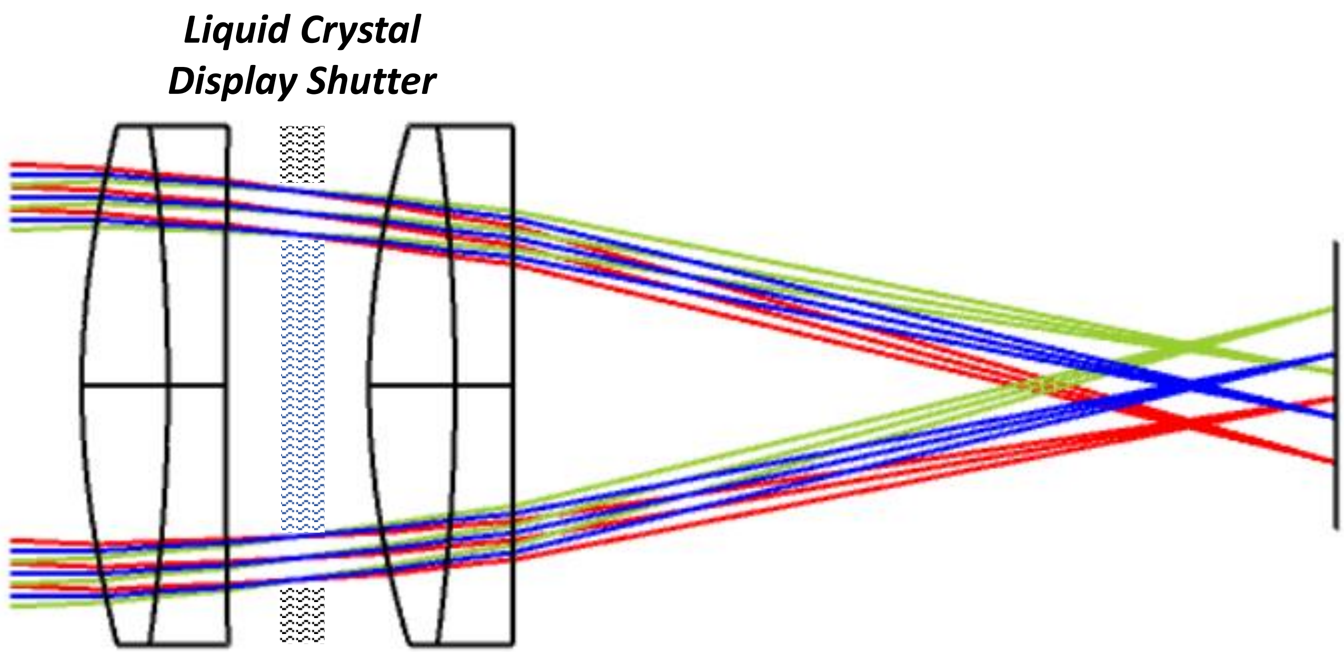
Potential Applications 1

- Variable focus without moving parts can be made possible if the stop is generated by a liquid crystal display (LCD) shutter (of course, provided that there is sufficient contrast ratio)



Potential Applications 2

By programming the LCD shutter to alternate between left and right shutters, and synchronizing this with a display of the left and right views, a 3D stereo image may be produced in *almost* real-time (and information may be extracted for range determination*)



* The sag profile MUST be modified such that the term Ayx^2 is made symmetric about the optic axis

Problems I have not solved

- Can you combine freeform surface modelling and ray tracing code with 3D rendering software (say, from Pixar or DreamWorks) and simulate left-right shutter image displays of a 3D object on a computer monitor (or project them onto a non-depolarizing screen)?

- How do you align such a lens? Apply nodal aberration theory and inspect the aberration field?

- How large can the NA and field of view get before running into trouble?

- Can you zoom with such a lens system? If so, how many freeform surfaces would be needed?

- I ended up with a simple “Petzval-like” design form, but what happens if you applied a double-Gauss or any other forms? Can we extend the performance (and application space)?

References

[1] K. E. Kuijk, "Optical Imaging System Having an Electronically Variable Focal Length and Optical Image Sensor Provided with such a System," U.S. Patent No. 4,927,241, (May 22, 1990).

[2] T. Gustafsson and S. Zyra, "Lens with Variable Focal Length," WIPO Patent Application No. WO/1998/027448, (Dec. 17, 1997).

Prior Art

[3] R. Siew, "Progressive lens approach to variable focus without moving parts in electronic imaging systems," Inopticalsolutions Open Access Technical Note (Jan. 14, 2018), doi: https://dx.doi.org/10.6084/m9.figshare.5786733.

Original Work

[4] W. T. Welford, *Aberrations of Optical Systems*, (IOP Publishing, 1986), pp. 185 – 190. → **T. Young's Astig. Eqs.**

[5] J. C. Valencia-Estrada and J. Garcia-Marquez, "Freeform geometrical optics I: Principles," App. Opt. **58**(34), 9455 – 9464 (2019)

[6] K. Fuerschbach, J. P. Rolland, and K. P. Thompson, "Theory of aberration fields for general optical systems with freeform surfaces," Opt. Express **22**(22), 26585 – 26606 (2014).

[7] G. W. Forbes, "Robust and fast computation for the polynomials of optics," Opt. Express **18**(13), 13851 – 13862 (2010).

[8] M. Jalie, *Ophthalmic Lenses & Dispensing*, 2nd Ed., (Elsevier Science, 2003), pp. 153 – 172.

[9] J. Alonso, J. A. Gomez-Pedrero, and J. A. Quiroga, *Modern Ophthalmic Optics*, (Cambridge University Press, 2019), pp. 284 – 328.

[10] G. Kelch, "Freeform Surfaces for Progressive Spectacle Lenses," in Renewable Energy and the Environment, OSA Technical Digest (online) (Optical Society of America, 2013), paper FM2B.2.

[11] W. T. Plummer, "Some milestones in the design, development, and manufacture of freeform optics," Proc. SPIE 10838, 9th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Advanced Optical Manufacturing Technologies, 1083802 (2019).

Misc. info on freeform lens design, nodal aberration theory…

[12] E. H. Adelson and J. Y. A. Yang, "Single Lens Stereo with a Plenoptic Camera," IEEE Transactions on Pattern Analysis and Machine Intelligence 14, 99 – 106 (1992).

[13] T. N. Mitchell, "Method and apparatus for generating three-dimensional image formation using a single imaging path," U.S. Patent 9298078B2, (Mar. 29, 2016).

Single lens stereo imaging

[14] S. Lukes, *Dynamic Agile Focusing in Microscopy: A Review*, (SPIE Press, 2016), pp. 12 – 13.

[15] W. Chi and N. George, "Electronic imaging using a logarithmic asphere," *Opt. Letters* **26**(12), 875 – 877 (2001).

[16] K. Khare, *Fourier Optics and Computational Imaging*, (Wiley, 2016), pp. 271 – 273.

More variable focus lenses

THANK YOU!

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