Lens Design
OPTI 517

College of Optical Sciences
University of Arizona

College of Optical Sciences
THE UNIVERSITY OF ARIZONA®

Overview

MULTI-CONFIGURATION SYSTEMS

What is a multi-configuration system?

- Any optical system which has more than one way for the light to travel from object to image
- The Multi-Configuration Editor (MCE) is used to specify the differences between the different modes
- Any system or surface property can be “switched” via the MCE, including:
  - Aperture size, type
  - Material
  - Fields, wavelengths
  - Thickness (including object)

Some types of MC systems

- Some applications requiring use of MCs include:
  - Zoom lenses
    - Position of elements varies
  - Athermalized lenses
    - Temperature and pressure varies
  - Multiple-path systems
    - Lenslet arrays
    - Interferometers
    - Beam splitters

Some types of MC systems

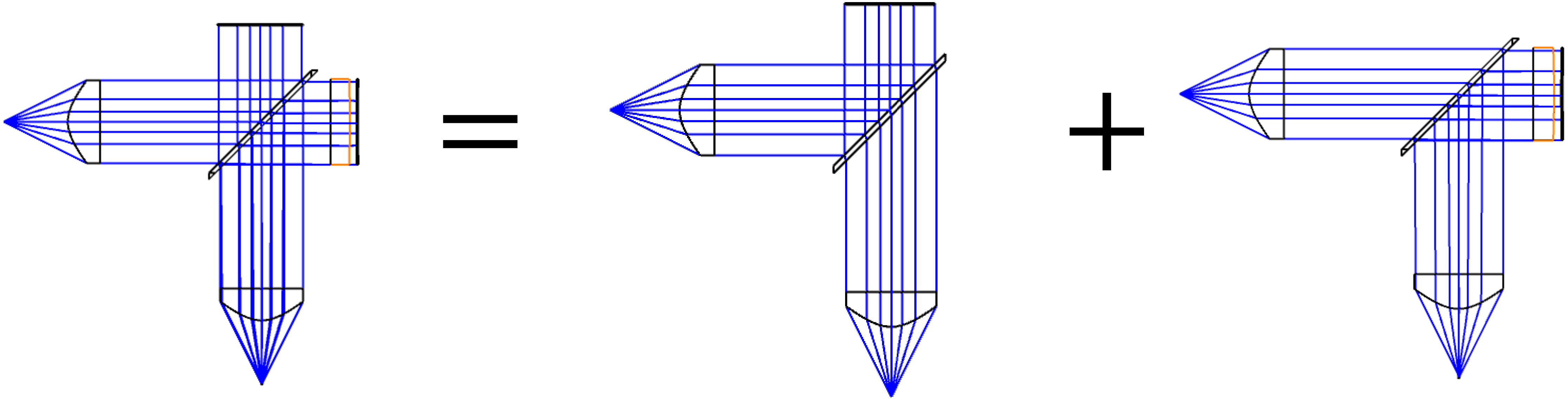
- … as well as:
  - – Scanning systems
    - Polygon scanners
    - F-θ scan lenses
  - – Switchable component systems
    - Discrete zooms
    - Combination optics such as objective-eye lens pairs
  - – Complex materials
    - Birefringent prisms

Limitations to MC

- Zemax is still sequential:
  - Each configuration represents a separate, independent sequential path
  - A separate MF is needed for each path to be optimized
    - Configurations can have relative weighting
    - Be "ignored" during optimization

MC systems

- What appears to be a multi-path system is actually independent designs, occupying some common space:

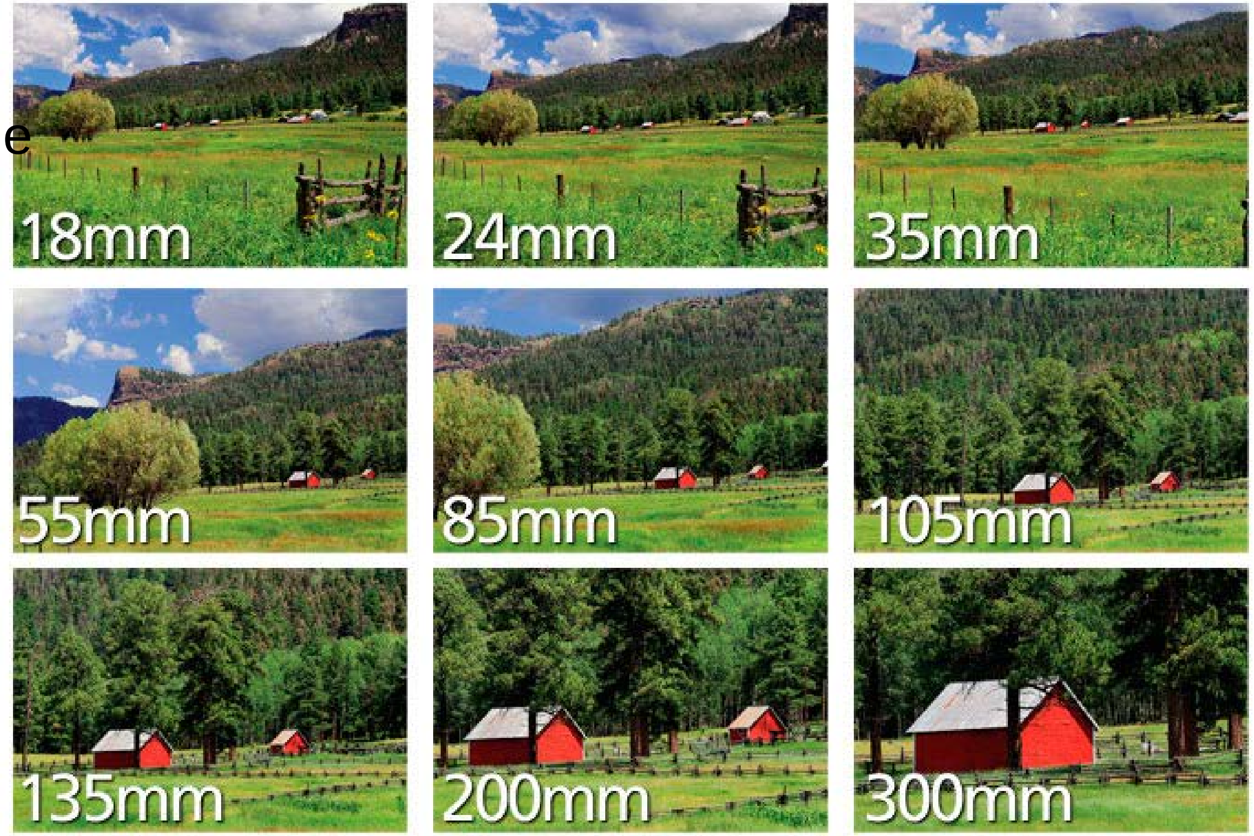


ZOOM LENSES

Zoom lenses

- A single optical system that can be adjusted for many focal lengths

Overall scene



http://blog.vidaao.com/wp-content/uploads/different-focal-lengths.png

Minute details

Zoom lens design

- Zoom lenses are a very common (almost the predominant) design task
- Most lenses are designed based on zoom/MC techniques
  - Not just FL, maybe conjugate distances, or other requirements
- Changing focal length also changes the field of view
- For constant aperture, F/# also changes
- Image distance “fixed”
  - Some shift may be built in (special cases)
  - Varifocal

Zoom lens design

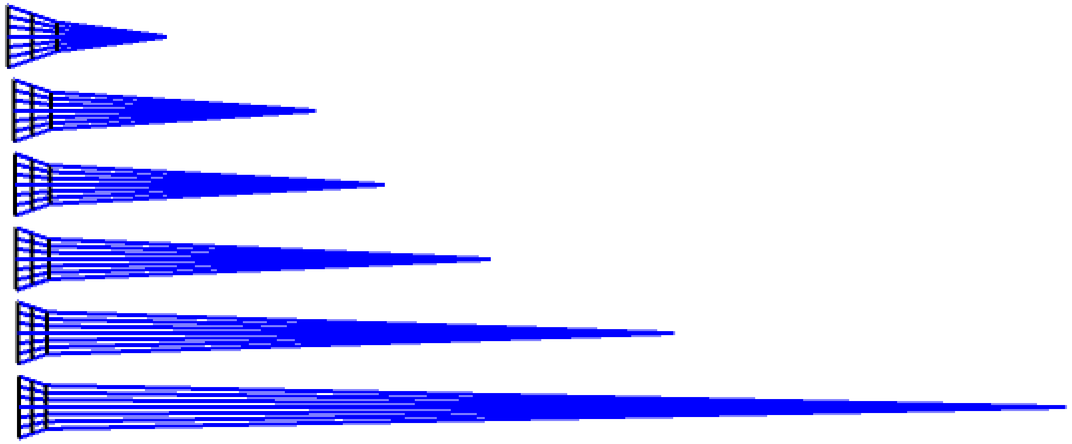
- A zoom lens is a system that can be used over a (usually) continuous range of focal lengths
  - The design process evaluates a limited number of fixed focal lengths over the defined range
  - At a minimum, short, midrange and long focal lengths
  - Each focal length is represented as a separate configuration in the MCE
- The MCE must be populated with all parameters that can differ between configurations
  - Thickness', also field of view, aperture, and possibly others

How does it work?

- Start with the lens power equation: $\emptyset = \emptyset_1 + \emptyset_2 - \emptyset_1 \emptyset_2 \tau$
- The power of an optical system formed by two given lenses varies with the separation between the lenses:
  - $F_1 = 74.34mm;\ F_2 = -55.88mm$
  - t= 40mm -> FL=195mm
  - t= 26mm -> FL=550mm
  - t= 22mm -> FL=1175mm

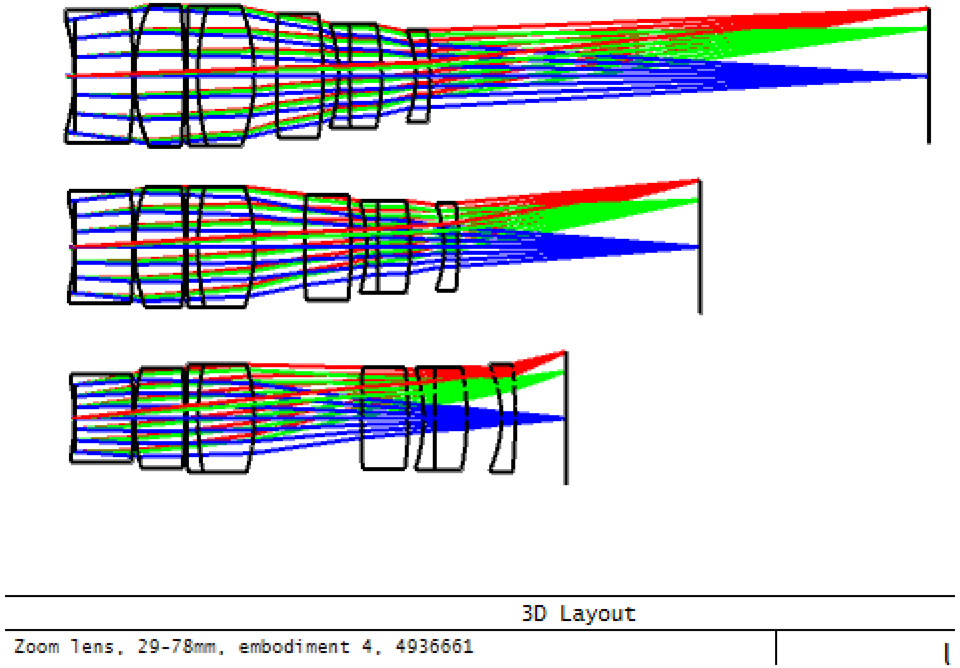
Problem

- Not useful as a “camera” lens
  - Useful to understand the process



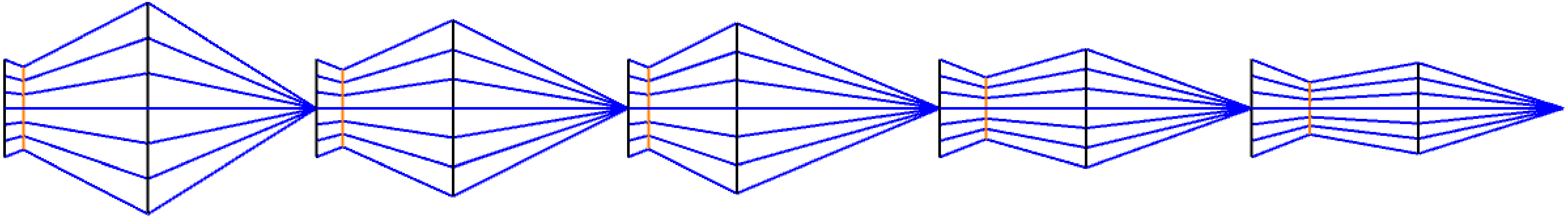
Zemax Sample

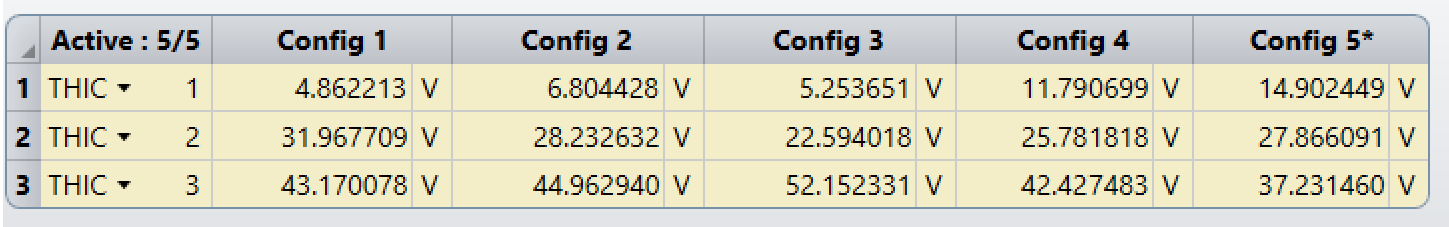
- With only 1 movement, common focus cannot be achieved



Adding a moving group

- Good news: constant length
- Bad news: your mechanical designer might not be your friend

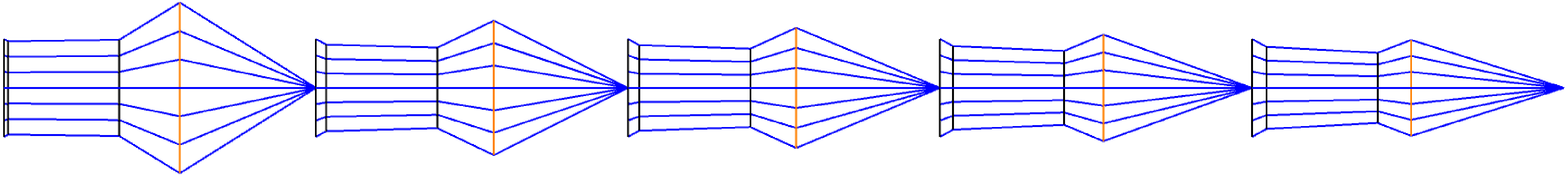


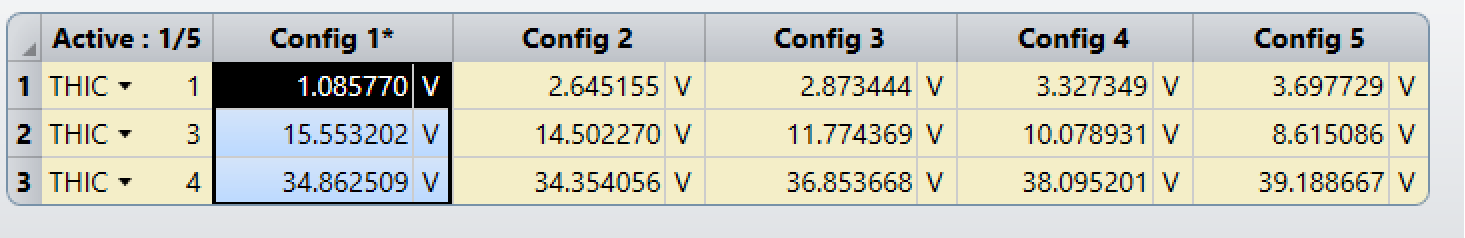


Active : 5/5		Config 1	Config 2	Config 3	Config 4	Config 5*
1	THIC ▾ 1	4.862213 V	6.804428 V	5.253651 V	11.790699 V	14.902449 V
2	THIC ▾ 2	31.967709 V	28.232632 V	22.594018 V	25.781818 V	27.866091 V
3	THIC ▾ 3	43.170078 V	44.962940 V	52.152331 V	42.427483 V	37.231460 V

2-group movement

- Better movement





	Active : 1/5		Config 1*		Config 2		Config 3		Config 4		Config 5	
1	THIC ▾	1	1.085770	V	2.645155	V	2.873444	V	3.327349	V	3.697729	V
2	THIC ▾	3	15.553202	V	14.502270	V	11.774369	V	10.078931	V	8.615086	V
3	THIC ▾	4	34.862509	V	34.354056	V	36.853668	V	38.095201	V	39.188667	V

Properties

ZOOM LENSES

Zoom lens properties

- Spacing between groups of optical elements change
  - Usually optics remain the same
    - “Discrete” zooms not covered here
- At least one spacing must change, usually 2-4
- Optimization is performed over all the configurations simultaneously
- More complexity to the designs
  - More components
  - Often aspherics (molded)
  - Spacings must be properly constrained (mechanical must be possible)

Design process

- Two basic design techniques used
  - Start with paraxial lenses to determine powers, spacings
    - Move to thin lenses
      - Determine number of moveable groups
  - Do a literature or patent search to get a starting point design
    - Basic ideas as to components, groups, materials
    - Don’t copy a patented deign
  - Most often, use a combination

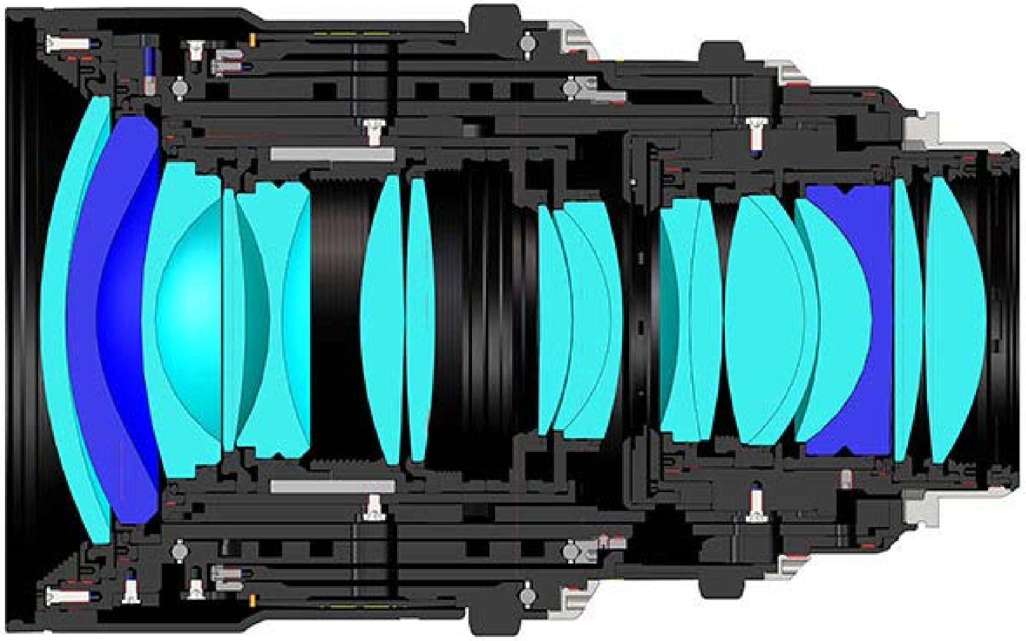
Zoom groups

- Zoom lens groups (Front to back)
  - Focusing group
    - Provides necessary focus by shifting forward or backward
  - Variator group
    - Varies the magnification of the focusing group
    - Performs most of the focal length change
  - Compensator group
    - Maintains correct focus as lens as focal length changes
    - Moves in conjunction with, but less than, the variator
  - Master group
    - Correction of field aberrations

Mechanical considerations

- It is often necessary to enforce proper relationships so cams smoothly vary with focal length

http://www.overgaard.dk/thorstenovergaardcom_copyrighted_graphics/442-018.001-000_Sectioned-by-andre-de-winter-640w.jpg



Design layout: paraxial

ZOOM LENSES

In Zemax: Paraxial

- Define a single FL system
  - – Perform some level of optimization
    - How rigorous will depend
      - – Design form, your personal approaches, etc
  - – Open the MCE
    - Add the minimum number of changeable parameters
      - – Usually thickness, maybe aperture, field
      - – Don’t add “everything” just because there is a button
  - – In MFE
    - Add appropriate boundary constraints
    - Generate the “default” MF: separate entries for each configuration are generated

Setting up a preliminary design

- Use paraxial lenses
  - – Separate lens for each group
  - – Use your PRTE spreadsheet to get an idea
- Set up 3-4 configurations over focal length range
  - – More can help smooth things out
  - – Will take more time
    - Increase only as required
- Optimize to get correct FLs
  - – Check range of shifts: Monotonic?

Real design

- Start by replacing the paraxial lenses with equivalent singlets
  - One option:
    - One wavelength, one material, on-axis field
  - For fast systems (F/# < ~2.8 – 3)
    - Start with a slower system
  - Optimize curvatures and spacings
  - Add additional elements
    - Replace singlets with doublets
    - Use aspheres (which may be replaced with doublets later)
  - Add appropriate field, aperture

Design layout: from existing

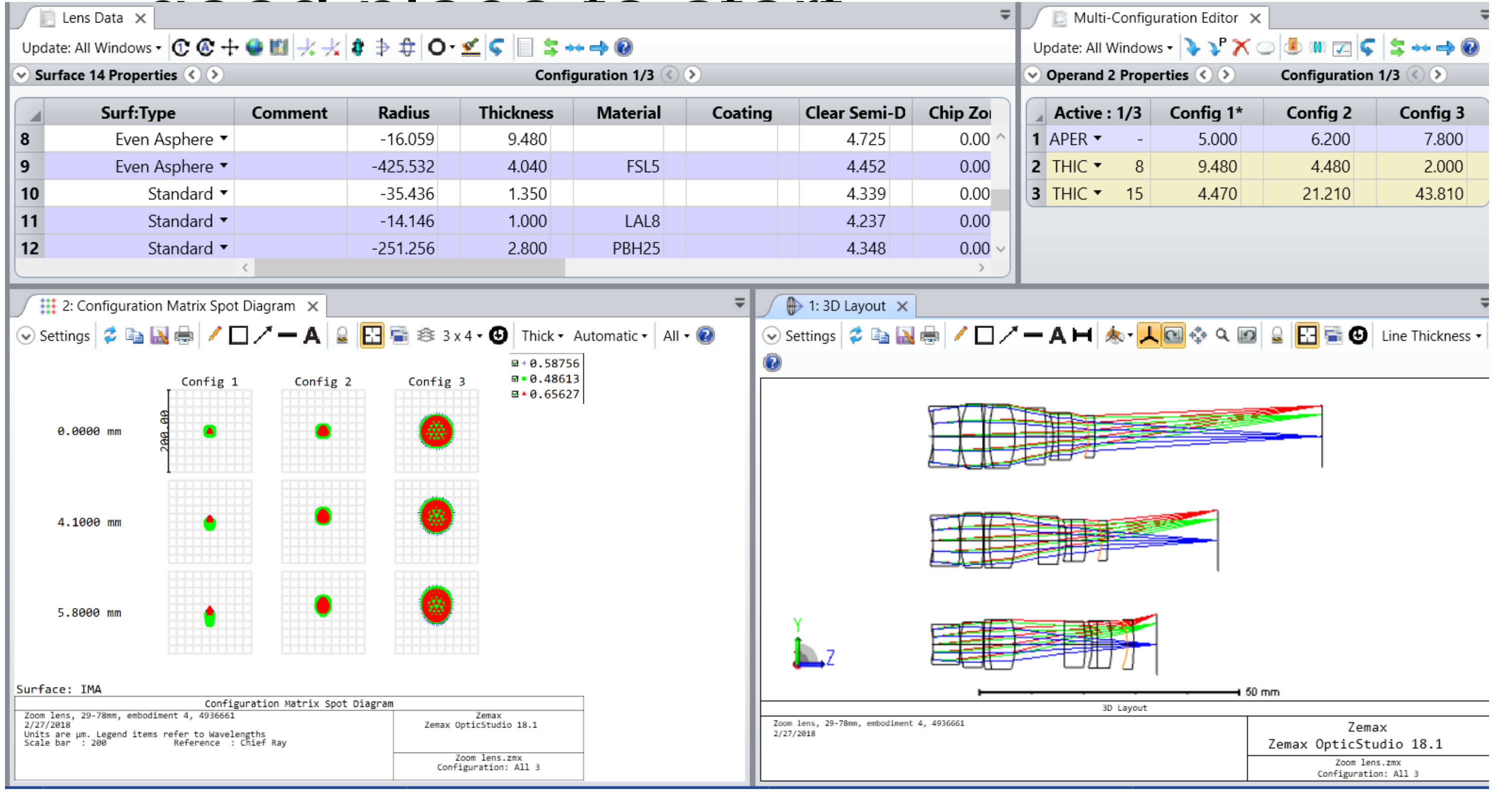
ZOOM LENSES

In Zemax: From existing

- Patents, in particular, are likely missing significant information
  - Can usually get to traceable starting point
- Enter the prescription into LDE
- Allow spacings to change for appropriate FLs
  - Use the MCE to establish variations
  - Make sure to include operands of all parameters that are FL dependent
    - THIC for a thickness change
  - The LDE can be change to represent each configuration (CRTL-A)
    - Updated to show information for current configuration

Example

- The Samples directory is always a good place to start



	Surf:Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-D	Chip Zo
8	Even Asphere		-16.059	9.480			4.725	0.00
9	Even Asphere		-425.532	4.040	FSL5		4.452	0.00
10	Standard		-35.436	1.350			4.339	0.00
11	Standard		-14.146	1.000	LAL8		4.237	0.00
12	Standard		-251.256	2.800	PBH25		4.348	0.00

	Active : 1/3		Config 1*	Config 2	Config 3
1	APER	-	5.000	6.200	7.800
2	THIC	8	9.480	4.480	2.000
3	THIC	15	4.470	21.210	43.810

Surface: IMA

Configuration Matrix Spot Diagram

Zoom lens, 29-78mm, embodiment 4, 4936661
2/27/2018
Units are µm. Legend items refer to Wavelengths
Scale bar : 200 Reference : Chief Ray

Zemax
Zemax OpticStudio 18.1

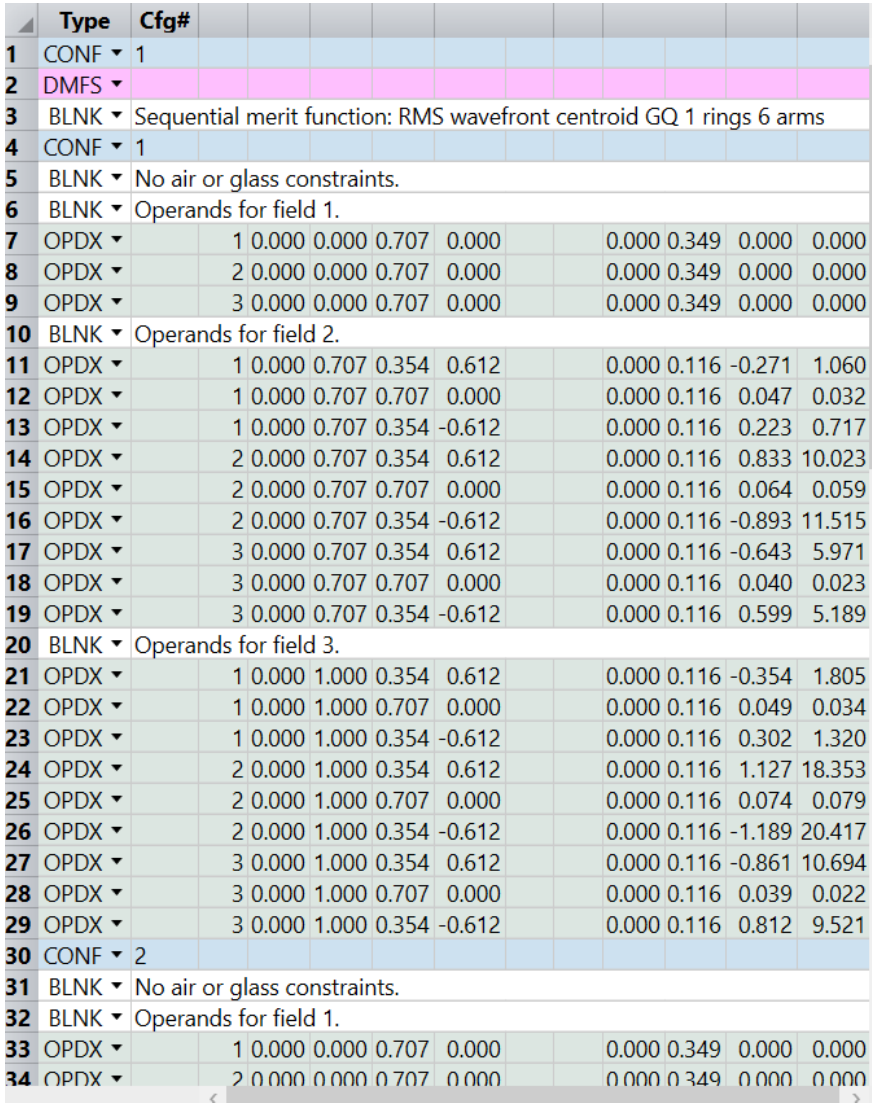
Zoom lens.zmx
Configuration: All 3

3D Layout

Zoom lens, 29-78mm, embodiment 4, 4936661
2/27/2018

Zemax
Zemax OpticStudio 18.1

Zoom lens.zmx
Configuration: All 3



	Type	Cfg#											
1	CONF	1											
2	DMFS												
3	BLNK	Sequential merit function: RMS wavefront centroid GQ 1 rings 6 arms											
4	CONF	1											
5	BLNK	No air or glass constraints.											
6	BLNK	Operands for field 1.											
7	OPDX		1	0.000	0.000	0.707	0.000			0.000	0.349	0.000	0.000
8	OPDX		2	0.000	0.000	0.707	0.000			0.000	0.349	0.000	0.000
9	OPDX		3	0.000	0.000	0.707	0.000			0.000	0.349	0.000	0.000
10	BLNK	Operands for field 2.											
11	OPDX		1	0.000	0.707	0.354	0.612			0.000	0.116	-0.271	1.060
12	OPDX		1	0.000	0.707	0.707	0.000			0.000	0.116	0.047	0.032
13	OPDX		1	0.000	0.707	0.354	-0.612			0.000	0.116	0.223	0.717
14	OPDX		2	0.000	0.707	0.354	0.612			0.000	0.116	0.833	10.023
15	OPDX		2	0.000	0.707	0.707	0.000			0.000	0.116	0.064	0.059
16	OPDX		2	0.000	0.707	0.354	-0.612			0.000	0.116	-0.893	11.515
17	OPDX		3	0.000	0.707	0.354	0.612			0.000	0.116	-0.643	5.971
18	OPDX		3	0.000	0.707	0.707	0.000			0.000	0.116	0.040	0.023
19	OPDX		3	0.000	0.707	0.354	-0.612			0.000	0.116	0.599	5.189
20	BLNK	Operands for field 3.											
21	OPDX		1	0.000	1.000	0.354	0.612			0.000	0.116	-0.354	1.805
22	OPDX		1	0.000	1.000	0.707	0.000			0.000	0.116	0.049	0.034
23	OPDX		1	0.000	1.000	0.354	-0.612			0.000	0.116	0.302	1.320
24	OPDX		2	0.000	1.000	0.354	0.612			0.000	0.116	1.127	18.353
25	OPDX		2	0.000	1.000	0.707	0.000			0.000	0.116	0.074	0.079
26	OPDX		2	0.000	1.000	0.354	-0.612			0.000	0.116	-1.189	20.417
27	OPDX		3	0.000	1.000	0.354	0.612			0.000	0.116	-0.861	10.694
28	OPDX		3	0.000	1.000	0.707	0.000			0.000	0.116	0.039	0.022
29	OPDX		3	0.000	1.000	0.354	-0.612			0.000	0.116	0.812	9.521
30	CONF	2											
31	BLNK	No air or glass constraints.											
32	BLNK	Operands for field 1.											
33	OPDX		1	0.000	0.000	0.707	0.000			0.000	0.349	0.000	0.000
34	OPDX		2	0.000	0.000	0.707	0.000			0.000	0.349	0.000	0.000

Setting up the MFE

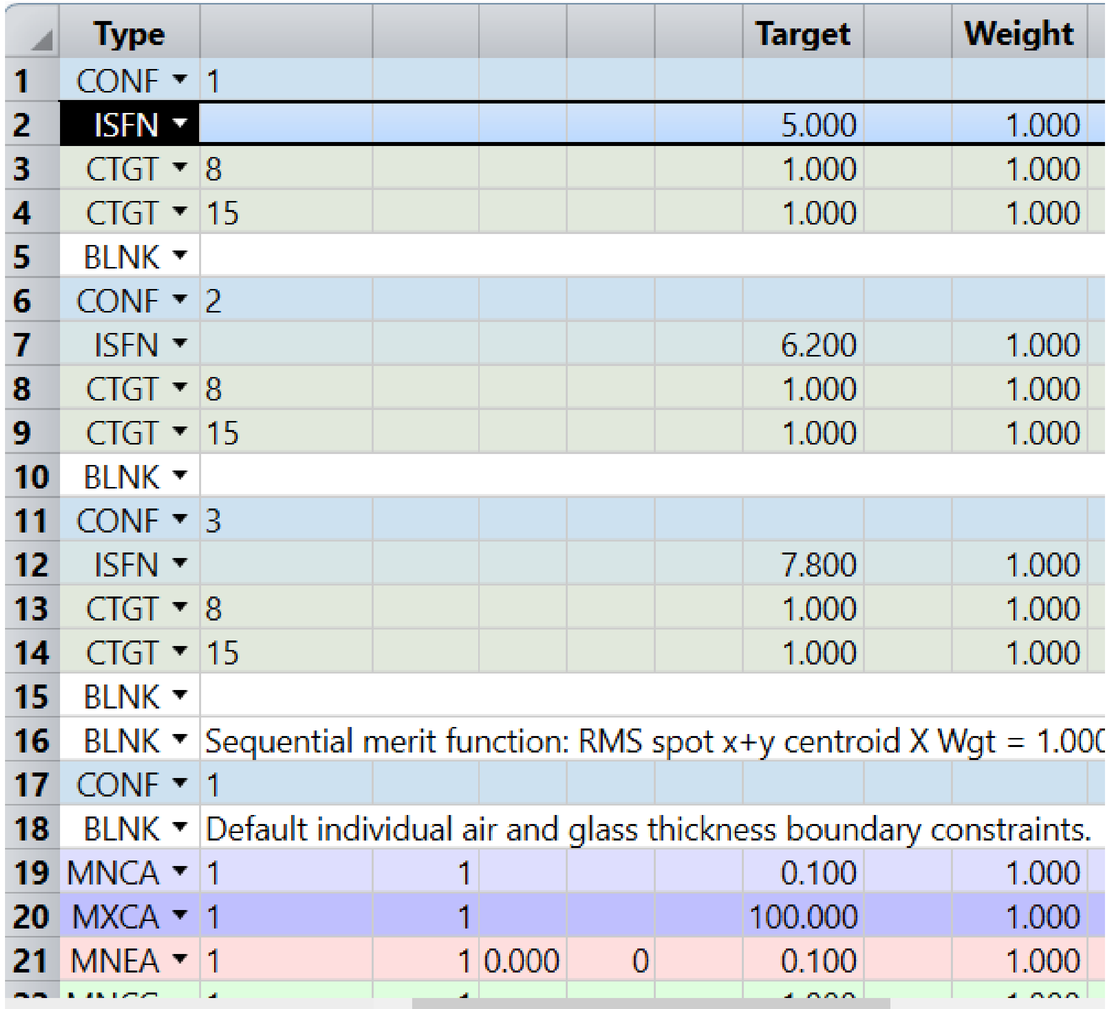
- The MFE must contain constraints and targets for each configuration
  - Use “Maximum” solve on semi-diameter, one set of “overall” boundary constraints
- For each configuration:
  - EFFL constraint
  - Boundary constraints for MC parameters
  - “Default” MF
    - Usually the same for all configurations
    - Automatically generated by Wizard

CONF

- The CONF n operand indicates the configuration all following operands apply to configuration n
  - Until next CONF n is encountered
- Zemax reloads system each time CONF n is issued
  - A bit of overhead, BUT
- HIGHLY RECOMMENDED technique:
- Put CONF operands up top for the specifically added items in each configuration
- Then below have separate CONF operands for sets of standard MF entries

MFE for MC Design

- Assemble the MF so constraints violations are readily seen



	Type						Target		Weight
1	CONF	1							
2	ISFN						5.000		1.000
3	CTGT	8					1.000		1.000
4	CTGT	15					1.000		1.000
5	BLNK								
6	CONF	2							
7	ISFN						6.200		1.000
8	CTGT	8					1.000		1.000
9	CTGT	15					1.000		1.000
10	BLNK								
11	CONF	3							
12	ISFN						7.800		1.000
13	CTGT	8					1.000		1.000
14	CTGT	15					1.000		1.000
15	BLNK								
16	BLNK	Sequential merit function: RMS spot x+y centroid X Wgt = 1.00							
17	CONF	1							
18	BLNK	Default individual air and glass thickness boundary constraints.							
19	MNCA	1	1				0.100		1.000
20	MXCA	1	1				100.000		1.000
21	MNEA	1	1	0.000	0		0.100		1.000

Zoom lens design: finishing steps

- Verify that groups do not collide at intermediate positions
- Verify finite-conjugate performance and group movements
- Examine performance trade-offs versus
  - – total length (track)
  - – back focus
- Check vignetting
- Examine the effect of reversing flint/crown ordering
- Complete tolerance analysis

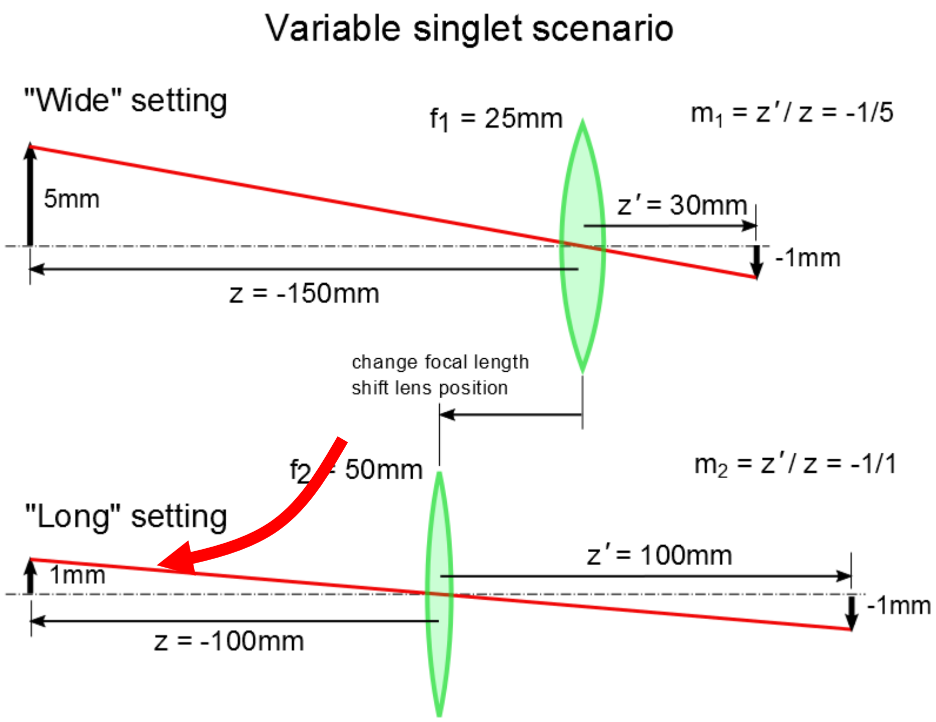
Kidger: Intermediate Optical Design, p. 67

Increasing complexity

ZOOM SYSTEMS

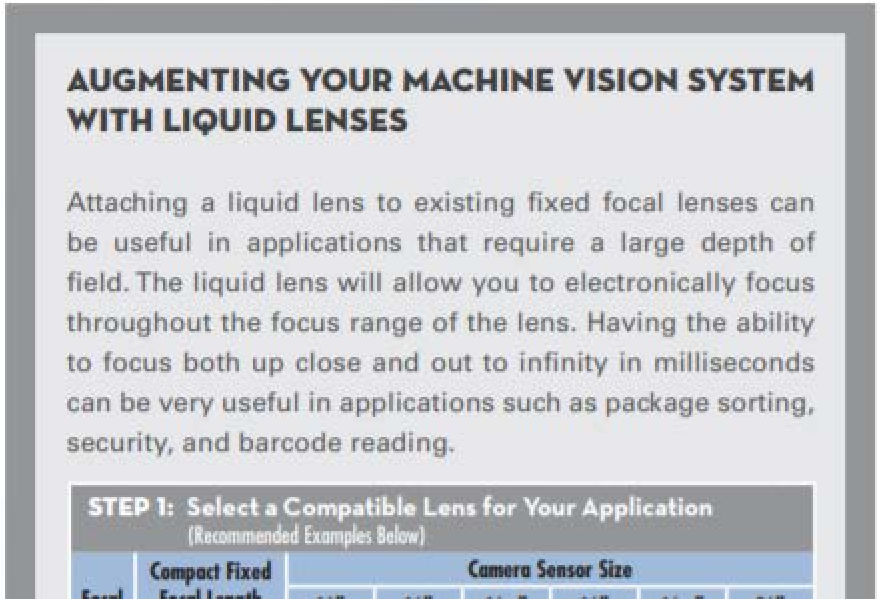
One-lens zoom: thin lens concept

- It is “possible” varying the focal length of a single lens
  - Current technology uses a liquid lens
  - Liquid crystal approach has been proposed
- Consider a lens changing focal length from 25 to 50mm
  - FOV decreases
  - Lens shifts
  - Image distance increases



Liquid lens

- Available, but limited



AUGMENTING YOUR MACHINE VISION SYSTEM WITH LIQUID LENSES

Attaching a liquid lens to existing fixed focal lenses can be useful in applications that require a large depth of field. The liquid lens will allow you to electronically focus throughout the focus range of the lens. Having the ability to focus both up close and out to infinity in milliseconds can be very useful in applications such as package sorting, security, and barcode reading.

STEP 1: Select a Compatible Lens for Your Application
(Recommended Examples Below)

Compact Fixed
Camera Sensor Size

https://www.edmundoptics.com/resources/video/tutorials/understanding-liquid-lens-technology/

Self-adjustable eyeglasses

- Rubber lens filled with glycerin
  - – Motors adjust the shape to focus objects in field of view of the wearer

Auto-focus eyeglasses rely on liquid lenses

While the prototype may be goofy-looking, you can't beat its versatility

BY **STEPHEN ORNES** APR 4, 2017 — 7:10 AM EST

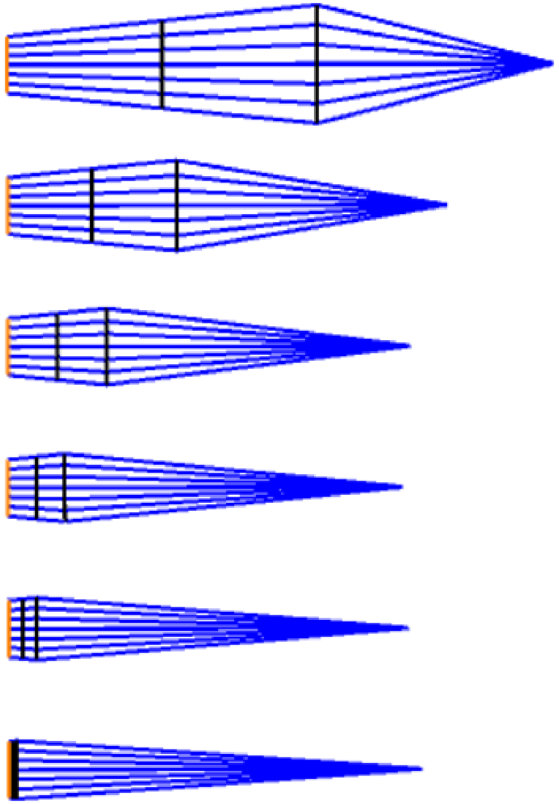
https://www.sciencenewsforstudents.org/article/auto-focus-eyeglasses-rely-liquid-lenses

Two group lens

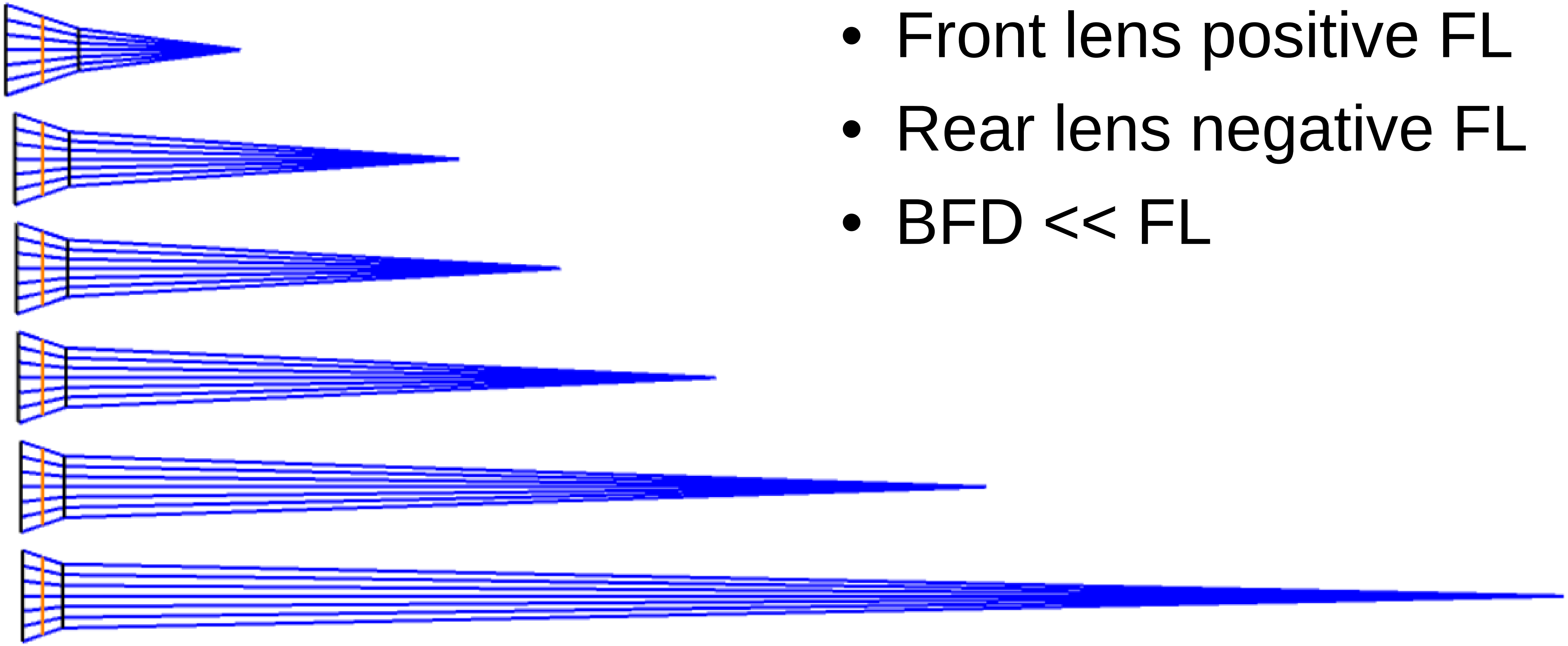
- Change the FL by changing the distance between the lens (groups)

$$\phi = \phi_1 + \phi_2 - \phi_1 \phi_2 t$$

- Negative, positive
  - Reverse telephoto
- FL range: 20mm-70mm
- Spacing range: 55mm –



Telephoto lens



- Front lens positive FL
- Rear lens negative FL
- BFD << FL

Increasing complexity

ZOOM SYSTEMS

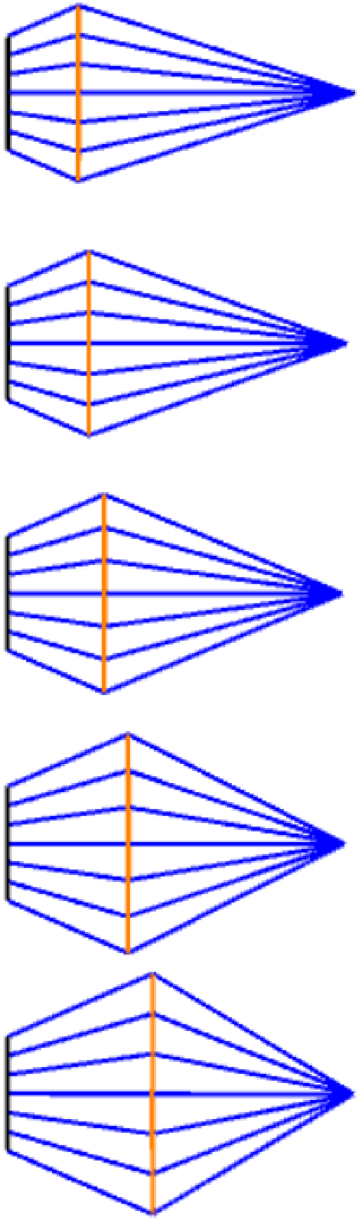
Two lens zoom

- Typically, zoom lens requires fixed image plane
  - Elements move relative to each other
  - Move relative to image plane

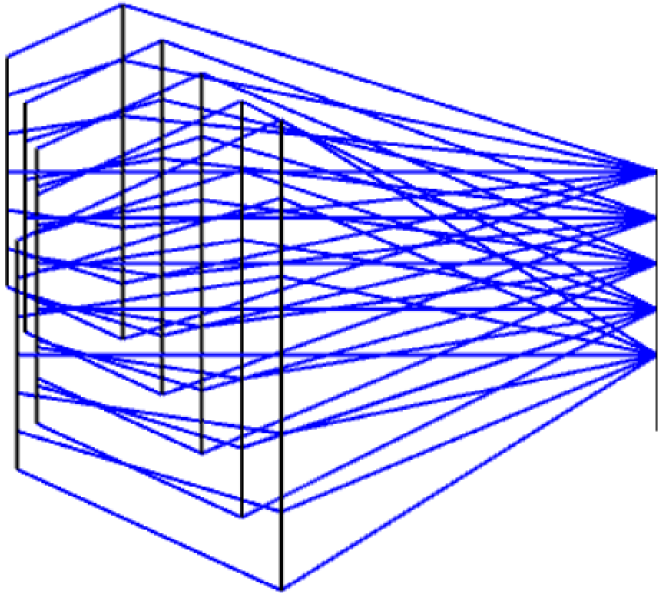
$$\phi = \phi_1 + \phi_2 - \phi_1\phi_2 t$$

$$BFD = f - \frac{\varphi_1}{\varphi} t$$

Reverse telephoto

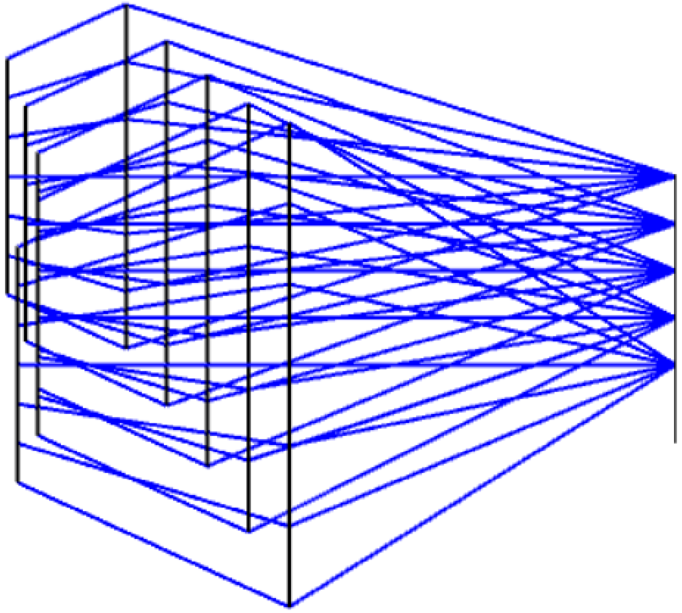


- Allowing both lenses to move allows desi almost com (TOTR)
- BFD > FL



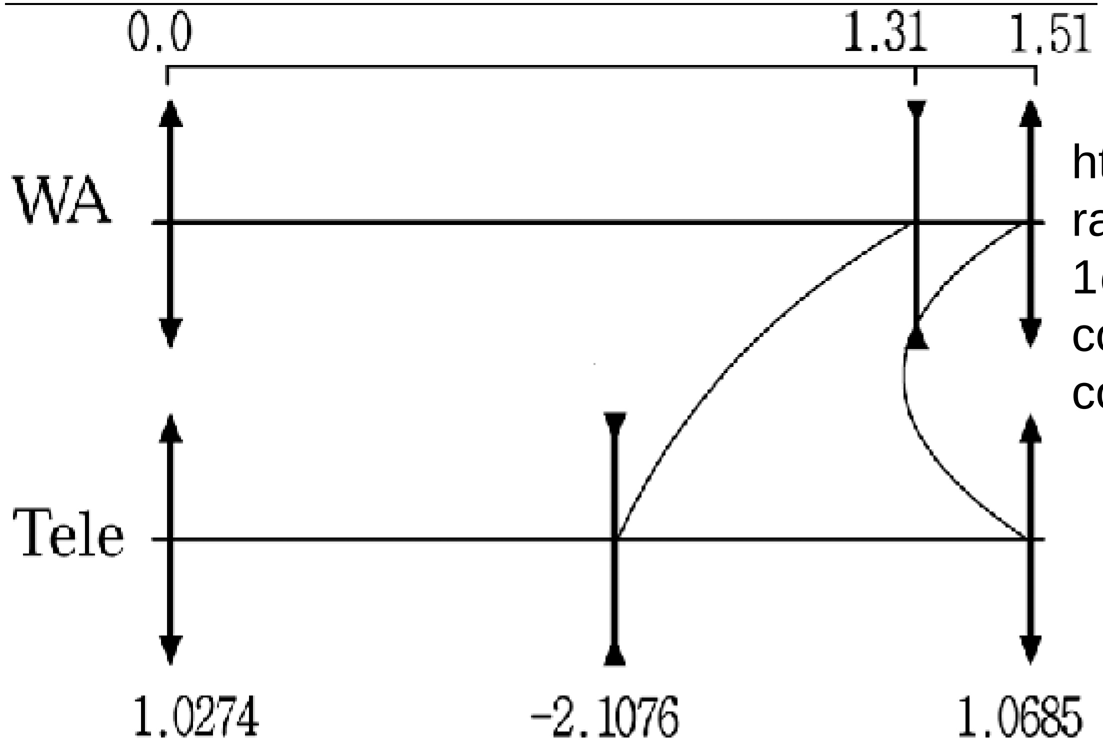
Closer look

- Notice curve to movement of front group
- Linear movement of rear group



3-component zoom

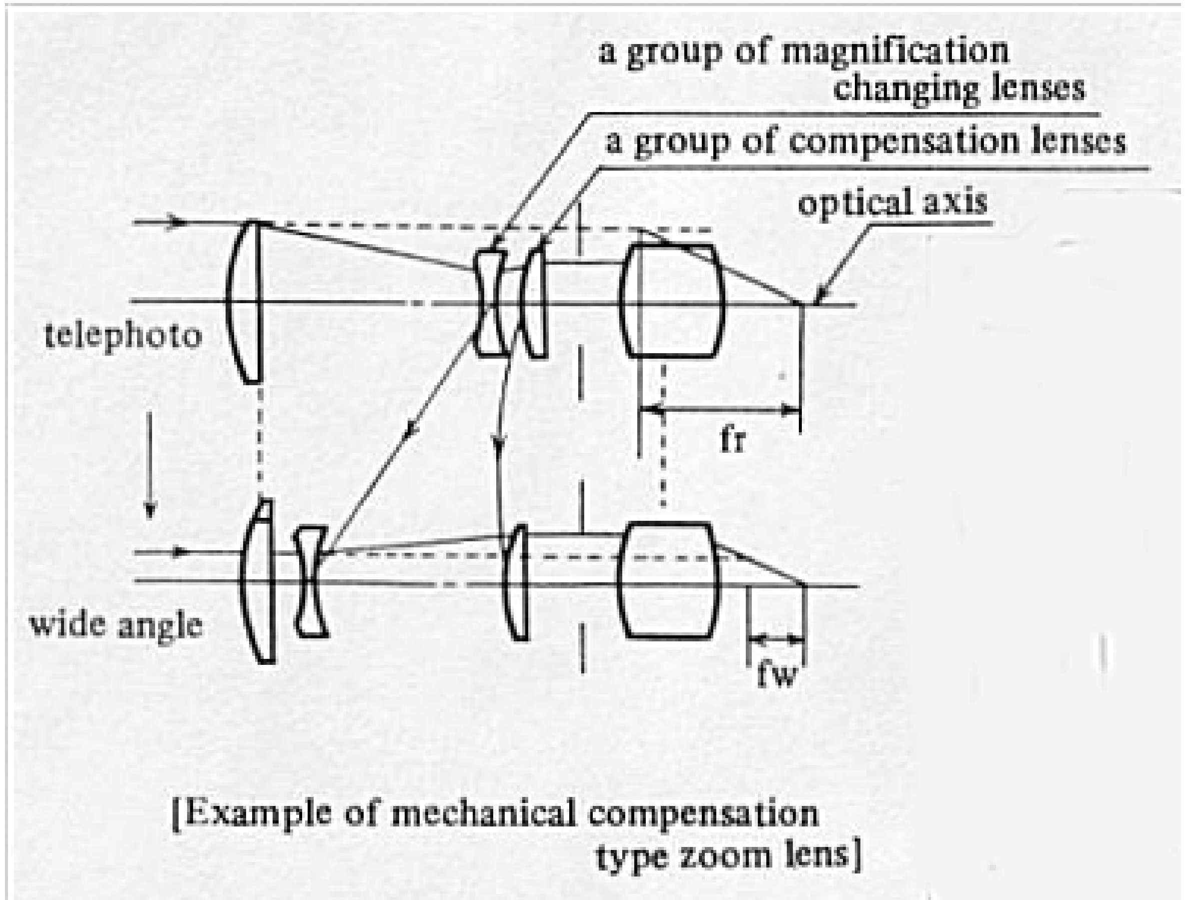
- The next step in complexity:



https://www.researchgate.net/profile/Lakshminarayan_Hazra/publication/236941815/figure/fig3/AS:393213228666881@1470760747107/A-three-component-mechanically-compensated-zoom-lens-Axial-positions-of-the-components.png

Mechanically compensated zoom lens

- With mechanical compensation, movements of the lens are changed by means of a cam



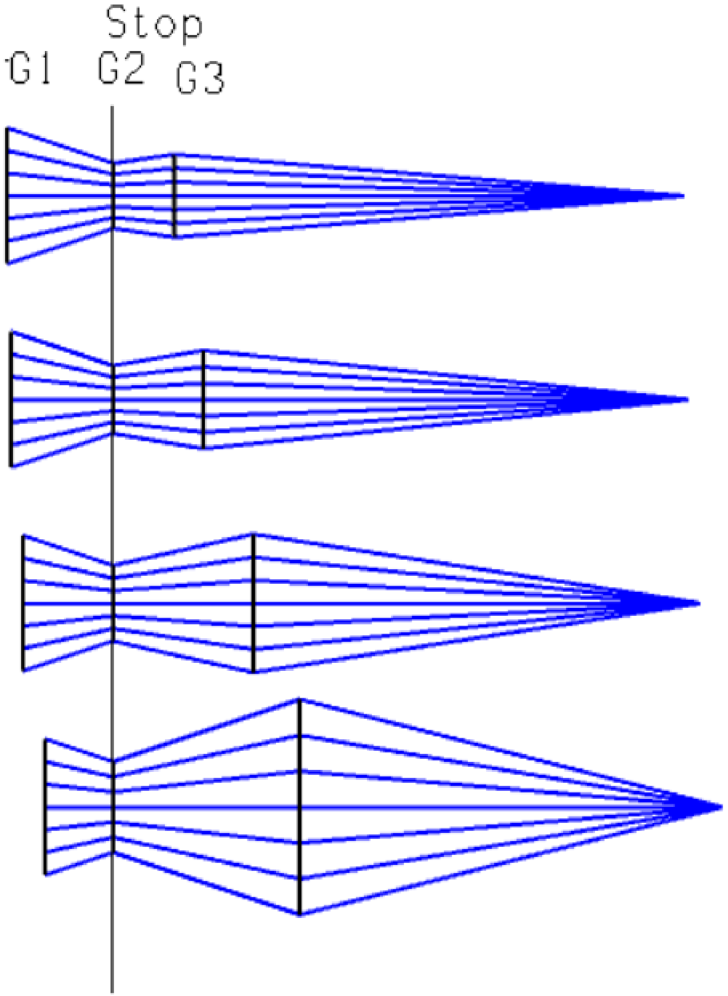
[Example of mechanical compensation type zoom lens]

Some design form examples

3-lens

ZOOM SYSTEMS

3-group zoom



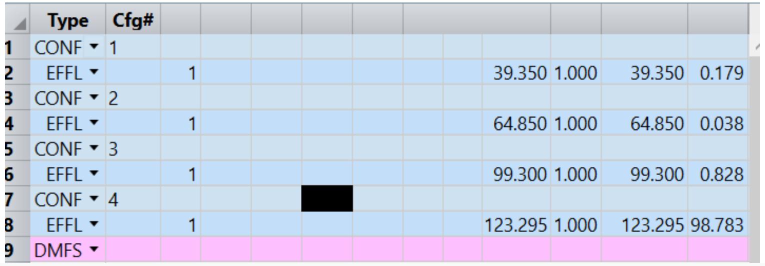
- Pan Cinor design
  - Late 1950s-1960s
- Positive-negative-positive group powers
- G1 and G3 move relative to G2 (Stop) to set power
- Total system length constant
- 4 co

Kingslake: Lens Design Fundamentals section 3.5.3

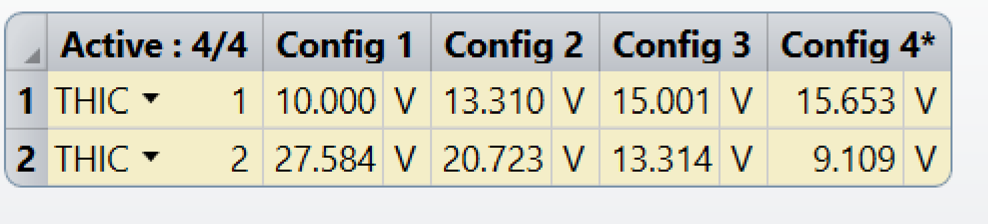
- Fixed aperture sizeNext steps would

First order, on-axis only

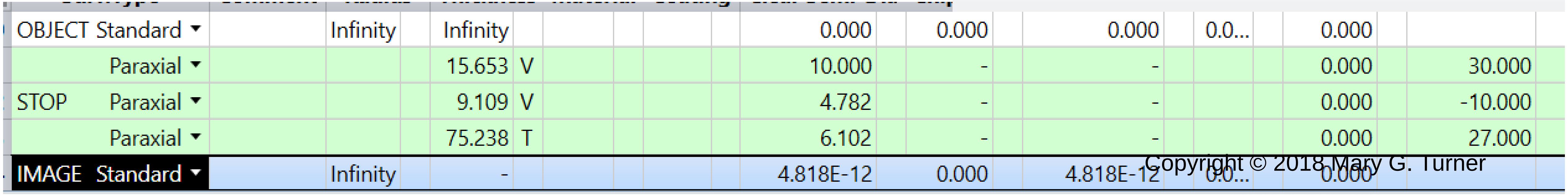
- “T”: position solve
  - Forces all configurations to have same distance between front and image
- Constrain focal lengths in MFE:
  - EFFL
- Vary spacing between configurations
  - THIC



	Type	Cfg#										
1	CONF	1										
2	EFFL		1						39.350	1.000	39.350	0.179
3	CONF	2										
4	EFFL		1						64.850	1.000	64.850	0.038
5	CONF	3										
6	EFFL		1						99.300	1.000	99.300	0.828
7	CONF	4			[redacted]							
8	EFFL		1						123.295	1.000	123.295	98.783
9	DMFS											



	Active : 4/4	Config 1	Config 2	Config 3	Config 4*
1	THIC 1	10.000 V	13.310 V	15.001 V	15.653 V
2	THIC 2	27.584 V	20.723 V	13.314 V	9.109 V



OBJECT	Standard		Infinity	Infinity				0.000	0.000	0.000	0.0...	0.000	
	Paraxial			15.653	V			10.000	-	-		0.000	30.000
STOP	Paraxial			9.109	V			4.782	-	-		0.000	-10.000
	Paraxial			75.238	T			6.102	-	-		0.000	27.000
IMAGE	Standard		Infinity	-				4.818E-12	0.000	4.818E-12	0.0...	0.000	

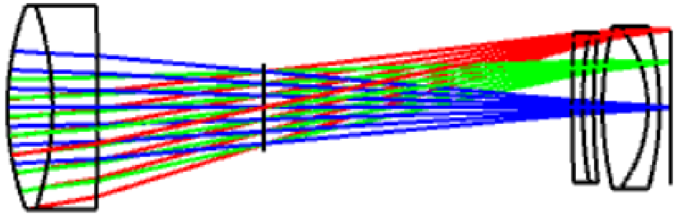
Next steps

- Substitute achromats for paraxial lenses
  - Similar power/focal length
- Maintain common total track
  - “Reasonably” at first
  - Tighten as design becomes finalized
- Consider “fixing” G1 and G2 and shifting negative G2
- Add fields
  - Correct for field aberrations

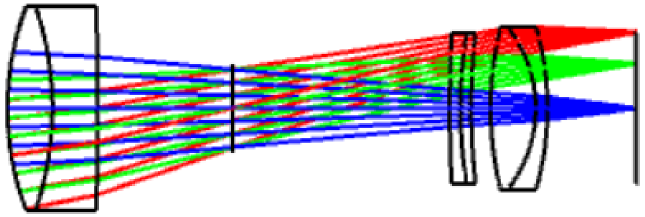
Zemax example

- From Users\Mary\Documents\Zemax\Samples\Short course\Archive folder
  - Aperture: 25mm EPD
  - Field: +/- 17mm image height

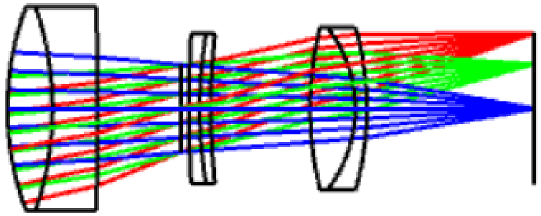
Configuration 3 :
FL = 125mm
F/# = 5
Telephoto range



Configuration 2 :
FL = 100mm
F/# = 4

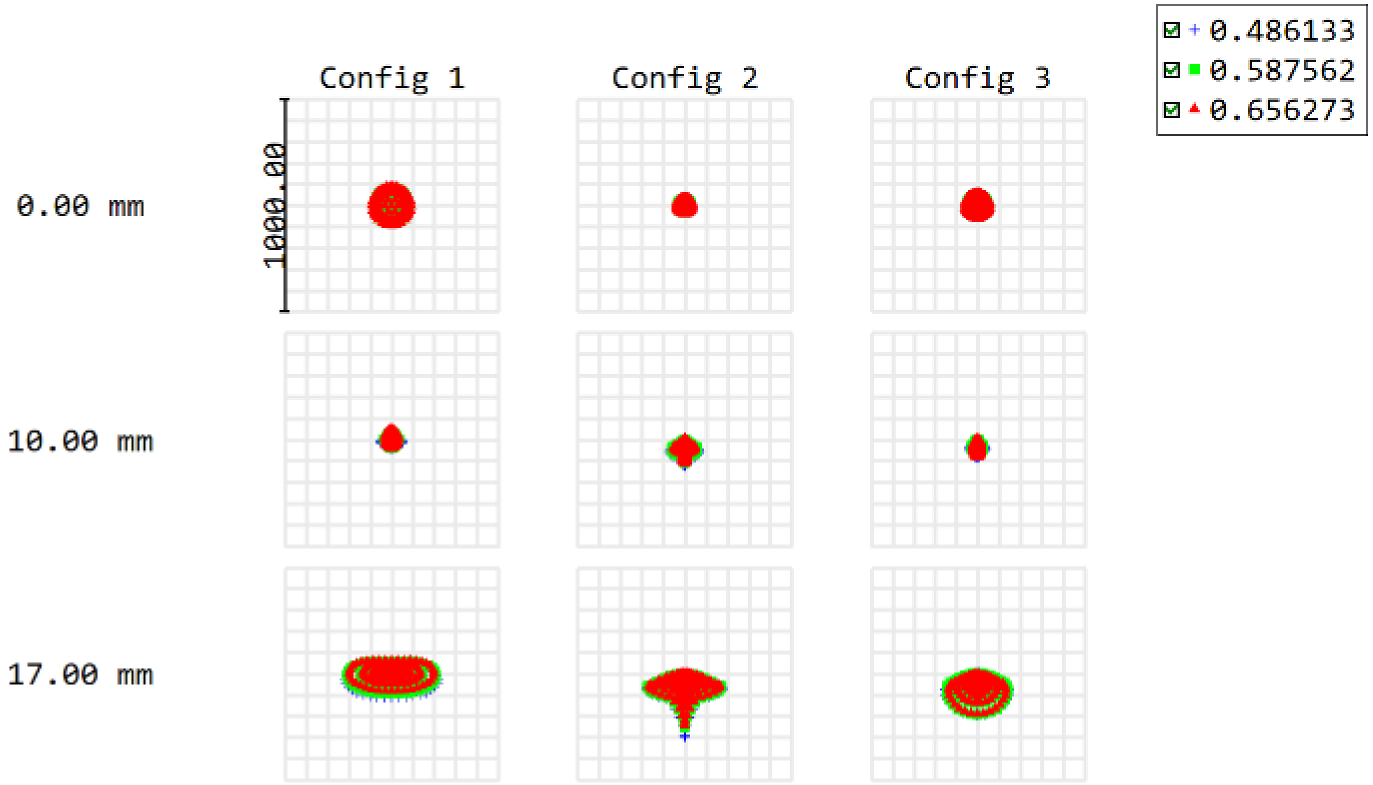


Configuration 1 :
FL = 75mm
F/# = 3
Wide angle



Zemax example

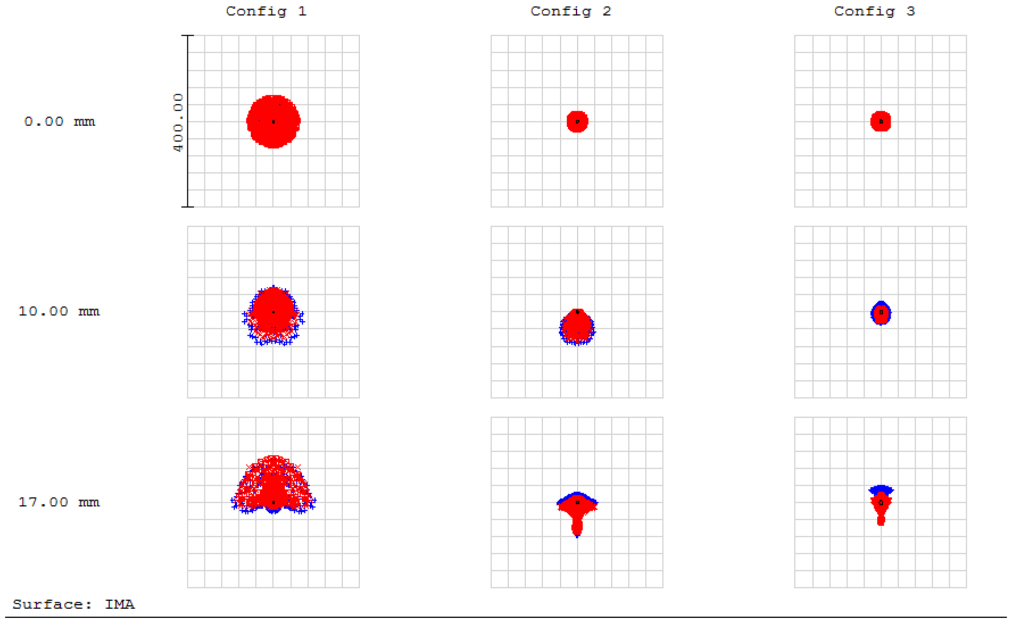
- Some data:
  - ON-AXIS: 20-40



Continuing Zemax short course zoom sample

RMS spot size ranges from

10 ~40um



Configuration 1	Configuration 2	Configuration 3
FL = 75mm	FL = 100mm	FL = 125mm
F/# =3	F/# =4	F/# =5
EP = 25mm	EP = 25mm	EP = 25mm

fixed and zoom expanders

BEAM EXPANDERS

Beam expanders

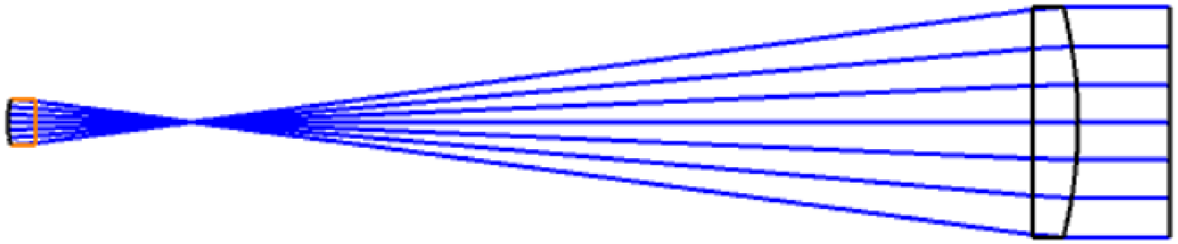
- Telescope, used in reverse
  - Small input, larger output
  - Beam reducer is a telescope
- Afocal system:
  - FL = Infinity (approximately)
  - Collimated light in / out
- Typical application: to expand size of laser beam
  - Quasi-monochromatic light

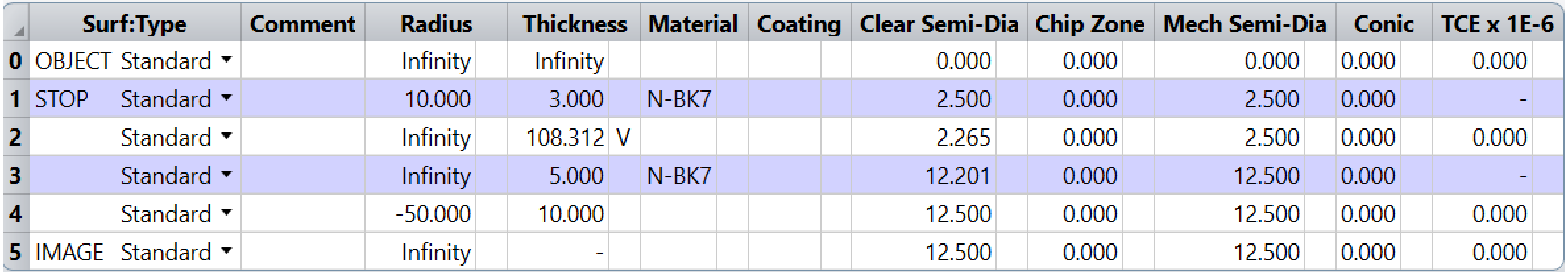
Beam expanders

- Two forms of refractive beam expanders:
  - Keplerian
  - Galilean

Keplerian

- Two positive elements
- Separated by sum of focal le
- Internal focus

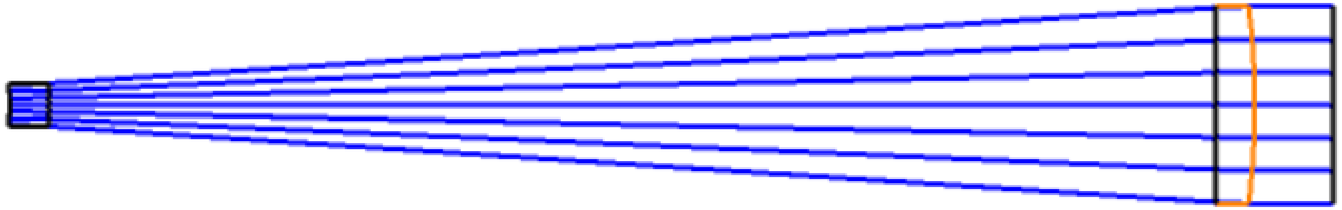




	Surf:Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT Standard		Infinity	Infinity			0.000	0.000	0.000	0.000	0.000
1	STOP Standard		10.000	3.000	N-BK7		2.500	0.000	2.500	0.000	-
2	Standard		Infinity	108.312 V			2.265	0.000	2.500	0.000	0.000
3	Standard		Infinity	5.000	N-BK7		12.201	0.000	12.500	0.000	-
4	Standard		-50.000	10.000			12.500	0.000	12.500	0.000	0.000
5	IMAGE Standard		Infinity	-			12.500	0.000	12.500	0.000	0.000

Galilean

- Positive – negative lens combination
- Separated by sum of focal lengths
- No internal focus



	Surf:Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT Standard		Infinity	Infinity			0.000	0.000	0.000	0.000	0.000
1	STOP Standard		-20.000	5.000	BK7		2.500	0.000	2.720	0.000	-
2	Standard		Infinity	148.356 V			2.720	0.000	2.720	0.000	0.000
3	Standard		Infinity	5.000	BK7		12.342	0.000	12.523	0.000	-
4	Standard		-100.000	10.000			12.523	0.000	12.523	0.000	0.000
5	IMAGE Standard		Infinity	-			12.521	0.000	12.521	0.000	0.000

In Zemax

- Only a couple changes:
- System Explorer/ Aperture
  - Check “Afocal Image Space”
    - Optimizer will minimize angular error
      - Can use Wavefront, not just spot with angular option
  - In MFE:
    - REAY operand to target half-height of on-axis chief ray
    - Make sure to consider the sign

Beam expander design in Zemax

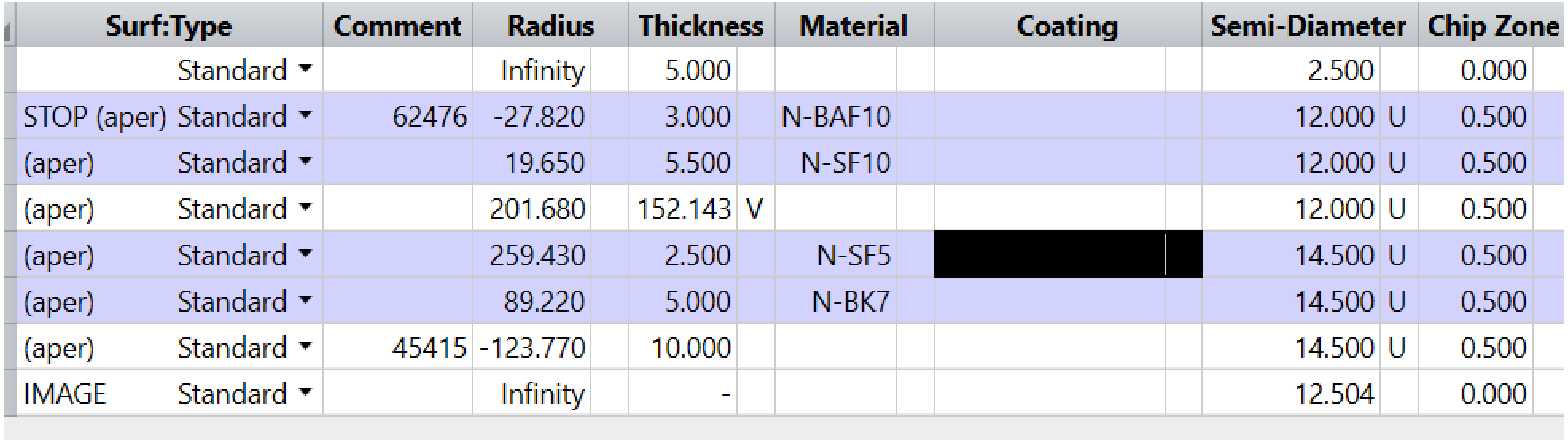
- To make 10x beam expander:
  - Afocal image space in Zemax
    - System Explorer Check Box
  - Entrance pupil diameter: full size of input beam
  - EPD/2: radial half size of input beam
  - REAY target:
    - 10*(EPD/2)

In Zemax

- For example:
- For a 10x beam expander having 20mm output beam diameter:
  - System aperture: 2mm
  - REAY: 10mm (at output surface)
    - Provides 10 times expansion
    - REAY is radial height
- Constraints: total length: TTHI with weight 0 and OPLT
  - Keeps the length to desired limits
  - Otherwise will go to infinity

10x Galilean beam expander

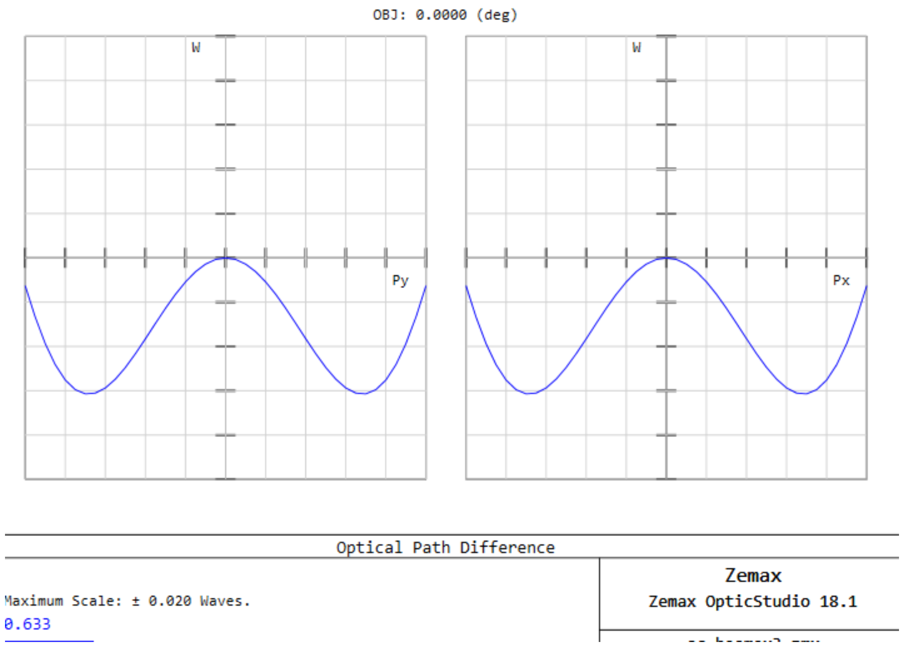
- A 10x Galilean beam expander, converted to stock lenses:

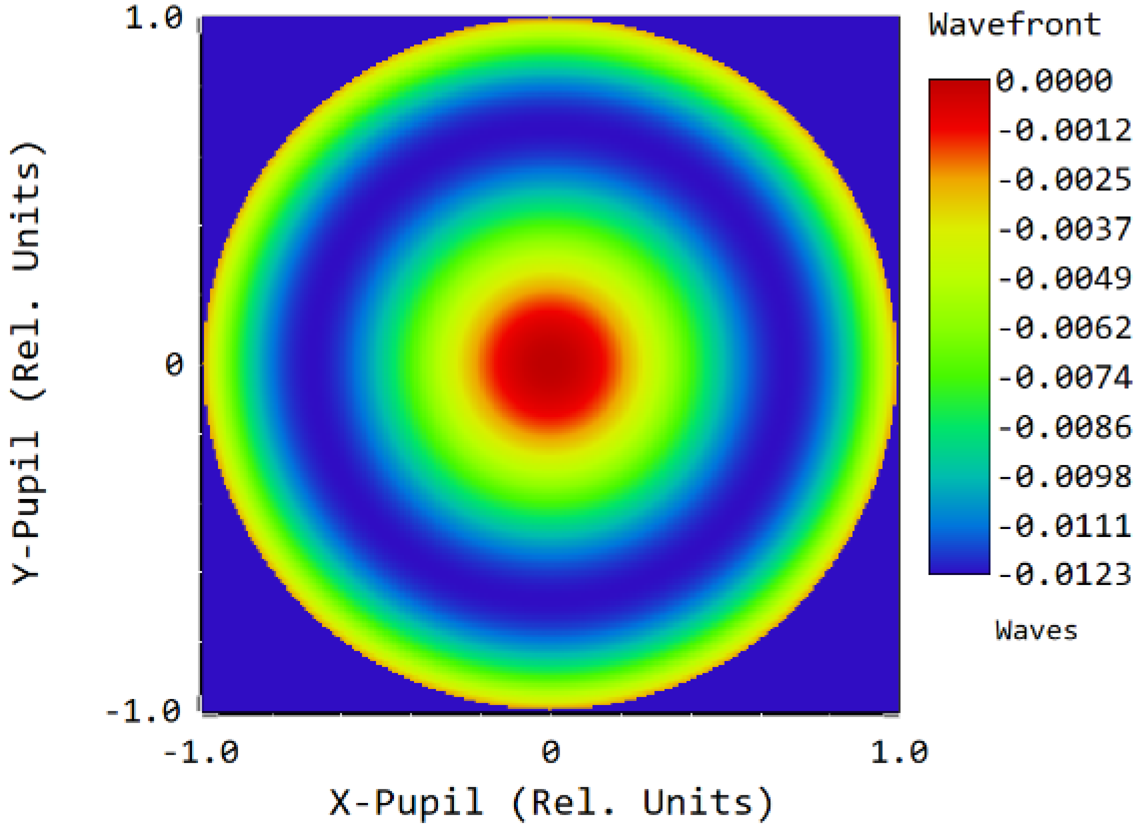


Surf:Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Chip Zone
Standard		Infinity	5.000			2.500	0.000
STOP (aper) Standard	62476	-27.820	3.000	N-BAF10		12.000 U	0.500
(aper) Standard		19.650	5.500	N-SF10		12.000 U	0.500
(aper) Standard		201.680	152.143 V			12.000 U	0.500
(aper) Standard		259.430	2.500	N-SF5	[redacted]	14.500 U	0.500
(aper) Standard		89.220	5.000	N-BK7		14.500 U	0.500
(aper) Standard	45415	-123.770	10.000			14.500 U	0.500
IMAGE Standard		Infinity	-			12.504	0.000

10X beam expander

- Some data:





Zoom type

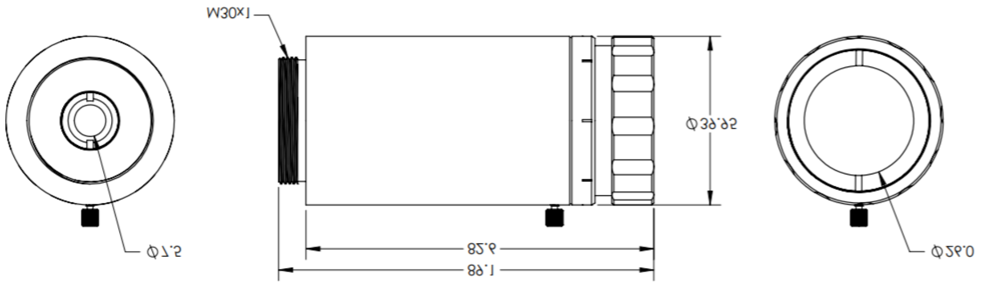
BEAM EXPANDERS

Fixed beam expander

- A commercial 10x beam expander

Specifications

Expansion Power:	10X	Design Wavelength DWL (nm):	355
Wavelength Range (nm):	340 - 380	Entrance Aperture (mm):	7.5
Exit Aperture (mm):	26	Transmitted Wavefront, P-V:	<λ/10 for 2.3mm input beam (nominal, λ = DWL)



Zoom beam expanders

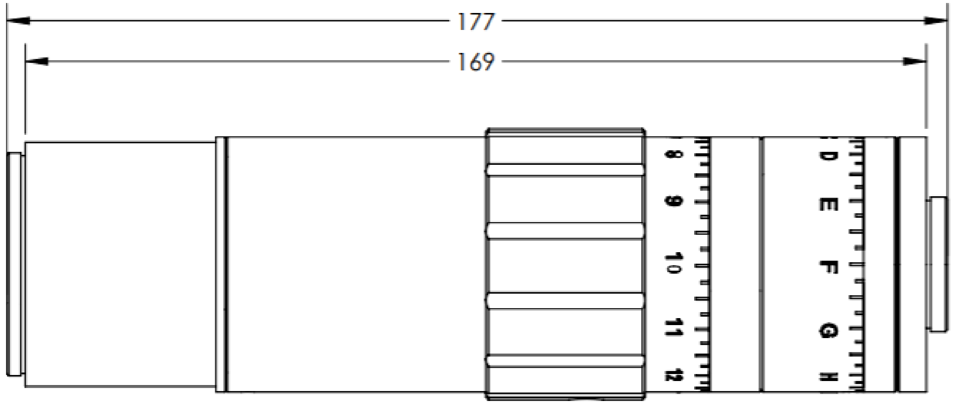
- Two forms:
  - Single magnification, multiple wavelengths
    - Such as YAG: 0.266, 0.355, 0.532, 1.064um
    - Vary separation
  - Single wavelength, multiple magnifications
    - Multiple group system

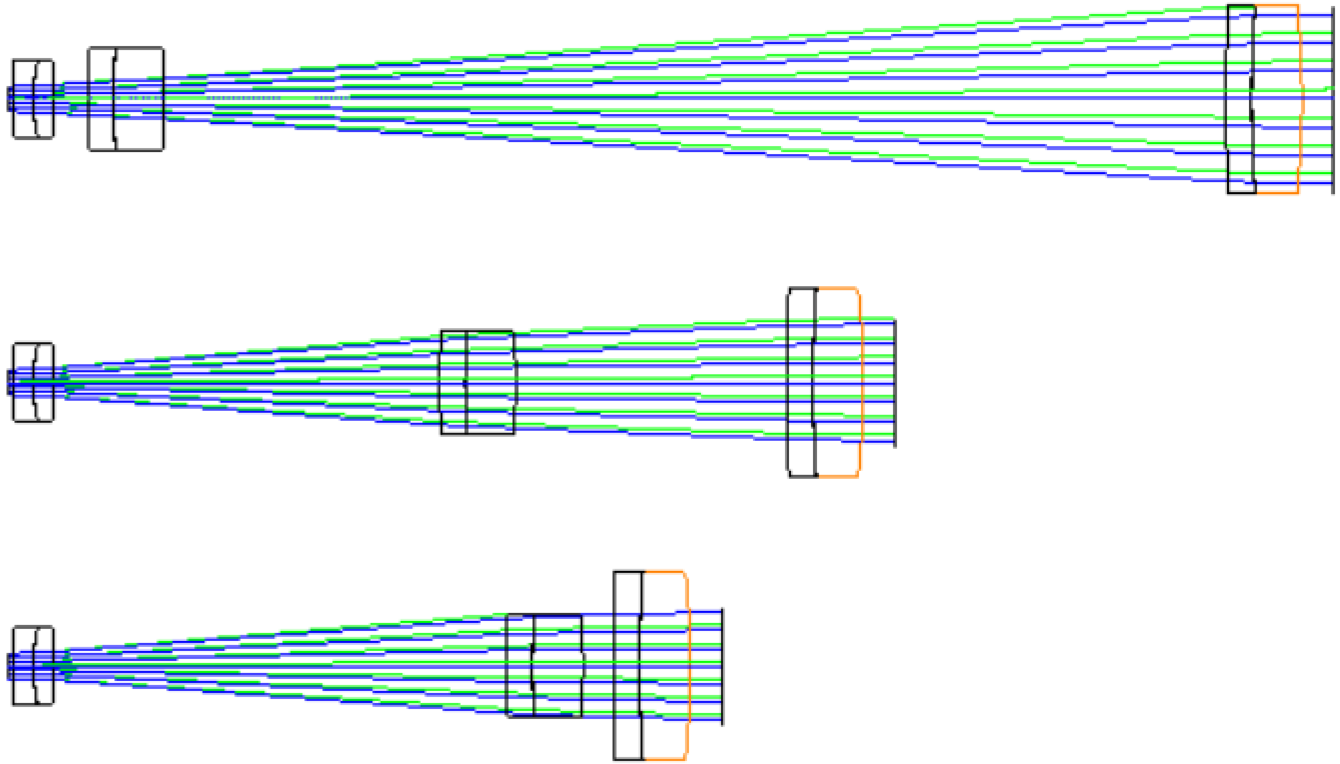
Zoom beam expander

- Define a set of configurations over the magnification range
- Define a multi-configuration merit function
- Performance at non-design magnifications may suffer
  - 5-10x expander use only at 5, 10, and maybe 7.5x
  - Verify performance at other magnification before use

Zoom beam expander example

- 3 doublet system
- 4.2X – 7X





https://www.edmundoptics.com/optics/laser-optics/laser-beam-expanders/research-grade-variable-beam-expanders/

5x/10x zoom beam expander

- An example design:
  - – 3 doublets
  - – OPD < 0.01 waves
  - – Length: 120mm@10x

45mm@5X