A STUDY ON ZOOM LENSES

by

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DEDICATION

Dedicated to my undergraduate cohort here at OSC. I never would've made it without you all.

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ABSTRACT

Varying the focal length of an optical system changes the magnification and field of view of the resulting image. By adding compensation to maintain a stationary image plane, a zoom lens is created. This optical zoom enables multi-function systems that are very desirable in photography, cinematography, microscopy and defense applications. Several design considerations like size, weight, and imaging performance are critical to control when creating a zoom system. This report will look into the background, characteristics and design forms and methods often used in the creation of these zoom lenses.

CHAPTER 1

INTRODUCTION

Vari-focal lenses have been commercially available since the 1890s, yet they saw limited appeal until well into the 20th-century. Early vari-focal designs could not be called ”zoom lenses” as the focal plane of the system was not fixed and the film location had to be manually adjusted by the operator to maintain focus at different focal lengths. A moving compensator was required to hold the image still throughout the different focal length positions. While not possible to hold perfect focus at all zoom locations, the image shift must be small enough for the image quality to be acceptable.

At first, zoom lenses were only considered practical for filmmakers as photographers could merely carry lenses of multiple focal lengths with them to swap out as needed. Only cameramen who needed to change image size throughout the shooting of the scene saw these zoom lenses as a necessity. Even then, widespread adoption was initially resisted by professional movie-makers until the advent of television as new cameramen adapted quickly to these new lenses. As zoom lenses were generally considered only useful for filmmakers, it took longer for zoom lens technology to spread to still photography. The initial difficulty in making these lenses available to photographers was from the much larger film format in standard still cameras. New design forms needed to be explored as enlarging designs for motion-picture cameras would result in very large and expensive systems, which was impractical.

In addition, without the fast optimization algorithms made possible by computers in the 60s, designing zoom lenses that minimized aberration was highly difficult using conventional methods. As manufacturing techniques and design tools progressed, designing zoom lenses quickly became much easier and zoom capable lenses can now be found in many different industries. Many design forms have been explored as these methods continue to improve into the modern day.

CHAPTER 2

KEY CONCEPTS

2.1 Basic Form

In general, zoom lenses tend to follow a few design forms. At its most basic level, there are two critical pieces. First, there is the variator or zooming group. This is made up of one or more groups of lenses that provide the focal length change to vary the magnification of the image as they move along the optical axis. To maintain focus at one location, there needs to be a compensator group that also moves. The ratio between the focal lengths of the maximum and minimum zoom positions is called the zoom range or zoom ratio.Initial zoom systems had ratios between 1 and 3, but modern zoom lenses can reach ratios over 12.

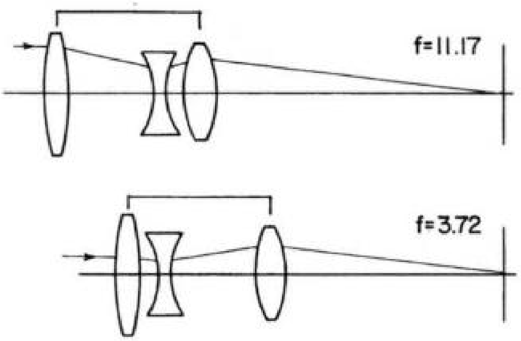


Figure 2.1: Simple optically compensated system. Note the positive elements move identically. Figure from Kingslake [1].

In some preliminary zoom designs, the variator and the compensator moved identically which produced what is known as an optically compensated zoom. Rarely seen today, optically compensated zoom lenses struggled to produce high quality images at all zooms. By coupling their movement like this, there are less variables available to minimize aberrations. By the 1960s, optically compensated lenses had faded from popularity for better design forms. Fig. 2.1 shows an example of basic optical compensation. Occasionally a form of optical compensation will appear in patent literature, but usually as a part of more complicated system. Pure optically compensated zooms are practically extinct.

Now, zoom lenses are nearly entirely mechanically compensated instead. In this case, the variator and compensator groups no longer move together but are allowed to have different motions when passing through different zoom positions. This is made possible by mechanical cams or slot and pin mechanisms that guide the motion of the lens as zoom is adjusted. Lens motion does not have to be linear and can vary quite dramatically from design to design. Fig. 2.2 illustrates this lens motion.

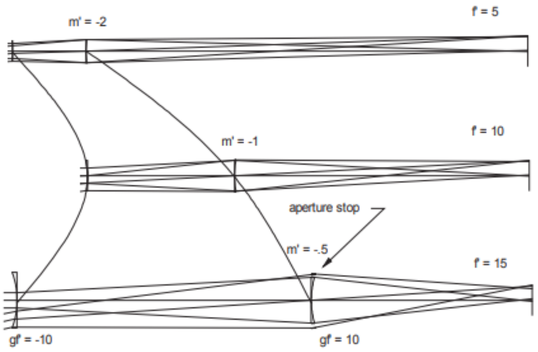


Figure 2.2: A simple example of a mechanically compensated system. Zoom and compensator kernels move independently from each other. From Youngworth [2].

Mechanically compensated systems increase design freedom by allowing for more optimal lens paths that better control aberrations present throughout the zoom. As computer technology developed, eventually optimization algorithms began to be developed for lens design that took much of the burden off of the engineer. This opened up design solutions previously unexplored as only the computer could take a brute force approach to improving the system design. Since these solutions had more complicated lens paths, mechanical motion of the elements needed to be more precise and repeatable. By the 1960s, slot and pin mechanisms had reduced in cost enough to be adopted widely in zoom systems. Changing zoom is now done by a simple twist of the lens housing, or even moved electronically with motors. Modern cellphone cameras have a small form of optical zoom where the lens motion is driven by magnetic actuators. An example of this mechanical zoom technology is shown in Fig. 2.3.

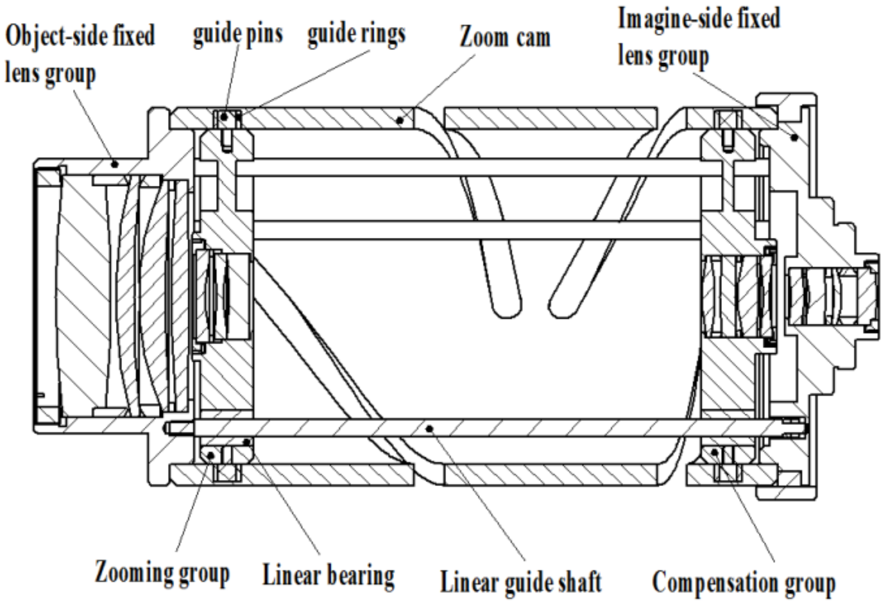


Figure 2.3: Mechanical zoom configuration. From Wang [3].

Aside from optically compensated systems, most zoom lenses are either two-component zoom, three-component zoom, or four-component zoom. Named for the number of moving or independent lens groupings within the system, these forms make up the majority of available systems. Some modern systems don't fit neatly into any well-defined type, but tend to still resemble these other forms. A zoom system cannot exist without moving elements, so it is natural for these designs to operate off of similar foundations.

2.2 Two-Component Zoom Lenses

The most basic possible zoom configuration, the two-group system works as a possible solution. Two-component systems can be easily designed for smaller zoom ratios, but greater complexity is needed for larger zoom ratios. For this reason, in addition to better aberration control and lens size reduction, commercial lenses now ubiquitously have more moving groups. It is possible to partially correct for 4th-order aberrations in a two group system, but this is generally more difficult to design for and is not the preferred method for today's lenses. With two groups, there are 4 different possible power configurations: positive-positive (PP or ++), positive-negative (PN or +-), negative-positive (NP or -+) and negative-negative (NN or --). These groupings can be as complex or simple as the designer wants. A two-group zoom may still have 4 or five individual lenses, just as long as the lenses are clearly grouped into the distinct variator and compensator units.

2.2.1 Positive-Positive Zoom

In understanding design methodology, we will look at each of these possible configurations for two-group systems and connect this to the design constraints lens designers of the past faced. The above configurations are realistic solutions to creating useful lenses, but demonstrate the operation of mechanical zoom configurations. In Fig. 2.4 we have a simple two element system with two positive lenses. This system was designed with the 35mm film format in mind.

Surface	Radius (mm)	Thickness (mm)	Glass
1	Dummy	101.3 – 211.07	
2	75.592	8.000	N-BK7
3	138.749	58.48 – 40.51	
Stop		203.89 – 56.37	
5	145.848	10.000	F5
6	-181.418	19.54 – 75.29	
Image			

Table 2.1: Prescription for PP system from Fig. 2.4

This system appears to perform well, and for a simple system like this, the monochromatic aberration correction is reasonable. But in a real system, something like this is impractical. The total length of the system at its largest extent is 300mm which is long for a system that only has a zoom ratio of 2. In addition, this system

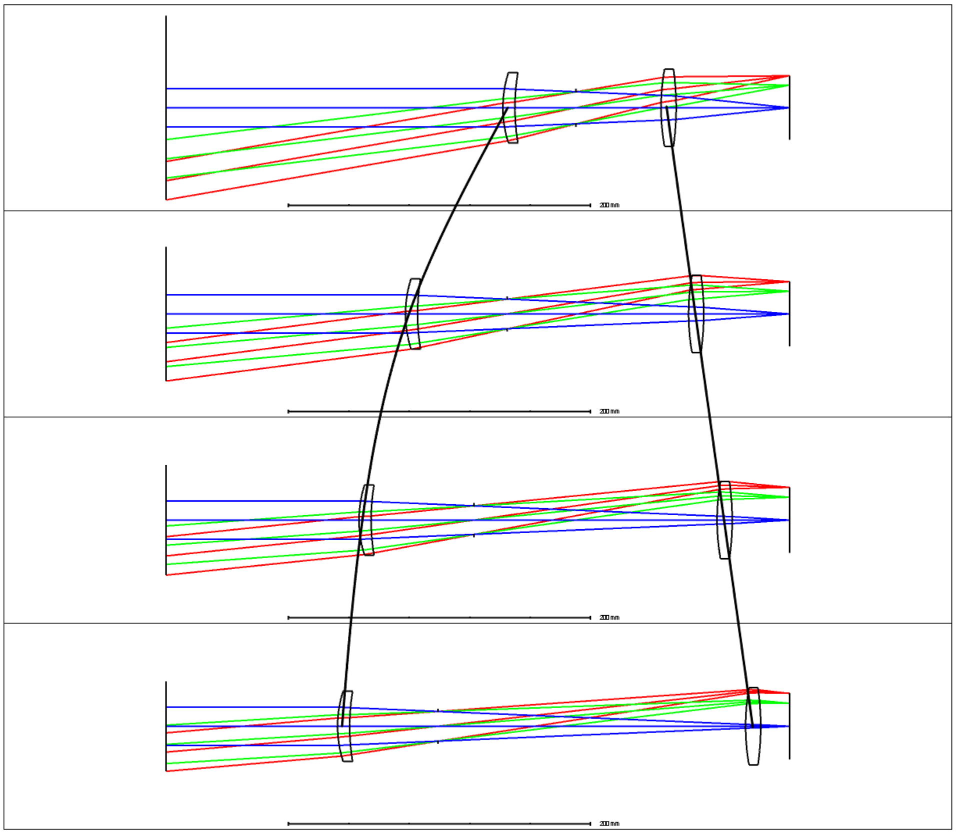


Figure 2.4: PP zoom system with a focal range of 125-250mm

would not be accepted for a standard SLR system as the back focal distance at some of the zoom positions is too short fit onto standard camera bodies. With this constraint in mind, now the zoom ratio is even smaller as a result. A lot of space and motion is required in this system for very little payoff. These problems are inherent to PP systems making them generally undesirable as design forms unless further complexity is added, making it no longer a two-group system.

2.2.2 Positive-Negative Zoom

The PN zoom system is often commonly known as a "Telephoto Zoom Lens" as a telephoto lens is simply a positive lens group followed by a negative lens group. This is advantageous, particularly with zoom systems as the focal length of the system is longer than its actual length, giving it a smaller mechanical footprint. Fig. 2.5

shows a simple example of a PN system.

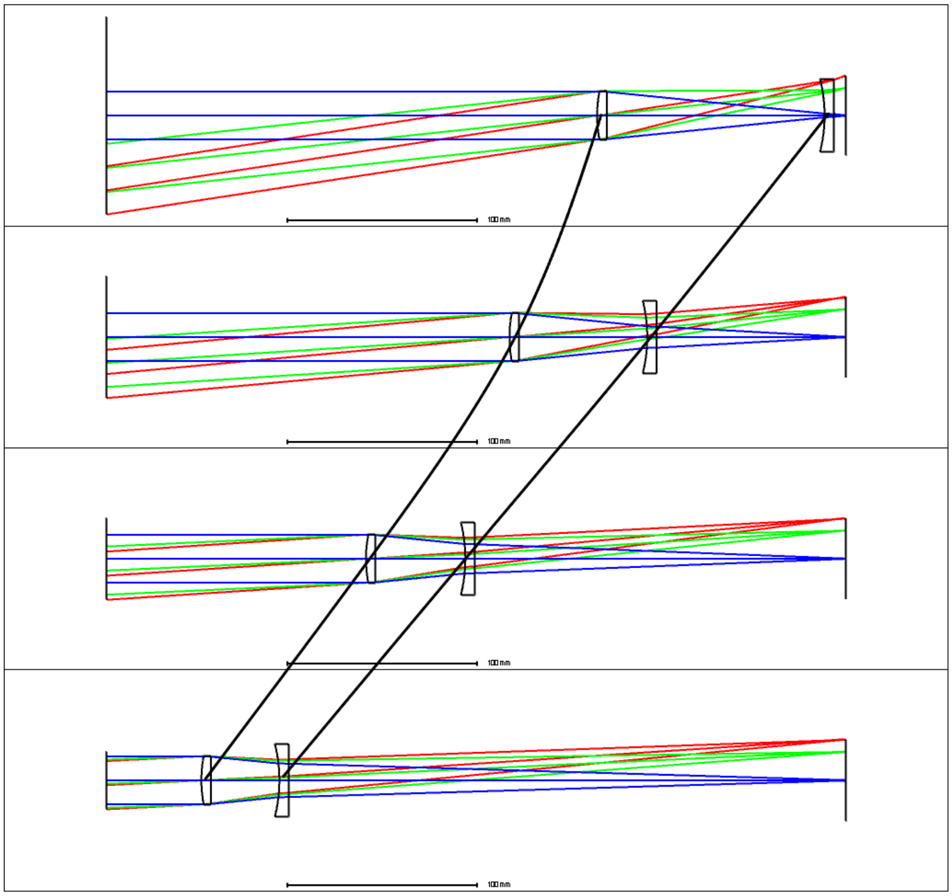


Figure 2.5: PN zoom system with a focal range of 141-425mm

We see here that though this system is able to reach higher zoom ratios than the PP system, it is still very limited by the back focal distance. The minimum focal length is found when the negative element is at the image location and the maximum is found when the zoom elements collide with each other. The maximum extent, however is very far from the image plane, and unrealistic. We also see a drastic decrease in the field of view of the system at the larger end of the zoom range. The telephoto system does have desirable qualities to it, but with just two elements, there is little improvement that can be done as far as the zoom mechanics of the system go.

Surface	Radius (mm)	Thickness (mm)	Glass
1	Dummy	258.84 – 50.0	
Stop	67.149	5.000	N-BK7
3	Plano	115.0 – 36.14	
4	-78.579	5.000	F5
5	Plano	6.09 – 293.791	
Image			

Table 2.2: Prescription for PN system from Fig. 2.5

2.2.3 Negative-Positive Zoom

The reverse of the previous system, this configuration is most often referred to as the "Reverse-Telephoto Zoom Lens". This configuration has the opposite feature of the telephoto zoom where in this case, the focal length of the system is shorter than the overall length of the system. While that initially sounds undesirable, when used in conjunction with more lens groupings, this lens then has some useful qualities to it. Fig. 2.6 displays a simple example of this kind of system.

Surface	Radius (mm)	Thickness (mm)	Glass
1	Dummy	116.5 – 25.8	
2	67.149	3.000	F5
3	Plano	78.13 – 24.8	
Stop	-78.579	8.000	N-BK7
5	Plano	144.37 – 288.4	
Image			

Table 2.3: Prescription for NP system from Fig. 2.6

This system has a zoom ratio of 3, and requires a shorter focal length to maintain similar track lengths as the other two configurations. When increasing the field of view at shorter focal lengths, element size rapidly increases and must be kept within a reasonable range for the designer's application. With this system, the back focal distance at all zoom locations is reasonable for typical SLR camera bodies. This extra space behind the elements makes this configuration attractive for more

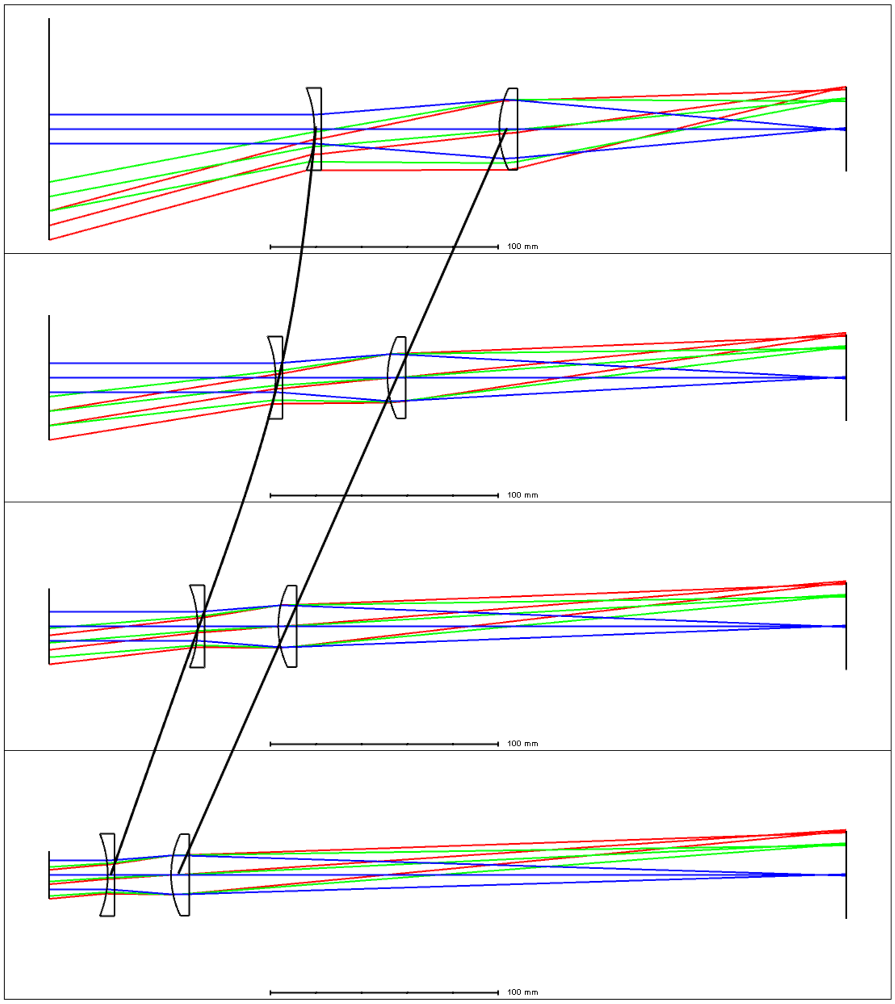


Figure 2.6: PN zoom system with a focal range of 80-240mm

complicated systems.

2.2.4 Negative-Negative Zoom

The NN zoom lens actually is not a real solution. Two negative elements are unable to focus collimated light. So really designers are limited to three options when it comes to two-group systems. Each of the possible solutions offer certain advantages over the others in terms of field of view, focal length, zoom ratio, aberration performance, and other design constraints. Of those three, the reverse-telephoto rises slightly above the others for its large back focal distance, larger zoom ratios, and simple lens motion.

As we've seen, however, none of the options are all that appealing, and no one possible solution really solves all of the problems and controls that need to be considered. 4th order aberrations in two-component zooms can be controlled by splitting the singlets into multi-element groups that move together or even allowing for some aspheric surfaces. Of course, manufacturing costs rise with addition of these improvements. An example of this type of improvement can be found in the patent literature, as seen in Fig. 2.7. Even with these improvements, some sacrifices needed to be made to maintain image size and quality. At the extent of the zoom range, there is some significant vignetting present at the edge of the field.

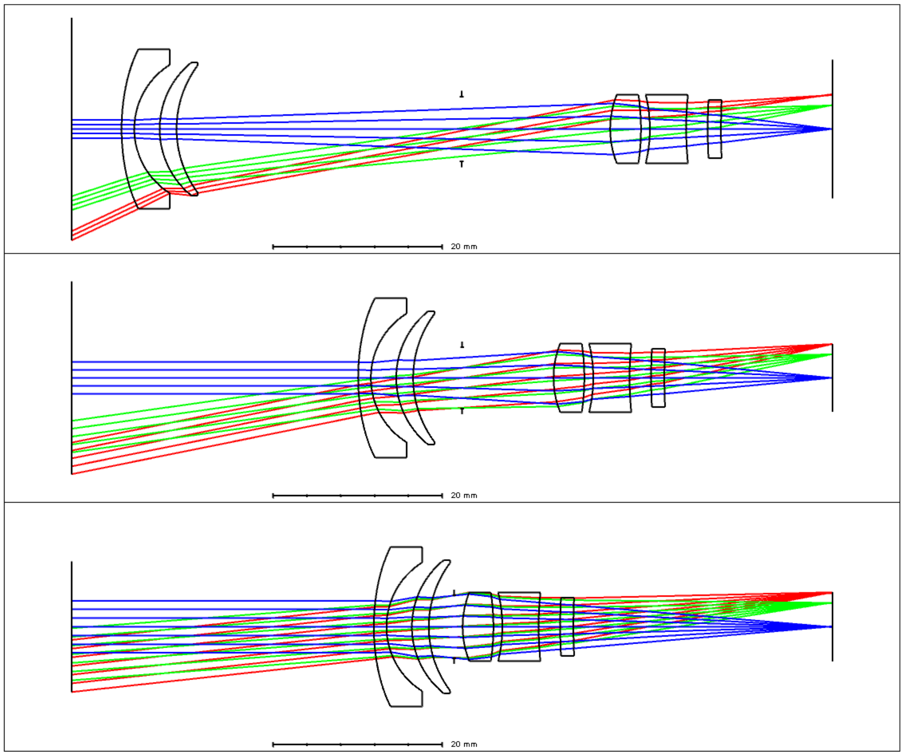


Figure 2.7: Aberration controlled two-group zoom lens with zoom ratio of 4. From US Patent 4,999,007 [4].

Adding design complexity by increasing the number of lens groupings in the system opens up many more design possibilities that are more interesting, and more appropriate for real commercial production. There is always a push to make these lenses smaller, lighter, and still maintain sharp images at all zooms leading to systems with over a dozen individual lenses in the system. Some of these two-group systems provide great baselines for zoom in conjunction with stationary groups in the front and rear of the zooming elements. The basic concepts of zoom systems are easily demonstrated in these more simple systems and can help provide understanding in the more complex cases.

2.3 Three and Four Group Zoom Lenses

By adding more lens groupings to the zoom lens, more options are available to the designer and can take a large variety of other forms. Even just adding a single lens group to the above systems can allow for better aberration control, increased zoom ratio, and decrease the length of the system. In pre-1970 zoom designs, it was considered advantageous to fix a positive final lens group. This final group was called the "prime" lens and it afforded certain benefits. with the final lens fixed, the previous elements could make up an afocal group that varied angular magnification. The prime lens would then always be able to focus the incoming light at the same focal plane. This required a new afocal zoom lens. In the case of a three-group zoom, this type of configuration is called a Donders telescope, named for Dutch ophthamologist F. C. Donders. The original idea was to create either a PNP or NPN system with the outer elements fixed and a sliding middle element. For small inner movements, the lenses remained approximately afocal, but larger motions require one of the outer elements to have some small motion to remain afocal. This system can be seen in Fig. 2.8 and Fig. 2.8.

While the afocal condition is not necessarily crucial, the Donders telescope is particularly useful when used in tandem with other lens groups. The idea is to combine a Donders telescope either before or after a normal focusing group and perform the zoom using only the Donders portion. This allows for great compactness and good image quality. A lens group in the rear would hold the image location still while the Donders telescope merely controls the angular magnification of the scene.

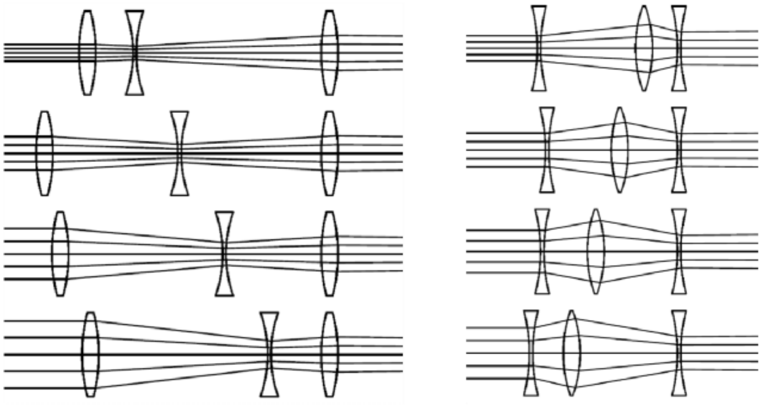


Figure 2.8: Donders telescope from Sasián [5]

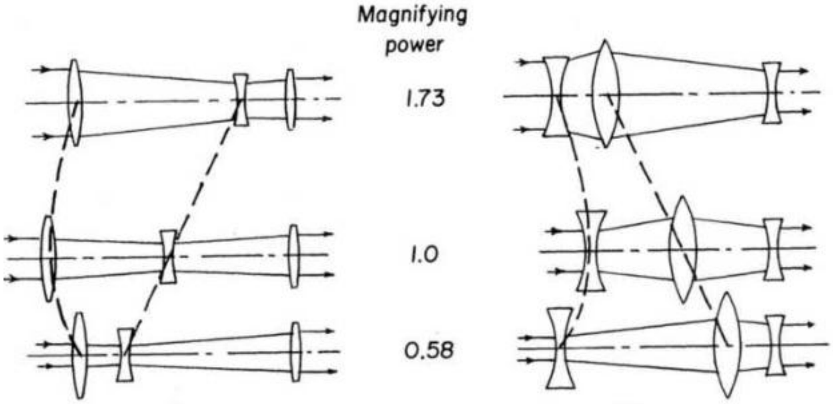


Figure 2.9: Donders telescope from Kingslake [1]

A fixed front group maintains a constant converging incident beam on the Donder portion. Vivitar in the mid 1970s created a zoom lens based on this very concept (Fig. 2.10). The only difference is they allowed the front lens group (the "A" group) to vary slightly to allow focus adjustments for more distant objects. This concept can then be even further extended to include both the front and rear stationary lens for greater design flexibility.

Understanding the history and development of zoom lenses helps inform future design decisions. Many configurations have been explored in the past, and each offers certain advantages and disadvantages over the others. It's up to the engineer to wisely look at these forms and decide which form best fits the need of the project.

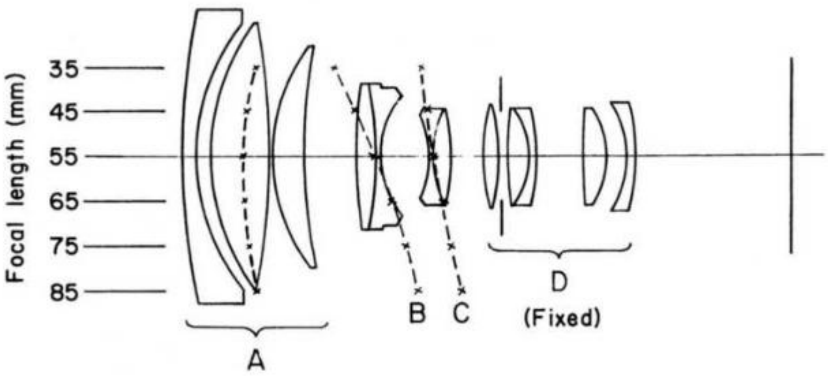


Figure 2.10: The Vivitar zoom lens based off of the Donders telescope. From Kingslake [1].

In the next chapter, we will design from scratch a three-element zoom lens using some of these previously developed ideas and methods.

CHAPTER 3

DESIGN STRATEGY

Designing a zoom lens can be a tricky task without having a good idea of common methods and practices. With the addition of many elements, there are practically infinite design forms to accomplish the same goal. Some design software, particularly Synopsys, have rather robust and quick automatic design algorithms that work quite well, given good inputs, and could potentially serve as starting points for a more refined design. Patent literature is also a fantastic place to begin looking at modern designs and modifying them to suit a different purpose. Patent documents also have value in that they are more than simple lens prescriptions, but they go into detail of what new methods are being brought to the table by this new design, how it has improved on past designs, and often reasons as to why other avenues explored were deemed undesirable or unrealistic.

Both automatic designs and patent documents can be a valuable tool in developing understanding and starting points for a zoom design, but without a fundamental understanding of typical methods, design forms for minimizing certain aberrations, and general lens design theory, it will be difficult to make effective designs and meaningful contributions. In this chapter, we will look at a step-by-step design of a zoom lens from scratch and see these techniques in practice.

3.1 First-Order Design

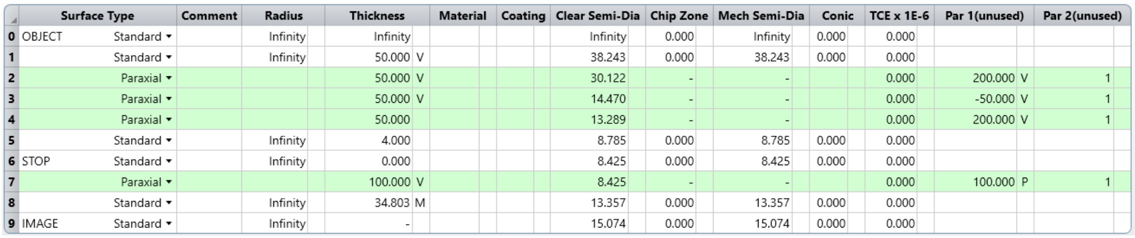
A good place to start when designing any system is to create a first order design that fits the design constraints given. We'll design according to a zoom lens we could potentially find for a typical Canon camera body. These design parameters are listed in Table 3.1.

In keeping with past conventions, we are going to make use of a prime lens to keep

Constraint	Value	Units
Sensor format	25.1x16.7	mm
Min. BFD	44	mm
Max. TTL	225	mm
Max. Diameter	70	mm
Zoom Range	75 – 225	mm
Focal Ratio	f/4 – f/8	

Table 3.1: Zoom lens design tutorial parameters

our focal plane at a single location throughout the zoom. In this case, it makes sense to use a Donders telescope in front and use that to generate our zoom conditions. To start out with, let's give it some appropriate focal lengths and spacings. The exact numbers don't matter too much, just something to get us into the ballpark range of where we want our system to be as we will take advantage of our design software's optimization algorithms to refine our selection. Fig. 3.1 and Fig. 3.2 show the starting parameters I chose for this particular system. I like to create a dummy surface at the start whose thickness can vary to keep total system length the same to easily see how the lenses translate throughout the zoom positions. This also gives some extra space if needed in the future.



	Surface Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6	Par 1(unused)	Par 2(unused)
0	OBJECT	Standard		Infinity	Infinity			Infinity	0.000	Infinity	0.000	0.000		
1		Standard		Infinity	50.000 V			38.243	0.000	38.243	0.000	0.000		
2		Paraxial			50.000 V			30.122	-	-		0.000	200.000 V	1
3		Paraxial			50.000 V			14.470	-	-		0.000	-50.000 V	1
4		Paraxial			50.000			13.289	-	-		0.000	200.000 V	1
5		Standard		Infinity	4.000			8.785	0.000	8.785	0.000	0.000		
6	STOP	Standard		Infinity	0.000			8.425	0.000	8.425	0.000	0.000		
7		Paraxial			100.000 V			8.425	-	-		0.000	100.000 P	1
8		Standard		Infinity	34.803 M			13.357	0.000	13.357	0.000	0.000		
9	IMAGE	Standard		Infinity	-			15.074	0.000	15.074	0.000	0.000		

Figure 3.1: Starting prescription for zoom lens design.

Luckily the starting focal length for this system is 93mm, which already lies within the range we want to design for. The system is significantly longer than our requirement, but that will be fixed shortly. Next we will optimize the lens locations and focal lengths for each of the zoom positions we want to design for. Before we set any optimization operands, we do have a choice to make. With a Donder's telescope,

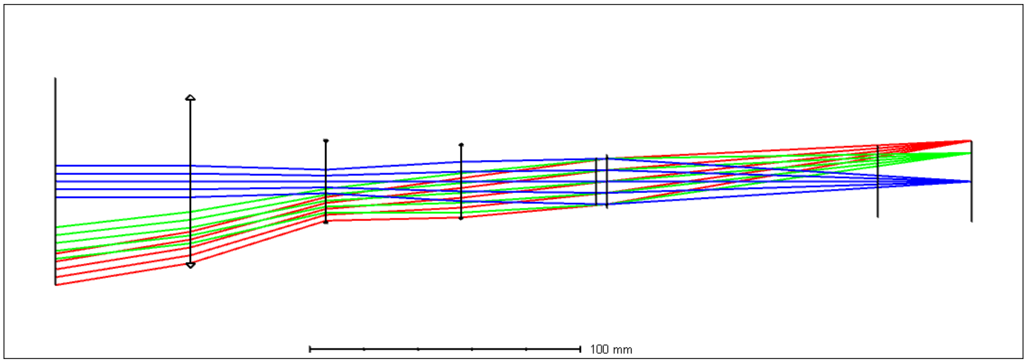


Figure 3.2: Starting layout for zoom lens design.

two elements move to change the angular magnification of the triplet. Fixing the front element and allowing the two middle elements move have an advantage in fixing the total length of the system and all lens motion is internal. On the other hand, allowing the two front elements to shift could reduce the overall length at a certain zoom, which may be attractive to a photographer needing to carry this lens with him/her and may want to keep things compact. In this tutorial, I opted for the latter option.

In the initial optimization run, we're just looking for approximate locations to place our lens groupings. Try to prevent the lenses from getting too close to each other, or getting too large if at all possible. Pick three focal lengths to design for. In this case, I chose the edge of the zoom range and a position in the middle. If the initial optimization run is sufficient, go ahead and replace the paraxial lenses with thin lenses of the same focal length.

Fig. 3.3 shows the result after the intial optimization. All elements fall within our specifications, so we'll move on to the next step. As long as no particular parameter is too far outside of the desired range, that can be corrected in future steps.

3.2 Monochromatic Design

After designing our first-order solution, we need to make this closer to a physically realizable system. At first, we will design only for the d-line wavelength and then

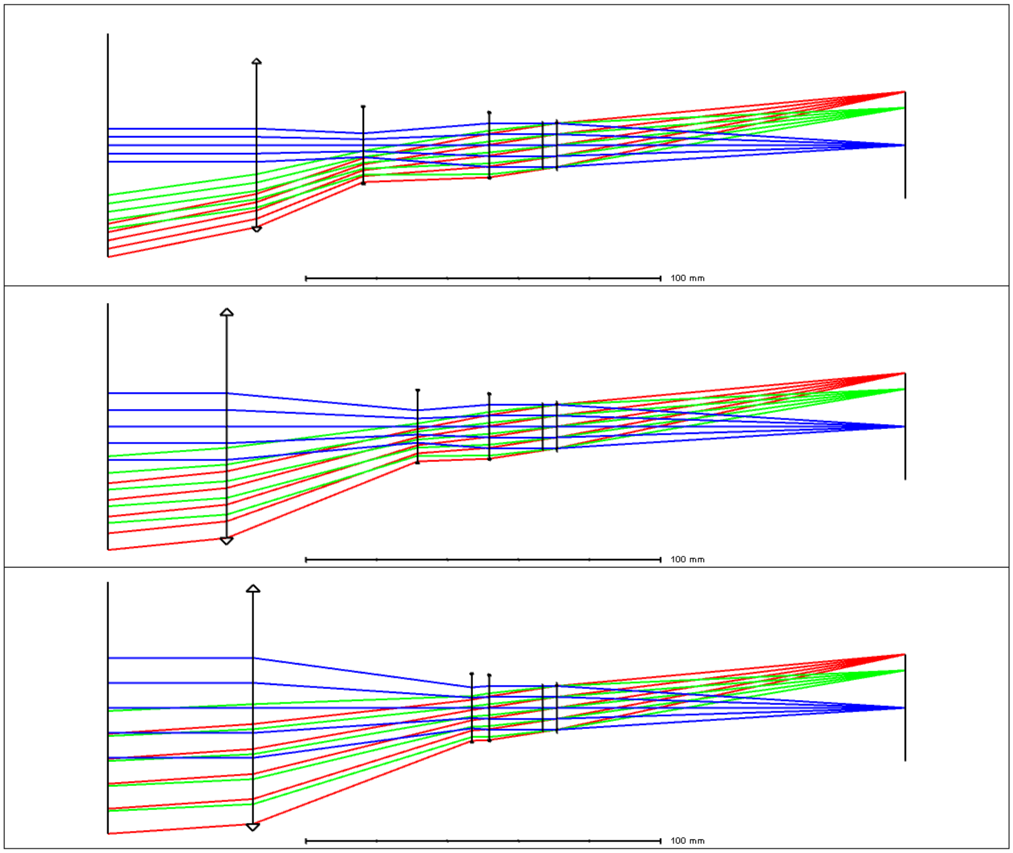


Figure 3.3: Paraxial zoom positions

add in chromatic aberration in the next section. Now swap the paraxial lenses out for thin lenses of the same focal length. As seen in Fig. 3.4 the first order solution only gets us as far as how approximate lens motion will behave. The actual performance of these thin lenses is quite poor.

Add some appropriate thicknesses to each element. I tend to opt around 4-7mm for positive elements and 2-4mm for negative elements depending how large they are. Avoid clipping around the lens edges. Try adjusting the stop position to see how the system changes. Pick the location that minimizes lens size and/or appears to control large aberrations the best. Optimize the system throughout this process to maintain the focal ratio desired, and catch any potential problems.

Occasionally through the process of optimization, the software try to drive the system into a direction you don't want to go. Sometimes this is okay and may reveal

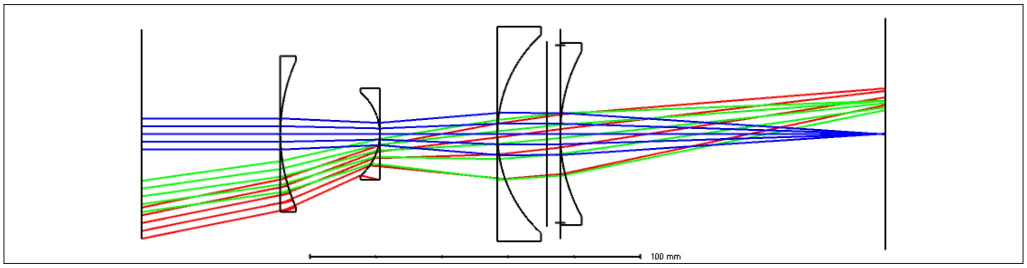


Figure 3.4: Initial thin lens substitution.

a solution that is better than the initial first-order design. In this case, after adding appropriate lens thicknesses and re-optimizing, I found that the final element of the system was no longer behaving as a prime lens, but had instead been changed into a negative lens (Fig. 3.5). Now the system is no longer a PNPP system, but a PNPN system. However, since the initial purpose of the fourth group was to be a prime lens, this fourth lens no longer could be considered its own distinct group. When added to the other stationary 3rd group, we find the system is now merely a PNP system. In this case, after examining the other possible solutions, changing this system to a PNP was found to have better performance for a simpler solution. If trying to force a particular lens form, be sure to control that in the optimization parameters.

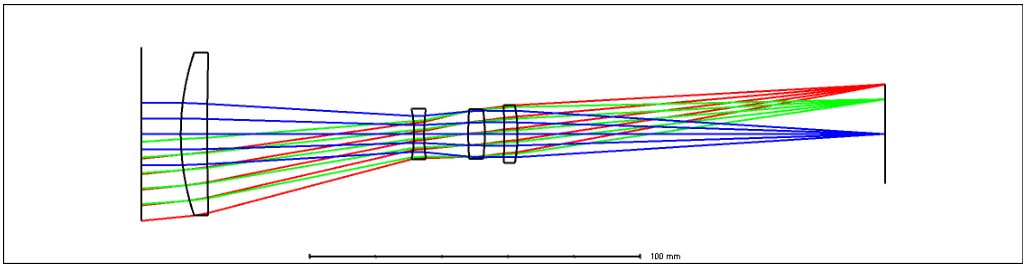


Figure 3.5: Monochromatic design.

With the lens performance now, it is sufficient for a monochromatic design. Be sure the different zooms are maintaining the correct focal ratio. Adding a couple aspheres could improve performance further at this point. However, a photographic objective is hardly useful to the photographer if there is no color correction. In the next section, we'll look at methods to achromatize this system.

3.3 Achromatic Design

In general, it is desirable to achromatize each zoom group individually. Because of the moving elements over the zooming range, attempting to balance chromatic aberration across the system is difficult and unreliable. If each group is independently corrected, chromatic aberration should remain correct at each zoom position. In this case, since this design remained simple, it was possible to merely convert each singlet into an achromatic doublet as seen in Fig. 3.6.

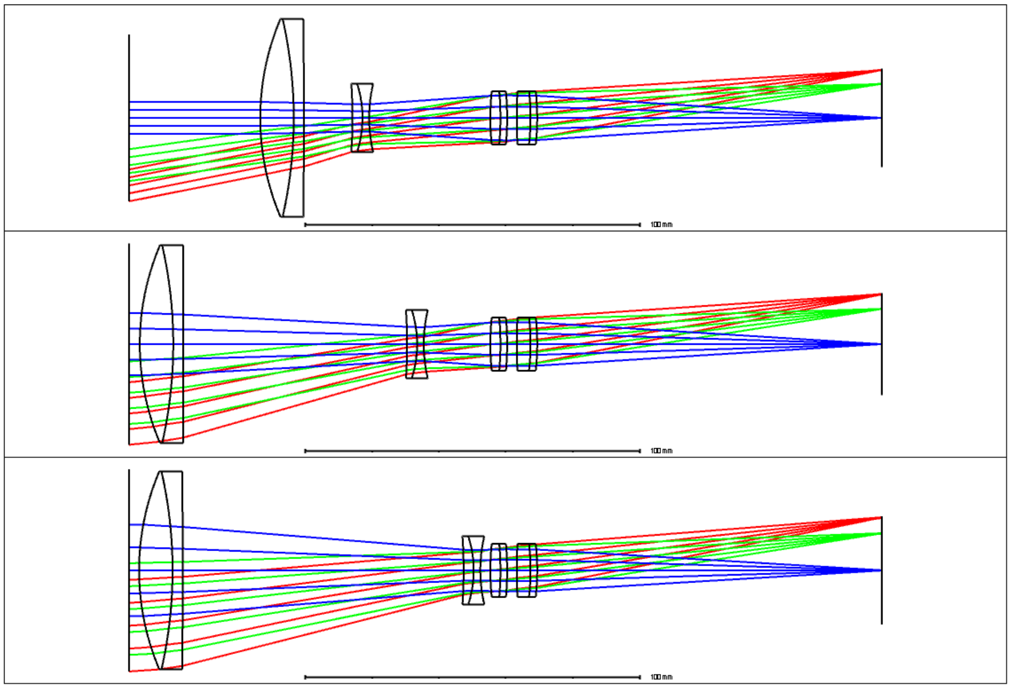
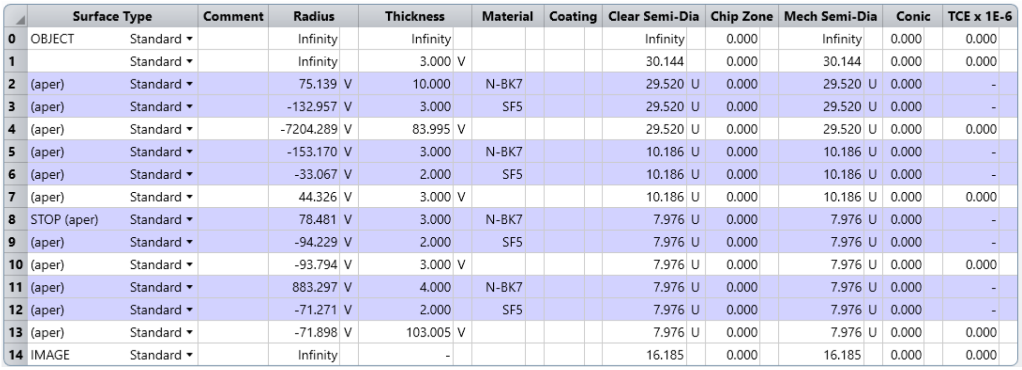


Figure 3.6: Achromatic zoom lens from $f = 75$mm to $f = 225$mm.

Thickness (mm)	$f = 75$mm	$f = 150$mm	$f = 225$mm
Surface 4	83.995	66.892	14.552
Surface 7	3.000	19.896	36.225

Table 3.2: Zoom positions for tutorial lens.

With this design, the initial design parameters are met, and the system performs reasonably well. System metrics can be found in Appendix A. Chromatic aberra-



	Surface Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT	Standard ▾		Infinity	Infinity			Infinity	0.000	Infinity	0.000	0.000
1		Standard ▾		Infinity	3.000 V			30.144	0.000	30.144	0.000	0.000
2	(aper)	Standard ▾		75.139 V	10.000	N-BK7		29.520 U	0.000	29.520 U	0.000	-
3	(aper)	Standard ▾		-132.957 V	3.000	SF5		29.520 U	0.000	29.520 U	0.000	-
4	(aper)	Standard ▾		-7204.289 V	83.995 V			29.520 U	0.000	29.520 U	0.000	0.000
5	(aper)	Standard ▾		-153.170 V	3.000	N-BK7		10.186 U	0.000	10.186 U	0.000	-
6	(aper)	Standard ▾		-33.067 V	2.000	SF5		10.186 U	0.000	10.186 U	0.000	-
7	(aper)	Standard ▾		44.326 V	3.000 V			10.186 U	0.000	10.186 U	0.000	0.000
8	STOP (aper)	Standard ▾		78.481 V	3.000	N-BK7		7.976 U	0.000	7.976 U	0.000	-
9	(aper)	Standard ▾		-94.229 V	2.000	SF5		7.976 U	0.000	7.976 U	0.000	-
10	(aper)	Standard ▾		-93.794 V	3.000 V			7.976 U	0.000	7.976 U	0.000	0.000
11	(aper)	Standard ▾		883.297 V	4.000	N-BK7		7.976 U	0.000	7.976 U	0.000	-
12	(aper)	Standard ▾		-71.271 V	2.000	SF5		7.976 U	0.000	7.976 U	0.000	-
13	(aper)	Standard ▾		-71.898 V	103.005 V			7.976 U	0.000	7.976 U	0.000	0.000
14	IMAGE	Standard ▾		Infinity	-			16.185	0.000	16.185	0.000	0.000

Figure 3.7: Prescription for Fig. 3.6. Zoom positions listed in Table 3.2.

tion is still not fully met, and there are rather dominant aberrations like distortion present in some of the zoom positions. Image performance is decent, but no photographer would be quite satisfied with this lens' current iteration. For a starting design, this works well enough, but there are still significant improvements to be done before this could be considered to be in a manufacturable state. Even with these things, this lens served to demonstrate some of the key concepts in zoom lens design.

3.4 Avenues for improvement and further design needs

- No surfaces in this design are aspheres. Adding aspheric surfaces could improve aberration performance
- Most modern systems tend do have 10 or more individual lenses. The design flexibility afforded by ten lenses over four is tremendous. Consider splitting zoom groups into more elements, or even exploring other design forms with different lens motion, or more than two moving groups.
- Only two glass types were used in this design. For better aberration control and chromatic correction, it is advantageous to look at other glasses. This alone could provide significant improvements to the current design.
- This lens has no focusing control. It was designed with purely collimated

light in mind, but a photographer will want to photograph things much closer. Adding another moving group to allow for this focus control is crucial for a commercial lens.

- The lenses are physically able to be manufactured in their current state, but the sharp corner on the positive portion of the first doublet is undesirable. Try to avoid sharp edges that could possibly chip or otherwise make manufacturing impossible.
- The motion of the lens from $f = 75$mm to $f = 150$mm is very different from the motion between $f = 150$mm and $f = 225$mm. In further optimization runs it will be necessary to add another zoom configuration between those points as there is potential for poor performance in that region. In addition, we currently do not know the exact path the lenses need to move throughout the entire zoom range and this is crucial to know when working with the mechanical design team. In short, increase the sampling along the zoom range.
- In future optimization iterations, it may be useful to utilize a reverse-tracing analysis to look at the aberrations present purely due to the motion of the zoom kernel itself. This process as detailed by Sasián [6] involves reversing the zoom lens at its middle zoom configuration and placing it behind itself. This creates an afocal system. For this middle configuration, the aberration present is zero. By holding the reversed lens and shifting the forward lens through the zoom configurations, the aberration difference between the different zooms can be analyzed.

This simple tutorial is only the beginning when it comes to making usable zoom lens designs for commercial photography. There is great value in knowing the current patent literature and building off of what others have already done. This is why starting from a patent is a powerful technique. The designer has a good foundation to build off of and through understanding the design methodology and history can avoid the potential pitfalls of their current design configuration.

CHAPTER 4

Conclusion

High quality zoom systems are an interesting design challenge that are largely powered by the computational power we have available in the modern day. They changed the landscape of cinematography and photography in monumental ways; introducing new capabilities and adding new tools to the artists arsenal. The camerawork and techniques easily recognizable in today's films is only made possible This report looked only at these photographic objectives, but zoom systems have broader applications than just the realm of the artist. Zoom lenses have found use within defense, microscopy, research, and more. In my own personal experience, I've worked on laser systems that utilize a variable beam expander, something very like the Donders telescope, to expand a high power laser beam and then focus it down to a smaller spot. The designs are quite different from the photographic types, but the concepts behind it are very much the same. Vari-focal systems have great utility in the professional environment.

Personally, I found that understanding zoom systems forced greater understanding and reinforcement of the basic concepts of lens design. All of these tools for fixed lens design need to be used in greater ways to design an effective zoom lens. I found that while zoom lenses open up a lot of room for flexibility, they also demanded tighter constraints be met. In designing or working with some of these lenses, I grew in my lens design chops and am a better optical engineer for in. In writing this report, I looked more at the patent literature than I ever had before, and I realized more fully the utility of building off of past work, and seeing how much I could learn off of the designs and methods of other lens designers.

APPENDIX A

Design Tutorial Related Figures

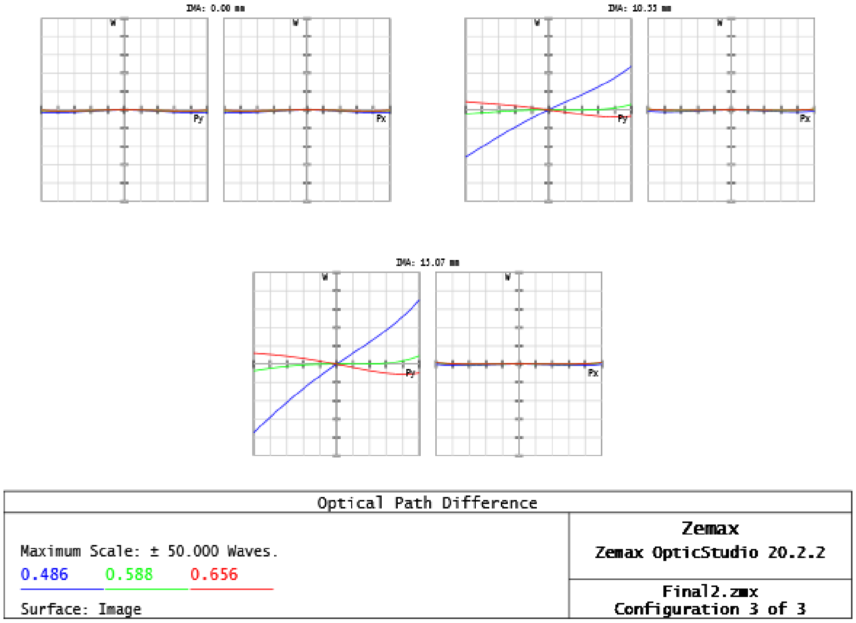


Figure A.1: OPD fans for $f = 75\text{mm}$.

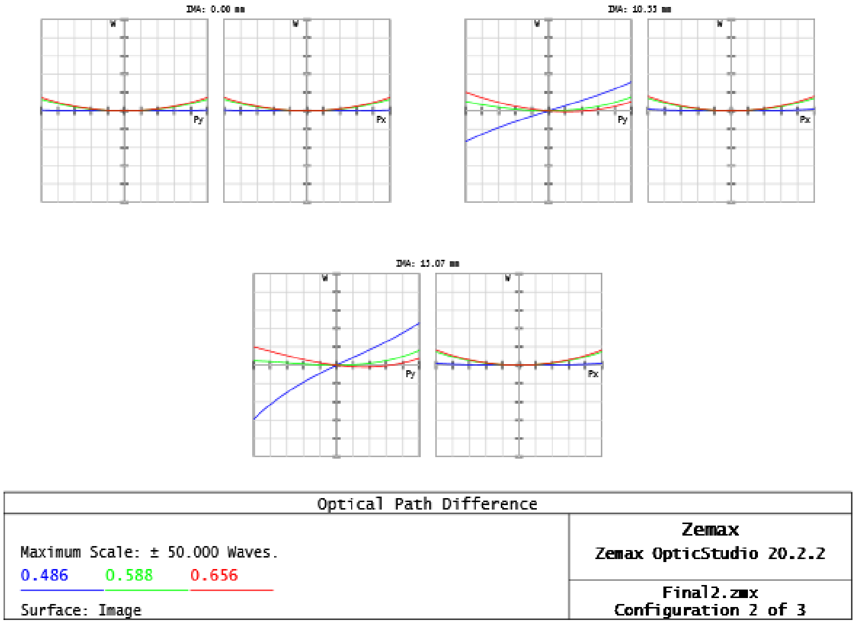


Figure A.2: OPD fans for f = 150mm.

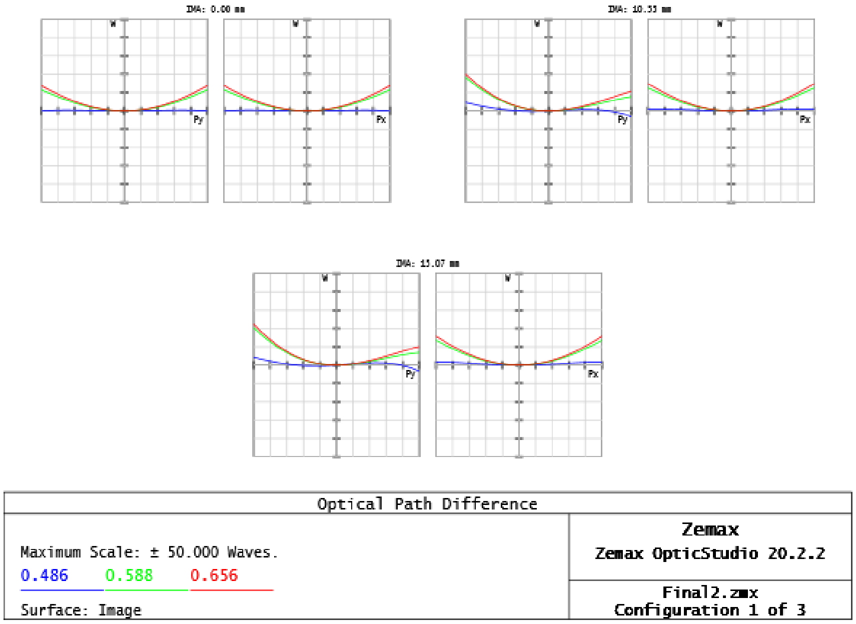
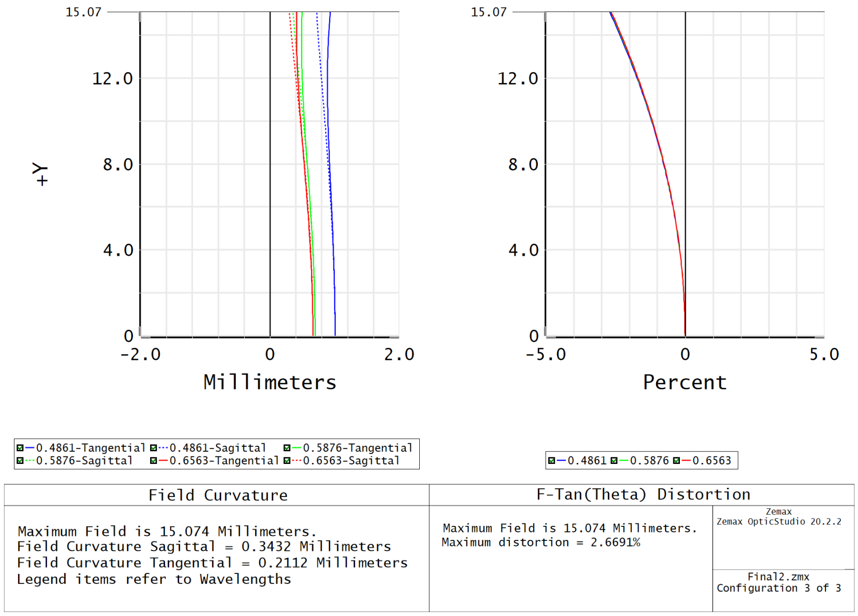


Figure A.3: OPD fans for f = 225mm.



Field Curvature

Maximum Field is 15.074 Millimeters.
Field Curvature Sagittal = 0.3432 Millimeters
Field Curvature Tangential = 0.2112 Millimeters
Legend items refer to Wavelengths

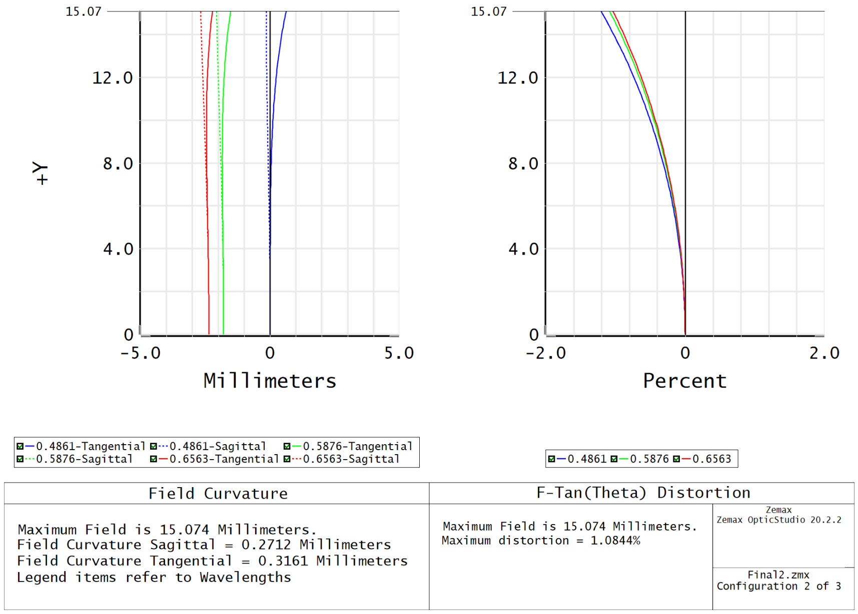
F-Tan(Theta) Distortion

Maximum Field is 15.074 Millimeters.
Maximum distortion = 2.6691%

Zemax
Zemax OpticStudio 20.2.2

Final2.zmx
Configuration 3 of 3

Figure A.4: Field and distortion curves for $f = 75$mm.



Field Curvature

Maximum Field is 15.074 Millimeters.
Field Curvature Sagittal = 0.2712 Millimeters
Field Curvature Tangential = 0.3161 Millimeters
Legend items refer to Wavelengths

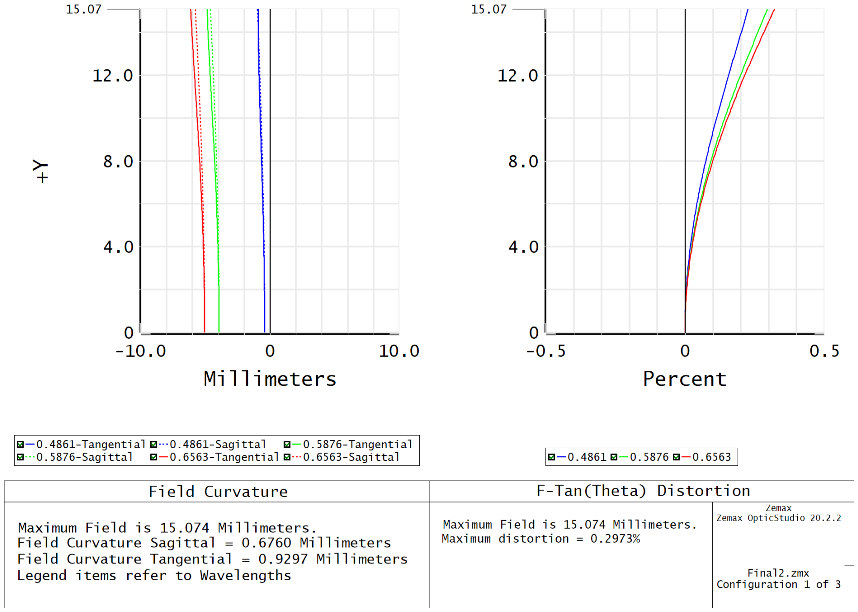
F-Tan(Theta) Distortion

Maximum Field is 15.074 Millimeters.
Maximum distortion = 1.0844%

Zemax
Zemax OpticStudio 20.2.2

Final2.zmx
Configuration 2 of 3

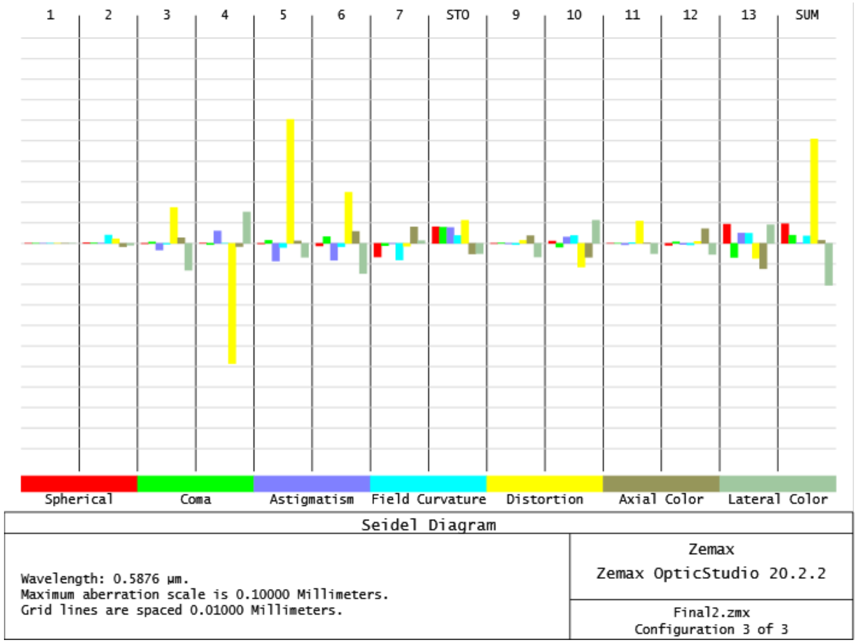
Figure A.5: Field and distortion curves for $f = 150$mm.



Maximum Field is 15.074 Millimeters.
Field Curvature Sagittal = 0.6760 Millimeters
Field Curvature Tangential = 0.9297 Millimeters
Legend items refer to Wavelengths

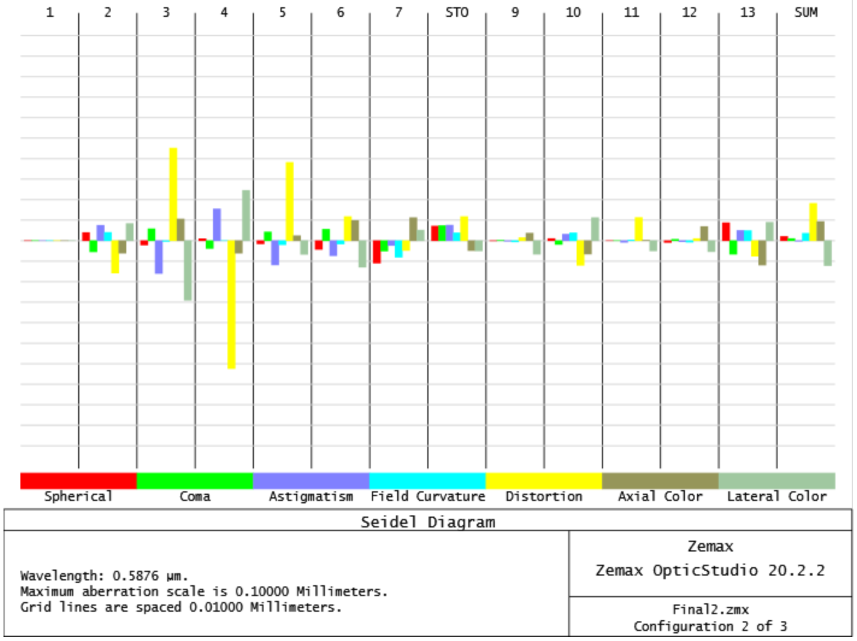
Maximum Field is 15.074 Millimeters.
Maximum distortion = 0.2973%

Figure A.6: Field and distortion curves for $f = 225\text{mm}$.



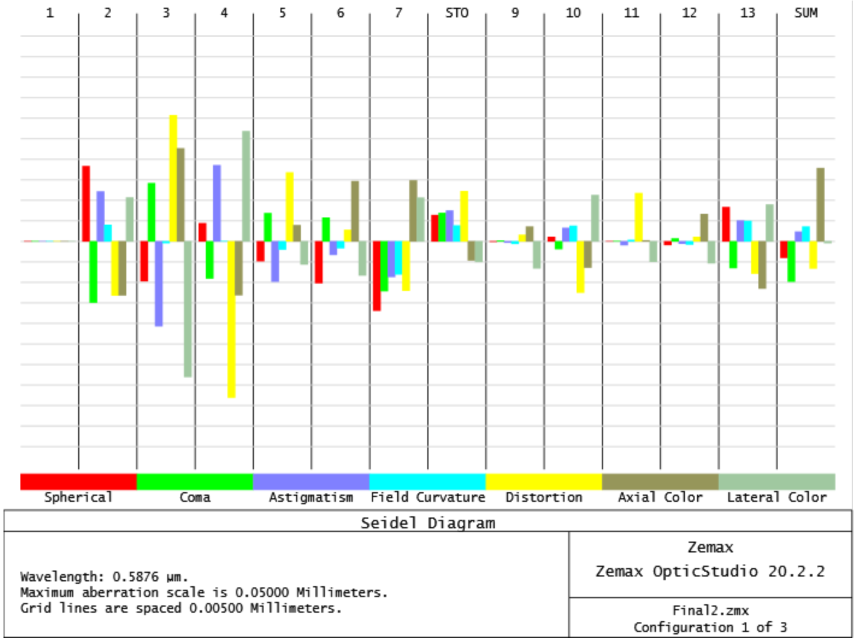
Wavelength: 0.5876 µm.
Maximum aberration scale is 0.10000 Millimeters.
Grid lines are spaced 0.01000 Millimeters.

Figure A.7: Seidel contributions for $f = 75\text{mm}$.



Wavelength: 0.5876 µm.
Maximum aberration scale is 0.10000 Millimeters.
Grid lines are spaced 0.01000 Millimeters.

Figure A.8: Seidel contributions for f = 150mm.



Wavelength: 0.5876 µm.
Maximum aberration scale is 0.05000 Millimeters.
Grid lines are spaced 0.00500 Millimeters.

Figure A.9: Seidel contributions for f = 225mm.

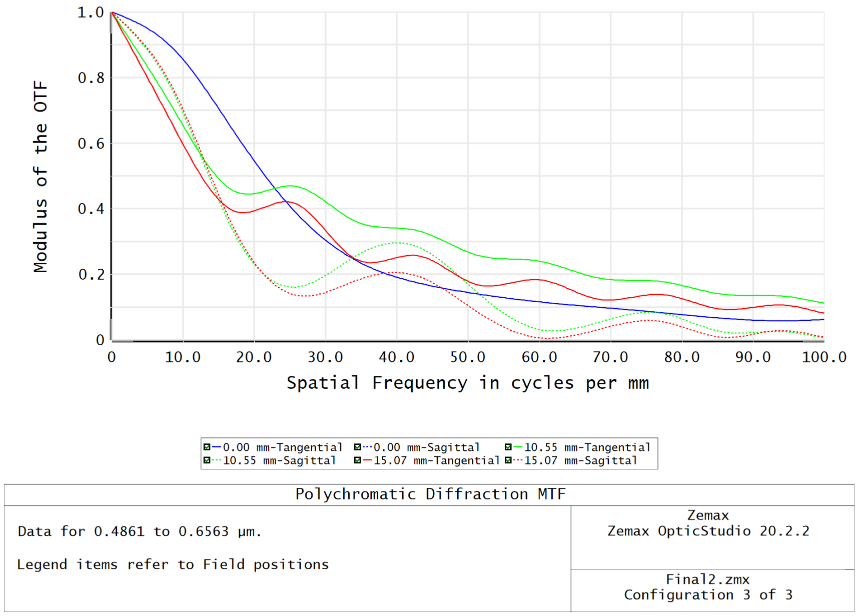


Figure A.10: MTF curves for $f = 75$mm.

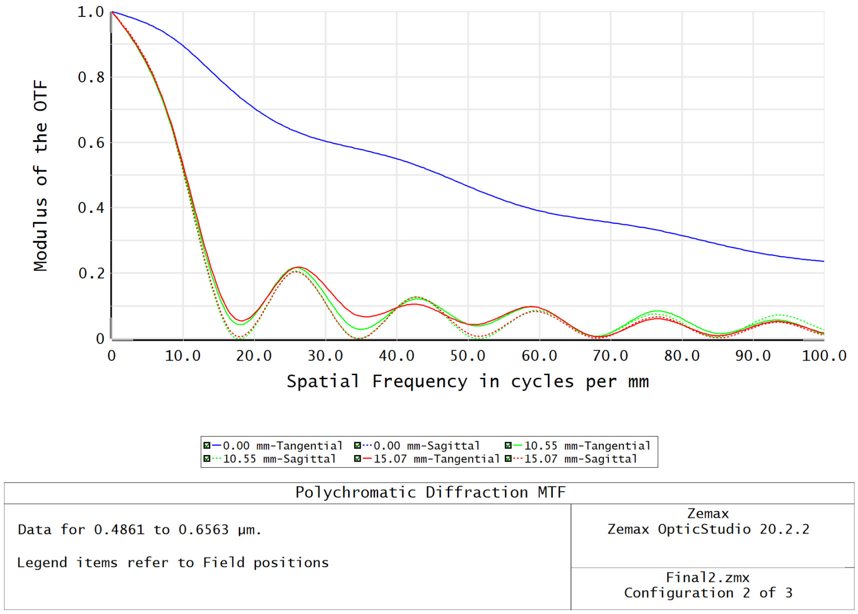


Figure A.11: MTF curves for $f = 150$mm.

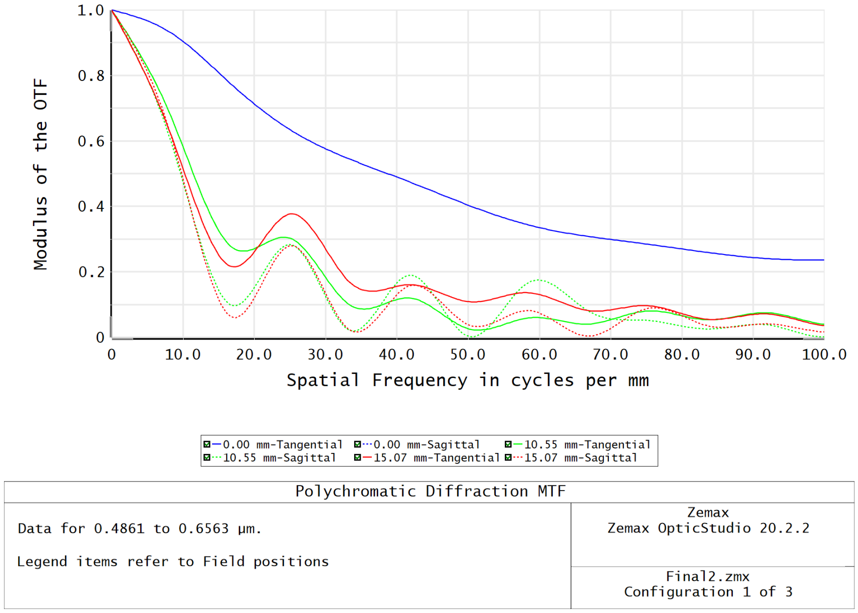


Figure A.12: MTF curves for $f = 225$mm.

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[6] José Sasián. Aberrations of zoom lens kernel. volume 11106, September 2019.