Design of Custom Achromatic Lenses Used For Optical Image Relay System For The OSU Petawatt Class Laser Amplifier Chain

Thesis

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Abstract

The Science Center for the Advanced Research on Lasers and Engineered Targets (SCARLET) laser system of the High Energy Density Physics research group at the Ohio State University is built to study laser-matter interactions at very high intensities. Ultrashort pulses are needed to generate such high intensities. Ultrashort pulses require large bandwidths. The SCARLET laser system is undergoing a major upgrade and part of the new system is a Keplerian telescope that relays the laser pulses. The function of the telescope is to magnify the pulse profile while relaying the image in its most intact form possible. The aberrations created by the lenses of the telescope need to be minimized in order to preserve the image quality. In this kind of application, the adverse effects of the thickness of the lenses and chromatic aberrations become apparent because of the broad spectrum. In order to focus all wavelengths (770 nm to 850 nm) at the same point and re-collimate them, custom designed multi-element lenses needed to be used.

After learning about achromats, aberrations and principles used to minimize the aberrations, lens design software OSLO was used for computer aided ray-tracing and analysis of optical performance. Ray tracing analysis shows that the custom designed lenses significantly outperform their singlet counterparts in terms of aberrations induced. The design was finalized after thorough review and was sent for

manufacturing. The lenses have been manufactured by an optics company and they are now utilized in the telescope with no problem with their optical performance.

This thesis discusses how such compound achromatic lenses work, how these lenses were designed and how their theoretical performance compares to that of simple plano-convex lenses.

Acknowledgments

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Introduction

The Science Center for the Advanced Research on Lasers and Engineered Targets

(SCARLET) laser system is part of the High Energy Density Physics (HEDP) research group

of the Ohio State University and is currently undergoing a major upgrade that will

increase the output power from 40 terawatt to 400 terawatt. The laser built to study

laser-matter interactions at very high intensities. To generate such high intensities,

ultrashort pulses are needed. The Heisenberg Uncertainty Principle, more specifically

the energy-time uncertainty principle, sets fundamental limits on the product of the

pulse duration and the wavelength range a laser pulse can have [3][4]. Essentially, a

short pulse requires a broad spectrum and vice versa. Therefore, ultrashort laser pulses

used in our application have a large bandwidth.

Part of the upgrade system uses a Keplerian telescope to magnify the profile of the laser

pulse after it exits from the terawatt amplifier and relays it to the Petawatt amplifier.

The function of this telescope is to increase the beam diameter to reduce the energy per

unit area of the pulse. This ensures that the pulse can be further amplified by the

terawatt amplifier without damaging the optics. A Keplerian telescope utilizes two

convex lenses held at a distance that equals the sum of their focal lengths, and will be

used to relay the image of a non-Gaussian laser beam from the object plane of one lens

to the image plane of the other. However, the adverse effects of the thickness of the lenses and the chromatic aberrations become apparent when the object to be imaged is the profile of a broad band laser pulse. In order to transmit the pulse in its original form, it is essential that all the wavelengths are focused at the same point and are re-collimated without experiencing significant chromatic divergence and aberrations. Multi-element lenses called achromatic lenses are necessary to preserve the quality of the laser pulse to such extent. The wavelength band in this project is 810nm +/- 40nm. As discussed later in this paper, these special lenses require designs that are very application specific and the gain in the performance at the design conditions comes at the expense of significant loss in performance at any operating conditions that are out of the design range. Ultimately, this meant that these lenses for the Scarlet upgrade telescope needed to be custom designed as it is not possible to find achromatic lenses off-the-shelf whose design conditions exactly match the operating conditions of the laser in the lab.

I designed these custom achromatic lenses that are optimized to reduce chromatic and spherical aberrations with the aid of lens design software OSLO. The lenses have already been manufactured by a lens manufacturing company and the Petawatt upgrade team has already constructed the telescope using the lenses.

Optical Aberrations

When the performance of an optical system deviate from what is expected for an ideal imaging system according to paraxial approximations, the effect is called optical aberration. In this paper I will only discuss the types of aberrations that our image-relay system is susceptible to and that can be corrected for by using achromatic lenses.

Chromatic aberration occurs when a lens does not focus different wavelengths of a beam to a common focal plane. In effect, the focal length for different wavelengths becomes significantly different. This happens because different wavelengths in the beam experiences different index of refraction.
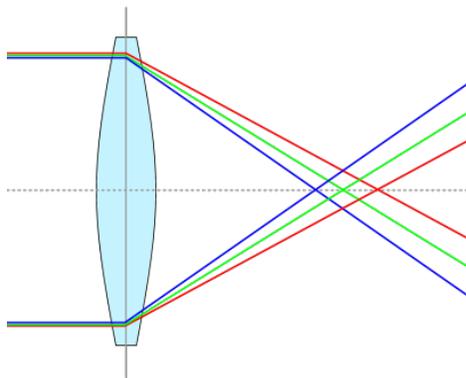

Figure 1 Illustration of Chromatic Aberration [10]

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As shown in Figure 1, light with smaller wavelengths will focus closer to the lens than the light with longer wavelengths. A telescope consists of two lenses positioned exactly sum of their focal lengths apart. The function of the second lens is to take the image (focus) created by the first lens and collimate it. For a broadband pulse, the (chromatic) shift in location of the focus for different wavelengths can be significant enough that the collimating lens cannot perfectly collimate all the wavelengths. Suppose that the collimating lens is aligned so that the center wavelength (810nm) is perfectly collimated. The lower end wavelengths (770nm) will converge ever so slightly while the redder end of the spectrum (850nm) will diverge with a small divergence angle because those wavelengths do not focus at the focal length of the second lens. The slight convergence or divergence of beam can still be very problematic for our application because of multiple passes through the amplifier crystal and the scale of the system. The overall path length is on the order of 10 m or even greater.

Thus, even a slight miscollimation can result in certain wavelengths completely missing the amplifier crystal. Also, the Scarlet laser uses Chirped Pulse Amplification (CPA). CPA is a method of amplifying an ultrashort pulse to petawatt level by stretching the pulse temporally and spectrally before amplification and recompressing the pulse after amplification using grating pairs. The method relies on the idea that the dispersion of the stretcher will exactly match the dispersion of the compressor except opposite in dispersive power [8][9]. The compressor requires a collimated pulse. Thus, it is

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extremely important that there is no additional dispersion or aberrations introduces by the telescope that magnifies the pulse.

Spherical aberration occurs when the location of the focus in the axial direction is a function of aperture height. In other words, rays entering from towards the edge (marginal rays) of the lens focus closer to the lens than the rays that pass from close to the center of the lens (paraxial rays). This is an effect of the paraxial approximation becoming less valid as the f-number of the lens decreases [2].
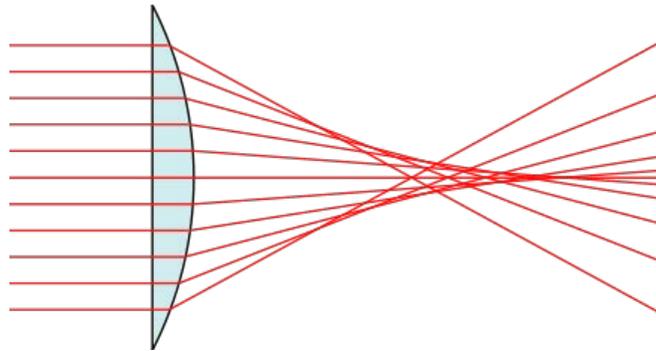

Figure 2 Illustration of Spherical Aberration [10]

In effect, the focus is not close to the same point which in effect results in a poor collimation and a poor image relay.

Achromatic Lens

An achromatic lens (or achromat) is a compound lens made with a combination of multiple lens elements (commonly 2). An achromat is designed to eliminate chromatic aberration and also some spherical aberration thereby preventing the laser system from experiencing problems mentioned before. It works on the principle that the chromatic separation created by the dispersive power of the first lens element can be undone by the dispersive power of the second lens element that has the opposite refractive power. For a positive achromat, the idea is to combine a strong positive element made from a low dispersion material with a weaker negative element of higher dispersive power [1].
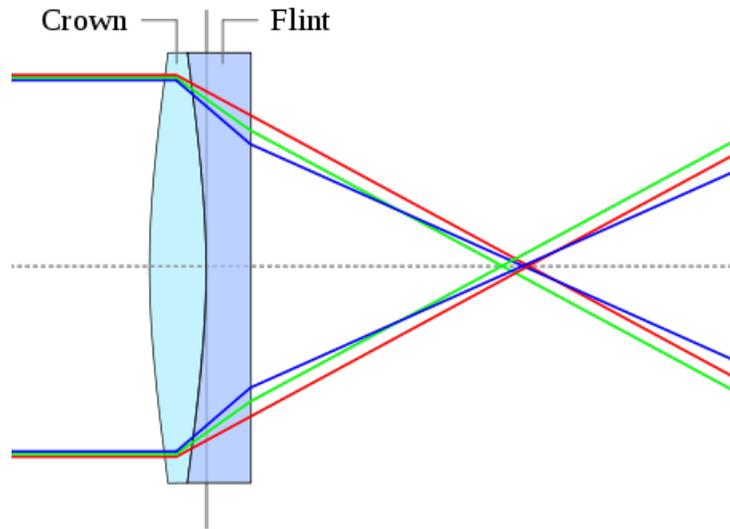
The surface curvatures of the elements have to be calculated such that the effective focal length of the achromat ends up being what is prescribed and yet the chromatic aberration is minimized. The same double-lens (doublet) configuration also helps minimize spherical aberration because the marginal rays that converge relatively faster than the paraxial rays also diverge relatively faster in a negative lens [2]. In terms of wavefront distortion, it is possible carefully design the curvatures of the second element such that the distortion caused by the first element is eliminated.

Physical Principle

Consider an achromat with two elements. The focal length of the first element is f1 and the focal length of the second element is f2. The focal length of a spherical optical element is given by the paraxial theory as:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R1} - \frac{1}{R2}\right) \tag{1}$$

where n is the index of refraction of that element and R1 and R2 are the radii of curvatures of the front and the back surface of the element. Replace the curvature terms such that $C = \left(\frac{1}{R1} - \frac{1}{R2}\right)$ [1].

Now we can describe the focal lengths of each element as:

$$\frac{1}{f_1} = (n_1 - 1)C1 \tag{2}$$

$$\frac{1}{f_2} = (n_2 - 1)C2 \tag{3}$$

The effective focal length of the combination of the two elements is given by:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2} \tag{4}$$

where d is the separation between the two elements. However, here we will exclude the separation term assuming close contact in order to keep a relatively simple derivation.

The idea is to create a combination of the two elements with the right index of refraction such that the red end of the spectrum and the blue end of the spectrum focuses at the same point. If f_r is the focal length for the red wavelength and f_b is the focal length for the blue wavelength, we want to find conditions when $\frac{1}{f_r} = \frac{1}{f_b}$ [1].

Using equation 4, we get:

$$\frac{1}{f_{1r}} + \frac{1}{f_{2r}} = \frac{1}{f_{1b}} + \frac{1}{f_{2b}} \qquad (5)$$

$$(n_{1r} - 1)C1 + (n_{2r} - 1)C2 = (n_{1b} - 1)C1 + (n_{2b} - 1)C2 \qquad (6)$$

From equation (2) and (3).

Equation (6) can be written as:

$$\frac{C1}{C2} = -\frac{n_{2b} - n_{2r}}{n_{1b} - n_{1r}} \qquad (7)$$

Similarly using equation (2) and (3) at the center wavelength we can get:

$$\frac{C1}{C2} = \frac{(n_{2i} - 1)f_{2i}}{(n_{1i} - 1)f_{1i}} \qquad (8)$$

Using equation (7) and (8) we have

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$$\frac{f_{2i}}{f_{1i}} = -\frac{\left(\frac{n_{2b} - n_{2r}}{n_{2i} - 1}\right)}{\left(\frac{n_{1b} - n_{1r}}{n_{1i} - 1}\right)} \tag{9}$$

The term $\left(\frac{n_b - n_r}{n_i - 1}\right)$ is defined as dispersive power (or the reciprocal of *Abbe number*).

If one selects two lens elements with the right index of refraction and curvatures such that equation (9) is obeyed, then the focal length for the red and the blue end of the spectrum will be the same. Typically, glass materials are selected such that $n_2 > n_1$ so that the overall spread of the focal shift can be minimized. A good rule of thumb is to select glasses so that the difference in the Abbe number for the two materials is greater than 20.

As a proof of concept, I started with calculations in an Excel sheet. After looking up Sellmeier Coefficients I calculated the wavelength dependent index of refraction and then the Abbe number for N-BK7 (crown glass) and SF2 (flint glass). I was able to verify that combinations of different values for f_1 and f_2 exist where the focal length for the two ends of our design wavelength band was the same.

Designing the Achromats

As discussed earlier, for this application there were four radii of curvatures to be calculated. There are multiple different combinations of curvatures for the four surfaces that can result in the same desired effective focal length. The trick is to find radii of curvatures for each surface in a way that corrections for the aberrations are balanced (i.e. correcting for one kind of aberration does not lead to a heavy penalty in terms of some other aberration). This is when lens design codes become very useful. The iterative tasks of calculating the Abbe numbers, radii of curvatures and ray tracing can be offloaded to lens design software that is not only much faster than doing manual calculations but can achieve a level optimization that is practically impossible to do by hand. Such software packages can account for dispersion, thickness of the lenses, paraxial approximations, and many other factors. The optimization routines can minimize many different kinds of aberrations based in the order of priority defined by the user. The built-in analysis tools eliminate ray tracing carefully by hand or exporting the curvature values into different software to run analysis.

For this project we used optical design software called OSLO (Optics Software for Layout and Optimization) – a product line of Sinclair Optics acquired by Lambda Research Corporation [7]. A free version of the software (OSLO EDU) was utilized as the features

provided were sufficient for this application. This also helped cut cost of the design process for the project.

The design started with the prescription with the given by members of the research group working on the laser upgrade.

Lens 1:

Number of surfaces: 4 (Air-spaced doublet)

Design wavelength: 810 nm +/- 40 nm

Entering beam radius: 7.49 mm

Focal length: 1150 mm

Lens radius: 19.05 mm (1.5 inch diameter – with radius approx. 0.5 inch larger than the beam radius)

Lens 2:

Number of surfaces: 4 (Air-spaced doublet)

Design wavelength: 810 nm +/- 40 nm

Entering beam radius: 25.1 mm

Focal length: 3850 mm

Lens radius: 50.8 mm (4 inch diameter – with radius approx. 1 inch larger than the beam radius)

The snapshot below shows the surface data editor spreadsheet where all the constraints

and input conditions can be defined.

Figure 4 Surface Data Editor in OSLO

A typical design procedure outline here was used to create preliminary designs of both

lenses. One of the first steps was to define the wavelength range, beam radius and

aperture radius (lens radius). The material of the lens was defined in the "glass" column

from the available Schott glass catalog. Note that in OSLO all distances are in the

"Thickness" column. For example, the object plane (OBJ) is located 1.0000E+20mm to

the left from the first surface of the assembly. At this point, radius of curvature for each

surface and the thickness between them was defined such that the effective focal length

(Efl) of the lens was close to the desired focal length. The Slider-Wheel Design tool

makes it easy to quickly change the radius of curvature of any surface to reach the
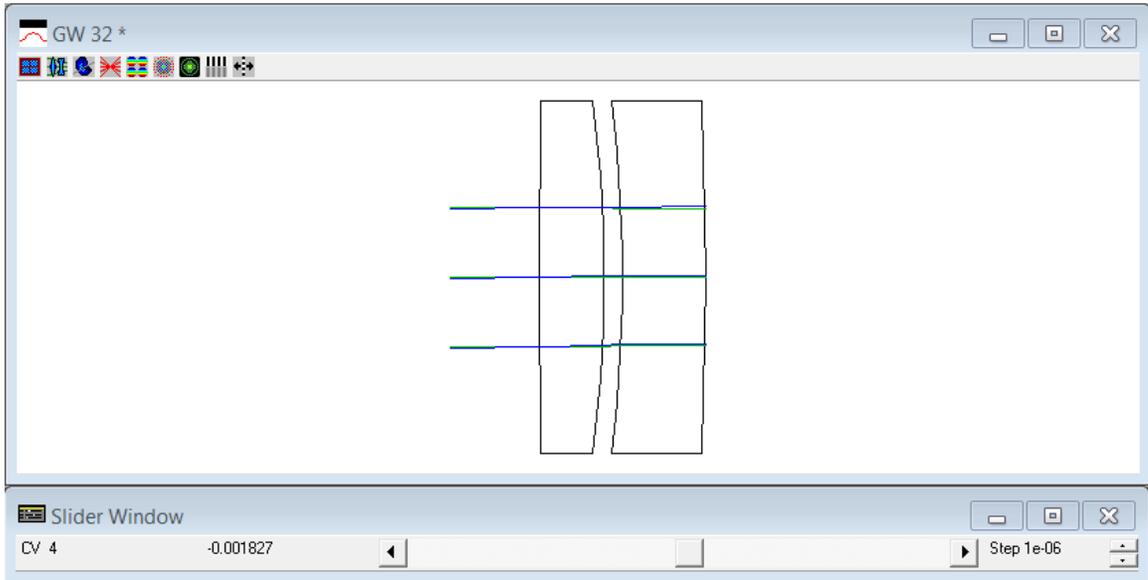
desired EFL.

Figure 5 Slider-Wheel Tool in OSLO

The image below shows the status of the surface data and the ray-intercept curves of

the lens. Note that the imaging surface is set to auto-focus at minimum RMS spot-size

(polychromatic). This can be done by clicking on the button next to the cell.
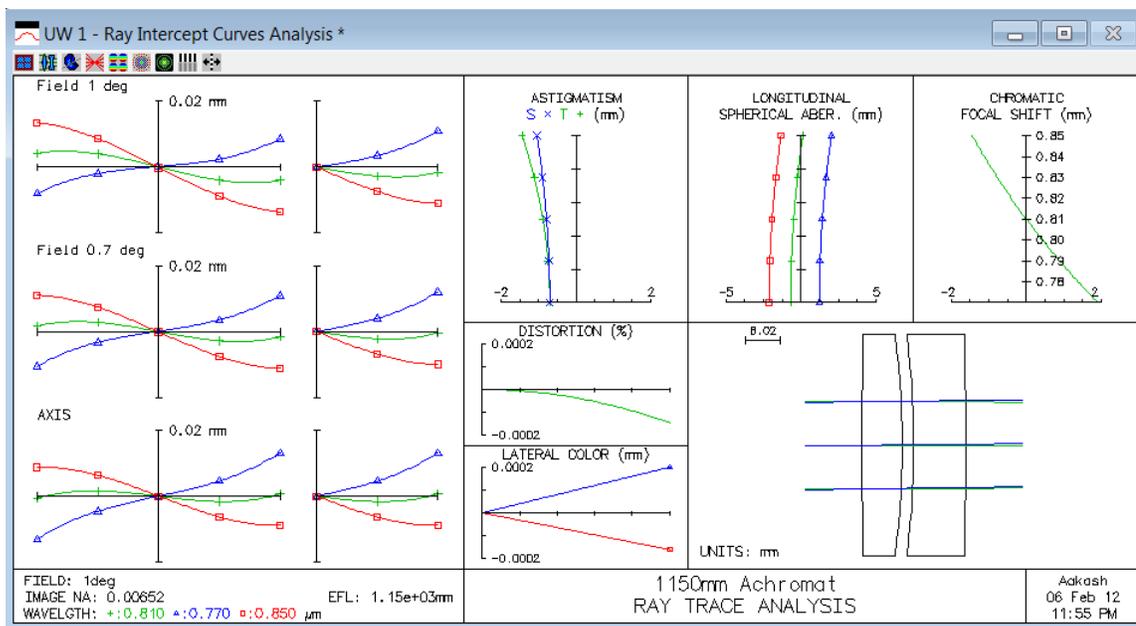
Figure 6 Auto-focusing the Image Plane in OSLO and Analysis Plots

At this point, the lens is ready for optimization. All four surfaces' radii and the three thicknesses were set to be variables. In the "Variables" tab, one can define minimum and maximum limits on the variables. This instructs OSLO to make sure that the values of the curvatures and thicknesses do not go out of bounds during the optimization process.

Figure 7 Defining Limits on Thickness in OSLO

The limits on the thickness are mainly set to ensure that the lens element can be easily

manufactured. Lens manufacturers prefer that the ratio of lens diameter to center

thickness is close to 6:1. The upper and lower limits here were set to about 7:1 and 5:1

respectively.

The elements were chosen to be air spaced for this application. A cemented doublet is a

more common design where the two elements are joined by optical cement. However,

the intensity of the pulses is so high for in this application that the light would easily

melt the cement and damage the lens. This was the primary reason for choosing an air-

gap design. Also, cemented achromat requires that the curvatures of the two middle

surfaces the same. This means that there would be only 3 surfaces that can be

optimized instead of 4. The optical cement also adds wavefront distortion to the

transmitted light according to CVI Melles Griot, an optics company [5]. Using air spacing

was the only option for this project. The reason why the air gap (surf. 2) was chosen to

be less than 2.5 mm was simply to minimize air gap and still retain the flexibility of changing the two middle surface curvatures independently.

The next step is to generate an error function from the "Optimize" menu. The "GENII Ray Aberration" error function at default values was used throughout this project. Using the "Iterate" command will start to rapidly change the surface data values until the program meets the minimum required percent change in the error function in order to minimize aberrations.
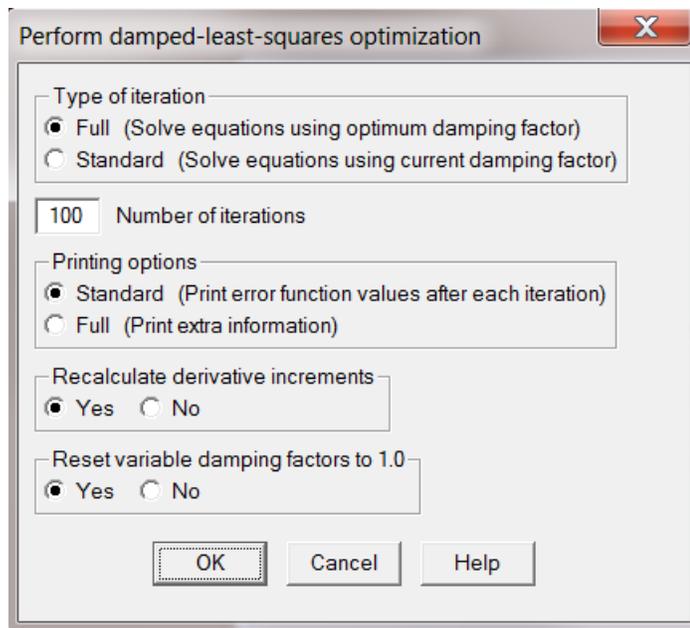

Figure 8 Optimization Window in OSLO

When this happens the EFL is likely changed; the image plane must be refocused and iteration process must be repeated until EFL meets the desired value. There are multiple

solutions that will result in minimum overall aberrations, so each optimization trial might result in a slightly different lens but very similar performance. The next image shows a resulting design created using the aforementioned constraints. The axes scales are kept identical to qualitatively check the decrease in aberrations.
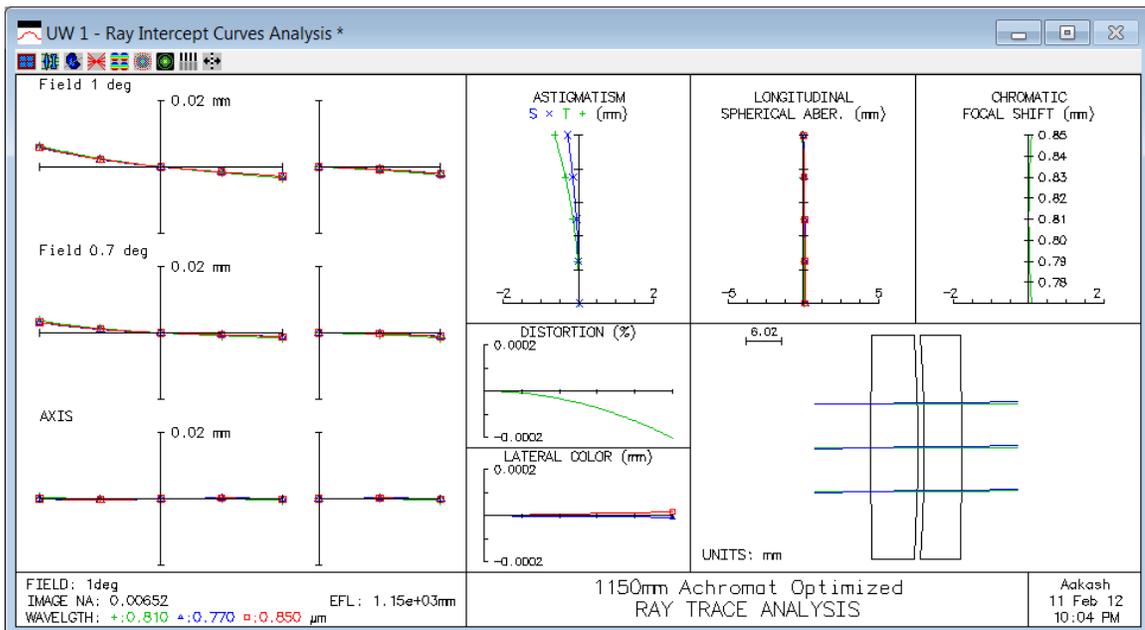

Figure 9 Sample Optimization of a Lens and Analysis Curves in OSLO

The optimization procedure outlined above was followed (with a few tweaks) to design the two achromats for the telescope. For each lens, the optimized designs went through numerous reviews from my project mentor. After the graduate students working on the Scarlet upgrade project modeled the telescope system in FRED optical software using the lenses designed in OSLO, further changes were made to the design constraints and the lenses were optimized. For example, one of the earlier variants of the 1150mm achromat produced strong and focusing back reflections on some of the other components in the system. The lenses were re-optimized such that their front and the back surfaces were almost flat.

Analysis and Results

In this section, the final designs of the two achromatic lenses are analyzed in contrast with single element lenses of the same respective design constraints and focal length. The singlet lenses are plano-convex lenses which is the lens shape commonly used for focusing down a laser beam and re-collimate it at a different magnification. We will refer to the singlet version of the lens 1 (f=1150 mm) as lens 1s and the singlet version of lens 2 (f=3850mm) as lens 2s.

Lens 1s:

Number of surfaces: 2 (Singlet)

Design wavelength: 810 nm +/- 40 nm

Entering beam radius: 7.49 mm

Focal length: 1150 mm

Lens radius: 19.05 mm

Lens 2s:

Number of surfaces: 2 (Singlet)

Design wavelength: 810 nm +/- 40 nm

Entering beam radius: 25.1 mm

Focal length: 3850 mm

Lens radius: 50.8 mm

To make a comparison between the size and aspect ratios of the lenses, a side view is shown here. In the subsequent comparison images the right side shows the drawings or performance plots of the optimized achromat L1 (f = 1150 mm).

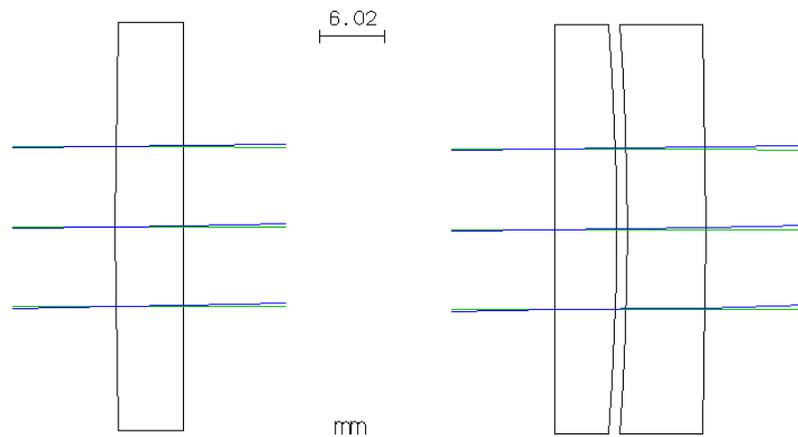Figure 10 (Left) Singlet Lens, (Right) Achromat (f = 1150 mm)

All plots are directly taken from the analysis window of OSLO.

The longitudinal spherical aberration plot (Figure 11) shows the shift in focus along the optic axis as a function of radial distance from the center of the lens. The red, green and

blue curves represent spherical aberration for 850nm, 810nm and 770nm component of the light respectively. The vertical axis is dimensionless and is meant to represent fraction of the entrance pupil. The achromat reduces the focal shift significantly.
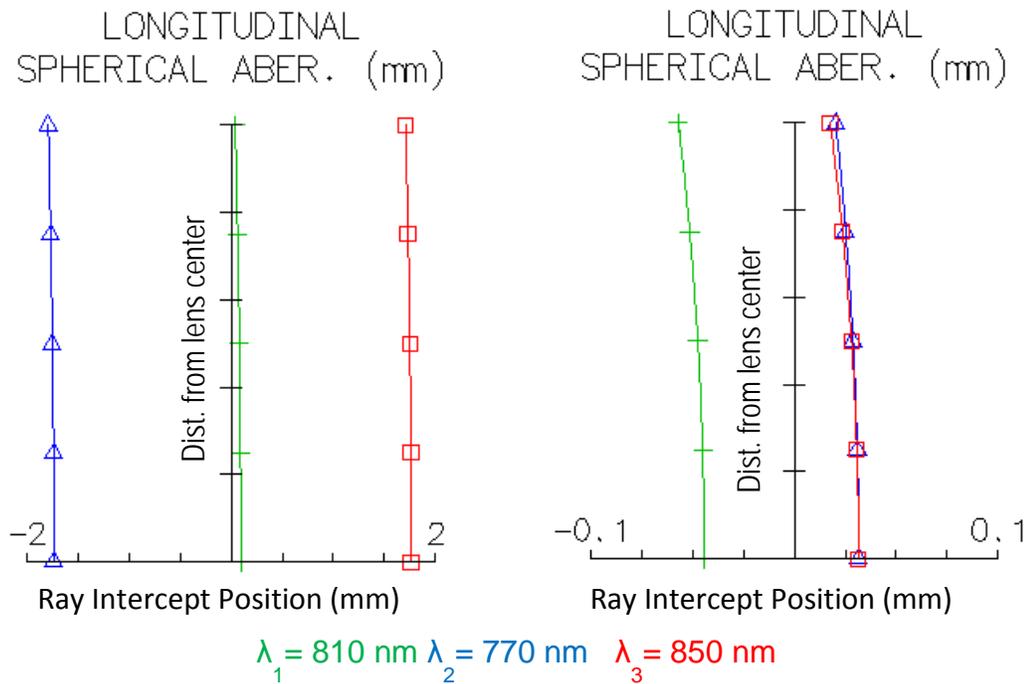

Figure 11 Lens 1 Spherical Aberration Plots, Singlet (left), Achromat (right)

The plots show the shift in focus as a function of the distance between the center of the lens and the height at which the ray enters. Thus, higher spherical aberration is represented by higher curvature of the plot curve. This feature is not very clearly evident by the plots above. However, figure 12 shows an overlap of the spherical aberration curve for 810nm wavelength for both, the singlet and the achromat, at the same scale.
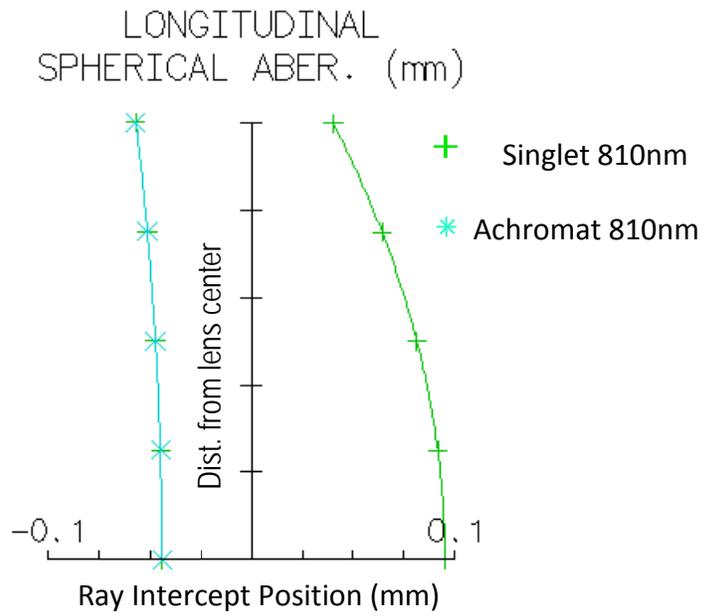
Figure 12 Overlay of Spherical Aberration Plot at 810nm for Singlet and Achromat

As shown above, the shift in the focal spot location is much less for the achromat than the singlet lens. Same is true for the 770mm and 850 nm wavelengths.

In the chromatic focal shift plot (Figure 12), the chromatic shift of the focal point is shown as a function of the wavelength in microns. Here it can be clearly seen that the achromat design reduced the chromatic shift to only 75 microns.
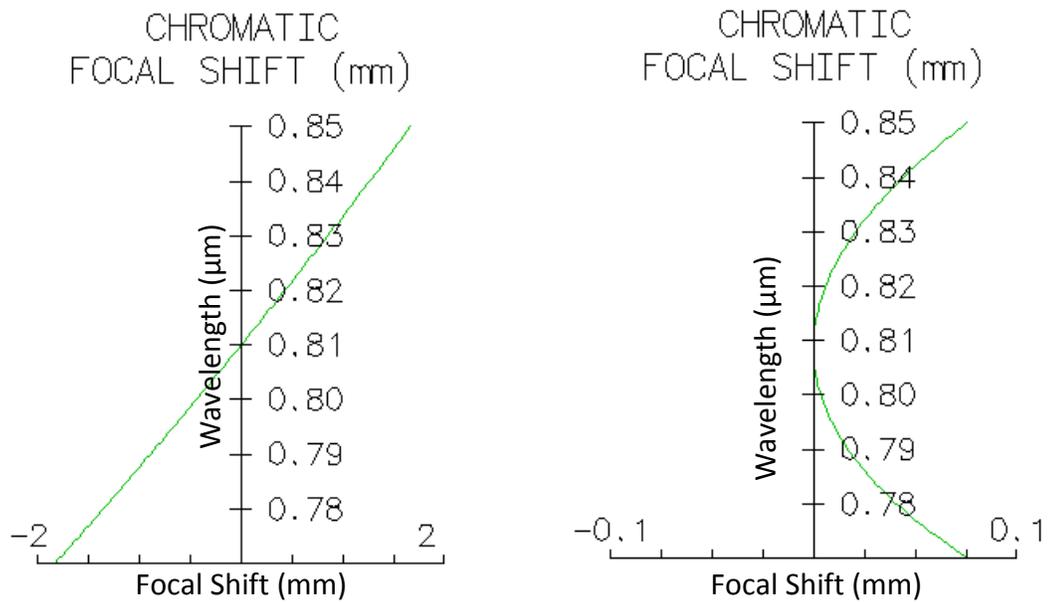
Figure 13 Lens 1 Chromatic Aberration Plots, Singlet (left), Achromat (right)

For a more visual approach to identify the effect chromatic aberration has on the focus a spot diagram is useful. One can clearly see that for a singlet, the blue end of the spectrum focuses much earlier than the green followed by red end of the spectrum. Chromatic focal shift created by the achromatic lens would be virtually nonexistent on the same scale.

Singlet

0.1

−2   −1   0   1   2

Achromat

0.04

−2   −1   0   1   2

(Units: mm) λ_1= 810 nm λ_2= 770 nm λ_3= 850 nm
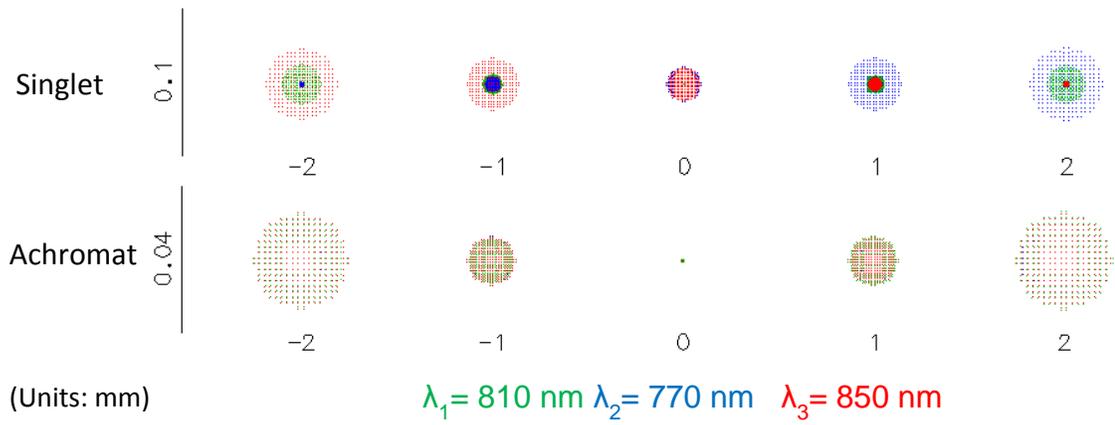
Figure 14 Lens 1 Apparent Chromatic Focal Shift in the Spot Diagram

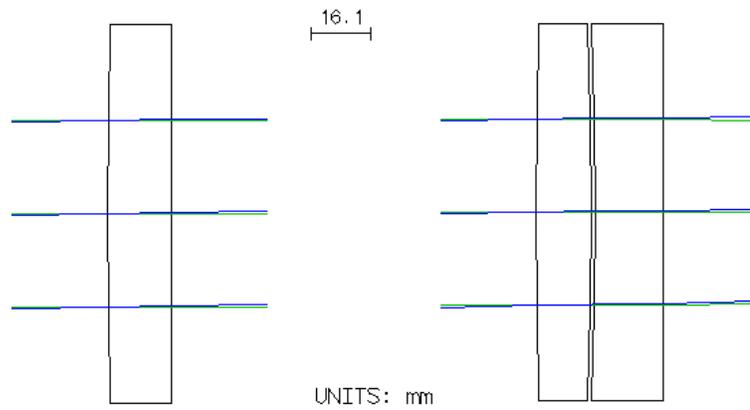On the next few pages similar plots make comparison between lens 2 and lens 2s.

16.1

UNITS: mm

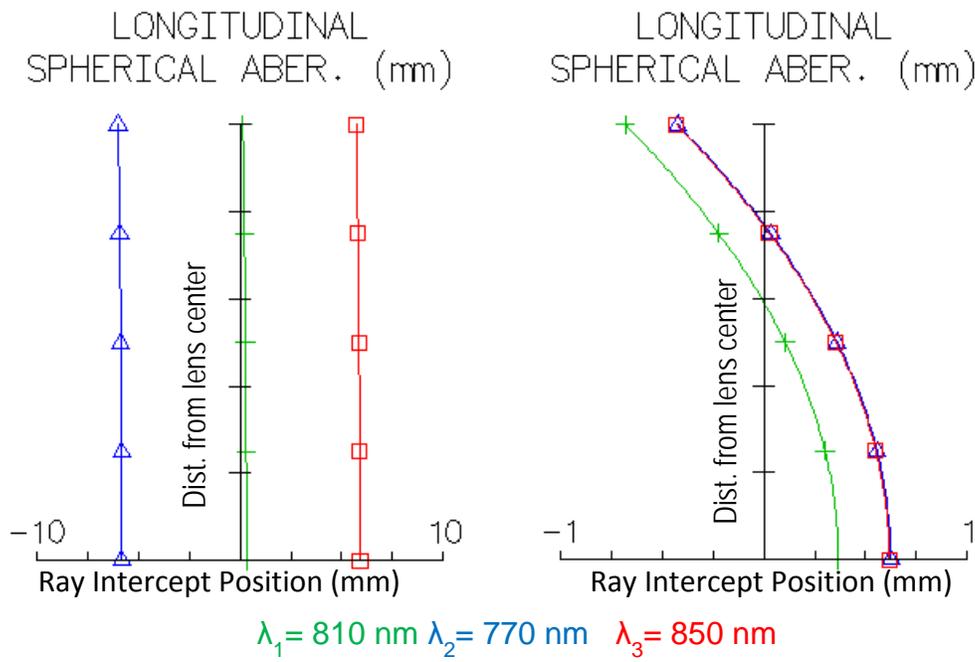**Figure 15 (Left) Singlet Lens, (Right) Achromat (f = 3850 mm)**

LONGITUDINAL
SPHERICAL ABER. (mm)

LONGITUDINAL
SPHERICAL ABER. (mm)

Dist. from lens center

Dist. from lens center

−10   10

−1   1

Ray Intercept Position (mm)

Ray Intercept Position (mm)

λ_1= 810 nm λ_2= 770 nm λ_3= 850 nm

Figure 16 Lens 2 Spherical Aberration Plots, Singlet (left), Achromat (right)

CHROMATIC
FOCAL SHIFT (mm)

CHROMATIC
FOCAL SHIFT (mm)

Wavelength (μm)

Wavelength (μm)

0.85
0.84
0.83
0.82
0.81
0.80
0.79
0.78

0.85
0.84
0.83
0.82
0.81
0.80
0.79
0.78

−10   10

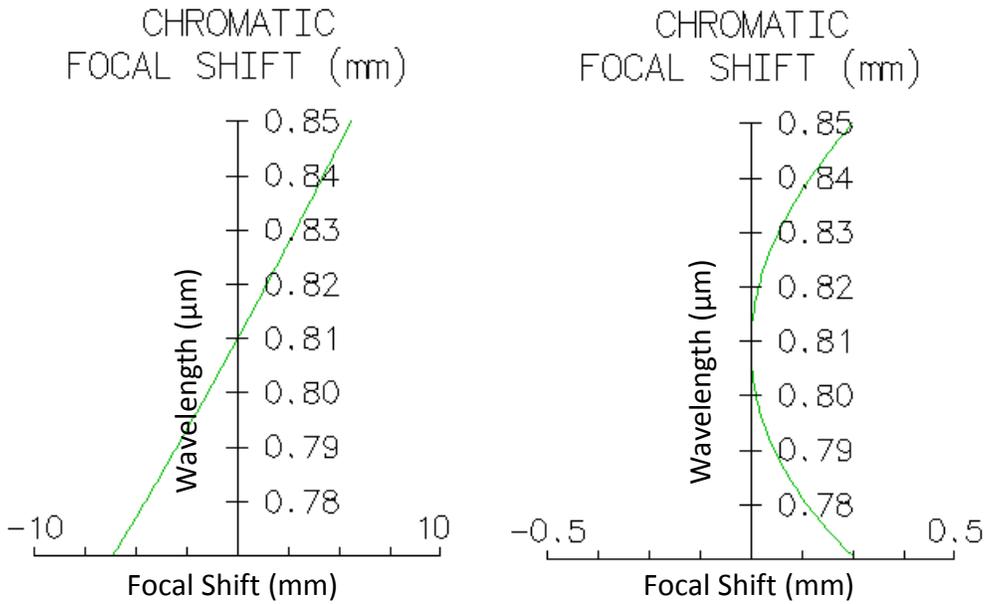−0.5   0.5

Focal Shift (mm)

Focal Shift (mm)

Figure 17 Lens 2 Chromatic Aberration Plots, Singlet (left), Achromat (right)

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Conclusion

As shown in the aberration plots achromatic lenses offer significant increase in optical performance compared to singlet lenses. The designs of these lenses were finalized after careful review by the Petawatt upgrade team and were sent to Rocky Mountain Instrument Co. for manufacturing. Both achromats have since been manufactured and are currently installed in the Scarlet laser facility where they relay laser pulse from the terawatt level optical amplifier to the Petawatt amplifier. As reported by the team, the lenses are working as expected in terms of aberrations and collimation.

While working on this project the experience and knowledge I gathered over the last year and half by working in the HEDP group proved to be very useful on top of the help that I received from my colleagues. By working on this project I learned even more about lenses, aberrations and optics in general. The experience of being involved in a design project that successfully turned into a real product is extremely satisfying.

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