Up.Periscope
Design Description Document

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Document Number 01

Revisions Level	Date
G	05-05-2017

Authentication Block

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Revision History

Rev.	Description	Date	Authorization
A	**Initial DDD**	01-27-2017	All
B	**First Revision:** Included Code V finding for relay system. Included images from tests of telescope and mirror system. Updated spring semester schedule.	02-08-2017	All
C	**Second Revision:** Began two mirror system design and analyzed results. Updated relay system design and analyzed results. Created appendix for previous designs.	02-24-2017	All
D	**Third Revision:** Included relay design process steps and most recent results. Updated telescope design process. Added two mirror system design results from LightTools and CAD. Included preliminary analysis of sky mirror. Updated costs of all systems and current concerns. Updated schedule and appendices.	03-03-2017	All
E	**Fourth Revision:** Completed relay system with eyepiece. Added optimized relay system for comparison. Updated costs for relay system. Added two mirror system results from Code V. Updated costs of mirrors and included comparison of materials.	04-10-2017	All
F	**Fifth Revision:** Finished relay system tolerance analysis. Updated costs of custom system. Added toroidal	04-28-2017	All

	mirror option analysis. Added telescope options and their costs. Created appendices for an Optimax custom order and tolerances tables.		
G	**Final Revision:** Added two mirror with multiple telescope schematic. Added performance images for two mirror system. Revised and edited document.	05-05-2017	All

Vision

The goal of the Up.Periscope project is to create an aesthetically pleasing periscope that employs analogue methods. The periscope ought to allow multiple individuals at once to view the New Rochelle waterfront from approximately one mile away from the middle of the downtown area.

Project Scope

We are responsible for completing a design study to explore and analyze various optical solutions to provide downtown New Rochelle with a view of the waterfront given the customer's constraints and requirements. It is necessary for this periscope to rise at least 70 feet to clear the downtown buildings and provide the desired view. Three design options were chosen to be explored: a relay system, a telescope with mirror system, and a two mirror "shipping container" system. A performance and cost analysis has been completed for each of these designs.

It is desirable that the final design have a multi-viewer display as well as provide adequate magnification to view the waterfront.

We are not responsible for the mechanical design of the housing for the optical system. The mechanical engineering team members we are working with are Catherine Yip, Michael Kaplan, Carolyn John, and Hiroyuki Asaga. They are responsible for all relevant environmental analyses and housing condition analyses. They are also responsible for a distortion analysis, especially for the large mirror designs, and building a prototype of our two mirror design.

Main System Overview

Relay System

<u>Initial Exploration</u>

This system encompasses multiple positive lenses (2f relay) to relay the image down a 70ft tube, which then is coupled with an eyepiece. We explored a variety of catalogue lenses to be used in this system. See Appendix C for initial design renderings.

Size of Lens (mm)	Focal Length (mm)	Number of Lenses	Calc FFOV (degrees)	Realistic FFOV (degrees)	Brightness/ Losses	Cost per Lens	Total Cost	Size of Image (in)
75	200	54	21.24	10.62	33.59%	$185.50	$10,017.00	2.95
75	300	36	14.25	7.13	48.32%	$198.80	$7,156.80	2.95
75	400	27	10.71	5.36	57.96%	$198.80	$5,367.60	2.95
102.31	1524.73	7	3.84	1.92	86.81%	$945.00	$6,615.00	4.03
116	1524.73	7	4.36	2.18	86.81%	$1,035.00	$7,245.00	4.57
128.02	1900.24	6	3.86	1.93	88.58%	$985.00	$5,910.00	5.04
140	1900.24	6	4.22	2.11	88.58%	$1,075.50	$6,453.00	5.51

Table 1: Comparison of the benefits of various parameters of the relay system. This table also provides additional information about the specifics of the design options.

Initial concerns associated with the relay system:

- Costs per lenses
- Diameter of lenses vs. number of lenses
- Diameter of lenses vs. field of view
- Image quality, specifically Petzval curvature and chromatic aberrations
- Transmission losses due to large number of lenses
- Cost of coatings

Resolution Requirements

Our resolution calculations are displayed below. The minimum acceptable MTF for reasonable contrast is 40%. Our goal is to achieve 40% MTF at 5 lp/mm. Thus, the spot size diameter in object space is 1.11 feet. For comparison, the resolving power of the unaided human eye (1 arc minute half field of view) corresponds to a spot size diameter in object space of 3.07 feet. The spot size diameters in object space were calculated using the geometry of our system and the equation, $h = ftan(\theta)$.

Resolution	Spot Size Diameter in Object Space
5 lp/mm	1.11 ft
10 lp/mm	0.56 ft

Table 2: Conversion of MTF specification to spot size in object space.

Relay Design

The 1900.24mm focal length, 128.02mm diameter lens (Edmund Optics 70163) was chosen to be used for the relay system. The relay system was modeled using 7 of these lenses, each being 2 focal lengths (3800mm) apart. The first, third, fifth and seventh lenses relay the image while the other lenses act as field lenses to bend the chief ray back into the system.

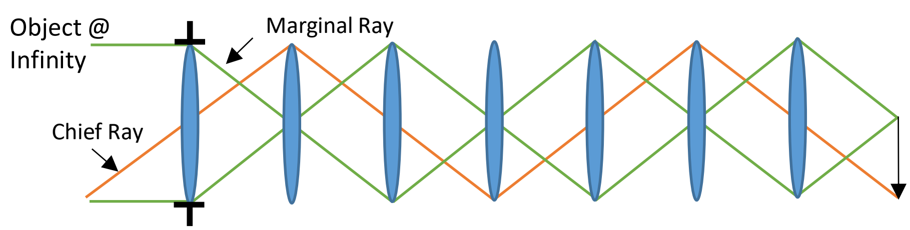

Figure 1: Diagram of relay system. Not drawn to scale.

Addition of Objective

Due to the long focal lengths of the relay lenses, only a very small field of view could be achieved (one-degree full field). To increase the field of view it was necessary to add an objective with a shorter focal length ($h = f \cdot tan\theta \rightarrow \theta = \arctan(h/f)$). With the addition of the objective, we needed to move the aperture stop to the front of the system so it could be properly imaged through the system. This also required the addition of an eighth relay lens. The lens chosen for the objective has an 18mm focal length and 90mm diameter (Edmund Optics 54567). This lens was chosen for its short focal length but large diameter.

Addition of Eyepiece

The next step in completing this system was to add the eyepiece which takes the internal image created by the relay and images it onto the eye. This eyepiece was chosen to provide an image that is approximately the same size as the entrance pupil of the human eye in sunlight, which is estimated to range from 2 to 4mm. The lens chosen for the eyepiece has a 160mm focal length and 40mm diameter (Edmund Optics 47740). This lens fills 3.06mm of the pupil. This eyepiece, along with our previously chosen objective, determines the magnification of the system, which is 5.3x.

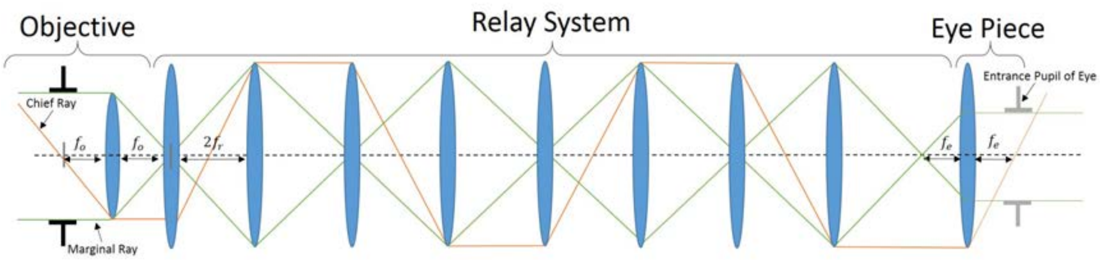

Figure 2: Diagram of relay system combined with objective and eyepiece. Not drawn to scale.

<u>Nominal Performance of Off-the-Shelf System</u>

The following charts show the performance of the relay system, with the addition of a “perfect lens” to account for the imaging of the human eye.

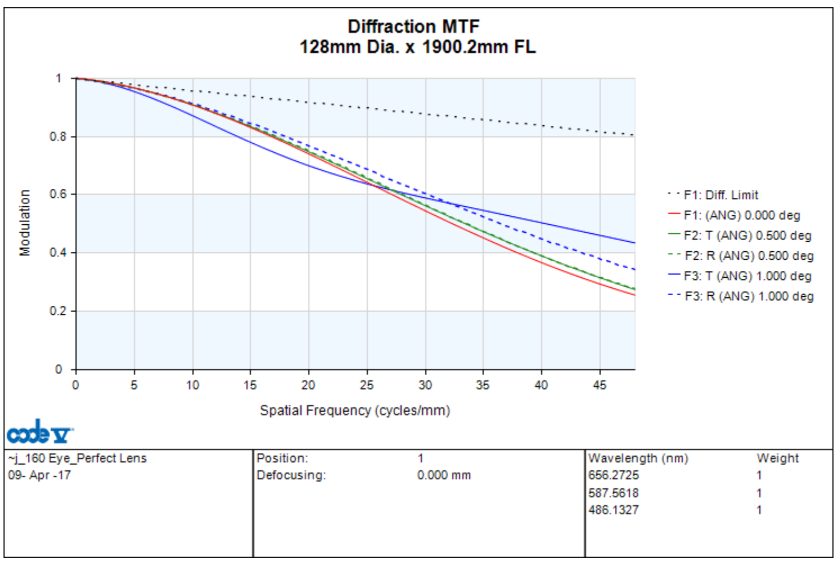

Figure 3: MTF performance for the off-the-shelf relay system. As mentioned above, the performance goal is 40% MTF at 5 lp/mm. This system achieves 95% MTF at 5 lp/mm, which more than exceeds our expectations.

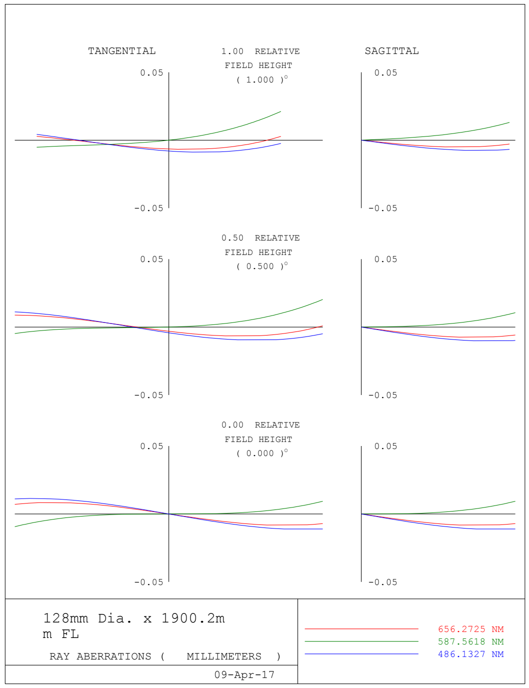

Figure 4: Transverse ray plots for the off-the-shelf relay system. This shows the presence of spherical aberration, lateral color and secondary color.

Figure 5: Image simulation for the off-the-shelf relay system.

Nominal Performance of Custom System

This relay system was designed to allow for a custom-made objective and eyepiece. This optimization allows for additional correction of aberrations. Both of the focal lengths of the objective and eyepiece were constrained, as well as distortion.

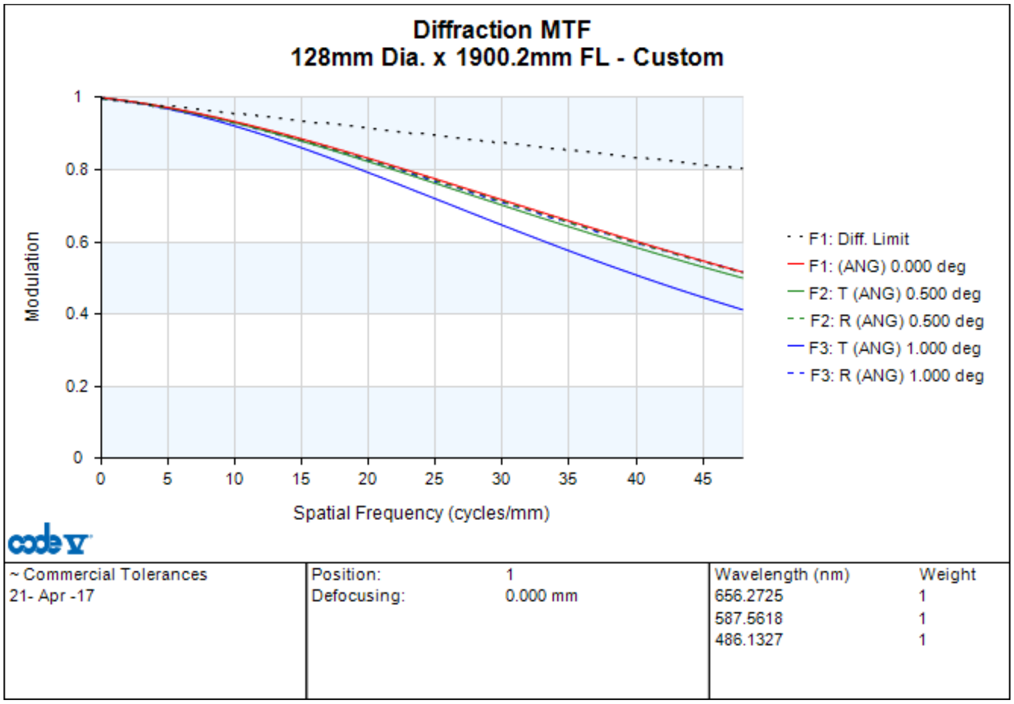

Figure 6: MTF performance of the custom relay system. After the optimization of the eyepiece and objective, the performance of the system greatly improved. The MTF at 40 lp/mm is about 50%, while the off-the-shelf system was about 38%.

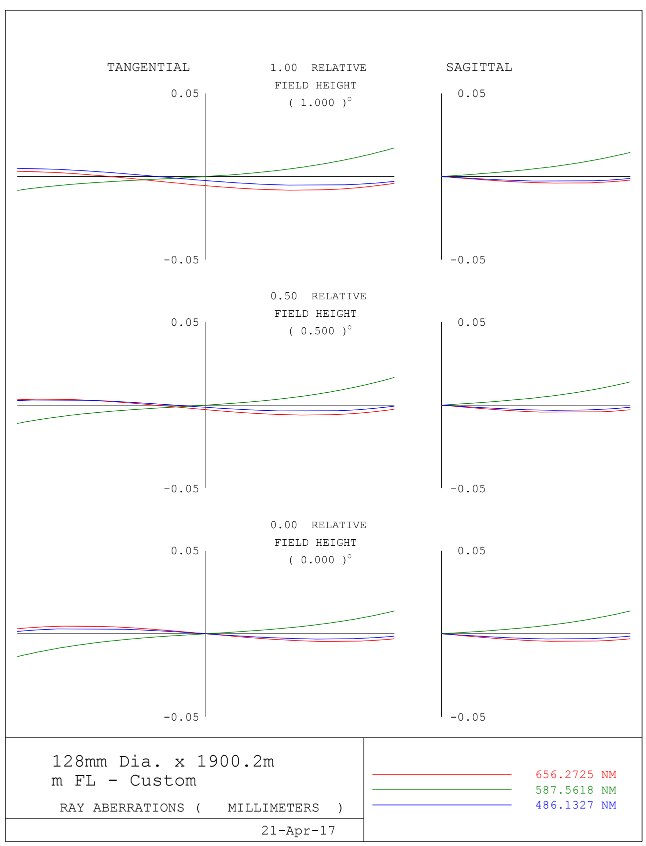

Figure 7: Transverse ray plots for the custom relay system. This shows a decrease in spherical and lateral color compared to the off-the-shelf system.

Figure 8: Image simulation for the custom relay system.

Tolerance Analysis

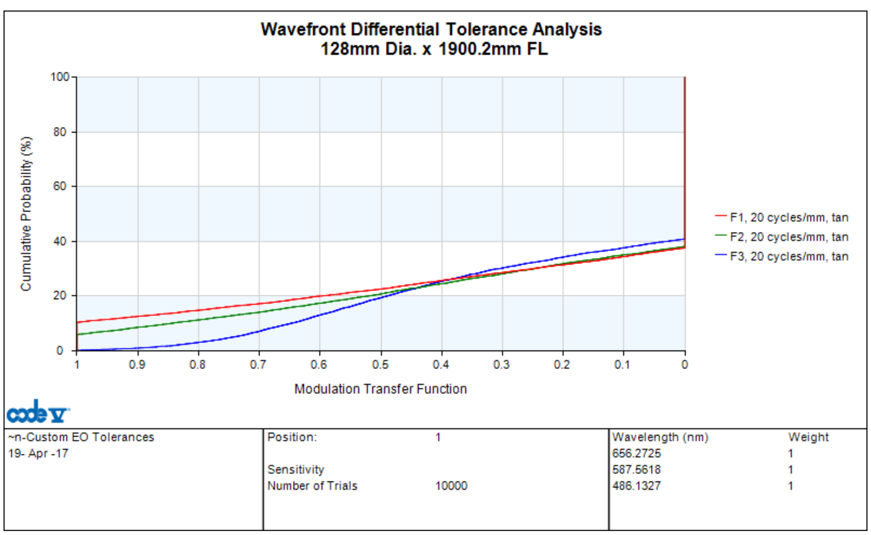

Figure 9: MTF tolerance analysis for the off-the-shelf system at 20 lp/mm. This system uses the Edmund Optics tolerances specified for each of their lenses.

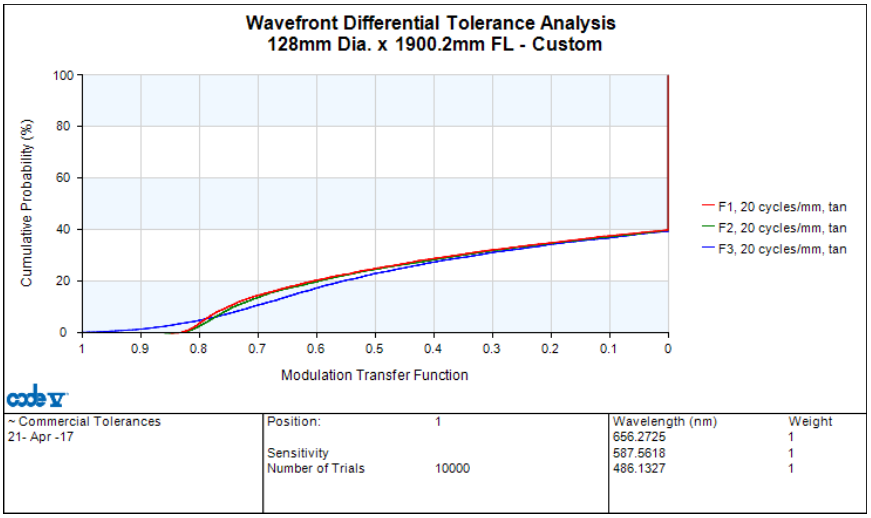

Figure 10: MTF tolerance analysis for the custom system at 20 lp/mm. This system uses the Edmund Optics tolerances specified for the relay lenses. The objective and eyepiece are custom lenses, so their tolerances are set by Optimax's commercial grade. Despite the use of Optimax's tighter tolerances, Edmund Optics' tolerances are so loose that the tighter tolerances on the objective and eyepiece cannot compensate in terms of as-built performance.

As can be observed in the tolerance analysis charts completed for each relay system, the MTF performance of each design is significantly decreased due to the variability in the Edmund Optics tolerances. While it is possible to achieve the nominal performance, only a very small percentage of the doublets provided by Edmund Optics will be acceptable. Thus, more than the required number of doublets would need to be ordered, increasing the total cost of the system, and the performance of each doublet would first need to be tested before using it in the relay system.

The following tolerance analysis was completed to determine how tight the tolerances would need to be to achieve close to the nominal performance, without requiring the testing and purchase of more than the necessary number of doublets. See Appendix B for the full tolerance tables.

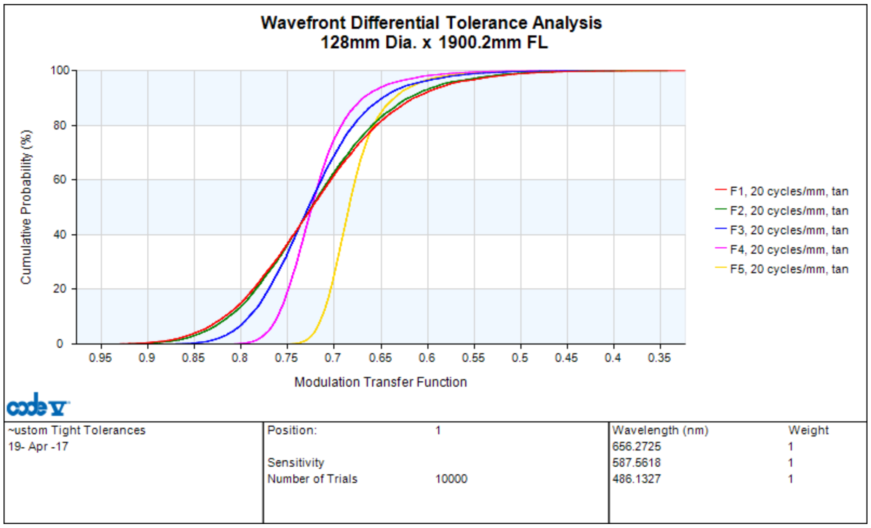

Figure 11: MTF tolerance analysis for the off-the-shelf system at 20 lp/mm. This tolerance analysis was completed to determine the required tolerances for each lens in order to achieve acceptable performance.

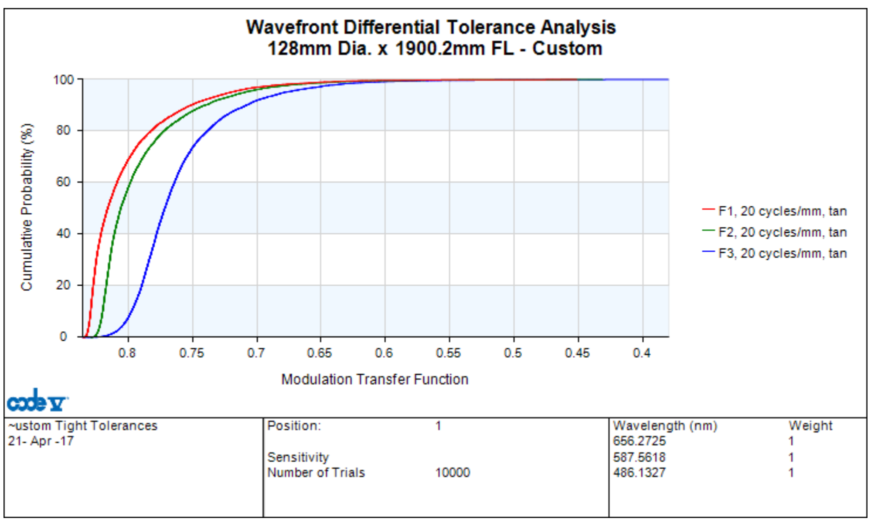

Figure 12: MTF tolerance analysis for the custom system at 20 lp/mm. This tolerance analysis was completed to determine the required tolerances for each lens in order to achieve acceptable performance.

	Tolerances Used	Radius (mm)	Power/ Irregularity (fringes)	Thickness (mm)	Index	V# (%)
Off-the-Shelf	Edmund Optics	0.025	5.0/1.00	0.86	0.001	0.80
	Required for Good Performance	0.01	0.5/0.10	0.01	0.0001	0.20

Custom	Edmund Optics & Optimax Commercial Grade	0.025	5.0/1.00	0.15	0.001	0.80
	Required for Good Performance	0.025	0.5/0.20	0.025	0.0001	0.20

Table 3: Comparison chart of tightest tolerances for each design. The "Required for Good Performance" rows are the tolerances necessary to achieve acceptable as-built performance.

Cost of Off-the-Shelf System

	Company/Part Number	Cost Per Lens (including mounts)	Amount Needed	Total Cost
Objective Lens	Edmund Optics #54567	$525.00	1	$525.00
Relay/Field Lenses	Edmund Optics #70163	$1,095.00	8	$8,760.00
Eyepiece	Edmund Optics #47740	$130.00	1	$130.00
TOTAL COST				**$9,415.00**

Table 4: The costs associated with the optical elements of the off-the-shelf relay system.

Cost of Custom System

	Company/Part Number	Cost Per Lens (including mounts)	Amount Needed	Total Cost
Objective Lens	Optimax Custom Doublet	$3,200.00	1	$3,200.00
Relay/Field Lenses	Edmund Optics #70163	$1,095.00	8	$8,760.00
Eyepiece	Optimax Custom Doublet	$1,590.00	1	$1,590.00
Optimax Additional Charges	N/A	$3,300.00	N/A	$3,300.00
TOTAL COST				**$16,850.00**

Table 5: The costs associated with optical elements of the custom relay system. The objective and eyepiece are custom and therefore are more expensive, while the relay/field lenses would still be purchased from Edmund Optics. The costs of the custom lenses are quotes from Optimax, using their commercial tolerances. See Appendix A for a list of Optimax's tolerances as well as additional information about a custom order.

Additional Considerations

This design is simply the vertical relay system. Note that mirrors are not included. An analysis of the use of mirrors and mirror quality is completed in the next design section. One of our biggest concerns with the relay system is the poor image quality, which can be viewed in the third order aberration and MTF plots above, as well as the image simulations for both the off-the-shelf design and the custom design. Our second main concern is that given the tolerance analysis, the nominal performance is not an accurate predictor of the actual performance of the system. It is necessary to consider these factors before choosing which system to build.

Two Mirror "Shipping Container" System

Initial Exploration

This system encompasses two flat mirrors that ultimately allow the view of the water to be displayed at ground level for an easy viewing experience.

Figure 13: Images of a two mirror display system using large mirrors and a shipping crate.[4]

Figure 14: Image of display from above system.[4]

Height of Periscope (ft)	Mirror Diameter (ft)	FFOV (°)
70	8	6.541
70	6	4.908
70	4	3.273

70	2	1.637

Table 6: Analysis of field of view achievable with varying mirror diameters.

Initial concerns with a two mirror system:

- Large in diameter
- Free standing system - will not be attached to a building
- Will not provide a magnified image
- Distortion will need to be considered and analyzed

Two Mirror System in CAD

A three-dimensional system consisting of two mirrors placed at a 45° angle relative to each other was modeled in Creo Parametric and is represented in Figure 15. This system could contain two flat mirrors, or a flat mirror coupled with a convex mirror at the top to allow for varied magnification and fields of view. The system was designed in this configuration because when the observer is facing the periscope, the water would be to their left. Upon further modeling and analysis, it was determined that this configuration is not possible because the image would be sideways.

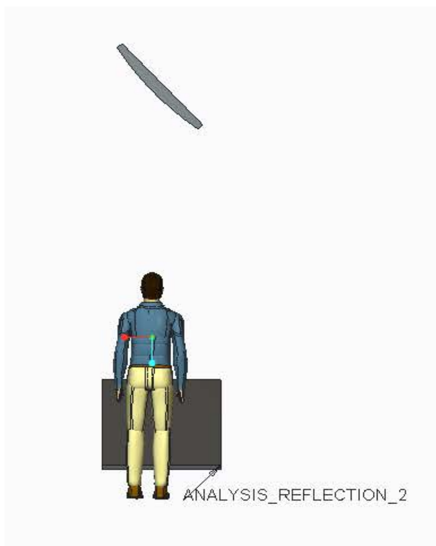

Figure 15: Image of two mirror system in Creo Parametric. The top mirror is convex and the bottom mirror is flat. With the mirrors configured in this way, the image would be sideways.

Two Mirror System in LightTools

Below are images of our two mirror system in LightTools. These mirrors are placed 70ft apart and the rays are traced, assuming a collimated light source at an object distance of infinity. The output irradiance distribution is also displayed below in Figure 17. As expected, the output irradiance is near 100%.

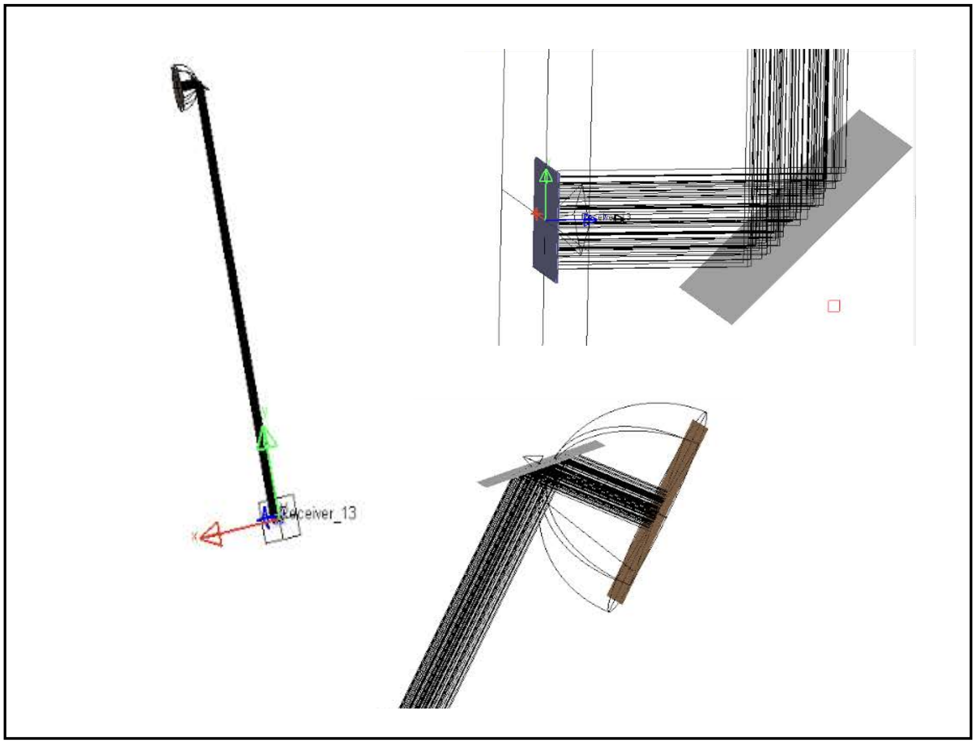

Figure 16: Images of two mirror system in LightTools.

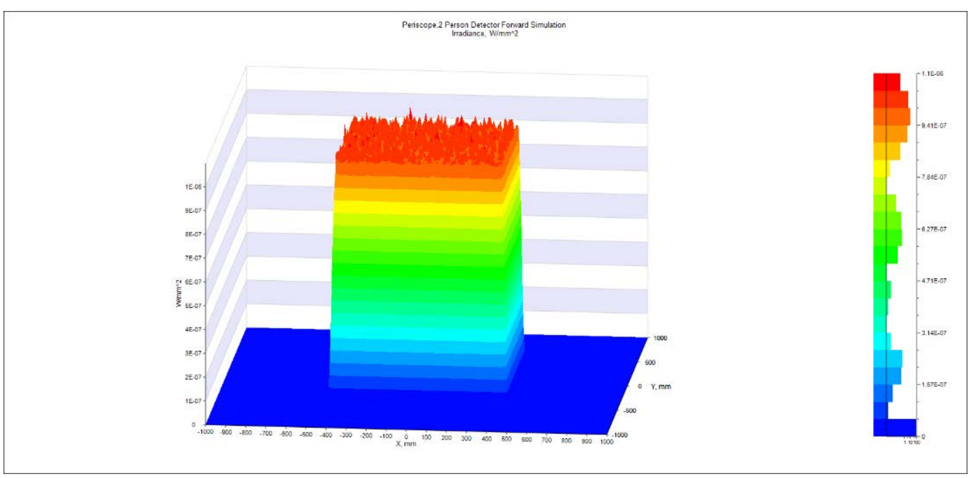

Figure 17: Image depicting the near-perfect irradiance output of the system.

<u>Two Mirror System in Code V</u>

To ensure that the system would produce an upright image, it was modeled in Code V. It was found that the only way to produce an acceptable image is for both mirrors to be angled at 45 degrees and parallel to each other. This configuration is shown below. This means a new location would have to be found for the periscope where the water is directly in front of the viewer.

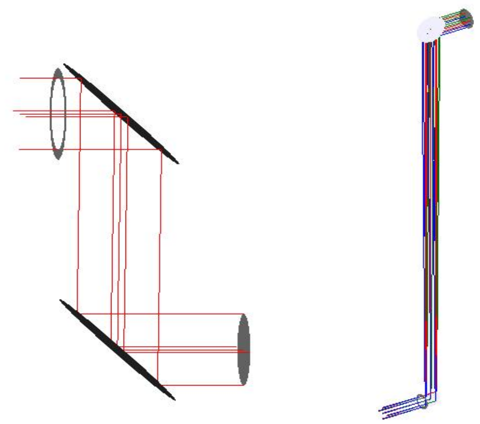

Figure 18: Image of two mirror system in Code V. This is the only way we can position the mirrors and still get an upright image.

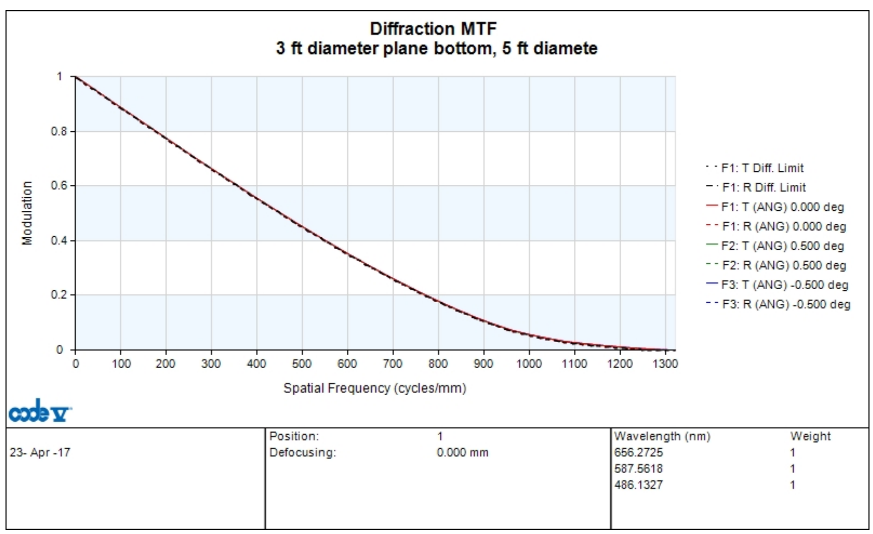

Figure 19: MTF performance of the two mirror system. As can be easily observed, the performance is diffraction limited.

Figure 20: Image simulation for the two mirror system.

Toroidal Mirror Option

A slight variation to our two mirror system is to replace the upper flat mirror with a mirror that has curvature, specifically a toroidal mirror, which allows for different horizontal and vertical curvatures. This then provides our system with the added benefit of magnification and increased field of view. The toroidal shape allows for more of the horizontal view to be captured. This is ideal since we are trying to capture more of the landscape. The radius of the toroid determines just how much of the landscape is captured. It is important to note that using a toroidal mirror introduces spherical aberration and distortion, but that is a sacrifice that may be worth making in order to get magnification.

Toroid Radius (mm)	Field of View (miles)
5000	0.185
3000	0.309
2000	0.468
1000	0.996

Table 7: Top mirror toroid radii and corresponding landscape captured. The field of view is calculated using a toroidal mirror with a diameter of 5ft.

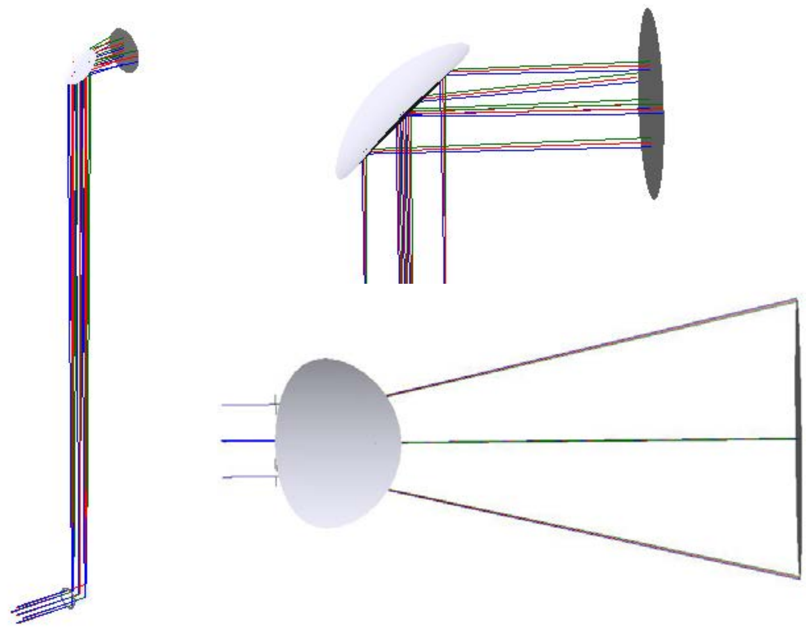

Figure 21: Images of the two mirror system in Code V, using a toroidal mirror.

The performance of this system is not quantifiable in Code V, due to the large amounts of distortion and spherical aberration. The performance of this system is best evaluated by testing a scaled down version. The results using one convex and one flat mirror are shown in the figures below. Note the only difference between the toroidal mirror displayed above and the convex mirror used in our demonstration is the toroidal mirror was designed to only have curvature horizontally, whereas the convex mirror has curvature in both the horizontal and vertical directions.

Figure 22: Images comparing the performance of a flat upper mirror versus a convex upper mirror. The convex mirror (on right) produces an image with an increased field of view, yet increased distortion and spherical aberration. Note the convex mirror is approximately 4 inches in diameter whereas the flat mirror is 1 foot in diameter.

Compared to the two flat mirrors, the convex mirror significantly increases the field of view, but also adds a significant amount of spherical aberration and distortion to the image. This can be seen by the curved horizon and curved-looking buildings in the image on the right. As noted above, the difference between the toroidal mirror and the convex mirror is that the toroidal mirror only has curvature in one direction. Therefore, a toroidal upper mirror would produce the horizontal distortion (the curved horizon), but would not produce the vertical distortion (the curved-looking buildings). This is what makes it a better option in terms of image quality.

<u>“Sky Mirror”</u>

“Sky mirrors” are one extreme example of convex/concave mirrors, made of polished stainless steel. They are public works of art, originally designed by artist Anish Kapoor, and are very rare and expensive. Images of the “sky mirror” that is currently in Rockefeller Center in New York City are provided below. The mirror is 35 feet in diameter and weighs 23 tons. While the cost of this exact mirror is unknown, we know that a “sky mirror” nearly half its size costs approximately $1.1 million.

Figure 23: Images of the “sky mirror” in Rockefeller Center. The image on the left is the convex side of the mirror and the image on the right is the concave side of the mirror. [3]

Incorporating the “sky mirror” into our two mirror design is unrealistic due to its size, weight, and cost. However, it exceeds our customer’s expectations in terms of performance and presentation.

Cost of Flat vs. Toroidal Mirrors

We estimate the cost of two flat mirrors to be at most $1200 combined. This assumes the use of two individual mirrors for each lower and upper mirror. The cost of the mechanical housing and rotation system still need to be accounted for.

Company	Mirror Type	Dimensions	Cost	SKU
McMaster-Carr	Polycarbonate	36"x24"	$136.79	2912K26
McMaster-Carr	Polycarbonate	48"x36"	$266.59	2912K25
McMaster-Carr	Acrylic	36"x24"	$55.75	3052K15
Home Depot	Acrylic	48"x36"	$83.99	AM3648S
McMaster-Carr	Acrylic	48"x36"	$123.75	3052K14
McMaster-Carr	Frameless Glass	36"x24"	$79.38	2875K22
McMaster-Carr	Stainless Steel	60"x24"	$252.18	2989K51

Table 8: Cost analysis of flat mirrors of varying sizes. The frameless glass mirror listed is the type that will be used in the prototype. However, polycarbonate plastic mirrors are suggested for the actual, life-size system because they are damage-resistant and shatter-proof. These are both useful qualities for long-term use. Acrylic mirrors are cheaper than polycarbonate mirrors and are scratch-resistant, but are not shatter-proof.

We estimate the cost of a 2-foot diameter toroidal mirror to be approximately $1000. Cost estimates from Thorlabs for mirrors up to 5ft in diameter are pending.

Additional Considerations

While this system is the only one of the three that provides an image for multiple viewers at one time without the use of an eyepiece, it is large in diameter, free standing, and only provides magnification at the expense of increased distortion. While the toroidal mirror allows for magnification, as well as an increased field of view, the additional benefits may not be worth the reduced image quality. The cost of toroidal mirrors significantly increases with size, so a cost benefit analysis is necessary once we have received formal cost estimates.

We are working with the mechanical engineering design team to design a housing for this two mirror system and a system that allows the mirrors to rotate a total of 90 degrees in the horizontal direction. Additionally, please refer to the mechanical engineering team’s final design results for a tolerance analysis of these large mirrors.

Telescope with Mirror

Initial Exploration

This system encompasses a mirror at the top to capture the field of view, which will then be seen by the viewer using a commercial telescope. The system may also have the capability to rotate and scan across the horizon by user control.

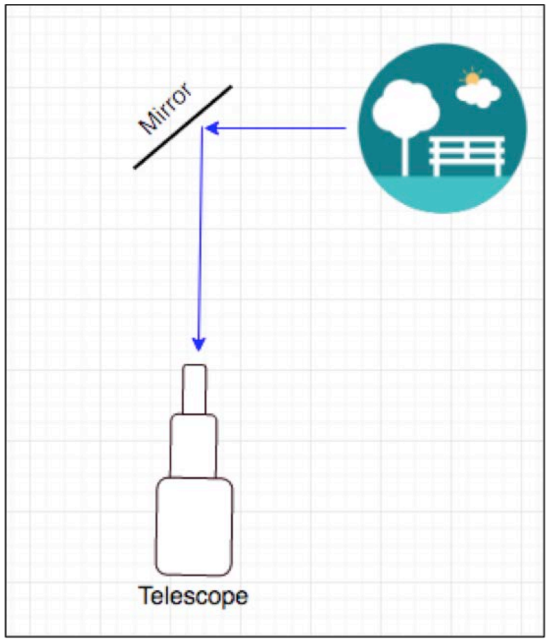

Figure 24: Diagram of telescope and mirror concept.

Initial concerns with the telescope system:

- Capturing acceptable field of view
- Rotating mirror capabilities
- Integrating desired display

Preliminary Testing of Telescope with Mirror System

Before working on this design, we decided to start by testing Professor Knox's telescope with a flat, 1x1ft mirror. The mirror was angled at approximately 45 degrees from the telescope objective and then rotated horizontally, to simulate a rotating mirror. Our results are displayed below. The images are of Rush Rhees Library from the fourth floor of Goergen, approximately 60 feet above the ground. As expected, the images are inverted and limited by the quality of the mirror and the focus of the telescope.

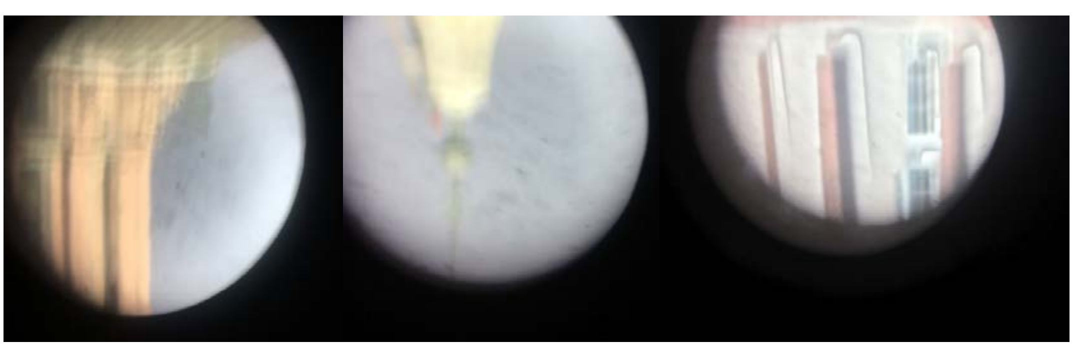

Figure 25: Images captured while testing telescope and mirror.

Design Logistics

This system is a variation of the two mirror design which adds magnification to the image seen by the viewer through the addition of a telescope. The field of view will be determined by the telescope chosen for the system which then determines the required diameter for the upper mirror. See the table below for possible telescope options and their related specifications.

Manufacturer and Model	Part or Model Number	Magnification	FFOV (°)	Required Mirror Diameter (ft)	Cost
Celestron Solar Observer 60	21041	8.57x-142x	1.2	2.073	$79.99
Celestron Hummingbird	52308	9x – 27x	4.22 - 1.85	7.295	$359.95
Vortex Diamondback	DBK-60A1	20x – 60x	2.2-1.0	3.802	$499.99
Vortex Viper	VPR-65A-HD	15x – 45x	2.7-1.2	4.666	$849.99
Nikon Fieldscope	16100	20x – 60x	<2.1	3.629	$1,599.95

Table 9: Table depicting possible telescope options for use with the single mirror setup. The required mirror diameter is given in feet and is calculated using the greatest field of view specification, with a mirror distance of 70 feet.

Additional telescopes may be added to the system to allow for additional viewers as shown in the diagram below. A second mirror may also be incorporated into the design if a telescope model that cannot be positioned completely vertical is chosen.

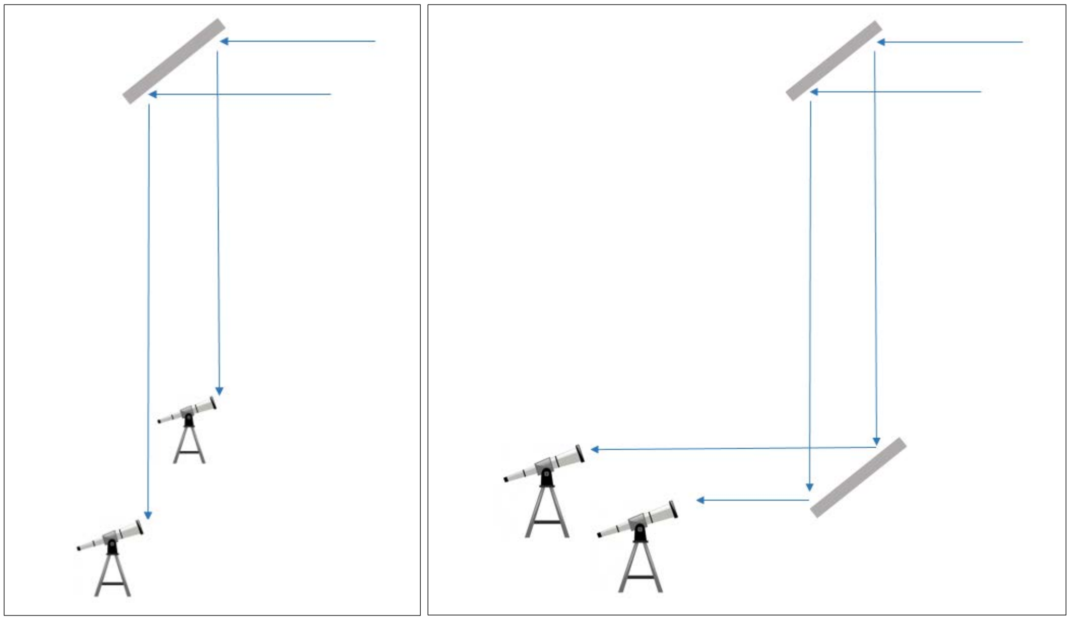

Figure 26: On the left is an image of the telescope and mirror system, with multiple telescopes. This allows the system to be used by more than one viewer at a time. A variation of this option is using multiple telescopes with a two mirror system, as shown on the right.

The performance of each system will be limited by the quality of the telescope(s) chosen.

Cost of System

Using the telescopes in the table above, and the mirrors listed in the previous design section, we estimate the optics will cost no more than $5500, but will vary greatly depending on the type of telescope and number needed.

Number of Telescopes	Range of Costs
1	$191.49 - $2,133.13
2	$271.48 - $3,733.08
3	$351.47 - $5,333.03

Table 10: Costs of this design system depending on the number of telescopes used. The lower estimate for each range is calculated assuming the use of the least expensive mirror and telescope options. The upper estimate for each range is calculated assuming the use of the most expensive mirror and telescope options. These prices assume the upper mirror will be formed by two of the individual mirrors listed in the previous design section.

This price estimate provided above includes the telescope(s) and the mirror, but not the mechanical housing or rotation system. The rotation system designed by the mechanical engineering team for the two mirror system can also be incorporated into this design, which would allow horizontal rotation.

Additional Considerations

After analyzing the images above, our biggest concern is the quality of the mirror and telescope, especially when coupled together. We know the telescope options vary greatly in terms of price, yet it may be worth the extra investment to purchase a more expensive telescope that provides better image quality. The focusing capabilities of the telescope also play a role in this.

Comparison of Designs

The following table compares the specification and image quality of each of the three main designs.

	Relay System	Two Mirror System	Telescope with Mirror System
FFOV	2 degrees	1.6-6.5 degrees	1-4.2 degrees
Diameter	5 inches	2-8 feet	2.1-7.3 feet
Size of Image	N/A	2-8 feet	N/A
Magnification	5.3x	Only if use toroidal mirror	8.6-142x (dependent on telescope chosen)
Number of Viewers	1	Multiple	1-3 (dependent on number of telescopes)
Image Quality	Mediocre (image quality dominated by spherical and chromatic aberrations)	Two flat mirrors: No aberrations or losses Toroidal option: High in spherical aberration and distortion	Minimal aberrations and losses
Costs	Off-the-Shelf: $9,415 Custom: $16,850	Two flat mirrors: $223-$1,066.36 (dependent on mirrors chosen) Toroidal option: ~$3,000 (pending formal quote)	1 Telescope: $191.49 - $2,133.13 2 Telescope: $271.48 - $3,733.08 3 Telescope: $351.47 - $5,333.03

Table 11: Comparison of the three main design systems. Includes a comparison of their specifications and performance in terms of image quality.

The relay system is the design option with the least amount of flexibility, whereas the two mirror system and telescope with mirror system allow for a wide range in specifications. The relay system is what our customer initially had in mind when he presented the project to us. Despite its smaller field of view, it is the smallest in diameter and provides magnification. Unfortunately, this system only allows for one viewer at a time and is the most expensive of the options.

While much larger in diameter than the customer expected, the two mirror system provides almost the exact image that the customer desires. It can be viewed on a large mirror by multiple people at once, without the need for an eyepiece. The main tradeoff in this system is its diameter versus its field of view. The larger the diameter, the larger the field of view. For example, it can achieve a full field of view up to 6.5 degrees, but only at its largest diameter of 8 feet. A possible solution to this tradeoff is to replace the upper flat mirror with a toroidal mirror. This type of mirror can increase the field of view, and provides magnification, without increasing the diameter of the mirrors used. However, these mirrors induce a significant amount of distortion and spherical aberration whereas the system with two flat mirrors produces an almost perfect image. Note that using two flat mirrors does not provide magnification and is the least expensive of the options.

The telescope with mirror system is a slight variation of the two mirror system. It provides a similar range of fields of view and diameters. Depending on the telescope chosen, it can achieve up to 142x magnification. Unfortunately, this design requires the use of an eyepiece, and only allows the same number of viewers as the number of telescopes used. The image quality of this option is dependent on the quality of the telescope(s), which in turn, determines the cost.

Citations

1. Faasch, Werner and Schade, Harry. Twin Lens Reflex Camera. Patent 2,963,950. 8 Jul. 1958.
2. Gardner, Danielle. "Hasselblad 500C Through the Viewfinder." *Flickr*. Yahoo!, 2014. Web. 14 Dec. 2016.
3. “Sky Mirror.” *Wikipedia.org.* 2017 Mar 2. Web.
4. “40-Foot Cargo Container Turned into World’s Tallest Periscope.” *Weburbanist.com.* 2015 Sept. 17. Web.

Appendices

Appendix A: Optimax Custom Order

OPTIMAX

To:	Jessica Bernstein	**Quote Date:**	April 21, 2017
Co.:	U of R		
Phone:	203-536-2522	**Optimax Quote #:**	Q104888
E-mail:	jberns17@u.rochester.edu	**Customer RFQ:**	Dated 4/18/17

Optimax is pleased to quote the following.....

ROM

Optimax Commercial Tolerances:

PN/Description	Lot Charge	Quantity	Unit Price	Total
NRE/Set Up Charge	$ 300.00			$ 300.00
VIS BBAR Ravg < 0.5% 420-700nm	$ 3,000.00			$ 3,000.00
Enhanced QA Data Package	Included			Included
Doublet #1		1	$ 3,200.00	$ 3,200.00
Doublet #2		1	$ 1,590.00	$ 1,590.00
Total - Standard Shipment 10-12 weeks ARO				**$ 8,090.00**

Optimax Precision Tolerances:

PN/Description	Lot Charge	Quantity	Unit Price	Total
NRE/Set Up Charge	$ 300.00			$ 300.00
VIS BBAR Ravg < 0.5% 420-700nm	$ 3,000.00			$ 3,000.00
Enhanced QA Data Package	Included			Included
Doublet #1		1	$ 4,100.00	$ 4,100.00
Doublet #2		1	$ 2,640.00	$ 2,640.00
Total - Standard Shipment 10-12 weeks ARO				**$ 10,040.00**

Notes/Exceptions

1. ROM (rough order of magnitude) - This quotation offers budgetary pricing only. A firm quotation will be provided upon receipt of manufacturing drawings and/or delivery schedule requirements.

Page 1 of 2

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Ontario, NY 14519
www.optimaxsi.com

Phone: 585-265-1020
sales@optimaxsi.com

DMS100790
Last updated: 2016-10-20

OPTIMAX

Terms of Offer

Optimax will review any applicable Customer Terms & Conditions upon receipt of a formal purchase order. Quoted pricing and delivery is subject to change pending receipt and review of said Terms & Conditions. Differences and/or requirements that may impact the quoted pricing and delivery will be communicated to the customer prior to final acceptance of order (Sales Order Acknowledgement) by Optimax.

This quotation defines the terms of offer associated with your request. Where unspecified, quoted prices assume the use of Optimax's Commercial/Precision Quality Manufacturing Tolerance Chart.

Overage: Optimax frequently starts more parts than your job requires. Should we yield overage on your project, parts will be offered at order completion at the contracted unit price.

Quote Validity: 15 days – For orders placed beyond the validity period, Optimax reserves the right to revise pricing and/or delivery time based upon our costs and available capacity at the time of order
Payment Terms: N30 days, USD

Shipping Terms & Delivery

Shipping: FCA Origin: Optimax Systems, Inc. Ontario, NY
Unless the customer shipping account information is provided, Optimax will prepay freight and bill customer.
Delivery: Quoted prices assume delivery will be a single shipment, unless otherwise noted. Splitting deliveries may require additional coating charges.
Holidays: Optimax reserves the right to adjust ship date at order placement due to holidays
Material Availability: This quotation assumes that optical materials are available in the marketplace within 3-4 weeks at the time of order. Optimax may use equivalents as available, fine annealed, n_d +/- 0.001, v_d +/- 0.8% and homogeneity +/- 0.0001. Material data will be supplied.

Additional Business Terms

To accept a PO and schedule delivery date(s), Optimax must receive the following;

- Purchase order referencing Optimax quotation and any applicable exceptions
- Manufacturing drawings and specifications – preferably in a .PDF format

Optical Coatings: Optimax provides a wide variety of AR and Mirror coatings. This quote assumes a 1.0 mm max rail mark, at two opposing positions, due to coating tooling. Where unspecified, coating reflectivity is taken as the average reflectivity calculated over the wavelength range and angle range for average polarization as measured on a witness sample.
Packaging Options: Standard packaging is included in the price of your parts. Other packaging options are available upon request.
DPAS Contracts: This quote assumes that the project is *not* DPAS rated. Optimax reserves the right to re-evaluate pricing & delivery of all DPAS rated contracts.
Sales Order Acknowledgement: A formal order acknowledgement is typically sent within one week of receipt of your purchase order. If you have placed an order and haven't received an acknowledgement, please contact the Sales office to confirm receipt of your purchase order.
Optimax Terms and Conditions, revised September, 2016 apply.

Page 2 of 2

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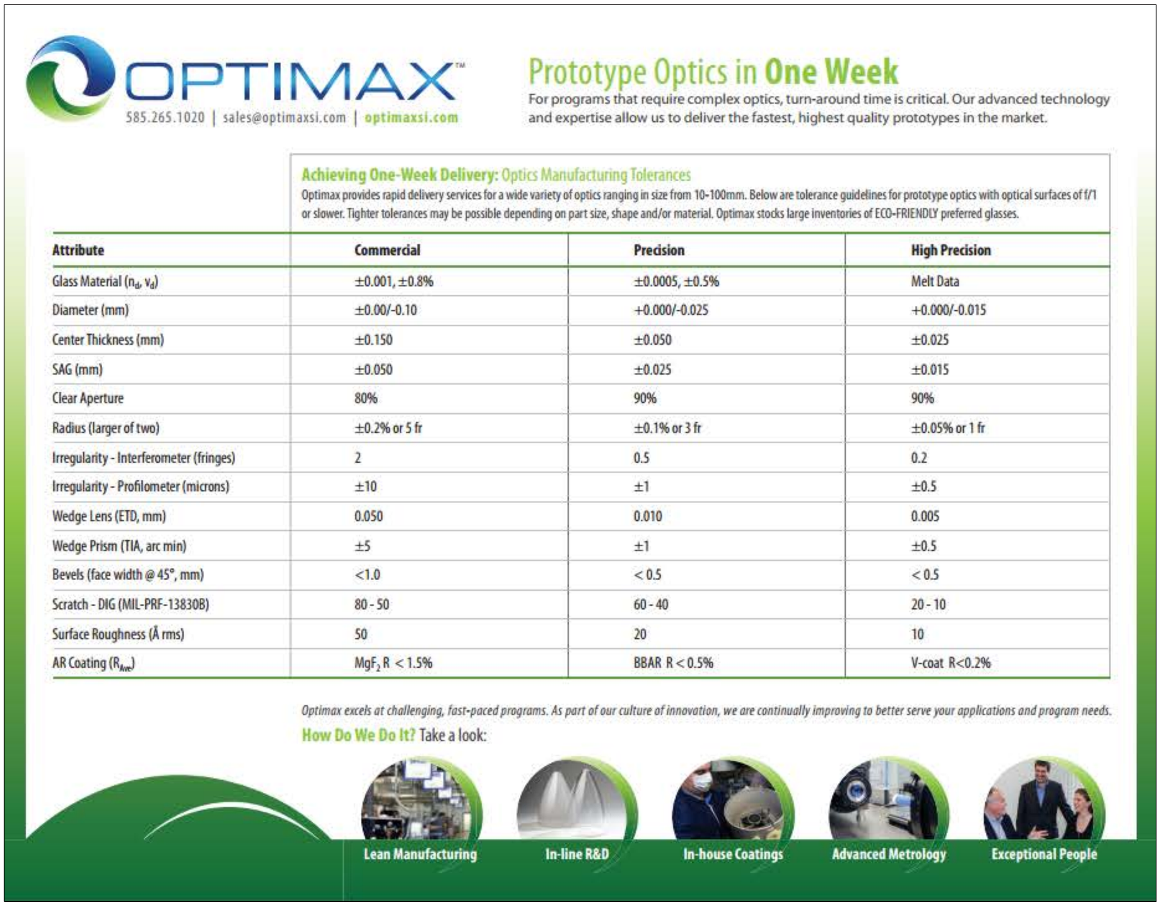
sales@optimaxsi.com

DMS100790
Last updated: 2016-10-20

Figure 27: Image of Optimax's notes on a custom order. Includes costs, shipping terms, delivery details, and additional notes.



Attribute	Commercial	Precision	High Precision
Glass Material (n_d, v_d)	±0.001, ±0.8%	±0.0005, ±0.5%	Melt Data
Diameter (mm)	±0.00/-0.10	+0.000/-0.025	+0.000/-0.015
Center Thickness (mm)	±0.150	±0.050	±0.025
SAG (mm)	±0.050	±0.025	±0.015
Clear Aperture	80%	90%	90%
Radius (larger of two)	±0.2% or 5 fr	±0.1% or 3 fr	±0.05% or 1 fr
Irregularity - Interferometer (fringes)	2	0.5	0.2
Irregularity - Profilometer (microns)	±10	±1	±0.5
Wedge Lens (ETD, mm)	0.050	0.010	0.005
Wedge Prism (TIA, arc min)	±5	±1	±0.5
Bevels (face width @ 45°, mm)	<1.0	< 0.5	< 0.5
Scratch - DIG (MIL-PRF-13830B)	80 - 50	60 - 40	20 - 10
Surface Roughness (Å rms)	50	20	10
AR Coating (R_{Ave})	MgF_2 R < 1.5%	BBAR R < 0.5%	V-coat R<0.2%

Figure 28: Image of Optimax's different tolerance grades. They offer a commercial grade, a precision grade, and a high precision grade.

Appendix B: Tolerance Tables

19-Apr-17 POSITION 1

C E N T E R E D
T O L E R A N C E S

128mm Dia. x 1900.2mm FL

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	V-NO (%)	INHOMO-GENEITY
1				846.25000	0.02500				
2	497.21000	0.0250	5.0/ 1.00	13.08000	0.86000	NBK7	0.00100	0.80	
3	-345.82000	0.0250	5.0/ 1.00	0.10000	0.86000				
4	-344.20000	0.0250	5.0/ 1.00	10.16000	0.86000	NSF2	0.00100	0.80	
5	-1227.86000	0.0250	5.0/ 1.00	838.69000	0.02500				
6	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
7	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
8	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
9	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
10	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
11	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
12	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
13	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
14	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
15	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
16	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
17	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
18	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
19	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
20	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
21	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
22	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
23	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
24	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
25	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
26	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
27	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
28	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
29	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
30	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
31	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
32	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
33	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
34	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
35	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
36	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
37	-2704.01000	0.0250	5.0/ 1.00	3826.94859	0.02500				
38				160.00000					
39	98.66000	0.0250	5.0/ 1.00	8.50000	0.20000	NBK7	0.00100	0.80	
40	-70.73000	0.0250	5.0/ 1.00	4.00000	0.20000	NSF5	0.00100	0.80	
41	-205.72000	0.0250	5.0/ 1.00	154.10000	0.02500				
42				0.00000					
43				17.17623					
44				0.00000					

Radius, radius tolerance, thickness and thickness tolerance are given in mm.

Fringes of power and irregularity are at 546.1 nm. over the clear aperture

Irregularity is defined as fringes of cylinder power in test plate fit

19-Apr-17 POSITION 1

D E C E N T E R E D
T O L E R A N C E S

128mm Dia. x 1900.2mm FL

ELEMENT NO.	FRONT RADIUS	BACK RADIUS	ELEMENT WEDGE TIR	ELEMENT WEDGE ARC MIN	ELEMENT TILT TIR	ELEMENT TILT ARC MIN	EL. DEC/ROLL(R) TIR	EL. DEC/ROLL(R) mm.
1	497.21000	-345.82000	0.0250	1.2	0.0720	3.4	0.0088	0.0250
2	-344.20000	-1227.86000	0.0250	1.2	0.0720	3.4	0.0038	0.0250
3	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
4	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
5	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
6	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
7	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
8	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
9	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
10	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
11	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
12	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
13	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
14	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
15	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
16	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
17	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250

18	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
19	98.66000	-70.73000	0.0250	2.5			0.0196	0.0250 (R)
19-20	98.66000	-205.72000			0.0340	3.4	0.0127	0.0250
20	-70.73000	-205.72000	0.0250	2.5				

Radii are given in units of mm.

For wedge and tilt, TIR is a single indicator measurement taken at the smaller of the two clear apertures. For decenter and roll, TIR is a measurement of the induced wedge and is the maximum difference in readings between two indicators, one for each surface, with both surfaces measured at their respective clear apertures. The direction of measurement is parallel to the original optical axis of the element before the perturbation is applied. TIR is measured in mm.

Decenter or roll is measured perpendicular to the optical axis in mm.

Figure 29: Tolerance tables for the off-the-shelf relay system, using Edmund Optics tolerances. This table displays every tolerance used for every surface/element.

21-Apr-17 POSITION 1

C E N T E R E D
T O L E R A N C E S

128mm Dia. x 1900.2mm FL - Custom

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	V-NO (%)	INHOMO-GENEITY
1				846.25000	0.02500				
2	198.87023	0.0250	5.0/ 1.00	14.63885	0.15000	NBAF52	0.00100	0.80	
3	-78.17890	0.0250	5.0/ 1.00	6.00000	0.15000	NKZFS11	0.00100	0.80	
4	403.23337	0.0250	5.0/ 1.00	838.69000	0.02500				
5	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
6	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
7	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
8	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
9	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
10	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
11	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
12	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
13	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
14	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
15	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
16	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
17	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
18	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
19	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
20	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
21	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
22	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
23	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
24	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
25	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
26	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
27	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
28	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
29	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
30	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
31	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
32	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
33	1131.72000	0.0250	5.0/ 1.00	15.42000	0.86000	NBK7	0.00100	0.80	
34	-780.87000	0.0250	5.0/ 1.00	0.10000	0.86000				
35	-779.37000	0.0250	5.0/ 1.00	10.92000	0.86000	NSF2	0.00100	0.80	
36	-2704.01000	0.0250	5.0/ 1.00	3826.94859	0.02500				
37				160.00000					
38	101.38917	0.0250	5.0/ 1.00	8.06504	0.15000	SNSL36	0.00100	0.80	
39	-83.11501	0.0250	5.0/ 1.00	4.00000	0.15000	SNBH56	0.00100	0.80	
40	-162.77896	0.0250	5.0/ 1.00	154.10000	0.02500				
41				17.00000					
42				0.00000					

Radius, radius tolerance, thickness and thickness tolerance are given in mm.

Fringes of power and irregularity are at 546.1 nm. over the clear aperture

Irregularity is defined as fringes of cylinder power in test plate fit

21-Apr-17 POSITION 1

D E C E N T E R E D
T O L E R A N C E S

128mm Dia. x 1900.2mm FL - Custom

ELEMENT	FRONT	BACK	ELEMENT WEDGE		ELEMENT TILT		EL. DEC/ROLL(R)	
NO.	RADIUS	RADIUS	TIR	ARC MIN	TIR	ARC MIN	TIR	mm.

1	198.87023	-78.17890	0.0500	3.8			0.0195	0.0250	(R)
1- 2	198.87023	403.23337			0.0450	3.4	0.0030	0.0250	
2	-78.17890	403.23337	0.0250	1.9					
3	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250	
4	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250	
5	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250	
6	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250	
7	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250	
8	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250	
9	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250	
10	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250	
11	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250	
12	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250	
13	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250	
14	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250	
15	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250	
16	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250	
17	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250	
18	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250	
19	101.38917	-83.11501	0.0500	5.2			0.0176	0.0250	(R)
19-20	101.38917	-162.77896			0.0331	3.4	0.0134	0.0250	
20	-83.11501	-162.77896	0.0250	2.6					

Radii are given in units of mm.

For wedge and tilt, TIR is a single indicator measurement taken at the smaller of the two clear apertures. For decenter and roll, TIR is a measurement of the induced wedge and is the maximum difference in readings between two indicators, one for each surface, with both surfaces measured at their respective clear apertures. The direction of measurement is parallel to the original optical axis of the element before the perturbation is applied. TIR is measured in mm.

Decenter or roll is measured perpendicular to the optical axis in mm.

Figure 30: Tolerance tables for the custom relay system, using Edmund Optics tolerances for the relay lenses and Optimax's commercial grade tolerances for the custom objective and eyepiece. This table displays every tolerance used for every surface/element.

19-Apr-17 POSITION 1

C E N T E R E D
T O L E R A N C E S

128mm Dia. x 1900.2mm FL

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	V-NO (%)	INHOMO-GENEITY
1				846.25000	0.02500				
2	497.21000	0.0250	0.5/ 1.00	13.08000	0.02500	NBK7	0.00010	0.80	
3	-345.82000	0.0250	1.0/ 1.00	0.10000	0.02500				
4	-344.20000	0.0250	0.5/ 0.50	10.16000	0.02500	NSF2	0.00010	0.80	
5	-1227.86000	0.0250	0.5/ 0.50	838.69000	0.02500				
6	1131.72000	0.0250	5.0/ 1.00	15.42000	0.02500	NBK7	0.00100	0.80	
7	-780.87000	0.0250	5.0/ 1.00	0.10000	0.02500				
8	-779.37000	0.0250	5.0/ 1.00	10.92000	0.02500	NSF2	0.00100	0.80	
9	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
10	1131.72000	0.0250	0.5/ 0.10	15.42000	0.02500	NBK7	0.00010	0.20	
11	-780.87000	0.0100	0.5/ 0.10	0.10000	0.01000				
12	-779.37000	0.0100	0.5/ 0.10	10.92000	0.02500	NSF2	0.00010	0.20	
13	-2704.01000	0.0250	0.5/ 0.10	3775.00000	0.02500				
14	1131.72000	0.0250	5.0/ 1.00	15.42000	0.02500	NBK7	0.00100	0.80	
15	-780.87000	0.0250	5.0/ 1.00	0.10000	0.02500				
16	-779.37000	0.0250	5.0/ 1.00	10.92000	0.02500	NSF2	0.00100	0.80	
17	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
18	1131.72000	0.0250	0.5/ 0.10	15.42000	0.02500	NBK7	0.00010	0.20	
19	-780.87000	0.0100	0.5/ 0.10	0.10000	0.01000				
20	-779.37000	0.0100	0.5/ 0.10	10.92000	0.02500	NSF2	0.00010	0.20	
21	-2704.01000	0.0250	0.5/ 0.10	3775.00000	0.02500				
22	1131.72000	0.0250	5.0/ 1.00	15.42000	0.02500	NBK7	0.00100	0.80	
23	-780.87000	0.0250	5.0/ 1.00	0.10000	0.02500				
24	-779.37000	0.0250	5.0/ 1.00	10.92000	0.02500	NSF2	0.00100	0.80	
25	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
26	1131.72000	0.0250	0.5/ 0.10	15.42000	0.02500	NBK7	0.00010	0.20	
27	-780.87000	0.0100	0.5/ 0.10	0.10000	0.01000				
28	-779.37000	0.0100	0.5/ 0.10	10.92000	0.02500	NSF2	0.00010	0.20	
29	-2704.01000	0.0250	0.5/ 0.10	3775.00000	0.02500				
30	1131.72000	0.0250	5.0/ 1.00	15.42000	0.02500	NBK7	0.00100	0.80	
31	-780.87000	0.0250	5.0/ 1.00	0.10000	0.02500				
32	-779.37000	0.0250	5.0/ 1.00	10.92000	0.02500	NSF2	0.00100	0.80	
33	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
34	1131.72000	0.0250	0.5/ 0.10	15.42000	0.02500	NBK7	0.00010	0.20	
35	-780.87000	0.0100	0.5/ 0.10	0.10000	0.01000				
36	-779.37000	0.0100	0.5/ 0.10	10.92000	0.02500	NSF2	0.00010	0.20	
37	-2704.01000	0.0250	0.5/ 0.10	3826.94859	0.02500				
38				160.00000					
39	98.66000	0.0250	5.0/ 1.00	8.50000	0.02500	NBK7	0.00010	0.80	
40	-70.73000	0.0250	5.0/ 1.00	4.00000	0.02500	NSF5	0.00050	0.80	

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL
41	-205.72000	0.0250	5.0/ 1.00	154.10000	0.02500
42				0.00000	
43				17.17623	
44				0.00000	

Radius, radius tolerance, thickness and thickness tolerance are given in mm.

Fringes of power and irregularity are at 546.1 nm. over the clear aperture

Irregularity is defined as fringes of cylinder power in test plate fit

19-Apr-17 POSITION 1

D E C E N T E R E D
T O L E R A N C E S

128mm Dia. x 1900.2mm FL

ELEMENT NO.	FRONT RADIUS	BACK RADIUS	ELEMENT WEDGE TIR	ELEMENT WEDGE ARC MIN	ELEMENT TILT TIR	ELEMENT TILT ARC MIN	EL. DEC/ROLL(R) TIR	EL. DEC/ROLL(R) mm.
1	497.21000	-345.82000	0.0250	1.2	0.0720	3.4	0.0088	0.0250
2	-344.20000	-1227.86000	0.0100	0.5	0.0720	3.4	0.0038	0.0250
3	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
4	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
5	1131.72000	-780.87000	0.0100	0.3	0.0218	0.7	0.0059	0.0250
6	-779.37000	-2704.01000	0.0050	0.2	0.0218	0.7	0.0025	0.0250
7	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
8	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
9	1131.72000	-780.87000	0.0100	0.3	0.0218	0.7	0.0059	0.0250
10	-779.37000	-2704.01000	0.0050	0.2	0.0218	0.7	0.0025	0.0250
11	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
12	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
13	1131.72000	-780.87000	0.0100	0.3	0.0218	0.7	0.0059	0.0250
14	-779.37000	-2704.01000	0.0050	0.2	0.0218	0.7	0.0025	0.0250
15	1131.72000	-780.87000	0.0100	0.3	0.1088	3.4	0.0059	0.0250
16	-779.37000	-2704.01000	0.0100	0.3	0.1088	3.4	0.0025	0.0250
17	1131.72000	-780.87000	0.0100	0.3	0.0218	0.7	0.0059	0.0250
18	-779.37000	-2704.01000	0.0050	0.2	0.0109	0.3	0.0025	0.0250
19	98.66000	-70.73000	0.0050	0.5			0.0039	0.0050 (R)
19-20	98.66000	-205.72000			0.0340	3.4	0.0051	0.0100
20	-70.73000	-205.72000	0.0020	0.2				

Radii are given in units of mm.

For wedge and tilt, TIR is a single indicator measurement taken at the smaller of the two clear apertures. For decenter and roll, TIR is a measurement of the induced wedge and is the maximum difference in readings between two indicators, one for each surface, with both surfaces measured at their respective clear apertures. The direction of measurement is parallel to the original optical axis of the element before the perturbation is applied. TIR is measured in mm.

Decenter or roll is measured perpendicular to the optical axis in mm

Figure 31: Tolerance tables for the off-the-shelf relay system, using the loosest tolerances that provide acceptable as-built performance. This table displays every tolerance used for every surface/element.

21-Apr-17 POSITION 1

C E N T E R E D
T O L E R A N C E S

128mm Dia. x 1900.2mm FL - Custom

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	V-NO (%)	INHOMO-GENEITY
1				846.25000	0.02500				
2	198.87023	0.0250	1.0/ 1.00	14.63885	0.02500	NBAF52	0.00010	0.20	
3	-78.17890	0.0250	5.0/ 1.00	6.00000	0.02500	NKZFS11	0.00010	0.20	
4	403.23337	0.0250	1.0/ 1.00	838.69000	0.02500				
5	1131.72000	0.0250	5.0/ 1.00	15.42000	0.02500	NBK7	0.00100	0.80	
6	-780.87000	0.0250	5.0/ 1.00	0.10000	0.02500				
7	-779.37000	0.0250	5.0/ 1.00	10.92000	0.02500	NSF2	0.00100	0.80	
8	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
9	1131.72000	0.0250	0.5/ 0.20	15.42000	0.02500	NBK7	0.00010	0.40	
10	-780.87000	0.0250	0.5/ 0.20	0.10000	0.02500				
11	-779.37000	0.0250	0.5/ 0.20	10.92000	0.02500	NSF2	0.00010	0.20	
12	-2704.01000	0.0250	0.5/ 0.20	3775.00000	0.02500				
13	1131.72000	0.0250	5.0/ 1.00	15.42000	0.02500	NBK7	0.00100	0.80	
14	-780.87000	0.0250	5.0/ 1.00	0.10000	0.02500				
15	-779.37000	0.0250	5.0/ 1.00	10.92000	0.02500	NSF2	0.00100	0.80	
16	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500				
17	1131.72000	0.0250	0.5/ 0.20	15.42000	0.02500	NBK7	0.00010	0.20	
18	-780.87000	0.0250	0.5/ 0.20	0.10000	0.02500				
19	-779.37000	0.0250	0.5/ 0.20	10.92000	0.02500	NSF2	0.00010	0.20	

20	-2704.01000	0.0250	0.5/ 0.20	3775.00000	0.02500			
21	1131.72000	0.0250	5.0/ 1.00	15.42000	0.02500	NBK7	0.00100	0.80
22	-780.87000	0.0250	5.0/ 1.00	0.10000	0.02500			
23	-779.37000	0.0250	5.0/ 1.00	10.92000	0.02500	NSF2	0.00100	0.80
24	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500			
25	1131.72000	0.0250	0.5/ 0.20	15.42000	0.02500	NBK7	0.00010	0.20
26	-780.87000	0.0250	0.5/ 0.20	0.10000	0.02500			
27	-779.37000	0.0250	0.5/ 0.20	10.92000	0.02500	NSF2	0.00010	0.20
28	-2704.01000	0.0250	0.5/ 0.20	3775.00000	0.02500			
29	1131.72000	0.0250	5.0/ 1.00	15.42000	0.02500	NBK7	0.00100	0.80
30	-780.87000	0.0250	5.0/ 1.00	0.10000	0.02500			
31	-779.37000	0.0250	5.0/ 1.00	10.92000	0.02500	NSF2	0.00100	0.80
32	-2704.01000	0.0250	5.0/ 1.00	3775.00000	0.02500			
33	1131.72000	0.0250	0.5/ 0.20	15.42000	0.02500	NBK7	0.00010	0.20
34	-780.87000	0.0250	0.5/ 0.20	0.10000	0.02500			
35	-779.37000	0.0250	0.5/ 0.20	10.92000	0.02500	NSF2	0.00010	0.20
36	-2704.01000	0.0250	0.5/ 0.20	3826.94859	0.02500			
37				160.00000				
38	101.38917	0.0250	5.0/ 1.00	8.06504	0.02500	SNSL36	0.00010	0.80
39	-83.11501	0.0250	5.0/ 1.00	4.00000	0.02500	SNBH56	0.00100	0.80
40	-162.77896	0.0250	5.0/ 1.00	154.10000	0.02500			
41				17.00000				
42				0.00000				

Radius, radius tolerance, thickness and thickness tolerance are given in mm.

Fringes of power and irregularity are at 546.1 nm. over the clear aperture

Irregularity is defined as fringes of cylinder power in test plate fit

21-Apr-17 POSITION 1

D E C E N T E R E D
T O L E R A N C E S

128mm Dia. x 1900.2mm FL - Custom

ELEMENT NO.	FRONT RADIUS	BACK RADIUS	ELEMENT WEDGE TIR	ARC MIN	ELEMENT TILT TIR	ARC MIN	EL. DEC/ROLL(R) TIR	mm.
1	198.87023	-78.17890	0.0250	1.9			0.0195	0.0250 (R)
1- 2	198.87023	403.23337			0.0450	3.4	0.0030	0.0250
2	-78.17890	403.23337	0.0250	1.9				
3	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
4	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
5	1131.72000	-780.87000	0.0100	0.3	0.1088	3.4	0.0059	0.0250
6	-779.37000	-2704.01000	0.0050	0.2	0.1088	3.4	0.0025	0.0250
7	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
8	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
9	1131.72000	-780.87000	0.0100	0.3	0.1088	3.4	0.0059	0.0250
10	-779.37000	-2704.01000	0.0050	0.2	0.1088	3.4	0.0025	0.0250
11	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
12	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
13	1131.72000	-780.87000	0.0100	0.3	0.1088	3.4	0.0059	0.0250
14	-779.37000	-2704.01000	0.0050	0.2	0.1088	3.4	0.0025	0.0250
15	1131.72000	-780.87000	0.0250	0.8	0.1088	3.4	0.0059	0.0250
16	-779.37000	-2704.01000	0.0250	0.8	0.1088	3.4	0.0025	0.0250
17	1131.72000	-780.87000	0.0100	0.3	0.1088	3.4	0.0059	0.0250
18	-779.37000	-2704.01000	0.0050	0.2	0.1088	3.4	0.0025	0.0250
19	101.38917	-83.11501	0.0100	1.0			0.0070	0.0100 (R)
19-20	101.38917	-162.77896			0.0331	3.4	0.0134	0.0250
20	-83.11501	-162.77896	0.0050	0.5				

Radii are given in units of mm.

For wedge and tilt, TIR is a single indicator measurement taken at the smaller of the two clear apertures. For decenter and roll, TIR is a measurement of the induced wedge and is the maximum difference in readings between two indicators, one for each surface, with both surfaces measured at their respective clear apertures. The direction of measurement is parallel to the original optical axis of the element before the perturbation is applied. TIR is measured in mm.

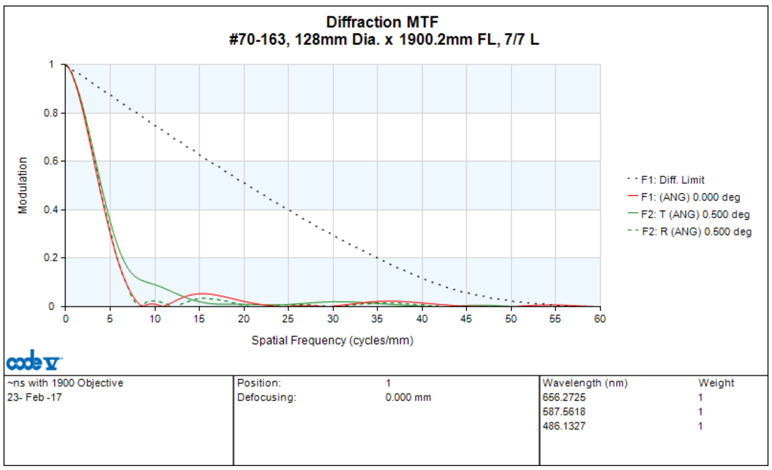
Decenter or roll is measured perpendicular to the optical axis in mm.

Figure 32: Tolerance tables for the custom relay system, using the loosest tolerances that provide acceptable as-built performance. This table displays every tolerance used for every surface/element.

Appendix C: Previous Designs

<u>Initial Relay System Configuration and Performance</u>

This analysis is only for the 7 lens relay of the system.




```
INFINITE CONJUGATES
  EFL      -1853.0653
  BFL       3691.9637
  FFL      -1847.9601
  FNO        -34.0588
  IMG DIS   3691.9637
  OAL      21085.0800
  PARAXIAL IMAGE
   HT         16.1715
   ANG         0.5000
  ENTRANCE PUPIL
   DIA        54.4078
   THI         0.0000
  EXIT PUPIL
   DIA        54.5581
   THI      1833.7791
```

Figure 33: MTF performance of 7 lens relay.

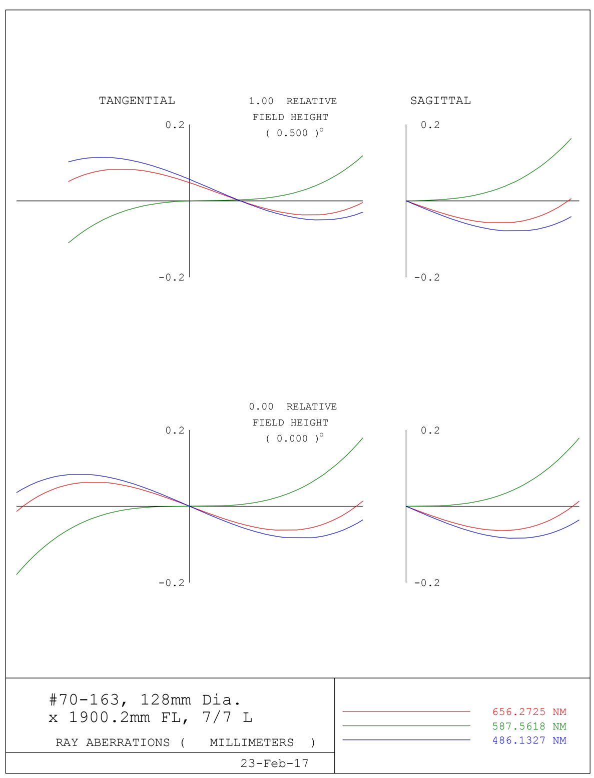


Figure 34: Transverse ray plots for 7 lens relay.

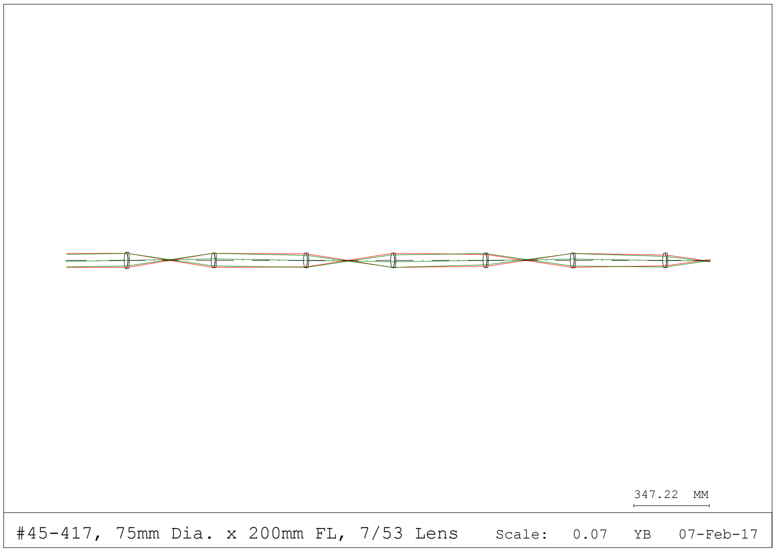
Figure 35: Image simulation for 7 lens relay. Left image is the sample. Right image shows system results.

Figure 36: Zoomed in image simulation for 7 lens relay. Left image is the sample. Right image shows system results.

Concerns after evaluation:

- Field of view
- Vignetting/relative illumination
- Poor MTF performance
- Image quality, specifically Petzval curvature
- Transmission losses due to large number of lenses

Edmund Optics #45-417, 75mm Dia. x 200mm FL, 53 Lenses Needed




```
INFINITE CONJUGATES
   EFL       -196.1617
   BFL        211.7213
   FFL       -150.2646
   FNO         -3.0766
   IMG DIS    194.7102
   OAL       2496.1164
   PARAXIAL IMAGE
    HT          3.4240
   ANG          1.0000
   ENTRANCE PUPIL
    DIA        63.7600
    THI         0.0000
   EXIT PUPIL
    DIA        83.2350
    THI       -44.3565
```

Figure 37: Lens drawing for relay system using specified lenses.

Transmission after 7 lenses: 85.46%

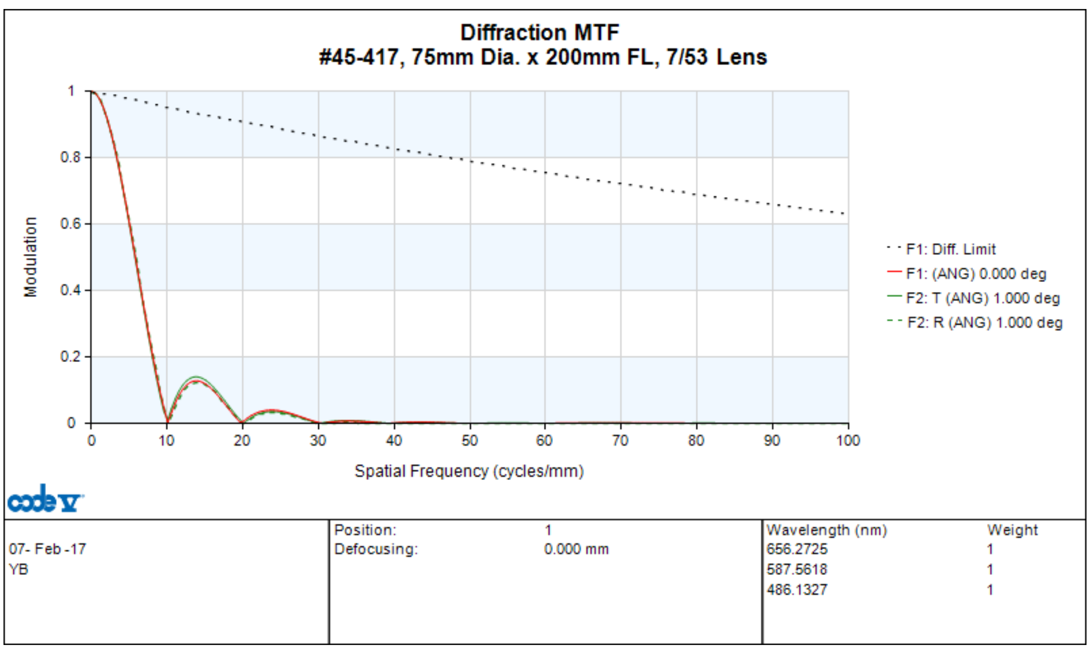


Figure 38: MTF plot for relay system using specified lenses.

Edmund Optics #70-163, 128mm Dia. x 1900.2mm FL, 7 Lenses Needed


```
INFINITE CONJUGATES
   EFL      -1900.1642
   BFL       1892.8351
   FFL      -1846.7182
   FNO        -17.4615
   IMG DIS   1892.8351
   OAL      22930.5653
   PARAXIAL IMAGE
    HT         33.1675
   ANG          1.0000
   ENTRANCE PUPIL
    DIA       108.8200
    THI         0.0000
   EXIT PUPIL
    DIA       111.9694
    THI       -62.3219
```

Figure 39: Lens drawing for relay system using specified lenses.

Transmission after 7 lenses: 71.0%

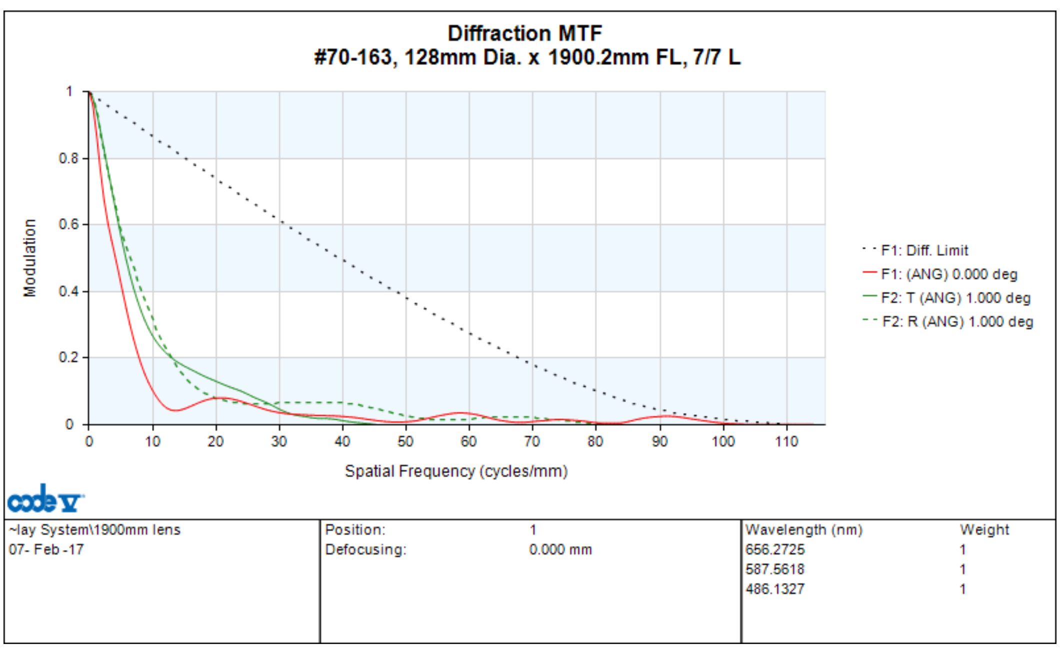


Figure 40: MTF plot for relay system using specified lenses.

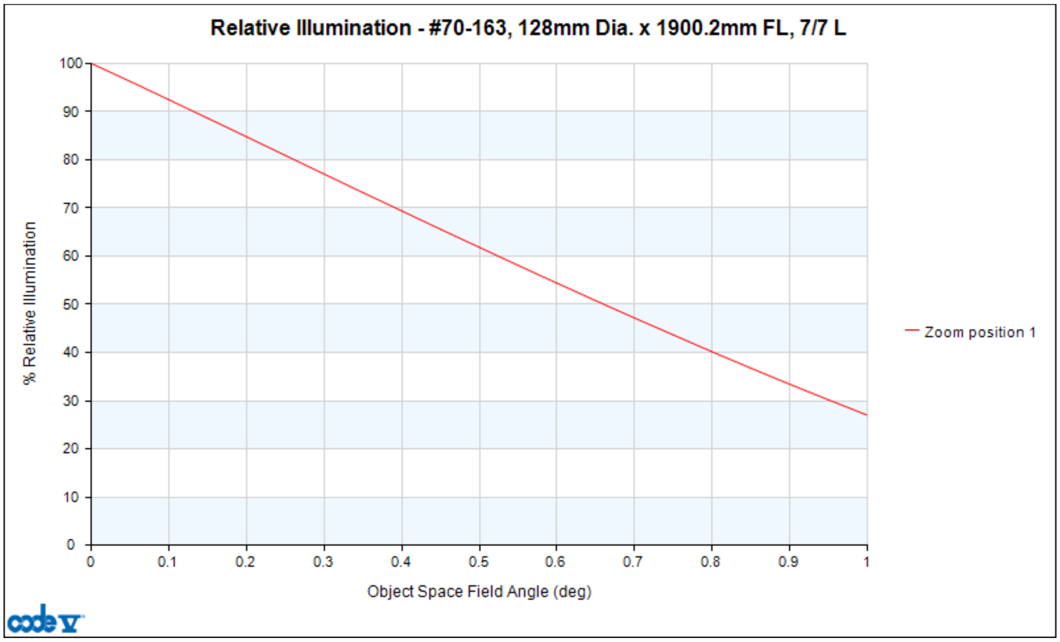


Figure 41: Relative illumination plot for relay system using specified lenses.

Appendix D: Display Options

Image Projected on Ground Glass

This viewfinder would encompass a system similar to a Hasselblad viewfinder. The image would be projected onto a focusing screen, ground glass.

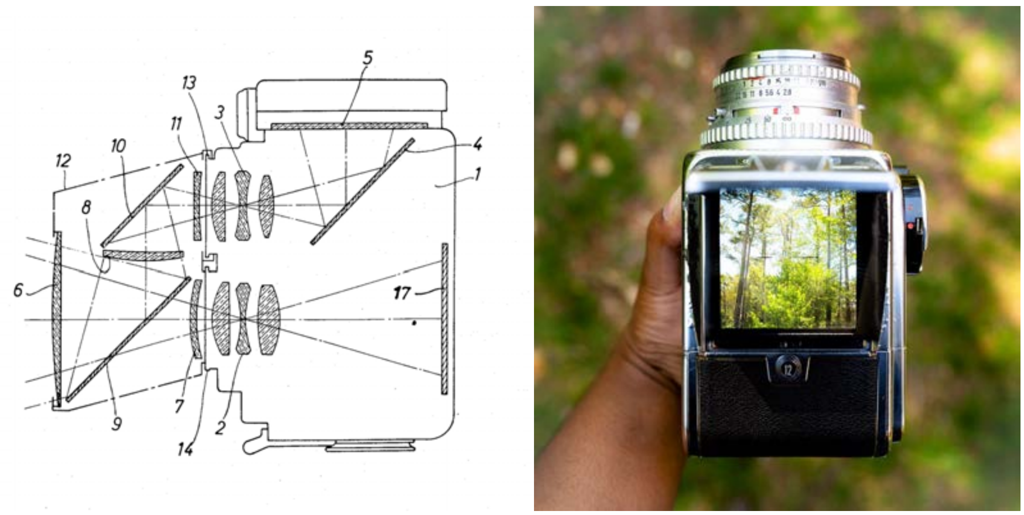


Figure 42: Left image represents the optical design of a two-lens reflex camera[1]. Right image depicts a Hasselblad viewfinder projected onto ground glass[2].

Initial concerns with a ground glass projection:

- Brightness of image may be insufficient for outdoor ambient lighting conditions
- Size of image will be restricted by lighting conditions
- Quality of image will likely be very low

Eyepiece

This system would encompass a standard eyepiece for viewers to use at ground level.

Initial concerns with an eyepiece:

- Viewing experience is limited to only a single viewer
- Not customer’s first choice due to the aforementioned single viewer drawback

Digital Display

This system would encompass an LCD display at ground level. This option would allow for a multiple person viewing experience.

Initial concerns with a digital display:

- Customer adamantly desires an analogue system
- Will retract from the old school appearance of the system once it has been installed

Mirror Display

This system would encompass a mirror at ground level displaying the image. This option would allow for a multiple person viewing experience.

Initial concerns with a mirror display:

- No magnification