Up.Periscope
Design Description Document

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### Revision History

<table>
<thead>
<tr>
<th>Rev.</th>
<th>Description</th>
<th>Date</th>
<th>Authorization</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>Initial DDD</td>
<td>01-27-2017</td>
<td>All</td>
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</table>
| 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: 05-05-2017 All
Added two mirror with multiple telescope schematic. Added performance images for two mirror system. Revised and edited document.

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

Initial Exploration

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.

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

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, $h = f \tan(\theta)$.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Spot Size Diameter in Object Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 lp/mm</td>
<td>1.11 ft</td>
</tr>
<tr>
<td>10 lp/mm</td>
<td>0.56 ft</td>
</tr>
</tbody>
</table>

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.](image)

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.](image)

Nominal Performance of Off-the-Shelf System

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.](image)
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.

![Transverse ray plots](image1.jpg)

**Figure 8:** Image simulation for the custom relay system.

**Tolerance Analysis**

![MTF tolerance analysis](image2.jpg)

**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.

### Tolerances Used

<table>
<thead>
<tr>
<th></th>
<th>Radius (mm)</th>
<th>Power/Irregularity (fringes)</th>
<th>Thickness (mm)</th>
<th>Index</th>
<th>V# (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off-the-Shelf</td>
<td>Edmund Optics</td>
<td>0.025</td>
<td>5.0/1.00</td>
<td>0.86</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Required for Good Performance</td>
<td>0.01</td>
<td>0.5/0.10</td>
<td>0.01</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

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.
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<table>
<thead>
<tr>
<th>Custom</th>
<th>Edmund Optics &amp; Optimax Commercial Grade</th>
<th>0.025</th>
<th>5.0/1.00</th>
<th>0.15</th>
<th>0.001</th>
<th>0.80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required for Good Performance</td>
<td>0.025</td>
<td>0.5/0.20</td>
<td>0.025</td>
<td>0.0001</td>
<td>0.20</td>
<td></td>
</tr>
</tbody>
</table>

**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**

<table>
<thead>
<tr>
<th>Company/Part Number</th>
<th>Cost Per Lens (including mounts)</th>
<th>Amount Needed</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Lens</td>
<td>Edmund Optics #54567</td>
<td>$525.00</td>
<td>1</td>
</tr>
<tr>
<td>Relay/Field Lenses</td>
<td>Edmund Optics #70163</td>
<td>$1,095.00</td>
<td>8</td>
</tr>
<tr>
<td>Eyepiece</td>
<td>Edmund Optics #47740</td>
<td>$130.00</td>
<td>1</td>
</tr>
<tr>
<td><strong>TOTAL COST</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

**Cost of Custom System**

<table>
<thead>
<tr>
<th>Company/Part Number</th>
<th>Cost Per Lens (including mounts)</th>
<th>Amount Needed</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Lens</td>
<td>Optimax Custom Doublet</td>
<td>$3,200.00</td>
<td>1</td>
</tr>
<tr>
<td>Relay/Field Lenses</td>
<td>Edmund Optics #70163</td>
<td>$1,095.00</td>
<td>8</td>
</tr>
<tr>
<td>Eyepiece</td>
<td>Optimax Custom Doublet</td>
<td>$1,590.00</td>
<td>1</td>
</tr>
<tr>
<td>Optimax Additional Charges</td>
<td>N/A</td>
<td>$3,300.00</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>TOTAL COST</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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]

<table>
<thead>
<tr>
<th>Height of Periscope (ft)</th>
<th>Mirror Diameter (ft)</th>
<th>FFOV (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>8</td>
<td>6.541</td>
</tr>
<tr>
<td>70</td>
<td>6</td>
<td>4.908</td>
</tr>
<tr>
<td>70</td>
<td>4</td>
<td>3.273</td>
</tr>
</tbody>
</table>
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.

Two Mirror System in Code V
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.

<table>
<thead>
<tr>
<th>Toroid Radius (mm)</th>
<th>Field of View (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>0.185</td>
</tr>
<tr>
<td>3000</td>
<td>0.309</td>
</tr>
<tr>
<td>2000</td>
<td>0.468</td>
</tr>
<tr>
<td>1000</td>
<td>0.996</td>
</tr>
</tbody>
</table>

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.

“Sky Mirror”

“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.

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.

<table>
<thead>
<tr>
<th>Company</th>
<th>Mirror Type</th>
<th>Dimensions</th>
<th>Cost</th>
<th>SKU</th>
</tr>
</thead>
<tbody>
<tr>
<td>McMaster-Carr</td>
<td>Polycarbonate</td>
<td>36&quot;x24&quot;</td>
<td>$136.79</td>
<td>2912K26</td>
</tr>
<tr>
<td>McMaster-Carr</td>
<td>Polycarbonate</td>
<td>48&quot;x36&quot;</td>
<td>$266.59</td>
<td>2912K25</td>
</tr>
<tr>
<td>McMaster-Carr</td>
<td>Acrylic</td>
<td>36&quot;x24&quot;</td>
<td>$55.75</td>
<td>3052K15</td>
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<tr>
<td>Home Depot</td>
<td>Acrylic</td>
<td>48&quot;x36&quot;</td>
<td>$83.99</td>
<td>AM3648S</td>
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<tr>
<td>McMaster-Carr</td>
<td>Acrylic</td>
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<td>$123.75</td>
<td>3052K14</td>
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<tr>
<td>McMaster-Carr</td>
<td>Frameless Glass</td>
<td>36&quot;x24&quot;</td>
<td>$79.38</td>
<td>2875K22</td>
</tr>
<tr>
<td>McMaster-Carr</td>
<td>Stainless Steel</td>
<td>60&quot;x24&quot;</td>
<td>$252.18</td>
<td>2989K51</td>
</tr>
</tbody>
</table>

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.
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.

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

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.

<table>
<thead>
<tr>
<th>Number of Telescopes</th>
<th>Range of Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$191.49 - $2,133.13</td>
</tr>
<tr>
<td>2</td>
<td>$271.48 - $3,733.08</td>
</tr>
<tr>
<td>3</td>
<td>$351.47 - $5,333.03</td>
</tr>
</tbody>
</table>

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.

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

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.

Appendices

Appendix A: Optimax Custom Order
Optimax is pleased to quote the following:

**ROM**

<table>
<thead>
<tr>
<th>PR/Description</th>
<th>Lot Charge</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRE/Int Up Charge</td>
<td>$300.00</td>
<td></td>
<td></td>
<td>$300.00</td>
</tr>
<tr>
<td>Vis BBAR Ra avg &lt; 0.4µm 0.4-0.7µm</td>
<td>$3,000.00</td>
<td></td>
<td>$3,000.00</td>
<td></td>
</tr>
<tr>
<td>Enhanced GQA Package</td>
<td>Included</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doublet #1</td>
<td>1</td>
<td></td>
<td>$3,200.00</td>
<td>$3,200.00</td>
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<tr>
<td>Doublet #2</td>
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<td></td>
<td>$1,590.00</td>
<td>$1,590.00</td>
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<tr>
<td><strong>Total - Standard Shipment 10-12 weeks ARO</strong></td>
<td></td>
<td></td>
<td></td>
<td>$8,090.00</td>
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</tbody>
</table>

**Optimax Precision Tolerances:**

<table>
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<tr>
<th>PR/Description</th>
<th>Lot Charge</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRE/Int Up Charge</td>
<td>$300.00</td>
<td></td>
<td></td>
<td>$300.00</td>
</tr>
<tr>
<td>Vis BBAR Ra avg &lt; 0.4µm 0.4-0.7µm</td>
<td>$3,000.00</td>
<td></td>
<td>$3,000.00</td>
<td></td>
</tr>
<tr>
<td>Enhanced GQA Package</td>
<td>Included</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Doublet #1</td>
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<td></td>
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<td>$4,100.00</td>
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<tr>
<td>Doublet #2</td>
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<td><strong>Total - Standard Shipment 10-12 weeks ARO</strong></td>
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<td>$15,740.00</td>
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</tbody>
</table>

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

<table>
<thead>
<tr>
<th>NO.</th>
<th>RADIUS</th>
<th>RADIUS TOL</th>
<th>FRINGES</th>
<th>THICKNESS</th>
<th>INDEX V-NO</th>
<th>INHOMO-GENEITY</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>846.25000</td>
<td>0.02500</td>
<td>0.0250</td>
<td>0.8</td>
<td>0.00100 0.80</td>
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<td>0.02500</td>
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<td>0.00100 0.80</td>
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<td>0.10000</td>
<td>0.02500</td>
<td>0.0250</td>
<td>0.8</td>
<td>0.00100 0.80</td>
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<tr>
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<td>0.02500</td>
<td>0.0250</td>
<td>0.8</td>
<td>0.00100 0.80</td>
</tr>
<tr>
<td>6</td>
<td>0.0250</td>
<td>15.42000</td>
<td>0.02500</td>
<td>0.0250</td>
<td>0.8</td>
<td>0.00100 0.80</td>
</tr>
<tr>
<td>7</td>
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<td>10.92000</td>
<td>0.02500</td>
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<td>0.00100 0.80</td>
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<td>0.02500</td>
<td>0.0250</td>
<td>0.8</td>
<td>0.00100 0.80</td>
</tr>
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<td>0.02500</td>
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<td>0.02500</td>
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<td>0.8</td>
<td>0.00100 0.80</td>
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<td>13</td>
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<td>3775.00000</td>
<td>0.02500</td>
<td>0.0250</td>
<td>0.8</td>
<td>0.00100 0.80</td>
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<tr>
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<td>0.8</td>
<td>0.00100 0.80</td>
</tr>
<tr>
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<td>0.8</td>
<td>0.00100 0.80</td>
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<td>0.00100 0.80</td>
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<td>0.02500</td>
<td>0.0250</td>
<td>0.8</td>
<td>0.00100 0.80</td>
</tr>
</tbody>
</table>

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.
This table displays every tolerance used for every surface/element.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>FRONT</th>
<th>BACK</th>
<th>ELEMENT WEDGE</th>
<th>ELEMENT TILT</th>
<th>EL. DEC/ROLL(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>128mm Dia. x 1900.2mm FL - Custom</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOLERANCES</td>
<td></td>
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<td>21-Apr-17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Radius, tilt, roll and wedge are measured perpendicular to the optical axis in mm.

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

Radii are given in units of mm.

For wedge and tilt, TIR is a single indicator measurement taken at the smallest 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.

For wedge and tilt, TIR is a single indicator measurement taken at the smallest 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.

**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.
### 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.

<table>
<thead>
<tr>
<th>SUR</th>
<th>RADIUS</th>
<th>TOL</th>
<th>POW/IRR</th>
<th>THICKNESS</th>
<th>TOL</th>
<th>GLASS</th>
<th>TOL</th>
<th>(%)</th>
<th>GENEITY</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

For wedge and tilt, TIR is a single indicator measurement taken at the smallest 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.

### Radii are given in units of mm.

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.

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.
## Up.Periscope Design Description Document

### 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.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>FRONT RADIUS</th>
<th>BACK RADIUS</th>
<th>ELEMENT WEDGE TIR</th>
<th>ELEMENT TILT TIR</th>
<th>EL. DEC/ROLL(R) TIR</th>
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### 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.
Table 3: 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.

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<th>RADIUS ELEMENT WEDGE</th>
<th>TIR ARC MIN</th>
<th>ELEMENT TILT</th>
<th>TIR ARC MIN</th>
<th>EL. DEC/ROLL(R)</th>
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</table>

Radial tolerances, thickness tolerance and thickness tolerance are given in mm.

Figure 32: 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.
Appendix C: Previous Designs

Initial Relay System Configuration and Performance

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

![MTF performance of 7 lens relay.](image)

**Figure 33:** MTF performance of 7 lens relay.

![Transverse ray plots for 7 lens relay.](image)

**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
GAL  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