Optical Design Description

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FEASIBILITY AND TRADE STUDIES

- **Coronal Magnetometry: A Feasibility Study** (P. Judge, R. Casini, S. Tomczyk, D. Edwards and E. Francis, NCAR/TN-446, 2001)
- **Measurement Errors for Coronal Magnetic Field Parameters** (S. Tomczyk, TN1, 2013) (We need to clean up folder containing this document, it’s confusing)
- **A Finite Element Analysis of Meter-Class Refracting Primary Objectives for Coronal Polarimetry** (P. Nelson, TN2, 2006)
- **Polarization in reflecting and refracting coronagraphs** (D. Elmore, TN3, 2006)
- **An Analysis of Scattered Light in Reflecting and Refracting Primary Objectives for Coronagraphs** (P. Nelson, TN4, 2006)
- **Trade Study Summary for Reflecting vs. Refracting Primary Objectives for the COSMO Large Coronagraph** (P. Nelson, D. Elmore and S. Tomczyk, TN5, 2006)
- **Some Considerations for a High Etendue Birefringent Filter** (S. Tomczyk, TN6, 2006)
- **Scattered Light from Internal Reflection in a Coronagraph Objective Lens** (S. Tomczyk, TN7, 2006)
- **A Thermal Analysis of a 1.5m f/5 Fused Silica Primary Lens For Solar Telescopes** (P. Nelson, TN13, 2007)
- **The feasibility of large refracting telescopes for solar coronal research** (P. Nelson, S. Tomczyk, D. Elmore and D. Kolinski, SPIE, 2008)
- **Chromatic Aberration in a Singlet Coronagraph Objective Lens** (S. Tomczyk, TN14, 2010)
- **Requirements for Crystals for Birefringent Filters** (S. Tomczyk, TN22, not completed)

ZEMAX DOCUMENTS

- Zemax File for Calculating nominal COSMO wavefront residual
  - COSMO-2014-10-8-Final.ZMX
1 INTRODUCTION

The COSMO LC optical design is a Lyot coronagraph that will operate from 530 to 1100 nm. The design was developed by Zhen Wu (NIAOT) and Dennis Gallagher (HAO). The 1.5 meter (O1) objective lens is F/5 with a 7.5 meter effective focal length (EFL) (@656 nm). There are more lenses in the COSMO Large Coronagraph design because the design is faster than most coronagraphs which are typically >F10. The effective focal length of the O1 changes from 7.43 meters at 530 nm to 7.62 meters due to dispersion of the O1 glass. This requires that the optical design use a variable size occulter so the Solar image is blocked by a 5% oversized occulter at any wavelength. The optical design uses a unique set of three optic groups that move relative to each other as the wavelength of the observation is changed which maintains an ~80% ensquared energy in a 15X15 µm pixel from 530-1100 nm. The final focus is of the COSMO LC is ~3.5 meters EFL with an F/ratio of F/2.3. This allows the COSMO LC to view a 1 degree full field with a 15 µm 4KX4K sensor. At the heart of the COSMO LC analysis optics are two Lyot birefringent filters (~0.1-.5 nm FWHM). The filters will use Lithium Niobate for the birefringent medium because of the large etendue that the high index (n=2.2) Lithium Niobate offers. A detailed description of how the COSMO LC performs polarization analysis and calibration are discussed in a later section of this PDR. A description of the COSMO LC optical follows.

1.1 OPTICAL SYSTEM LAYOUT

The overall layout of the COSMO optical system is shown in Figure 1, and a closer detailed view of the aft optics section is shown in Figure 2. The COSMO design will operate from 530-1083 nm. The O1 lens is F/5 and is a super polished singlet uncoated lens (Corning C79-80) to reduce stray light. After the O1 is the occulter and six lenses (lenses #1-#6: Figure 2) which form an image of the O1 at the Lyot stop. The image of the O1 needs to be of sufficient quality so that the bright diffraction ring, caused by the O1 aperture and the occulter + lenses #1 #2 (see Figure 4) aperture, can be blocked to further reduce stray light. Following the Lyot stop are another set of lenses (lenses #7-#11: Figure 2) that form the final image of the sun. Light from these lenses passes through another set of non-powered optics used to analyze the wavelength and polarization nature of the light from the corona for diagnostics of coronal plasma. The first non-powered optic is the band pass filter which will isolate a narrow band of light centered on a coronal line (~1 nm FWHM). The next non-powered optic is the modulator which is a multiple set of wave plates used to modulate the Stokes parameters (I,Q,U,V) of the incoming light. This optic is followed by a polarizing beam splitter that will reflect and transmit orthogonal polarizations to each of the two Lyot filters. This setup allows for simultaneous observations of the sun in the orthogonal polarization states. Detailed discussion of the operation of the modulator, polarizing beam splitter, and Lyot filters are not presented here and these optics will be treated as plane parallel glass windows (with wedge, figure, and de-space errors) when optical design and tolerances of the COSMO design are discussed.
Figure 1 Overview of the COSMO optical layout. The instrument will have a total track of ~9.4 meters. The instrument is dominated by the large 1.5 meter O1 lens.
Figure 2 Detail view of the oculter, AFT optics, and Lyot filters
1.1.1 Optical Compensators

The COSMO achieves its wide wavelength range of operation through optical compensation. There are three optical compensators in the COSMO design where optical compensation, repositioning of optic groups, are used to broaden the useful wavelength coverage of COSMO. The compensators are the distance between the O1 and the occulter, the distance between lens#6 and the Lyot stop, and the distance of between the final focus and the Lyot filter. These changes in spacing are additive in the sense that any change in spacing between the O1 and the occulter requires that the occulter and all the optics aft of the occulter move relative to the O1. Then on top of that motion the Lyot stop and all optics aft of the Lyot stop must move position relative to lens #6. Then finally the sensor changes focus position relative to the Lyot filter. This can be achieved by putting the all the optics, post of the occulter, on a stacked three stage system. Figure 3 shows this schematically. Note there are no optic change outs to configure the COSMO to work from 530-1083nm. This optical spacing compensation operation is very similar to how a zoom lens moves optics in groups to control magnification of a final image.

To configure COSMO to a different observation wavelength the O1 to occulter distance is adjusted, the Lyot stop focus (O1 focus) is adjusted, and the final focus on the sensor is adjusted. So there are two optics groups and the sensor that move to focus an image of the sun on the occulter, an image of the O1 on the Lyot stop, and an image of the sun on the sensor at any wavelength of observation between 530-1083nm. Between the shortest wavelength 530nm and the longest wavelength 1083nm there is ~180mm of axial chromatic aberration from the O1 to image the sun on the occulter. The distance between the O1 and the occulter must be adjusted by this amount (180mm) to focus the sun on the occulter for wavelengths 530nm and 1083nm. The required motion shift for the Lyot focus adjustment is much less than the O1 to occulter focus shift and is on order ~15mm for the 530-1083nm wave length range. Lastly the spacing from the Lyot filter to the sensor changes focus. This range of motion is yet still smaller than the Lyot stop focus change and is on order ~3.5mm for the 530-1083nm wave length range. Table 1 shows the nominal spacing for the three compensators for the three configuration design wavelengths 530nm, 656nm, and 1083nm.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>530nm</th>
<th>656nm</th>
<th>1083nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1 to occulter (sun focus)</td>
<td>7338.9mm</td>
<td>7410.82mm</td>
<td>7527.00mm</td>
</tr>
<tr>
<td>Lens #6 to Lyot stop (O1 focus)</td>
<td>30.791mm</td>
<td>37.642mm</td>
<td>45.930mm</td>
</tr>
<tr>
<td>Lyot filter window to Final sun focus</td>
<td>48.452mm</td>
<td>44.903mm</td>
<td>44.917mm</td>
</tr>
</tbody>
</table>

Table 1 List of compensator spacing’s use to operate COSMO

Note: The occulter must change diameter to properly block the solar image due to changes in the effective focal length of the O1 between 530-1083nm (68.3-70.1mm diameter).
Figure 3 Concept of moving the optics to configure COSMO to operate from 530-1083nm. Only the straight through beam is shown through the PBS. The bottom stage will have a range of motion of ~180mm, the middle stage a range of motion of ~15mm, and the top stage.
2 OPTICAL DESIGN PERFORMANCE

2.1 STRAY LIGHT DESIGN
There are other aspects in the design of a Lyot coronagraph to reduce stray light than only having a super polished O1 objective lens. Image quality at the occulter and the Lyot stop can impact stray light in the final image of a coronagraph.

2.1.1 Stray light design at the Occulter
To summarize, the COSMO LC instrument forms an image of the sun at the occulter followed by an image of the O1 at the Lyot stop (system pupil) and then a final image of the sun is formed at the sensor. The COSMO optical design was derived in Zemax using three design configurations with three wavelengths that span the COSMO LC operating wavelength range. These wavelengths are 530nm, 656nm, and 1083nm. Each configuration’s wavelength was given a band pass range to account for the intrinsic spectral line widths of the solar coronal lines. Specifically each configuration has a center wavelength and two other wavelengths that are plus and minus the center wavelength. The three wavelengths for each configuration are 530±0.3nm, 656±0.4nm, and 1083±0.6nm for a total of nine wavelengths for all configurations. This requirement was set so the COSMO instrument did not have to adjust the compensator spacings (described in section 1.1.1) during a wavelength scan through a coronal line via tuning of the Lyot filter. Figure 4 shows the performance of the COSMO design at field angles from 0.27, 0.35, 0.45, and 0.5 degrees using the wavelength pass bands as described above for each configuration. The spot diagrams in Figure 4 show the imaging quality of the COSMO design at the occulter. Note 0.27 degrees represents the angle to the limb of the sun.

Figure 4 COSMO spot diagrams at the occulter for configurations with center wavelengths 530, 656, and 1083nm. Field points 0.27, 0.35, 0.45, and 0.5 degrees are shown. Only the 0.27 field point is critical to the discussion on stray light and occulter size. [Blue=530nm, Green=656nm, Red=1083nm]
The focus of the solar limb at the occulter is important in terms of stray light reduction. Any light from the solar disk that spills past the occulter will increase stray light into the image of the corona. For COSMO the occulter size requirement is that it is 5% oversized to the solar disk image or 50 arcseconds. Let’s assume for example the COSMO has an exact 7500mm EFL. This means the image of the solar disk at the focus from the O1, located at the occulter, will have a radius of 34.906mm (using solar radius of 0.26667 degrees). A 5% oversized occulter means the edge of the occulter will fall 1.745mm beyond the image of the solar limb. If any light from the solar disk image falls beyond 1.745mm then this light will spill over the occulter and increase stray light into the image of the corona. The requirement for disk light spilling past the occulter is very tight because the overall stray light budget for COSMO LC is on order 5 millionths of the solar disk. This means that the performance of COSMO LC for a point source ~0.27 off-axis must have ~>99.9995% of its energy inside a 1.745mm radius (Note the exact calculation requires convolving a COSMO LC PSF with a solar disk which show the light fall of is less steep the just for a singles PSF). To achieve the required image quality at the solar limb requires that the COSMO LC O1 lens have at least one aspheric surface. A COSMO O1 without the aspheric term would have a spot size ~6mm in diameter or 2.75 arcminutes across. Figure 5 through Figure 7 show normalized PSF plots at 0.27 degrees (solar limb) for COSMO at the occulter for the three configurations using wavelengths as describe above. One can see from Figure 5 thru Figure 7 that the PSF falls below 1e-5 of its peak well inside the 1.745mm requirement. Note the half width of the extended wings of the PSF need to meet the requirement of <1.745mm since half the PSF goes towards the sun and the other half towards the occulter edge. This shows the design of the COSMO O1 will have sufficient image quality (small extended image wings) for imaging the corona down to 50 arcseconds from the solar limb.

Out of band light that passes the occulter will need to be blocked by the band pass filter which will have a high out of band light rejection (~>1e5).
Figure 5 529.7-530.3nm PSF at Occulter 0.27 degree off axis (solar limb)
Figure 6 655.6-656.4nm PSF at Occulter 0.27 degree off axis (solar limb)
2.1.2 Stray light design at the Lyot stop

Another critical area for stray light is the imaging of the O1 at the Lyot stop. While not as critical as the imaging of the sun from the O1 at the occulter the image at the Lyot stop needs to be of sufficient quality so as not to pass light from the bright diffraction ring at the edge of the image of the O1. Figure 8 shows a ray trace of COSMO in the configuration where point sources at the edge of the O1 are imaged to a point sources at the Lyot stop. At the Lyot stop is an image of the O1. This image has some unique features. It is formed by of course diffraction from the O1 aperture and then diffraction from the field lens aperture which has its aperture obscured by the field occulter. The image of the O1 is surround be a bright diffraction ring follow by a central bright spot due to multiple reflections from the O1 and a central diffraction peak due to diffraction from the field lens occulter aperture. The size of the Lyot stop was determined from diffraction theory to be a size that is 85% of the size of the image of the O1. This has heritage with our other HAO instruments (e.g. K-Coronagraph). Looking at the size of the image of the O1 for the three configuration its size is smallest when COSMO is configured for 1083nm where the O1 image size is \( R_{O1\,\text{image}} = 58.3 \text{mm} \). It is desirable to have 99% of the energy from an image of a spot at the edge of the O1 to fall inside a radius \((1-85\%) \times 58.3 \text{mm} = 8.75 \text{ mm}\) to avoid having diffracted light from the O1 field lens apertures from passing the Lyot stop onto the focal plane. Figure 9 shows spot diagrams from a point source at the edge of the O1 and how it is imaged for the three configurations at 530, 656, and 1080nm at the Lyot stop. Clearly the image of the O1 at the Lyot stop exceeds imaging requirements in the COSMO LC design (~100µm spot size geometric is \(<8.75\text{mm}, \text{see Figure 9}\)). The Lyot stop for the COSMO LC will be a variable aperture that will always be 85% of the size of the image of the O1.

Figure 7 1082.4-1083.6nm PSF at Occulter 0.27 degree off axis (solar limb)
Figure 8 Raytrace showing the edge of the O1 images at the Lyot Stop.

Figure 9 Spot diagrams for a point source at the edge of the O1 imaged at the Lyot stop. Wavelength pass bands are those as describe above for spot diagrams at the occulter. [Blue=530nm, Green=656nm, Red=1083nm]
2.2 Final Focus

Spot diagrams of the final image at the focal plane are shown in Figure 10. These were derived for the band pass and field angles for the spot diagrams at the occulter in Figure 4 (0.27, 0.35, 0.45, and 0.5 degrees off-axis). The diffraction disk is also shown in the plots.

![Matrix Spot Diagram](image)

Figure 10 COSMO spot diagrams at the focal plane for each configuration at center wavelengths of 530, 656, and 1083nm. Field points 0.27, 0.35, 0.45, and 0.5 degrees off-axis are shown. The plot scale in upper left is 30µm. [Blue=530nm, Green=656nm, Red=1083nm]

The imaging requirement for COSMO at the final focus is 84% of the energy from a point source fall inside a 2X2 arc-seconds split between seeing and optics. The COSMO sensor will have 15µm pixels (~0.9 arc-seconds per pixel), so a 2X2 arc-second region is 33X33 µm region at the COSMO focal plane (assuming an EFL ~3.5meters). This requirement is for when COSMO is imaging in its full pass band as described in section 2.1.1. Even though COSMO will operate in a monochromatic mode for each image during a scan through a coronal line, the plan is not to implement optical compensation, as described in section 1.1.1. So this requires that the imaging requirement for COSMO be placed across a pass band and not a single monochromatic wavelength. This was optically a very difficult requirement to meet while maintaining optical performance over the large 530-1083nm range. Figure 11 through Figure 13 show plots of the diffraction ensquared energy for the nominal COSMO design using the band pass and wavelengths of each configuration (Section 2.1.1 ). It is clear the nominal COSMO design meets the design goal of >=84% energy in a 2X2 arc-second (33X33 µm) region for all wavelengths. Another point to make is the through field image quality of COSMO design is very uniform clear out to 0.5 degrees off-axis.
Figure 11 COSMO Ensquared energy at 530±0.3nm. Note the X axis is in image radius.

Figure 12 COSMO Ensquared energy at 656±0.4nm
Figure 13 COSMO ensquared energy at 1083±0.6nm

Figure 14 shows plots of the Modulation Transfer Function (MTF) through field at the final COSMO focus for the configuration @ 656nm. The next plot shows optical distortion. The COSMO design has an very uniform response through field with minimal optical distortion.
Figure 14 Optical MTF of COSMO at the final focus for 15µm pixels (lower curve 33 cycles/mm) and 2X2 and 3X3 pixels (upper curves 16.7 and 8.3 cycles/mm). The response of COSMO through field is very uniform. Only the 656nm configuration is shown here, the field response at other wave length is equally uniform. The full pass band (see section 2.1.1) was used for this analysis.
2.2.1 Final focus monochromatic performance

Not all observations with COSMO are going to involve lines scan through coronal lines. Some observation will be done at single wavelengths. The performance of COSMO at a single wavelength far exceeds the performance in a pass band as described in the prior section. Figure 16 shows spot diagrams using only the central wavelength of each configuration. In this configuration COSMO is near diffraction limited allowing for very high resolution image of the solar coronal or prominences. The diffraction limit of the 1.5 meter aperture COSMO is close to 0.1 arcseconds. This is beyond most ground base seeing conditions. At a single wavelength the performance of COSMO will be nearly limited by the local seeing conditions of the atmosphere.

Figure 15 Optical distortion at the final focus of COSMO. Distortion is less than 0.1% out to 0.5 degree off-axis for all wave lengths (656nm is shown). This will simplify data analysis when determining shock speeds of coronal mass ejection features.
2.2.2 Final focus performance through wavelength coverage 530-1083nm

One issue to check is the COSMO performance at wavelengths other than the three design wavelengths (pass bands) used in the three configurations discussed above. Figure 17 shows the RMS spot sizes at the occulter, Lyot Stop, and the final focus as the COSMO is adjusted to continuously from 530-1083nm. One can see the COSMO design performs smoothly from 530-1083nm and there are no areas that experience a significant degradation in performance relative to other wavelengths at the final focus. It is not surprising that the focus of the O1 at the occulter is a smooth with no inflections since this curve only involves the dispersion of the single element of Corning C79-80 glass. COSMO will operate uniformly at any wavelength between 530-1083nm.
Figure 17  COSMO RMS spot size as a function of wavelength at a field angle of 0.27 degrees (~limb of sun). This plot was generated while applying compensation motion to the compensators in the COSMO design. The final focus was designed to have the smallest RMS spot size since this is the final image of the corona.
3 PREDICTED AS-BUILT PERFORMANCE

3.1 OPTICAL FABRICATION TOLERANCES

All the COSMO optics aft of the occulter are designed using only spherical or flat surfaces and all optics use Ohara or Schott glass. One exception is the O1 which is made from Corning C79-80 quartz material and its S1 front surface is aspheric. The surface polish of the O1 needs to be a super polish to reduce scattered light. This requirement is discussed in the Stray light section of this PDR document. Computer controlled polishing techniques have improved greatly in recent years and accurate surface roughness measurements are routine now, so making the O1 should not be any riskier than any other 1.5 meter lens. All the Schott and Ohara glass blanks and the O1 Corning blank required for the COSMO LC are available from the vendors. Table 2, through 4 shows the design parameters and tolerances of the COSMO LC optical design.

The optical tolerances for the COSMO optical design were first chosen by trading manufacturing costs with tolerance values. The bases for the optical tolerances were derived for image quality. The idea is to first choose loose tolerances that can be achieved for reasonable cost and then tighten only those that are not allowing COSMO to meet its imaging requirements. For example, the spherical surfaces of the lenses #1 through #11 have been chosen to be \( \lambda/8 \) peak-to-valley; a standard optical tolerance that can be achieved for average costs. The cost savings to reduce the figure requirement for these surfaces to \( \lambda/2 \) wave peak-to-valley would be minimal and the cost increase to make these surfaces \( \lambda/20 \) would be very large. If a surface requires better than \( \lambda/8 \) peak-to-valley then the surface would have its tolerances tightened. For COSMO no optical surface was required to be better than \( \lambda/8 \) peak-to-valley. The O1 has \( \lambda/4 \) peak-to-valley surfaces to keep costs down since \( \lambda/8 \) peak-to-valley on a large 1.5 meter optic would be very expensive. This approach produces the lowest cost optical design that meets COSMO imaging requirements. This same general philosophy was applied to optical radii, wedge, and thickness tolerances. All radii were started at the 1% tolerance level, but as can be seen in Table 2 (the manufacturing tolerances) many radii are approaching the 0.1% tolerance level because the COSMO imaging requirements required these tolerances to be tighter.

Table 3 shows the optical alignment requirements for the individual optics. Table 4 shows tolerances that describe how optic groups can move and tilt relative to each other. These tolerances are applicable to the design of the large structure that will hold the COSMO optics. For example the group of optics around the Lyot stop have very tight (~25\( \mu \)m) decenter tolerances relative to each other, but looking at Table 4 one can see if these optics move or tilt as a group while holding their relative (~25\( \mu \)m) decenter the group of optics can move and tilt more as a whole entity. Lens #3 through Lens #11 are treated as a group and have much larger tolerance values when moved together. Note the compensator for Lyot stop focus, where the lenses aft of the Lyot stop must move, must also hold their ~25\( \mu \)m decenter tolerance during focusing of the Lyot stop. This is not a problem where standard linear stages have linear motions accuracy on order ~<1\( \mu \)m decenter. The optics after lens #11 (beam splitter, and Lyot filters), are not sensitive to de-center error. Mechanically grouping the optics in this manner loosens the requirements on the structure holding these optic groups. This is an important point to make. There are many times where an optical model has tolerances applied with no thought to the macro motions of optic groups. Not grouping optics and looking into how they move has a group can place excessively tight and expensive requirements on the macro structure holding the optics; like the telescope tube for COSMO. Table 5 shows the list of optical compensators and their nominal values for each configuration.
## COSMO Optical Element Design Parameters with manufacturing tolerances

<table>
<thead>
<tr>
<th></th>
<th>Dia.(mm)</th>
<th>Material</th>
<th>Radius S1(mm)</th>
<th>Radius S2(mm)</th>
<th>Thic. (mm)</th>
<th>S1-S2Wedge (arcsec)</th>
<th>S1,S2 PV Fig. @633nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1 Lens</td>
<td>1550</td>
<td>Corning C79-80</td>
<td>6778.1±10</td>
<td>-24650±150</td>
<td>150.0±0.25</td>
<td>±18</td>
<td>λ/4</td>
</tr>
<tr>
<td>Lens #1</td>
<td>160</td>
<td>Schott N-K5</td>
<td>-1243.2±12</td>
<td>390.84±3.0</td>
<td>15.0±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #2</td>
<td>170</td>
<td>Schott N-BASF64</td>
<td>447.84±4.0</td>
<td>-979.11±9.0</td>
<td>20.00±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #3</td>
<td>280</td>
<td>Ohara S-PHM52</td>
<td>564.39±2.0</td>
<td>flat</td>
<td>32.0±0.50</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #4</td>
<td>210</td>
<td>Ohara S-BSM14</td>
<td>494.65±2.0</td>
<td>-1261.5±10</td>
<td>27.0±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #5</td>
<td>200</td>
<td>Ohara S-BSM14</td>
<td>171.87±0.15</td>
<td>462.82±2.0</td>
<td>30.00±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #6</td>
<td>150</td>
<td>Ohara S-TIM22</td>
<td>2130.2±15</td>
<td>118.87±0.10</td>
<td>24.00±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #7</td>
<td>110</td>
<td>Ohara S-TIH11</td>
<td>-142.85±0.20</td>
<td>-703.41±2.0</td>
<td>10.00±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #8</td>
<td>130</td>
<td>Schott N-SF66</td>
<td>-125.400±0.50</td>
<td>-576.70±0.50</td>
<td>16.00±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #9</td>
<td>160</td>
<td>Ohara S-LAH51</td>
<td>-363.61±0.5</td>
<td>-146.73±0.10</td>
<td>25.00±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #10</td>
<td>165</td>
<td>Ohara S-LAH53</td>
<td>flat</td>
<td>-212.08±0.1</td>
<td>25.00±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>Lens #11</td>
<td>180</td>
<td>Ohara S-LAL7</td>
<td>393.26±1.0</td>
<td>-966.89±3.0</td>
<td>33.00±0.05</td>
<td>±18</td>
<td>λ/8</td>
</tr>
<tr>
<td>BandPass filter</td>
<td>170</td>
<td>Fused Silica+various</td>
<td>flat</td>
<td>flat</td>
<td>10.00±0.10</td>
<td>±72</td>
<td>λ/4</td>
</tr>
<tr>
<td>Modulator</td>
<td>170</td>
<td>Fused Silica+various</td>
<td>flat</td>
<td>flat</td>
<td>30.00±0.50</td>
<td>±72</td>
<td>λ/4</td>
</tr>
<tr>
<td>Beam splitter</td>
<td>140X140sq</td>
<td>Schott SF1</td>
<td>flat</td>
<td>flat</td>
<td>70.00±0.25</td>
<td>±101</td>
<td>λ/4</td>
</tr>
<tr>
<td>Lyot Filter</td>
<td>100</td>
<td>LiNbO3+various</td>
<td>flat</td>
<td>flat</td>
<td>33.00±0.50</td>
<td>±72</td>
<td>λ/2</td>
</tr>
</tbody>
</table>

*Lyot filter includes various materials such as the retarder material, linear variable retarders (liquid crystals), polarizers, and fused silica.*

*All index and Abbe tolerances are 1% except the SF1 beam splitter which has a 0.1% Abbe tolerance. This will require melt data form the glass vendor or determined through other tests.

---

## COSMO Optical-Mechanical Design- Position and Tip/Tilt Parameters

<table>
<thead>
<tr>
<th></th>
<th>Decenter(mm)</th>
<th>Tilt (arcsec)</th>
<th>Next surface spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1 Lens</td>
<td>±1</td>
<td>±72</td>
<td>O1 to occulter compensated</td>
</tr>
<tr>
<td>occulter edge</td>
<td>n/a</td>
<td>n/a</td>
<td>95.000±0.25</td>
</tr>
<tr>
<td>Lens #1</td>
<td>±0.1</td>
<td>±30</td>
<td>2.000±0.05</td>
</tr>
<tr>
<td>Lens #2</td>
<td>±0.1</td>
<td>±30</td>
<td>795.58±1.0</td>
</tr>
<tr>
<td>Lens #3</td>
<td>±0.125</td>
<td>±72</td>
<td>334.28±1.0</td>
</tr>
<tr>
<td>Lens #4</td>
<td>±0.05</td>
<td>±15</td>
<td>2.000±0.10</td>
</tr>
<tr>
<td>Lens #5</td>
<td>±0.05</td>
<td>±15</td>
<td>42.249±0.10</td>
</tr>
<tr>
<td>Lens #6</td>
<td>±0.025</td>
<td>±15</td>
<td>Lens#6 to lyot stop compensated</td>
</tr>
<tr>
<td>Group Error</td>
<td>Decenter</td>
<td>Tilt</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>----------</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td>Lens #1 and Lens #2</td>
<td>±0.1 mm</td>
<td>±36 arc-seconds (about lens#1)</td>
<td></td>
</tr>
<tr>
<td>Lens #3 through Lens #11</td>
<td>±0.5mm</td>
<td>±72 arc-seconds (about lens#3)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 Macro Tolerances. These are large motions of tip/tilt and de-center of the AFT optics grouped as a single entity. These numbers are useful for determining large structural rigidity requirements for the COSMO instrument. The occultor is the datum reference.

### 3.2 TOLERANCE ANALYSIS

From the prior sections it is clear that the COSMO design meets all its imaging requirements. It is important to determine how well the COSMO design will meet its imaging goals when fabrication and assembly errors are included. There is no such thing as a “perfect” built design; all “as built” instruments have errors. The COSMO optical tolerances given in Table 2 in section 3.1 were used to derive optical performance. The COSMO tolerances analysis was performed using Zemax optical software.

#### 3.2.1 Setup

The following values were set in Zemax and a RMS wavefront analysis was performed for each configuration:

1. Sampling of 4
2. Field of view angles (0.27, 0.35, 0.45, 0.50)
3. Wavelength based on configuration (530±0.3, 656±0.4, and 1083±0.6 nm)
4. Compensators: Optimize All (DLS)
5. Monte Carlo 200 runs for the full instrument.

#### 3.2.2 Compensators

When performing tolerance analysis the compensators described in Table 5 were allowed to vary during optimization. In other words the numbers for the spacing’s of the optics given by Table 2 were allowed to have slight variations to account for the variations in the COSMO optics for each tolerance run. This can be thought of as allowing the design compensators to better compensate for the “as built design” during optimization. Table 1 contains the base value of the compensator and the tolerance analysis will derive
the expected variation about that number when optical tolerances are included. Table 1 is shown again as Table 5 below with the expected variations to the compensator due to optical tolerances.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>530nm</th>
<th>656nm</th>
<th>1083nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1 to occulter (sun focus)</td>
<td>7338.9±18.4 mm</td>
<td>7410.82±19.32 mm</td>
<td>7527.00±18.44 mm</td>
</tr>
<tr>
<td>Lens #6 to Lyot stop (O1 focus)</td>
<td>30.791±3.850 mm</td>
<td>37.642±3.794 mm</td>
<td>45.930±3.850 mm</td>
</tr>
<tr>
<td>Lyot filter window to Final sun focus</td>
<td>48.452±5.963 mm</td>
<td>44.903±6.162 mm</td>
<td>44.917±5.963 mm</td>
</tr>
</tbody>
</table>

Table 5 List of compensator spacings used to operate COSMO along with variation due to optical tolerances.

To summarize the compensators are defined as the following:

1. **O1 focus position** – this will be necessary regardless to compensate for the COSMO as-built design.
2. **Lyot Stop Focus** – this will be necessary to keep a sharp in focus O1 image on the Lyot stop.
3. **Camera Focus** – this distance is normally adjustable focusing of the sensor after a wavelength change.

3.2.3 Assumptions

The COMOS optical error budget product is a sophisticated analysis that relies upon certain assumptions that the COSMO program has determined to be reasonable and prudent. These assumptions are listed below:

1) The rotational alignment along the optical axis (i.e. roll) of all lenses is not subjected to tolerancing as these optics are assumed to be roll symmetric.
2) Wedges to optical lenses were applied to only one surface of an element. Since wedge (often specified as total indicated run out) is specified on an entire element, running this tolerance on both surfaces would be double counting the error.
3) As vendors who fabricate filters typically quote a transmitted wavefront error, we only specify surface figure on one surface of the filters.
4) An assumption to a conversion between RMS surface error and PV surface error using a factor of four \( \sigma_{PV} = 4 \times \sigma_{RMS} \). Convention for this factor varies, and often depends on the nature of the surface error. Regardless, this factor of 4 is generally seen as reasonable.
5) The surface error calculations that zemax runs create a statistically random surface error based on Zernike terms. Only Zerniky terms 4-11 were utilized to improve simulation speed.
6) Our typical values for wedge on lenses are +/−18 arc-sec, which falls within standard optical fabrication capabilities (~17μm total indicated run out on a 100mm diameter optic). We believe our tolerances for these to be reasonable.

3.2.4 Zemax Calculations

Tolerance analysis using Zemax was done to predict the performance of COSMO. A Monte Carlo tolerance run was done where 200 random designs were saved for each configuration, 530, 656, and 1083nm. Tolerances for COSMO were derived over the full pass band as described in section 2.1.1. The Monte Carlo generated designs were sorted to allow inspection of any probability. One can look at the 10,20,30, and...90% designs and form a plot that shows the statistical performance prediction for COSMO. Note these performance predictions are based at doing nothing to improve/compensate the design such as adjusting single optic positions, or using “as built”
numbers for radii, thicknesses, and other aspects of the optical parameters. So these performance predictions can be considered to be conservative. Figure 18 shows the probability plot for wave front. The COSMO design has a ~80% probability of meeting a wave front of ~<300nm RMS for all wavelengths from 530-1083nm.

![COMOS wavefront error probability plot](image)

**Figure 18** Results of the statistical tolerance analysis for wave front.

The science requirement for COSMO is stated that COSMO deliver 84% ensquared energy inside a 2X2 arcsecond region or 33X33µm at the focal plane. The 200 Zemax files that were generated by the Monte Carlo process for the wave front error were mined using Python software to generate ensquared energy and then ordered in increasing ensquared energy. Figure 19 shows a probability plot of the expected ensquared energy for the COSMO design. From Figure 19 it is clear COSMO will meet its imaging requirements at the 80% confidence. For comparison an ensquared energy plot is also shown in Figure 19 for a single wave monochromatic wavelength at 656nm. For a single monochromatic wavelength operation COSMO will exceed its (84% energy inside 33X33µm) imaging requirement by a large margin exceeding 84% in a single 15µm pixel at 656nm.
3.2.5 Largest error contributors

It can also be useful to examine the most sensitive operands in a tolerance analysis, colloquially referred to as a “worst offenders” list. Table 6 details the most sensitive operands for the COSMO design. These errors are not configuration specific. The list of worst case offenders were derived for each configuration. Note all the configurations used to design COSMO use the same optics so this was deemed as the best way to treat all the worse case offenders in the COSMO optical design. Also de-center or tilt errors were automatically included for both axes since in some cases only one direction was flag due to the statistical nature of the tolerance analysis (COSMO is a symmetrical optical design). The worst offenders from all configurations were grouped in a list of 30. The errors were converted in to nanometers of wave front error. The 10 worst offenders are shown below in Table 6. Note if an error source was the same in all configurations the error was only treated as a single error and located in Table 6 in its worse error contribution level. There were no wavelengths in the COSMO design that were treated with extra weight in the tolerance analysis. COSMO was designed to work uniformly from 530-1083nm.
<table>
<thead>
<tr>
<th>Error type</th>
<th>Lens or Surface That has error</th>
<th>Tolerance Bound</th>
<th>Resultant Criterion [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>S1 Lens #8</td>
<td>±0.50 mm</td>
<td>16.86058</td>
</tr>
<tr>
<td>Radius</td>
<td>S2 Lens #6</td>
<td>±0.10 mm</td>
<td>16.32142</td>
</tr>
<tr>
<td>De-center</td>
<td>Lens #9</td>
<td>±0.025 mm</td>
<td>15.81712</td>
</tr>
<tr>
<td>De-center</td>
<td>Lens #5</td>
<td>±0.050 mm</td>
<td>15.79232</td>
</tr>
<tr>
<td>De-center</td>
<td>Lens #8</td>
<td>±0.025 mm</td>
<td>12.7807</td>
</tr>
<tr>
<td>Radius</td>
<td>S1 Lens #5</td>
<td>±0.15 mm</td>
<td>12.54833</td>
</tr>
<tr>
<td>Distance</td>
<td>Lens #8 to Lens #9</td>
<td>±0.05 mm</td>
<td>12.33178</td>
</tr>
<tr>
<td>De-center</td>
<td>Lens #10</td>
<td>±0.025 mm</td>
<td>10.88733</td>
</tr>
<tr>
<td>De-Center</td>
<td>Lens #7</td>
<td>±0.025 mm</td>
<td>9.388744</td>
</tr>
<tr>
<td>De-Center</td>
<td>Lens #3</td>
<td>±0.15 mm</td>
<td>9.364073</td>
</tr>
</tbody>
</table>

Table 6  List of worst offenders for all configurations of COSMO. S1 refers to the side of lens towards the sun and S2 refers to side away from sun.