Mechanical Design Description

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1 Overview

This document presents a preliminary design for major mechanical systems within the COSMO Large Coronagraph project. We have focused our efforts on preliminary design considerations for those systems representing areas of greatest cost and technical risk.

![Rendering of major COSMO subsystems with Mauna Kea in the background (~20 miles away across the saddle road valley)](image)

Figure 1 Rendering of major COSMO subsystems with Mauna Kea in the background (~20 miles away across the saddle road valley)

Using the WBS structure shown in Figure 2 and the model rendering in Figure 1, it is convenient to separate the COSMO mechanical design effort into five broad categories largely based on phasing and management divisions.

1. Site work and foundations
2. Observer control building and vestibule
3. 5/8th Dome and enclosure building
4. Large coronagraph telescope and mount
5. Filtergraph instrument
COSMO–DE–7100 (Mechanical Design Description)

1.1 Site and Access Overview

COSMO is being proposed for the summit of Mauna Loa and within the boundaries of the Mauna Loa Observatory operated by the National Oceanic and Atmospheric Administration as shown in Figure 3 below. A separate site analysis and selection document within the PDR Binder also considers the suitability of the summit of Haleakala for siting COSMO.

Figure 3 - Proposed construction site for COSMO is located within the blue circle. The existing facility housing K-COR is shown in the red circle. The red boxes represent existing NOAA land. Currently NOAA is undergoing an effort to swap the dashed red box for the dashed blue box. For scale, the COSMO dome is 15m in diameter.
Figure 4 Extended view of the MLO site showing the bulldozed (rough) road splitting from the paved road ~200m North of the site. The orange lines indicate the existing high voltage lines powering summit operations while the green line indicates the proposed routing a new access road for COSMO construction and subsequent operations. North is oriented upwards.

Figure 5 Photograph from the paved access road (just after the split shown in Figure 4) depicting typical topography and geological soil types found at MLO.
Figure 5 shows the wide variety of rocky ‘soil’ type found in the relatively recent lava flows at the mountains’ summit. These are described in great detail in Section 1.3 Error! Reference source not found. and range from fine lava ‘gravel’ to large clinkers, and even boulders.

1.2 Required Site Work and Infrastructure Upgrades

The addition of a new access road to the site indicated in Figure 3 will require bulldozing and grading. Similar heavy soil movement activities will be required to modify the existing lava diversion burm shown in Figure 6. The foundation of the telescope pier (mechanically and vibration separating the telescope from the surrounding building structures) will also require a fair amount of “probe and grout” work in which holes are drilled to identify voids that are then filled with concrete. The underlying basalt lava will be used to support the foundations but is extremely hard and difficult to work. Local crews experienced with pouring foundations in this environment will be essential. Furthermore, given the ~1.5 hour travel time between the nearest large city (Hilo), special consideration will be required for mixtures, transit and pouring time.

Figure 6 - 1982 USGS survey showing actual position of lava diversion burm. NOAA management has suggested siting COSMO within the red circle to avoid clean air sector and live of sight measurements. This would likely require some level of bulldozing and grading activities to re-position the lava diversion system.
1.3 Foundations and Telescope Pier

Building any structure on the summit of Mauna Loa is subject to some very unique challenges due to the nature of the 'recent' lava flows on which all structures must be built. A Geotechnical Report was commissioned by NOAA in 1994 which gives an overview of the issues (including the reclassification of the site to a Zone 4 rating by the Hawaii State Earthquake Advisory Board). The entire report has been re-printed at the end of this PDR Binder.

Given the variability revealed by four exploratory borings ranging from 24.5 to 25 feet beneath the existing ground surface and 12 probes ranging in depth from 11 to 26 feet beneath the existing ground surface it is anticipated that the COSMO Project will have to conduct similar borings in the specific proposed construction site. The main findings of the 1994 report are repeated here:

"We recommend that site grading filling be minimized, and the proposed Observatory foundations be supported on shallow foundations founded on hard, basaltic rock. We also recommend that all foundation locations be probed to check for voids and the probe holes backfilled with cemented grout. For properly probed and grouted areas, an allowable bearing pressure of 6000 pounds per square foot (psf) can be used for footings embedded at least 24 inches below adjacent finished grade and 12 inches into hard rock. Due to the site's potential exposure to very high seismic loads, we recommend that (any) steep terrain in the proposed building area be flattened to a 5H:1V slope, to reduce the potential of ground instability during future destructive earthquakes. Based on the available earthquakes and geotechnical data, slope stability analysis indicated permanent cut slopes in loose clinkers and fractured rock, and permanent fill slopes should not be steeper than 5H:1V. Alternatively, cut or fill areas can be protected by appropriately designed and properly constructed walls or grouted rip rap."

HAO has not made further geotechnical investigations beyond obtaining this report from NOAA. It is expected that a similar, though more site specific, report will be commissioned by the Project in post-PDR exercise. While constructing a seismically safe foundation is expected to be challenging, it does not represent a very high risk to the project.

The telescope pier will likely be a steel reinforced concrete structure, mechanically isolated from the surrounding dome enclosure structure and its foundation. Embedded within this structure will be various 4" conduit channels for running power, control signals and data paths. The pier is designed to put the telescope aperture at a height of 14.7 meters at zenith.
2 Observer Control Building

The COSMO observer control building will be a simple ‘pre-fab’ design similar to the existing MLSO control building shown below in Figure 7 - Figure 9. It is a simple structure, probably pre-fabricated in Hilo and transported in sections to Mauna Loa. It serves to house control computers, data servers and provide observers with a general workspace area. Additionally, it houses the observer station to control the facility. A simple slab on grade foundation with appropriate footings is sufficient. Materials will be chosen that comply with NOAA’s list of banned materials.

![Existing MLSO control building and dome enclosure. Dome is approximately 5m in diameter.](image)

![Proposed COSMO observer control building layout](image)
The vestibule area serves as the normal human access point to the observing floor and support lab from the adjacent observer control building. It will have viewing windows on both sides to allow observers to perform visual inspections of the large coronagraph without having to enter the space. It will also be slightly pressurized to ensure the air cleanliness within. Finally, it will have the necessary equipment for the cleaning and gowning of two persons, before accessing the observing floor. An air treatment unit will be used to filter this space to Class 10,000 (ISO 7).
3 Large Coronagraph Dome & Enclosure

The dome design draws from the Themis observatory on Tenerife, designed and built by the European Industrial Engineering (EIE) from Italy. This $\frac{5}{8}$'s style dome has seen widespread use by the astronomical community. The shape is designed to protect against vibrations induced by wind flows around the dome while the rotating circular aperture allows the observatory to have the minimum aperture needed for observations. This minimal aperture also allows the dome to be closed quickly in the event of weather or other necessity. This helps maintain the cleanliness of the interior space from small dust particles entrained from the outside. The dome and building will be painted with a reflective paint in the visible and high emissivity in the infrared for thermal concerns. Paint will be chosen to minimize visual impact.

Standard encoder based positioning control, slip rings for power distribution and cable drape systems will be incorporated into the COSMO Project. A ~2m diameter aperture will be sufficient for the telescope FOV while minimizing inflow of air and dust. Additionally this aperture can be closed in less than one minute in case of weather and/or safety concerns. The aperture and dome will be capable of being powered on and configured within the 30 minute setup time. The buildings and equipment within will be designed to meet requirements over the expected temperature/humidity/etc ranges.

The dome will also have a movable bridge crane for the lifting and movement of large equipment and sub-assemblies within the dome structure. The observing floor will have a video / audio feed so that the observing floor is visible from the control building.

![Figure 11 Large Coronagraph Dome - Major Elements](image-url)
3.1 Support Lab

The support lab contains all the equipment and tools required to troubleshoot, maintain and repair the COSMO facility systems. It also includes a combination of 19" racks and NEMA enclosures for powering various operations including the dome azimuth and aperture control, the telescope pointing control system, the large coronagraph, the filtergraph and the building cleanliness control (HEPA) system. There is a lift to move equipment between the support lab and observing floor.

This room has various optics benches (with vibration damping legs) for testing, as well as cleaning and storage equipment.

Figure 12 Sub-floor laboratory and maintenance space. Lift provides access to observing floor for large assemblies.
3.2 HEPA Filtered Air System

The entire volume of air above the observing floor and beneath the dome enclosure is maintained to a high degree of cleanliness using a 66,000 CFM HEPA filter bank (one half of which is) shown in Figure 14. A balance of cost and performance suggest that ISO 7 is the target cleanliness level as described in Figure 13. Note that it's the ~2,930 particles > 5 microns in diameter that present the greatest effects on scattered light performance if they adhere to the large coronagraphs' objective lens so periodic cleaning of large particles is expected to be required. This system will keep the objective lens at the CL220 level needed, particularly with periodic cleanings.

As a result, it is planned to locate all support equipment within the sub-floor support lab and leave this space clear as shown in Figure 15. Not shown is the air duct distribution network distributing clean air throughout the enclosure. HAO has considerable experience in designing and maintaining cleanroom facilities of this quality (Operational Standard for the NCAR Vacuum Tunnel Facility Cleanroom Operated by the High Altitude Observatory – G. Card 2002)
Figure 14 Flanders 33,000 CFM HEPA System (Drawing from Super-Tech, Denver, CO)
Figure 15 Observing floor is planned to remain free of equipment and other dust generating materials. This volume is positively pressurized using a bank of HEPA filters. The fans themselves will be located outside (behind) the dome enclosure building. The internal duct work within the dome is not shown and will be developed in the next design phase.
4 Large Coronagraph Telescope and Mount

An annotated rendering of the large coronagraph systems and mount are shown below. The main OTA is approximately 10m long and 1.7m in diameter.

Figure 16 Annotated depiction of the Large Coronagraph major systems
4.1 Optical Tube Assembly and Objective Lens Cell

The central component of the COSMO Large Coronagraph telescope is the Optical Tube Assembly (OTA) which is a structural element with interfaces to both the objective lens cell (on the front end) and the Filtergraph Science Instrument (on the rear end).

![Image of Optical Tube Assembly](image)

Figure 17 Optical Tube Assembly (COSMO-8721-SW-41001)

Additional details, such as access ports, windows, electrical/liquid feedthroughs, interior lighting, etc. are not shown on this simplified model. These logistics details will be inserted as the requirements are refined. Additionally a mass counterbalance system will likely be needed to maintain proper mass balancing as mechanisms are moved. This will be detailed once masses are known.

4.1.1 Finite Element Analysis of Optical Telescope Structure

This study was conducted to evaluate the feasibility of a strut-based Optical Telescope Assembly (OTA). As in all FEA work, there is a trade between the 'fidelity' of a model (how close the model is to a realistic structure) and the ability to actually mesh and calculate the model. Because of this the results should be considered preliminary.

The model developed in Figure 18 is based on a Serrurier truss to support the primary lens and instrument enclosure. A central 1.5m diameter, 7.5m long tube prevents stray light from entering the system and is supported only from the central bearing 'box' and is not supported at the ends by the struts since it is purely for light exclusion and is not structurally important. While not containing fine detail, the model is sufficient to estimate misalignment of the optical path due to gravitational deformation as well as the resonant frequencies of the structure. The model lacks many of the finer details of the OTA. For simulation purposes, the front lens cell (with lens) was set to 1,500kg. The rear instrument enclosure is set to 1,000kg. The OTA is 10.4m long, centered on the bearing axis. Other components were modified to ensure the center-of-mass was within a few mm of the bearing axis. The model shown is a starting point: specifics can be modified according to requirements and FEA results, of which those presented here, are the first.
Prime focus (shown as a blue plane above) is 500mm from the rear bulkhead of the telescope. This is needed for the prime focus occulting station, focus adjustment to accommodate wavelength diversity, and for calibration optics. At 1 micron wavelengths, there is 2.6m of post-prime focus space for the instrument. For modeling, all telescope entities are alloy steel, including the 1.5m I.D. tubes. Steel is easily fabricated and has an excellent strength to weight ratio. The central light tubes have 5mm walls which should be adequate to support baffles, the safety shutter, calibration optics, etc. Three 1m square access hatches are shown. The doors for these hatches do not significantly contribute to the calculations and are left out of the model.

For a conservative calculation, the front cell, center box and rear cell are all heavier than required even after considering the missing components (lens shutters, cal optics, the prime focus package, etc.) The following table shows the breakdown of the masses in the model:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front lens cell &amp; lens</td>
<td>1,502</td>
</tr>
<tr>
<td>Center box</td>
<td>5,786</td>
</tr>
<tr>
<td>Rear bulkhead</td>
<td>1,841</td>
</tr>
<tr>
<td>Instrument package</td>
<td>1,000 (guess)</td>
</tr>
<tr>
<td>Front struts (solid ends, 10mm walls x 100mm OD)</td>
<td>783 (total for 8)</td>
</tr>
<tr>
<td>Rear struts</td>
<td>286 (total for 8)</td>
</tr>
<tr>
<td>Front tube</td>
<td>797</td>
</tr>
<tr>
<td>Rear tube</td>
<td>460</td>
</tr>
<tr>
<td>Lens only (for reference)</td>
<td>457</td>
</tr>
<tr>
<td><strong>TOTAL (approximate)</strong></td>
<td><strong>12,500</strong></td>
</tr>
</tbody>
</table>

The model can be iterated to reduce weight and increase strength as the components gain definition.
Note that the following FEA results are the results of an iterated process: The wall thickness of the rear struts (4mm) was made thinner than the front struts (10mm) so the instrument package would sag by approximately the same amount as the lens cell, preserving optical alignment. Another approach could be to change the OD of the struts. In this model all the struts have a 100mm OD (except for those supporting the instrument).

4.1.1.1 FEA displacement results

Below is a plot showing the displacements in the horizontal orientation. The graphical displacement is shown as 100x the actual displacement:

![FEA displacement results](image)

Figure 19 Serrurier truss FEA displacement results

There are several important things to note from this first result:

1) The model is held by the central bearing (0.75m hole at the center). As noted, the telescope is balanced so the torque on the bearing is zero.
2) The front lens cell sags by 0.66mm in a nearly parallel fashion. The rear cell sags by 0.45mm, with the difference being 0.21mm (a factor of 10 below the decenter requirement for the O1).
3) The light tubes are connected to the central box but not at the lens cell or rear bulkhead. Though they are deflecting under their own weight (by about 0.1mm) they are not adding to the support of the lens cell.
4) The struts themselves sag significantly under their own weight, as is shown (100x the real motion).
5) The tilt of the front plate is approximately 10 arc seconds. The rear plate tilts by about twice as much (20 arc seconds) due to the fact that the center of mass of the rear load is not located in the same plane as the rear strut attachment points.
6) The instrument enclosure tilts by about 100 arc seconds. Of note is that the design presented here is totally passive. Active alignment or a traditional mirror cell type counterweight system could reduce this misalignment to near zero.
7) The FEA shows that changing the strength of the rear struts can make the vertical deflection of the lens cell match that of the instrument. This was only done to the 30% level here since that exceeds the alignment criteria by a factor of 10. Note the matching ignores the displacement of the lens in its cell, if any.
The Serrurier truss design shows a high level of flexibility. The struts can be easily changed later if it is found the weights and/or deflections are different from the modeling. In addition, the design is very simple, portable, and easy to fabricate.

4.1.1.2 **FEA stress results**

The stress plot below shows the Von Mises stresses calculated by the FEA.

![Serrurier truss design stress results](image)

Figure 20 Serrurier truss design stress results

It can be seen from this plot that the side Serrurier trusses carry all of the stress of supporting the lens cell and the rear instrument. The front struts are heavier than the rear and have a factor of safety is about 70. The rear struts are thin walled and have a factor of safety of about 40.
4.1.1.3 FEA frequency results

The FEA is also used to calculate the first few resonant frequencies of the structure. Many of these are degenerate (lens cell oscillating in X and Y are the same). The lowest mode is dominated by translation of the instrument enclosure at 16.7Hz.

The next mode is dominated by translation of the lens cell. This mode has a resonant frequency of 18.8Hz. Note that this mode is likely to change as trusses are added to support the rear enclosure.

These frequencies are consistent with the static deflection of the telescope and are within the bounds of what is manageable for the telescope pointing control system. The amplitude of the modes can be controlled with damping devices placed between the spars of the telescope. Note that Solid Works does not support modeling of damping.
4.1.2 Objective Lens Cell

Drawing from COSMO-RQ-6003 (Telescope Requirements Document), the objective lens is a super-polished 1.5m diameter, 20cm thick singlet manufactured from high purity fused silica (Corning C79-80). The mass is approximately 420 kg. An elastomeric mount concept for this large singlet is shown in Figure 21 and Figure 22. This cell will be marked and clocked to ensure proper installation. For safety this cell will have a protective cover for transportation / storage and will meet the environmental safety requirements.

The lens cell will also have an air blowing mechanism to automatically clean the surfaces and remove any particulates.

![Figure 21 Objective Lens Cell (LCT-SW-241000)](image)

From a risk perspective, it is highly desirable to engage with a lens figuring and polishing vendor who can also mount the lens within this cell and perform subsequent metrology all within their facility. HAO would only be responsible for integrating the final lens/cell assembly onto the telescope structure.
4.1.3 Safety Shutter

In order to protect opto-mechanical systems at or near prime focus in the event that the telescope pointing control system is unable to maintain the occulting system in position, the COSMO LC requires a safety shutter which can be closed in a matter of seconds in the event of an un-desired off pointing event (including a loss of power to the observatory). The mechanism requires power to remain open, therefore a loss of power by nature of its design will cause it to close within 1 second. The mechanism does have a locking feature to maintain it open during appropriate testing.

![Figure 23 Large Coronagraph Safety Shutter (LCT-SW-240005)](image)

The mechanism was intentionally designed so that the closing petals do not touch. This is to help prevent the creation of particulates. Additionally, the petals do not fully cut off all light. There is a central aperture the passes through unimpeded. This allows pointing verification, alignment, and other activities to be performed with safer levels of sunlight. The safety shutter is meant to limit the amount of light to safe levels, not to used as a dark shutter.
4.1.4 Calibration Diffuser Insertion Mechanism

Figure 24 depicts the diffuser insertion mechanism. This mechanism is a simple fold in/out of the diffuser optic. The alignment of this optic is not precise, and therefore the mechanism can be relatively simple. Due to its simplicity, the diffuser will be inserted within the required timeframe of 5 seconds.

![Figure 24 Large Coronagraph Calibration Diffuser Mechanism](image)
4.1.5 **Occulter Station**

The occulter station includes:

- Calibration station (shielded from sunlight when out of the beam)
- Occulter (with thermal and motion systems)
- Heat dump
- Lens 1-2
- Focus mechanism (Aerotech PRO560)

![Figure 25 Large Coronagraph Occulter Station (LCT-SW-240036)](image)

4.1.5.1 **Polarization Calibration System**

The calibration system is composed of four motion mechanisms. There are two PRO225 linear stages capable of moving the polarizer and retarder in and out of the optical beam. Additionally there are two ALAR 250 rotational stages capable of rotating the polarizer/retarder to the correct angle. These COTS stages can rotate at 90rpm, which easily meets rotational velocity requirements. Figure 26 shows these mechanisms in their “out of beam” state. These mechanisms can move the optics into the beam within the 5 second requirement.
4.1.5.2  Occulting Disk Design Study

The LC occulting disk has extraordinary requirements. Approximately 2,300W of power are focused onto a disk of ~70mm diameter with about 450W absorbed. This requires liquid cooling. This is complicated by the requirement that the disk occult down to $1.05R_\odot$ with an accuracy of ~5 arc seconds and the occulter’s size may vary depending on the wavelength of observation.

Due to the size of the telescope, frequency the disk needs changing, lack of space and the hazardous conditions near prime focus, swapping disks in and out from a library (either manually or robotically) is difficult. As a result we adopt the continuously-variable occulter design shown below. This will allow the occulter to grow or shrink to properly occult the sun year-round even as the sun’s apparent diameter changes.
The 10-blade version shown above is round to about the 1% level, or ~+/-5 arc seconds in image space at full size. All parts exposed to the sunlight are copper. The ‘main body’ is liquid cooled and has a polished cone to reflect 80%+ of the incident light energy. The blades are moved in and out via a ‘drive disk’ that is rotated by a cable that runs up and down the post that supports the occulter (not shown).

Figure 28 shows six figures of the assembly in the normal (non-exploded) configuration. The top row shows the occulter set to the minimum size while the bottom row shows the occulter set to the maximum size.
Modeling seeing effects due to heating of the occulter is extremely difficult. From past experience we know that occulting disks can reach temperatures in excess of 100°C without affecting performance. Given the high resolution and polarization capabilities of the LC, the temperature should be kept within ~50°C of ambient. The temperature of the occulter disk will be monitored and reported to the control system.

We analyze the expected temperature rise using SolidWorks Flow™. To do this we select a narrow but fairly tall post to hold the occulter. The aspect ratio of the post determines a trade between totally blocked field of view and vignetted field of view and the choice presented here does not necessarily represent a final design. We also select a thermal joint compound to use between the blades and the body. SolidWorks Flow then evaluated the cooling performance in terms of final steady-state temperatures, coolant volumetric flow and pressure drops.

The results are shown below. The ΔT of the water is approximately 5°C with a flow rate of 20cc/s. Figure 29 shows the pressure drop of the fluid as it moves up the post, mixes in the front of the occulter, and drains back out the post. The total pressure drop across the assembly is only 0.3psi, which is easily obtainable.

Figure 29: Coolant flow lines showing pressure drop

Figure 30 shows the flow simulation results for the temperature profile in section though the center of the assembly that includes both the fluid and metal components. The model shows that the maximum temperature of the front surface of the cone is ~55°C – cool enough to touch! The outer
blades have the poorest cooling and their maximum temperature reaches 65°C. Well within the expected acceptable level for good telescope performance.

![Temperature field](image)

**Figure 30:** The results of the FEA for the metal components.

In conclusion, the thermal control of the variable occulter is well within levels that will meet the LC's requirements. So much so that a final design may allow for a smaller post with less impact on the field of view.

### 4.1.5.3 Occulter Motion Control for Offset Pointing

The occulter is mounted on an R-θ stage for controlling the radial and azimuthal position of the scence. These stages allow the occulter to be centered on the Sun anywhere within the 1 degree field of view of the telescope within 5 seconds. This allows the sun to be off-centered should an observer want to track coronal events to larger distances. Figure 31 shows these two hardware stages.
4.1.5.4 Heat Dump

Figure 32 shows a conceptual design of a heat dump system. Chilled water is piped through a series of tubes designed to cool the heat dump. This system is much easier to cool than the occulter due to its larger size and thermal mass. The heat dump temperature will be monitored and reported to the control system.

4.1.6 OTA to Mount Interface

Little in the way of a preliminary design for the OTA to mount interface currently exists though we have two concepts shown below for Truss and Tube based OTA approaches (Figure 33 and Figure 34). Several of the potential vendor partners identified during the RFI process have substantial experience designing and building meter class telescopes so this not believed to be a problem under our project plan. Both main shaft and yoke axes will be supported by couples of tapered roller
bearings, moved by counteracting pinion-gear motors and controlled by encoders fixed to the bearing supports (Figure 35)

Figure 33 OTA to Mount Interface for a truss based OTA structure

Figure 34 OTA to Mount Interface for a tube based OTA structure
Under either of these concepts the key is to identify and specify the correct bearing architecture that meets the load requirements under all pointing positions. We have worked at a very preliminary level with Timken and have identified likely classes of bearing shown below. The weight of the main shaft bearing shown in Figure 36 is 133.7 Kg, with a bore measuring 305mm and an outer cup diameter of 560mm. The bearing width is 136mm. Basic load ratings for this type of tapered roller bearing are 180,000 lbf (dynamic radial) and 122,000 (dynamic thrust).

For the yoke bearings Timken has suggested using two pair (one pair on each side of OTA) of 3MM319WI-DUH. These would have a heavy custom pre-load (>2000 pounds) set at the manufacture so that axially clamping the bearings together automatically generates the set pre-load during installation. The dimensions of the yoke bearings are 95mm bore, 200mm outer cup diameter and a bearing width of 90mm.
Super Precision

Medium ISO 03 Series
2(3)MM300WI

Super Precision MM
Running accuracy and performance meet ABEC 9 (ISO P2) levels. Other features conform to ABEC 7 (ISO P4) requirements.

4.1.7 OTA to Filtergraph Interface
The interface between the OTA and Filtergraph is a simple flange with a windowed aperture. The window is meant to maintain the thermal stability of the Filtergraph, and limit dust transport between the OTA and Filtergraph (particularly before and during installation).
Figure 38 OTA to Filtergraph Flange Interface (8721-SW-620105)
4.1.8 Counterweight System
Given the number of moving mechanisms and various ranges of motion, a counterweight system will need to be implemented to ensure a properly balanced system at all times. This type of balancing system is common and is not yet shown integrated into our OTA.

4.2 Equatorial Mount
The basic PDR mount concept was generated by Haiying Zhang of the Nanjing Institute of Astronomical Optics & Technology (NIAOT) and is shown below in Figure 39. It is an equatorial yoke mount with provision for tip/tilt built into the attachment flange between the mount and the pier. This will help correct for any polar misalignment caused by fabrication tolerances. This mount will allow for continuous viewing of the sun during daylight year-round.

The hardware and control system will be designed to allow for at least 1 degree of motion per second (10 degrees or higher is a goal for this system).

The mount will have a locking mechanism to prevent motion of the mount/telescope. This is especially important for safety concerns during installation / troubleshooting when there is potential for an unbalanced system.

Figure 39 PDR Design for Large Coronagraph Equatorial Mount (Haiying Zhang, NIAOT)
5 Filtergraph Instrument

The Filtergraph is a stand-alone structure that can be built up, assembled, tested and then integrated onto the large coronagraph optical telescope assembly. Figure 40 and Figure 41 show the instrument (without covering panels) and the full optical raytrace model (in red) for perspective.

![Filtergraph Instrument](image)

*Figure 40 - Filtergraph instrument depicted along the Zemax optical ray-trace behind the occulter station.*

The filtergraph will weigh several hundred kilograms and so it will likely require additional coupling to the OTA beyond simply bolting it to the interface plate described earlier. Trusses like those modeled in Figure 20 will be used to minimize deflections of the filtergraph optics from the large coronagraph optical center line.
5.1 Focus Mechanisms

As the Large Coronagraph has a singlet objective lens, there is significant chromatic aberrations over the spectral bandpass. There are four locations in the Filtergraph (and a fifth in the OTA itself) where focusing is required. These are detailed in Table 1. These stages are all capable of meeting the setup / re-configure times required for the instrument (typically 5 seconds to change wavelengths). Additionally these stages will operate appropriately in any gravity vector as the telescope is moved across the sky.

<table>
<thead>
<tr>
<th>Location</th>
<th>Motion Mechanism</th>
<th>Total Travel [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occulter station in OTA (Occulter and lens 2-3)</td>
<td>Aerotech PRO560LM</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(includes expanded bandpass for potential future instruments)</td>
</tr>
<tr>
<td>Instrument (lens 3 through camera)</td>
<td>Aerotech PRO560LM</td>
<td>250</td>
</tr>
<tr>
<td>Lyot Stop (Lyot stop through cameras)</td>
<td>Aerotech PRO280LM</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 1 - List of focus mechanisms

<table>
<thead>
<tr>
<th>Camera 1</th>
<th>Aerotech PRO225</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera 2</td>
<td>Aerotech PRO225</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 42 Side view of filergraph showing three compensator stages required in optical design.

5.2 Pre-Filter Assembly

The current pre-filter mechanism is designed to hold 22 pre-filters. These filters are ~250mm in diameter, and thus a single traditional filter wheel is not practical. A nested set of wheels is a possible solution, but this still requires a substantial footprint. A different approach has been taken here, utilizing a filter cassette to insert one filter from a tray of filters (see Figure 43). The tray is moved along the enclosure until the appropriate filter is in place to be lowered into the optical beam. This design has been matured for the Visible Spectro Polarimeter (ViSP) instrument that HAO is constructing for the DKIST observatory. We intend to leverage that development effort to reduce costs for the Filtergraph pre-filter mechanism design. The design will have to be modified for the number/size of filters, to accommodate a changing gravity vector, to insert them within the 5 second wavelength change time, and to insert them to the needed accuracy (1mm and 1 degree). However, the result is a substantial reduction in footprint.

The filters themselves will have individual cells that are keyed and labeled to ensure the correct orientation of the filters in the filter mechanism.
5.3 Lens 3 Cell

Lens 3 is a simple singlet lens with a flat back surface. The mounting approach taken here is an injected adhesive (RTV 6-1104) that is a controlled volatility sealant (i.e. low outgassing) commonly found in optical applications. Figure 44 - Figure 47 show overview and detailed views of the assembly. Precision pins are used to control cell to mount interfaces, while precision shims are used to adjust the mount to instrument interface. Table 2 details an estimate of how accurately this can be machined / epoxied and aligned to the optical beam.
Figure 44 - Lens 3 cell overview

Figure 45 - Lens 3 cell exploded/labeled view
Figure 46 - Lens 3 cross section view

Figure 47 - Underside of lens 3 mount
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate of decentration [microns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy process (fixtures, precision shims, etc.)</td>
<td>±25</td>
</tr>
<tr>
<td>Precision shims (mount to cell interface)</td>
<td>±50</td>
</tr>
<tr>
<td>Precision shims (mount to structure interface)</td>
<td>±25</td>
</tr>
<tr>
<td>Total (RSS)</td>
<td>±61</td>
</tr>
</tbody>
</table>

**Table 2- Estimate of mounting accuracy**

5.4 **Lens 4-6 Assembly**

Lenses 4-6 are a dedicated subassembly that will be mounted together in a cell. This cell will then be aligned to the instrument. A similar approach is utilized here as in cell 3. Each of the lenses has its own subcell made of SS 416 to obtain a similar CTE to the glass. The lens is epoxied (again using RTV 6-1104) within the subcell. The thicknesses of the adhesive bonds are precisely calculated using Bayar/Herbert equation and are: 0.47, 0.52, 0.15 mm for lenses 4-6 respectively. These thicknesses are set to athermalize the design. Now the epoxy expands/contracts at just the right amount to keep the lenses stabilized over our operational temperature range.

After mounting each lens in the subcells, they are then slide into the housing in a “poker chip” style. This design architecture has proven to be very successful (Yoder 2008) and a case study is published by Fischer (1991) showing the successful achievement of 12.5 micron tolerances over survival temperature ranges of -55 to +95 C.
Precision spacers used to control lens centering during epoxy process

Epoxy syringe hole
5.5 **Lens 7-11 Assembly**

An alternative approach is shown for lenses 7-11. These lenses have similar requirements to lenses 4-6, but depending upon alignment techniques and vendor specific metrology and/or fabrication techniques a different approach might be superior. This design utilizes a precision lathed approach, where the housing is cut using a lathe in one operation to ensure precise concentricity of each lens. Figure 52 - Figure 54 show details of this design. The lenses are inserted one at a time and are held by pressure of the entire assembly. Threaded spacers are inserted and locked with set screws to ensure stability. This approach also has substantial history in opto-mechanical mounting (Yoder 2008).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate of decentration [microns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy process (fixtures, precision shims, etc.)</td>
<td>±12.5</td>
</tr>
<tr>
<td>Subcell to housing interface</td>
<td>±12.5</td>
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<tr>
<td>Precision shims (mount to structure interface)</td>
<td>±12.5</td>
</tr>
<tr>
<td>Total (RSS)</td>
<td>±22</td>
</tr>
</tbody>
</table>
Figure 52 - Lens 7-11 overview

Figure 53 - Lens 7-11 exploded view
5.6 Modulator

The modulator is mounted in a commercial off the shelf rotation stage. Aerotech has a custom metrology lab where specific measurements can be made using our modulator or a dummy mass to ensure compliance with modulator rotation requirements. The stage utilized in our design is the ALAR 200-LP. This stage is capable of 360 degree continuous motion with repeatability of ±0.5 arcseconds. This stage will function in any gravity vector orientation with a velocity of at least 90 rpm. This provides a maximum polarimetric modulation rate (for a 8 state system) of 24 Hz.
5.7 PBS / Lyot Filter Assembly

Due to severe space constraints in the optical design, the lyot filters and polarizing beam splitters have been mounted in a super assembly concept as shown in Figure 56.

While the LiNbO3 based Lyot Filter design has not yet been detailed, Figure 57 shows a typical HAO filter assembly structure. Individual optical elements are installed within ‘rotatable’ hexagonal holder mounts and subsequently stacked between guide rails. The entire stack is held under ~6 pounds of spring force between entrance and exit windows. Electrical (including some high voltage required to tune LiNbO3) connections to the electro-optically active elements are routed to the external enclosure and the entire stack is thermally controlled and (probably) compensated through precision thermometry throughout the filter assembly. This thermal control will allow the filter to maintain wavelength stability and repeatability during observations. Index matching gel is used between all optical surfaces. Figure 58 and Figure 59 depict HAO Lyot filter construction techniques used for similar instruments.
Alignment of optical elements to a common coordinate reference frame before application of RTV.

Figure 58 Method used to determine precise rotational alignment of Lyot Filter optics within their mounts

Figure 59 Lyot Filter assembly stack-up procedure in progress
5.8 Camera Subsystems

Figure 60 shows the GLS Hawaii 4RG structure (with cooling mechanisms and electronics) mounted on an Aerotech PRO 225 to allow for focusing over the spectral bandpass. The design presented here is entirely the modeling work of GL Scientific and represents a packaging effort they have done for other telescopes. The Stirling Cooler Cryostat (SCC) design has three structures fairly closely nestled into each other: inner sanctum, radiation shield and cryostat shell. The mass of the unit is around 50 pounds (with addition instrumentation located off the filtegraph in a rack within the sub-floor lab).

Figure 60 - GLS Hawaii 4RG Stirling Cooler Cryostat Detector System

5.9 Filtergraph Thermal Control

Due to high temperature differentials between the dome floor and the thermally stabilized Lyot Filters, (up to approximately 30 C) a thermal control system is needed for the instrument enclosure. Figure 61 shows an instrument panel design that has been successful on previous HAO instruments with high temperature gradients. The green part is the heating element, while the red box is an air heat exchanger with the outside. The gray box underneath it (and slightly to the left) is a simple LCD screen to monitor and verify the heating system is performing to specifications. Figure 62 shows a cross section of the panel showing insulation (green) between aluminum skins.
Figure 61 – Instrument panel with heating system

Figure 62  Panel Heater construction cross-section (amount of insulation may vary). Green layers are insulators, gray layers are aluminum skins and orange layer is a low wattage sheet heater.