Electrical and Software
Control Systems Design Description

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1 INTRODUCTION

This chapter presents a preliminary design description for the COSMO electrical and software control systems. These systems address the requirements developed and presented earlier in the PDR Binder. The COSMO deliverables include a centralized observer control building and an adjoining 5/8th’s dome enclosure in which resides the Large Coronagraph telescope and Filtergraph instrument.

1.1 TOP LEVEL BLOCK DIAGRAM

A block diagram of the complete COSMO facilities is shown in Figure 1. The Large Coronagraph facility will comprise the following control systems: (i) Dome and aperture control, (ii) Telescope control system and (iii) the Filtergraph control system.

The Spar Facility, not discussed beyond this point, comprises: (i) Dome and aperture control, (ii) Spar Guiding System, and Instrumental Control systems for the K-Cor and ChroMag Instruments.

The COSMO project plans to utilize a Distributed Control System (DCS) for everything mentioned above using a common control platform for the entire observatory. Additionally there will be common infrastructure to both facilities from a centralized control building. The control building will include an observatory control system (OCS) and a data handling system (DHS). Observer monitoring and control of these systems will be accomplished via the observer operator station (OOS). All facility services including power, network, etc. will be provided to the entire observatory from the control building. This preliminary design description will focus mainly on the Large Coronagraph facility and the Control Building. The figure on the following page shows the inter-relationships between the major top level systems of the entire observatory with the COSMO suite of instruments and its ancillary functions as described.

1.2 OBSERVATORY CONTROL SYSTEM OVERVIEW

The observatory control system will consist of two functional computing platforms: supervisory control and data acquisition computers (SCADA), and local control computers. The supervisory control and data acquisition computers will perform top level "supervisory" control of the all functional areas of the facility and will be accessed by a single member of observatory staff via observatory operator station. This will be an "event-driven state machine" architecture running daily observing programs for facility and instrument control. The events generated from the daily observing programs will communicate over TCP/IP to vendor specific software platforms within local control computers for controlling hardware. For example if an observatory staff member uses the coronagraph facility control GUI to “stow” the coronagraph, an event will be generated in the supervisory control and data acquisition computer which sends commands to the dome control software and the telescope control software which will then interact with the appropriate hardware to safely stow the coronagraph in an automated fashion. The top level architecture depicting this approach for the large coronagraph is shown in Figure 2.

The software architecture will follow a “command”, “acknowledgement” paradigm where the SCADA computer will generate a command to a distributed local control computer and will then wait for command acknowledgment from that receiving distributed node as shown in Figure 3. Upon receiving the command, the receiving distributed node will then perform appropriate range checking and context to verify a correct command. An adjustable window for acknowledgment of commands will be used, to ensure that the SCADA computer always gets a reply from the distributed node. In the event that a negative response occurs to a command, (i.e. hardware not responding properly) an error will be generated. All errors will have a severity, traceability, and notification standard to ensure proper subsystem reporting. Lastly, alarm monitoring of all subsystems will be performed in each respective distributed node with severity, notification, and logging occurring back at the SCADA computer.
Figure 1 COSMO Control Systems Top Level Block Diagram
Figure 2 Large Coronagraph Control Systems Overview
COSMO Large Coronagraph – Software Environment

Figure 3 Large Coronagraph Software Environment
1.3 **Observatory Data Handling System Overview**

Instrument control programs running within the OCS computers will be used for acquiring all raw level 0 data from facility instruments. The raw level 0 data will append appropriate metadata and be sent to the on mountain data handling computer for short term storage on a localized RAID system. From there, this data will go to the off mountain data processing system which will grab packets of the level 0 data at regular intervals for long term storage and to perform data processing to level 1, 2, etc. Acquired data from on-mountain computers will be viewable by operators for quality assurance via the Observatory Operator Station. Details of the observatory data handling system can be referenced in COSMOLC-PL-8002 (Data Processing and Calibration Plan).
2 FACILITY CONTROL SYSTEMS

2.1 FACILITY SERVICES

2.1.1 Power Distribution

The COSMO Project will utilize a 208/120 VAC 3Phase 4 wire electrical service stemming from the NOAA Mauna Loa mountain top facilities. Initial power estimates of the entire facility are shown below in Table 1. Detailed information on the source of these estimates can be referenced from COSMOLC-BU-7210 (Observatory Power Budget). The COSMO facility power will go to a UPS system so that critical facility and instrumentation systems can remain operational during short-term power loss periods and can be prioritized and perform controlled shutdowns during long-term power loss periods.

<table>
<thead>
<tr>
<th>Voltage Service (VAC)</th>
<th>Estimated Power (kW)</th>
<th>Estimated Power Factor</th>
<th>Estimated Power (kVA)</th>
<th>Estimated Current Load (A)</th>
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<td>208/120 3PH.</td>
<td>79.6</td>
<td>0.8</td>
<td>66.4</td>
<td>185</td>
</tr>
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</table>

Table 1. COSMO Observatory Estimated Power

The estimated distribution of power across the observatory is shown in Figure 4. The large coronagraph dome facility itself is estimated to consume the largest amount of power followed by the network and controls for the observatory.

![Estimated Observatory Power Breakdown in Percent](image-url)
Within just the Large Coronagraph dome facility, the distribution of power consumption is shown in Figure. As will be discussed later, the largest portion of power usage is expected to feed the large blower fan’s within the dome’s HEPA system. This system is responsible for maintaining the very high level of cleanliness on the objective lens required to meet the telescopes scattered light requirement. Note that the duty cycle of this HEPA system is expected to be continuous during daytime operations when the dome aperture is open but which can be throttled back when the dome is closed to conserve power.

![Estimated LC Dome Facility Power Breakdown in Percent](image_url)

*Figure 5 Large Coronagraph Facility Distribution of Power in % of Total Capacity*
2.1.2 Network Design

The COSMO network and data architecture will be designed with a clear separation between the Observatory Control System (OCS) and the Data Handling System (DHS). The OCS will serve as a distributed control system using Ethernet for communications stemming from the control building to each control system shown in the top level architecture. This will comprise of Ethernet Switch 2 (Control Building) with fiber optic connections to both Ethernet Switch 3 (The Large Coronagraph Facility) and Ethernet Switch 4 (The Spar Facility). The DHS will have Cameralink data connections from instrument cameras to observatory control system computers (Control Building) which will also have connections to Ethernet Switch 1 to tie into short term storage and off-mountain infrastructure. An overview of the network and data architecture is shown in Figure 6. Remote access to Ethernet switch 2 will give full accessibility for remotely monitoring and controlling the OCS. Remote access to Ethernet switch 1 will give full accessibility to the COSMO on-mountain DHS. Remote access will be password and firewall protected. Login and password credentials will allow access, but all remote logins will be logged for security traceability.
Figure 7 COSMO Top Level Network Architecture
2.2 **Observatory Operator Station**

This system has two basic functions: to facilitate observatory level control and data monitoring of the entire facility from a single centralized location. The COSMO Observatory Operator Station (OOS) is conceived as a multi-screen, coordinated environment where, from a single chair, observers can monitor, diagnose and troubleshoot any of the observatory instruments, observatory networking and data storage status, and any other ancillary observatory system which may be developed in the future (e.g. computer controlled dome aperture and rotation systems, observatory precision timing backbone, observatory weather station data, closed circuit television cameras, etc.).

The OOS shall be designed to facilitate future expansion. Control and data acquisition computers will be extended utilizing KVM hardware for easy access to all observatory controls and monitoring. Thus it is anticipated that it will contain a minimum of 5 screens:

1. Large Coronagraph Facility/Telescope Controls and Status Monitoring
2. Spar Facility Controls and Status Monitoring
3. Filtergraph Instrument Controls, Status, and Quick Look Data Viewing
4. K-Coronagraph Instrument Controls, Status, and Quick Look Data Viewing
5. Chromag Instrument Controls, Status, and Quick Look Data Viewing

*Figure 8 Operator at multi-screen console (Image courtesy of NOAA)*
2.3 **DOME ROTATION AND Aperture Control System**

Large Coronagraph facility infrastructure including the dome rotation and aperture control system has been part of an external competitive bid process and will most likely be completed by an outside contractor. Discretion of the control system architecture will be left up to the outside contractor with the exception that appropriate hardware and software ICDs are met and that the platform chosen will need to be able to reside and communicate on the Observatory Control System (OCS) network as described earlier. One critical aspect of the dome control software will be the ability to offset its position when the telescope is not centered within dome opening. (i.e. perform positional corrections).

The dome rotation and aperture control will need to interface with both the facility telescope pointing control system for coordinated motion and the Large Coronagraph Control Systems to guarantee proper safety and function of the coronagraph. This can be accomplished through hardware interlocks and/or communications between systems on the OCS network. An example control system design that could be used for this application would utilize a dome control unit that would control two axes of motion for dome positioning and one axis of motion for aperture control. Position referencing for solar tracking would be generated from a control computer (based on an algorithm for the solar ephemeris) in the control building and sent across the network to the telescope dome control unit. Both axes would have relative position encoders on the dome axes. This control system would generally use a nested loop consisting of an inner velocity loop (for dome dynamic corrections) and an outer position loop (for pointing accuracy).

Dome slew speed requirements are minimum speed of 10 degrees/sec and maximum speed of 3 degrees/sec. Additionally a position error signal between the telescope pointing control system and the dome rotation control system should be used for pointing corrections to the dome based on the telescope position. The dome aperture requirements are an opening/closing time of less than 1 minute. Initial conversations with external vendors in the astronomical field suggest that these requirements are readily achievable with the architecture described above in combination with appropriately selected components.
Figure 9 Dome Rotation and Aperture Control System
3 LARGE CORONAGRAPH CONTROL SYSTEMS

3.1 TELESCOPE POINTING CONTROL SYSTEM

Large Coronagraph facility infrastructure including the telescope pointing control system has been part of an external competitive bid process and will most likely be completed by an outside contractor. Full discretion of the control system architecture will be left up to the outside contractor with the exception that the hardware platform chosen will need to be able to reside and communicate on the Observatory Control System (OCS) network as described earlier.

The telescope pointing control will need to interface with both the facility dome rotation control system for coordinated motion and the Large Coronagraph Control Systems to guarantee proper safety and function of the coronagraph. This can be accomplished through hardware interlocks and/or communications between systems on the OCS network. An example control system design appropriate for this application would utilize a pointing control unit that would control two axes of motion for telescope pointing. Position referencing for solar tracking would be generated from a control computer (based on an algorithm for the solar ephemeris) in the control building and sent across the network to the telescope pointing control unit. Both axes would have absolute position encoders on the telescope to close position servos based on the solar tracking position reference. This control system would generally use a nested loop consisting of an inner velocity loop (for telescope dynamic corrections) and an outer position loop (for pointing accuracy).

Telescope pointing accuracy requirements are 10 arc seconds. Optionally, a guide telescope could be added to the control system for use in a mode of operation that performs pointing corrections based on the solar disk itself. This can be implemented a couple of different ways including, using the “guide” signal to feed corrections into the position loop control for the telescope itself or being used to correct an active optical element which corrects line of sight while leaving the telescope pointing control loop unchanged. Initial conversations with external vendors for telescope control systems suggest that these requirements are readily achievable with the architecture described above in combination with appropriately selected components.
Large Coronagraph Facility
Telescope Pointing Control System

- Polar Axis Drive Motor
- Declination Axis Drive Motor
- Inc. Encoder/Hall Sensors
- PWM Reference
- (+) End of Travel
- (-) End of Travel
- NPN N/O Digital Input
- Sun Tracking Reference
- Dome Control System
- Large Coronagraph Control System
- Telescope Pointing Control Unit
- Abs Pos
- Declination Axis Absolute Angle Encoder
- Declination (-) End of Travel

Figure 10 Telescope Pointing Control System
3.1.1 HAO Legacy Spar Guiding System

The HAO Instrumentation group has prior experience with designing and commissioning telescope pointing platforms utilizing an inner velocity servo (for telescope dynamics) and an outer position servo based on a guide telescope (i.e. non-ephemeris based pointing) with a 10 Hz sampling rate. These platforms have met requirements such as: (a) slewing at rates of ~1 degree per second, (b) solar tracking at a precision of 2.0 arc-seconds (RMS) over a 15 second period and (c) absolute pointing accuracy of 5.5 arc-seconds.

The parameters on the guide telescope were as follows:
- Sensor FOV (capture range) is ~2 solar diameters
- Summer (min) diameter is ~1888 arcsec
- Winter (max) diameter is ~1952 arcsec
- Equinox diameter is ~1920 arcsec
- Solar irradiance at sea-level is ~1 W nm\(^{-1}\) m\(^{-2}\)

Additionally, the guide telescope utilized appropriate band pass and ND filters to operate position sensors in linear regime and for maximum resolution (e.g. 1mW for Thorlabs Quadrant Sensor PDQ80). A design rendering of this guide telescope is shown below.

![Figure 11 Telescope Pointing Guide Telescope used on HAO Legacy Spar Guiding System](image-url)
Details of the legacy systems designed by the HAO instrumentation group can be seen in the figures on the pages ahead. In summary, an error signal from the guide telescope is conditioned with both analog and digital filters and processed on a computer-based control system for the telescope pointing position loop. The output of the position loop is then used as an analog reference voltage (or digital signal) to a pair of motor amplifiers (RA and DEC) that closes a velocity servos to corresponding brushless DC (BLDC) servo motors. Guide telescope error signals can be displayed on a GUI in many formats for analysis of the telescope pointing performance.
Right Ascension (RA) Control

Figure 13 Design Concept for Right Ascension Drive Control Loop
Declination (DEC) Control

Figure 14 Design Concept for Declination Drive Control Loop
Figure 15 HAO Spar Guiding System Performance
3.2 LARGE CORONAGRAPH MECHANISM CONTROL

Beyond the telescope pointing control system the large coronagraph has several functions which must be accommodated in the overall telescope control system. There is a very close interface between the telescope control system and the filtergraph instrument control system described later within this document.

All functions of the coronagraph outside of telescope pointing will be controlled by the Large Coronagraph Control System. It is envisioned that a single control unit comprised of a multi-axis industrial controller will be used to control discrete mechanisms currently identified. The multi-axis controller will also contain appropriate provisions for I/O to handle current and future ancillary sensing and control needs. Examples of coronagraph features currently identified to utilize I/O would be the occulter cooling system and safety shutter system. This control unit will need to interface with the telescope pointing control unit and the Filtergraph instrument to guarantee proper safety and function of the coronagraph. This can be accomplished through hardware interlocks and/or communications between systems on the OCS network. A control computer back at the control building would be used for monitoring and controlling the LC control systems. A system that meets these needs and has heritage within the organization is a COTS industrial controller from ACS motion control shown in Figure . The Top Level block diagram for the COSMO Large Coronagraph is shown below.

![Figure 16 Large Coronagraph Systems Block Diagram](image-url)
3.2.1 Linear and Rotary Stage Mechanism Control Overview

Throughout the next sections, a variety of linear and rotational stage mechanisms are discussed. HAO has identified at least one vendor with (a) a wide range of stage capacities and travel ranges and (b) a large amount of experience modifying their stock product line for customized applications. The COSMO Project has established a cost baseline surrounding these Aerotech products and has established that all required customizations are within their capabilities. Shown below are two representative photographs of these systems. Variations on these will be called out under the descriptions for specific coronagraph and filtergraph applications. These stages are depicted within their assemblies in the COSMO Mechanical Design Description Chapter of this PDR Binder. In a very few instances, completely custom stages and control are likely including the diffuser insertion mechanism and the safety shutter mechanism.
3.2.2 Safety Shutter Mechanism

The large coronagraph must have a built-in safety shutter used to protect sensitive internal instrumentation from damage when the coronagraph is not occulting the sun. This control mechanism must be a hardware only solution that operates in a normally closed configuration for power loss related safety. A simple solution that meets this need would entail a photocell similar to Thorlabs quadrant sensor PDQ80 that will be used to detect solar occulting and output an analog signal to a custom interface board made up of analog comparators that will output a digital signal based on whether the sun is occulted or not. The digital output from the interface board will then trigger a COTS safety relay that will source/dropout power to the shutter drive electronics accordingly. The position of the safety shutter will be monitored by the large coronagraph control system which can broadcast the status of the safety shutter on the OCS network, and take whatever subsequent actions are needed during safety closure and recovery.

Figure 19 Aerotech PRO560 Mechanical-Bearing Ball-Screw Linear Stage (Image courtesy of Aerotech).

Figure 20 Safety Shutter Hardware Interlock Concept
3.2.3 Diffuser Insertion Mechanism

The diffuser mechanism will require a single motion controller axis, utilizing a DC servo or stepper motor driven linear travel mechanism with end of travel (EOT) switches depicting the IN/OUT states of the mechanism relative to the beam. The mechanism will be setup such that the positive (+) direction of travel moves the Diffuser INTO the beam. The +EOT switch will be located at the position where the Diffuser is IN the beam. The –EOT switch will be located at the position where the Diffuser is OUT of the beam.

3.2.4 Linear Polarizer Insertion Mechanism

The calibration linear polarizer insertion mechanism will require a single motion controller axis, utilizing a DC servo or stepper motor driven linear stage with end of travel (EOT) switches depicting the IN/OUT states of the mechanism relative to the beam. The mechanism will be setup such that the positive (+) direction of travel moves the calibration optics 1 mechanism INTO the beam. The +EOT (End of travel) switch will be located at the position where the calibration optics 1 mechanism is IN the beam. The –EOT (End of travel) switch will be located at the position where the calibration optics 1 mechanism is OUT of the beam. An example of a COTS linear stage that meets the design criteria from Aerotech is the PRO225.

3.2.5 Linear Polarizer Rotation Mechanism

The rotation of the calibration linear polarizer will require a single motion controller axis, utilizing a single DC servo motor driven rotational stage and geared to the appropriate speed with encoder feedback and a single home switch depicting the home position of the optics. The mechanism will be setup such that the positive (+) direction of travel moves the rotation calibration optics CLOCKWISE as looking from the occulter towards the Sun. On mechanism control system startup, reset or a HOME command, the rotation calibration optics 1 shall be homed using a modified “Home & Index Search” model using the mechanism’s home switch and a zero index from the encoder. The home switch shall be initially approached from the CCW direction at normal operating speed until the home switch is detected. When the home switch is detected, the motor direction shall be reversed (CW) and driven off the home switch by 5 degrees (0.9 rad). The motor direction shall be reversed again (CCW) at 50% normal velocity until the home switch is detected and then reversed (CW) to the index of the encoder. An example of a COTS rotary stage that meets the design criteria from Aerotech is the ALAR250.

3.2.6 Waveplate Insertion Mechanism

The 2nd calibration optic mechanism will require a single motion controller axis utilizing a single DC servo or stepper motor driven linear stage with end of travel (EOT) switches depicting will be setup such that the positive (+) direction of travel moves the calibration optics 2 mechanism INTO the beam. The +EOT (End of travel) switch will be located at the position where the calibration optics 1 mechanism is IN the beam. The –EOT (End of travel) switch will be located at the position where the calibration optics 1 mechanism is OUT of the beam. An example of a COTS linear stage that meets the design criteria from Aerotech is the PRO225.

3.2.7 Waveplate Rotation Mechanism

The rotation of the calibration waveplate will require a single motion controller axis utilizing a single DC servo motor driven rotational stage geared to the appropriate speed with encoder feedback and a home switch depicting the home rotational position of the optics. The mechanism will be setup such that the positive (+) direction of travel moves the rotation calibration optics CLOCKWISE as looking from the
occulters towards the Sun. On mechanism control system startup, reset or a HOME command, the rotation calibration optics 2 shall be homed using a modified “Home & Index Search” model using the mechanism’s home switch and a zero index from the encoder. The home switch shall be initially approached from the CCW direction at normal operating speed until the home switch is detected. When the home switch is detected, the motor direction shall be reversed (CW) and driven off the home switch by 5 degrees (0.9 rad). The motor direction shall be reversed again (CCW) at 50% normal velocity until the home switch is detected and then reversed (CW) to the index of the encoder. An example of a COTS rotary stage that meets the design criteria from Aerotech is the ALAR250.

3.2.8 Occulter Station Mechanisms

3.2.8.1 Occulter Station Focus
The occulter station focus mechanism will require a single motion controller axis utilizing a single DC servo motor driven linear stage with absolute encoder feedback and end of travel (EOT) switches for stopping the focus mechanism at each focus extreme. The +EOT (End of travel) switch will be located at the position where the occulter focus mechanism is at its extent of travel closest to the sun. The –EOT (End of travel) switch will be located at the position where the occulter focus mechanism is at its extent of travel farthest from the sun. An example of a COTS linear stage that meets the design criteria from Aerotech is the PRO560. This mechanism will be controlled to remain fixed at its current position in the event of a power loss.

3.2.8.2 Occulter Radial Translation
The occulter station translation mechanism will require a single motion controller axis utilizing a single DC servo motor driven linear stage with absolute encoder feedback and end of travel (EOT) switches for stopping the translate mechanism at each extreme. The +EOT (End of travel) switch will be located at the position where the occulter translate mechanism is at its extent of travel closest to the right side of the OTA wrt the sun. The –EOT (End of travel) switch will be located at the position where the occulter translate mechanism is at its extent of travel closest to the left side of the OTA wrt the sun. An example of a COTS linear stage that meets the design criteria from Aerotech is the PRO560. This mechanism will be controlled to remain fixed at its current position in the event of a power loss.

3.2.8.3 Occulter Azimuth Rotation
The occulter azimuth rotation mechanism will require a single motion controller axis utilizing a single DC servo motor driven rotational stage geared to the appropriate speed with encoder feedback and a home switch depicting the home rotational position of the element. The mechanism will be setup such that the positive (+) direction of travel moves the rotation calibration optics CLOCKWISE as looking from the occulter towards the Sun. On mechanism control system startup, reset or a HOME command, the occulter azimuth shall be homed using a modified “Home & Index Search” model using the mechanism’s home switch and a zero index from the encoder. The home switch shall be initially approached from the CCW direction at normal operating speed until the home switch is detected. When the home switch is detected, the motor direction shall be reversed (CW) and driven off the home switch by 5 degrees (0.9 rad). The motor direction shall be reversed again (CCW) at 50% normal velocity until the home switch is detected and then reversed (CW) to the index of the encoder. An example of a COTS rotary stage that meets the design criteria from Aerotech is the ALAR325. This mechanism will be controlled to remain fixed at its current position in the event of a power loss.
3.2.8.4 **Occulter Size Control**
The occulter size control mechanism will be an HAO custom-built mechanism used to expand and retract the overall diameter of the occulting disk. This will require a single motion controller axis utilizing a single DC servo motor geared to the appropriate speed with encoder feedback and end of travel (EOT) switches for stopping the mechanism at each extreme. The mechanism will be setup such that the positive (+) direction of travel moves the size control mechanism CW and the negative (-) direction of travel moves the size control mechanism CCW. The +EOT (End of travel) switch will be located at the position where the occulter translate mechanism is at its CW extent of travel, and –EOT (End of travel) switch will be located at the position where the occulter translate mechanism is at its CCW extent of travel. Additionally, the drive electronics will need to be setup to monitor appropriate torque limits of this mechanism. This mechanism will be controlled to remain fixed at its current size in the event of a power loss.

3.2.8.5 **Occulter Cooling System**
Due to excessive heat loading on the occulter, a thermal control system capable of keeping the occulter to a temperature of < 60°C will need to be utilized. A technical note was written that describes the details of the heat loading to the occulter and a proposed thermostiphon thermal management strategy using water as the heat transfer media. The figure below shows the thermostiphon approach applied to an occulting disk using a magnetically coupled pump to provide the necessary volume of water needed to achieve proper cooling with a return line and radiator used for condensing the vapor back into liquid, and a reservoir for storing the liquid.

![Occulter station cooling control system concept](image)

**Figure 21 Occulter station cooling control system concept**
3.2.9 Environmental Monitoring and Control

Environmental monitoring and control will be a subset of the facility control system comprising of two distributed nodes (1 per facility). Each node will consist of an environmental control PLC with Ethernet communications to a computer located in the control building. The computer will act as a SCADA (Supervisory Control and Data Acquisition) for the entire observatory environment and will perform all necessary environmental data logging. Typically environmental sensors throughout the observatory consisting of temperature, humidity, particulates and pressure would be interfaced as inputs to each PLC. In addition, typical outputs from each PLC would consist of heaters, fans, etc. An example COTS platform that meets this need would be a Rockwell Automation 1756 Controllogix plc. A block diagram of this system can be seen on the following page.

![Figure 22 Rockwell Automation Controllogix plc (Image Courtesy of Rockwell Automation)](image)

3.2.10 Safety Systems

Safety systems will be a subset of the facility control system comprising of two distributed nodes (1 per facility). Each node will consist of a safety interlock system with Ethernet communications to a computer located in the control building. The computer will act only to monitor the status of the safety interlock system via alarms on the screen. An example COTS platform that meets this need would be a Rockwell Automation 1752 SmartGuard 600 controller that features 16 safety-rated inputs, and 8 safety-rated outputs and an Ethernet port. A block diagram of this system can be seen on the following page.

![Figure 23 Rockwell Automation 1752 SmartGuard 600 Controller (Image Courtesy of Rockwell Automation)](image)
Figure 24 Observatory Environmental and Safety Monitoring Systems
4 FILTERGRAPH CONTROL SYSTEMS

The first-light scientific instrument to be mounted to the large coronagraph tube assembly will be a filtergraph instrument. At the core of the instrument is a National Instruments PXIe chassis used to trigger 2 Hawaii 4RG Cameras in synchronicity with a polarization modulator and Lyot filter for appropriate coronal polarization state image collection. PXIe platforms for triggered data acquisition has heritage within the organization. Ancillary to the PXIe system will be a mechanism control system to operate filtergraph mechanisms. It is envisioned that a single control unit comprised of a multi-axis industrial controller will be used to control the 7 discrete mechanisms currently identified. The multi-axis controller will also contain appropriate provisions for I/O to handle current and future ancillary sensing and control needs. This control unit will need to interface with the large coronagraph control unit for proper safety and function of the filtergraph. This can be accomplished through hardware interlocks and/or communications between systems on the OCS network. A control computer back at the control building would be used for monitoring and controlling the Filtergraph instrument control systems. A system that meets these needs and has heritage within the organization is a COTS industrial controller from ACS motion control.

Figure 25 Filtergraph Block Diagram
4.1.1 Filtergraph Mechanism Control

4.1.1.1 Instrument Focus Mechanism (Prime Focus)
The instrument focus mechanism will require a single motion controller axis utilizing a single DC servo motor driven linear stage with absolute encoder feedback and end of travel (EOT) switches for stopping the focus mechanism at each focus extreme. The +EOT (End of travel) switch will be located at the position where the instrument focus mechanism is at its extent of travel closest to the sun. The –EOT (End of travel) switch will be located at the position where the instrument focus mechanism is at its extent of travel farthest from the sun. An example of a COTS linear stage that meets the design criteria from Aerotech is the PRO560.

4.1.1.2 Camera Focus Mechanism
The camera focus mechanism will require a two motion controller axes utilizing two DC servo motor driven linear stages (1 for each camera) with absolute encoder feedback and end of travel (EOT) switches for stopping the focus mechanism at each focus extreme. The +EOT (End of travel) switch will be located at the position where the camera focus mechanism is at its extent of travel closest to the sun. The –EOT (End of travel) switch will be located at the position where the camera focus mechanism is at its extent of travel farthest from the sun. An example of a COTS linear stage that meets the design criteria from Aerotech is the PRO225.

4.1.1.3 Lyot Stop Focus Mechanism
The Lyot stop focus mechanism will require a single motion controller axis utilizing a single DC servo motor driven linear stage with absolute encoder feedback and end of travel (EOT) switches for stopping the focus mechanism at each focus extreme. The +EOT (End of travel) switch will be located at the position where the Lyot stop focus mechanism is at its extent of travel closest to the sun. The –EOT (End of travel) switch will be located at the position where the Lyot stop focus mechanism is at its extent of travel farthest from the sun. An example of a COTS linear stage that meets the design criteria from Aerotech is the PRO280.

4.1.1.4 Polarization Modulator Mechanism
The polarization modulator mechanism will require a single motion controller axis utilizing a single DC servo motor driven rotational stage geared to the appropriate speed with absolute encoder feedback. The mechanism will be setup such that the positive (+) direction of travel moves the polarization modulator optics CLOCKWISE as looking from the occultor towards the Sun. Because the timing of polarimetric states will need to be synchronized with camera triggered acquisition, synchronization and timing electronics are required for this mechanism. An example of a COTS rotary stage that meets the design criteria from Aerotech is the ALAR150.

4.1.1.5 Pre-Filter Mechanism
The pre-filter mechanism will require at least 2 motion controller axes utilizing DC servo motors geared to appropriate custom stages for insertion and removal of appropriate pre-filters. Custom filter mechanisms have been designed by HAO engineers on past projects.
4.1.2 Filtergraph Lyot Filter Wavelength Tuning Control

The Filtergraph Lyot Filter will be a custom design requiring both strict temperature and tuning requirements. A temperature stability requirement of 5mK will be met utilizing COTS ILX Lightwave laser diode thermoelectric temperature controller for the Lyot filter temperature controls. The controls use a highly synchronized series of wavelength tuning analog output waveforms, camera exposure triggering waveforms, and proper rotational state of the modulator mechanism. The use of Lithium Niobate (LN) within the filter requires the application of high voltage signals for effective wavelength tuning. A concept on how this can be accomplished is through the use of a National Instruments DAQ board for low voltage waveform generation triggering a zero-crossing high voltage dc power supply for high voltage application. The NI platform used for both wavelength tuning and camera triggering must receive a master timing signal from an outside source to ensure system level timing synchronization to the rotational state of the modulator mechanism. This concept can be shown in Figure 26. Please refer to COSMOLC–DE–7001(Tunable Filter Design and Development) for all details pertaining to COSMO wavelength tuning.

Figure 26 High Voltage Wavelength Tuning Concept.
HAO has legacy experience designing and fabricating wavelength tuning systems utilizing the National Instruments PXIe chassis architecture and ILX Lightwave temperature controller as shown in Figure 30:

Figure 27 National Instruments PXIe chassis solution for Lyot Filter control and image acquisition.
4.1.3 Filtergraph Camera Control

HAO will partner with GL Scientific in the packaging and control of the Teledyne Hawaii 4RG focal plane and associated ASIC readout chipsets contained into a Sterling Dewar. The camera will utilize a Cameralink full mode data interface to a PXIe Cameralink framegrabber module (NI 1483R) which is configured and controlled from the Filtergraph instrument computer.

Figure 28 Packaging and electrical interfaces to Hawaii 4RG focal plane (Teledyne) by GL Scientific
4.1.3.1 Real-Time Image Processing

In addition to the basic image acquisition, it is likely that the best scientific results will be enabled through a variety of real-time processing algorithms including:

1. Look up table (LUT) application for linearization of read-out amplifiers and removal of bit-errors
2. Aerosol (and other signal artifact) removal using digital filtering techniques implemented in an FPGA. A second order digital filter applied to individual modulation states before co-averaging would be optimal. We would need to maintain two input and two output history buffers to implement the difference equations in:

\[ y(n) = b_0x(n) + b_1x(n-1) + b_2x(n-2) - a_1y(n-1) - a_2y(n-2) \]

Where \( b_0, b_1 \) and \( b_2 \) determine zeros, and \( a_1, a_2 \) determine the position of the poles

![Figure 29 Direct form for basic 2nd order digital filter for real-time aerosol removal. Must be implemented by FPGA](image)

3. Attachment of meta-data to all images to ensure traceability including, but not limited to the following:
   - Time- and date-stamp
   - Polarization state (e.g. I+Q, I-Q …)
   - Beam ID (e.g. S-beam, P-beam)
   - Exposure Time
   - Position of Calibration diffuser (in, out)
   - Position of Calibration polarizer (in, out and angular position)
   - Position of dark shutter (in, out)

FPGA image processing will be implemented using a pair of NI 1483R plug in boards for PXIe within Figure.
4.1.4 Filtergraph Enclosure Thermal Control

The Filtergraph instrument itself will need a thermal management system for its enclosure to meet both survival and operational requirements imposed by the project. The HAO Instrumentation group has experience designing instrument enclosure thermal controls typically utilizing COTS temperature control units with appropriately sized and distributed heaters and/or fans. Proper insulation of the instrument is also a key factor in the performance of the system. An example of a legacy thermal management system designed and fabricated by HAO is shown below.
For the enclosure thermal control system, HAO will implement a four-zone PID temperature control system based upon a Rockwell Automation Micro 820. Only two of these zones are required to maintain the Filtergraph enclosure temperature (one heating and one cooling zone). The Micro 820 PLC will regulate the temperature of the internal environment through user input through the Allen-Bradley LCD touch pad and LabVIEW software. If additional zones are found to optimize the control system, the system is easily extended for that purpose.

Enclosure heating is accomplished through the application of sheet heaters mounted to the enclosure panel inner-faces, electrically connected in parallel to generate a maximum of ~80W of heating capacity. 80W is not a great amount of power so each of the panels are also insulated with Reflectix (http://reflectixinc.com) Double Reflective Insulation. The only other appreciable heat loads within the system are the Hawaii 4RG (power dissipation is TBD pending further discussions with GL Scientific) and the Lyot Filter (expected to produce ~10W at steady stage when operated at 35C within the surrounding enclosure environment of 28C. Because the Hawaii 4RG camera heat loads are expected to be significantly greater than the Lyot Filter, physical separation between the 2 subsystems would be desirable.
4.2 FILTERGRAPH OBSERVATION CONTROL

4.2.1 Observing Scripts

Filtergraph observations of the solar corona are made through the use of daily observing programs. These daily observer programs run a collection of scripts which intelligently run a collection of parameter sets that perform instrument manipulations for both observing and calibration (i.e. observation parameter sets, and calibration parameter sets). The observer will load a daily observer program (by default a synoptic observing program will be run each day) and control the GUI to execute scripts. The ICS will process an entire script, one parameter set at a time. When all of the parameter sets in a script have been completed by the Filtergraph ICS, the daily observing program will stop execution, and return the ICS to a “waiting” state.

Parameter sets can be as simple as only one command to move a filter wheel, or more complicated such as a sequence of data taken at various wavelengths. Parameter set files consist of two or three numbers separated by tabs. The first number is the function, and the second two numbers are values. The syntax of the parameter set commands is shown in Table 2. Generally, mechanism control parameter sets contain only one line, while data collection parameter sets contain many lines.

Table 2. Parameter Set Syntax

<table>
<thead>
<tr>
<th>Column 1 Value</th>
<th>Column 2 Value</th>
<th>Column 3 Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>acquire data</td>
<td>Straight/folded</td>
<td>wavelength (nm)</td>
</tr>
<tr>
<td>diffuser</td>
<td>in/out</td>
<td></td>
</tr>
<tr>
<td>calibration wheel</td>
<td>wavelength (nm)</td>
<td></td>
</tr>
<tr>
<td>filter wheel</td>
<td>wavelength (nm)</td>
<td></td>
</tr>
<tr>
<td>rotate instrument</td>
<td>angle (deg)</td>
<td></td>
</tr>
<tr>
<td>focus O1</td>
<td>focus value (mm)</td>
<td></td>
</tr>
<tr>
<td>set exposure time</td>
<td>exposuretime(ms)</td>
<td></td>
</tr>
</tbody>
</table>

For example, a parameter set to move the diffuser into the beam will have one line:

diffuser in

Note that the values are separated by a tab.

An HAO legacy instrument known as “CoMP-S” used this approach referring to parameter sets as “recipes”, and scripts as “cookbooks”. CoMP-S recipes and cookbooks are stored on Camera-2 under C:\CoMP-S Cookbooks and Recipes. This recipe is stored in the file diffuser-in.rcp. Recipes exist in C:\CoMP-S Cookbooks and Recipes to perform all basic mechanism functions.

The calibration and filter wheel positions are defined as follows:

<table>
<thead>
<tr>
<th>Calibration Wheel Positions</th>
<th>Filter Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark</td>
<td>530.3</td>
</tr>
<tr>
<td>Clear</td>
<td>587.6</td>
</tr>
<tr>
<td>Exchange Lens</td>
<td>637.5</td>
</tr>
</tbody>
</table>
Another example is a recipe to obtain images at 5 wavelengths separated by 0.1 nm in the vicinity of the 656.3 H-α line. This would look like:

<table>
<thead>
<tr>
<th>Action</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>acquire data straight</td>
<td>656.1</td>
</tr>
<tr>
<td>acquire data straight</td>
<td>656.2</td>
</tr>
<tr>
<td>acquire data straight</td>
<td>656.3</td>
</tr>
<tr>
<td>acquire data straight</td>
<td>656.4</td>
</tr>
<tr>
<td>acquire data straight</td>
<td>656.5</td>
</tr>
<tr>
<td>acquire data folded</td>
<td>656.1</td>
</tr>
<tr>
<td>acquire data folded</td>
<td>656.2</td>
</tr>
<tr>
<td>acquire data folded</td>
<td>656.3</td>
</tr>
<tr>
<td>acquire data folded</td>
<td>656.4</td>
</tr>
<tr>
<td>acquire data folded</td>
<td>656.5</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Note that this recipe first takes images in all four modulation states tuned to 656.1 nm, followed by 656.2, etc. The beam set to “straight” causes the stated wavelength to be tuned onto the straight through camera (#2) and the continuum bands to be tuned on the folded camera (#1). The sense of the wavelength tuning on the cameras is swapped by setting the beam to “folded”; the wavelengths here are scanned again with the beams swapped. Note that data recipes have an extra line as the last line of the cookbook. It contains a 0, the number of lines in the recipe (here 10), and the number modulation cycles to observe. Since it is 1 here, this recipe will obtain 4 images (one for each modulation cycle) in each of the 10 wavelengths, for a total of 40 images. Setting the last number on the last line to 2 would cause the recipe to obtain 2 sets of 4 modulation cycles in each wavelength for a total of 80 images. This recipe is stored as 656-scan_5.rcp.

Cookbooks (.cbk suffix) are ascii text files containing one or more lines each with the file name of a recipe. As an example, a cookbook that would put the calibration wheel in the open position, put the 656.3 interference filter in the beam and scan the 656.3 line using the recipe above would look like:

cal-open.rcp
filter-656.rcp
656-scan_5.rcp
4.2.2 Filtergraph Timing and Synchronization

As with all Large Coronagraph facility instrument systems, all time shall be based on a standard Universal Time Clock (UTC). All data posted to SCADA computers from all subsystems shall report time stamps along with the posted data. The following timing diagrams have been generated to show the synchronization patterns needed for the different optical elements and mechanisms used on the Filtergraph.

1. Initial Setup
2. Standard Observation Sequence
3. Calibration Sequence
### Figure 34 Timing Diagram Setup Phase

<table>
<thead>
<tr>
<th>Time Requirement [seconds]</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cameras 1 &amp; 2</td>
<td></td>
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<td></td>
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<tr>
<td>Modulator</td>
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<tr>
<td>Safety Shutter</td>
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<tr>
<td>Diffuser Insertion</td>
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<tr>
<td>Occultor Size Control</td>
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<tr>
<td>Insertion Calibration</td>
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<tr>
<td>Optic #1</td>
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<tr>
<td>Rotation Calibration</td>
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<tr>
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<tr>
<td>Filtergraph Focus</td>
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<td>Pre-Filter Selector</td>
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<tr>
<td>Pre-Filter Insertion</td>
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<td>Lyot Stop Focus</td>
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<tr>
<td>Camera #1 and #2 Focus</td>
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</table>
Figure 35 Filtergraph Timing Diagram Standard Observation
### Polarimetric Calibration Recipe

<table>
<thead>
<tr>
<th>Time Requirement [seconds]</th>
<th>0</th>
<th>5</th>
<th>X</th>
<th>X+1</th>
<th>Y</th>
<th>Y+1</th>
<th>Z</th>
<th>Z+1</th>
<th>ZZ</th>
<th>ZZ+1</th>
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<td>Camera #1 and #2 Focus</td>
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Figure 36 Filtergraph Timing Diagram: Typical Calibration Sequence
4.2.3 Filtergraph Instrument Software Architecture

The Filtergraph instrument control software is an independent system for acquiring coronal imagery from the LC Filtergraph camera systems. It uses the “command”, “acknowledge” software architecture described in section 1.

4.2.3.1 Software Development Environment

The COSMO Large Coronagraph is the evolutionary next step from HAO’s Coronal Multi-Channel Polarimeter (CoMP) instrument and the software development shall continue from this foundation. The LC Filtergraph Control Software shall be written using either an object oriented language such as C++ or an interpretive language such as LabVIEW running on a 64-bit Windows operating system. Additionally, the ICS will utilize C/C++ DLL’s for low level image acquisition and real time processing.

4.2.3.2 Software Design Pattern

C++ design patterns are class-based. A Class contains all methods and attributes of an entity. Subclasses inherit all methods and attributes from their parent classes and extend new methods and attributes for unique attributes for specific implementations. This allows highly efficient coding as each hardware component is an instance of the same identical C++ code with only a few changes in attributes and extended methods. Multithreading in C++ is robust and predictable. Thread priorities may be set to insure low priority threads do not interfere with the execution of time critical threads. Rendezvous of separate threads (i.e. parallel motions of hardware, monitoring of environment, etc) is easily accomplished using mutexes. Socket based communications to sub-systems are easy and transparent. Parsing of scripts into C/C++ code is easily implemented using pointers to functions. HAO has a wealth of C++ code which has done part or all of the above and can be easily adapted.

Using LabVIEW, design patterns are standard VI (virtual instrument) architectures that solve common software design problems. They represent techniques which have proven themselves time and time again having evolved from the efforts of many developers. Utilizing design patterns promote reuse, productivity, communication and quality. Various design patterns and their higher level cousins ‘application frameworks’ are discussed in various places including “The LabVIEW Style Book by Peter Blume” and from within the NI Developer Zone.

The LC Filtergraph ICS has 6 principal functions:

1. Process observation scripts to control the overall integration of dome, mount, large coronagraph and filtergraph control systems to obtain Level-0 data products for scientific analysis as defined in the Concept of Operations Document.
2. Utilize PXIe hardware and multifunction DAQmx routines to generate the required polarization modulator control voltages, and the associated camera trigger and synchronization digital I/O signals.
3. Interfaces to the camera API to initiate camera exposure sequences and any required real-time acquisition processes (e.g. bit error correction, polarization state accumulation, etc.)
4. Performs mechanism control of the filtergraph stages and emission line filter station.
5. Calls Large Coronagraph control system routines for overall observation sequence control (e.g. diffuser and calibration optic manipulations, occulter station control, etc.)
6. Monitor engineering and environmental data from the instrument.
7. Respond to observer input using a graphical user interface (GUI).
8. Receive, process and log Alarm and Error events.
The basic design pattern proposed for use by the LC Filtergraph ICS is a multi-threaded “Event-Driven State Machine” or the “Event Machine”. An event structure is used to capture GUI events in a very efficient manner (no polling necessary). It also serves as a state queued state machine in that both GUI events and User events (custom defined events) are created, registered and fired programatically.

Separate threads monitor GUI inputs, script importation and execution, hardware motions, camera exposures, environmental monitoring and writing of data to disk. Thread priorities are set to insure time critical functions are not hindered and there is no data loss. Messaging between threads are handled efficiently by non-poled signals such a mutexes.

An additional part of the design will use initialization files or a ‘database’ which will contain, for example mappings of:

- filter wavelengths to the position of those filters in a filter wheel
- camera serial numbers
- motor encoder counts to scientific units (mm or In/Out)
- motor limits
- desired temperatures and limits
- which mechanisms are running and operational.

(Note: This is not a complete list).

This design maximizes overall performance and efficiency. It allows a framework for graceful and organized expansion to unanticipated requirements.

4.2.3.3 High Level Filtergraph Control

The LC Filtergraph Control Software shall perform the following functions.

1. Startup ICS
   a. Control Dark Shutter (In)
   b. Control Diffuser (In)
   c. Control Calibration Optics (In)
   d. Send Startup message to observer log

2. Shutdown ICS
   a. Control Dark Shutter (In)
   b. Control Diffuser (In)
   c. Control Calibration Optics (In)
   d. Send Shutdown message to observer log
   e. Control Modulator (off)

3. Monitor ICS
   a. Monitor Mechanism States (In/Out/Position/Limits)
   b. Monitor UPS Status
   c. Monitor Dome HEPA status
   d. Monitor PXI Chassis Status
   e. Monitor Modulator Temperature
   f. Monitor Telescope Pointing Control System Updates
   g. Monitor Spar Guider and solar disk brightness intensity (if implemented)
   h. Send Engineering Data message to engineering data log

4. Acquire LC Filtergraph Calibration Data Set
a. Control Dark Shutter (In)
b. Control Dark Shutter (Out)
c. Control Diffuser (In)
d. Control Calibration Optics (In)
e. Load Calibration Sequence (angles, exposure times, delays, etc.)
f. Control Cameras (Set cameras…)
g. Control Modulator (Turn Modulator Waveform ON)
h. Control Cameras (Grab Image Sequence (triggered) (a sequence can be a sequence of 1)
i. Control Calibration Optics (Out)
j. Control Diffuser (Out)

5. Start Synoptic Mode
   a. Control Shutter (Out)
b. Control Diffuser (Out)
c. Dark Shutter (Out)
d. Control Calibration Optics (Out)
e. Control Cameras (Setup Acquisition)
f. Control Modulator (Turn Modulator ON)
g. Control Cameras (Grab Image Sequence)
   i. Data Processing (Create and Save FITS)
   ii. Monitor ‘Stop Synoptic Observations’ Interrupt from GUI
   iii. Monitor ICS (and update engineering log)
   iv. Update Display

6. Testing Software Modules
   a. Acquire Photon Transfer Curve Data
   b. Exercise Shutter
   c. Exercise Diffuser
   d. Exercise Calibration Optics
   e. Exercise O1
   f. Exercise Camera Stations

7. UPS Control and AC Power Control via Pulizzi
   a. Sense UPS Capacity
   b. Graceful shutdown of AC power systems in case UPS battery is < 10% capacity

4.2.3.4 Low Level Filtergraph Control
The following lower level routines will be used to control specific mechanisms and to interface with other observatory software control sub-systems.

1. Monitor Power System
   a. Monitor Power Distribution System Voltages
   b. Monitor UPS Status
   c. Send Power Distribution System warning to observer log
2. Monitor HEPA System
a. Monitor HEPA status by measuring and plotting the absolute pressure gauge at the HEPA fan outlet (monitors action) and by measuring and plotting the differential pressure gauges across the HEPA filter (monitors cleanliness)

b. Send HEPA warning to observer log

3. Monitor PXI System (if applicable)
   a. Monitor PXI Chassis status (voltages, temperatures)
   b. Send PXI Chassis warning to observer log

4. Control Lens Cover
   a. Move Lens Cover In
   b. Move Lens Cover Out
   c. Sense Lens Cover In
   d. Sense Lens Cover Out
   e. Send Lens Cover Warning to observer log

5. Control Diffuser
   a. Move Diffuser In
   b. Move Diffuser Out
   c. Sense Diffuser In
   d. Sense Diffuser Out
   e. Send diffuser warning to observer log

6. Control Calibration Optics
   a. Move Cal Optics In
   b. Move Cal Optics Out
   c. Home Cal Rotate
   d. Rotate Cal Optics
   e. Sense Cal Optics In
   f. Sense Cal Optics Out
   g. Monitor Cal Optics Rotation Encoder
   h. Send cal optics warning to observer log

7. Control Camera Stations
   a. Adjust Camera 1 Focus
   b. Adjust Camera 2 Focus
   c. Sense Camera 1 Fore Limit
   d. Sense Camera 1 Aft Limit
   e. Sense Camera 2 Fore Limit
   f. Sense Camera 2 Aft Limit
   g. Send camera station warning to observer log

8. Control Modulator
   a. Turn Modulator Waveform ON
   b. Turn Modulator Waveform OFF
   c. Monitor Modulator Temp & Power (via ILX Lightwave using USB interface)
   d. Send modulator warning to observer log

9. Control Dark Shutter
   a. Close Dark Shutter
   b. Open Dark Shutter
   c. Sense Dark Shutter Open
d. Sense Dark Shutter Closed
e. Send dark shutter warning to observer log

10. Monitor Spar Guider
   a. Monitor Spar RA Error Signal
   b. Monitor Spar DEC Error Signal
   c. Monitor Sky Transmission Signal
d. Send spar guider warning to observer log

11. Monitor Data Storage System
   a. Sense Data Storage Status (connected/disconnected)
b. Sense Data Storage read/write speed
c. Sense Data Storage Remaining Space
d. Send Data Storage Warning to observer log

12. Control Cameras
   a. Open/Initialize camera 1
   b. Open/Initialize camera 2
c. Set camera 1 exposure time
d. Set camera 2 exposure time
e. Set camera 1 trigger mode and delay
f. Set camera 2 trigger mode and delay
g. Grab Image Sequence camera 1 (free running)
h. Grab Image Sequence camera 2 (free running)
i. Grab Image Sequence camera 1 (triggered)
j. Grab Image Sequence camera 2 (triggered)

13. Data Processing (Low Level)
   a. Create FITS
   b. Save FITS to Data Storage System

14. Update Display
   a. Update raw FITS images every 15 seconds
   b. Update Disk Storage System status (space remaining)
c. Update Housekeeping Data Displays

15. Real-Time Interface (Maintenance and Troubleshooting)
   a. Update LUT
   b. View LUT
c. View Timestamp/Modulation State
4.2.3.5 Filtergraph Graphical User Interface Prototypes

A COSMO Filtergraph GUI might look something like the following (developed for an earlier Lyot Filter coronagraph project)

![Figure 37 Prototype COSMO Filtergraph Instrument Control System GUI](image1)

![Figure 38 Filtergraph engineering housekeeping GUI prototype](image2)
Figure 39 GUI - Low Level Camera Control Tab

Figure 40 GUI - Modulation Tab
4.2.3.6 **Synoptic Operations Display**

The main ‘script’ based operational mode will have its own, simplified display for use by observers. It will permit just a few basic operations:

1. Load Operations Script
2. Run Script
3. Stop Script
4. Shutdown and Stow Instrument

Each of the operations are scripts that configure the instrument, insert and rotate optics, set camera exposure parameters, etc. These scripts are text based, and easily editable by scientists and observers. Backup copies of all scripts and other configuration information will be supported.

![Filtergraph Cookbook Interface Design](image)
5 COSMO SOFTWARE DEVELOPMENT PLAN

The suite of software control systems required for the COSMO Large Coronagraph will likely be developed by multiple independent software teams whose overall actions will be coordinated by the COSMO management team at the High Altitude Observatory as shown below in Table 3.

Table 3 Large Coronagraph Software Development Plan Overview

<table>
<thead>
<tr>
<th>Software Sub-System</th>
<th>Lead Developer</th>
<th>Main Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dome Control</td>
<td>Dome Vendor</td>
<td>None forseen</td>
</tr>
<tr>
<td>Equatorial Mount Control</td>
<td>Mount Vendor</td>
<td>10 arc second blind pointing accuracy requirement and 1 arc-second RMS pointing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>stability over 10-minutes</td>
</tr>
<tr>
<td>Large Coronagraph Control</td>
<td>HAO Instrumentation Group</td>
<td>Safety Shutter Operation, Occulter System Thermal Control</td>
</tr>
<tr>
<td>Filtergraph Instrument Control</td>
<td>HAO Instrumentation Group and GL</td>
<td>Camera Readout Development</td>
</tr>
<tr>
<td></td>
<td>Scientific</td>
<td></td>
</tr>
<tr>
<td>Environmental Monitoring and Control</td>
<td>HAO Instrumentation Group</td>
<td>None forseen</td>
</tr>
<tr>
<td>Data Handling (On-Mountain)</td>
<td>COSMO Group</td>
<td>Developing reliable, high capacity data transfer systems</td>
</tr>
<tr>
<td>Pipeline and Science Data Processing</td>
<td>COSMO Group</td>
<td>Developing reliable, high capacity data transfer systems</td>
</tr>
<tr>
<td>COSMO Safety System</td>
<td>HAO with Vendor Input</td>
<td>Software will only be used for monitoring purposes.</td>
</tr>
</tbody>
</table>
5.1 SOFTWARE QUALITY PLAN

5.1.1 Revision control policy
All LC Filtergraph software module source code will be revision controlled using the NCAR supported Subversion software control system. All team members will be given training on how to use this system.

5.1.2 Software Review Policy
Code will be reviewed by at least one member of the NCAR staff not responsible for writing the code itself. All software modules will furthermore be subject to internal review both at the architecture level as well as the detailed implementation level. The basic guidelines for a code review will include:

- Identifiable location within the overall system architecture based on the top level software flow diagram
- Readability (including comments and notes residing in the code itself)
- Modularity (can individual sections of the code be independently tested and verified)
- Scalability (can the software be easily scaled/extended for future performance enhancements)

5.1.3 Software Verification and Validation Plan
Software modules will be tested individually before being assembled to work as a system. When hardware interfaces are utilized, software/hardware systems should be tested and verified with stand alone test code. Software should be tested by someone other than the code writer to account for usability and robustness.

5.1.4 Software Documentation
Hard copies of the following will reside at both COSMO and at HAO. An electronic PDF distribution will also be made available on line within the HAO firewall.

1. LC Filtergraph Observer’s Manual
2. LC Filtergraph Electrical Documentation Data Set
3. LC Filtergraph Mechanical Documentation Data Set
4. LC Filtergraph Deployment Test Results (Baseline Instrumental Performance)

5.1.5 Software Maintenance and Distribution Plan
As features or bugs become identified and documented (again, utilizing NCAR’s subversion system). The HAO staff will prioritize and identify upgrade paths. These will be made either at HAO or at COSMO depending on the nature of the upgrade. Following a successful upgrade, an updated version of the software module will be committed to the subversion vault. Decisions regarding substantial operating system or SDK upgrades will be made only after conferring with all of the stakeholders and be limited to situations where clear advantage can be had or where obsolescence or lack of support make upgrading imperative.

The LC Filtergraph software will be distributed and installed by HAO staff members. Since it will be revision controlled under NCAR’s Subversion system, distribution and installation will start by checking out the most recent ‘working’ copy from the vault on site (either from COSMO in the case of the instrument control software module or at HAO for subsequent processing modules).
• Upgrades will be distributed over the internet facilitated by NCAR’s Subversion System.

• Recalling that our release nomenclature consists of a X.Y.Z designation. Where ‘X’ is a major revision, ‘Y’ is a moderate revision (increased functionality) and ‘Z’ is a minor update (e.g. cosmetic or display based). The Instrument PI is the only person able to authorize the installation of an upgraded version at the ‘X’ and ‘Y’ levels. Staff engineers are authorized to upgrade the system at the ‘Z’ level. All planned upgrades must be vetted by the LC Filtergraph email list prior to implementing!

• Upgrades will be performed at night so as not to impact observations.