Development and Deployment of Remotely Operable Optical Communication Terminals

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Outline

- System Overview
- Installation
- Opto-mechanical Design
- Hardware Architecture
- Software Architecture
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Optical Ground System Overview

Drivers

- Until 2021, all lasercomm capable AeroCubes serviced by a single, manually operated terminal located in El Segundo, CA.
- Limited pass opportunities due to weather events and significant labor investment made system prohibitive for running regular passes on multiple vehicles.
- To address this, we installed two remote optical ground terminals in Maui, HI and Albuquerque, NM. with third planned at a TBD location.

Objectives

- Sites with minimal annual precipitation and geographically dispersed locations that are independent from one another's weather systems.
- Economical design using COTS components to the greatest extent possible yielding a total cost for three stations of under $1 million dollars.
- Operates via REST API that lends itself to minimal manual input and high degree of automation.
- Design supports receive only so Laser Clearinghouse (LCH) and Federal Aviation Administration (FAA) coordination aren't necessary for the ground segment, greatly reducing regulatory requirements.

Dome and electronics enclosure At Albuquerque, NM site.

Alternate view with dome open showing telescope assembly.

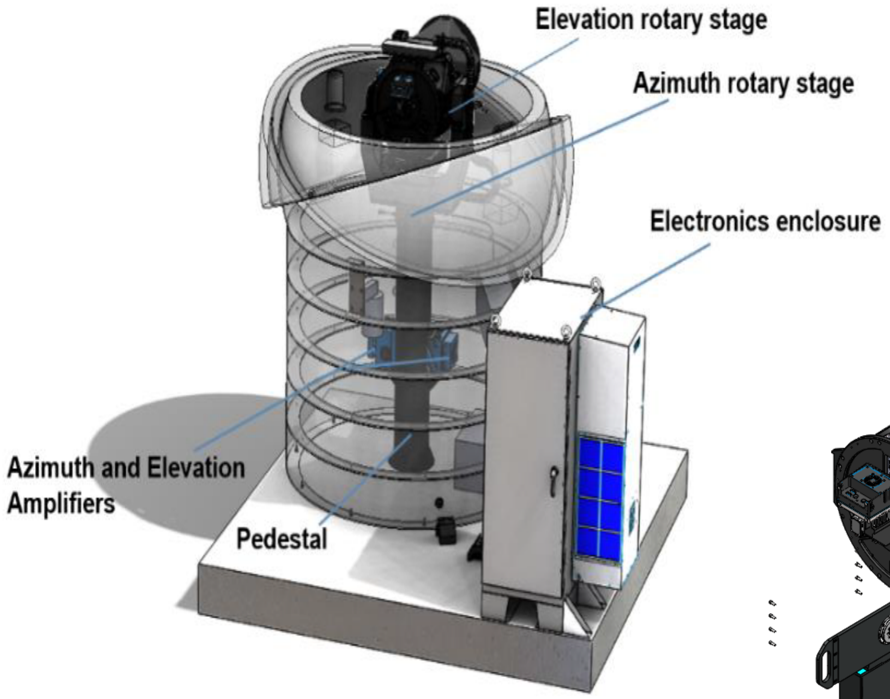
Optical Ground System Overview

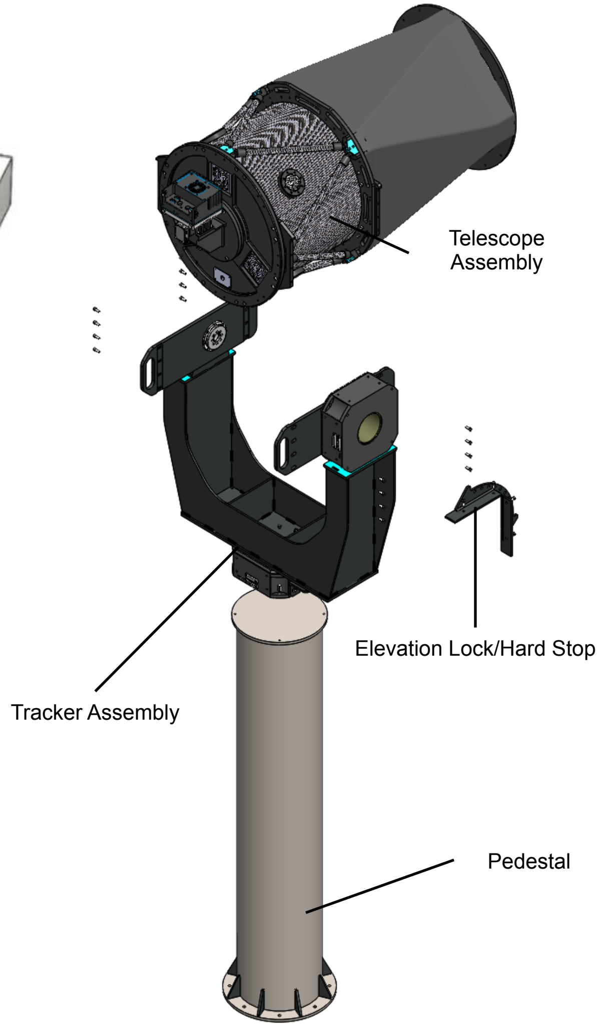
- Two exterior components, 7ft diameter Astro Haven clamshell dome and a 60”x24”x34” electronics housing enclosure mounted on 10’x10’ concrete pad connected by weatherproof conduit.

- 17 inch Planewave telescope mounted on an in-house fabricated, welded aluminum gimbal equipped with two azimuth and elevation Aerotech rotary stages. The azimuth and elevation drive amplifiers are mounted to the pedestal.

- Telescope normally operates over a field of regard of AZ=[-270,+270], EL=[0,70]deg. The AZ range is mechanically limited by specially designed rocker stops.

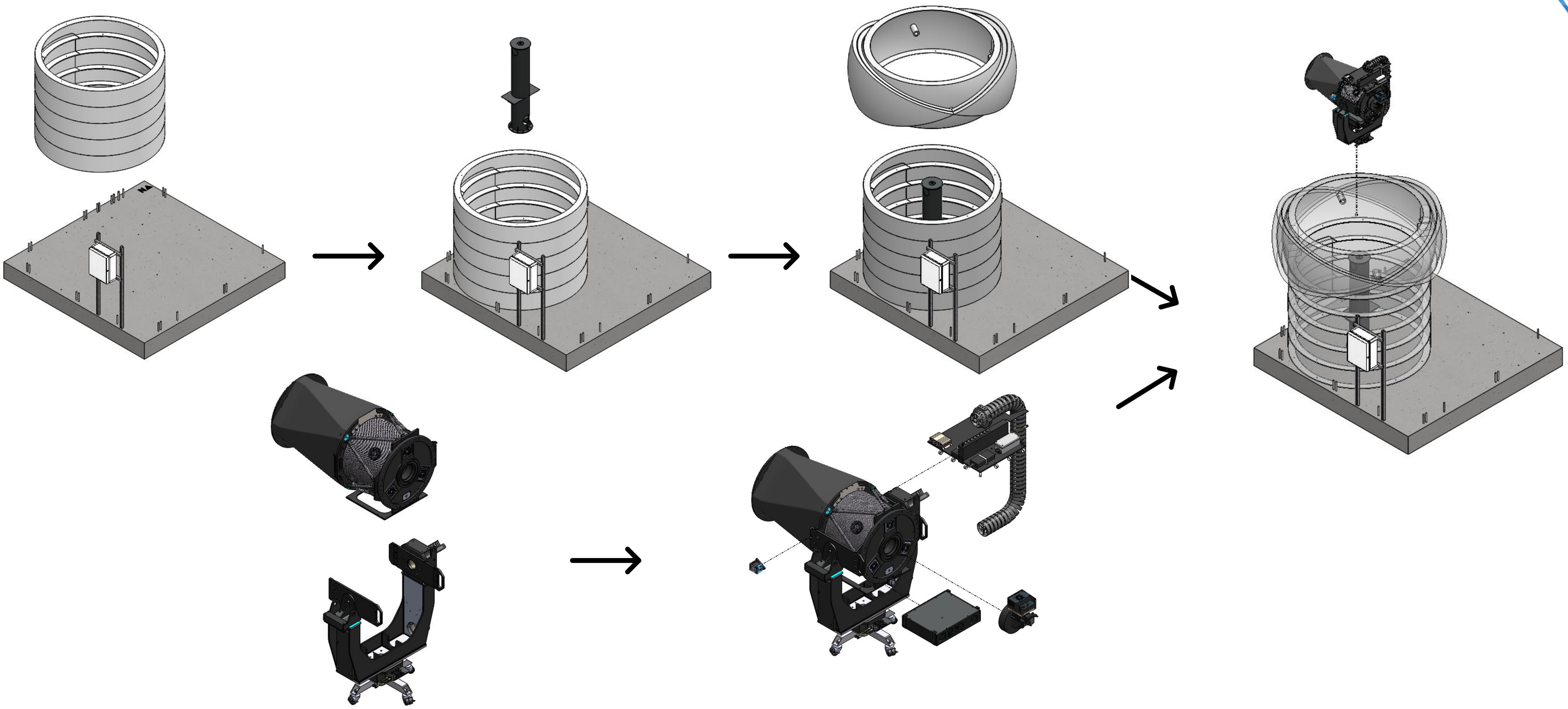
- rocker stops are also equipped with proximity sensors, whose signals provide coarse position information to the control software during start-up.





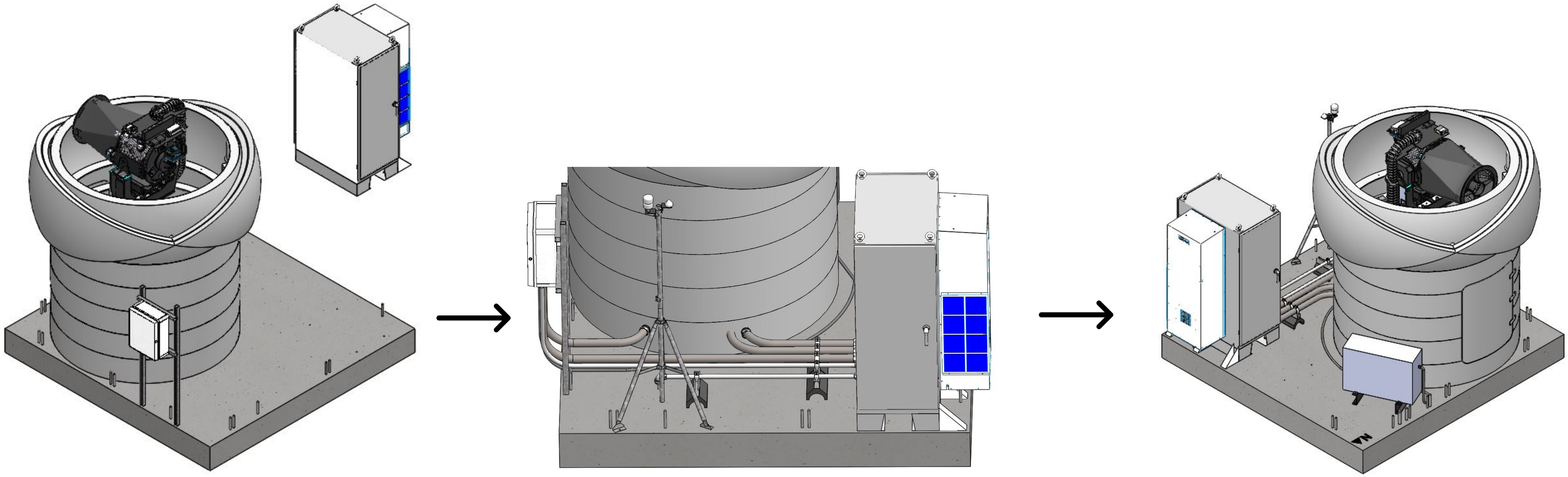
Terminal Installation

Mechanical Assembly



Terminal Installation

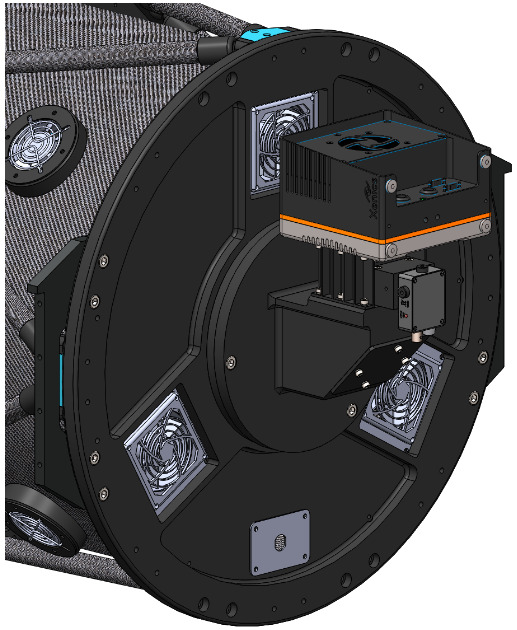
Mechanical Assembly

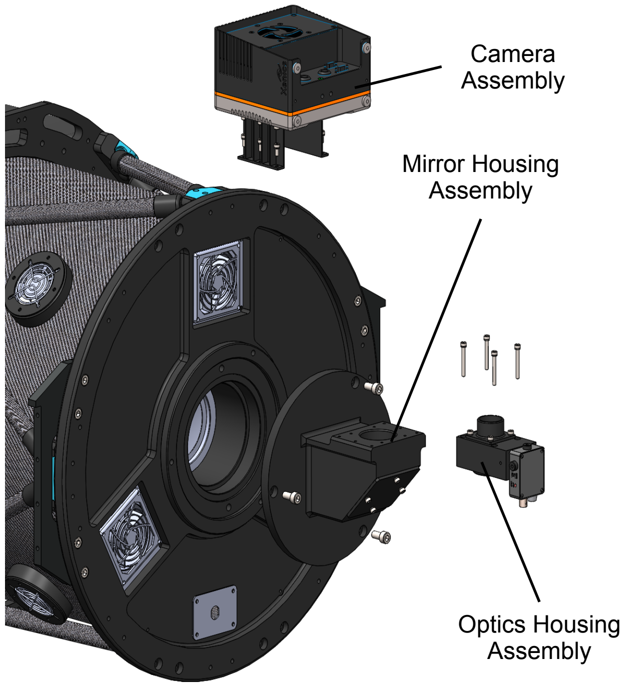


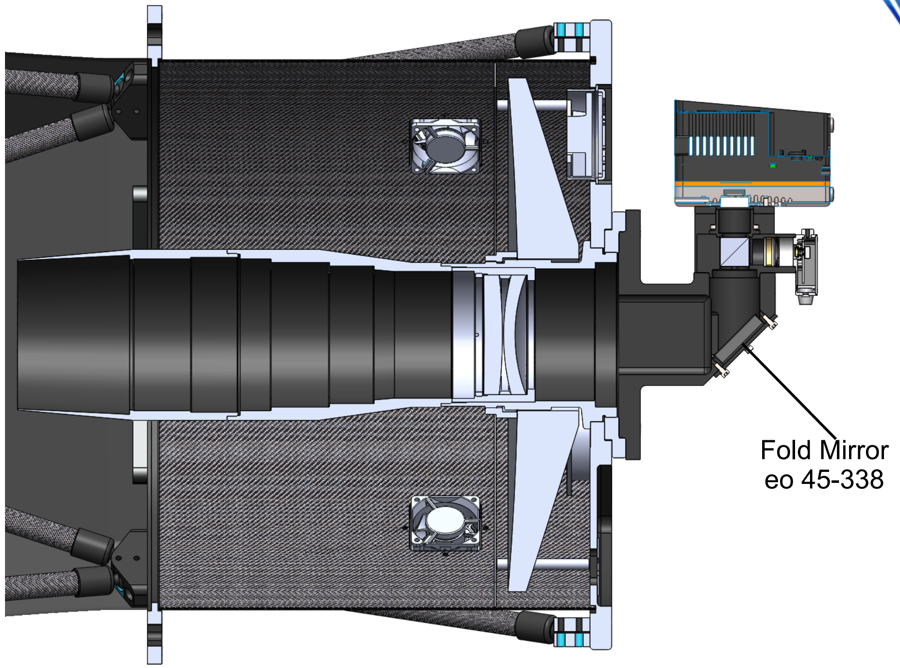
- Mechanical assembly is the first phase of installation, performed by up to five people and a forklift over the course of a week, excluding concrete pad which is poured in advance.
- Additional support from contractors for electrical panels, HVAC systems, and network support.

Opto-mechanical Design

Design Mirror Housing and Camera Assembly







Comprised of the mirror housing, optics housing, and camera subassemblies

Mirror Housing

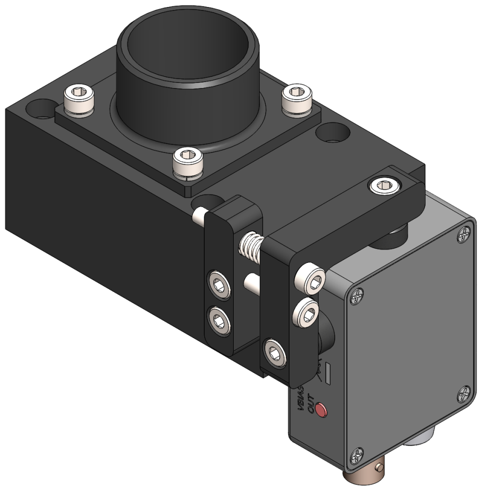
- Fixed to the back of the telescope and provides mounting locations for the other two subassemblies. It contains a fold mirror which directs the optical path to a 1″ Thorlabs BS030 non-polarizing beam splitter inside the optics housing subassembly.

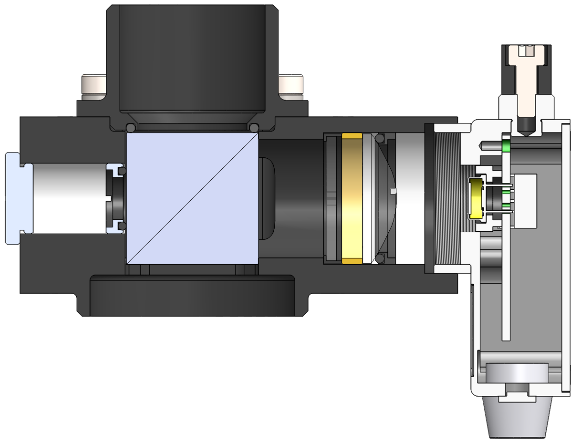
Camera Assembly

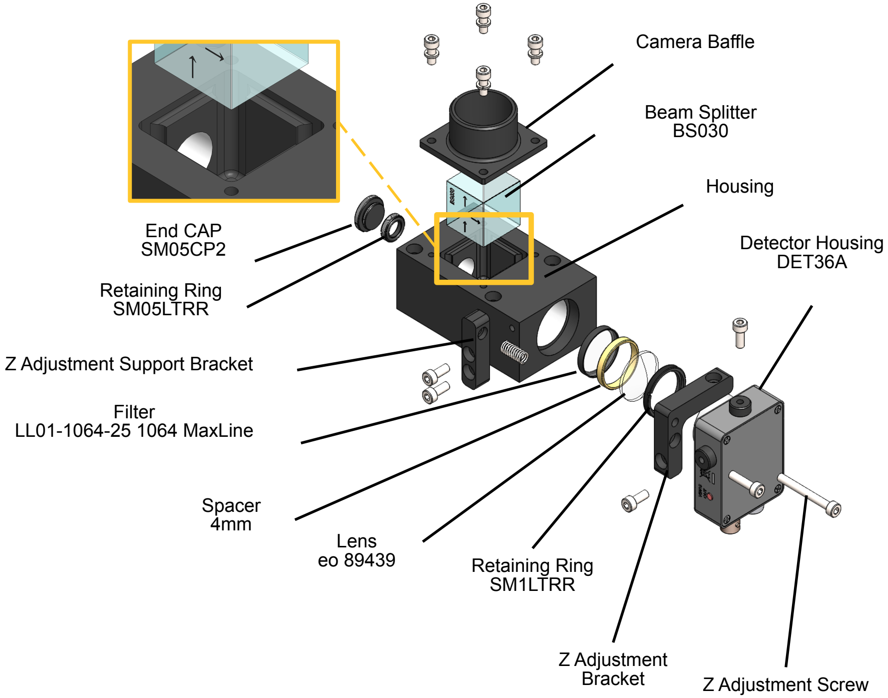
- NFOV camera is a Cheetah 640 TE1 400, mounted to the mirror housing assembly with its line of sight perpendicular to that of the APD in the optics housing.

Opto-mechanical Design

Optics Housing Assembly





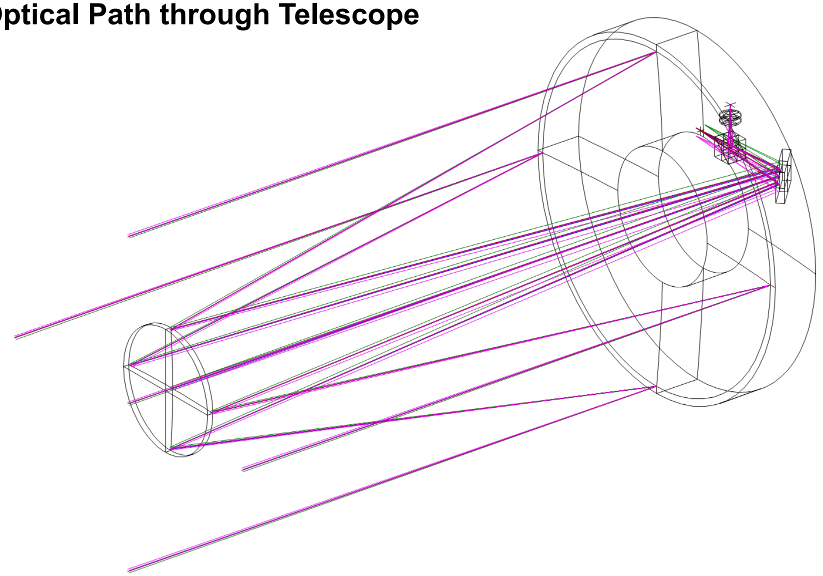


- Optical path to the APD includes LL01-1064-25 1064 MaxLine bandpass filter and a lens with v-coating optimized for 1064nm. Lens focuses the signal onto the APD enclosed in the detector housing.
- The detector housing is mounted on a z-translation stage, which provides APD focus adjustment.

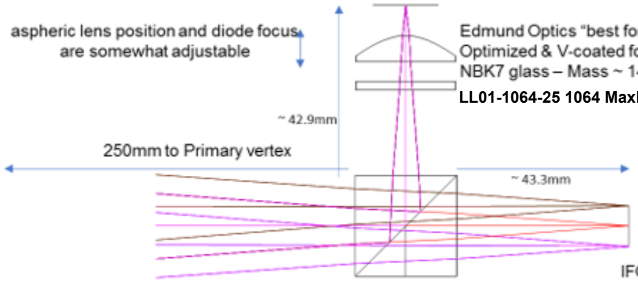
Opto-mechanical Design

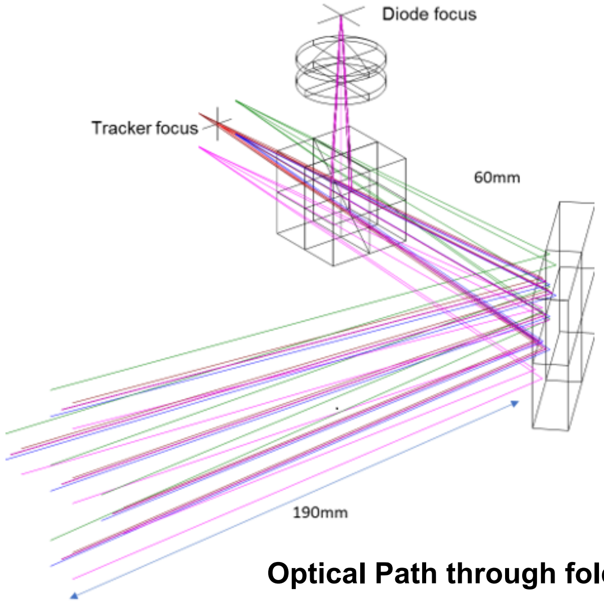
Optical Path

Optical Path through Telescope



Optical Path through beamsplitter, APD, and NFOV





Optical Path through fold mirror

Portion of Optical Path	Transmittance
Central obstruction of primary mirror	~84%
Primary, secondary, and fold mirror optical reflection	~84%
Beam Splitter	10% to NFOV, 90% to APD
Band pass filter (APD only)	95%
Total path to APD	**60.3%**
Total path to NFOV	**7.1%**

Transmission loss along optical path

System Design

Tracking Hardware Architecture

Brandywine Communication NFS-220

- 1 PPS, 10 MHz, and UTC Time to Timing Box.
- IRIG-B to SYNCCLOCK32 card in Tracking PC

Timing Box

- Appends GPS time stamps to incoming frames from the NFOV and WFOV and then to respective frame grabbers
- Allows the Camera Software to correlate the time of each frame with the extracted centroids.

Camera PC

- WFOV and NFOV Camera Software applications for processing frames, extracting centroids.

Tracking PC

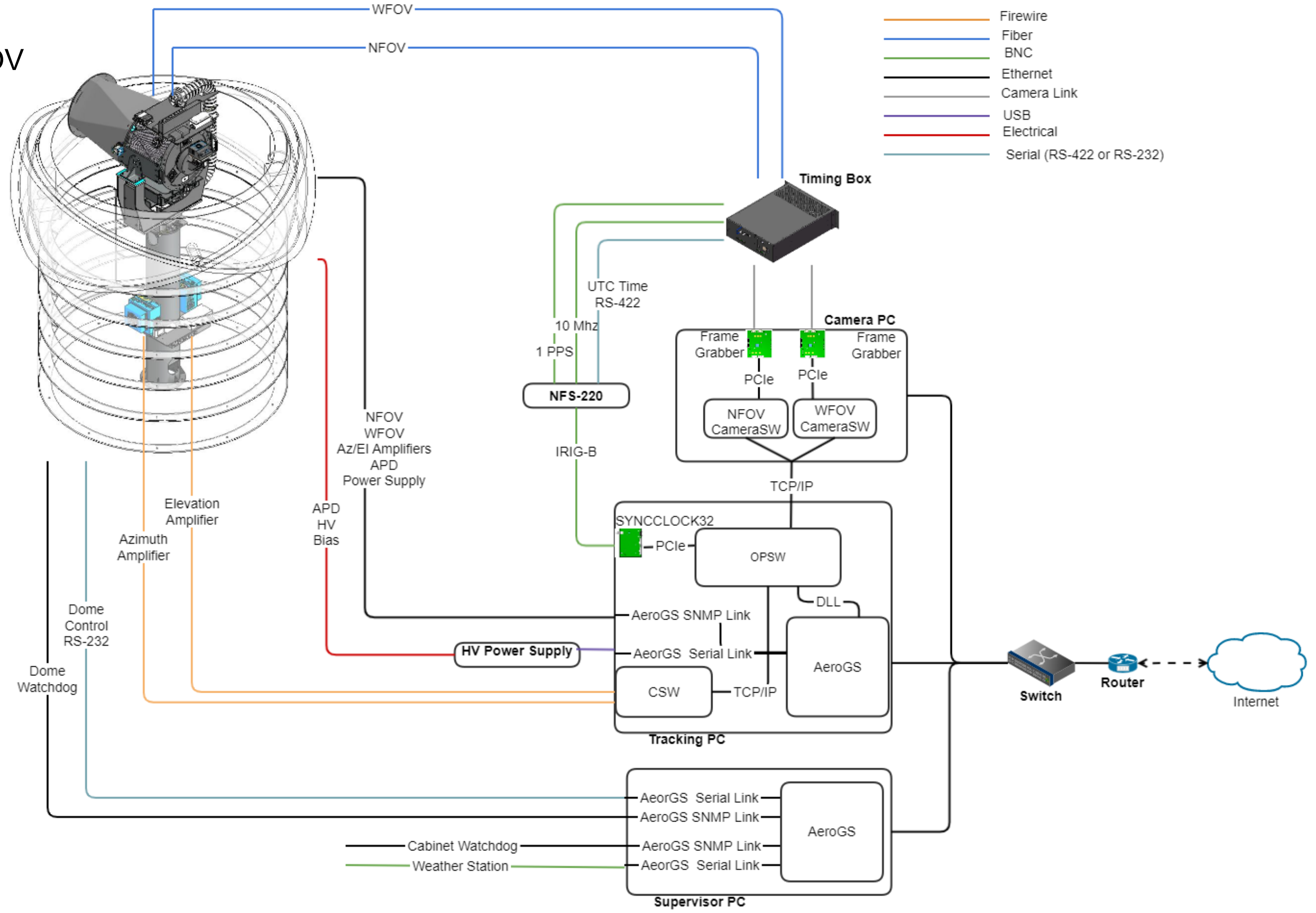
- Hosts AeroGS instance, OPSW, and CSW applications.
- Receives Telescope C&C commands from remote user which are processed into gimbal Az/El commands by the OPSW and CSW.
- Commanding for high voltage power supply and network PDU's providing power to hardware in the dome.

Supervisor PC

- Facilitates dome control and return dome and electronics enclosure temperature/humidity telemetry in addition to weather data.

High Voltage Power Supply

- Provides bias voltage to APD.
- Bias voltage level dependent on APD modal and ambient temperature.



System Design

Closed and Open Loop Tracking Software Architecture

AeroCube Ground Software (AeroGS)

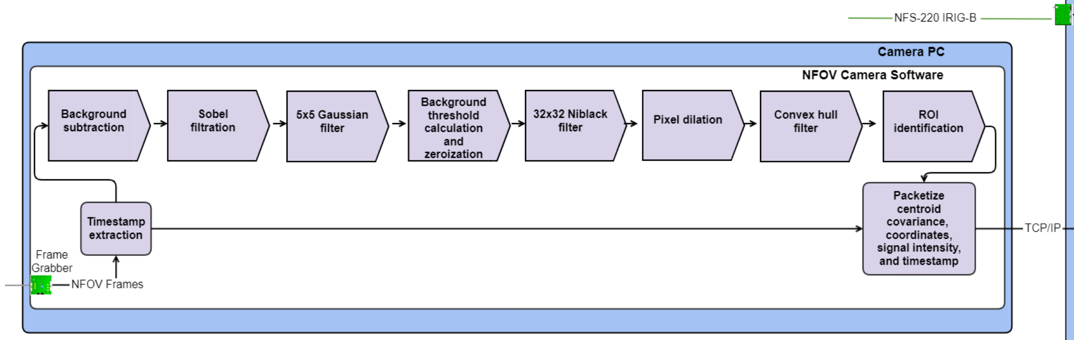
- Modular and extensible python platform that facilitates ground segment services
- Acts as C&C interface between user and telescope as well as peripheral devices
- Instances of AeroGS are run as aiohttp servers, exposing services via REST API
- User defined configuration files contain software or device-specific interface parameter

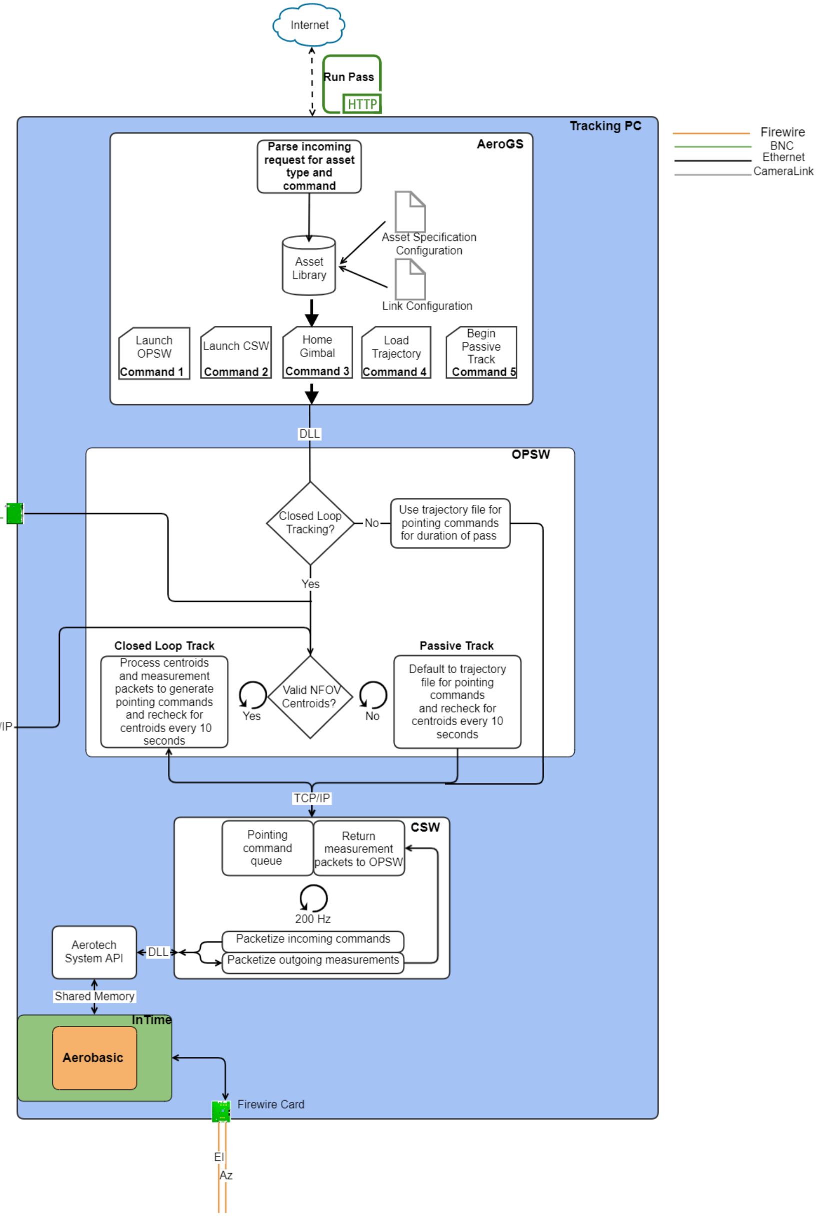
Camera Software

- Identifies region of interest in incoming camera frames and sends packets containing centroid coordinates, covariance, signal intensity, and associated timestamp to OPSW.

Operational Software (OPSW)

- Responsible for interfacing with the system hardware, processing centroid data from the cameras and controlling the gimbals to follow tracked objects.



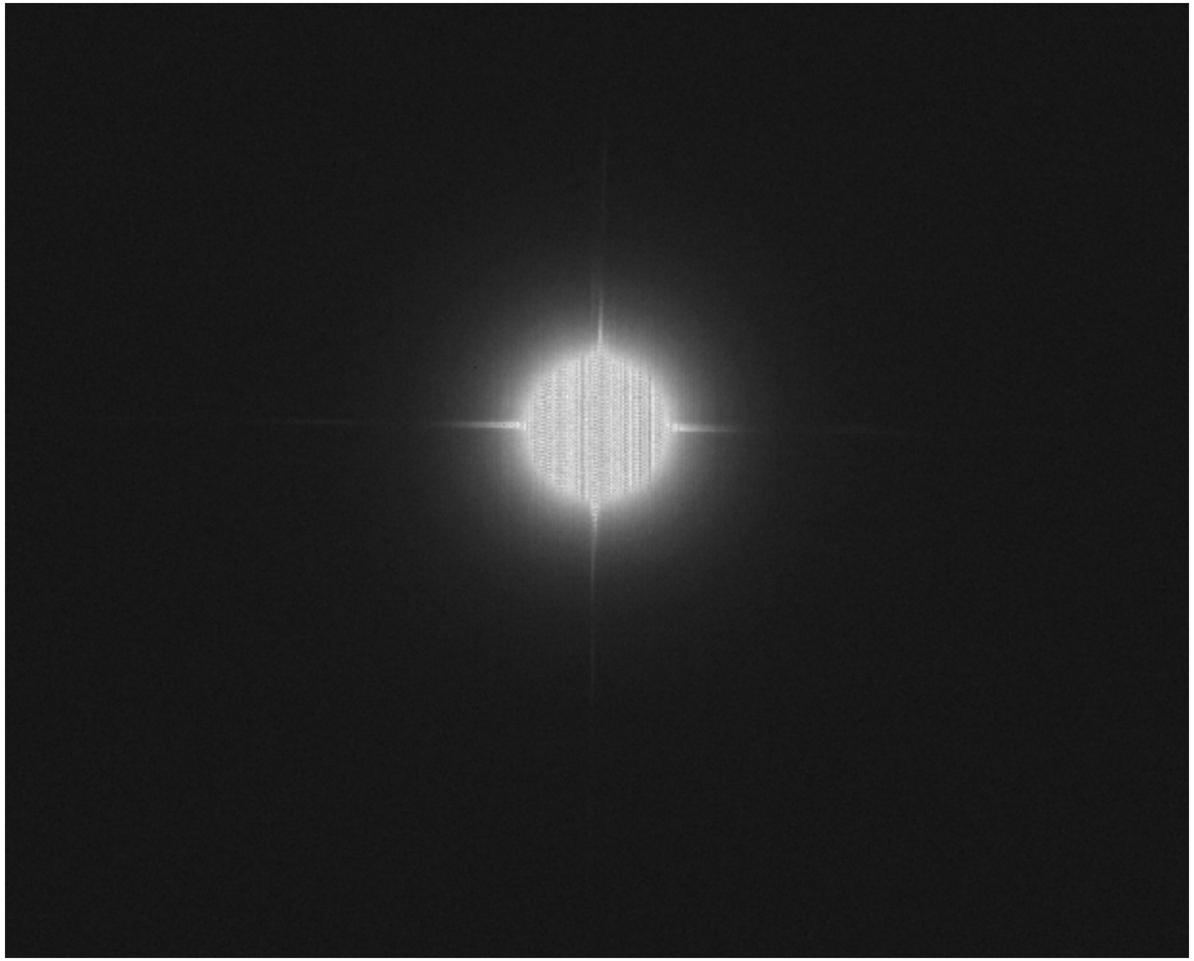


Controls Software (CSW)

- Provides an interface between the OPSW and the gimbal hardware.
- Continuously poll a TCP/IP message buffer for messages from the OPSW for commands CSW transforms these commands to gimbal motor commands using a gimbal pointing model containing misalignment terms calibrated against off-line stellar observations.

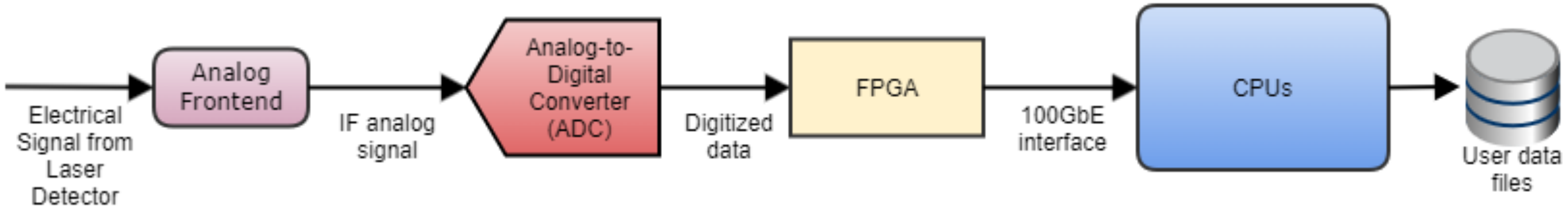
- AeroCube-15B laser post NFOV Camera Software image processing.

- Seen by NFOV Cheetah 640 TE1 400 SWIR camera with an integration time of 20 millisecond during downlink at Albuquerque, NM terminal



Modem Hardware

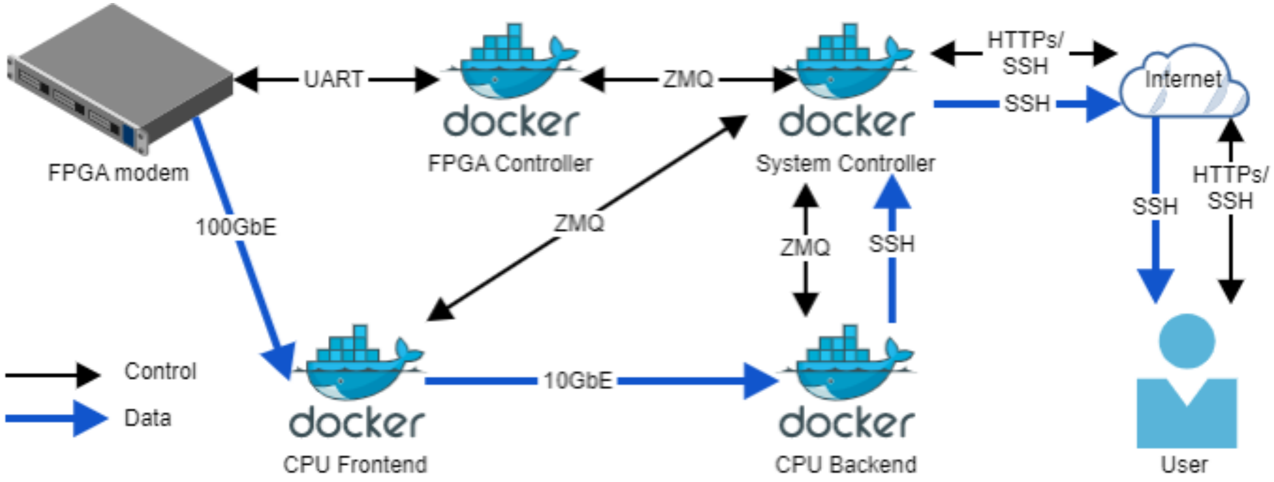
Architectural Overview



- Consists wholly of COTS components
- Receives On-Off-Keyed signals from the APD via BNC
- Handles clock recovery, low-density parity-check, error correction decoding, HDLC packet extraction, and file handling, with the result being files which hold mission data from the satellite.
- An analog frontend converts the baseband electrical signal from the laser detector into an intermediate frequency for digitization by the analog to digital converter.
- 5Gsps ADC produces digitized samples of the analog input.
- . The FPGA handles sample-rate signal processing of the raw data including digital IF demodulation, timing and tracking, line-decoding, error-correction block synchronization, and data packetizing
- CPUs handle symbol-rate and bit-rate processing and file handling which includes forward error correction decoding, linear feedback shift register synchronization for bit error rate measurements, HDLC packet deframing, and file handling. Finally, CPUs run the user interface and allows remote network access operation of the modem.

Modem Operations

Data Flow and Control



System Controller

- Provides the HTTP RESTful interface for user. Internally, the System Controller converts the HTTP commands into custom component-specific commands which are sent using ZMQ (ZeroMQ).

FPGA Controller

- Provides an interface to hardware registers in the FPGA as well as the ADC/DAC and QSFP28 modules. On the user facing side, it provides commands to operate the hardware through a custom protocol over ZMQ. Additional functionality includes raw data capture capability at various points in the FPGA signal chain as well as running the deskewing algorithm on the ADC and DAC

Container Orchestration

- Orchestrated accomplished with both Docker Compose and SSH. Docker Compose controls FPGA and System Controllers, since those are run on the same machine. SSH is used by the System Controller to start and stop the CPU Frontend and Backend containers as needed. SSH allows flexibility in running the CPU processing containers on separate machines from the System Controller.

Summary

- The Aerospace Corporation has installed two remote optical terminals in Maui, HI and Albuquerque, NM, with plans to install a third at a location to be determined.

- Installation sites were selected to be historically dry locations, and geographically dispersed enough that multiple stations would not likely be impacted by the same weather system(s)

- The terminals have demonstrated downlink speeds up to 200 mbps with and without forward error correction. On the ground segment, bandwidth is currently constrained by the installed APDs, however the modem is capable of input speeds up to 622 mbps

- Development to support remote operation via RESTful interface has additionally enabled a great degree of automation, eliminating a substantial portion of the labor burden previously associated with manual operation in El Segundo

- By leveraging primarily COTS components and extending functionality of multiple existing software packages used to support our manually operated terminals, we have found a scalable, low-cost approach that will ultimately consist of a network of three remote terminals for at a total cost of under 1 million dollars.