



# **Current Status of NASA's Low-Cost Optical Terminal (LCOT) at Goddard Space Flight Center**

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# NASA's Optical Communications Ground Terminals



- ❑ Ground terminals built to support previous NASA laser communications demonstrations (such as the Lunar Laser Communication Demonstration (LLCD) and the Laser Communication Relay Demonstration (LCRD) ) have been built to support those missions only
- ❑ Re-use of these terminals for another optical downlink using a different format or wavelengths would require significant re-work
- ❑ If a NASA science mission wishes to take advantage of the high data rates offered by optical communication, it not only must finance the optical space terminal, but it must also finance the creation of ground terminals to meet its needs.
- ❑ If a mission is willing to pay for the design and fabrication of a ground terminal, most likely that ground terminal will also likely be tailored to meet the needs of that mission only.
- ❑ This means that once the mission is over, the ground terminals will not easily be re-used for the next mission
- ❑ The cost of optical communication use will be too high for most missions if each mission wanting to use optical communication must develop and build their own ground network.
- ❑ This is not cost efficient and will prevent the widespread adoption of optical communication.



# The Need for a Flexible Multi-Mission Ground Terminal



- What is needed is the development of a single ground terminal design that can support a wide range of downlink formats from a wide range of distances
- Ground terminals built for one mission could then go on to serve as ground terminals for the next mission
- This would allow the ground terminal network to grow organically as demand grows.
- Such a design should be able to support multiple downlink formats with little or no re-configuration
- It should use COTS parts as much as possible
- It should have a small facility footprint
- Finally, the design should be modular and able to be quickly reconfigured.



# The Low-Cost Optical Terminal (LCOT) Receive Telescope



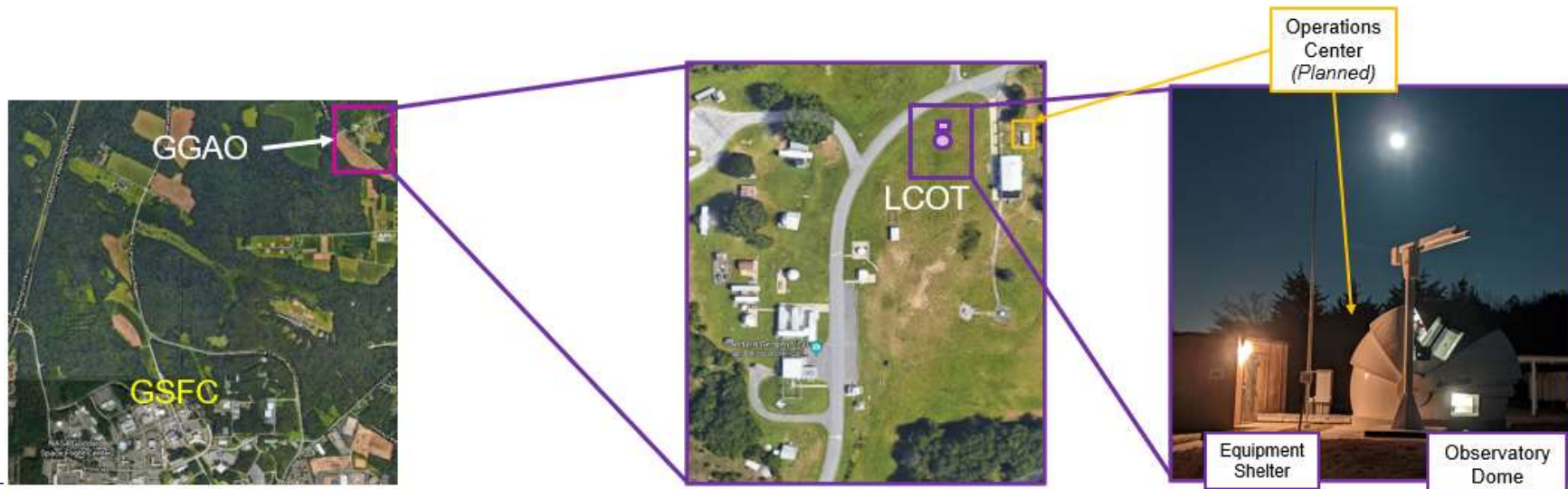
- ❑ Engineers at Goddard Space Flight Center (GSFC) worked to develop a concept for a flexible ground terminal design
  - A single optical design able to serve as a ground terminal receive telescope for missions in LEO, GEO and Lunar orbits
  - Compact design that keeps facility costs low
  - Use of COTS parts wherever possible
  - Modular design, highly reconfigurable
  
- ❑ Conceptual design for a flexible receive telescope was developed
  - Naysmyth architecture chosen, optics benches would be mounted on the side of the telescope- allows for modularity and flexibility, more compact and lower facility cost than a Coudé design.
  - Rotating tertiary mirror would allow received light to be directed to one of two optics benches mounted on either side of the Receive telescope
  - Receive telescope diameter >60cm
  - Able to accurately track LEO spacecraft
  - Transmit Optical Array mounted on top of the receive telescope
  
- ❑ Looked at commercial options and found none that met all our requirements; however, Planewave Instruments had a design that came close
  - We contracted Planewave to construct a heavily modified version of their corrected Dall-Kirkham 70cm telescope (CDK-700)
  - Telescope structure and gimbal were modified to support additional mass
  - Secondary obscuration was greatly reduced
  - The resulting telescope was a 70cm Ritchey-Chrétien telescope (the RC-700).



# The LCOT Facility



- ❑ Facility was constructed at the Goddard Geophysical and Astronomical Observatory (GGAO) located ~2miles NE of GSFC main campus in Greenbelt, Maryland.
- ❑ 16-foot diameter dome and isolated concrete pier, 10x14 foot shelter for equipment, ample power, and optical fiber connectivity to GSFC campus
- ❑ Larger operations center designed for facility
- ❑ Telescope installed in dome July 2021
- ❑ Undergoing testing and integration with subsystems



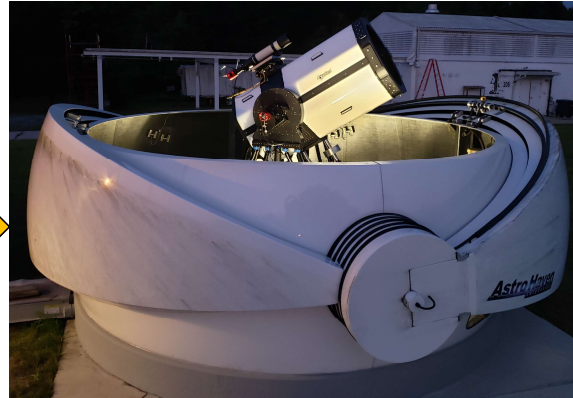


# LCOT Facility at GGAO



LCOT resources are divided between three structures:

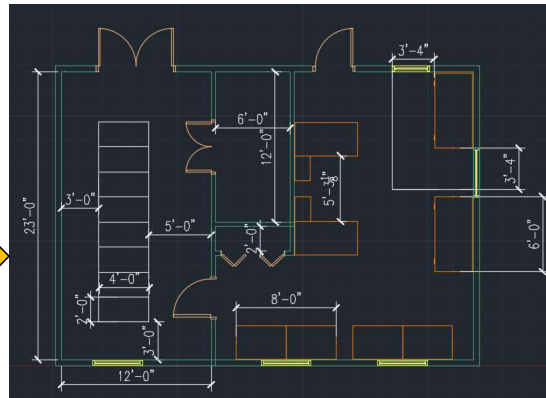
**Observatory (Existing):** Houses the Free-space optical subsystem (FSOS) and components of the Amplifier Subsystem (AS) and Monitor and Control Subsystem (MCS) that need to be on or immediately adjacent to the gimbal.



**Equipment Shelter (Existing):** Houses components of the AS, MCS, and Transceiver Subsystem (TS) that need to be within 10m of the gimbal.



**Operations Center (Planned):** Houses all component that are not location sensitive and provides working space for staff.





# LCOT System Reference (As installed at GGAO)



## Free Space Optical Subsystem (FSOS):

Direct free space optical signals and hardware

## Transceiver Subsystem (TS):

Interface with externally provided experimenter TSs

## Amplifier Subsystem (AS):

Includes the amplifiers and associated electronics

## Monitor and Control Subsystem (MCS):

The MCS provides overall commanding, monitoring, and control for the other LCOT subsystems

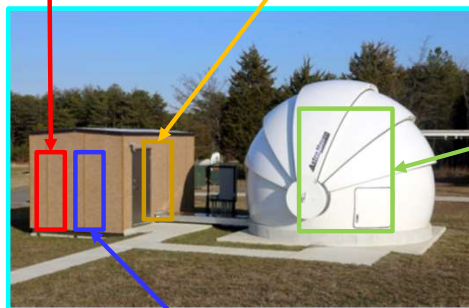
## Observatory Infrastructure Subsystem (OIS):

Infrastructure and supporting services

Transceiver Subsystem (TS)



Amplifier Subsystem (AS)

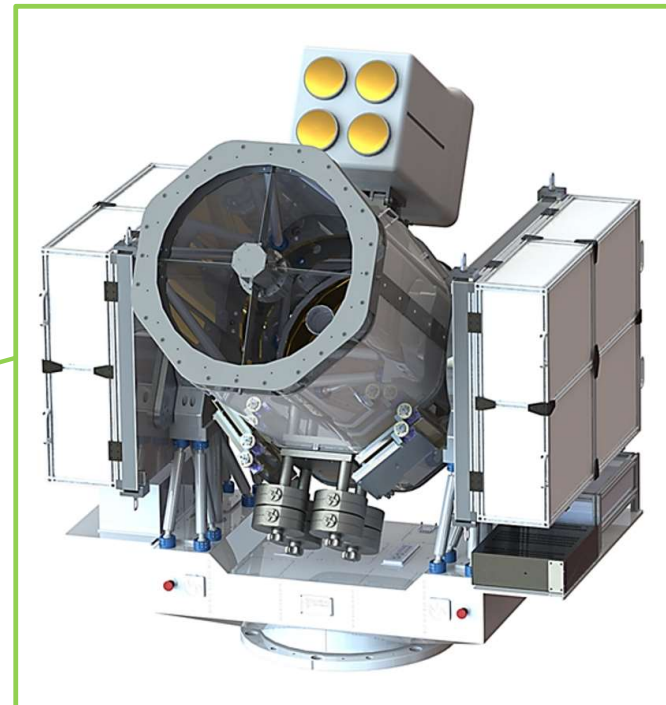


Monitor and Control Subsystem (MCS)



Observatory Infrastructure Subsystem (OIS)

Free Space Optical Subsystem (FSOS)



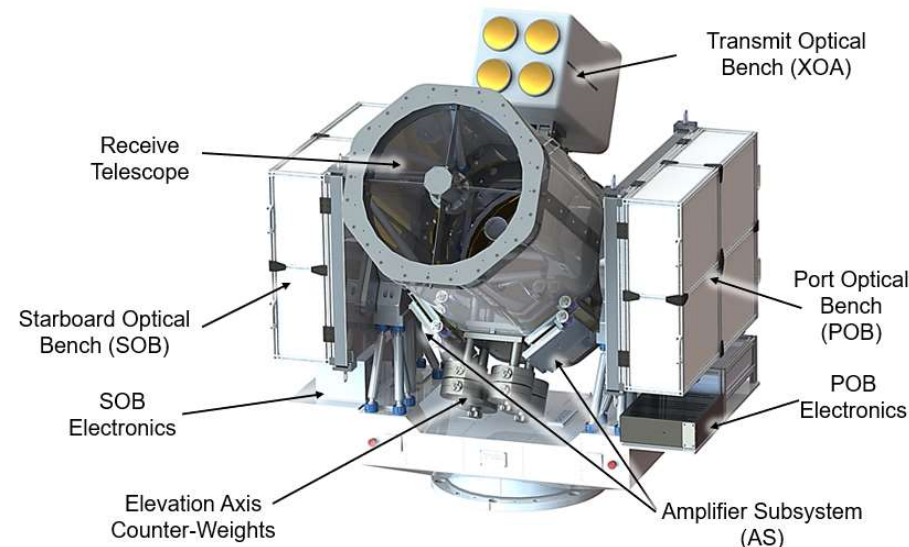


# Planned Final LCOT Optical Sub-System



- ❑ Telescope installed at GGAO in July 2021, undergoing testing and integration as optical bench being assembled and tested in the lab
- ❑ Port optical bench with AO installed planned to be installed on the telescope early 2023
- ❑ Preliminary transmit array design created by GSFC optical engineers
- ❑ Contract to refine transmit array design awarded to University of Arizona, design finalized at end of 2022
- ❑ The figure below shows the planned final configuration of the LCOT optical assembly
- ❑ Port optics bench will be completed first and will be used in initial tests.

- ❑ Transmit assembly will be mounted on the 'Robotic Piggyback Mount' (RPM)
- ❑ The RPM is a computer-controlled tilt stage that compensates for misalignment between transmit and receive optical axes as telescope changes elevation angle.
- ❑ One large task in progress is developing the software to allow the telescope to auto-track
- ❑ Once a downlink has been acquired, the tracking camera (on the optical bench) will be used to adjust telescope motion to keep the downlink centered in the field of view.



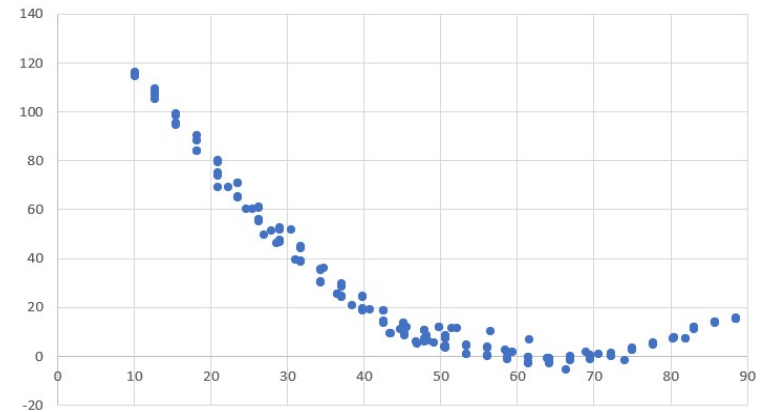


# RPM Performance

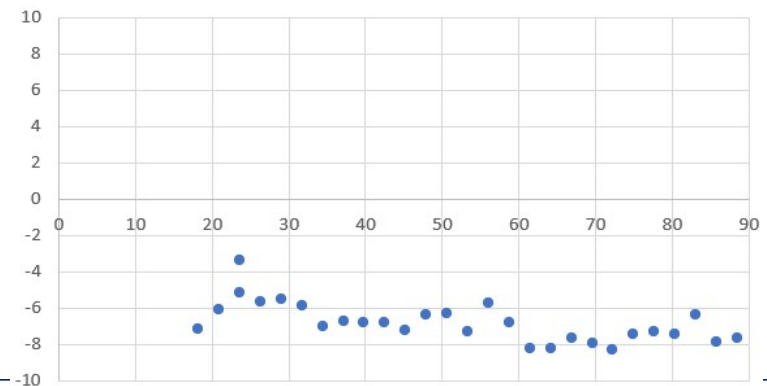


- ❑ Since telescope structure is not completely rigid, as the telescope moves in elevation the pointing of the top-mounted transmit optical assembly drifts relative to the optical axis of the 70cm receive telescope as the telescope moves in elevation.
- ❑ To compensate for this differential flexure, we use the RPM- a tilt stage that can automatically remove this misalignment as a function of telescope elevation setting.
- ❑ Top figure shows the misalignment of the transmit and receive optical axes as a function of telescope elevation
- ❑ Bottom figure shows the misalignment between transmit and receive optical axes after RPM has been calibrated and activated.

Elevation error (arcsec)- No RPM Correction



Elevation error (arcsec) with RPM correction

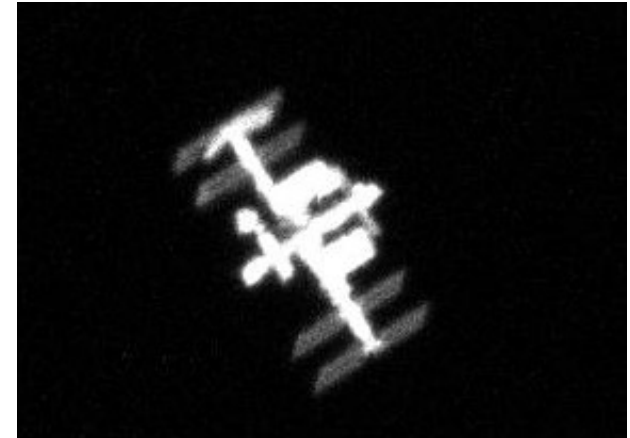




# Telescope Performance



- ❑ Factory acceptance testing of telescope performed on 7-2-2021. Tracking and imaging testing was performed with 1200lbs of added weights on telescope to simulate the planned equipment it would need to support.
- ❑ Numerous satellites with different orbital altitudes were tracked over the night, seeing was as good as 1 arcsec (5micro-rad).
- ❑ Due to the mount design, tracking satellites as they pass near zenith require very high azimuth motor velocity.
- ❑ As a result, there is a 'keyhole' around zenith where tracking a satellite would require exceeding the azimuth motor velocity limits. The size of this keyhole is largely a function of the orbital altitude of the satellite.
- ❑ Many satellites that passed over near zenith were selected to explore the tracking behavior near this keyhole



*ISS imaged during factory testing*



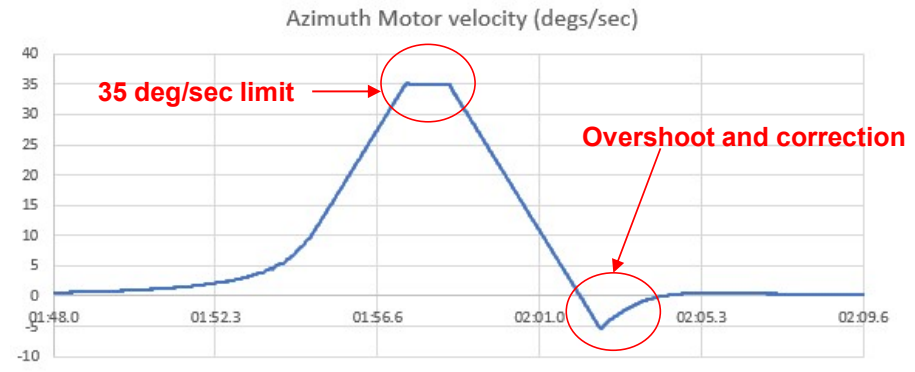
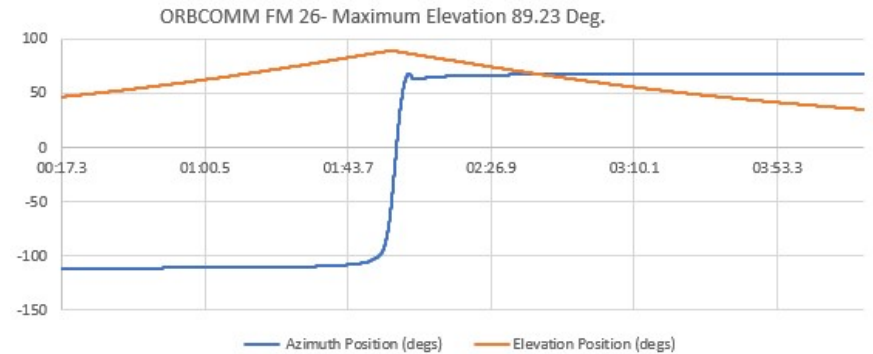
# Telescope Performance



- Tracking example: ORBCOMM FM 26- Max elevation angle 89.23 degrees, orbital altitude ~790km.
- Azimuth motor velocity limit was 35 deg/sec
- As satellite approached zenith tracking was lost as required azimuth velocity exceeded the 35 deg/sec limit.
- Tracking recovered after ~10 seconds. (Video sped up by factor of 5)



Video sped up %500





# Telescope Performance

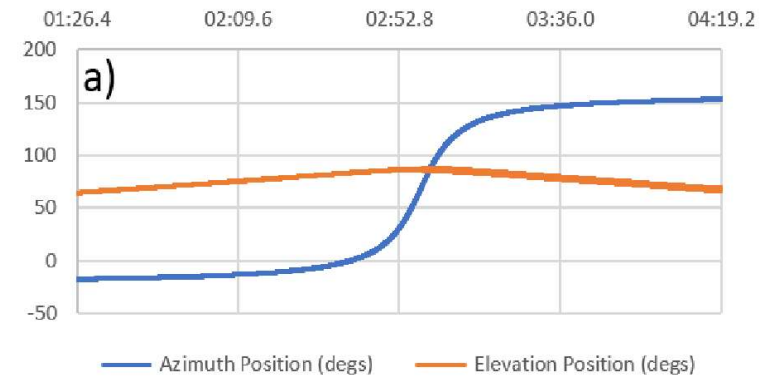


- Tracking example: COSMOS 1194, Max elevation angle 87.56 degrees, Orbital altitude: perigee 1439km, apogee 1481km
- Despite coming within 2.44 degrees of zenith, tracking was not lost
- The slightly larger distance from zenith and higher altitude reduced the maximum required azimuth velocity to just under 8 degrees/sec

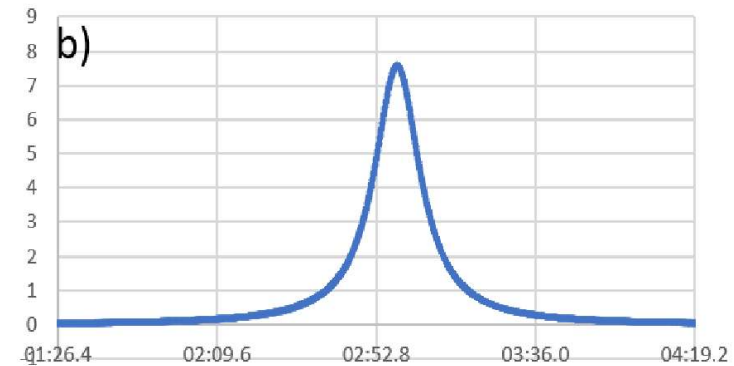


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Cosmos 1194- Maximum Elevation 87.56 Deg.



Azimuth Motor velocity (degs/sec)

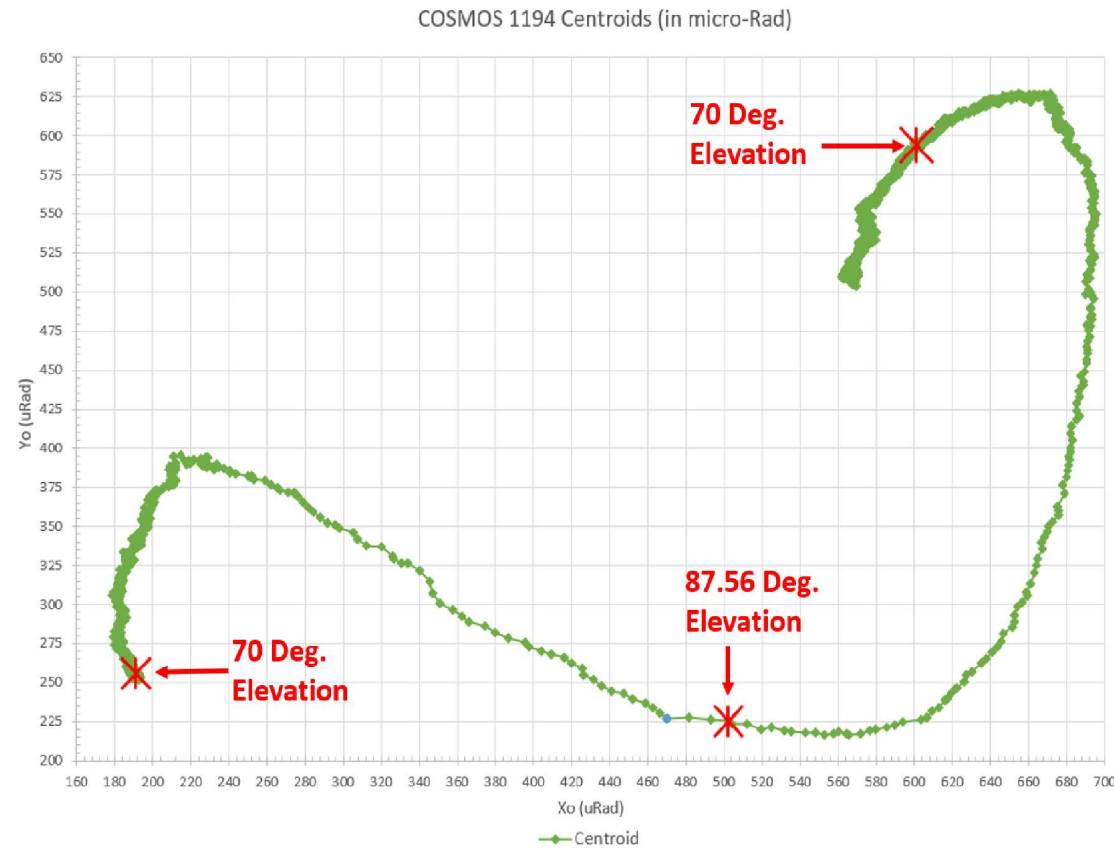




# Telescope Performance



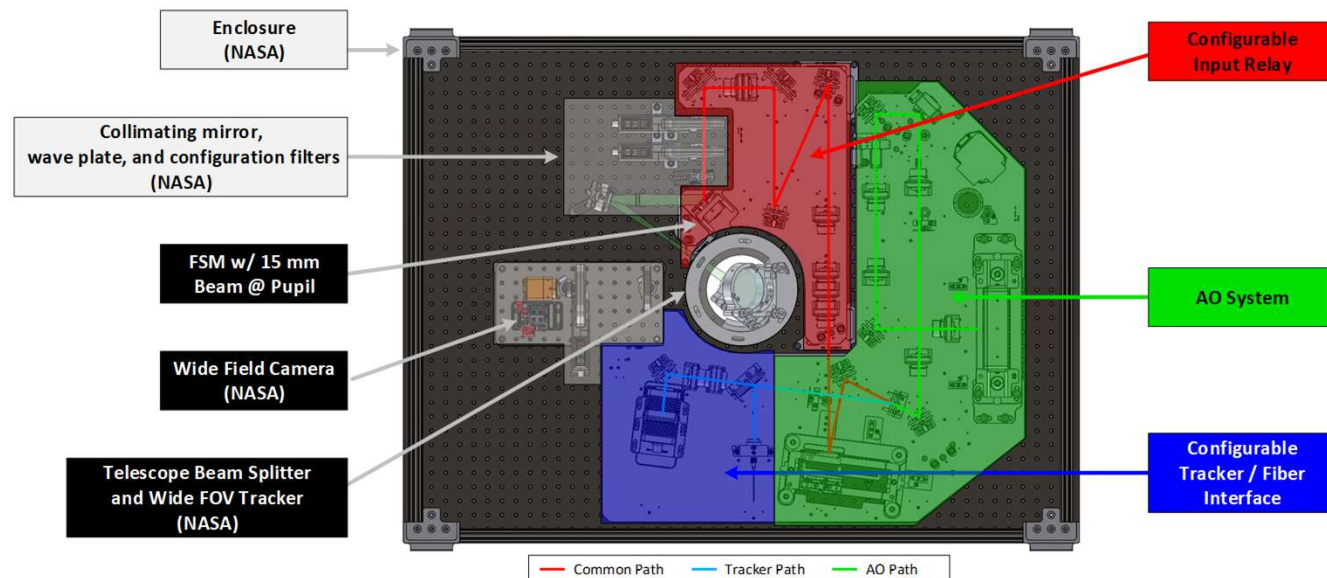
- ❑ Inaccuracy in the satellite ephemeris and the fact that the satellite was not in the center of the field of view leads the image of the satellite to wander on the camera as the telescope slews and rotates to track the satellite.
- ❑ Plot shows the wander of the centroid of the satellite image on the camera sensor. (Plate scale applied to convert the pixel position to on-sky angular distance)
- ❑ One major task is to implement auto-tracking in the telescope. The image of the satellite on the tracking camera will be used to guide the mount to keep the satellite near the optical axis of the telescope.
- ❑ Fast steering mirror will compensate for any higher frequency jitter



# The Adaptive Optics Sub-system

- ❑ Coherent communication formats (as well as Quantum communications) typically must be coupled into a single mode fiber (SMF) for processing
- ❑ Unfortunately, turbulence induced wavefront error leads to blurring of the light from the downlink so that its image is much larger than the SMF
- ❑ The wavefront error must be removed using Adaptive Optics (AO), and if it is going to correct while the telescope is slewing to track a LEO spacecraft, it must apply these corrections at a very high rate.

- ❑ LCOT procured AO from Guidestar Optical Systems (Subsequently acquired by General Atomics).
- ❑ Designed to support reception of a downlink from a LEO spacecraft.
- ❑ Designed to allow reconfiguration (filter wheels, relay optics, fiber coupling optics)
- ❑ Figure shows layout on our optics bench

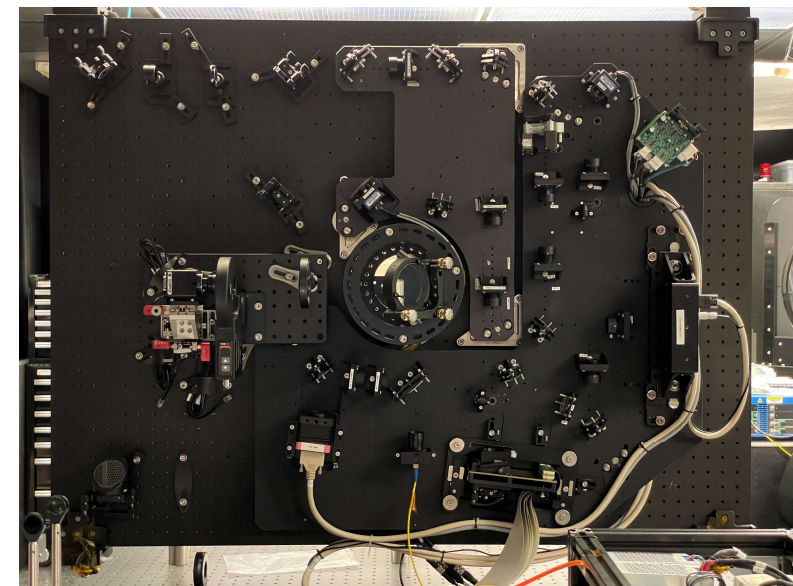




# The Adaptive Optics Sub-system



- ❑ The AO system will be discussed in more detail in another talk in this session – (see papers by Dan Paulson and Patrick Thompson)
- ❑ Delivered to GSFC August 2021
- ❑ Underwent extensive testing and characterization in the lab. Integrated onto port optical bench and tested in vertical configuration in preparation for installation on telescope
- ❑ The optical bench will be enclosed and temperature controlled.
- ❑ Higher-order correction can be bypassed with only tip-tilt correction implemented
- ❑ Relay optics and fiber coupling optics are reconfigurable.





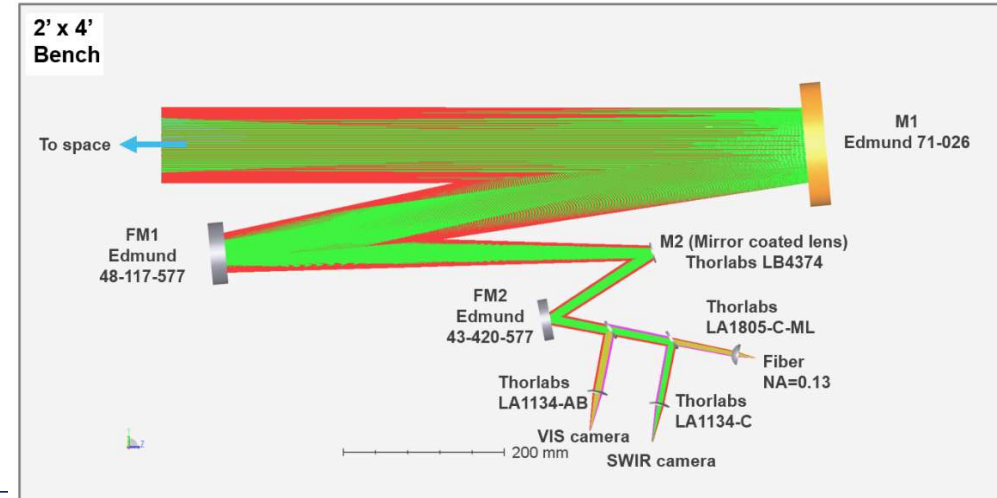
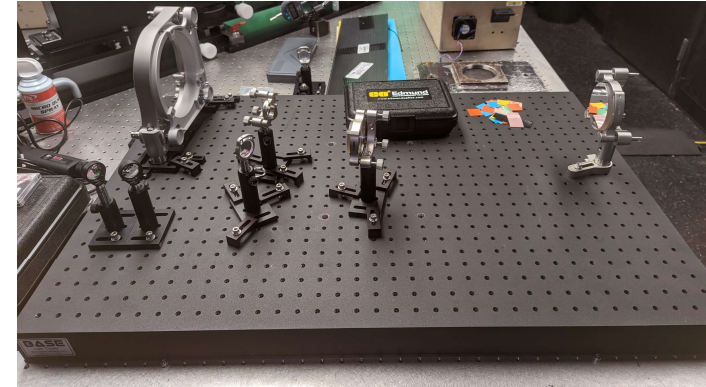
# Transmit Optical Assembly



- ❑ For the final system it is planned to have a cluster of four transmit telescopes mounted on the Robotic Piggyback Mount on top of the telescope tube. Four telescopes are needed for mitigation of turbulence effects, and to allow transmission of greater total power.
- ❑ Previous ground terminals for NASA optical communication missions such as the Lunar Laser Communications Demonstration (LLCD) and the Laser Communication Relay Demonstration (LCRD) used refractor telescopes to transmit the uplink.
- ❑ In order to make the LCOT as wavelength agnostic as possible, it was decided that the LCOT transmit assembly would use reflecting telescopes. This also helps to mitigate back-reflections that could blind tracking cameras.
- ❑ Off-axis Parabolic telescope design chosen to avoid having a central obscuration.
- ❑ LCOT's optical team drew up a preliminary design for the transmit telescopes, and a contract was awarded to the University of Arizona College of Optical Sciences to refine the design and create a blueprint for a fully engineered transmit assembly.
- ❑ Design is completed and design review held in December 2022.
- ❑ Each of the four telescopes will be able to transmit
- ❑ Please see paper and talk in this session by Patrick Thompson for a detailed discussion on the transmit assembly.

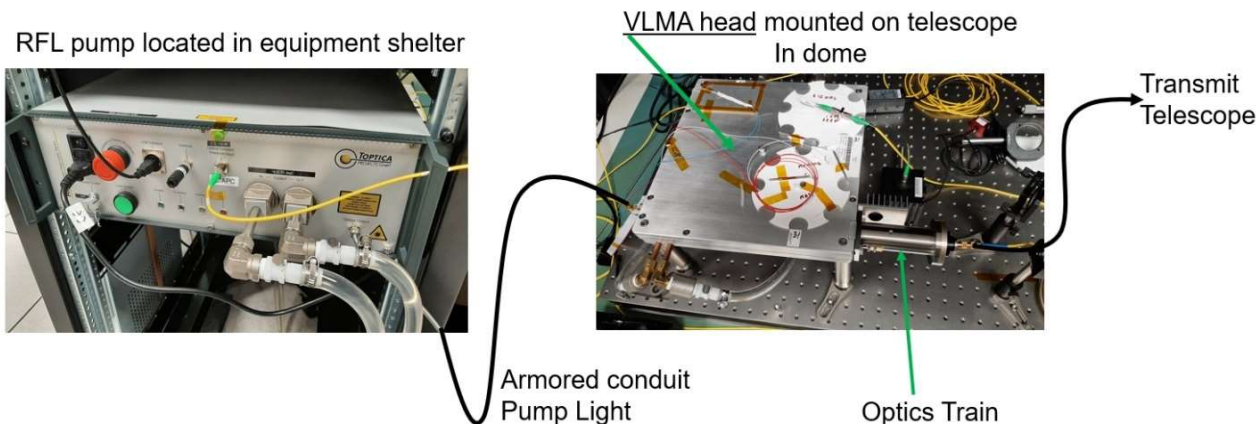
# The Temporary Transmit Assembly

- ❑ The four telescope transmit array will ultimately be needed in order to transmit the uplink to the Artemis II mission at the moon.
- ❑ However, the initial tests of the LCOT system will be with LCRD which is in Geosynchronous orbit. These initial tests can be done with a single transmit telescope.
- ❑ Initial tests with LCRD will only need to transmit a widely diverged beacon so that the space terminal can track the ground station and direct a downlink at LCOT.
- ❑ With a divergence of  $\sim 200$  micro-rad ( $1/e^2$  half angle), a fast-steering mirror should not be needed.
- ❑ Initial tests will test optical performance of telescope and adaptive optics. Measuring downlink power coupled into fiber.



# Amplifier Subsystem

- ❑ Due to the high peak powers required for some optical communication formats, finding high power fiber amplifiers that can amplify the uplink signal has been a challenge.
- ❑ Once the peak power exceeds a few hundred Watts nonlinear effects can distort the amplified signal- Self Phase Modulation (SPM) can broaden the spectrum of amplified pulses, Four Wave Mixing (FWM) can generate additional frequency components.
- ❑ The nonlinearities are a function of the peak power, the fiber cross-sectional area, and the fiber length.
- ❑ LCOT is using a relatively new Very Large Mode Area fiber amplifier- the gain medium is a short fiber with a very large cross-sectional area compared to standard single mode fiber.
- ❑ As a result, it can amplify high peak power pulses without distortion. The VLMA is able to handle peak power an order of magnitude higher than standard single mode fiber amplifiers we have tested in previous programs.
- ❑ The VLMA is described in detail in: "High-peak power fiber amplifier for deep-space laser communications," Proc. SPIE 10524, Free-Space Laser Communication and Atmospheric Propagation XXX, 105241C (15 February 2018); <https://doi.org/10.1117/12.2290864>





# LCOT Capabilities



- ❑ The LCOT was designed from the ground up to support a wide range of missions ranging in distance from Low Earth Orbit to Lunar distances.
- ❑ The 70cm aperture should allow LCOT to receive the 80Mbps downlink from Artemis II at the moon with considerable margin.
- ❑ The 70cm aperture coupled with the AO system should allow LCOT to receive all data rates from the LCRD space terminal at Geo-synchronous orbit.
- ❑ The LCOT should be able to receive the 200Gbps from the TBIRD cubesat in LEO.
- ❑ The large aperture and AO system should allow LCOT to serve as a receiver for some future Quantum Communications experiments.
- ❑ Arrays of LCOT telescopes could be used to receive downlinks from even greater distances.
- ❑ In addition, the modular design and replaceable optical benches allows reconfiguration for other applications (such as space debris tracking, LIDAR experiments, etc.) beyond optical communications.



# Summary



- ❑ In addition to developing a blueprint for a flexible multi-mission optical ground terminal, the LCOT at the GGAO will be a powerful testbed for optical communication technologies.
  
- ❑ LCOT will allow laser communication tests to be done essentially on site at GSFC
  
- ❑ It is planned to have extensive weather and turbulence monitoring at the LCOT site. This will be useful for future site selection.
  
- ❑ LCOT will allow testing of new technologies and processes that might reduce the costs of future ground terminals.
  
- ❑ By developing the blueprint for a flexible multi-mission ground terminal, the development costs for future ground terminals will be greatly reduced. By using and creating COTS components the procurement costs of future ground terminals will also be reduced.
  
- ❑ While LCOT is 70cm diameter, the modular design means that what is developed can easily be applied to larger versions of the LCOT telescope.
  
- ❑ Engineers and scientists at GSFC will be able to gain experience with optical communications technologies.