NASA's LCOT (Low-Cost Optical Terminal) FSOS (Free-Space Optical Subsystem) : Concept, Design, Build, & Test

Patrick L. Thompson *[a], Armen Caroglanian [a], Jeffrey A. Guzek [b], Stephen A. Hall [c], Robert E. Lafon [a], Kristoffer C. Olsen [d], Daniel A. Paulson [e], Haleh Safavi [a], Predrag Sekulic [f], Oscar Ta [d], Mark E. Wilson [f]

[a] NASA / GSFC, Greenbelt, MD, USA 20771 ;
[b] Design Interface, Inc. ;
[c] Cimarron Software Services, Inc. ;
[d] Genesis Engineering Solutions, Inc. ;
[e] Science Systems and Applications, Inc. ;
[f] KBR Wyle Services, LLC / KBR Inc. ;

ABSTRACT

We present the status of ongoing work at NASA's Goddard Space Flight Center (GSFC) to build a prototype, low-cost-of-production, flexibly-configured ground terminal for space optical communication. For laser telecommunication to be cost effective for future missions, a wide-spread global network of operationally responsive optical terminals should be established. There has been a decades-old need for a *single* modular open systems approach (MOSA) ground terminal *architecture* capable of supporting multiple space missions ranging from LEO to Lunar distances with 2-way laser communications.

At the heart of LCOT's design concept is the Free-Space Optical Subsytem (FSOS). The major subassemblies of LCOT/FSOS that address most optical comms configurations are : (1) Single 700mm F/12 Nasmyth folded Rx R-C Telescope, (2) Four independent 150mm diameter high-power all-reflective Tx beam directors (XOA), (3) Non-coherent direct detection Rx bench on starboard side of telescope (SOB), and (4) Coherent (possibly Quantum) optical communications bench on port side (POB).

The Low-Cost Optical Terminal (LCOT) research and development (R&D) prototype is designed to be a *generalized system* that can be quickly field-reconfigured to support a *wide variety* of laser communications missions past, present, & future.

Keywords: COTS, Artemis, GEO, Adaptive Optics, Tracking, LIDAR, Orbital Debris, RSO, Space, Ground Terminal, NASA, Goddard, LCOT, Free-Space, Optical Communications, Modular, MOSA, LEO, Lunar, Quantum, Laser

1. INTRODUCTION

Free-Space Optical Communications (FSOC) have been in use for at least eight millennia in one form or another (i.e. smoke, fire, flags, & mirror glint signals[1]). However, only after the invention of laser technology c.1960 did both the Guided Wave Optical (GWOC) and FSOC become practical and even economical due to their superior potential communications bandwidths, beyond Radio Frequencies (RF), which scale with the carrier frequency. In early 1968, the first crude argon laser signals, launched from Earth's night side (KPNO & Table Mt.), were detected by NASA's Surveyor-7 lander imaging system while on the Moon.[2] Later efforts between 1985-1995 produced detections of Earth-

*Patrick.L.Thompson@NASA.gov ; phone +1 301 286-1495 ; https://ETD.GSFC.NASA.gov/550/Code551.php

based lasers by various robotic spacecraft testing Pointing, Acquisition, & Tracking (PAT), culminating in an intensive effort by the Japanese government (JAXA & NICT) to perform bidirectional FSOC with downlink over 1Mb/s using lasers on the ground (beacons) and in Geostationary Transfer Orbit (GTO) [3,4]. Now today, some 30 years later, NASA is working to incorporate all the hard lessons-learned from countless development efforts globally into a modern, *very low-cost of production,* self-contained, mostly Commercial Off-The-Shelf (COTS) system we call LCOT.[5]

The LCOT R&D project ultimately seeks to bring an unprecedented level of infrared (IR) FSOC capability to NASA's currently RF-centric Space Communication and Navigation (SCaN) network, other US government organizations, university researchers, and commercial sectors. Modular, interchangeable FS optics, GW electro-optics, and optical modems are combined with a 70cm receive (Rx) aperture and newly developed COTS gimbal for high stability, fast tracking in an integrated scalable architectural concept. Onboard Rx Adaptive Optics (AO) tuned to the downlink space terminal beacon is designed to address challenging and emerging technologies (esp. coherent & quantum comms) under clear atmospheric turbulence conditions night or day from most locations globally. LCOT will provide a common test platform available for free space IR systems of any modulation scheme through almost any atmospheric window of optical frequencies. Past investments starting in 2018 have provided the compact observatory infrastructure, RTA+gimbal, AOS, optical amplifiers, and laboratory space for further developments. Continued financial support for materials and personnel will lead to completion of the core LCOT system, transmit (Tx) telescopes, transceiver, and operations center. First light on-sky PAT testing of the observatory with Receive Telescope Assembly (RTA) alone is shown in Figure 1 showing its near diffraction-limited performance under clear calm skies even at visible wavelengths.[6]

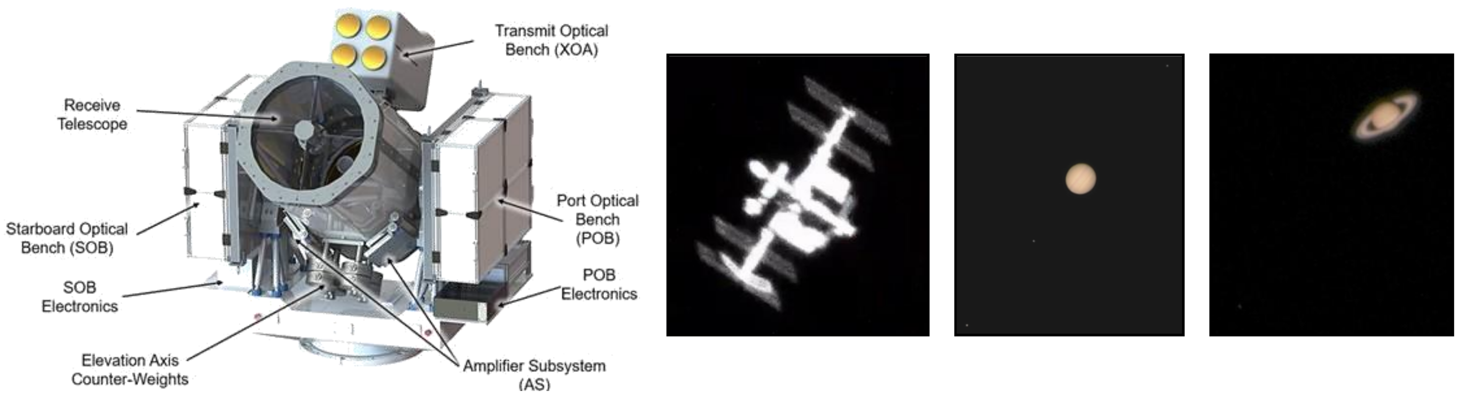

Figure 1. LCOT FSOS (a) Overview, (b) Initial on-sky RTA+MGA imaging (no AO) : ISS, Jupiter, & Saturn systems.

Our LCOT architectural approach is composed chiefly of the following subsystems and assemblies : Observatory Infrastructure (OIS), Free-Space Optical (FSOS), Amplifier (AS) with Very-Large Mode Area (VLMA) fed by Raman Fiber Lasers (RFL), Transceiver (TS), and Monitor & Control (MCS). This paper only addresses in detail the FSOS itself. The FSOS in turn is constructed of the following assemblies : Receive Telescope (RTA), Mount & Gimbal (MGA), Starboard Optic Bench (SOB), Port Optical Bench (POB) which houses the Adaptive Optics (AO), and the 4-aperture Transmit Optics (XOA).

Although LCOT is *not* a NASA classed flight, operational, or otherwise *critical* GSE (Ground Support Equipment) project (that would mandate rigorous requirements flow-down), the following is a concise delineation of our current internal *"working"* key & driving requirements most relevant to FSOS (for R&D) at Levels 2, 3, & 4.

<u>The LCOT System (L2) shall</u> :

- Build an optical ground terminal to enable optical communication experiments with spacecraft from Low Earth Orbit to at least Lunar orbits.
- Demonstrate/enable commercial capabilities for free space optical communication ground stations.
- Accommodate testing of major and minor optical ground terminal subsystems, assemblies, and components and be able to provide system data relevant to the items under test.
- Be modular for switching & testing between experimental prototype technologies for development of new standards.
- Be a test facility and shall not be designed to provide a regular communications service.
- Be able to perform target of opportunity testing with cooperative space missions.

The FSOS (L3 & L4) shall be able to :

- Support modulation formats for downlink and uplink services as listed in LCOT-201-ICD-LCOT/TS (LCOT to Transceiver Subsystem Interface Control Document).
- Meet all requirements for r0 ≥ 7.5cm for a 1550nm signal when using adaptive optics.
- Meet all requirements for Greenwood frequency ≤150Hz for a 1550nm signal when using adaptive optics.
- Meet all requirements for atmospheric attenuation below 1.5dB for a 1550nm carrier signal under AO correction.
- Accommodate the installation of solar windows on all apertures (RTA primarily).
- Achieve 1-σ open-loop pointing error of ≤ 50μrad (RTA/MGA)
- Achieve 1-σ jitter of ≤ 10μrad (FSM's on POB & SOB).
- Independently transmit and steer spatially diverse uplink signals (XOA).
- Include an Adaptive Optics (AO) capability (POB).
- Support scanning around the programmed pointing angles (Fine/Fast Scanning Mirrors - FSM's on POB & SOB).
- Combined transmit power up to 20W per transmit channel (XOA).
- Be reconfigurable for polarization control of uplink and downlink signals (All optics).
- Produce a transmit beamwidth ≤ 20μrad & ≥ 200μrad FWHM (XOA).
- Slew in azimuth & elevation at rates > 0.53rad/s (MGA).

2. OBSERVATORY (OIS) & RECIEVE TELESCOPE ASSEMBLY (RTA)

At the core of LCOT is the newly launched PlaneWave™ Instruments (PWI) product model RC700 RTA (with direct-drive MGA) housed inside an AstroHaven™ Enterprises 16ft-class enclosure (i.e. non-rotating dome), both of which are COTS catalog items. Adjacent to the dome is an environmentally-sealed, climate-controlled electronics equipment shed which can seat two onsite technicians at desks. Between the dome and the shed is an elevated accessible conduit box for electrical power, signal/data cables, VLMA pump fiber[10], and POB/SOB Rx fiber cables. The dome itself can only be humidity and temperature controlled while tightly closed in its stowed configuration.

2.1 GGAO Facility & Horizon Scan

The Goddard Geophysical and Astronomical Observatory (GGAO) site[7], ~2miles directly NE from the GSFC main campus, is uniquely situated to accommodate NASA's future ground-to-space FSOC on the US East Coast while also being only ~14miles NE from Washington, DC. An overview of GGAO is shown in Figure 2 with the LCOT dome and equipment shed clearly identifiable on the right (with parked cars for scale). North is up on each photo.

Figure 2. GGAO, Springfield Rd, Glenn Dale, MD 20769 : (a) Overview of facility, (b) LCOT/OIS site position & extent.

At the LCOT site, we have a predominately unobstructed view of the full sky dome with 360deg azimuth all the way down to ~13deg elevation with some views down to ~4deg at certain azimuths. There is a lift crane shown in Figure 3 at the west direction that can be dismantled and stored while LCOT is in operation, However, there is still one tall tree that extends up to 18.5deg elevation at that directly west azimuth The single tall thin pole at the north-west position is a permanently installed lightning bolt diverter. There are no overhead encumbrances (e.g. electrical/telephone lines, overhangs, or suspensions).

Figure 3. LCOT @ GGAO : RTA Horizon Scan shows mostly unobstructed elevations above 13deg over 360deg azimuths.

The dome structure is placed on top of a facility-installed custom concrete pad and around a permanent concrete pier that is well rooted into the ground at the center. There is dome access through a small square door near the bottom at the west side, electrical utility lighting, switches, and outlets, along with a built-in dehumidifier on the inner south wall. The PlaneWave™ RC700 RTA sits on top of the center pier with azimuth zero set towards true north.

2.2 COTS RTA Design & Development

The current RTA design form and mechanism performance was specified by the NASA/GSFC LCOT team in cooperation with PlaneWave™ Instruments, Inc. of Adrian, MI in 2019. After substantial trials at GGAO with smaller telescopes of varying construction (e.g. refractive, reflective, central obscuration size, F/#, etc.) since 2015, LCOT decided to move towards a larger aperture COTS model by PWI which they call the CDK (Corrected Dall-Kirkham). Unfortunately, that product line design was optimized for visible astronomical imaging and not IR FSOC. Thus, with a large central obscuration and dispersive refractive correction optics inside the M1 annulus baffle (also generating faint ghosts), changes had to be made. This is new design is shown in Figure 4.

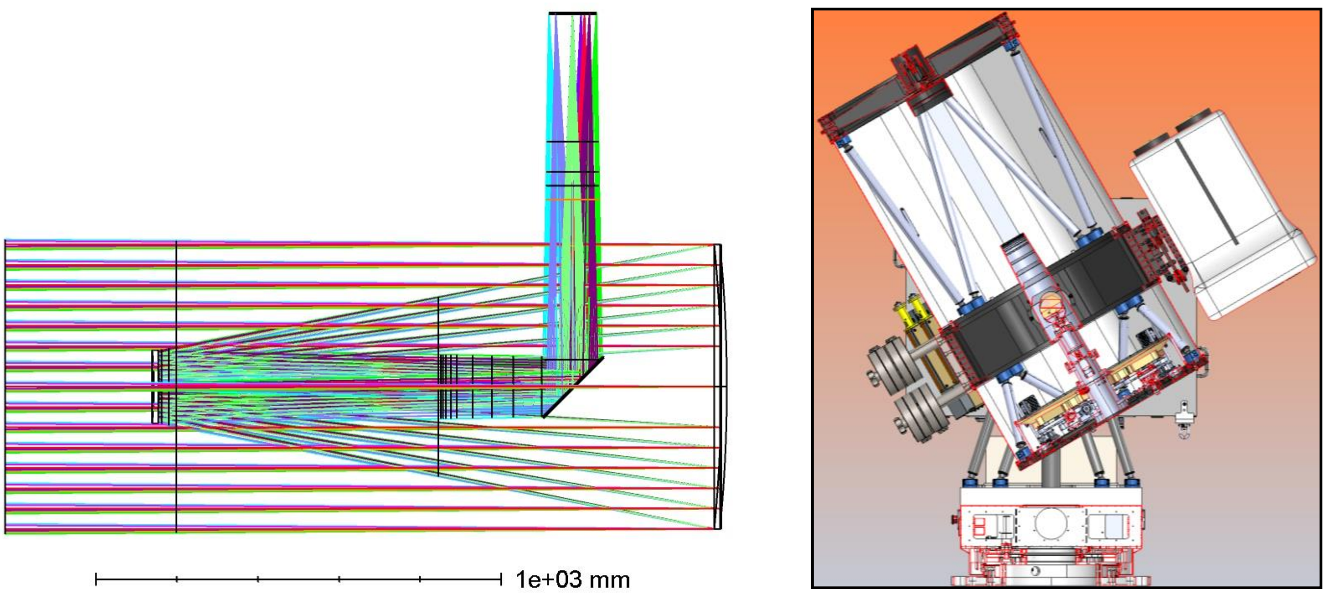

Figure 4. RTA overview : (a) Zemax optical design showing RC-Nasmyth design form, over-all size, ray traces, limiting apertures, and full FoV, (b) Optomechanical design cross-section showing metering structures and mount accommodations.

PWI agreed to restart their Ritchey-Chrétien telescope *development* which had proven in the past too expensive even for the prosumer market. After a two year internal product development funded by LCOT, PWI emerged with a telescope system (RTA) that had no refractives, much smaller area obscuration ratio, and a dual-Nasmyth selector "M3" 45deg fold flat on a 180deg rotary mechanism, replacing the aberration-correcting lenses that were necessary in their CDK product line to address coma. Thus, the cost barrier for R-C telescopes with robust Nasmyth ports had been surmounted.[8]

The first successful R-C telescope (600mm diameter) was made by George Ritchey himself and is now almost a century old and consists of a large concave sightly hyperbolic (aparabolic) primary mirror (M1) optimally matched with a much smaller very hyperbolic convex secondary mirror (M2), which also creates a central obscuration. This is an evolutionary step beyond the prior Cassegrains which have a purely parabolic M1. The change in conic constants of M1 & M2 provide a wider field-of-view (FoV) that is simultaneously free of all spherical and linear coma aberrations, although quadratic astigmatism and benign field-curvature remain to be corrected downstream. However, the R-C approach makes optical component testing significantly more difficult (i.e. expensive null test equipment), but allows less design & build effort for the back-end instrument optics while removing the need for refractive corrector lenses that create unacceptable chromatic aberrations and in-field stray light (i.e. glints & ghosts).

Table 1. RTA (RC700-001) optical & mechanical as-built and tested system performance.[9]

Parameter	Value	Units	Comments
RTA Design Form	2 + 1	mirrors	Ritchey-Chretien, centrally obscured, 4x radial spiders, dual-Nasmyth, Cass focus access only after removal of "M3" fold flat. Silica mirrors, carbon composite truss metering, steel space frame.
Assembly Mass	1134	kg	Telescope & Alt-Az mount, w/out added payload mass.
Payload Added Mass	< 700	kg	Total added mass limits (e.g. XOA, POB, SOB, VMLA's, counter-weights, elec. boxes, etc.).
Bounding Box Volume	2439 x 964 x 1519	mm^3	Includes Alt-Az mount, but *not* XOA, POB, SOB, elec. boxes. Hight pointing zenith x Depth telescope tube diameter x Width diagonal of azimuth stage.
Input Power	120	VAC	< 30A at 60Hz. US household electrical wiring options.
Entrance Pupil Diameter	700	mm	System Aperture Stop (SAS) located at M1.
Effective Focal Length	8411	mm	F/12 system.
Pupil Obscurations	< 10	%-area	Includes central M2 outer, M1 inner baffles, & 4 spiders.
Usable FoV	7.948	mrad-diam	Up to 50% vignetting, limited by M3 baffle, fold flat, and downstream apertures (e.g. Nasmyth bearing rings).
Spectral Bandpass	> 500	nm	Protected gold mirror coatings : < 10% @ 500nm, > 75% @ 800, > 94% @ 1550.
System WFE @ Zenith	48	nm-rms	Mostly field curvature, spherical (primary then higher orders), & primary astigmatism increasing with lower elevation. RMS spot-sizes of < 1µm diam on-axis, 8.2µm 11mm off-axis, 27.5µm 20.5mm off-axis in RTA image space.
Azimuth FoR	+/- 350	deg	Absolute limits are +/- 354 from true north, "no wrap" protection.
Elevation FoR	+10 to +85	deg	Absolute limits are +5 to +99 from horizon.
Open-Loop Point Error	< 10	µrad-rms	After mount model look-up table calibration using bright stars.
Closed-Loop Track Jitter	< 1	µrad-rms	Unidirectional. Stiction increases bidirectional error by ~10x.

In general, FSOC ground terminals can potentially utilize any of the Earth's approximately 10 "optical atmospheric windows" of various widths from 400nm to almost 12μm wavelength. Proliferation of FSOC terminals in these windows is however mostly limited by *high-power* communications-quality laser technology at those wavelengths. The LCOT optical system is design mainly around the 1550nm window as that has been the most prevalent in GWOC over the past several decades as well as being maximally eye-safe even at our higher powers from the XOA. Another consideration for selecting design wavelengths is the ability to align the various terminal optical paths 'on-sky' with natural celestial point sources (e.g. bright stars & planets) as well being able to perform PAT detections using *only* reflected sunlight from non-cooperating spacecraft (i.e. no reciprocal beacons). Thus, with the RTA and downstream optics being designed as wide-band and wide-FoV as feasible, one can cheaply and quickly just change the solar windows at the RTA entrance aperture, or reconfigure different field or pupil stops, or switch-out various long-pass or band-pass filters downstream in the POB or SOB optics trains while at the field site between operational FSOC intervals.

In Table 1, we list key & driving parameters with as-built & tested values for the LCOT **RC700-001** made by PWI under direction of NASA/GSFC. As the "-001" number suggests, this was the first unit of the now COTS product series. Of particular note are specs for the power consumption (household vs. industrial), low pupil obscuration area, diffraction-limited system wavefront error (WFE), and the very low jitter while tracking even w/out FSM's engaged.

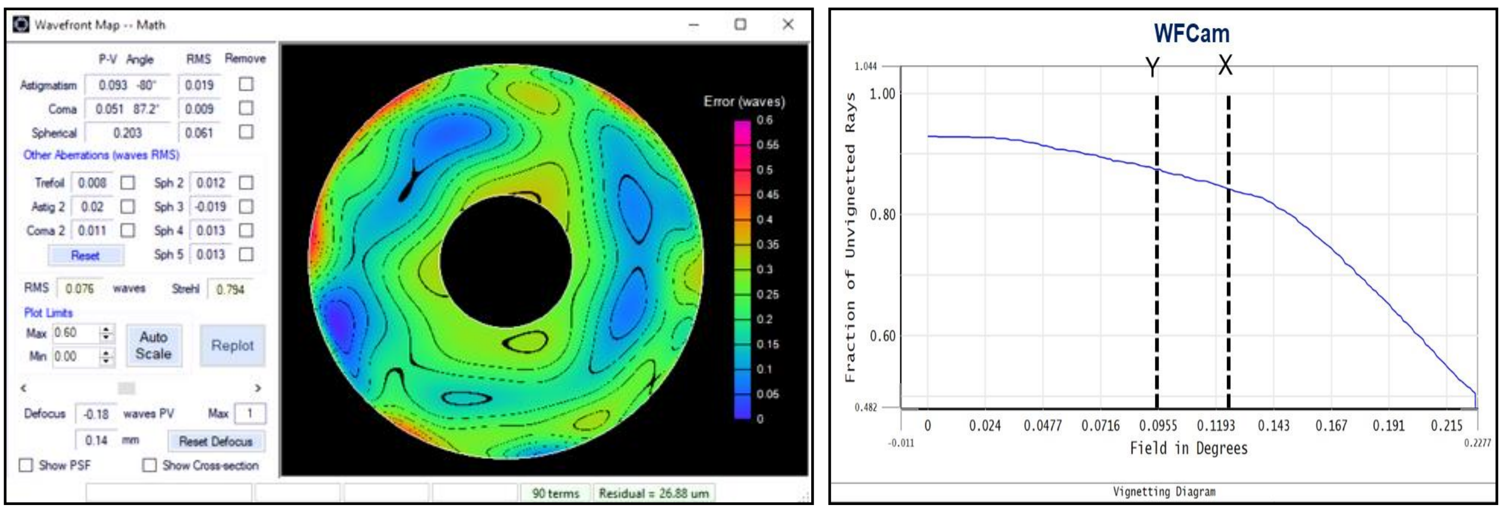

Figure 5. RTA RC700-001 System (a) Single pass WFE map, zenith elevation, spiders excluded, at 635nm test wavelength, (b) Vignetting analysis shows FoV limited largely by intermediate baffle vanes. This should be addressed in future designs.

Optical interferometric testing was performed at the factory (FAT) and utilized a well-calibrated, full-aperture, Auto-Collimation Flat (ACF) suspended from the ceiling and facing down towards the RC700-001's front aperture. With the interferometer feed situated at the back end, an on-axis < F/12 cone point-source was injected at the focal plane towards the AC flat through the telescope. The ACF was aligned in tip-tilt until double-pass fringes were formed and then recorded at the 635nm laser test wavelength. After several captures in various tip-tilt states, the complete fringe dataset was processed and divided by two (for single-pass) to yield a System WFE map as shown in Figure 5(a). Note the 48nm-rms measurement that indicates *diffraction-limited* imaging performance on-axis for wavelengths > 644nm. Bear in mind that with in-line, closed-loop AO activated, we can effectively remove *any fixed residual aberration* in the RTA along with that induced by atmospheric turbulence !

One (small) unexpected issue was the combined effects of interior baffle vanes, M3 size, and the Nasmyth exit port diameters on vignetting at the image plane located outside the two elevation gimbal mounts (i.e. interfaces with POB & SOB. Figures 4(a) & 5(b) show the results of Zemax ray-trace analysis utilizing all internal limiting apertures. After the first central obscuration up front, there are clearly at least two other limiting apertures delineated by the two different slopes of the vignetting curve while moving further off axis. We expect to provide feedback and advice about how to minimize this behavior for future possibly >1m diameter systems of same general construction.

2.3 Factory and Site Acceptance Testing (FAT & SAT)

The following is a compendium of executive summaries from the two formal RTA acceptance test campaign reports executed by PWI under NASA/GSFC/LCOT technical supervision :

On **June 27 - July 2, 2021**, Robert Lafon and Steve Hall traveled to PlaneWave's **(PWI) factory in Adrian, MI** to witness the Factory Acceptance Test (FAT) for LCOT's receive-telescope assembly (RTA), which is comprised of a 70cm Ritchey-Cretien telescope (f/12) and robotic piggyback mount (RPM), and a ruggedized mount gimbal assembly (MGA). This report documents the conditions, results, and conclusions of the tests performed, and concludes the RTA and MGA, as-built in PlaneWave's factory, meets requirements and is ready for delivery and installation at the Goddard Geophysical and Astronomical Observatory (GGAO). On Monday **June 28th**, the LCOT travel team witnessed indoor functional and drive testing (including range of travel / hard stops and simulated high-elevation/stressing passes), and also reviewed recorded demonstrations from preliminary outdoor testing (from a clear-sky event on June 16th), which included 3 satellite passes. Before dawn on Friday **July 2nd**, weather permitted the LCOT travel team to witness outdoor test and demonstration of the RTA and MGA, to include focusing the secondary mirror, building the mount model, creating RPM flexure model and demonstrating the flexure correction, and tracking 6 satellites, including a high-elevation pass of the International Space Station (ISS).

On **July 27 - 28, 2021**, PWI personnel traveled to the Goddard Geophysical Astronomical Observatory (**GGAO**) to install, checkout, and perform a Site Acceptance Test (SAT) of LCOT's receive-telescope assembly (RTA), which is comprised of a 70cm Ritchey-Cretien telescope (f/12), robotic piggyback mount (RPM), and a ruggedized mount gimbal assembly (MGA). Kevin Ivarsen (also PWI) supported checkout, testing, and training remotely via Microsoft Teams.

3. TRANSMIT OPTICAL ASSEMBLY (XOA)

LCOT's transmit optics present an unusual engineering challenge. While many optical terminals are in operation today, the breadth of missions which LCOT will support is unprecedented, and this fact leads to requirements that are unique in optical systems. Supporting LEO operations requires a lightweight system with broad divergence while supporting lunar operations at reasonable power levels requires a high degree of stability with a narrow, precisely tracked beam. The transmit optics must be precise in operation but quickly reconfigurable. The system must be agnostic to polarization and be able to accommodate multiple uplink signals for communications and tracking. In short, the XOA must be a versatile and flexible assembly in world that so far has focused almost exclusively on narrowly-optimized systems that are unusable outside their original application. Further, the XOA itself must be replaceable to allow for future requirements outside the scope thus far considered.

3.1 Requirements

The broad requirements listed above are necessarily decomposed into narrow, buildable, testable requirements. The LCOT team has worked to balance creating as versatile an assembly as possible against operating within the range of what is achievable with a minimum of custom components. The easy modification required by the uncertain scope of possible future missions is likewise balanced against a system that requires as little modification as possible for the most likely prospective missions.

The XOA requirements include several *qualitative* factors :

- The XOA must be mountable to and removable from the Robotic Piggyback Mount (RPM) at LCOT's dorsal mounting position.
- The XOA must provide spatial and wavelength diversity through at least 4 independent uplink beams. This approach is intended to minimize the impacts of atmospheric turbulence in the absence of predictive adaptive optics,
- As each beam will see an independent atmospheric path, each beam must be individually tracked and steered.
- The XOA must be able to accommodate communications formats that include multiple wavelengths per beam.
- The XOA must allow for changing of mission specific elements for optical filtering and polarization.
- Uplink beams must have zero pupil obscuration to minimize losses and diffractive effects.

A selection of additional pertinent quantitative requirements is shown in Table 2.

Table 2. XOA optical and mechanical performance requirements (from RFP).

Parameter	Value	Units	Comments
Waveband	1500 -1600	nm	2dB loss on transmit acceptable within 1520 - 1580nm, with 4dB loss acceptable for the remainder of the band.
System WFE	< 100	nm - rms	Each of the four XOA apertures will launch diffraction-limited, low-apodised Gaussian beams at all pointing angles & site temperatures.
Adjustable Divergence	20 - 200	µrad - FWHM	Suitable for bright LEO links and dim cis-Lunar links.
Pointing Error	≤ 0.5	µrad / µrad	Cannot exceed half the divergence diameter increase.
Pointing Jitter	≤ 20	µrad - rms	During adjustment of beam divergence.
50% Encircled Energy at Tracking Cameras	≤ 15	µrad - diam	Required for detection and tracking of cis-Lunar terminals.
Tracking Camera FoV	≥ ± 1	mrad	For detection, pointing, & tracking of LEO terminals.
Uplink Power	≥ 20	W / aperture	In expectation of future mission requirements.
Internal Backscatter	≤ 10	%	With respect to tracking camera pixel well depth.
Elevation Angle Range	15 - 85	degrees	Can extend range to 0 – 90 if convenient.
Coarse Tracking BW	≥ 40	Hz	Within 120urad of programmed pointing angles, levied on tracking camera and FSM.
Fine Tracking BW	≥ 800	Hz	Within 60urad of programmed pointing angles, levied on tracking camera and FSM.
Assembly Mass	165	kg	Does not include tracking electronics.
Bounding Box Volume	1200 x 900 x 750	mm^3	Does not include tracking electronics.
Ambient Temp. Range	-10 to +45	°C	External, temp-controlled, air or liquid lines allowed.
Ambient Humidity Range	20 - 80	%	May use external, temperature-controlled source of air or liquid medium. Must not condense onto sensitive components.

3.2 Design Concept

The initial concept design, created by the NASA team at GSFC, leveraged the successful Lunar Laser Ground Terminal (LLGT) transmit optics originally designed by MIT's Lincoln Laboratory, with the primary deviation being a switch to an all-reflective design to eliminate chromatic issues across the large waveband. This design was executed both to study the feasibility of the requirements and to provide context for procurement of the XOA.

The design assumes a fiber launcher for the uplink signal and incorporates a fast-steering mirror that is controlled using a high-speed tracking camera, allowing for fast and precise tracking of a downlink signal on the independent atmospheric channel unique to each aperture. As shown in Figure 6(b), the output of the uplink fiber launcher is collimated, passed through an annular beam scraper and laser-line beam splitter, reflected off the fast-steering mirror, and expanded through a pair of off-axis parabolic mirrors. The downlink shares the same optical path until the laser-line beam splitter, at which it is reflected, passed through a pair of filters, and focused onto the tracking camera. The two paths are coaligned through the use of a movable retroreflector, which directs an attenuated uplink beam onto the camera path.

As the fast-steering mirror is on the shared uplink/downlink path, tracking of the downlink also enables accurate direction of the uplink beam. This requires knowledge of the space terminal's orbital path to determine a point-ahead angle that accounts for the round-trip time of flight. The tracking control loop and the implementation of the point-ahead angle are both performed by a dedicated tracker external to the XOA. This tracker is being designed internally by the NASA team and will include electronics co-located but external and separate to the XOA.

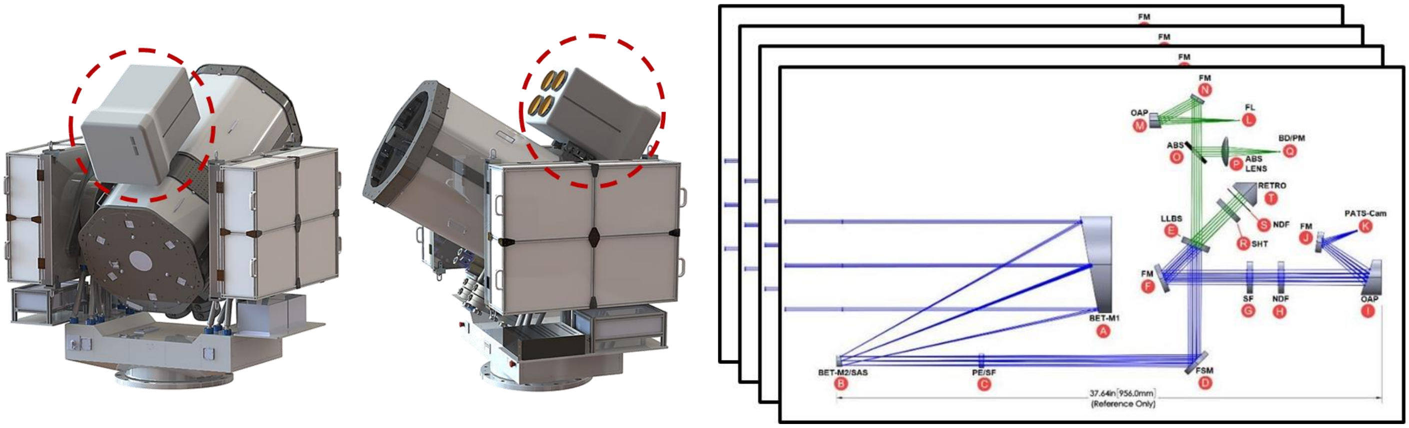

Figure 6. NASA/GSFC architectural concept provided with RFP, showing (a) RTA elevation axis 'robotic piggy-back' mounting scheme, (b) Internal optical design concept of each independent high-power beam director.

3.3 Manufacture

While LCOT is strongly motivated to use COTS parts and assemblies wherever possible, the unique requirements of the XOA could not be resolved using any current COTS optical assemblies. NASA is strongly motivated to encourage the development of industry partners in procurements, and to this end contracted the acquisition of the XOA to Peraton, Inc., a contractor under the SENSE (now ACCESS) project. Peraton broadly advertised a request for information (RFI) in May of 2021 and an industry day was held on May 12th, 2021 to allow for direct discussion with potential vendors. Information received in RFI responses allowed for refinement of objectives in line with industry capabilities, and using this, a request for proposals (RFP) was issued in November of 2021, with industry days on November 3rd and 23rd, 2021. Evaluation of the proposals by Peraton and subsequent negotiations resulted in an award to the University of Arizona's Wyant College of Optical Sciences on May 9th, 2022, for the design and manufacture of the XOA.

While the awarded contract does not require adherence to the concept design provided by NASA, the University of Arizona team, led by Dr. Gregory Smith, has elected to refine the concept design and develop it into a manufacturable design. This has allowed them to accelerate the pace of their work, which has included extensive analysis of optical performance, backscatter, and thermal impacts and management. The effort has attempted to maximize the use of COTS components while maintaining performance under the RFP requirements, focused on a design appropriate to low-rate production for future incarnations of LCOT. Additional derived requirements have been developed during the design process that place further restrictions on the optical and mechanical designs, but these requirements are withheld until the completion of the XOA system design review (SDR). At the time of writing the XOA design team is progressing towards an SDR in December, 2022, with an expected delivery of the XOA in Q4, 2023.

3.4 "Temporary XOA"

Given the XOA procurement schedule and the extensive amount of on-sky testing needed for the development of the LCOT system as a whole, the LCOT team has decided to create a single aperture "Temporary XOA" (Temp-XOA) to meet intermediate testing needs. The Temp-XOA is constructed with purely COTS catalog parts and descoped to remove closed-loop control of an FSM, which will allow for testing with select LEO and GSO space terminals prior to the availability of the XOA. The Temp-XOA is composed of only spherical and flat mirrors with easily procured breadboard, long-pass beam-splitters, hollow corner cube, and two cameras (one visible, another NIR) to allow for co-alignment with the receive telescope. Layout of the Temp-XOA is presented at this SPIE/FSLC-35 conference by the LCOT PI Robert Lafon[6]. The Temp-XOA will first be utilized for our LCRD uplink exercise in early CY2023.

4. DIRECT DETECTION - STARBOARD OPTICAL BENCH (SOB)

The Starboard Optical Bench design philosophy is centered on a simple, all COTS, wavelength agnostic design which feeds the light received by the telescope and reflected off a beam splitter into a pointing and tracking (PAT) system camera and a set of fiber optics. Pointing is achieved by a fast steering mirror (FSM), which is placed at the pupil after the refractive collimator. Placing the FSM at the pupil means less beam-walk on the fiber at larger FOV angles through the telescope. The final split is accomplished with a 50/50 cube beam splitter. It also has a set of two filter wheels in between the collimating lens and the FSM which can accommodate a wide array of ND filters, waveplates, and spectral filters for specific missions. The collimating lens itself will be mounted in a linear translatable mount such that it can move to accommodate collimation of multiple wavelengths, while keeping the beam diameter within specification. An aperture at the intermediate focus is used to mitigate stray light.

Table 3. Example catalog parts list (partial) showing some of the SOB optics & mechanics.

Part Name	Assy.	Build	Spare	Catalog	Product #	Unit Cost
Adjustable Aperture (field-stop) 2"	SOB	2	3	Thorlabs	SM3D50D	$153.91
Beam-Splitter Cube 2"	SOB	2	3	Edmund	49-006	$585.00
Collimator 2"	SOB	2	3	Thorlabs	LB1607-C	$52.42
Filters 2"	SOB	2	3	Edmund	86-094	$715.00
Focusing Lens (CCD) 2"	SOB	2	3	Thorlabs	AL5040M-C	$540.38
Focusing Lens (Fibers) 1"	SOB	2	3	Thorlabs	AL2550M-C	$296.98
Quarter-Wave Plate 2"	SOB	2	3	Edmund	16-892	$1,325.00

The SOB optics are all 2” COTS apart from the variable aperture placed at the intermediate focus. Example procured elements of Figure 7(b) are listed in Table 3 that meet the working requirements shown in Table 4.

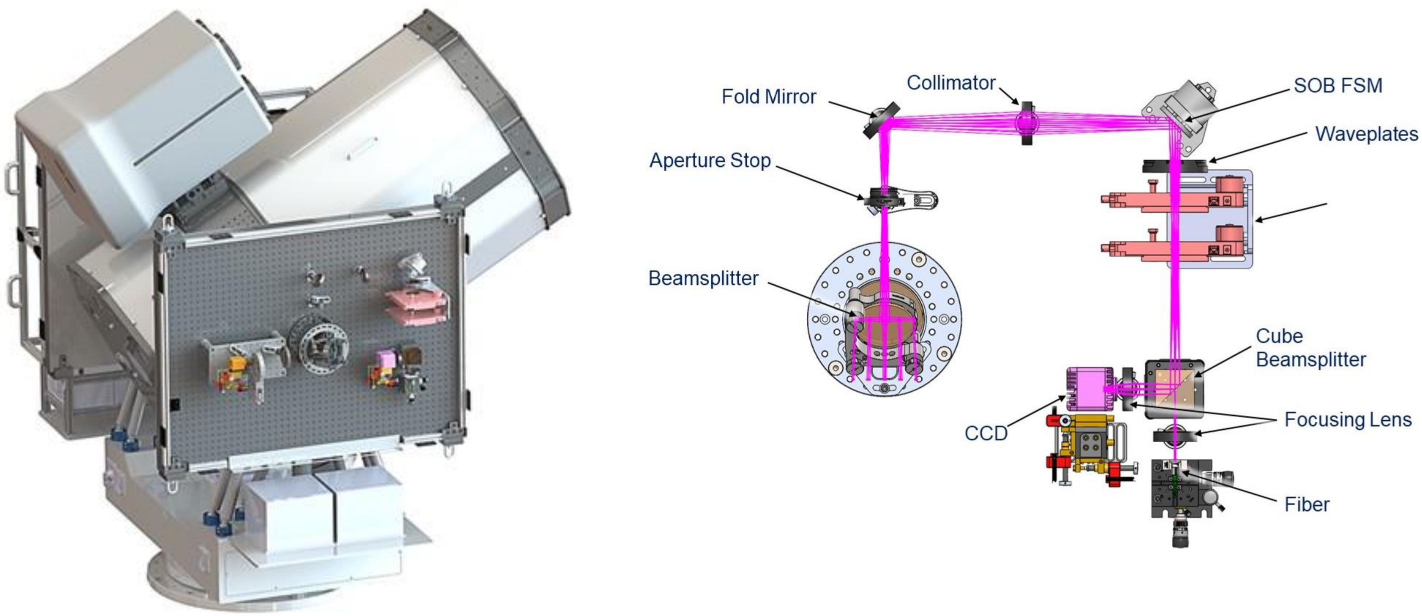

Figure 7. SOB overview: (a) Optical bench configuration on RTA Nasmyth elevation mount including WFCam (cover off), and (b) Optical & mechanical design of just the receiver path to NFCam & large mode area fiber.

Table 4. SOB optical and mechanical performance requirements.

Parameter	Value	Units	Comments
Beam Diameter	14.9	mm	FSM Footprint, Full FoV @ 1550nm wavelength.
Spectral Bandpass	1050 - 1700	nm	Coating of current lenses using a Thorlabs C coating.
Usable FoV	375	μrad	Half-Field of View for PAT system camera.
PAT System EFL	1950	mm	Effective Focal Length of entire system including telescope.
NA into Fiber	0.142	-	Numerical Aperture slightly underfills fiber NA @1550nm.
80% EE Diam. @ Fiber	12.56	μm	Encircled Energy Diameter. On-axis fiber end @ 1550nm.
80% EE Diam. @ PATS	13.95	μm	Encircled Energy Diameter. Full FoV @ 1550nm.

This can be changed out to fit different mission requirements. The collimator has a linear shift mechanism to adjust to the changing focal length of the lens with wavelength. Filters, up to two in series, can also be added. At this stage the mechanical and optical components have been procured and will be assembled in the beginning of 2023. The list of components can be seen in table 4. Filters for populating the filter wheels have not yet been procured.

5. COHERENT DETECTION - PORT OPTICAL BENCH (POB)

With the help of its Adaptive Optics System (AOS), the Port Optics Bench (POB) supports coherent and non-coherent optical communication formats, allowing to couple the received coherent signal into a single mode fiber. The POB has been designed to be modular and reconfigurable for future projects allowing interchangeable optics payloads. In order to reduce cost for future systems and to increase modularity, this bench is using as much as Commercial-Off-The-Shelf (COTS) components as possible. Figures 8(b) and 9 show the optical and mechanical layout of these COTS elements.

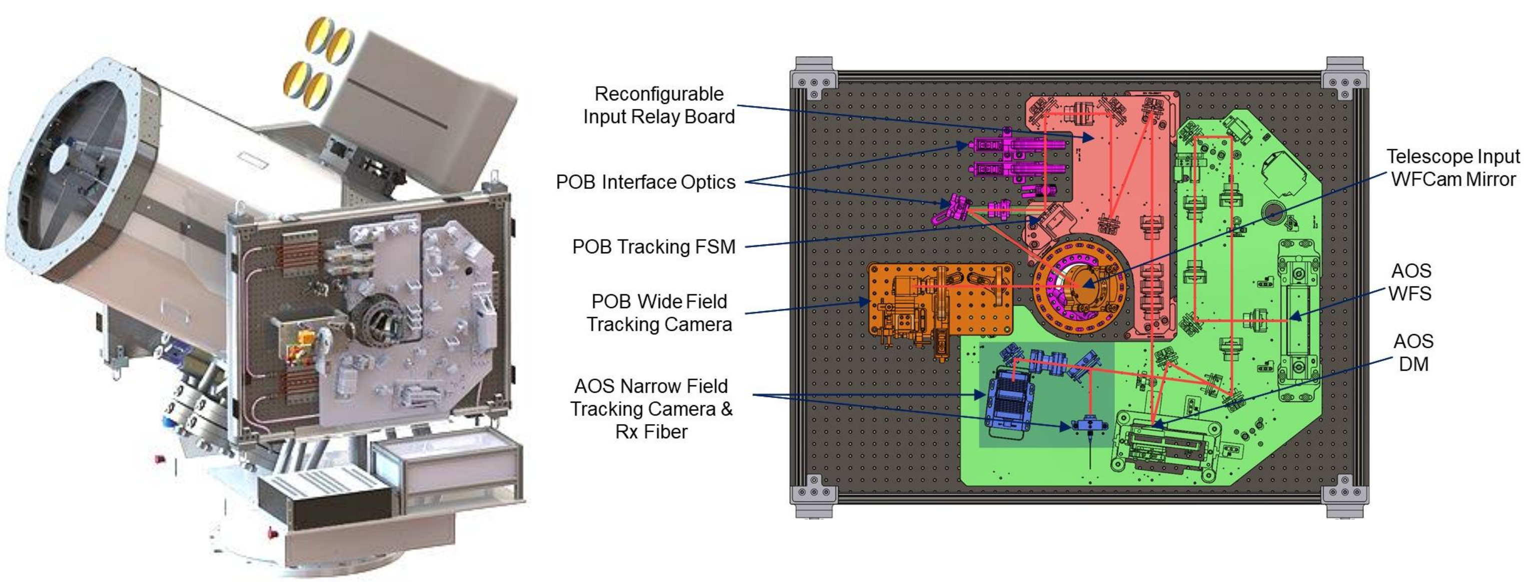

Figure 8. Port Optical Bench overview (a) POB on RTA alt mount and (b) POB AOS & WFCam layout .

The POB is a 3'x4' honeycomb bench used in vertical position and installed at one of the telescope's Nasmyth port. The downlink beam feeds the AOS and the WFCam (Wide Field Camera) through a POB central hole. The backside of the POB is attached to the telescope via an Optical Bench Adapter Plate pinned to the Receive Telescope Interface (RTA). This configuration has the advantage to have the POB altitude-independent, meaning that the POB rotates only when the azimuth angle of the telescope mount changes and always stays vertical. This modular design allows an easy bench exchange for future reconfigurations.

The POB optical layout is presented on figure 9. The WFCam serves as a large field tracking system that locks the telescope pointing and tracking to the downlink signal. This will allow to get the signal in the range of the narrow field tracking camera and to lock the AO.

The light arriving from the telescope M3 mirror is split in two arms through a wedged parallel plate beamplitter. Its coating has been designed to send the reflected beam, representing 93% at 1550 nm, towards the AOS. The transmitted beam, in the order of 3% at 1550nm, is reflected by the telescope input WFCam mirror and sent to the WFCam. This broadband coating keeps this level of performance from 750 nm to above 1650 nm for both s- and p-polarization. At 580 nm, the beamsplitting ratio is in the order of 90/10.

The POB optical setup is mainly divided into two arms, one for the AOS and one for the WFCam. The beam enters the AOS through the Interface Optics and transits via a reconfigurable input relay board whose role is to resize the beam to fit the Deformable Mirror (DM) and to reimage the pupil from the Fast-Steering Mirror (FSM) to the DM. The AOS itself has two functions: tracking and wavefront correction. Tracking is performed with the FSM and a tracking camera. Wavefront correction is achieved with a Shack-Hartman wavefront sensor and the DM.

<u>In addition to the AOS and WFCam, the POB has additional sub-systems that play important role</u> :

- The Interface Optics picks up the reflected beam coming from the beamsplitter and creates a collimated beam sized for the AOS. The role of the Interface Optics is also to reimage the telescope pupil on the FSM that is then reimaged on the AOS DM allowing accurate wavefront correction. The Interface Optics also includes systems for beam polarization control and filtering via a set of spectral and neutral density filters.
- An enclosure to isolate the POB systems from the external environment and to maintain a controlled atmosphere. It is also designed to provide access to its sub-assemblies for any maintenance, repair, or modifications in the field.
- A thermal system to keep the optical systems at stable ambient temperature during operation and minimize thermal gradients inside the POB enclosure.

5.1 Wide Field Cameras (WFCams)

The Wide Field of View Camera (WFCam) is an imaging system allowing Pointing, Acquisition, and Tracking in a relatively large field of view. Two identical WFCams has been designed to be suitable for the POB and SOB. The assemblies will be installed on the telescope on each side of the elevation axis.

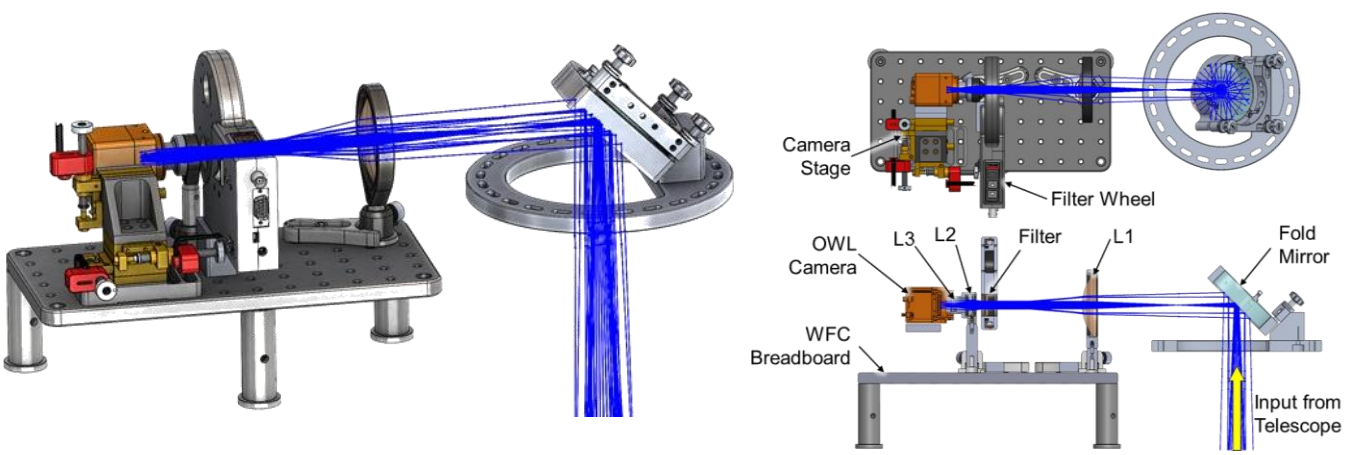

Figure 9. POB/SOB WFCams optomechanical overview (a) Isometric view (b) POB AOS & WFCam layout .

The WFCam optical design has been optimized to accommodate an encircled energy greater than 50% for 15 µm spot radii at a telecentric focal plane. The focused spot covers 2 pixels, representing 13 µrad field on sky. The detector is a Raptor Photonics camera OWL 640M with a pixel pitch of 15 microns and size of 640 x 512 pixels. The corresponding field of view of 4230 µrad x 3380 µrad is then defined by the camera size. The WFCam will provides full performances in infrared between 1500 and 1600 nm, and in visible for wavelengths greater than 580 nm. The camera is mounted on a focusing stage allowing to select the working spectral range by adjusting the defocus. Figure 9 show this layout.

The WFCam system includes a fold mirror, a collimating lens L1, a filter wheel aligned at the pupil position, an imaging lens system (L2, L3), and a camera functioning at visible and infrared wavelengths. All optical elements are COTS except L3, an aspheric custom lens. L1 and L2 are COTS aspherical lenses. The six-position motorized filter wheel includes a set of six Ø1" spectral and neutral density filters that can be changed during LCOT operational phase.

During the Integration & Test (I&T) phase, an initial inspection and metrology has been performed to verify performances of all individual COTS and custom components. Each sub-system has then been integrated and tested individually before installation on the POB. A combination of the optical and mechanical CADs using SpatialAnalyzer® (SA) software allowed to initially pre-position each individual component in the sub-systems and on the POB with a 7-axis Hexagon Absolute Coordinate Measuring Machine (CMM) Arm having 43 µm accuracy over the 3 meters range. An interferometric wavefront measurement has been done to measure the WFCam optical performance and compare to the expected design wavefront error. Table 5 delineates these working requirements.

Each individual element has been aligned on the WFCam breadboard with respect to the CAD by using mounts surfaces metrology. Position (X, Y, Z) and tip-tilt have been aligned with the CMM arm with an accuracy better than 100 µm for X, Y, and Z and better than 0.1 degree for tip-tilt. Additionally, an interferometrically precision sphere (CaliBallTM) has been aligned at the design telescope focus position. After this initial mechanical alignment, the WFCam transmission wavefront error (WFE) has been measured by aligning the interferometer focus on the CaliBallTM center of curvature as shown in Figure 10. This center defines the center of the field of WFCam. The WFCam has been placed in front of the interferometer in vertical position as it will be on the POB, so any gravity effect would be measured. The measured transmission WFE is 66 nm rms and no residual alignment have been noticed, meaning that the initial mechanical alignment with the CMM arm allowed to achieve final alignment and did not require additional correction with the interferometer. The design WFE at the center of the field is 10 nm rms; the measured WFE is mainly due to residual polishing errors created by the aspherical surface. After extracting the measured Zernike and injecting them in the Zemax model to create the as-built model, the impact on the encircled energy is a loss of 1% of the design 61% encircled energy. This difference is negligeable and fully acceptable.

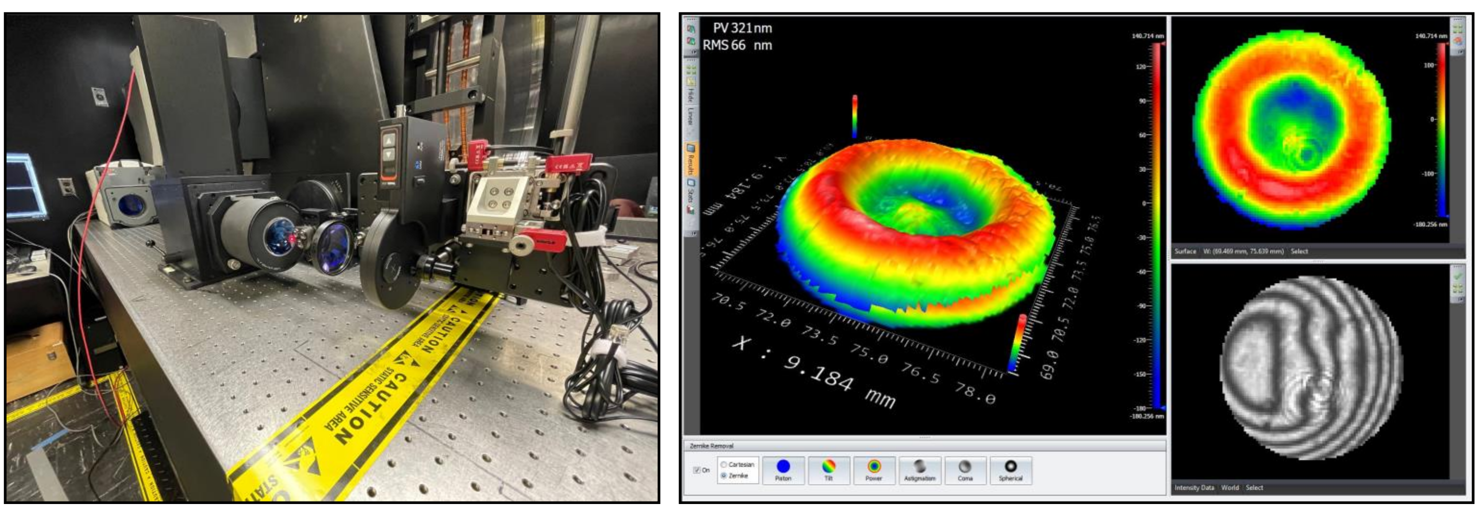

Figure 10. WFCam Testing : (a) Interferometric test by Zygo Verifire MST, and (b) Resulting wavefront error map.

The Raptor OWL 640M camera has been aligned on its 3-axis picomotor stage by using the interferometer focus aligned at the CaliBallTM center of curvature. Images have been acquired and the stages have been adjusted to center the interferometer focus on the center pixel of the camera and by minimizing the diameter of the spot. This initial position defines a reference at 632.8 nm wavelength and the Zemax model will provide the defocus required to position the camera at 1550 nm.

The WFCam has been installed on the POB and still require final assembly alignment with respect to the POB interfaces. This step will be performed with the CMM arm by measuring the WFCam references known from previous CMM measurement. The final I&T step will be to test the WFCam with a 1550nm telescope focus simulator in conjunction with AOS testing in order to boresight the two POB sub-systems simultaneously.

Table 5. WFCams optical performance requirements.

Parameter	Value	Units	Comments
Entrance Pupil Diameter	700	mm	Same as feed RTA.
Effective Focal Length	2090	mm	To match available RTA FoV to sensor area short direction.
Usable FoV	4230 x 3380	µrad	Determined by vignetting of RTA internal baffles vanes.
Spectral Bandpass	480 - 1600	nm	Determined by RTA coatings.
Transmitted WFE	66	nm - rms	Minimized by choice of COTS elements.
Encircled Energy	90	%	@ 15 µm spot radii – center field
Filter Wheel Elements	6	#	Needed for various bandpass, centers, widths, or polarizations.

5.2 Adaptive Optics System (AOS)[11]

Commonly, astronomical observatories use adaptive optics to correct images from atmospheric turbulence in order to improve spatial resolution. Optical communication telescopes require adaptive optics to maximize the power injected into a single mode fiber. The AO will correct the wavefront to allow resolving closer to the diffraction limit thereby minimizing the spot size and tilt error so that it couples more efficiently into single mode fiber. The POB includes an Adaptive Optics System (AOS) used to correct the wavefront and to maximize the light coupling into a single mode fiber. The AOS allows optical signal processing and heterodyne detection used with coherent modulations. The AO principle is to measure wavefront distortion caused by atmospheric turbulence with a Shack-Hartman Wavefront Sensor (SHWFS) using a microlens array and an infrared camera. The atmospheric optical turbulence disturbs the amplitude and phase of coherent laser downlink light. By applying an inverse distortion to a deformable mirror, the turbulence induced wavefront error will be cancelled out. This will then allow signal to be imaged closer to the diffraction limit of the telescope and the light will be focused to a sharper point for fiber coupling improvements.

The LCOT AOS was built by General Atomics and delivered to GSFC in August 2021. It was designed to correct atmospheric turbulence of a downlink signal from a LEO satellite. The AOS is capable of very high rate in order to correct while the telescope is tracking a LEO satellite and slewing through the atmosphere. Based on observations at the LCOT site, the AO has been specified for a typical nighttime Fried parameter r0 of 7.5 cm at 1550nm.

Since its delivery, the AOS was tested in the lab and integrated onto the POB. The AOS has been tested extensively at Orion Artemis II Optical Communications System (O2O) and Laser Communications Relay Demonstration (LCRD) wavelengths, for Greenwood frequencies ranging from 48.8 Hz and 154.5 Hz, and for different Rytov variances. Further tests are planned in vertical position to verify that gravity does not affect its performances. Figure 11 shows the layout of the AOS and its main components. The AOS can be reconfigured for different use cases by switching the input relay board lenses, allowing to adjust the beam diameter on the DM. The AO tracker system includes the Fast Steering Mirror (FSM) that keeps the received light centered on the receive fiber. The AO Wavefront sensor includes the SHWFS and the DM to correct for wavefront distortion and minimize the spot size at the fiber.

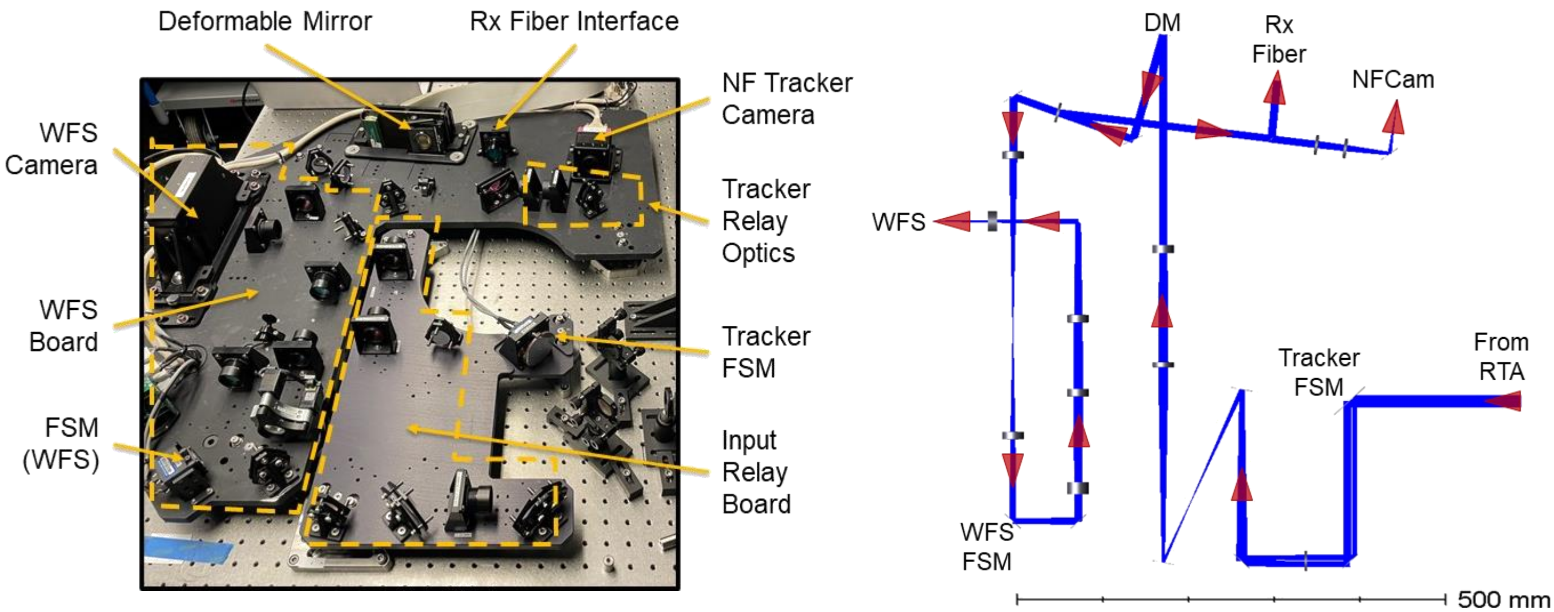

Figure 11. AOS overview (a) Lab acceptance test photo (b) Optical ray-trace layout with afocal input at right.

For laboratory testing of the AOS, a 4f relay optics has been setup to provide a 15 mm diameter collimated beam at 1550 nm, O2O, and LCRD wavelengths. A phase screen has been developed to create atmospheric turbulence at r0 = 7.5 cm and dimensioned specifically for the LCOT AOS. The relay optics system allows also to reimage the phase screen to the AOS FSM and select the Rytov variance to its nominal value of 0.3 by adjusting the phase screen position relative to its nominal position. A central obscuration emulator has been fabricated and used to simulate the telescope secondary mirror obscuration. The output of the single mode fiber is connected to a power meter to measure the power before and after the fiber in order to calculate the coupling efficiency. This is shown in Figure 12.

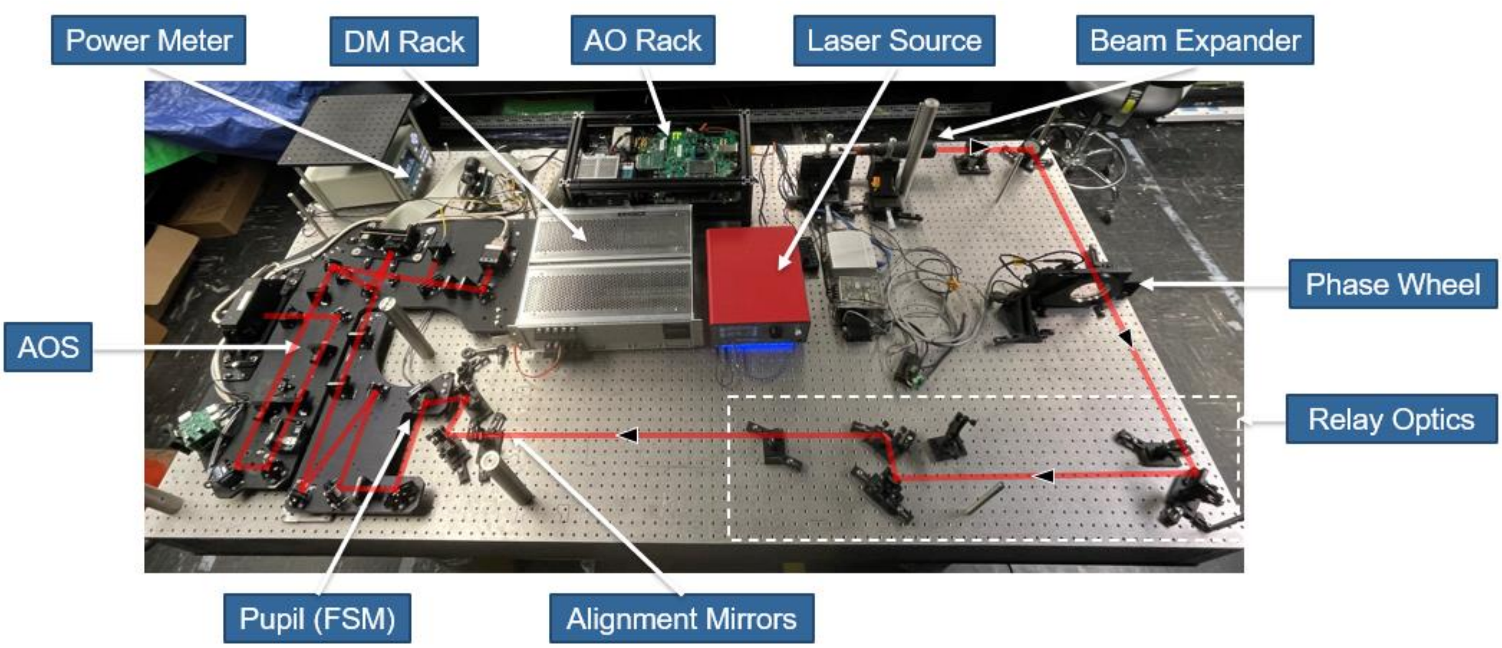

Figure 12. AOS lab test setup layout with a 4-f relay optics system.

The next step of AOS testing in laboratory will be done in vertical position to verify that the gravity effect does not impact the AO performance. Final tests will be performed with a 1550 nm telescope beam simulator that will create a focused beam at the telescope focal plane position and will propagate through the beamsplitter into the Interface Optics and AOS in the first arm, and into the WFCam in the second arm. This test will allow to co-boresight these two systems and to test the AOS with its Interface Optics.

The Table 6 provides a summary of the main characteristics of the AOS and initial performances measured in laboratory at the GSFC:

Table 6. AOS as-built specifications and performance

Parameter	Value	Units	Comments
Wavelength Range	1520 - 1580	nm	Near term expected comms band.
Beam Diameter	6.4	mm	Allows for wide selection of ~1” diam. COTS catalog optics.
WFS Sub-Apertures	16 x 16	#	COTS WFS.
WFS Frame Rate	10	kHz	Driven by max. expected Greenwood frequency at GGAO.
DM Actuators	22 x 22	#	Allows super-sampled actuation wrt. WFS.
DM Actuators Stroke	3.5	μm	Driven by maximum atmospheric induced WFE.
DM Actuators Pitch	400	μm	Driven by beam max. diameter and actuator segment config.
Max. Coupling Efficiency	32 & 41	%	*With & Without* central obscuration emulator @ fG = 109 Hz

5.3 Interface Optics (POB/AOS & SOB)

The Port Optical Bench Interface Optics design philosophy is centered on a simple, all COTS, wavelength agnostic design which feeds the light received by the telescope and reflected off a beamsplitter into the AOS. As shown in Figure 13, the optics are composed of an aperture stop for stray light mitigation at the telescope intermediate focus, a 1” protected silver coated fold mirror, a COTS collimator lens, a 2” fast steering mirror (FSM), and two filter wheels with 1” filters. It is designed to be similar to the SOB design apart from requiring a different layout due to the nature of FSM location in relation to the AOS. Pointing is achieved by the FSM which is placed as close to the pupil as possible.

Table 7. POB Interface Optics performance requirements.

Parameter	Value	Units	Comments
Beam Diameter	14.72	mm	FSM footprint. On axis.
Bandpass	1050 - 1700	nm	Coating of current lenses using a Thorlabs C coating.
Usable FoV	330	μrad	Half-Field of View for input into AOS.
On-Axis WFE	0.017	λ - rms	@ 1550nm wavelength.
Off-Axis WFE	0.016	λ - rms	Maximum FoV. @ 1550nm.

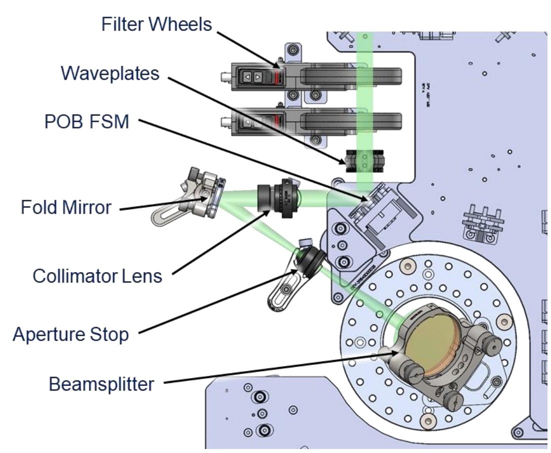

Figure 13. POB Interface Optics.

6. CONCLUSIONS & PATH FORWARD

Over the past two years, the LCOT/FSOS team at NASA/GSFC has grown to include detailed optical & mechanical designers, and now we are adding thermal design expertise to that list. In our overriding quest to produce a self-contained, high-performance, maximum reconfigurability, and *lowest cost-of-reproduction* FSOC ground terminal, we have arrived at a practical prototype architecture that we believe will evolve to satisfy the future of NASA's multi-GB/s needs between *any* ground base and crewed (or robotic) space assets *throughout* the volume of space encompassing the Earth-Moon system (e.g. NASA's LunaNet).[12] Figure 14 shows our progress on core hardware as of December 2022.

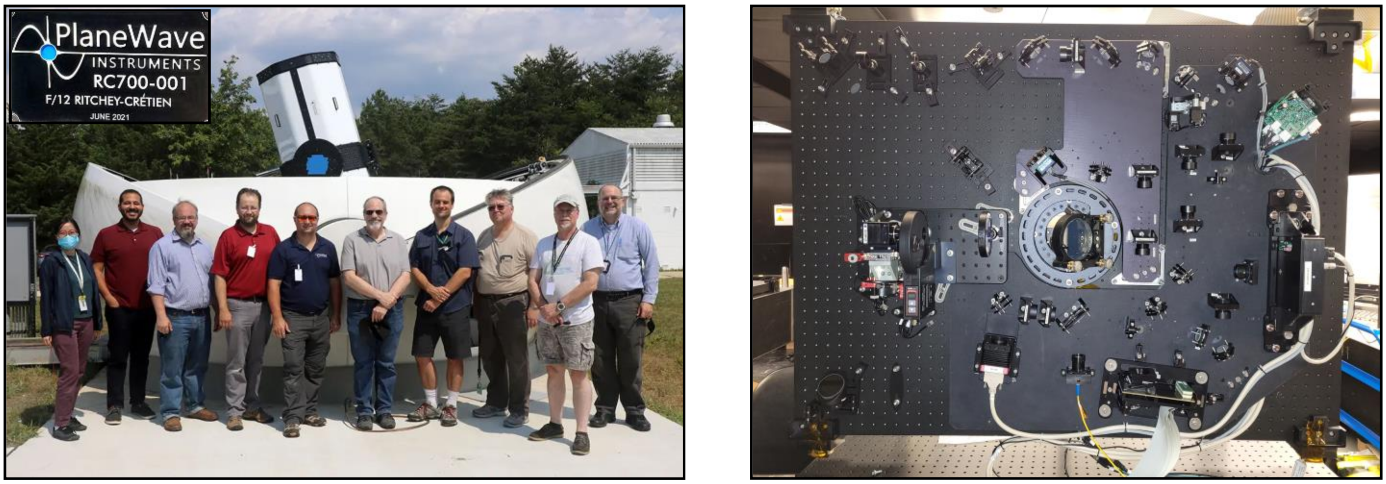

Figure 14. LCOT hardware photos : (a) New RTA at GGAO site with installation team[9], (b) Nearly complete coherent comms POB w/ AOS undergoing lab vertical testing.

Going forward into the 2023 calendar year, we expect to have demonstrated our new LCOT FSOC ground terminal system in the field at GSFC's GGAO with a variety of space terminals spanning high- & low-inclination LEO, MEO, and GEO orbits. These collaborations are expected to include current or imminently operating missions such as PTD-3/TBIRD, ISS/ILLUMA-T, and STPSat-6/LCRD.[12]

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- General Atomics / Guidestar Optical Systems, Inc. (Longmont, CO) : " https://www.ga.com/general-atomics-acquires-the-business-of-guidestar-optical-systems-inc "

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