

NCU OCT: Opto-Mechanical Design and Assembly of a Compact CubeSat Optical Communication Telescope Module

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ABSTRACT

This paper presents NCU OCT, a compact optical communication payload developed for CubeSat-scale free-space optical communication and pointing validation. Its telescope module serves as the collimating optical front-end of the payload and supports multiple near-infrared channels within a volume compatible with a payload smaller than 2U, including receive channels around 976 nm and 1536 nm and a transmit channel around 1550 nm. The optical module is designed to balance beam collimation, pointing feedback, fiber coupling, packaging efficiency, and practical alignment capability.

The design uses a five-lens afocal configuration based on a Keplerian telescope concept, providing a 45 mm aperture and a field of view of ± 0.5 degrees. The optical system integrates a spherical-lens afocal telescope section, dichroic mirrors, a MEMS-based fast steering mirror, fiber-coupling optics, a quadrant-detector path, and a beacon camera path. Aspheric optics are used in the fiber-coupling section. Dichroic mirrors separate and combine the three channels, directing the beacon path to the quadrant detector and beacon camera and the communication paths to the transmit and receive fiber interfaces. To maximize volume utilization and reduce vibration-induced structural stress, the optical paths are not constrained to a single plane.

The assembly approach combines optical and mechanical adjustment to improve coupling and pointing performance. Engineering models have been completed to verify the optical design and assembly approach, integrating the telescope barrel, fast-steering-mirror assembly, fiber-coupling ports, quadrant detector module, and supporting electronics into a compact optical module package. The afocal telescope section is assembled using an optical centering machine, while the rear optical modules are aligned based on fiber-coupling efficiency. Both fiber interfaces provide six-degree-of-freedom adjustment, and the fast steering mirror provides axial adjustment to reduce the boresight offset between the quadrant-detector spot and the fiber-coupling optimum.

As a result, the five-lens design achieves a Strehl ratio of approximately 0.98 at a 0.25-degree field and remains above 0.8 even at a 0.5-degree field. The transmit path is coupled to a standard single-mode fiber, while the receive path uses a multimode fiber to increase the collected optical power. This architecture maintains more than 90% of the coupling power across the full ± 0.5 -degree field, reducing the requirements on pointing accuracy and pointing stability. These results show that NCU OCT can support compact CubeSat optical communication payload development with practical alignment, packaging, and coupling performance.

Keywords: optical communication payload; CubeSat; telescope module; optomechanics; fast steering mirror; quadrant detector; fiber coupling; alignment

1. INTRODUCTION

Small-spacecraft optical communication can support high-throughput links with compact terminals, but the narrow transmitted beam makes pointing, acquisition, tracking, and structural stability central design drivers. The Nanosatellite Optical Downlink Experiment established a representative architecture in which a beacon sensor, fine-steering mirror, and compact optical terminal bridge spacecraft body pointing and the downlink line of sight [1]. Related calibration work showed that the relationship among a beacon detector, a fast-steering mirror (FSM), and the transmitted line of sight must be measured rather than assumed [2]. Recent in-orbit results further show that internal reflections, stray light, and angle-dependent detector offsets can materially affect acquisition and tracking [3].

These results highlight the need to treat optical routing, mechanical registration, and alignment as one payload-level problem. Satellite optical terminals are sensitive not only to the nominal prescription but also to structural, thermal, and alignment effects [4]. Pointing accuracy and aperture size also directly influence feasible link geometries in both classical and quantum communication concepts [5]. A compact terminal must therefore preserve the relationships among the telescope axis, FSM, quadrant detector (QD), and transmit and receive fiber interfaces throughout assembly and verification.

This paper presents the optomechanical design and assembly approach of NCU OCT. The contribution is threefold. First, side and oblique three-dimensional ray layouts document the non-coplanar routing of the 976-nm acquisition, 1536-nm receive, and 1550-nm transmit channels. Second, optical analyses quantify field-dependent image quality and FSM control of the 976-nm footprint on the QD. Third, the mechanical design separates locating, adjustment, and clamping functions through precision-machined interfaces, locating pins, optical-centering fixtures, and adjustable fiber heads, and connects them to a staged assembly and alignment method.

2. PAYLOAD ARCHITECTURE

NCU OCT is organized around a five-lens, 45-mm-aperture afocal telescope feeding a folded rear optical module. The filter set places an RG850 long-pass element at the telescope entrance, two dichroic elements in the rear module to separate the three wavelength channels, a 976-nm band-pass filter in the acquisition branch, and an additional RG850 element in the beacon-camera branch. The 976-nm light is directed toward the QD and beacon camera, while the 1536-nm receive and 1550-nm transmit channels connect to their respective fiber interfaces. L1 and L2 are the only custom lenses; the remaining lenses are commercial catalog components selected to control cost.

The optomechanical structure is predominantly aluminum, with stainless steel used selectively for the MainPlate, FSM mount, precision pins, and fasteners. Most lenses are actively centered with radial clearance and then bonded in place, avoiding direct clamping preload while preserving alignment travel. A single MainPlate provides the payload's mechanical interface to the spacecraft bus. Consolidating the external load path at this interface is intended to limit the transfer of bus-induced distortion into the aligned optical assembly. The packaged optical path occupies an approximately 72-mm transverse extent and a 140-mm length.

The payload is partitioned into mechanically distinct but optically coupled subassemblies: the entrance-barrel stack, MainPlate and rear support structure, FSM module, QD and beacon-camera branch, and the transmit and receive fiber heads. Optical-facing optomechanical parts are specified with black surface treatment covering 900–1550 nm; selected surfaces additionally use a sandblasted matte finish, and dedicated stops, baffles, and light-blocking features reduce stray-light paths. Figure 1 presents both the folded optical routing and the integrated CAD configuration.

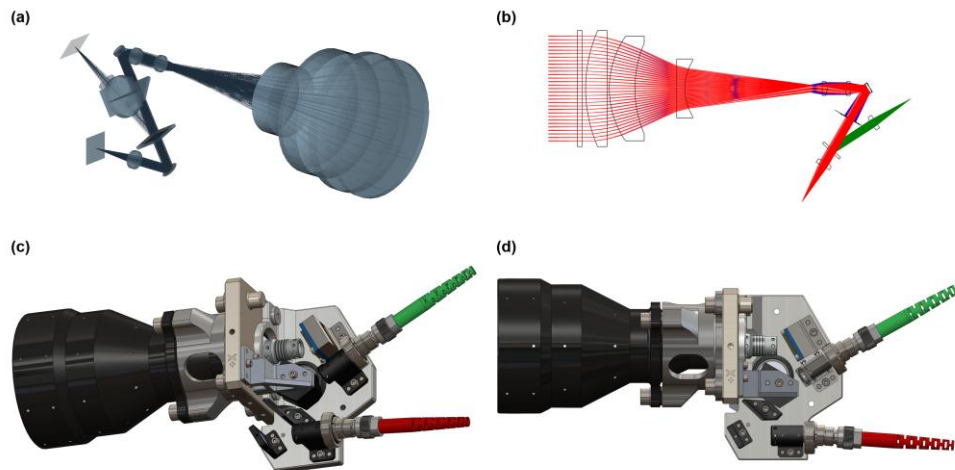


Figure 1. NCU OCT payload architecture: (a) neutral-color oblique optical-element/ray geometry from the synchronized CODE V STEP export, (b) side/elevation optical-model view, and (c, d) oblique and orthographic CAD views. Channel colors are retained only in (b): blue, green, and red denote 976-nm acquisition, 1536-nm receive, and 1550-nm transmit, respectively. All panels are design representations.

3. OPTICAL PERFORMANCE AND QD FOOTPRINT CONTROL

The optical train begins with the 45-mm entrance aperture and five-lens front-optics group. Downstream optics divide the acquisition-sensing and communication branches. The MEMS FSM is placed at the exit pupil of the front optics, where its rotation provides the field-dependent steering used by the QD and fiber-interface paths. The 976-nm branch uses a telecentric relay, diffuser, and QD, whereas the 1536-nm receive and 1550-nm transmit paths use the communication-side fiber interfaces.

Optical analysis [6] evaluates three 1536-nm receive-channel field conditions: on axis, 0.25° with 1.82° FSM rotation, and 0.50° with 3.64° FSM rotation. Table 1 summarizes the corresponding RMS geometrical spot metrics. The calculated Strehl ratio is approximately 0.98 at the 0.25° field and remains above 0.8 at the 0.50° field.

Table 1. Calculated 1536-nm receive-channel geometrical spot metrics.

Field case	FSM rotation	RMS spot metric (μm)
On axis	0°	1.306
0.25°	1.82°	4.325
0.50°	3.64°	13.295

The transmit path uses a standard single-mode fiber, whereas the receive path uses a multimode fiber to provide a larger acceptance area for the field-dependent focal footprint.

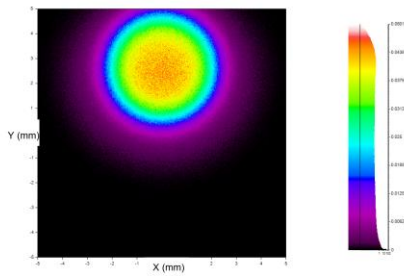
For the 976-nm acquisition branch, scattering simulation of the diffuser was used deliberately to broaden the QD footprint to approximately 4.5 mm in diameter. At all evaluated field points, the simulated footprint remains approximately circular, with no appreciable deformation or change in extent. This diameter balances inter-quadrant-gap sensitivity against active-area clipping. The four quadrant signals A–D are combined as

$$E_x = \frac{(A + D) - (B + C)}{A + B + C + D}$$

$$E_y = \frac{(A + B) - (C + D)}{A + B + C + D}$$

Figure 2 shows the corresponding steering action at the 0.50° field. Without correction, the footprint approaches the detector boundary; a 3.64° FSM rotation recenters it while retaining approximately the same size and shape. The panels use independent irradiance scales, so the comparison concerns footprint position and geometry rather than absolute irradiance.

(a) 0.50° field; no FSM correction



(b) 0.50° field; FSM rotation 3.64°

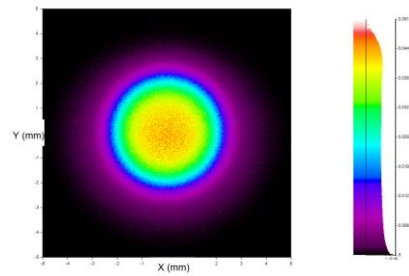


Figure 2. Simulated 976-nm irradiance on the 10×10 mm QD at the 0.50° field: (a) without FSM correction and (b) after a 3.64° FSM rotation. The scattering-designed footprint is approximately 4.5 mm in diameter and is recentered while retaining approximately the same size and shape. Independent irradiance scales are used.

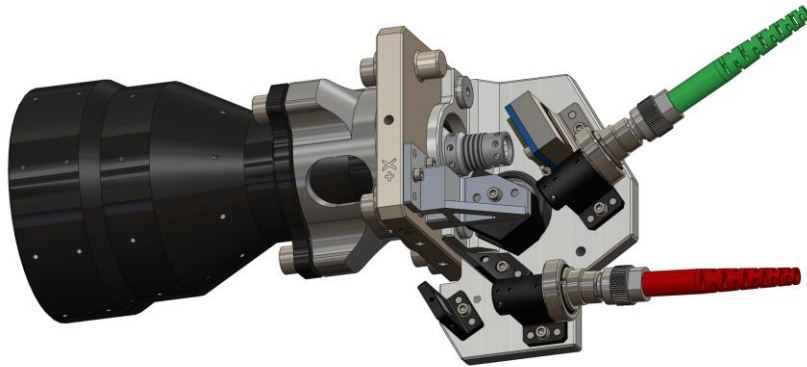
4. OPTOMECHANICAL DESIGN AND ASSEMBLY

The payload assembly contains the entrance-barrel stack, central support, FSM region, QD module, two communication-fiber heads, support plates, and electronics interfaces. The design separates deterministic registration from the mechanisms used during optical alignment, following a locate-then-adjust approach demonstrated for compact optical terminals [7]. Precision-machined mating features and locating pins establish deterministic starting positions, while mount-specific adjustments are retained for the detector and fiber paths.

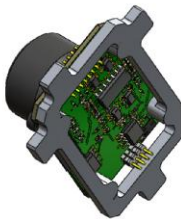
At the telescope-barrel/MainPlate interface, precision-machined mating features and locating pins simplify installation and provide high-accuracy radial and clocking registration. Fasteners then supply the clamping load without being used as the primary locating features. This separation reduces the alignment variables that must be recovered when the barrel stack is installed.

Each communication-fiber head uses a nested inner carrier and outer housing. The two interfaces retain access for centering, angular correction, axial focus, and locking while coupled power is monitored. Figure 3 provides an overall assembly context together with enlarged views of the QD receiver and the two adjustable fiber interfaces.

(a) Overall payload assembly



(b) QD receiver module



(c) Adjustable fiber interfaces

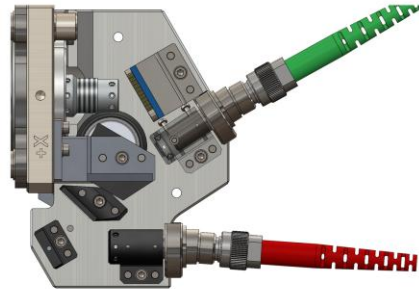


Figure 3. NCU OCT optomechanical implementation: (a) overall payload assembly, (b) QD receiver module, and (c) adjustable receive and transmit fiber interfaces. Precision-machined mating features and locating pins establish nominal assembly positions, while the detector and fiber modules retain alignment and locking access.

The rear-optics SupportPlate likewise uses precision locating pins to define the nominal in-plane positions and clocking of the rear optical subassemblies. This deterministic registration simplifies installation and provides a controlled starting point for subsequent optical alignment, as shown in Figure 4.

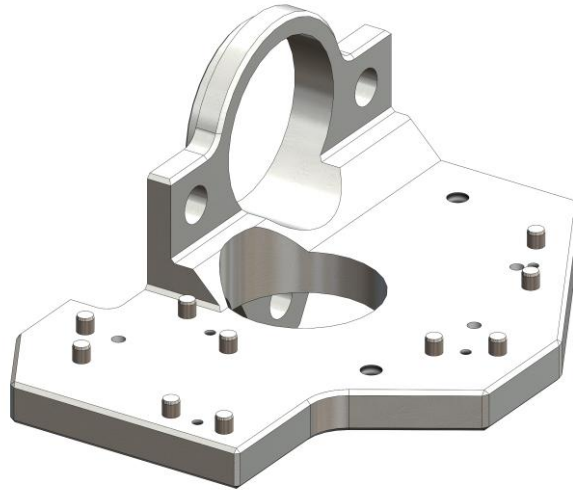


Figure 4. Rear-optics SupportPlate with precision locating pins. The pin pattern defines the nominal in-plane positions and clocking of the rear optical subassemblies before optical alignment.

Stray-light control is integrated into the mechanical design. Optical-facing optomechanical components are specified with black treatment over the 900–1550-nm operating range, selected surfaces receive an additional sandblasted matte finish, and dedicated stops, baffles, and light-blocking features intercept paths that could otherwise degrade the detected signal.

5. CUSTOM L1/L2 MANUFACTURING VERIFICATION

L1 and L2 are the only custom lenses in the payload. Their drawings define material, focal power, dimensions, clear aperture, and surface requirements. The supplier quality-assurance package includes dimensional and interferometric inspection, optical-axis error, coating-witness spectra, and glass melt data [8]. Three pieces of each lens were sampled on 23 April 2026, and all six sampled parts were accepted. Table 2 summarizes the principal design and inspection results.

Table 2. Principal L1/L2 specifications and supplier-reported inspection results.

Item	L1	L2
Glass	S-LAM2	S-LAH88
EFL	84.37 ± 0.05 mm	146.52 ± 0.15 mm
Accepted sampled parts	3 of 3	3 of 3
Measured outer diameter	49.962–49.965 mm	44.970–44.989 mm
Optical-axis error	10–13 arcsec	16–18 arcsec

The supplier-reported dimensional, centering, and surface-figure results satisfied the applicable drawing criteria. Coating witness coupons measured at 5° angle of incidence met the stated average-reflectance limits over 900–1000 nm and 1500–1600 nm and the listed discrete-wavelength limits. The reported glass melt indices and Abbe numbers were also consistent with the drawing values. Together, these records provide component-level confirmation before payload integration.

6. ASSEMBLY, INTEGRATION, AND VERIFICATION METHOD

The afocal telescope is assembled hierarchically. The front and lower optical groups are first centered within their respective barrels using the optical-centering fixtures shown in Figure 5. The barrel subassemblies are then mutually aligned and registered to the MainPlate. The QD and fiber interfaces are adjusted only after the telescope axis has been established, reducing interaction among alignment variables.

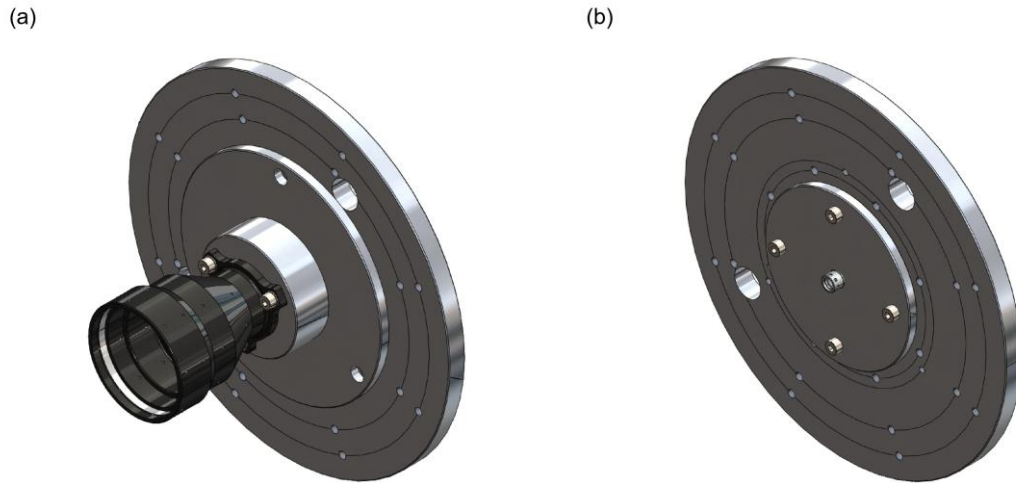


Figure 5. Optical-centering fixtures for (a) the front-barrel and (b) lower-barrel subassemblies. The fixtures establish component-to-barrel centering before the barrel subassemblies are registered to the payload structure.

The two communication-fiber interfaces are aligned independently. First, an autocollimation flat (AC flat) is placed in front of the telescope and adjusted in a double-pass interferometric configuration until it is normal to the established system optical axis. This provides a common return reference for the selected communication path.

A temporary, wavelength- and fiber-type-matched bidirectional fiber launch/receive test unit is then connected to the selected adapter. It launches light through the telescope toward the AC flat and monitors the retroreflected power coupled back through the same interface. The adapter position and attitude are adjusted to maximize the returned coupled power and are then locked. The temporary test connection is removed and the corresponding flight fiber is installed. The procedure is repeated separately for the 1536-nm receive and 1550-nm transmit interfaces. Figure 6 summarizes the two alignment steps.

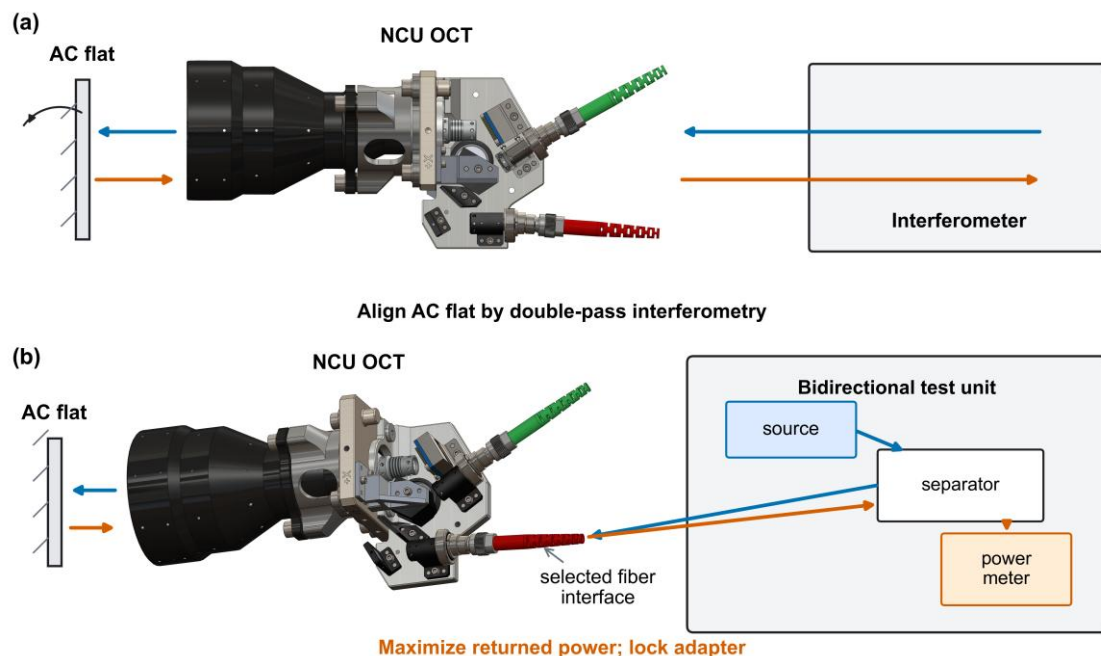


Figure 6. Fiber-interface alignment sequence: (a) double-pass interferometric alignment of the AC flat normal to the telescope axis and (b) adapter adjustment using a bidirectional launch/return test unit. Blue and orange arrows denote outgoing and returned light, respectively. The CAD views identify payload orientation; external equipment is schematic.

7. CONCLUSION

NCU OCT combines a five-lens, 45-mm-aperture afocal telescope with non-coplanar 976-nm acquisition, 1536-nm receive, and 1550-nm transmit branches in a CubeSat-scale package. Its optical analysis defines field performance and a scattering-designed 4.5-mm QD footprint steered by an FSM at the front-optics exit pupil. The optomechanical design combines a single MainPlate bus interface, centered-and-bonded optics, pin-referenced subassemblies, blackened stray-light features, accessible QD and fiber adjustments, and supplier-verified custom L1/L2 lenses. The hierarchical centering and double-pass return-power procedures provide a practical path to final payload alignment and verification.

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