

SCOT80 Telescope: Achieving High-Volume, Low-Cost Production for Optical Communication Terminals

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ABSTRACT

To meet the growing demand of the New Space satellite constellation market, optical communication terminals (OCTs) must be produced at scale and at low cost. For TESAT, transitioning from traditional OCTs—such as the LCT135 used in the European Data Relay System (EDRS) [1]—to a Low Earth Orbit (LEO) constellation application required a production rate increase of at least 100 times and a cost reduction by a factor of approximately 50. To bridge this gap, we developed the SCOT80 terminal, focusing on innovative design and manufacturing approaches to enable serial production. A significant contribution to achieving these goals lies in rethinking the telescope design, which is a primary cost driver. This paper outlines the realized telescope design and the resulting system performance. This design iteration enables the delivery of over 100 units per year at a competitive price, providing a roadmap for future volumes exceeding 1,000 units per year.

Keywords: Optical Communication, Telescope, New Space, Constellations

1. INTRODUCTION

With the advent of Low Earth Orbit (LEO) satellite constellations and increasing customer demand for high data rates, the need for mass-produced, cost-effective optical communication terminals has become apparent. For TESAT, this presented a significant challenge, as existing OCT designs were optimized for the extreme performance requirements of Geostationary or Medium Earth Orbits. These high-performance designs resulted in uncompetitive pricing, size, and weight for this new market, with production limited to only a few units per year.

To resolve this, the main components of the OCT required fundamental redesigns. To address these requirements, the Scalable Optical Terminal (SCOT) was introduced. The SCOT platform utilizes a modular design to allow component reuse across different applications with minimal modifications. Throughout the design process, industrialization and cost-optimization were primary objectives. Leveraging the heritage of the LCT135 and SMART OCTs, this new platform utilizes proven technologies optimized for modern constellation demands. A critical component is the primary telescope; while the achievable link range is highly dependent on aperture size, the telescope is also a primary driver of cost, mass, and volume.

2. OPTICAL DESIGN AND CONCEPT

To serve as an LEO constellation network node or an access terminal, a link range of 8,000 km was required. Because aperture size dominates the feasibility of this target, an aperture of approximately 80 mm was selected to achieve the range with reasonable laser power and optical loss. This terminal is thus designated the SCOT80 (figure 1).

The chosen optical design is a purely reflective Ritchey-Chrétien telescope in an off-axis configuration. It is an afocal system, utilizing an ocular for recollimation. This recollimation simplifies functions such as full-duplex design and link acquisition. The telescope features a magnification of approximately 10 and consists of four individual mirrors, all featuring highly reflective coatings to minimize transmission loss (figure 2). Furthermore, the off-axis design significantly suppresses transmit laser back-reflection compared to on-axis designs. Polished glass mirrors with low surface roughness are used to minimize scattering and stray light. An aspherical mirror design is employed to meet an overall wavefront error limit of below 120 nm rms.

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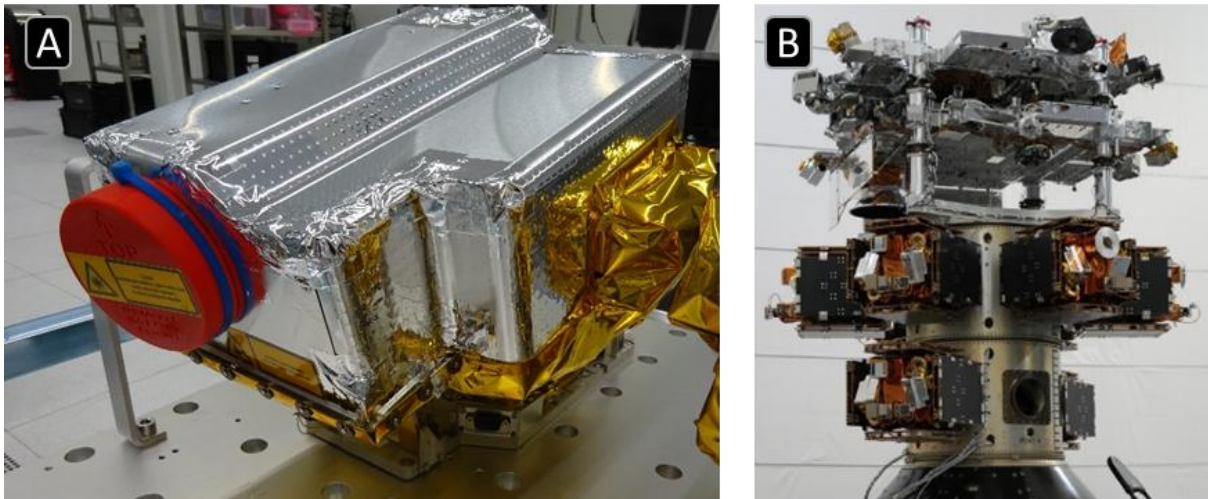


Figure 1. (A) Fully assembled SCOT80 optical head with the red laser protection cap at the telescope entrance aperture; (B) SCOT80 terminals integrated on York satellites for the Space Development Agency constellation stack.[4]

The optical design remains influenced by previous off-axis OCT architectures. At this stage, a robust design with sufficient backscatter suppression and conservative margins for wavefront and pointing error was preferred over more aggressive changes, such as an on-axis design. Given a 1.5-year development timeframe and the fact that this was TESAT's first internal telescope development, the approach prioritized moderate, low-risk technological changes.

3. OPTOMECHANICAL DESIGN AND MATERIAL SELECTION

The optical design imposes several mechanical constraints: the establishment of a common reference level, the manufacturing and positioning of mirror pairs on that level, and the precise adjustment of those pairs relative to one another. Furthermore, the SCOT80 must be compatible with various launch vehicles, requiring resilience against random vibration up to 44 grms and up to 700g pyro shock loads. Additionally, the system must survive a non-operating range of -50°C to $+80^{\circ}\text{C}$ as well as inevitable thermal changes and gradients during operation.

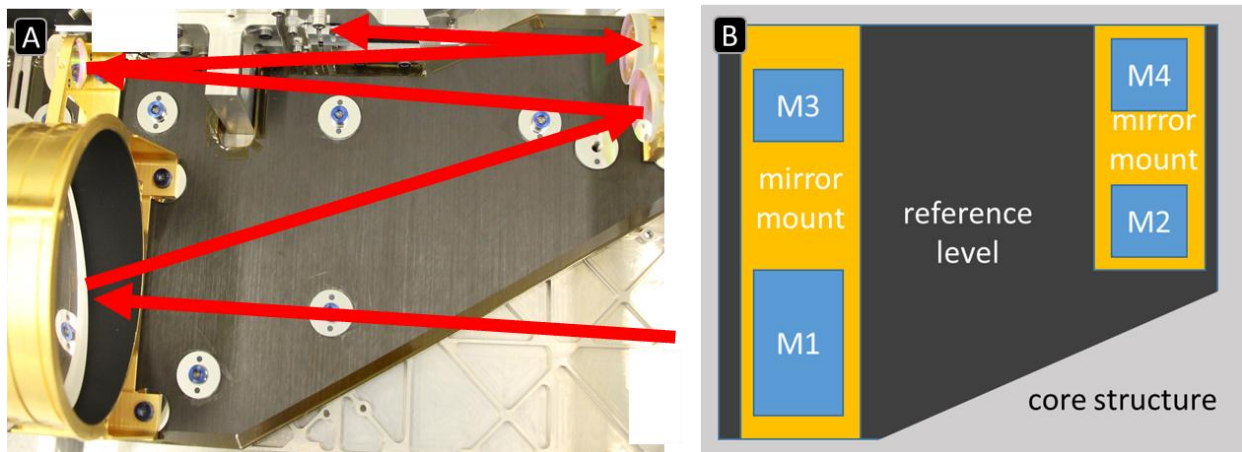


Figure 2. (A) optical path of the telescope (B) block diagram of parts

To free budget for lower manufacturing demands, an athermal design with a Coefficient of Thermal Expansion (CTE) close to zero was chosen. We selected fused silica for the mirror substrate, a specialized Invar with a matching CTE for the mirror mounts, and a carbon fiber reinforced polymer (CFRP) honeycomb plate as the reference level.

The mirrors are bonded to the mounts, which are then screwed to the reference level. The CFRP plate is mounted to an aluminum core structure. The aluminum-to-CFRP interface utilizes solid-state joints to provide sufficient elasticity for thermal expansion/compression while maintaining optical tolerances.

Single-material designs (e.g., aluminum or SiC) were evaluated. However, bare aluminum performance was insufficient, nickel-finished aluminum proved too costly, and SiC was disregarded due to price constraints. Replacing fused silica with ultra-low expansion (ULE) glass was also considered but rejected due to the superior CTE matching between Invar and fused silica. The adhesive joint interface between the mirrors and mounts are balanced to provide sufficient mechanical strength while not introducing intolerable thermal loads.

Finally, the telescope is directly exposed to the space environment. To mitigate risks from ionizing radiation, UV, atomic oxygen (ATOX), and micrometeoroids, a lightweight metallic shroud provides a thermal barrier and internal light baffling.

4. MANUFACTURING AND INDUSTRIALIZATION STRATEGY

To minimize the cost, multiple tasks were performed. First, optimize the requirement distribution between all optical systems with the target to shift functions and requirements at the part with the lowest cost impact. Second, distribute the required tolerances inside the telescope to the least costly component or process. Third, optimize the assembly and test campaign with respect to throughput time and performance.

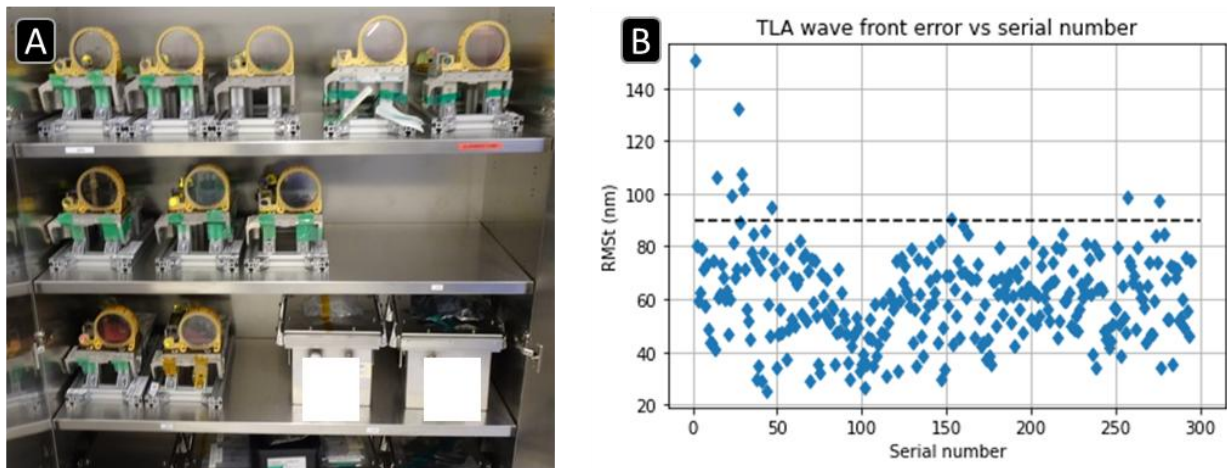


Figure 3. (A): incoming buffer storage for TLAs; (B): wave front over serial number, with target of below 90nm rms

Whereas TESAT's previous telescopes required alignments of basically every optical element with respect to all others, the SCOT80 design was passively aligned and only one active alignment step is performed at the end of the assembly. This is also reflected in the design. All mirrors are manufactured with alignment interfaces to connect to the mounts. Two mirrors are placed together facing the other two mirrors. Assembly is done by passive alignment with dedicated alignment jigs. These two mount assemblies are used in the final alignment step to be optimized with respect to the achieved wavefront. The mirror assemblies are placed on an extremely strictly tolerated common reference plane made of a CFRP honeycomb structure with inserts used as mounting points. This reference plane is finally mounted to the interface structure that provides all interfaces to the other components. The interface structure also provides the position references for the telescope and all other optical units. Based on this alignment interface a sophisticated alignment jig optimizes the optical assembly by aligning the smaller optical subassembly with respect to the interface structure. To further reduce the assembly time, a model-based prediction algorithm is used to provide the optimization direction and magnitude.

While TESAT designed and qualified the telescope, manufacturing and assembly are performed by external partners. For most components, a multi-supplier strategy is used, e.g. four manufacturers provided mirrors. In the end, this strategy provided a robust supply chain. However, it required additional effort to verify the compliance of each supplier. Especially for the very complex metrology of the primary off-axis aspherical mirrors required a cross-supplier measurement campaign.

After the initial pilot production including the different suppliers, a stable supply of telescopes could be provided with a wavefront around a target value of below 90 nm RMSt. In total, from the beginning of 2022 to July 2026 around 300 telescope flight models were produced.

The telescope performance could even be optimized with the existing design. By improving the mirror manufacturing and the assembly process an overachieving of the target wavefront at around serial number 100 can be identified (see figure 3). Subsequently, these improvements were used to reduce manufacturing and assembly efforts while still maintaining the wavefront target. Furthermore, pairing of the optical subassemblies could improve the performance, however, with a higher handling effort leading to a higher price tag.

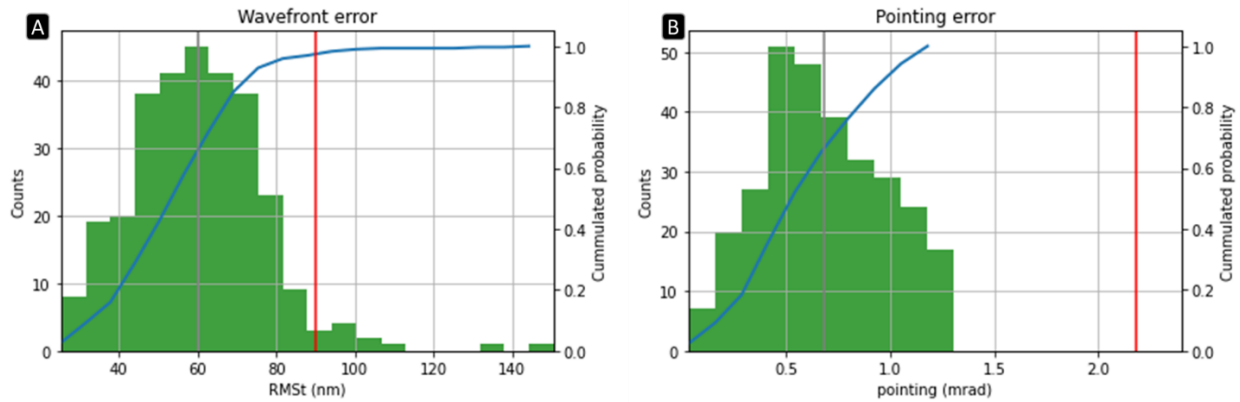


Figure 4. Histogram of the as build wavefront error (A) and the as build pointing error (B) including in red the design budget limits

In figure 4 a histogram of the wavefront and pointing for all manufactured telescopes is computed. Would you remove the initial pilot production, only 2 from about 300 units would have exceeded the target of 90nm rms wavefront error. On average a wavefront error of 60nm was achieved. The pointing error of all manufactured units is also well below its design goal.

5. MODELING AND SIMULATION

A Structural, Thermal, and Optical Performance (STOP) analysis was performed, covering ground effects (gravity, moisture, assembly imperfections, test conditions), launch loads (vibration), and in-orbit thermal effects. For the workflow see figure 5.

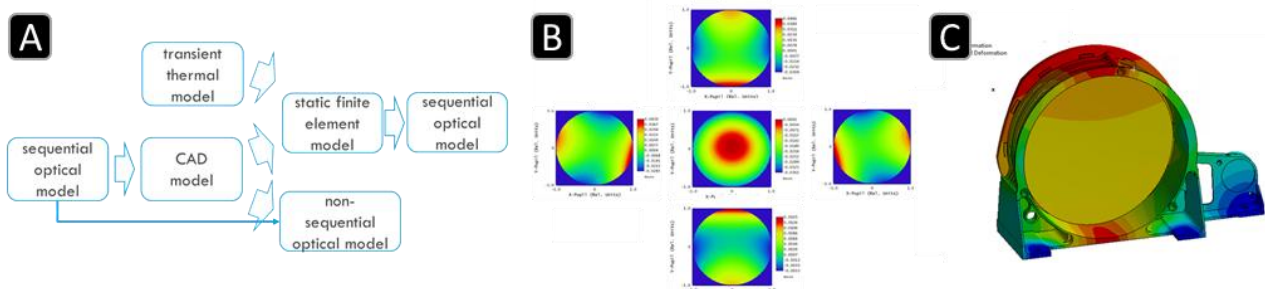


Figure 5. Simulation flow; (A) simulation connection to generate STOP and straylight simulations; (B) example of sequential wavefront simulations at different fields; (C) example of finite element total deformation used as input to optical simulations

Optical and mechanical CAD models were integrated into a Finite Element Analysis (FEA) workflow. The FEA utilized static thermal distributions derived from transient thermal orbit calculations and was used for sensitivity analyses regarding thermal gradients and CTE/CME variations. From the FEA, deformation data was exported to the optical model and the optical impact was calculated.

In a second workflow, the optical and mechanical models were transferred to a non-sequential optical model to evaluate stray light effects. To minimize cost, implementation of baffles or surface treatments were minimized. The stray light analysis was performed by Hembach Photonik.

Extensive tolerance analysis was conducted to iteratively optimize the tolerance budget with suppliers, minimizing total part cost. Where material data was insufficient, dedicated testing was performed. This implied material data as well as tolerance distributions for the Monte Carlo tolerance analysis.

6. EXPERIMENTAL VERIFICATION

Verification was conducted at the material, subassembly, and full-assembly levels. Were reasonable the tests were done on several levels in parallel to reduce the required overall development time. This approach was critical due to the rapid 1.5-year development cycle. To mitigate risks early, conservative mechanical load estimates were used at the telescope interface, including random vibration at 44 grms, pyro shocks up to 700g and a launch lock release that is mounted below the telescope that reaches 4000g at high frequencies. An iterative design optimization, involving above 10 variants of the primary mirror mount, was conducted to meet these requirements. These iterations included improvements to adhesive processes, surface treatments, and mount geometries.

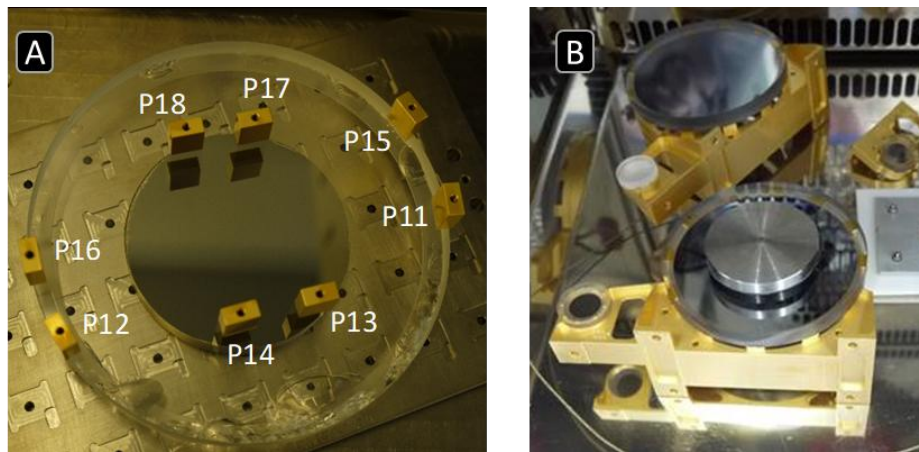


Figure 6. (A) Initial glue samples for pull-out tests; (B) mirror mounts for thermal fatigue test in temperature chamber

Subsequent vibration and shock tests on the higher assembly level verified the design. Thermal fatigue testing of the mirror-to-mount adhesive joints showed no measurable degradation after 500 cycles between -50°C and +80°C. Moisture expansion risks were mitigated by material testing and repeated testing of the assembly over longer storage times and before and after vacuum bake-out; deviations remained within the allocated error budget. Finally, thermovacuum tests of the OCT qualification model verified the STOP analysis, measuring a wavefront variation of less than $\pm 13\text{nm}$ rms across the full operational temperature range. All mechanical environmental tests were passed with changes below the measurement uncertainty.

From the about 300 manufactured telescopes about 250 are delivered as part of an OCT to the customers and about 150 of these are in orbit. The telescope as well as the full terminal has successfully reached TRL9.

7. CONCLUSION AND FUTURE OUTLOOK

The SCOT80 telescope represents a significant advancement for TESAT, enabling a production ramp-up from single units to approximately 100 units per year. While the current design exceeds performance requirements, further cost optimization must be realized to meet even higher volumes and more aggressive price targets.

The next generation of SCOT80 systems (called type 3) that are currently in verification, utilize an on-axis telescope design to further reduce complexity and cost [2]. While on-axis systems are inherently less efficient regarding back-reflection suppression and require larger optics to compensate for central obscuration, they offer for TESAT a straightforward path to the 1,000 units per year target. The current off-axis architecture (type 2) will remain available for high-link-range projects.

type	SCOT135	SCOT80 type 1 & 2	SCOT80 type 3	SCOT30	SCOT20
telescope	Off-axis, reflective	Off-axis, reflective	On axis, catadioptric	On axis, refractive	On axis, refractive
Laser power	≤40W	≤10W	≤5W	≤2W	≤1W
Link range	≤ 80,000km	≤10,000km	≤8000km	≤4000km	≤1000km
Mass	~30kg	~12kg	~12kg	~5kg	~2kg



Figure 7. Pictures and core features of the currently available and in development SCOT product family. The SCOT30 is an early fair mockup, all other terminals are flight model representative

The differentiation in telescope architecture is reflected in the entire SCOT family. The SCOT135, TESAT's largest terminal, is equipped with an off-axis, fully reflective telescope [3], utilizing up to 40 W laser power, leading to 80,000 km link range—about ten times the link range of an SCOT80. Conversely, the smallest terminal, the SCOT20, utilizes an on-axis system providing a favorable balance between price and performance. The currently developed SCOT30 also employs an on-axis telescope system. It will be available in 2028.

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