

Structural-Thermal-Optical-Performance (STOP) Analysis of the SCOT135 Telescope for Spaceborne Laser Communication

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ABSTRACT

This article focuses on the structural, thermal, and optical performance (STOP) evaluation of the transmitter and receiver telescope of Tesat-Spacecom’s scalable optical communication terminal (SCOT135) under multiple varying environmental scenarios. The design follows an athermal concept based on metal mirrors and a housing structure, all manufactured from the same aluminum alloy (Al 6061). Due to its multi-orbit connectivity, tight optical specifications, and harsh environmental conditions, a comprehensive analysis of the operational optical performance is required. Therefore, a custom workflow has been developed that combines the nominal optical performance with actual manufacturing errors, performance-reducing effects from assembly and integration procedures, and load-case-induced aberrations arising from changing thermal and mechanical operational conditions. The analyses are carried out semi-automatically and include plausibility checks, e.g., on data fit quality, as well as interfaces that guarantee full access to the results along the entire analysis chain. The general workflow and data flow are presented, and the scope and depth of the evaluations are demonstrated using one representative load case. The holistic character of the developed STOP analysis tool enables the assessment of this complex and challenging high-performance optical system, thereby supporting the optimization of the system design to achieve compliance with all specifications.

Keywords: STOP Analysis, Laser Communication, Space Telescope, Metal Mirror Optics

1. INTRODUCTION

Spaceborne laser communication promises a significant increase in data transmission rates and availability compared to conventional radio links by relay-based technologies, such as the European Data Relay System (EDRS).¹ The scalable optical communication terminal (SCOT135) with a maximum capability of transmitting 100 Gbps of data is designed to operate in middle earth orbit (MEO) and geostationary orbit (GEO) constellations.² This allows data transmission up to a maximum of 80 000 km in link configurations between GEO and GEO.³ Scalability and multi-orbit suitability are challenges for the development process due to the harsh launch conditions and the various mechanical and thermal operational scenarios. The combination of cost-effective manufacturing of high-performance metal optics and stringent optical requirements demands comprehensive and detailed analyses of the optical system performance under constantly changing environmental conditions. Therefore, a custom workflow has been developed that enables the semi-automated evaluation of structural-thermal-optical performance (STOP) analysis. The workflow provides full transparency of the analysis chain, complete access to intermediate results, and flexibility in integrating outputs from heterogeneous simulation environments.

A comprehensive STOP analysis is required to ensure optical system compliance under operational loads. Mechanical loads, such as preload effects from bolt connections and higher system integration, thermo-mechanically induced forces and moments from downstream support structures and rotating bearing loads, are evaluated alongside critical thermal scenarios. These scenarios include stationary gradients induced by the environment

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and transmitted laser power as well as transient effects during heater operation. These loads induce deformations on the mirror surfaces, deviating from their nominal description and introducing wavefront aberrations, which affect the optical system performance. To enable efficient assessment, a semi-automated Python workflow has been developed. The script processes the node-based deformation data from finite element analysis (FEA), fits the induced surface errors into Zernike Fringe polynomials and exports the results into Zemax OpticStudio (ZMX) for optical performance evaluation. Furthermore, the integration of measured manufacturing data of the mirrors is supported, bridging simulation and as-built system performance to inform alignment and integration procedures. This approach enables repeatable and traceable assessment of optical performance across multiple environmental scenarios. It has been successfully applied to the SCOT135 telescope, significantly enhancing the reliability and efficiency of high-precision optical system design.

2. SYSTEM DESCRIPTION AND ENVIRONMENTAL CONDITIONS

The largest laser communication terminal (LCT) in the SCOT family from Tesat to date is the SCOT135 system. It consists of the telescope unit (TLU) and a sun blocking filter (SBFT), which are mounted as one unit on a rotational axis to the telescope fork mount (TFM) of the optical head (OH), see details in Figure 1. The TFM structure is mounted on another rotary axis, thus enabling the system to achieve a wide field of regard, which is one key to the system's multi-orbit connectivity. An azimuth ranging from -170° to 150° and an elevation ranging from -15° to 195° allows communication across almost an entire hemisphere. The primary unit of the

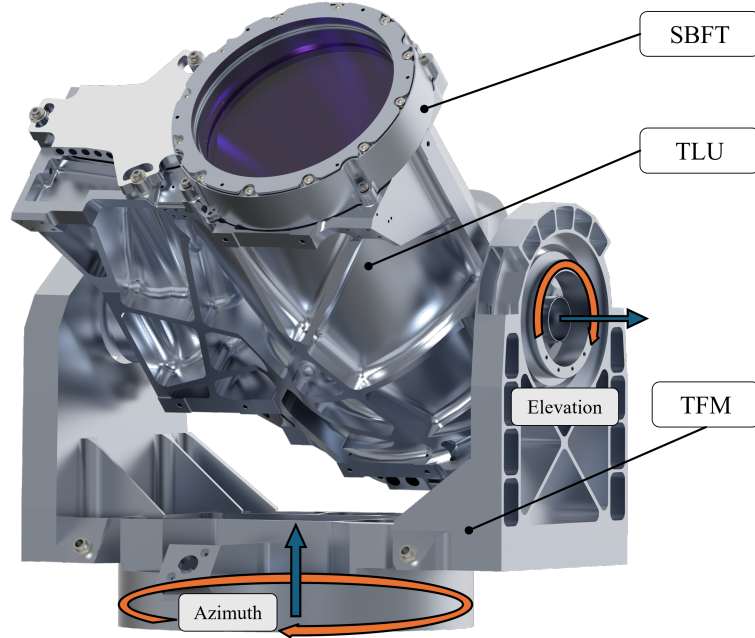


Figure 1: Exemplary illustration of the SCOT135 TLU mounted in the TFM of the OH

SCOT135 system is the optical TLU. The function of the TLU is to magnify (in transmission mode) or reduce (in receiving mode) laser beam diameters. It operates as an optical antenna and serves as both a transmitter and a receiver telescope over vast distances of up to 80 000 km. The optical design is employed by a modified three-mirror anastigmatic (TMA) telescope with an additional aspheric mirror to overcome mechanical design limitations. A fold mirror at the exit of the telescope aligns the exit pupil with downstream optics. As indicated by its nomenclature, the entrance aperture of 135 mm in diameter is the defining characteristic of the system. For reduction of thermal gradients during in-orbit operation of the LCT, a thermal shroud encloses the TLU and shields it from highly asymmetric radiative loads such as direct sunlight and the cold background of deep space.

2.1 System Properties

The modified TMA optical design developed by Fraunhofer IOF provides diffraction-limited performance over a wide field of view and an angular magnification factor of 20.25. With the modification of an additional aspheric and a plane surface as fold mirror for alignment to the exit pupil, the telescope consists out of five optical surfaces. The arrangement of the optical surfaces allows the combination of mirror pairs on common substrates. Consequently, mirror M1 and M3 are placed on one double mirror substrate (M1M3), mirrors M2 and M4 are placed on another double mirror substrate (M2M4), and fold mirror M5 is manufactured on a single substrate. In total, the TLU comprises three mirror modules (M1M3, M2M4, and M5) and a housing structure (see Figure 2). All optical surfaces as well as the mechanical interfaces between the mirror substrates and the housing are ultraprecisely diamond (UP) turned, thus enabling the snap-together approach, which allows fast and effective system integration by reducing the number of degrees of freedom (DOF) requiring alignment.⁴⁻⁶ In receiving mode the light enters at the entrance aperture and propagates through the system via M1M3 and M2M4 onto the fold mirror M5, which guides the beam path through the flange at the interface (IF) of the subordinate optical subunit (OSU). The housing limits the optical beam path, prevents false light from entering and carries

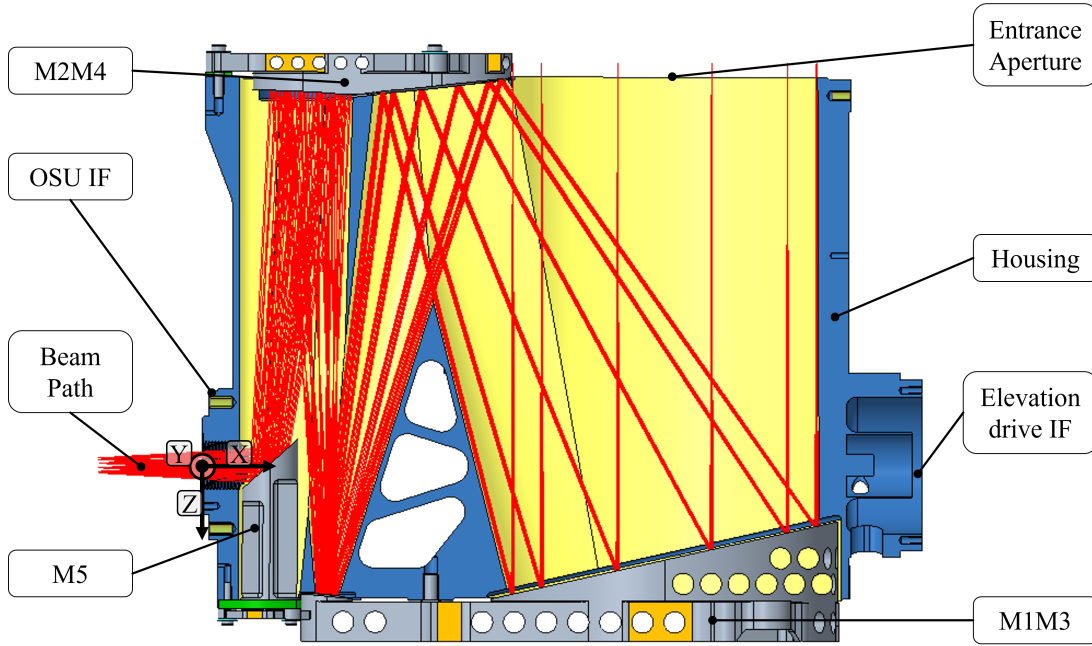


Figure 2: Cross-section view through the TLU with illustration of the mirrors, housing, and optical beam path

the mirror substrates. The TLU is mounted inside the TFM via the flanges at the OSU IF (left side) and the elevation drive IF at the right side of the housing. All parts of the TLU assembly are manufactured of aluminum 6061, thus enabling athermal properties due to the isotropic material deformation of the entire telescope under isothermal temperature changes.

2.2 Definition of Mechanical and Thermal Load Cases

The environmental conditions experienced by optical space systems vary significantly and pose distinct challenges throughout all phases of the system's lifetime. During the design phase on ground, mechanical, and optical tolerances are defined based on the nominal optical design. These tolerances account for manufacturing errors of the mirrors, such as form and roughness deviations from their nominal description, and mounting deformations from assembly and integration procedures. As a result, the nominal wave front error (WFE) defined by the optical design increases to its as-built value. The subsequent phase, the ground-to-orbit (GTO) transfer, is governed by several characteristic load cases, including gravity release effects, launch loads, such as sinusoidal and random

vibration as well as shock, and environmental temperature variations. With the exception of gravity release, these loads are of non-operational nature and are therefore excluded from the following STOP evaluation. Following the GTO transfer, the in-orbit operational phase begins. Multiple mechanical and thermal operational scenarios are specified, each requiring an assessment of its impact on optical system performance. In the following, the operational mechanical loads are presented first, followed by the operational thermal scenarios.

The primary mechanical load case (MLC) is derived from the integration process of the mirror substrates to the housing structure. These components are assembled with threaded fastener joints, to guarantee force-fit connections with enough margin of safety against slipping and gapping under all critical launch loads. The bolt preload is applied with high accuracy using a torque-free tensioning tool (TFFT), which prevents the introduction of additional torsional loading into the axial preload and thus, reduces the induced mirror deformations and consequently the optical aberrations. This load case will be later integrated into the tolerancing analysis since it is a pre-applied initial condition of the TLU and its effects are mostly adjustable during integration. Another initial applied MLC is a predominantly axial force induced at the elevation drive interface at the right side of the housing by a wave spring, which is required for the integration of the TLU into the TFM. The effect of this mechanical load is considered as primary load step for all later analysed thermal scenarios. Further mechanical loads are the gravity release effects along the three cartesian coordinate axes x, y, and z, rotational effects during movement of the TLU around the elevation axis, and forces that are induced by blocking the rotation. A summary of all MLCs is given on the left side of Table 1.

Table 1: Summary of all mechanical and thermal load cases

Mechanical Load Cases (MLC)		Thermal Load Cases (TLC)	
Numbering	Description	Numbering	Description
MLC-1	Bolt preload by TFFT	TLC-1a	Max. ΔT M1M3/M2M4
MLC-2	Axial load at elevation IF	TLC-1b	Max. ΔT M1M3/M2M4 with heater influence
MLC-3	Gravity Release in X	TLC-2	Max. ΔT M2M4/M1M3
MLC-4	Gravity Release in Y	TLC-3	Max. ΔT OSU - Elevation
MLC-5	Gravity Release in Z	TLC-4	Max. ΔT Elevation - OSU
MLC-6	Rotation of TLU in OH	TLC-5	Max. ΔT Housing Top - Bottom
MLC-7	Blocked Rotation of TLU	TLC-6	T_{Max} at TRP
		TLC-7	T_{Min} at TRP
		TLC-8a	Transient with max. heating power
		TLC-8b	Transient with 40 % heating power
		TLC-9a	Initial T from TLC-1a with 12.5 % input power
		TLC-9b	Initial T from TLC-1a with 50 % input power

To regulate the TLU temperature during operation, eight heater IFs are integrated into the TLU housing. The heating power is distributed evenly across these eight heaters by one heating circuit. The temperature is monitored at the temperature reference point, which is centrally placed on the housing structure and used to control the heater operation. All analysed thermal scenarios are based on initial temperature distributions obtained from higher-level transient system simulations of the orbit constellations. These stationary input temperatures are superimposed at the TLU level with the absorbed fractions of the laser transmission power, thereby capturing the local thermal effects at the mirror surfaces for the subsequent STOP analysis. In total, twelve thermal load cases (TLCs) are considered. Ten of these are determining the performance of maximum and minimum temperatures as well as of maximum temperature gradients occurring across the TLU. Two scenarios (TLC8a and TLC8b) represent transient heater conditions, evaluated for two levels of total heating power (maximum and about 40 %). For the transient operation of the heaters, a thermostatic control loop is implemented in the simulation environment. This allows the thermal system behaviour to be monitored over several heating cycles in order to identify the most critical state of the TLU for the subsequent evaluation of optical performance. Prior to applying the thermal boundary conditions, all thermal scenarios are superimposed with MLC-2. For load cases TLC-1a to TLC-8b, the absorbed fractions of the maximum available laser input power are applied, whereas for TLC-9a and TLC-9b the input laser power is reduced to 12.5 % and 50 %, respectively. A summary of all TLCs is provided in Table 1.

3. STRUCTURAL, THERMAL, AND OPTICAL PERFORMANCE EVALUATION

3.1 General analysis procedure and data flow

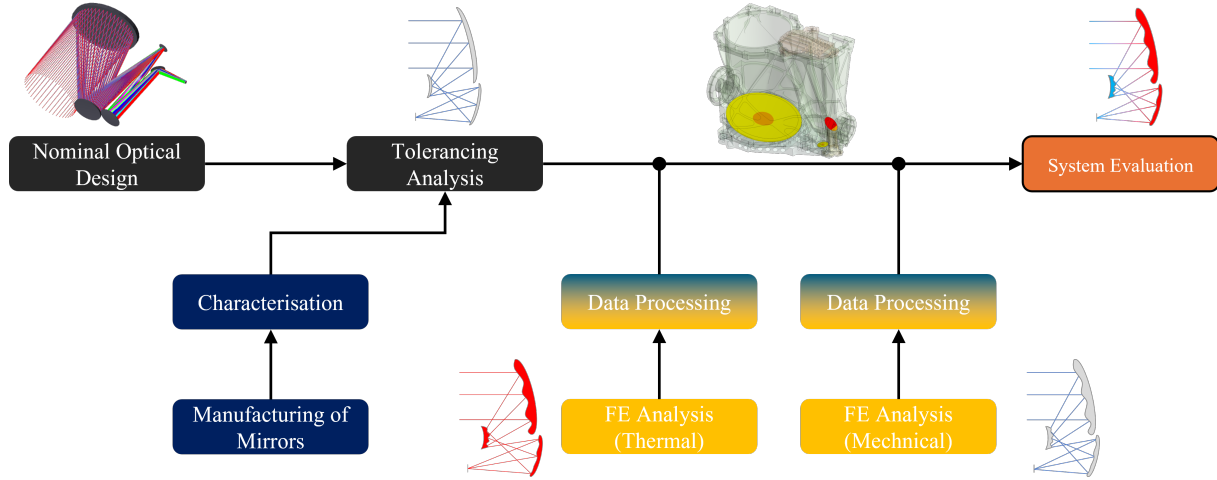


Figure 3: Overview of the general STOP analysis procedure

The assessment of the optical system performance under varying structural and thermal environment conditions requires the interaction of several software environments. ZMX is used for the development of the nominal optical design, for all tolerancing analyses (Monte Carlo simulations), and for the subsequent calculation of the optical system performance under different operational loads. The deformational impact of the mechanical and thermal loads is determined using the finite element method (FEM). Static-structural, steady-state thermal and transient thermal analyses are performed with the finite element analysis (FEA) software Ansys, enabling each load to be assessed with respect to its resulting mirror deformations. With the Ansys customization toolkit (ACT), an interface was developed to import the local optical coordinate systems (CS) of each mirror from ZMX. This allows the extraction of the node-based deformation data of each mirror in its respective optical CS, depending on the selected finite element (FE) mesh quality. The deformation data obtained from the mechanical and thermal FEA are subsequently processed such that they can be imported into ZMX to evaluate the optical performance criteria relative to the nominal design. With Python scripted modules the data processing, the data implementation into ZMX, and the performance evaluation is carried out. This enables a customized semi-automated STOP analysis with full access and traceability of all data throughout the entire evaluation process. In Figure 3, a flow chart is depicted with the overview of the general analysis procedure. To evaluate the effects of each load case, following optical system parameters are analysed:

- Wavefront error of field points
- Pupil shift in x, y, and z coordinates
- Changes in pointing
- Changes in angular magnification

3.2 Description of the Analysis Tool

As illustrated in the flow chart in Figure 3, the interface between FEA software Ansys and optical design and evaluation software ZMX is implemented through three principal Python modules, each providing functions for a distinct subtask. The first module, the data fit module, handles the post-processing of the deformation data generated by FEA. It comprises all functions required to fit the node-based deformations to a continuous Zernike Fringe surface, which models the optical surface irregularities using up to 36 Zernike polynomials.^{7,8} For thermal load cases, the module accounts for the components of isotropic expansion of the imported deformations. At this

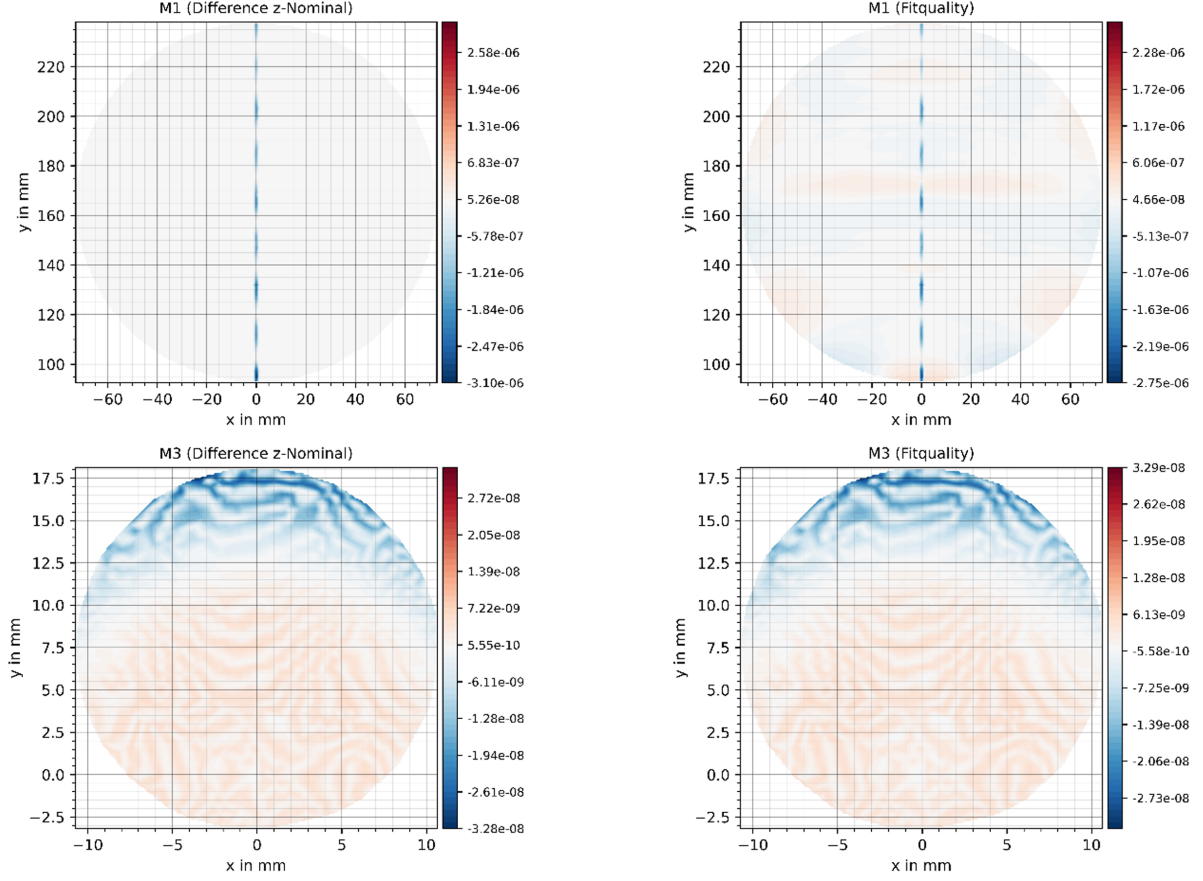


Figure 4: Plausibility checks of nominal and fitted data for the example of mirror module M1M3

stage, two plausibility checks are performed. The first compares the nominal mirror surface description from the FEA with the corresponding nominal surface in ZMX, thereby identifying nominal deviations between the FEM and ray-tracing software. The second compares the fitted continuous surface with the node-based deformation data to assess the quality of the data fit. As an example, the difference between nominal data sets and the fit quality are illustrated in Figure 4 for the mirror module M1M3. The central vertical line of the plausibility checks of M1 are an artefact from the computer aided design (CAD) import into FEA. The order of magnitude lies in the nm regime and thus, is comparably low. The fit quality plot of M1 also shows the vertical artefact, which means that the spatial frequency of the artefact is too high to be fitted and thus is not imported into ZMX. The wave-like patterns for the plausibility checks of M3 are two orders of magnitude smaller than M1, which is such low that these effects are identified as numerical noise from FEA.

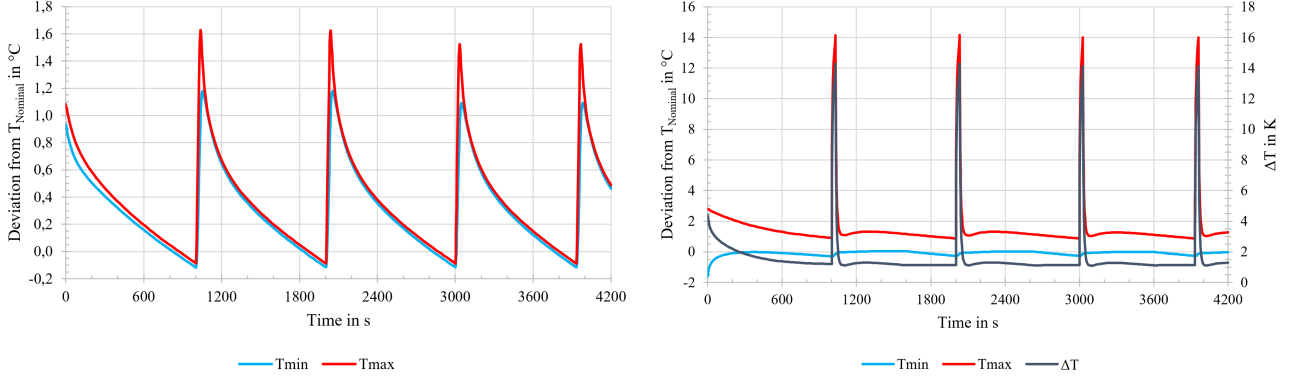
The second principal Python module is the communication module. It uses the ZEMAX OpticStudio Application Programming Interface (ZOS API), which is a programming interface that enables the automation of analyses and scripting of design changes. Through this module, ZMX parameters are read and set programmatically, allowing the fitted deformation surfaces to be transferred directly into the optical model without manual interaction. Additionally, the module handles the user interface for defining the general analysis settings (thermal or mechanical load cases) and the optical performance metrics to be evaluated. The earlier described plausibility checks are also initiated through this module. It coordinates the data exchange between all implemented Python modules, thereby serving as the central hub of the STOP analysis tool.

The evaluation and calculation module is the third implemented Python module. It evaluates the load-case-induced optical aberrations, which are still calculated by ray-tracing in ZMX. It offers the possibility to implement manufacturing deviations of the mirrors. The visualization and storage of the results is also controlled by

this module. For each load case, the results are exported in a standardised form and comprise the deformation data of each mirror, expressed as the first 36 Zernike polynomials, wavefront maps for all field points, the changes in pointing and pupil shift, and the resulting wavefront changes for all field points. In the following section, one exemplary load case is evaluated in detail.

3.3 Optical Performance Evaluation of an Example Load Case

For demonstration purposes, one representative load case is selected for comprehensive evaluation, namely the transient scenario from which TLC-8a is derived. The initial ambient thermal conditions are identical to those of TLC-7, but are additionally combined with transient heater operation at maximum available power. The



(a) Maximum and minimum temperature levels at the TRP (b) Maximum and minimum temperature levels and corresponding gradient of the TLU over time

Figure 5: Temperatures at TRP and entire TLU during heater operation

transient thermal analysis is carried out over a period of 4200 s to cover at least three complete heating cycles. A thermostatic boundary condition is assigned to the interface surfaces of the eight heater positions. The heater is activated when the temperature falls 0.1 K below the nominal temperature level. The maximum available heating power is then applied and maintained until the temperature exceeds the nominal temperature by more than 1.1 K, at which point the heater is switched off. Thus, the operating temperature at the TRP is maintained in between a narrow range of 1.2 K by a heating duration of approximately 60 s with maximum available heating power. Figure 5a shows the minimum and maximum temperature deviations from the nominal temperature level at the TRP during the transient operational sequence. Because the time available for heat dissipation into the housing is relatively short, this heating scenario leads to high local temperature gradients across the TLU. The resulting minimum and maximum temperatures, as well as the temperature gradient across the TLU are presented in Figure 5b. In total, four peaks of the maximum temperature and the temperature gradient occur. The maximum temperature gradient of 14.3 K across the TLU arises at approximately 2000 s and coincides with the maximum observed temperature increase above the nominal level of 14.2 °C. This instant is identified as the most critical temperature distribution and is evaluated as load case TLC-8a with respect to its impact on optical performance. The resulting node-based deformation data of this load case are imported into the STOP analysis tool, as described in Sections 3.1 and 3.2.

The first output of the semi-automated evaluation workflow is the load-case-induced deformation of each individual mirror. As an example, Figure 6 shows the deformation of mirror M1 in terms of the first 36 Zernike Fringe polynomials. The left illustration visualizes the induced deformation as a heat map, while the bar charts document the Zernike Fringe fits, divided into two sections. The center bar chart shows terms Z1 to Z3, which corresponds to piston, tip, and tilt. These first order aberrations can later be corrected during system integration. The second bar chart lists the terms Z4 to Z36. These cannot be easily corrected by alignment of one of the follow-up optics, which makes their evaluation with respect to the optical system performance particularly important. The dominant terms on M1 are Z4 and Z5, representing defocus and astigmatism, respectively. Pointing and pupil shift of the exit pupil of the TLU are specified system parameters that need to be evaluated under operational environment conditions. All relevant evaluations are summarised in Figure 7. The left

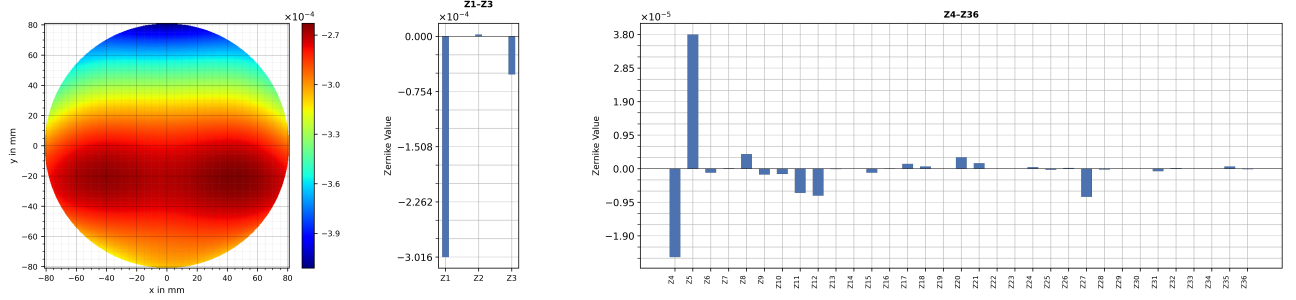


Figure 6: Load-case-induced deformation of the mirror M1 in form of the first 36 Zernike Fringe polynomials

illustration shows the footprint diagram of the reference and the load case, which are perfectly aligned together indicating that no significant changes are induced by the environmental load. In the middle are illustrated the pupilshift in plane (y-z plane) and out of plane (in x direction). The change in pointing is shown on the right illustration with a minimal degradation in the y-cosine direction with 0.08 mrad. Changes in Pupil shift occur in the y-z plane with maximum $9.4\mu\text{m}$ in z direction and $0.9\mu\text{m}$ in y direction, while out of plane pupilshift changes by $-41.4\mu\text{m}$.

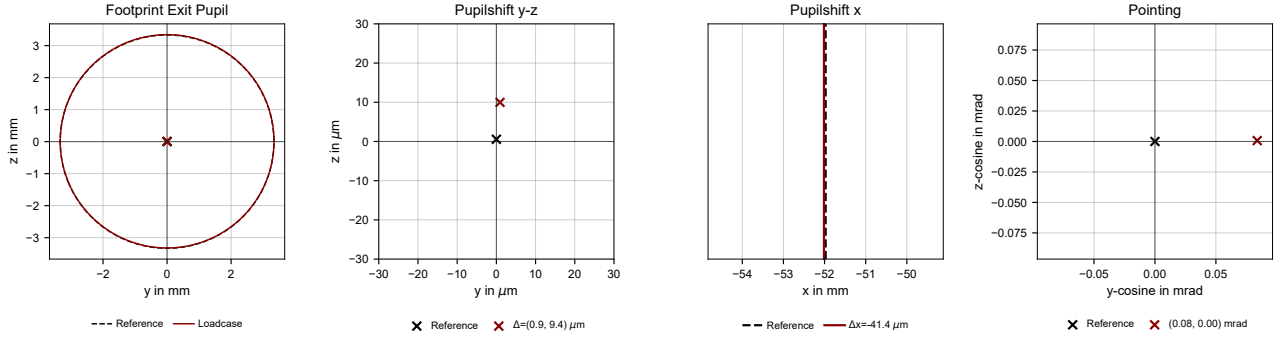


Figure 7: Pupil shift and pointing changes for TLC-8a

The wavefront maps are calculated and plotted to visualize the nominal case (reference), the resulting load case, and the difference between the reference and the load case, thereby assessing the pure effect induced by the load case. The wavefront maps of all field points (FPs) are illustrated. For this project, 25 FPs are defined and distributed across the entire inner and outer field to account for all asymmetries in the load-induced effects. Figure 8 shows the wavefront maps of all FPs as the difference between the reference and the load case. The effects induced by the dominant aberrations defocus (Z4) and astigmatism (Z5) of mirror M1 (compare Figure 6) can also be observed in the resulting wavefront maps. In particular, the characteristic astigmatic shape of the inner field (FP1 to FP9) resembles the inverse of the deformation of mirror M1. In contrast, at the outer field points, the characteristic astigmatism is superimposed with a systematic defocus term. The final evaluation plot presents the load-case-induced changes in wavefront error (WFE), expressed as the root-mean-square (rms) value for each FP normalized to the specified wavefront budget of the inner and outer field. Figure 9 lists all values in two tables. The left table shows the nominal and resulting WFE rms values over all considered FPs. The right table lists the corresponding changes in WFE rms as a percentage deviation. The highest induced changes in WFE reduce the specified WFE budget by approximately 22 % for the inner field and by around 11 % for the outer field.

With this generated WFE rms values, a comprehensive optical performance evaluation can be performed by superposition with the WFE budget from the optical tolerance analysis, including manufacturing, assembly, and integration (MAIT) results. In general, the superposition of WFE values can be realised using three different modelling approaches. The linear superposition represents the maximum errors summed in magnitude, disregard-

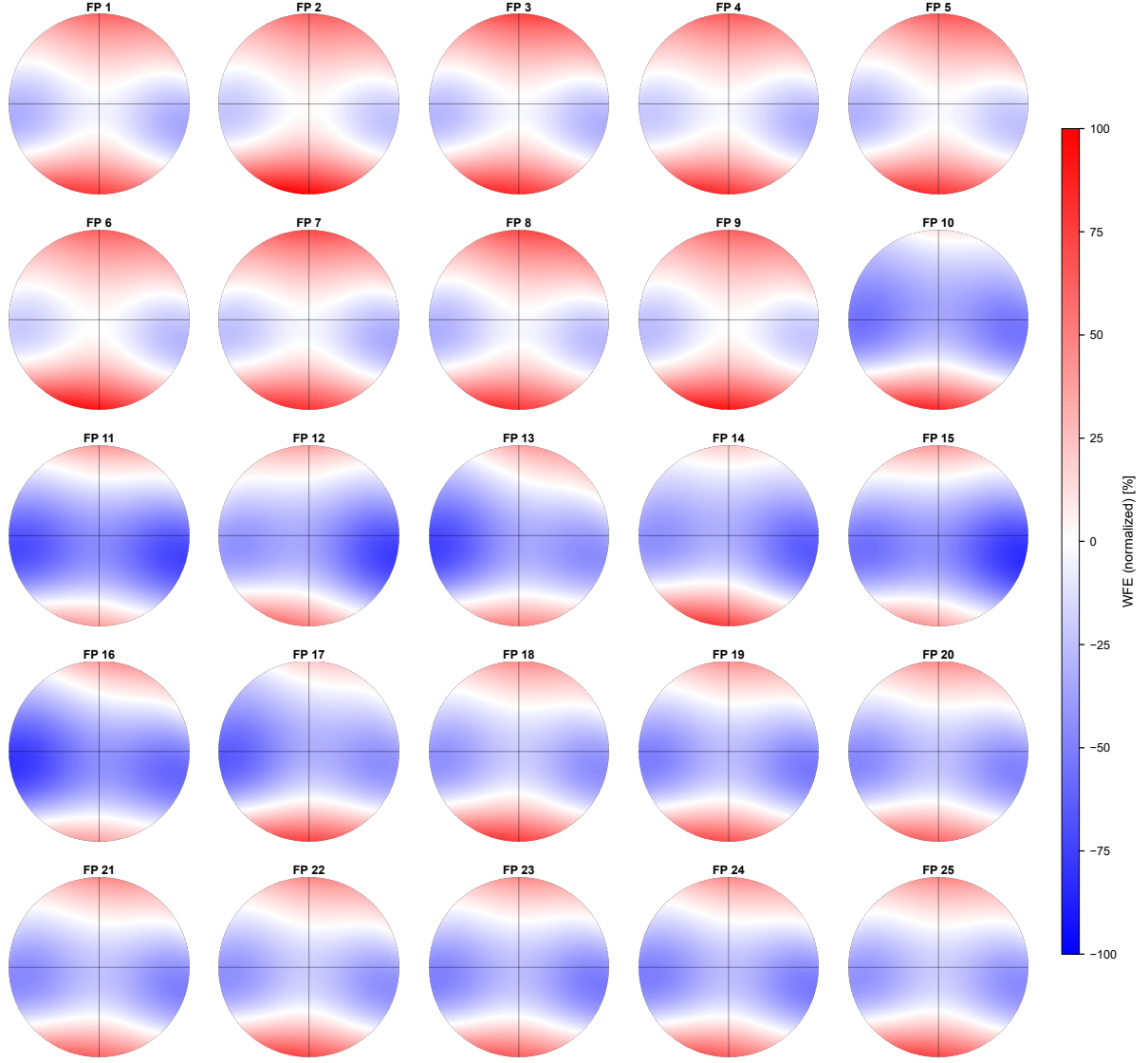


Figure 8: Differential wavefront map of all field points for TLC-8a

ing any interactions or interdependencies between tolerances, and thus corresponds to the worst case scenario. The statistical superposition is based on the assumption that the tolerances are statistically independent and is calculated as the square root of the sum of squares. The R antsch superposition is defined as the geometric mean of the results from the linear and statistical superposition and can be applied in the case of unknown system behaviour or for initial estimations.⁹ The calculation methods of the three superposition models are summarised in the following equations:

$$\sigma_{\text{Linear}} = \sigma_{\text{Load Case}} + \sigma_{\text{MAIT}} \quad (1)$$

$$\sigma_{\text{Statistical}} = \sqrt{\sigma_{\text{Load Case}}^2 + \sigma_{\text{MAIT}}^2} \quad (2)$$

$$\sigma_{\text{R antsch}} = \sqrt{\sigma_{\text{Linear}} \cdot \sigma_{\text{Statistical}}} \quad (3)$$

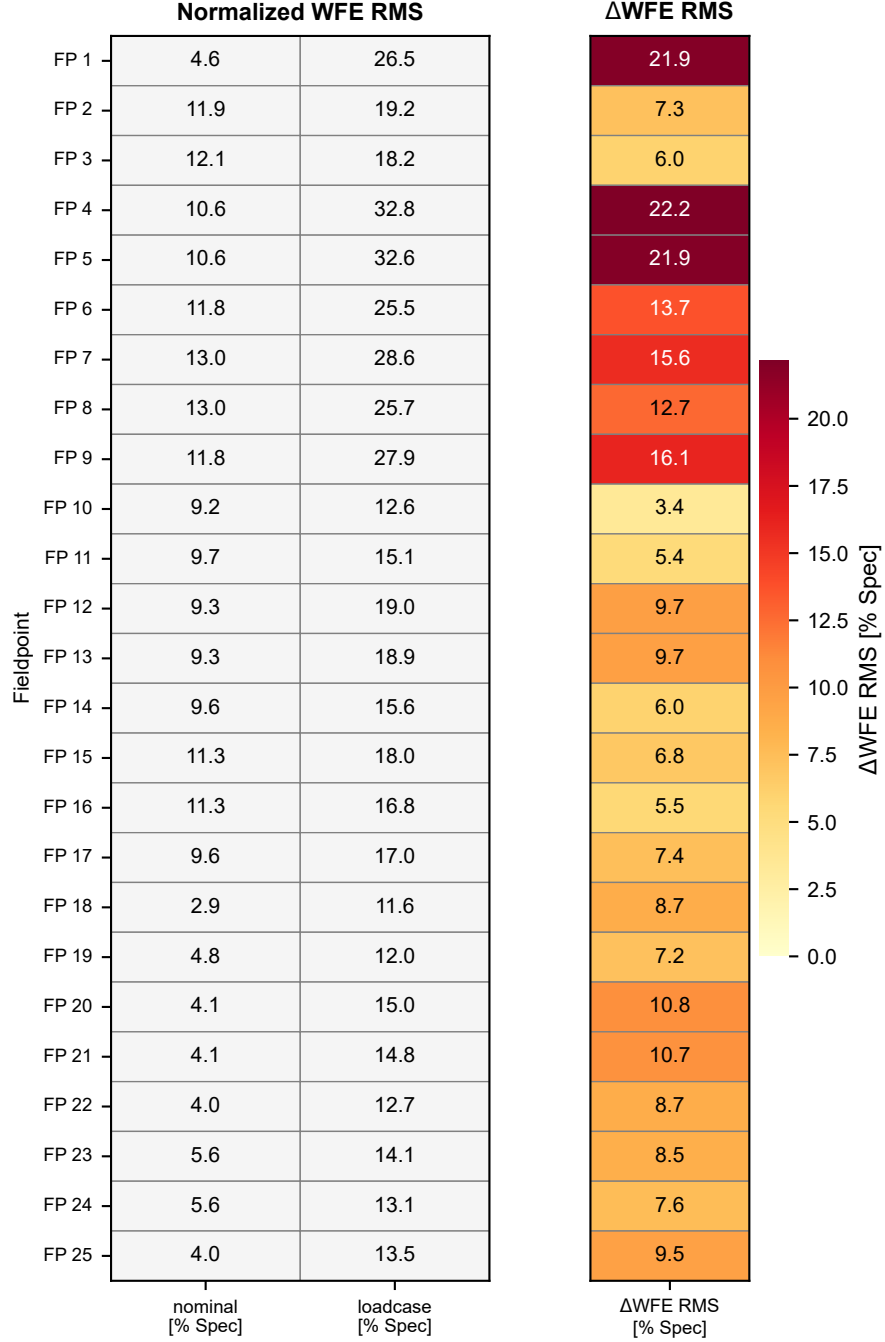


Figure 9: Changes in wavefront error rms for TLC-8a

4. CONCLUSION AND OUTLOOK

This article focuses on the STOP analysis of the SCOT135 telescope, which serves as both transmitter and receiver for spaceborne laser communication across the vast distances of multi-orbit constellations. Under operating conditions, several effects superimpose and degrade the optical performance: temperature changes and gradients induced by different thermal orbit scenarios, local thermo-elastic deformations on the mirrors caused by absorbed laser power and on the housing caused by heater operation, as well as mechanical deformations

arising from preload effects during integration into the higher-level system. Together, these effects reduce the available budget of key optical parameters, such as the WFE, and therefore require a comprehensive and reliable assessment to validate compliance under varying and overlaying environmental conditions. To address this, a semi-automated, script-based workflow has been developed that enables the evaluation of combined influences on optical performance. Within the evaluation process, load-case-induced aberrations can be superimposed with manufacturing errors and with deviations from integration and alignment procedures. The key advantages of this customized solution are that it provides full access to, and complete traceability of, all processed data as well as its modular extensibility for optimisation purposes.

The capabilities of the STOP evaluation tool have been demonstrated in detail for one representative load case. On this basis, all relevant load cases of the SCOT135 TLU were evaluated and compared against the specification. The analyses show that the telescope design is robust against mechanical and thermal loads, and that the resulting changes in the optical performance comply with the system specification. Due to its modular flexibility, the tool was successfully employed to optimize a range of performance-relevant development activities, including assembly processes, load-case-specific design adaptations, and the adjustment of critical operational scenarios. These results confirm that the developed STOP analysis workflow is a robust and traceable tool for validating optical performance under realistic operating conditions, and that it is readily transferable to upcoming high-performance optical space applications.

ACKNOWLEDGMENTS

The development of the SCOT135 system is funded by ESA's Advanced Research in Telecommunications Systems (ARTES 4.0) generic programme lines (GPL). The consortium comprises Tesat-Spacecom GmbH & Co. KG as the main contractor responsible for overall system development, the Fraunhofer Institute of Applied Optics and Precision Engineering IOF for the development, analysis, and qualification of the optical telescope unit, and SPACEOPTIX GmbH for industrial mass-production of the optical telescope unit.

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