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OPTICAL OVERVIEW AND QUALIFICATION OF THE LLCD SPACE TERMINAL

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ABSTRACT

In October 2013 the Lunar Laser Communications Demonstration (LLCD) made communications history by successfully demonstrating 622 megabits per second laser communication from the moon's orbit to earth. The LLCD consisted of the Lunar Laser Communication Space Terminal (LLST), developed by MIT Lincoln Laboratory, mounted on NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft and a primary ground terminal located in New Mexico, the Lunar Laser Communications Ground Terminal (LLGT), and two alternate ground terminals.

This paper presents the optical layout of the LLST, the approach for testing the optical subsystems, and the results of the optical qualification of the LLST. Also described is the optical test set used to qualify the LLST. The architecture philosophy for the optics was to keep a small, simple optical backend that provided excellent boresighting and high isolation between the optical paths, high quality wavefront on axis, with minimal throughput losses on all paths. The front end large optics consisted of a Cassegrain 107mm telescope with an $f/0.7$ parabolic primary mirror and a solar window to reduce the thermal load on the telescope and to minimize background light received at the sensors.

I. INTRODUCTION

For space based applications, free-space optical communication has long been seen as the path to supporting higher data rates than present day radio frequency systems while simultaneously reducing the overhead in terms of size, weight and power. NASA's five year investment in the Lunar Laser Communications Demonstration (LLCD) program paid off in the fall of 2013 when, with just one month of operations, the goals of demonstrating a duplex link between the Lunar Laser Communications Space Terminal (LLST) and the Lunar Laser Communications Ground Terminal (LLGT) in varying operational conditions, such as broad daylight and operations near the horizon, were achieved [1].

The LLCD experiment demonstrated that a small inertially stabilized optical system, the LLST, could successfully point, acquire and track an optical signal at distances $\geq 400,000\text{km}$. The LLST comprised three modules, the optical module (OM), a modem module, and a controller electronics module. The OM, Figure 1, consisted of the LLST optical assembly (OA) attached to the Magneto-Hydrodynamic Inertial Unit (MIRU) which was mounted on a stepper motor driven, two-axis gimbal. The unique requirements of the locally stabilized OA drove the need for an extremely stiff, yet light weight free space optical module [2].

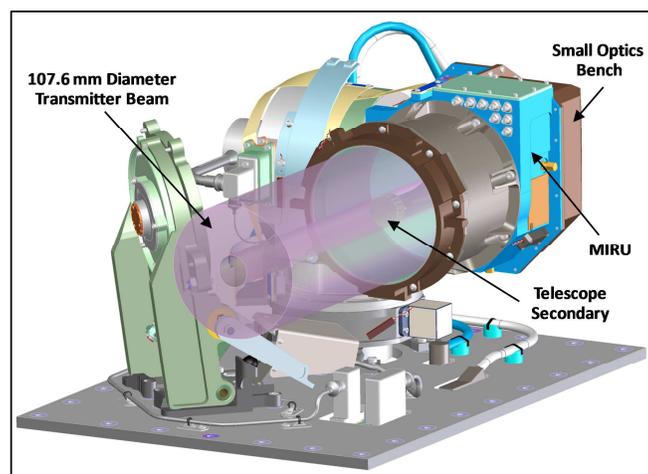


Figure 1. The LLST Optical Module

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The LLST OA consisted of three parts, the solar window (SW), a 47x magnification telescope and the back-end small optics assembly (SOA). The telescope and the bench for the SOA were beryllium, meeting the stiffness and weight requirements of the LLST pointing system. The telescope and SOA were built and tested in parallel to confirm performance before bringing the assemblies together. The OA was characterized for its optical performance (wavefront, throughput, polarization, beam profile) using the Optical Test Set (OTS) before, and after integration into the OM. The performance of the OM was further qualified in environmental vibration and thermal vacuum testing.

II. OPTICAL OVERVIEW

A. System Description

The LLST optics, Figure 2, were conceptually simple: a solar window, telescope, two dichroics to separate the system wavelengths, two fold flats, two lenses for fiber collimating/focusing into and out of the system fibers and a lens plus narrow bandpass filter for the acquisition quad cell. The goal of the optical configuration was to minimize the number of optical surfaces to yield a relatively simple, but still high quality optical system. The powered optics, telescope and lenses, shaped and optimized the profiles of the incoming and outgoing beams. The filtering optics, the SW, dichroics, bandpass filter, and optical folds, directed the incoming and outgoing beams, suppressed unwanted background signals, and isolated the sensors from the downlink transmit beam.

The LLST was a three wavelength system, operating in the 1550nm band, consisting of one downlink communications wavelength, the transmit wavelength, and two uplink wavelengths, the acquisition wavelength and the receive communications wavelength. The three wavelengths were separated by ~20nm in total. Dichroic optics were used to route and separate the beams within the SOA. On the outgoing transmit path, the beam exiting the transmit fiber was collimated, apertured, and folded into the telescope via a fold mirror and Dichroic A. On the incoming acquisition path Dichroic A transmitted, Dichroic B reflected, and the acquisition fold mirror directed the beam into the acquisition quadrant cell. On the incoming receive path, the two dichroics passed the receive beam and the aspheric focused the beam into the receive fiber. The reflectivity of the two dichroics is plotted in Figure 3.

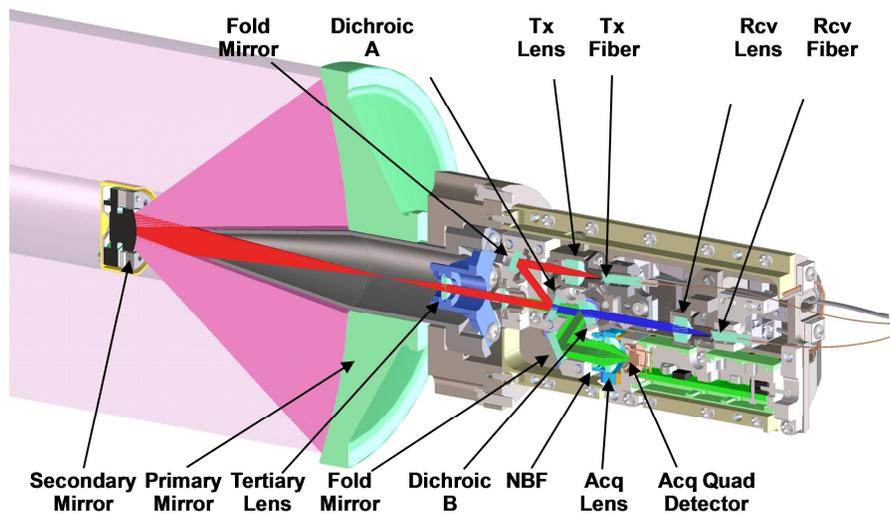


Figure 2. The LLST Optical Train and Optical Assembly

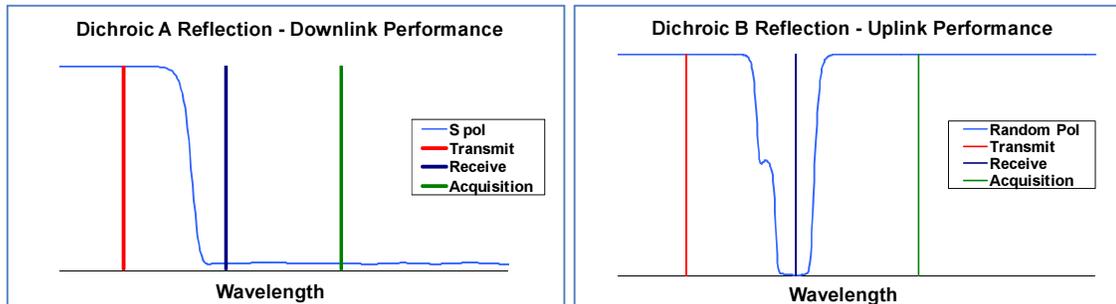


Figure 3. Dichroic Filter Performance

The telescope magnification of 47x supported the implementation of commercially available aspheric lenses for the entire OA, allowing for a compact SOA. All lenses, the two fiber lenses, the acquisition lens, and the telescope tertiary were inexpensive anti-reflection coated molded aspheres. From the lens lots purchased, the lenses with the best on-axis wavefront performance were selected for the LLST. Additional material screening was performed for optical transmission and radiation resistance at 1550nm.

The two communications paths, downlink transmit and uplink receive, required excellent on axis wavefront performance. On the downlink transmit path, high wavefront performance was required to maximize the energy density in the far-field at the earth's ground stations. On the uplink receive path, high quality wavefront performance was required to maximize the coupling into the receive fiber. The acquisition path, however had somewhat different requirements. The acquisition quadrant cell had a coarse FOV of ± 1 mrad and a smaller linear FOV of approximately ± 30 urad. Outside the linear region of the quadrant detector, the quality of the beam at the detector was not required to be perfect. This allowed for a relaxation of the off-axis wavefront requirements for the telescope.

As the optical system was being configured, minimization of stray light was an important consideration. Isolation of the quadrant detector from the transmitter was easily achieved with the dichroic and narrow bandpass filters. Isolation of the quadrant detector from earth background, and solar scatter was a bit more of a challenge. An end-to-end solution that cascaded the performance of the SW, both dichroic filters, the acquisition fold mirror, and the narrow bandpass filter provided the needed isolation from all scattering and background sources.

The SW performed the primary function of blocking solar energy from entering the telescope, minimizing uneven heating of the telescope optics and structure thus reducing distortion of the telescope optics. The SW contributed to the blocking of outside wavelengths that were in the quadrant detector's sensitivity band of 0.9 μ m to 1.7 μ m, while allowing the system wavelengths to pass.

B. LLST Telescope

The afocal beryllium LLST telescope was a Cassegrain configuration with a 108mm diameter, F/0.7 primary, hyperbolic secondary and an aspheric tertiary lens. The telescope had an intermediary focus between the secondary and the tertiary and an exit pupil located on the small SOA. The aligned and assembled telescope was required to have excellent on-axis transmitted wavefront error with allowances for minor degradation in wavefront error at full field as discussed above. The telescope mirrors were diamond turned, nickel plated, polished, and coated with an enhanced reflective gold coating.

C. LLST Small Optics Assembly

The SOA, Figure 4, was a compact optical system that routed the three system wavelengths from and to the system fibers and sensors. The fold and dichroic optics were all fused silica with the exception of the narrow bandpass filter, which was BK7G18. With the ± 1 mrad system FOV and the 47x telescope, the angular extent on the SOA could reach as much as ± 2.7 degrees during acquisition. Thus all of the optics on the acquisition path had to be sized appropriately and, more importantly, the wavelength sensitive optics (dichroics, acquisition fold, and narrow bandpass filter) had to meet stringent requirements of transmission and reflectivity over the full field at the acquisition wavelength. The other two system wavelengths were close to on-axis for all operations.

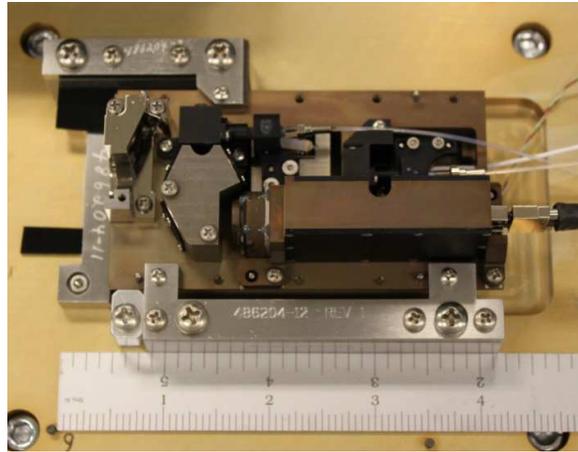


Figure 4 Small Optics Assembly on its alignment bench

The SOA transmit and receive fibers were mounted on 2-axis lateral piezo positioning stages that imparted an angular movement of the beam in object space by moving the fiber tip in the focal plane of the transmit and receive lenses [2]. On the transmit path, the positioner allows for the appropriate point ahead, and on the receive path, the positioner allows for nutation tracking of the receive beam [4].

The acquisition path utilized a 1mm diameter commercial quadrant cell with a $30\mu\text{m}$ gap between the 4 elements. The acquisition assembly, lens and detector, was aligned, and the defocus optimized, before integration into the SOA.

II. OPTICAL QUALIFICATION

In this section is described the optical qualification of the OM including telescope and SOA performance, OA performance before integration onto the MIRU platform and two axis gimbal, and OM optical system performance during and after environmental testing.

The OTS was configured to test the OM in its various states of completion: from the initial mating of the telescope and SOA, to the final pre-ship thermal vacuum qualification of the full OM.

Wavefront, throughput, beam profile, and polarization were measured for each of the three optical paths (transmit, receive, and acquisition). While measurement of the transmit path was straight forward, the measurement of the two other paths was made indirectly. The receive path was characterized in a reverse manner, by sending the receive wavelength backwards out of the receive fiber through the OM. The acquisition path was characterized by measuring the signals at the acquisition detector, comparing to expected levels and measuring the linear field of view.

A. Telescope Alignment and Qualification

The three element telescope was aligned using a $1.55\mu\text{m}$ Zygo interferometer to measure wavefront performance. The telescope went through the steps of alignment, optical verification, thermal cycling, optical verification, final grouting, optical verification, thermal cycling, optical verification, vacuum bake, and final optical verification. The telescope transmitted wavefront, on-axis and at full field, exceeded specifications with a transmitted wavefront error of 0.02λ rms on-axis and 0.04λ rms at the full 1mrad field, Figure 5.

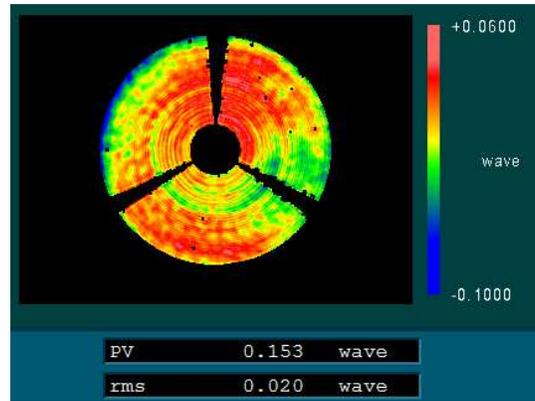


Figure 5. Telescope On-Axis Wavefront @1550 nm

B. Small Optics Assembly Alignment and Qualification

The integrated OA, Figure 6, was systematically assembled, tested, and thermally cycled as the individual components populated the SOA. After each set of components were aligned to the SOA, and then thermally cycled, optical measurements of the wavefront, beam profile, and beam pointing were made. First the receive lens and fiber were aligned, collimated, pointed, and the receive beam was optically tested. The transmit lens and fiber were similarly aligned and tested. The SOA was thermally cycled and the two beam paths optically tested. The two dichroics and acquisition fold mirror were placed into the beam directory assembly housing, the assembly was aligned to the SOA, and the two beam paths were tested. The SOA was thermally cycled, and again optical measured. The acquisition lens and detector were aligned independently as a unit, and then added to the SOA. The $\lambda/4$ waveplate was the last component aligned to the SOA. The completed SOA then went through a final vacuum bake and optical verification.

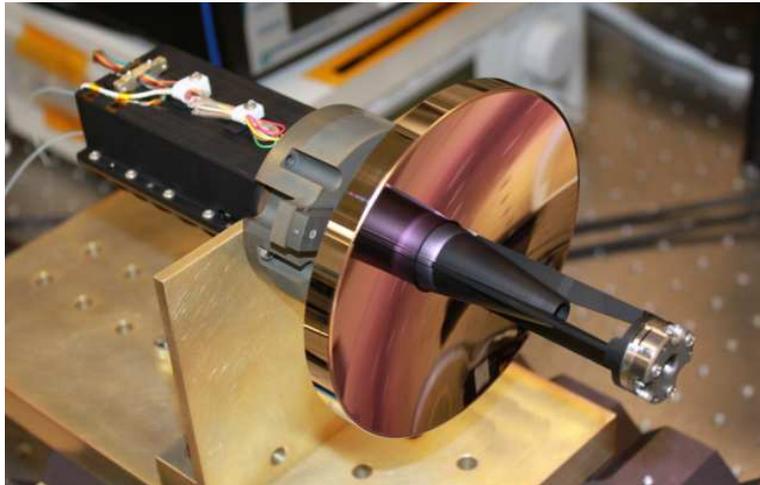


Figure 6. Integrated OA: Telescope and Small Optics Assembly

C. Optical Test Set

The OTS, block diagram, Figure 7, and layout, Figure 8, was configured to both simulate the function of a ground terminal (generating uplink beams and receiving OM beams) and quantify the performance of the received OM beam. The OTS was comprised of a telescope, free space optics and sensors, on a large optical bench, and the remotely controlled fiber-based Uplink/Downlink Emulator (UDEM) which provided the proper wavelengths, power levels, polarization states, and fading capability to the OTS bench via a fiber optic link for simulation of the uplink signals. As the OA, and then the OM, were qualified as standalone units without modem support, the UDEM provided the optical signals for the OM downlink transmit path and for the reverse optical testing of the receive path. The OTS also provided a fiber detector for testing the receive path.

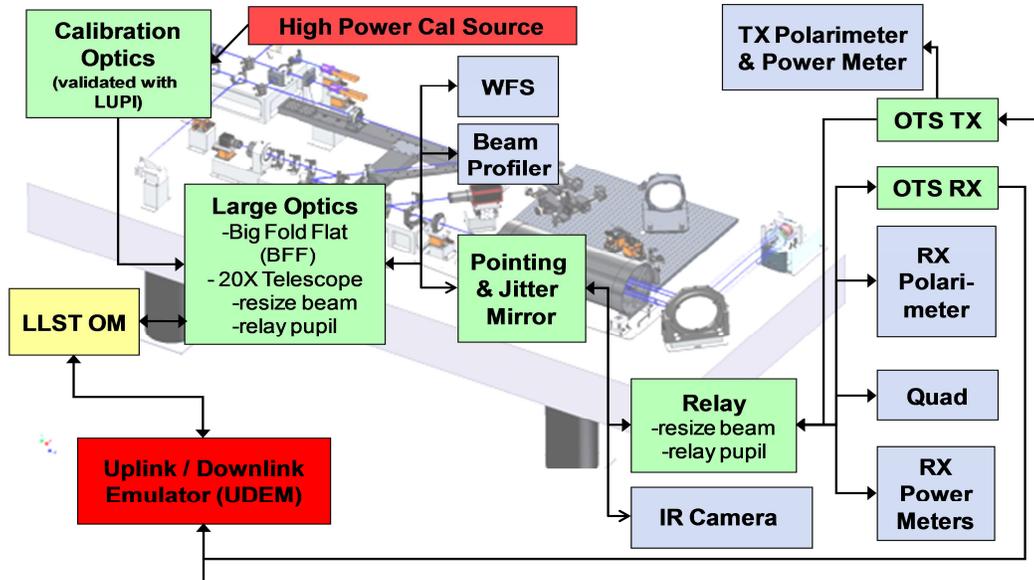


Figure 7. OTS Block Diagram, optics in green, sensors in blue, sources in red, and system under test in yellow

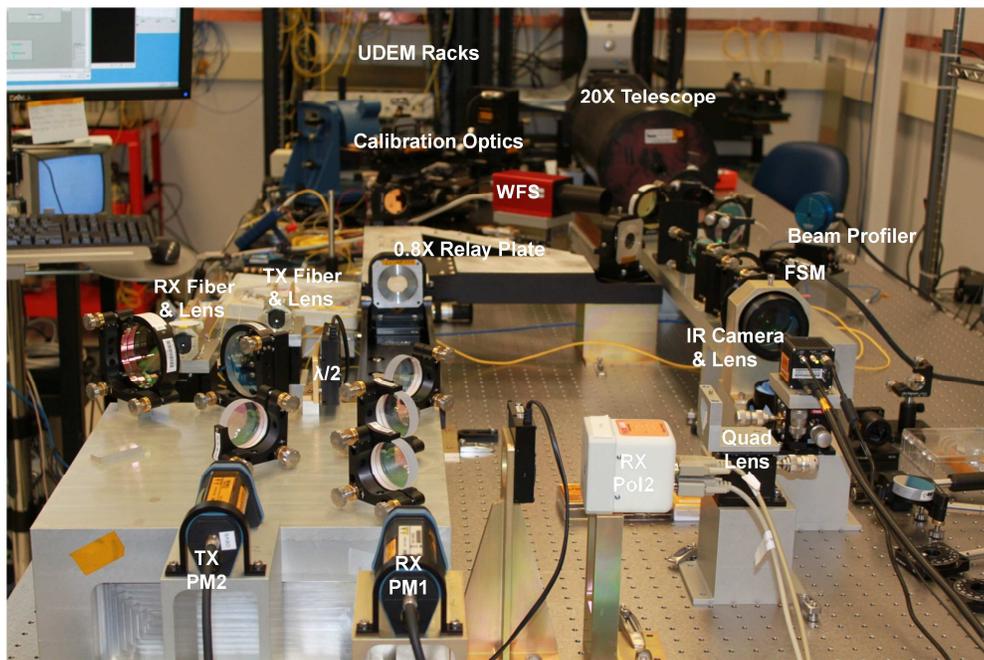


Figure 8. Optical Test Set Layout

The OTS sensors measured the downlink wavefront quality, beam profile, optical throughput, and polarization state. The OTS provided calibrated uplink beams that were used to characterize the OM's acquisition path throughput and FOV, and the OM's receive path throughput and fiber coupling efficiency.

On the downlink, the OTS large optics, a large fold flat and a 20x telescope, directed the OM beam under test into OTS optical system resizing the beam and relaying the OM exit pupil onto a fast steering mirror (FSM) and onto the wavefront sensor and beam profiling camera (via low reflectance beamsplitters). After the FSM, a beam splitter picked off a portion of the beam and sent it to an IR camera while the remainder of the beam continued to relay that mapped the exit pupil onto the small aperture power meters and polarimeters, and then coupled the beam into a simulated ground receive fiber.

For the OTS uplink simulation, the OTS generated a uniform intensity beam by overfilling a collimating lens and clipping off the Gaussian wings. Using beamsplitters, the beam was locally sampled by a power meter and a polarimeter. The uplink beam continued on through the relay, off of the FSM, through the OTS telescope, to the OA.

Quantifying the wavefront performance of the OM was a primary requirement of the OTS. A calibration source, similar to that described in [3] was utilized to provide a known, high quality, wavefront for characterizing the OTS optics. The calibration beam was used to measure the wavefront error through the OTS optics to the wavefront sensor. Multiple files were averaged and an OTS reference file was generated. This reference file was subtracted from all subsequent measurements of the OM wavefront.

The beam profiler camera was used to capture near field profiles of the exit pupil of the OM. Using the profile data, the far-field beam pattern was determined analytically.

D. Optical Module Optical Qualification

The OTS was used to qualify the OM's optical and system performance in a series of integration and test steps:

- The OA was tested for wavefront, optical throughput, beam profile, and polarization state.
- After integration of the OA, MIRU, and gimbals the OM underwent a rigid series of pointing, acquisition and tracking testing utilizing the OTS
- The OM covers were installed, the OM was moved to a separate jitter test station, and pointed across the cleanroom laboratory into the OTS. The OTS validated the performance of the OM in the presence of jitter.
- In the final test suite, the entire LLST system, OM, modem module, and control electronics, were tested in a thermal vacuum chamber. The vacuum chamber included a high quality optical window coated specifically for testing of the LLST. The OM pointed out the vacuum tank onto the OTS.

The wavefront performance of the completed OM, Figure 9, at all stages exceeded the system specifications. In ambient test conditions, the OA wavefront of the transmit and received paths measured 0.045λ rms and 0.04λ rms. After integration into the OM, and completion of thermal vacuum testing, the wavefront measured 0.051λ rms and 0.047λ rms on the transmit and receive paths, Figure 10. During the thermal vacuum testing the wavefront on the transmit path varied by an insignificant $\pm 0.005\lambda$ rms.

The beam profile measurements, when propagated analytically into the far-field, showed that the FWHM beam divergence was $16.2\mu\text{rad}$, Figure 11.

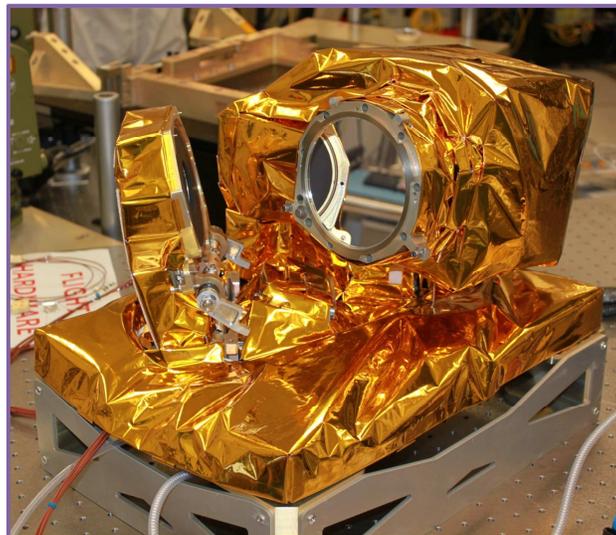


Figure 9. LLST Optical Module Assembly

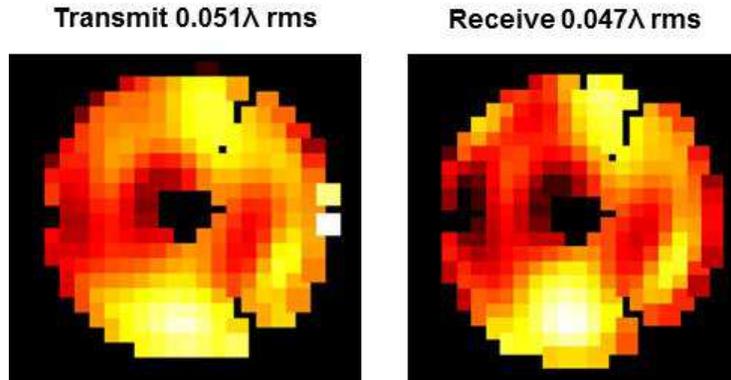


Figure 10. Final OM Wavefront Measurements

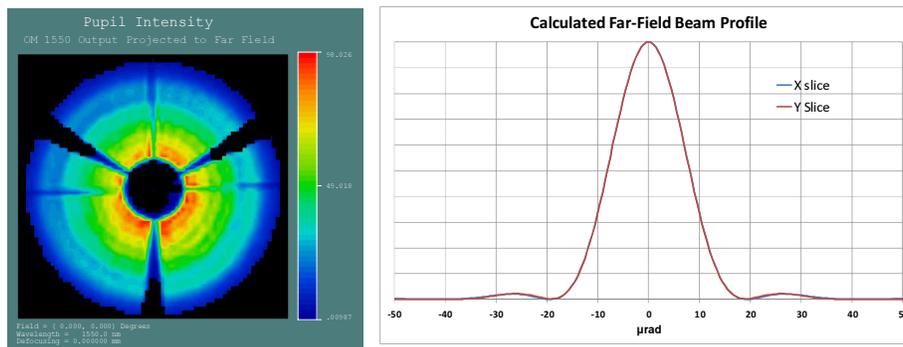


Figure 11. Transmit Beam Near-Field Measurement and Far-Field Profile

The optical throughput measurements on all three paths were close to predicted. The solar window, dichroic filters, and the rest of the OA optics performed as expected over both wavelength and field of view for the three system wavelengths.

III. SUMMARY

The optical qualification of the LLST, utilizing the OTS to characterize the system, was a success. End-to-end the optics met most of the individual system requirements and together left extra margin for the system link budget optical allocation. While important, the results reported in this paper are only the optical subset of the many tests performed to insure that the LLCD was a success.

ACKNOWLEDGEMENT

The authors listed on this paper here were only a small part portion of the LLST and LLCD effort. Many people were involved, over a number of years, in making this program a success.

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