On-Orbit Measurements of Solar Exclusion Angle for Modular Agile Scalable Optical Terminal (MAScOT) on the ILLUMA-T Mission

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ABSTRACT

The Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) optical communications payload operated on the International Space Station (ISS) for 8 months, concluding in June 2024. ILLUMA-T made the ISS the first space-based user to communicate with NASA's Laser Communications Relay Demonstration (LCRD). ILLUMA-T was also the first flight demonstration of the Modular, Agile, Scalable Optical Terminal (MAScOT) which will also be used in the Orion Artemis II Optical Communications (O2O) program, where it will provide an optical communications link for the crew aboard the Artemis II mission. Often optical and radio frequency communications systems have outages when they are pointing close to the Sun, where unwanted incident and scattered solar energy significantly reduces or prohibits operations. The MAScOT was designed to reduce the impact of any solar scatter through optical design, material choices, surface treatments and high cleanliness levels. Based on optical scattering models, a solar exclusion angle of 10 degrees was established for ILLUMA-T. This paper presents optical scattering modeling predictions, pre-launch laboratory testing results, and on-orbit measurements of solar scatter at angles ranging from 3 to 25 degrees.

Keywords: Lasercom, scatter, solar exclusion, stray light, optical communications

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1. INTRODUCTION

The Modular, Agile, Scalable Optical Terminal (MAScOT) was designed as a follow on to the highly successful Lunar Laser Communications Demonstration (LLCD), which in 2013 demonstrated a 622 Mbps optical downlink with a 20 Mbps optical uplink from and to a lunar orbit on NASA's LADEE mission.[1] NASA adapted the LLCD design and concept to requirements of the Laser Communications Relay Demonstration (LCRD), which launched in 2021 and has been demonstrating GEO to ground communications links since 2022. The MAScOT architecture was designed to have a large field of regard (±120° elevation and ±175° azimuth), is modular to facilitate future upgrades and adaptations, and scalable for use in LEO, GEO and deep-space applications.[2,3,4] The MAScOT was employed as part of the Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) optical communications payload which was installed on the International Space Station (ISS) in November 2023 and was the first LEO user of the LCRD optical comm link. The MAScOT is also presently integrated in the Orion Artemis II Optical Communications (O2O) payload for the Artemis II mission which is presently projected to launch in 2026. For both missions, the MAScOT was integrated into the space terminal subassembly, along with system modem, controller and power unit, at MITLL and delivered to NASA for further integration onto the flight payloads.

Performance for both MAScOT missions can be impacted, and even experience communications outages when operating links close to the sun. Solar scatter can result from many sources and due diligence was required during the MAScOT design phase to implement best practices, run in-depth scatter analyses, identify potential scatterers such as structures and glint edges, and provide mitigation solutions. A limited set of laboratory scatter test data was taken before delivery to NASA. For the ILLUMA-T mission there were some unique opportunities to make on-orbit measurements of scatter. During the mission life span, there were periods when communication links could not be established due to ISS-related issues and LCRD availability. It was during several of these "down days" that time blocks were allocated for scatter measurement. This on-orbit data was then correlated to the scatter analysis and the laboratory test data. After all the communications experiments were completed, on the final day before decommissioning, there was an opportunity, that is very rare in the world of optical systems and telescopes, to purposely point the system directly at the sun and to access impact on basic system performance.

The following discussion outlines the opto-mechanical design of the MAScOT, highlighting the choices made during the design and build to minimize potential scatter.

2. MODULAR, AGILE, SCALABLE OPTICAL TERMINAL DESCRIPTION

The MAScOT Optical Module (OM), Figure 1, was designed by MITLL, used subsystems from L3Harris and ATA, and was built, integrated and tested at MITLL. The OM features a front-end gimbaled telescope with a front mounted solar window designed to isolate the OM both thermally, to reduce structural deformation of the telescope, and optically to minimize direct and scattered solar light from the system's sensors. The OM's Backend Optical Assembly (BOA) consists of transmit and receive fiber assemblies, a wide field of view tracking quadrant detector, beam shaping optics, fast steering mirrors for jitter rejection, optical edge filters for wavelength separation and narrow band optical filters for additional stray light suppression. The combination of the solar window and the narrow band pass filter reduces the solar spectrum bandpass to ≤ 1.7nm. For any optical communications system, the two main contributors to stray light as observed at the system optical sensors are solar illumination scattered forward into the system and back reflections and scatter of the outgoing communications beam. If the scatter is too large, the system will be unable to track and no communication link can be established and/or maintained.

For ILLUMA-T, the minimum signal required for coarse tracking was -73dBm as measured at the system's pointing, acquisition, and tracking (PAT) quadrant detector. The noise floor of the PAT detector was ~-84dBm, so the design and implementation goals were to keep the amount of scatter near or below this level. The scatter budget allocation was roughly split between incident solar and the outgoing communications beam.

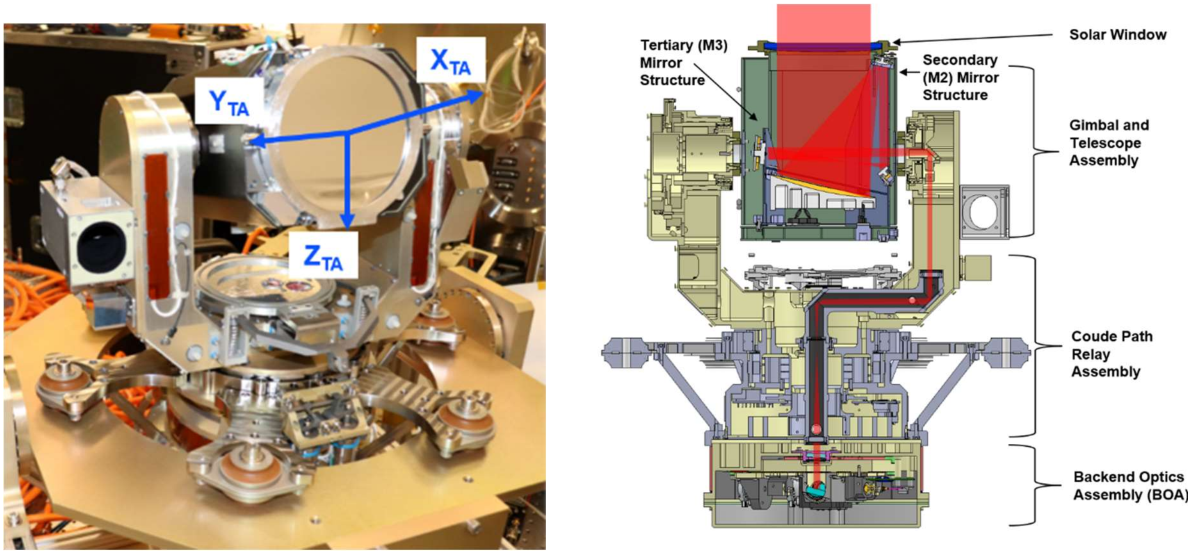

Figure 1. The optical module consists of a solar window, gimbal and 25x telescope assembly, 1.73x optical relay and the Backend Optics Assembly (BOA). The observation reference frame of the telescope is marked by the axes X_{TA} (telescope optical axis & line of site axis), Y_{TA} (parallel to the elevation axis of the gimbal), and Z_{TA}. All laboratory and on-orbit data are reported in this reference frame.

The two MAScOt optical modules for ILLUMA-T and O2O have different tolerances for stray light due to the design requirements dictated by their different pointing, acquisition, and tracking designs. The receive acquisition signal transmitted from LCRD and acquired and tracked at ILLUMA-T is seen as a DC signal; any stray light would be detected as part of the background signal. In contrast, the signal transmitted from the O2O ground stations to O2O will be modulated, where high pass filtering of the electrical signal can remove much of the DC background signal resulting from stray light. This allows O2O to tolerate more scatter, up to -60dBm, and thus can operate closer to the sun. The O2O solar exclusion angle is nominally 3 degrees where ILLUMA-T had a solar exclusion angle of 10 degrees.

2.1 Design for Scatter Mitigation

Sources of optical scatter must be addressed at all phases of the optical module design, fabrication, and build. Starting with the optical design, the use of a front-end solar window, internal field and Lyot stops, and back-end narrow bandpass filters provided the bulk of the stray light suppression. Precision fabrication requirements on optical surface roughness and surface quality along with properly chosen mechanical surface treatments provided additional stray light mitigation.

Spectral filtering is provided by a combination of the front-end solar window and the BOA narrow bandpass filters reducing the solar bandpass to ≤ 1.7nm centered on the receive wavelength. The solar window, mounted on the front of the telescope, was designed to reflect > 92% of the incident solar energy from 300nm to 3000nm at angles up to 45°, while transmitting the in-band communication wavelengths.

A field stop located at the intermediate focus of the relay assembly reduces the amount of light collected outside the nominal system field of view. A Lyot stop, located at the BOA system pupil, reduces the amount of internal telescope surfaces seen by the PAT sensor. Except for the structures holding the secondary and tertiary mirrors, most of the exposed mechanical surfaces in the telescope and BOA were treated with low reflectivity paint.

2.2 Stray Light Analysis

Considerable time and effort were spent building and optimizing a full stray light model using the optical engineering software program FRED. The model is a hybrid of imported mechanical CAD models and FRED primitive elements. BSDF (bidirectional scattering distribution function) contributors were built for each optical surface (including roughness, scratch-dig and cleanliness level at end of life) and aperture effects (diffraction and glints). The BSDF response of the telescope structure material was measured and provided by the telescope vendor L3Harris. Figure 2 plots the BSDF from the OM stray light contributors and the scatter map resulting from the FRED analysis, for a full +/-180 degrees in phi and from 3 to 53 degrees in theta. Beyond 53 degrees the scatter was negligible.

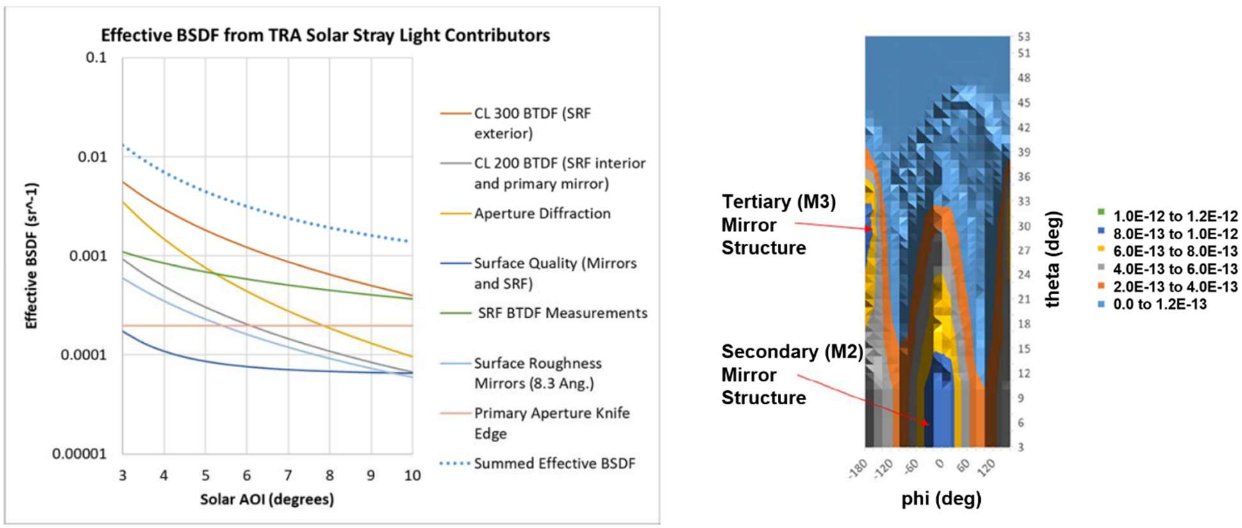

Figure 2. BSDF from Telescope Relay Assembly (TRA) contributors fed to the FRED analysis and plotted results (stray light in W at the PAT detector). The telescope mirror structures, holding M2 and M3, were identified as scatter sources

The analysis shows scatter originating from features of the telescope, primarily the structures that hold the telescope's secondary (M2) and tertiary (M3) mirrors. Because of the high scatter off of the mirror fixtures identified by the FRED analysis, MITLL worked with the L3Harris, the telescope vendor, to add additional specialized surface treatments to mitigate grazing incidence scatter.

This scatter analysis is generally applicable to both ILLUMA-T and to O2O implementations, and the mitigation steps were the same for both systems. A primary outcome of the analysis was the establishment of 10 degrees as the baseline solar exclusion angle for ILLUMA-T. To add a level of conservativism, the field of view of the OM, set by a field stop in the coude path relay, was reduced from ±1mrad for O2O (LLCD and LCRD were the same) to ±0.5mrad for ILLUMA-T.

3. TESTING

3.1 Laboratory testing

Comprehensive solar stray light testing typically needs dedicated, specialized equipment such as a full-field-of-regard solar simulator test bed. Limited time and resources were available, so the laboratory testing approach for measuring scatter into the OM was to utilize the MOTS (MAScOT Optical Test Set) as a solar simulator. The MOTS primary purpose was to emulate the free space link for testing the PAT and communication performance of ILLUMA-T. In addition to the primary flat-top uniform, low power beam delivered for performance testing, the MOTS also generated a separate 6" diameter, higher power, collimated Gaussian profile beam normally used for internal MOTS calibration. This calibration beam was used as an in band "solar simulator", providing, at a single wavelength, the power equivalent to the 3.7mW of solar power within the band of the ILLUMA-T 1.7nm narrow band pass filters. The MOTS pointed the calibration beam at the OM and the OM was slowly stepped in azimuth and then in elevation to scan the test set beam along the two axes of the telescope gimbal. The MOTS to OM alignment was tweaked to reach the higher azimuth angles measured. Figure 3 illustrates the technique used to scan the test beam on the OM.

The laboratory tests were made on the O2O system, simulating the operational conditions of the ILLUMA-T system (which was not available for stray light testing). For ILLUMA-T, any solar stray light is seen as DC background on the PAT detector which is expecting a received DC acquisition signal from the remote LCRD terminal. To simulate the ILLUMA-T stray light conditions, the stray light testing with the O2O system was performed by modulating the test beam at the frequency expected by the O2O PAT detector, and a 6dB correction factor was applied to the measurement data to account for the larger FOV of the O2O system.

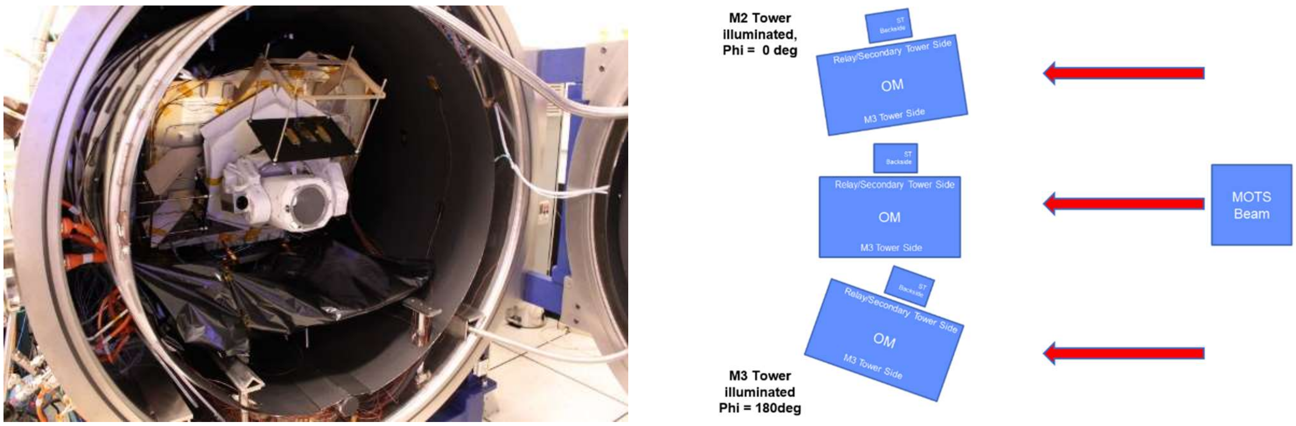

Figure 3. ILLUMA-T OM shown in TVAC chamber on left; TA-Y scan pattern for laboratory measurements shown on right

During these measurements, the power incident on the OM was always kept below the saturation level of the PAT detector using a calibrated optical attenuator. As the OM was stepped in azimuth and elevation away from the on-axis start point, the attenuation was reduced. Figure 4 plots the equivalent solar power on the detector using the measured attenuation and PAT detector calibration. The amount of data acquired, simple scans along the primary axes of the gimbal, was limited by the system's availability. The results are plotted in the Telescope Assembly (TA) reference frame shown in Figure 1.

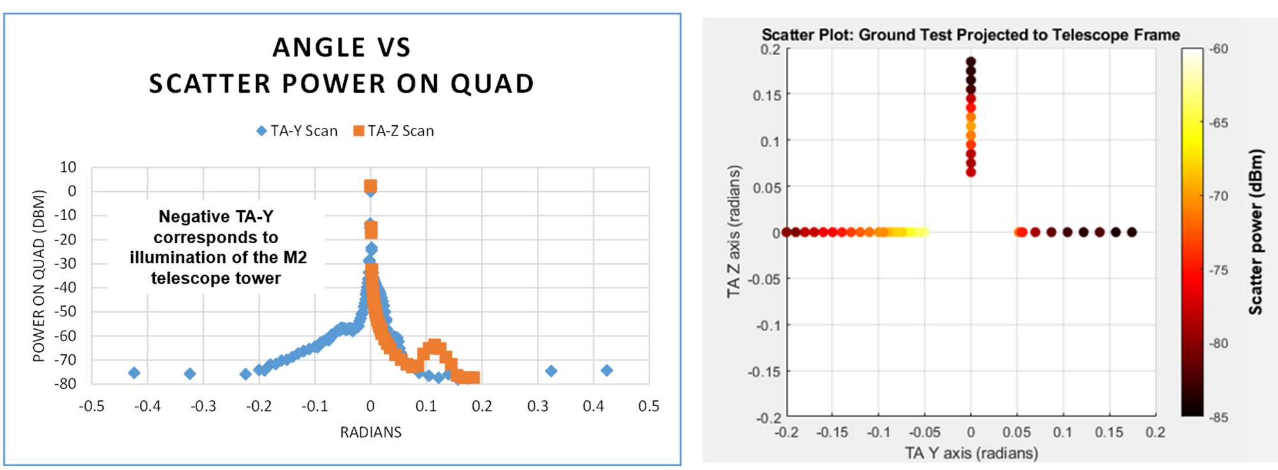

Figure 4. Laboratory measurements. On the left, solar simulation scatter data on the O2O PAT detector, on the right same data plotted using a color scale (dBm), with an added 6dB ILLUMA-T correction factor. Note that the inner data corresponding to 3degrees inside the O2O solar exclusion was omitted from the right plot

The negative TA-Y data showed more scattering than the positive data, mapping the higher scatter to an illumination of the Telescope Assembly M2 structure. What was unexected was the scatter in the positive TA-Z scan (no negative TA-Z data was acquired due to time constraints). Regardless, the scattered power measured outside of ILLUMA-T's 10 degree solar exclusion angle was low and below a level that could impact system tracking and thus communication performance.

3.2 On Orbit Testing: Pointing Circles About the Sun

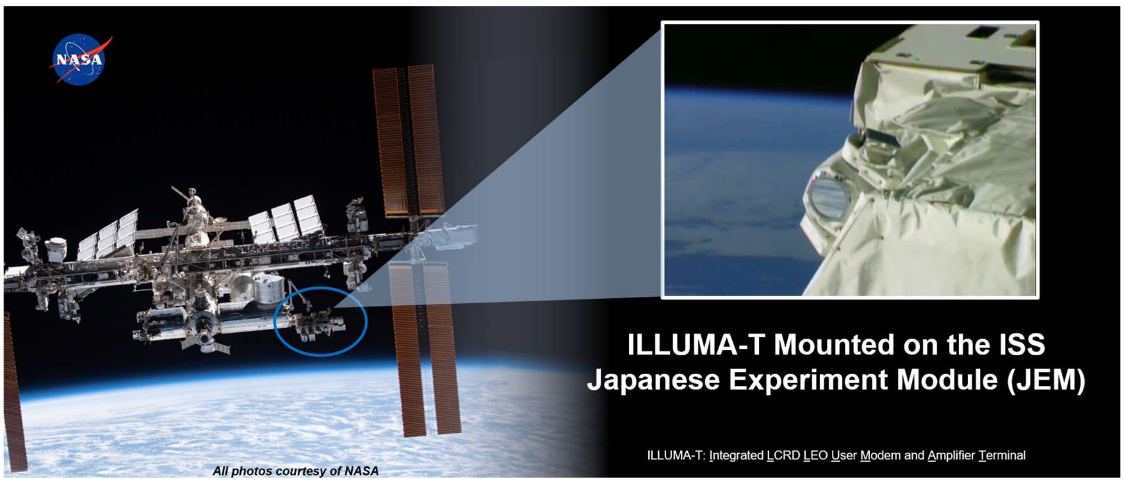

Figure 5. ILLUMA-T's location on the ISS; ILLUMA-T's solar window is visible

ILLUMA-T launched in November 2023 with communications experiments beginning December and running through June 2024. Figure 5 shows ILLUMA-T mounted on the ISS Japanese Experiment Module (JEM). During the experiment period, three blocks of "down time" between April and May were identified where ILLUMA-T was available for non-communications, stray light experiments. Typically, there were 4-6 solar contact passes available each day, and each data collect pass lasted 20-40 minutes. The general process was to identify a block of available time, the Mission Operations team, located at NASA Goddard, would plan the scan pattern for each pass, and the team would generate an ephemeris file a few days ahead.

For each pass, pointing and power on the PAT detector data was collected in telemetry for viewing in real time as well as off-line processing. Utilizing the gimbal encoder readouts, system calibration factors and ECI pointing path, a calculation could be made of the sun vector projected on to the Telescope Assembly (TA) frame of reference, and plotted against the power measured on the PAT detector.

The stray light measurement experiment design started conservatively, allowing time for refining scan design, data collect and analysis refinement. The first block of measurements, which included test scans in a circular pattern around the moon and spirals away from the sun, were taken in April, and the results were generally inconclusive. Implementation and data processing lessons were learned from this first block, and confidence in the process became established.

For the next two blocks, measurements made in May and June, the ephemeris files were designed to center on the sun, and scan the pointing vector in smooth concentric circles about the sun at radii ranging from 3 degrees to 25degrees. Four complete passes were achieved in May at 3 degrees, 6 degrees, 9 degrees and 12 degrees. Figure 6 plots the vector in the TA coordinate system. Note that no scattered light was observed outside the solar exclusion zone and all scattered light was below the levels required for operation of the PAT detector.

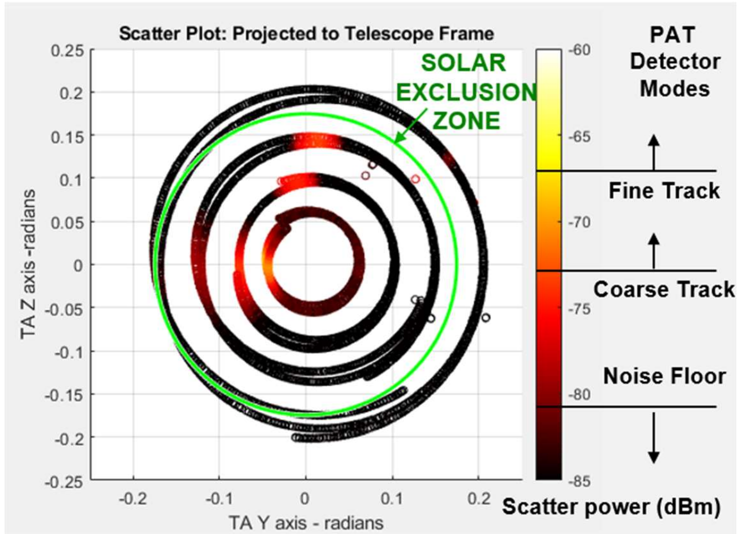

Figure 6. May 2024 data. Measured stray light observed on the PAT detector for 3deg, 6deg, 9deg, and 12deg scans.

Four additional passes were made in June repeating the 9 degree radius scan, and measuring additional 4.5 degrees, 20 degrees, and 25 degrees, shown in Figure 7. For comparison, also in Figure 7, the two 9 degree data sets, one from May and the 2nd from June are plotted togeather. Though the two sets of 9-degree scan data was taken a month apart, the scattering was unchanged in nature.

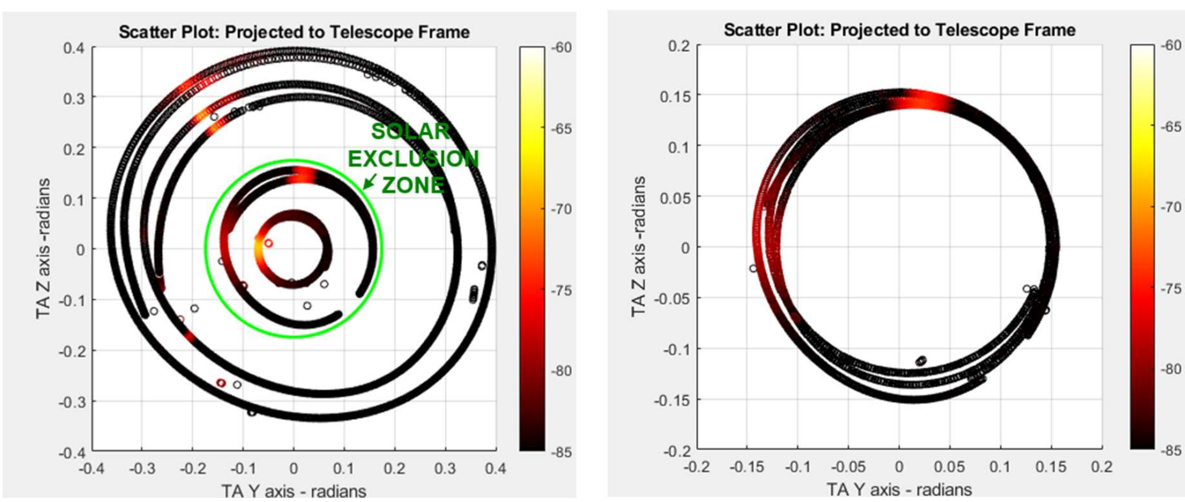

Figure 7. On left, scan vector shown in telescope frame of reference for June data 4.5deg, 9deg, 20deg and 25deg with the color scale showing the power (dBm) observed on the PAT detector; On right 9deg data sets shown from both May and June, demonstrating repeatability.

Figures 8 shows a compilation of the May and June data. Note how the ECI, earth-centered inertial, pointing shifted in the one-month period between data sets.

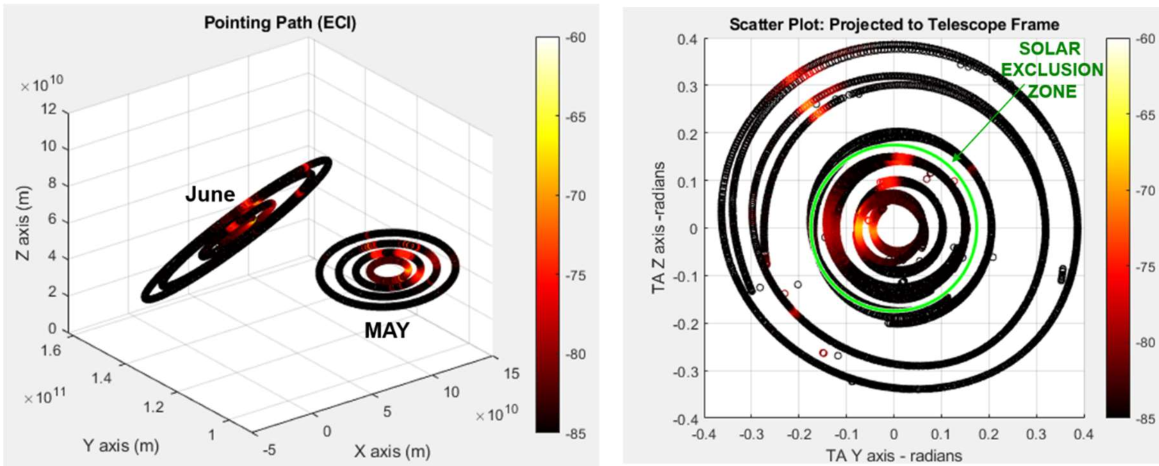

Figure 8. On left, ECI pointing plot shows the two sets of data from May and June. On the right are the same sets of data in the telescope frame of reference. Color scale in dBm at the PAT detector

Figure 9 overlays the laboratory data from Figure 4 with the on-orbit data from Figure 8. The trends of the data are consistent. The higher, negative TA-Y data is observed for both on-orbit and laboratory, correlating to the FRED scatter model of scatter from the M2 telescope structure. The highest amount of scatter was observed inside the 10 degree solar exclusion angle. Outside the exclusion zone, the data for the 12-degree scan and larger scans showed minimal scatter, meeting the low scatter goal.

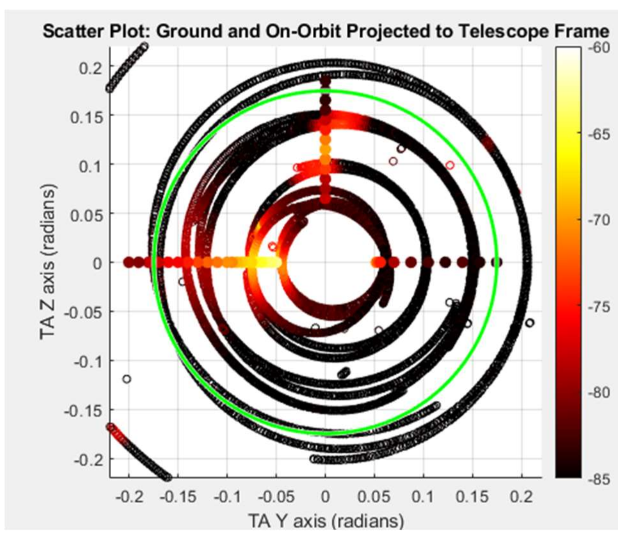

Figure 9. Zoomed in scan data from May and June (ringed data) combined with laboratory data (cross pattern). Color scale in dBm at the PAT detector

The scatter seen in the lab on the positive TA-Z axis, inside the exclusion zone, was also observed in the on-orbit scatter measurements, though it was not predicted by the scatter model. The source was most likely an aspect of the internal telescope structure that was not part of the CAD model at the time of the FRED analysis. The larger two scans in Figure 8, 20 degrees and 25 degrees, showed scatter that did not align with the telescope axes nor was it predicted by the FRED analysis. The source is unknown, but one possibility is reflections/glare from ISS external structures, such as the solar arrays. The NASA operations team had noted spikes a number of times during experimental communication operations that were attributed to external structures.

The mitigating steps taken during the design of the OM, applying the specialized surface treatment to reduce the scatter modeled in FRED, reducing the nominal field of view, and the many other design decisions led to a successful demonstration of scatter reduction. Ultimately leading to a successful ILLUMA-T mission where scatter did not impact mission operations.

3.3 Last Pass Testing: Direct Solar Exposure

With all communication experiments having been successfully completed, the team designed one additional solar illumination experiment for the last set of passes before ILLUMA-T was decommissioned: direct solar exposure. The system was designed to survive all sun angles, including solar illumination directly within the field of view of the telescope. With the full 3.7mW of solar power incident at the PAT detector, the sensor was expected to saturate but remain undamaged.

The pass started with a standard system closed-cover-test (CCT), with the telescope assembly in the stowed position. This CCT was run periodically throughout the mission and used to monitor system and optical health. The terminal was then directed to point towards the sun and attempt to coarse track on the solar light signal. For approximately 6 minutes the terminal pointed and tracked through most of the pass. At the end of the pass the telescope was stowed for the last time, and a second CCT was performed. Analysis of the CCT data showed no observable changes. A successful demonstration that the MAScOT design can survive direct solar illumination with no observed negative impact!

4. CONCLUSIONS

Optical scattering modeling predictions, pre-launch laboratory testing, and on-orbit measurements of solar scatter at angles ranging from 3 to 25 degrees combined to demonstrate that the MAScOT design on ILLUMA-T provided sufficient stray light mitigation for the mission to meet its laser communications performance objectives. Last day direct solar exposure experiments further demonstrated the robustness of the design, including tracking on the sun. The successful demonstration with ILLUMA-T paves the path for a successful upcoming O2O mission on Artemis II.

REFERENCES

[1] Boroson, D. M., Robinson, B. S., Murphy, D. V., Burianek, D. A., Khatri, F., Kovalik, J. M., Sodnik, Z., and Cornwell, D. M., "Overview and results of the lunar laser communication demonstration," in [Free-Space Laser Communication and Atmospheric Propagation XXVI], Proc. SPIE 8971 (2014).

[2] Gilmer, S.R., Smeaton C.V., Burnside, J.W., Torres, J., Hubbard, W., Bennett, C., DeVoe, C., Wellman, J.A., Rey, J.J., Zervas, M.J., Khatri, F.I., Shih, T., Guldner, O., Padula, M., Robinson, B.S., "Demonstration of a modular, scalable, laser communication terminal for manned space flight missions, " in [Optical Engineering + Applications], Proc. SPIE 11816 (2021)

[3] Khatri, F. I., Gonnsen, Z., Wang, J.P., Mikulina, O., Schulein, R.T., Chang, J., Veselka, J., DeVoe, C., Gillmer, S., Han, D., Matt, A., Smeaton, C., Torres, J., Spellmeyer, N., McAnney, K., Buchanan, R., Karlicek, A., Howe, D., Stevens, M., Randazzo, T., Lidwa, E., Robinson, B.S., Padula, M., Sayal, C., "System level TVAC Functional testing for the Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) payload destined for the International Space Station

[4] Shih, T., Guldner, O., Khatri, F., DeVoe, C., Hubbard, W., Constantine, S., Torres, J., and Robinson, R., "a modular, agile, scalable optical terminal architecture for space communications, IEEEE ICSOS Conference (2017)