ICESat-2 Laser Technology Readiness Level Evolution

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ABSTRACT

We report on the completion of the space qualification testing program for NASA Goddard Space Flight Center's (GSFC) Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2) program. This paper describes the final performance results of the fully integrated (laser and electronics) flight laser system with an emphasis on the system design evolution from a breadboard demonstration to a fully space-qualified laser system. The 532 nm ICESat-2 laser transmitter generates diffraction limited pulse energies of 1 mJ, pulsewidths of < 1.5 ns, and 10 kHz pulse repetition frequency and has minimum lifetime of 1 trillion pulses on-orbit. A combination of engineering design units and correlated structural thermal optical analysis was used to systematically improve reliability and performance over the operating environment. The laser system qualification and acceptance test programs included electromagnetic interference (EMI), vibration, and thermal vacuum (TVAC) testing. This paper presents key laser performance results and lessons learned on the multi-year laser development to facilitate future space-qualified laser developments, improve reliability, and increase performance.

Keywords: Space-Qualified Laser, Diode-Pumped Solid State, DPSS, 532 nm, ICESat

1. INTRODUCTION

This paper describes the successful completion of the laser qualification and proto-flight test programs supporting NASA GSFC's ICESat-2 Advanced Topographical Laser Altimeter System (ATLAS). The ICESat-2 program is NASA's flagship earth science altimetry lidar used to measure ice sheet elevation change and sea ice thickness, while also generating an estimate of global vegetation biomass [1]. The ICESat-2 mission requirements drove several advances in the current state of the art of space-qualified laser systems and detectors [2]. The ATLAS lasers output consists of diffraction limited, narrow linewidth 532 nm pulses with pulse energies of more than 1 mJ and pulsewidths < 1.5 ns. The lasers are required to operate continuously for more than 27,000 hours, accumulating more than 1 trillion shots. In addition to the laser systems, Fibertek provided numerous space-qualified sub-systems to the ATLAS instrument (Figure 1) [3].

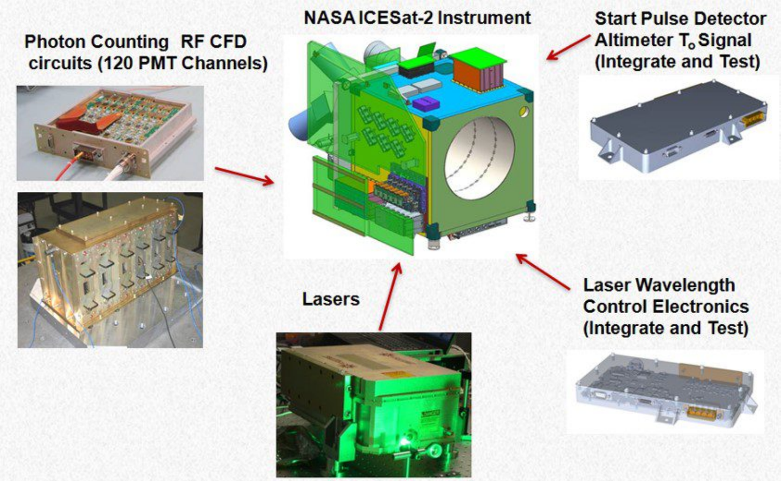

Figure 1. Fibertek provided spaceflight hardware for the ICESat-2 ATLAS instrument including a photon-counting Gbps detector module (left side), lasers (bottom), start pulse electronics (upper right), and wavelength control electronics.

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The successful completion of the laser qualification testing is a result of more than 5 years of research, development, and numerous architecture trade studies across multiple vendors and represents a significant advancement in spaceflight laser hardware.

2. LASER TRANSMITTER SYSTEM DESIGN

The test and analysis–centric laser development program started with early brassboard system-level prototype builds to validate system performance, laser gain models, and Structural Thermal Optical models (Figure 2). The early prototypes were transitioned to life-test units. The early start of the life-test units provided actionable data in terms of system performance over multiple years of continuous runtime. The lessons learned were incorporated into the flight design, processes, and operations. In addition to multiple breadboard prototypes, three engineering design units (EDU) were built and environmentally tested to NASA General Environmental Verification Standard (GEVS) [4]. Each EDU resulted in incremental design improvements and modeling refinements [5].

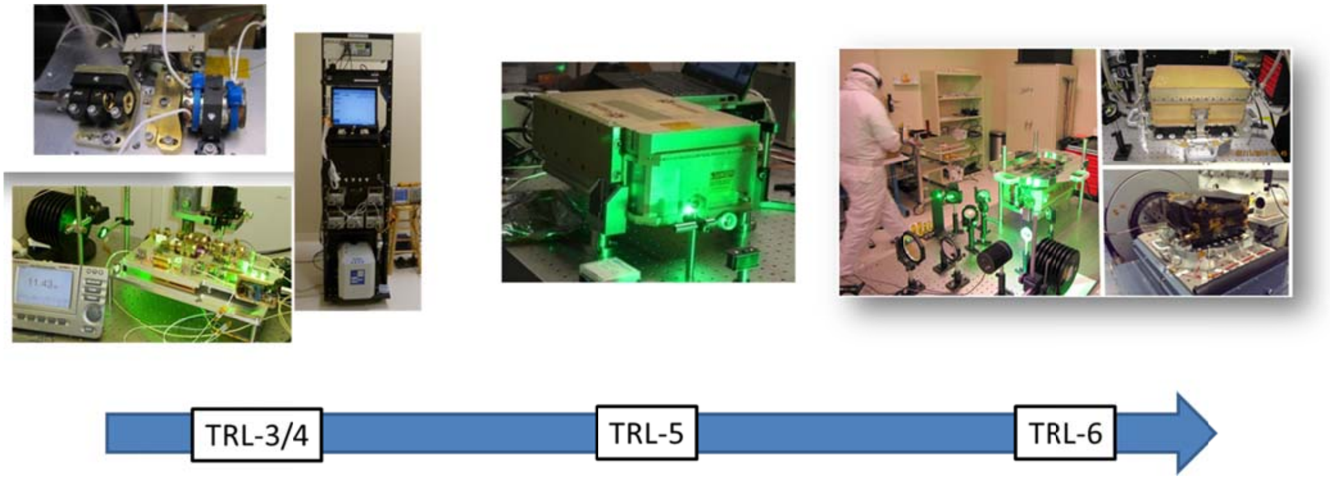
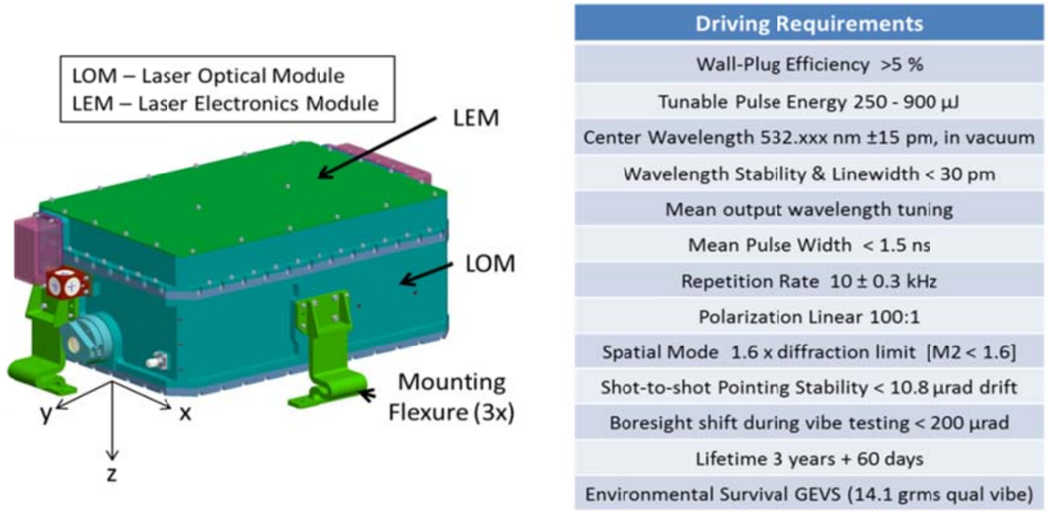


Figure 2. The evolution of the ICESat-2 laser TRL-3 through TRL-6.

A master oscillator/power amplifier (MOPA) architecture was chosen in order to generate the required infrared pulse energies, and is subsequently frequency doubled to 532 nm. The end-pumped Nd:YVO_4 gain heads were derived from commercially mature designs used for laser marking systems. The custom designed master oscillator generates 200 µJ infrared pulses with < 1.5 ns pulsewidths and is frequency tunable mode-hope free over more than 50 pm. The oscillator output is amplified via two amplification stages to more than 1.6 mJ while preserving the short pulsewidth and a near diffraction-limited beam quality. The amplified infrared light is frequency doubled via a temperature controlled LBO crystal with conversion efficiencies of > 65%. The overall electrical-to-optical wall-plug efficiency of the 532 nm laser system is > 7%. Additional design details have been previously presented [6] [7] [8]. The laser has the capability to operate in up to 32 pre-programmed energy modes ranging in output energies from 250 µJ to 1,200 µJ while maintaining all requirements. In addition to the large output energy operating range, the laser is required to tune over a 25 pm range. Figure 3 provides a view of the laser transmitter and requirements.



Driving Requirements
Wall-Plug Efficiency >5 %
Tunable Pulse Energy 250 - 900 μJ
Center Wavelength 532.xxx nm ±15 pm, in vacuum
Wavelength Stability & Linewidth < 30 pm
Mean output wavelength tuning
Mean Pulse Width < 1.5 ns
Repetition Rate 10 ± 0.3 kHz
Polarization Linear 100:1
Spatial Mode 1.6 x diffraction limit [M2 < 1.6]
Shot-to-shot Pointing Stability < 10.8 μrad drift
Boresight shift during vibe testing < 200 μrad
Lifetime 3 years + 60 days
Environmental Survival GEVS (14.1 grms qual vibe)

Figure 3. External view of the laser transmitter and the laser driving requirements.

2.1 Laser Reliability Considerations

Fibertek has a rich heritage of successful spaceflight laser systems and has fine-tuned the process of transitioning low Technology Readiness Level (TRL) laser systems to full-fledge space hardware [3] [9], as evidenced by the CALIPSO lasers being operational since June 2006 [10]. Fibertek's spaceflight hardware development philosophy is centered on system reliability being the prime consideration at the earliest design stages. The key principles in structuring a plan for laser reliability are outlined in Table 1.

Table 1. Key principles used in structuring a design, development, and build of a high-reliability laser system.

Key Laser Reliability Principles
Base the flight laser design on mature laser technologies
Execute lifetime and key environmental tests early in the program
Give careful consideration of all material cleanliness and 100% verification (i.e., screening) of material cleanliness
Use sealed and air pressurized laser canister with an acceptable leak rate
Use alignment insensitive optical designs
Ensure at least 3X derating relative to optical damage thresholds
Derate pump diodes by at least 25% of spec levels
Start flight electronics designs as early as possible
Staff with expert I&T personnel well versed in high-reliability systems

A systematic life-testing plan, including high-risk components (e.g., active Q-Switch, optical coating, and diode chiplets and modules), sub-systems (oscillators), and complete systems, was executed. The lessons learned in terms of designs, processes, and model validations were discovered early enough in the program to be implemented in the flight design. A prime example is the long-term degradation due to trace-level contaminants, where early life-tests showed an unacceptable level of surface contamination build-up on the 532 nm optical train. The contamination effects were quantified, and as a result material screening, processes, and system designs were improved to mitigate the contamination effects. The improvements were validated via an accelerated life-test of the system, maintaining performance over 1 trillion shots (Figure 5). Additional information regarding the diode module space-qualification program and optical coating validations has been previously published [11] [12] [13].

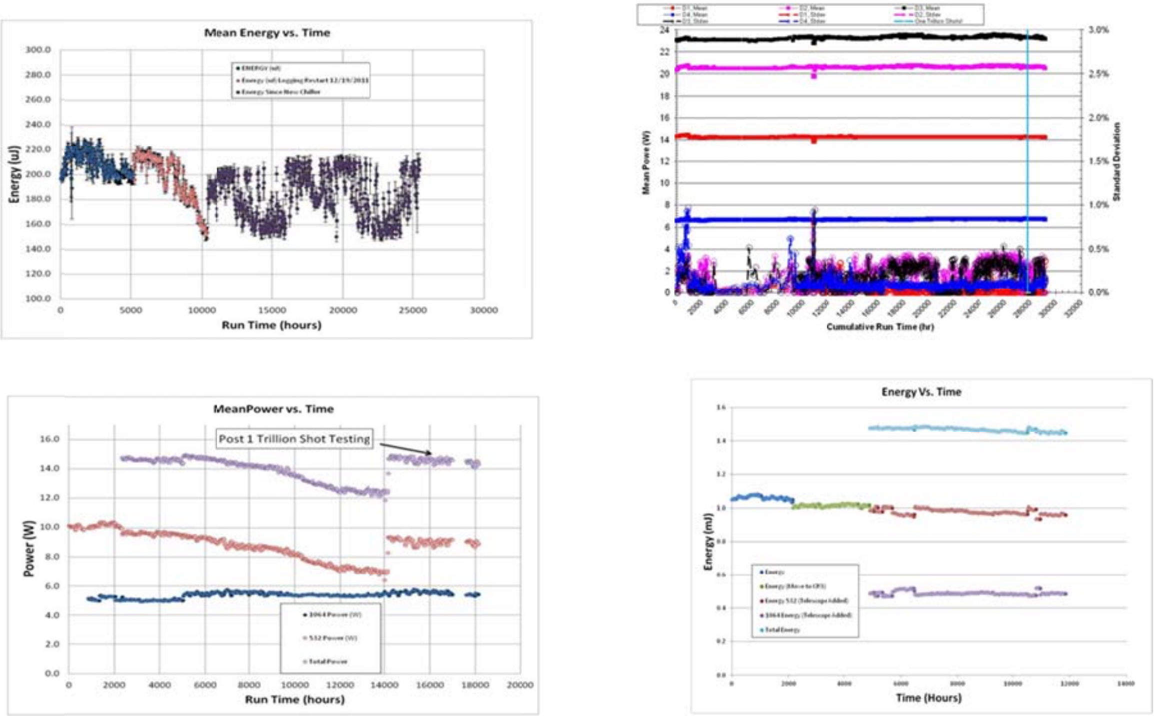


Figure 4. A subset of the multiple laser life-test units. Oscillator life-test (top left), four unit diode module life-test (top right), Brassboard MOPA system test (bottom left), and Brassboard MOPA 2 system test (bottom right). Extended life-tests have demonstrated lifetimes in excess of the required 3-year mission life.

3. ENVIRONMENTAL TEST PROGRAM

The environmental qualification test program followed a test-as-you-fly philosophy including EMI, vibration, and TVAC testing. Radiation qualification was performed via heritage, analysis, and sub-assembly testing for components and systems lacking spaceflight heritage. The qualification laser is expected to start life-testing in early 2015. The top-level environmental test flow is outlined in Figure 5.

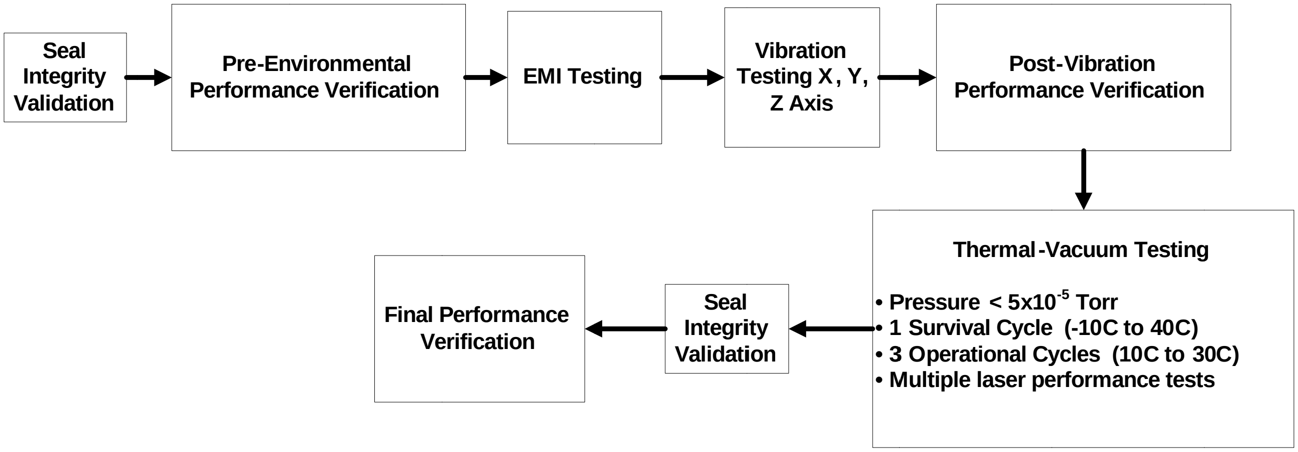


Figure 5. Environmental test flow. Performance verification steps included verification of laser/optical requirements and performance is trended throughout the testing phases.

3.1 Electromagnetic Interference Testing

EMI/EMC testing included Conducted Common Mode and Differential Mode Emissions, Radiated Emissions, Conductive Susceptibility, and Radiated Susceptibility testing. The laser was operational at the nominal power levels throughout EMI/EMC testing with all telemetry being actively monitored. Testing was conducted in accordance with MIL-SPEC-461C and 462.

The Laser was wrapped in a RF Transparent material throughout tests for contamination control, Figure 6. The laser is wrapped in a black radio-frequency transparent wrap on the right of the photo. The test cable set was similar in design to the production cables, including the use of a copper ground strap. A thermal sensor was mounted to the optical cavity to protect the area from beam escape and provide monitoring of beam power. A continuous monitoring system was implemented to alert of any system behavior outside nominal, including the test equipment in the control room.

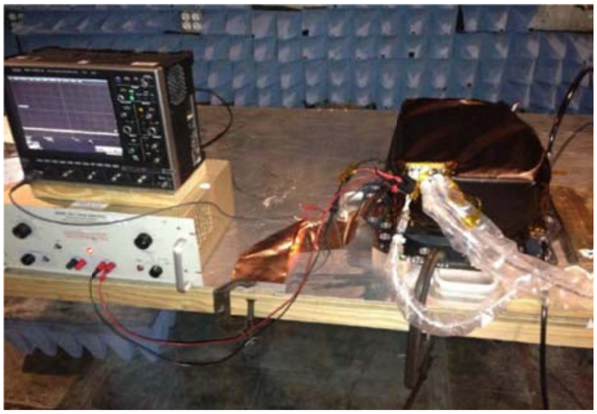


Figure 6. The laser is wrapped in a black radio-frequency transparent wrap on the right of the photo.

The Laser performed nominally throughout testing. Most issues encountered were attributed to the test equipment located in the control room and the test facility. The Laser passed CE01, CS02, and RS03 with no outages or susceptibilities. Outages observed in CE03, and RE02 testing resulted in waivers. CE03 outages were found to originate from the switching frequency of the Laser Diode Power Supplies and the Laser Repetition Rate of 10kHz. RE02 passed the traditional MIL-STD-461C limits, but had a very minor outage in one notched frequency range. This notched frequency range ultimately was not applicable in our application.

3.2 Vibration Testing

The qualification laser was successfully exposed to the proto-flight sine vibration and random vibration test levels defined below. Laser optical performance was verified prior to and after testing and found to meet all optical requirements. The following test levels were executed in all three axes: sine vibration of 0.63 in DA at 5-20 Hz and 12.5 g at 20-50 Hz in all three axes, random vibration of 7.5 GRMS in the X and Y axes at 20-20,000 Hz, and random vibration 8.8 GRMS in the Z axis at 20-2000 Hz. The following acceleration limiting scheme was implemented throughout testing at the diode and oscillator wall accelerometers: sine vibration response was limited to 12.5 g at 20-50 Hz for all three input axes, random vibration response was limited to 1.0 G^2/Hz for X and Y axes and 2.0 G^2/Hz for the Z axis at 75-250 Hz.

Measured data showed negligible amplification of the sine vibration levels while the following maximum random vibration responses were observed: X-axis excitation produced 11.7 GRMS in Z at the oscillator wall, Y-axis excitation produced 7.8 GRMS in Y at the LEM corner, and Z-axis excitation produced 8.5 GRMS in Z at the oscillator wall. The max resulting random vibe control notches were -13.6 dB, -15.6 dB, and -4.3 dB in the X, Y, and Z axes, respectively. Overall laser canister pointing was also measured between the external alignment cube and reference mirror on the boresight plate before and after each axis was shaken. The observed boresight shift was relatively low and met specification (< 200 μrad): X-axis resulted in 0 μrad in azimuth and -59 μrad in elevation, Y-axis resulted in 6 μrad in azimuth and -12 µrad in elevation, and Z-axis resulted in -17 µrad in azimuth and -8 µrad in elevation. The measured responses under vibration testing were in good agreement with the analytical model (Figure 7).

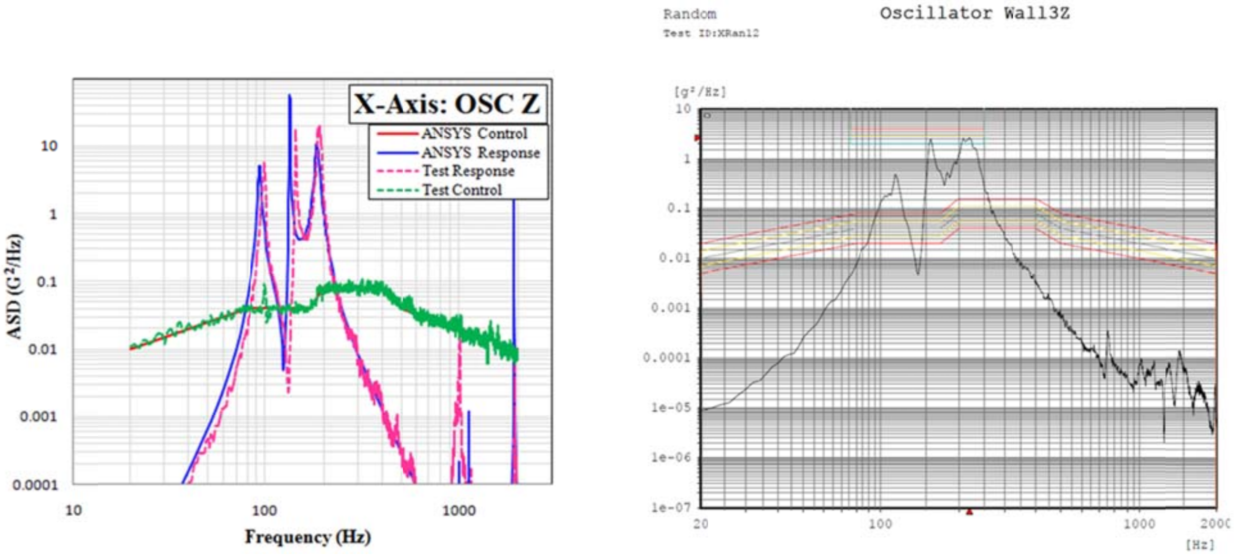


Figure 7. Mass simulator vibration testing predicted and actual response for excitation in the x-axis (right), and qualification laser vibration response with an x-axis excitation (left). The lasers vibration response agreed well with analysis.

3.3 Thermal Vacuum Testing

The qualification laser was successfully exposed to one thermal vacuum survival cycle (Figure 8). Laser optical performance was verified prior to, during, and after testing and found to meet all optical requirements. Several thermal and optical measurements were recorded. Hot and cold survival soaks were performed as well,

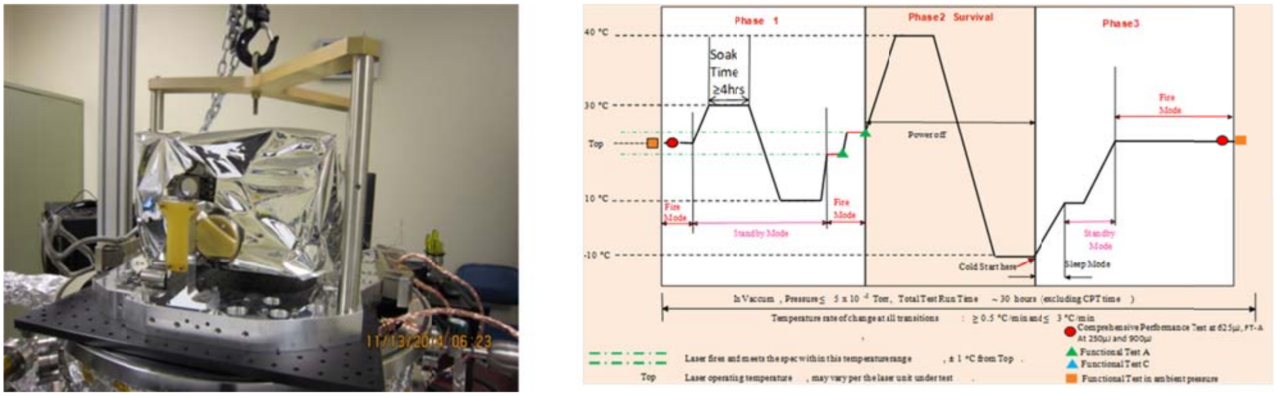


Figure 8. Qualification laser wrapped in Single Layer Insulation (SLI) being lowered into the TVAC chamber (left), and TVAC thermal cycle and test profile (right).

At the beginning of testing, when the qualification laser was transitioned from ambient to vacuum there was an optical energy drop of 70 µJ or (7.5%), which was caused by a slightly different thermal gradient in the laser housing (due to convection), as well as a change in the chiller EGW mixture and an imbalance between diode temperatures. All other optical parameters remained stable and the resulting energy drop was not an issue with the GSFC systems team.

3.4 Laser Performance

The qualification laser passed all optical laser performance specifications throughout environmental testing with margin. Typically all optical performance parameters had greater than 10% margin before going over specification. No degradation in energy was observed pre- versus post-testing, and as of the final acceptance testing the qualification laser still has a 20% margin over the maximum required energy (Figure 9). The performance of the Integration and Test Laser (ITL) through the qualification program shows the laser design is qualified for flight.

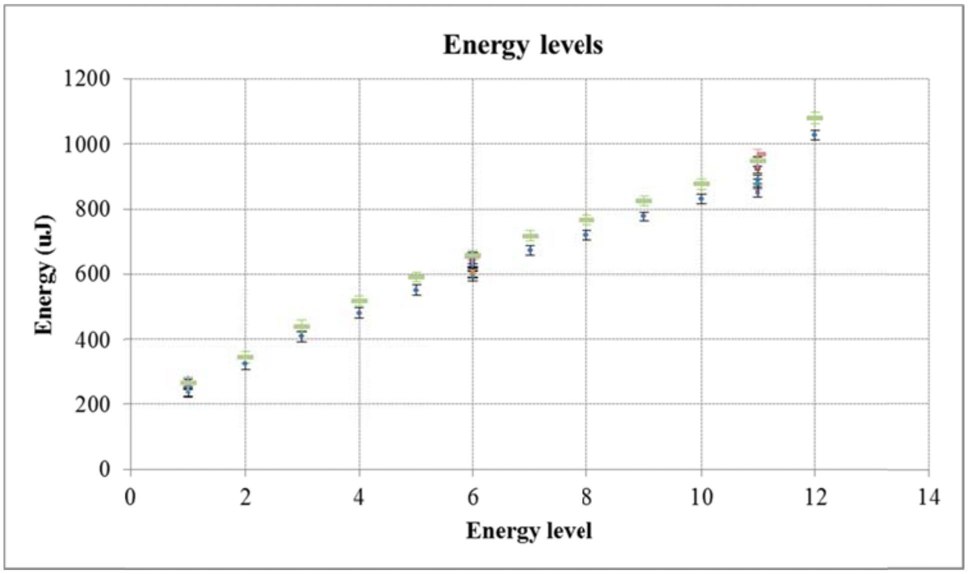


Figure 9. Laser output energy at 12 energy modes ranging from 250 µJ to 1,100 µJ. The data represents all testing results throughout EMI, vibration, and TVAC testing. The laser output energy was nominally unchanged through all environmental testing.

The laser boresight relative to the optical bench shifted < 100 µrad throughout the entire environmental testing program, and the majority of boresight shift is attributed to a small amount of slippage between the optical enclosure and the mounting flexure. The pointing shift and output beam location, as a result of the increased pressure differential of the laser canister during TVAC testing, was measured to be approximately 20 µrad, compared to the STOP analysis predicted value of 35 µrad, and the output beam location shifted by 200 µm compared to a predicted shift of 320 µm. The close agreement of the STOP analysis with measured performance during environmental testing is a product of a systematic STOP analysis approach that was correlated to brassboard and EDU laser performance.

The laser divergence as a function of energy level varies from 80 µrad to 97 µrad with corresponding beam diameters of 0.88 mm and 1.00 mm across energy modes. The output divergence was unchanged throughout vibration and TVAC testing (Figure 10).

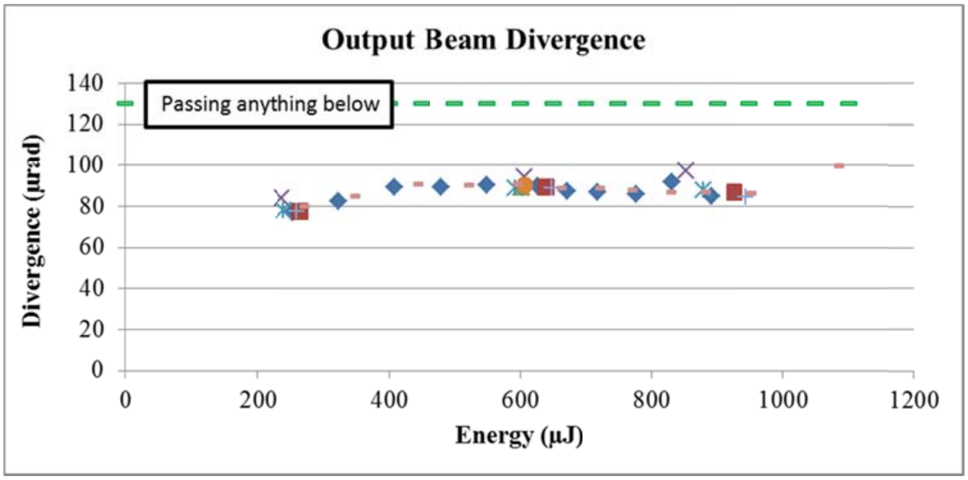


Figure 10. Laser output beam divergence measured throughout the environmental testing program.

4. CONCLUSIONS

The qualification test laser successfully completed the qualification testing as defined by the ICESat-2 program, which included EMI, vibration, and TVAC testing. The laser performance was stable throughout all testing, and performance agreed well with predicted values. The success of the qualification program was a direct result of the systematic approach taken by Fibertek in transitioning the laser technology from a laboratory demonstration to fully qualified spaceflight hardware.

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