PERFORMANCE OF THE GLAS LASER TRANSMITTER IN SPACE

Anthony W. Yu (1), **Robert S. Afzal** (2), **Joseph L. Dallas** (3), **Anthony Melak** (1), **Alan Lukemire** (4),
Luis Ramos-Izquierdo (5) **and William Mamakos** (6)
(1) NASA-GSFC, Laser & Electro-Optics Branch, MC554, Greenbelt, MD 20771, USA, E-mail: anthony.w.yu@nasa.gov
(2) Aculight Corp., 11805 North Creek Parkway S., Ste 113, Bothell, WA 98011, Email: robert.afzal@aculight.com
(3) Avo Photonics, 700 Business Center Drive, Suite #125, Horsham, PA 19044, USA, E-mail: jdallas@avophotonics.com
(4) Space Power Electronics Inc., 108 Audrey Way, Kathleen, GA 31047, USA, Email: alan@spacepower.com
(5) NASA-GSFC, Optics Branch, MC551, Greenbelt, MD 20771, USA, Email: lramos@pop900.gsfc.nasa.gov
(6) Design Interface Inc., 3451 Gamber Road, Finksburg, MD 21048, USA, Email: DI@transsys.com

ABSTRACT

The Geoscience Laser Altimeter System (GLAS), launched in January 2003, is a laser altimeter and lidar for the Earth Observing System's (EOS) ICESat mission. The laser transmitter requirements, design and qualification test results and in-flight performance for this space-based remote sensing instrument is summarized and presented.

1. INTRODUCTION

The Geoscience Laser Altimeter System (GLAS) [1] launched January 12, 2003 at 4:45 PST on board a Boeing Delta II expendable launch vehicle from Vandenberg Air Force Base, CA, is the sole instrument for the ICESat [2] (Ice, Cloud and Land Elevation Satellite) mission. GLAS is a satellite laser altimeter and atmospheric lidar whose primary mission is the global monitoring of the Earth's ice sheet mass balance. GLAS also provides high precision land topography and global monitoring of aerosols and cirrus cloud heights. Combining a 1-m beryllium telescope, 1 GHz digitizer, Analog and Photon counting Si APD's, an on-board laser beam pointing measurement system [3], variable conductance heat pipes for thermal management, and a 2-color diode-pumped solid-state laser, the GLAS instrument is providing an unprecedented high precision and accuracy data set (5 cm vertical accuracy, 2.4 cm precision) on the vertical structure of the Earth surface and Atmosphere. GLAS is designed to accommodate 3 transmitters intended to be operated sequentially on a common optical bench opposite the laser beam point measurement system known as the stellar reference system**.** Fig. 1 shows the location of the lasers on the GLAS instrument. The GLAS lasers [4,5] represent the next generation of space-based remote sensing laser transmitters. The previous state-of-the-art in space based solid-state lasers is the Mars Orbiting Laser Altimeter (MOLA) [6,7], on the Mars Global Surveyor spacecraft collecting topography data of Mars [8].

The GLAS lasers generally have an order-of-magnitude higher performance than MOLA in power, beam quality, improved efficiency, and other technological advances.

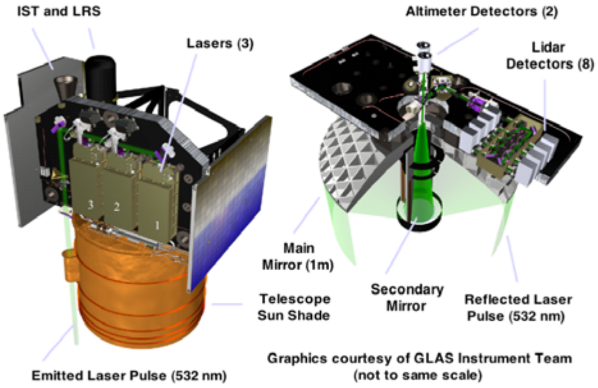

Fig. 1. Graphic showing the location of the lasers in relation to the other elements of the instrument optical path.

2. LASER DESIGN

The top level performance requirements for the lasers are summarized in Table 1.

Table 1. Top level optical requirements and resources.

Property	**Specification**
Pulse Energy (total)	110 mJ
1064 nm	75 mJ
532 nm	35 mJ
Repetition Rate	40 Hz
Wavelength (Vacuum)	λ1=1064.5 nm ±100 pm
	λ2=532.2 nm ± 50 pm
λ2 linewidth (FWHM)	≤ 15 pm shot-to-shot
Pulse width	< 6 ns
Divergence	110 (+23, -10) µrad
Far Field Circularity	> 0.67
Pointing Jitter	± 11 µrad (1 σ)
Boresight Reference	< 1000 µrad (±50 µrad)
Boresight Stability over	± 50 µrad
Prime Power	110 W
Mass	15.2 Kg
Volume	54x15x25 cm^3

Additionally the laser needs to operate from 10°C to 35°C and survive non-operating from 0°C to 50°C. The expected launch loads were up to 8 grms for 1 minute. The mission life is for 3 years with a 5 year goal. Under continuous operation at 40 Hz the lasers will accumulate 1.26 billion shots per year.

Particularly challenging in simultaneously meeting these requirements is the combination of short pulse width, high pulse energy and excellent beam quality. Short pulses are typically generated by short cavities with high gain. Shorter cavities tend to allow for higher order transverse modes in high gain lasers unless the pulse energies are low. To keep the transmitters optics small and to avoid the use of large beam expanders to meet the divergence requirements, the final beam quality needed to be in the range of $M^2 \approx 2$. Although ruggedized lasers tend to be crossed-porro power oscillators, a master-oscillator, power-amplifier (MOPA) design was the most promising architecture for meeting the transmitter performance objectives [9]. In this particular case, a short pulse TEM_{00} oscillator is followed by 2 amplification stages to meet the final energy level. Optical aberrations were minimized by utilizing zig-zab slabs, and beam image inversions from prisms between the first and the second amplifier passes.

The oscillator, pumped by two 100 W Q-cw diode-bars, is passively Q-switched, and generates 2 mJ, 5 ns near diffraction limited ($M^2 < 1.1$) pulses at 40 Hz. The output pulses are expanded by a 2x telescope, and amplified by a double-pass preamplifier stage pumped by 8, 100 W bars resulting in 15 mJ pulses with an $M^2 \approx 1.4$. This stage utilizes a polarization coupled double pass, zig-zag slab with a porro-prism for beam symmetrization. After another 2.2x expansion, the beam enters a power amplifier pumped by 44, 100 W bars. The pulses are amplified to 110 mJ after a double pass with an $M^2 \approx 1.8$. The peak laser fluence in the final amplifier is 4 J/cm^2. The full power beam is then directed to a Lithium Triborate (LBO) doubler designed to convert 30% of the power into the green, followed by an achromatic, 6x final beam expander. The far-field beam divergence is "Gaussian-like" with a 110 μrad full angle divergence and an $M^2 \approx 2$. *Fig. 2* shows the output energy of the 2 colors as a function of diode drive current. To improve laser lifetime [10], oscillator diodes are derated to 65 W/bar (85 A) and amplifier diodes derated to 85 W/bar (100 A) [11,12].

Since the laser is not actively Q-switched, the timing of the pulse emission from the oscillator is actively controlled through the diode drive current. The Laser Diode Power Electronics (LDPE) delivers 100 A of current to diodes that are electrically in series. A by-pass FET diverts nominally 15 A of current around the oscillator diodes thereby further derating these diodes in current. When current is delivered to the diodes a counter counts the time until an internal photodetector detects the emission of the laser pulse. A feedback loop then adjusts the by-pass current to allow for more or less current to pass through the oscillator diodes to maintain a diode pump time of 200 μs. This loop is necessary to maintain the synchronization of the oscillator pulse emission to the maximum stored energy and gain of the amplifiers.

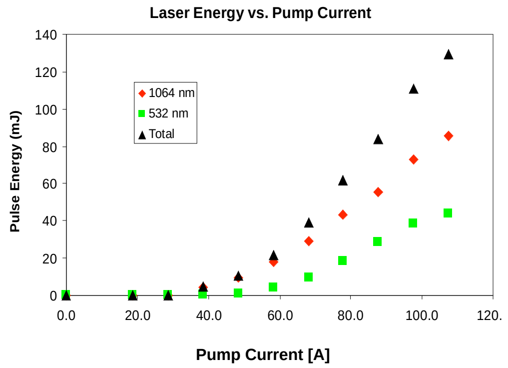

Fig. 2. Laser Pulse Energy as a function of peak diode drive current. The operational design point was a drive current of 100 A.

The laser is all conductively cooled with the thermal interface to the spacecraft being a heat pipe mounted to a side-wall of the laser housing where the largest heat sources, the amplifier heads are also mounted. Thermal control of the oscillator diodes and the doubling crystal must be accommodated and accounted for internal to the laser, leading to a final prime power draw of 110 W @ 30V input. The mechanical design consists of a single block of aluminum milled out on two sides. One side contains the laser optics, pump heads, doubler and final beam expander. The opposite side contains all the electronics. Power to the diodes and other signals are fed though a minimum number of connectors and feed-throughs in the floor of the box from the electronics to optics side. This design is inherently rigid, and allows the separation of the electronics from the optics to maintain cleanliness and facilitate the fabrication process. Fig. 3 shows a photo of the flight laser ready for delivery.

Fig. 3. External photograph of the GLAS laser serial number 2. Visible is the output port of the laser beam, the mounting flexures, quick disconnects (remove before flight) for venting and purging with air, and a reference mirror used to align the pointing of the laser beam referenced to the mounting feet.

All materials and construction techniques were carefully considered to ensure radiation tolerance, vacuum compatibility and opto-mechanical stability. All piece parts followed a rigorous cleaning and vacuum baking procedure. Final laser bakeouts were conducted at 10^{-7} torr and monitored by a quadrupole mass spectrometer.

3. TESTING SUMMARY

Pre-launch testing consisted of 3-axis vibrational survivability tests, EMC/EMI compatibility tests, magnetic, and thermal-vacuum temperature cycling. The flight lasers were vibrated to 8 grms for 1 minute each axis. The design had previously been verified with an as-built engineering test unit vibrated to 10.6 grms each axis for 1 minute. Thermal vacuum testing (TVAC) consisted of 2 modes. First, the laser underwent 4 temperature cycles in vacuum over the operation and survival temperature ranges. The laser optics cavity was then sealed and back-filled with 16 psia dry air. The laser then under went one full survival cycle to characterize the laser in this configuration. To minimize the risk of contamination being introduced to the laser optical compartment after full vacuum testing was completed by the laser subsystem, the optics cavity was sealed for delivery to the instrument. During instrument and spacecraft TVAC testing the laser optics cavity remained sealed. Upon launch a burst-disc installed on the laser ruptured and vented the lasers to space. The lasers operate in-flight, completely evacuated on both the electronics and optics side of the laser. All 3 lasers went though the full qualification process. At the time of launch, the lasers had each accumulated 142 million shots on average throughout all testing, which is 11% of the 3-year mission total.

4. IN-FLIGHT OPERATION

On February 20, 2002 Laser 1 was activated and the GLAS instrument began continuous date collection. 35 days and 120 million shots later, Laser 1 unexpectedly ceased operation. Fig. 4 and Fig. 5 show the 1064 nm and 532 nm pulse energies for all 3 lasers accumulated so far on-orbit. An Independent GLAS Anomaly Review Board (IGARB) was formed to investigate the cause. The IGARB determined the most likely cause was an unexpected catastrophic failure of a diode pump array [13]. The root cause of the pump array failure was probably related to "manufacturing of the laser diode arrays introduced excessive indium solder that resulted in a metallurgical reaction that progressively eroded the gold conductors through the formation of a non-conducting gold-indium intermetallic, gold-indide, at a rate dependent on temperature [13]." Based on this hypothesis it was recommended to reduce the operating temperatures of the lasers from an initial set point of 29°C, to slow down the potential Au-In growth rate. Additionally, the mission operation scenario was modified to operate the lasers in 30 or 45 day campaigns to ensure seasonal mapping of polar ice while preserving laser lifetime. This reduced the laser operation duty cycle from 100% to 27% on-time.

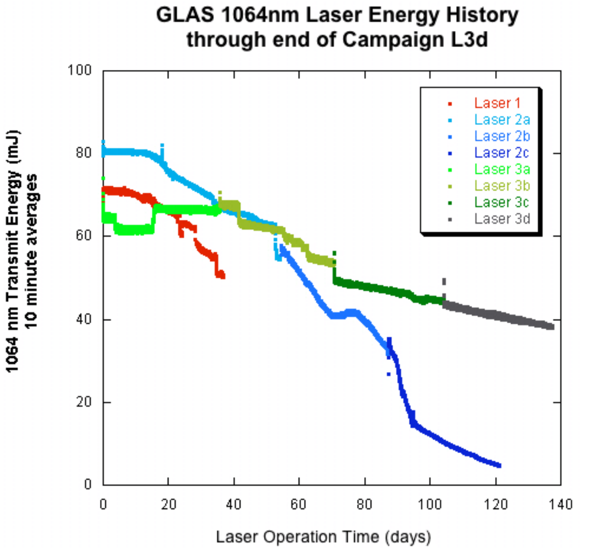

Fig. 4. 1064 nm energy history accumulated over 8 campaigns. Some energy step down's or ups are associated with laser temperature changes. Others are hypothesized to be diode bar drop outs.

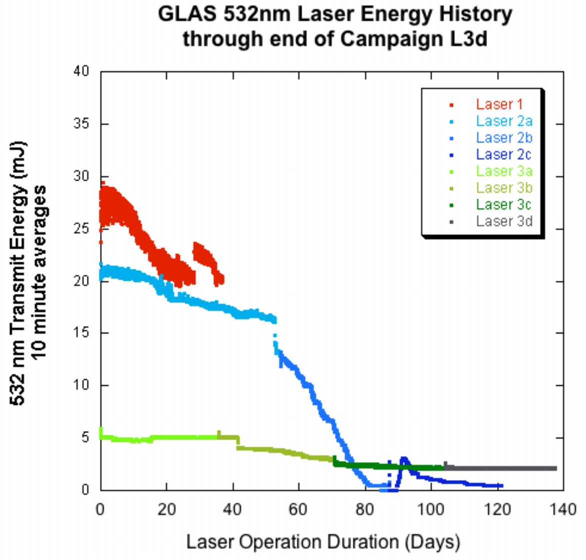

Fig. 5. 532 nm energy history accumulated over 8 campaigns. Some energy step down's or ups are associated with laser temperature changes. Others are hypothesized to be due to diode bar drop outs.

Laser 2 was operated for 3 campaigns accumulating over 420 million shots on-orbit at temperatures from 25°C to 17°C. Although there was no catastrophic failure of Laser 2, the degradation rate was faster than pre-launch predictions. It is hypothesized this decline is due to the interaction of the intense 532 nm beam with trace outgassing materials inside the laser. Based on this hypothesis it was recommended to further reduce the temperature of Laser 3 to 13°C. Laser 3 has now completed 5 campaigns and accumulated over 600 million shots on-orbit. With the reduced operating temperature and lower 532 nm conversion efficiency, Laser 3 is demonstrating a significantly reduced degradation rate. A linear projection on the lifetime of Laser 3 would put it out beyond the 1 billion shot mark which was in-line with prelaunch projections. As an instrument, ICESat has now accumulated over 1 Billion shots in space.

5. SUMMARY

The Geoscience Laser Altimeter System on NASA's ICESat mission has been operating in space for over 3 years. The lasers so far have emitted a cumulative number of shots exceeding 1 billion. For an overview of the scientific results form ICESat see the special issues of Geophysical Research Letters [14]. (also see the ICESat web site: http://icesat.gsfc.nasa.gov/) GLAS is a pioneering instrument and the instrument performance is truly extraordinary. The lasers' pulsewidth, energy, beam quality, and stability, have helped enable 2.4 cm precision, 5 cm accuracy altimetry measurements from a 600 km orbit, in a size, weight and efficiency within mission constraints. Despite the earlier unexpected loss of Laser 1, a larger than anticipate degradation rate in Laser 2, the GLAS lasers continue to collect high resolution vertical profiles of the Earth's atmosphere and land surface. With the current projections on the lifetime of Laser 3, it is still possible the GLAS instrument will meet or exceed prelaunch expectations.

Acknowledgements: The authors would like to thank J. Abshire and the GLAS instrument team and especially the staffs at the SLTC for their hard work and dedication in developing the GLAS lasers. We also would like to thank P. Liiva and Haris Riris for in space operation data processing.

6. REFERENCES

1. Abshire, J.B, et. al, "Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance," *Geophysical Research Letters*, Vol. 32, L21S02, 2005.

2. Zwally, H. J., et. al., "ICESat's laser measurements of polar ice, atmosphere, ocean, and land," *Journal of Geodynamics*, Vol. 34 405–445, 2002.

3. Sirota, J. M., et. al., "The transmitter pointing determination in the Geoscience Laser Altimeter System," Geophys. Res. Lett., Vol. 32, L22S11, 2005.

4. Afzal, R. S., et. al., "The Geoscience Laser Altimeter System Laser Transmitter," *OSA Conference on Lasers and Electro-Optics* Digest, CMJ2, 2000.

5. Afzal, R. S., et. al., "Space Qualification of the Geoscience Laser Altimeter System," *OSA Conference on Lasers and Electro-Optics* Digest, CWN4, 2002.

6. Afzal, R. S., "Mars Observer Laser Altimeter: Laser Transmitter," *Applied Optics*, (33), 15, 20 May, 1994, p. 3184.

7. Afzal, R. S., "Space Operation of the MOLA Laser," OSA Advanced Solid State Laser Topical Meeting, Davos, CH, 2000.

8. Smith D.E., et. al., "Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars," Journal of Geophysical Research-Planets, Vol. 10, 2001.

9. Afzal, R. S., et. al., "The GLAS Laser Transmitter Breadboard," OSA TOPS Vol. 10, Advanced Solid State Lasers, p. 102 Orlando, FL, Jan. 27 - Jan. 29, 1997.

10. Stephen, M. A, et. al., "Multi-billion shot, High-Fluence Exposure of Cr4+:YAG Passive Q-switch," *SPIE Proceedings from 29th Annual Boulder Damage Symposium*, Vol. 3244, p. 517, 1997.

11. Stephen, M. A., et. al., "Quasi-CW Laser Diode Bar Life Tests," *SPIE Proceedings from 29th Annual Boulder Damage Symposium*, Vol. 3244, Boulder, CO, p. 598, 1997.

12. Krainak, M., et. al., "Performance Tests of Quasi-CW Diode Pump Arrays Conducted or Sponsored by NASA Goddard Space Flight Center," *1997 Digest of the LEOS Summer Topical Meetings: Advanced Semiconductor Lasers and Applications*, 1997, p. 78.

13. Kichak, R.A., *IGARB Executive Summary*, http://icesat.gsfc.nasa.gov/publications.htm.

14. Results from the Ice, Cloud, and land Elevation Satellite (ICESat) Mission, Geophysical Research Letters, Vol. 32, No. 21 and 22, 2005.