WE ARE ON

OSA Laser Systems Technical Group

Engineering Laser Systems for Aerospace & Defense Applications

Nicholas Sawruk, Fibertek, Inc.

The OSA Laser Systems Technical Group Welcomes You!

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OSA Laser Systems Technical Group

Technical Group at a Glance

- Focus
  - This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications.
- Mission
  - To benefit *YOU*
  - Webinars, e-Presence, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at TGLaserSystems@osa.org.
- Find us here
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Today’s Webinar

Engineering Laser Systems for Aerospace and Defense Applications

Nicholas Sawruk

Fibertek, Inc.

Speaker’s Short Bio:

Nicholas Sawruk is the Director of Laser & Optical Engineering at Fibertek, Inc. Mr. Sawruk has over 15 years of experience developing, designing, integrating, and testing laser/EO systems. His support experience includes the NASA Ice Cloud and Elevation Satellite laser systems where he served as the principal investigator and program manager of a high reliability laser system for a national asset space satellite. Over his career, Mr. Sawruk developed, matured and delivered state of the art laser systems including chemical, gas, solid state and fiber lasers for a wide range of defense and science sensing missions. He received a bachelors of science degree in Physics and Mathematics from the United States Air Force Academy and a masters of science degree from the University of New Mexico.

ENGINEERING LASERS FOR MILITARY AND SPACE APPLICATIONS

2020 OSA WEBINAR
17 JULY 2020

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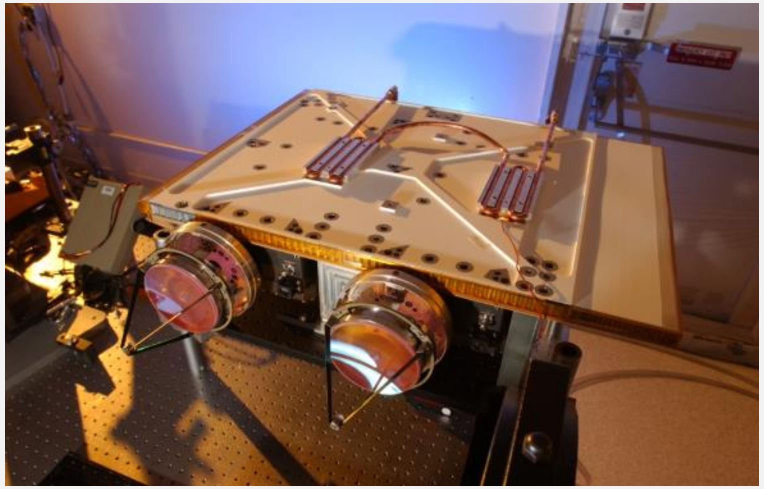
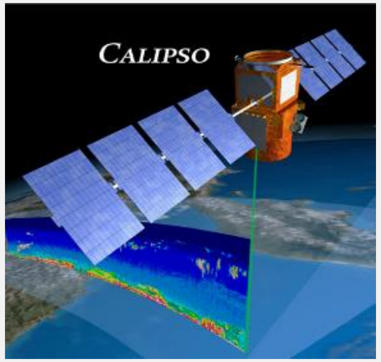
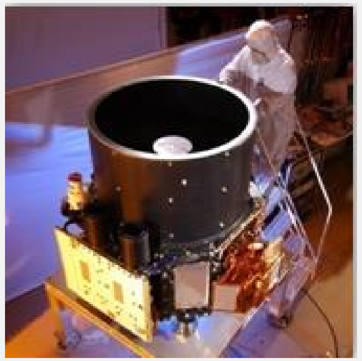
Fibertek Active EO Systems for Space & Military Applications

CALIPSO (launched 2006)

12+ years 24/7 operation (3-year design life)

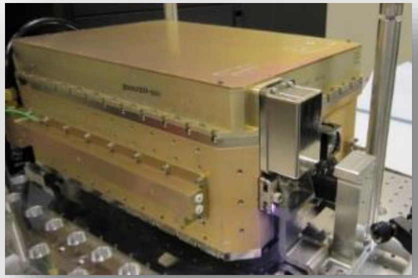


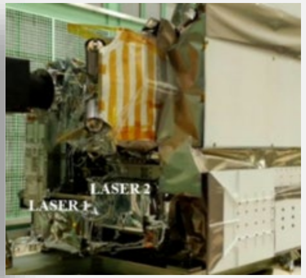




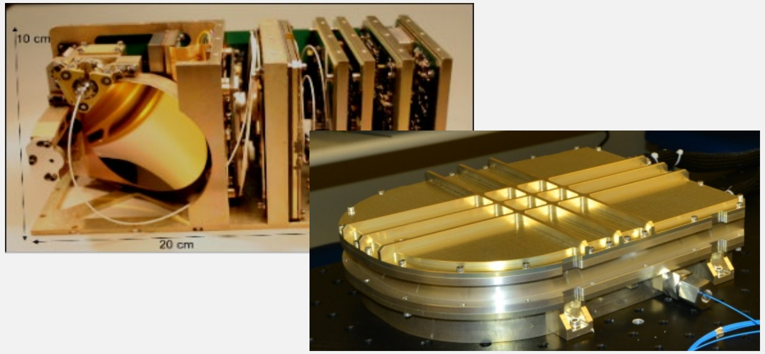
ICESat-2 (launched 2018)

The only TRL9 multi-Watt, multi-kHz, high-efficiency nanosecond space laser.
>500 Gshots to-date – more than any other NASA space laser



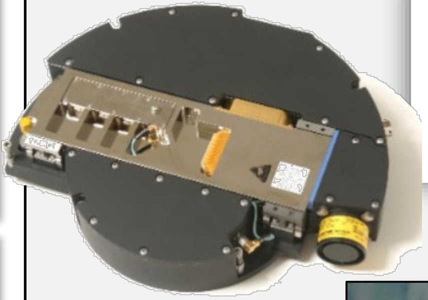


Lasercom



Military Lasers

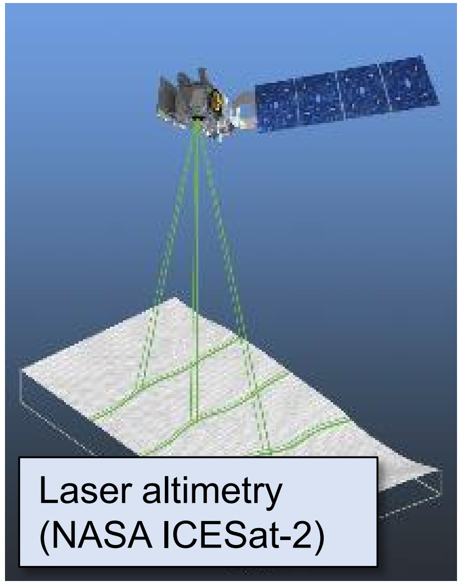
LIDAR illuminators, designators, range-finders, and infrared counter-measures

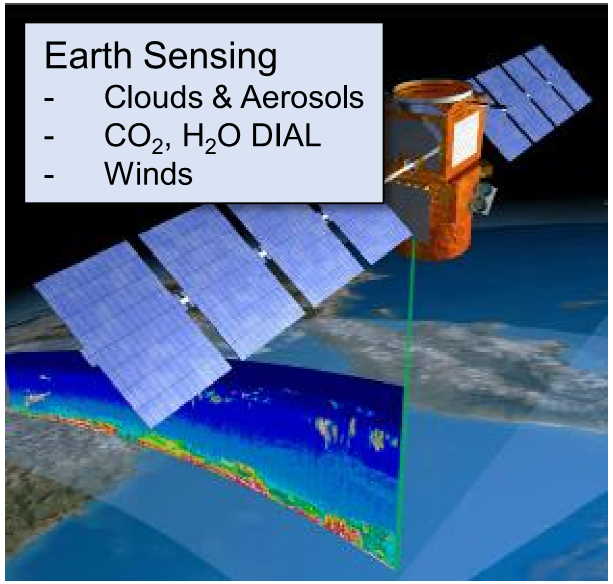


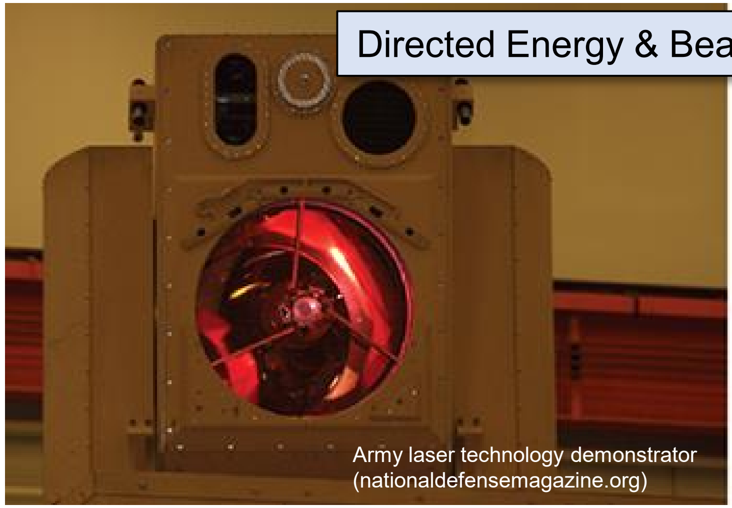
Fibertek has engineered lasers and active E-O systems for space and military applications for ~35 years

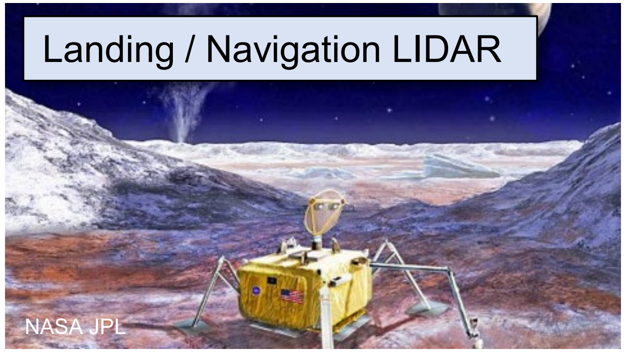
Aerospace & Military Applications

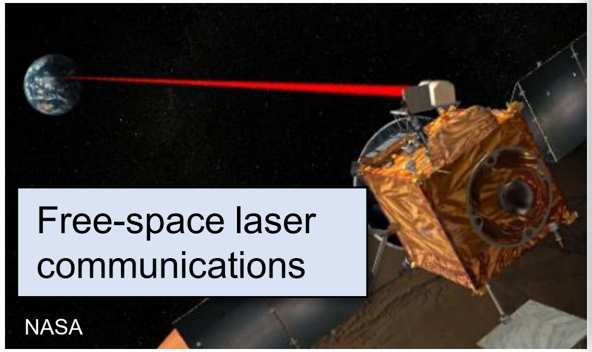
FIBERTEK, INC.

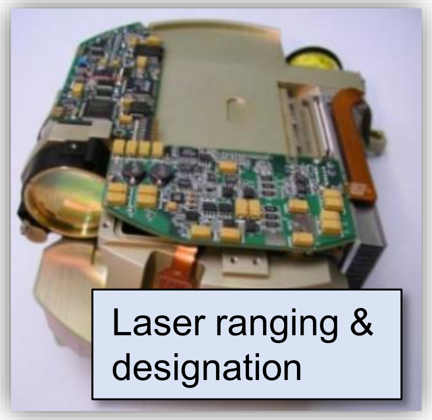


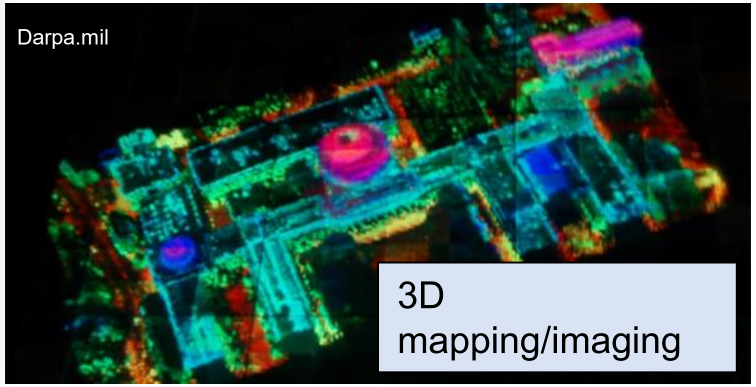












Laser-based sensors are critical technologies for military & aerospace missions

Laser Design Drivers

FIBERTEK, INC.

Laser Properties	Military & Aerospace		Industrial & Scientific	
	Motivation	Priority	Motivation	Priority
Power	Extends range for standoff sensors & effects	High	Increases throughput, yield, etc.	Med
Efficiency	Platforms have limited power and/or heat dissipation	High	Industrial & commercial applications typically have more available power & thermal capacity	Low
Reliability	Mission criticality and difficult service & replacement	Highest	Decreases life cycle cost	High
Compact size	Platforms (esp. air & space) are highly sensitive to size & weight	High	Commercial/industrial applications may be less sensitive to size & weight	Med
Conduction (or forced air) cooling	Reduces size & weight, compatibility with environments	Med	Frequently able to utilize liquid heat exchangers or chillers	Low
Cost	Important, after high-priorities are met	Med	Market competition	High
Mission-specific performance (wavelength, tailored waveforms, etc.)	Leading-edge performance is often required	High	Implementation can often adapt to available technologies to reduce cost, versatility may be favored to expand market access	Low
Mission-specific environments	Operability is required over a wide range of conditions	High	Users have some control over operating conditions	Med
Modularity/versatility	Frequently compromised for mission-specific needs	Low	Amplifies return on product development investments	High

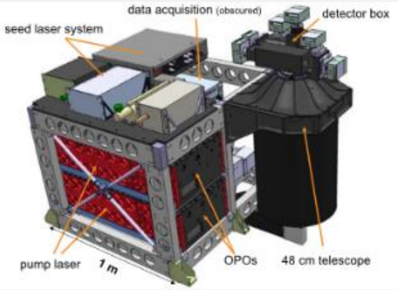
Design priorities for military and aerospace lasers are more driven by reliability, mission performance, environments, and SWaP (size, weight, & power) vs. commercial/industrial lasers.

Mission Enabling Laser System Examples

FIBERTEK, INC.

WALES, the Airborne Demonstrator for a Water Vapor Differential Absorption LIDAR in Space

- *4-λ system at specific & non-standard wavelengths (~935 nm)*
- *Single frequency Optical Parametric Oscillator*
- *45 mJ Energy @ 100 Hz*
- *>500 hours of airborne operation*



Wirth M., et al. The airborne multi-wavelength water vapor differential absorption lidar WALES: system design and performance, Applied Physics B: Lasers and Optics, 2009, 1, 201-213

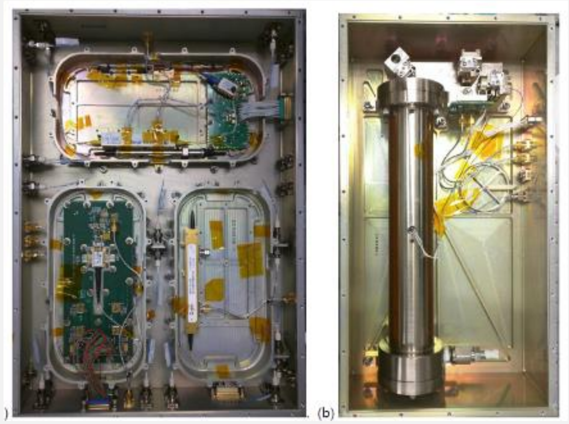
Aeolus – UV Doppler Wind Lidar *Frequency Stabilized, High Energy UV Laser in Space*

- *Atmospheric wind profiles form the ground to the lower stratosphere on global scale*
- *50.5 Hz, >100 mJ, 20 ns @ UV*
- *1.9 B shots in 15-months of operation in space*

Lux O, Wernham D, Bravetti P, et al. High-power and frequency-stable ultraviolet laser performance in space for the wind lidar on Aeolus. Opt Lett. 2020;45(6):1443-1446. doi:10.1364/OL.387728

NASA GSFC ASCENDS Fiber MOPA for CH_4 & CO_2 Sensing

- Rapidly-tunable single frequency output at specific λ
- 450 µJ , 7.5 kHz and > 20 dB polarization extinction ratio
- Compact & survive the rigors of launch & space applications



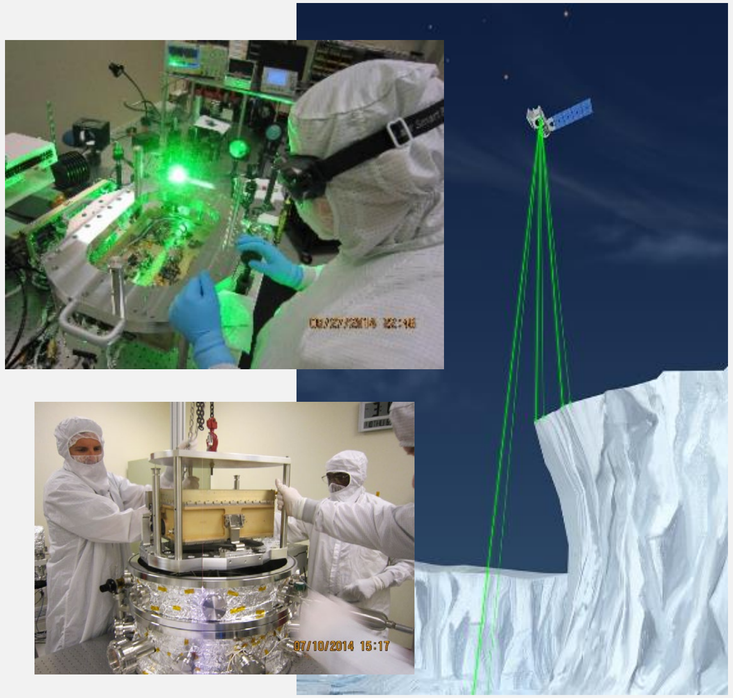
Mark Stephen, et al., "Fiber-based laser MOPA transmitter packaging for space environment," Proc. SPIE 10513,Components and Packaging for Laser Systems IV, 1051308 (20 February 2018); doi: 10.1117/12.2290720

Examples demonstrate a range of mission specific requirements in terms of wavelength, linewidth & performance in diverse operational environments and all with a priority on minimal SWaP

Fibertek Laser System Examples

ICESat-2 (launched 2018)

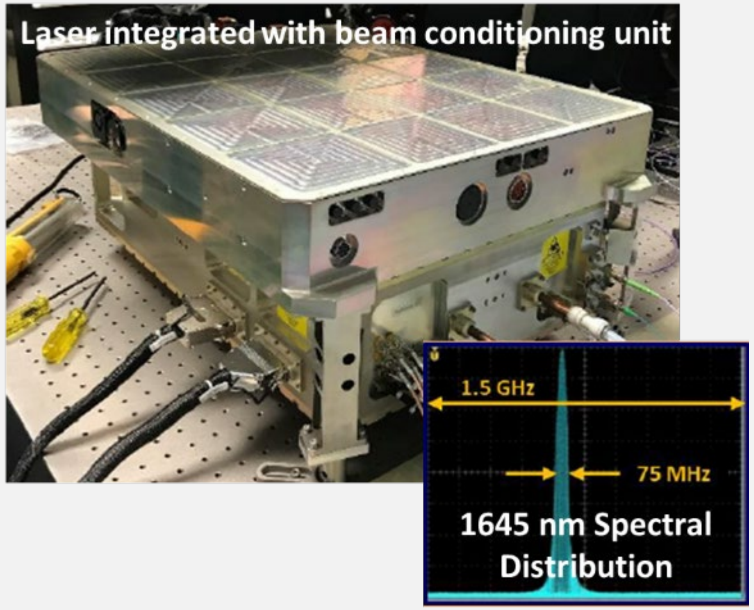
- *Key challenge: high-reliability design for 24/7 operation over 3 years & >1 Trillion laser shots*
- *>10x shot count of other remote-sensing space lasers*



Airborne DIAL

Key challenges:

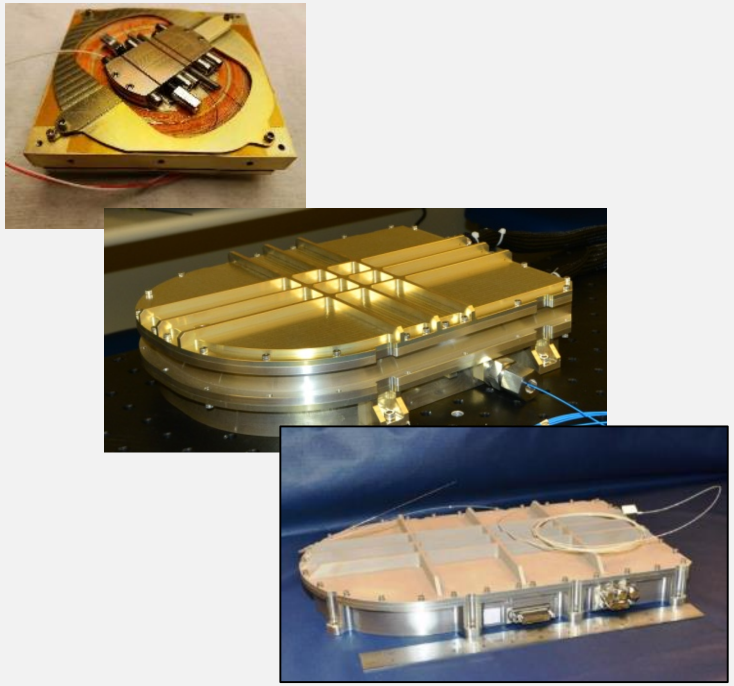
- *Precise frequency control in an airborne environment*
- *Advancing the technology toward space*



Pulsed fiber lasers

Key challenges:

- *Peak-power (pulse energy) performance*
- *Component qualification (temperature & radiation)*



3 examples show how design challenges for have been met to deliver reliable lasers for aerospace missions

ICESat-2 Laser Transmitter

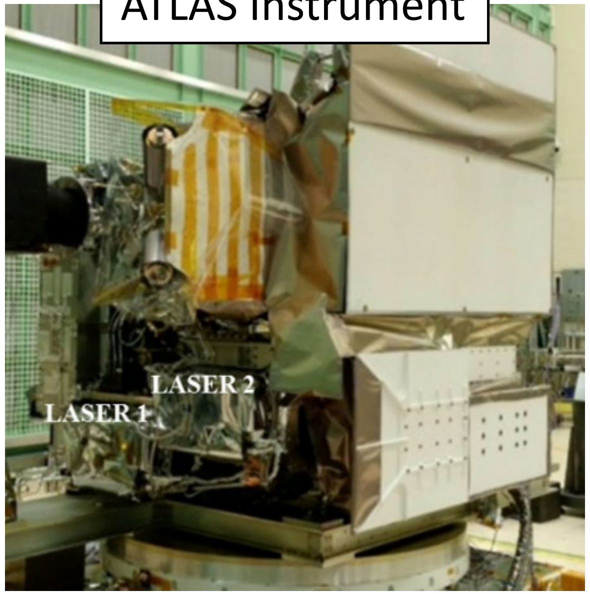
Example of a high reliability laser transmitter for a 3-year duration space mission.

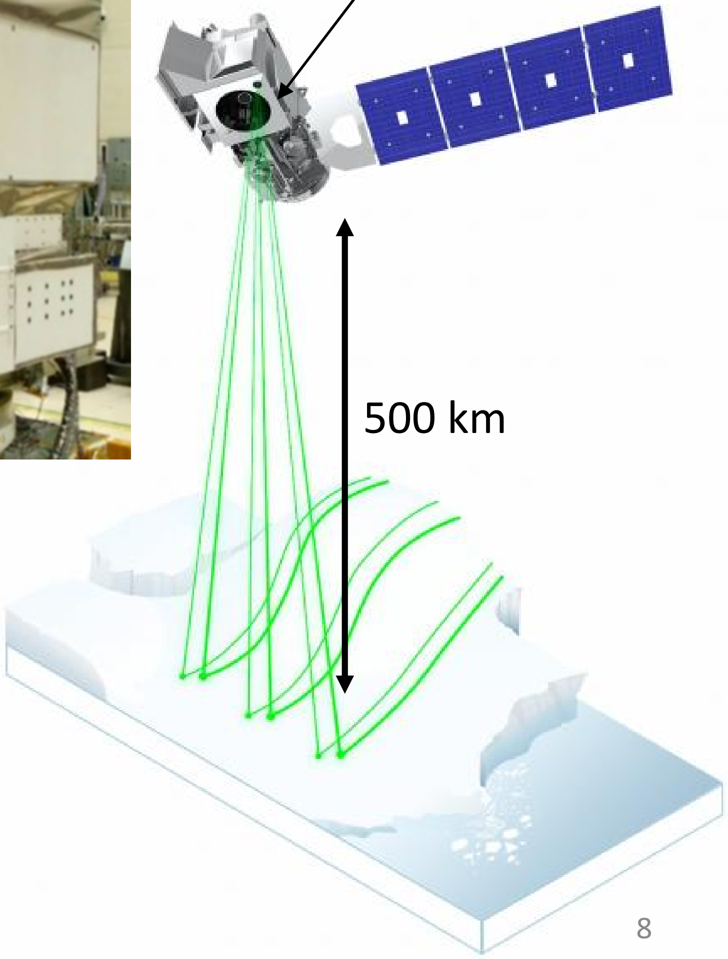
NASA ICESat-2 Mission Overview

Ice Cloud and land Elevation Satellite

- ICESat-2 carries a single instrument – the Advanced Topographic Laser Altimeter System (ATLAS).
  - ATLAS measures the travel times of lasers pulses to calculate the distance between the spacecraft and Earth's surface
  - ATLAS carries two redundant lasers, one primary and one backup.
- The four ICESat-2 science objectives are
  - Measure melting ice sheets and investigate how this effects sea level rise
  - Measure and investigate changes in the mass of ice sheets and glaciers
  - Estimate and study sea ice thickness
  - Measure the height of vegetation in forests and other ecosystems worldwide

ATLAS Instrument





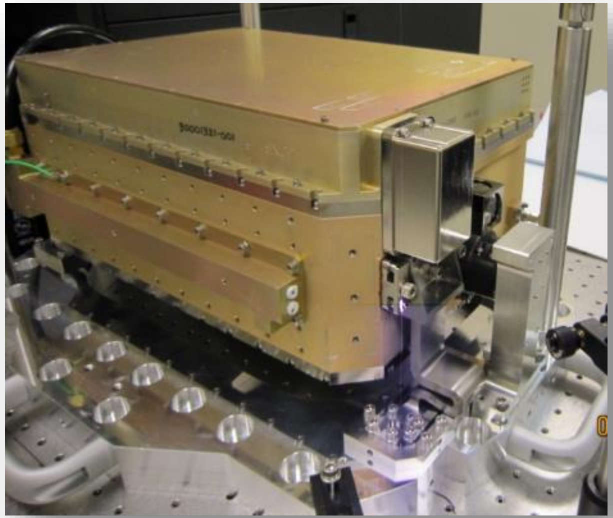
ICESat-2 Laser Driving Requirements & Resulting Enabling Capability

FIBERTEK, INC.

Parameter	Requirement	Flight Lasers	Enabling Lidar Capability
Energy (μJ)	250-900	250-1,370	Required pulse energy for multi-beam (6x) altimeter per laser shot, i.e. single output beam is split into 6 beams providing dense cross track sampling required for surface slope measurements.
Pulse Rate (kHz)	10	10	Fine ground sampling distance, measurements every 70 cm.
Pulse Width (ns)	1.5	<1.3	Fine height measurement resolution.
Divergence (μrad)	<130	91	<1.5x diffraction limited BQ – Minimal illuminated spot on the ground.
Tunable Wavelength (nm)	532.27±0.015	532.27±0.015	Absolute wavelength tunable to match etalon receiver transmission – minimizing background contributions.
Linewidth (pm)	<30	<5	Enables a narrow linewidth receiver filter – minimizing background contributions.
Efficiency	>5%	8.2%	High efficiency – reducing spacecraft thermal management & power distribution requirements.
Operational Run-Time	3.5 years (> 1 T shots)	Life test Lasers (> 1 T shots)	Demonstrate reliability required for long duration lidar missions – allows for long term trend measurements.

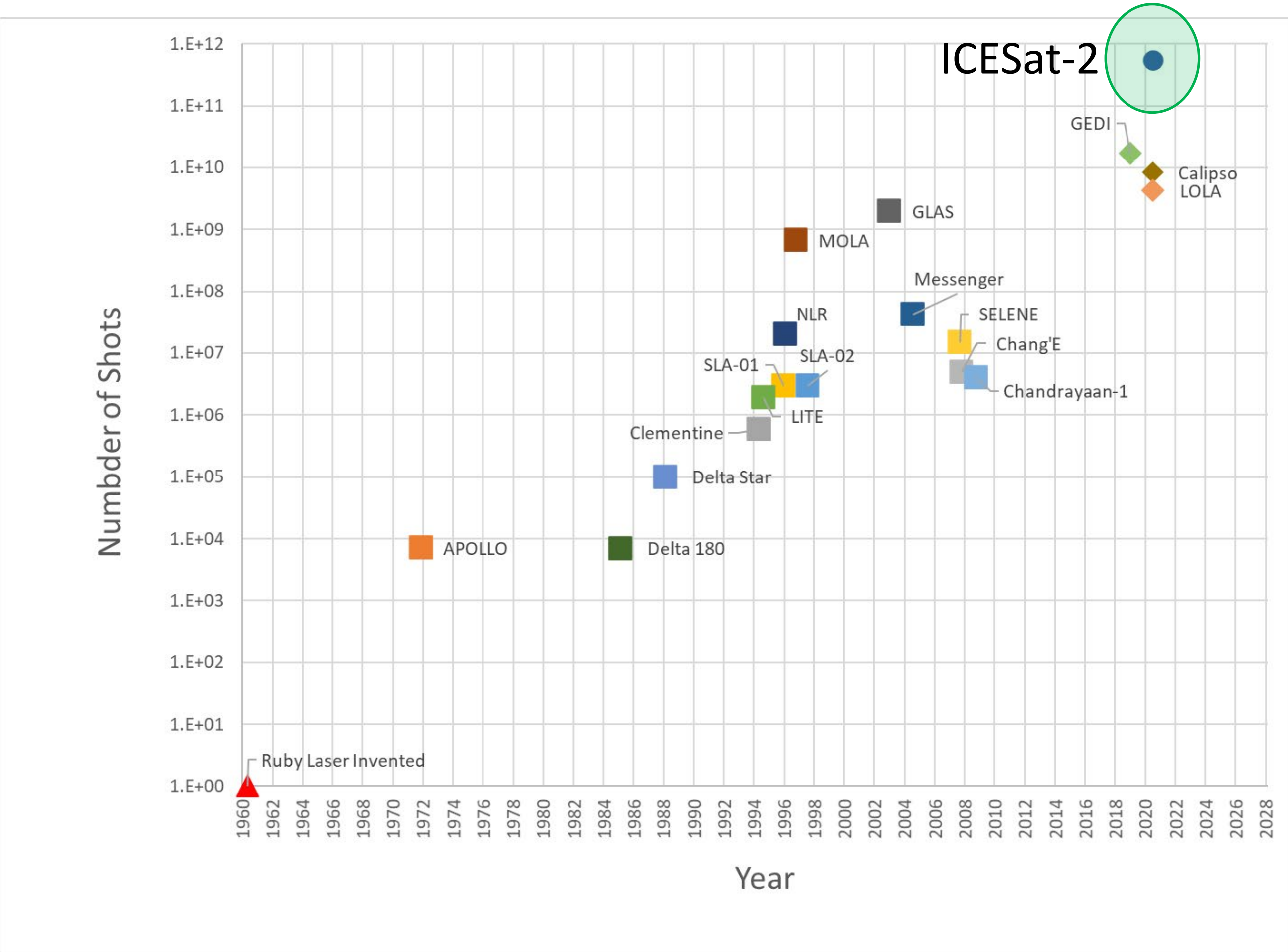
ICESat-2 Laser Overview

FIBERTEK, INC.



- **Integrated and ruggedized packaging – single unit with power and command inputs and 532 nm photons out.**
  - 30 cm x 50 cm x 15 cm, 19 kg
  - Flexure mounted laser system with hermitically seal laser module and vented electronics module in a single unit.

- **ICESat-2 lasers are State-of-the-Art space qualified lasers simultaneously requiring short pulse width, high average power, frequency tunability, near diffraction limited beam quality and a minimum life-time shot count of 1 Trillion shots.**

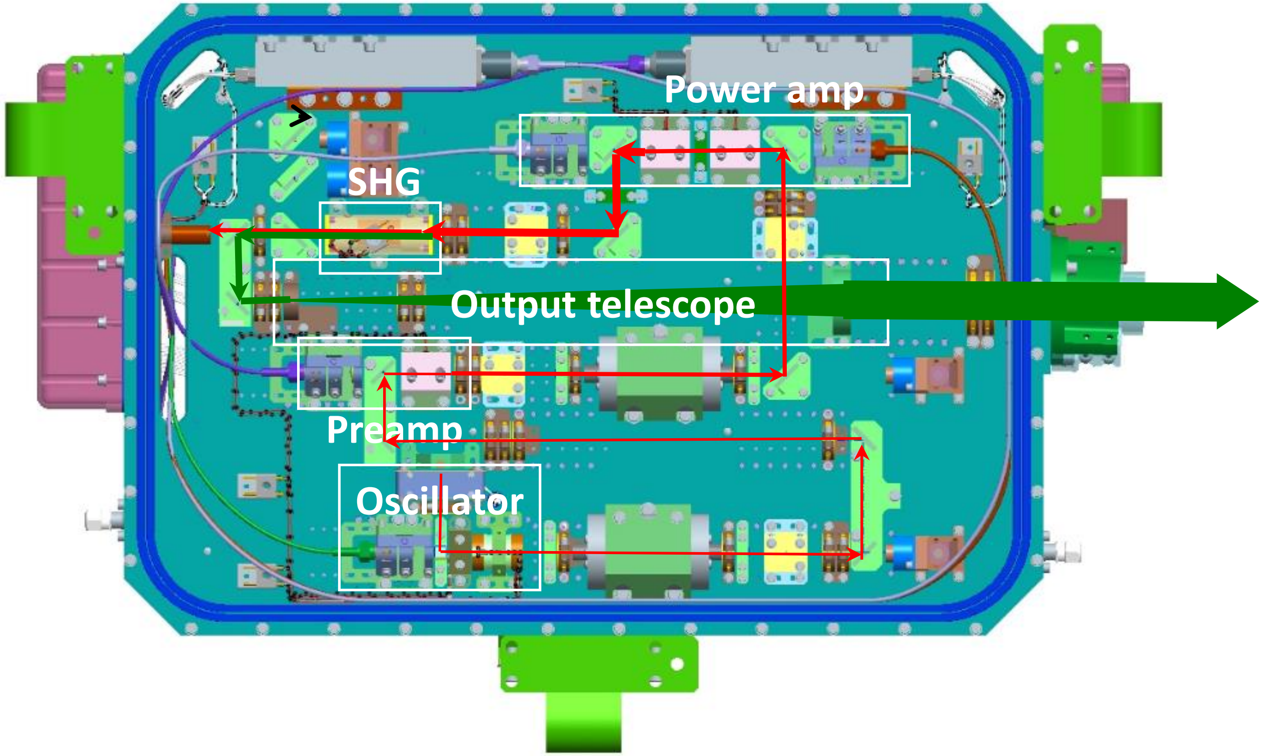


ICESat-2 mission requires ~3-orders of magnitude more laser shots, with the most stringent wavelength control and temporal pulse width requirements of any NASA spaceflight laser altimeter to date.

ICESat-2 Laser Design Features

- **Short, electro-optical Q-Switched oscillator generating key performance:**
  - Short pulse widths, diffraction limited BQ, 10 kHz PRF, and wavelength tunable w/ narrow linewidth.
- **End-Pumped amplifier chain**
  - Excellent Efficiency (40% Optical to Optical)
  - Preserves beam quality (M^2 ~1.3)
  - Enable by high brightness fiber coupled diode pumps.
- **Pulsed-Pumped w/ variable phasing and pump duration**
  - Energy tuning from 250 µJ to > 1,000 µJ
  - Constant thermal loading, i.e. minimal changes in beam divergence, pointing, & position.
- **High efficiency frequency conversion via critically phased match LBO**
- **Wall Plug Efficiency @ Full Energy: >7%**

1064 nm Master Oscillator Power Amplifier Frequency Doubled to 532 nm

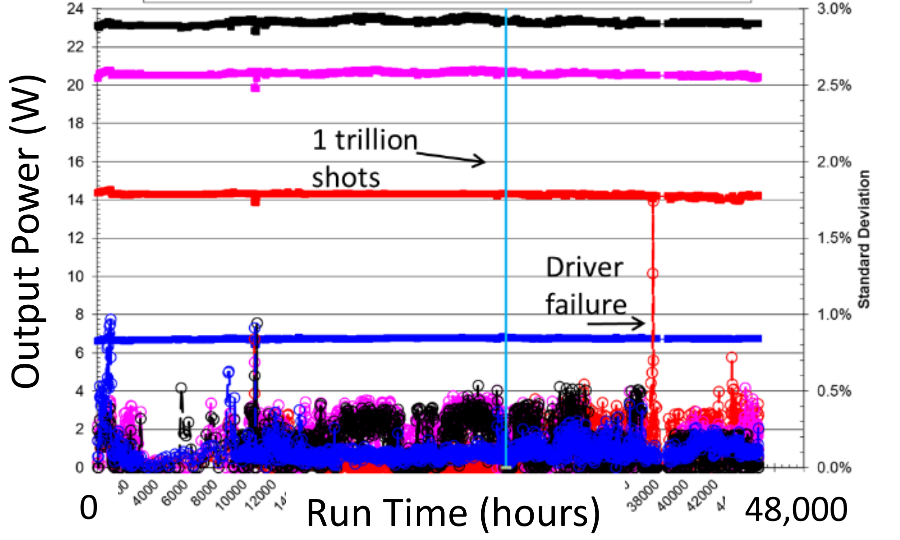


Laser Diode Pump Module Qualification

Component Qualification	Component Certification	Module Certification	Module Qualification	Module Capability Testing
Qualify component reliability and robustness in terms of particular mission requirements.	Lot certification of components used in module builds. If lot certification is not feasible, 100% screen and select.	100% test & screen of modules required.	Qualify a subset of modules to demonstrate reliability and robustness in terms of particular mission requirements.	Capability testing above and beyond mission requirements to demonstrate design margin.
GOAL: Demonstrate plausibility the system will satisfy mission environmental and reliability requirements.	**GOAL: Certify all components used in flight modules are of the highest quality and free of anomalies.**	**GOAL: Certify modules for the mission via 100% unit testing and screening.**	**GOAL: Demonstrate module design is capable of meeting the mission environmental and reliability requirements.**	**GOAL: Demonstrate and understand the module's headroom above mission requirements.**
Subset of Components for Flight Modules	**100% of Components for Flight Modules**	**100% of Flight Modules**	**Subset of Certificed Modules**	**Subset of Qualification Modules**
Radiation Testing	Lot Certify Components	Lot Certify if Possible or 100% Test & Screen	Environmental Tests (Vibe, Shock, Thermal, Radiation, etc.)	Test Subset of Modules to Failure (or sufficiently beyond mission requirements)
Component Accelerated Life Testing	Chiplet Burn-In	Acceptance Level Environmental Tests		
Compliant w/ Operational Environment (high vac, etc.)	Pedigree Review	Additional Module Burn-In At Elevated Conditions		
Chiplet Multicell Testing	Active Component Burn-In (fibers, optics, etc.)	Detailed Pedigree Review (Out of Family Modules Discarded)		

Diode Life Test (QTY 4 Units)

<0.5 % drop in output power over >45,000 hrs & 1.6 trillion shots -- 1.6 times planned mission life.



A test centric diode laser space certification program consisting of several key phases including a technology plausibility study, component and LDM pedigree reviews, and environmental acceptance was developed and successfully executed.

This program is well documented & adaptable to future space missions.

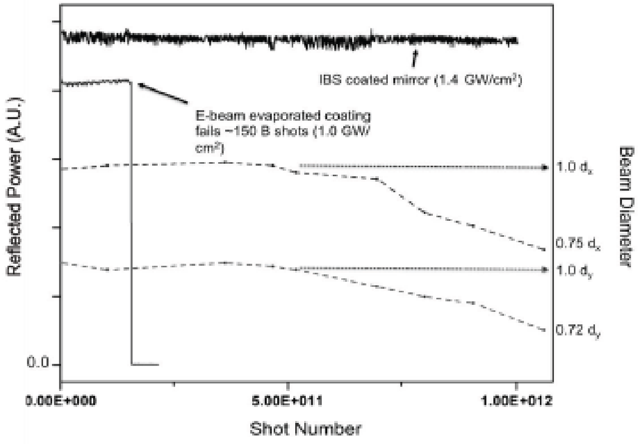
N. W. Sawruk, et al, "Space certification and qualification programs for laser diode modules on the NASA ICESat-2 Mission," SPIE 8872, 2013.

Supply Chain Management of Optical Components for Space

- **Space qualified optical components are not a commodity, lacking industry accepted standardized processes and/or certification procedures common to electronic components for space applications.**
  - Typically small companies with relatively high turn over and consolidation rates complicate reuse of the developed supply chain.
  - Optical component supply chain management is challenging requiring a balance between design updates and maintaining an established process.
- **Optical coating technology, lot certification and qualification.**
  - Vendor survey & down select based on coating requirements.
- **Faraday Rotators compatible with environments were not commercially available.**
  - Incompatible materials, not vacuum compatible and not robust to GEVS random vibe.
  - Worked closely with the rotator vendor and collaboratively upgraded the rotator design and executed a qualification program.

IBS & e-beam vs Shot Count

e-beam damaged @ ~150B shots



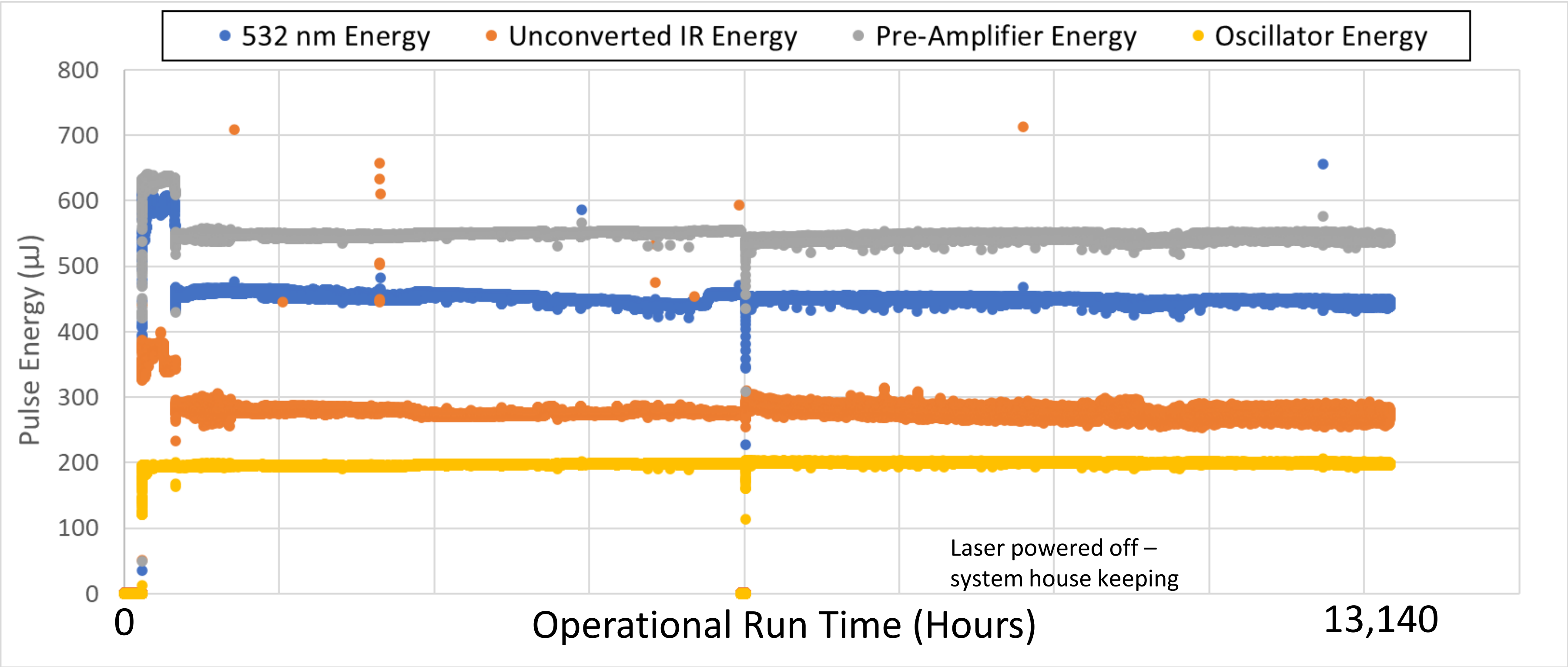
D. Poulios, et al, "Performance of multilayer optical coatings under long term 532 nm laser exposure," *Proc. SPIE 8885,* 2013.

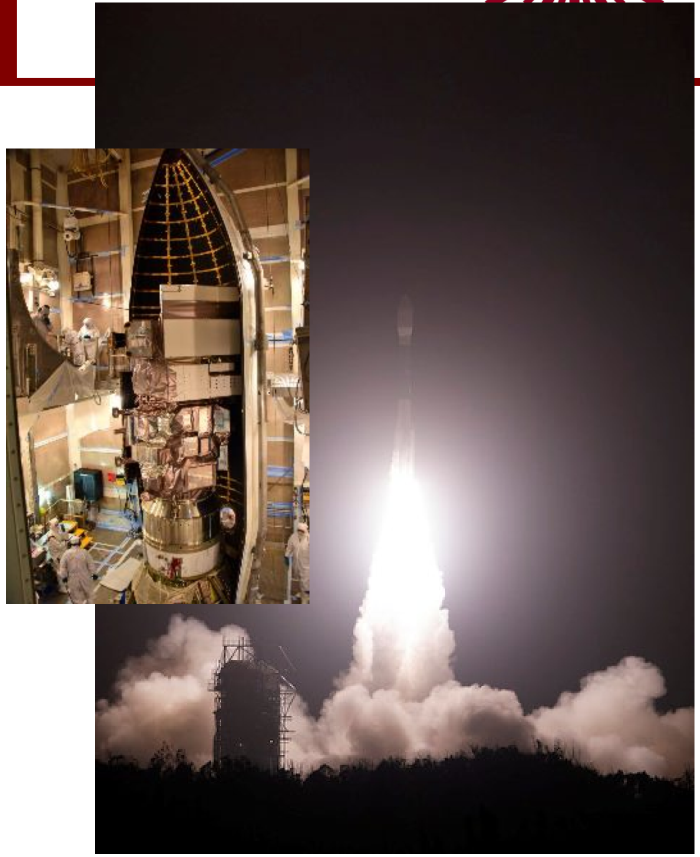
Faraday Rotator

Space-Qualified

Fibertek successfully developed screening procedures and guided designs of key optical components from commercial vendors.

ICESat-2 18-Months Operational Performance





- Laser was initially operated at 600 µJ for several days. The output energy was decreased to 450 µJ due to better than expected signal returns.

- 2.6% drop in 532 nm pulse energy over 18 months of operation is better than anticipated (~2x less than early life test lasers) indicating the contamination mitigation protocols are successful.

Space-Based Laser Lessons Learned

- Mature technologies are required for the rapid advancement of technology readiness levels (TRL) required on recent programs.

- A robust and comprehensive test program, in relevant environments, early in the program surfaces design issues and allows for the implementation of corrective actions.

- Mitigation of contamination sources is a key to long term reliability.

- De-rating the top-level system and sub-systems results in a higher reliability system.

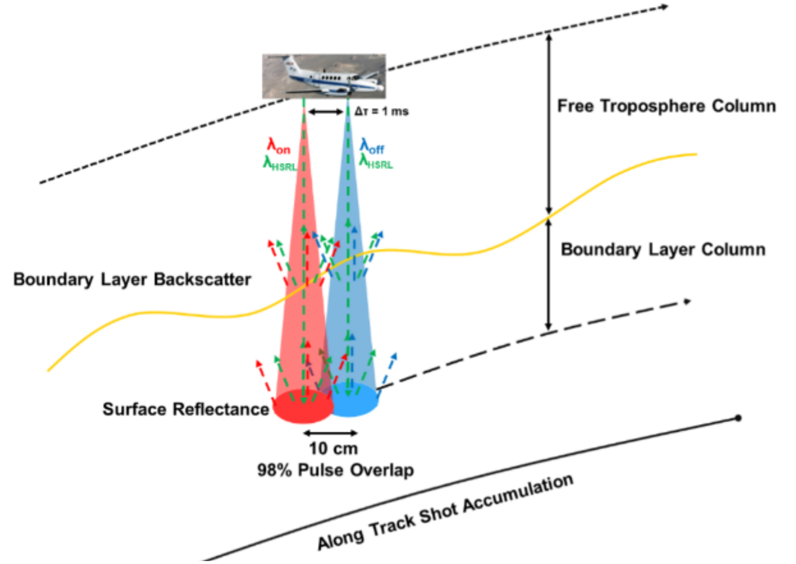
- Process rigor and discipline during all phases (design, procurement, component processing, system integration and test, etc.) of the program are required for consistent high reliability laser systems
  - Culture of building high-reliably and well documented space systems.

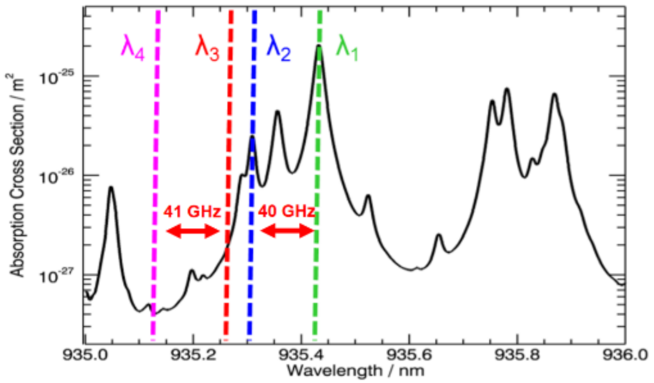
Airborne Differential Absorption Lidar Transmitter

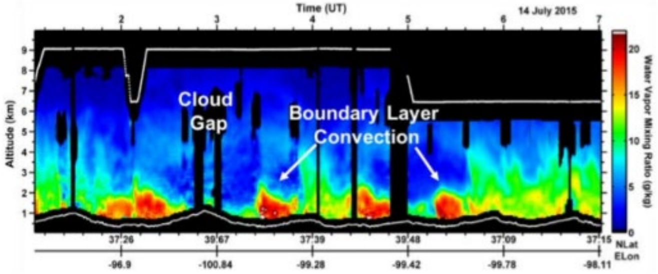
Single frequency laser operating at a specific & non-standard wavelength with >1000:1 spectral purity in an airborne environment.

Airborne Differential Absorption Lidar

- Integrated path differential absorption (IPDA) measurement between transmitted energy signal and surface return at on-line (absorbed) and off-line (unabsorbed) wavelengths.
- Combined lidar profiles of water vapor, methane, aerosols and clouds to better understand weather & dynamics.



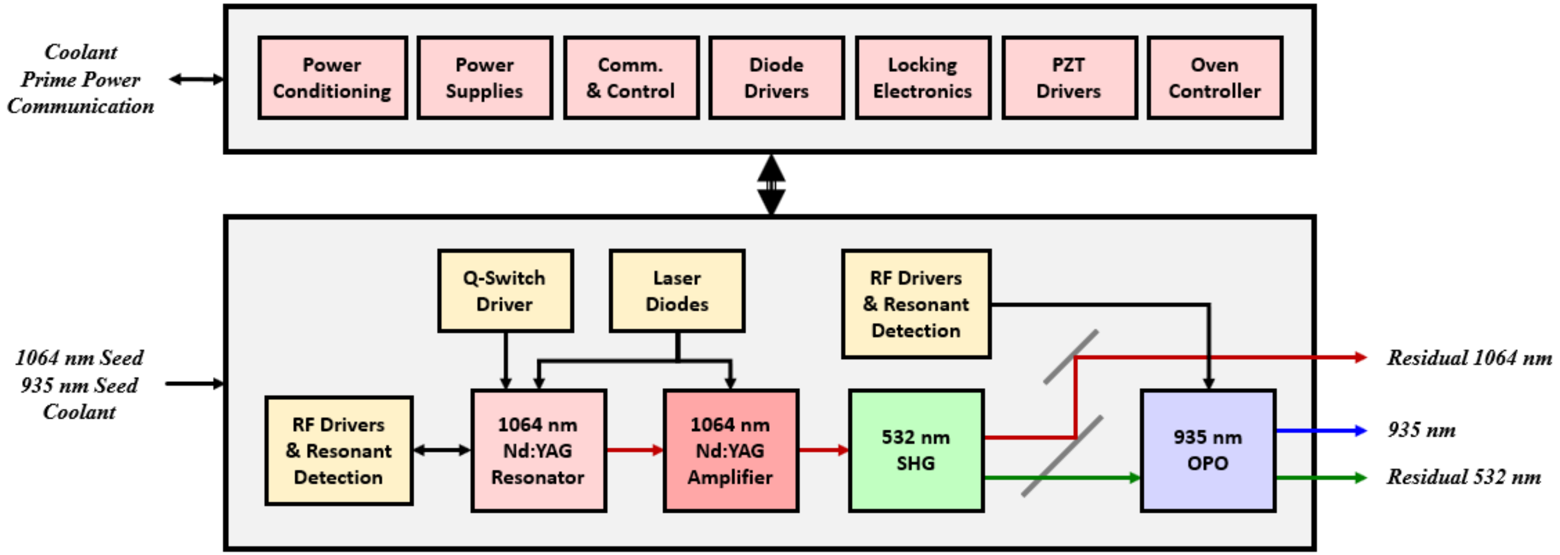




Nehrir, A. et al., *"The High Altitude Lidar Observatory (HALO): A multi-function lidarand technology test-bed for airborne and space-based measurements of water vapor and methane" ESTO Technology Forum, June 2018*

Water Vapor DIAL Transmitter

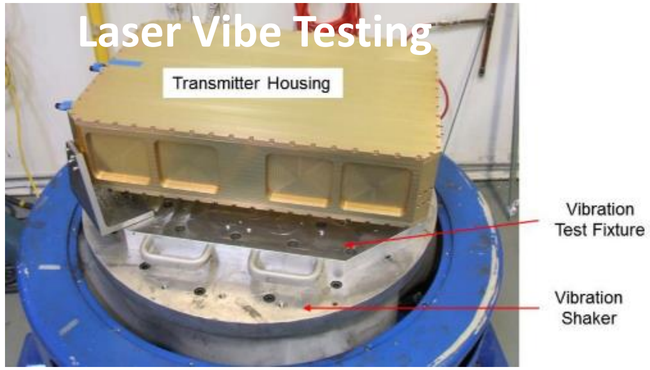
Parameter	Design Value	Enabling Lidar Capability
System Pulse Rate	1.0 kHz	Fast pulse rate required for two subsequent pulses to sample the same air volume from an airborne platform.
935 nm Wavelength	935.685 nm	Wavelength is coincident with a water vapor absorption line. Off-line wavelength is several GHz from the absorption line center.
935 nm Pulse Energy	2.5 mJ	Required pulse energy for airborne ranges, aperture and detector sensitivity.
935 nm Spectral Purity	99.9 %	Transform limited linewidth (40 MHz) and smooth spectral content is required for high resolution (ppm) water vapor measurements.
Temperature	20±10° C	Typical research airborne lidar platform operational environment
Altitude	10 kft	
Vibration	1.5 g_{rms} 10-2,000 Hz	



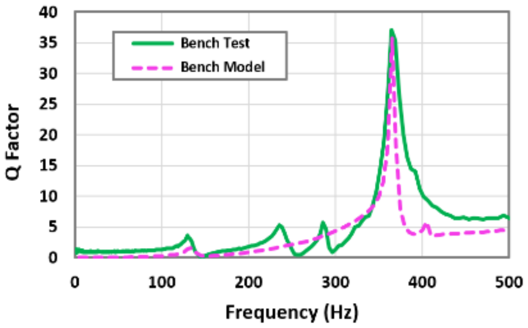
- The Water Vapor Laser is based on an injection-seeded Nd:YAG master-oscillator power-amplifier architecture operating at a wavelength of 1064 nm.
- This IR radiation is then frequency doubled to 532 nm and used to optically drive an injection-seeded optical parametric oscillator (OPO) operating at the 935 nm water vapor absorption line.

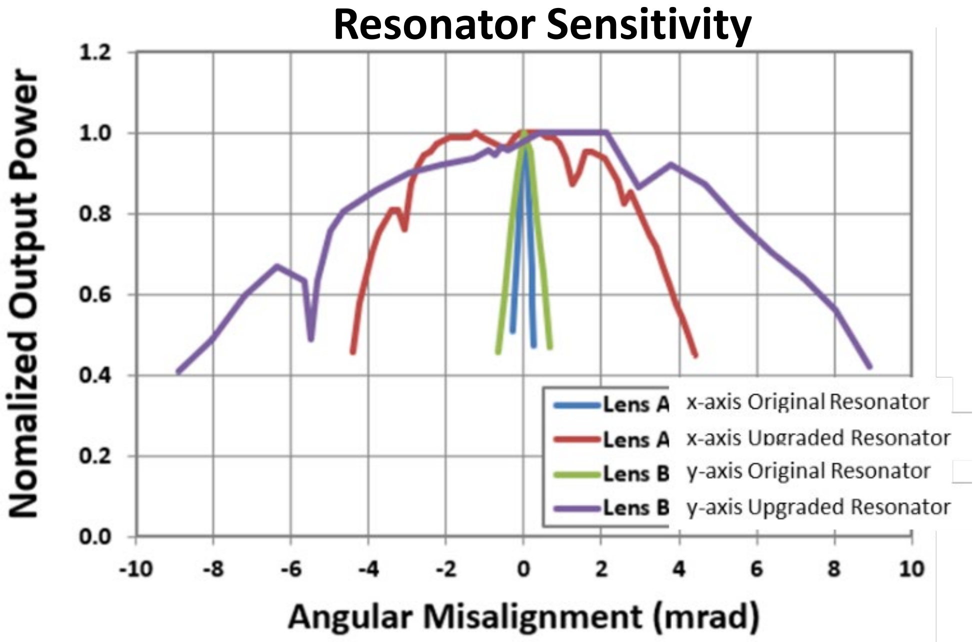
Operation in Airborne Environment

- The primary environmental impact to the performance of the Water Vapor transmitter is optical misalignment induced by vibration.
- Optical misalignment negatively impacted output power, beam pointing, and spectral purity – three parameters fundamental to any absorption lidar system.
- Three major updates mitigated the laser performance degradation while operating under a dynamic environment.
  - Decouple and flexure mount the internal laser cold plate from the laser optical bench.
  - Increase the stiffness of the optical bench increasing the frequency of the first resonator mode from 250 Hz to 365 Hz.
  - Updated laser resonator design with significantly reduced alignment sensitivity.



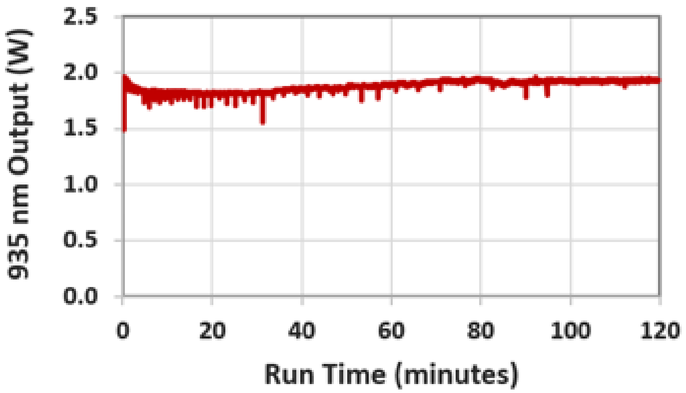
Modeled & Measured Frequency Response

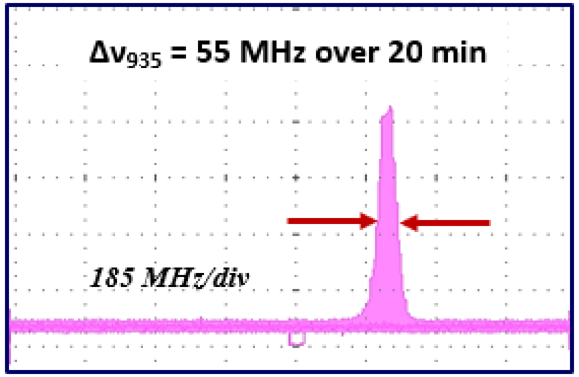


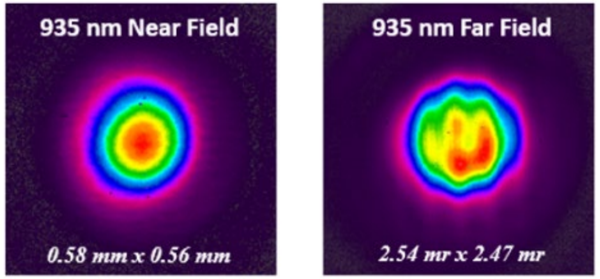


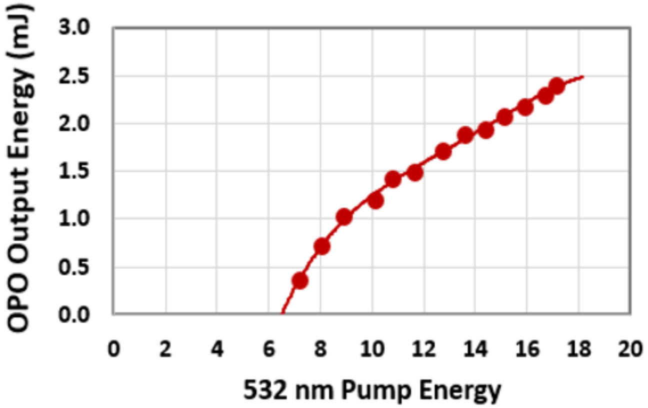
Key Laser Performance

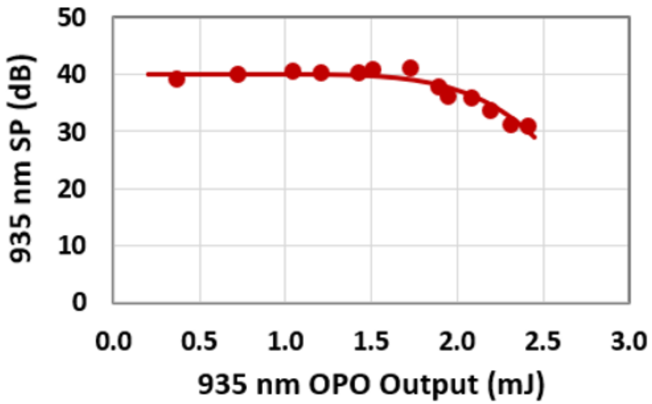
- The OPO produced a high-quality spatial pulse with an M^2 value of <1.2 and maintained a near transform spectral width of ~40 MHz, well within the 70 MHz objective.
- Preliminary airborne flights were successful.











Fiber Lasers

Examples of space-qualified laser systems for high bandwidth and long range optical communication.

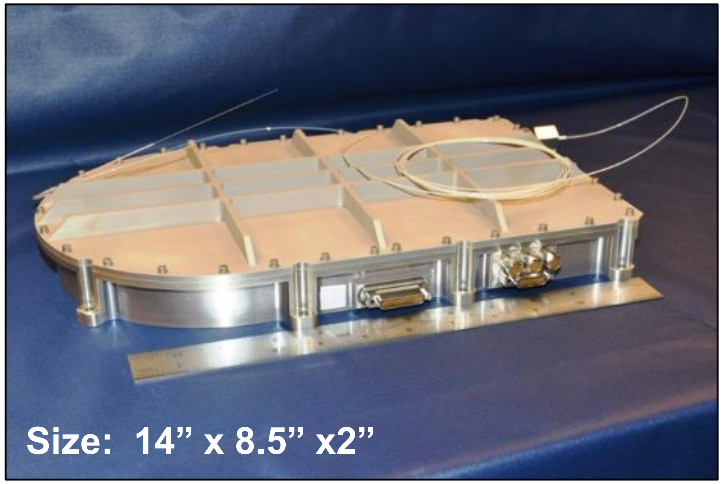
Fiber Laser Transmitters

- Advantages of Fiber Lasers
  - Spatial confinement → signal brightness is maintained over long distance, improving beam quality
  - Distributed gain → low-gain ions (ytterbium, erbium, & thulium) can achieve significant gain (typically 20-30 dB per stage) with meter-length fibers
  - Distributed heat load → simplified thermal management in comparison to solid-state lasers
  - High efficiency → above advantages lead to deep saturation of lasers and amplifiers, resulting in high efficiency (>40% E-O in Yb:fiber, >20% in Er:fiber or Tm:fiber)
- Disadvantages
  - Nonlinear behavior → spatial confinement leads to accumulated nonlinear behavior (SBS, SRS, FWM, SPM, XPM, etc.)
  - Limited peak power → Fibertek has demonstrated >1 MW peak power in Yb:fiber, but practical limits in fielded systems are typically ~50-100 kW
  - Radiation hardness

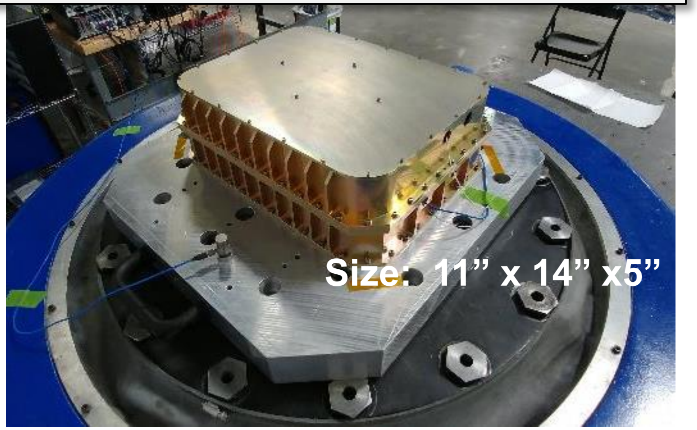
Tremendous advances have been made in fiber lasers, pushing average power per diffraction-limited aperture to ~3-4 kW for terrestrial – but peak power performance is limited and power and thermal management for space remain a challenge

Examples of TRL-6+ Fiber Lasers for Space

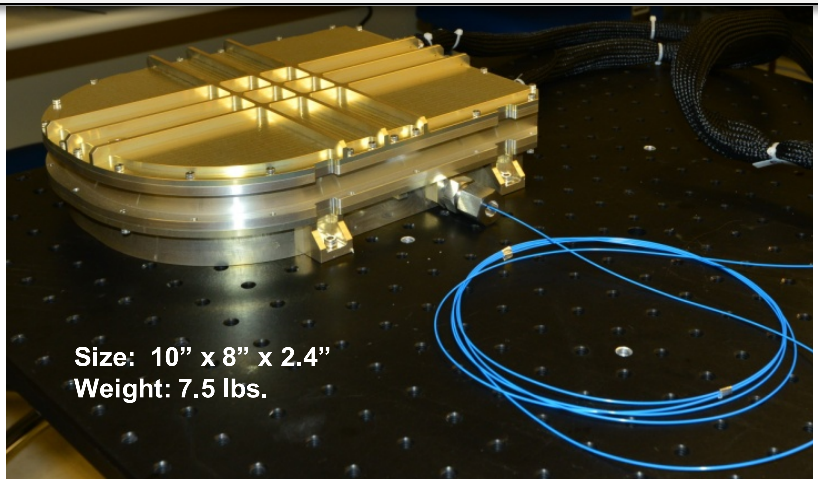
20 W CW 1.5 um fiber amplifier for NASA Ascends



100 W CW 1.9 um Tm:fiber laser will be TRL5+ in 2019. Photo shows housing & components in vibration testing.
A 50 W pulsed 1.5 um fiber amplifier is also being developed for deep space communications, and will use similar packaging.

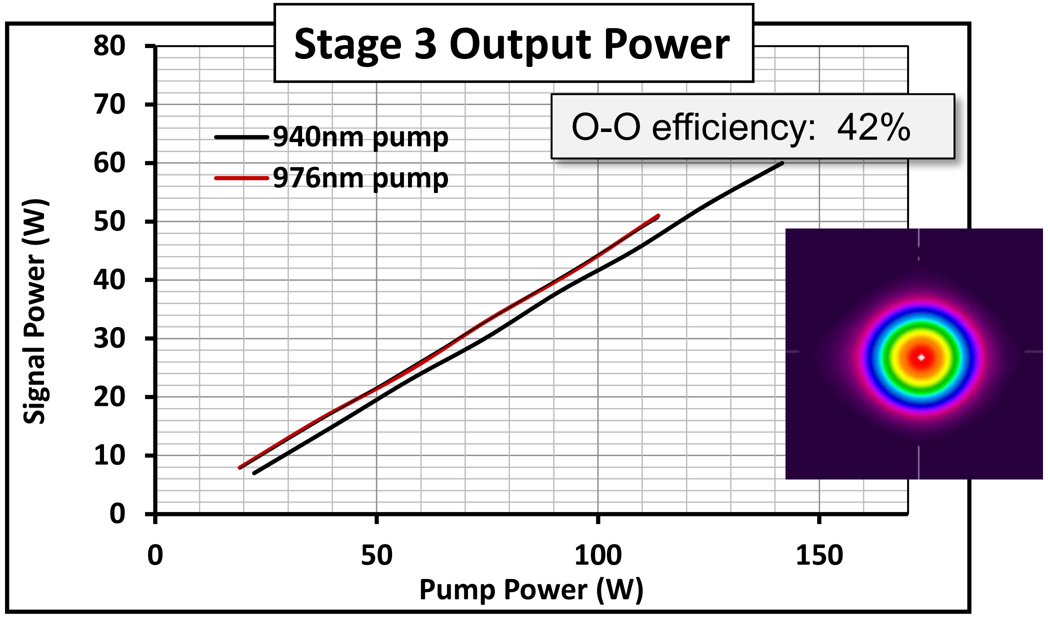


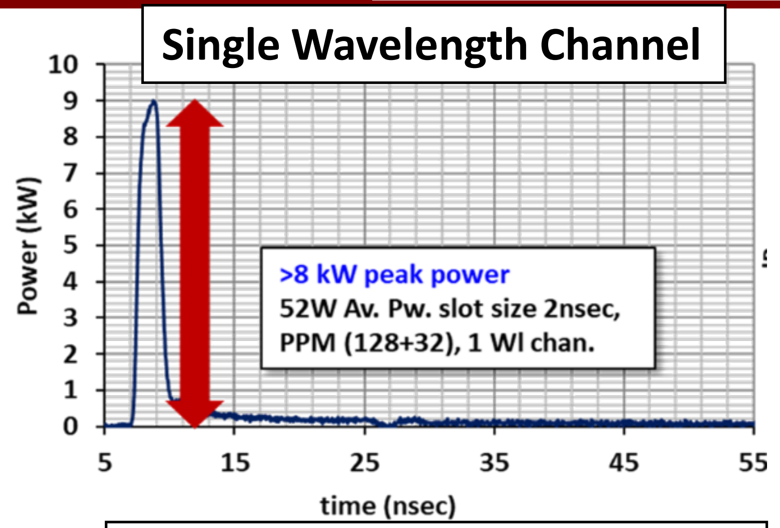
6 W PPM transmitter for deep-space laser communications
15% E-O efficiency
>1 kW peak power

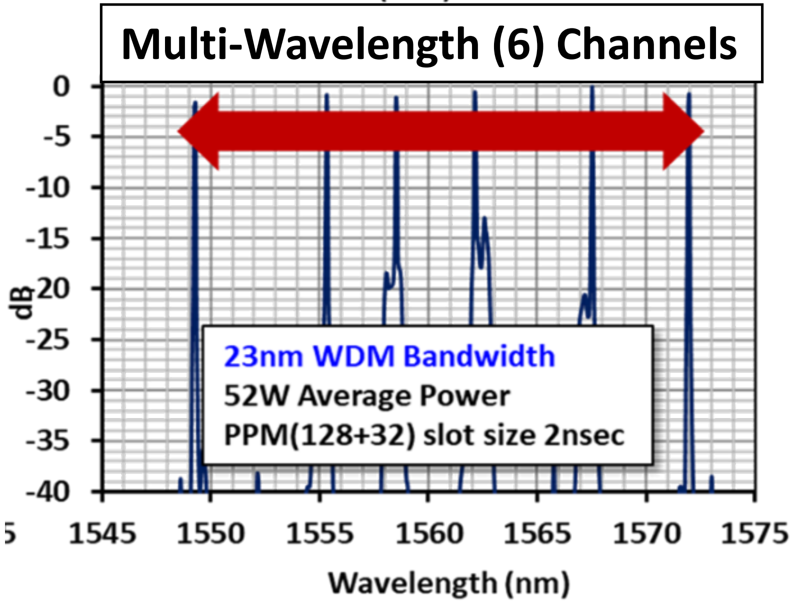


Fibertek has built engineered space-qualifiable fiber laser & amplifier systems at power levels from <1 to >100 W average power, up to 100 kW peak power, CW & pulsed, and at 1 um, 1.5 um, and 2 um wavelengths.

Example: 1.5 µm Fiber MOPA Power







- High power 1.5 µm fiber-laser developed for high bandwidth, wavelength multi-plexed, deep-space optical communication links.
- High-efficiency, high-power performance is consistent with design predictions.
- Results show the same average power performance for a single-channel and multi-channel output, enabling flexible implementation to optimize data rates in deep space.

Component Qualification: Comparison with Telcordia

FIBERTEK, INC.

Environment Specification	Typical Military	Typical Space Flight	Commercial Telecom	Design Considerations
Reference standard or document	MIL-STD-810G	NASA GEVS	Telcordia	
Temperature	Mission-dependent, -75C to +85 C in extreme cases	Mission-dependent, -20C to 50C is a common survival temp	-40°C/min to +85°C/max	- Adhesives & seals must maintain integrity over temperature - CTE-matching for critically-aligned components - Actively control temperature-sensitive optics & electronics
Thermal shock	~30C/min or greater	<<30 C/min typical	ΔT = 100°C/ sec	Commercial thermal shock (ice & boiling water) for Telcordia components is more severe
Pressure / Altitude	Up to 70,000 ft.	Vacuum-compatible	NA	Cleanliness of optics, photochemistry, and optical/electrical breakdown all must be considered
Moisture and humidity	RH ≤ 90%	N/A	RH 85%/85°C	Sealed enclosures may be the most effective remedy
Random Vibration	>20 gRMS in extreme tactical cases	~14 gRMS (non-operating)	20 g peak	- Survival: mounting & positioning must be maintained through vibe (e.g. space launch) - Operational: design to maintain critical alignments & beam-pointing can be very challenging
Radiation	N/A	Mission Dependent Few kRad to MRad	N/A	- Space-rated electronics → expensive, long-lead - Space-rated laser optical components don't generally exist → radiation susceptibilitytesting is typical for space-laser programs

Military lasers:
Design driven significantly by temperature & vibration

Space lasers:
Launch vibration & radiation are added design constraints

Commercial:
Commercial standards can be useful in selecting components, but do not represent qualification for most military & space environments

Component Remarks

FIBERTEK, INC.

Active components

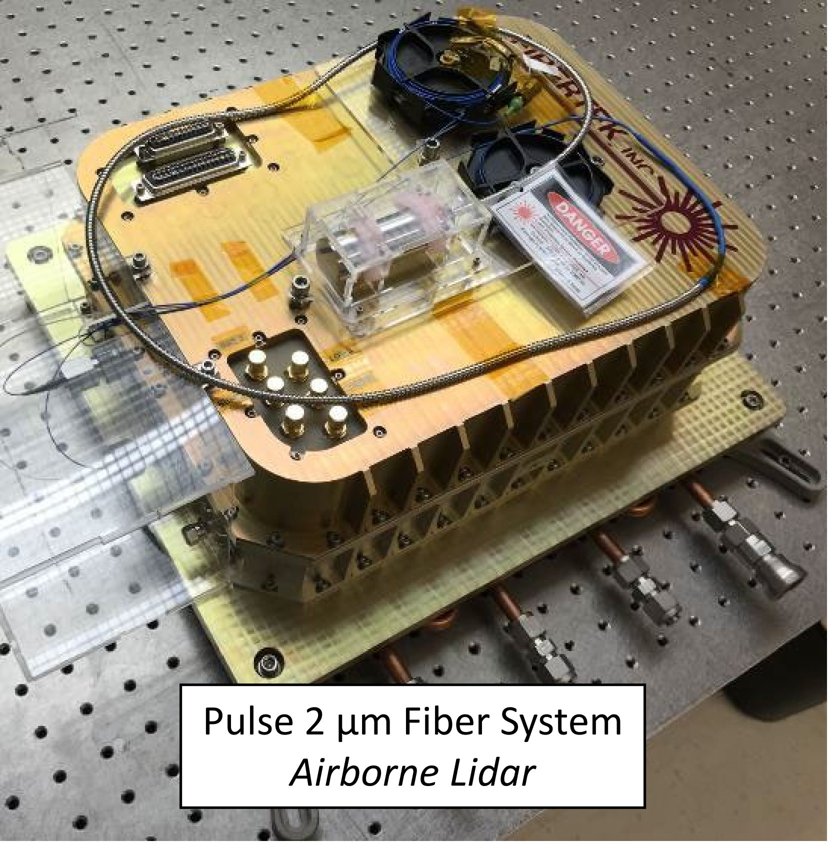
- **Seed laser diodes**
  - Pre-screening qualification if need
  - Qualifiability per design, material, and process
  - Typically Telcordia qualified with multiple supplier options
- **Low-power pump laser diodes**
  - Mature package design and process
  - Typically Telcordia qualified, high reliability device
- **High power pump laser diodes**
  - Designed for industrial applications
  - Not typically Telcordia qualified
  - Some test data for space (performed by suppliers, Fibertek, NASA, and/or others)
- **Fiber-optic modulators**
  - Some limited space qualification data from ESA/NASA
  - Details of qualification testing is not widely available

Passive components

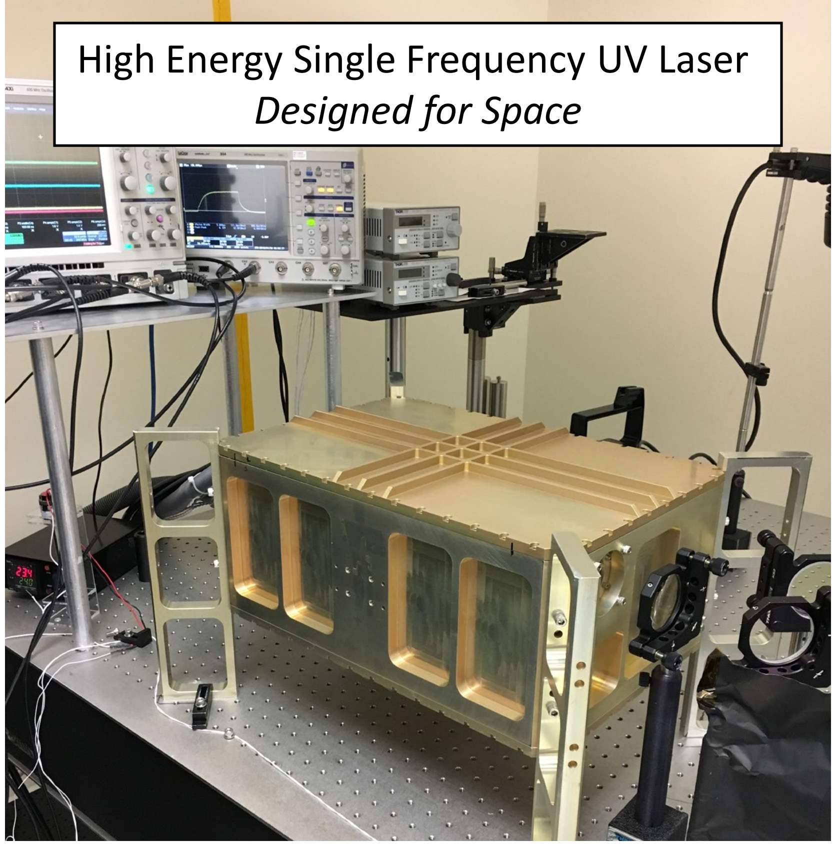
- **Fused fiber optic components**
  - Typically Telcordia-qualified, very high reliability components
  - Assuming qualification per similarity is reasonable (similar material, design, and process)
- **Fiber pigtailed micro-optics components**
  - Typically Telcordia qualified, high reliability components
  - Assuming qualification per similarity is reasonable (similar material, design, and process)
- **High power high strength fiber splices**
  - Splice joints are considered as components from viewpoint of reliability
  - Splice process must be qualified & applied to fiber-based systems

Radiation: data is very limited on radiation susceptibility of fiber-optic components, and qualification testing is typically required

Rapidly growing utility of fiber lasers in space is leading to a growing catalog of qualified components



Pulse 2 µm Fiber System
Airborne Lidar



High Energy Single Frequency UV Laser
Designed for Space

High Energy Laser
Planetary Landing Flash Lidar

Laser Communication Terminal
LEO & GEO Missions

- Laser systems and technologies have an enabling role in LIDAR-based remote sensing systems in military and aerospace communities.

- Lasers for aerospace applications pose a unique set of challenges including harsh environments, limited volumes, power and thermal capacity of platforms.

- Several examples of lasers transitioned from the lab to operational environments were presented enabling new capabilities in lidar and communication systems.