NASA Goddard Space Flight Center
Parts, Packaging and Advanced Technologies Office
Electrical Engineering Division
Engineering Directorate
8800 Greenbelt Rd
Greenbelt, MD 20771

CODE 562 PHOTONICS Group @ GSFC

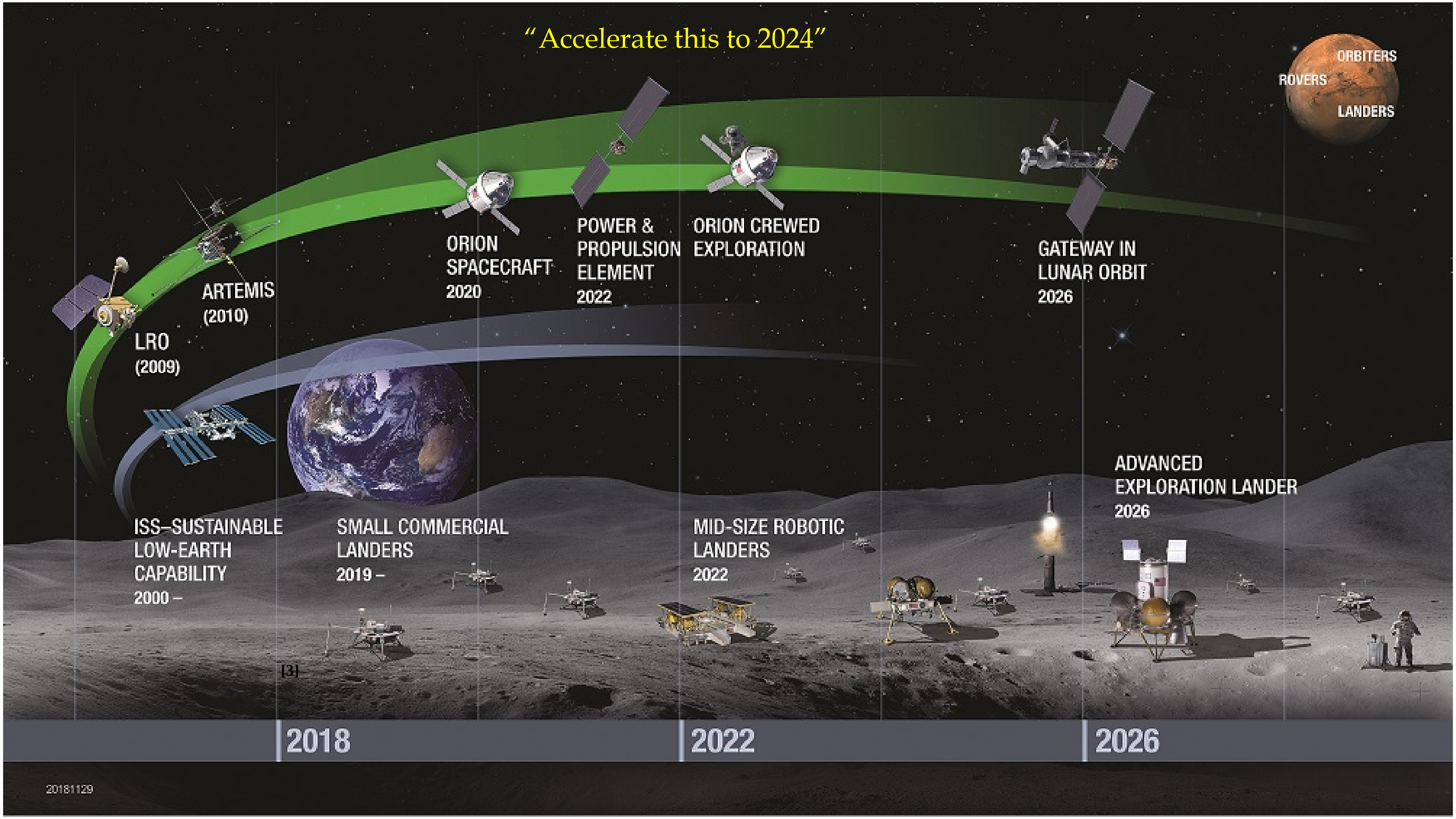
NASA Parts & Packaging Program Commercial Miniature LiDAR

Survey and Test Evaluation

Melanie Ott, Alexandros Bontzos, Joe Thomes, Cameron Parvini, Marc Matyseck

Gateway Roadmap

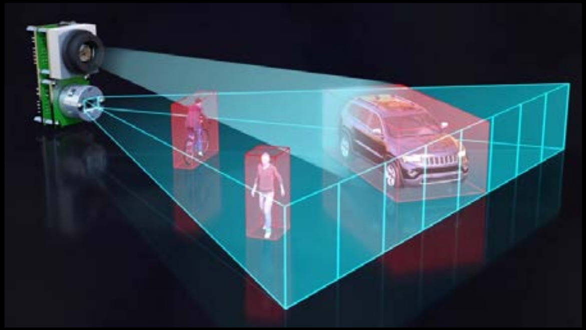
https://spacenews.com/is-the-gateway-the-right-way-to-the-moon/



Qualifying and Producing Navigational LiDARs for Lander Autonomous Rendezvous Applications

- Space Technology Mission Directorate, Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE) Program:
  - ✓ GSFC Hazard Detection LiDAR – engineering unit hardware design and builds.
  - ✓ LaRC's Navigational Doppler LiDAR – qualification and component selection.

- NASA Parts and Packaging Program: Evaluation of Compact Industrial LiDAR components.
- Kodiak: for autonomous rendezvous and refueling of Landsat-7.



https://www.allaboutcircuits.com/news/solid-state-LiDAR-is-coming-to-an-autonomous-vehicle-near-you/

COTS LiDAR instruments have generated interest for use in space applications including:

- Docking
- Real-time hazard avoidance
- Remote sensing
- Improved lander and rover autonomy
- Rendezvous with asteroids and other spacecraft

https://www.nasa.gov/content/morpheus-prototype-uses-hazard-detection-system-to-land-safely-in-dark

NEPP Commercial Mini LiDAR
Selection Criteria

Objective: Determine if lower priced Commercial-Off-The-Shelf (COTS) LiDARs could be viable for spaceflight missions by picking some representative examples and performing technology maturation environmental testing.

LiDAR candidates were chosen using the following top-level requirements for technology maturation viability:

- ✓ Inexpensive, trying to stay with devices of less than $1000.
  - One was $3K but was packaged for rugged industrial environments with built-in shock and vibration isolation
  - The Advanced Exploration Program, Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE) program was looking into medium priced $10K - $25K for moon landers.
- ✓ No moving parts or mechanisms.
- ✓ For the scope of this investigation, more basic and simplistic LiDARs would act as a basis for those which are more complex to potentially investigate in the future.
  - Software drivers available or interface easy to work.

CODE 562 PHOTONICS Group @ GSFC

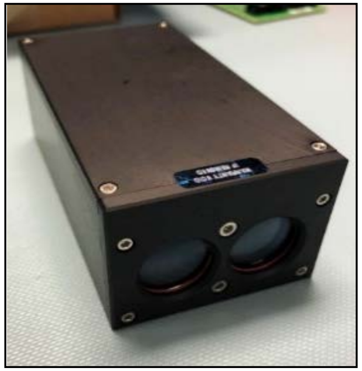
LiDAR Survey Candidate List

Rank	Part	Price each	Qty Ord.	Range	Op. Temp Range	Accuracy	λ	Source Config *Requires Trig
1	Garmin LIDAR-Lite v3HP	$149	4	5cm - 40m	-20 to 60C	+/- 2.5 cm @ > 2 m; +/- 5 cm @ < 2m	905 nm	*Collimated laser diodes
2	Carlson ILM 150m	$3,000	2	0.5 -150m	-35 to 80C	10 cm	905 nm	Collimated laser diode
3	Benewake TF02 LIDAR	$99	3	0.4 - 22m	-10 to 60C	5 cm	850 nm	Multi - LED
4	TeraRanger Duo ToF Rangerfinder with Sonar Sensor	$219	3	0.2 -14m	to 40C (orig. not listed)	+/- 2 cm in precision mode	850 nm	3 laser diodes
7	IS16 Leddar RS-485 Industrial Distance Sensor	$940	2	0 to 50m	-40 to 50C	5 cm	940 nm	Multi-LED 45°
6	Phidget VINT Distance Sensor (170mm)	$28.50	6	4-170mm	-40 to 85C	1 mm	850 nm	*Laser Diode
5	LeddarTech LeddarOne Optical Rangefinder (RS-485)	$115	3	0 to 15m	-45 to 85C	5 cm	850 nm	Multi-LED
8	LIDAR-Lite 3 Laser Rangefinder	$129	4	40m	-20 to 60C	+/- 2.5 cm	905 nm	*Collimated laser diodes
9	Benewake TF01 LIDAR LED Rangefinder (10 m)	$139	3	10m	-10 to 60C	5 cm	850 nm	Collimated laser diodes

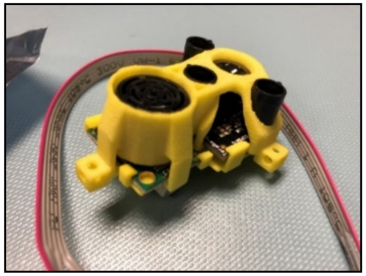
(red) = Replaced by newer versions/may be obsolete

NEPP Commercial Mini LiDAR
Test & Environmental Evaluation Summary

Test Name	LiDAR Candidate			
	1	2	3	4
Initial Characterization	X	X	X	X
Acceptance Level Vibration (GEVS 9.8 Grms)	X	X	X	
Performance Characterization	X	X	X	
Thermal Cycling & Characterization	X	X		
Performance Characterization	X	X		



X	Completed
X	Anomaly



CODE 562 PHOTONICS Group @ GSFC

NEPP Commercial Mini LiDAR
Performance Evaluation Experimental Setup

Target surface simulations

- Utilizes mirrors and targets of different optical properties (reflectivity/ transmissivity/ absorption).

Longer distance simulation: optical fiber delay line

- Couples light through optical fibers of various lengths.

Short distance simulation, electrically generated delay

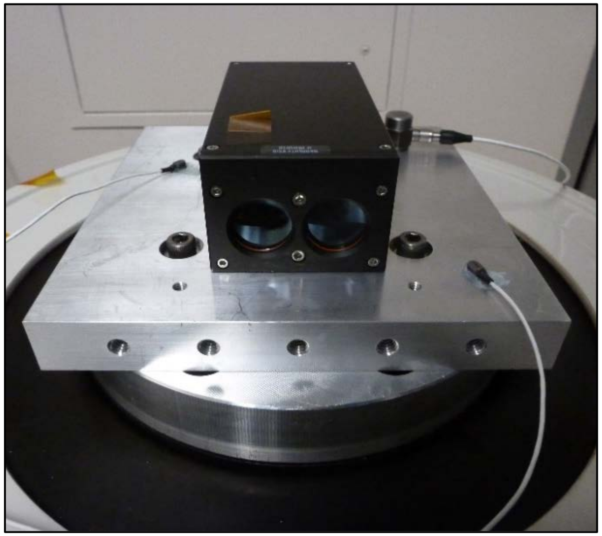
- Distance simulated using trigger delays, attenuation, and phase shift.

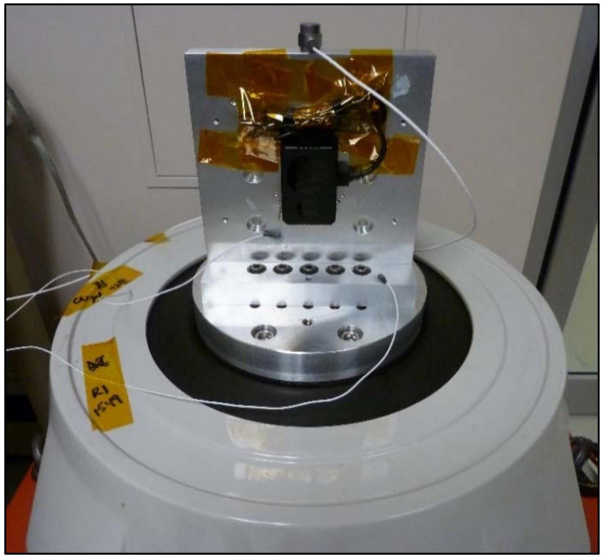
Random Vibration Test & Evaluation

Acceptance level
GEVS

Random Vibration,
3 minutes per axis (X,Y,Z)

Frequency (Hz)	Level
20	0.013 g^2/Hz
20-50	+6 dB/octave
50-800	0.08 g^2/Hz
800-2000	-6 dB/octave
2000	0.013 g^2/Hz
Overall	9.8 grms

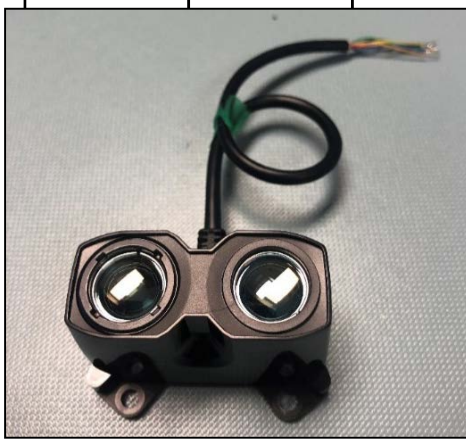




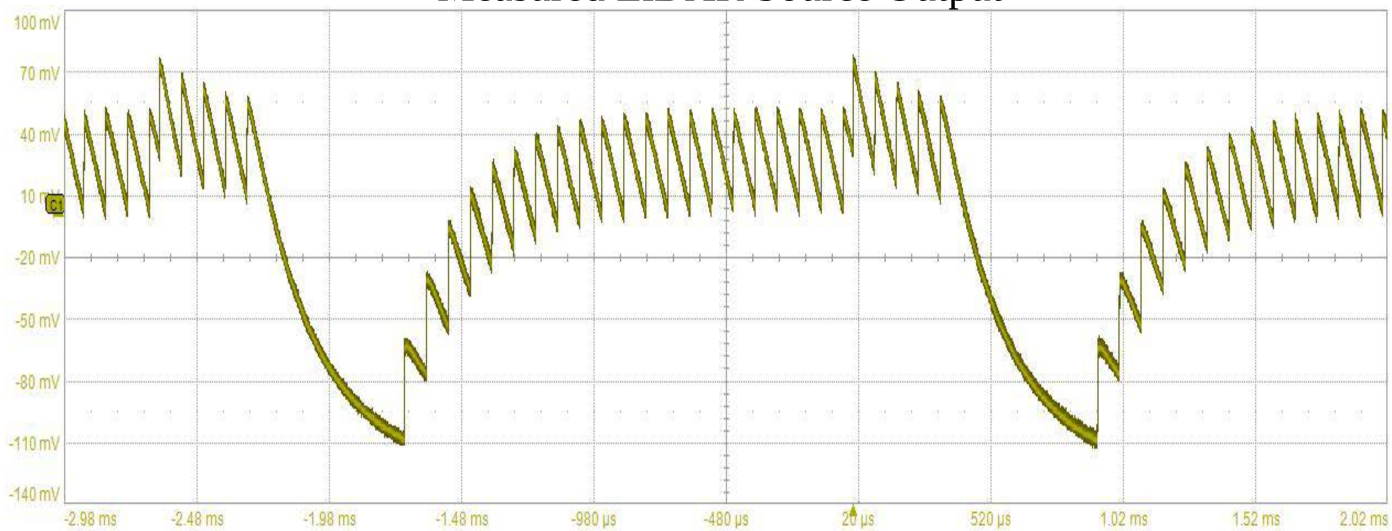
Garmin LIDAR-Lite v3HP

Candidate Rank - 1

Price	Range	Op. Temp Range	Positives	Negatives	Specifications	Performance
$149.00	40m	-20 to 60C	• Customizable triggering advantageous for test setup. • Nominal beam dimensions & collimated source. • I2C communications allow for fast data rate. • Exceptional performance over temperature.	• Complex modulated pulse characteristics (see below; can be a pro for noise reduction & con for customizable testing) • Precision ~ 2cm at room ambient temperatures. (Worse precision & more noise than candidate 2). • Requires triggering, cannot operate with only a power supply.	• Supply Voltage: 4.75-5VDC; 6V Max • Current consumption: 65ma idle; 85ma during acquisition • Weight: 34g (1.2oz) • UART Communications	• Wavelength: 905 nm • Peak power: 1.3 W • Accuracy: +/- 2 cm at distances >2 m • Resolution: 1 cm • Divergence: 8 mRadian • Sampling rate: Greater than 1 kHz



Measured LiDAR Source Output



Conclusions

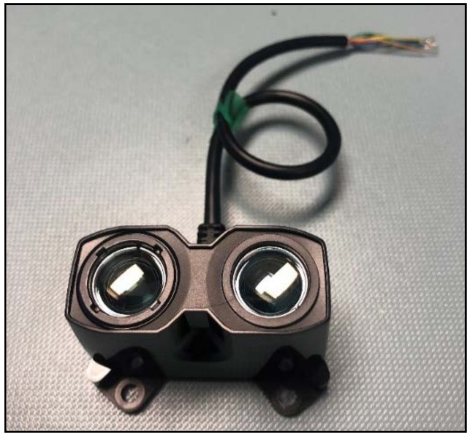
Garmin LiDAR-Lite v3HP

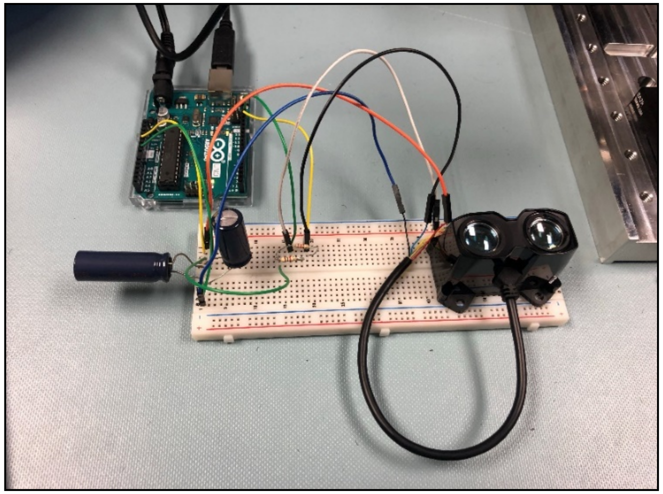
Candidate Rank – 1

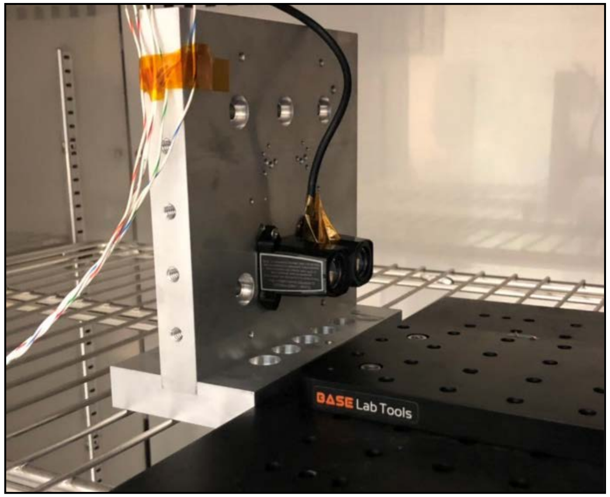
✓ The Garmin v3HP LiDAR displayed superior accuracy performance relative to other candidates and nominal precision performance over room-ambient evaluations, thermal cycling and vibration testing.

✓ The v3HP was also more consistently accurate when implementing various targets of unique surface reflectivity.

✓ <u>Overall, the v3HP LiDAR was the top performing LiDAR candidate for this evaluation.</u>



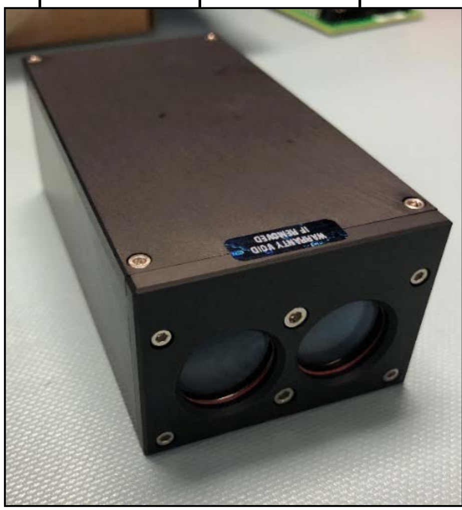




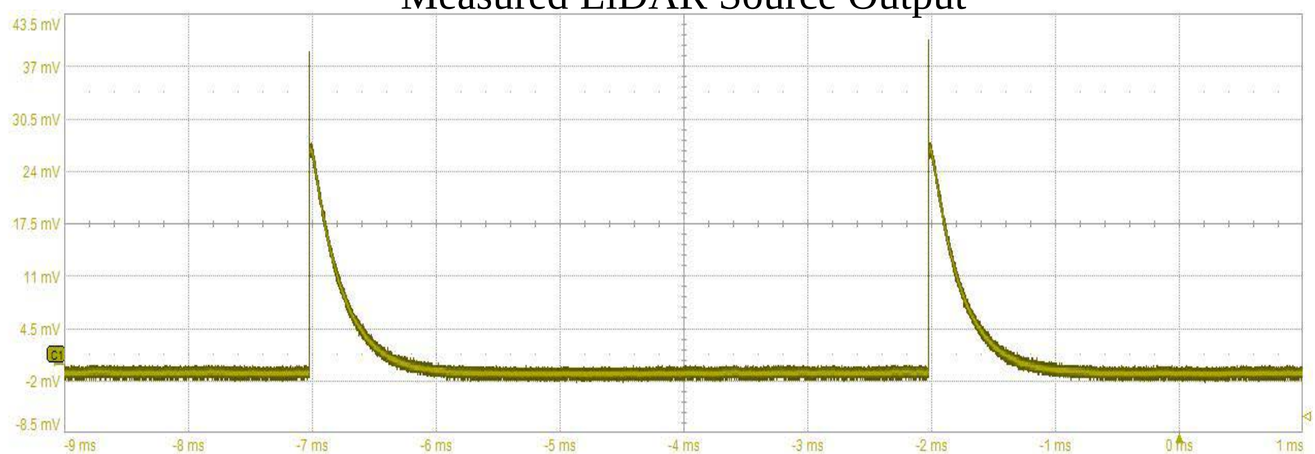
Carlson ILM 150m

Candidate Ranking - 2

Price	Range	Op. Temp Range	Positives	Negatives	Specifications	Performance
$3,000	150m	-35 to 80C	• Large measurement range and operating temp range relative to other candidates. • Simplistic auto-triggering and pulse characteristics (see below) • Best precision performance (see slide 27)	• Expensive • Was not able to write commands to device, only read and only in a continuous mode. • Range strongly dependent on surface reflectivity. • Poor range stability/precision over temperature (see slide 24)	• Power: < 5 W • Supply Voltage: 9-24 V DC • Weight: 320 g • Data Rate Out: 9 Hz • Housing Materials – Anodised aluminum	• Wavelength: 905 nm • Divergence: 2.45 x 1.50 mRadians • Spot size @ dist: 0.386 x 0.243 m (150 m) • InGaAs Laser Diode • Pulse Energy = 306 nJ • Meas Range: .5 m to 75 m (18% refl.) or 150 m (90%) • Accuracy: 10 cm • Resolution: 1 cm



Measured LiDAR Source Output



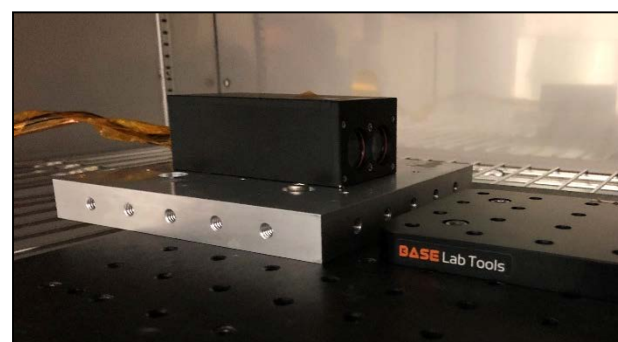
Conclusions

Carlson ILM 150m

✓ The Carlson ILM 150m LiDAR displayed superior precision performance relative to other candidates over room-ambient evaluations and vibration testing.

- This candidate, however, was observed to be less accurate overall, less consistently accurate and less precise over thermal cycling in comparison to the Garmin v3HP LiDAR.
    - Larger drift in readings during thermal cycling
    - Continuous drop-outs/ false ranging during post-thermal cycling characterization.

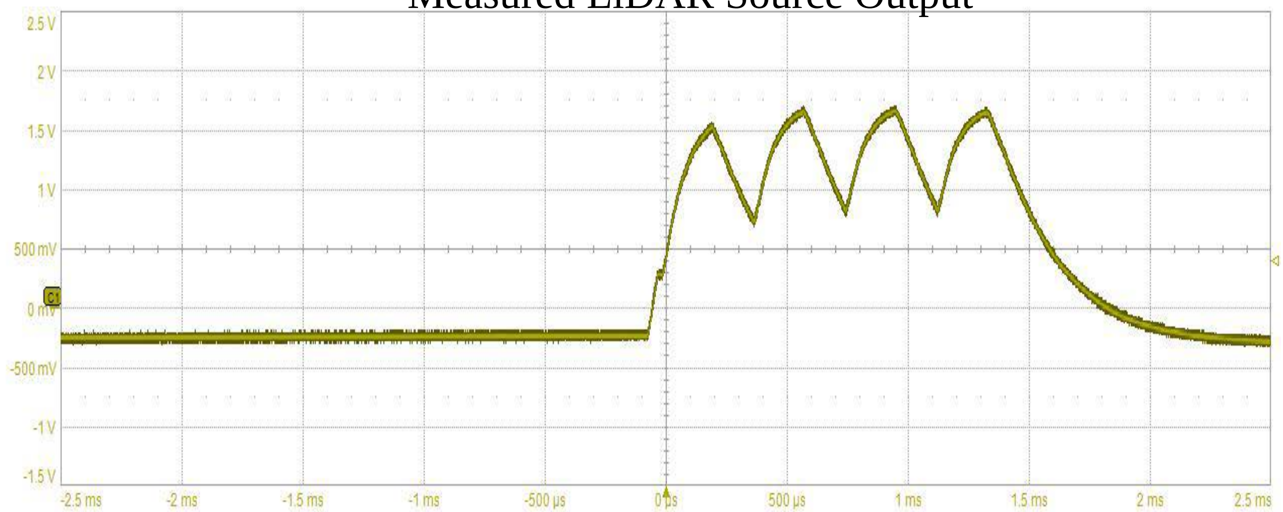
- <u>Overall, the ILM 150 LiDAR performed as the second best LiDAR candidate for this evaluation.</u>



Benewake TF02 LiDAR
Candidate Rank - 3

Price	Range	Op. Temp Range	Positives	Negatives	Specifications	Performance
$99.00	22m	-10 to 60C	• Cost-efficient. • Straightforward design and packaging. • Helpful manufacturer software. • Begins ranging once powered on.	• Testing on this candidate was discontinued due to highly inaccurate, inconsistent readings across entire range. • Large beam dimensions, very divergent. • Trigger rate not adjustable. • Very unstable and inconsistent ranging.	• Power: 5VDC • UART/TTL Communication.	• Detection Frequency: 100Hz • Protection level: IP65 Anti-ambient light: Function under 100k Lux ambient light

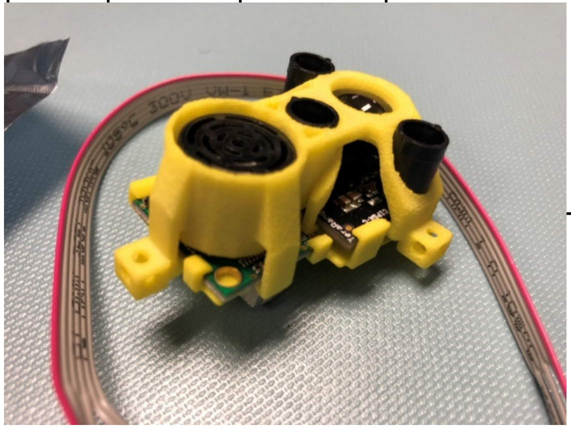
Measured LiDAR Source Output

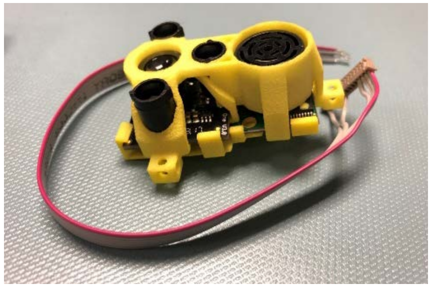


TeraRanger Duo ToF Rangefinder w Sonar

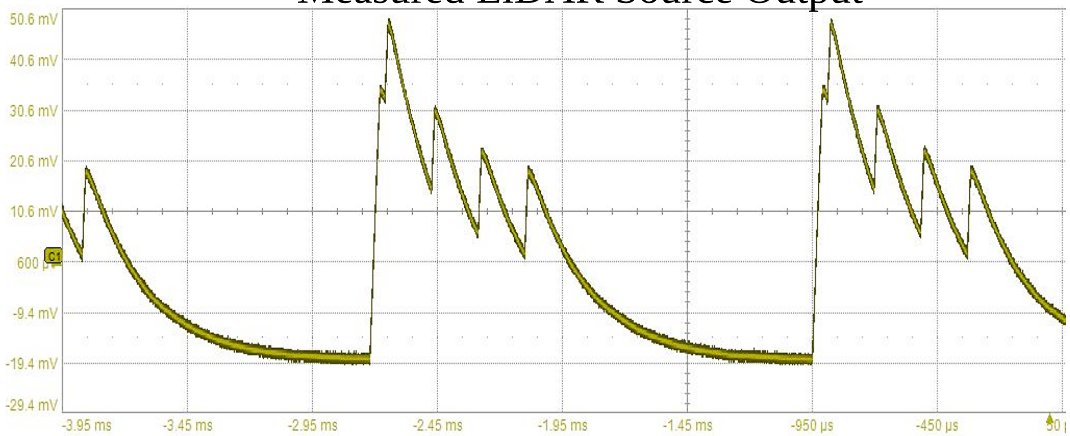
Candidate Rank - 4

Price	Range	Op. Temp Range	Positives	Negatives	Specifications	Performance
$219.00	14m Sonar up to 7.65m	not listed	• Sonar sensor included • Collimated sources • Begins ranging when powered on. • Compact, low-dead spot source/detector geometries.	• Testing on this candidate was discontinued due to very high noise, low stability measurements. • 3D printed (fragile) housing. • 3 sources in triangle formation cause fiber-coupling to be difficult. • Limited laser/optical performance specifications provided	• Supply voltage: 10 -20V DC • Supply current: 50mA@12V = average consumption, 100mA@12V = peak consumption	• Update rate:1kHz (speed mode) - up to 600Hz (precision mode) • Sonar 1-20HzNB: the ratio between speed ToF/sonar can change according torequests (default is ToF in precision mode and sonar at 1Hz) • Range resolution: 0.5cm for ToF,1 cm for Sonar • Accuracy: ± 2cm (precision mode) for ToF • Field of view: 3.4° for ToF, usual flame shape for Sonar (larger than 3.4°)





Measured LiDAR Source Output



Conclusions

- Lower priced COTS LiDARs can be viable candidates for future spaceflight missions with proper screening, qualification, and implementation
  - Technologies, configurations, manufacturing methods, support software, etc. are evolving rapidly in this technology area
    - Within the year of this study some products became obsolete, some were updated by the vendors, and new offerings became available
  - Performance, environmental susceptibility, and reliability can vary greatly between different manufacturers and product lines
  - Environmental testing showed that some candidates survived vibration and thermal cycling with little to no degradation
  - Radiation testing would be required in addition to the performed tests, but was outside the scope of this funded activity
- Different testing setups are required based on the range and precision of the LiDAR under test
  - Three different test setups were utilized for this evaluation to accurately measure the LiDAR ranges from millimeters to hundreds of meters
- The methodologies and test setups used are based on a long history and lessons learned from performing technology maturation for spaceflight LiDARs

Acronyms

- ASTM = American Society for Testing and Materials
- ASU = Arizona State University
- ATLAS = Advanced Topographic Laser Altimeter System
- CATS = Cloud-Aerosol Transport System
- COTS = Commercial Off the Shelf
- DIY = Do It Yourself
- EEE = Electrical, Electronic, and Electromechanical
- FC = Field Connector
- GCD = Game Changing Development
- GEDI = Global Ecosystem Dynamics Investigation
- GEVs = Goddard Environmental Specification
- GEO = Geosynchronous Orbit
- GOES-R = Geostationary Operational Environmental Satellite-R Series
- GLAS = Geoscience Laser Altimeter System
- GSFC = Goddard Space Flight Center
- ICESat = Ice, Cloud, and land Elevation Satellite
- InP PIC = Indium-Phosphide Photonic Integrated Circuits
- ISS = International Space Station
- JWST = James Webb Space Telescope
- LADEE = Lunar Atmosphere Dust Environment Explorer
- LED = Light Emitting Diode
- LEO = Lower Earth Orbit
- LiDAR = Light Detection and Ranging
- LIV=Light-Current-Voltage
- LOLA = Lunar Orbiter Laser Altimeter
- LRO = Lunar Reconnaissance Orbiter
- MAVEN = Mars Atmosphere and Volatile Evolution Mission
- MESSENGER = Mercury Laser Altimeter on Mercury Surface, Space Environment, Geochemistry and Ranging
- MEO = Medium Earth Orbit
- MIL-STD = Military Standards
- MLA = Mercury Laser Altimeter
- MOLA = Mars Orbiter Laser Altimeter
- MOMA = Mars Organic Molecule Analyzer
- NEPP = NASA Electronic Parts and Packaging Program
- OTES = OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer) Thermal Emission Spectrometer
- PER = Polarization Extinction Ratio
- SAA = Space Act Agreement
- SM APC= Single Mode Angled Physical Contact
- SEM = Scanning Electron Microscope
- SPLICE = Space Technology Mission Directorate, Safe and Precise Landing – Integrated Capabilities Evolution Program
- SSCO = Space Servicing Capabilities Office
- SSCP = Space Servicing Capabilities Project
- SWaP = Size, Weight and Power
- TEC = Thermoelectric Cooler
- TID = Total Ionizing Dose
- TSIS = Total and Spectral Solar Irradiance Sensor
- TRL = Technical Readiness Level
- VSS = Vision Sensor Subsytem

References

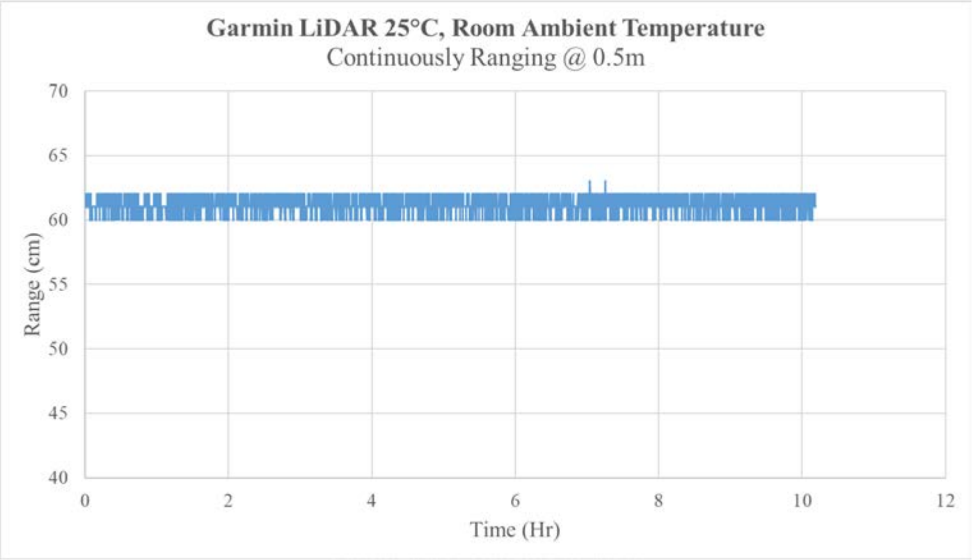
1. Melanie N. Ott et al. "Optical fiber cable assembly characterization for the mercury laser altimeter", Proc. SPIE 5104, Enabling Photonic Technologies for Aerospace Applications V, (14 July 2003) https://photonics.gsfc.nasa.gov/tva/meldoc/spieavims2003.pdf
2. Dave Smith et al. “Two-Way Laser Link over Interplanetary Distance,” Science Magazine, (www.sciencemag.org) Vol. 311 (5757) January 6, 2006, pp 53. https://science.sciencemag.org/content/311/5757/53
3. Melanie N. Ott et al. "Development, qualification, and integration of the optical fiber array assemblies for the Lunar Reconnaissance Orbiter", Proc. SPIE 7095, Nanophotonics and Macrophotonics for Space Environments II, 70950P (26 August 2008). https://photonics.gsfc.nasa.gov/tva/meldoc/SPIE/2008/SPIE-MNOTT-7095-28.pdf
4. Melanie N. Ott et al. "The fiber optic system for the advanced topographic laser altimeter system instrument (ATLAS)", Proc. SPIE 9981, Planetary Defense and Space Environment Applications, 99810C (19 September 2016). https://photonics.gsfc.nasa.gov/tva/meldoc/SPIE/2016/SPIE-2016-ICESat-2-ATLAS-Fiber-System.pdf
5. C. A. Lindensmith et al. "Development and qualification of a fiber optic cable for Martian environments", Proc. SPIE 10565, International Conference on Space Optics — ICSO 2010, 1056519 (20 November 2017). https://photonics.gsfc.nasa.gov/tva/meldoc/ICSO/2010/ChemCam-Assemblies-ICSO2010.pdf
6. Melanie N. Ott. “Space Flight Requirements for Fiber Optic Components; Qualification Testing and Lessons Learned, Invited paper”, International Society for Optical Engineering, SPIE Europe Conference on Reliability of Optical Fiber Components, Devices, Systems and Networks III, Vol. 6193 (April 2006). https://photonics.gsfc.nasa.gov/tva/meldoc/spie-6193-7-MOtt.pdf
7. Melanie N. Ott. Optical Society of America Frontiers in Optics, Session on Space Qualification of Materials and Devices for Laser Remote Sensing Instruments I, Invited Tutorial (September 2007). https://photonics.gsfc.nasa.gov/tva/meldoc/OSA-07-MOTT.pdf
8. Melanie N. Ott. “Implementation and Qualification Lessons Learned for Space Flight Photonic Components”, Invited Tutorial, International Conference on Space Optics, Rhodes Greece (October 2010) https://photonics.gsfc.nasa.gov/tva/meldoc/ICSO/2010/MOTT-NASA-Prod-ICSO_2010.pdf
9. “OSIRIS-REx Instruments.” spaceflight101.Com, 2019, https://www.spaceflight101.com/osiris-rex/osiris-rex-instruments/.
10. Alessandro, Adrienne. "NASA’s Restore-L Mission to Refuel Landsat 7, Demonstrate Crosscutting Technologies." NASA’s Goddard Space Flight Center (2016), https://www.nasa.gov/feature/nasa-s-restore-l-mission-to-refuel-landsat-7-demonstrate-crosscutting-technologies/
11. “Smallsat Developers Focus on Improving Reliability.” SpaceNews.com, 8 Aug. 2018, https://spacenews.com/smallsat-developers-focus-on-improving-reliability/
12. Grush, Loren. “After Making History, NASA's Tiny Deep-Space Satellites Go Silent.” The Verge, The Verge, 6 Feb. 2019, www.theverge.com/2019/2/6/18213594/nasa-marco-cubesats-deep-space-insight-mars-mission-communications-silent.
13. Foust, Jeff. “Is the Gateway the Right Way to the Moon?” SpaceNews.com, 30 Jan. 2019, https://spacenews.com/is-the-gateway-the-right-way-to-the-moon/
14. Hughes, Mark. “Solid-State LiDAR Is Coming to an Autonomous Vehicle Near You.” All About Circuits, 20 Feb. 2018, https://www.allaboutcircuits.com/news/solid-state-LiDAR-is-coming-to-an-autonomous-vehicle-near-you/
15. Loff, Sarah. “Morpheus Prototype Uses Hazard Detection System to Land Safely in Dark.” NASA, NASA, 13 Mar. 2015, https://www.nasa.gov/content/morpheus-prototype-uses-hazard-detection-system-to-land-safely-in-dark
16. Melanie N. Ott et al, "Applications of optical fiber assemblies in harsh environments: the journey past, present, and future", Proc. SPIE 7070, Optical Technologies for Arming, Safing, Fuzing, and Firing IV, 707009 (3 September 2008). https://photonics.gsfc.nasa.gov/tva/meldoc/SPIE/2008/SPIE-MNOTT-7070-8.pdf

CODE 562 PHOTONICS Group @ GSFC

BackUp

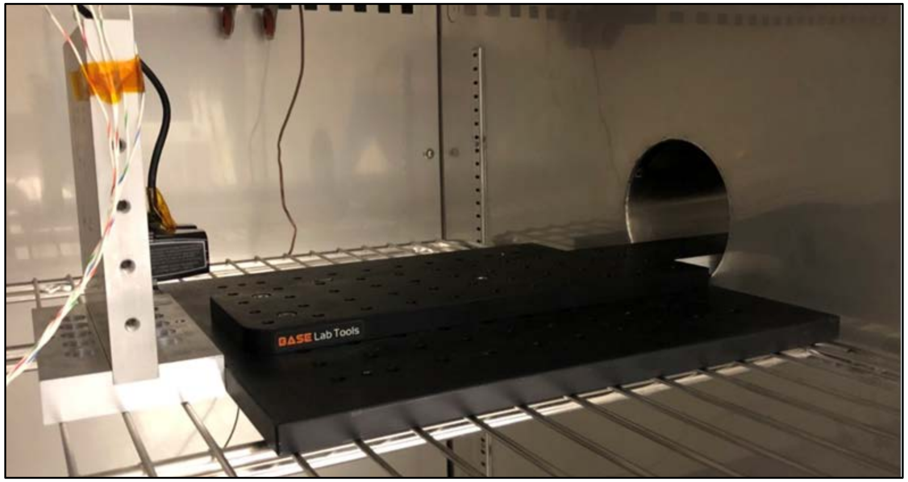
Thermal Cycling
Garmin LiDAR-Lite v3HP

- Five operation thermal cycles: 10°C to +60°C, 1°C/min, 30 minute dwell at extremes.
  - Powered, system functional, in-situ measurements.
- Two survival cycles: -20°C to +70°C, powered off.



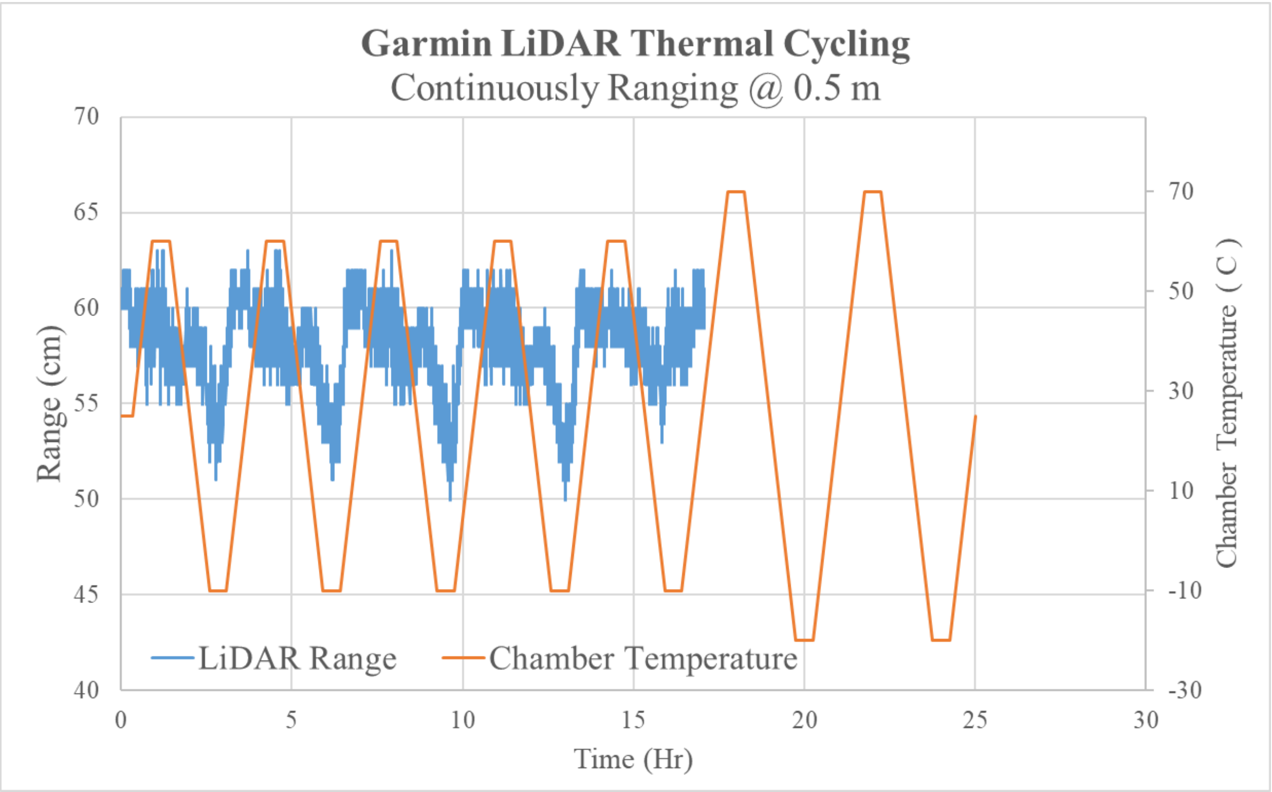
Mini LiDAR stability monitoring: data matches specified noise jitter:

- Range max = 63 cm; Range min = 60 cm
- Accuracy = 11.5 cm; Precision = 3 cm



Mini LiDAR in thermal chamber pointed to the target at then end of the chamber feedthrough hole.

Thermal Cycling
Garmin LiDAR-Lite v3HP

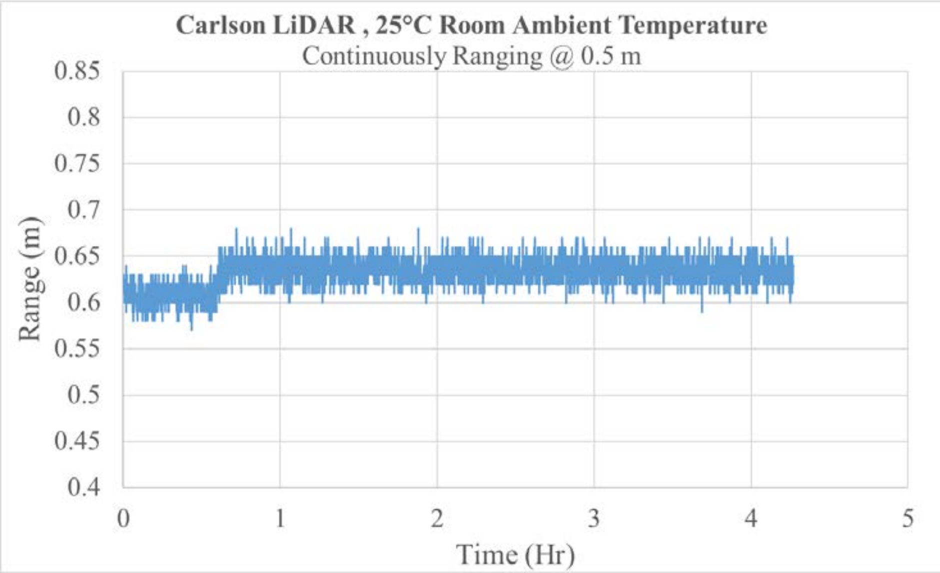


Range max = 63.0 cm
Range min= 50.0 cm

Accuracy = 6.5 cm
Precision = 13.0 cm

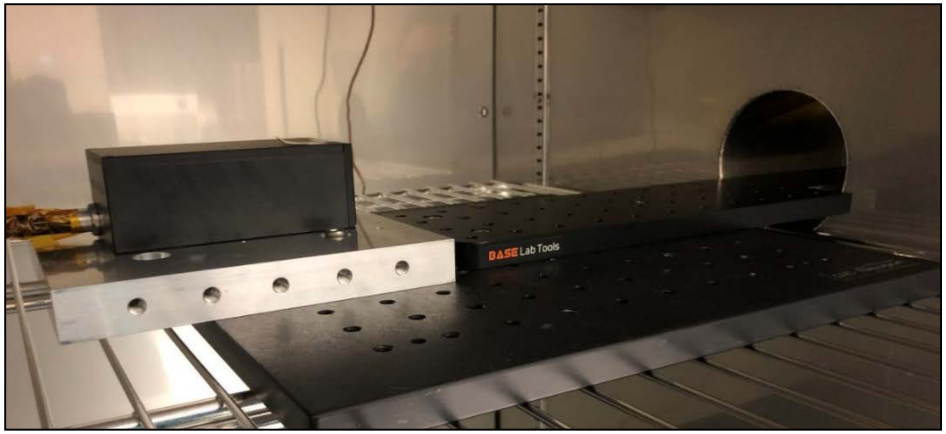
Thermal Cycling
Carlson ILM 150m

- Five operation thermal cycles: 10°C to +60°C, 1°C/min, 30 minute dwell at extremes.
  - Powered, system functional, in-situ measurements.
- Two survival cycles: -20°C to +70°C, powered off.



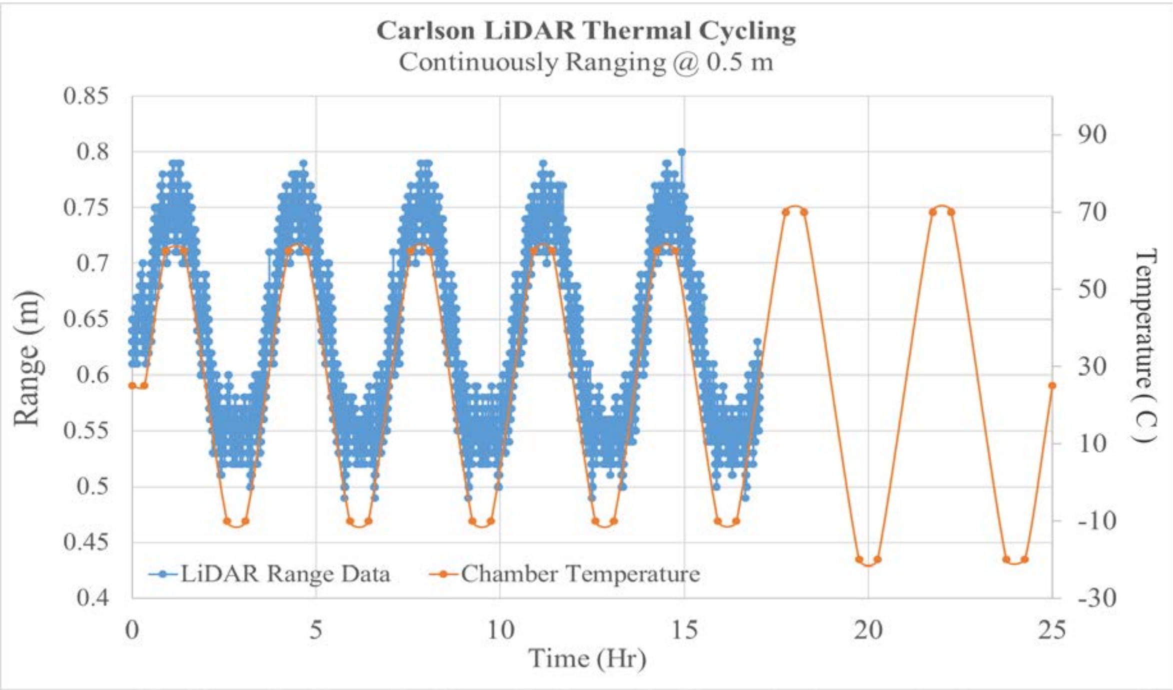
Mini LiDAR stability monitoring: data matches specified noise jitter:

- Range max = 68.0 cm; Range min = 57.0 cm
- Accuracy = 14.5 cm; Precision = 11 cm



Mini LiDAR in thermal chamber pointed to the target at then end of the chamber feedthrough hole.

Thermal Cycling
Carlson ILM 150m



Range max = 80.0 cm
Range min= 49.0 cm

Accuracy = 14.5 cm
Precision = 31 cm