Global Shutter Solid State Flash LIDAR for Spacecraft Navigation and Docking Applications

Beth A. Sornsin, Bradley W. Short, Tyler N. Bourbeau, and Michael J. Dahlin
Advanced Scientific Concepts, 135 East Ortega Street, Santa Barbara, CA USA 93101

ABSTRACT

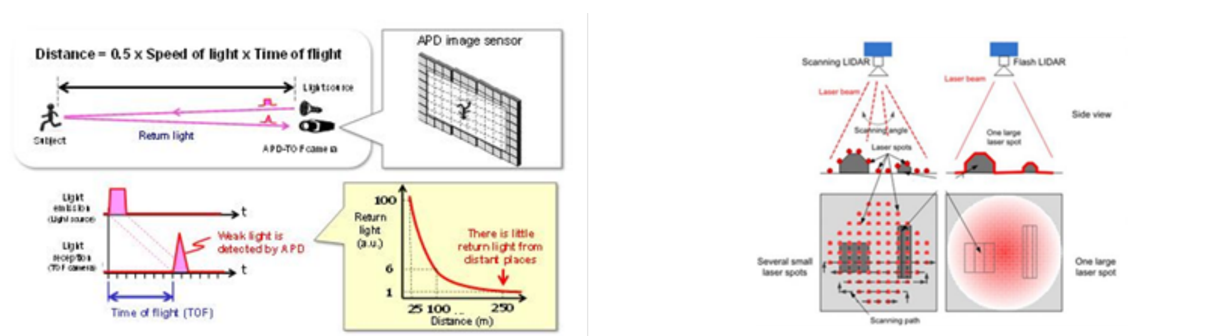
Global shutter flash LIDAR is the sensor of choice for space-based autonomous relative navigation applications. Advanced Scientific Concepts (ASC) has recently delivered LIDAR cameras to the NASA / Lockheed- Martin OSIRS-Rex and the NASA / Boeing CST-100 Starliner programs. These are two of the first operational space programs to use global shutter, flash LIDAR based relative navigation systems. The OSIRIS-REx spacecraft was launched in September 2016 and is the first opportunity to understand how global shutter flash LIDAR performance and reliability is impacted by long term exposure to the deep space environment.

1. INTRODUCTION

Robust relative navigation systems and sensors are required to ensure successful autonomous spacecraft-to-small celestial body (asteroids, comets) rendezvous operations, spacecraft proximal/docking maneuvers, and planetary body entry, decent, and landing (EDL) missions. Within the last 5 years, global shutter flash LIDAR has emerged as the sensor of choice for these relative navigation mission domains. Compared to other LIDAR modalities, global shutter flash LIDARs have superior size, weight, and power (SWaP) performance, are capable of generating real-time organized point-clouds, and simultaneously track multiple objects. Two of the first operational space programs to use global shutter flash LIDAR relative navigational sensors designed and manufactured by Advanced Scientific Concepts LLC (ASC) are the NASA / Lockheed Martin OSRIS-Rex and NASA / Boeing's CST-100 Starliner (Crew Space Transportation) missions. The OSIRS-REx mission is of particular interest since it is the first time flash LIDAR deep space reliability data has been has been collected.

2. GLOBAL SHUTTER, SOLID STATE, FLASH LIDAR

Global shutter flash LIDAR is a range imaging sensor that employs time-of-flight techniques (Figure 1) to measure the distances between the LIDAR and objects in the scene. Global shutter refers to the technique where the entire scene is illuminated and simultaneously sampled with each laser pulse. This methodology captures complete spatial and temporal scene data (Figure 2, Figure 3), allowing rapid acquisition and rapid real-time processing of scene information for time-sensitive navigation operations.



(a) Time-of-Flight Principle (ToF)

(b) Global shutter feature provides simultaneous scene sampling

Figure 1. ASC's global shutter flash LIDAR uses a 128 x 128 ToF InGaAs APD FPA to provide high resolution real time 3D scene video.

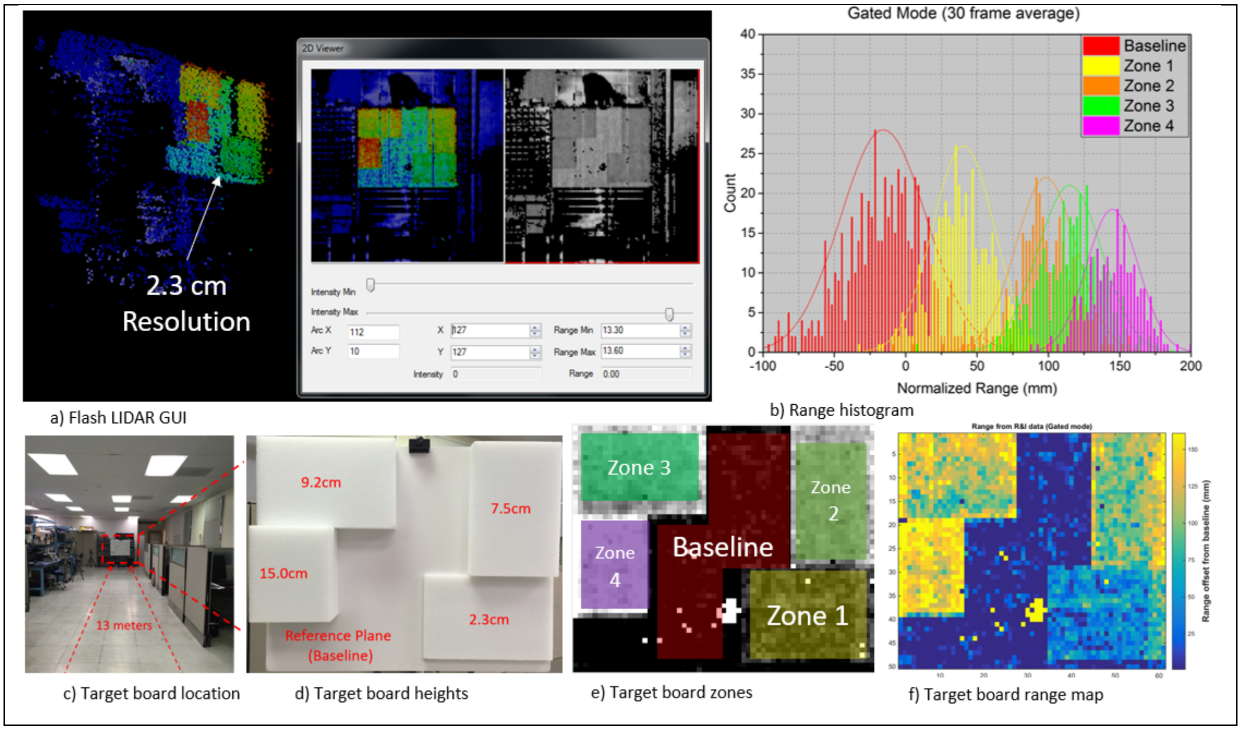


Figure 2. Global shutter flash LIDAR produces accurate real-time scene depth and intensity maps.

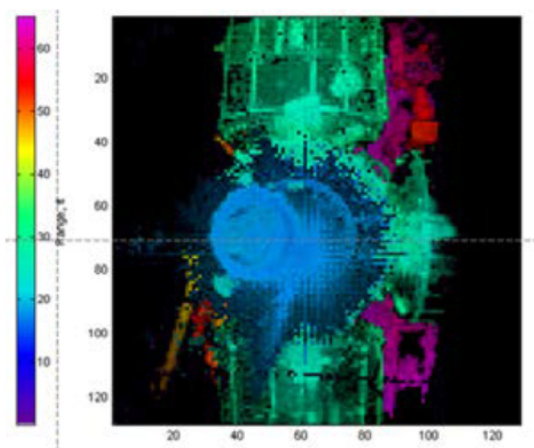


Figure 3. Global shutter flash LIDAR produces organized point clouds which enables the ability to perform efficient real-time object pose (range, position, orientation) measurements.

3. UNMANNED SPACECRAFT TO SMALL CELSTIAL BODY NAVIGATION: OSRIS REX MISSION

OSRIS-REx Mission

The OSIRIS-REx spacecraft (Figure 4) is traveling to Bennu, a carbonaceous asteroid whose regolith may record the earliest history of our solar system. Bennu may contain the molecular precursors to the origin of life and the Earth's oceans. Bennu is also one of the most potentially hazardous asteroids, as it has a relatively high probability of impacting the Earth late in the 22nd century. The OSIRIS-REx mission goal is to determine Bennu's physical and chemical properties, which is critical to know in the event of an impact mitigation mission, and return a regolith sample to Earth.

OSIRIS-REx launched from Cape Canaveral, Florida, on an Atlas V 411 rocket on Sept. 8, 2016 at 7:05 pm EDT. In August 2018, OSIRIS-REx's approach to Bennu began. The spacecraft used an array of small rocket thrusters to match Bennu's velocity and rendezvoused with the asteroid on Dec. 3, 2018.

The OSIRIS-REx spacecraft is comprised of the following principal components: the spacecraft bus (containing the spacecraft structure and all supporting subsystems for the operation and control of the vehicle), the Touch And Go Sample Acquisition Mechanism (TAGSAM), the Sample Return Capsule (SRC)S, and the five science instruments responsible for the remote-sensing campaign at Bennu. The redundant guidance, navigation, and control (GN&C) LIDARs provide information about the spacecraft range to Bennu's surface during the TAG Rehearsal and TAG Maneuver, to ensure that the spacecraft maintains a safe distance from Bennu. The key LIDAR features are summarized in Figure 5.

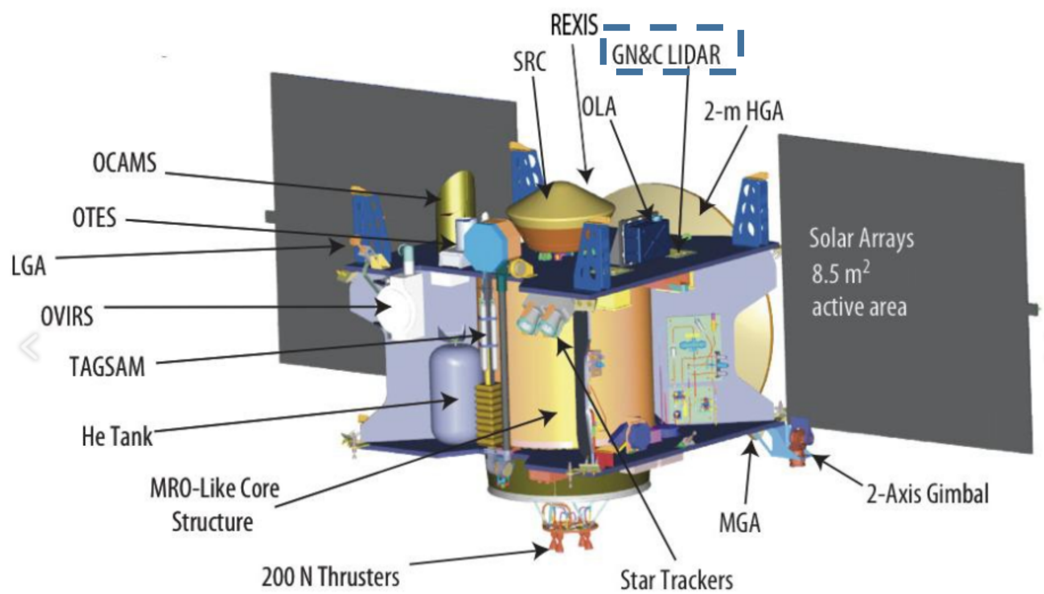
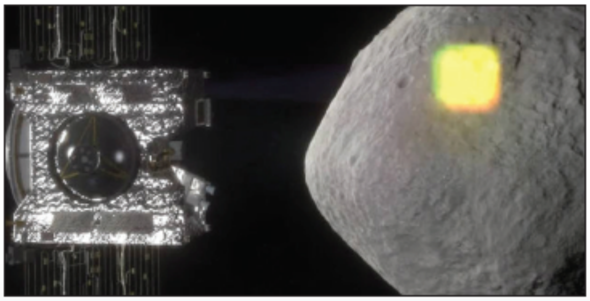
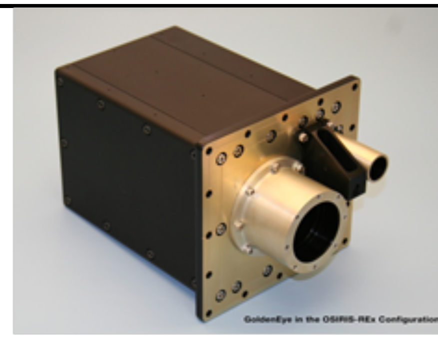


Figure 4 Location of the redundant global shutter flash GN&C LIDAR on the OSIRIS-REx spacecraft.

Credit: NASA/Goddard/University of Arizona



Credit: NASA/Goddard/University of Arizona



Key Features

- **Range : 2.8 m to 1 km**
- **Range Error: $\leq$ (10 cm + 1% of range)**
- **Receiver FOV: 6 degrees**
- **User selectable laser diffuser setting (one spot, four spot, full)**
- **Frame Rate: 10 Hz**
- **Laser: 1064 nm; 7 mJ; 5 nsec pulse width**
- **APD FPA Format: 128 x 128 @ 100um pitch**
- **Communication Bus: RS422 / redundant**
- **Data Bus: High Speed Serial (LVDS) / redundant**
- **Rad Hard: 100 krad (Si)**
- **Size: 6.9” x 6.5” x 8.6**
- **Weight: 6.9kg**
- **Power: 50 Watts (max)**

Figure 5. OSRIS-REx GN&C global shutter flash LIDAR key features.

Performance measurements consisted of ground based range truth measurements and in-orbit health measurements. Ground based range truth measurements were performed on the center 64 x 64 region of the flash LIDAR APD sensor prior to the camera delivery (Figure 6). These measurements were performed using proprietary calibrated time-of-flight techniques. The range measurement results are summarized in Table 1.

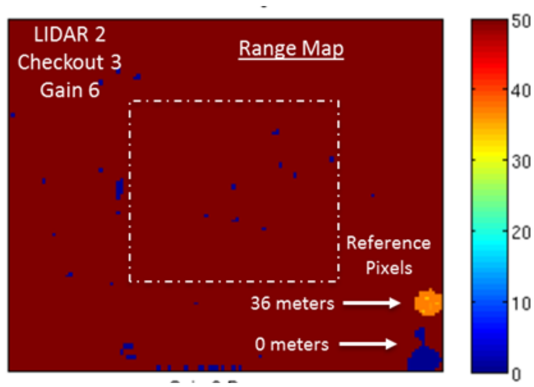


Figure 6. Ground based range truth measurements are performed the center 64 x 64 elements, In-flight short / open tests are performed on the entire 128 x 128 element FPA. In- flight pixel health measurements are performed on two groups of peripheral 3X3 group of reference pixels that are illuminated with calibrated time-of-flight laser illumination.

Table 1 OSRIS-REx GN&C LIDAR-1 and LIDAR-2 pre-flight range measurements.

Range Truth [m]	Measured Performance				Range Error Specification [m]
	LIDAR-1		LIDAR-2		
	Mean Range [m]	RMS Range Error [m]	Mean Range [m]	RMS Range Error [m]	
2.8	**2.89**	**0.157**	**2.71**	**0.160**	**≤ 0.13**
8.0	**8.11**	**0.218**	**7.97**	**0.110**	**≤ 0.18**
30.7	**30.5**	**0.18**	**30.3**	**0.125**	**≤ 0.41**
102	**102.2**	**0.295**	**30.2**	**0.136**	**≤ 0.40**
354	**354.2**	**0.305**	**354**	**0.336**	**≤ 3.64**
1009	**1009.6**	**0.261**	**1010**	**0.765**	**≤ 10.2**

The OSIRIS-REx mission is the first deep space deployment of a global shutter flash LIDAR so understanding the impacts of the deep space environment on the camera performance and reliability is extremely important for future space missions. The in-flight health monitoring consisted of pixel operability, range stability, intensity stability, thermal stability, laser current stability, and detector voltage stability. Both LIDARs aboard the OSIRIS-REx spacecraft have completed 4 total performance checkouts. The initial performance checkout was performed on the spacecraft prior to launch, and 3 separate performance checkouts were performed in-flight. The in-flight checkouts were performed May 2017, January 2018 and August 2018 [7]. The LIDAR will provide range data in June 2019 and Sample Capture will be conducted in July 2020.

Pixel Operability Stability

Dark images (no laser light) are taken during each performance checkout and the data is analyzed to count and trend the number of “bad” pixels in the 128x128=16384 array. A bad pixel in a dark image is any pixel that reports a range of 0.0m. The number of bad pixels is compared to the first checkout prior to launch to determine sensor degradation over the mission life. Figure 7 and Figure 8 show pixel maps from pre-launch, checkout 1 and checkout 3. LIDAR 1 has 0 “new” bad pixels from pre-launch checkout, to 3rd checkout (in-flight/cruise). LIDAR 2 has 12 “new” bad pixels from pre-launch checkout, to the 2nd checkout and 0 new bad pixels at the 3rd checkout.

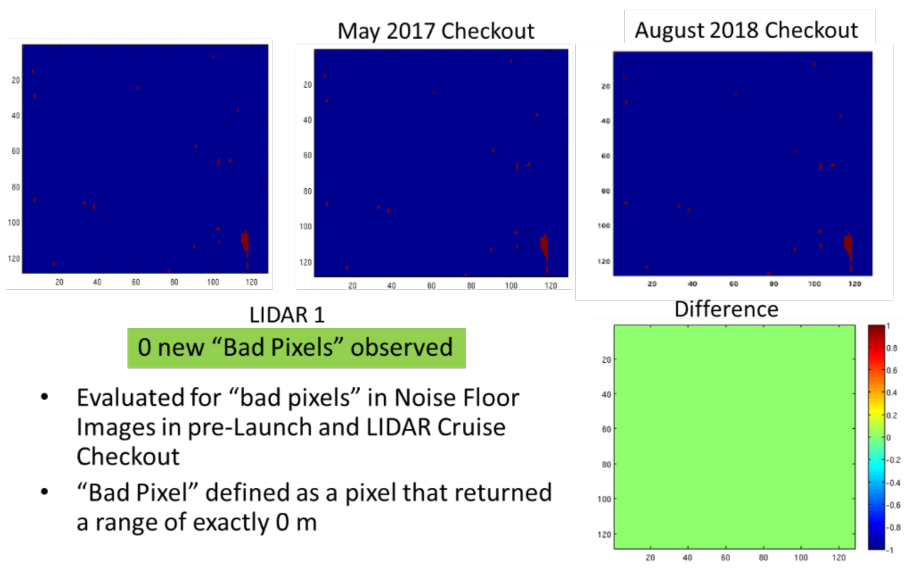


Figure 7 In-flight LIDAR 1, pixel operability is stable.

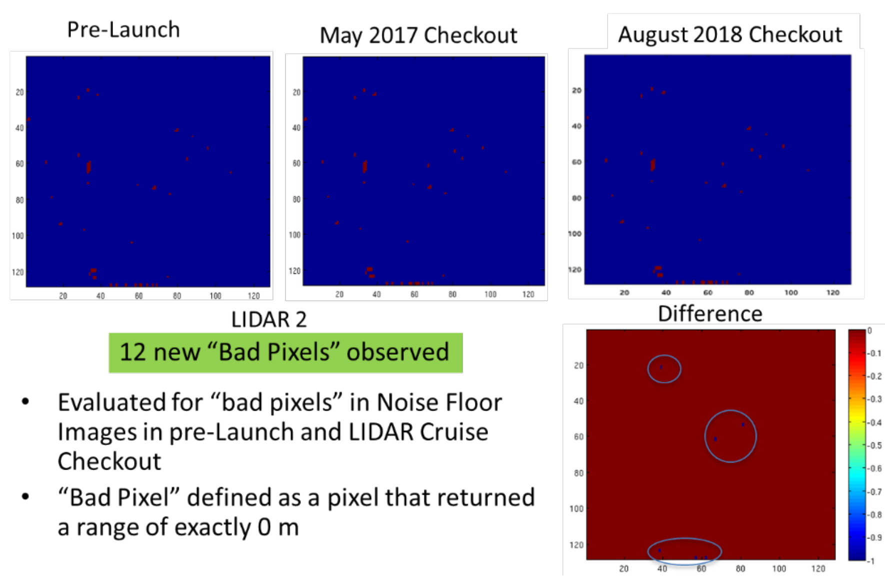


Figure 8. In-fight LIDAR-2, pixel operability is stable. In-flight pixel maps indicate the number of inoperable pixels increased by 12 out of 16,384.

Range Stability

The range stability monitor occupies 18 pixels on the detector array in two 3x3 regions. The two reference regions on the FPA consist of a short reference loop and a long reference loop. The ToF of the short reference is set to 0 meters on LIDAR 1 for LdrAPShort11 and approximately 36.5 meters for the long reference (LdrAPLong11). For LIDAR 2 they are set to 0.11 meters and 36.4 meters respectively. All 9 pixels are trended for range and intensity during the performance checkouts. The range measurements are generated by imaging for 400 frames over 6 different detector gain voltages, taking the average pixel values over the 400 frames. Figure 5 shows the range trends over the subsequent in-flight tests for both LIDARs. Preflight testing of LIDAR 1 showed some stray light in the long reference and adds noise to the LIDAR 1 Long Reference Range Trend data, while LIDAR 2 shows better stability.

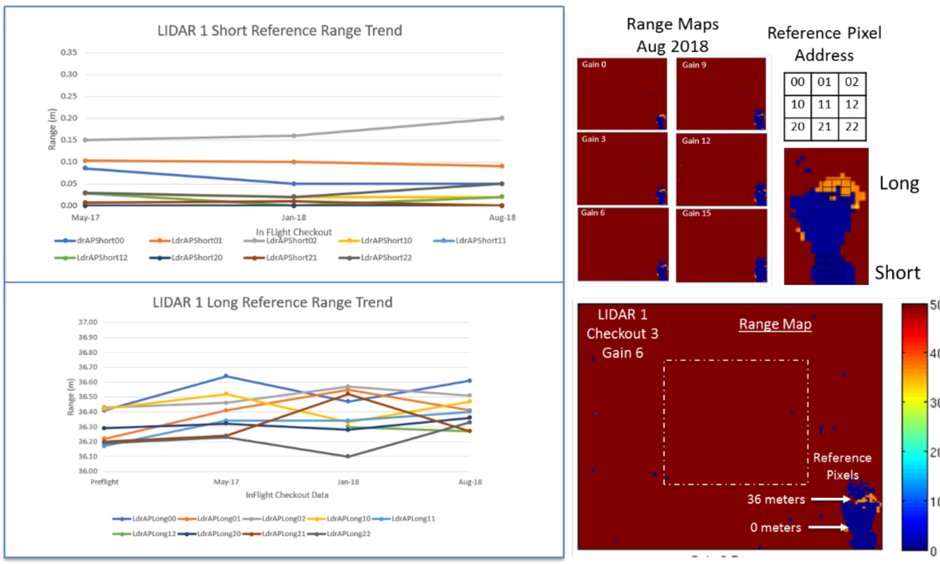


Figure 9. In-flight LIDAR-1 range performance stable.

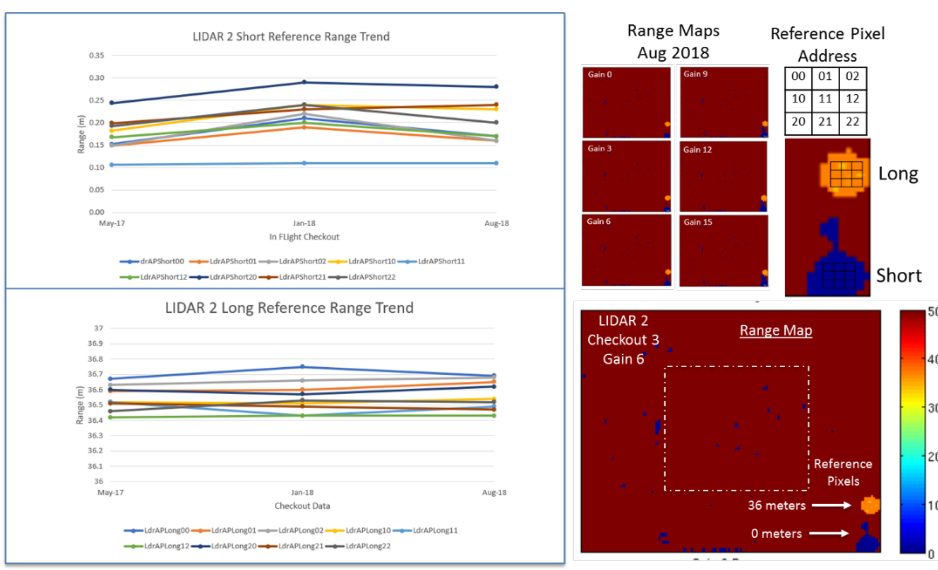


Figure 10. In-flight LIDAR-2 range performance is stable

Intensity Stability

The intensity stability monitor uses the same 18 pixels used to monitor range stability. Figure 11 and 12, show the intensity trends over the subsequent in-flight tests for both LIDARs. Both LIDARs show stable intensity indicating that the laser output and detector sensitivity are stable post launch.

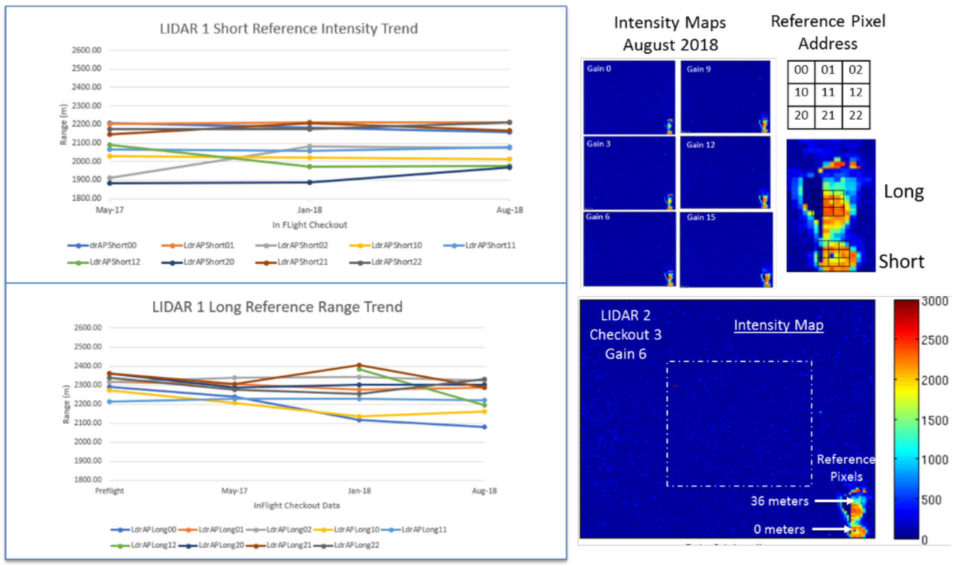


Figure 11. In-flight LIDAR-1 intensity performance is stable.

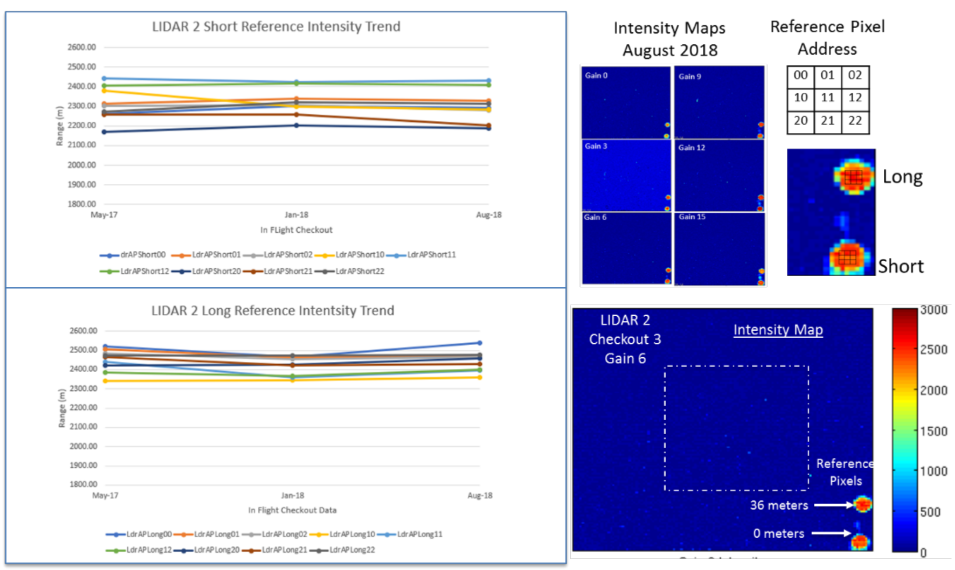


Figure 12. In-flight LIDAR-2 intensity performance is stable.

Thermal Stability

Laser crystal, laser diode, FPA and chassis temperatures are monitored. There is closed loop thermal control for all but the chassis temperature. Figure 13 shows the temperature of each of the thermistors for LIDAR 1 and LIDAR 2, during the 1st checkout in May 2017 and the 3rd checkout in Aug 2018. Five thermistors are monitor for the feedback loops and control circuits. In-flight checkout shows stable thermal performance for both LIDARs.

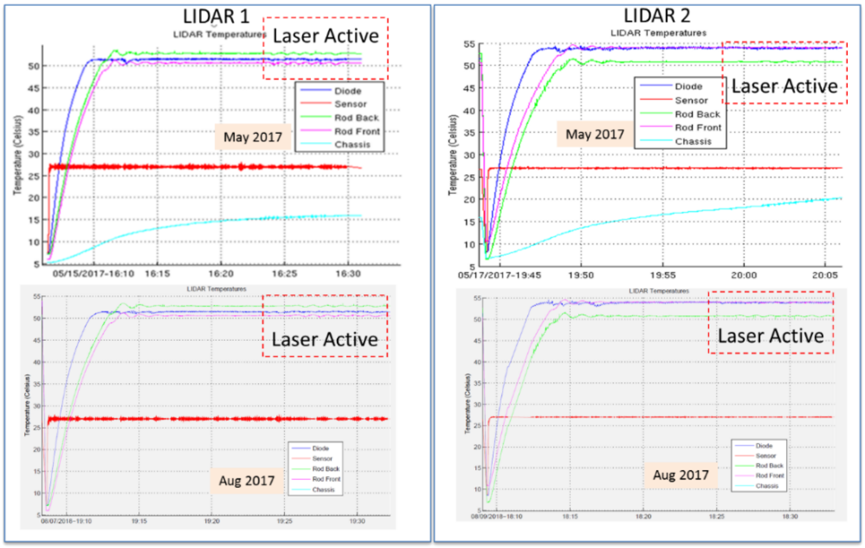


Figure 13. In-flight LIDAR-1 and LIDAR-2 thermal operability is stable. Temperatures are repeatable and the control loops are stable from test to test and during the acquisition cycles. Laser temperatures and FPA temperatures continue to be maintained at the pre-flight set points.

Laser Current Stability

The OSIRIS-REx lasers are passively q-switched Diode Pumped Solid State (DPSS) Lasers. The laser was qualified for the mission through life testing of 40,000,000 laser shots. The laser diode current pump duration and the output energy was monitored. The current and energy can vary with temperature. The flight configuration shows stable temperature though out the checkouts leading to stable pump times (Figure 9). Although the laser output energy is not directly measured Figure 6 shows stable intensities from the reference loops during the in-flight checkouts. Figure 14 shows constant laser pump durations across both LIDARs during all tests.

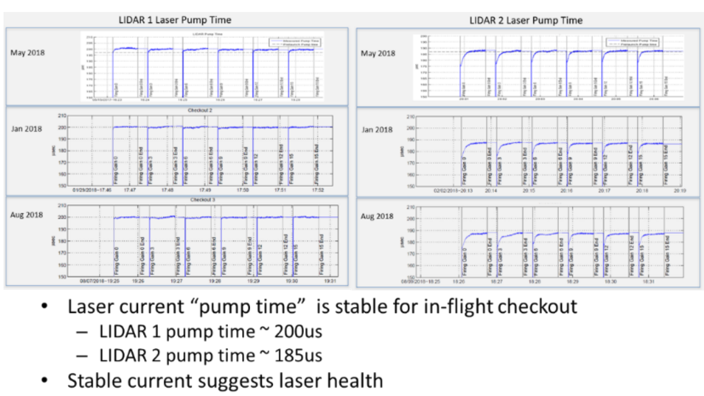


Figure 14. In-flight laser current is stable. Stable input current and stable intensities indicates healthy lasers for both LIDAR 1 and LIDAR 2.

Detector Voltage Stability

Sixteen APD gain settings are selectable in the Flash LIDAR by adjustable detector bias voltages. Figure 15 shows the voltage monitoring of the LIDARs at each in-flight checkout. During the in-flight tests 6 different gains were used during the data collection. At each setting the voltage is measured and reported. Voltages are stable across all settings and checkout tests.

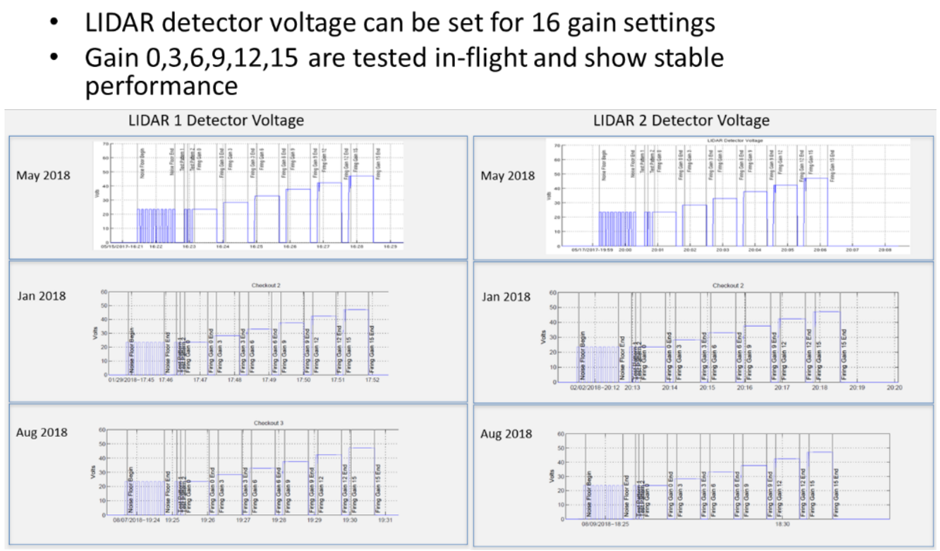


Figure 15. LIDAR-1 and LIDAR-2 in-flight detector voltage is stable.

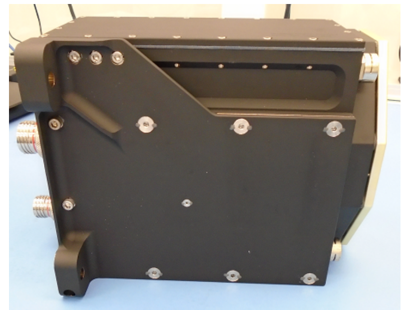
4. MANNED SPACE CRAFT AUTONOMOUS NAVIGATION AND DOCKING OPERATIONS: CST-100 STARLINER

CST-100 Starliner Mission

Boeing's Crew Space Transportation (CST)-100 Starliner spacecraft is being developed in collaboration with NASA's Commercial Crew Program. The Starliner was designed to accommodate seven passengers, or a mix of crew and cargo, for missions to low-Earth orbit. For NASA service missions to the International Space Station, it will carry up to four NASA-sponsored crew members and time-critical scientific research. When the Starliner approaches the International Space Station, the docking will be fully autonomous as the spacecraft maneuvers toward the docking port for commercial spacecraft. This will free up astronauts for other tasks during the final approach to the space station.

CST-100 Starliner LADAR

The global shutter flash LADAR sensor provides the ISS relative position, attitude and range relative to the CTS-100 spacecraft (Figure 16). For the CST-100 program, ASC's GoldenEye sensor has been designated a "LADAR" by the program; this difference is only in terminology, the function is identical the other LIDAR products. The LADAR is used for navigation from a distance of 2 kilometers into the docking ring and is optimized for a broad range performance, low Earth orbit environments, and crew safety. As part of the Vision-based, Electro-Optical Sensor Tracking Assembly (VESTA) the LADAR works in cooperation with other sensors and processors to provide the mission data to the crew capsule. As of publication, the LADAR and subassemblies have passed autonomous docking simulation testing and are being prepared for a test flight in late 2019.



Key Features

- **Range : 2m to 2 km**
- **Range Error: ≤ (10 cm + 1% of range)**
- **FOV: 15 degrees**
- **Frame Rate: 10Hz**
- **Laser: 1570nm @ 0.4mJ**
- **APD FPA Format: 128 x 128 @ 100um pitch**
- **Rad Hard: 100 krad (Si)**
- **Size: 7.0” x 6.3” 8.4”**
- **Weight: 5.0 kg**
- **Power: 28 Watts (max)**

Figure 16 CTS GN&C global shutter flash LIDAR key features. Left image credit: NASA.

Table 2 CTS-100 Flight Unit 3 masured range performance (center 64x64).

Range Truth [m]	Measured Performance		
	Flight Unit 3		Range Error Specification [m]
	Mean Range [m]	RMS Range Error [m]	
11.77	11.83	0.06	0.22
51.79	51.84	0.06	0.62
301.9	301.6	0.04	3.1
1004.7	1004.7	0.09	10.14
2009.7	2009.4	0.35	20.19

5. CONCLUSION

ASCs Flash LIDAR meets the OSIRIS-REx and Starliner mission requirements and has shown robust operation in deep space post launch testing. In July 2020 the OSIRIS-REx GN&C will be used in actual operation to provide terminal guidance for the TAG phase of the mission. Although the Global Shutter LIDAR being used for both missions meets the SWaP and range resolution requirements (5cm to10cm + 1% of range), ground testing and further modeling show that future iterations, using the current FPA, can have significantly reduced SWaP with improved range performance (<2.5cm).

6. AKNOWLEDGEMENTS

The authors would like to thank NASA, Lockheed Martin, and Keith Mahoney for support and permission to publish the OSIRIS-Rex data. The authors would also like to thank the Boeing Commercial Crew and VESTA teams for support and permission to publish data about the VESTA LADAR Starliner mission.

REFERENCES

[1] Utilization of 3-D Imaging Flash Lidar Technology for Autonomous Safe Landing on Planetary Bodies, NASA Langley Research Center, Hampton, Virginia 23681, USA, Farzin Amzajerdian, Michael Vanek, Larry Petway, Diego Pierrottet, George Busch, Alexander Bulyshev.

[2] Analysis of Flash Lidar Field Test Data for Safe Lunar Landing, Andrew E. Johnson, Jason A. Keim and Tonislav Ivanov, Jet Propulsion Laboratory, California Institute of Technology, Pasadena.

[3] 3-D Flash Lidar Performance in Flight Testing on the Morpheus Autonomous, Rocket-Propelled Lander to a Lunar-Like Hazard Field Vincent E. Roback, Farzin Amzajerdian, Alexander E. Bulyshev, Paul F. Brewster, and Bruce W. Barnes.

[4] libSLAD Safe Landing Area Determination Library User's Guide, Version 1, US Army Aeroflightdynamics Directorate Flight Control & Cockpit Integration Division, University Affilitated Research Center (UARC).

[5] Field-Testing of a Helicopter UAV Obstacle Field Navigation and Landing System, Matthew Whalley and Marc Takahashi, Aeroflightdynamics Directorate (AMRDEC), US Army Research, Development, & Engineering Command, Ames Research Center, Moffett Field, CA 94035

[6] Flight Trials of a Rotorcraft Unmanned Aerial Vehicle Landing Autonomously at Unprepared Sites Colin Theodore Dale Rowley San Jose State Foundation Ames Research Center, CA David Hubbard Brigham Young University Provo, UT Adnan Ansar Larry Matthies Steve Goldberg Jet Propulsion Laboratory, CA Matthew Whalley Aeroflightdynamics Directorate (AMRDEC) Ames Research Center, CA

[7] Lockheed Martin. OSIRIS-REx Spaceflight LIDAR Checkout1 (5/15/17, 5/17/17) Curtis Miller, Checkout2 (1/29/18, 2/2/18), Checkout3 (8/7/18, 8/9/18).