National Aeronautics and Space Administration

An Overview of NASA Lidar Technologies for Precision Safe Landing on Planetary Bodies

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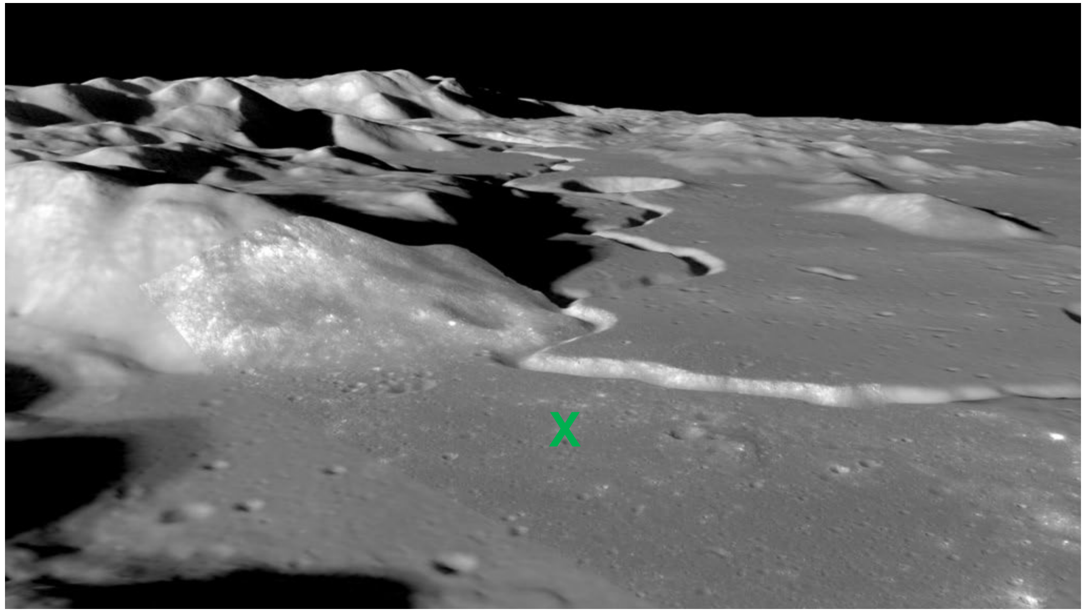
2023 MSS Active EO Systems Conference

Landing missions are progressively more ambitious

- **Past landing missions generally selected benign terrains**
- **Objectives of future landing missions:**
  - Sustainable human presence at the Moon and continued human exploration on towards Mars
  - Exploration of Jupiter and Saturn Moons (e.g., Titan, Europa), and Asteroids

Apollo 15 Landing Site



Artemis Landing Site

Lidar Plays an Important Role in Future Landing Missions

- **Future missions require precise navigation and landing at challenging locations near escarpments and craters**
  - For example south pole of the Moon where water ice may be present
- **Lidar technology can enable precisely land payloads and avoid landing hazards**
  - Provide relative position knowledge (Altimetry and Terrain Relative Navigation)
  - Provide precision velocity vector
  - Detect terrain hazards and identify safe landing locations

Landing Lidar Sensors Under Development at NASA

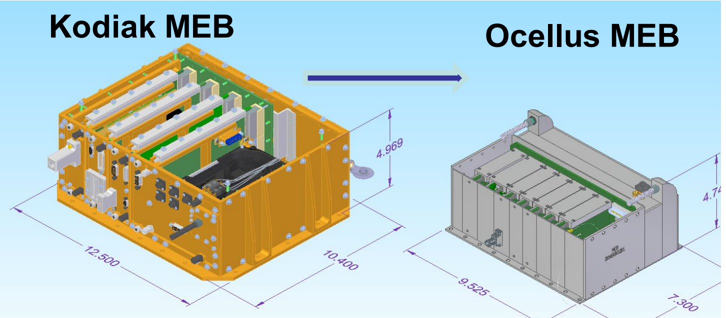
Lidar Sensor	Type	POC	Functions
Ocellus	Scanning	*Nathaniel Gill*/GSFC	Hazard Detection and Altimetry
SPLICE HDL	Scanning	J. Bryan Blair/GSFC	
ELSA MIT-LL Lidar	Hybrid Scanning/Flash	Anup Katake/JPL	Hazard Detection, Altimetry and Terrain Relative Navigation (TRN)
ELSA Sigma Lidar	Hybrid Scanning/Flash	Anup Katake/JPL	
HAPN Lidar	Flash	Farzin Amzajerdian/LaRC	
Navigation Doppler Lidar	FMCW	Farzin Amzajerdian/LaRC	Velocity and Altimetry

Ocellus Lidar for Landing on Titan

PI: Nathaniel Gill, NASA-GSFC, nathaniel.a.gill@nasa.gov

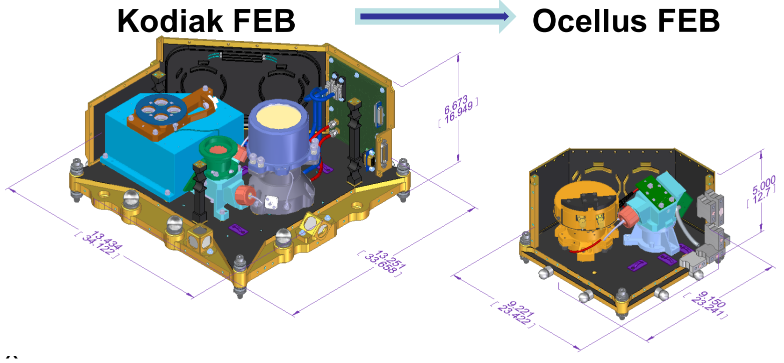
Overview

- Hazard avoidance sensor and altimeter for Dragonfly Lander
- Used in altimeter mode at higher altitude to provide range to the ground, 200m-2km
- Used in imaging mode 20-200m altitude for hazard detection, terrain slope measurement, and safe landing zone assessment



Kodiak MEB: 31.75 x 26.42 x 12.95 cm 8.3kg

Ocellus MEB: 24.19 x 18.54 x 12.04 cm 3.145kg CBE*



Kodiak FEB: 34.12 x 33.66 x 16.95 cm 8.56kg

Ocellus FEB: 23.4 x 23.2 x 12.7 cm 3.017kg CBE*

Approach

- Leveraging OSAM-1 Kodiak design
- Ocellus is being developed simultaneously with SQRLi lidar on common platform
- Key Specs:
  - 15° Field of view, 200Hz horizontal scan
  - 2cm accuracy 3D point cloud output
  - 0.21° pointing knowledge in jitter environment
  - 120kHz imaging mode
  - 1064nm wavelength

Key Milestones

- PDR September 2022
- ETU1 Delivery Fall 2023 for helicopter testing
- ETU2 with AlBeMet MEB
  - Delivery Summer 2024 for Qual Testing
- CDR Early 2024
- Flight Unit Delivery Early 2025

NASA/GSFC: Hazard Detection Lidar

Principal Investigator: J. Bryan Blair, NASA/GSFC. James.B.Blair@nasa.gov

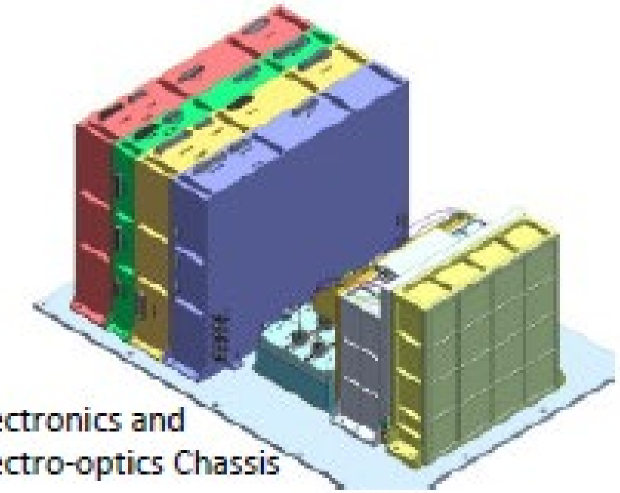
Hazard Detection Lidar Overview

- HDL is a hybrid, scanning-imaging lidar consisting of an optical head (with focal plane imaging and a Risley-prism scanner mechanism) fiber coupled to an electronics box (laser, detectors, and signal processing electronics)
- ETU version in subsystem build now. Integration and Assembly planned for June 2023

Rapid 3-D landing site imaging with real-time Digital Elevation Map (DEM) generation

- Surface Imaging and DEM production all in 1-2 seconds. 8 Million range measurements per second.
- 5 cm spatial resolution and 1 centimeter range precision from nominal operational altitude of 500 m.
- Analog detection. Wide dynamic range. 1 cm single shot precision.
- High-speed spinning optical wedges sweep across large angular field-of-view quickly and accurately
- Spiral sampling pattern is robust to motion and rotation during imaging
- Motion and rotation are corrected in real-time to produce DEM
- From 500-m above the surface, HDL produces a DEM covering a 100m diameter area with 5-cm spatial resolution and 4X oversampling. DEM is collected and processed all within 2 seconds.
- Meets range precision requirements without averaging - oversampling is for robustness to motion & rotation

- Long-range altimeter. Single beam capable of ranging >20 km with < 10 cm range precision. Supports Active-TRN (Terrain Relative Navigation). Longer ranges possible.



Electronics and Electro-optics Chassis

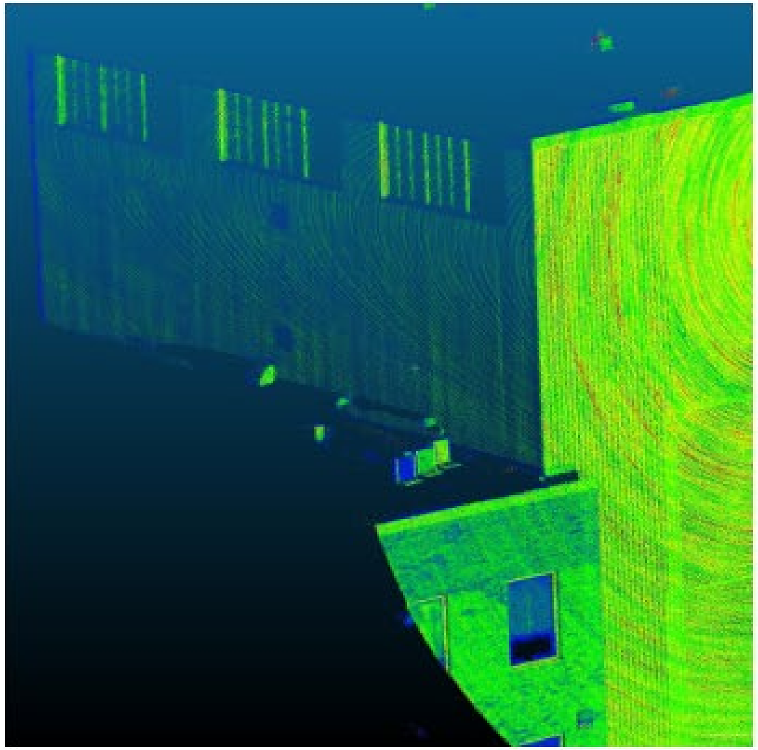
Altimeter Head

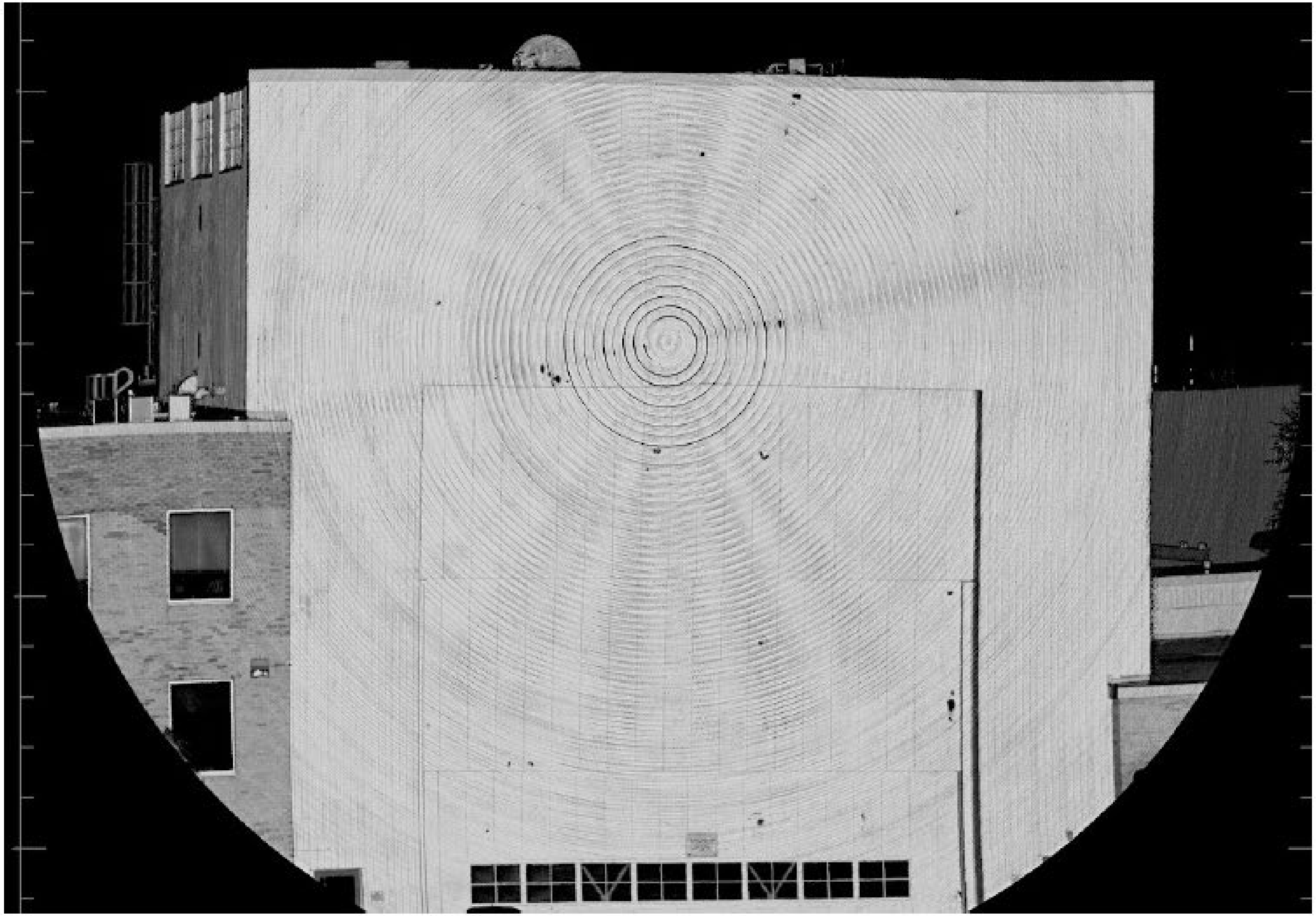
Imaging Head

HDL EDU Static Demonstration Data

- HDL Test DEM (Digital Elevation Model) generated from data set consisting of 16 Million ranges collected in 2 seconds with scanner operating at full speed (6,000 rpm).
- 1 cm range precision demonstrated at equivalent return signal strength for 500 m distance and 17% surface reflectance.

(Images shaded by calibrated return signal strength)





Europa Lidar Sensor Assembly (ELSA)

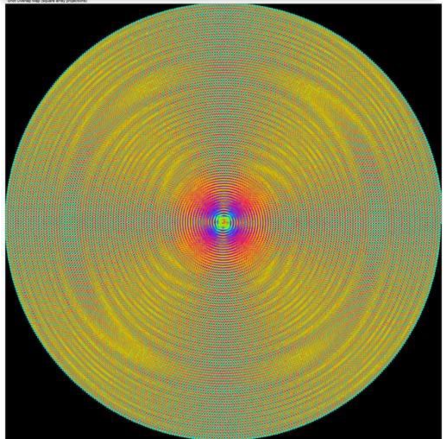
POC: Anup Katake, NASA-JPL, anup.b.katake@jpl.nasa.gov

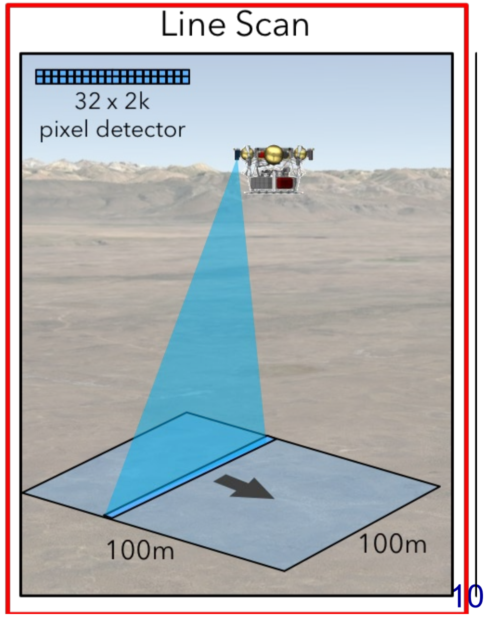
- **Hazard detection from ~ 500 m altitude and altimetry from ~ 10 km**
- **ELSA must survive extreme radiation environments of Europa**
- **2 lidar sensor systems being developed:**
  - MIT/LL - Gieger mode hybrid scanning/flash
  - Sigma Space – Linear mode hybrid scanning/flash

ELSA Lidars under Development

	Sigma Space	MIT Lincoln Labs
Modality	Photon counting, linear	Geiger
Lidar Type	Hybrid scanning/flash	Hybrid scanning/flash
Detector	Photo-multiplier-tube	Silicon
Detector Size	16 x16 pixels	2048 x 32 pixels
Pixel IFOV	100µrad	100µrad
Detector Readout	Rad-hard custom application specific integrated circuit (ASIC)	Rad-hard custom readout integrated circuit (ROIC)
Scan Mechanism, Pattern	2-axis Fast steering mirror, spiral scan	2-axis fast steering mirror, single axis scan
Laser Pulse Energy & PRF	100µJ @ 14kHz – 18kHz	Dual 25µJ @ 10kHz
Operating Wavelength	532nm	532nm
Range Accuracy	< 5cm	< 5cm
Scan & DEM Acquisition Times	1.8s for Fine DEM (2000 x 2000 pixel)	0.8s for Fine DEM
	4s for Coarse DEM (500 x 500 pixel)	8s for Coarse DEM
Altimetry	>10km @ 10Hz	>10km @ 10Hz
Radiation Tolerance	>300krad	>300krad
BBU Delivery	March-2023	Aug-2023

Sigma Spiral Scan

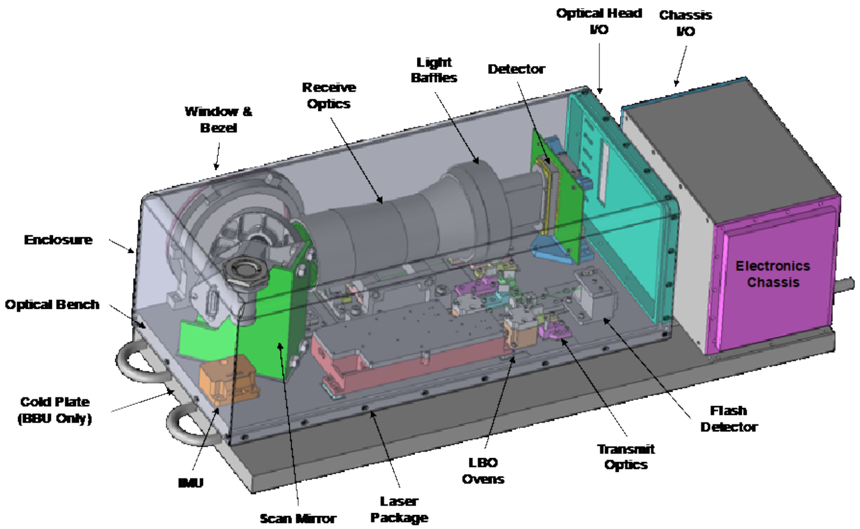




ELSA Breadboard Units

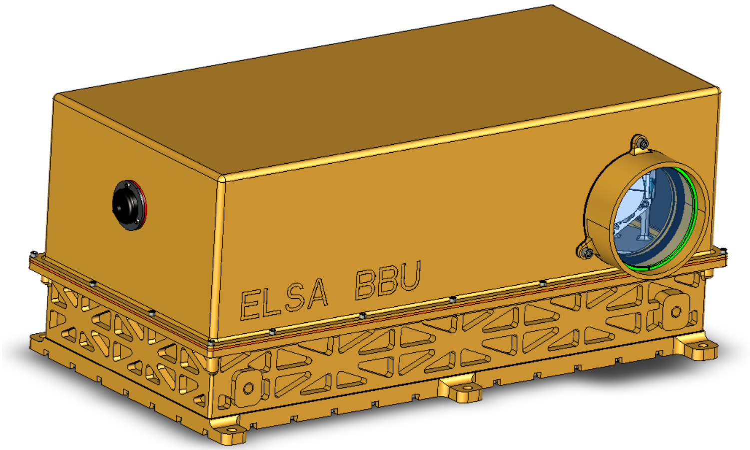
MIT/Lincoln Labs

Parameter	BBU
Size	580 x ? x ? mm^3
Volume	15625 cm^3
Mass	14.5 kg
Power	100 W



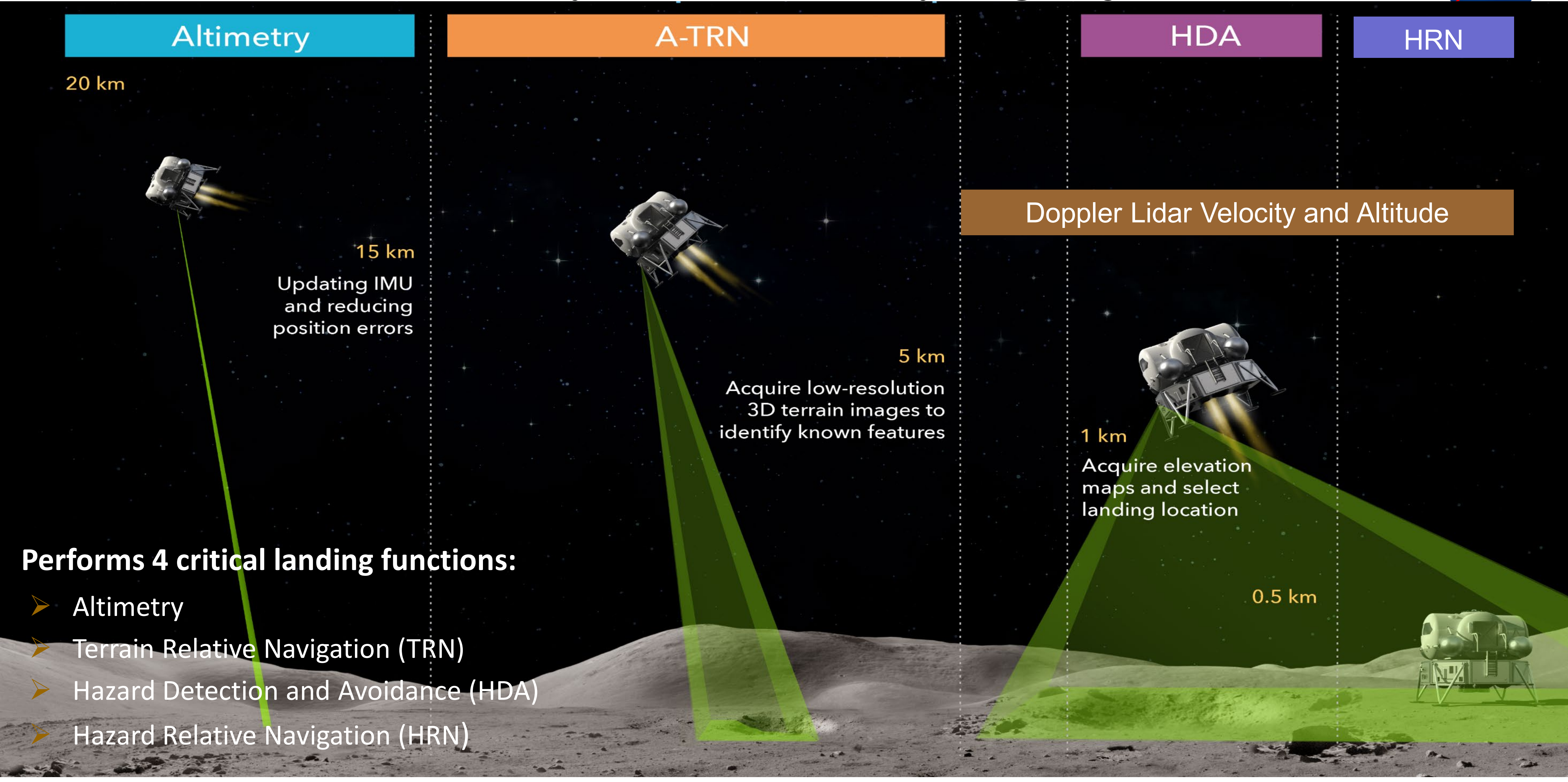
Sigma Space

Parameter	BBU
Size	430 x 259 x 181 mm^3
Volume	21049 cm^3
Mass	12.9 kg Flight: ~9kg CBE
Power:	
Altimetry	76 W
Imaging	300W x 1.8 s



Multi-Functional Flash Lidar Sensor

Farzin Amzajerdian, NASA-LaRC, f.amzajerdian@nasa.gov



Performs 4 critical landing functions:

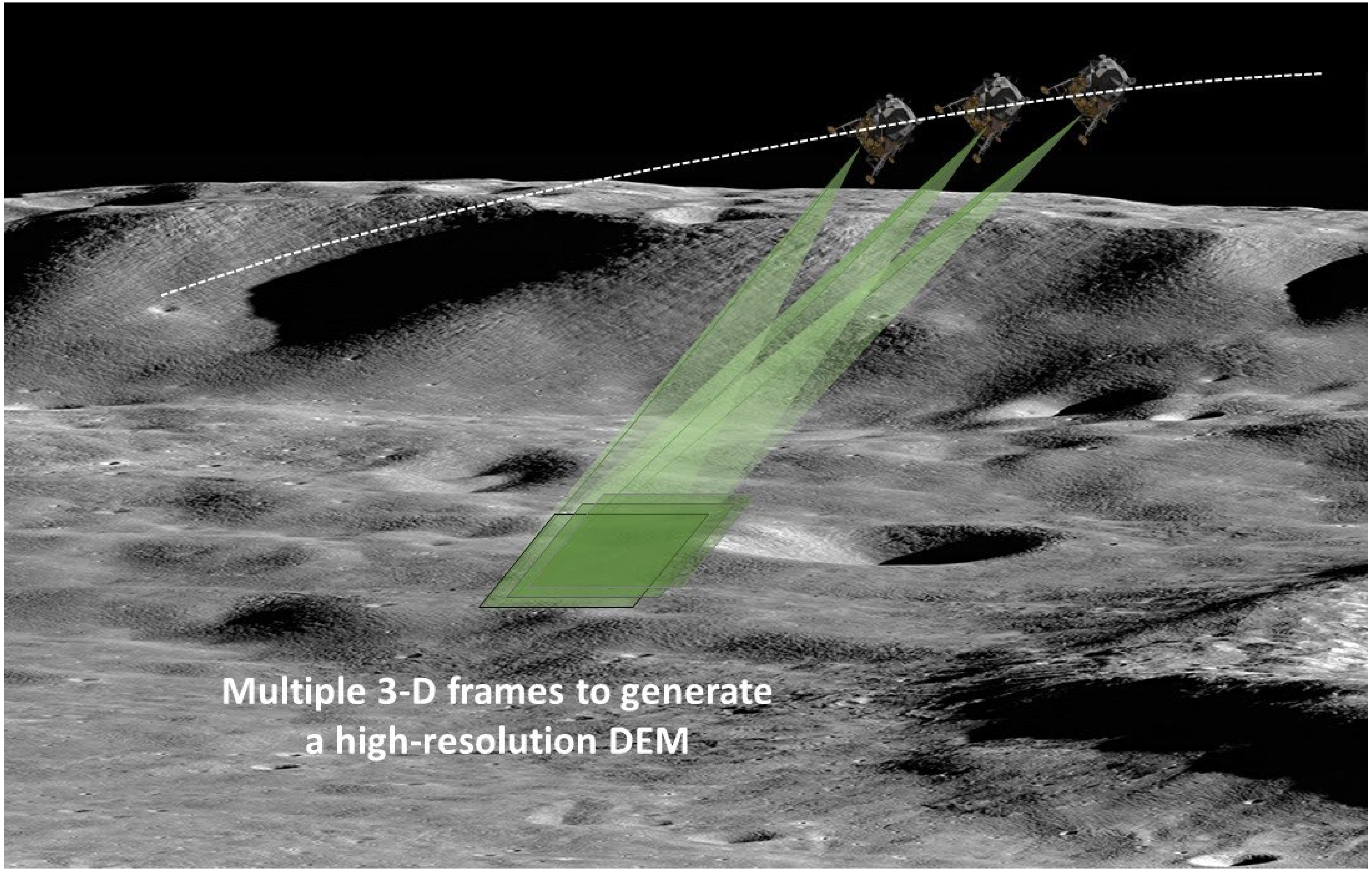
- Altimetry
- Terrain Relative Navigation (TRN)
- Hazard Detection and Avoidance (HDA)
- Hazard Relative Navigation (HRN)

Flash Lidar as a Landing Sensor

- **Commercial linear-mode flash lidar camera has 128 x 128 = 16.4k pixels**
- **Mapping 70 m x 70 m area with 10 cm Ground Sample Distance (GSD) requires 0.5 M pixels**
  - 10 cm GSD is required to detect 30 cm diameter hazards
- **Developed a Super-Resolution algorithm to meet HDA requirements without a need for a mechanical gimbal**

Flash Lidar Super-Resolution Algorithm

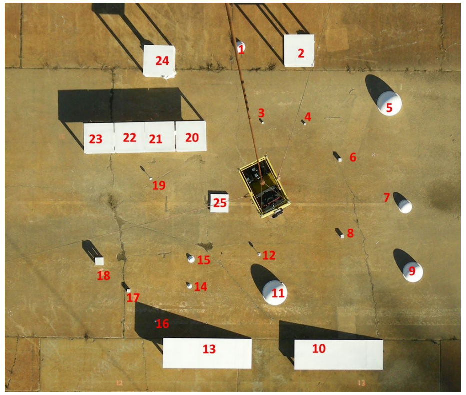
- **Super-Resolution (SR) technique uses a set of consecutive frames, from slightly different positions and angles (resulting from platform motion), to generate a high-resolution DEM**
- **Generates high-res DEMs at 1 Hz rate using 20 frames**



Development and Testing of Flash Lidar with Real-Time SR Algorithm at NASA LaRC

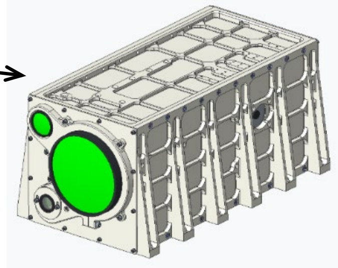
Gantry Test

Flash Lidar



Drone Test

LaRC Breadboard Flash Lidar

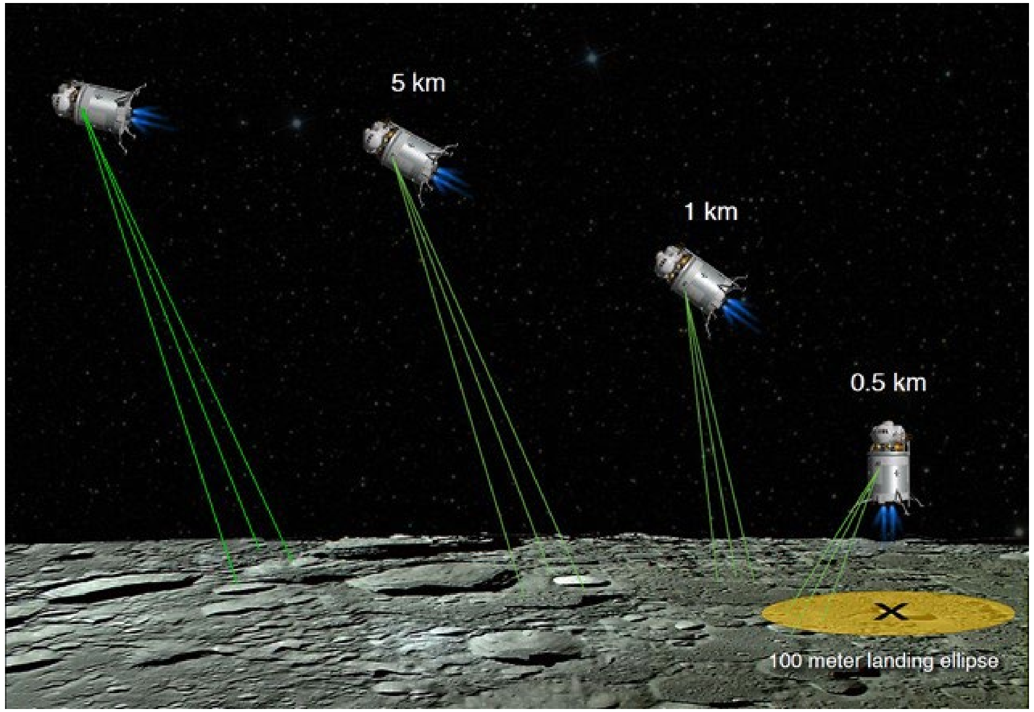


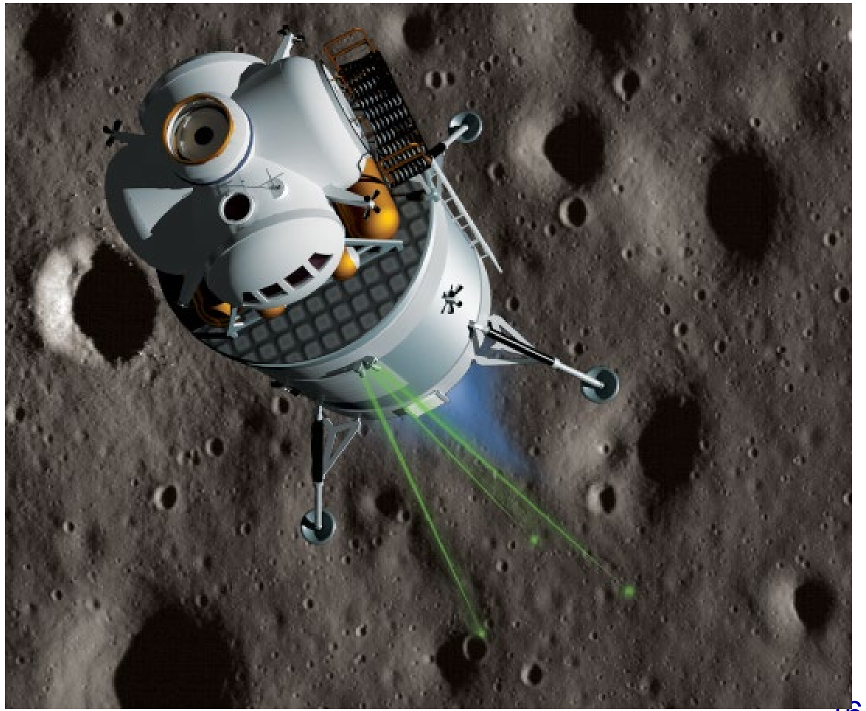
➢ Next generation breadboard	2023
➢ Aircraft flight tests	2023
➢ ETU for a lunar mission	2024

Navigation Doppler Lidar (NDL)

Farzin Amzajerdian, NASA-LaRC, f.amzajerdian@nasa.gov

- **NDL provides vehicle precision vector velocity and altitude data**
- **Viable replacement for radars with an order of magnitude higher precision and much better data quality**
  - Enables "***precision navigation***" to the designated landing location
  - Enables "***well-controlled***" descent, landing, and ascent maneuvers to within a few cm/sec





Spaceflight Engineering Test Units (ETUs)

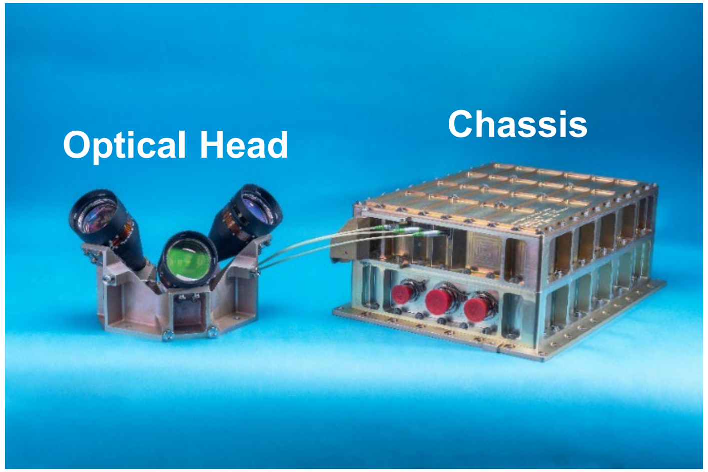
4 ETUs have been built

 # 1 – Aircraft flight tests (2021 -)

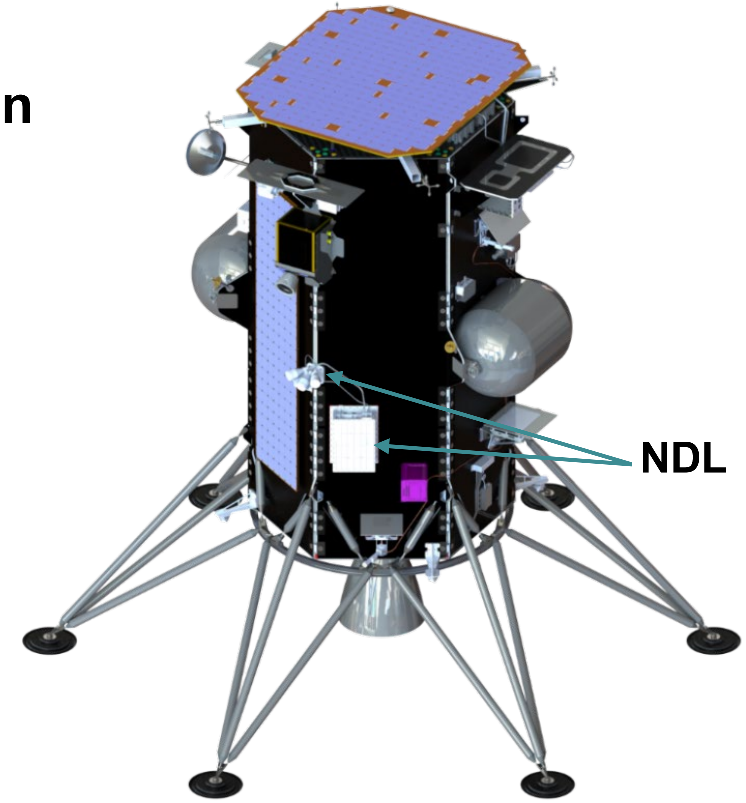
 # 2 – Suborbital flight test on Blue Origin New Shepard vehicle (2020,2021)

 # 3 – Lunar Landing Mission onboard Intuitive Machines lander (6/2023)

 # 4 – Lunar Landing Mission onboard Astrobotic lander (5/2023)



Intuitive Machines Nova-C Vehicle



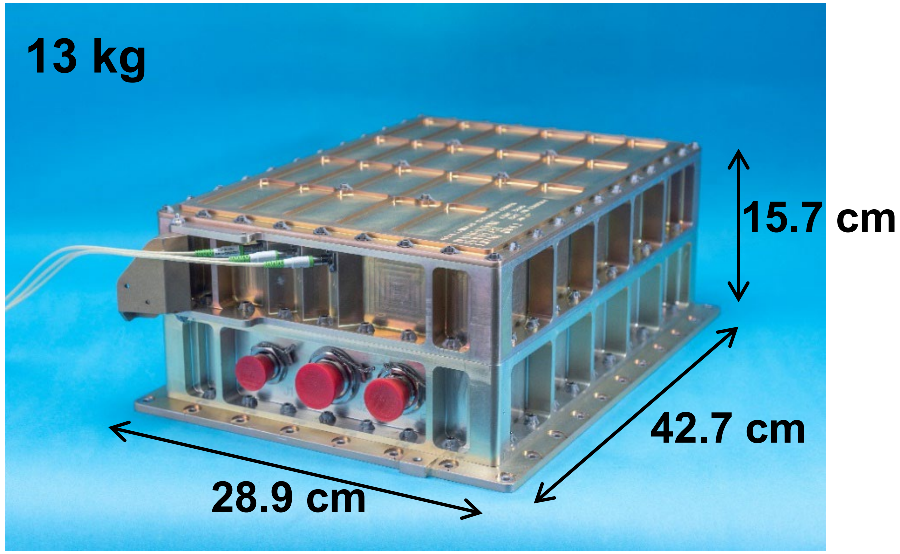
Astrobotic Peregrine Vehicle

NDL ETU Specifications

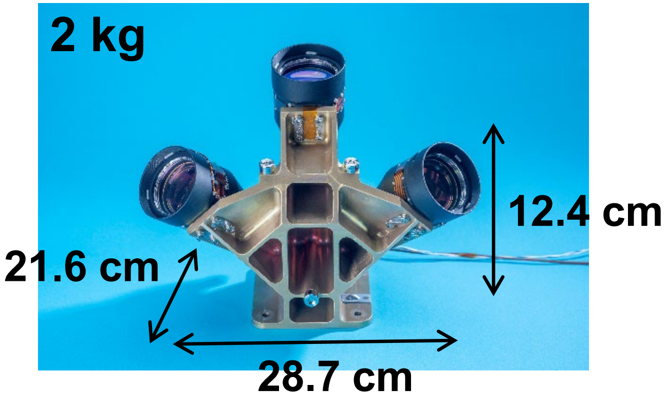
Parameter	Static Platform	Landing Vehicle
Maximum LOS Range	~ 14 km	7.0 km
Maximum LOS Velocity	+/- 218 m/sec	+/- 218 m/sec
LOS Velocity Noise @ 3000 m	0.09 cm/sec	8.3 cm/sec
LOS Range Noise @ 3000 m	0.10 m	8.2 m
Data Rate	20 Hz	

- **NDL ETU Performance is dominated by the vehicle vibration**
- **NDL ETU meets/exceeds landing requirements and outperforms radar sensors by about an order of magnitude in precision**
- **Next NDL build will extend operational range to 10 km and improve velocity and range precision to 2 cm/sec and 2 m regardless of host vehicle dynamics**

Chassis



Optical Head



Closing Remarks

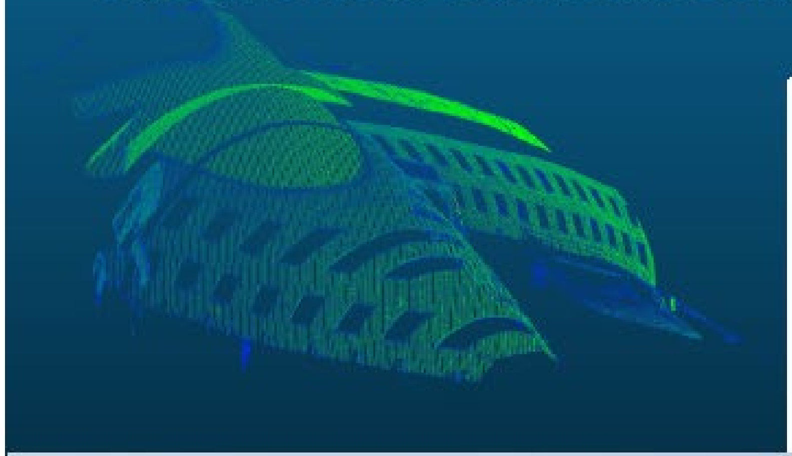
- **Lidar sensors being developed to perform:**
  - Hazard detection and avoidance
  - Terrain Relative Navigation
  - Vector velocity and altitude
- **Lidar sensor being development or demonstrated:**
  - Ocellus: Short range 3-D lidar, launch to Titan in 2027
  - SPLICE HDL: Medium range 3-D lidar, helicopter flight test in 2023
  - ELSA: Medium range 3-D lidar, breadboards in 2023
  - Multi-Functional Flash Lidar: Long range 3-D lidar, helicopter, fixed-wind, and drone flight tests in 2023
  - NDL: Velocity and altitude lidar, Lunar missions in 2023
- **These lidars with some modifications can be used for RPOD and Rovers**
- **NASA landing lidar sensor efforts may benefit terrestrial applications including autonomous vehicles and GPS-deprived navigation**

Backup

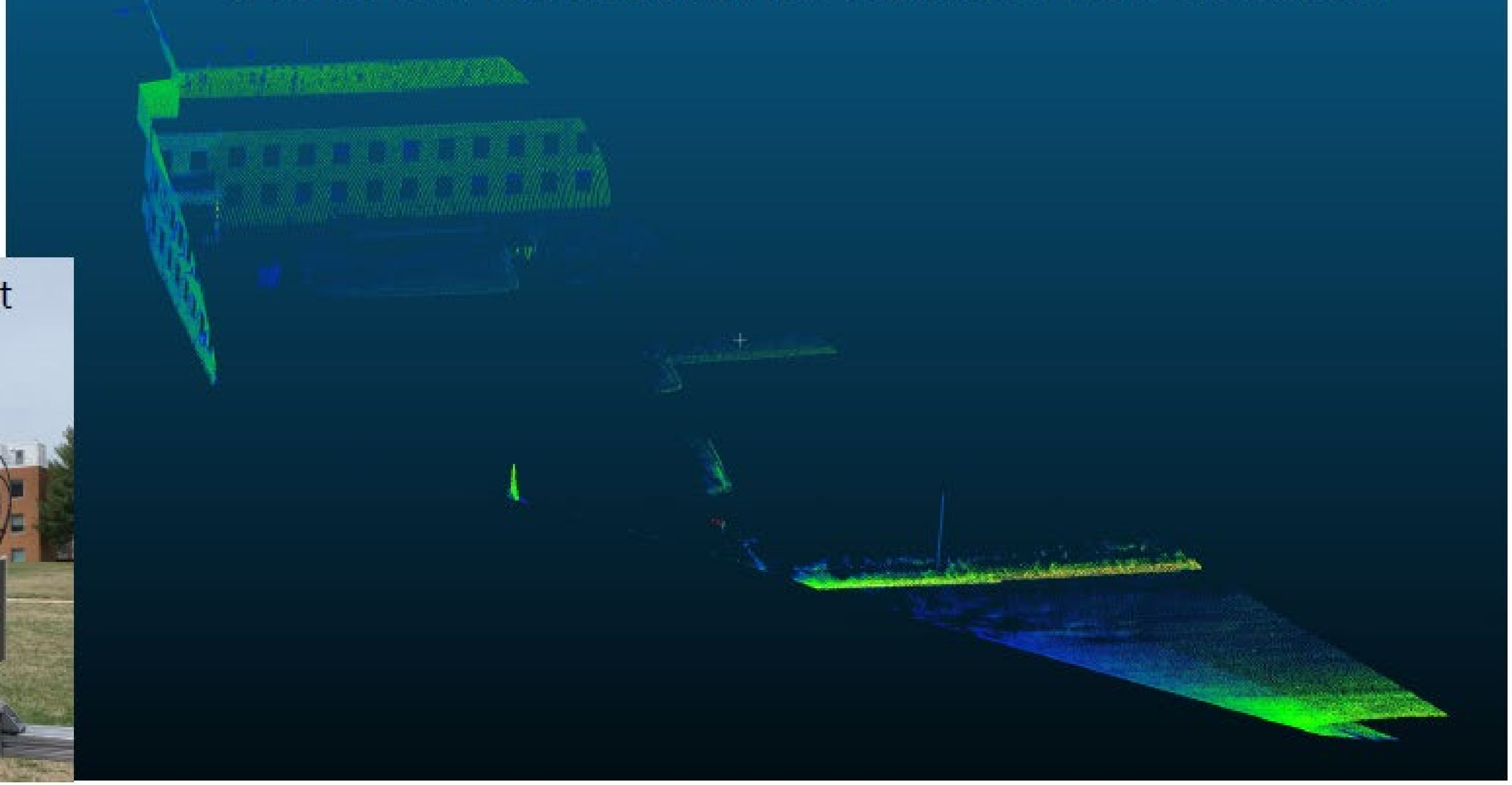
HDL EDU Dynamic Demonstration Data

Motion and Rotation Correction

Uncorrected: Data collected from moving and rotating vehicle



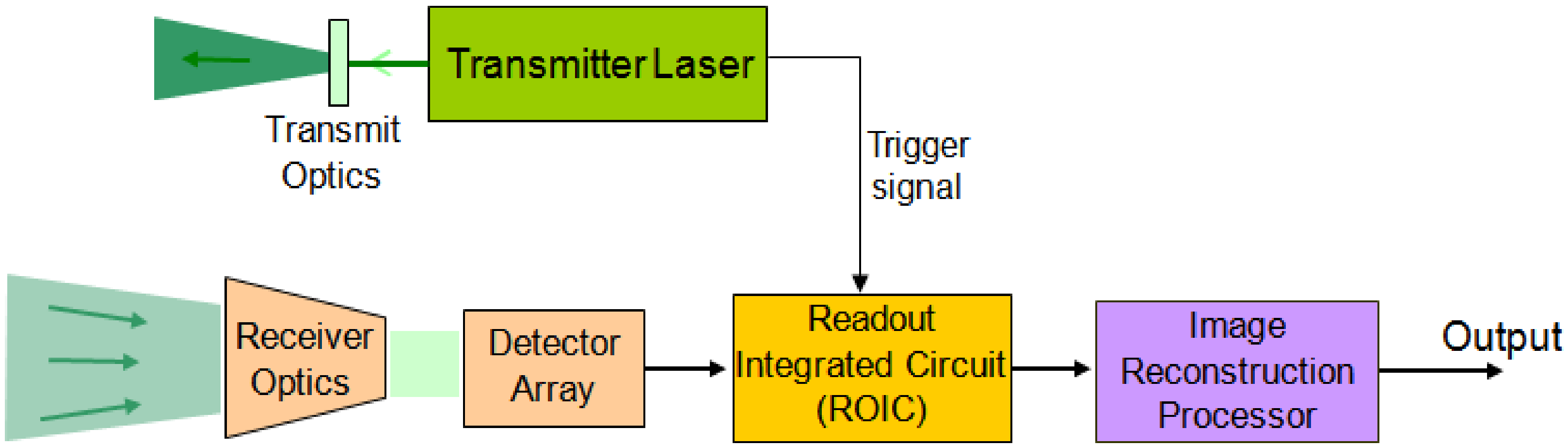
3-D DEM: Corrected for motion and rotation



Sensor head and support equipment

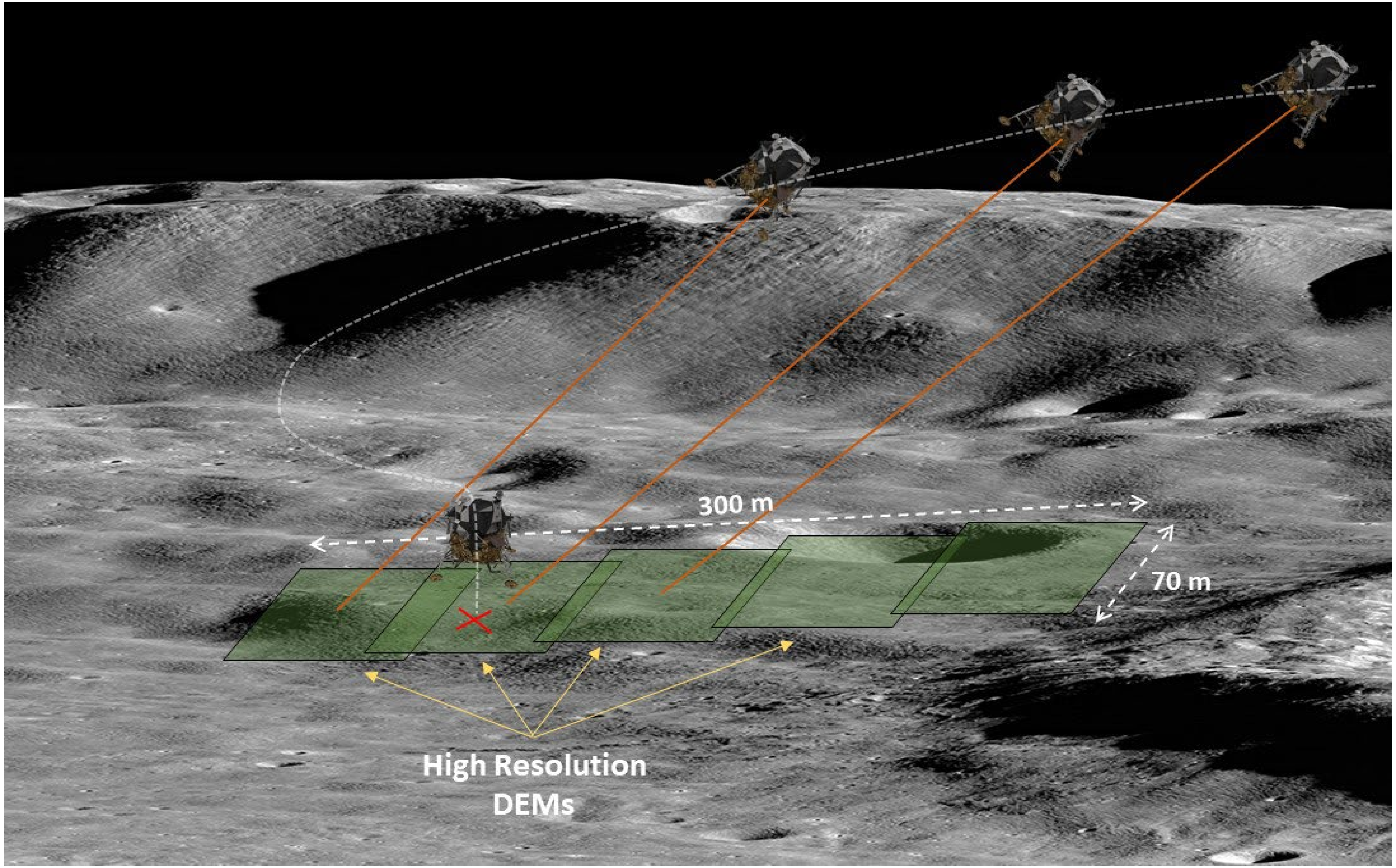
Multi-Functional 3-D Flash Lidar Sensor

- **Flash lidar presents several advantages over scanning lidars for hazard detection and safe landing on planetary bodies**
  - Does not require vehicle motion correction
  - Able to perform other functions critical for precision navigation



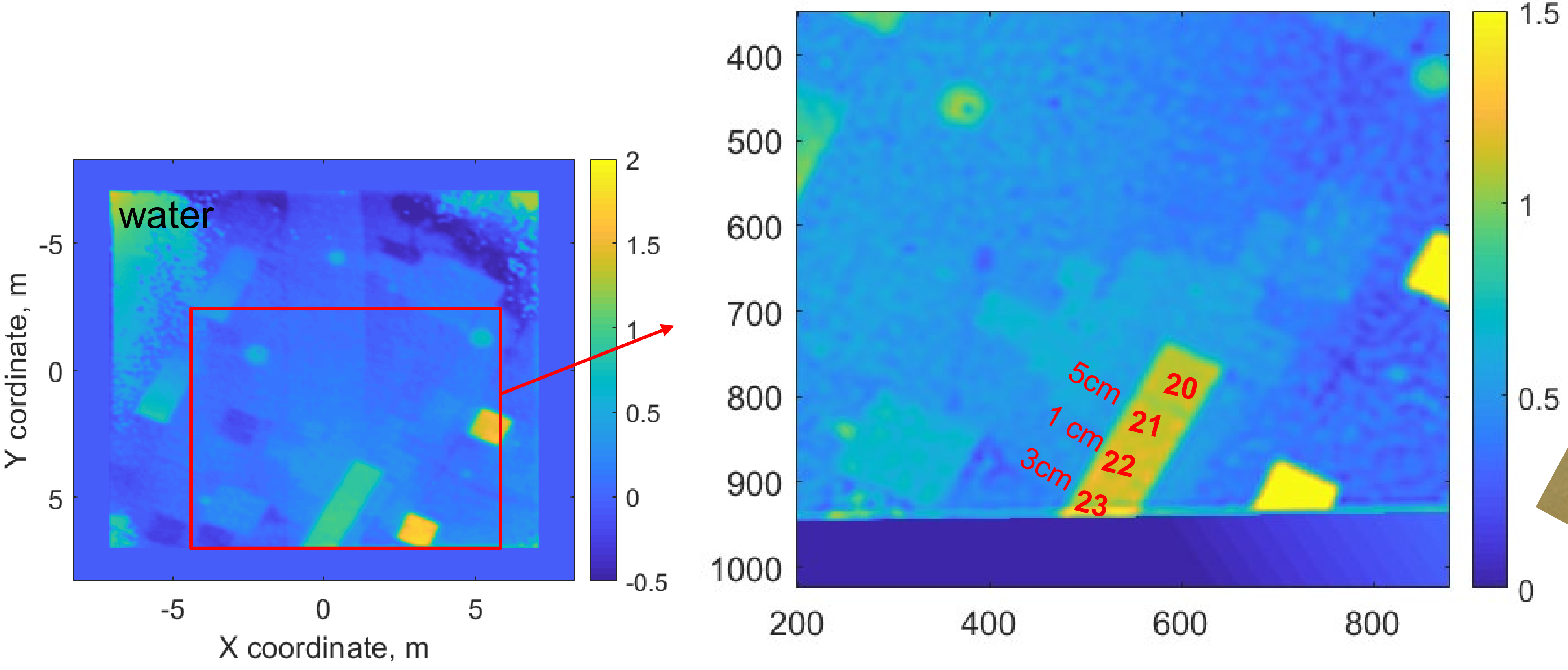
Flash Lidar Generates Multiple High-Resolution DEMs

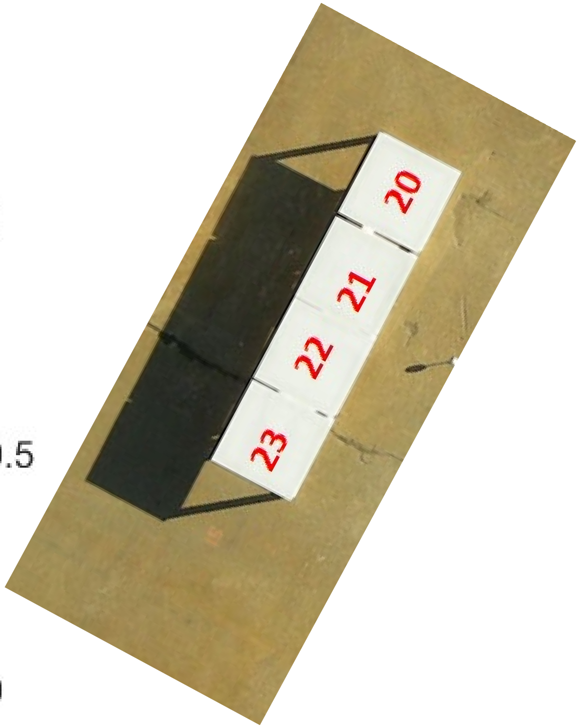
~ 70 m x 300 m high-resolution DEM for hazard detection and safe landing location selection



Resolution Enhancement by SR Algorithm

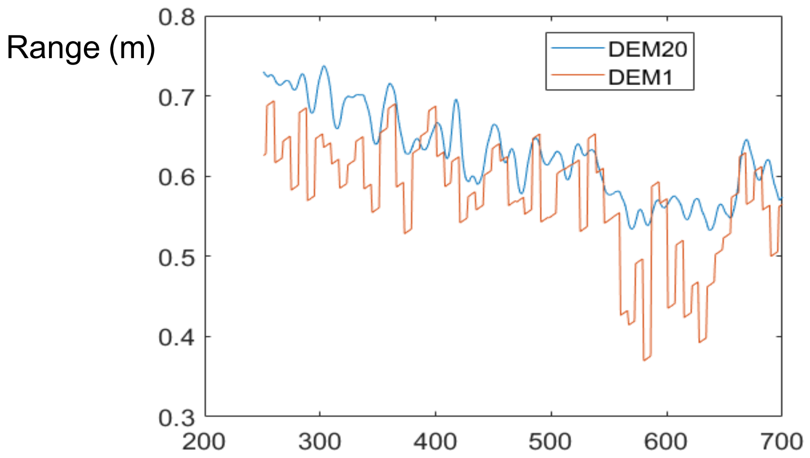
- **Resolved 3 cm gap with 12 cm GSD**
- **> 4X linear magnification (16X resolution enhancement)**

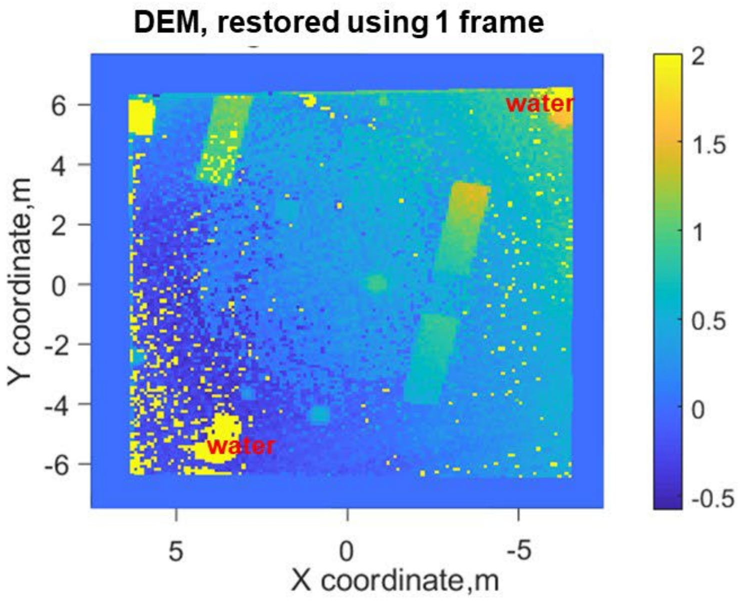


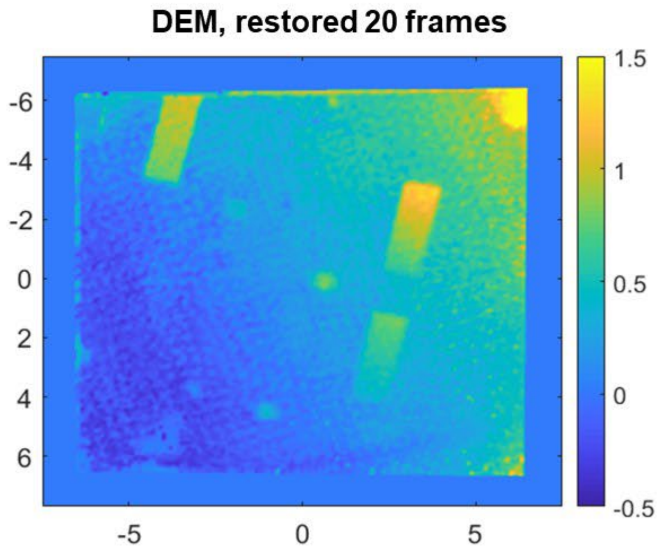


Performance of Real-Time Super-Resolution Algorithm

- Generated DEMs at 1 Hz rate
- Resolution enhancement by > 16X (> 0.26M pixels)
- Range resolution enhancement by 2X (4 cm)
- Range noise reduction by > 2X (3 cm)
- Effectively recovered dark pixels

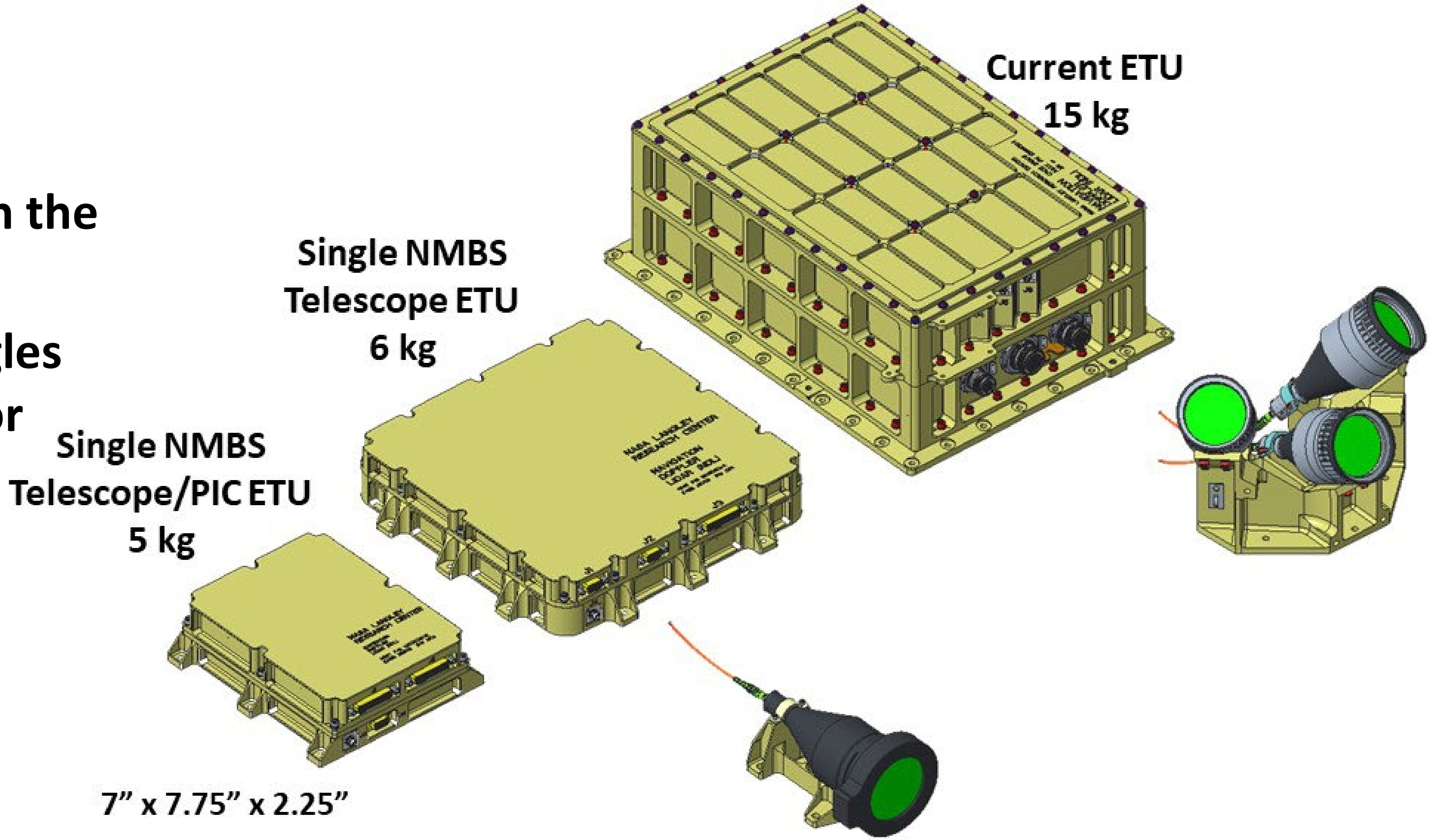






Next Generation NDL

- Leverages lessons learned from build and test of ETUs
- Minimize effects of vehicle vibration
- Utilizes advanced photonic technologies
- Reduce size by 9X and mass by 3X
- Expand operational capabilities:
  - Extend operational range to > 10 km on the Moon and Mars
  - Incorporate air data (air speed and angles of attack and sideslip) measurement for atmospheric landing



NDL: On Path for Widespread Use

- **Upcoming lunar missions will pave the path for future missions**
- **Commercialization is well underway by licensee (Psionic) for both space and non-space markets:**

Autonomous ground and air vehicles

Spaceflight units for landing and Rendezvous Proximity Operations and Docking (RPOD)

Autonomous Rovers

Space Domain Awareness

27

Aircraft navigation in GPS-deprived environment