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

Farzin Amzajerdian
NASA Langley Research Center

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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
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

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<td>Hazard Detection and Altimetry</td>
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<tr>
<td>SPLICE HDL</td>
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<td>Flash</td>
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<td>FMCW</td>
<td>Farzin Amzajerdian/LaRC</td>
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**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

### 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

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**Kodiak MEB**
- Kodiak MEB: 31.75 x 26.42 x 12.95 cm
- 8.3kg

**Ocellus MEB**
- Ocellus MEB: 24.19 x 18.54 cm
- 3.145kg

**Kodiak FEB**
- Kodiak FEB: 34.12 x 33.66 x 16.95 cm
- 8.56kg

**Ocellus FEB**
- Ocellus FEB: 23.4 x 23.2 x 12.7 cm
- 3.017kg
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.

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 x 16 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  

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# ELSA Breadboard Units

## MIT/Lincoln Labs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BBU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>580 x ? x ? mm³</td>
</tr>
<tr>
<td>Volume</td>
<td>15625 cm³</td>
</tr>
<tr>
<td>Mass</td>
<td>14.5 kg</td>
</tr>
<tr>
<td>Power</td>
<td>100 W</td>
</tr>
</tbody>
</table>

## Sigma Space

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BBU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>430 x 259 x 181 mm³</td>
</tr>
<tr>
<td>Volume</td>
<td>21049 cm³</td>
</tr>
<tr>
<td>Mass</td>
<td>12.9 kg</td>
</tr>
<tr>
<td>Flight</td>
<td>~9kg CBE</td>
</tr>
<tr>
<td>Power:</td>
<td></td>
</tr>
<tr>
<td>Altimetry</td>
<td>76 W</td>
</tr>
<tr>
<td>Imaging</td>
<td>300W x 1.8 s</td>
</tr>
</tbody>
</table>
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)

Altimetry:
- 20 km

A-TRN:
- 15 km
- Updating IMU and reducing position errors
- Acquire low-resolution 3D terrain images to identify known features

HDA:
- 5 km

HRN:
- 1 km
- Acquire elevation maps and select landing location
Flash Lidar as a Landing Sensor

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

Multiple 3-D frames to generate a high-resolution DEM.
Development and Testing of Flash Lidar with Real-Time SR Algorithm at NASA LaRC

- 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
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)
NDL ETU Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Static Platform</th>
<th>Landing Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum LOS Range</td>
<td>~ 14 km</td>
<td>7.0 km</td>
</tr>
<tr>
<td>Maximum LOS Velocity</td>
<td>+/- 218 m/sec</td>
<td>+/- 218 m/sec</td>
</tr>
<tr>
<td>LOS Velocity Noise @ 3000 m</td>
<td>0.09 cm/sec</td>
<td>8.3 cm/sec</td>
</tr>
<tr>
<td>LOS Range Noise @ 3000 m</td>
<td>0.10 m</td>
<td>8.2 m</td>
</tr>
<tr>
<td>Data Rate</td>
<td>20 Hz</td>
<td></td>
</tr>
</tbody>
</table>

- 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
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
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
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
- Aircraft navigation in GPS-deprived environment
- Space Domain Awareness