Recent Advances in Photon-Counting, 3D Imaging Lidars

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Why Photon Counting?

- Most efficient 3D lidar imager possible; each range measurement requires only one detected photon as opposed to hundreds or thousands in conventional laser pulse time of flight (TOF) altimeters.

- High efficiency translates to either
  - significantly less mass, volume, and prime power; or
  - orders of magnitude more imaging capability.

- Single photon sensitivity combined with fast recovery multistop timing capability enables lidar to penetrate porous obscurations such as vegetation, ground fog, thin clouds, water columns, camouflage, etc.

- Makes contiguous, high resolution topographic mapping and surveying on a single overflight possible with very modest laser powers and telescope apertures – even from orbital altitudes.
2nd Generation USAF “Leafcutter”

- Transmitter is a low-energy (6 μJ), high rep-rate (to 22 kHz), frequency doubled (532 nm), passively Q-switched microchip laser with a 710 psec FWHM pulsewidth.

- Diffractive Optical Element (DOE) splits green output into 100 beamlets (~50 nJ @ 20 kHz = 1 mW per beamlet) in a 10 x 10 array. Residual 1064 nm energy can be used for polarimetry.

- Returns from individual beamlets are imaged by a 3 inch diameter telescope onto matching anodes of a 10x10 segmented anode micro-channel plate photomultiplier.

- Each anode output is input to one channel of a 100 channel multi-stop timer to form a 100 pixel 3D image on each pulse. Individual images are contiguously mosaiced together via the aircraft motion and an optical scanner (100 pixels @ 22 kHz = 2.2 million 3D pixels/sec!).

- The high speed, 4” aperture, dual wedge scanner can generate a wide variety of patterns. The transmitter and receiver share a common telescope and scanner.
Sample Data from “Leafcutter”

Single Overflight at AGLs between 2 kft (left) and 8.2 kft (right)
Applications: Forest Management, Biomass Measurement, Under Canopy Surveillance

10 m wide strips
NASA Mini-ATM for Cryospheric Studies

Designed for Viking 300 UAV
Weight: 28 lbs (including IMU)
Volume: ~1 cu ft (0.028m³)
First flight data: 10/3/2012

100 beams, 25 pixels (4 beams per anode)
Holographic conical scanner to ± 45 deg
Design speed = 56 knots

Manned Test Flight: 10/3/12; 1.5 kft

6 sec of data, Mojave Desert, CA
Mini-ATM Performance vs AGL (@ 56 knots)
(for cryosphere studies – exceeds ATM* performance at all AGLs)

*ATM = Airborne Topographic Mapper (NASA)
HRQLS
(High Resolution Quantum Lidar System)

Size: 0.48m x 0.63m x 0.83 m (0.25m³)
Measurement Rate: up to 2.5 million 3D pixels/sec
A/C Design Velocity: <200 knots
AGL Range: 6.5 to 18 kft

Two wide angle cameras
Dual Wedge Scanner
Variable Cone Angle: 0 to ± 20°

Laser
Telescope
Multichannel Ranging Receiver
HRQLS Performance vs AGL

(@200 knots with maximum 20° scan angle*)

- Limit AGL range between 7 and 18 kft (end of single pulse in flight)
- Swath, km
- 0 0.5 1 1.5 2 2.5 3 3.5 4
- 6 7 8 9 10 11 12 13 14 15 16 17 18

- Areal Coverage, sq km/hr
- 0.01 0.1 1 10 100
- 7 8 9 10 11 12 13 14 15 16 17 18

- Mean Photoelectrons per Pixel
- 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
- 7 8 9 10 11 12 13 14 15 16 17 18

- Per Pixel Prob. of Detection
- 0.1 1 10 100
- 7 8 9 10 11 12 13 14 15 16 17 18

- Measurements per Square Meter
- 10
- 30
- 7 8 9 10 11 12 13 14 15 16 17 18

Red/Mag=snow/ice; brown=soil; green=vegetation; blue=water
SPL 3D mapping of Garrett County, MD (1700 km$^2$) in 12 hours for NASA Carbon Monitoring Study.
HRQLS 3D mapping of Garrett County, MD in 12 hours for NASA Carbon Monitoring Study

Rapid 3D mapping of an entire county (1,700 km²) in high spatial resolution

Velocity = 150 knot (278 km/hr)
Scan Angle = ±10 deg
AGL = 7500 ft (2.3 km)
Swath = 0.81 km
Coverage: 224 km²/hr
Garrett County Coal Mine

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Scan Angle = ±10 deg
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Coverage: 224 km²/hr
HRQLS: Tree Canopies

Heavily Forested, Mountainous Area in Garrett County, Maryland
Elevation: Blue (725 m) to Red (795 m); Delta = 70 m
HRQLS: Bathymetry of Muddy Drainage Pond

From an AGL of ~2000 ft, HRQLS could penetrate to the bottom of a muddy construction drainage pond to its maximum depth of ~3 m (10 ft), corrected for water index of refraction. Particulate density appears to decrease near shoreline.
Nominal Atmospheric Corrections*

- Uses Marini-Murray Spherical Shell Model of the Atmosphere
- Model also takes into account effects of aircraft pitch, yaw, and roll. (These plots assume all attitude angles are zero)

*Geolocation error is nominally a few cm at HRQLS AMSLs but grows to decimeter levels at higher altitudes. 

![Nominal Radial Correction (m)](image)

![Nominal Vertical Correction](image)

Surface Elevation Above Sea Level
Red = 0 kft
Blue = 2 kft
Green = 5 kft
Customer: NASA Goddard Space Flight Center
• Completed in 10 months
• 24 beam pushbroom lidar (16@532 nm, 8@1064 nm)
• First Flights: December 2010
• Operational AGL: 65,000 ft
• Precursor instrument to NASA ATLAS PC Lidar on ICESat-2 spacecraft to be launched into 500 km near-polar orbit

Sigma provided:
• Electronic subsystems including proprietary TOF electronics
• Mechanical subsystems
• Thermal Control Systems
• Integration, test, and field operations support
Photon-Counting in Greenland in daylight from 65,000 ft
(24 channels: 8 @ 1064 nm; 16@532 nm)

- April 24, 2012
- Sample Channel #6 profiling results (532 nm)
- 10 kHz laser fire rate
**JIM0 3D Imaging Goals**
- Globally map three Jovian moons
- Horizontal Resolution: <10 m
- Vertical Resolution: <1 m

**Worst Case Constraints**
- Europa (last stop) map must be completed within 30 days due to strong radiation field*
  - 348 orbits at 100 km altitude
  - 14.5 km mean spacing between JIMO ground tracks
- Surface Area: 31 million km²

* More recent JPL studies have indicated that, with proper shielding, Europa operations could possibly be extended to 3 or 4 months, allowing higher resolution maps.
Contiguous Mapping of the Jovian Moons

\( h = 100 \text{ km} \) = nominal spacecraft altitude for JIMO mission
\( v_g = 1.30 \text{ to } 1.83 \text{ km/sec} \) = range of spacecraft ground velocities at Jovian moons
\( \alpha = 5.72^\circ \) = scanner cone half angle overfills mean 14.5 km gaps between groundtracks
\( \delta = 10 \text{ m} \) = minimum horizontal spatial resolution per pixel
\( N^2 = 100 \) = number of beamlets/detector pixels in 10x10 array
\( \rho = 0.15^\circ \) = nominal surface reflectance of Earth soil at 532 nm [*conservative since Visual Geometric Albedo = 0.68 (Europa), 0.44 (Ganymede), and 0.19 (Callisto)]
\( n_p = 3 \) = minimum signal photoelectrons per pixel (implies \( P_d >95\% \) but forward and backward looks at the same pixel give \( P_d \sim 99.8\% \).

Scanner Frequency, \( f_{\text{scan}} \): 
(ensures contiguous alongtrack coverage)

\[
f_{\text{scan}} \geq \frac{v_g}{N\delta}
\]

Laser Repetition Rate, \( f_{qs} \): 
(ensures contiguous coverage along conical scan circumference)

\[
f_{qs} \geq \frac{2v_g h \tan \alpha}{(N\delta)^2}
\]

Power-Aperture Product, \( PA \): 
(ensures desired signal strength)

\[
PA = f_{qs} E_t A_r > f_{qs} \frac{n_p \pi h v N^2 h^2 \sec^2 \alpha}{\eta_t \eta_c \eta_r \rho \cos \sigma T_0^2}
\]
**JIMO Mission Requirements**

<table>
<thead>
<tr>
<th>Jovian Moon</th>
<th>Europa</th>
<th>Callisto</th>
<th>Ganymede</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar Mass, $M$ (kg)</td>
<td>$4.80 \times 10^{22}$</td>
<td>$1.08 \times 10^{23}$</td>
<td>$1.48 \times 10^{23}$</td>
</tr>
<tr>
<td>Mean Volumetric Radius, $R$, km</td>
<td>1569</td>
<td>2400</td>
<td>2643</td>
</tr>
<tr>
<td>Surface Area, $10^6$ km$^2$</td>
<td>31</td>
<td>72</td>
<td>87</td>
</tr>
<tr>
<td>Satellite Altitude, $h$ (km)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Ground Velocity, $v_g$ (km/sec)</td>
<td>1.30</td>
<td>1.63</td>
<td>1.83</td>
</tr>
<tr>
<td>Satellite Orbital Period, min</td>
<td>126</td>
<td>154</td>
<td>151</td>
</tr>
<tr>
<td>Mission Duration, $D_i$ (Days)</td>
<td>30</td>
<td>56</td>
<td>60</td>
</tr>
<tr>
<td>3D Imager Resolution, $\delta$ (m)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Minimum Swath Width, $S$ (km)</td>
<td>14.4</td>
<td>14.4</td>
<td>14.4</td>
</tr>
<tr>
<td>Scanner FOV Half Angle, (deg)</td>
<td>5.72</td>
<td>5.72</td>
<td>5.72</td>
</tr>
<tr>
<td>Minimum Scan Frequency, Hz</td>
<td>13.0</td>
<td>16.3</td>
<td>18.3</td>
</tr>
<tr>
<td>Minimum Laser Fire Rate, $f_{qs}$ (kHz)</td>
<td>5.89</td>
<td>7.37</td>
<td>8.27</td>
</tr>
<tr>
<td>Minimum Lidar PA-Product, W-m$^2$</td>
<td>0.80</td>
<td>1.00</td>
<td>1.12</td>
</tr>
</tbody>
</table>

**Bolded red** numbers indicate which Moon is determining the instrument requirement.

The 5.72 deg scan half angle provides ~20 km swath vs 14.5 km mean ground track separation. The large telescope FOV favors a conical scanner to easily correct for spherical aberration effects.
Laser Power – Telescope Aperture Trade

Power-Aperture Product: 1.12 W-m² (Worst Case Ganymede)
Min. Prob. of Detection per Pixel: \( P_d = 95\% \) (15% surface reflectance)

**ICESat-2 Laser @ 532 nm**
Power: 0.5 mJ @10 kHz = 5 W

**Mars Orbiter Laser Altimeter**
Telescope Diameter: 50 cm

Since each 10m x 10 m ground pixel is looked at twice - i.e. in the forward and backward scan segments – the actual probability of detecting a given pixel is

\[
P_D = P_d (2 - P_d) = 0.95 (1.05) = 0.9975
\]
Scan Patterns at Ganymede

- Forward and backward scans provide two looks at each ground pixel per pass.

Conical Scan Pattern at Ganymede

- Along Track, x
- Cross Track, y

- 20 km Swath
- 14.5 km mean ground track spacing

- Single Scan (0.055 sec @18.3Hz)
- 200 scans (10.9 sec)

- 14.5 km Mean Groundtrack Spacing
- 100 m gap
- \( v_g = 1.83 \text{ km/sec} \)
Projected DSN Data Rates*

Surface Range Measurements per Second: 100 beamlets @ 8.3 kHz = 0.83 MHz
Bits per Raw Range Measurement @ 100 km: 24 (1cm); 17 (1m resolution)
Raw Data Rate: 17 bits x 0.83 MHz = 14 Mbps (noise editing and no compression)
After Lossless Compression (Rice): (17+99*12) bits*8.3 kHz)/2 = 5 Mbps
For 2020 DSN rates from Jupiter: 1 sec of data requires 1 sec of DSN station time
Sending cm accuracy topographic data from Mars or its moons would be trivial!

<table>
<thead>
<tr>
<th>Spacecraft Capabilities</th>
<th>Data Rate Today</th>
<th>Data Rate ~2020</th>
<th>Data Rate ~2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>DSN Antennas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mars (0.6 AU)</td>
<td>7 Mbps</td>
<td>20 Mbps</td>
<td>400 Mbps</td>
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<tr>
<td></td>
<td>355 Kbps</td>
<td>1 Mbps</td>
<td>*1.2 Gbps</td>
</tr>
<tr>
<td>Mars (2.6 AU)</td>
<td>83 Kbps</td>
<td>250 Kbps</td>
<td>21 Mbps</td>
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<tr>
<td></td>
<td>16 Mbps</td>
<td>115 Mbps</td>
<td>4.7 Mbps</td>
</tr>
<tr>
<td>Jupiter</td>
<td>24 Kbps</td>
<td>71 Kbps</td>
<td>4 Mbps</td>
</tr>
<tr>
<td></td>
<td>16 Mbps</td>
<td>115 Mbps</td>
<td>4.7 Mbps</td>
</tr>
<tr>
<td>Saturn</td>
<td>3 Kbps</td>
<td>8 Kbps</td>
<td>160 Kbps</td>
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<tr>
<td></td>
<td>245 Kbps</td>
<td>19 Kbps</td>
<td>4.7 Mbps</td>
</tr>
<tr>
<td>Neptune</td>
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</table>

Summary

• Our 100 beam scanning lidars have provided decimeter level (horizontal) and few cm (vertical) resolution topographic maps from aircraft AGLs up to 28 kft*. Data rates vary between 2.2 and 3.2 million 3D pixels per second.

• The multibeam pushbroom NASA MABEL lidar has operated successfully at AGLs up to 65 kft.

• Our low deadtime (1.6 nsec) detectors and range receivers permit multiple range measurements per pixel on a single pulse.

• Our moderate to high altitude lidars built to date have been designed to provide contiguous topographic coverage on a single overflight at aircraft speeds up to 220 knots (407 km/hr).

• We are currently implementing inflight algorithms to edit out solar and/or electronic noise and to correct for atmospheric effects in preparation for near realtime 3D imaging.

• Our smallest lidar, Mini-ATM, designed for cryospheric measurements, weighs only 28 pounds (12.7 kg), occupies 1 ft³ (0.028 m³), has a ± 45 degree conical scan, fits in a mini-UAV, and covers more area with higher spatial resolution than the much larger and heavier predecessor NASA ATM system.

• Using a laser comparable to that developed for the ATLAS lidar on ICESat-2 and a MOLA-sized telescope (~50 cm) in a 100 km orbit, one could globally map the three Jovian moons with better than 5 m horizontal resolution in 1 month (Europa) or 2 months (Ganymede and Callisto) each.

*Sigma customer has not yet given permission to show 28 kft data but spatial resolution is comparable to HRQLS images at almost 4x the AGL.