Compact Lightweight Lidar for UAV-based Topographic and Bathymetric Mapping

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**PILLS*: A Compact Lightweight Lidar**

- **PILLS: System overview**
  - Performance goals
  - Pushbroom Imaging lidar concept of operations
  - PILLS design and as-built configuration

- **System test and evaluation**
  - Ocean flight test
  - Riverene flight tests

- **Next steps**
  - Measurement refinement
  - System upgrades
  - Manned/unmanned flight tests

*PILLS: Pushbroom Imaging Lidar for Littoral Surveillance*
Compact Lightweight Lidar for Topographic and Bathymetric Mapping (history)

- ONR SBIR program to develop compact lightweight lidar system compatible with Navy Tier II UAV for bathymetry, terrain, and urban area mapping
  - Measurement performance equal or better than existing manned systems:
    - 1000’ swath, 1m horiz. sampling, 2m absolute geodetic registration
    - 25cm absolute vertical precision (ref to geoid), 3kD depth performance
  - Physical constraints:
    - Compatible with Navy Tier II UAV: RQ-21A Integrator
      - < 1 cu ft, 240 W prime power (max), ~ 30 lbs

- Solution: Pushbroom Imaging Lidar
  - Leverages mature HW from airborne mine countermeasures systems

- ONR Phase 2 SBIR completed with bathymetric flight test and performance characterization in September 2013 (manned flight test)
  - Lidar radiometric, ranging, and resolution within spec
  - Absolute registration (to geoid) requires nav system refinement
Pushbroom Imaging Lidar Approach

Single Pulse Range-Azimuth Image

3D Map Constructed from Multiple Pulses
**Pushbroom Lidar Legacy: MCM Systems**

**Airborne Laser Mine Detection System**
- Detection and classification of surface and near-surface mines
- Status: in low-rate initial production

**Electro-Optic Identification (EOID) for AQS-20 towed minehunting system**
- Identification of bottom mines
- Status: in low rate initial production
### PILLS Performance Objectives

<table>
<thead>
<tr>
<th>Measurement performance</th>
<th>PILLS Objective</th>
<th>Design Point</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath width</td>
<td>300m @ 1000' (0.9 x alt)</td>
<td>+/- 25 degrees from nadir</td>
<td>1000' nominal flight altitude</td>
</tr>
<tr>
<td>Horizontal sampling density</td>
<td>1m x 1m</td>
<td>30 Hz PRF, 275pixels</td>
<td>Subsampled from MCM systems</td>
</tr>
<tr>
<td>Maximum depth</td>
<td>3kD</td>
<td>30mJ/pulse</td>
<td>1W DPSS Nd:YAG laser (air cooled)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36mm aperture</td>
<td></td>
</tr>
<tr>
<td>Horizontal accuracy</td>
<td>&lt; 2.0m, 1 sigma</td>
<td>Dedicated IMU (attitude)</td>
<td>MMQ with post-processing</td>
</tr>
<tr>
<td>Vertical accuracy</td>
<td>25 cm, 1 sigma</td>
<td>GPS Precise Point Positioning</td>
<td>Novatel with post-processing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nsec pulsewidth, 1 nsec sampling</td>
<td>10-15cm ranging precision</td>
</tr>
</tbody>
</table>

**Physical characteristics**

- **Platform**: RQ-21A Integrator (UAV) Integrator Payload bay
- **Platform speed**: 55-90kts (typical) 60kt cruise
- **Scanner**: No scanner
- **System cooling**: Ambient air
- **Power required**: <7A @ 28VDC (200W) 231W (max), 150W (typ)
- **Total system volume**: 0.8 cubic feet
- **Total system weight**: ~ 30 lbs 37lbs (carbon fiber) 44 lbs as-built (Al), ~ 32 lbs with AIRTRAC laser
- **Nominal operational altitude**: 300m
- **Min eye safe altitude**: 25m
- **Processing**: Post-processing Post-processing nav correction

**Performance comparable to current manned systems (IHO standards), in a configuration compatible with STUAS (RQ-21A)**
Physical Layout in RQ-21 STUAS (design)

PILLS fits entirely within 4” x 9” x 39” Integrator payload bay weighs ~ 32lbs, draws < 240W, occupies < 0.9 ft³
Pushbroom Imaging Lidar: As-Built Configuration

Built on aluminum strongback to facilitate flight operations (total weight ~ 44 lbs)
System Integration Completed 2012
PILLS Aircraft Integration Experience

- PILLS has been installed onto 4 different aircraft
  - Mechanical interface: compatible with industry-standard PAV mount
  - Electrical interfaces:
    - Power: 10A at 28VDC (standard on survey aircraft)
    - Tap aircraft GPS antenna or use dedicated antenna (suction cup mount)
  - Operations: Single operator with laptop
- Each different install extremely fast and easy
  - All four aircraft had not been fit checked until day of flight test
  - Installs would take first part of test day morning
- Sensor removal and pack up would take less than 30min
**PILLS Flight Log (through June 2014)**

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Aircraft</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/18/2013</td>
<td>Wilcox Playa</td>
<td>Cessna 310</td>
<td>Terrestrial. Sensor performance initial check</td>
</tr>
<tr>
<td>8/14/2013</td>
<td>Catalina Island</td>
<td>Cessna 310</td>
<td>Terrestrial/Bathy. Flew over harbors and along coastlines. Also flew over section of CO river.</td>
</tr>
<tr>
<td>9/25/2013</td>
<td>Ft Lauderdale</td>
<td>Cessna 210</td>
<td>Terrestrial/Bathy. Flew over different regions of the area.</td>
</tr>
<tr>
<td>11/27/2013</td>
<td>Wilcox Playa</td>
<td>Cessna 320</td>
<td>Terrestrial. Flew over ground truth targets in multiple directions for sensor bias ID.</td>
</tr>
<tr>
<td>5/20/2014</td>
<td>Tucson</td>
<td>Cessna 310</td>
<td>Terrestrial. Flew over ground truth targets in multiple directions for sensor bias ID.</td>
</tr>
<tr>
<td>5/21-22/2014</td>
<td>Colorado River</td>
<td>Cessna 310</td>
<td>Simultaneous lidar/MWIR collection for current and bathymetric retrieval</td>
</tr>
<tr>
<td>6/17-20/2014</td>
<td>San Diego</td>
<td>Piper Navajo</td>
<td>Simultaneous lidar/multispectral collection for high resolution imaging and bathymetry</td>
</tr>
</tbody>
</table>

*Note: all flights on “platform of opportunity” (commercial photogrammetry aircraft)*
PILLS Bathymetric Flight Test (Ft Lauderdale)
Ft Lauderdale Bathymetric Comparison
Bathymetric Comparison Summary (Dec 2013)

- Initial comparison of PILLS bathymetry and truth (NOAA charts and SHOALS data) is very encouraging
  - Features align very well over 2km span from shallow (<10m) to deep (>35m) water; however,
  - Offset of < 1m observed in PILLS data (possible tidal effect?)
    - PILLS depth measured relative to local surface elevation

- Refinements in work:
  - Hardware:
    - Implement full post-processing corrections to GPS and IMU data
    - Measure and remove static bias between optical axis and IMU
    - Measure and remove static distortion (optical train)
  - Software:
    - Implement surface elevation estimation and correction
    - *Make processing software more robust!*
Riverene Flight Test (Colorado River – May 2014)

• Simultaneous lidar/MWIR collection for measurement of bathymetry (lidar), surface gradient (lidar), and surface current (MWIR)
  – Primary factors for discharge modeling and estimation
Raw PILLS data: Colorado River
Colorado Flight Test Images (May 2014)

- Evaluating alternative applications under NAVAIR SBIR
  - Hardware system improvements (in-work)
    - Improved narrowband filter for better daylight noise rejection
    - Advanced receiver for increased dynamic range and lower noise
    - Implement on-board real-time processing system (detection)

- Anticipate initiation of UAV integration and flight test
  - Hardware adaptation for unmanned flight:
    - Weight reduction and form factor for RQ-21 payload bay
    - RF link for remote operation
  - Software adaptation for unmanned flight:
    - Automatic surface following (timing control)
    - Adaptation for man-in-loop remote operation
    - On-board real-time point cloud generation TBD

- Software will evolve through all efforts to improve measurement precision and robustness

- Anticipate ongoing flight test over land and water (ocean and riverine), including simultaneous passive/active collections
  - Capability for simultaneous measurement of:
    - bathymetry, surface current, directional wave spectra, etc

<table>
<thead>
<tr>
<th>Data Products</th>
<th>IRIS</th>
<th>PILLS</th>
<th>Inverse Model</th>
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</thead>
<tbody>
<tr>
<td>Depth - Lidar</td>
<td></td>
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<td></td>
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<tr>
<td>River bank topography</td>
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<td>Turbidity</td>
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<td>Water slope</td>
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<tr>
<td>Surface temperature</td>
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<tr>
<td>Surface currents</td>
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<tr>
<td>Bottom roughness</td>
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<tr>
<td>Depth - Inversion</td>
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<td>✓</td>
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*IRIS: Infra-red Imaging System*
Summary

- PILLS demonstrated potential to provide high resolution bathymetry/topography from a small UAV
- Rapidly maturing processing software for robust point-cloud generation for a broad range of operating conditions
  - Paves the way for on-board real-time processing
- Compact lightweight configuration provides a cost-effective roll-on/roll-off bathymetric capability for manned aircraft
- Simultaneous lidar+EO measurement will provide new capabilities for investigation of ocean and riverine dynamics
  - Directional wave spectra and surface currents (open ocean)
  - Bathymetry, surface gradient, surface current (riverine)
Backup
Example IRIS + Lidar for Riverene dynamics

Measured by airborne remote sensing:
- Currents
- Bathymetry
- Waterlines
- Water Slope
- Discharge

Data from Columbia River
- LIDAR data (2011) provided by PNNL (Marshal Richmond)
- IRIS data by Areté (2010) under DARPA funding

Excellent Agreement with USGS discharge

Columbia River discharge calculated at ~0400 PDT on 10/8/2011

Discharge using only airborne measurements

Surface slope using only airborne measurements

IRIS/LIDAR Water Surface Elevation
## Integrated Passive/Active for Littoral/Open Ocean

<table>
<thead>
<tr>
<th>Data Products</th>
<th>PILLS</th>
<th>Mid-wave IR (IRIS)</th>
<th>EO (ROCIS)</th>
<th>EO (nadir)</th>
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<tbody>
<tr>
<td>Depth - Lidar</td>
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<tr>
<td>Turbidity</td>
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