NASA ESTO Lidar Technologies Investment Strategy

2016 Decadal Update

Azita Valinia & George J. Komar

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NASA Earth Science Technology Office

David M. Tratt, William Lotshaw, Kevin Gaab, David Mayo

The Aerospace Corporation
ESTO Programs

ESTO manages, on average, 120 active technology development projects. Most are funded through the five primary program lines below. Nearly 700 projects have completed since 1998.

<table>
<thead>
<tr>
<th><strong>Observation</strong></th>
<th><strong>Information</strong></th>
<th><strong>Validation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument Incubator Program (IIP)</td>
<td>Advanced Component Technologies (ACT)</td>
<td>Sustainable Land Imaging-Technology (SLI-T)</td>
</tr>
<tr>
<td>Innovative remote sensing instrument development from concept through breadboard and demonstration (<em>Average award: $1.5M per year over three years</em>)</td>
<td>Critical components and subsystems for advanced instruments and observing systems (<em>average award: $300K per year over three years</em>)</td>
<td>New technologies and reduced costs for future land imaging (Landsat) measurements (<em>First solicitation released in FY16 (average award: TBD)</em>)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Advanced Information Systems Technology (AIST)</strong></th>
<th><strong>Lidar Investment</strong></th>
<th><strong>TRL</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovative on-orbit and ground capabilities for communication, processing, and management of remotely sensed data and the efficient generation of data products (<em>average award: $500K per year over two years</em>)</td>
<td>TRL 3-6</td>
<td>Lidar Investment</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th><strong>In-Space Validation of Earth Science Technologies (InVEST)</strong></th>
<th><strong>Lidar Investment</strong></th>
<th><strong>TRL</strong></th>
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<tr>
<td>On-orbit technology validation and risk reduction for small instruments and instrument systems that could not otherwise be fully tested on the ground or airborne systems (<em>average award: $1-1.8M per year over three years</em>)</td>
<td>TRL 2-5</td>
<td>Lidar Investment</td>
</tr>
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</table>
Objectives:

- Survey the 2016 state-of-the-art in lidar technology as it pertains to Earth science measurements
  - Last survey was done in 2006

- Identify capability gaps needed to enable Earth science goals

- Adjust investment strategy as needed

[Diagram with dates and workshops]

[Link: https://esto.nasa.gov/LidarStrategies/index.html]
Scope of the Survey: Laser Remote Sensing Applications & Techniques

Differential Absorption Lidar (DIAL)
- Carbon Dioxide
- Ozone, Water Vapor

Doppler Lidar
- Wind Field

Backscatter Lidar
- Clouds
- Aerosols
- Phytoplankton Physiology
- Ocean Carbon/Particle Abundance

High-Precision Ranging & Altimetry
- Geodetic Imaging
- Vegetation Structure/Biomass
- Earth Gravity Field
ESTO Projects Distribution According to Science Measurement

- Risk Reduction: 19%
- Cross Cutting: 18%
- Winds: 12%
- Atmospheric Composition: 35%
- Topography/Ranging: 14%
- Biological/Physical Oceanography: 2%
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TRL Advancement for Completed Laser Related ESTO Tasks

![Graph showing TRL advancement for different programs.](image)

**Program**
- IIP: Avg. TRL_In = 3.0, Avg. TRL_Out = 4.8
- ACT: Avg. TRL_In = 2.6, Avg. TRL_Out = 4.0
- ATI: Avg. TRL_In = 3.2, Avg. TRL_Out = 4.0
- LRRP: Avg. TRL_In = 3.1, Avg. TRL_Out = 3.7
- Other: Avg. TRL_In = 2.2, Avg. TRL_Out = 2.5

**Percentage of Tasks**
- TRL Advancement:
  - 0: 25.0%
  - 1: 40.0%
  - 2: 25.0%
  - 3: 10.0%

- Final TRL:
  - 0: 0.05
  - 1: 0.15
  - 2: 0.4
  - 3: 0.5
  - 4: 0.4
  - 5: 0.2
  - 6: 0.15
  - 7: 0.05

**Program**
- IIP
- ACT
- ATI
- LRRP
- Other
The Lidar Technology Needs Landscape

- **Wavelength Band**
  - **UV**: Tropospheric Ozone, Tropospheric Winds
  - **VIS**: Clouds & Aerosols, Water Vapor, Ocean Mixed Layer, Phytoplankton
  - **NIR**: Clouds & Aerosols, Water Vapor, 3D Biomass, Gravity Field
  - **SWIR**: Methane, Water Vapor, Carbon Dioxide, Tropospheric Winds
  - **MWIR**: Methane

- **Measurement**
  - 1 µm Primary
  - Harmonic Converters
  - Cascaded & Parametric Converters
  - 1.5 - 1.7 µm Primary
  - 2 µm Primary
  - 1 µm Primary

- **Technology Transmitters**
  - High-Efficiency Array Detectors
  - High-Bandwidth Array Detectors
  - High-Efficiency Cryogenic Array
  - Multiple Apertures

- **Technology Receivers**
  - lightweight Deployable >2m Collectors
  - Wide Field-of-View Receivers
  - On-Board Processing and Compression

- **Technology Information Systems**
  - Intelligent Sensor Management, Health, & Safety
  - Radiation-Hardened Deep-Submicron Microelectronics

- **Technique Sensor System Type**
  - Differential Absorption Lidar
  - Elastic Backscatter Lidar
  - Direct Detection Doppler Lidar
  - Fluorescence Lidar
  - Laser Altimeter
  - Laser Ranger
  - Coherent Doppler Lidar
  - Integrated-Path Differential Absorption
Adapted and updated from: Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing (NRC, 2014).
Laser Remote Sensing Taxonomy: Space

Adapted and updated from: Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing (NRC, 2014).
NASA Earth Science 2007 Decadal Survey Missions

- Mapping laser altimeter system
  - LIDAR Surface Topography (LIST)
  - Laser satellite-to-satellite interferometer
    - Gravity Recovery and Climate Experiment - II (GRACE - II)
  - Precipitation and Hydrology (PATH)
  - Snow and Cold Land Processes (SCLP)
  - Global Mission (GACM)

- 1.57 or 2.06 µm column lidar
  - Coherent and/or direct detection Doppler wind lidar(s)
  - Three-Dimensional Winds from Space Lidar (3D-Winds)

- Lasers
  - 1 µm laser altimeter
  - Ice, Cloud, and Land Elevation Satellite II (ICESat-II)
  - Pre-Aerosol - Cloud - Ecosystems (PACE)
  - Soil Moisture Active Passive (SMAP)

- Active Sensing of CO2 Emissions (ASCENDS)
- Deformation, Ecosystem Structure and Dynamics of Ice (Radar (DESDynI -R)

- Climate Absolute Radiance and Refractivity (CARR)
- Multibeam cross-track dual-wavelength lidar

- LIDAR Surface Topography (LIST)
  - Mapping laser altimeter system
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- Three-Dimensional Winds from Space Lidar (3D-Winds)
## 2007 Decadal Survey Technology Capability Gaps

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Capability Gap</th>
<th>TRL</th>
<th>“Greatest Challenge” TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ (ASCENDS)</td>
<td>Maturity and readiness of tunable lasers meeting measurement requirements</td>
<td>3-4</td>
<td>1.57-µm power amplifier</td>
</tr>
<tr>
<td>CO₂ (ASCENDS)</td>
<td>High-efficiency detectors in 1.5-2 µm range</td>
<td>5</td>
<td>Space qualification/ radhard assurance</td>
</tr>
<tr>
<td>Aerosol/Clouds/Ecosystems (ACE)</td>
<td>Readiness of laser systems</td>
<td>4-5</td>
<td>Space qualification</td>
</tr>
<tr>
<td>Aerosol/Clouds/Ecosystems (ACE)</td>
<td>Field-widened interferometric receiver</td>
<td>4</td>
<td>Wavefront error</td>
</tr>
<tr>
<td>3D Biomass (NISAR/GEDI, formerly DESDynl)</td>
<td>Readiness of laser systems High-bandwidth, high-sensitivity detector arrays</td>
<td>4-5</td>
<td>Space qualification</td>
</tr>
<tr>
<td>Topography (LIST in 2007 Decadal)</td>
<td>Multiple aperture transmitter</td>
<td>4-5</td>
<td>Multiple aperture system</td>
</tr>
<tr>
<td>Topography (LIST in 2007 Decadal)</td>
<td>Multiple aperture/beam receiver</td>
<td>3</td>
<td>Large-area detector with high readout bandwidth</td>
</tr>
<tr>
<td>3D Winds</td>
<td>Reliable 355-nm transmitters meeting measurement requirements; 2-µm technology readiness and reliability</td>
<td>3-4</td>
<td>Laser reliability, readiness</td>
</tr>
<tr>
<td>3D Winds</td>
<td>Single telescope supporting multiple look angles</td>
<td>3</td>
<td>Large-aperture receive optics (HOE/DOE, interferometer)</td>
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### New Measurement Concept (since 2007) Capability Gaps

<table>
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<th>Capability Gap</th>
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<th>TRL Assessment; Greatest TRL Challenge</th>
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<td>Phytoplankton</td>
<td>Blue-green laser technology readiness</td>
<td>3</td>
<td>2: Robust and reliable laser and frequency conversion system</td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>Detector performance</td>
<td>2</td>
<td>Dead-time, afterpulsing</td>
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<tr>
<td>Ocean Mixed Layer</td>
<td>Blue-green laser technology readiness</td>
<td>2</td>
<td>Robust and reliable laser and frequency conversion system</td>
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<tr>
<td>Ocean Mixed Layer</td>
<td>Detector performance</td>
<td>2</td>
<td>Dead-time, afterpulsing</td>
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<tr>
<td>Non-CO₂ Greenhouse Gases</td>
<td>Tunable laser transmitter for CH₄ IPDA</td>
<td>4-5</td>
<td>3-4: Er:YAG and seed sources</td>
</tr>
<tr>
<td>Non-CO₂ Greenhouse Gases</td>
<td>Low-noise, few-photon-sensitive detector array</td>
<td>5</td>
<td>Space qualification</td>
</tr>
<tr>
<td>Ozone</td>
<td>Robust UV laser transmitter</td>
<td>2</td>
<td>2: Robust and reliable UV generation 290-320 nm</td>
</tr>
<tr>
<td>Ozone</td>
<td>Large-aperture collector; detector efficiency</td>
<td>4</td>
<td>Deployability</td>
</tr>
<tr>
<td>Water vapor profiles</td>
<td>Multi-wavelength NIR laser transmitter readiness</td>
<td>2</td>
<td>2: Robust and reliable 720-nm, 820-nm sources</td>
</tr>
<tr>
<td>Water vapor profiles</td>
<td>Detector performance</td>
<td>4</td>
<td>Low-noise, few-photon-sensitive detector array</td>
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Transmitter Technologies

• Since the last Decadal, fiber-laser average power capability now rivals that of traditional bulk solid-state systems and may be used in more of the science measurement scenarios. Fiber lasers have the distinct advantage of being compact, immune to misalignment, and offer higher WPE. Fiber/bulk solid-state hybrid laser technologies present potential solutions to difficult performance and wavelength requirements.

• Emerging laser materials (e.g., Cr:ZnSe) and improvements in nonlinear optical (NLO) materials have expanded options for wavelength generation in near-UV, SWIR/MWIR. Dramatic improvements in pump laser-diode electrical efficiency have significantly improved the WPE of both bulk solid-state and fiber-based lasers.

• High power lasers and adequate thermal systems are among biggest challenges. High conductivity thermal materials are needed.
Receiver Technologies

- There remains *a need for improved detector performance*, particularly in the area of radiation-hardened multi-element architectures with high quantum efficiency, low noise, low timing jitter, and low afterpulsing.
- Greatest challenge is in the area of under 1 micron in detector performance.
- Reduction in size and weight for receiver telescopes benefit all measurement scenarios.
- Deployable apertures could relax requirements on transmitter technologies and enable measurement scenarios from smaller satellite platforms.
- *Need to develop and mature U.S. industrial base* required for critical system components in the area of: detectors and nonlinear conversion material.
Emerging Technologies

- **New technologies in the area of detectors, lightweight apertures, as well as second and third harmonic generation at lower TRLs** are coming to market that could benefit from further exploration.

- SmallSats have emerged onto the scene in the last decade and demand greater attention to miniaturization. Cross-cutting emerging technologies such as integrated photonics circuitry and deep-submicron microelectronic architectures can prove enabling for SmallSat-based lidar missions and significant SWAP improvements.

- **Model–based systems engineering (MBSE)** should be more effectively employed as an arbitrator between evolving technology options, by enabling parametric trades between aperture size, detector efficiency, laser power, waveform diversity, etc. that could circumvent technological hurdles.

- **MBSE requires robust, high-fidelity modeling and simulation capabilities** in both the environmental and sensor performance domains, which will require strengthening and further development of concurrent engineering tool.