NASA ESTO Lidar Technologies Investment Strategy

2016 Decadal Update

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The Aerospace Corporation

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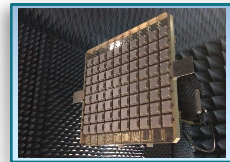
ESTO Programs

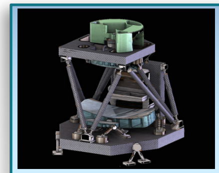
ESTO manages, on average, 120 active technology development projects. Most are funded through the five primary program lines below. Nearly 700 projects have completed since 1998.

Observation

Instrument Incubator Program (IIP) Lidar Investment TRL 3-6
Innovative remote sensing instrument development from concept through breadboard and demonstration *(Average award: $1.5M per year over three years)*



Advanced Component Technologies (ACT) Lidar Investment TRL 2-5
critical components and subsystems for advanced instruments and observing systems
(average award: $300K per year over three years)

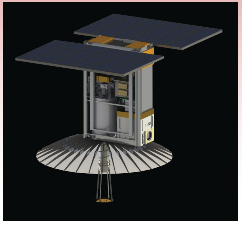


Sustainable Land Imaging-Technology (SLI-T)
new technologies and reduced costs for future land imaging (Landsat) measurements
First solicitation released in FY16 (average award: TBD)

Information

Advanced Information Systems Technology (AIST)
innovative on-orbit and ground capabilities for communication, processing, and management of remotely sensed data and the efficient generation of data products
(average award: $500K per year over two years)

Validation

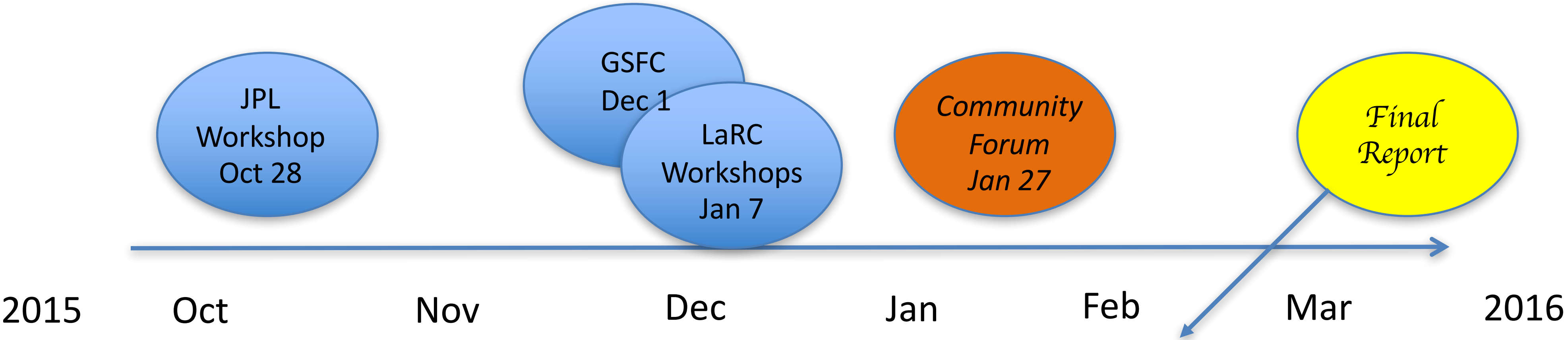


In-Space Validation of Earth Science Technologies (InVEST)
on-orbit technology validation and risk reduction for small instruments and instrument systems that could not otherwise be fully tested on the ground or airborne systems
(average award: $1-1.8M per year over three years)

ESTO 2016 Lidar Investment Strategy Update

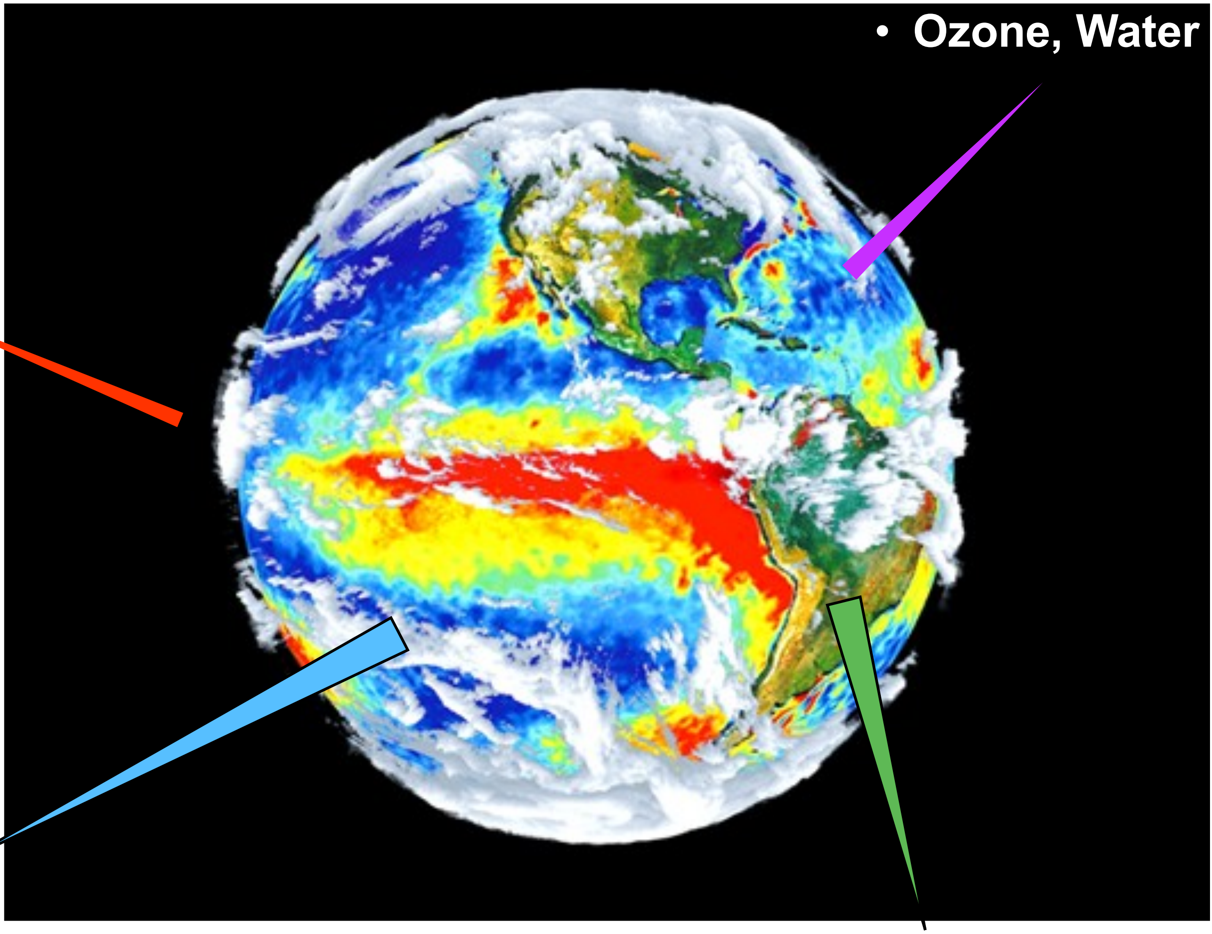
Objectives:

- 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



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

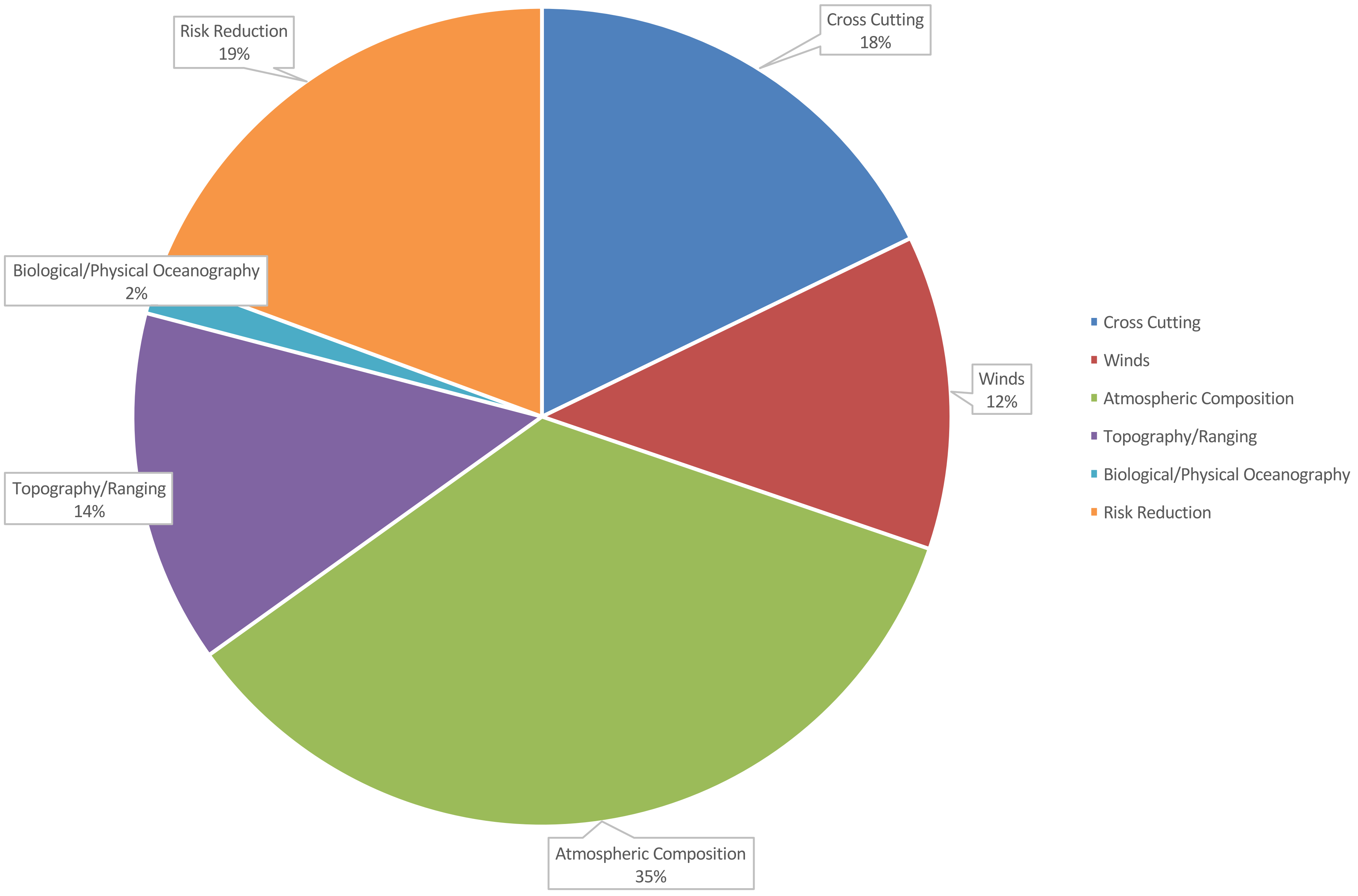
Backscatter Lidar

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

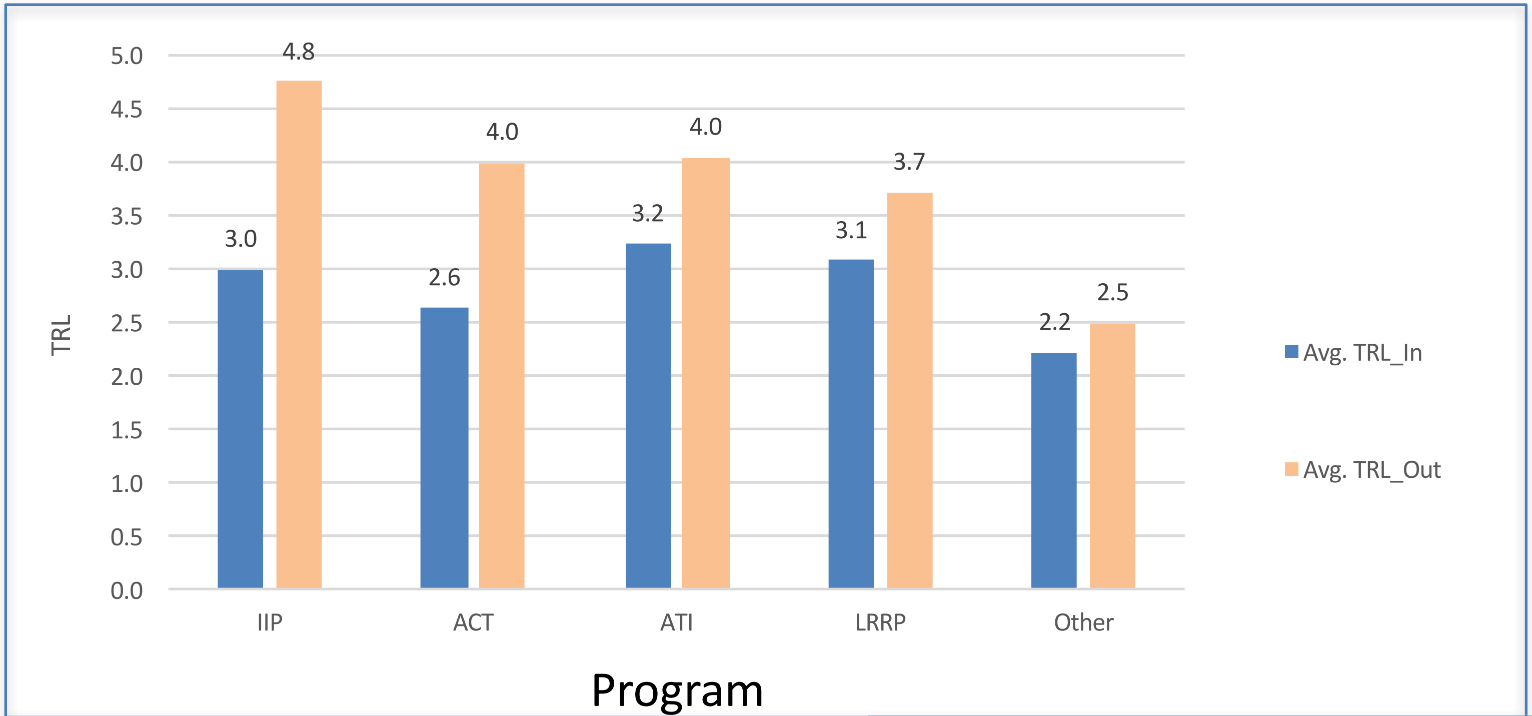
High-Precision Ranging & Altimetry

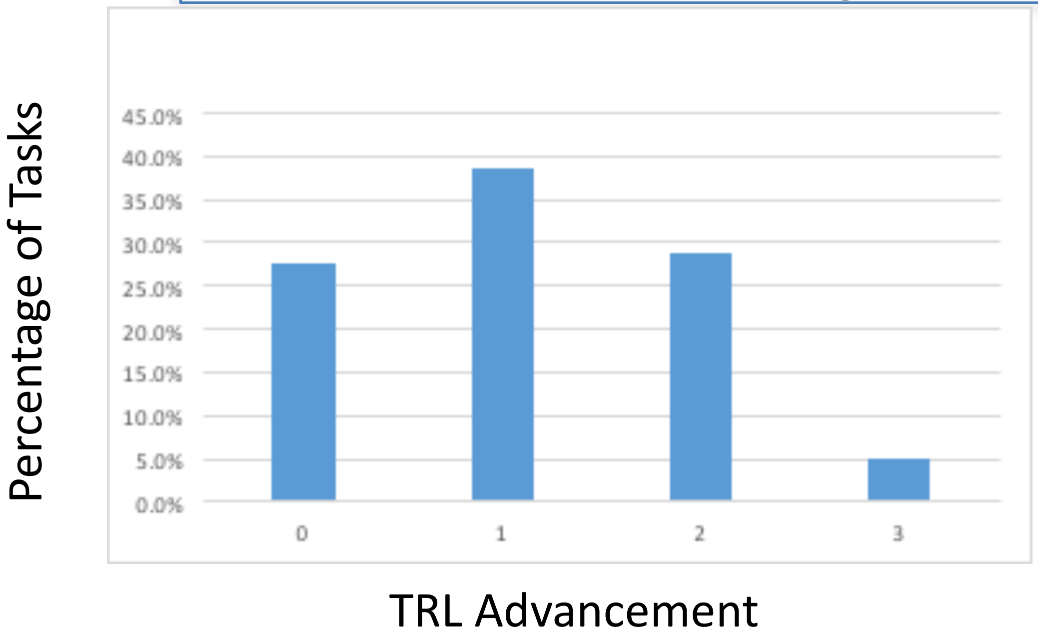
- Geodetic Imaging
- Vegetation Structure/Biomass
- Earth Gravity Field

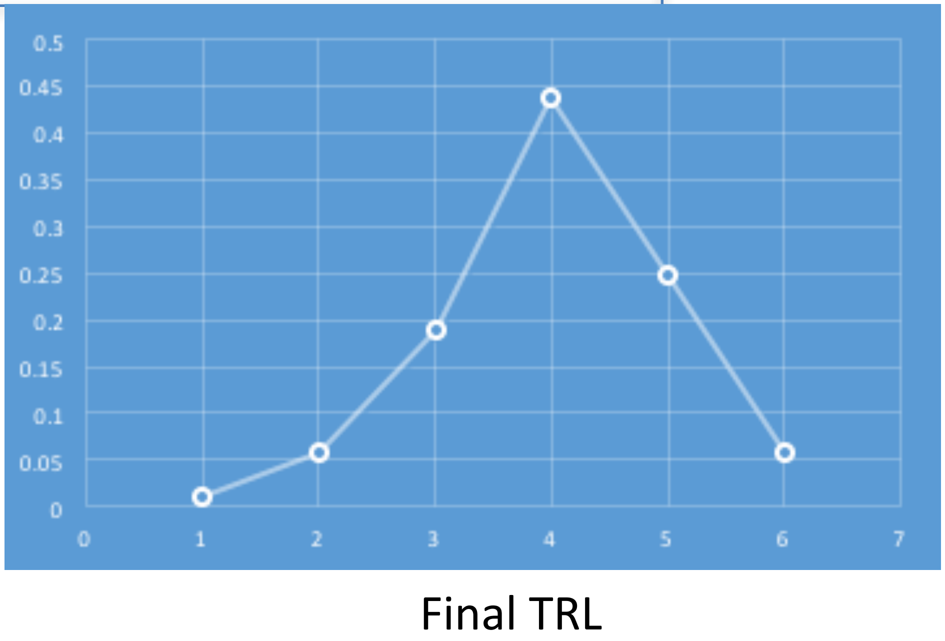
ESTO Projects Distribution According to Science Measurement



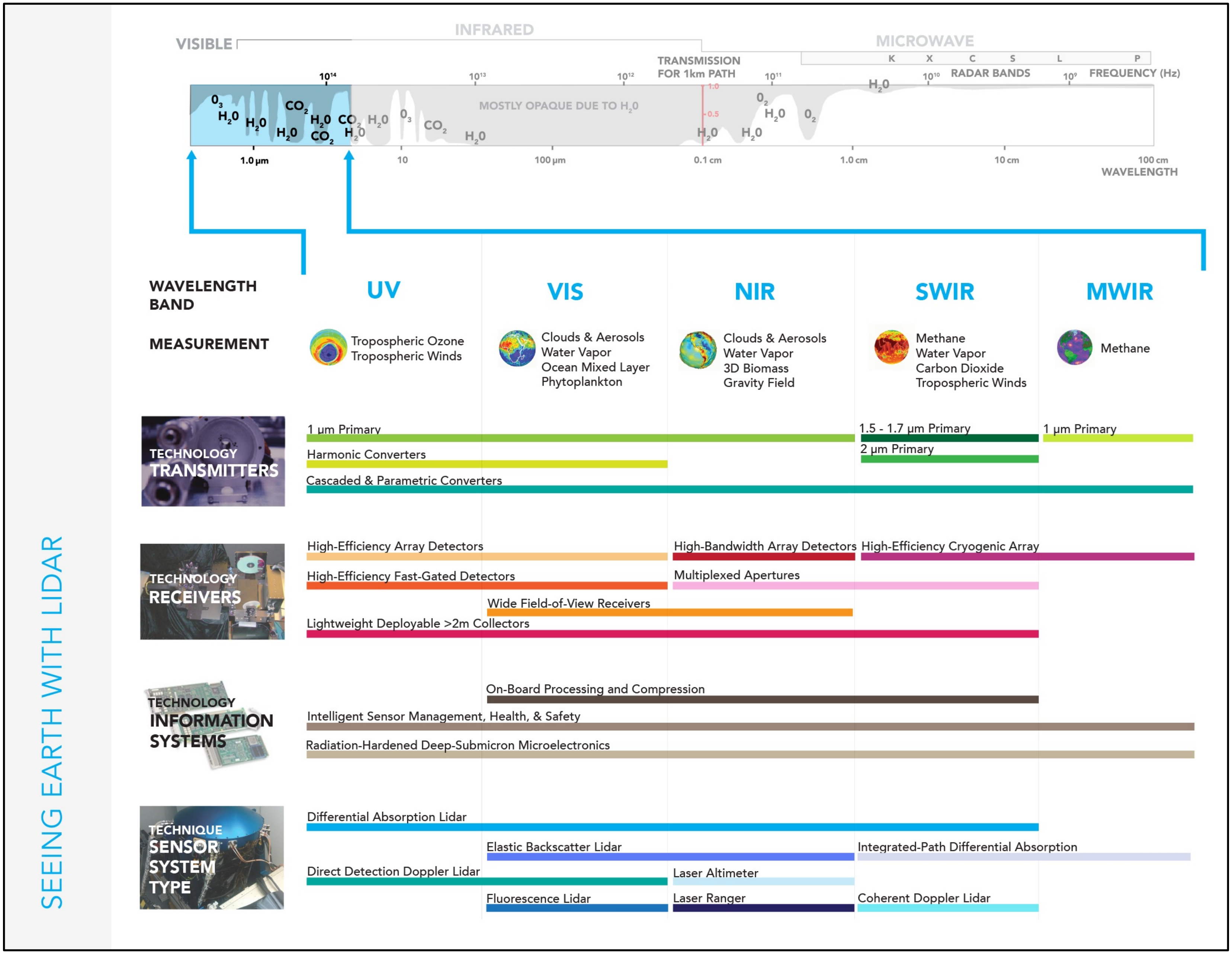
TRL Advancement for Completed Laser Related ESTO Tasks







The Lidar Technology Needs Landscape



WAVELENGTH BAND: UV | VIS | NIR | SWIR | MWIR

MEASUREMENT

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

TECHNOLOGY TRANSMITTERS

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

TECHNOLOGY RECEIVERS

High-Efficiency Array Detectors
High-Bandwidth Array Detectors
High-Efficiency Cryogenic Array
High-Efficiency Fast-Gated Detectors
Multiplexed Apertures
Wide Field-of-View Receivers
Lightweight Deployable >2m Collectors

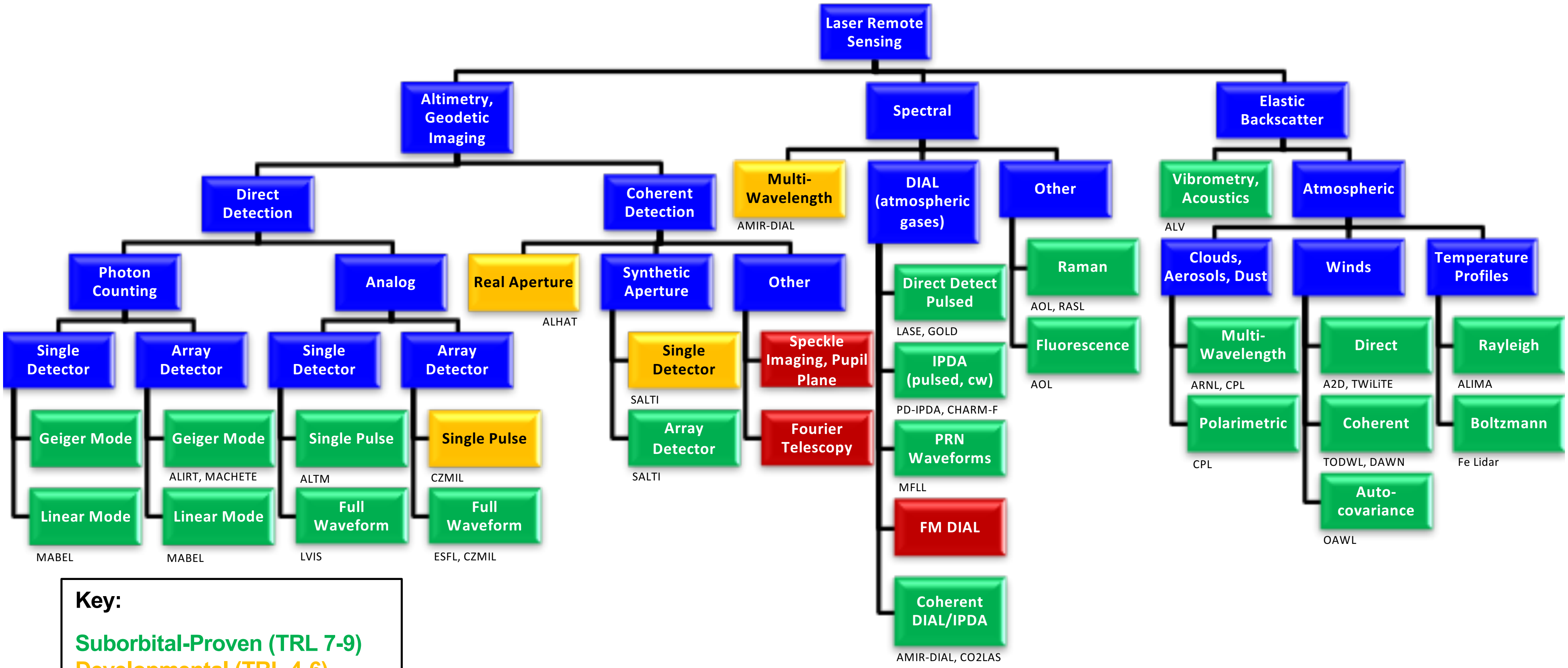
TECHNOLOGY INFORMATION SYSTEMS

On-Board Processing and Compression
Intelligent Sensor Management, Health, & Safety
Radiation-Hardened Deep-Submicron Microelectronics

TECHNIQUE SENSOR SYSTEM TYPE

Differential Absorption Lidar
Elastic Backscatter Lidar
Integrated-Path Differential Absorption
Direct Detection Doppler Lidar
Laser Altimeter
Fluorescence Lidar
Laser Ranger
Coherent Doppler Lidar

Laser Remote Sensing Taxonomy: Suborbital



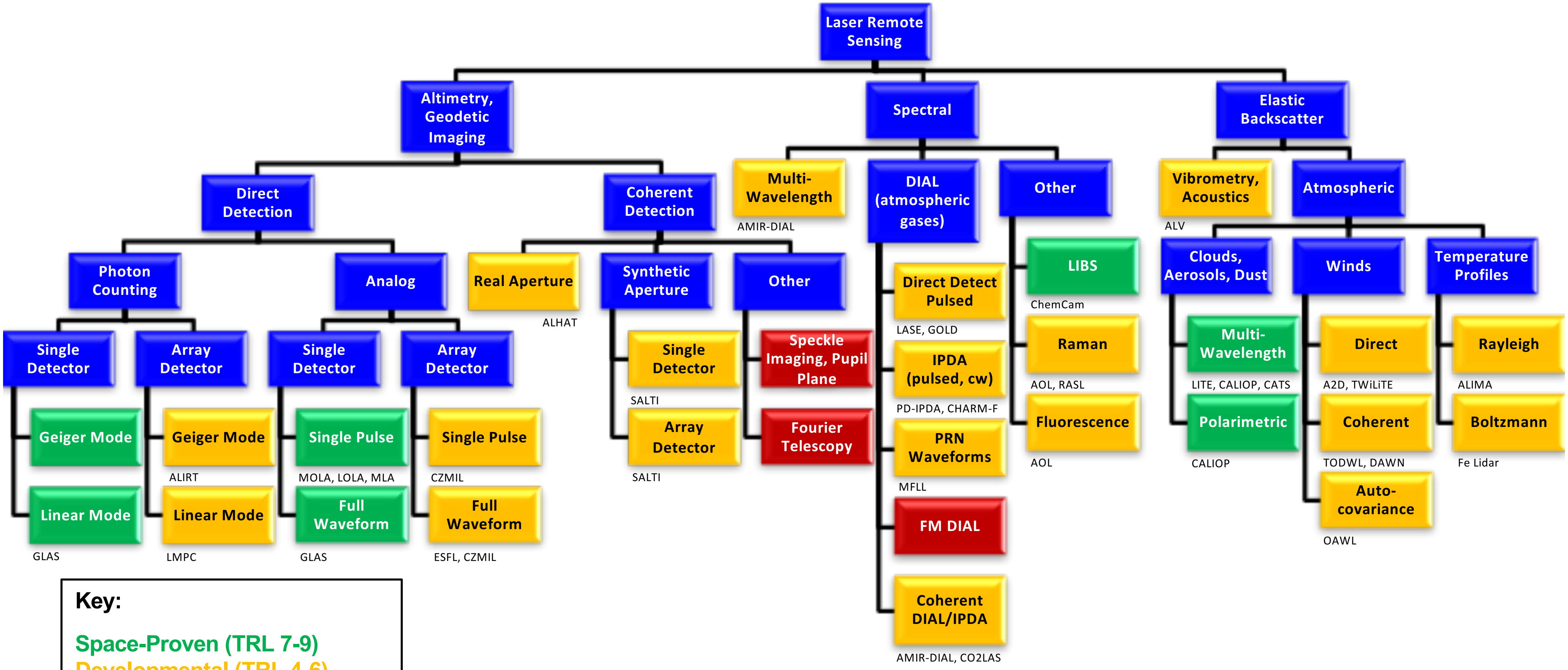
- Laser Remote Sensing
  - Altimetry, Geodetic Imaging
    - Direct Detection
      - Photon Counting
        - Single Detector
          - Geiger Mode
          - Linear Mode — MABEL
        - Array Detector
          - Geiger Mode — ALIRT, MACHETE
          - Linear Mode — MABEL
      - Analog
        - Single Detector
          - Single Pulse — ALTM
          - Full Waveform — LVIS
        - Array Detector
          - Single Pulse — CZMIL
          - Full Waveform — ESFL, CZMIL
    - Coherent Detection
      - Real Aperture — ALHAT
      - Synthetic Aperture
        - Single Detector — SALTI
        - Array Detector — SALTI
      - Other
        - Speckle Imaging, Pupil Plane
        - Fourier Telescopy
  - Spectral
    - Multi-Wavelength — AMIR-DIAL
    - DIAL (atmospheric gases)
      - Direct Detect Pulsed — LASE, GOLD
      - IPDA (pulsed, cw) — PD-IPDA, CHARM-F
      - PRN Waveforms — MFLL
      - FM DIAL
      - Coherent DIAL/IPDA — AMIR-DIAL, CO2LAS
    - Other
      - Raman — AOL, RASL
      - Fluorescence — AOL
  - Elastic Backscatter
    - Vibrometry, Acoustics — ALV
    - Atmospheric
      - Clouds, Aerosols, Dust
        - Multi-Wavelength — ARNL, CPL
        - Polarimetric — CPL
      - Winds
        - Direct — A2D, TWiLiTE
        - Coherent — TODWL, DAWN
        - Auto-covariance — OAWL
      - Temperature Profiles
        - Rayleigh — ALIMA
        - Boltzmann — Fe Lidar

Key:

Suborbital-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Adapted and updated from: *Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing* (NRC, 2014).

Laser Remote Sensing Taxonomy: Space



- Laser Remote Sensing
  - Altimetry, Geodetic Imaging
    - Direct Detection
      - Photon Counting
        - Single Detector
          - 🟩 Geiger Mode
          - 🟩 Linear Mode — GLAS
        - Array Detector
          - 🟨 Geiger Mode — ALIRT
          - 🟨 Linear Mode — LMPC
      - Analog
        - Single Detector
          - 🟩 Single Pulse — MOLA, LOLA, MLA
          - 🟩 Full Waveform — GLAS
        - Array Detector
          - 🟨 Single Pulse — CZMIL
          - 🟨 Full Waveform — ESFL, CZMIL
    - Coherent Detection
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      - 🟨 PRN Waveforms — MFLL
      - 🟥 FM DIAL
      - 🟨 Coherent DIAL/IPDA — AMIR-DIAL, CO2LAS
    - Other
      - 🟩 LIBS — ChemCam
      - 🟨 Raman — AOL, RASL
      - 🟨 Fluorescence — AOL
  - Elastic Backscatter
    - 🟨 Vibrometry, Acoustics — ALV
    - Atmospheric
      - Clouds, Aerosols, Dust
        - 🟩 Multi-Wavelength — LITE, CALIOP, CATS
        - 🟩 Polarimetric — CALIOP
      - Winds
        - 🟨 Direct — A2D, TWiLiTE
        - 🟨 Coherent — TODWL, DAWN
        - 🟨 Auto-covariance — OAWL
      - Temperature Profiles
        - 🟨 Rayleigh — ALIMA
        - 🟨 Boltzmann — Fe Lidar

Key:

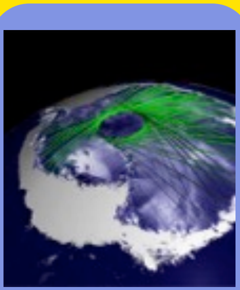
Space-Proven (TRL 7-9)
Developmental (TRL 4-6)
Experimental (TRL 1-3)

Adapted and updated from: *Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing* (NRC, 2014).

NASA Earth Science 2007 Decadal Survey Missions

Soil Moisture Active Passive (SMAP)

1 µm laser altimeter



Ice, Cloud,and land Elevation Satellite II **(ICESat-II)**

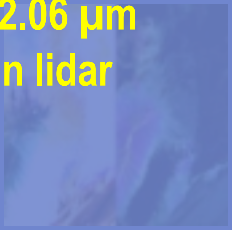
Surface Water and Ocean Topography **(SWOT)**

Pre-Aerosol - Cloud - Ecosystems ***(PACE)***

Active Sensing of CO2 Emissions **(ASCENDS)**

1.57 or 2.06 µm column lidar

Hyperspectral Infrared Imager **(HYSPIRI)**

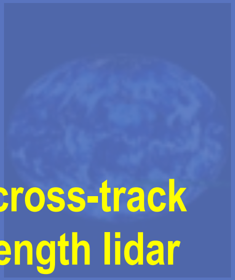


Geostationary Coastal and Air Pollution Events **(GEO-CAPE)**

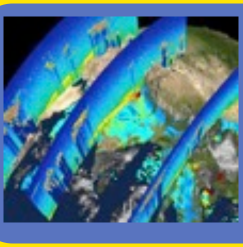
Mapping laser altimeter system

Deformation, Ecosystem Structure and Dynamics of Ice (Radar) **(DESDynI -R)**

Climate Absolute Radiance and Refractivity Observatory **(CLARREO)**

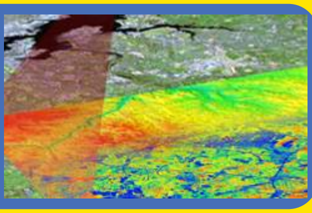


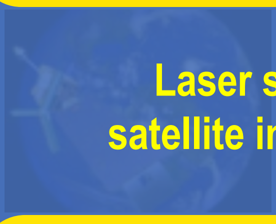
Multibeam cross-track dual-wavelength lidar



Aerosol - Cloud - Ecosystems **(ACE)**

LIDAR Surface Topography **(LIST)**

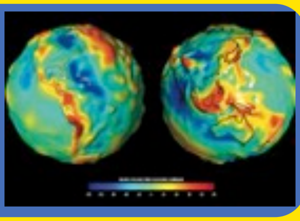




Precipitation and All-weather Temperature and Humidity **(PATH)**

Laser satellite-to-satellite interferometer

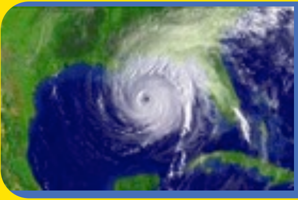
Gravity Recovery and Climate Experiment - II **(GRACE - II)**



Snow and Cold Land Processes **(SCLP)**

Global Atmospheric Composition Mission **(GACM)**

Coherent and/or direct detection Doppler wind lidar(s)



Three-Dimensional Winds from Space Lidar **(3D-Winds)**

Lasers

2007 Decadal Survey Technology Capability Gaps

Measurement	Capability Gap	TRL	“Greatest Challenge” TRL
CO_2 (ASCENDS)	Maturity and readiness of tunable lasers meeting measurement requirements	3-4	1.57-µm power amplifier
CO_2 (ASCENDS)	High-efficiency detectors in 1.5-2 µm range	5	Space qualification/ radhard assurance
Aerosol/Clouds/Ecosystems (ACE)	Readiness of laser systems	4-5	Space qualification
Aerosol/Clouds/Ecosystems (ACE)	Field-widened interferometric receiver	4	Wavefront error
3D Biomass (NISAR/GEDI, formerly DESDynI)	Readiness of laser systems High-bandwidth, high-sensitivity detector arrays	4-5	Space qualification
Topography (LIST in 2007 Decadal)	Multiple aperture transmitter	4-5	Multiple aperture system
Topography (LIST in 2007 Decadal)	Multiple aperture/beam receiver	3	Large-area detector with high readout bandwidth
3D Winds	Reliable 355-nm transmitters meeting measurement requirements; 2-µm technology readiness and reliability	3-4	Laser reliability, readiness
3D Winds	Single telescope supporting multiple look angles	3	Large-aperture receive optics (HOE/DOE, interferometer)

New Measurement Concept (since 2007) Capability Gaps

Measurement	Capability Gap	TRL	TRL Assessment; Greatest TRL Challenge
Phytoplankton	Blue-green laser technology readiness	3	2: Robust and reliable laser and frequency conversion system
Phytoplankton	Detector performance	2	Dead-time, afterpulsing
Ocean Mixed Layer	Blue-green laser technology readiness	2	Robust and reliable laser and frequency conversion system
Ocean Mixed Layer	Detector performance	2	Dead-time, afterpulsing
Non-CO_2 Greenhouse Gases	Tunable laser transmitter for CH_4 IPDA	4-5	3-4: Er:YAG and seed sources
Non-CO_2 Greenhouse Gases	Low-noise, few-photon-sensitive detector array	5	Space qualification
Ozone	Robust UV laser transmitter	2	2: Robust and reliable UV generation 290-320 nm
Ozone	Large-aperture collector; detector efficiency	4	Deployability
Water vapor profiles	Multi-wavelength NIR laser transmitter readiness	2	2: Robust and reliable 720-nm, 820-nm sources
Water vapor profiles	Detector performance	4	Low-noise, few-photon-sensitive detector array

Summary of the Findings (1 of 3)

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.

Summary of the Findings (2 of 3)

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.

Summary of the Findings (3 of 3)

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.