NASA ESTO Lidar Technology Community Forum

February 24, 2016

EST/PST:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:30/08:30	Transmitters State-of-the-Art and Future Requirements (W. Lotshaw, Aerospace)
12:30/09:30	Data Utilization and Acquisition Future Requirements (L. Pearson, Aerospace)
13:15/10:15	*Break*
13:30/10:30	Receivers State-of-the-Art and Future Requirements (K. Gaab, Aerospace)
14:30/11:30	Emerging Technologies and Trends (D. Tratt, Aerospace)
15:15/12:15	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

WELCOME!

Before we begin, a few guidelines….

- Please MUTE your microphones
- Please do not interrupt presentations in progress
- Please send questions via WebEx to the moderator: David Mayo (under the WebEx “Chat” feature). The moderator will pass the questions to the presenter, and they will be addressed during the Q&A. You will either receive a verbal response after the presentation or a written response (if we are time constrained).

Thank You!

Overview of NASA ESTO Lidar Investment Strategy Update

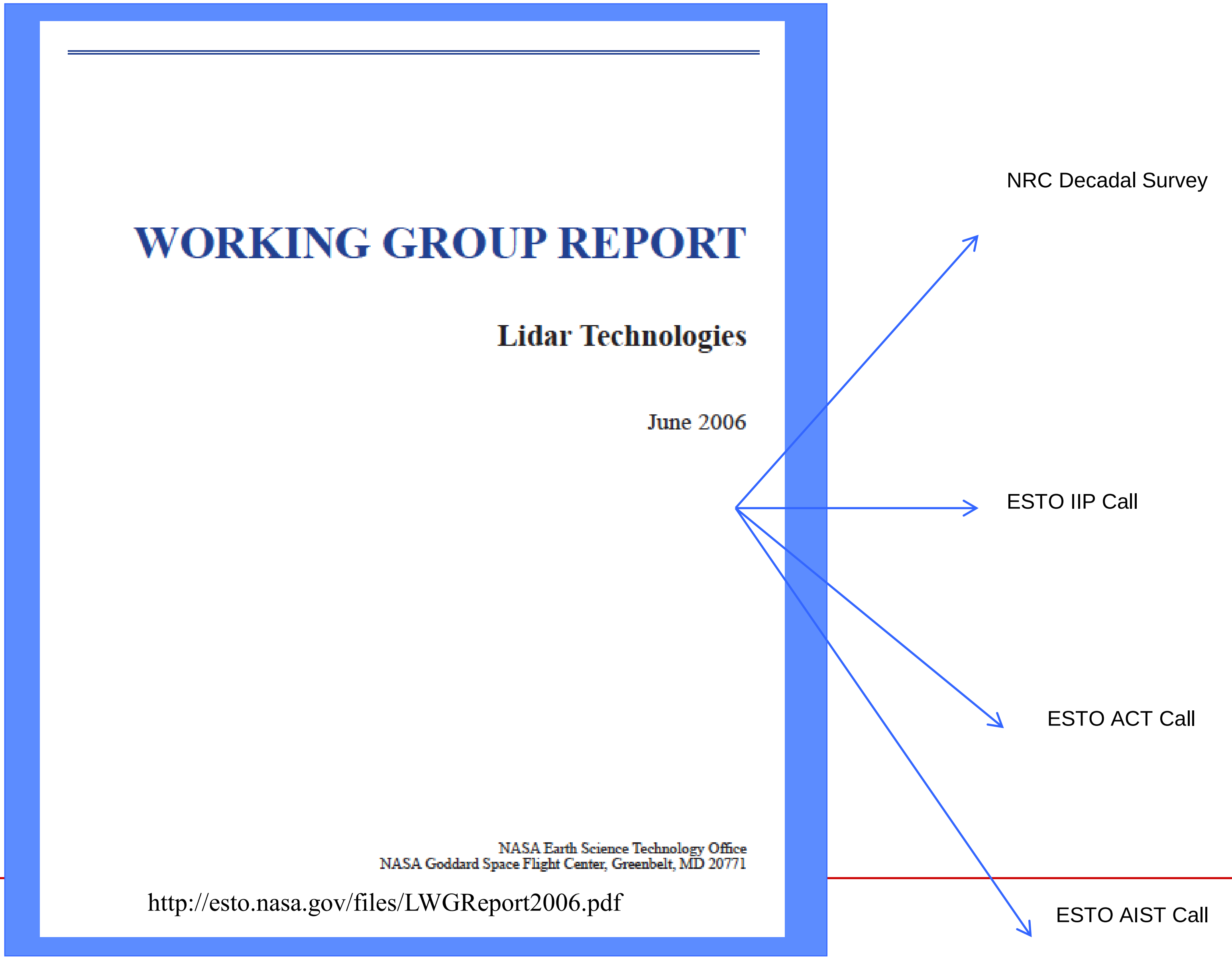
Purpose of the ESTO 2016 Lidar Strategy Update

- The last ESTO Lidar investment strategy is almost a decade old. State of the art has progressed and new areas have been entering the scene (e.g., SmallSat instruments)

- Update strategy by identifying and summarizing key technology requirements and performance parameters based on measurement themes: Atmospheric composition, Atmospheric dynamics, Oceanic measurements, and Land topography

- Opportunity for community to give input and play a role in shaping ESTO's future investment strategy

2006 Lidar Technologies Strategy



WORKING GROUP REPORT

Lidar Technologies

June 2006

NASA Earth Science Technology Office
NASA Goddard Space Flight Center, Greenbelt, MD 20771

http://esto.nasa.gov/files/LWGReport2006.pdf

How will the final report be used?

- Use the input for upcoming ESTO AOs to inform ESTO's investment strategy
- Inform the Decadal Survey on the status of technology maturity
- Seek partnership opportunities with other agencies, industry, academia
- Identify emerging new technology trends and help infuse them into existing and future concepts

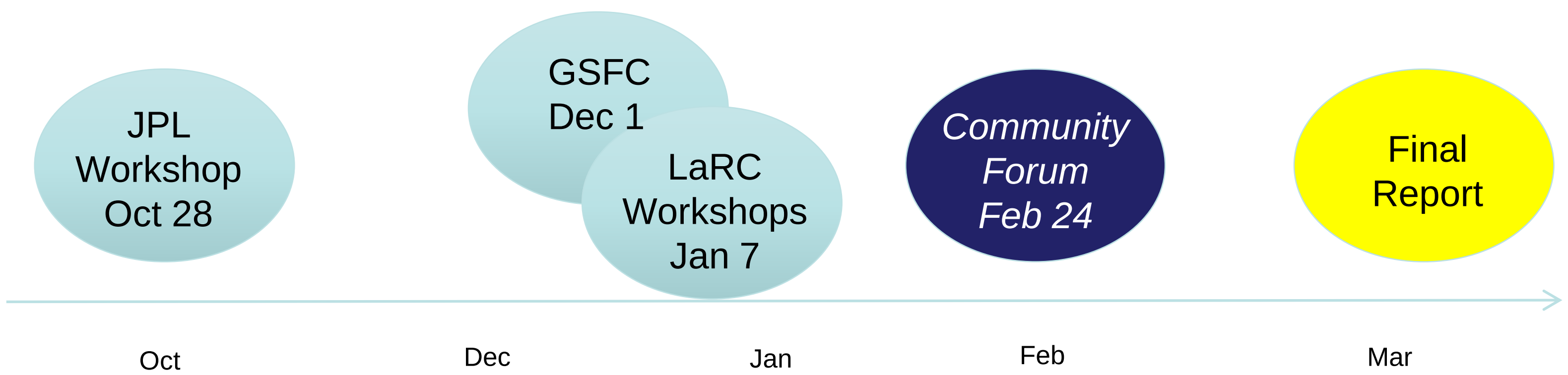
Lidar Study Core Team

- Azita Valinia – NASA/ESTO Study Lead
- David Tratt – Aerospace Lead
- William Lotshaw – Aerospace Transmitter SME
- Kevin Gaab – Aerospace Receiver SME
- Lesley Pearson – Aerospace Data Systems SME
- David Mayo – Aerospace Coordinator
- Jason Hyon – JPL Lead
- Terry Doiron – GSFC Lead
- Keith Murray – LaRC Lead

Process & Timeline

- 3 1-day workshops
  - GSFC, JPL, LaRC (80 participants)
- Community Forum *rescheduled (due to snow blizzard) to February 24 (Virtual)*

Today, the Core Lidar Study Team will brief Forum participants on how they have integrated inputs so far, and the emerging findings and investment strategy. Feedback and additional input welcome before finalizing the investment strategy.



Questions?

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NASA ESTO Lidar Technology Status Evaluation

Transmitter Technologies Assessment

Contents

- **Summary of transmitter technology needs**
  - *From 2007 decadal survey measurements*
    - **High resolution topography (LIST), Winds (3D Wind Demo), CO_2 (ASCENDS), Gravity (GRACE II), aerosol (ACE)**
  - *New or re-emphasized measurement concepts since 2007 Decadal Survey*
    - **3D biomass, phytoplankton, mixed layer depth, non-CO_2 green-house gases (GHG), atmospheric composition**
- **Overview of technology status and development needs**
- **Conclusions and Recommendations**
- **Q&A**

Unmet Transmitter Technology Needs from 2007 Decadal Survey

Capability Gap	Measurements	TRL (Respondents)	"Greatest Challenge" TRL
Maturity and readiness of tunable lasers meeting measurement requirements	CO_2 (ASCENDS)	3-4	Power amplifier
Readiness	Aerosol/Clouds/Ecosystems (ACE)	4-5	Space qualification
Similar to LIST	3D Biomass (NISAR/GEDI, formerly DESDynI)	4-5	Space qualification
Readiness of laser systems	Gravity (GRACE II)	2-3	U.S. laser supplier
Multiple aperture transmitter	Topography (LIST in 2007 Decadal)	4-5	Multiple aperture system
Reliable UV transmitters meeting measurement requirements; 2 μm technology readiness and reliability	3D Winds	3-4	Laser readiness, reliability

Technology Needs for New Measurement Concepts

Capability Gap	Measurement	TRL (Respondents)	"Greatest Challenge" TRL
Blue-green laser technology readiness	Phytoplankton	3	2: Robust and reliable laser and frequency conversion system
Blue-green laser technology readiness	Ocean Mixed Layer	2	Robust and reliable laser and frequency conversion system
Tunable laser transmitter for CH_4 IPDA	Non-CO_2 Greenhouse Gases	4-5	3-4: Er:YAG and seed sources
Robust UV laser transmitter	Ozone	2, 4	2: Robust and reliable UV generation 290-320 nm
Multi-λ NIR laser transmitter readiness	Water vapor profiles	2 (LaRC); 5 (GSFC)	2: Robust and reliable 720 nm, 820 nm sources

Red/bold numbers in right column Represent reviewer revision of TRL

General Observations

- The 2006 report contained 7 laser technology areas:
  - *mJ class 1 μm lasers* (*high PRF*)
  - *Joule-class 1 μm lasers* (*low PRF*)
  - *1-100 W, 1.5-1.6 μm, various PRF and energies*
  - *1-20 W, 2 μm lasers, various PRF and energies*
  - *Wavelength conversion to UV-VIS*
  - *Wavelength conversion to NIR*
  - *"Other lasers"*
- Areas Added/Dropped in 2016 (intended to simplify the technology landscape and eliminate duplications, see next chart)
  - *Drop "other lasers" category*
  - *Restructure "Wavelength conversions"*:
    - List harmonic generation with the fundamental λ laser driving the conversion (*e.g.*, 1, 1.5, 2 μm lasers)
    - List tunable or fixed wavelength parametric conversion as group according to type (*e.g.*, OPO, OPA, sum/difference, *etc*.)
  - *Add seed/signal source lasers needed for MOPA or frequency conversion linewidth control*

Technology Areas 2016

Technical Area	2006 Report	2016 Report	Rationale
1) mJ-class 1 μm lasers	X	**X**	Cross-cutting technology to several measurements
2) J-class 1 μm lasers	X	**X**	Cross-cutting technology to several measurements
3) 1-100 W 1.5-1.6+ μm lasers	X	**X**	Cross-cutting technology to several measurements
4) 1-20 W 2 μm lasers	X	**X**	Cross-cutting technology to several measurements
5) Seed and amplifier laser diodes		**X**	Cross-cutting component in laser technologies of many measurements
6) Parametric wavelength generation		**X**	Integrated with source laser, critical to specific measurements (*e.g.*, O_3, H_2O_v), *etc.*)
Harmonic wavelength conversions to UV-VIS/NIR	X	Drop, list with lasers 1) – 4)	Inextricably integrated with source laser
Other lasers	X	Drop, list with lasers 1) – 4)	Typically correlated parametric wavelength conversion

Specific Observations: Transmitters

- Laser component technology has evolved significantly
  - *Available wavelengths and WPE of pump and signal/seed laser diodes have changed significantly*
  - *Some new laser and nonlinear optical materials have emerged*
  - *Integration of photonic components into (much) smaller form factors with increased functional capabilities*
- Fiber laser *average* power capability now rivals traditional bulk solid-state systems
  - *"All" fiber architecture*: *compact and immune to misalignment*
    - Fused fiber pump combiners, fiber-integrated filters, fused fiber diagnostic taps
  - *Power scaling in "large mode area fiber"*
  - *Peak power limited by fiber core area; finite prospects for peak power scaling*
- Laser system architecture is evolving to take advantage of new capabilities
  - *Hybrid fiber/bulk solid-state systems*
    - Utilize best attributes of each technology: SWaP and misalignment immunity of fiber; peak power and energy scaling of bulk solid-state
    - *The* path to energy and peak power scaling of fiber lasers, and to waveform agility of bulk solid-state systems

Specific Observations: Transmitters

- General trends in laser component technology (*e.g.,* fibers, pump diodes, subsystem integration):
  - *Supplier issues*:
    - Foreign/domestic technology origin, manufacturing
      - ITAR/EAR
      - U.S. interests not necessarily a priority for foreign vendors
  - *Pump diode efficiency can be $\geq$ 60% at wavelengths $<$ 1 μm*
    - $\leq$ 40% for "in-band" pumping of Er, much less at longer λ's ("in-band" for Tm)
  - *Fiber technology has improved dramatically, especially in average power scaling*
    - Yb, Er, Tm provide tunable laser output at 1-1.1, 1.5-1.6, and 1.8-2+ μm
    - "Telecom" type signal laser diodes enable large variation in temporal waveform (pulse rate/format)
    - Wide range of pulse durations are supported, including picosecond/femtosecond and "frequency comb" operation
    - Management of non-linearities is critical
- Transmitter (transceiver) pulse rate:
  - *If measurements can support pulse rates $\geq$ 10 kHz, fiber lasers may be enabling*
  - *For pulse rates $\leq$ 5 kHz fiber laser suitability will depend on specifics of laser operation, may still be valuable*

Specific Observations: Transmitters

- Synergistic DoD Contractor development
  - *National security programs in several measurement areas have focused on performance, SWaP advancements and space qualification*
  - *Average power, peak power, waveform/wavelength agility at 1, 1.5, 2, and 2-4 μm*
    - Waveform agility is a priority for a range of national security lidar applications, and development of waveform generation infrastructure is progressing to relatively advanced stage via contractor effort *under both internal and gov't funding*
      - *Includes FM/IM. scripted PRF variation and burst formats*
    - Significant advances have been made in high energy laser sources at 1 and 2 μm wavelengths
      - *Pulse energy up to ~ 1 J at PRF to ~ 5 kHz*
      - *Pulse energy to ≥ 10 mJ at PRF to 10's of kHz*
      - *cw "single aperture" MOPAs 10 ~ 20 kW* (@ 1 μm)
      - *Beam-combining* (*aperture summing, both coherent and incoherent*)
- Cross-cutting trends:
  - *Integrated Photonic Subsystems* (T_x, R_x, signal processing and mgmt., see full report)
    - Both monolithic and heterogeneous chip-scale integration promise dramatic improvements in performance, capability, and SWaP:
      - *Compact and EMI resistant transmitters/receivers, modulators and waveform generation, optical signal processing/routing, optical to electronic transduction*
    - SWaP improvements are critical enablers for small-sat missions (esp. pico-sats)
  - *New pump diodes and fiber-MOPAs enable significant improvement in WPE*
  - *Hybrid fiber/bulk solid-state systems enable high power with waveform agility, SWaP*

Challenges

- Supplier issues
  - *U.S. investment strategy/vehicle for domestic technology companies and/or universities, e.g., SBIR, ACT, may not be adequate and needs higher level attention.*
- Emerging laser technologies
  - *Nonlinear optical materials for wavelength conversion*
    - Materials with improved nonlinear properties and/or phase-matching properties are needed. These are continuously evolving in several wavelength ranges via academic and industrial R&D
  - *Coatings*
    - Improved durability and damage resistant reflective and anti-reflective coatings are needed for laser optics, filter applications.
  - *Fiber lasers*
    - Interface components matched to emerging fibers are evolving continuously, are difficult to obtain.
      - *Filters, isolators, pump-combiners must be in form suitable for a continuous waveguide structure*
    - Nonlinear optical properties are often a critical impediment to end performance requirements
      - *The driving force for new fiber designs and material compositions* (*e.g*., non-silicate glasses)
    - New glass compositions are needed that enable wider range of laser ion doping and linear/nonlinear optical property control: explicitly *Materials Science* R&D <u>with potentially long gestation period</u>
  - *Hybrid Fiber/Bulk Solid-state Architectures*
    - Using fiber-MOPAs as the seed source with high-power bulk solid-state amplifiers may uniquely enable lidar measurements that simultaneously require high pulse energy and high average power
      - *The development of "hybrid" laser systems requires expertise in both technologies that may not be available in well-established technology development laboratories*
      - *Inter-organizational collaborations may be critical to establishing these development programs*

Challenges

- Slower than expected technology maturation
  - *Achieving SWaP goals*
    - An asymptotic process often characterized by incremental improvements
  - *Achieving reliability goals*
    - An asymptotic process often characterized by incremental improvements
  - *New technology insertion*
    - **Are there situations where abandoning a long development path is appropriate?**

Technology Needs Charts

- Following charts are not *comprehensive* recapitulation of 2006 Transmitter Technologies
  - *Tables enumerate technology categories and high-level status*
  - *For comprehensive status update see Final Report*

2007 Decadal Survey Needs: 1 μm Solid-State Laser Transmitters

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
Topography, aerosol and T profiles	Pulse Rate ≤ 500 Hz, Solid-state Laser	λ ≈1 micron, ≥ 0.25 J @ 150 Hz PRF, WPE ~ 10%, 1 MHz linewidth, $M^2 < 1.5$[1]	λ ≈1 micron, 0.5 J @ 50 Hz PRF, WPE 6%, 1 MHz linewidth, $M^2 < 1.5$	Reliability, packaging, space qualification
Topography, aerosol and T profiles	Pulse Rate ≥ 1 kHz, Solid-state Laser	λ ≈1 micron: 1) **bulk,** ≥ 0.8 J @ 5 kHz PRF, WPE ~ 6%[2]; 2) **fiber,** > 1-4 mJ @ 10 kHz, WPE > 15%, GHz linewidth, $M^2 < 1.5$[3]	λ ≈1 micron, ~ 100's μJ @ ≥ 2.5 kHz PRF, WPE 6%, 1-MHz linewidth, $M^2 < 1.5$	Reliability, packaging, space qualification
Gravity	*cw* Solid-state Single Frequency Laser	λ ≈1 micron, ~ 15 kW, WPE ~ 10%, ~100 kHz linewidth, $M^2 < 1.5$[4]	1 micron, ≥ 20 mW, sub-Hz linewidth[5] (?)	Grace FO focused on frequency reference. MO (incl. λ) and details of locking scheme still in flux.
Atmospheric Composition, DWL, ocean mixing-layer	Frequency Conversion	see "Fixed Wavelength Conversion" and "Tunable Wavelength Conversion" charts	Harmonic generation of 532, 355 nm; parametric generation to fixed and **tunable λ's VIS-MWIR**	Improved nonlinear optical materials and anti-reflective coatings
Topography, aerosol and T, oceanography	**Fiber/Hybrid (bulk+fiber)**	10-100+ W at 1 μm (typically < 1 mJ), PRF 20-100+ kHz, $M^2 \sim 1$, WPE ≥ 20%	1, 1.5, 2 μm, ~ 0.1-few mJ @ ≥ 2.5 kHz PRF, WPE ≥ 15%, range of linewidths, $M^2 < 1.5$	Fiber-integrated components, low-nonlinearity gain fiber, higher WPE pump diodes
High resolution aerosol, $H_2O_{(v)}$, oceanography	Single λ signal laser diodes, amplifiers	10 kHz-few MHz linewidth, 20-100 mW P_{ave}	linewidth from kHz to MHz at variety of λ in VIS-SWIR range	Linewidth in ~ 10 kHz range, wavelengths > telecom

Red font indicates "Emerging Technology"

2007 Decadal Survey Needs: 1.5, 2 μm Solid-State Laser Transmitters

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
CO_2, Coherent DWL (aerosol)	Pulsed 2 μm, 1.57 μm laser	CO_2: ≥ 30% conversion to 1530-1625 nm via DFG w/ 1064 nm fiber-MOPA at high PRF. DWL: 2 μm Tm/Ho system under development at LaRC[6], > 1J @ ~ 200 ns.	CO_2: Pulsed 1.57 μm sources w/ P_{ave} ~ 5-20+ W, ~ 10 kHz PRF, ~ 1 μs pulsewidth, tunable. DWL: Pulsed 2 μm source @ 5-300 Hz @ $E_{Pulse} \times$SQRT(PRF) > 0.6 $JHz^{1/2}$, 8-GHz tunable frequency-agility, M^2 < 1.2, WPE > 5%.	CO_2: technology reliability and maturation, SWaP optimization. DWL: technology reliability and maturation, SWaP optimization.
CO_2	*cw* 1.57 and 2 μm laser	*Literature review in progress (see Final Report)*	3-5 W cw @ 2.05 microns, linewidth <50 kHz, 1-GHz tunable, λ stabilization to < MHz, FM/IM capability; 10% WPE. 10 W 1.57 μm tunable *cw* sources.	IM/FM waveform generation and control, technology maturation
CH_4	Pulsed ~1.65 μm laser	Few mJ, kHz Er:YAG, < 10% WPE, uses NPRO injection seed[7]	10 mJ/pulse, 1-3 kHz PRF, 10's of ns pulsewidth @ 1645 nm, tunable for DIAL	Q-switched oscillator, amplifier, WPE, SWaP
CO_2, CH_4	Fiber/Hybrid (bulk+fiber)	In active development, work to date focused on high PRF	~ 10 W P_{ave}, kHz PRF, ~ 1 μs pulsewidth or *cw*, tunable at selected λ	Integration of fiber-MOPA w/ bulk amplifiers; < 20 kHz PRF (Q-cw pumping of fiber amps) or *cw*
CO_2, CH_4	Single λ signal laser diodes	10 kHz-few MHz linewidth, < few mW P_{ave}	linewidth from kHz to MHz for DIAL tunable wavelength converters	Maturation of materials and designs for 1.6 – 2+ μm devices

Red font indicates "Emerging Technology"

2007 Decadal Survey Needs: Fixed Wavelength Conversion Transmitters

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
Aerosol, $H_2O_{(v)}$, T, oceanography (at 532 nm w/ less penetration than ~450-480 nm)	Second Harmonic Generation	~ 70% 1064nm → 532 nm (> 24 W @ 150 Hz, P_{pk} = 16 MW)[1]; > 50%, 1064nm → 532 nm (> 200 W)	> 100 mJ @ 532 nm, 10-200 Hz PRF; 2-5 mJ @ 532 nm, 2.5-20 kHz PRF	Incremental performance and reliability improvements
O_2	Second Harmonic Generation	> 50% 1530nm→765nm	1 J, 10 Hz.	Scale telecom technology lasers to much higher energy
DWL; aerosol and T profiles	Third Harmonic Generation	~ 6 W, ~ 50% 1064+532 → 355 nm (20 kHz, P_{pk} ~ 1 MW); ~ 20+% at 150-300 Hz PRF	~ 6 W, ~ 30% 1064+532 → 355 nm (200 Hz, P_{pk} ~ 10 MW	High efficiency, high reliability UV generation
None specified	Fourth Harmonic Generation	~ 20% 1064 → 532→266 nm (~ 10 W @ 20 kHz, P_{pk} = 0.25 MW)	< 10 Hz and > kHz systems 1-20 W range (in reference to O_3 meas)	High efficiency, high reliability UV generation

2007 Decadal Survey Needs: Tunable Wavelength Conversion Transmitters

Measure-ment(s)	Technology	State of the Art	Requirements	Development Need
$H_2O_{(v)}$, oceanography	OPO (vis-nir)	~ 17% conversion to ~ 450 nm via OPO+sum frequency w/ 1064 nm fundamental.[10] 532 nm pumped OPO/DFG for 700-1000 nm should be similar	**On/off resonance $H_2O_{(v)}$ NIR lines (720, 820, 940 nm); Optimized λ for ocean water transmission 400-480 nm**	High efficiency, high reliability VIS-NIR generation
GHG	OPO (SW/MWIR)	$\geq$ 30% conversion of 1 μm laser to 1530-1625 nm via DFG w/ 1064 nm fiber-MOPA at high PRF.[11]	Tunable source 1570-1650 nm for GHG DIAL, ~ 10 mJ @ kHz PRF	Average and peak power scaling, operation at PRF < 10 kHz, extension to λ > 1625 nm
O_3,	Cascaded Parametric (UV-VIS, NIR)	*Literature review in progress, similar to Fourth Harmonic Generation + sum frequency to reach 290-320 nm*	< 10 Hz and > kHz systems 1-20 W range to support **290-320 nm tunable systems**	High efficiency, high reliability UV generation
GHG	DFG/OPA (SW/MWIR)	> 10% DFG to 3-3.8 μm range demonstrated at high PRF using PPLN+1064 nm fiber MOPA	Tunable source 3-3.3 μm for CH_4 DIAL	Average and peak power scaling, operation at PRF < 10 kHz

Red font indicates “Emerging Technology”

Technology Needs Summary

	UV 355-400 nm	VIS 400-650 nm	NIR/SWIR 700-2000 nm	MWIR 3-5 micron
Measurement	3D Winds; Water vapor; Trop. ozone	Physical/biological oceanography; aerosols; topography	3D Winds; GHG; water vapor; O_2; topography; aerosols	GHG (CH_4)
Transmitter	**THG, OPO/OPA of 1-μm sources; multi-stage non-linear wavelength conversion**	**SHG of 1-μm sources; multi-stage non-linear wavelength conversion**	**1, 1.5, 1.8-2.6 μm sources; SHG of 1.5, 2 μm sources; OPO/OPA of 1 μm sources**	**OPO/OPA of 1, 1.5, 2 μm sources; narrow-gap laser diodes**
Detector	GaN, MCP, DD-CCD; Low-noise multi-element arrays, QE > 50% @ 355 nm	Si-APD, PMT; Gateable <50 ns, QE 50-70% @ 450/532 nm	Lm HgCdTe APD; Gm InGaAs APD; PMT (to ~ 1.4 μm) MCP (to ~ 900 nm)	Lm HgCdTe APD HgCdTe FPAs SL/nBn FPAs
Aperture	>1.5-m aperture; areal density <25 kg/m^2	>1.5-m aperture; areal density <25 kg/m^2	>1.5 m aperture; areal density <25 kg/m^2	>1.5-m aperture; areal density <25 kg/m^2
IT*	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization

* Cross-cutting across multiple measurements and sensor modalities.

Preliminary Conclusions and Recommendations

<u>Conclusions</u>

- 1 μm bulk solid-state (BSS) laser technology and associated harmonic generations to VIS/UV are fairly mature
  - *Development needed for reliability, continuous improvement of WPE of base laser technology*
  - *Development specifically needed durability and reliability of UV harmonic generation (wavelengths < 400 nm).*
    - NLO materials and crystal coatings are improvement areas

- 1 μm fiber-laser technology is rapidly approaching BSS laser technology for P_{ave} and linewidth performance, lags in P_{pk} and low PRF parameters. Harmonic generations to VIS/UV are fairly mature.
  - *Waveform agility a priority for a range of national security lidar applications, development of waveform generation infrastructure progressing to relatively advanced stage*
  - *Fiber technology development needed to scale peak power capability at 1 μm*
    - Large mode area fiber and new glass compositions will be key

Preliminary Conclusions and Recommendations

Conclusions

- Telecom-type single-mode laser diodes and optical amplifiers are well-established at 1480-1625 nm and ~ 1000 nm λ (Nd^{3+}, Yb^{3+}); emerging in 1625-2000+ nm range
  - *Continued Development needed for reliability, improvement of WPE for established ranges*
  - *1625-2000+ nm signal lasers currently have low power, optical amplifiers lacking or at early stage of development.*

- 1.5 and 2 μm BSS and fiber-laser technology is in varying stages of development.
  - *High power fiber-MOPA performance in Tm-fiber rapidly advancing*
    - Large mode area fiber and new glass compositions will be key, led by technology start-ups
    - 793 nm pump diode technology fairly mature, longer λ pumps in development
    - Signal diodes and semiconductor amplifiers relatively immature
  - *High power fiber-MOPA performance in Er-fiber lags*
    - Product base strongly oriented to telecom performance requirements. Large mode area and PM fibers not nearly as widely available as in Yb-fiber
    - Pump diodes on the order of 30-35% electrical efficiency

Preliminary Conclusions and Recommendations

Recommendations

- *Photonic Integrated Circuits* (PIC's) represent opportunity to consolidate signal generation, amplification, frequency/waveform formatting with significant SWaP improvements
  - *Development of monolithic and heterogeneous Integrated Photonic modules is well established in 1550 nm telecom band, emerging at 1000 nm and 1800-2000+ nm*
- *Pump diode development needs to continue* for improved electrical efficiency and reliability in 790-1000 nm range, especially at wavelengths needed for direct-pumping Er, Tm, Ho.
- *Investigate fiber/BSS hybrid technologies*. Potential solutions to difficult performance and wavelength requirements
  - *At high PRF fiber-based MO+preamp subsystems or fiber-MOPAs enable significant SWaP benefits and potentially unprecedented waveform agility*
    - Especially true for 1020-1100 nm, 1500-1600 nm, 1800-2100 nm wavelength ranges
    - Development of new glass hosts and new fiber designs should continue
  - *At lower PRF* (< 10 kHz) *fiber-based systems/subsystems probably require development for QCW-pumping and ASE/nonlinear penalty control and mitigation*
- Although good nonlinear optical (NLO) materials are available for many measurements requiring harmonic and parametric wavelength conversion, NLO materials for 200-400 nm and 1600-2700 nm ranges can be improved
  - *AR coatings and NLO crystals suffer from environmental and damage susceptibilities, and continued development is needed*
  - *Quasi phase-matched material development in lithium niobate, lithium tantalite, GaAs should continue for power scaling, efficiency optimization, robustness*

Questions & Comments

Backup

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NASA ESTO Lidar Technology Status Evaluation:

Data Acquisition & Data Utilization (Command & Data Handling) Technology Assessment

Contents

- **Summary of information technology needs assessment for measurements from the 2007 decadal survey**
  - *Topography (LIST), Winds (3D Wind Demo), CO_2 (ASCENDS), Gravity (GRACE II), Aerosols (ACE)*
- **Summary of information technology needs for new measurement concepts**
  - *Biomass, phytoplankton, ocean mixed layer depth, non-CO_2 GHG, other atmospheric composition*
- **Overview of information technology development needs**
  - *Onboard processing*
  - *Spacecraft control and communication*
  - *Ground processing*
  - *Algorithms/models*
- **Overview of emerging information technology trends**
- **Recommendations**
- **Q&A**

C&DH Assessment for 2007 Decadal Survey Measurement Recommendations

Capability Gap	Measurements	TRL
Cloud detection, instrument pointing (<4 µrad), health monitoring	CO_2 (ASCENDS)	4
Instrument pointing knowledge, compression	Aerosol (ACE)	4
None (met by GEDI)	3D Biomass (DESDynl)	6
None (met by GRACE FO, Sat-to-Sat communication)	Gravity (GRACE II)	6
Onboard processing, compression, laser life prognosis (<days)	Topography (LIST)	3
Autonomous acquisition, real-time LOS wind, validation (<1hr), OSSE	3D Winds (Demo)	5

Enabling Technologies for New Concepts

Capability	Concept	TRL	Challenge
Cross-cutting	3D biomass	3	Onboard compression, calibration & validation
Algorithm	Phytoplankton	4	Event detection
Algorithm	Ocean mixed layer depth	5	Cloud detection
Technology	Non-CO_2 GHG	5	Instrument pointing
Health & Monitoring	Atmospheric composition	4	Instrument pointing, laser life prognosis

General Observations

- **Four categories of development needs**
  - *Technology*
  - *Engineering*
  - *Cross-cutting*
  - *Algorithms*

- **Engineering needs are mission specific based on instrument, power, and spacecraft**
  - *It is not feasible to start the development until phase A*

- **Cross-cutting needs require long term investment and standardization**
  - *Onboard processor and storage*
  - *Instrument interface, telecommunication, data compression*
  - *Ground data processing, data analytics*

- **Algorithms**
  - *Instrument specific*
  - *Model-specific data*

Technology Areas

- **Utilized 2006 Survey as the starting point**
- **Input received from various groups broke into the following overarching areas:**
  - *Data Collection & On-board Processing*
  - *Spacecraft Control & Communication (Data Transmission)*
  - *Ground Processing*
  - *Algorithms/Models*
  - *Enabling Technology*

Onboard Processing

- **Optimize data collection**

- **Effort is to reduce the amount of data initially collected, i.e., don't simply operate sensor in always-on mode. Use information from a variety of sources to do this, thereby reducing resource impacts downstream.**

    - *Adaptive Sensor Operations: with knowledge from another platform, another on-board sensor, the data from the active sensor or a pre-loaded dataset, automatically reconfigure the sensor collection parameters to collect the right data or the right target*
        - On-board Sensor Control
        - Standardization of Interfaces and Controls
        - Spacecraft Area Network
        - Formation Flying

    - *Science model-driven adaptive targeting*

Onboard Processing (Cont.)

- **Even with the effort to reduce the amount of data collected, data volumes are expected to continue to increase. Need to store, process, and compress it on-board to meet various mission needs.**
  - *On-board Storage*
    - Space-qualified Terabyte storage Hardware
  - *On-board Processing*
    - Space-qualified HPC HW & programming tools
    - On-board near real-time data processing
    - Real-Time wind profiles
    - Mission error Budgets
  - *Software Compressive Sensing*
- **On-Board Data Compression**
- **Development of compression algorithms to reduce the amount of data retained and transmitted. Development of "policy" on the use of lossy compression – is it ever acceptable not to transmit/archive the original data?**
  - *Space-qualified HPC HW & programming tools*
  - *Data Compression: Lossless*
  - *Data Compression: Lossy*

Onboard Processing (Cont.)

- **Health Monitoring & Control**

- **Need both autonomous on-board sensor health monitoring & correcting capabilities, combined with the use of "ground truth" data from both airborne and ground-based lidar systems for calibration and data validation.**

    - *Intelligent sensor health & safety*
    - *Airborne lidar validation systems*
    - *Ground lidar validation systems*

- **Pointing & tracking**

Spacecraft Control and Communication

- **Transmit (& Receive) the Data**

- **A platform/sensor can be expected to transmit data to another on-board sensor, to another satellite or to the ground. Standards and protocols need to be established to facilitate. Quantity of data is continuing to increase, advanced data transmission capabilities need to be developed (i.e., laser communications). A platform can also be either producer or consumer of this satellite-to-satellite data.**

  - *Transmit the data to another Sensor*
    - Standardization of Interfaces & Protocols
  - *Transmit the data to another Satellite*
    - Standardization of Interfaces & Protocols
  - *Transmit the data to Ground*
    - Large Volume Data Downlink: Laser Communications

Ground Processing

- **Ground Systems**

- **Once the data has been transmitted to the ground, it must support various levels of processing: near real-time Decision Support Applications, Science Products and further science research.**

  - *Knowledge Discovery*

  - *Cloud-based Processing*
    - Establish cloud-based service oriented architecture for processing data once it reaches the ground allows for rapid expansion and contraction of capacity eliminating the need to maintain large local processing clusters for each mission.

  - *Storage & Archive*
    - Data Management/Service Oriented Architecture
    - Cloud-based Storage: Establishing cloud-based storage capability will allow cloud-based data holdings to be published to a variety of architectures as a service. Raw data can be archived to offline storage, while processed (more actively used data/products) can be maintained online for faster access.

Ground Processing (Cont.)

- **Data Dissemination**

- **Data delivery should be flexible enough to provide the requestor with the exact data and metadata needed, in the format needed. Additionally, the ability to provide online visualization of data should be a part of the concept of operations, if the data content allows.**

  - *Data Compression: Lossless*
  - *Data Compression: Lossy*
  - *Data Visualization*

Algorithms/Models

- **This is not a technology development. Most of the development needs should be addressed by mission and ROSES R&A**

- **Modeling**
  - *Observation System Simulation Experiments (OSSE)*
  - *Model lidar data resampling techniques*

- **Algorithms**
  - *Instrument specific algorithms and theories*
  - *Ancillary data processing*
  - *Calibration and validation campaigns*

Enabling Technologies

- Cloud detection – optimization of compute intensive processing
- Coordinate sensing and event detection – onboard real-time data architecture
- Onboard processing and storage – space qualification of device technology
- Laser life prognosis – laser characterization, interactive sensing based on event detection

Emerging Technology Trends

- **FPGA**
  - *IBM Coherent Accelerator Processor Interface (CAPI), PCIe*
  - *Xilinx Virtex-5QV; Microsemi RTG4; Xilinx Zynq (non-rad-hard processor plus FPGA) Future Interface technologies; JEDEC JEDS204B high-speed serial interface ADC/DAC converters.*
- **MEMEX**
  - *Grobid (GeneRation Of BIbliographic Data machine learning framework)*
  - *Apache Tika (detects and extracts metadata and text from over various file formats)*
  - *NLTK (natural language toolkit)*
- **CARACAS – onboard Control Architecture for Robotic Agent Command and Sensing**
- **Observations for model intercomparison projects (obs4MIPs)**
- **Cloud computing and network**

C&DH Capability Advancement Recommendations

- **Establish testbed in order to test onboard capabilities**

- **Cross-cutting needs**
  - Address instrument specific interfaces and requirements

- **Quantitative goals are needed to address Instrument specific compression and innovative retrieval algorithms**
  - Free flyer vs. hosted payload, processing power, platform specific

- **Establish calibration and validation sensor network for remote sensing instruments**

- **Sample/synthetic data needed to test processing algorithms**

Quantifying C&DH Capability

Capability	Instrument/Platform Specific	Quantitative Goal
On-board sensor control	Data latency, algorithm, Processing power	<3hr, FPGA Virtex 5
Spacecraft area network	Formation control and knowledge, bandwidth	<wavelength/2, LOS, Ka vs. X
On-board processing	Cloud screening, event detection (e.g. storm/storm front, fire), water vapor estimation	% clouds along with confidence, <3hr for weather events Water vapor: <10% uncertainty @ 500m range resolution
On-board compression	FFT, image, buffer management	10:1, 7000 MIPS*
Intelligent sensor health & safety	Life time estimation, monitoring	Catastrophic parameter detection < 1 hour
Point and tracking	Attitude control	Integrated tracking sensors < 4 microrad
Ground Processing	Network, cloud computing	Capability will be met by NISAR and SWOT (1700 nodes, 26 Gbps, 150 Pbytes storage)

* To process 300-MB raw file in 5 seconds.

Preliminary Conclusions and Recommendations

- **Measurement requirements must be clearly defined.**
  - Quantitative requirements then follow
- **Technology requirements for each measurement in the areas of transmitters, receiver systems, and DADU/C&DH are tightly coupled.**
  - Subsystems are not implementable if top-down requirements are not defined in terms of mass, power, volume, interface, mechanical/thermal, data rate, and mission life
- **Technology development to satisfy the priority measurement(s) must then be targeted and coordinated in the three categories in order to achieve maximum return on investment.**

Questions & Comments

Sample from the Inputs

Technology	Lidar TC Capability	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need
Science model-driven adaptive targeting	**Technology & systems approach to autonomously acquire data based on inputs from prediction models or other sensors (scheduling & control target acq, quantify meas error characteristics)**	Technologies to allow for rapid data acquisition based on conditions determined by model predictions (e.g., estimated location of storm front). May also require inputs from other sensors (e.g., cloud detection)	Quantification of error characteristics of measurements, quality control, and other instrument characteristics. Quantification of spacecraft capabilities. Advanced information system to perform event scheduling, command and control, quality control of targeting. Scientific targeting scheme (i.e., adjoin methods) need to identify "critical regions" of the atmosphere. Overarching targeting control system to link all elements together.	Subset of capabilities have been demonstrated on the Electronically Steerable Flash Lidar IIP-2008, and Forest Carbon AITT 2011. New Predictive Control Architecture AIST program is now funded which utilizes a model predictive control structure. Focus of this development is on surface mapping. Broader weather tracking remains to be added.	Simulation of end-to-end adaptive targeting environment is necessary: OSSEs to simulate LIDAR data, model/assimilation system to provide products; targeting scheme for data capture; delivery and evaluation of science data products. Now added tightly integrated multiple sensor approach with multiple lidar steerable beams.
Standardization of interfaces and protocols	**Multi-sensor integration**	Standards and protocols like publish and subscribe architectures to share data onboard satellites and possibly between satellites			Simplified means to integrate selective data from various source for local use and data fusion
Standardization of interfaces and protocols	**Ground Development**	Modular design for LIDAR/Laser systems to accelerate technology development and reduce collateral burden to LIDAR developers.			Modular architecture and design (e.g., seed laser control, line-lock, data acquisition) for LIDAR systems. For example, a configurable seed laser unit to cover the range of LIDAR wavelenghts as a design applied to multiple measurements. Increases reliability and experience with modular systems and reduces electronics development burden for LIDAR researchers and scientists

Yellow: Technology
Green: Engineering
Blue: Cross-cutting development needs

NASA ESTO Lidar Technology Community Forum

February 24, 2016

EST/PST:	
11:00/08:00	Welcome/Overview of ESTO Investment Strategy Update (A. Valinia, NASA/ESTO)
11:30/08:30	Transmitters State-of-the-Art and Future Requirements (W. Lotshaw, Aerospace)
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15:15/12:15	Additional Input from Workshop Participants (All)
16:00/13:00	*Adjourn*

NASA ESTO Lidar Technology Status Evaluation

Receiver Technologies Assessment

Contents

- **Summary of receiver technology assessment for measurements from the 2007 decadal survey**
  - *Topography (LIST), Winds (3D Wind Demo), CO_2 (ASCENDS), Gravity (GRACE II), Aerosols (ACE)*
- **Summary of receiver technology needs for new measurement concepts**
  - *3D biomass, phytoplankton, ocean mixed layer depth, non-CO_2 GHG, other atmospheric composition*
- **Overview of technology vs engineering development needs**
- **Overview of emerging technology trends**
- **Recommendations**
- **Q&A**

Receiver Assessment for the 2007 Decadal Survey Measurements

Capability Gap	Measurements	TRL	"Greatest Challenge" TRL
High-efficiency detectors in 1.5-2 micron range	CO_2 (ASCENDS)	5	Space qualification/radhard assurance
Field-widened interferometric receiver	Aerosol/Clouds/Ecosystems (ACE)	4	Wavefront error
High-bandwidth, high-sensitivity detector arrays	3D Biomass (NISAR/GEDI, formerly DESDynI)	5	N/A
None	Gravity (GRACE II)	6	N/A
Multiple aperture/beam receiver	Topography (LIST in 2007 Decadal)	3	Large-area detector with high readout b/w
Single telescope supporting multiple look angles	3D Winds	3	Large-aperture receive optics (HOE/DOE, interferometer)

Enabling Technologies for New Measurement Concepts

Capability Gap	Concept	TRL	"Greatest Challenge" TRL
Detector performance	Phytoplankton	2	Dead-time, afterpulsing
Detector performance	Ocean Mixed Layer	2	Dead-time, afterpulsing
Low-noise, few-photon-sensitive detector array	Non-CO_2 Green House Gases	5	Space qualification
Large-aperture collector; detector efficiency	Ozone	4	Deployability
Detector performance	Water vapor profiles	4	Low-noise, photon-sensitive detector array

Background

- **The 2006 report contained 9 technology areas:**
  - *Alignment Maintenance*
  - *Scanning Systems*
  - *Large Effective Area, Light-weight Telescopes*
  - *Mechanical Metering (e.g., thermally stable, lightweight optical bench, trusses)*
  - *Specialty Optics (e.g., high transmission optics, fibers, polarization)*
  - *Narrowband Optical Filters*
  - *Detectors and Amplifiers*
  - *Optical High Resolution Spectral Analyzers*
  - *Detection Electronics (e.g., high-speed ADC, multi-channel scaler)*
- **Areas changed in 2016 report**
  - Added Cryocoolers
    - Compact, low power cryocoolers critical for infrared detectors
  - Removed Mechanical Metering
    - Quantitative requirements not reported
    - Recognized as a key part of system design and can be used to relax active alignment and focus control requirements in systems (e.g., SiC structure and optics in ADM-Aeolus ALADIN)

Technology Areas 2016

Technical Area	2006	2016	Rationale
Alignment Maintenance	X	**X**	Cross-cutting technology.
Scanning Systems	X	**X**	Cross-cutting technology for measurements requiring multiple look angles or specific look angles on command
Large Effective Area, Light-weight Telescopes	X	**X**	Cross-cutting technology for virtually all measurements
Mechanical Metering	X	**-**	No quantitative requirements were levied
Specialty Optics	X	**X**	Cross-cutting component
Narrowband Optical Filters	X	**X**	Core technology for each measurement
Detectors and Amplifiers	X	**X**	Core technology for each measurement
Optical High Resolution Spectral Analyzers	X	**X**	Needed for HSRL systems to ocean profiling, aerosol
Detection Electronics	X	**X**	Cross-cutting technology
Cryocoolers	-	**X**	Required for low-noise, high QE detectors in the NIR/SWIR/MWIR (e.g., HgCdTe Lm-APD)

Observations

- **Alignment maintenance is generally still challenging at the ~5-10 μrad regime, but significant improvements have been made in the past 10 years**
  - *ICESat-2 ATLAS will meet 2006 requirement for altimeters when launched*
  - *Has not been demonstrated for smallsats*
  - *Implementation at this level is primarily an engineering challenge and not a technology development effort, with the exception of a few areas (i.e., lag-angle compensation, SWIR)*
- **Cross-cutting technology: large, light-weight apertures**
  - *Power-aperture product: larger apertures or higher power lasers (or both)*
  - *Current SOA space-based telescopes are 1-2 m diameter*
  - *Lighter-weight, cost-effective apertures in the 1-2 m range would improve system SWaP trades (additive manufacture)*
  - *Deployable apertures larger that >1.5-2 m would enable reduced laser power or improve system performance*
  - *Smaller deployable apertures could enable some missions from smallsats*

Observations (cont.)

- **All measurement scenarios would benefit from improved detector performance**
  - *Multi-element detectors with high QE/PDE, low noise, low timing jitter*
  - *Full-waveform capabilities and large dynamic range (single-photon to high count rates)*
  - *For cooled arrays, higher operating temp and/or improved cryocoolers needed*
    - *State-of-the-art Dewar-cooler technologies, particularly linear-drive technology, are getting as small as 5x5x5 cm and power consumption of a few watts.*
    - *MEMS-based coolers are under development*
  - *Strong belief that domestic industry base is not currently able to respond to lidar community needs for affordable, low-volume, custom detector designs*
  - *International collaboration on custom detectors challenging due to ITAR/EAR restrictions*

- **Cross cutting: additive manufacturing for improved mechanical and thermal stability, reduced size and weight**

- **As in the case of transmitters, opportunities for synergistic DoD contractor development**

Technology Needs: Alignment

Measurement	Technology	State of the Art	Requirements	Development Need
Wind	Voice-coil actuated 2-axis beam control with reference camera star-tracker and INS system	5-10 μrad co-alignment demonstrated in the Vis/NIR for ground and airborne systems. ~5 μrad will be demonstrated in a satellite system on ATLAS with LRS. Lag-Angle Compensation: Still being evaluated; designs for ~1 μrad LAC developed, 10s of μrad demonstrated	5 microrad roundtrip (5 msec) lag angle compensation (coherent) 50 microrad active T/R boresite alignment (direct)	• Develop optical lag angle compensator • Prelaunch lidar alignment subsystem; highly quality beam reducing telescope; > 50 cm diameter for space application for far-field • On-orbit pointing knowledge subsystem (alignment sensor+INS) needs to be demonstrated at 2 micron. Needs high-efficiency, high-sensitivity SWIR star tracker, high temp (TEC or room temp.) • Develop active optical boresite alignment device
CO_2			50 microradian standard deviation on a zero mean Maintain transmit/receive overlap on the signal detector(s) to within 10% of ideal	On-orbit pointing knowledge subsystem (alignment sensor+INS) needs to be demonstrated at 2 micron. Needs high-efficiency, high-sensitivity SWIR star tracker, high temp (TEC or room temp.)

Technology Needs: Scanning Systems

Measurement	Technology	State of the Art	Requirements	Development Need
Wind	*Still under review*	TWiLiTE telescope uses a 40 cm diameter HOE as the receiver collecting and focusing aperture	30 deg nadir angle wide field of view telescope designs	Develop >75 cm holographic or diffractive optic telescope and step stare rotating mechanism including momentum compensation.
Topography	Polarization Gratings (cycloidal diffractive waveplates) *and/or* SEEOR (LC-clad waveguide) Switchable fiber arrays	SEEOR: Vis-NIR operation, 60x15 degree FOV 2D scan GFSC has demonstrated benchtop fiber array for FOV selection	addressable FOV across 1 - 2 degrees	Develop solid-state approach of selecting individual fields-of-view at high switching rates.
Wind, Topography, T and Water	*Still under review*	10 cm devices with acceptable efficiencies have recently been demonstrated.		Non-mechanical large aperture (> 25 cm) beam steering and receiver pointing devices.

Technology Needs: Telescopes

Measurement	Technology	State of the Art	Requirements	Development Need
Wind, Aerosols	Beryllium or SiC Field lens-corrected Ritchey-Chretien or other Cassegrain receive telescope	Single aperture, 1-1.5 m, ~0.2-0.5 mrad FOV	Light-weight telescopes > 1 m	Light-weight, deployable telescopes > 2 m diameter*
Aerosol, Ocean, Non-CO2, Phytoplankton			2-5 meter primary mirror telescope for space based lidar, <F/1 primary, <100 micron blur circle, high transmission (>95%) at target wavelength(s), low thermal distortion, high rigidity	
Topography			1 - 1.5 m diameter, < 10 microradian blur circle	
CO_2, Ozone			3m diameter deployable, ~100 mrad FOV, areal density <25 Kg/m2	

* Aperture size requirement is dependent on transmitter.

Technology Needs: Specialty Optics

Measurement	Technology	State of the Art	Requirements	Development Need
Wind	Pure silica or Hollow-core photonic crystal fiber	Commercially available options, but may not meet requirements in both UV and Vis, may not be space qualified	Fiber couplers and fiber optics with high performance at 355 and 532, rad hardened	Improve UV rad-hard fiber couplers and fiber optics
Phytoplankton, aerosol, ocean mixed layer	Hard coated rugate or other interference filter	Meets or exceeds specification except possibly at UV edge	1-3 nm half-height or better, D > 5, 90% transmission or better in 380-800 nm range	Develop the 532 nm notch filter that meets or exceeds the specification
CO_2	SiO_2/GeO_2	PM single mode passive optical fibers are commercially available but are not rad hard, may not meet transmission efficiency requirements	Polarization maintaining, radiation tolerant 2 micron single mode fiber with transmission efficiency > 95%/m	Assess radiation hardness and improve transmission of fibers

Technology Needs: Narrowband Optical Filters

Measurement	Technology	State of the Art	Requirements	Development Need
Wind, Aerosol, Ocean	Quasi-monolithic field-widened Michelson or Mach-Zender interfero-meters	~1 degree, 25 mm aperture 0.1-1 m OPDs Demonstrated 25:1-50:1 transmission ratios with Michelson design. Wavefront error limits contrast	Increase interferometer to > 10 mrad to support large telescopes. 0.1-1 m OPDs. GHz resolution or less, Mie transmission ratio of >100:1, goal of 1000:1 to support HSRL measurement in clouds	Athermal field-widened interferometers to support larger apertures
CO_2	Hard coated oxide interference filters	Few 100 picometers FWHM, >80% T, rounded transmission peak, OD9 out of band rejection	100s of pm, >90% T, flat top profile	Stable, flat top filters need to reduce filter distortion, improve SNR
Water	*Still under review*	*Still under review*	high transmission (>80%), fast temporal response (<100 microseconds), <10-20 pm optical bandpass, large free spectral range (>100-300 pm), high contrast ratio (> 100/ contrast ratio), etendue >50mm-mrad	Tunable interferometric filter for implementation in high PRF multi-wavelength DIAL in the VIS-NIR

Technology Needs: Detectors

Measurement	Technology	State of the Art	Requirements	Development Need
Wind (direct or hybrid), Aerosol	PMTs,, Si APD, or Accumulation CCDs	PMTs, QE ~25% Si APD, >65% QE, < 300 cps DCR, < 50 ns dead time ACCD: 85% QE, 16x16 pixels, 25 x 2.1 us range gates, 7 noise e- per pixel, 16-bit ADC	Single element or array detectors with single photon counting sensitivity, QE> 50 %, internal gain 10^6, dark current <1 kcps, active area > 2 mm2	Develop and demonstrate photon counting detector arrays for increased dynamic range
Wind (coherent) CO2, non-CO2 GHG, water	HgCdTe APD arrays	80K, 2x8 pixel arrays, 75% QE, 200 kHz DCR, few photon sensitive, 10 MHz bandwidth, 400-4200 nm responsivity	Multipixel arrays, >75% QE, <200 kHz DCR, few photon sensitive, 10 MHz bandwidth, 750-3400 nm responsivity, low power consumption (<5W including cooler)	Develop and demonstrate arrays
Ocean Mixed Layer	Si APD or PMT	PMTs, QE ~25% Si APD, >65% QE, < 300 cps DCR, < 50 ns dead time	Gated on and off within 20-50 ns, high quantum efficiency (>50%, goal >70%), Excess noise factor <2 (variance domain), low afterpulsing , large dynamic range, large aperture (>1 mm^2), low dark noise, Gain 10^5- 10^6	Develop and demonstrate arrays
Topography, 3D biomass, Aerosol	Si APD or PMT (532 nm) InGaAs or HgCdTe APD (1064 nm)	InGaAs: 256x64 pixel arrays, 35% QE, < 10 kHz DCR, single photon sensitive, ~350 ps timing jitter, asynchronous HgCdTe: 80K, 2x8 pixel arrays, 75% QE, 200 kHz DCR, few photon sensitive, 10 MHz bandwidth, 400-4200 nm responsivity	Large arrays (256x256), high-efficiency (>50%), high-bandwidth (1 GHz), low-timing jitter (<100 ps) arrays with high count rates (>100 Mcps).	Low-cost, high efficiency, larger format, radiation hard photon counting arrays

Technology Needs: High Resolution Spectral Analyzers

Measurement	Technology	State of the Art	Requirements	Development Need
Phytoplankton, ocean mixed layer	*Still under review*	Although there are commercial prototypes, none of them meets the specified quantitative requirements and is a space-qualified product.	LSE detection in 520-800 nm (optional: 370-800 nm, TBD) range, 1-3 nm resolution, adjustable gating with 40-100 ns pulses synchronized with the LSE backscatter arrivals, photon counting capability, high quantum (QE) efficiency (50% or better), low noise	Develop a space-qualified LSE spectral detector/analyzer that meets or exceed the listed requirements

Technology Needs: Detection Electronics

Measurement	Technology	State of the Art	Requirements	Development Need
Wind	*Still under review*	*Still under review*	FPGA based Real time processors for LOS winds from multiple lines of sight with variable platform motion	on-board processing of sensor (e.g. Star tracker pointing + lidar Doppler shift) information into data product (e.g. wind) estimates
CO_2	*Still under review*	*Still under review*	20 MHz, 16 bit ADC	High speed, high resolution ADC
Topography	*Still under review*	*Still under review*	low power(<50W),12 bit, 1 Gsamp/s, 9 channel digitizer streaming digitizer, 1 Gsamp/s, 10-12 bit resolution with integrated pulse identification and time tagging	Develop a low power option for return pulse digitization with 10-12 bits of dynamic range at sampling rates of 1 Gsamp/s. Integrated return-pulse identification and processing is desired. Couple a high-speed A/D converter with a high-speed FPGA capable of continuous digitization and real-time return-pulse identification.

Technology Needs Trades

	UV 355-400 nm	VIS 400-650 nm	NIR/SWIR 700-2000 nm	MWIR 3-5 micron
Measurement	3D Winds; Water vapor; Trop. ozone	Physical/biological oceanography; aerosols; topography	3D Winds; GHG; water vapor; O_2; topography; aerosols	GHG (CH_4)
Transmitter	THG of 1-μm sources; multi-stage non-linear wavelength conversion	SHG of 1-μm sources; multi-stage non-linear wavelength conversion	1, 1.5, 1.8-2.6 μm sources; SHG of 1.5, 2 μm sources; OPO/OPA of 1 μm sources	OPO/OPA of 1, 1.5, 2 μm sources; narrow-gap laser diodes
Detector	**GaN, MCP, DD-CCD; Low-noise multi-element arrays, QE > 50% @ 355 nm**	**Si-APD, PMT; Gateable <50 ns, QE 50-70% @ 450/532 nm**	**Lm HgCdTe APD; Gm InGaAs APD; PMT (to ~ 1.4 μm) MCP (to ~ 900 nm)**	**Lm HgCdTe APD HgCdTe FPAs SL/nBn FPAs**
Aperture	**>1.5-m aperture; areal density <25 kg/m²**	**>1.5-m aperture; areal density <25 kg/m²**	**>1.5 m aperture; areal density <25 kg/m²**	**>1.5-m aperture; areal density <25 kg/m²**
IT*	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization

* Cross-cutting across multiple measurements and sensor modalities.

Preliminary Conclusions and Recommendations

- **Improvements in detector performance needed for all measurement scenarios**
  - Develop techniques for radiation hardening of single-photon detectors.
  - Improved low defect/defect-free fabrication and processing techniques that result in arrays with the required pixel densities and low cross talk and dark counts
  - Expand detector dynamic ranges to support photon-number resolving and higher count rates
  - Increase detector bandwidths, match to the available transmitter PRF
  - Strengthen domestic vendor base for novel detector development
  - Leverage DoD investment next-gen detector development
- **Deployable apertures could relax requirements on transmitter technologies and enable measurement scenarios from smaller satellite platforms**
- **Reductions in size and weight for receive telescopes would benefit all measurement scenarios**
  - Dependent on system trades against receive optics train throughput, detector performance and laser transmitter power
- **Novel manufacturing and design in mechanical metering may relieve active alignment requirements**
  - **Integrated structural, thermal, and optical modeing of receive systems needed**
- **Athermal large aperture field-widened interferometers needed for wind and aerosols**

Questions & Comments

NASA ESTO Lidar Technology Community Forum

February 24, 2016

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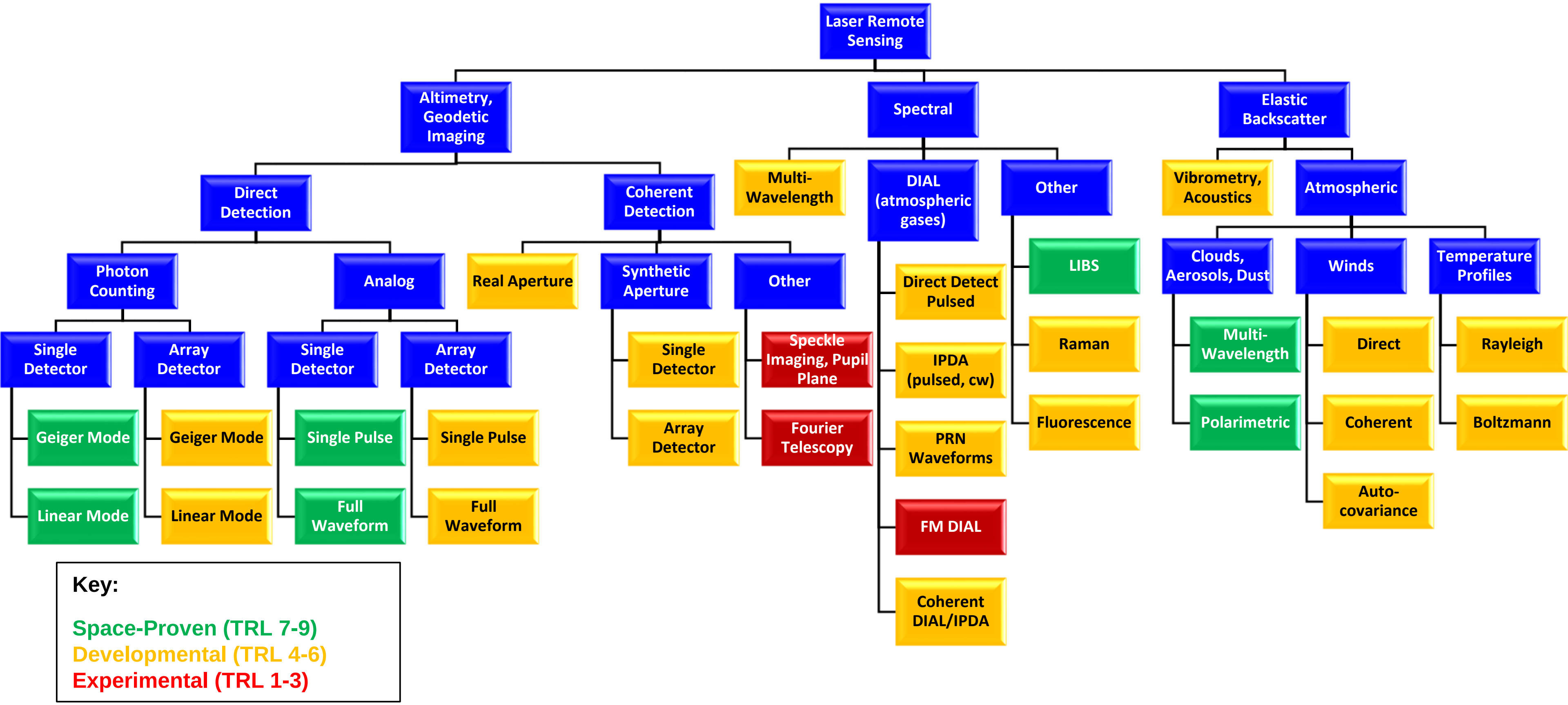
NASA ESTO Lidar Technology Status Evaluation:

Emerging Technologies Assessment

Contents

- **Definition of emerging technologies**
- **Summary of emerging technology needs assessment for measurements from the 2007 decadal survey**
  - *Topography (LIST), Winds (3D Wind Demo), CO_2 (ASCENDS), Gravity (GRACE II), Aerosols (ACE)*
- **Summary of emerging technology needs for new measurement concepts**
  - *3D biomass, phytoplankton, ocean mixed layer depth, non-CO_2 GHG, other atmospheric composition*
- **Overview of emerging technology development needs**
  - *Transmitter technologies*
  - *Receiver technologies*
  - *Information technologies (C&DH)*
- **Summary and Recommendations**
- **Q&A**

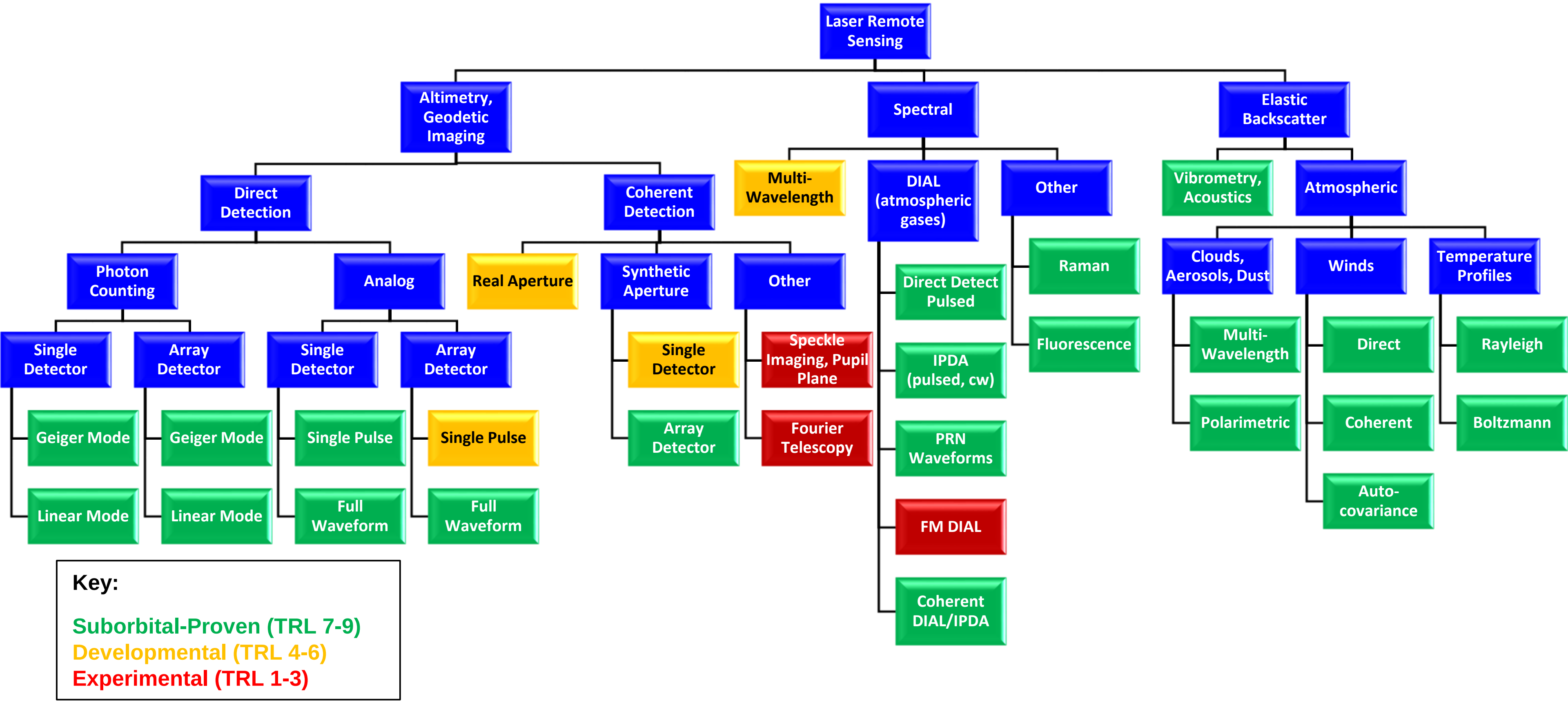
Laser Remote Sensing Taxonomy: Space



Each sensor/measurement has its own Command and Data Handling 'shadow', in addition to the cross-cutting IT challenges.

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

Laser Remote Sensing Taxonomy: Suborbital



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

Emerging Technology Definitions

- **Since the 2006 report there has been a revolution in smallsat/hosted payload concepts, fueled in part by an increasingly (even aggressively) cost-constrained environment**
  - *In this paradigm miniaturization is key*
  - *The burgeoning additive manufacturing field offers potential solutions for previously impossible enabling constructs (e.g., large-area mirrors that are lightweighted in ways that cannot be accomplished through other means)*
  - *Integrated photonics approaches are being used to dramatically compact optical designs*
- **The decision to actively address this emerging technologies in the 2016 report reflects a realization that new capabilities could determine the success of more stringent measurement requirements and that they should be defined and their development accelerated**
- **"Emerging technologies are technologies that are perceived as capable of changing the status quo" (*Wikipedia)***
  - *Potential game changers*
- **For the current purpose we defined emerging technologies as being at a maturity level of <TRL3**
  - *TRL 2 is the entry point for ESTO's ACT and AIST programs*
- **System engineering as an emerging technology**
  - *Trades between aperture size, detector efficiency, laser power, and waveform can mitigate technological hurdles*
  - *Requires robust, high-fidelity modeling and simulation capabilities*

Unmet Technology Needs Since Prior Decadal Survey

Capability Gap	Measurements	Current TRL
SWIR optical mux	CO_2 (ASCENDS)	2
Tunable NIR laser; High-QE UV/Vis detectors; Narrowband wide-acceptance filter	Aerosol (ACE)	1-2
Intelligent performance management	3D Biomass (DESDynI)	2-3
Demonstrated by GRACE FO*	Gravity (GRACE II)	—
Intelligent performance management	Topography (LIST)	2-3
High-QE multi-element UV/SWIR detector arrays	3D Winds (Demo)	2
Intelligent performance management; Rad-hard deep-submicron microelectronics	All	2-3

* Laser supplied by DLR (Germany).

Emerging Needs for New Measurement Concepts

Capability	Measurement	Current TRL
Intelligent performance management	3D biomass	2-3
Narrowband blocking filter; High-resolution spectral analyzer	Phytoplankton	2
Moderate PRF blue laser	Ocean mixed layer depth	2
SWIR optical mux	GHG	2
Tunable NIR laser; NIR optical mux; Photonic crystal fiber gas reference cell; Large collection aperture; Narrowband wide-acceptance filter	Other atmospheric composition (water vapor)	1-2
Tunable UV laser; Large collection aperture	Other atmospheric composition (ozone)	2
Tunable NIR laser; High-QE UV/Vis detectors; Narrowband wide-acceptance filter	Other atmospheric composition (clouds and aerosols)	1-2
Intelligent performance management; Rad-hard deep-submicron microelectronics	All	2-3

General Observations

- **Six primary categories of lidar-specific development need**
  - *Nonlinear wavelength generation in the UV thru NIR*
  - *High-QE detector arrays and fast gateable single elements*
  - *Deployable large collection apertures*
  - *Narrowband blocking filters and spectrum analyzers*
  - *Photonic integrated circuits*
  - *Performance management to maximize laser life*

- **One broad cross-cutting need that would benefit multiple other sensor technologies**
  - *Radiation hardened deep-submicron microelectronic technology*

Emerging Transmitter Laser Technologies

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Blue laser	Ocean temperature profiles (mixed layer depth)	SHG/THG of 940/1320 nm Nd:YAG; OPO w/Nd:YAG 3rd harmonic	400-480 nm; PRF ≤ 500 Hz; 30-100 mJ
UV laser	Tropospheric ozone profiles	High-energy pumped multi-stage cascaded non-linear optical scheme	UV pairs separated by 10-20 nm; space: 305-320 nm; airborne: 290-320 nm; high efficiency, 100-1000 Hz, 20-100 mJ, M^2 <2, linewidth <1 Å, pulse width 10-30 ns
NIR laser	Water vapor and aerosol/cloud profiles	Current Ti:Sapphire lab solution not viable for space; 532-nm pumped OPO or cascaded non-linear optical scheme with high-WPE 1/1.5-μm pump laser	720 nm, WPE 5-10%, 20-40 W at 1000-3000 Hz, or 100 mJ at 100 Hz double pulsed within 200-300 microseconds, spectral purity >5000/1, pulsewidth <20 ns, linewidth <100 MHz

Emerging Ancillary Transmitter Technologies

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Optical switches	Water vapor and methane profiles/columns	Up to 4x1 switches exist with acceptable response time at TRL 5. Improved optical cross talk and increased input channels desired to improve spectral purity and reduce physical footprint for space applications. Need wavelength agility to execute measurement	Multi-input (4x1) switch to multiplex varying wavelength seed lasers onto a single fiber for injection seeding pulsed DIAL wavelengths (700-1000 nm, 1650 nm)
Gas reference cells	Water vapor profiles	Photonic crystal fiber gas cells in current use for spectroscopic applications, but little research dedicated to sealing the cells with a fixed amount of gas for long term unattended operation	Compact cell for water vapor DIAL laser line locking. Photonic crystal fiber that can be sealed and spliced to commercially available single mode fiber; <20 dB/km optical loss @ 760/820/940 nm

Emerging Detector Technologies

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Detectors (Including Arrays) and Amplifiers	3-D winds	InGaAs arrays with extended response to 2 microns previously demonstrated but vendors are no longer working in this area; may require alignment of fibers to each detector element to maintain heterodyne efficiency	Multi-element arrays; QE > 80%, BW > 200MHz @ 2 microns; QE > 50%, dark counts <1 kct/s @ 355 nm; QE > 70%, dark counts <1 kct/s @ 532 nm
Detectors (Including Arrays) and Amplifiers	Aerosol profiles	Non-U.S. vendors not an option due to export control/MCTL/ ITAR	Gateable within 20-50 ns, QE 50-70% @ 355/450/532 nm, low afterpulsing, large dynamic range, low dark noise

Emerging Ancillary Receiver Technologies (1/2)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Large Effective Area, Lightweight Telescopes (including stray light control)	Trace gas profiles	Demonstrations of deployable structures; single-petal reflector including the latch and hinge mechanisms for mechanical stability	3-m aperture with deployable mechanisms; areal density <25 kg/m^2
Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)	Phytoplankton	Iodine-filled cell	Narrow-band 532-nm notch filter to reduce laser backscatter to the level comparable with fluorescence and Raman components in the laser-stimulated backscatter signal
Narrowband Optical Filters	Water vapor & aerosol profiles	Metamaterials with large angular acceptance; volume Bragg gratings are an alternative for ~10 pm	Tunable interferometric filter for implementation in high PRF multi-wavelength DIALs operating in the VNIR (500-1000 nm)

Emerging Ancillary Receiver Technologies (2/2)

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Optical High Resolution Spectral Analyzers	Phytoplankton	Commercial prototypes exist, but none meet the specified quantitative requirements and are space-traceable	Laser-stimulated emission (LSE) spectral detector/ analyzer; 370-800 nm, 1-3 nm resolution, adjustable gating
Photonic Integrated Circuits*	Lidar/lasercomm smallsat constellations	Utilize lasercomm components beyond lasers/amplifiers	Dramatic SWaP reductions to enable smallsat applications; 1-2 microns

* Cross-cutting across multiple measurements.

Emerging Information System Technologies

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Intelligent sensor health and safety*	Autonomous monitoring & control of lidar H&S (laser performance/ degradation, laser life optimization strategy)	Trim laser output power based on performance degradation tracking	Sensors for use in predicting lidar health; control software including degradation mode models and cost functions for optimizing instrument performance and/or instrument life
Space-qualified HPC HW and programming tools†	Enabling technology for smallsat and hosted payloads	Current radiation hardened technology is at 0.35 and 0.25 microns. Large investment needed to satisfy future processing needs	Radiation hardened at deep-submicron microelectronic technology (0.25, 0.18, 0.15 and 0.09 micron)

*Cross-cutting across multiple measurements.
†Cross-cutting across multiple sensor modalities (not specific to lidar).

Emerging Technology Needs Roll-Up

	UV 355-400 nm	VIS 400-650 nm	NIR/SWIR 700-2000 nm	MWIR 3-5 micron
Measurement	3D Winds; Water vapor; Trop. ozone	Physical/biological oceanography; aerosols; topography	3D Winds; GHG; water vapor; O_2; topography; aerosols	GHG (CH_4)
Transmitter	THG of 1-μm sources; multi-stage non-linear wavelength conversion	SHG of 1-μm sources; multi-stage non-linear wavelength conversion	1, 1.5, 1.8-2.6 μm sources; SHG of 1.5, 2 μm sources; OPO/OPA of 1 μm sources	OPO/OPA of 1, 1.5, 2-μm sources; narrow-gap laser diodes
Detector	GaN, MCP, DD-CCD; Low-noise multi-element arrays, QE > 50% @ 355 nm	Si-APD, PMT; Gateable <50 ns, QE 50-70% @ 450/532 nm	Lm HgCdTe APD; Gm InGaAs APD; PMT (to ~1.4 μm); MCP (to ~900 nm)	Lm HgCdTe APD; HgCdTe FPAs; SL/nBn FPAs
Aperture	3-m aperture; areal density <25 kg/m^2	–	3-m aperture; areal density <25 kg/m^2	–
IT*	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization	Sub-μm HPC hardware and tools; intelligent sensor management for laser life optimization

* Cross-cutting across multiple measurements and sensor modalities.

Preliminary Conclusions and Recommendations

- **Cross-cutting technologies were identified that are relevant to component and subsystem miniaturization**
  - *Each constitutes a waypoint on the smallsat/U-class constellation roadmap*
  - *Photonic integrated circuits*
    - Enables large reductions in optical system SWaP
    - Applicable across the spectrum of lidar and lasercomm concepts
  - *Rad-hard, deep-submicron microelectronics technologies*
    - Requires large investment need
    - Payoff reaches beyond lidar applications into all other sensor modalities
- **System engineering as an arbitrator between technology options**
  - *Trades between aperture size, detector efficiency, laser power, and waveform can mitigate technological hurdles*
  - *Requires robust, high-fidelity modeling and simulation capabilities, in both the environmental and sensor performance domains*
- **Need to develop and mature U.S. industrial base required for critical system components**
  - *Detectors*
  - *Laser media and nonlinear conversion materials*

Questions & Comments

NASA ESTO Lidar Technology Status Evaluation:

Community Input

Community Feedback: Q&A (1/3)

Q1. Will we be able to download a copy of the charts presented today?

Ans – Yes, within two weeks.

Q2. What is the driver for 2-µm wavelength transmitters for wind lidar?

Ans – The answer to this question has roots going back ~25 years, when it was believed that the 1.5-µm materials didn't have the energy storage capacity to produce the large pulses considered necessary, whereas modeling had indicated that the 2-µm materials would be able to do so. Given the advances in 1.5-µm technology since it would be prudent to re-evaluate this question.

Q3. Is there a reason the water vapor profiling wavelengths are focused on 700-900 nm? Have telecomm wavelengths been ruled out?

Ans – Current techniques are in line with water transitions – that's why those wavelengths were chosen.
Ans – There are strong bands within the 1.5-µm band, but you don't get the same scattering. They can be used for column measurements but most aren't focusing on that.

Q4. Adaptive sensors as future technology were not addressed under transmitters, does this need to be developed for both C&DH and transmitter or each?

Ans – No, fiber front ends offer adaptability for controlling signal properties.
Ans – Define an instrument suite to address the health of the laser. We can use this info to predict and monitor the health of the transmitter.
Ans – It also comes in with active manipulation of both transmitter and receiver subsystems.

Community Feedback: Q&A (2/3)

Q5. Concerning free-space optical comms for downlink, what about leveraging multiple platforms?

Ans – There is a trade with how much info can be compressed. There is a limit before losing resolution of what you're trying to track. You can also use relays (TDRS type of advancements). Each mission would have to balance smart sensing/compressive sensing, data compression, and downlink capabilities during their engineering phase.

Q6. Why no mention of larger arrays and higher QE needs? Are there new types of telescopes (DARPA)?

Ans – Large arrays are an area of interest and we are attempting to highlight this in the presentation. There are some promising candidates for solid state detectors.

Q7. Is there info on link budgets, array size, timing jitter, and system trades? MIT has been working on asynchronous arrays.

Ans – Will direct this question to the NASA center POCs.
Ans – POCs are also in the report.
Ans – I am familiar with the MIT work and will reach out.

Q8. Wavefront agility is a ~TRL2 emerging technology under development for advanced lidar concepts.

Ans – We will ensure that it is discussed in the Final Report.

Q9. Will NASA fund ozone measurements?

Ans – It remains to be seen what NASA chooses in their responses to solicitations.

Community Feedback: Q&A (3/3)

Q10. Titanium carbide for radiation hardening? Could you discuss rad-hard materials?

Ans – Titanium-sapphire has been used, the doubler for CALIPSO is discussed. LBO is very durable and is often the material of choice.

Q11. Is there an interest in distributed aperture receivers?

Ans – Yes, and these will be treated in the Final Report.

Q12. 400-480 nm is probably too blue for oceanographic measurements. The optimum is ~480 nm.

Ans – We will revisit the issue with the originators and correct if necessary.

Q13. There seems to be no mention of off-axis multiple scattering lidar concepts?

Ans – Although not explicitly mentioned in today's presentations, the multiple scattering aerosol lidar concept is treated in the draft Final Report. Its signature technical requirement comes through in our charts as a need for wide-angle acceptance receiver technologies.

Q14. There seems to be no mention of frequency combs?

Ans – They were not mentioned today, but will be treated in the Final Report.

Q15. How long will you continue receiving White Papers?

Ans – The on-line repository will remain open until about mid-March.

Community Feedback: Comments

C1. Repository for white papers: http://dev.blinex.com/LIDARUpload/

C2. Currently, there is an interest in blue lasers, but the statement that the focus is mainly on oceanographic measurements is an understatement. Also, there is interest in other atmospheric gases (e.g., NOx, ammonia).

C3. Autonomous software (algorithms) for improving performance developed for the ground is not time intensive. Need algorithms to perform better on orbit. System Engineering and System ("Integrated") Modeling for various performance parameters throughout. This may help with cost for an overall mission and also with upfront design.

C4. GRACE-FO optical link met the needs for GRACE-II, but that was based on the 2007 decadal survey and the community is now asking for other approaches to deal with aliasing effects.

Backup

TRL Definitions

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated	Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof-of- concept	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.

TRL Definitions (cont.)

TRL	Definition	Hardware Description	Software Description	Exit Criteria
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to final operating environment.	Key, functionality critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.

TRL Definitions (cont.)

TRL	Definition	Hardware Description	Software Description	Exit Criteria
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.