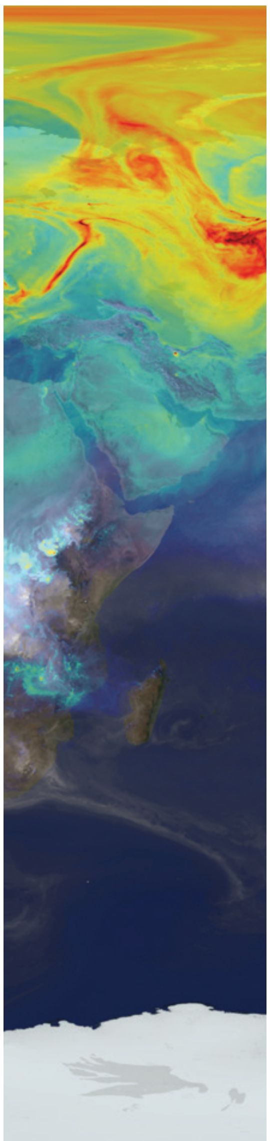
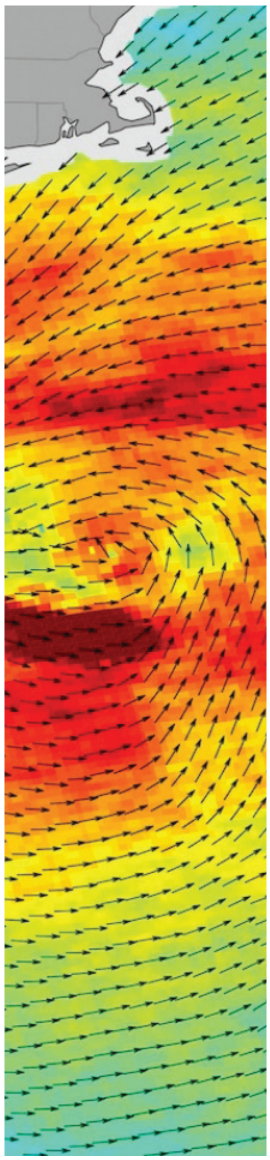
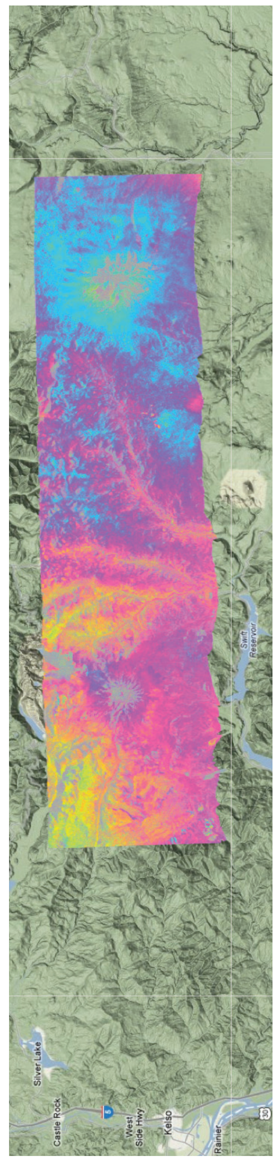
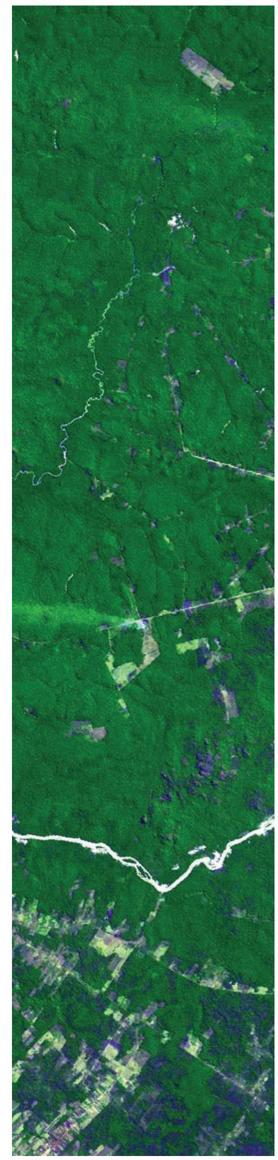
National Aeronautics and Space Administration

2016 Lidar Technologies Review and Strategy





NASA Earth Science Technology Office

2016 NASA Earth Science Technology Office (ESTO)
Lidar Technologies Review and Strategy

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Executive Summary

This study summarizes the 2016 state-of-the-art in lidar technology as it pertains to Earth science and discusses needed capabilities for achieving NASA's Earth science measurement goals. It updates the last Earth Science Technology Office (ESTO) lidar investment strategy, documented a decade ago [*ESTO,* 2006], which laid out the scientific basis and key technology developments needed to achieve NASA's Earth science goals.

The overall space-based lidar applications landscape is illustrated in Figure 1, which has been adapted and expanded from *NRC* [2014]. From this figure it can be seen that up to the present time comparatively little of the total technology trade space can claim actual space heritage, leaving considerable scope for further development and exploitation.

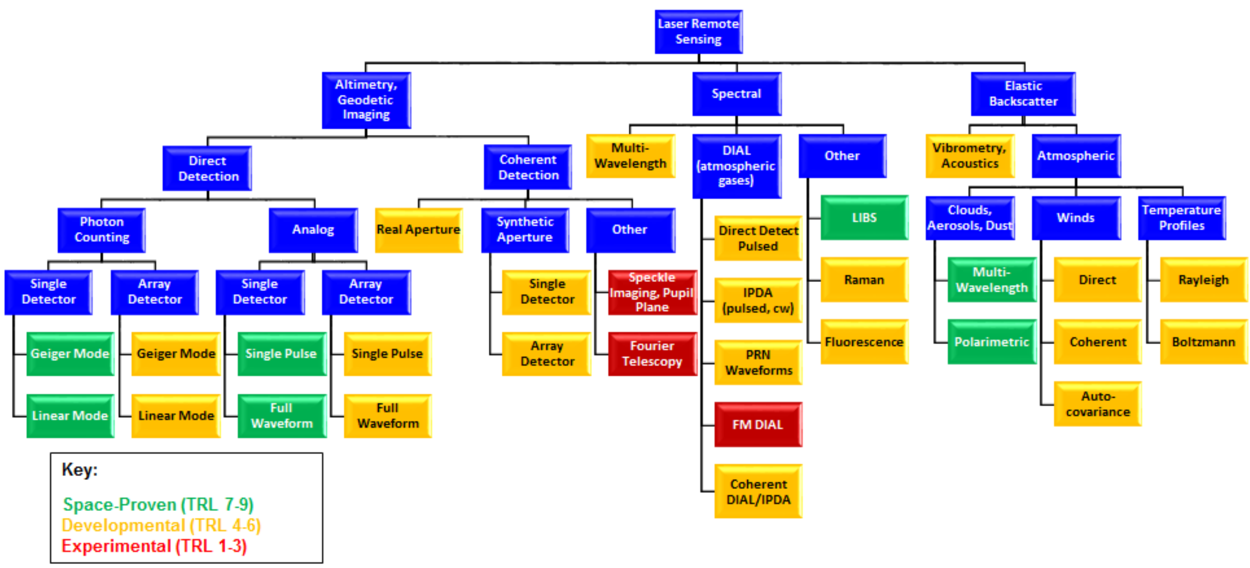

Figure 1. Cross-sector taxonomy of space-based lidar applications and associated sensor options.

However, the analogous situation for airborne ("suborbital" in NASA parlance) lidar, depicted in Figure 2, indicates that a substantial reservoir of experience and heritage is available in that domain to draw on for seeding future development of space-based implementations. Note that Figure 2 applies the modified TRL definitions that have been formulated for the suborbital domain (airbornescience.nasa.gov/sites/default/files/documents/TRL%20Levels.pdf).

In the realm of lidar-specific technologies, progress in the last decade has been mixed. Some emerging laser materials (*e.g.*, Cr:ZnSe) and improvements in nonlinear optical (NLO) materials have expanded options for wavelength generation both in the near-UV and SWIR/MWIR, while dramatic improvements in pump laser-diode electrical efficiency have significantly improved the wall-plug efficiency (WPE) of both bulk solid-state and fiber-based lasers.

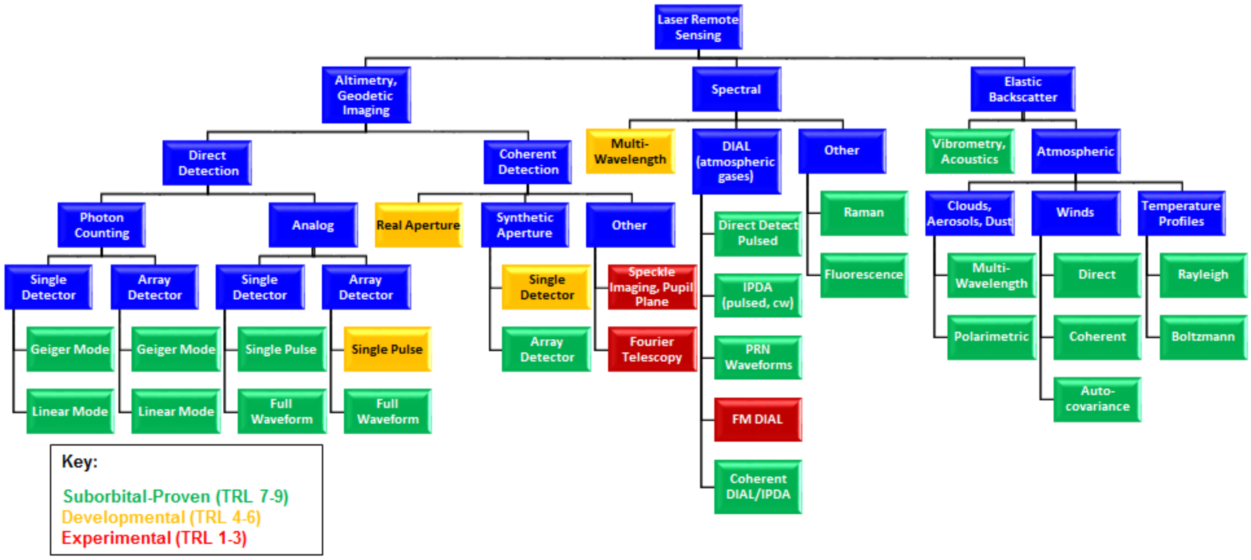

Figure 2. Cross-sector taxonomy of suborbital lidar applications and associated sensor options.

An especially important consequence of laser technology development over the past decade is that *fiber-laser average power capability now rivals that of traditional bulk solid-state systems*, which is a distinct advantage in that all-fiber architectures are both compact, immune to misalignment, and typically exhibit higher WPE than conventional bulk solid-state lasers. The significance of these developments is that previously the restricted performance envelope of fiber-based lasers had ruled them out of consideration for measurement applications requiring high average power or moderate (*i.e.*, ~mJ) pulse energy. Developments of the past decade merit a re-evaluation in some of these scenarios. For instance, high pulse repetition frequency (PRF) transmitters have generally been regarded as inconsistent with the typical laser altimetry CONOPS (Concept of Operations) because of a perceived tendency for ranging ambiguity when there are multiple pulses in contention. However, the waveform agility of telecom-heritage signal laser diodes enables novel temporal waveforms that would permit disambiguation of range/altimetry measurements in such cases, and moreover would do so with the corollary SWaP (size, weight, and power) benefits of fiber lasers, as well as the additional advantages named above.

While the relief offered to laser performance requirements by improved detectors has long been recognized, technological investment has remained heavily biased toward laser development. *A consistent theme expressed across all measurement scenarios was the need for improved detector performance, particularly radiation-hardened multi-element architectures with high quantum efficiency, low noise, low timing jitter, and low afterpulsing*. Improved materials growth and device fabrication and processing techniques, particularly for complex band-engineered materials, could increase detector yield as well as improve device dark count rates, afterpulsing performance, and non-uniformity, which will be necessary for the new generation of array detectors. The astronomy and astrophysics communities pursue major detector development programs that could also be leveraged in this regard.

A summary of scientific measurements and associated technology needs (without prioritization of technology development) is shown in Figure 3.

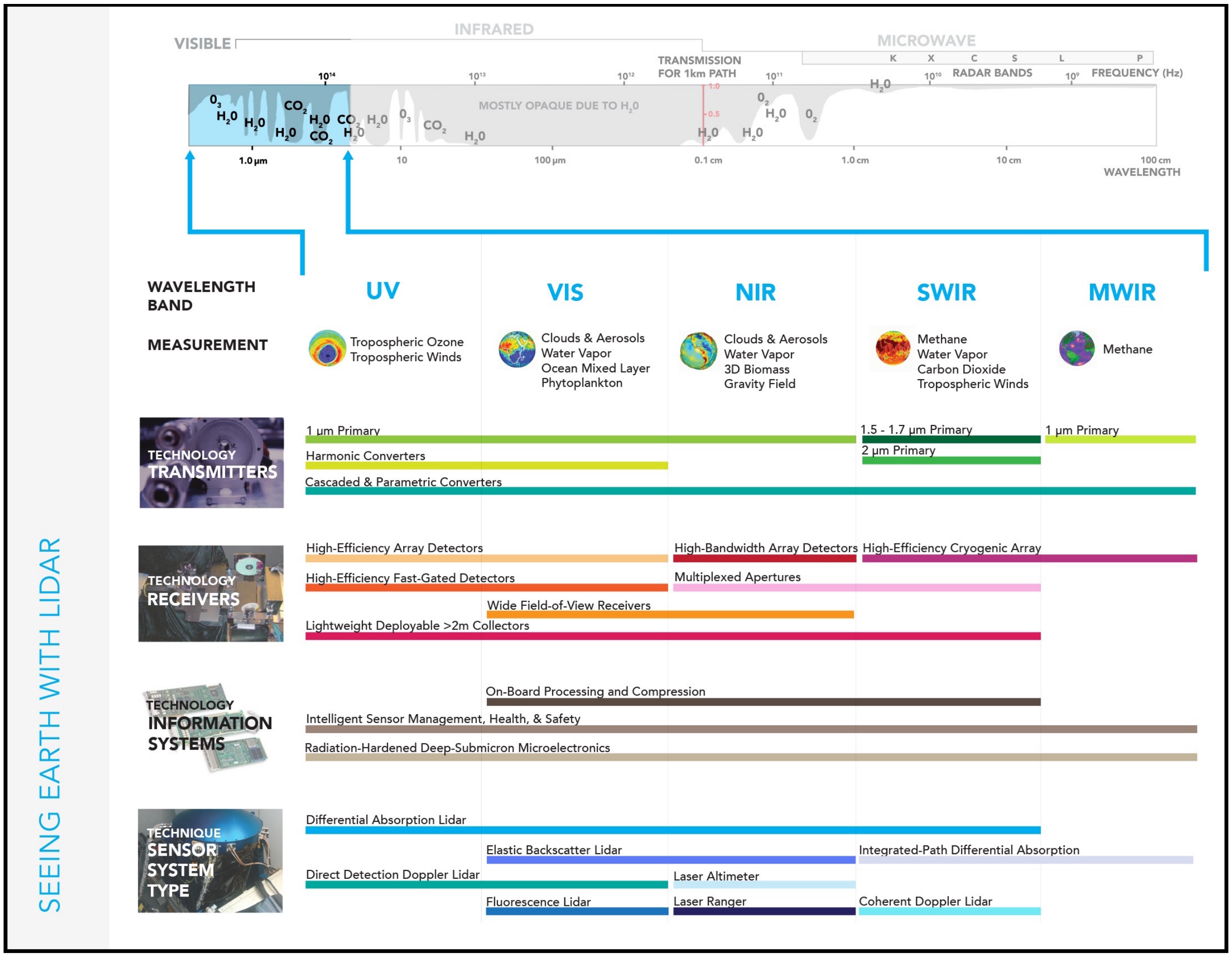

Figure 3. Summary of Earth science lidar applications and associated top-level technology needs.

Of the laser technologies covered in the 2006 report and this update, solid-state systems operating at 1 µm and lidars using harmonics thereof are by far the most mature and closest to insertion once the arduous task of space qualification is accomplished. The laser technologies required for direct detection UV Doppler wind measurements, and NIR/Vis/UV atmospheric aerosol/cloud/ecosystem measurements, have one remaining obstacle which should be within reach: improving the damage resistance and reliability of harmonic generation components. This task principally requires improved contamination control and more robust anti- and high-reflection coatings at UV wavelengths. Fiber-laser and fiber/bulk solid-state analogs of high-PRF, moderate energy (≤1 mJ) bulk solid-state systems are also rapidly approaching the critical TRL6 benchmark and could displace the bulk solid-state technology entirely in a few years. It is instructive to note that the NFIRE (Near-Field InfraRed Experiment) space-based lasercomm experiment [*Fields et al.*, 2011] has been operational for 9 years, using relatively primitive fiber amplifier components.

As the current analysis progressed it became evident that a number of technology areas identified as important in the 2006 report [*ESTO*, 2006] had not advanced significantly in the ensuing decade and on that basis are being carried forward into this report. Based on community inputs to this 2016 update (Appendix 3A), 1570-nm sources for ASCENDS, 2-μm sources for coherent winds, and even 1064/532/355-nm sources for aerosol/clouds/ecosystem measurements appear to have shown little TRL advancement when compared to the equivalent entries in the 2006 report [*ESTO*, 2006, Appendix 5A]. The technology enterprise should consider re-prioritization of these efforts once the current Decadal Survey panel has communicated its recommended science priorities. For this reason, the current update avoids assignment of priorities to either the measurement objectives listed or the associated technology requirements.

It is important to note that the 2016 survey of lidar technologies was conducted against the background of a radical retooling of the space sensing arena occasioned by an explosion of SmallSat and/or hosted payload concepts that have evolved in response to an increasingly cost-constrained environment. SmallSats, especially the U-class concepts currently in vogue, demand a greater degree of attention to miniaturization and efficiency than has heretofore been necessary. *Hence, in addition to the conventional lidar technologies that dominated the 2006 survey, the current analysis also advocates a number of technologies such as integrated photonic circuitry and deep-submicron microelectronic architectures that, while non-lidar specific, nevertheless offer considerable advantages (in some cases enabling) to lidar measurement concepts intended to be compatible with SmallSat/U-class buses.* In this respect, the emergence of innovative manufacturing techniques in the last decade offers pathways to the creation of, for instance, structural elements and large-area reflectors that are lightweighted in ways not feasible through conventional means.

It is the recommendation of this report that the Earth science technology portfolio be actively partitioned to create a more symbiotic balance between emerging technologies and the ongoing development of more mature technologies. Emerging technologies such as integrated photonics, high-PRF fiber lasers, array detectors, and tunable NLO (nonlinear optical) schemes are some areas that might be leveraged under such a redirected program.

It is further recommended that provisions for classified technology development proposal appendices be instituted, analogous to the policy implemented by the NASA Earth Venture program. This would provide a mechanism whereby technological advances developed by the national security community could be leveraged by proposers in an environment where ESTO could be assured that the technologies in question are truly viable.

Several critical technology areas (notably NLO materials and associated optical coatings, and also detectors) continue to suffer from a significant shortfall in domestic capability, with many system and component technologies being dominated by non-U.S. vendors. This presents challenges to U.S.-based mission planners due to the prohibition on explicitly advising or guiding foreign technology development imposed by ITAR/EAR regulations. It is therefore recommended that these areas of need be brought to the attention of the Committee on National Security Systems (CNSS) Supply Chain Risk Management (SCRM). At the time of this writing, the SCRM was engaged in reviewing changes to CNSS 505 in order to address the full spectrum of SCRM policy across the entire U.S. Government. The updated document is scheduled for release in the April/May 2016 timeframe.

Finally, systems engineering 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. *To be successful, this approach 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 tools.* A significant body of knowledge relating to model-based system engineering (MBSE) exists within the defense community, where specialized analyses are routinely conducted within a generalized MBSE construct.

The MBSE paradigm offers an approach for independently arbitrating a number of questions prevailing within the lidar community. For example, three decades of effort have thus far failed to produce a viable solution for a perennial high-priority measurement, namely 3-D tropospheric winds. This particular question has been so resistant to resolution that instead of converging on an optimum approach the number of candidate options has instead expanded in recent years. The search for a technological pathway to the ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons) mission currently threatens to follow a similar trajectory, with at least three options under concurrent investigation and an absence of concerted pressure to converge on an optimal approach. Another question that could be addressed by a rigorous MBSE analysis would be whether the global topography mission is most efficiently mounted using a single platform or a distributed architecture involving SmallSat constellations. Each of the analyses identified above would help to resolve long-running uncertainties, enabling NASA to more effectively target available resources.

In the preparation of this report, ESTO actively solicited and received input from the community. Written inputs by the community were submitted through ESTO's white paper input site. ESTO also organized three workshops with subject matter experts at NASA Goddard Space Flight Center (GSFC), NASA Langley Research Center (LaRC), and NASA Jet Propulsion Laboratory (JPL). ESTO also convened a virtual community forum to gather additional input from the community at large.

1. Introduction

The NASA Earth Science Technology Office (ESTO) published its last lidar technology investment strategy in 2006 [*ESTO*, 2006]. That strategy laid out a decadal lidar technology implementation plan, investment strategy, and related technology roadmaps to enable NASA's Earth Science measurement goals.

This current (2016) report assesses the state-of-the-art in lidar technologies a decade later. Lidar technology maturation in the past decade has been evaluated, and the ESTO investment strategy is updated and laid out in this report according to the current NASA Earth science measurement needs and new emerging technologies.

Azita Valinia (NASA/ESTO) served as the study lead for the ESTO lidar technology investment strategy team that assembled this report. The core study team consisted of The Aerospace Corporation's independent subject matter experts: David Tratt, William Lotshaw, Kevin Gaab, and Lesley Pearson. David Mayo from Aerospace Corp. served as the coordinator. Terence Doiron (NASA/GSFC), Jason Hyon (NASA/JPL), and Keith Murray (NASA/LaRC) served as lead representatives for their respective NASA Centers.

For the purpose of gathering community input, the team conducted three lidar technology workshops at NASA Centers. These workshops were held on October 28, 2015 at NASA JPL, December 1, 2015 at NASA GSFC, and January 7, 2016 at NASA LaRC. A list of attendees at the workshops is provided in Appendix 1. Additionally, a white paper input site was created and a request for information was issued by ESTO for the community to submit their input. The list of submitted white papers is available in Appendix 2. A large amount of input was received during the workshops, which is summarized in spreadsheet format in Appendix 3.

On February 24, 2016, the ESTO lidar strategy team convened a virtual lidar technology Community Forum to brief the community on the status of inputs gathered thus far. Members of the core study team gave presentations on how they have integrated the community input received to date, and the emerging technology requirements and trends. Additional input and feedback was requested from the community before finalizing the ESTO lidar technology investment strategy for the next decade. The Community Forum briefing package is available at: esto.nasa.gov/LidarStrategies/CommunityForumCharts.pdf.

This report is the culmination of the community inputs and the integration and analysis of the inputs leading to an investment strategy and path forward for enabling NASA's Earth Science Measurement goals. The technology requirements discussed in this report address three major scientific measurement areas: Atmospheric Chemistry; Atmospheric Dynamics; Topography and Oceans. These scientific measurements are summarized in Figure 4.

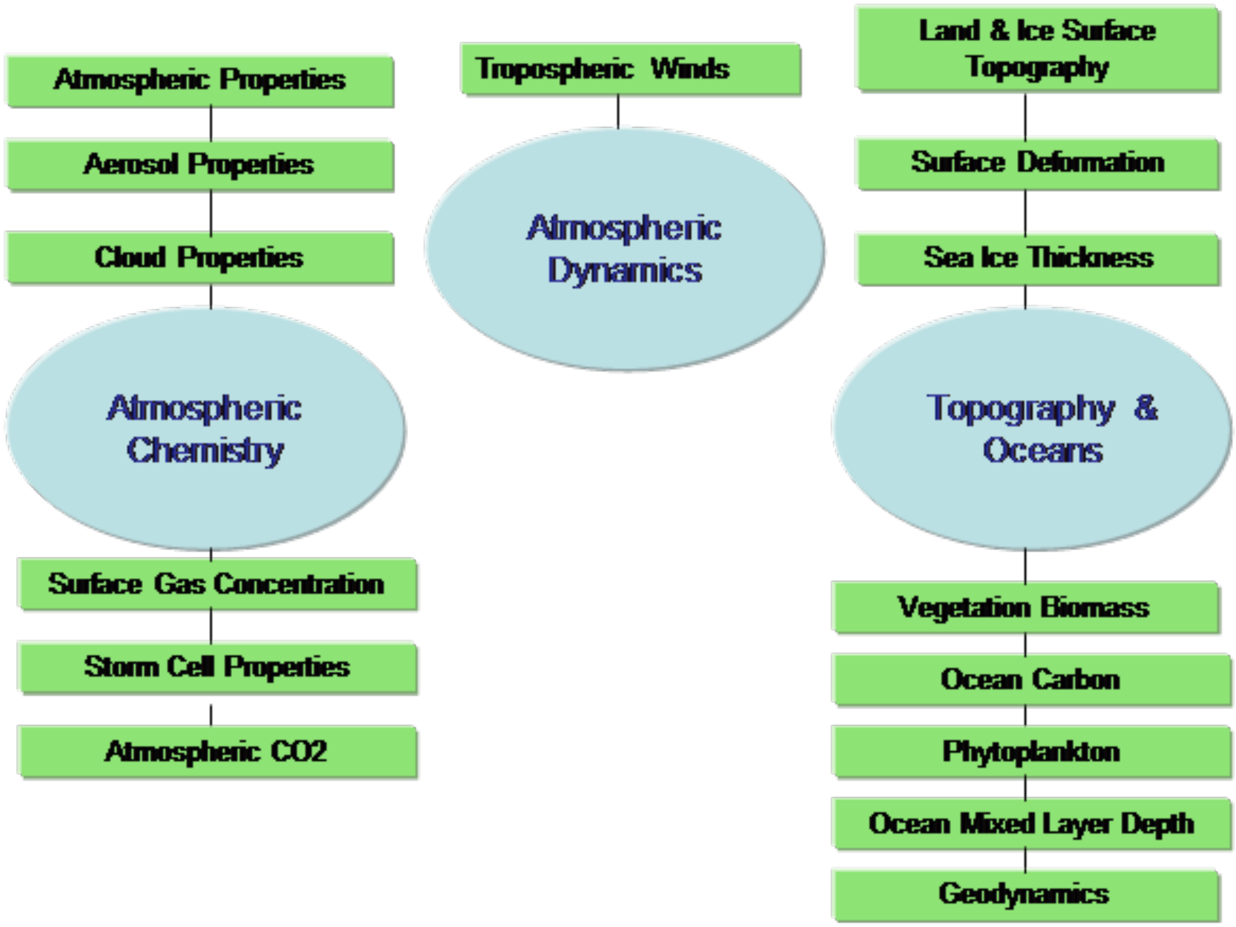

Figure 4. Scope of science subgroups.

Technology requirements are organized in three focused areas: Laser transmitters; detection, processing and optics (receivers); and data acquisition and utilization.

Chapter 2 of this report summarizes the scientific basis for lidar technology development.

Chapter 3 outlines the technology requirements in the three technology subgroup areas (transmitters, receivers, information systems).

Chapter 4 discusses emerging technology trends since publication of the last ESTO lidar technology investment strategy [*ESTO*, 2006].

Finally, Chapter 5 lays out the plan forward regarding current investment strategy needs.

2. Scientific Basis for Technology Development

The NASA Earth Sciences Program is structured around six principal focus areas:

- Atmospheric Composition
- Carbon and Ecosystems
- Climate Variability and Change
- Earth Surface and Interior Structure
- Water and Energy Cycle
- Weather

Lidar observations provide explicit atmospheric, oceanographic, terrestrial, and cryospheric environmental parameters that directly address the objectives of the six focus areas [*ESTO*, 2006, Table 2-1; *NRC*, 2007]. These parameters fall into four broad measurement categories, which are treated separately in the following subsections.

2.1. Atmospheric Composition

As defined here, atmospheric composition incorporates both gas-phase and particulate materials. Seven salient gaseous components are considered and the particulates encompass both aerosols and clouds.

<u>Carbon Dioxide</u>

Carbon dioxide (CO_2) has been recognized as a greenhouse agent for over a century and is generally acknowledged to be the most significant of the common greenhouse gases (GHGs) present in the atmosphere. Global-scale CO_2 mixing ratios are currently provided by the passive sensors AIRS, TES, GOSAT, and OCO-2. However, the ground sample distance (GSD) of these sensors is in the 10-100 km range and often inadequate for unequivocal attribution of emission sources. For this reason, the 2007 Decadal Survey [*NRC*, 2007] identified an active CO_2 mission as a priority and advanced ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons) as a reference mission concept [*Jucks et al.*, 2015].

By international agreement satellites are not subject to over-flight restrictions. High-resolution space-based measurements capable of attributing CO_2 emissions to their source will therefore form an important component of future international GHG reduction compliance monitoring protocols [*NRC*, 2010]. Although much useful risk reduction has been conducted with airborne demonstrators [*Dobler et al.*, 2013; *Abshire et al.*, 2014; *Menzies et al.*, 2014], definition of a viable ASCENDS mission has nevertheless been impeded by lidar-based technological challenges, which are therefore being carried forward into the second Decadal era.

<u>Carbon Monoxide</u>

Carbon monoxide (CO) is, *inter alia*, an important tracer that discriminates CO_2 deriving from biomass burning and fossil fuel consumption. It is also one of six “criteria pollutants” (www.epa.gov/criteria-air-pollutants) recognized by the U.S. Environmental Protection Agency (EPA). As a consequence of its importance to a fuller understanding of the carbon cycle, global vertically-resolved satellite measurements of CO were recommended, alongside the greenhouse agents CO_2 and methane (CH_4), by a recent workshop on the carbon-climate system [*NASA*, 2015b].

Methane

On decadal timescales CH_4 is a considerably more significant greenhouse agent than CO_2 [*IPCC*, 2007], yet there remain large uncertainties for many CH_4 sources [*IPCC*, 2014]. The importance of CH_4 in climate change scenarios is exacerbated by increasing land temperatures in permafrost regions that are causing sequestered methane to be released into the atmosphere. Despite these factors, the 2007 Decadal Survey [*NRC*, 2007] did not treat CH_4 atmospheric abundance as a measurement of interest – an omission that is expected to be remedied in the 2017 report.

Global atmospheric CH_4 abundance products have been available in recent years from space-based passive sensors such as AIRS, TES, SCIAMACHY, GOSAT, and IASI. However, as for CO_2, the desire for higher resolution 3-D CH_4 distribution knowledge, especially in the critical high-latitude regions where passive sensors lack adequate sensitivity, is fueling a search for lidar-based options. Indeed, a European team already has such a mission in formulation based on a measurement approach analogous to that proposed for ASCENDS [*Kiemle et al.*, 2011].

Nitrogen Dioxide

Nitrogen dioxide (NO_2) is primarily a product of combustion and is one of EPA's six criteria pollutants (www.epa.gov/criteria-air-pollutants). It is also implicated in the formation of tropospheric ozone, which is another of EPA's criteria pollutants (see below). NO_2 was identified as a target of interest during the workshops, however as yet no requirements have been levied against it by the community.

Oxygen

The oxygen column is important to characterize because several of the ASCENDS candidate mission concepts have baselined it as the primary means for normalizing CO_2 retrievals with respect to atmospheric density – a necessary prerequisite for deriving the absolute CO_2 mixing ratio [*e.g.*, *Riris et al.*, 2013]. It is therefore regarded as necessary to co-manifest this capability along with the CO_2 sounding channel aboard any eventual ASCENDS implementation.

Ozone (Tropospheric)

Ozone is another one of EPA's six criteria pollutants (www.epa.gov/criteria-air-pollutants). Its abundance in the troposphere is primarily due to photochemical action on hydrocarbons and nitrogen oxides, which are ubiquitous in the urban-industrial environment. Its importance lay in its deleterious impact on crop and human health.

Water Vapor

Water vapor is a primary meteorological variable and a contributor to global radiative forcing. Its abundance in the atmosphere is increasing as warming trends persist, making it a key positive feedback agent in global climate change overall. Furthermore, water vapor generated in the troposphere migrates across the tropopause due to tropospheric-stratospheric exchange, where it plays an increasing role in stratospheric ozone chemistry [*Kirk-Davidoff et al.*, 1999]. Yet there remain uncertainties in the distribution and variability of water vapor in this critical transition region [*Jiang et al.*, 2015]. These considerations are driving an interest in obtaining more precise information on the vertical structure of the water vapor than can be gleaned from the current suite of passive sounders on orbit. Lidar water vapor profiling techniques are consequently being examined as a potential means for meeting this need [*Wulfmeyer et al.*, 2005].

It is also true that measurements of the CO_2 mixing ratio can be biased by the presence of water vapor in the atmospheric column [*Singh et al.*, 2015]. To alleviate this problem measurements of column water vapor distribution, particularly in the lower troposphere where most of the vapor is concentrated, are desired. This implies that such a capability should be included as an ancillary measurement for an eventual ASCENDS implementation.

<u>Clouds and Aerosols</u>

The Fourth IPCC Climate Assessment Report identified aerosol distribution and microphysical parameterization as one of the single largest uncertainties impacting the fidelity of climate prediction models [*IPCC*, 2007]. Since that time the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) mission [*Winker et al.*, 2010] has, in its nine years of operation, accumulated an unprecedented wealth of dual-wavelength polarimetric lidar data on the geographic, vertical, and temporal distribution of clouds and aerosols [*e.g.*, *Nair and Rajeev*, 2014].

Since the launch of CALIPSO a new generation of aerosol lidars has come to the fore. For example, the high spectral resolution lidar (HSRL) technique is capable of separating and directly measuring the aerosol and molecular scattering components with a single, self-contained multi-wavelength instrument that avoids recourse to ancillary measurements [*e.g.*, *Burton et al.*, 2012]. Future space-based aerosol lidar concepts will be the primary beneficiary of this technology.

Methodologies for characterizing clouds by means of their multiple scattering properties [*Cahalan et al.*, 2005; *Polonsky et al.*, 2005] require lidar systems with wide-angle acceptance that capture off-axis backscatter. Such measurements are not available from narrow-FOV systems such as the CALIPSO lidar mentioned above, so concepts for adaptive wide-FOV lidar receiver subsystems are required in order to meet this need.

2.2. Atmospheric Dynamics

High spatiotemporal resolution measurements of 3-D tropospheric winds, delivered on a global scale, are critical for understanding weather systems and is the single biggest factor influencing the forecasting skill of numerical weather models. For instance, knowledge of the 3-D wind field is regarded as crucial for improving prediction accuracy of severe weather events, especially hurricane tracks [*Atlas et al.*, 2003].

For the last several decades the accepted wisdom has been that Doppler lidar was the only methodology capable of acquiring 3-D winds with the required spatiotemporal resolution, yet the past decade has recorded no progress towards a LEO implementation, although further study of the problem with the help of OSSEs (Observing System Simulation Experiments) has resulted in gradual relaxation of the lidar performance requirements compared to previous expectations [*Kavaya et al.*, 2007].

Investments in Doppler wind lidar (DWL) technology over the past decade have been in three competing technological approaches. For coherent (or heterodyne) wind lidars development has focused on the 2-μm laser and detector technologies [*Kavaya et al.*, 2014], whereas in the area of incoherent wind lidars, UV lasers and edge detection approaches have been advanced [*Gentry et al.*, 2006, 2007]. A third, more recent, development has been the Optical Autocovariance Wind Lidar (OAWL), which utilizes an interferometric detection scheme [*Tucker et al.*, 2015]. All three techniques have been demonstrated on airborne platforms (though each of these trials exposed the need for further significant development), while concurrent engineering and OSSE evaluations of each approach for implementation in LEO have confirmed their potential impact on improving NWP (Numerical Weather Prediction) skill.

Given the high priority placed on the 3-D winds measurement by the weather community [*Baker et al.*, 2005; 2014], it is imperative that efforts be redoubled in this area, and promising emerging approaches will form an important element in this regard. In fact, recent research indicates that a passive technique may be able to meet NWP community requirements on wind resolution and gridding, even though it cannot compete with lidar on an intrinsic performance level [*Maschhoff et al.*, 2015]. If continued development bears out this promise, then it would offer a less complex, lower risk alternative to DWL.

Syndergaard and Kirchengast [2016] have recently suggested a novel laser-based technique for retrieving line-of-sight wind speed using LEO satellite-to-satellite laser occultation. This approach is reliant on 2-μm lineshape measurement of the ^{18}OCO isotopologue to achieve estimated accuracies of ~0.3 m/s in the 15-35 km altitude range (*i.e.*, stratospheric rather than tropospheric). However, since there exists at this time only analytical support for these predictions, the methodology consequently resides at TRL2.

2.3. Topography, Ranging, and Interferometry

Topography and Geodetic Imaging

Precise measurements of Earth surface topography continue to be critical for a wide range of scientific investigations, such as ice sheet volume on seasonal-to-interannual timescales, to track the rapid evolution now evident in polar regions. High-density laser geodetic imagery is also required for the construction of baseline digital elevation models (DEMs) against which assessments of vulnerability to earthquakes, volcanism, landslides, coastal and interior erosion, flooding, and land subsidence may be made.

A very important end goal of such studies is the potential for accurate forecasting of solid-Earth natural hazard events. For example, in order to characterize a full earthquake cycle, surface deformation observations are necessary at local-to-regional spatial scales and over timescales from minutes to decades. Space-based geodetic imaging observations of surface change using high-resolution lidar technology constitute a valuable complementary adjunct to the InSAR measurements that in recent years have enabled significant advances in the understanding of seismic zone dynamics.

3-D Biomass

An accurate documentation of global-scale terrestrial vegetation cover encompassing both its 3-D structure and variability is a primary component of the carbon budget [*Le Quéré et al.*, 2015]. Forests typically comprise a heterogeneous mix of stands with different successional ages, where both ecosystem structure and carbon fluxes vary strongly with successional status. Estimates of vegetation cover and structure at the resolution scales required to address this topic are not available from current space-based assets.

Lidar is the only remote sensing technique capable of providing vertical structure information at the needed resolution, and continuing interest in such measurements is attested to by the recent selection of GEDI (Global Ecosystem Dynamics Investigation) as an Earth Venture Instrument mission. However, while GEDI would provide much groundbreaking vegetation measurements from orbit, its vantage point aboard the ISS cannot deliver global coverage.

Gravity and Satellite-to-Satellite Ranging

Gravity field mapping is required to understand ice-mass distribution, ground water depletion, ocean tide variations, long-term climate effects, monitoring of global resources, and elucidation of the solid Earth structure (*e.g.*, lithographic thickness and composition, lateral mantle density heterogeneity, translational oscillation between core and mantle, *etc.*). The GRACE-1 (Earth) and GRAIL (Moon) missions have amply demonstrated full-body gravimetry through precise monitoring of inter-satellite motion using microwave ranging.

The GRACE Follow-On (continuity) mission currently in development will include a laser interferometer technology demonstration payload [*Sheard et al.*, 2012] to achieve improved sensitivity and accuracy relative to the primary microwave inter-satellite ranging instrument of both GRACE-1 and GRACE-FO. Success of the GRACE-FO demonstration payload would motivate implementation of laser interferometry as the primary inter-satellite ranging payload for GRACE-2. Alternatively, another approach to gravitational mapping that could be used on GRACE-2 (aka, Next Generation Gravity Mission, NGGM) would utilize a Quantum Gravity Gradiometer (QGG) [*Snadden et al.*, 1998; *Yu et al.*, 2006]. The QGG instrument requires only a single spacecraft and would represent a significant departure from the GRACE-1 and GRACE-FO sensors.

2.4. Physical and Biological Oceanography

Oceanographic applications were treated in the 2006 report [*ESTO*, 2006], however they have received increased emphasis since that time. Although lidar measurements are hampered by strong attenuation through oceanic waters, a limited number of shallow-water phenomena may nevertheless be studied in the visible spectral region. Increased interest and emphasis on lidar probes of the ocean have rekindled blue-green laser R&D with an emphasis on wavelengths in the range 450-500 nm, where significant gains in penetration depth (~2-3 x) can be realized relative to commercially available 532-nm laser technology.

Mixing Layer and Mixed Layer Depths

Analogous to the atmospheric boundary layer, the ocean mixing layer and mixed layer facilitate gas, energy, and momentum exchange between the highly dynamic atmosphere and the much less variable benthic ocean on sub-diurnal to climatic timescales. Flux rates of energy, chemical substances, and biological material between the ocean surface and sub-surface water column are determined in part by the mixed layer depth (MLD), which is at present the most significant ocean variable that remains unmeasured on a global basis.

MLD is also important to tropical storm dynamics, since simulations and observations indicate a strong sensitivity of hurricane strength to mixed layer heat content (*i.e.*, to MLD). Hurricane strength prediction is a very compelling justification for space-based observations of MLD, since the only source of this measurement currently is a sparse *in situ* array of instrumented buoys. Lidar-based approaches in the blue-green water window are proposed to address this application.

Lidar measurements of physical properties (such as temperature, salinity, turbulence, and bubbles) in the mixing layer and mixed layer bridge existing satellite measurements of the atmosphere and ocean with *in situ* measurements made by Argo floats, as well as providing critical information to constrain and improve coupled oceanic and atmospheric models.

Global Primary Productivity and Carbon Biomass

Constituent-specific fluorophores prevalent in optically complex coastal waters may be selective excited through laser-induced fluorescence. Hyperspectral analysis of the resulting backscattered radiation is seen as an important tool to assist in unraveling the optical complexity of coastal environments.

The Arctic is one of the areas of the world where climate change is having particularly radical effects. As water temperatures in Polar regions rise the changing conditions favor expansion of phytoplankton blooms in ocean regimes where they were previously rare [*Yool et al.*, 2015]. Current passive techniques for monitoring phytoplankton blooms [*Behrenfeld et al.*, 2009] are challenged by the solar insolation conditions at high latitudes, so there is a *prima facie* need to develop active methods including laser-induced fluorescence from chlorophyll and accessory pigments such as phycobiliproteins to fill this gap.

CALIPSO in its ongoing ten years of operation has been used to study the ocean surface and subsurface and represents a pathfinder for future space-based lidar missions for remote sensing of the oceans from space. Ocean surface wind studies have shown good correlation with traditional microwave methods, even demonstrating fewer problems with saturation under high wind conditions [*Hu et al.*, 2008]. While the CALIPSO 532-nm lidar receiver was not designed for the high vertical resolution required for ocean profiling, its cross-polarized channel has proven to be a powerful method to collect integrated ocean subsurface scattering [*Lu et al.*, 2014]. CALIOP has especially shown its value at studying the ocean subsurface at high latitudes, which is a critical area for biology as sea ice recedes.

3. Technology Requirements

This chapter summarizes the high-level technology needs identified in this survey, classified according to three broadly scoped technology areas: Transmitter technologies, receiver technologies, and information handling systems.

3.1. Transmitter Technologies

Laser component technology has evolved significantly since the 2006 study. Some new laser materials have emerged, and improvements in nonlinear optical materials have been made, resulting in expanded options for wavelength generation both in the near-UV and SWIR/MWIR. Dramatic improvements have been realized in the electrical efficiency of pump laser diodes, significantly improving the WPE of traditional bulk solid-state lasers and fiber-lasers in particular. The monolithic and heterogeneous integration of photonic components (*i.e.*, integrated photonics) has resulted in increased functional capabilities at substantially improved SWaP, especially in the area of Yb and Nd pump diodes, which are now available in small form-factor fiber-coupled modules with average powers >100 W.

An especially important consequence of laser technology development over the past 10 years is that fiber-laser average power capability now rivals traditional bulk solid-state systems, which is a distinct advantage in that all-fiber architectures are both compact and immune to misalignment. However, power scaling in large mode-area fiber is limited by the fiber core cross-section and management of the associated nonlinearities becomes critical. Yb, Er, and Tm doped fibers provide tunable output at 1-1.1, 1.5-1.6, and 1.8-2+ μm, respectively.

Laser system architectures are evolving to take advantage of recent technology advances, and this trend is exemplified by growing interest and activity in the design and development of hybrid fiber/bulk solid-state systems. This approach utilizes the best attributes of each technology by marrying the low SWaP and misalignment immunity of fiber lasers to the peak power and energy scaling advantages of bulk solid-state materials and structures. This approach offers solutions for the limited energy and peak power scalability of fiber lasers and the difficulties inherent in implementing waveform agility in systems using bulk solid-state master oscillators to generate the sensing laser signal. By contrast, telecom type signal laser diodes have an intrinsic ability to replicate electrical waveforms in the optical domain, with wide capabilities in temporal waveform (pulse rate/format) at pulse durations down to the picosecond/femtosecond timescales. Furthermore, the nonlinear optical characteristics that can limit fiber-laser power scaling can also enable the generation of stable, high-bandwidth frequency combs that have been the object of intensive applications development in metrology, spectroscopy-based remote sensing, and time-keeping at NIST and in academic laboratories. In the past two years DLR (Germany) has twice launched femtosecond frequency comb-based clocks (FFC) on sounding rocket missions. The second of these launches used the FFC to compare Rb, K, and crystal oscillator clocks throughout the flight (www.menlosystems.com/events/news-press-releases/view/2343).

High performance laser systems in general continue to be beset by supplier issues, with many system and component technologies being dominated by non-U.S. vendors. In some quarters this presents ITAR/EAR restrictions because of the inability of domestic users to explicitly advise or guide foreign technology development.

The previous study [*ESTO*, 2006] recognized 7 distinct 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 convertors for the UV-Vis
- Wavelength convertors for the NIR
- Other lasers

This classification is updated in this report in order to simplify the technology landscape and eliminate duplication. Specifically, the "Other Lasers" category was eliminated and the two wavelength conversion categories were restructured by integrating harmonic generation schemes with the fundamental pump wavelength lasers (*e.g.*, 1-, 1.5-, 2-µm) driving each (since technologically the harmonic generation is integrated with the source laser), and breaking out parametric wavelength conversion (*e.g.*, sum/difference, OPO, OPA, *etc*.) as a separate category.

An additional class of laser sources has also been invoked to cover seed/signal lasers required for master-oscillator/power-amplifier (MOPA) systems and frequency conversion linewidth control. As a result the laser classification is recast as:

- mJ-class 1-µm lasers
- Joule-class 1-µm lasers
- 1-100 W, 1.5-1.6+ µm lasers
- 1-20 W, 2-µm lasers
- Seed and amplifier laser diodes
- Parametric wavelength generation

A number of transmitter technology capability gaps were identified that affect measurements recommended by the 2007 Decadal Survey [*NRC*, 2007], and an analogous set of gaps for the measurements that have received increased emphasis since the 2007 report. These capability gaps are summarized in Tables 3.1 and 3.2, respectively.

The transmitter technology needs summaries broken down by laser technology classification are provided in the subsections that follow. In these subsections table items in red text indicate emerging technologies.

Table 3.1. Unmet transmitter technology needs from 2007 Decadal Survey.

Capability Gap	Measurements	Current TRL	"Greatest Challenge" TRL
Maturity and readiness of tunable lasers meeting measurement requirements	CO_2 (ASCENDS)	3-4	1.57-μm power amplifier
Readiness of laser systems	Aerosol/Clouds/Eco-systems (ACE)	4-5	Space qualification
Readiness of laser systems	3D Biomass (NISAR/GEDI, formerly DESDynI)	4-5	Space qualification
Readiness of laser systems	Gravity (GRACE-2)	2-3	U.S. laser supplier
Multiple aperture transmitter	Topography (LIST in 2007 Decadal)	4-5	Multiple aperture system
Reliable 355-nm transmitters meeting measurement requirements; 2-μm technology readiness and reliability	3D Winds	3-4	Laser reliability, readiness

Table 3.2. Transmitter technology needs for new measurement concepts.

Capability Gap	Measurement	Current TRL	TRL Assessment; Greatest TRL Challenge
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

3.1.1. 1-µm Laser Technology Needs

The status of 1-µm laser technology is summarized in Table 3.3. 1-µm bulk solid-state laser technology and associated harmonic generation methods to UV/Vis wavelengths are fairly mature. However, further development is needed to assure reliability (*i.e.*, resistance to lifetime limiting factors) and continuous WPE improvement of the base laser technology. In particular, work is needed to improve the durability and reliability of nonlinear materials and associated coatings for UV-Vis harmonic generation.

Table 3.3. 1-µm laser technology needs summary.

Measurement	Technology	State-of-the-Art	Requirements	Development Need
Topography, aerosol and temp. profiles	Pulse Rate ≤ 500 Hz, Solid-state Laser	λ ≈ 1 µm, ≥ 0.25 J @ 150-Hz PRF, WPE ~ 10%, 1-MHz linewidth, M^2 < 1.5[a]	λ ≈ 1 µm, 0.5 J @ 50-Hz PRF, WPE 6%, 1-MHz linewidth, M^2 < 1.5	Reliability, packaging, space qualification
Topography, aerosol and temp. profiles	Pulse Rate ≥ 1 kHz, Solid-state Laser	λ ≈ 1 µm: 1) **bulk,** ≥ 0.8 J @ 5 kHz PRF, WPE > 5%[b]; 2) **fiber,** > 1-4 mJ @ 10 kHz, WPE > 15%, GHz linewidth, M^2 < 1.5[c]	λ ≈ 1 µm, ~ 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 µm, ~ 15 kW, WPE ~ 10%, ~100-kHz linewidth, M^2 < 1.5[d]	1 µm, ≥20 mW, sub-Hz linewidth[e]	GRACE-FO is focused on demonstration of frequency reference, incl. locking scheme
Atmospheric Composition, winds, ocean mixing-layer	Frequency Conversion	See "Fixed Wavelength Conversion" and "Tunable Wavelength Conversion" sections	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 ~ 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

* Emerging technology.

[a] *Albert et al.* [2015]; [b] *Brossus et al.* [2007]; [c] *Brooks and Di Teodoro* [2006]; [d] *Redmond et al.* [2007]; [e] *Folkner et al.* [2011].

1-µm fiber-laser technology is rapidly approaching bulk solid-state technology with respect to average power and linewidth performance, but lags in peak power capability (for which large mode area fiber and new glass compositions will be key) and low-PRF parameters.

The Earth science community should cultivate awareness of laser technology development for national security applications (in both fiber and bulk solid-state categories), which in many cases is relevant to NASA needs and should be evaluated for use in laser sensors for Earth observation. The fiber/bulk solid-state hybrid architectures noted in Section 3.1 are strongly leveraged by recent developments in both fiber-laser and bulk solid-state planar waveguide (PWG) amplifier technology [*Baker et al.*, 2002]. PWG amplifiers have demonstrated improved efficiency and beam quality performance relative to conventional bulk solid-state laser amplifiers, especially in high pulse energy and average power systems [*Wagner et al.*, 2011].

The emerging capability of fiber-laser technology is in some respects disruptive: fiber lasers are very competitive with bulk solid-state lasers on a power basis but perform best at high PRFs which are not consistent with legacy measurement CONOPS, specifically with respect to issues of range ambiguity when there are "multiple pulses in the air." However, the waveform agility of telecom-heritage signal laser diodes enables the realization of novel temporal waveforms that may enable the resolution of this problem with the corollary SWaP benefits of fiber lasers: compact form-factor, high WPE, immunity to misalignment, and a technology that naturally accommodates multiple emission apertures. For these reasons high-PRF lidars using fiber lasers may represent a beneficial paradigm shift and should not be summarily rejected due to non-conformity with legacy measurement CONOPS.

3.1.2. 1.5-, 2-µm Laser Technology Needs

The status of 1.5- and 2-µm laser technologies is summarized in Table 3.4. Telecom-type single-mode laser diodes and optical amplifiers are well-established at 1480-1625 nm (International Telecommunication Union, ITU, grid) and ~1000-nm wavelengths (compatible with Nd^{3+} and Yb^{3+} based 1-µm lasers), but are "emerging" as COTS components in the 1625-2000+ nm range with the exception of SWIR-MWIR DFB (distributed feedback) lasers developed for GHG detection and interplanetary instruments [*Bagheri et al.*, 2015, and references therein]. Continued development is still needed to improve reliability and WPE for the established ITU grid and 1-µm technologies, and 1625-2000+ nm signal lasers and optical amplifiers are at a relatively early stage of development.

1.5- and 2-µm bulk and fiber-laser technologies are in varying stages of development. High power fiber-MOPA performance in Tm-fiber is advancing rapidly, but as is the case for 1-µm systems large mode area fiber and new glass compositions (currently being pursued by technology start-ups) will be key. The required 793-nm pump diode technology is fairly mature, but longer wavelength pumps are in development to reduce losses caused by the pump quantum defect in Er and address the concentration dependence of the 2-for-1 pumping scheme in Tm.

High power fiber-MOPA performance in Er-fiber lasers currently lags that of Yb-fiber lasers because the product base is strongly oriented to telecom performance requirements. Large mode area and polarization-maintaining (PM) fibers are much less widely available than for Yb-fiber, and pump diodes for efficient "in-band" pumping of Er^{3+} (~1530 nm) are not nearly as powerful or efficient as those for Yb fiber amplifiers.

Table 3.4. 1.5-, 2-μm laser technology needs summary.

Measurement	Technology	State-of-the-Art	Requirements	Development Need
CO_2, Coherent DWL (aerosol)	Pulsed 2-μm, 1.57-μm laser	$\underline{CO_2}$: ≥30% conversion to 1530-1625 nm via DFG w/1064-nm fiber-MOPA at high PRF. DWL: >1J @ ~ 200 ns 2-μm Tm/Ho system under development[a].	$\underline{CO_2}$: 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 @ $E_{Pulse} \cdot (PRF)^{1/2} > 0.6$ J-$Hz^{1/2}$, 8-GHz tunable frequency-agility, $M^2 < 1.2$, WPE > 5%.	$\underline{CO_2}$: Technology reliability and maturation, SWaP optimization. DWL: technology reliability and maturation, SWaP optimization.
CO_2	*cw* 1.57- and 2-μm laser		3-5 W cw @ 2.05 μm, 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[b]	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 <u>or</u> *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

[a] *Yu et al.* [2006]; [b] *Chen et al.* [2011].

The development of new glass rare-earth host materials is a relatively recent but promising topic area in laser technology development. Non-silicate glasses enable substantially increased doping density and greater refinement in large mode-area (LMA) fiber designs that result in shorter gain length and improved mitigation of parasitic and destructive nonlinear effects in all three fiber wavelength bands (at 1, 1.5, and 2 µm). In Tm fiber the range of wavelength operation has been extended to ~1825 nm, thereby enabling the development of tunable direct emission sources in the 1825-2000 nm range. Similarly, new highly doped Yb LMA fiber amplifiers are being investigated for enhanced power scaling and reduced nonlinear effects. As noted above, pump and signal-guiding bulk solid-state planar waveguide (PWG) structures are being developed using both crystalline and glass host materials, and exhibit significantly improved optical slope efficiency and beam quality compared to conventional bulk solid-state amplifiers. The emergence of PWG amplifiers at 1.5 and 2 µm, coupled to corresponding development of fiber-lasers at these wavelengths, may result in new fiber/planar waveguide hybrid architectures capable of operating with unprecedented WPE and waveform agility that could surpass 1.5- and 2-µm technologies that have stalled in their development. For example, despite over 20 years of investment in bulk solid-state 2-µm laser technology for coherent wind lidar, it may be prudent to reconsider other options. The choice of a 2-µm transmitter using engineered crystalline host materials dates to the 1990s when it was believed that 1.5-µm materials would not have the energy storage capacity to produce the energetic pulses required for wind measurements. Given the advances in the fiber and planar waveguide technologies since that decision was made, along with the reduced pulse energy now believed necessary for the wind measurement [*Kavaya et al.*, 2007], the legacy system trades may merit revisiting.

3.1.3. Fixed Wavelength Conversion Transmitters

The status of harmonic wavelength conversion technologies is summarized in Table 3.5. Relatively mature nonlinear optical (NLO) materials are available for many measurements requiring harmonic wavelength conversion of 1-, 1.5-, and 2-µm lasers. However, NLO materials for 200-400 nm and 1600-2700 nm wavelength ranges need improvement for durability and reliability. Quasi phase-matched materials such as periodically-poled lithium niobate and lithium tantalate, and orientation-patterned gallium arsenide have demonstrated very high performance potential but require further development to improve power scaling, efficiency optimization, and robustness.

Continued development is also needed to improve the susceptibility of antireflection coatings and NLO crystals to damage from environmentally-induced degradation and high laser fluence.

Table 3.5. Fixed wavelength conversion technology needs summary.

Measurement	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)[a]; >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% 1530 nm→765 nm	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

[a] *Albert et al.* [2015].

3.1.4. Tunable Wavelength Conversion Transmitters

The status of tunable parametric wavelength conversion technologies is summarized in Table 3.6. NLO materials are also available for many measurements requiring tunable parametric wavelength conversion. As with harmonic generation, the materials for the 200-400 nm and 1600-2700 nm ranges can be improved in both performance and damage resistance.

Continued development is also needed to improve the susceptibility of antireflection coatings to damage from environmentally-induced degradation and high laser fluence. For DIAL measurements at wavelengths in the UV and mid-visible ranges there is often more than one cascade of wavelength conversions to the wavelengths needed for a specific measurement, such as O_3 density profiles (290-320 nm), probes of ocean biomass and MLD (450-530 nm), and water vapor profiling in the 700-950 nm wavelength range. These alternatives can be distinguished on the basis of overall conversion efficiency, reliability, and damage and the damage susceptibility of NLO materials and optical coatings. In these cases it is important to select laser sources and nonlinear conversion schemes that balance risks, performance, and reliability. The risks include issues such as system (mis)alignment susceptibility: for example, optical parametric oscillators can yield high conversion efficiency but have stringent alignment requirements, while parametric amplifiers can tolerate relatively coarse alignment while maintaining adequate conversion efficiency. As a result, the choice of the conversion scheme (and the control architecture it requires) is critical to the development of a robust DIAL sensor system.

Table 3.6. Tunable wavelength conversion technology needs summary.

Measurement	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[a]. 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 for ocean water transmission 475-485 nm*	High efficiency, high reliability Vis-NIR generation
GHG	OPO (SW/MWIR)	≥30% conversion of 1-µm laser to 1530-1625 nm via DFG w/1064 nm fiber-MOPA at high PRF[b].	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)	Fourth harmonic generation + sum frequency to produce 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

* Emerging technology.
[a] *Willis et al.* [2015]; [b] *Belden et al.* [2015].

3.1.5. Transmitter Conclusions and Recommendations

The potential leverage of laser technology development for national security applications, and also that of fiber/bulk solid-state hybrid architectures for waveform-agile high power laser systems, was noted in the introduction to this Section (3.1) and in Section 3.1.2 (1.5-, 2-µm Laser Technology Needs). These technologies, coupled to continued refinement of NLO wavelength conversion schemes and the continued improvement of associated optical coatings, have high potential to address the current technology gaps in the measurement of UV Doppler winds, O_3, H_2O, and CO_2, and may be pertinent to the measurement of coherent Doppler winds and CO_2 at 2 µm. The potential of telecom-heritage fiber-MOPA and/or fiber-MOPA/bulk solid-state hybrid architectures for yielding wide-ranges of temporal waveform and wavelength agility (when coupled to wavelength division multiplexing elements) is a technology area with unparalleled potential and a tractable development pathway to TRL6.

3.2. Receiver Technologies

Various receiver technology capability gaps were identified that impact measurements recommended by the 2007 Decadal Survey [*NRC*, 2007] and an analogous set of gaps was also identified for the measurements that have received emphasis in the current study. These capability gaps are summarized in Tables 3.7 and 3.8, respectively.

Table 3.7. Unmet receiver technology needs from 2007 Decadal Survey.

Capability Gap	Measurements	Current TRL	"Greatest Challenge" TRL
High-efficiency detectors in 1.5-2 μm 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-2)	6	N/A
Multiple aperture/beam receiver	Topography (LIST in 2007 Decadal)	3	Large-area detector with high readout bandwidth
Single telescope supporting multiple look angles	3D Winds	3	Large-aperture receive optics (HOE/DOE, interferometer)

Table 3.8. Receiver technology needs for new measurement concepts.

Capability Gap	Concept	Current 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, few-photon-sensitive detector array

The previous study [*ESTO*, 2006] recognized the following distinct receiver technology classes:

- 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)

For the current study Mechanical Metering was removed. While it is a key design feature of some systems and can be used to relax active alignment and focus control requirements (*e.g.*, the SiC structure and optics in the ADM-Aeolus ALADIN), no quantitative requirements for this function were provided for any of the measurement scenarios.

3.2.1. Alignment Maintenance

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 will meet the 2006 requirement for altimeters once demonstrated on orbit [*Hinkle*, 2015; *Blumenstock et al.*, 2016], but an equivalent capability that can be manifested aboard SmallSats has yet to be demonstrated. The demonstration of these accuracies has primarily been done with systems operating at 1 μm. While extension to other visible or NIR wavelengths is seen as relatively straightforward, extension to 2 μm remains to be demonstrated. The primary need here is a sufficiently high performance SWIR star tracker that can meet size, weight, and power requirements. Depending on the approach used for the wind lidar measurements, lag-angle compensation systems at the 1-μrad level may be necessary. Several optical designs have been proposed, but no evidence experimentally demonstration was evident. With a few exceptions, active alignment maintenance is seen primarily as an engineering challenge rather than a technology development effort.

Table 3.9. Alignment maintenance technology needs summary.

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.[a] Lag-angle compensation: Still being evaluated; designs for ~1 µrad LAC developed, 10s of µrad demonstrated	5 µrad roundtrip (5 ms) lag-angle compensation (coherent); 50-µrad 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 µm. Needs high-efficiency, high-sensitivity SWIR star tracker, high temp (TEC or room temp.) Develop active optical boresite alignment device
CO_2			50 µrad 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 µm. Needs high-efficiency, high-sensitivity SWIR star tracker, high temp (TEC or room temp.)

[a] *Hinkle* [2015], *Blumenstock et al.* [2016].

3.2.2. Scanning Systems

Scanning systems remain an important technology need, particularly for wind lidar and topography measurements. Significant improvements in diffractive and holographic optical elements have been made since the 2006 survey. The optics have been utilized in airborne platforms at aperture sizes of tens of centimeters. Development of larger diffractive and holographic optical elements is needed to support wide field-of-view telescopes for space missions. The development of these optics would be an enabling technology for several measurements, including IR DIAL measurements of atmospheric temperature and water vapor, and also may extend the capabilities of other missions by improving coverage or measurement repeat cycle times.

Table 3.10. Scanning technology needs summary.

Measurement	Technology	State-of-the-Art	Requirements	Development Need
Wind	Volume Bragg HOE	TWiLiTE telescope uses a 40-cm diameter HOE as the receiver collecting and focusing aperture[a]	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.
Wind, Topography, T and Water	Polarization gratings (cycloidal diffractive waveplates)[b] SEEOR (LC-clad waveguide)[c] Switchable fiber arrays	SEEOR: Vis-NIR operation, 60x15 degree FOV 2-D scan. GFSC has demonstrated benchtop fiber array for FOV selection 10-cm devices with acceptable efficiencies have recently been demonstrated.	Addressable FOV across 1-2 degrees	Develop solid-state approach of selecting individual fields-of-view at high switching rates. Non-mechanical large aperture (> 25 cm) beam steering and receiver pointing devices.

[a] *Gentry et al.* [2006]; [b] *Smith et al.* [2006]; [c] *Davis et al.* [2015].

3.2.3. Large Effective-Area, Lightweight Telescopes

Large, lightweight apertures are a cross-cutting technology with the current space-based state-of-the-art being 1-2 m diameter. Deployable apertures larger than ~1.5-2 m would enable reduced laser power or improve system performance. Several advances in deployable apertures have been made in the last few years, although the systems remain complex and expensive. The James Webb Space Telescope, expected to launch in 2018, will be the largest deployable aperture system in space, and will launch with a 6.5-m diameter gold-coated beryllium reflector composed of 18 hexagonal segments. DARPA is developing large deployable diffractive telescopes for GEO applications through the Membrane Optical Imager for Real-time

Exploration (MOIRE) program with a 20-m aperture as the ultimate goal. Although the current transmission of these polymer thin-film optics is relatively low, two prototype segments were used successfully in 2014 to perform a ground-based end-to-end imaging demonstration [*Domber et al.*, 2014]. The same approach may also be viable for SmallSat systems [*Footdale et al.*, 2011].

An alternative to deployable aperture systems in some scenarios would be distributed constellations of SmallSats. Distributed aperture systems have been proposed for synthetic aperture FMCW (frequency-modulated continuous wave) 3-D imaging lidars [*Reibel et al.*, 2010]. This approach is low TRL and would require very high precision knowledge of each satellite's position and pointing similar to that used for optical communication [*Janson and Welle*, 2013].

Table 3.11. Large-area aperture technology needs summary.

Measurement	Technology	State-of-the-Art	Requirements	Development Need
Wind, Aerosols	Beryllium or SiC field lens-corrected Ritchey-Chrétien 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-CO_2, Phytoplankton			2-5 m primary mirror telescope for space based lidar, <F/1 primary, <100-μm blur circle, high transmission (>95%) at target wavelength(s), low thermal distortion, high rigidity	
Topography	Deployable large aperture diffractive primary and corrector optics[a]	Sub-aperture elements of 5-m primary used for imaging	1 - 1.5 m diameter, <10-μrad blur circle	
CO_2, Ozone			3-m diameter deployable, ~100-mrad FOV, areal density <25 kg/m^2	

* Aperture size requirement is dependent on transmitter.
[a] *Domber et al.* [2014].

3.2.4. Specialty Optics

Low-loss optical receivers continue to require radiation hardened, environmentally stable bulk substrate materials and optical fibers. In particular, rad-hardened fiber optics and fiber optic couplers in the UV and NIR were identified as needs for the wind and greenhouse gas measurement scenarios. Although updated requirements were not put forth for high transmission and wavefront quality optics for polarization analysis and control or wavefront compensation and control, these would be required for lag-angle compensation optics for coherent DWL and coherent DIAL systems. They would also be necessary for any emergent measurement techniques that would utilize photon orbital angular momentum states [*Sun et al.*, 2016]. Specialty optics are an enabling technology for measurements of phytoplankton physiology and ocean mixed layer depth, and enable independent measurements of aerosol extinction and backscatter.

Table 3.12. Specialty optics technology needs summary.

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 nm, rad hardened	Improve UV rad-hard fiber couplers and fiber optics
CO_2	SiO_2/GeO_2	PM single mode passive optical fibers are commercially available but are not rad hard, may not meet transmission requirements	Polarization maintaining, radiation tolerant 2-µm single mode fiber with transmission efficiency > 95%/m	Assess radiation hardness and improve transmission of fibers

3.2.5. Narrowband Optical Filters

Narrowband optical bandpass filters are used in lidar receivers to maximize the SNR by reducing the background radiation incident on the detector. Significant improvements in field-widened interferometers have been demonstrated in the last decade [*Baker et al.*, 2014]. Double-edge Fabry-Pérot étalon interferometers have been used in the Tropospheric Wind Lidar Technology Experiment (TWiLITE) and hybrid DWL demonstrations [*Gentry et al.*, 2007; *Marx et al.*, 2013]. Fringe-imaging systems have been investigated as well, and is currently being used in the aerosol channel of the European ADM-Aeolus instrument. Optical autocovariance receivers have also been modified to use a larger field of view Mach-Zehnder interferometer [*Tucker et al.*, 2015]. Developing larger aperture athermal field-widened interferometers is necessary for both the wind and HSRL measurements. Narrowband optical filters are an enabling technology for differential absorption measurements of atmospheric CO_2, temperature, aerosol, and ozone; and independent measurements of aerosol extinction and backscatter. Achieving filters with sub-nm bandwidths, flat top transmission profiles, and >90% transmission would be beneficial. Rapidly tunable filters would be an enabling technology, particularly for water and aerosol measurements. Improvements in the filter transmission result in a decrease in laser energy required to obtain the same lidar performance. This technology is also cost-reducing for many different types of measurements.

Table 3.13. Narrowband filter technology needs summary.

Measurement	Technology	State-of-the-Art	Requirements	Development Need
Wind, Aerosol, Ocean	Quasi-monolithic field-widened Michelson or Mach-Zehnder interferometers	~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
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	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	Etched liquid crystal or micro-opto-electromechanical Fabry-Pérot interferometers	Multi stage LCFP assemblies. Transmissions 40-80% typical, ms response times, pm spectral resolution	High transmission (>80%), fast temporal response (<100 μs), <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

Electronically tunable filters based on either etched liquid crystal Fabry-Pérot (LCFP) interferometers or micro-optoelectromechanical (MOEM) Fabry-Pérot interferometers (FPI) have seen significant development in the past decade [*Noto et al.*, 2009; *Blomberg et al*., 2010; *Rissanen et al.*, 2015]. LCFP is a relatively mature technology and has been demonstrated across the visible and infrared and is being space qualified for LEO operations. MOEM FPI designs have been used for compact hyperspectral imagers in the visible and NIR, although generally these systems have relaxed optical bandpass requirements relative to lidar systems.

3.2.6. Detectors (Including Arrays) and Amplifiers

A consistent theme across all measurement scenarios is the need for improved detector performance, particularly multi-element architectures with high quantum efficiency, low noise, low timing jitter, and low afterpulsing. Detector dynamic ranges need extension to support photon-number resolving and higher count rates, while increased bandwidths are required to support full-waveform capabilities. Several new detector technologies have emerged since the previous review which could meet these needs [*Krainak et al.*, 2010].

The development and commercialization of InP-based Geiger mode (Gm) avalanche photodiode (APD) arrays, and the more recent emergence of linear mode (Lm) mercury cadmium telluride (HgCdTe) APD arrays, have had a significant impact on commercial and defense lidar systems, particularly in the areas of topography and ranging [*Itzler et al.*, 2011; *McKeag et al.*, 2011; *Beck et al.*, 2014]. These detectors are also being considered for deep-space optical communications applications. While these detector materials are well-matched to existing laser wavelengths, the focal plane architectures can in some cases be extended for use in other wavelength regimes through different active detector materials (including band-structure engineered materials such as ternary alloys or superlattices) or by substrate thinning to improve the visible response.

In the UV, several different technologies have been pursued in the past decade, principally targeting the development of solar-blind detectors for UV astronomy and imaging applications [*Reine et al.*, 2006; *Suvarna et al.*, 2013]. Microchannel plate (MCP) detectors have been the primary UV imaging technology for decades and have a strong space heritage, but require a sealed vacuum envelope and can suffer from pattern noise, non-linearity, and throughput issues [*Vallerga et al.*, 2011]. Band-structure engineering in silicon or III-N materials (*e.g.*, GaN, AlGaN) has been applied to a variety of detector architectures including APD designs, CCDs, CMOS hybrid focal plane arrays, and photocathodes. The development of hybrid architectures such as the Intensified Imaging Photon Counting (I^2PC) scheme present opportunities for larger format focal plane arrays, which could enable larger fields-of-view and higher spatial resolutions [*Grund and Harwit*, 2010].

Radiation hardening of single-photon detectors still requires additional development, although some progress has been made on this front in the past several years by reducing the pixel active area while maintaining the detector fill factor with a microlens array. While this approach may be effective in some cases, it can put limitations on the telescope optical design. Improved materials growth and device fabrication and processing techniques, particularly for complex band-engineered materials, could improve detector yield as well as improve device dark count rates, afterpulsing performance, and non-uniformity, which will be necessary for the new generation of array detectors.

Higher operating temperature detectors and/or improved cryocoolers are required for cooled detector arrays. State-of-the-art Dewar-cooler technologies, particularly linear-drive technology, are at the 5 x 5 x 5 cm point with power consumptions of a few watts. Ultraminiature MEMS-based coolers are under development [*NRC*, 2007]. The ability to support low f-number optical systems with relatively short back focal lengths was identified as a potential challenge with existing designs.

A general consensus is that the U.S. industrial base is not currently able to respond to all lidar community needs for affordable, low-volume, custom detector designs. However, international collaboration on custom detectors is challenging due to ITAR/EAR considerations. The oft-stated need for a renewed domestic commitment to product development in this area still stands. It will also be important to investigate the possibility of leveraging DoD investments in advanced detector development.

Table 3.14. Detector technology needs summary.

Measurement	Technology	State-of-the-Art	Requirements	Development Need
Wind (direct or hybrid), Aerosol	MCP PMT, CMOS Delta-doped Si III-N PIN arrays or APD	PMTs, QE ~25% Si APD, >65% QE, <300 cps DCR, <50 ns dead time ACCD: 85% QE, 16x16 pixels, 25 x 2.1 μs range gates, 7 noise e^- per pixel, 16-bit ADC I^2PC: 40% PDE, 256x256 pixels, 10s of ps	Single element or array detectors with single photon counting sensitivity, PDE > 50%, internal gain 10^6, dark current <1 kcps, active area >2 mm^2	Develop and demonstrate photon counting detector arrays for increased dynamic range
Wind (coherent) CO_2, non-CO_2 GHG, water	HgCdTe APD arrays	80-K, 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 (<5 W 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: 80-K, 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

3.2.7. Optical High Resolution Spectral Analyzers

Spectral frequency analyzers (*e.g.*, interferometers or grating spectrometers) are required for analysis of multiwavelength lidar returns or fluorescence. Potential technologies include gratings, Michelson or Mach-Zehnder interferometers, Fabry-Pérot étalons, and atomic vapor filters. This technology enables measurement of phytoplankton physiology and independent measurements of aerosol extinction and backscatter. Although commercial prototypes are available, this is a relatively low TRL technology that requires development to meet space-qualification.

Table 3.15. Spectral analyzer technology needs summary.

Measurement	Technology	State-of-the-Art	Requirements	Development Need
Phytoplankton, ocean mixed layer	Polychromator or spectrograph with time-gated CCD or PMT array	Although there are commercial prototypes, none of them meets the specified quantitative requirements and is a space-qualified product.	Laser stimulated emission (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

3.2.8. Detection Electronics

This topic addresses technology requirements for post-detection processing, including high-speed ADC, photon-counting thresholding and accumulation electronics, *etc*. In general these components are used for signal conditioning and processing as part of the data acquisition subsystem. Detection electronics are enabling for altimetry measurements; differential absorption measurements of atmospheric temperature and water vapor; and ocean mixed layer depth measurements. In general, the requirements and development needs for the various measurement scenarios are not particularly stressing given the significant improvements in electronics in the past decade. Development in this area could offer savings in cost or SWaP. In particular, power considerations are likely to become more challenging if SmallSat or distributed architectures are utilized.

In most cases, commercial grade parts exist that meet the data handling requirements for currently envisioned lidar systems. These parts do not have radiation hard designs and may not be packaged appropriately for space applications. Radiation hardness assurance testing—including total integrated dose measurements and single event effect measurements—to evaluate these parts could determine that they are viable for certain measurements, depending on the system architecture and the nature of the radiation effects. In some cases, radiation hardness levels can be improved by non-standard packaging, such as RADPAK flat-pack packages [*Agarwal et al.*, 2010].

Table 3.16. Detection electronics technology needs summary.

Measurement	Technology	State-of-the-Art	Requirements	Development Need
Wind	Ruggedized flip chip packaging, 65-nm copper CMOS process, 1.0V core voltage	Rad hard by design FPGAs with up to 450 MHz DSP with embedded processing	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	CMOS, SOI/CMOS, Bipolar/SOI	Multiple commercial 16-bit high speed (>20 Msps) ADCs are available but not in space-qualified designs	20-MHz, 16-bit ADC	Rad-hard, space qualified high speed, high resolution ADC
Topography	Hardened memory protection and rad-hard FPGA and components	12-bit 3.2 GSPS ADC /12-bit Dual 1.6 GSPS ADC (1.71 W per channel) 10-bit, 2 Gsps space-qualified digital receiver	Low power (<50 W),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.

3.3. Information Systems

As reported in the 2006 Lidar Working Group Report [*ESTO*, 2006], information technology is present at every stage of a space mission. Dramatic leaps in capability lay the foundation for enhanced laser/lidar system functionality and ultimately, new lidar data products. Past efforts to quantify remote sensing technology requirements focused on information technology directly related to instrument concepts expressed in measurement scenarios.

During the 2016 working group discussions, the team reassessed the measurement requirements from the 2007 NRC Decadal Survey for NASA Earth Science [*NRC*, 2007]. Furthermore, the team has solicited new measurement concepts which could be considered for the 2017 NRC Decadal Survey. The team has mainly focused on specific technologies which are replaced with breakthrough technologies or alternative approaches. Each scenario describes the flow of data acquisition, identified interfaces with instruments and associated technology, and specified the resulting data and products. Information technology is multi-purpose and supports many lidar measurement scenarios with similar operations or data use constraints. This analysis approach allowed the team to derive information technology requirements representative of the needs of future lidar systems in general. However, it was observed that information technology is often an afterthought due to a nature of instrument development cycle; thus, it was not possible to gather significant additional inputs to fully refresh the information technology needs.

Some technologies were excluded that are inherent in modeling and analysis, but lack any specific tie to the new laser enabled measurements. For example, visualization technology to enhance understanding of the impact of wind profiles on storm fronts is not included because the visualization issue is not unique to lidar measurements. Hence many information technology requirements needed to improve data understanding, data management and modeling performance are beyond the scope of this assessment as was the case in 2007.

The Information technology development needs were categorized by *Onboard processing*, *Spacecraft control and communication*, *Ground processing*, *Algorithms/models, and enabling technology.* It was noted that there are four categories of development approaches: *Technology development, Engineering implementation, Cross-cutting and longer term investment, and Algorithm research.* It is understood that most of the "technology" needs are evenly categorized into the four development approaches. Thus, they are heavily dependent on a specific instrument development approach with host platform, power, mass, and volume as key requirements. Technology requirements for each measurement in the area of information technology are tightly coupled to those of the transmitter and receiver subsystems. Subsystems are not implementable if top-down requirements are not defined in terms of SWaP, interface, mechanical/thermal, data rate, and mission life. Technology development to satisfy the priority measurement(s) must be coordinated between the technology categories in order to achieve maximum return on investment. It is not feasible to start these information technology developments until phase A. Cross-cutting needs require long term investment and standardization of interfaces for cost effectiveness and risk reduction purposes. The following areas belong to this category: Onboard processor and storage, Instrument interface, telecommunication, data compression, Ground data processing, data analytics, Algorithms, Instrument specific command and control, and Model-specific data processing.

3.3.1. Assessment of technology gaps for measurement scenarios

A number of information technology capability gaps were identified that impact measurements recommended by the 2007 Decadal Survey [*NRC*, 2007] and an analogous set of gaps was also identified for the measurements that have received emphasis in the current study. These capability gaps are summarized in Tables 3.17 and 3.18, respectively.

Table 3.17. Enabling information system technologies for 2007 Decadal Survey recommendations.

Capability Gap	Measurements	Current 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 (DESDynI)	6
None (met by GRACE-FO, Sat-to-Sat communication)	Gravity (GRACE-2)	6
Onboard processing, compression, laser life prognosis (<days)	Topography (LIST)	3
Autonomous acquisition, real-time LOS wind, validation (<1 hr), OSSE	3D Winds (Demo)	5

Table 3.18. Enabling information system technologies for 2016 measurement emphases.

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

3.3.2. Information Technology Breakdown

<u>On Board Processing</u>

The main effort is to reduce and manage the amount of data initially collected onboard, *i.e.*, not to simply operate sensor in always-on mode. Use of information from a variety of sources would enable a paradigm change thereby reducing resource impacts downstream. Even with the effort to reduce the amount of data collected, data volumes are expected to continue to increase. The need to store, process, and compress it on-board is still required 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 the topic of on-board data compression, developments of compression algorithms is critical 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

Health Monitoring & Control requires both autonomous on-board sensor health monitoring and 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

<u>Spacecraft Control and communication</u>

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. The following areas have been identified as technology development needs:

- On-board Sensor Control
- Standardization of Interfaces and Controls
- Spacecraft Area Network
- Formation Flying
- Science model-driven adaptive targeting

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 handling of increasing data volumes, for which advanced data transmission capabilities also 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

Table 3.19. C&DH technology needs.

Capability	Instrument/Platform Specific	Quantitative Goal
On-board sensor control	Data latency, algorithm, Processing power	<3 hr, FPGA Virtex 5
Spacecraft area network	Formation control and knowledge, bandwidth	<Wavelength/2, LOS, Ka- vs. X-band
On-board processing	Cloud screening, event detection (e.g., storm/storm front, fire), water vapor estimation	% clouds along with confidence, <3 hr for weather events Water vapor: <10% uncertainty @ 500-m range resolution
On-board compression	FFT, image, buffer management	10:1, 7000 MIPS*
Intelligent sensor health & safety	Lifetime estimation, monitoring	Catastrophic parameter detection <1 hr
Point and tracking	Attitude control	Integrated tracking sensors <4 μrad
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.

<u>Ground Processing</u>

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
    - Efficient mining of data sets to extract salient information.
- 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.

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
- The team concluded that this is not a technology development. Most of the development needs should be addressed by missions and ROSES R&A opportunities.

<u>Modeling and Algorithms</u>

Determination of development needs in modeling and algorithms are beyond the scope of information technology. It is therefore recommended that instrument developers should utilize existing R&A programs to advance these capabilities in order to establish instrument performance requirements and mature data processing algorithms to produce measurements fully validated and calibrated.

  - Observation System Simulation Experiments (OSSE)
  - Model lidar data resampling techniques
  - Algorithms
  - Instrument specific algorithms and theories
  - Ancillary data processing
  - Calibration and validation campaigns

<u>Enabling technologies</u>

NASA has made prior investments in the following areas:

- 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

Further investments in these area will enhance instrument life and reduce cost of missions.

3.3.3. Emerging technologies

The team has identified a few emerging technologies from commercial markets and DoD. For FPGA areas, the following industry trends should be taken advantage of:

- 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.

For big data and data science areas, many technology developments have matured to infuse into NASA's data management and analysis frameworks.

- 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)

For onboard processing architecture, Control Architecture for Robotic Agent Command and Sensing (CARACAS) has been used on board MSL and other platforms. Adaptation of this architecture could enable infusion of specific onboard capabilities to be tested and evaluated. For modeling and high performance computing, Observations for Model Intercomparison Projects (obs4MIPs) is developed to validate and verify models with remote sensing data. Optimizing and utilizing cloud computing and network technology are being actively utilized to support processing needs from missions like OCO-2, SMAP, and upcoming missions.

3.3.4. Recommendations

During discussions with information technologists, the following recommendations for technology acceleration and development were formulated:

- Establish testbed in order to test onboard capabilities
    - Cross-cutting needs that apply to multiple sensor and measurement types.
    - Address instrument specific interfaces and requirements
- Quantitative goals are needed to address Instrument specific compression and innovative retrieval algorithms in a relevant environment
    - Free flyer vs. hosted payload, processing power, platform specific
- Establish a calibration and validation sensor network for remote sensing instruments
- Sample/synthetic instrument data needed to test processing algorithms

It is also recommended that a specific instrument platform should be defined in order to evaluate and collaborate technology developments in information technology areas.

3.3.5 Conclusions

Based on inputs from the participants, it was agreed that measurement requirements must be clearly defined. Only then, quantitative requirements then follow. However, since these requirements are still in flux, it was a challenge to define technology requirements quantitatively. It was also observed that technology requirements for each measurement in the areas of transmitters, receiver systems, and DADU/C&DH are tightly coupled. Furthermore, 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. It is further recommended that technology development to satisfy the priority measurement(s) be targeted and coordinated in the three categories in order to achieve maximum return on investment.

4. Emerging Technology Trends

Qualitatively, emerging technologies are regarded as being those perceived as potential game changers for a given measurement scenario. In this report a maturity level of <TRL3 is deemed emergent, consistent with ESTO's ACT (Advanced Component Technologies) and AIST (Advanced Information Systems Technology) programs, for which the minimum entry point is TRL2 (esto.nasa.gov/technologists_trl.html). The emerging technologies roll-up summary is provided in Table 4.1, with details contained in the following sub-sections.

Table 4.1. Emerging technology requirements top-level summary.

	UV 355-400 nm	Vis 400-650 nm	NIR/SWIR 700-2000 nm	MWIR 3-5 micron
Measurement	3D Winds; Water vapor; Tropospheric 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 conversion to fixed or tunable wavelengths	SHG of 1-µm sources; multi-stage non-linear conversion to fixed or tunable wavelengths	1, 1.5-1.6, 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. (These technologies are cross-cutting and applicable to all measurements, as well as other sensor classes.)			

Since the 2006 report [*ESTO*, 2006] there has been a revolution in SmallSat/hosted payload concepts, fueled in part by an aggressively cost-constrained environment. For SmallSats, and especially U-class concepts, miniaturization and availability of COTS components are key considerations. In this respect, integrated photonic subsystems and systems are increasingly being sought (and where available used) to dramatically reduce the SWaP of optical designs. In addition, the burgeoning additive manufacturing field offers pathways to the creation of previously impossible enabling constructs, such as large-area mirrors that are lightweighted in ways that cannot be accomplished through conventional means.

Additive manufacturing is also considered a key enabling capability for carrying out in-space "self-fabrication" of structures that could potentially scale to dimensions in the hundreds-of-meters range [*Hoyt et al.*, 2013]. Metrology of such structures could be accomplished using established processes such as stereo-imaging that are adapted from commercial manufacturing operations. Techniques such as these are already being investigated for large self-assembled RF antennas and it is conceivable that a similar approach might be applicable to the development of large space-based optical apertures ("light buckets").

Distributed apertures and disaggregated SmallSat lidar constellations (*i.e.*, transmitter and receiver on different platforms in a so-called bistatic configuration) are also emerging approaches under consideration for future advanced concepts.

Computational simulation tools for systems engineering can act as effective arbitrators of evolving technology options by enabling quantitative trades between measurement system parameters such as aperture size, detector efficiency, laser power, and waveform diversity that could mitigate technological hurdles. To be successful, this approach requires robust, high-fidelity models and high performance computational algorithms in both the environmental and sensor performance domains.

In this report emerging technologies are explicitly addressed, reflecting a realization that such capabilities could determine the success of ambitious future mission concepts, and that they should therefore be defined and their development accelerated. Deliberations with the lidar practitioner community also raised the recurring lack of U.S. suppliers capable of providing critical system components, especially high-performance detectors. Because this inevitably raises export control concerns it continues to be important that a robust U.S. industrial base be nurtured in the affected technology areas.

4.1. Transmitter Technologies

In the transmitter laser category all the identified emerging technologies cite nonlinear conversion from a ~1-µm fundamental wavelength (*i.e.*, Nd and Yb gain media). Hence, for the blue wavelength(s) required by the ocean mixed layer depth measurement the 2nd harmonic of the 940-nm and the 3rd harmonic of the 1320-nm Nd^{3+} lines in YAG were identified as options, along with optical parametric generation using a 3rd harmonic (355 nm) pumped OPO or a cascaded scheme in which the 2nd harmonic of a 1064-nm laser is mixed with the idler of a parametric downconverter also pumped by 1064 nm. The UV wavelength pairs needed for tropospheric ozone measurement can similarly be based on cascaded nonlinear conversions using a high-energy 1064-nm pump, while the water vapor and cloud/aerosol profiling applications at wavelengths in the 700-950 nm range could utilize either an optical parametric oscillator pumped by the 2nd-harmonic of a 1064 nm source or a cascaded nonlinear scheme pumped by a 1-1.5 micron laser. The requirements and associated technology options are summarized in Table 4.2.

Current research into "wavefront-agile" lidar systems that make use of information encoded in the orbital angular momentum of the transmit signal is predicated on the belief that new methods of solar background rejection, separation of single and multiple scattering contributions, and enhanced turbulence detection may result. This work is at a very early stage of development [*Sun et al.*, 2016] and has an estimated maturity of TRL2.

Another emerging technology that could be both disruptive and beneficial from several perspectives is the waveform-agile laser based on fiber/bulk solid-state hybrid architectures. As mentioned previously, fiber-MOPAs, especially those based on Yb: and Er:fiber amplifiers, utilize telecom heritage master-oscillators that have quasi-arbitrary temporal waveform capabilities pertinent to both direct-detection and coherent measurement modalities, including variation of pulsewidth, pulse repetition rate, and amplitude/phase modulation. As noted above, fiber-MOPAs are most efficient when operating at high pulse repetition rate, which has been identified by the ESTO lidar community as an obstacle to technology insertion due to range ambiguities arising from multiple pulses "in the air" during a measurement cycle. The waveform agility of these sources may offer resolutions to range ambiguity *via* coded marking of the transmitter waveform, but could also require significant modifications to measurement protocols.

Table 4.2. Emerging transmitter laser technology requirements.

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 with Nd:YAG 3rd harmonic, cascaded nonlinear conversions	475-485 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; for space platforms: 305-320 nm; for 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(s)	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
Fiber/bulk hybrid architectures	Range-resolved measurements	Fixed pulsewidth, pulse repetition rate (PRR), intensity/phase modulation	Capability to support scripted sequences of laser output with variation in pulse width, PRR, modulations

In the realm of ancillary (*i.e.*, non-laser) transmitter technologies, optical muxes (multiplexers) operable in the NIR and SWIR spectral regions are required to combine multiple seed lasers for injection frequency control of DIAL transmitters. Gas-filled photonic fibers are also needed to act as NIR wavelength references to lock the transmit laser to the spectral feature being probed. There is a significant lab-based heritage in such gas-filled fibers, but insufficient knowledge concerning techniques for guaranteeing extended fill lifetime. These requirements and associated technology options are summarized in Table 4.3.

Table 4.3. Emerging ancillary transmitter technology requirements.

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

4.2. Receiver Technologies

Emerging technologies in the detector category center on the need for high quantum efficiency (QE) multi-element arrays in the UV, mid-visible, and SWIR for the 3D Wind measurement application. A particularly critical need was voiced in the area of rapidly gateable high-QE, low-noise detectors in the UV thru mid-visible. This technology is moribund in the U.S. and foreign suppliers are often ruled out on export control grounds. This is a prime area where the U.S. industrial base needs to be augmented and matured. These detector needs are summarized in Table 4.4.

Table 4.4. Emerging detector technology requirements.

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 μm 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

Table 4.5. Emerging ancillary receiver technology requirements.

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)
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/lasercom SmallSat constellations	Utilize lasercom components beyond lasers/amplifiers	Dramatic SWaP reductions to enable SmallSat applications; 1-2 μm

* Cross-cutting across multiple measurements.

4.3. Information Systems

In the realm of information systems, it has been recognized for some time that laser shot management offers considerable potential to enhance mission life by reducing unnecessary strain on the instrument hardware. While such capability has not yet been built into spaceflight lidar command and control systems, the introduction of intelligent sensor control is seen as pivotal for efficiently optimizing instrument performance and lifetime. In addition, the capability would be relevant to all lidar measurement scenarios.

Another area of cross-cutting advancement would be the demonstration of space-qualified, radiation hardened, deep-submicron microelectronic technologies. Although this capability is coupled to a large investment need, the payoff reaches beyond lidar applications into all other sensor modalities, as well as constituting a waypoint on the SmallSat constellation roadmap. The emerging information systems technology elements are summarized in Table 4.6.

Table 4.6. Emerging information system technology requirements.

Technology Thrust Area	Measurement	State-of-the-Art	Notional Requirements
Intelligent sensor health and safety*	Autonomous monitoring & control of lidar health and safety (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 µm. Large investment needed to satisfy future processing needs	Radiation hardened deep-submicron microelectronic technology (0.25, 0.18, 0.15, and 0.09 µm)

* Cross-cutting across multiple measurements.

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

5. Summary and Plan Forward

The foregoing chapters reviewed the state-of-the-art in the areas of transmitter, receiver, and information technologies as they pertain to lidar systems. An overview of current challenges and technology needs for enabling NASA's Earth science measurement goals has also been provided. Axiomatically, all of the needed technology capabilities described require future investment in order to reach a level of maturity commensurate with their infusion into space missions. However, given the limited resources of the technology program, there is a need for prioritization. In the 2006 strategy [*ESTO*, 2006], the technology prioritization was based on the following criteria (in descending order of importance):

1. *Scientific Impact*: The degree to which the proposed lidar-acquired measurement will impact scientific understanding of the Earth System and help answer the overarching questions defined in the NASA Earth Science Research Strategy.

2. *Societal Benefit*: The degree to which the proposed measurement has the potential to improve life on Earth (*e.g.*, by improving the accuracy of natural disaster forecasts).

3. *Measurement Scenario Utility*: Whether the lidar approach is the primary or unique methodology for enabling the proposed measurement. Another factor is whether the scenario meets or exceed threshold or goal science requirements, or meets requirements for a demonstration mission.

4. *Technology Development Criticality*: Whether the development of the proposed technology enables new measurement capabilities or provides incremental improvement in the measurement.

5. *Technology Utility*: The degree to which the technology makes a significant contribution to more than one measurement application. The utility can be measured by the number of different measurement scenarios the technology enables.

6. *Measurement Timeline*: Determined by the time horizon when a particular measurement is needed, as articulated in NASA's Earth Science Research Strategy.

7. *Risk Reduction*: The degree to which the new technology mitigates the risk of mission failure.

These criteria remain valid in developing a robust technology development portfolio and indeed were used in the prioritization of the technology investment portfolio by ESTO. The Earth Science Decadal Survey of 2007 outlined the scientific measurements that were of priority in three distinct tiers [*NRC*, 2007]. Recommended measurements that required lidar technology investments were: ICESat-2 (ice topography), ASCENDS (CO_2), ACE (aerosols and clouds), DESDynI (biomass), GRACE-2 (gravity), LIST (topography), and 3D Winds (tropospheric winds). The ESTO lidar technology investment strategy was aligned with these scientific measurement priorities.

Of the 2007 decadal recommended missions, ICESat-2 is scheduled to be launched in late 2017 and there are no unmet technology challenges. The DESDynI mission (which consisted of both a lidar and radar on a single platform) followed a different implementation approach. The lidar instrument (Global Ecosystem Dynamics Investigation, or GEDI, which was selected through the Earth Venture Instrument program) is planned to be manifested on the International Space Station (ISS) in the 2018-19 timeframe. ACE has currently morphed into the PACE (Pre-Aerosol, Clouds, and ocean Ecosystem) mission, which will not include a lidar. The GRACE-2 mission is being mounted in collaboration with Europe, with the lasers anticipated to be provided by non-U.S. suppliers.

While much R&D has been invested in the last decade to enable both the ASCENDS and 3D Winds mission, the system TRLs are still insufficiently advanced to implement those missions. The greatest challenge in the case of ASCENDS has been maturity and readiness of tunable lasers meeting measurement requirements, with power amplifiers being a particular issue. In the case of 3D Winds, the reliability and readiness of the required UV and 2-μm transmitter technologies continue to be among the greatest challenges.

If the Decadal Survey of 2017 affirms the importance and priority of the above measurements, then the ESTO investment strategy should accordingly be harmonized to assign higher priority to maturation of the related lidar technologies through a combination of focused investments and leveraging of prior lidar investments by other government agencies, as well as international partners. Closer partnerships are needed in order to enable future Earth science lidar missions.

Because the scientific direction of the 2017 Decadal Survey and the priorities they will levy on measurements are unclear at the time of this writing, assessments were solely based on the current state-of-the-art, emerging trends, and priorities of the 2007 Decadal Survey. The ESTO lidar technology investment strategy will be revised once the 2017 Decadal Survey recommended priorities become known.

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Appendix 2: Listing of Submitted Materials

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Abshire, James	NASA/GSFC	2014 IEEE international space lidar workshop - chapter on using lidar for greenhouse gas measurements
Abshire, James	NASA/GSFC	ASCENDS - Mission Study White paper (April 2015)
Abshire, James	NASA/GSFC	2015 Carbon-Climate Workshop Report
Davis, Anthony	Jet Propulsion Laboratory	Multiple-scattering/Wide-FOV Cloud Lidar from Space: The technological key that can unlock the marine stratocumulus – climate challenge
Kavaya, Michael	NASA/LaRC	Coherent-Detection, Pulsed Wind Lidar Laser Figure of Merit
Mercer, Allison	Georgia Institute of Technology	Infrared lidar observations of stratospheric aerosols
Phillips, Mark	Lockheed Martin Corporation	Reconfigurable Multi-Functional Sensor for Earth Science
Schumann, Guy	Remote Sensing Solutions, Inc. (USA) / University of Bristol (UK)	The need for a high-accuracy, open-access global DEM
Singh, Upendra	NASA/LaRC	Reducing NASA's Cost And Risk For An Earth-Orbiting Hybrid Doppler Wind Lidar System That Will Provide Vertical Profiles of Horizontal Vector Wind
Tucker, Sara	Ball Aerospace	Comparing and contrasting the Optical Autocovariance Wind Lidar
Tucker, Sara	Ball Aerospace	The ATHENA-OAWL s Mission
Tucker, Sara	Ball Aerospace	Optical Autocovariance Wind Lidar (OAWL)
Tucker, Sara	Ball Aerospace	Lidar-Measured Wind Profiles: The Missing Link in the Global Observing System
Tucker, Sara	Ball Aerospace	Observing System Simulation Experiments (OSSEs) to Evaluate the Potential Impact of an Optical Autocovariance Wind Lidar (OAWL) on Numerical Weather Prediction
Várnai, Tamás	UMBC/JCET and NASA/GSFC	Multiple field-of-view lidars for cloud remote sensing
Weimer, Carl	Ball Aerospace	Adaptive Lidar for Topographic and Forest Mapping
Weimer, Carl	Ball Aerospace	Ocean Subsurface Studies with the CALIPSO spaceborne lidar
Weimer, Carl	Ball Aerospace	SmallSat Grace II
Weimer, Carl	Ball Aerospace	UV Lifetime Laser Demonstrator for Space-Based Applications
Weimer, Carl	Ball Aerospace	Space Lidar Technologies Supporting Upcoming NASA Earth Science & Laser Communication Missions
Weimer, Carl	Ball Aerospace	Highly Efficient, narrow-linewidth, and single frequency actively and passively Q-switched fiber-bulk hybrid Er:YAG lasers operating at 1645 nm
Weimer, Carl	Ball Aerospace	Searching for applications with a fine-tooth comb
Weimer, Carl	Ball Aerospace	MOIRE - Ground Demonstration of a Large Aperture Diffractive Transmissive Telescope

Weimer, Carl	Ball Aerospace	Intensified imaging photon counting technology for enhanced flash lidar performance
Weimer, Carl	Ball Aerospace	CALIPSO Lidar Description and Performance Assessment
Weimer, Carl	Ball Aerospace	A FDTD solution of scattering of laser beam with orbital angular momentum by dielectric particles: Far-field characteristics
Weimer, Carl	Ball Aerospace	Lidar Orbital Angular Momentum Sensing (LOAMS)
Weimer, Carl	Ball Aerospace	Comparing seven candidate mission configurations for temporal gravity field retrieval through full-scale numerical simulation

Appendix 3A: Transmitter Technology Capability Breakdown Matrix

Technology	Measurement	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Emerging Technology (Y/N)	Comments on Updated Rqmts	TRL @ Start	Development Time to TRL 6 (years)
Low PRF, ~1-micron laser (≤500 Hz), 1-100 W, 10's-100's of mJ; w/HG	Atmospheric Profiles	Backscatter lidar	1064/532 nm	Polarimetric multiwavelength cloud/aerosol properties	100 mJ/20 Hz at 532 and 1064 nm. Polarization purity >99% at 532 nm, divergence 100 microrads, injection-seeded linewidth 1 GHz or less.-- Calipso was 10 G	1. Oscillator: 2.5-20 kHz, 0.1-5 ns, 100-500 mW. 2. Slab amplifier 5-100 W. 3. Fiber amplifier offers higher efficiency but lower energy/pulse (max. 10 mJ/fiber). 4. Monolithic solid state laser oscillator: 2.5-20 kHz, 0.1-5 ns, 100-1000 mW. 5. Laser Array: NxN laser elements, each with 2.5-20 kHz, 0.1-5 ns, 100-500 mW.	N	0.1-1 Joule-class diode pumped 1-micron systems are in early stages of development. Source for DWL, HSRL, DIAL types of measurements.	4	2
		Multi-Wavelength HSRL	355/532/1064	Aerosol, Cloud, Ocean Profiling HSRL	High efficiency (>12%Wall plug), 100-500 Hz, 50-100W (0.2-0.5 J), $M^2 < 1.5$, single frequency, high spectral purity (>10,000/1), 5-10 ns pulse width	Power efficiency is critical (all services).	N	Seeded laser.		
	Atmospheric Profiles with near sea-surface	Backscatter lidar	1064/532 nm	Profile absorbing aerosols from 15m below ocean surface to stratosphere	100 mJ/20 Hz at 532 and 1064 nm	1. Oscillator: 2.5-20 kHz, 0.1-5 ns, 100-500 mW. 2. Slab amplifier 5-100 W. 3. Fiber amplifier offers higher efficiency but lower energy/pulse (max. 10 mJ/fiber). 4. Monolithic solid state laser oscillator: 2.5-20 kHz, 0.1-5 ns, 100-1000 mW. 5. Laser Array: NxN laser elements, each with 2.5-20 kHz, 0.1-5 ns, 100-500 mW.	N	0.1-1 Joule-class diode pumped 1-micron systems are in early stages of development. Source for DWL, HSRL, DIAL types of measurements.	4	2
	Topography	Laser altimeter	1064/532 nm	Map solid earth and aquatic surface elevations, including vegetation height and vertical structure	50 mJ/100 Hz, <5 ns pulsewidth					
	Topography, FOPEN	Laser altimeter	1064/532 nm	Land surface topography below vegetation	10-20 mJ/100-300 Hz at 532 and 1064 nm, 4 ns pulsewidth. Linewidth: <2 pm (single frequency desirable)					
	Atmospheric Profiles (*incl* Wind)	Doppler lidar, Backscatter lidar	355 nm	Tropospheric wind profiles	1 J/100 Hz, single frequency, WPE 6-8%	1. Oscillator: 10-200 Hz, 0.5-30 ns, 100-500 mW, 10 kHz-1 GHz linewidth. 2. Slab amplifier 10-200 Hz, 5-100 W. 3. Nd:YAG 40 W, 150 Hz, 270 mJ@1064, single-frequency. Intended for multiwavelength use. Maximize WPE.	N	0.1-1 Joule-class diode pumped 1-micron systems are in early stages of development. Source for DWL, HSRL, DIAL types of measurements.	5	2
	Atmospheric Profiles	Backscatter lidar	1064/532 nm	Polarimetric multiwavelength cloud/aerosol properties	100 mJ/20 Hz at 532 and 1064 nm. Polarization purity >99% at 532 nm, divergence 100 microrads, injection-seeded linewidth 1 GHz or less.					
	Atmospheric Profiles (*incl* Wind)	Backscatter/DWL/DIAL/ altimetry lidar	355 nm	Airborne profiling of cloud/aerosol optical properties	>300 mJ/>50 Hz @ 355 nm; ~1 J at 1064 nm fundamental					
	Ocean Biomass	Fluorescence lidar	532 nm	Hyperspectral measurement of laser-stimulated emission and natural fluorescence from the ocean	1 J/20-100 Hz, single frequency @ 1064 nm, WPE 6-8%					
	Atmospheric Profiles with near sea-surface	Backscatter/DWL/DIAL/ altimetry lidar	1064/532 nm	Profile absorbing aerosols from 15m below ocean surface to stratosphere	100 mJ/20 Hz at 532 and 1064 nm					
	Topography, Altimetry	Laser altimeter	1064/532 nm	Map polar ice sheets to characterize ice mass changes	100 mJ/100 Hz at 532 and 1064 nm					
	Atmospheric Profiles (*incl* Wind)	Backscatter, Doppler, Raman lidar	355 nm	Tropospheric wind profiles, aerosol/clouds, polarimetry, temperature	340 mJ/100 Hz at 355 nm, single frequency with conversion efficiency from 1064 nm of 40% or better	2x and 3x frequency multipliers for 1064-nm fundamental, average incident power handling 100W, 30-ns pulselength.	N	Source for DWL, HSRL, DIAL types of measurements. Avoids direct generation of required vis/UV thru HG of 1-micron, which is more readily available from space qualified systems.	4	2
	Atmospheric Profiles with near sea-surface	Backscatter lidar	532 nm	Profile absorbing aerosols from 15m below ocean surface to stratosphere	100 mJ/20 Hz at 532 nm					
	Atmospheric Profiles	Backscatter lidar	532 nm	Polarimetric multiwavelength cloud/aerosol properties	100 mJ/20 Hz at 532 nm. Polarization purity >99% at 532 nm, divergence 100 microrads.					
	Biomass Est.	Fluorescence Lidar	532 nm	Measurement of laser-stimulated and natural fluorescence from the oceans	~500 mJ/20-100 Hz at 532 nm with conversion efficiency from 1064 nm of 50% or better					
	Topography, FOPEN	Laser altimeter	532 nm	Land surface topography below vegetation	10-20 mJ/100-200 Hz at 532 nm, 4 ns pulsewidth.					
	Atmospheric Profiles	Backscatter lidar	1064/532 nm	Polarimetric multiwavelength cloud/aerosol properties	Conductively cooled laser transmitters with >1-kHz PRF, linewidth ~5 pm, pulse energy ~50 micro-J @ 355 and 1064 nm.	1. Oscillator: 2.5-20 kHz, 0.1-5 ns, 100-500 mW. 2. Slab amplifier 5-100 W. 3. Fiber amplifier offers higher efficiency but lower energy/pulse (max. 10 mJ/fiber). 4. Monolithic solid state laser oscillator: 2.5-20	N	High-PRF systems not yet demonstrated in space. CATS at 5 kHz, ICESat-2 at 10 kHz in work. ATLAS laser will be the	4	2
	Atmospheric Profiles O_3	DIAL	1064/532 nm, 290-330 nm	Tropospheric ozone profiles along aircraft flight track	Conductively cooled laser transmitters with 1-kHz PRF @ 290-330 and 1064 nm.					
	Topography, Altimetry	Laser altimeter	1064/532 nm	Map solid earth, ice and aquatic surface elevation	4 mJ/1 kHz, WPE >3%, pulselength 1 ns					

Technology	Measurement	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Emerging Technology (Y/N)	Comments on Updated Rqmts	TRL @ Start	Development Time to TRL 6 (years)
High PRF, ~1-micron laser, (≥1 kHz), 1-100 W, ~ 0.1-50 mJ; w/ HG	Topography, Altimetry, FOPEN	Laser altimeter	1064/532 nm	Map solid earth and aquatic surface elevations, including vegetation height and vertical structure	0.1 mJ/75 kHz (multiple transmitters), pulselength ~5 ns, WPE ~10%	kHz, 0.1-5 ns, 100-1000 mW. 5. Laser Array: NxN laser elements, each with 2.5-20 kHz, 0.1-5 ns, 100-500 mW.		first high-PRF laser in space.		
	Topography, Altimetry, FOPEN (same as above?)	Laser altimeter	1064/532 nm	Map solid earth, ice and aquatic surface elevation from orbit/UAV	5-20 micro-J/>10 kHz, pulselength <1 ns, linewidth <2 pm, linearly polarized					
	Topography, Altimetry, FOPEN	Laser altimeter/IPDA	1064 nm; 1.5 and 2 μ versions possible	Map solid earth and aquatic surface elevations, including vegetation height and vertical structure			N	LM CASA Laser MOPA: 20 kHz PRF, pulse duration 0.5 ns (plan to make adaptable to 0.5 to 20 ns in 2016), 100-200W average output power. Optical assembly and laser electronics power module at TRL 6. Short pulse format compatible with terrain/canopy mapping. Long pulse format compatible with NLO conversion for GHG mapping.	6	N/A
	Atmospheric Profiles (*incl* Wind)	Backscatter lidar	355 nm	Airborne Polarimetric multiwavelength cloud/aerosol properties	50 micro-J/>1-kHz, linewidth ~5 pm @ 355 nm.	2x and 3x frequency multipliers for 1064-nm fundamental, average incident power handling 100W, 30-ns pulselength.	N	Avoids direct generation of required vis/UV thru upconversion of 1-micron, which is more readily available from space qualified systems.	4	2
1-100 W 1.5-micron laser	Atmospheric O_2	IPDA-LAS	1530 nm (SHG to 765 nm)	Atmospheric temperature profiles	>1 J/10 Hz double-pulsed @ 765-nm 2nd harmonic		N	Space qualification of commercially derived optical communication equipment is high priority. TRL-6 effort on-going with fiber-based, multiple aperture approach to generate needed energy.	5	1-2
	Atmospheric CO_2	IPDA-LAS	1570 nm	Lower tropospheric CO_2 fluxes	10 W cw, 5-MHz long-term linewidth, tunable; fiber or 1064-nm pumped OPO	1. Oscillator: Tunable 1560-1575 nm, 5-10 mW, kHz wavelength agility. 2. Single-mode polarized fiber amplifier 10-W average, 100-W peak power. Amplitude stability 1000:1 between on-/off-resonance lines. 3. Multiple aperture laser transmitter to provide				
	Atmospheric CO_2	IPDA-LAS	1570 nm	Lower atmospheric CO_2 fluxes	0.1 mJ/100 kHz, linewidth <10 MHz, pulselength 1000 ns, single freq.					
	Atmospheric CH_4	DIAL	1650 nm	Tropospheric methane fluxes		1.65-micron pulsed Er:YAG 1 KHz, 10 mJ, single frequency, wallplug efficiency > 5%, with > 15 % goal, commercially available from Princeton Lightwave, IPG	N		4	3
	Atmospheric IPDA, CO_2	IPDA-LAS	1570 nm	Lower tropospheric CO_2 fluxes	10 W *cw*, 5-MHz long-term linewidth, tunable; fiber or 1064-nm pumped OPO	1. Oscillator: Tunable 1560-1575 nm, 5-10 mW, kHz wavelength agility.		Fiber amplifier offers higher efficiency and high energy (60 W) for continuous-wave (IM-cw, 1570 nm for CO2, ~ 300 kHz stability, < 1-3 MHz linewidth)		
	Atmospheric IPDA, CO_2	IPDA-LAS	1570 nm	Lower tropospheric CO_2 fluxes	0.1 mJ/100 kHz, linewidth <10 MHz, pulselength 1000 ns, single freq.	2. Single-mode polarized fiber amplifier 10-W average, 100-W peak power. Amplitude stability 1000:1 between on-/off-resonance lines.				
	Atmospheric IPDA, CH_4	IPDA-LAS	1645 nm	methane DIAL and aerosol cloud profiling	High wall plug efficiency (>5-10%), 5-10 W at 1000-3000 Hz, injection seeded single frequency, frequency agile (online and offline wavelength switching on shot-to-shot basis), high spectral purity >5000/1, pulse width <20 ns, linewdith<100 MHz, frequency stability <10 MHz, $M^2 < 2$		N	OPO and new Er:YAG solid state laser technolgy currently being investigated. Invstments needed to improve efficiency, reduce wavelength switching time (shot-to-shot basis), and environmental test for space based implimentation. Effic critical. PRF issues same as water, ozone lines above.	4-5	3-10
	Gravitational Field Mapping	Laser interferometer	1550 nm	Terrestrial gravity field		1-W femtosecond laser frequency comb - 1550 nm	N	Low-cost precision laser ranging for Earth gravity. Multiple low-cost satellite pairs allow improved spatial and temporal gravity measurements to complement GRACE-FO and GRACE-2. Flight demo: DLR FOKUS sounding rocket.	3	2
2-micron laser, Low PRF, 5-20 W, triple pulsed	Atmospheric Profiles, Wind	Coherent Doppler lidar	2050 nm	Tropospheric wind profiles	0.5 J/10 Hz, single frequency, WPE 1.4%	Pulse repetition frequency (PRF) between 5 and 300 Hz, Pulse Energy times SQRT(PRF) > 0.6 J-SQRT(Hz) held constant, single frequency, 8-GHz tunable frequency-agile reference oscillator, M^2 < 1.2, linearly polarized, WPE > 2% (goal >/= 5%).	N		4	4-5
	Atmospheric IPDA, CO_2	DIAL	2050 nm	Tropospheric CO_2 profiles	1 J/10 Hz double-pulsed with spectral purity >99.5%, wavelength stability <0.02 pm, WPE 3-5%, 250 μs separation	1. Seeded oscillator: 50 Hz, 25 mJ, >30-50 ns near-transform limited, M^2 < 1.2. 2. Amplifier 50 Hz, 0.05-0.1 J, >30-50 ns near-transform limited, ~2% WPE, M^2 < 1.2. 4. 30-GHz tunable frequency-agile reference oscillator. (E/O)	N	Seed laser is in hand (15 mW). Want more power from seeder (laser diode). Have investigated BSS seeder, but want better effic/perf.	4	4-5
1.5-2 micron laser, High PRF	Atmospheric IPDA, Wind	Doppler Winds and DIAL	1540-2090 nm	3-D winds, CO_2, methane	100 W (100 mJ, 1kHz), single-frequency.	Compact, efficient (> 10% WPE), pulsed single frequency lasers operating in eye-safe wavelength regime (> 1.5 micron). Pulse energies in 100 mJ regime at repetition rates greater than 1 KHz. 100 W class (PRF agnostic?) >200 ns pulse for winds; ~ns for DIAL. Transform-limited linewidth. Effic goal >/= 20%. SWaP critical.	N	Efficiency and size of current lasers is prohibitive for many space applications. Several novel concepts being pursued using bulk solid state and fiber optic laser techniques.	3	5
	Atmospheric CO_2	IPDA-LAS	2050 nm	Lower tropospheric CO_2 fluxes	3-5 W cw @ 2.05 microns, linewidth <50 kHz over 0.1 ms, 1-GHz tunable, stabilization to +/-2 MHz, 2% WPE	50 W IM-cw @ 2.05 microns, linewidth <50 kHz over 0.1 ms, 1-GHz tunable, stabilization to +/-500 kHz, 2% WPE				

Technology	Measurement	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Emerging Technology (Y/N)	Comments on Updated Rqmts	TRL @ Start	Development Time to TRL 6 (years)
cw 2-micron laser	Atmospheric IPDA, CO_2	Integrated Path Differential Absorption Lidar	2050 nm	Lower tropospheric CO_2 fluxes	3-5 W cw @ 2.05 microns, linewidth <50 kHz over 0.1 ms, 1-GHz tunable, stabilization to +/-2 MHz, 2% WPE	5-20 W IM-CW @ 2.05 microns, linewidth <50 kHz over 0.1 ms, 1-GHz tunable, stabilization to +/-2 MHz, >10% WPE				
	Atmospheric IPDA, CO_2	Integrated Path Differential Absorption Lidar	2050 nm	3-5 W cw @ 2.05 microns, linewidth <50 kHz over 0.1 ms, 1-GHz tunable, stabilization to +/-2 MHz, 2% WPE	5 W cw @ 2.05 microns, linewidth <50 kHz over 0.1 ms, 1-GHz tunable, stabilization to +/-2 MHz, 2% WPE	Current availability: 1. Fiber amp-based transmitter: 70 W broadband cw, M^2 ~ 1.2, WPE 8-10%. 2. Seed sources for MOs, amps: 100 mW, linewidth 100 kHz over 50 ms, 20-dB SOA. 3. Semiconductor pump lasers: 100W at 793 nm, WPE 50%, TRL 6; TBD @ 1.9 micron, TRL 2. 4. Fiber integrable passive components: Pump combiners: 10W power handling in signal channel; 100W per port on pump channels (1-2 micron); filters: 500mW at 2 micron, 5W at 1 micron. 6. Phase modulators/shifters: 20 GHz modulation bandwidth. 7. Robust freq. reference cell using gas-filled photonic fibers.	N			
Tunable wavelength conversion from 1 micron	Atmospheric Profiles, O_3	DIAL	308/320 nm	Tropospheric ozone profiles	>0.5 J/5 Hz (308/320 nm on/off each), tunable OPO, spectral purity ~99%, pulsewidth and stability 50 pm (each beam: divergence 0.2 mrad, pulse width ~30 ns)	1. Optical parametric convertors (OPO, OPA, mixers) for 308-320 nm, 10-W incident pump power. 2. 10-20 mJ/100-200 Hz, 308-320 nm, linewidth <2 pm, pulselength 4 ns.	N		4	2
	Atmospheric Profiles, H_2O (vapor and aerosol)	DIAL	940 nm	Atmospheric water vapor and aerosol profiles	0.5 J/10 Hz (double pulsed) at 940 nm, beam divergence 0.2 mrad, pulse width ~100 ns, spectral purity ~99%. Compositionally tuned Nd:garnet, or 532-pumped OPO	1. Oscillator: 10-200 Hz, 0.5-30 ns, 100-500 mW, 10 kHz-1 GHz linewidth. 2. Slab amplifier 20-200 Hz, 5-100 W. 3. Nd:YAG 40 W, 150 Hz, 270 mJ@1064, single-frequency. Intended for multiwavelength use. Maximize WPE.	N	Alternatives include 532 nm pumped OPO/OPA; HG from tunable Tm source (custom glass fiber laser?).	5	2
	Physical Oceanography	Ocean T lidar	400-480 nm	Ocean water T profile	Oscillator: 30-100 Hz, 1.5-3 W (15-100 mJ), 8-20 ns, 400-480 nm	SHG/THG of 940/1320 nm Nd laser, 30 mJ - 100 mJ. PRF can be higher, depends on measurment details, platform, recvr. (incl airborne?, as segue to space or dedicated mission.) Separate specs for distinct paltforms/meas scenarios. mJ pulse E at high PRF (airborne).	Y	Brillouim lidar to measure ocean temperature profile up to 100m below sea surface (physical ocenaography)	2	3-5
	Atmospheric Profiles, Biomass	Ocean Profiling HSRL (biomass est.)	450	Aerosol, Cloud, Ocean (+biomass) Profiling HSRL	High efficiency, 100-500 Hz, 3-10W (20-30 mJ), M^2 <2, single frequency, high spectral purity (10,000/1), 5-10 ns pulse width (soft rqmt)	1) High power high energy pump laser 2) Non-linear optics conversion module 3) Novel laser technology for direct laser generation (other wavelengths would be utilized for multi-wavelength aerosol cloud HSRL measurements)	N	Exact wavelength is not critical. Wavelength centered around 450 +/- 40 nm will suffice. Particulate backscatter. Measurement wants high pulse E for daytime. "HSRL" needed for aerosol characterization.	3	5-10
	Atmospheric Profiles, O_3	Airborne/Space based Ozone DIAL	290-320	Ozone and aerosol cloud profiling DIAL	High efficiency, 100-1000 Hz, 10-20 W (20-100 mJ), M^2 <2, laser linewidth <1 Angstrom, pulse width (10-30 ns)	1) High power high energy pump laser. 2) Non-linear optical wavelength converter OPO current path, others schemes possible.	Y	Need UV wavelength pairs separated by 10-20 nm. Sequential or simultaneously transmitted wavelength pairs space: 305-320 nm; airborne: 290-320 nm. Upper bound on PRF TBD, relates to issues incl range ambiguity, background subtraction	2	5-10
	Atmospheric Profiles, O_3	Ground Based Ozone DIAL	290-305	Ozone and aerosol cloud profiling DIAL	500-5000 Hz, > 0.2W (100 uJ-1 mJ), M^2 <2, laser linewidth <10 pm.	Pulse duration 10-30 ns, parametric wavelength generation via crystals, Raman, etc.	N	Generate two to three wavelengths either simultaneously or sequentially. Compact and robust laser (extended autonomous operation greater than 1 year), low cost (<~ $150k-200k)	4	2-5
	Atmospheric Profiles, H_2O (vapor and aerosol)	Space based tropospheric water vapor DIAL	720 nm	Water vapor and aerosol/cloud profiling	High wall plug efficiency (>5-10%), 20-40 W at 1000-3000 Hz, or 100 mJ at 100 Hz double pulsed within 200-300 microseconds, injection seeded single frequency, frequency agile (online and offline wavelength switching on shot-to-shot basis), high spectral purity >5000/1, pulse width <20 ns, linewidth<100 MHz, frequency stability <10 MHz, M^2 < 2.	Novel solid state laser technology employing either direct laser generation or parametric wavelength generation in the 720 nm spectral band for tropospheric water vapor profiling	Y	Direct or parametric generation of laser radiation near the 720 nm spectral band is required for tropospheric water vapor profiling. High power and robust laser required for space based observations. Low power and high rep rate architecture accetable for airborne demonstrations. (group 720, 820, 940 nm lasers to address water bands) need tunability around each wavelength. PRF constraints similar to ozone DIAL.	1-2	3-10
	Atmospheric Profiles, H_2O (vapor and aerosol)	Space based tropospheric water vapor DIAL	820 nm	Water vapor and aerosol/cloud profiling	Same as 720 nm	Novel solid state laser technology employing either direct laser generation or parametric wavelength generation in the 820 nm spectral band for tropospheric water vapor profiling	Y	Direct or parametric generation of laser radiation near the 820 nm spectral band is required for tropospheric water vapor profiling. High power and robust laser required for space based observations. Low power and high rep rate architecture accetable for airborne demonstrations. Ti:Saphhire lasers have been developed, but are inefficient and too large for space implementation.	1-2	3-10

Technology	Measurement	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Emerging Technology (Y/N)	Comments on Updated Rqmts	TRL @ Start	Development Time to TRL 6 (years)
	Atmospheric Profiles, H_2O (vapor and aerosol)	Space based tropospheric and stratospheric water vapor DIAL	940 nm	Water vapor and aerosol/cloud profiling	Same as 720 nm	Novel solid state laser technology employing either direct laser generation or parametric wavelength generation in the 920 nm spectral band for full tropospheric and stratospheric water vapor profiling	Y	Direct or parametric generation of laser radiation near the 940 nm spectral band is required for full tropospheric and stratospheric water vapor profiling. High power and robust laser required for space based observations. Low power and high rep rate architecture accetable for airborne demonstrations.	1-2	3-10
Harmonic generation of 1550 nm laser	Atmospheric Profiles, T (via what species, H_2O?)	DIAL	760 nm	Atmospheric temperature profiles	>1 J/10 Hz double-pulsed @ 760-nm, tunability >80 pm, spectral purity 99.5%	Fixed on-/off-line at ~760 nm, 20 Hz, 500 mJ using freq. doublers.	N		4	2-3
cw freq-stabilized laser	Geophysical Potential Mapping	Laser interferometer	780/850 nm	Geopotential reference surface and terrestrial gravity field	10-30 mW cw, single mode, 2nd harmonic generation	Frequency noise <100 mHz over 100s; frequency stability 10^-15 rms over 100 seconds	N	GRACE-FO demo of laser interferometer is 1-micron NPRO	4	2-3
	Gravitational Field Mapping	Laser interferometer	1064, 1560, 1700 nm	Geopotential reference surface and terrestrial gravity field	10-30 mW cw when frequency doubled, single mode	Frequency noise <100 mHz over 100s; frequency stability 10^-15 rms over 100 seconds 1700-nm laser requires pushing erbium amplifier technology to longer wavelengths than currently available 1064-nm laser in GRACE-FO				
	Gravitational Field Mapping	Laser interferometer	1560-1700 nm; 1020-1090 nm	10-30 mW cw when frequency doubled, single mode	Frequency noise <100 mHz over 100s; frequency stability 10^-15 rms over 100 seconds. 1700-nm laser requires pushing erbium amplifier technology to longer wavelengths than currently available.	100s of watts at 100-kHz bandwidth now available from single-aperture devices at 1020-1090 nm. All 1500-nm telecomm capabilities from 2005 era are now available at 1 micron with higher power, higher peak power, and higher WPE at equivalent TRL. Pushing Er technology to the extent asked for in 2006 is now regarded as unfeasible.	N	In GRACE-FO laser ranging demonstrator, main emphasis was frequency stabilization subsystem. Default for laser is 1-micron NPRO w/fiber amplifer.	3	
VIS laser	Geophysical Potential Mapping	Laser magnetometer	589 nm	Terrestrial magnetic field	N/A	1-W quasi-CW 589-nm semiconductor laser transmitter	N	Earth laser magnetometer using remote sensing of sodium vapor, Raman laser based on 1-micron pump laser.	3	2
CO_2 laser	Atmospheric O_3	Active limb sounder	9.1-10.4 microns	Tropospheric ozone profiles	100-Hz PRF single mode, tunable 9.1-10.4 micron CO_2 laser	Demonstrate reproducible tuning between on/off line wavelengths with settling time <10 ms, intraline tuning range ~10 cm^-1.	N	Long-term viability of CO_2 gas laser technology in space demonstrated by Aura Microwave Limb Sounder OH-channel laser local oscillator.	7	N/A
cw Laser Diodes	DIAL Components	DIAL and HSRL	Various (see LaRC input)	< 10 MHz linewidth seed sources for DIAL	Trace gas, aerosol, cloud, ocean profiling. 50-100 mW CW, 1-10 MHz linewidth, linelock to external reference, offset locking capability when needed	1) Stable CW source at desired wavelength (integrated with below) for DIAL measurements (specifics can be provided by LaRC staff). 2) Hermetically sealed 14 pin butterfly package (integrated TEC, Thermistor, and isolator). 3) Novel line locking references. 4) Compact and efficient modulation approaches for line locking. 5) Harmonic generation where needed.	N	Generating compact, integrated and line locked seed laser systems for injection seeded pulsed lasers. Require sources to overlap with molecular absorption lines associated with various DIAL and HSRL measurements.	3-6 (depending on wavelength and application)	0-5
Optical switches	DIAL Components	Trace gas DIAL	700-1000 nm, 1650 nm	Rapid wavelength switching of injection seeding source(s) for DIAL pulsed lasers. Water vapor and methane profiles/columns	4x1 (varying inputs of greater than 2 wavelengths) optical switch, fast temporal response (<100 ns), low insertion loss (<1db), low optical-optical cross talk (<40 dB), low power consumption (<2 W), polarization maintaining	Multi input switch to multiplex varying wavelength seed lasers onto a single fiber for injection seeding pulsed DIAL wavelengths (water vapor and methane).	Y	2x1 switches exist with acceptable respone time. Improved optical cross talk and increased input channels desired to improve spectral purity and reduce physical footprint for space applications. Existing TRL is 5. need agility to execute measurement. 4x1 meets current rqmts. Speed, isolation, IL are optimization parameters.	2	2-4
Gas reference cells	DIAL Components	Water vapor DIAL	760, 820, 940 nm	Fiber based gas cell for water vapor laser line locking. Required for accurate water vapor profiling	Low optical loss (<20 d/km) photonic crystal fiber, sealed fiber cavity with 1-20 Torr water vapor, leak rate <1 Torr/year, interaction length 1-100 m	1. Compact and rugged gas cell for water vapor DIAL laser line locking. 2. Photonic crystal fiber (air gap guiding section) acts as long gas cell (without need for any relay optics) that can be sealed and spliced to commercially available single mode fiber.	Y	Photonic crystal fibers have been used as open gas cells for spectroscopic applications, however, little research has been dedicated to sealing the cells with a fixed amounts of gas (specifically water vapor) for long term unattended operation. CO2 also. Fiber embodiments for long interaction lengths.	2	2-3

Appendix 3B: Receiver Technology Capability Breakdown Matrix

Technology	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need	Emerging Technology (Y/N)	Comments	TRL @ Start	Development Period to TRL 6 (years)
Alignment Maintenance	Hybrid Doppler Lidar	2 micron (coherent) channel	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit	5 microrad roundtrip (5 ms) lag angle compensation (coherent)	5 microrad roundtrip (5 ms) lag angle compensation (coherent)	1. Develop optical lag angle compensator 2. Prelaunch lidar alignment subsystem; highly quality beam reducing telescope; > 50 cm diameter for space application for far-field 3 .On-orbit pointing knowledge subsystem. GSFC has demonstrated at 1 micron (routed pick off of laser to star tracker + INS); needs to be demonstrated at 2 micron. Needs high-efficiency, high-sensitivity SWIR star tracker, high temp (TEC or room temp)	Y	Lidar optics positions, spatial orientation and angles must remain aligned Develop and demonstrate opto-mechanical methods to comensate for lag angle offset and image rotation	2	4
	Laser altimeter	1-micron	Narrow swath profiles of 3-dimensional structure of land and vegetation	Co-alignment of the transmitter beam and the detector array needs to be maintained to within ~ 10 microrad	Co-alignment of the transmitter beam and the detector array needs to be maintained to within ~10 microrad	Develop an active optical alignment system to monitor and maintain co-alignment between laser output beam and receiver FOV to within 10 microrad relative angle.	N	ICESat-2 will demonstrate 2006 requirement.		
	IPDA LAS for CO2	2.051 microns	The LAS transmits two wavelengths simultaneously. The transmitted spots must be overlapped on the ground in the cross-track direction	50 microrad standard deviation on a zero mean	50 microrad standard deviation on a zero mean		N			
	IPDA LAS for CO2	2.051 microns	Internal alignment maintenance to ensure efficient heterodyne mixing efficiency	Maintain transmit/receive overlap on the signal detector(s) to within 10% of ideal	Maintain transmit/receive overlap on the signal detector(s) to within 10% of ideal		N			
	Hybrid Doppler Lidar	355 nm (direct) channel	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit	50 microrad active T/R boresite alignment (direct)	50 microrad active T/R boresite alignment (direct)	Develop acitive optical boresite alignment device	N	Lidar optics positions, spatial orientation, and angles must remain aligned Develop and demonstrate opto-mechanical methods to actively maintain far field laser beam and telescope FOV	3	4
	Photon-counting laser altimeter	532 nm	Single-photon range images across a 300-m swath	Co-alignment of the transmitter beam and the detector array needs to be maintained to within ~ 10 microrad	Co-alignment of the transmitter beam and the detector array needs to be maintained to within ~10 microrad		N	ICESat-2 will demonstrate 2006 requirement.		
	All systems					Passive adaptive co-alignment of transmitter-receiver		Needed for all types of space lidar		
Detection Electronics, e.g., high speed ADC, multi-channel scaler, and boxcar averager	IMCW	1.57 & 2 micron			20 MHz, 16 bit ADC	High speed, high resolution ADC	N	Data sampling rate and precision requirements		
	Laser altimeter	1-micron	3-dimensional measures of the Earth's surface (land, ice, and ocean) topography	Low power(<50 W), 10 bit, 1 Gsamp/s digitizer			N			
	Laser altimeter	1-micron	3-dimensional measures of vegetation vertical structure and surface (land, ice, and ocean) topography	Low power (<20 W), >= 500 Msamp/sec digitizer with 10 effective bits of dynamic range			N			
	Laser altimeter	1-micron		Low power (<50 W), 12 bit, 1 Gsamp/s, 9 channel digitizer		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.	N	Return-pulse digitization is a proven technique for precise altimetry especially in the presence of vegetation. Multiple beams may require more digitizer channels and thus lower power options are needed. >10-bit dynamic range is required to capture the vegetation and ground returns in a single pulse in the presence of variable atmospheric attenuation and surface albedo variations.	4	2
	Laser altimeter	1-micron	Wide-swath (i.e., 10 km) 3-dimensional measures of vegetation vertical structure and surface (land, ice, and ocean) topography	Streaming digitizer, 500-1000 Msamp/s, 6-8 bit resolution with integrated pulse identification and time tagging	Streaming digitizer, 1 Gsamp/s, 10-12 bit resolution with integrated pulse identification and time tagging	Couple a high-speed A/D converter with a high-speed FPGA capable of continuous digitization and real-time return-pulse identification.	N	Return-pulse digitization is a proven technique for precise altimetry especially in the presence of vegetation. High pulse rates are required to achieve wide data swaths. Real-time return-pulse identification is required to sustain the high rep-rate data collection.	3	2
	Direct Detection Optical Autocovariance Lidar	355 or 532 nm (direct)	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit	N/A	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	N	Real time processing enables faster data availability for Numerical Weather Prediction. Virtex5 FPGA demonstrations in space enable this tech.	3	2
	Photon-counting laser altimeter	532 nm	Single-photon range images across a 300-m swath	100 channel, 0.5 ns resolution, multi-stop digital timing device; 20 Mcount/sec capability			N			
	Hybrid Doppler Lidar	2 micron (coherent) channel	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit	5 element array 2 micron detector, QE > 80%, BW > 200MHz	5 element array 2 micron detector, QE > 80%, BW > 200MHz	Develop and demonstrate detectors On-orbit pointing knowledge subsystem. Demonstrated at 1 micron (routed pick off of laser to star tracker + INS); needs to be demonstrated at 2 micron. Needs high-efficiency, high-sensitivity SWIR star tracker, high temp (TEC or room temp.)	Y	5-element detectors at 2 microns will improve alignment maintenance options 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.	2	4

Technology	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need	Emerging Technology (Y/N)	Comments	TRL @ Start	Development Period to TRL 6 (years)
Detectors (Including Arrays) and Amplifiers	CO2 DIAL	1.57 and 2-micron	Range resolved CO2 mixing ratio in lower troposphere and aerosol distributions	High efficiency (QE 50% or better), low noise (2e-15 W/Sq.rt.Hz) detector.			N			
	IPDA LAS for CO2	1.571 and 2.051 microns	Radiation tolerant 2 micron heterodyne detector	Radiation tolerant, >1 mm^2 area, heterodyne detector for 2 micron wavelength		Linear mode arrays at 2 microns	N			
	Atmospheric profilers	1064/532/1550 nm	Gas and particulate profiles		Photon counting arrays, 256x256 with nanosecond time resolutions and full waveform capability ROICs.	1064/532 nm: APD based. UV/Vis: Microchannel plate, electronic-multiplying CCD. High sensitivity, rad, hard	N	New requirement. Spatial coverage and cloud loss are two major limitations of lidars. Moving towards multi-beam adaptive lidars helps reduce these limitations. Have flown in space in some configurations already (ORION/STORRM mission). Higher sensitivity versions with full waveform capability demonstrated on aircraft but need path to space. Requires both detector array plus ROIC development.	4	3
	Interferometer	1550 nm	Laser ranging for spacecraft gravity sensing	N/A	Sub-ps receiver, few-photon sensitive	Correlation receiver for frequency combs	Y			
	Laser altimeter	1-micron	Wide-swath (i.e., 10 km) 3-dimensional measures of vegetation vertical structure and surface (land, ice, and ocean) topography		High-efficiency (>50%), high-bandwidth (150 MHz), low-timing jitter (<100 ps) arrays with high count rates (>100 Mcps).		N	Full waveform analog LM Si APD (GEDI)		
	Photon-counting laser altimeter	1-micron			High-efficiency (>50%), high-bandwidth (1 GHz), low-timing jitter (<100 ps) arrays with high count rates (>100 Mcps).	Low-cost photon counting arrays	N	Commercialized in Si and InGaAs arrays. SENSL and async Gm-APD arrays PLI. Resonant cavity silicon APD to improve QE at 1 micron	3	3
	UV DIAL	305-320 nm	Height-resolved measurements of tropospheric ozone along the satellite ground track	PMT with QE > 40% photon counting with internal gain 10^6, dark current <10 cps, single photon sensitivity		Improved PMTs Solid state detectors to replace PMTs for UV systems	N			
	Doppler Lidar, Airborne, Scanning	355 nm (direct)/ 2 micron (coherent)	Measure wind structure in and around storm cells using an airborne Doppler wind lidar	1. 5 element array 2 micron detector QE> 80%, BW > 200MHz 2. single element or array UV detectors and detection electronics with single photon counting sensitivity, QE > 50 %, NEP < 2 e-15 W/SqRt Hz, active area >2 mm^^{2}	1. 5 element array 2 micron detector QE> 80%, BW > 200MHz 2. single element or array UV detectors and detection electronics with single photon counting sensitivity, QE> 50 %, NEP< 2 e-15 W/SqRt Hz , active area > 2 mm^2	Develop and demonstrate detectors	Y	355-nm detector QE improvement permits relaxation of laser and optics requirements; 5-element detectors at 2 microns will improve alignment maintenance options	2	2
	Direct Detection Lidar	355 nm or 532 nm direct	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit		Increased Dynamic Range for lidar detection (photon counting through analog)	Space qualification of multi-pixel photon counting detectors for increased dynamic range	N	Increased dynamic range permits relaxation of detector and detector electronics requirements	3	3
	Hybrid Doppler Lidar	355 or 532 nm direct	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit	Single element or array UV detectors and detection electronics with single photon counting sensitivity, QE > 50 %, dark counts < 1 kct/s , active area >2 mm^^{2}	1. Single element or array UV detectors and detection electronics with single photon counting sensitivity, QE > 50 %, dark counts <1 kct/s , active area >2 mm^2 2. Single element or array 532-nm detectors and detection electronics with single photon counting sensitivity, QE > 70 %, dark counts <1 kct/s , active area >2 mm^2	Develop and demonstrate detectors	Y	355-nm detector QE improvement permits relaxation of laser and optics requirements	2	4
	Hybrid Doppler Lidar	355 or 532 nm direct	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit	Single element or array UV detectors and detection electronics with single photon counting sensitivity, QE > 50 %, dark counts <1 kct/s , active area >2 mm^^{2}	1. Single element or array UV detectors and detection electronics with single photon counting sensitivity, QE > 50 %, dark counts < 1 kct/s , active area >2 mm^2 2. Single element or array 532-nm detectors and detection electronics with single photon counting sensitivity, QE > 70 %, dark counts <1 kct/s , active area >2 mm^2	Develop and demonstrate detectors	N	532-nm detector QE improvement permits relaxation of laser and optics requirements	3	3
	HSRL/Ocean Profiling	355/450/532 nm	Detector for atmosphere and ocean profiling of aerosols, clouds, and ocean		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, U.S. manufacturer Gain 10^5-10^6	Newly emerging detector architecture/material. Development of capability within U.S. would enhance speed of technology development.	Y	Low afterpulsing, short holdoff times needed to reject specular reflection from ocean surface MCP detectors are possible solution. No U.S. vendor who can do one-off, high performance detectors (e.g., integrating SOA MCP into detector package). Cannot work with foreign vendors due to MCTL/export control/ITAR. Need to develop and mature U.S. industrial base in detectors for lidar applications.	1?	3-10
	Direct Sea Ice Thickness Lidar	530-550 nm	Direct measurement of sea ice thickness from space	High QE > 60% single photon counting detector array			Y		2	4

Technology	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need	Emerging Technology (Y/N)	Comments	TRL @ Start	Development Period to TRL 6 (years)
	Photon-counting laser altimeter	532 nm	Single-photon range images across a 300-m swath		High-efficiency (>50%), high-bandwidth (1 GHz), low-timing jitter (<100 ps) arrays with high count rates (>100 Mcps).	Low-cost photon counting arrays	N		3	3
	Space Based Trace Gas DIAL	720-940, 1650 nm	Water vapor profiling/methane profiling (airborne) and column (space)		High quantum efficiency (>80%), low dark current (<0.5 nA), low excess noise (<1.5), high gain > 500, 0.5-5 mm aperture, short working distance (distance between window and detector <3 mm), low power consumption (<5 W including cooler)	Develop and demonstrate detector for water vapor and methane DIAL applications.	N	HgCdTe detector shows promise, but biggest constraint is working distance between window and detector chip. This limitation is primarily due to the geometry of the cold filter due to detector response in IR portion of spectrum. Stitching HgCdTe pixels greatly reduces digitizer complexity Improve cryocooler performance or move to TEC-cooled designs.	4	2-5
	IPDA LAS for CO2, methane, water, O2	760-3200 nm	Column integrated gas density and range (and profiles if available)		Linear mode HgCdTe APD with ROIC, > 10 MHz bandwidth, QE > 75%, DCR < 200 kHz, active area >400 microns, radiation hardness in LEO	Desirable to raise temperature to >80 K, larger array sizes				
	CO2 and CH4 DIAL	For CO2 (1.5711 μm), For O2 (0.76 or 1.27) μm.	Column measurements of CO2, surface elevation and aerosol and cloud distributions.	1.57-micron photon counting detector, QE > 10%, dark counts < 1.0 KHz, lifetime > 3 years, active diameter > 2 mm, operating temp > -50 C, max count rate >20 M counts/s						
			Cryocooler for 80-K HgCdTe arrays	N/A	Low vibration, low power, low size. Improve vibration and power and extend space lifetime of tactical cryocoolers		N		5	3
Large Effective Area, Lightweight Telescopes (Including stray light control)	Ocean Particle and Aerosol Lidar	1064, 532nm	Aerosol heights, phytoplankton carbon, particulate organic and inorganic carbon (POC & PIC), suspended sediments	1.2-1.5 m diameter/ ~60-150 mrad FOV		Develop a 1-1.5 m diameter lightweight telescope	N		3	2
	High Spectral Resolution Lidar (HSRL) for aerosol characterization	1-micron	3-D measurement of aerosol microphysical properties, absorption and abundance	1.5-m segmented or deployable telescope		1) Develop a 1.5-m diameter telescope with deployable mechanisms and validate as part of a lidar ground-based system. 2) Space-based demonstation	Y	ESTO has funded work to model a deployable telescope. A single petal including the latch and hinge mechanisms are being characterized for mechanical stability	2	4
	Laser altimeter	1-micron	Narrow swath profiles of 3-dimensional structure of land and vegetation	1.5 m telescope, 4 microrad blur circle						
	Laser altimeter	1-micron	Wide-swath (i.e., 10 km) 3-dimensional measures of vegetation vertical structure and surface (land, ice, and ocean) topography	1.5-2m telescope, 20 microrad blur circle		Develop, light-weighted, 2 m diameter, thermally-stable, diffraction-limited telescope.	N	Large aperture (1.5- 2 m) required to meet signal-to-noise requirements of system.	4	3
	Photon-counting laser altimeter	1-micron	Single-photon range images across a 300-m swath	1 - 1.5 m diameter, < 10 microrad blur circle						
	IPDA LAS for CO2	2.051 microns	Lightweight 0.5 m telescope operating at 2 microns	0.5 m diffraction limited @ 2 microns beam expander						
	HSRL and DIAL	200-2000 nm	High efficiency telescope for aerosol/cloud/ocean/trace gas profiling lidar		2-5 m 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	Novel telescope design/material to enable large area collection aperture to reduce required laser energy.	Y	Large area telescope reduces requirements in other areas (e.g., reduced laser power). Trade studies needed including faring sizes and deployable architectures.	1	3-10
	CO2 DIAL	2-micron	Range resolved CO2 mixing ratio in lower troposphere and aerosol distributions	3 m diameter/ ~100 mrad FOV, areal density, <25 kg/m^2		1) Develop a 3-m diameter telescope with deployable mechanisms and validate as part of a lidar ground-based system. 2) Space-based demonstation	Y	ESTO has funded work to model a deployable telescope. A single petal including the latch and hinge mechanisms are being characterized for mechanical stability	2	4
	Direct Detection Doppler Wind Lidar, HSRL	355 nm or 532 nm direct	Reduce SWAP of Doppler wind lidar systems to enable smaller spacecraft	N/A	Light weight deployable telescopes (>1-m diameter)	Reduce telescope cost and mass while maintaining collection aperture	Y	Reduced mass telescopes can provide low-cost approach to multiple lines-of-sight for Doppler wind measurements	2	4
	Direct Sea Ice Thickness Lidar	530-550 nm	Direct measurement of sea ice thickness from space	>1-m diameter receive telescope. Transmit <2.5 microrad collimated beam or focus laser to 1-m spot on ice surface		Develop transmitter optics capable of producing 1-m spot on ice	Y	Transmitted laser spot on the ice must have size comparable to sea ice thickness, ~1 m	1	4
	Photon-counting laser altimeter	532 nm	Single-photon range images across a 300-m swath	1 m diameter, 1 microrad blur circle (to minmize crosstalk between adjacent pixels)						
	IR-DIAL Temperature and Water Vapor DIAL	760-940 nm	Range resolved measurements of water vapor and temperature including aerosol and cloud distributions.	3-m diameter deployable, ~100 mrad FOV, areal density <25 kg/m^2		1) Develop a 3-m diameter telescope with deployable mechanisms and validate as part of a lidar ground-based system. 2) Space-based demonstration	Y	ESTO has funded work to model a deployable telescope. A single petal including the latch and hinge mechanisms are being characterized for mechanical stability	2	4

Technology	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need	Emerging Technology (Y/N)	Comments	TRL @ Start	Development Period to TRL 6 (years)
	Ozone DIAL	DIAL technique, 1st wavelegth 305-308nm, 2nd wavelength 315-320nm. Must have a difference of 10 nm between wavelengths	Range resolved measurements of ozone including aerosol and cloud distributions	3 m diameter/ 0.3 mrad FOV, areal density <25 kg/m^2		1) Develop a 3-m diameter telescope with deployable mechanisms and validate as part of a lidar ground-based system. 2) Space-based demonstration	Y	ESTO has funded work to model a deployable telescope. A single petal including the latch and hinge mechanisms are being characterized for mechanical stability	2	4
	Fluorescence Lidar	Laser: 532 nm (Optional: 355 and 532 nm, TBD) Detector: 520-800 nm (Optional: 370-800 nm, TBD)	Measure water Raman, fluorescence and algal pigments	2-3 m (TBD) diameter/ ~200-300 mrad FOV, areal density: <25 kg/m^2		Develop a 2-3 m diameter lightweight telescope with deployable mechanism	Y	The telescope diameter should be determined on the basis of the trade-off analysis in conjuction with the laser trasmitter selection for the FLAPS sensor	2	4
Narrowband Optical Filters	IPDA LiDAR	1.57, 1.64, 2.05 micron				Stable, flat top filters to reduce filter distortion. Improves SNR by 2x during daytime measurements	N			
	High Spectral Resolution Lidar (HSRL) for aerosol characterization	1-micron	3-D measurement of aerosol microphysical properties, absorbtion and abundance	Bandpass daylight rejection etalon filter: <50 pm FWHM, T>70%			N			
	CO2 DIAL	2.05 micron	Range resolved CO2 mixing ratio in lower troposphere and aerosol distributions	200 pm, 60% transmission			N			
	Aerosol lidar	355/532/1064 nm	Spectrally resolved lidar return		0.1-1 m OPDs.	Athermal field-widened interferometers.	N	Broadly applicable for both linear and nonlinear types of laser scattering.	4	3
	Direct Sea Ice Thickness Lidar	530-550 nm	Direct measurement of sea ice thickness from space	200 pm, 60% transmission, wide acceptance angle (>10 deg) for mutliple off-axis FOV		Develop and demonstrate filters with narrow bandwidth and uniform spectral response over wide input angles	Y	Narrow bandwith required for background rejection. Wide acceptance angle needed to capture multiple off-axis beams required to sample multiple scattering.	2	4
	Water vapor DIAL	700-1000 nm	Range resolved water vapor profile measurement		High transmission (>80%), fast temporal respons (<100 microsec), <10-20 pm optical bandpass, large free spectral range (>100-300 pm), high contrast ratio (> 100/ contrast ratio), etendue >50 mm-mrad	Develop and demonstrate tunable interferometric filter for implementation in high PRF multi-wavelength DIAL systems operating in the VIS-NIR (500-1000 nm) spectral band.	Y	Narrow band and frequency agile filter will increase SNR for mulit-wavelength DIAL insruments with DIAL pairs spaced >50 pm, and potentially reduce requirments in other areas (e.g., transmitted laser power) Also for CO2 and greenhouse gas measurements, although benefit may be less than in the vis-NIR application space. No need for polarization. Depol channel would be upstream of this filter if doing cloud/aerosol depol	1	
	CO2 DIAL	For CO2 (1.5711 µm), For O2 (0.76 or 1.27) µm.	Column measurements of CO2, surface elevation and aerosol and cloud distributions.							
	Aerosol lidar	UV-1064 nm	Improved background rejection filters with high transmission.				Y	Metamaterials for new surface and filter techniques, including higher damage thresholds, contamination insensitivity. Volume Bragg gratings are an aternative at ~10 pm with large angular acceptance	2	5
	Direct Detection Wind Lidar, HSRL	355 or 532 nm direct	Measure tropospheric winds with 2D vector component using a direct detection Doppler wind lidar in low Earth orbit		Increase interferometer (e.g., Fabry-Perot or Quadrature Mach-Zehnder) to > 10 mrad to support large telescopes. 1-m telescope diameter with 200 microrad FOV scaled to a 2-cm receiver beam results in a 10-mrad FOV receiver requirement.	Larger telescopes allow use of less laser power, but increase the required receiver FOV for a given interferometer aperture. Additional increases to telescope FOV reduce alignment/overlap requirements, but flow into receiver requirements.	N	Current OAWL interferometer FOV is ~5 mrad. New build will likely be larger	3	3
	HSRL/Ocean Profiling	355/450/532	Optical element (bandpass seperation and filtering) for atmosphere and ocean profiling of aerosols, clouds, and ocean		GHz resolution or less, Mie transmission ratio of >100:1, goal of 1000:1 to support HSRL measurement in clouds			Have demonstrated 25:1-50:1 with Michelson design. Wavefront error limits contrast		
Optical High Resolution Spectral Analyzers	Fluorescence Lidar	Laser: 532 nm (Optional: 355 and 532 nm, TBD) Detector: 520-800 nm (Optional: 370-800 nm, TBD)	High-resolution measurments of laser-stimulated emission (LSE) from the upper ocean layer	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 exceeds the listed requirements	Y	Although there are commercial prototypes, none meet the specified quantitative requirements and is a space-qualified product. This development is enabling for the FLAPS measurement scenario	2	3
	High Spectral Resolution Lidar (HSRL) for aerosol characterization	Transmitter 1-micron; receiver 355 and 532 nm	3-D measurement of aerosol microphysical properties, absorption and abundance	Resolution of 1-GHz FWHH over range of 20GHz centered at laser wavelength of either 355 or 532 nm; etendue >100 mm-mrad; transmission >70% +/-0.1%/hr; freq drift <1 MHz/hr						
Photonic Integrated Circuits	Lidar/lasercom/constellations	1 - 2 micron	Low SWAP optical receive technologies, filters, modulators, etx	N/A	Identify new ways to dramatically decrease the SWAP of lidar technologies to enable SmallSat lidar concepts		Y	Lasercom components should be utilized beyond lasers/amplifiers.	2	5
	Laser altimeter	1-micron	Wide-swath (i.e., 10 km) 3-D measures of vegetation vertical structure and surface (land, ice, and ocean) topography	Addressable FOV across 1 - 2 degrees		Develop solid-state approach of selecting individual fields-of-view at high switching rates.	N	Benchtop fiber array for FOV selection demonstrated	4	2

Technology	Instrument Type	Operating Wavelength	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need	Emerging Technology (Y/N)	Comments	TRL @ Start	Development Period to TRL 6 (years)
Scanning Systems	Hybrid Doppler Lidar	355 nm (direct) channel	Measure tropospheric winds with 2D vector component using a hybrid Doppler wind lidar in low Earth orbit	30-45 deg nadir angle, 0.75-m diam., <50 microrad blur circle conical step-stare scanning telescope		Develop >75 cm holographic or diffractive optic telescope and step stare rotating mechanism including momentum compensation.	N	LOS winds from multiple azimuth angles are required to determine horizontal wind field. HOE/DOE technology allows simplified combination of telescope and scanning function in one optical element. Improved efficiency of holographic and diffractive elements. Commonly used now in beam splitting.	3	4
	Direct Detection Lidar	355 or 532 nm direct	Measure tropospheric winds with 2D vector component using a direct detection Doppler wind lidar in low Earth orbit	30 deg nadir angle wide field of view telescope designs		Single telescope capable of supporting multiple look angles (may be achieved via optical design, HOE, etc.)				
	Photon-counting laser altimeter	532 nm	Single-photon range images across a 300 m swath	Simultaneous scanning of transmitted laser beam and receiver FOV (with phasing to compensate for forward velocity and nadir-maintaining pitching)						
	IR-DIAL Temperature and Water Vapor DIAL	760-940 nm	Range resolved measurements of water vapor and temperature including aerosol and cloud distributions.	Nadir angle +/- 10 degrees continuous cross track		Determine performance requirements for DIAL transmitter/reciever scanner system. Using requirements, leverage existing technology to develop airborne version for demonstration	N		3	2
	Any scanning lidar					Non-mechanical large aperture (> 25 cm) beam steering and receiver pointing devices.	N	Many lidar applications require measurements at multiple laser beam look angles or require measurements at specific look angle on command. These applications include 3-D winds, surface profiling, and atmospheric molecular trace gas measurements. +/- 30 deg angular scan, effic. > 90%	3	5
Specialty Optics: High Transmission Optics, Fibers, Polarization Control, Wavefront Phase Control (Mode Matching)	IPDA LAS for CO2	2.051 microns	Radiation resistant efficient 2 micron transmitting fibers	Polarization maintaining, radiation tolerant 2 micron single mode fiber with transmission efficiency >95%/m						
	Direct Detection Doppler Wind Lidar, HSRL	355 or 532 nm direct	Reduce size, weight, and power (SWAP) of Doppler wind lidar systems to enable smaller spacecraft	N/A	Fiber couplers and fiber optics with high performance at 355 and 532 nm, rad hardened		N		3	3
	Direct Sea Ice Thickness Lidar	530-550 nm	Direct measurement of sea ice thickness from space	Optical fiber bundles to convey photons from telescope focal plane to an array of single photon counting detectors. The concentric fiber bundle annuli increase outward to keep the signal strength sufficient for multiple fields-of-view		1. Develop fiber bundles with high transmission and coupling efficiency at 530 nm. 2. Efficient close packed bundles of concentric rings coupled to photon counting detectors.	Y	Multiple FOV fiber bundles with high efficiency at 532 and 1064 nm have been demonstrated on MLA and LOLA Is this technology still needed or available from other systems? Need may have been met with demonstrated developments in holographic optical elements.	2	4
	Fluorescence Lidar	Laser: 532 nm (Optional: 355 and 532 nm) Detector: 520-800 nm (Optional: 370-800 nm)	Narrow-band notch filter to reduce laser backscatter to levels comparable with fluorescence and Raman components in the laser-stimulated backscatter signal	1-3 nm FWHH or better, D>5, 90% transmission or better in 380-800 nm range		Develop 532 nm notch filter that meets or exceeds the specification	Y	Utilization of the 532 nm notch filter is critical for the FLAPS measurements if the optional 355 nm transmitter wavelength is selected for the LSE excitation along with 532 nm.	2	3

Appendix 3C: Information System Technology Capability Breakdown Matrix

Technology	Lidar TC Capability	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need	Emerging Technology (Y/N)	Comments	TRL at Start	Development Time to TRL 6 (years)
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.	N	This technology isn't emerging, but the capability from having it would be.	3	2
	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	N	This technology isn't emerging, but the capability from having it would be.	3	2
Airborne/Ground lidar validation systems	Technology & systems approach to enable rapid cal/val of lidar data (low-cost in-situ systems, calibration strategy to resolve spatial/temporal co registration).	Technology & system approach to enable rapid validation & calibration of lidar data, integrating data from in situ sensors, H&S sensor parameters, platform ancillary data, etc. May also incorporate small, cheap, efficient in situ lidar system nodes.	Analysis suite of tools to produce calibration and validation strategy with available optimum set of in situ sensors based on time or event requirements.	Extended array or network of ground sites are needed to cal/val airborne or space-based lidar measurements to account for spatiotemporal variability of observed variables.	OSSE based sensor web design environment; develop such a system using existing commodity equipment; leverage fiber laser amplifiers from Telco and other similar systems.	Y	This task provides a simulation based testing and validation capability to optimize science return and to meet timing requirements for wind.	2/3	5
			1. Aerosols (0.1-100 microns). 2. Molecular identification (O3, CO2, Water Vapor). 3. General greenhouse gases plus O2 for mixing ratio.	Better than 0.5 ppm for CO2.	1. Develop commercially-supplied ground-based and/or airborne lidar instruments. Consider leveraging fiber laser amplifiers from Telco. The instruments should consist of Tunable Laser Spectrometer to measure CO2 at <1 ppm and water vapor at <1% and Laser Absorption Spectrometer (LAS) to measure CO2. 2. Establish a capability to calibrate space instruments using ground and/or airborne standard reference equipment.	N	This task provides the scientific basis for the validity of the data obtained from space-based lidar instruments. This task will also allow an intercomparison of data from different instruments produced over time and for the degradation in instrument performance as they age.	3	4
Intelligent sensor health & safety	Technology to enable autonomous monitoring & control of lidar H&S (laser performance/degradation, laser life optimization strategy).	Technologies to enable autonomous monitoring of lidar health and status and a decision tree of actions to take if anomalous conditions are observed.	Instrumentation suite for monitoring H&S 1) lidar temperature drift/gradients, 2) lidar frequency stability, 3) lidar degradation modes including radiation effects, 4) Optical particulate contamination		1) Develop sensors that can be integrated into lidar system for use in predicting lidar health. 2) Develop lidar health software that includes degradation mode models and cost functions for optimizing instrument performance and/or instrument life.	Y	This task provides the knowledge-based approach to increasing lidar life. The current lasers flown in space have a very poor performance lifetime record. One way to extend the operational capabilities of our space assets is to model the degradation mechanisms and then to operate the instruments so as to optimize a characteristic such as instrument life.	2/3	5
			Instrumentation suite to monitor H&S.		develop integrated prototypes based on a common base module that contains the processor/memory/ADC/interface	Y		2/3	5
			Monitor and summarize health and status.		Prototype monitoring and diagnosis software. Parts run onboard and parts on the ground.	N		4	3
			Detect, diagnose and initiate response to fault conditions within minutes response time and accuracy, where a response time can be instrument specific. Of particular importance are lidar-specific faults.		Prototype diagnosis and response software (onboard)	N		4	4
			Prognosis: predict upcoming failures with sufficient lead time and accuracy to minimize impact on mission. Exact requirement depends on system and mission specifications.		Demonstrate diagnosis software (ground or onboard) that meets the performance metrics.	N	Demonstrate performance in the target (flight-like) environment.	3	3
On-board sensor control	Sensor control to enable autonomous data acquisition & support formation flying (precision pointing, fault handling).	Technologies to enable autonomous data acquisition based on a set of defined conditions (e.g., acquire only if cloud free). Supports formation flying, sensor web scenarios.	precision pointing (0.25 degree or 4 mrad accuracy); Power from the electrical power subsystem is supplied to the IPDA system. Key driver on power consumption is the thermal control system for cooling the lasers and diode pumps. (3-4kw avg)		Based on engineering data and attitude information, develop a control architecture to meet specific goals for optimum operations.	N		3	4
			Localize detected events with accuracy equal to pointing accuracy.		Prototype event localization software; assumes spacecraft localization system (see above).	N	Localization of detected events must exceed pointing accuracy to enable detected target to be sensed on later pass.	3	3
			Detect, diagnose, and respond to errors in the control system, cooling, etc. with sufficient speed to maintain pointing accuracy.		Prototype diagnosis and response software as a component of the control system.	N	Goal based control system is desired.	4	5
			Detect events with sufficient speed and accuracy for specified science event triggers (e.g., cloud detection).		Prototype lidar-specific event detectors. These are often compute-intensive. Task may include hardware implementations or onboard science co-processors to meet speed & accuracy reqt's.	N	Onboard event detection is in regular use on ASE.	4	2
Spacecraft area network	Inter-spacecraft level network (spacecraft area network) standards.	Technologies needed to interconnect sensors on multiple spacecraft or in situ platforms to support rapid sharing of status and control data (e.g., comm. protocols). Supports formation flying, sensor web scenarios.	1. Determine Data Volume, Data Rate, and Transmitter Bandwidth. 2. Use Packetizing Standards e.g. CCSDS, CFDP. 3. Use Bus Protocols, e.g., MIL-STD-1553B, LVDS, RS-422, etc.		Develop new architecture and implement a generic design. Current technology does not allow interaction between instruments. In the future instruments should share information.	N	Need proof of concept and demo of the prototype. May be able to get funding from future projects.	3	2
			1. Ranging measurement noise <100 pm rms.		1a. Develop space-qualified single-mode 30 mW laser.	N	1a. Cost of US EM ~$3M. N/ASA/SIM project will probably fund development.	3	2
					2a. Develop space-qualified laser frequency reference, including required fiber injection and electro-optic modulator.	N	2a(i). Need cavity with extreme dimensional stability yet survive launch vibration.	3	2

Technology	Lidar TC Capability	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need	Emerging Technology (Y/N)	Comments	TRL at Start	Development Time to TRL 6 (years)
Formation flying	Metrology & control.	Technologies to enable satellite to satellite communications (e.g., transmitters/receivers, comm architectures). Supports scenarios such as a cloud detection sensor flying in advance of lidar satellite. Precision pointing of lasers between spacecraft to reduce laser power and thus increase laser lifetime. Precision range between spacecraft.	2. Laser frequency stabilization, Allan deviation 1E-13.			N	2a(ii). EOM needed to compare laser frequency to cavity.	3	2
						N	2a(iii). Need fibers and fiber positioners to intact light to cavity while withstanding launch vibration and radiation environment.	3	1
			3. Acceleration noise on the spacecraft <1e-14 m/s/s rms. 3a. Test mass position readout <10 nm rms. 3b. Thruster, drag compensation, 2-5 mN, 0.005 mN rms. 3c. Thruster, position control, 0.005-0.050 mN, 0.0001 mN rms.		3a. Develop test mass and position sensor.	N	3a. cost of developing U.S. supplier estimated to be ~$30M, based on RFI response fro N/ASA/LISA project.	6	3
					3b. Develop diagnostics for noise measurement and extend life of 5 mN Hall or Xe-ion engine.	N	3b(i). Noise of thruster that counters high drag force has never been used in drag-free control loop.	3	1
						N	3b(ii). In two-stage propulsion system, noise in main thruster needs to be measured so that smaller thruster can be commanded to compensate.	4	1
						N	3b(iii). Hall engines have only be validated to ~60 days of operation compared with 5 year lifetime needed; alternative may be new development of small Xe-ion engine.	3	3
					3c. Develop extended life of precision low-thrust electric propulsion system.	N	3c(i). Micro-newton thrusters with 90 day life developed for N/ASA/ST7 project; 5 year life needed.	3	2
			4. Data simulation software/hardware to solve for gravity field to degree and order 300.		4. Develop software and hardware for inversion of 200,000 by 200,000 matrix for gravity field estimation.	N/A	4a. Inversion of matrix is needed to optimizing mission design; currently exceeds file handling capability.	N/A (not for flight)	1
						N/A	4b. Inversion of matrix is needed to optimizing mission design; currently exceeds takes ~10 days on Beowulf cluster.	N/A (not for flight)	2
On-board near Real-Time data processing	Technology & programming tools (pattern recognition, event detection, on-board calibration) to enable real-time processing (reconfigurable, parallel techniques) for cal/val, event detection.	Technologies to allow reconfigurable processing of Level 1 or Level 2 data from calibrated lidar data. May address associated SW programming tools.	Fully automated retrieval of water vapor profiles with: (a) Range resolution 500 m or better. (b) Water vapor uncertainty 10% or less. (c) CO2 and CH4.		Development of an integrated, parallel-processing algorithm suite implementing all numerical methods required for DIAL retrieval: 1. Background subtraction; 2. Horizontal and vertical averaging; 3. Numerical differentiation; 4. RT deconvolution; 5. On-board storage space.	N	Water vapor profiles required within 3 hours of measurement for effective use in weather forecasting models; all specs derived from the CAPES white paper from the NRC decadal study.	4	3
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.		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.	N	Simulation environment will help determine optimal configuration of future lidar instruments/platforms.	3	5
Space-qualified TB storage HW	Rad-hardening & space packaging of high volume solid state storage modules to support flight processing.	Technology supporting non-volatile solid state storage of raw sensor data, related telemetry, and possible SW processing tables to support imaging lidar. Also supports near RT data production.	Capacity: 1-10 TB (EoL) Mass: 10 Kg Interfaces: multiple standards (IEEE 1355, SCSI, PCI, etc.) Data rate: support ~100 Mbps Power: < 100W Reliability: 0.98 (5 year mission time, cold redundant controller and power supply) Bit error rate: ~ 2 x 10-12 (EOL) Temp. Range: -40 to +80 degC Includes EDAC - Error Detection And Correction	See QR for GHG	Develop SQ versions of high speed flash memory (non-volatile) leveraging commercial development; key challenge is to scale up storage volume while keeping size (volume) and power low.	N	This refers to non-volatile solid state storage systems for use on-board the spacecraft. It will allow for mass storage of large quantities of sensor and related telemetry data. Current flash memory technology (e.g., USB flash drives) are available for space at low storage volume and high power. The commercial marked is being driven to large storage volume (~10 GB) with roughly constant form factor and power.	4	4
Space-qualified HPC HW & programming tools	Rad-hardening & space packaging of flight computers & chip programming tools to support flight processing.	Technology supporting on-board HW processing requirements (CPUs, DSP boards, FPGA) to support intelligent sensor monitoring & control and near RT data production. This area addresses the need for very high performance computing in space. The needs are for multi-core CPUs and high performance FPGAs. This also involves the develop of the processor and memory chips required for on-board data processing.	3 year mission lifetime.		DEVICES TECHNOLOGY: radiation hardened at deep-submicron microelectronic technology (0.25, 0.18, 0.15 and 0.09 micron process technology) and microelectronic design tools for ultra low power ICs, MEMS, ASICs, Gate Arrays, FPGAs, SOCs, DSPs, Microprocessors, Memory (NVRAM, SRAM, SDRAM), using SiGe, InP, InAs, SOI, CMOS processes.	Y	Current radiation hardened technology is at 0.35 and 0.25 microns, usually 2 or 3 generations behind commercial technology. Large government investment is needed to satisfy its future high processing needs. As devices ever get denser and tightly integrated (e.g., system on a chip), innovative advanced radiation hardened technology is highly sought. It is also possible to leapfrog the currently acceptable technology in the commercial world, and try to propose something entirely novel. To ensure uninterrupted data stream for continuous scientific observation and modeling, the High-Performance RHP should constantly process data during the minimum mission lifetime, usually of three years, with graceful degradation thereafter.	2	5

Technology	Lidar TC Capability	Needed Functional Product	Quantitative Requirement (2006)	Quantitative Requirement (Updated)	Technology Need	Emerging Technology (Y/N)	Comments	TRL at Start	Development Time to TRL 6 (years)
Large Volume Data Downlink	Laser communication system for high data transfer rate.	Technology for low mass, power and volume laser comm terminal in orbit and autonomously operating ground terminals.			Prototype in orbit and ground terminals adapting technologies developed for geo-sync Laser Comm Demonstration Mission.	N	>5-Gbps bidirectional LEO-to-ground rate has been demonstrated by NFIRE mission.	8	N/A
Pointing & Tracking		Pointing and/or stability requirements budget for LOS wind speed estimation errors.		Provide quantitative understanding of the effects of pointing (controlled or uncontrolled), platform motion (orbital dynamics), and vibration (uncontrolled) on Doppler wind lidar LOS velocity estimates. Flow these requirements into mission (pointing control, tracking requirements) and instrument design. Results will be different for coherent or direct detection systems.		N/A		N/A	N/A
Real-Time wind profiles		Realtime LOS wind speed estimation including platform motion and bias removal to reduce data latency for Numerical Weather Prediction.		FPGA-based real-time on-board processing of LOS wind speeds.		N		4	1
Mission Error Budgets		Full error budget for Doppler Wind lidar mission (including pointing, optics, electronics, downlinks, etc.).		Error budget down to subsystem levels (optical transmission, detector QE/Noise, background filtering, mixing efficiency/fringe contrast, etc.)		N/A	Few error budgets have been provided for DWL missions.	N/A	N/A
Observation System Simulation Experiments		Study trades between LOS wind speed precision and coverage (e.g. multiple lines of sight) to inform technologists for mission cost/benefit analysis		Use OSSEs to inform technology development. Requires new Nature runs.		N/A	New nature run is always needed - possible to do studies with a single run?	N/A	N/A
Model lidar data resampling techniques	Algorithms and software to resample lidar data to model grids and other assimilation tools.	Techniques to address lidar data ingest and assimilation issues (e.g., algorithms to enable rapid resampling of data to various model grid specifications).	Terrestrial use much less time critical – resample only if data production exceeds I/O rate or capacity storage and processing of high resolution (25m) measurements with annual updates and releases: 1. Ingest rate (t). 2. Computation (order) to produce Level 3 georeferencing. 3. Information loss.		1. Model use will require Level 3 (domain georeference) reprojection to domain grids (e.g., ice, land, atmosphere). 2. Algorithms sample data from domain grids into parameter fields for models. 3. Methods to measure information loss.	N	1. Model use requires level 3 projections (domain based). 2. Reprojection is costly computationally and often redone. 3. Land processes are slow and can be observed annual so sampling not as big an issue. 4. Keep high res-grids and on-fly resample based on best practices for users.	3	2
Knowledge Discovery	Techniques to enable rapid use of lidar measurements by analysis and decision support applications/systems (near real time, automated, quicklook).	1. First principle forward models (physical model) and machine access to them. 2. Data driven models: model accuracy & robustness, number of training data needed. 3. Weather forecast for air pollution, hurricane in <3 hr.		1a. Sensor model parametric representation of the sensor response. 1b. 3-D photon propagation model atmosphere into canopy/surface and back. 1c. Describe and access models using SensorML. 2a. Training examples: physical measurements of land types and lidar data. 2b. Reinforcement of learning methods to build models.		N	Two approaches: First principle methods will be most accurate but costly to generate. These are helpful for scientists to separate noise and artifacts and use in decision support for accurate and defensible assessments. Photon propagating methods may be a joint or science lead activity. Reinforcement learning methods are easy and rapidly adaptable to new problems but require training data and are built from the data, not physical models. Good for unanticipated uses of the data and for hard to model problems. Assume computational assets are available - some effort to engineer software on systems. Software only efforts in this estimate. Model development is part of sensor development and used in ATBDs. Algorithm development requires adequate sample data availability.	3	2
		Detect events in near real time < 3 hours		Develop algorithms and framework to infuse new modules. Open well-documented Application Programmer's Interface for any system established will allow developers to access data for their algorithms.		N	Algorithm development requires adequate sample data availability.	4	5
Data compression	Data Compression: Lossy and lossless.	Techniques to increase number of measurements with reduced accuracy due to lossy compression but adequate for model inputs (e.g., wind in upper troposphere). Supports near real-time data production.	Compression algorithms 1. Resource usage; algorithm complexity (# of branches), computational complexity (#nested loops), memory footprint (bytes). 2. Performance: % compressed, capability to reproduce summary stats of data [mode, mean, variance, skew, kurtosis, etc.), data loss %, % of outliers. 3. Robustness: across instrument designs, across land cover types (e.g., flat ice to complex terrain with mixed forest), faults and data gaps, on-the-fly re-configurable.		1a. Science programs provide example/simulated cover type lidar data. 1b. Measure computational performance and ability to run algorithms on space qualified types including FPGA. 2. Compress and reproduce data. Conduct cost/performance experiments between lossy and lossless. 3. Experimentation with designs and cost of adaptable methods for reconfigurable compression rates for on-the-fly compression.	N	Science programs must supply engineers and IT researchers with example data from suborbital instruments used in real science missions/ investigations for meaningful experimentation to met reqs. 1-3. Some testbed hardware should be applied to compression algorithms for testing.	5	1
			Lossless		Optimized for height data (vs. image data), Waveforms, photon point clouds.				
			Lossy		Optimized for height data (vs. image data) while preserving necessary science content.				

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Data Management/Service Oriented Architecture	Data Architectures & Frameworks/Data Grid Technology (Storage/Archive, Processing, Dissemination, Standards).	Techniques needed to provide data management of lidar data, including rich metadata descriptions & ontology of both data & resources to enable efficient search, retrieval & processing. Service Oriented Architecture (SOA) enables lidar software community to share algorithms & techniques and leverage web services. Also address real-time requirements for quality of service and fault tolerance for GDS.	Development of large data portals (e.g., EOSDIS, DAACs) with terabyte to petabyte on-line storage and appropriately powerful servers to execute web-based applications.	Data Retrieval Time, Data Processing Time. Development of Cloud-based data portals on commodity infrastructure (Amazon Web Services, Microsoft Cloud, etc.) with hierarchical storage concept of operations (online, near line and offline) based on some pre-determined schema like age of data or processing level (e.g., Level 0-1 stored offline). Definition of Cloud (NIST): On-demand self-service, Broad network access, Resource pooling, Rapid elasticity, Measured service. cloud solutions mandated - http://ocio.os.doc.gov/ITPolicyandPrograms/Policy___Standards/PROD01_009505	Community-based standards for archival / delivery; accepted dataset formats, other standards to enable wide distribution and integration of services (e.g., OGC). Establishment of metadata standards to allow a one-to-many relationship for export formats, including filters to select on desired data and metadata. Metadata catalog needs to be written. Detailed Application Programmer's Interface needs to be written and exposed to users who can write their own tools to access data.	N	Seamless access to various product levels. Higher-level products should be managed under measurement themes as opposed to being categorized by instrument. Data should be accessed via instrument, date, measurement theme, location, etc. Metadata requirements need to be written to allow for that. It is important to stress the ability to separate content from composition (format). This is the purpose of Data Abstraction Libraries. A (small) performance trade-off is made in exchange for being able to write code generically against content without much regard to format. There will always be new point cloud formats. PDAL/GDAL exists based on that assumption. Application drives format.	6+	N/A
	Data/Product Visualization.	2D, 3D, 4D.		JPIP, Greyhound/Entwine Streaming.			Need sample data for algorithm development.		